



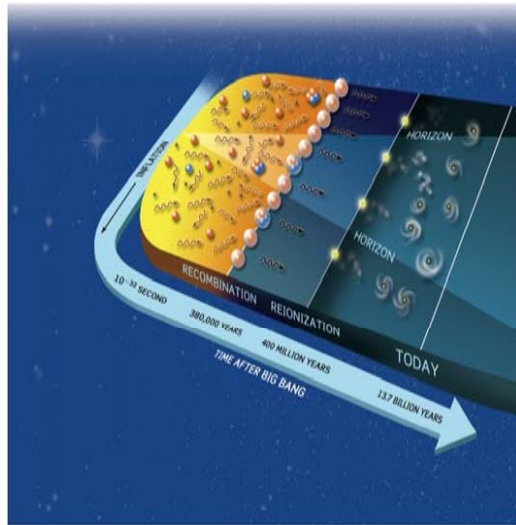
Astronomy and Cosmologies

Spring 2013, Zita

Crisis in Cosmology

Planck Time

Candidate solutions



Crisis in Cosmology



Black hole:

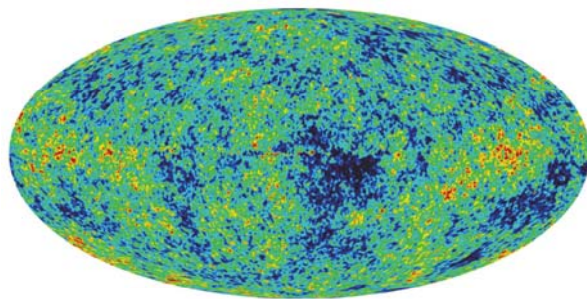
Singularity of great mass with an “event horizon”

Big Bang: Singularity of enormous mass.

You’ve heard that “the laws of physics break down” in the earliest moment.

Black holes can help us understand what that means.

Evidence for the Big Bang



-200 -100 0 +100 +200
Temperature difference from average (μK)

The 3-degree cosmic microwave background radiation (CMBR) reveals the origin of structure in the universe

More evidence for the Big Bang:

- * Expansion of the universe: further galaxies appear to be receding faster
- * Primordial abundances of Hydrogen, Helium and metals
- * 3K radiation: universe has cooled to the present
- * Early Inflation: solves the horizon and flatness problems

Questions about the Big Bang:

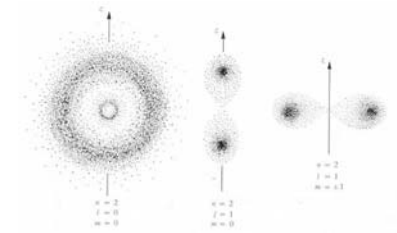
What happened in the first tenth of a millionth of a billionth of a billionth of a billionth of a second (10^{-43} sec)?

The universe was very small, so ask **Quantum Mechanics.**

The universe was very massive and dense, so ask **General Relativity.**

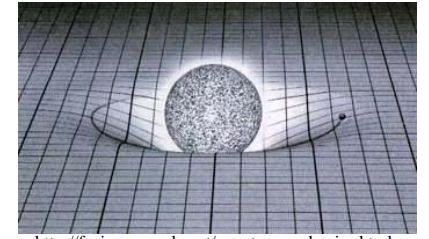
Current paradigms in physics

Quantum Mechanics
explains the very small



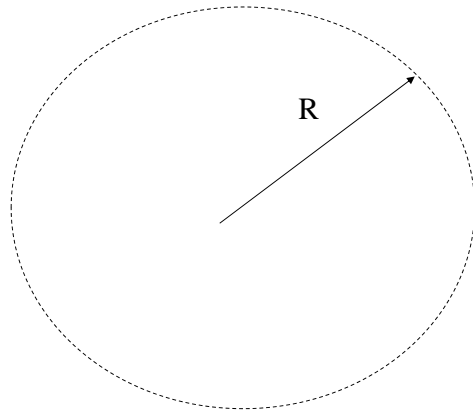
<http://universe-review.ca/I12-06-wave.jpg>

General Relativity
explains the very massive (theory of gravity)



<http://fusionanomaly.net/quantummechanics.html>

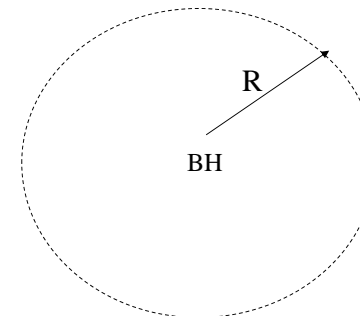
How big was the universe in the beginning?



What physics describes the beginning of the universe – the Big Bang?

General Relativity (gravity)

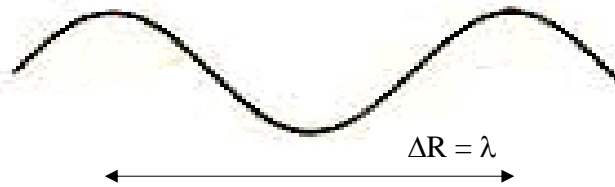
The early universe was a singularity –
mathematically like a black hole (BH).



Event horizon R = distance inside which everything (including light) is trapped near a BH.

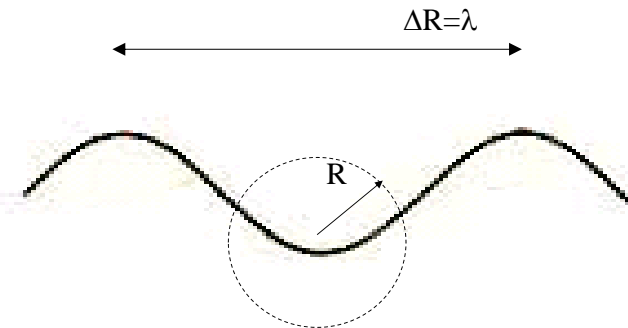
Quantum Mechanics

The early universe was very small – a point.



Small quantum objects have an uncertain size / location ΔR , or wavelength λ

Problem: could the early singularity be outside its own event horizon?!



On such a small scale, the “Planck scale,” the “laws of physics would break down”

Calculating the Planck scales:

1. Use classic energy conservation to find the GRAVITATIONAL size of a black hole, its Schwarzschild radius R . This is very close to the General Relativistic (GR) derivation.
2. Next, use the energy of light to calculate the QUANTUM MECHANICAL (QM) size of a black hole, its De Broglie wavelength λ .
3. Then, equate the QM size with the Gravitational size to find the PLANCK MASS M_p of the smallest sensible black hole.

Calculating the Planck scales...

4. Finally, substitute M_p into R to find the PLANCK LENGTH L_p
5. then calculate both M_p and L_p , and the Planck time, τ_p .
6. These are the smallest scales that we can describe with both GR and QM.

At smaller scales, GR and QM are mutually inconsistent – then the QM wavelength of the tiny early Universe could, for example, be bigger than its GR size – which would be nonsense.

1a. Gravitational size of a Black Hole

We can use energy conservation to find the size of a black hole. K = kinetic energy, U = potential energy. Find the escape velocity v from an object with mass M and radius R :

$$K_{\text{initial}} + U_{\text{initial}} = K_{\text{final}} + U_{\text{final}}$$

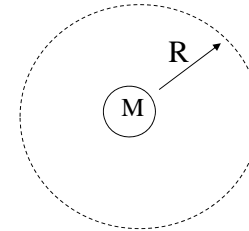
$$\frac{1}{2} mv^2 - GmM/R = 0 + 0$$

Solve for $v^2 = \underline{\hspace{2cm}}$



1b. Gravitational size of a Black Hole

For a black hole with mass M , the escape velocity $v=c$ at the event horizon R = Schwarzschild radius



Find R in terms of G , M , and c .

(The exact GR calculation yields $R/2$ of the classical value we just derived.)

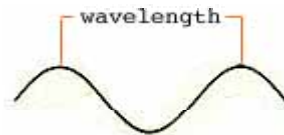
2. Quantum Mechanical size of a Black Hole

Energy E of photon \rightarrow wavelength λ of particle

$$E = \frac{hc}{\lambda} = pc \quad \rightarrow \quad \text{momentum } p = Mc = \frac{h}{\lambda}$$

Solve for wavelength λ in terms of M, c, h :

$$\lambda = \underline{\hspace{2cm}}$$



The deBroglie wavelength, λ , describes the smallest region of space in which a particle (or a black hole) of mass M can be localized, according to Quantum Mechanics.

3. Find the Planck mass, M_p

Schwarzschild radius = deBroglie wavelength

$$R_{\text{gravity}} = \lambda_{\text{quantum}}$$

$$\frac{GM_p}{c^2} = \frac{h}{M_p c}$$

Solve for the Planck mass:

$$M_p^2 = \underline{\hspace{2cm}}$$

If a black hole had a mass less than the Planck mass M_p , its quantum-mechanical size could be outside its event horizon. This wouldn't make sense, so M_p is the smallest possible black hole.

4. Find the Planck length, L_p

Substitute your Planck mass, $M_p = \sqrt{hc/G}$, into either R or λ :

$$R = \frac{GM_p}{c^2} = \underline{\hspace{2cm}}$$

$$\lambda = \frac{h}{M_p c} = \underline{\hspace{2cm}}$$

These both yield the Planck length, L_p . Any black hole smaller than this could have its singularity outside its event horizon. That wouldn't make sense, so L_p is the smallest possible black hole we can describe with both QM and GR, our current theory of gravity.

and the Planck length $L_p = \frac{GM_p}{c^2} = \underline{\hspace{2cm}}$

These are smallest scales we can describe with both QM and GR.

5. Calculate the Planck length and mass

Use these fundamental constants:

$$h \approx 6.626 \times 10^{-34} \frac{\text{kg m}^2}{\text{s}}, \quad c \approx 3 \times 10^8 \frac{\text{m}}{\text{s}}, \quad G \approx \frac{20}{3} \times 10^{-11} \frac{\text{m}^3}{\text{kg s}^2}$$

to evaluate the Planck mass, $M_p = \sqrt{\frac{hc}{G}} = \underline{\hspace{2cm}}$

6. Calculate the Planck time

Consider the time it would take for light to cross the Planck length:

$$\text{Speed} = \text{distance} / \text{time}$$

$$c = L_p / \tau_p$$

Solve for the Planck time τ_p :

Planck scales

You should find roughly these values for the:

$$\text{Planck mass} = M_p = \sqrt{\frac{hc}{G}} \sim 3 \times 10^{-8} \text{ kg}$$

$$\text{Planck length } L_p = \sqrt{\frac{hG}{c^3}} \sim 4 \times 10^{-35} \text{ m}$$

(A black hole smaller than this could be outside its own event horizon, so QM and gravity are not both consistent at this scale.)

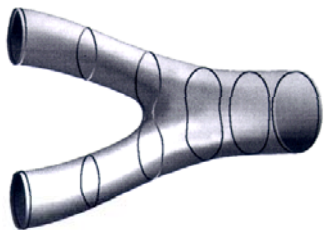
$$\text{Planck time } \tau_p = \sqrt{\frac{hG}{c^5}} \sim 10^{-43} \text{ s}$$

(At earlier times, our familiar laws of physics “break down”.)

Outstanding cosmological questions

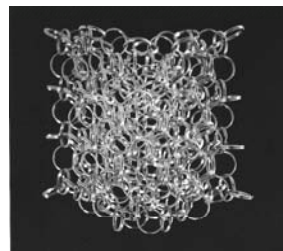
- **What physics operated before the Planck time?**
- **What is gravity?** Higgs? Graviton? Other?
- **What is dark matter?** sneutrinos? Wimps?
- **What is dark energy?** Why does the universe’s expansion accelerate?
- **How to unite gravity with QM?** Loop quantum gravity? Superstrings? D-branes? Supersymmetric particles?

We need a new theory of “quantum gravity”



String theory?

http://www.columbia.edu/cu/record/archives/vol23/vol23_iss18/28c.gif



Loop quantum gravity?

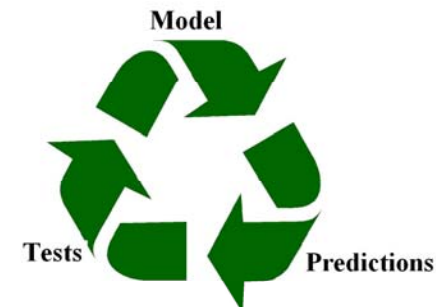
<http://www.cpt.univ-mrs.fr/~rovelli/rovelli.html>

Will one of these (or another?) resolve the crisis and become our ultimate Grand Unified Theory?

How to choose which model?

Criteria:

- * New model answers old Q
- * Predictions pass tests
- * New puzzles solvable
- * Simplicity, beauty
- * More?



*My generation articulated these questions.
Your generation will find the answers.*