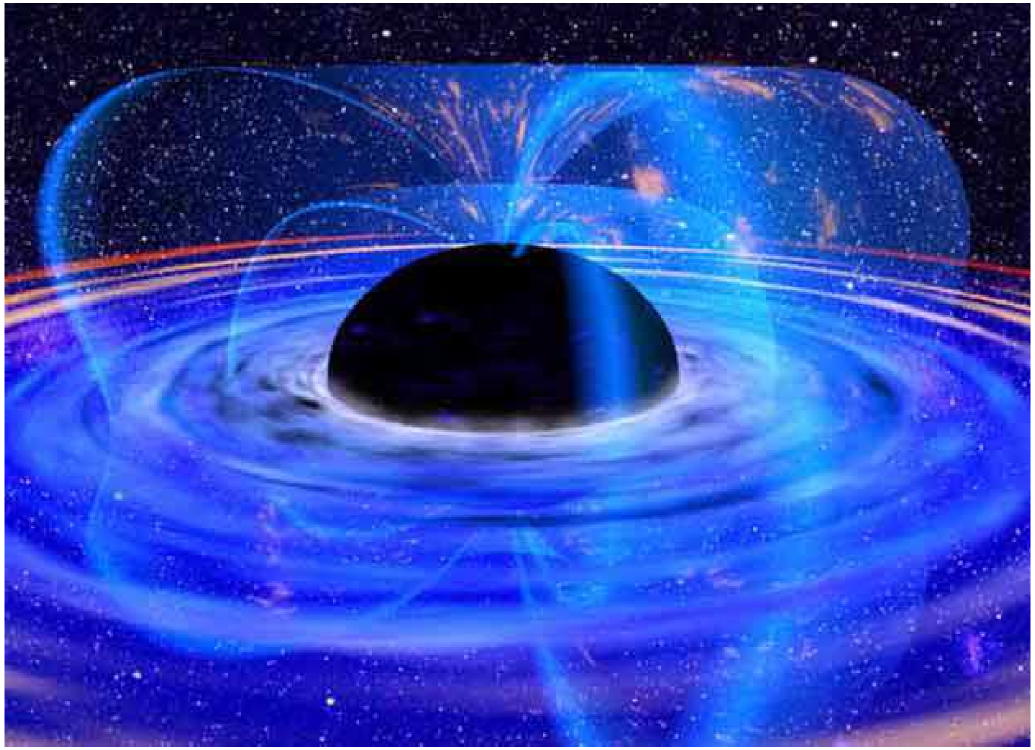
Cosmology, Imaginary Black Holes

and Extra Dimensions



John Wang @USTC-ICTS on March 18 2005

Outline

· Quick Summary of Results

· Standard Model, Cosmology: Comparing Theory versus Experiments

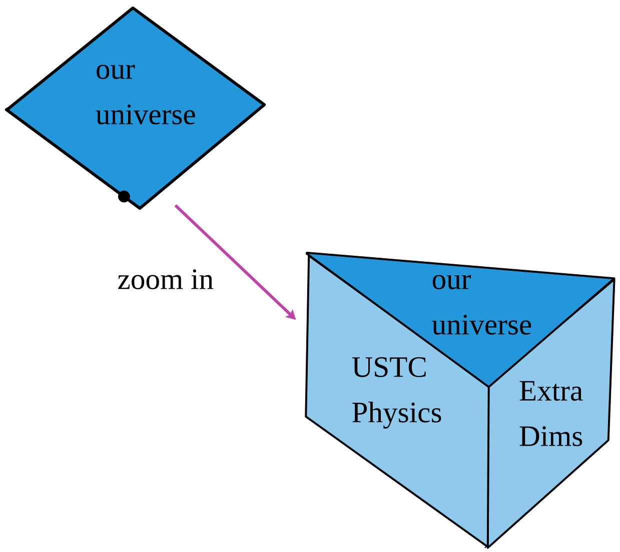
· Extra Dimensions, Imaginary Black Holes and String Formation

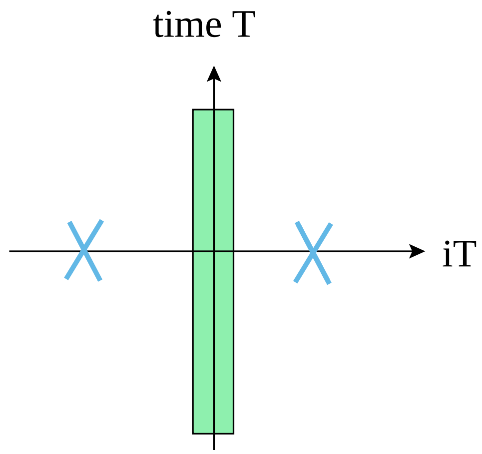
Most relevant references

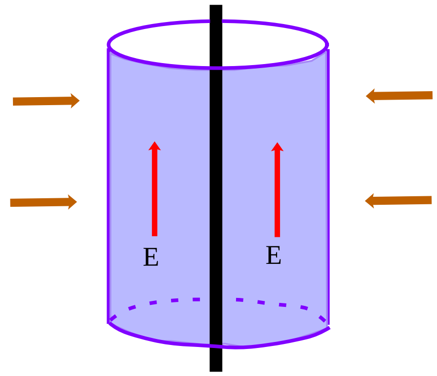
· C-M Chen, P-M Ho, I. Neupane and J. E. Wang, *JHEP*, hep-th/0304177

· G. C. Jones and J. E. Wang, *PRD* hep-th/0409070

· K. Hashimoto, P-M Ho and J. E. Wang, *Phys. Rev. Lett.*, hep-th/0211090

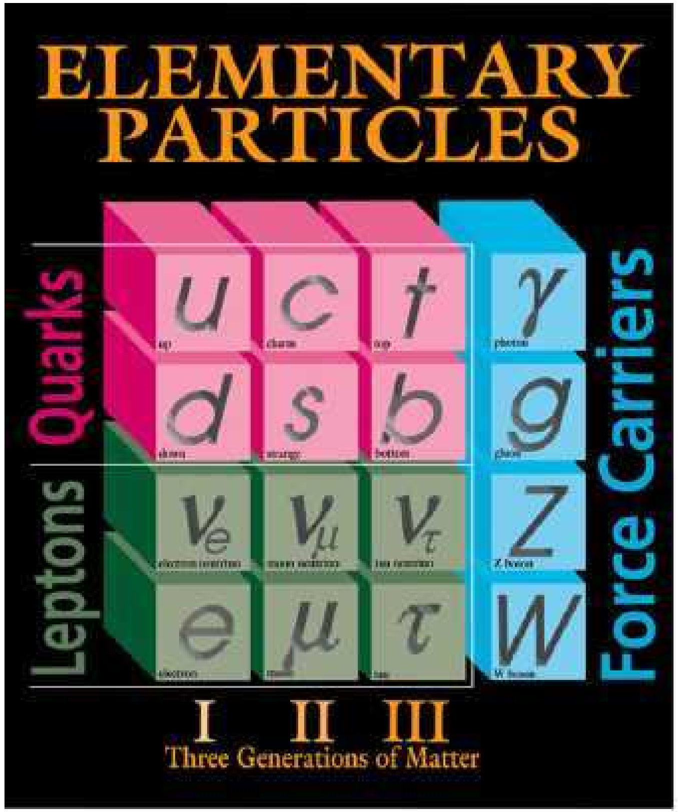






Recent projects include- 1)extra dimensions can drive cosmic acceleration 2) Imaginary black holes are consistent and related to de Sitter space 3)cosmic string nucleation can be smoothly described

In the 1980's and 1990's the growing accumulation of laboratory data supported the now standard model of gauge interactions $SU(3) \times SU(2) \times U(1)$ plus gravity. All observable and testable phenomenon seemed to fit.



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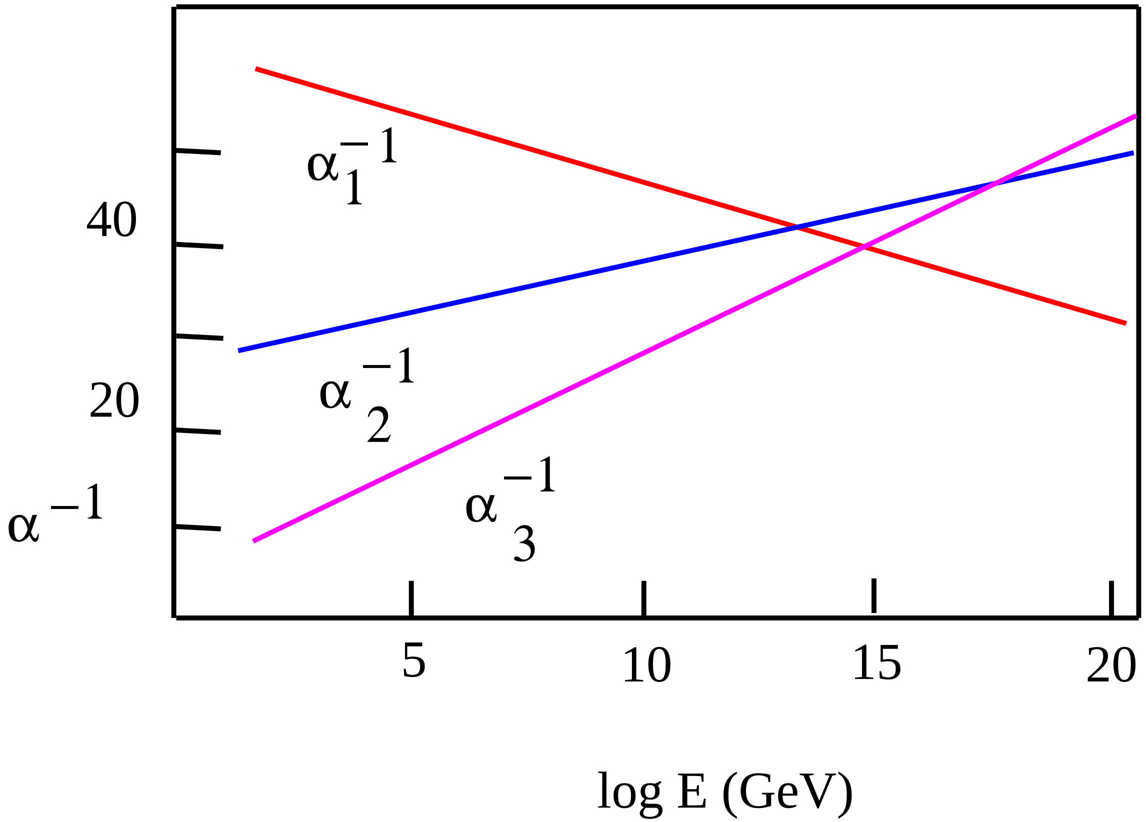
Conceivably the SM would continue to be explain all physics up to at least 10^{13} GeV where the gauge couplings appear to unify. Such new high energy physics related to grand unified theories, superstrings or something else might never be seen.

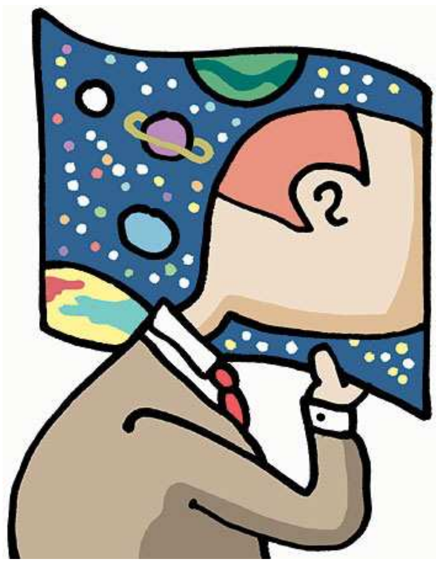


However...

In spite of these successes, there appears to be growing evidence for a potential **REVOLUTION** in physics!

This new mysterious physics has been named dark matter and dark energy.

We can explain earth bound physics in accelerators and laboratories, but understanding cosmological phenomena appears to require a change in our basics concepts of physics!



Recent observation show a surprising acceleration to our universe on the largest scales. Not only is our universe expanding but it is undergoing accelerated expansion! Dark energy is the term used to describe the apparent cosmological acceleration. Cosmologists observe that the stars in our universe are not only moving away from us but doing so at ever increasing speeds!

Gravity is an attractive force and so our expectation is that there must be an energy source to accelerate objects away from each other in our universe.

How then do we explain this dark energy?

Standard Cosmology

To attempt to answer this question let me be more concrete and discuss the status of cosmology and the underlying observational assumptions.

Over large scales covering many galaxies, it appears that our universe is approximately uniform. The density of stars (and planets) is roughly the same everywhere.

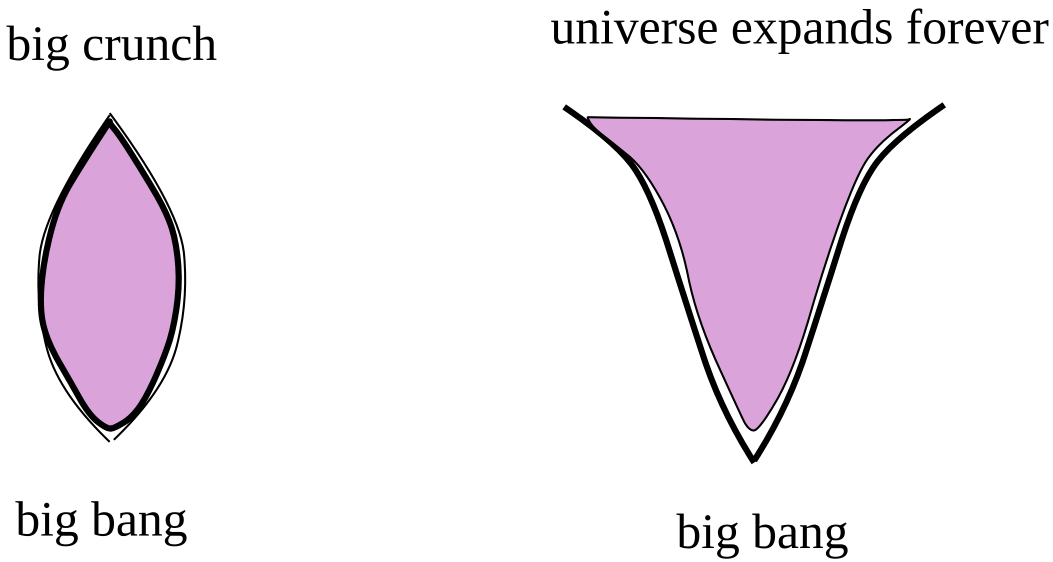
As an approximation let us take our model of the universe to be *exactly* uniform. This is what is called a F(riedman)R(oberston)W(alker) universe specified in Einstein's language by a metric

$$ds^2 = -dt^2 + 1 \times \left[dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right] \tag{1}$$

$$ds^2_{FRW} = -dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right] \tag{2}$$

$$S = \int d^4x \ \mathcal{R} \tag{3}$$

As time passes, the universe expands and has two possible fates. It can either expand at ever slower rates or collapse in a big crunch.



FRW is not our present universe!

Einstein gravity also allows for the addition of what is called a cosmological constant Λ.

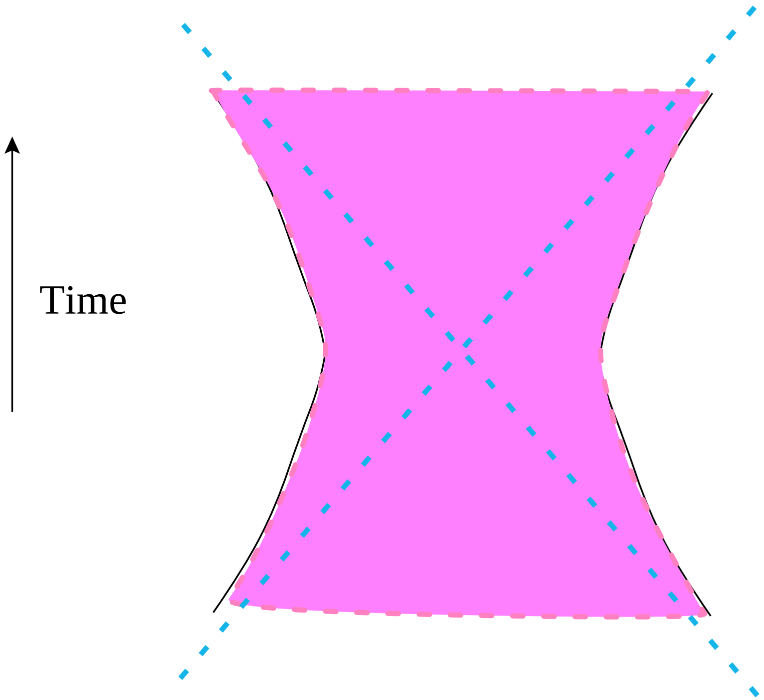
$$S = \int d^4x(\mathcal{R} + \Lambda) \tag{4}$$

This term can be added without spoiling the theoretical consistency of the equations. Physically this term can arise due to the vacuum energy of various fields, ie zero point energy.

A positive cosmological constant causes spacetime to expand, counteracting the usual gravity between masses.

A homogeneous universe with a positive cosmological constant is called de Sitter space

$$ds^2 = -dt^2 + \cosh^2 t \left[d\theta^2 + \sin^2 \theta d\phi^2 + \cos^2 \theta d\psi^2 \right] \quad (5)$$



Recent acceleration observations combined with the apparent uniformity of our universe show our universe is approximately de Sitter.

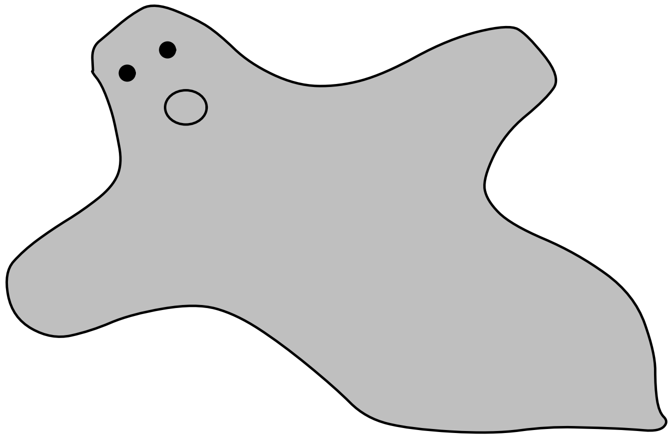
The problem is that our universe's current would be cosmological constant is about $(10^{-3}eV)^4$ which is a very small. How do we explain such a small number when our scales in physics are typically much larger? This is the so called cosmological constant problem.

One suggestion is that the acceleration is not caused by a cosmological constant but by something which only acts similarly to it. Our acceleration might be more easily explained in this manner.

Let us attack these new open problems from cosmology!

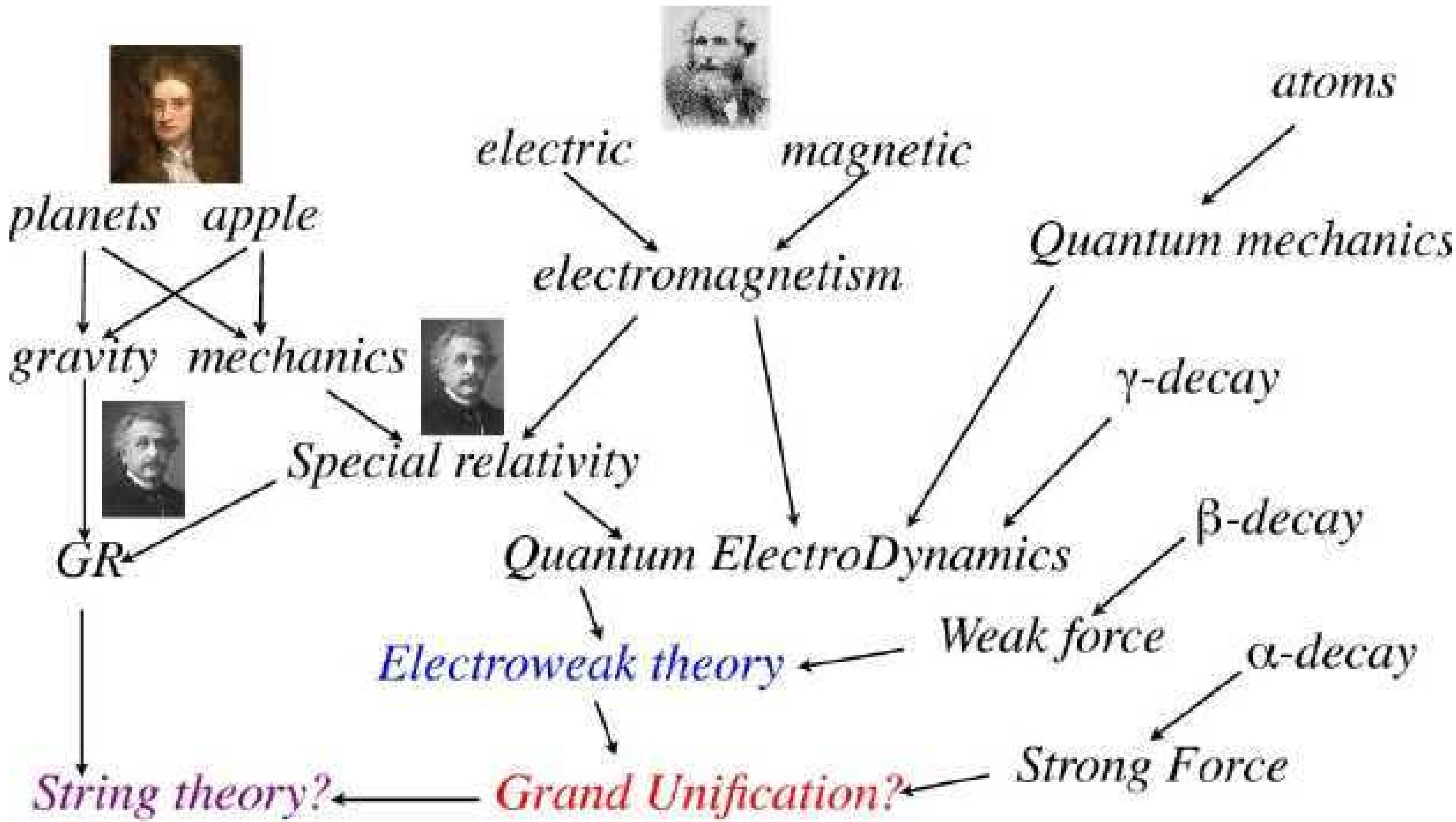
There have been many proposals to explain what dark energy might be. Almost all of these proposals are essentially guesses in that they introduce new physical interactions (= fields).

· inflatons, phantom matter, tachyon matter, ghosts



Can we establish what dark energy and dark matter are with less guessing?

One approach is to try to start with the string theory which began as a theory for strong interactions and evolved to a theory encompassing gauge interactions, gravity and quantum mechanics !



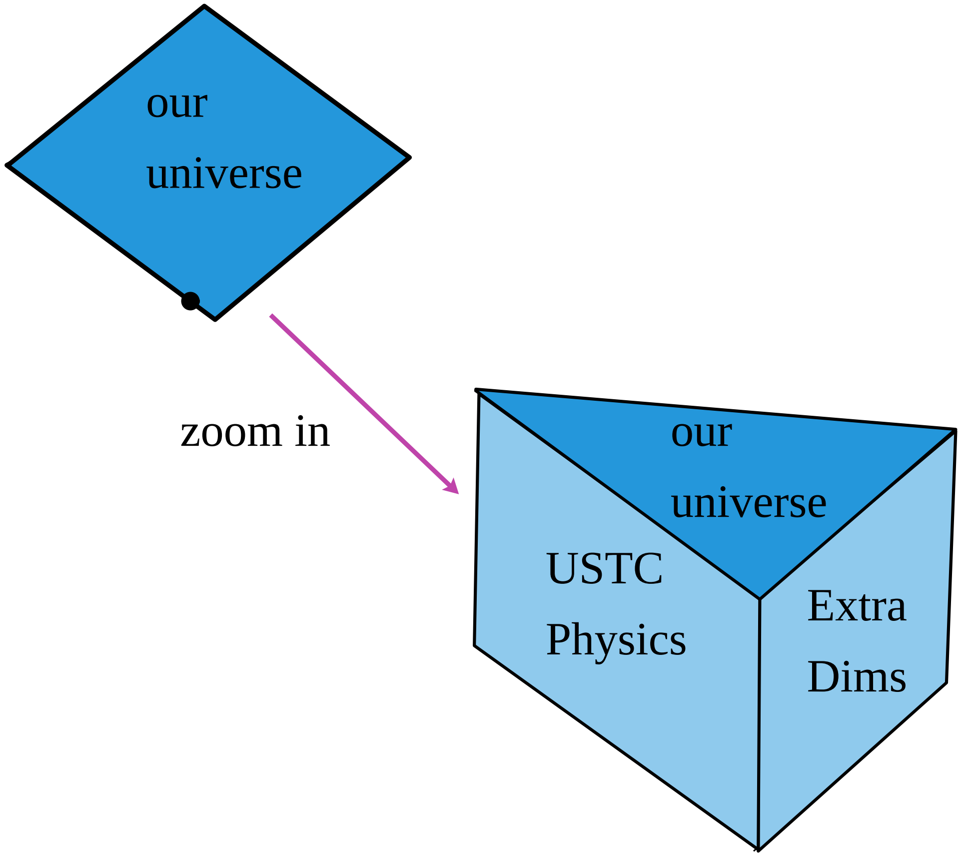
Extra Dimensions:

As a candidate theory of our universe, can string theory provide us with a sensible source of dark energy?

To answer this question it is important to know what is different or new about string theory. One relevant fact about string theory is that it requires 10 dimensions for space and time!

How do we deal with the fact that our universe has four apparent dimensions?

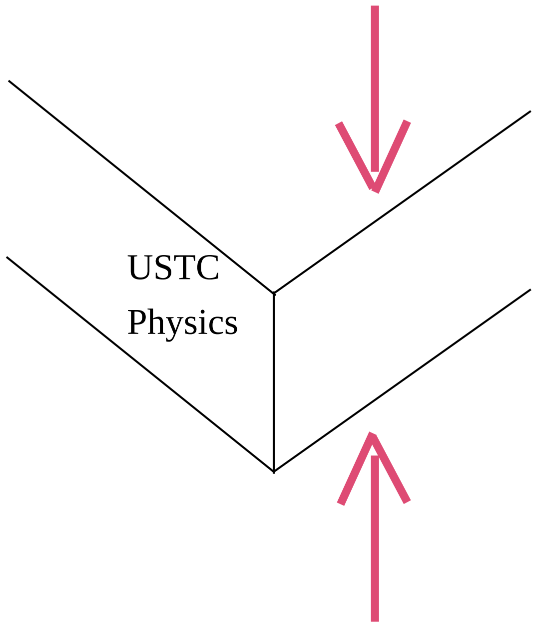
One idea is to divide the ten dimensions of string theory into large four dimensions and six small dimensions.

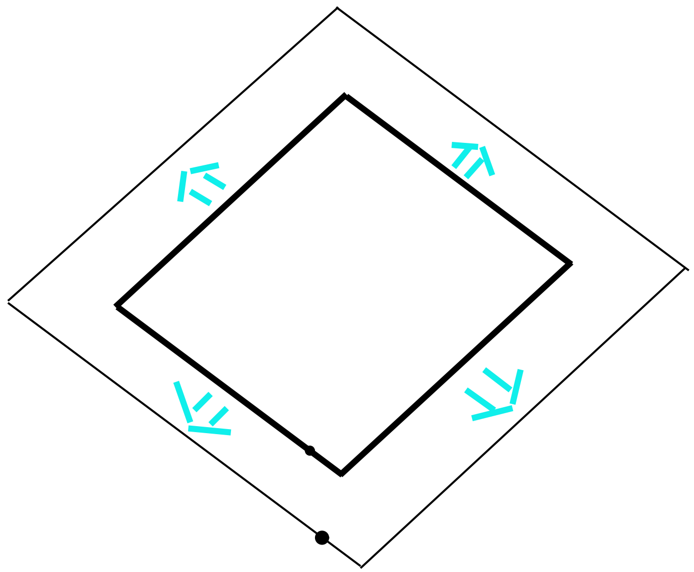


Despite their small size, since string theory has extra dimensions, my collaborators and I checked to see if they are relevant to cosmology.

We found that even small dimensions can accelerate our large dimensions! This is surprising since we earlier said that without Λ there is no acceleration.

Specially chosen time dependent extra dimensions provide energy as seen by the large four dimensions.





We examined the spacetime solution of Einstein gravity

$$R^{1,3} \times H_6 \tag{6}$$

$$ds^2 = \alpha^2(t)\left[-a^6(t)dt^2 + a^2(t)dx_3^2\right] + \alpha^{-2/3}(t)\left[d\psi^2 + \sinh^2\psi d\Omega_5^2\right] \tag{7}$$

Dimensionally reduce this to four dimensions to find the spacetime as seen by the four dimensional observers, us!

$$S = \int d^4x[\mathcal{R} - (\partial\phi)^2 - 15e^{3\phi/8}] \sim \int d^4x[\mathcal{R} - \Lambda(= 15e^{3\phi/8})] \quad (8)$$

This is gravity and a scalar theory which produces acceleration when $\partial\phi \sim 0$. To a four dimensional observer, extra dimensions act like a scalar field.

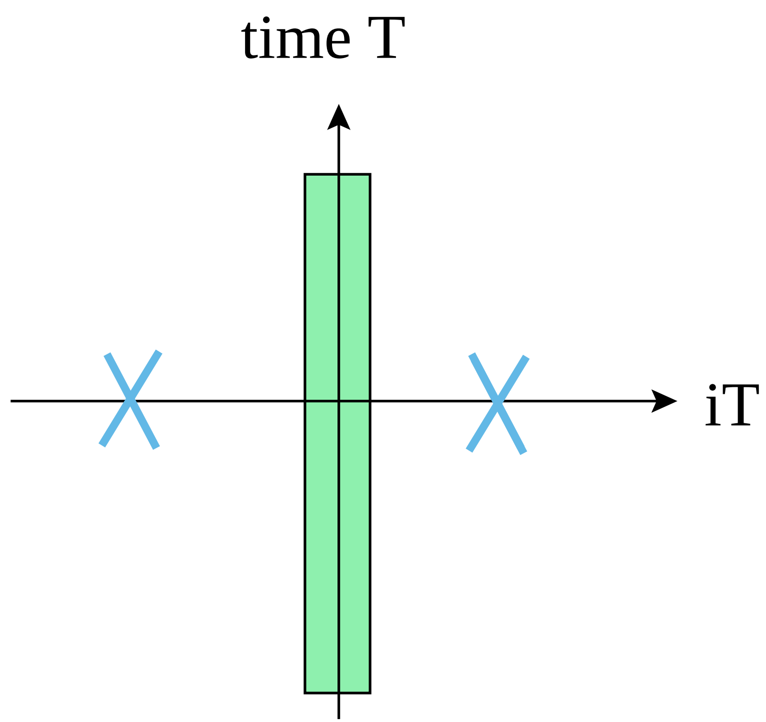
In fact as opposed to more phenomenological models, the inflaton here is not arbitrary but determined by gravity!

Imaginary Black Holes:

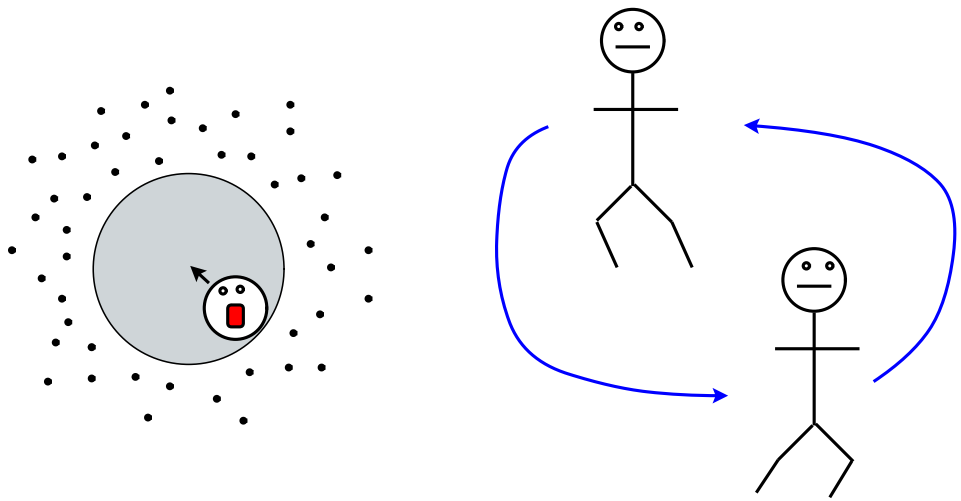
Black holes are crazy, interesting and have been extremely useful in better understanding quantum gravity! They are fascinating and today I have the pleasure to discuss an interesting twist on the usual story and will describe their application in a new setting.

The point I wish to get across is that there is a natural concept of imaginary black holes which is consistent, has useful applications and after this talk I hope you will agree that they are not so strange!

Before going into details I want to summarize my main point. Imaginary black holes are black holes placed at imaginary coordinate values for example imaginary time. They produce time dependent spacetimes with interesting properties.



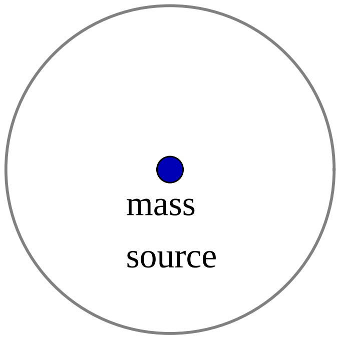
A black hole is the spacetime created by a point-like source with mass. Far away from this source then we are move around as we want but if we pass the black hole horizon then we are doomed!

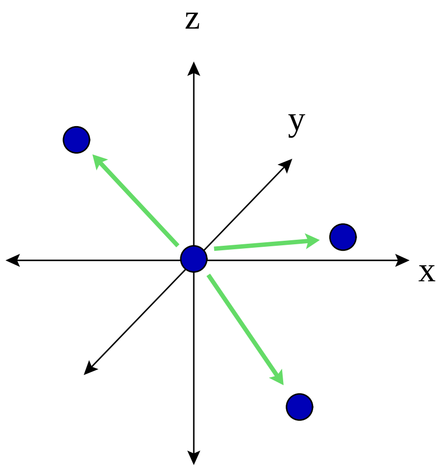


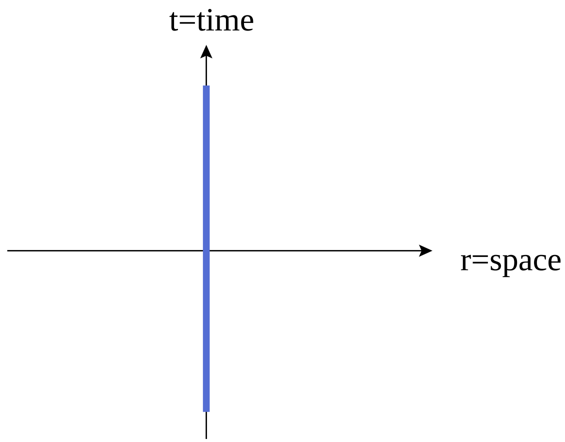
The simplest Schwarzschild black hole solution is

$$ds^2_{BH} = -(1 - \frac{2M}{r})dt^2 + \frac{dr^2}{1 - \frac{2M}{r}} + r^2(d\theta^2 + \sin^2\theta d\phi^2) \qquad (9)$$

However let us strip away all these complexities of black holes like their non-linearity, horizon structure. This is a complexity of the Einstein action. We want to just deal with the essence of a black hole which is its massive point-like object source which we can move around in space.

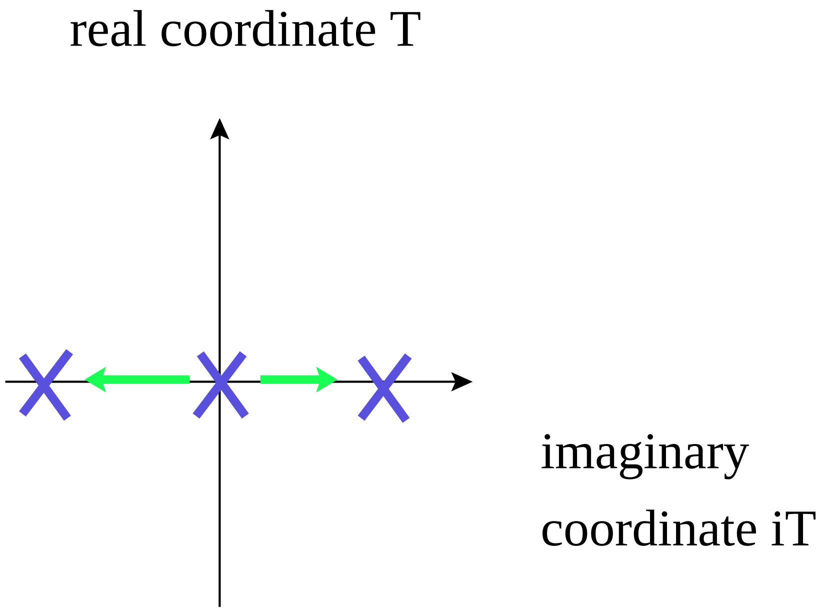






Note we have spacetime not space and the source exists for all time.

The four real coordinates of our universe are t, x, y, z. We live in the "real" world BUT what about moving sources in complex coordinates?



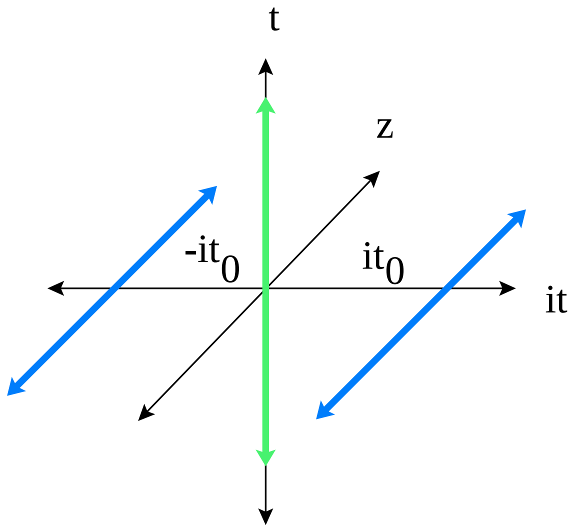
In other words while before we discussed moving the black hole source in real value of spacetime, now we move the black hole source into complex values of spacetime. Hence these are imaginary black holes.

To create a real source we adding two complex sources,
$z + z^* = (x + iy) + (x - iy) \in R$ for all $z \in C$.

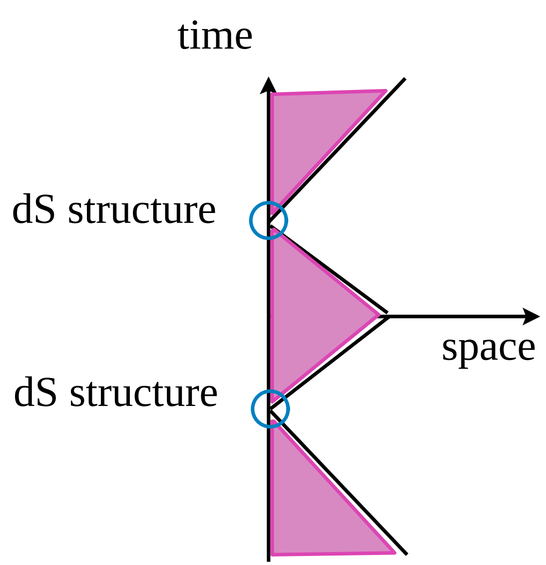
$$\text{BH source} \qquad \delta(\sqrt{x^2 + y^2 + z^2})$$

Imag BH source
$$\delta(\sqrt{x^2 + y^2 - (t - it_0)^2}) + \delta(\sqrt{x^2 + y^2 - (t + it_0)^2}) \tag{10}$$

Take the black hole source and 1) rotate it so it is now extended in a spatial direction and not time 2)move it from the origin in pairs



$$
\begin{aligned}
ds^2 &= (1-\frac{2Mt}{\Sigma})^2\Big[(dx^4)^2 + \frac{\Sigma^4}{(\Delta+(a^2-M^2)\sinh^2\theta)^3}(-\frac{dt^2}{\Delta}+d\theta^2)\Big] \\
&\quad + \frac{\Delta\sinh^2\theta}{(1-\frac{2Mt}{\Sigma})^2}d\phi^2 \\
A &= \frac{2aMt\sinh^2\theta}{\Delta+a^2\sinh^2\theta}d\phi \\
\Delta &= t^2-2Mt+a^2, \qquad \Sigma = t^2+a^2\cosh^2\theta
\end{aligned}
$$



Imaginary black holes source a fibered de Sitter without relying on a cosmological constant! This new result may extend field theory/string theory dualities to time dependent systems.

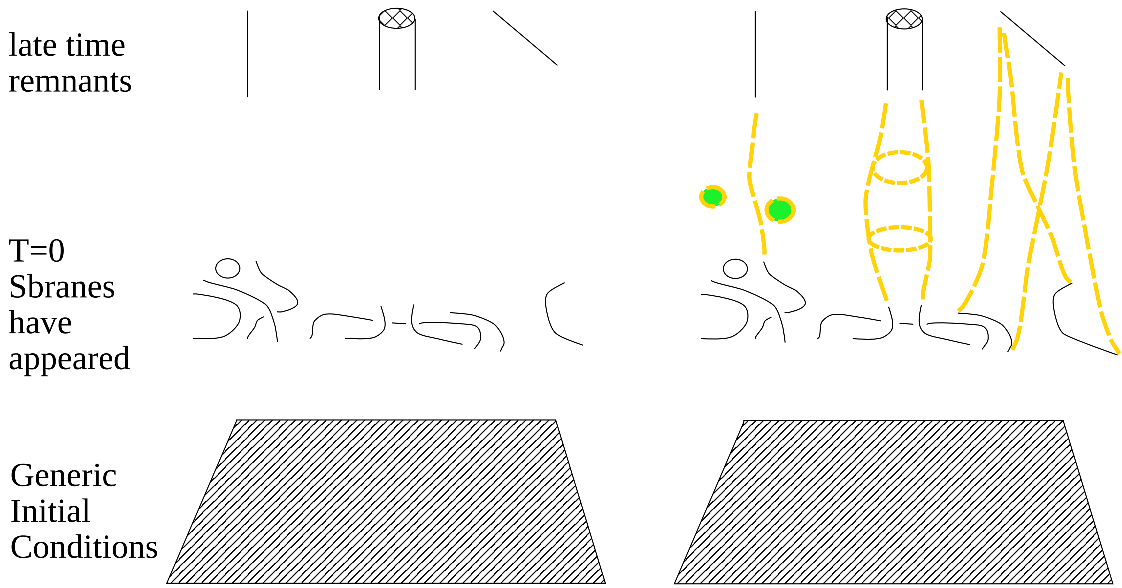
$$
\begin{aligned}
ds^2 &= ((M^2 - a^2)\cosh^2\eta + a^2\sinh^2\eta)^2 \Big(\frac{\sigma^2 (dx^4)^2}{\Sigma_+^2} \\
&\quad + \frac{\Sigma_+^2}{(M^2-a^2)^3}(-d\sigma^2/4\sigma^2 + d\eta^2)\Big) \\
&\quad + \frac{(M^2-a^2)\Sigma_+^2 \cosh^2\eta \sinh^2\eta d\phi^2}{((M^2-a^2)\cosh^2\eta + a^2\sinh^2\eta)^2}, \\
A &= \frac{2aMt_+^{\mathrm{KH}} d\phi}{a^2 + (M^2-a^2)\coth^2\eta}
\end{aligned}
$$

$\Sigma_+ = (t_+^{\mathrm{KH}})^2 + a^2$. Fibering of dS_2 over the η direction for $\eta \geq 0$.

String/defect formation: Pointlike objects such as black holes, or spatially extended objects like massive strings, can form in the early universe due to the universe's small size and hence high energies.

In some theories, strings arise as confined flux tubes. Is this possible even in string theory where the fundamental objects are strings? YES!

If we have defects, how do we see their formation?



First, a string is a one dimensional spatial object. To form a string we need to start from some other object which is similar to a string. In other words we need the correct initial conditions.

A simple starting point for example is a cylindrical tube. If the size of the tube collapses then we will form a string.

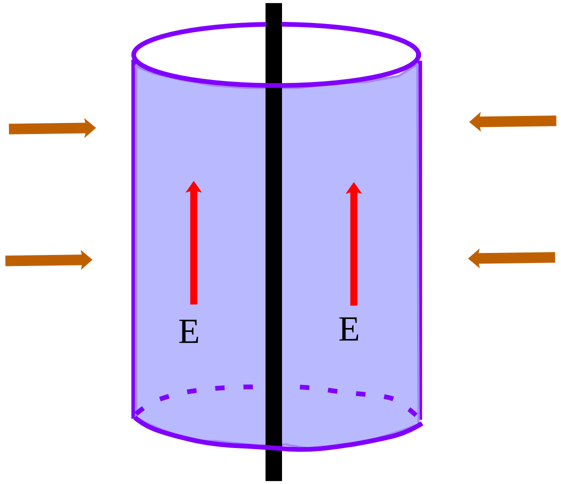
Starting from string theory, we derived an action to describe how to interpolate between the initial conditions and the final strings/defect.

We also found analytic solutions which describe how fluxtubes form into strings.

$$S = S_0 \int d^{3+1}x \sqrt{\mathsf{det}(\delta_{ij} - \partial_i t \partial_j t + F_{ij})} \tag{11}$$

For example this is the action for a cylinder with 3+1 worldvolume dimensions, located at positions $\mathbf{x^i}$ and with F_{ij} field strength ie electric and magnetic fields.

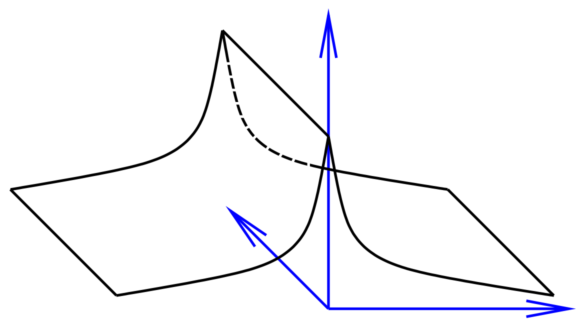
Searching for interesting solutions we found those representing time dependent collapse of tubes of electric flux into thin lines.



$$r = \frac{c}{t} \qquad E = 1 = \text{critical value} \tag{12}$$

The formation of such objects, which typically are called topological defects, has been studied before although with two difficulties.

Before solutions were either numerical or collapsed in finite time so the solutions could not be trusted at the collapsed degenerate point. This is the first time an analytic and non-singular solution has been found!



What is perhaps most amazing is that we are describing the formation of strings in a string theory!

Summary

· Lots of unexplained phenomenon

· Extra dimensions can be related to cosmic acceleration

· Imaginary black holes make sense! and have de Sitter uses too

· New non-singular time dependent solutions describing string formation

Thanks for the invitation!