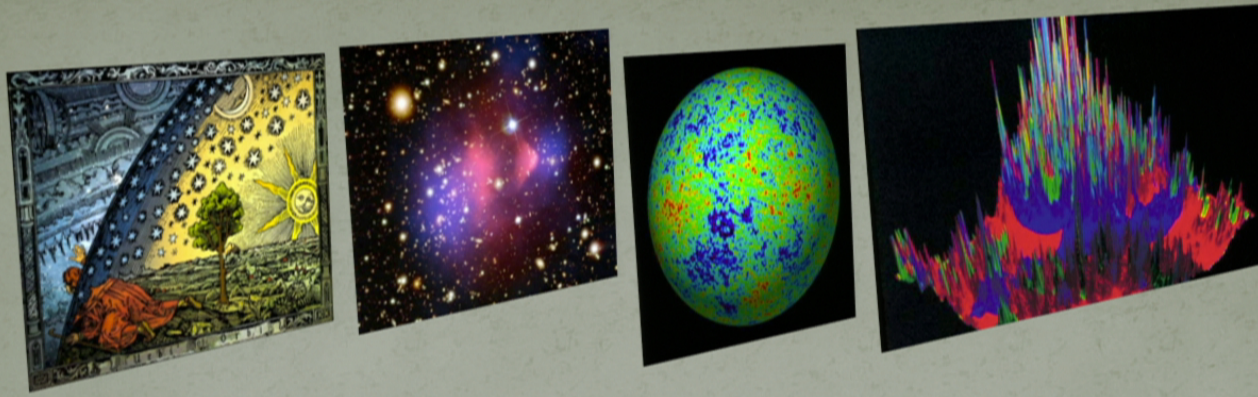


Title: Modern Cosmology

Date: Jul 09, 2012 10:30 AM

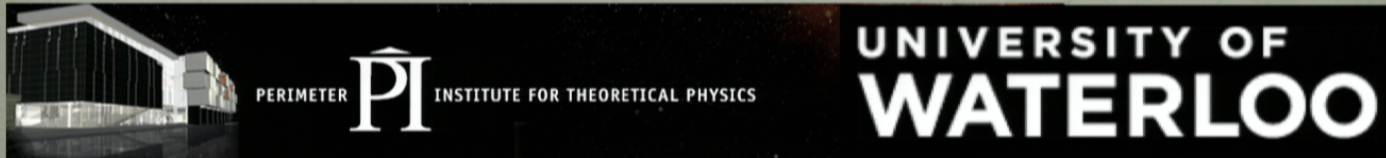
URL: <http://pirsa.org/12070003>

Abstract: This presentation will cover a number of topics in cosmology today including dark energy, dark matter and the cosmological constant.



Geometry of the Universe

Niayesh Afshordi



Geometry v.s. Cosmometry!



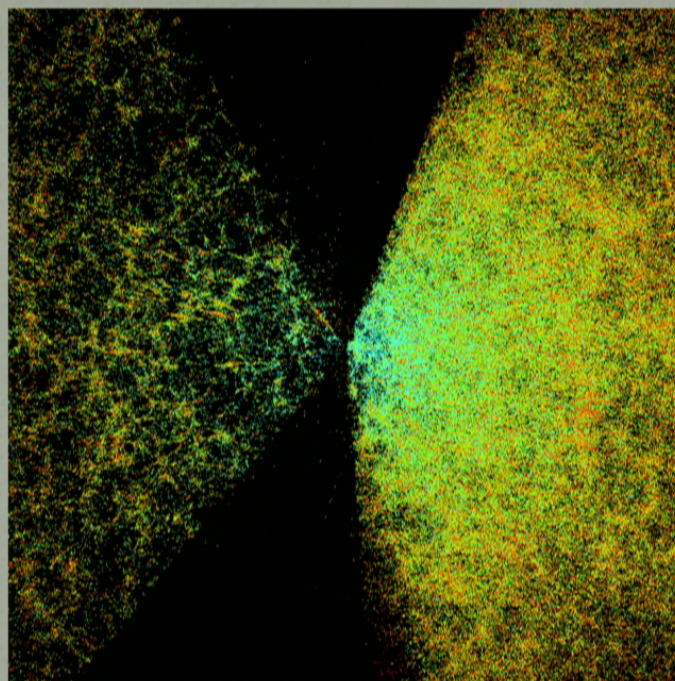
Ptolemy's 150 AD World Map, 10⁹ cm

Geometry v.s. Cosmometry!



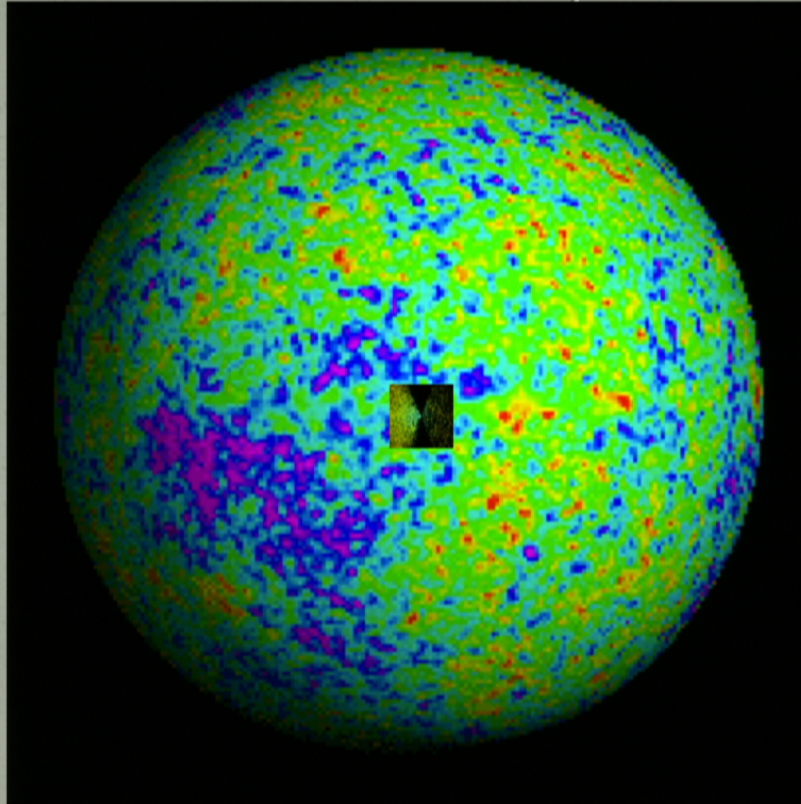
Ptolemy's 150 AD World Map, 10^9 cm

Geometry v.s. Cosmometry!



Sloan Digital Sky Survey: 1 Gpc $\sim 10^{28}$ cm (due to Mike Blanton)

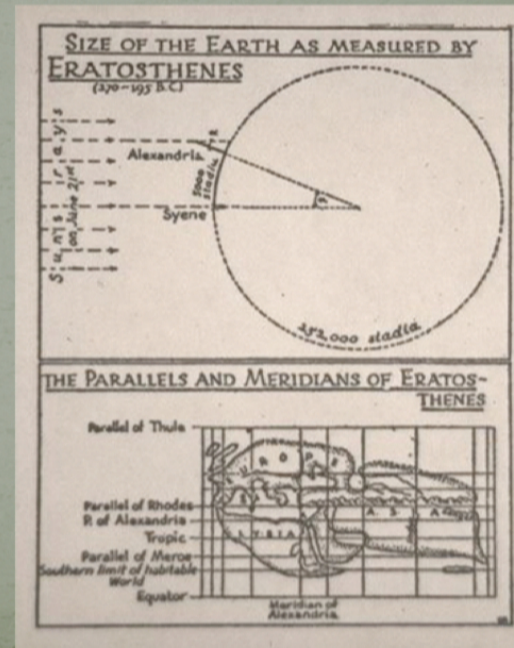
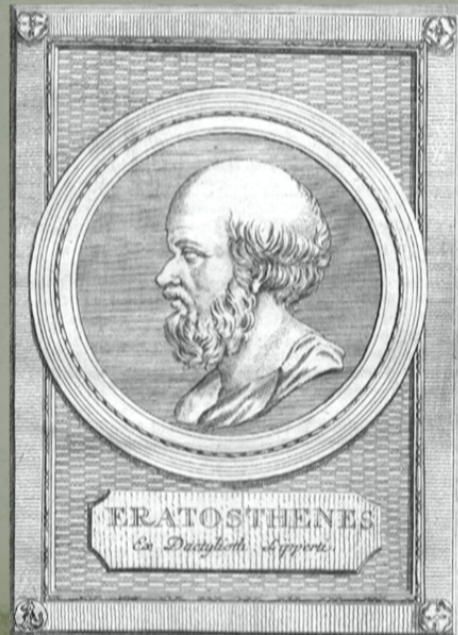
Geometry v.s. Cosmometry!



Wilkinson Microwave Anisotropy Probe: 10 Gpc $\sim 10^{29}$ cm (due to Max Tegmark)

Our Horizon through time

- 4×10^9 cm (200 BC): Eratosthenes measured the earth circumference to 1% → (Columbus, Magellan 15th-16th century)

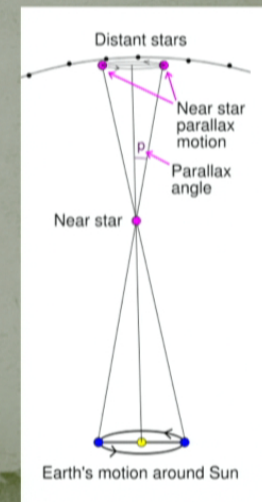


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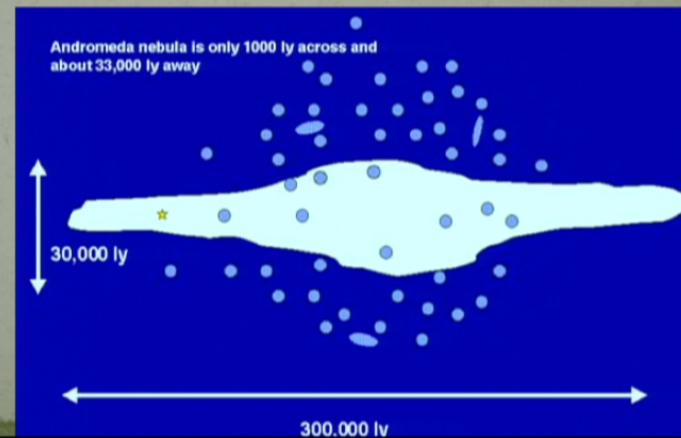
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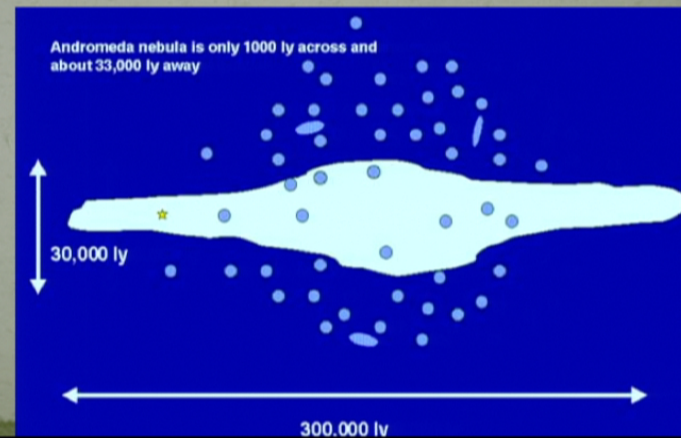
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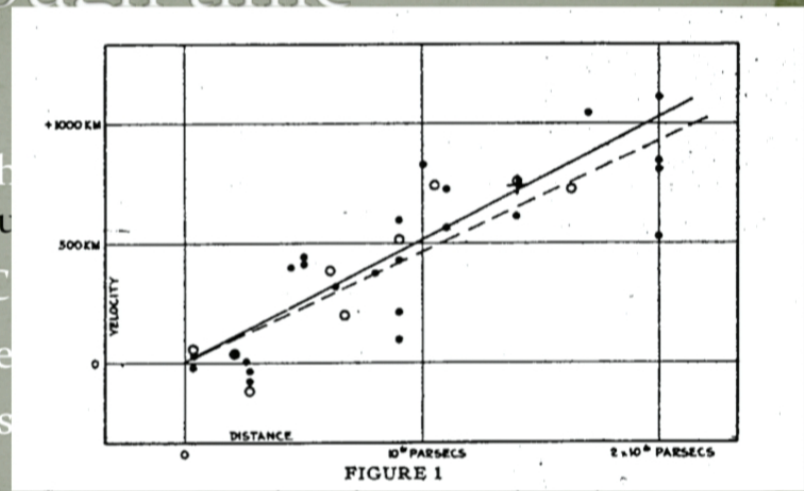


Our Universe through time

- 4×10^{17} km
circumference
- 10^{14} - 10^{15} km
radius
- 10^{19} cm
radius
- 10^{22} cm
radius
- Debate



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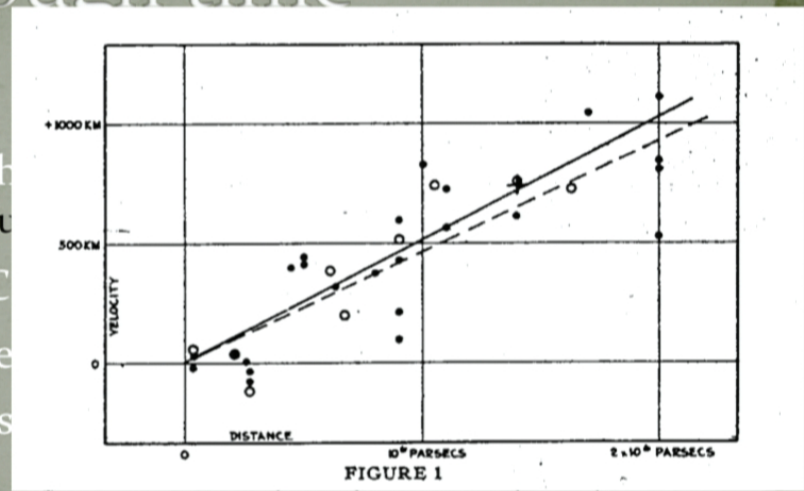
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Our Universe through time

- 4×10^{17} km
- 10^{14-15} km
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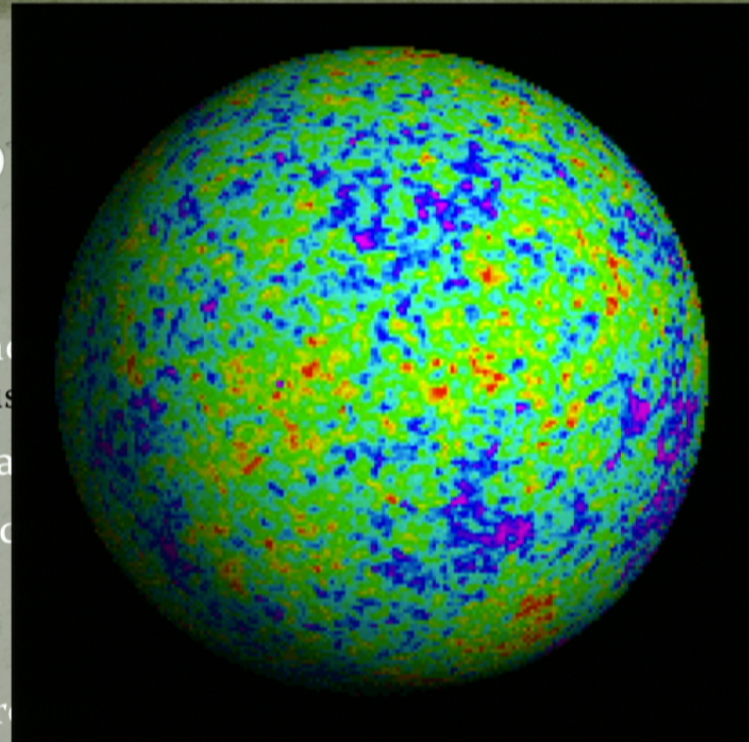
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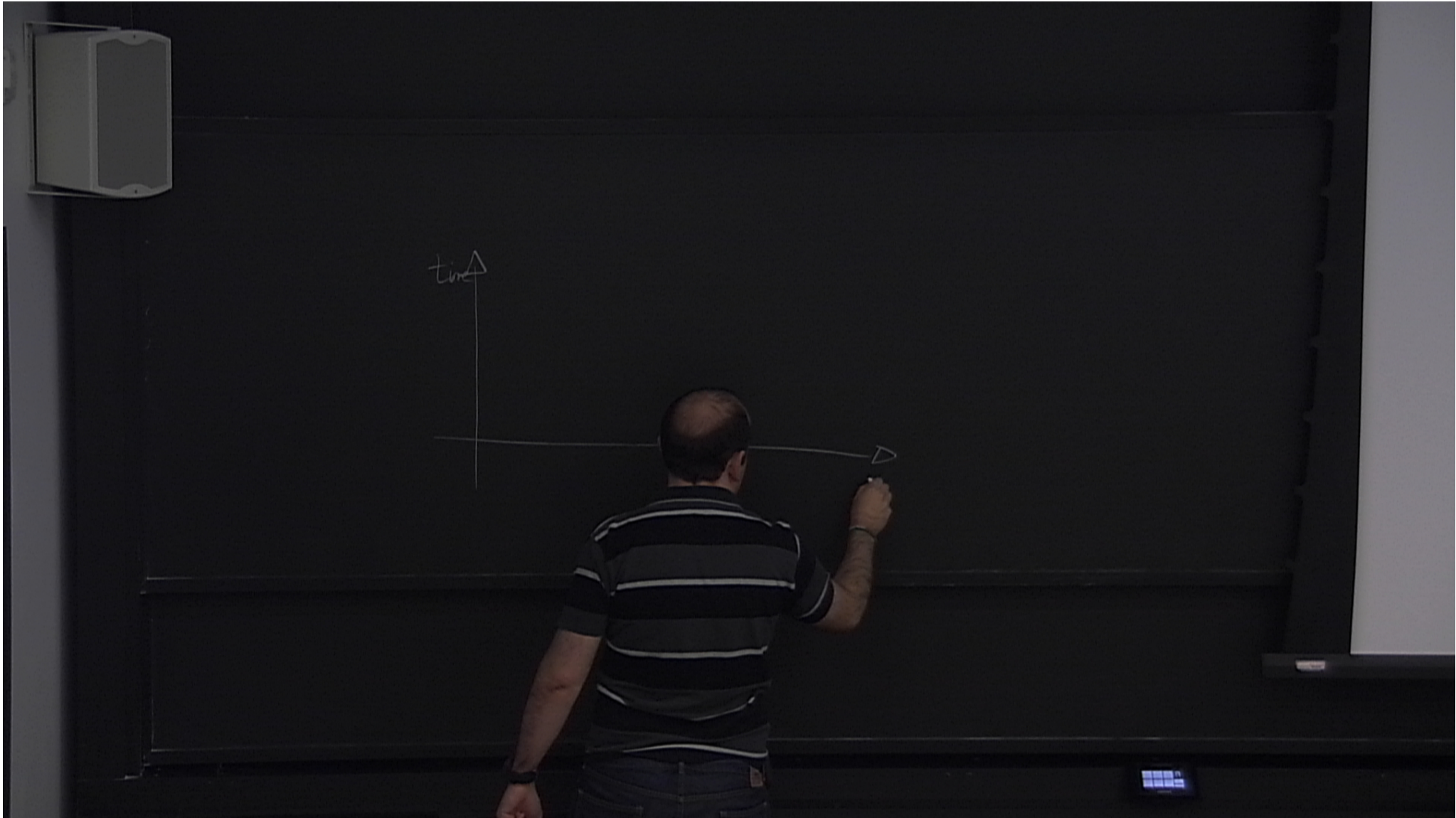


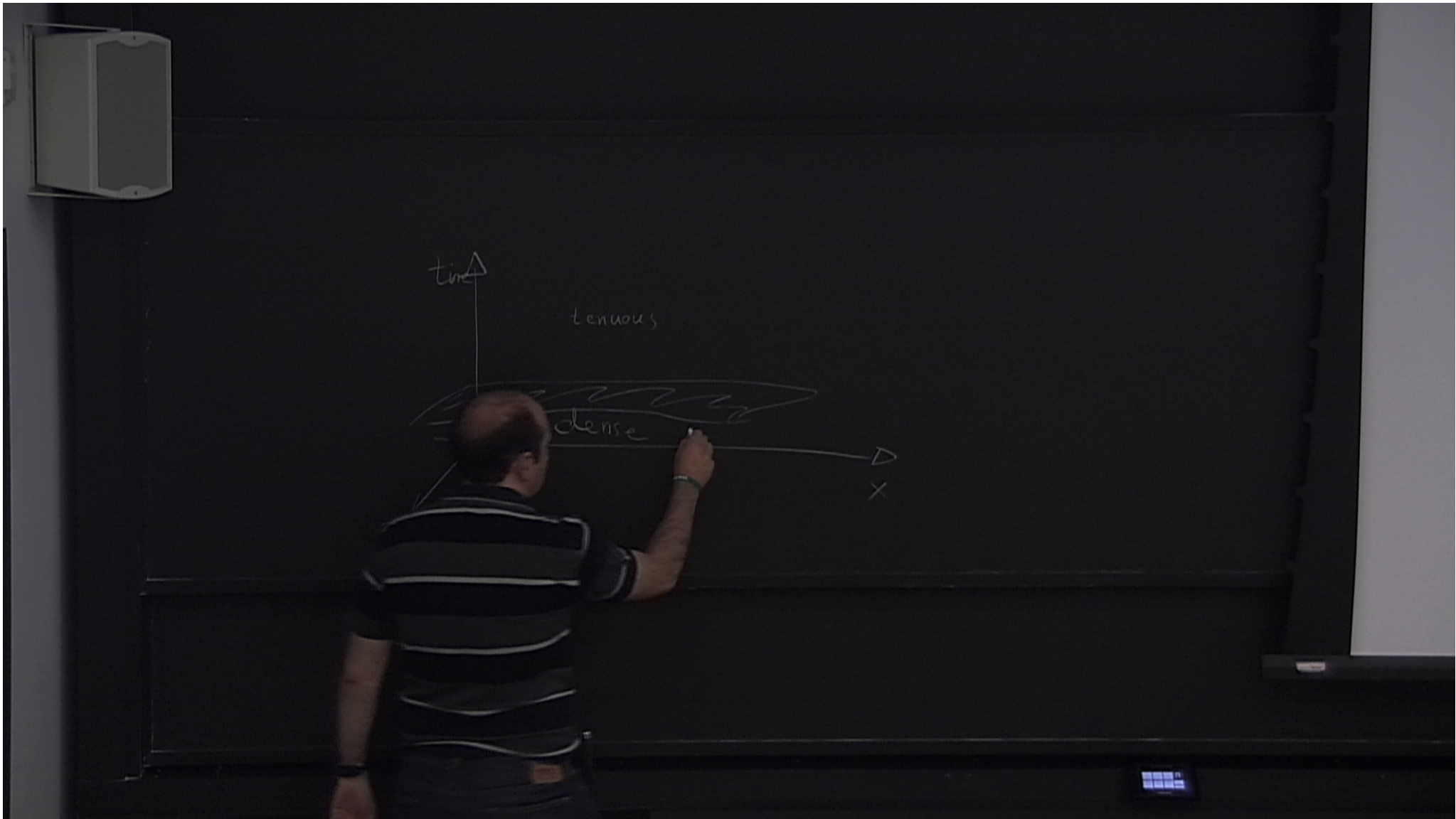
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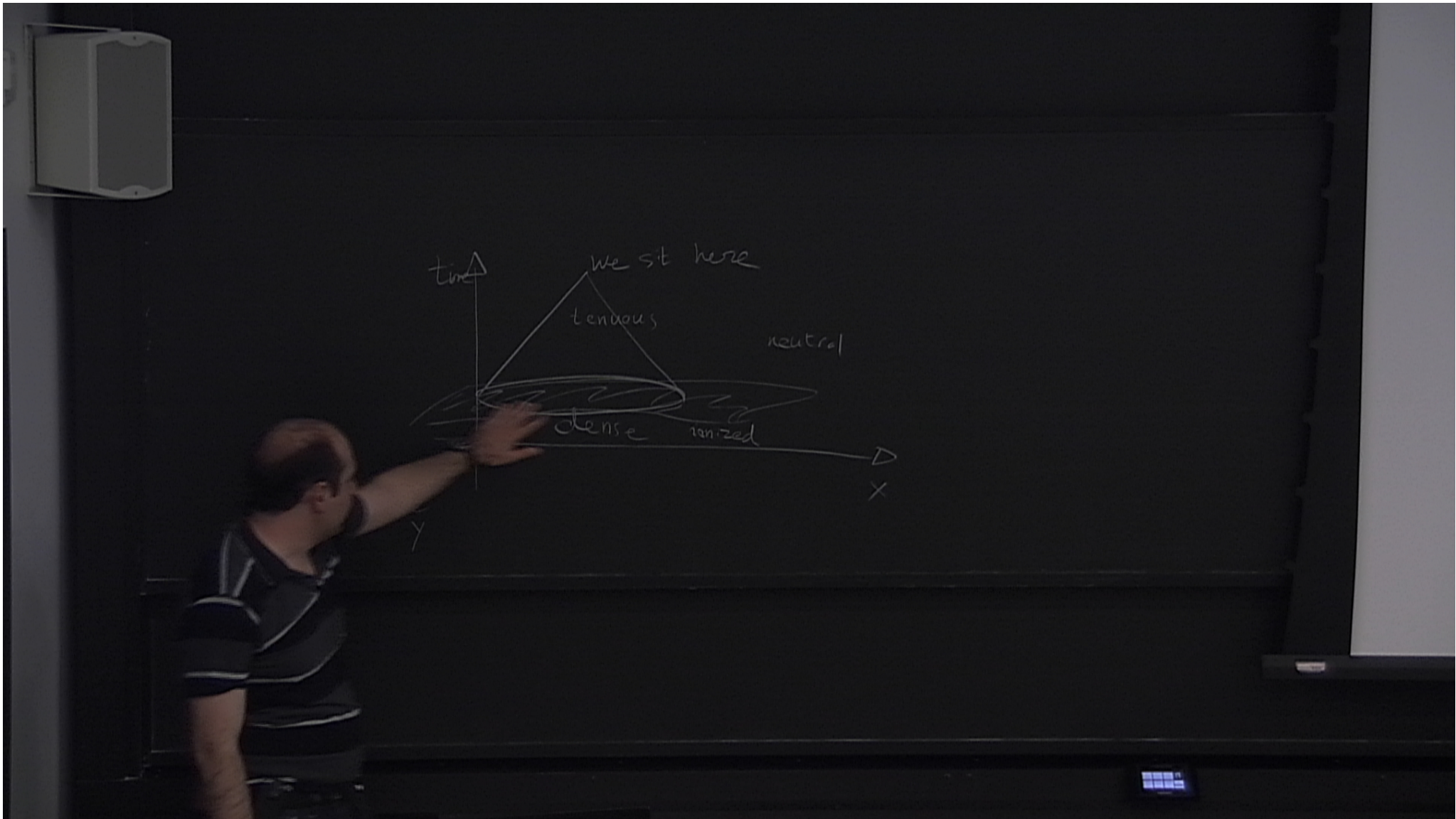
Our Horizon thro

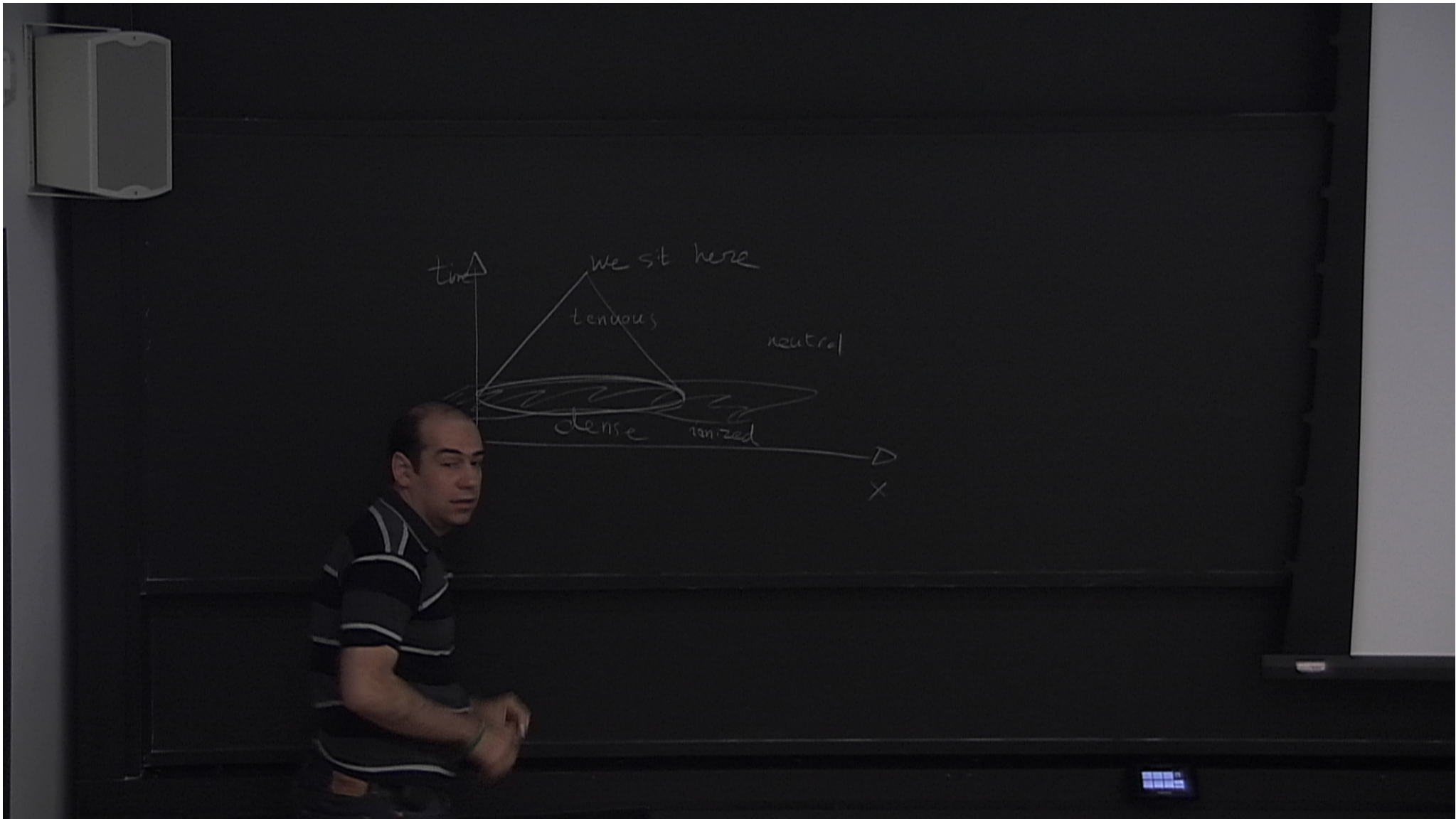
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- 10^{29} cm (1965): Penzias and Wilson discover the Cosmic Microwave Background (CMB)

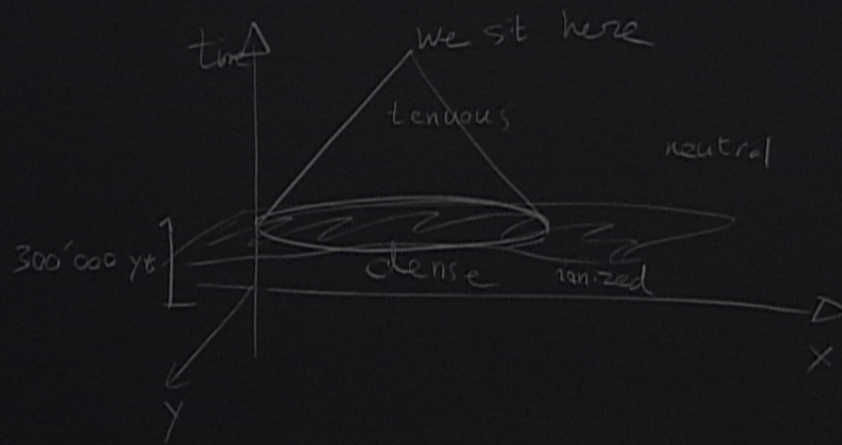


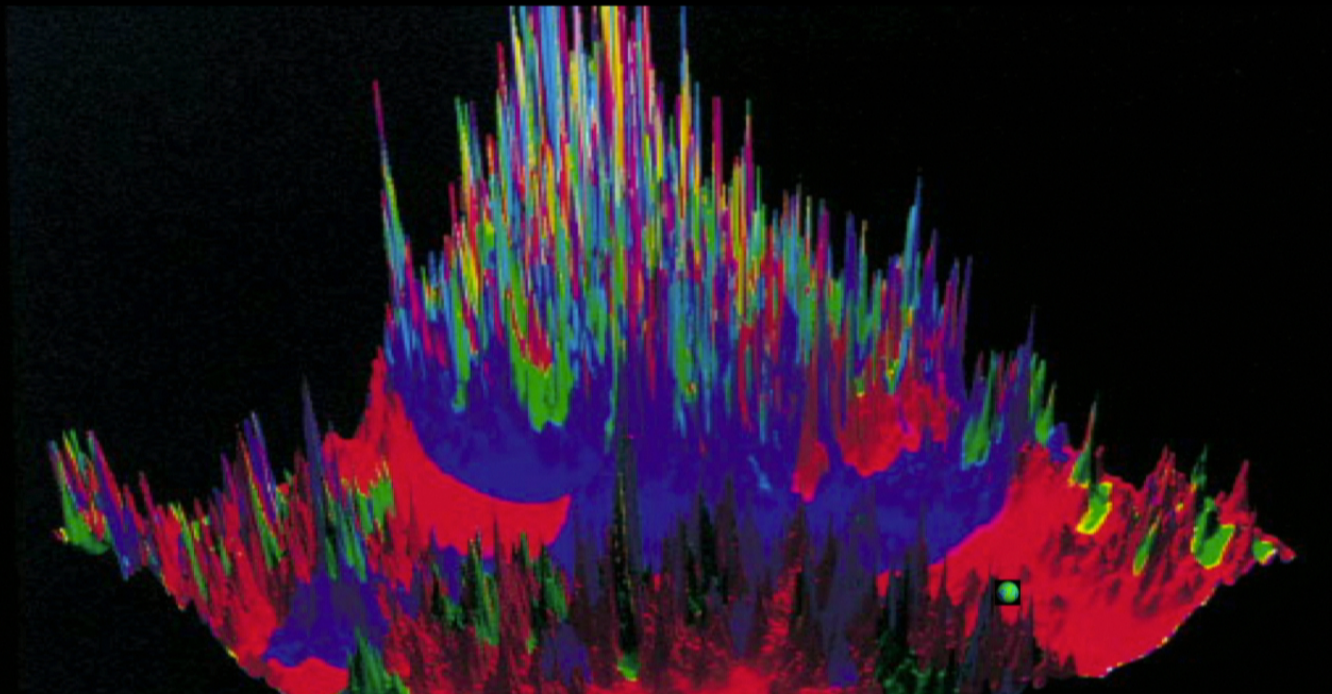












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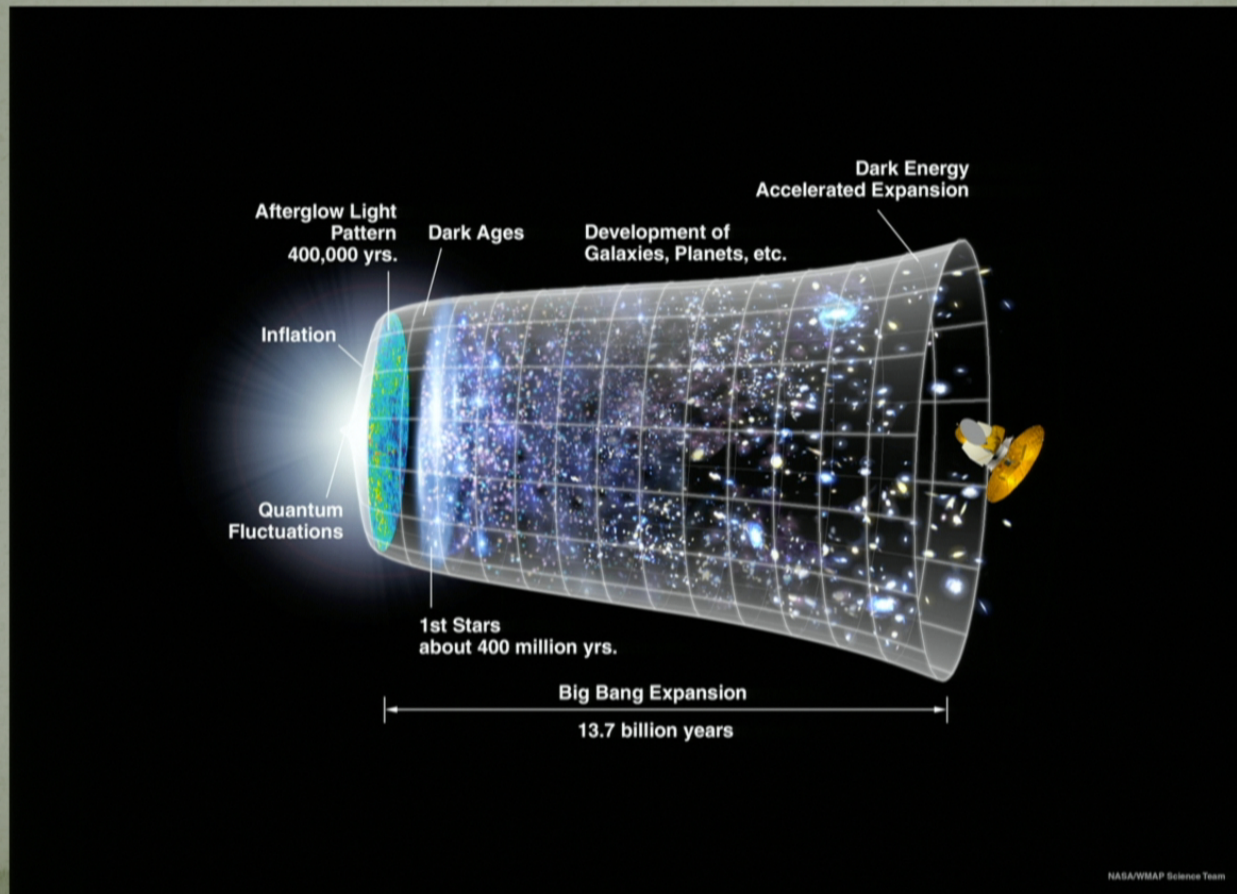
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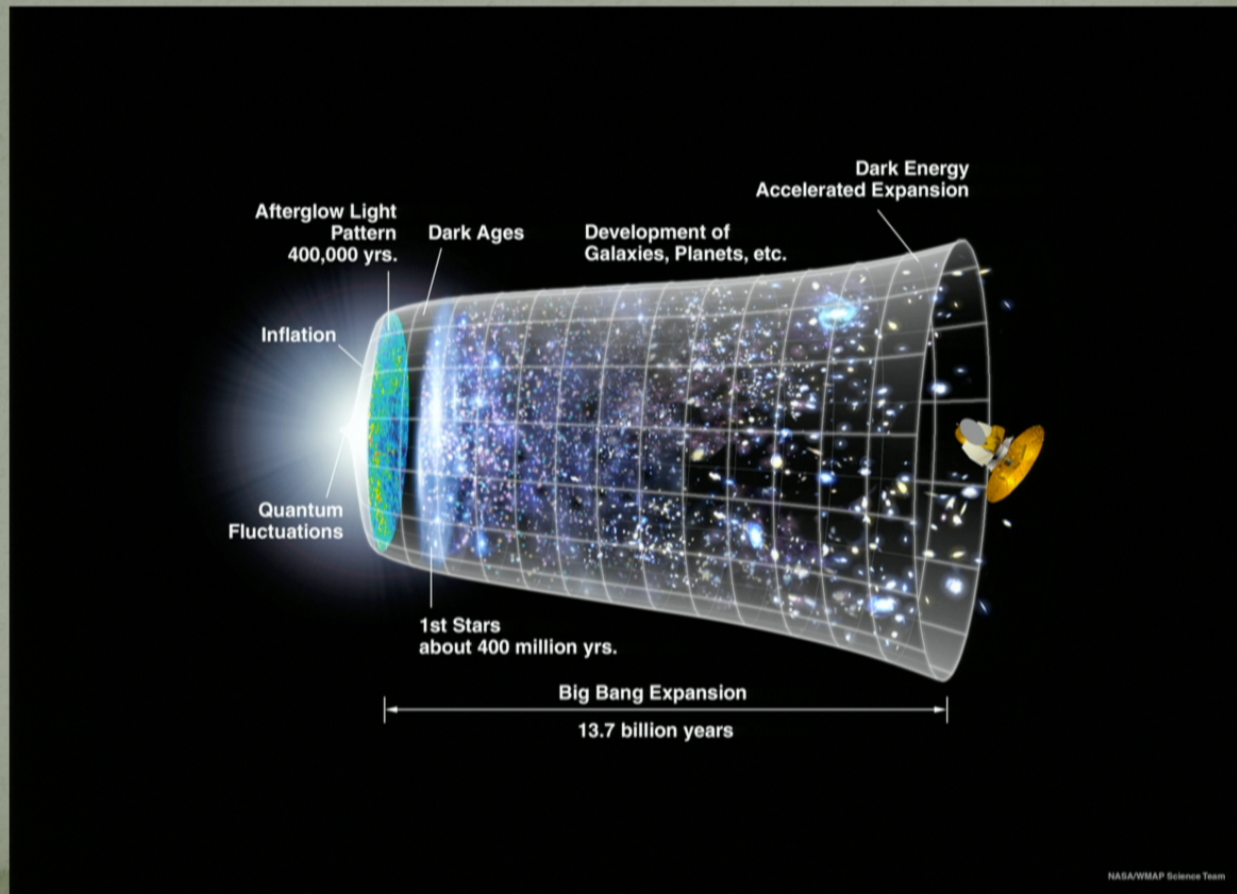
HERE BE DRAGONS!

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Cosmic History



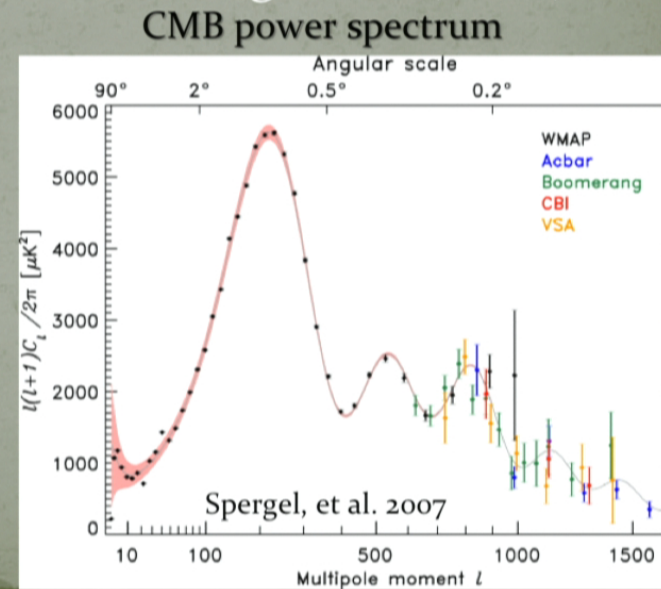
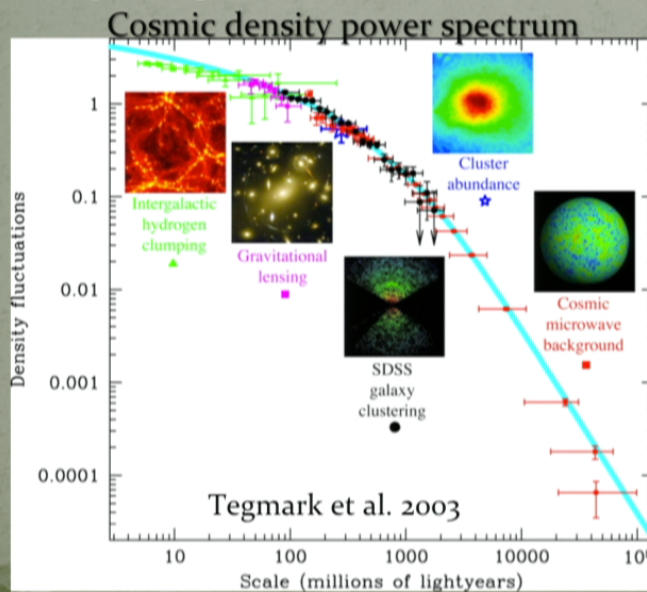
Cosmic History



Cosmology: the Golden Era

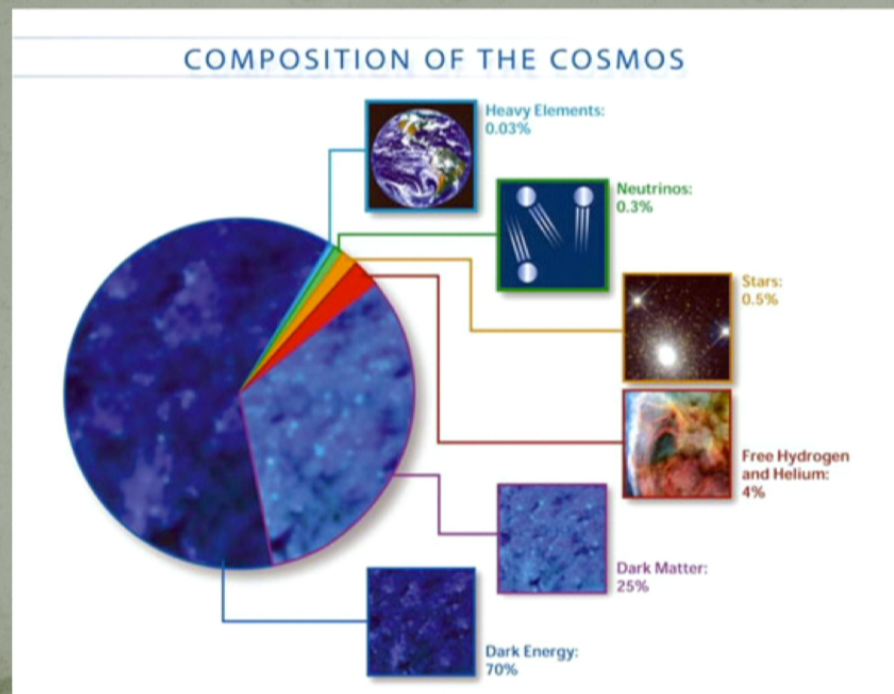
Cosmology: the Golden Era

- Cosmology is experiencing its renaissance
- A six-parameter model can now explain (almost) all observations, ranging from the intergalactic neutral hydrogen to the Cosmic Microwave Background (CMB)



Price of Precision

- More than 99% of the energy content of the Universe is unidentified/invisible



Outline

- Euclid's Heritage
- Einstein's Geometrodynamics
- Observing Cosmic Geometry
- Mysteries of Cosmic Geometry

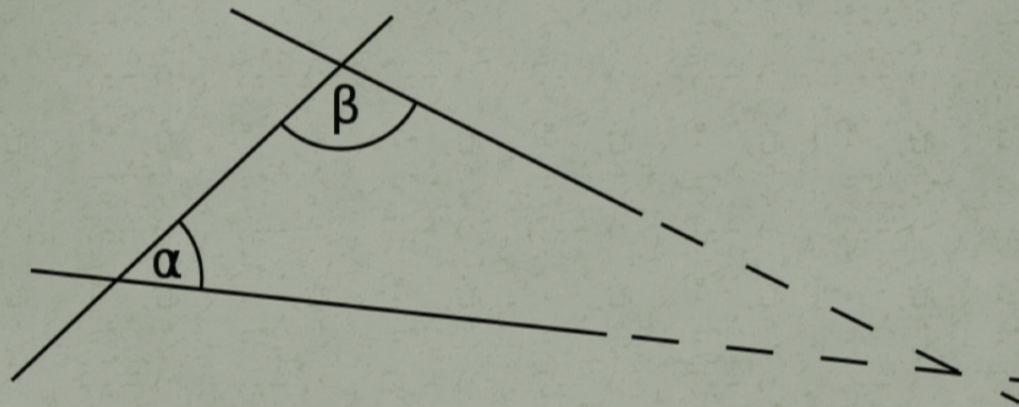
Euclid's Heritage (book of Elements)

- Let the following be postulated:
 - 1 To draw a **straight line** from any point to any point.
 - 2 To produce [extend] a **finite straight line** continuously in a straight line.
 - 3 To describe a **circle** with any centre and radius.
 - 4 That all **right angles** are equal to one another.
 - 5 The *parallel postulate*: That, if a straight line falling on two straight lines make the interior angles on the same side less than two right angles, the two straight lines, if produced indefinitely, meet on that side on which are the angles less than the two right angles.

Euclid's Heritage (book of Elements)

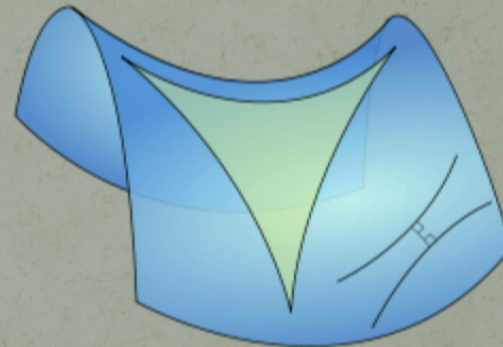
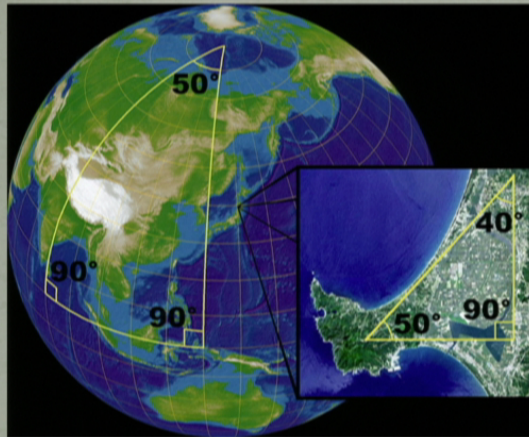
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Parallel Postulate



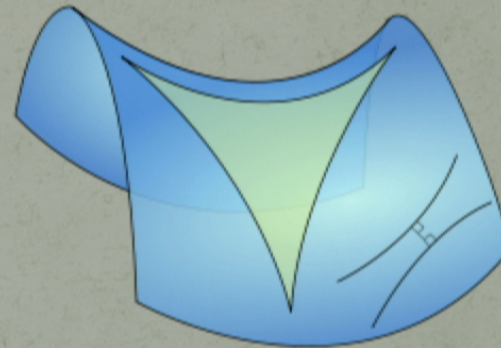
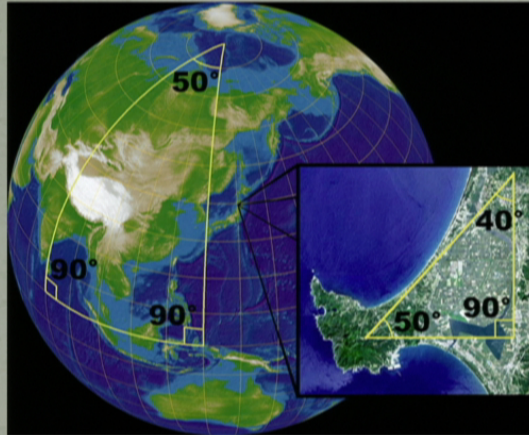
Violating Parallel Postulate: Non-Euclidean Geometry

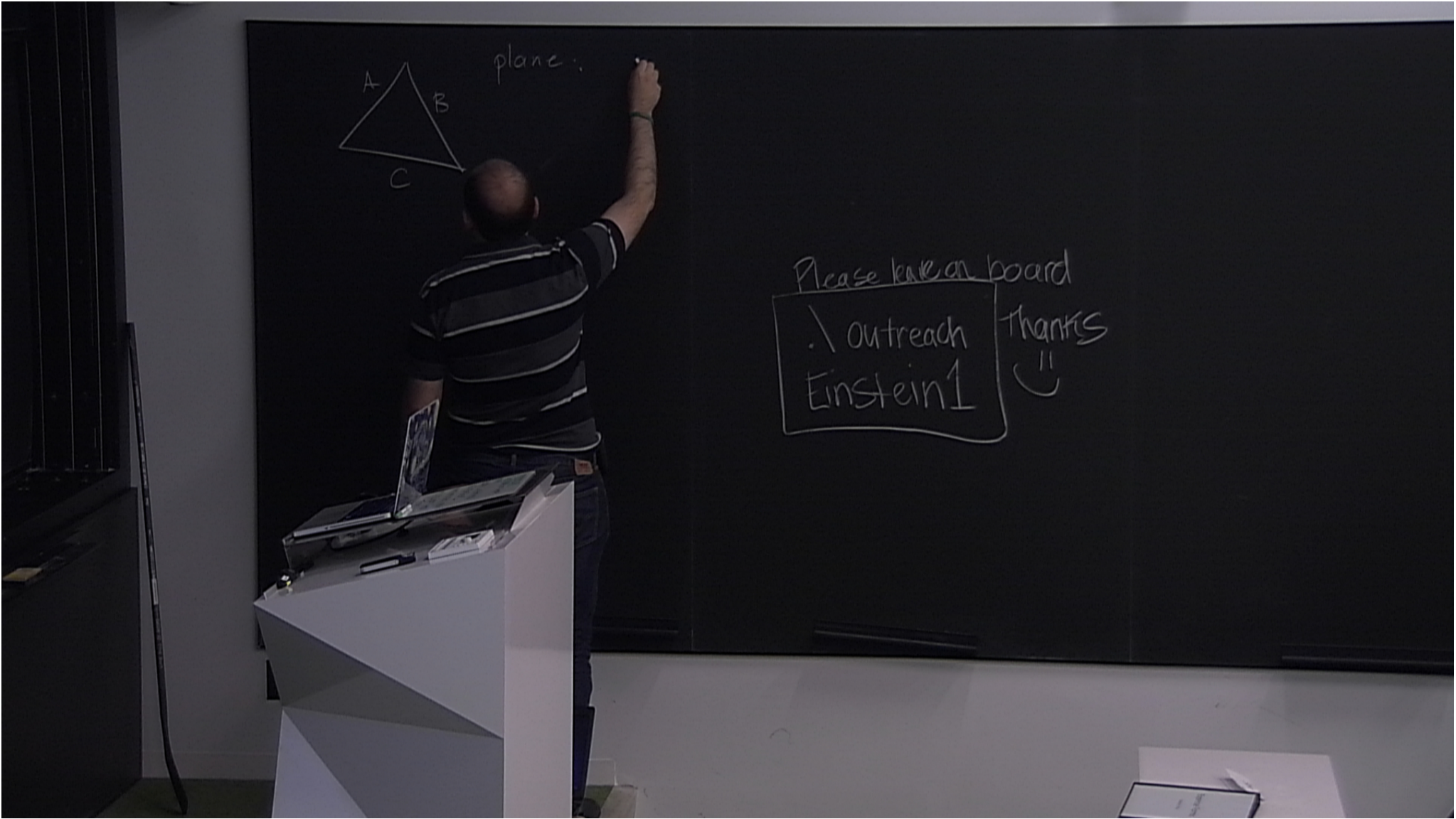
- Deviations from Euclidean geometry can be tested empirically

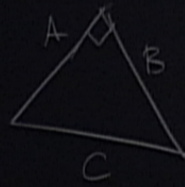


Violating Parallel Postulate: Non-Euclidean Geometry

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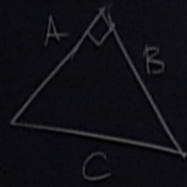


plane: $C^2 = A^2 + B^2$

sphere: $\cos\left[\frac{C}{R}\right] = \cos\left[\frac{A}{R}\right] \cos\left[\frac{B}{R}\right]$

hyp.: $\cosh\left[\frac{C}{R}\right]$

Please join on board
Outreach Einstein1
Thanks
😊



plane: $C^2 = A^2 + B^2$

sphere: $\cos\left[\frac{C}{R}\right] = \cos\left[\frac{A}{R}\right] \cos\left[\frac{B}{R}\right]$

hyperboloid: $\cosh\left[\frac{C}{R}\right] = \cosh\left[\frac{A}{R}\right] \cosh\left[\frac{B}{R}\right]$

Please talk on board
Outreach Einstein1
Thanks
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Einstein's insight: Geometrodynamics

- *Equivalence principle*: motion of test objects under the influence of gravity is independent of their mass, composition, etc.

- Gravity can be thought of as space-time geometry:

- Space v.s. Space-Time (special relativity)

$$s^2 = \Delta x^2 + \Delta y^2 + \Delta z^2 \quad s^2 = \Delta x^2 + \Delta y^2 + \Delta z^2 - c^2 \Delta t^2$$

- Space v.s. Space-Time (general relativity)

$$s^2 = \sum_{ij} g_{ij}(\mathbf{x}) \Delta x^i \Delta x^j \quad s^2 = \sum_{ij} g_{ij}(\mathbf{x}) \Delta x^i \Delta x^j - N(\mathbf{x})^2 \Delta t^2$$

- Evolution/Curvature of $g_{ij} \propto$ matter energy/pressure

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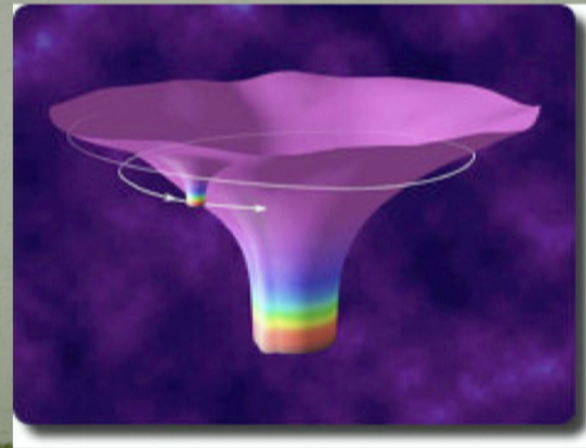
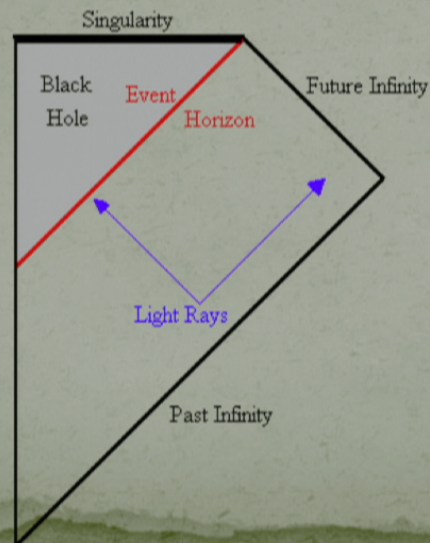
- Evolution/Curvature of $g_{ij} \propto$ matter energy/pressure

Black Hole (Schwarzschild) geometry

- Spherically symmetric gravity in vacuum ($r_s = 2GM/c^2$)

$$c^2 d\tau^2 = \left(1 - \frac{r_s}{r}\right) c^2 dt^2 - \left(1 - \frac{r_s}{r}\right)^{-1} dr^2 - r^2 (d\theta^2 + \sin^2 \theta d\varphi^2)$$

- Black Holes form on the death of massive stars and accumulate at the centers of galaxies

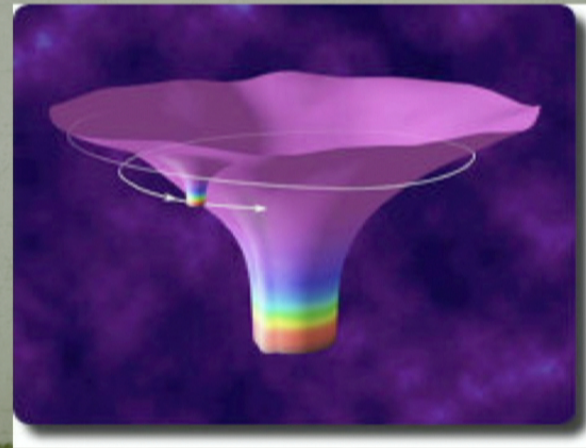
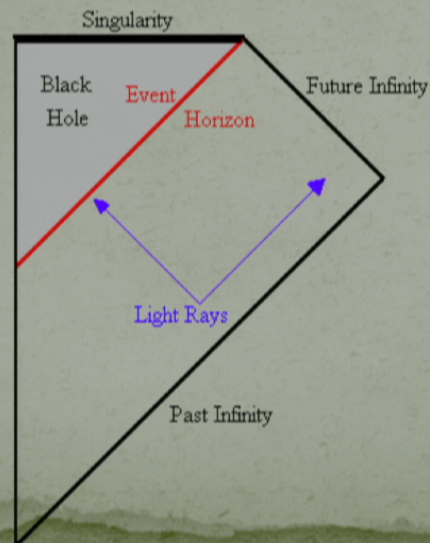


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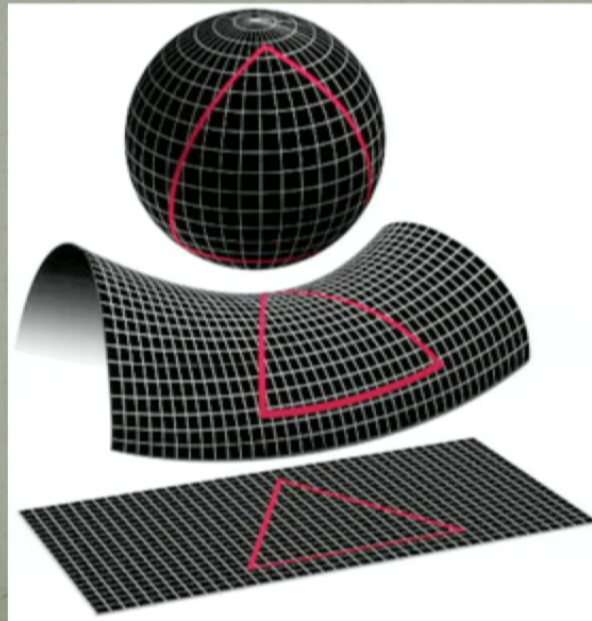
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Cosmological (FLRW) Geometry

- *Cosmological Principle*: On large scales, Universe is homogeneous and isotropic!

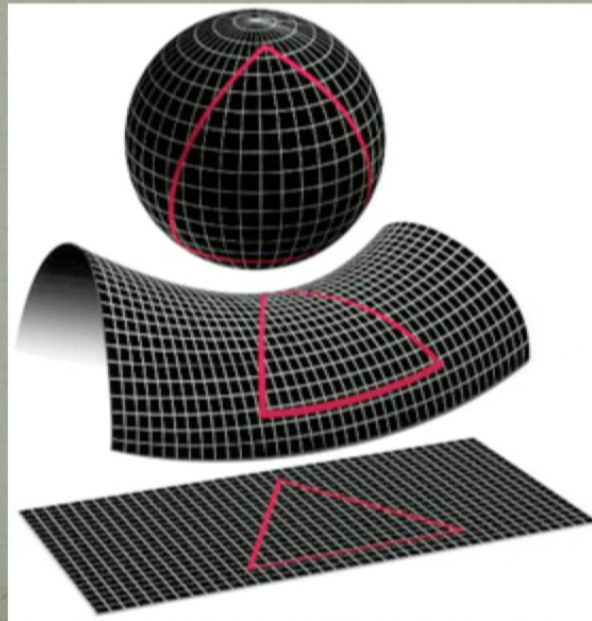
$$ds^2 = -c^2 dt^2 + a(t)^2 d\Sigma^2$$



Cosmological (FLRW) Geometry

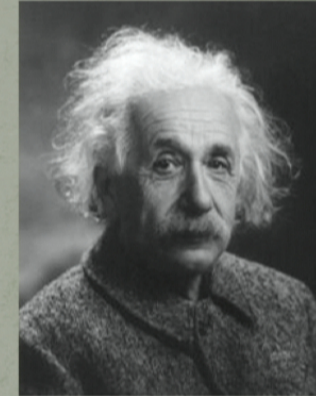
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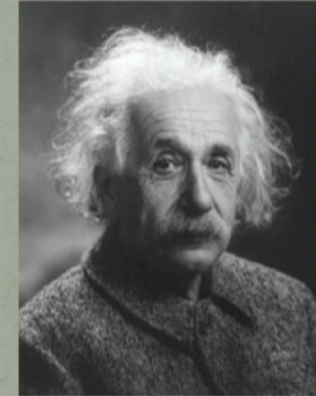
Birth of Modern Cosmology: Hubble vs. Einstein

- 1917: Einstein's General Relativity



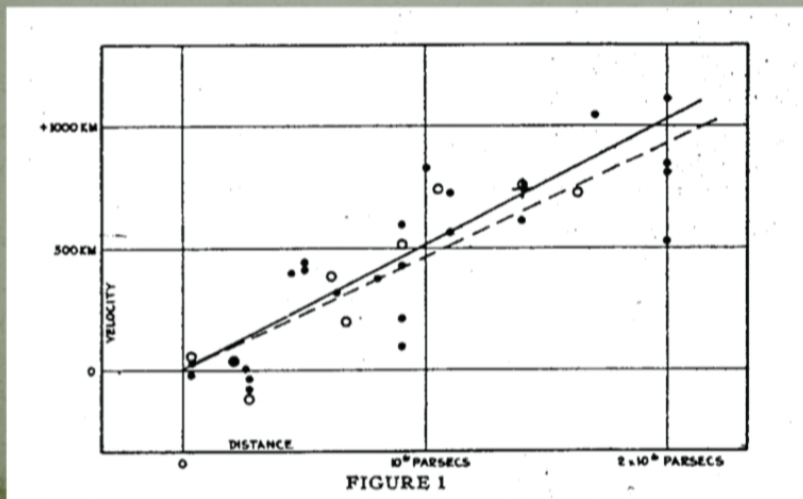
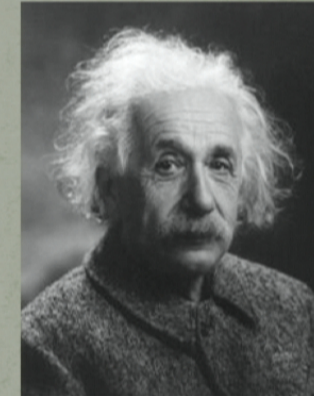
Birth of Modern Cosmology: Hubble vs. Einstein

- 1917: Einstein's General Relativity
 - Curvature = Energy/Momentum + constant
 - Static Universe needs a cosmological constant

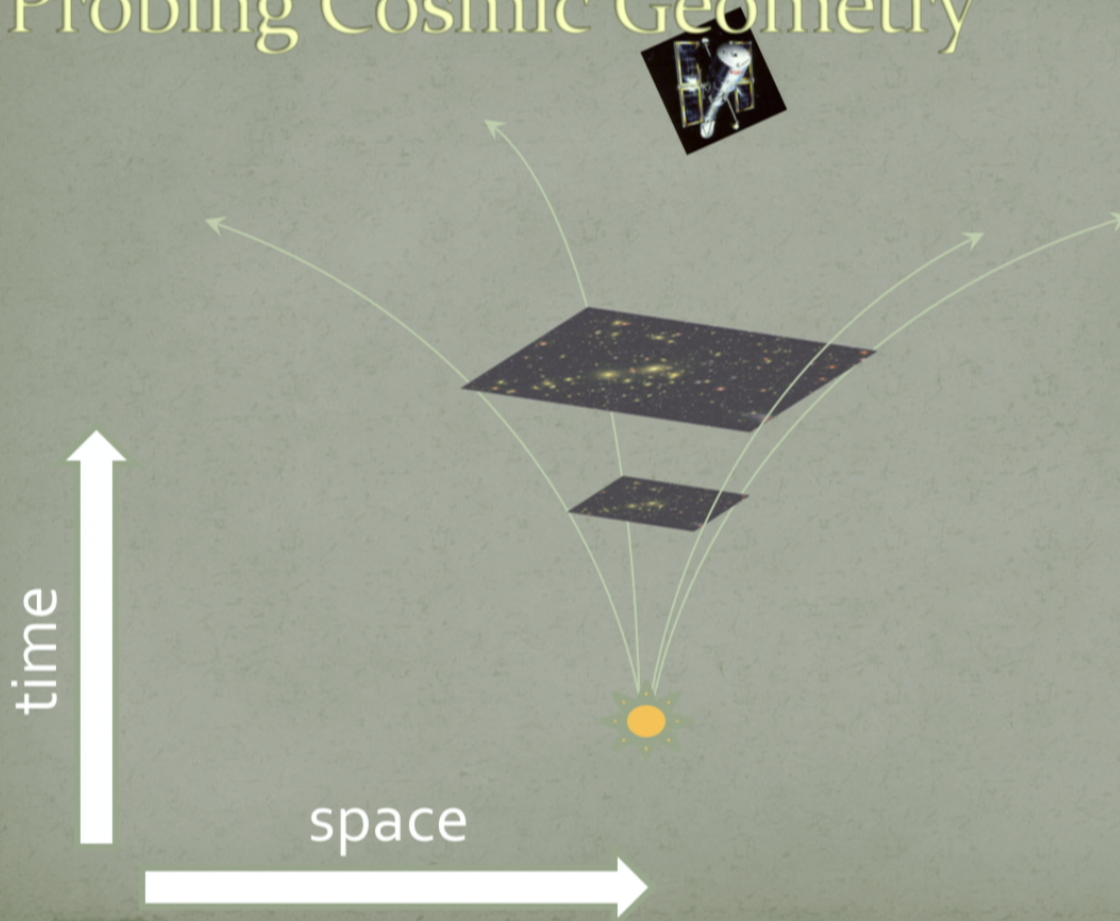


Birth of Modern Cosmology: Hubble vs. Einstein

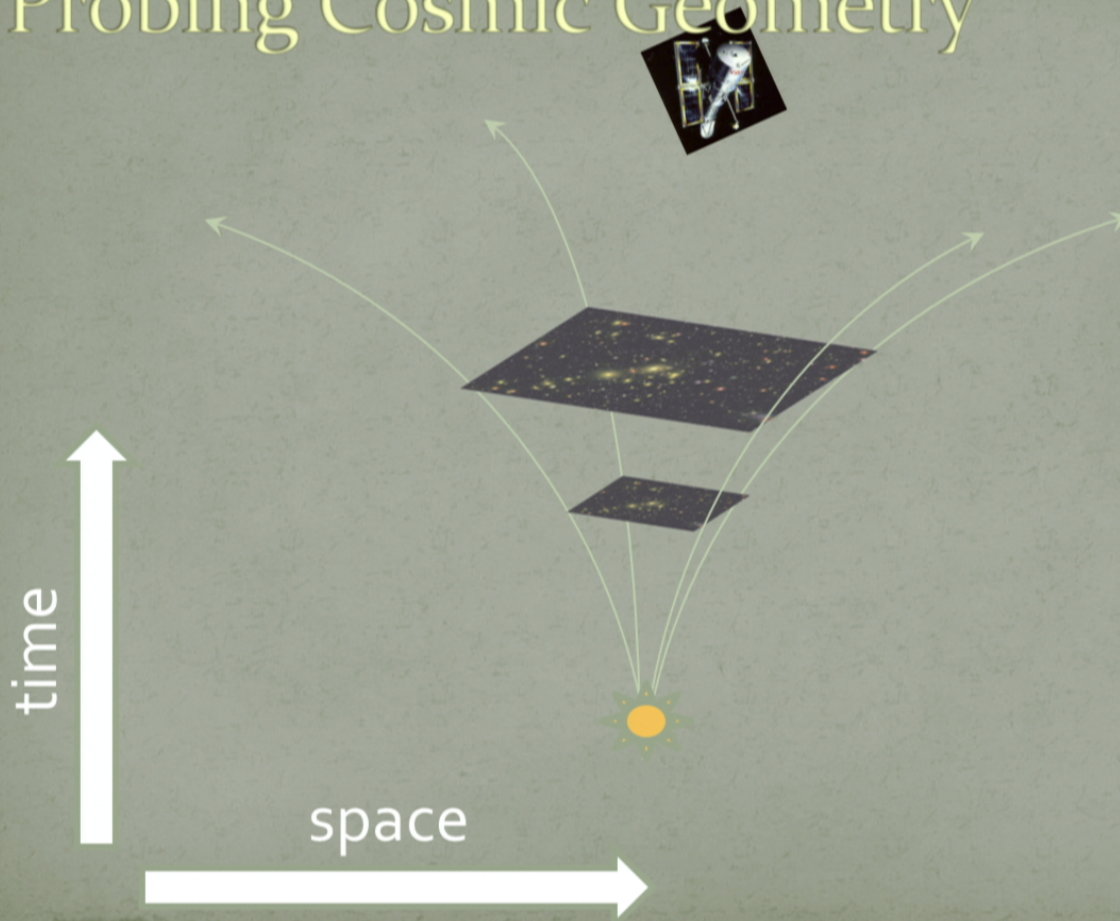
- 1917: Einstein's General Relativity
 - Curvature = Energy/Momentum + constant
 - Static Universe needs a cosmological constant
- 1929: Hubble discovers that the universe isn't static



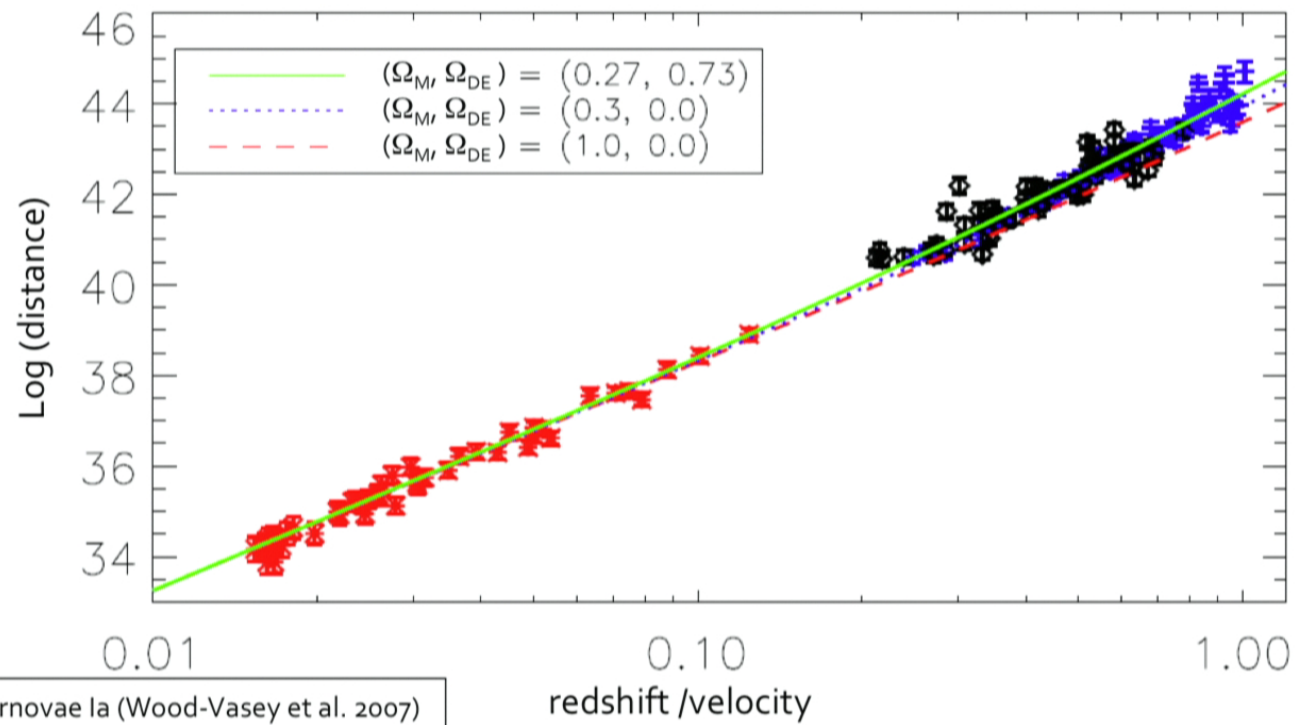
Probing Cosmic Geometry



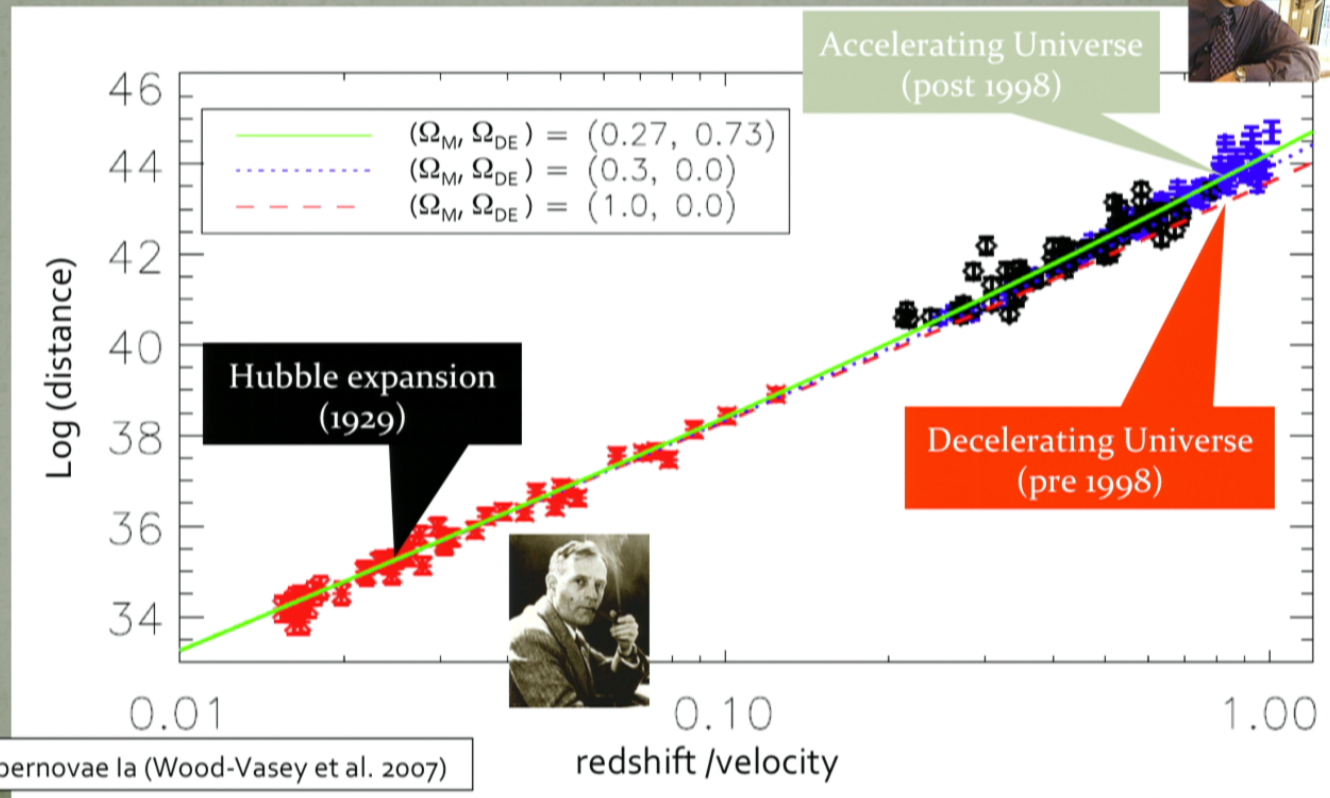
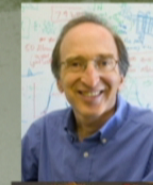
Probing Cosmic Geometry



Return of Cosmological Constant! (or Dark Energy)

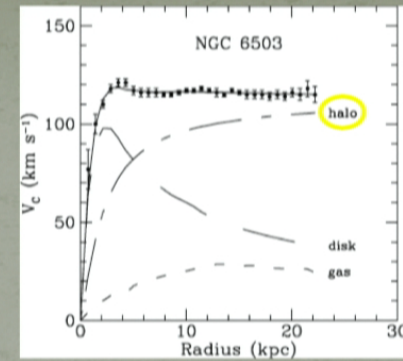


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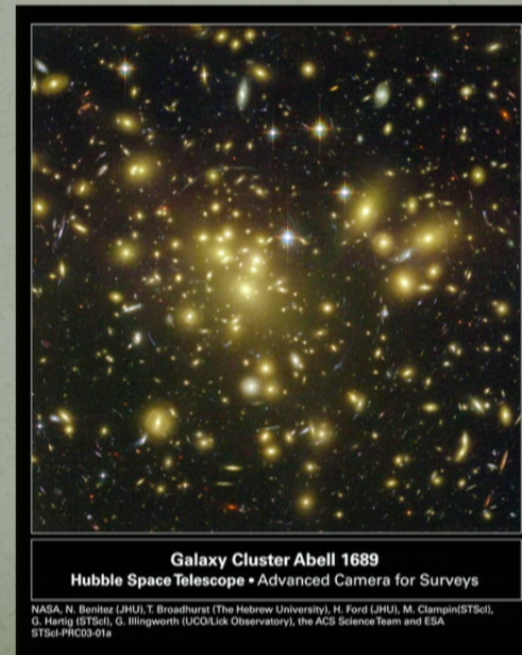
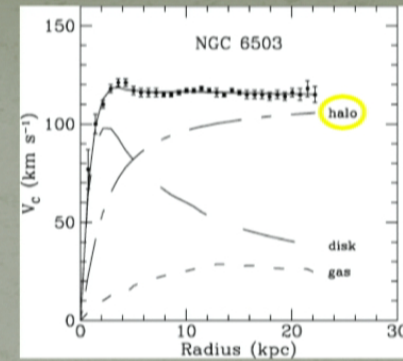
Dark Matter

- Stellar mass is not enough to explain rotation velocities
 - in clusters of galaxies (Zwicky)
 - in galaxies (Vera Rubin)
- Gravitational lensing



Dark Matter

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The other 99 percent

The other 99 percent

- Dark (Vacuum) Energy (~70%)

Parametrizing the Dark Universe

Redshift (measured from spectrum)

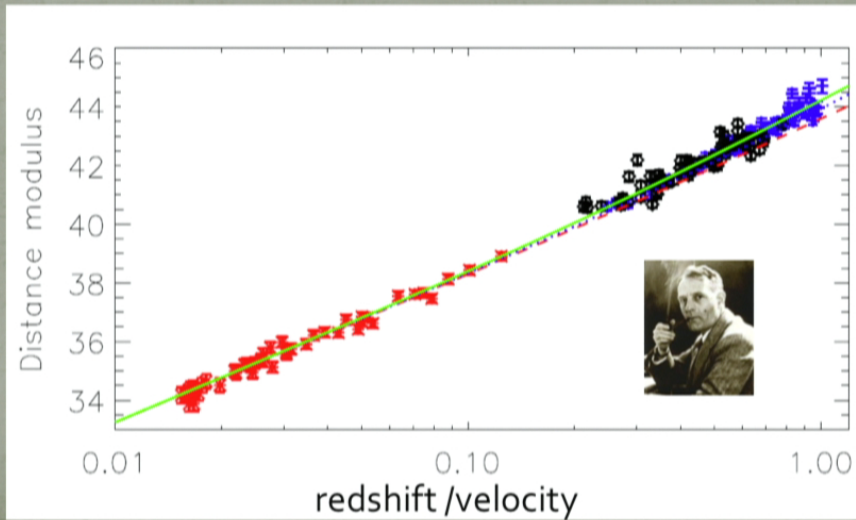
Age of the Universe!

- Hubble Constant, $\text{velocity} = H \times \text{distance}$
 - $H \approx 70 \text{ km/s/Mpc} \approx (14 \text{ Gyr})^{-1}$
 - $\rho_{\text{crit}} = 3H^2/(8\pi G) \approx 10^{-29} \text{ g/cm}^3$
(The density required to have geometrically flat space)
- Density Parameters
 - Dark Energy: $\Omega_{\text{DE}} = \rho_{\text{DE}}/\rho_{\text{crit}} \approx 0.70$
 - Dark Matter: $\Omega_{\text{DM}} = \rho_{\text{DM}}/\rho_{\text{crit}} \approx 0.26$
 - Baryons: $\Omega_{\text{B}} = \rho_{\text{B}}/\rho_{\text{crit}} \approx 0.04$
- Space is flat! $\Omega_{\text{DE}} + \Omega_{\text{DM}} + \Omega_{\text{B}} = 1 \pm 0.01$

Parametrizing the Dark Universe

Redshift (measured from spectrum)

- Hubble Constant, $\text{velocity} = H \times \text{distance}$
 - $H \cong 70 \text{ km/s/Mpc} \cong (14 \text{ Gyr})^{-1}$
 - $\rho_{\text{crit}} = 3H^2/(8\pi G) \cong 10^{-29} \text{ g/cm}^3$
(The density required to have geometrically flat space)



Parametrizing the Dark Universe

Redshift (measured from spectrum)

Age of the Universe!

- Hubble Constant, velocity = H x distance

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- $\rho_{\text{crit}} = 3H^2/(8\pi G) \approx 10^{-29} \text{ g/cm}^3$

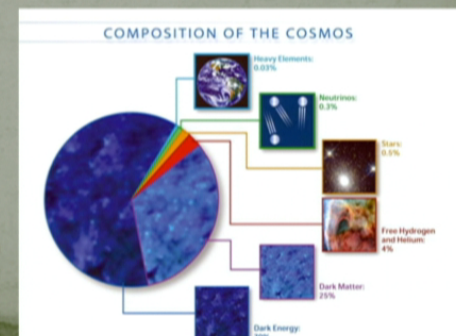
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- Density Parameters

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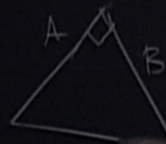


The other 99 percent

- Dark (Vacuum) Energy (~70%)
 - Only seen through its gravity (causes acceleration of cosmic expansion)
 - 60 orders of magnitude smaller than standard model prediction! (cosmological constant problem)

State of Cosmic Geometry

- Cosmological Space is flat (to 1% precision), with observed fluctuations of 1 part in 10^5



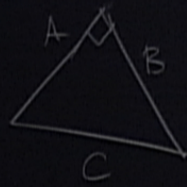
plane: $C^2 = A^2 + B^2$

sphere: $\cos\left[\frac{C}{R}\right] = \cos\left[\frac{A}{R}\right] \cos\left[\frac{B}{R}\right]$

hyperboloid: $\cosh\left[\frac{C}{R}\right] = \cosh\left[\frac{A}{R}\right] \cosh\left[\frac{B}{R}\right]$

Φ

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.\ Outreach Einstein1
Thanks
☺



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$$\frac{g_{11}}{-1} = \frac{\Phi}{C^2} = \frac{V^2}{C^2}$$

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State of Cosmic Geometry

- Cosmological Space is flat (to 1% precision), with observed fluctuations of 1 part in 10^5
- A six-parameter model (Λ CDM) is consistent with all measurements:
 - Dark matter: **what is it?**
 - Dark energy: **cosmological constant problem**
 - Baryons, galaxy formation: **where are they?**