COSMOLOGY 101
1

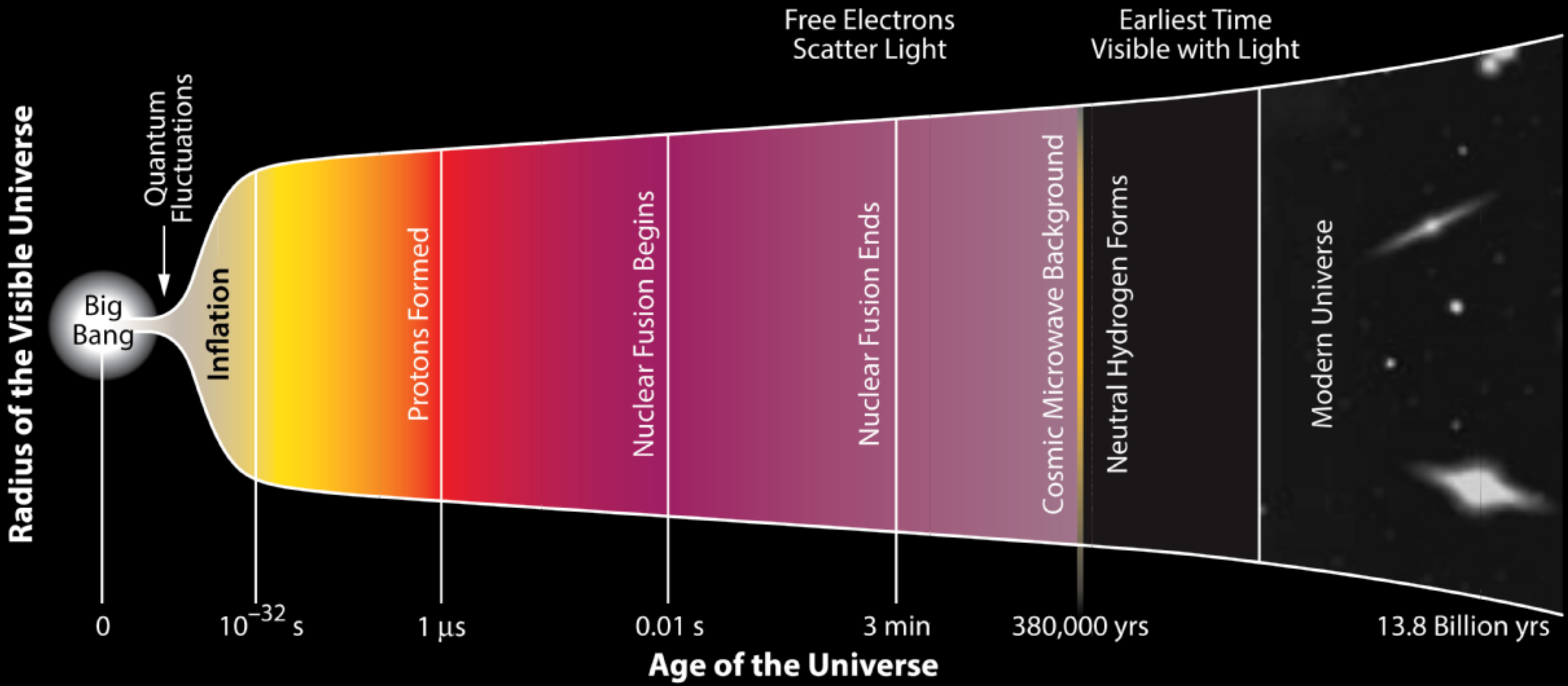
Chris Pearson : RAL Space

July 2015

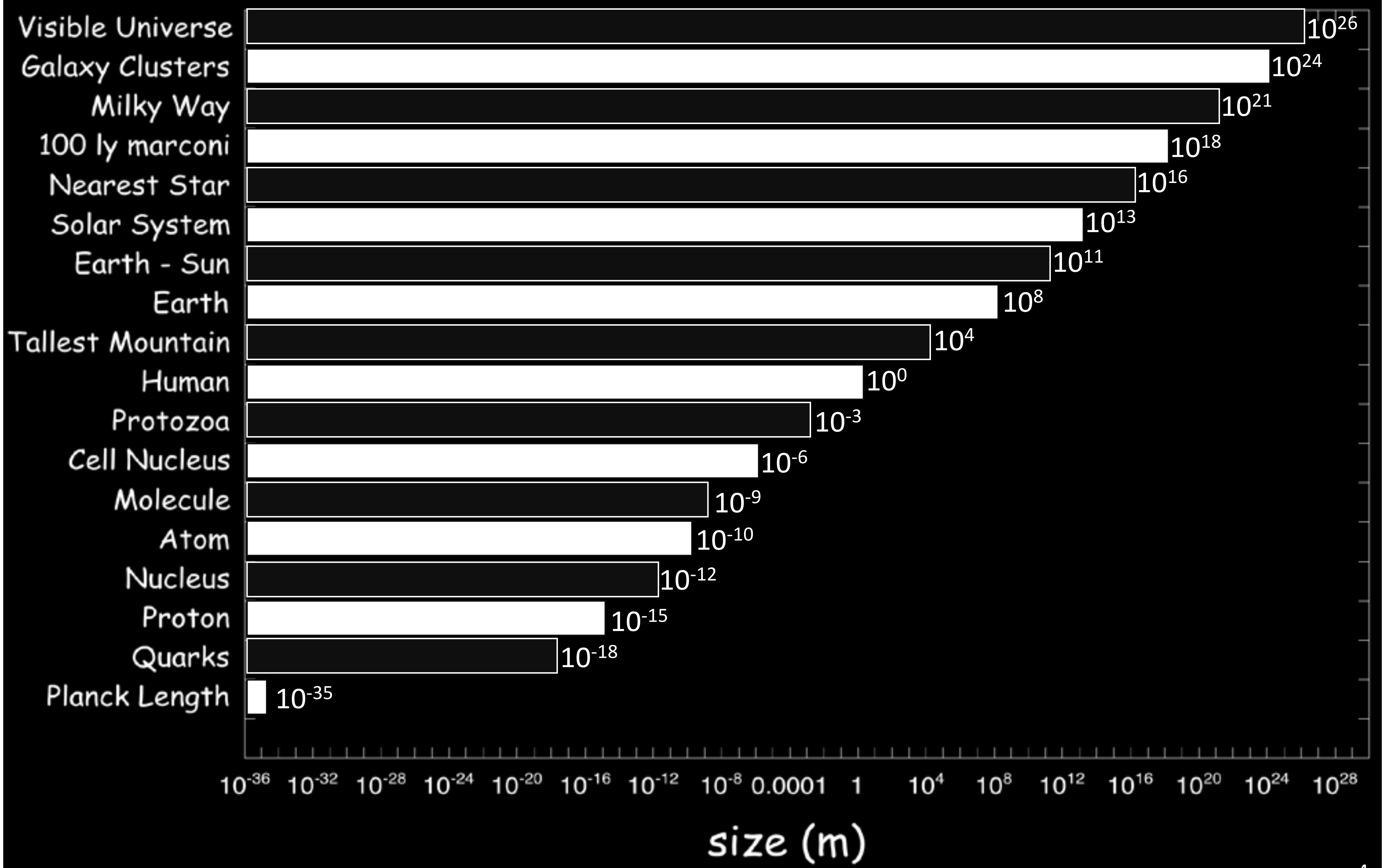
COSMOLOGY

- How did the Universe Begin ?
- How old is the Universe ?
- How big is the Universe ?
- Where are we in the Universe ?
- What is the Universe made of ?
- Will the Universe end ?

A Very Brief History of Time



The Scale of the Universe



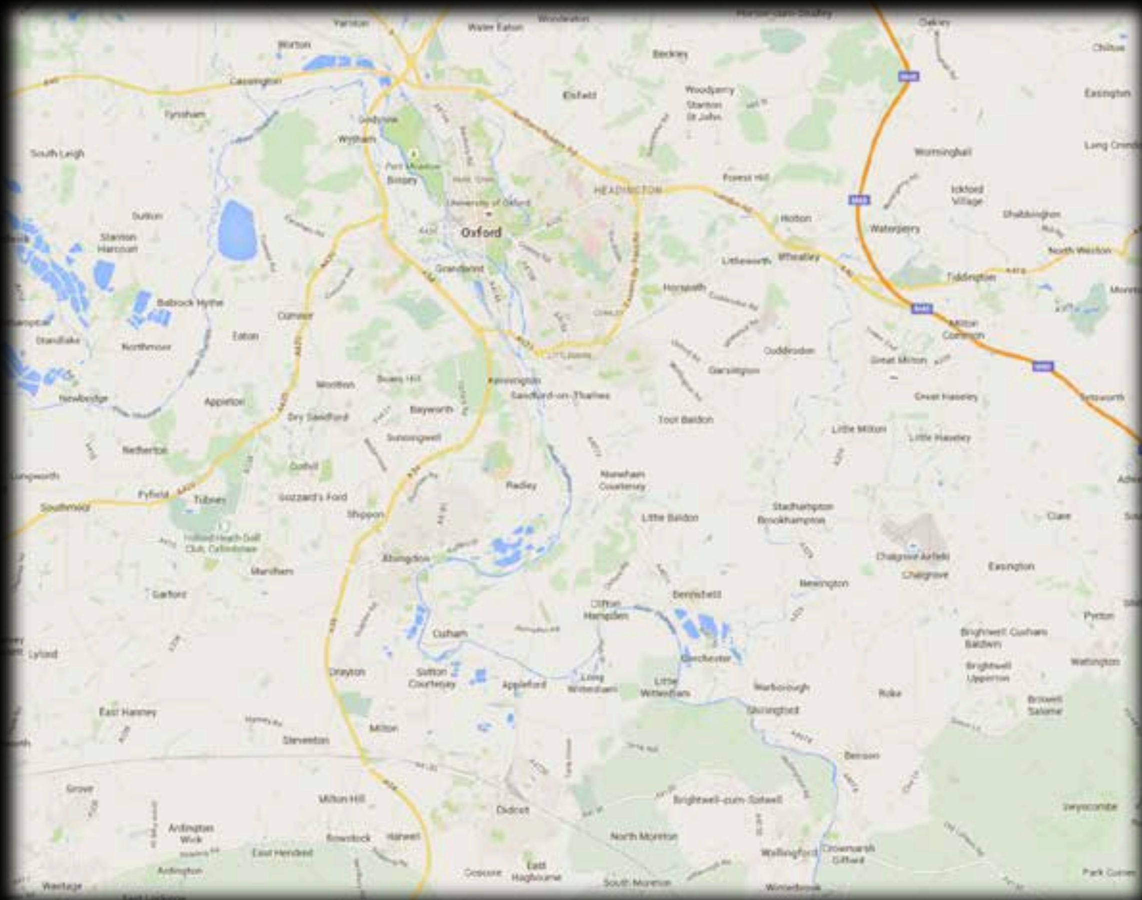
Our Place in the Universe

Rutherford Appleton Laboratory

Scale ~ 1 km

Our Place in the Universe

Rutherford Appleton Laboratory
Oxfordshire



Scale ~ 10 km

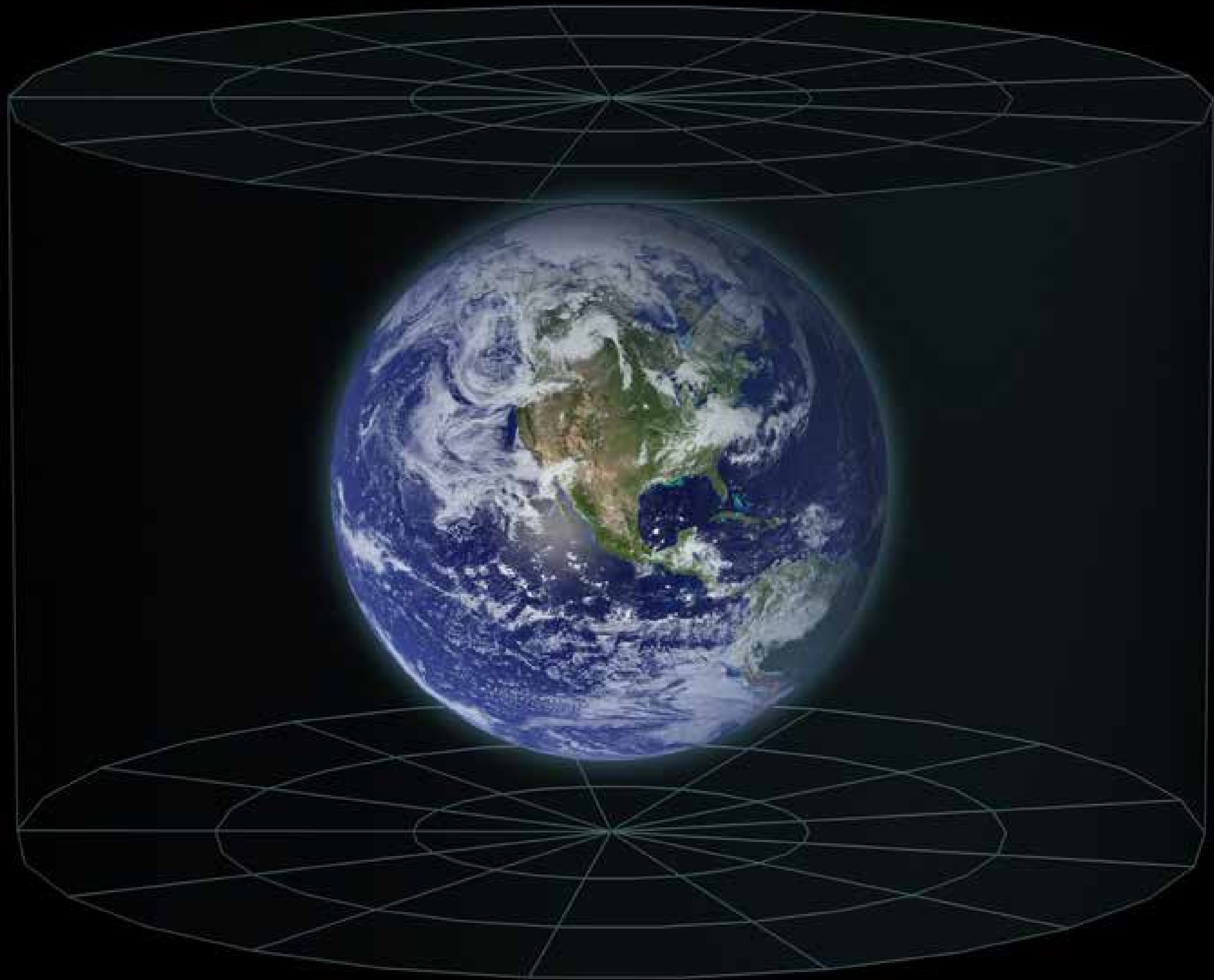
Our Place in the Universe

Rutherford Appleton Laboratory
Oxfordshire
United Kingdom

Scale ~ 100 km

Our Place in the Universe

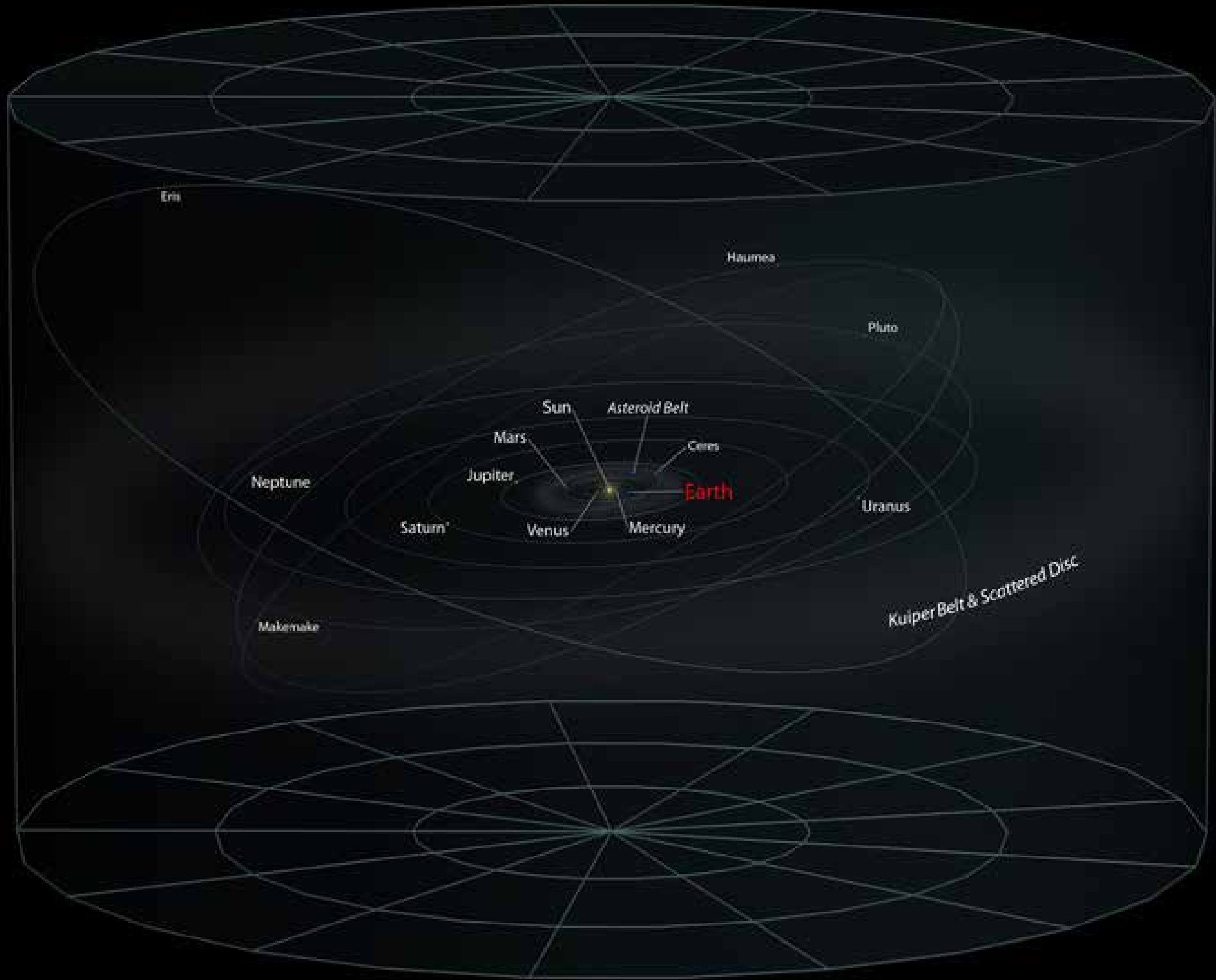
Rutherford Appleton Laboratory
Oxfordshire
United Kingdom
Planet Earth



Scale ~ 1000 km

Our Place in the Universe

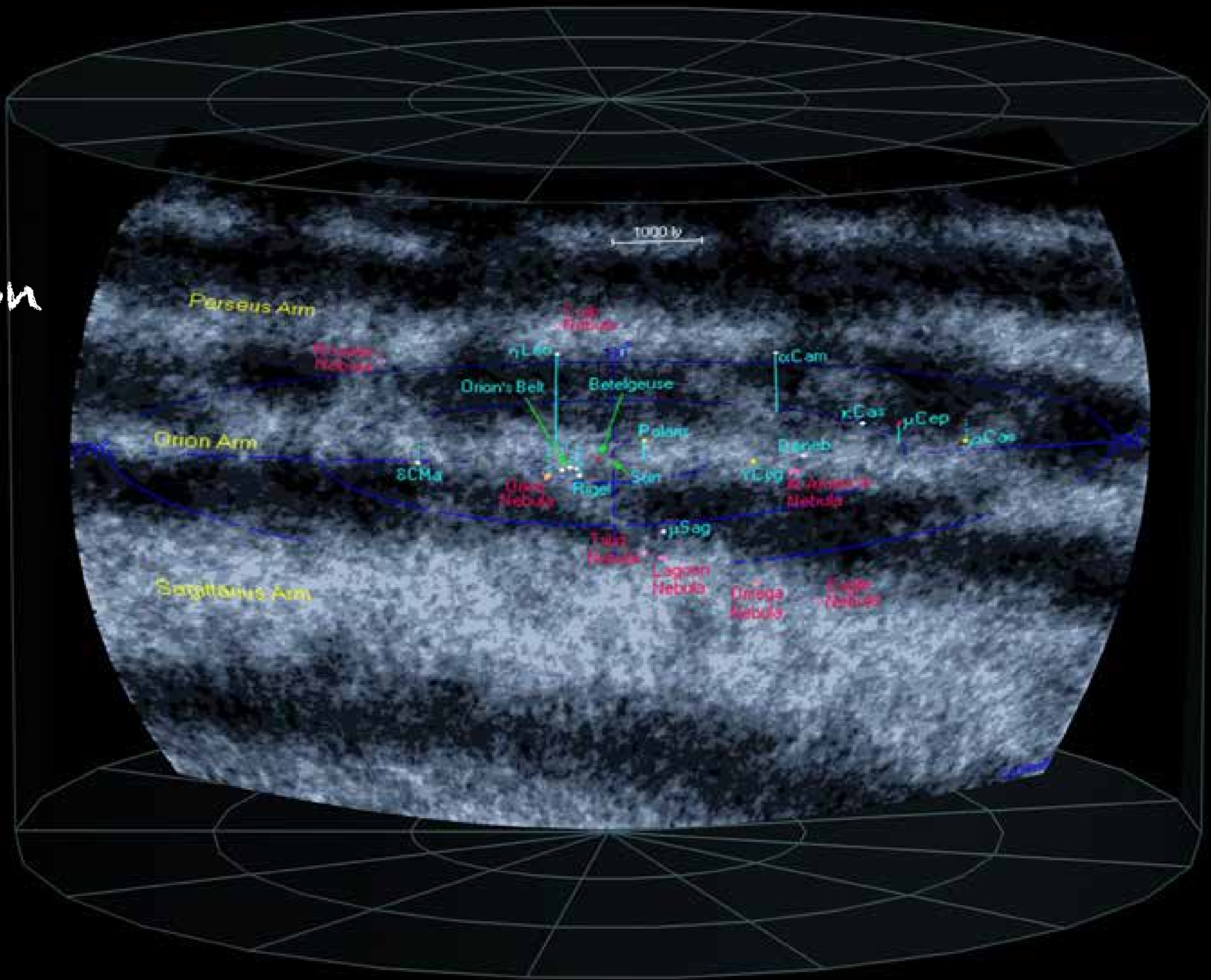
Rutherford Appleton Laboratory
Oxfordshire
United Kingdom
Planet Earth
Solar System



Scale ~ 1 A.U. = 1.5×10^8 km or 7 lm

Our Place in the Universe

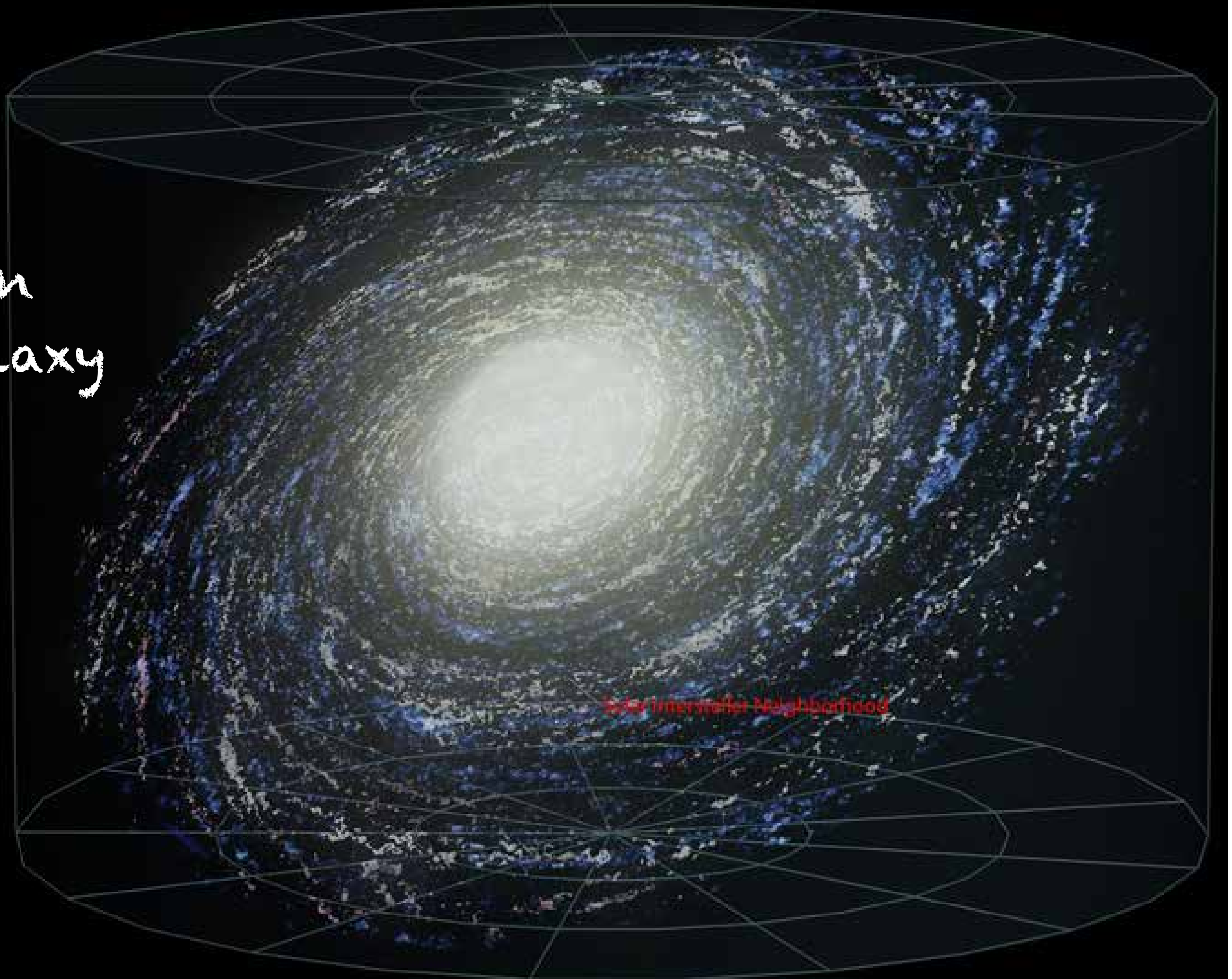
Rutherford Appleton Laboratory
Oxfordshire
United Kingdom
Planet Earth
Solar System
Spiral Arm of Orion



Scale ~ 1000 light years = 9.5×10^{15} km

Our Place in the Universe

Rutherford Appleton Laboratory
Oxfordshire
United Kingdom
Planet Earth
Solar System
Spiral Arm of Orion
The Milky Way Galaxy



Scale ~ 100,000 light years ~ 30 kpc

Our Place in the Universe

Rutherford Appleton Laboratory
Oxfordshire
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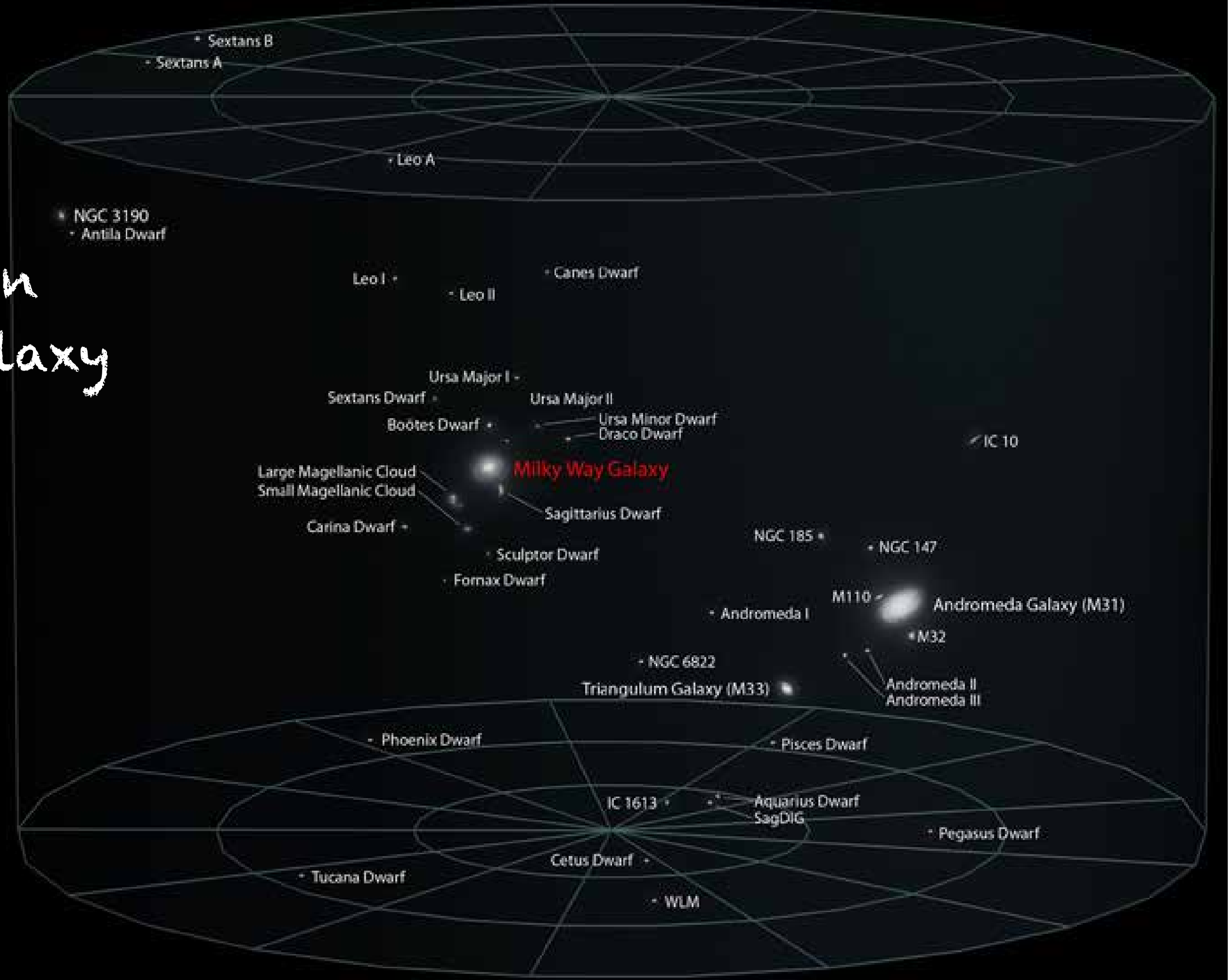
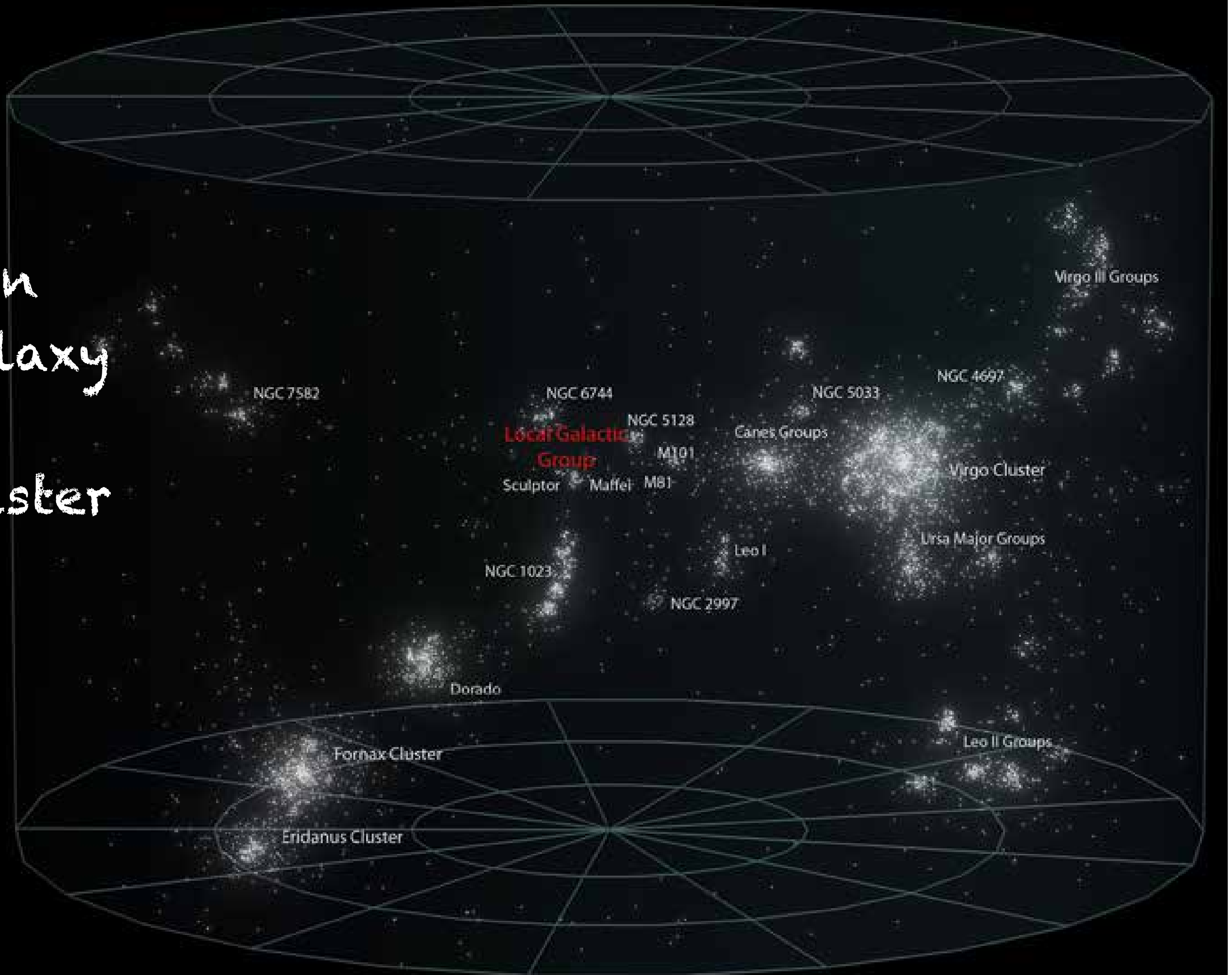
Planet Earth
Solar System
Spiral Arm of Orion
The Milky Way Galaxy
The Local Group



Scale ~ 1 million light years ~ 0.5 Mpc

Our Place in the Universe

Rutherford Appleton Laboratory
Oxfordshire
United Kingdom
Planet Earth
Solar System
Spiral Arm of Orion
The Milky Way Galaxy
The Local Group
Near the Virgo Cluster



Scale ~ 50 million light years

Our Place in the Universe

Rutherford Appleton Laboratory
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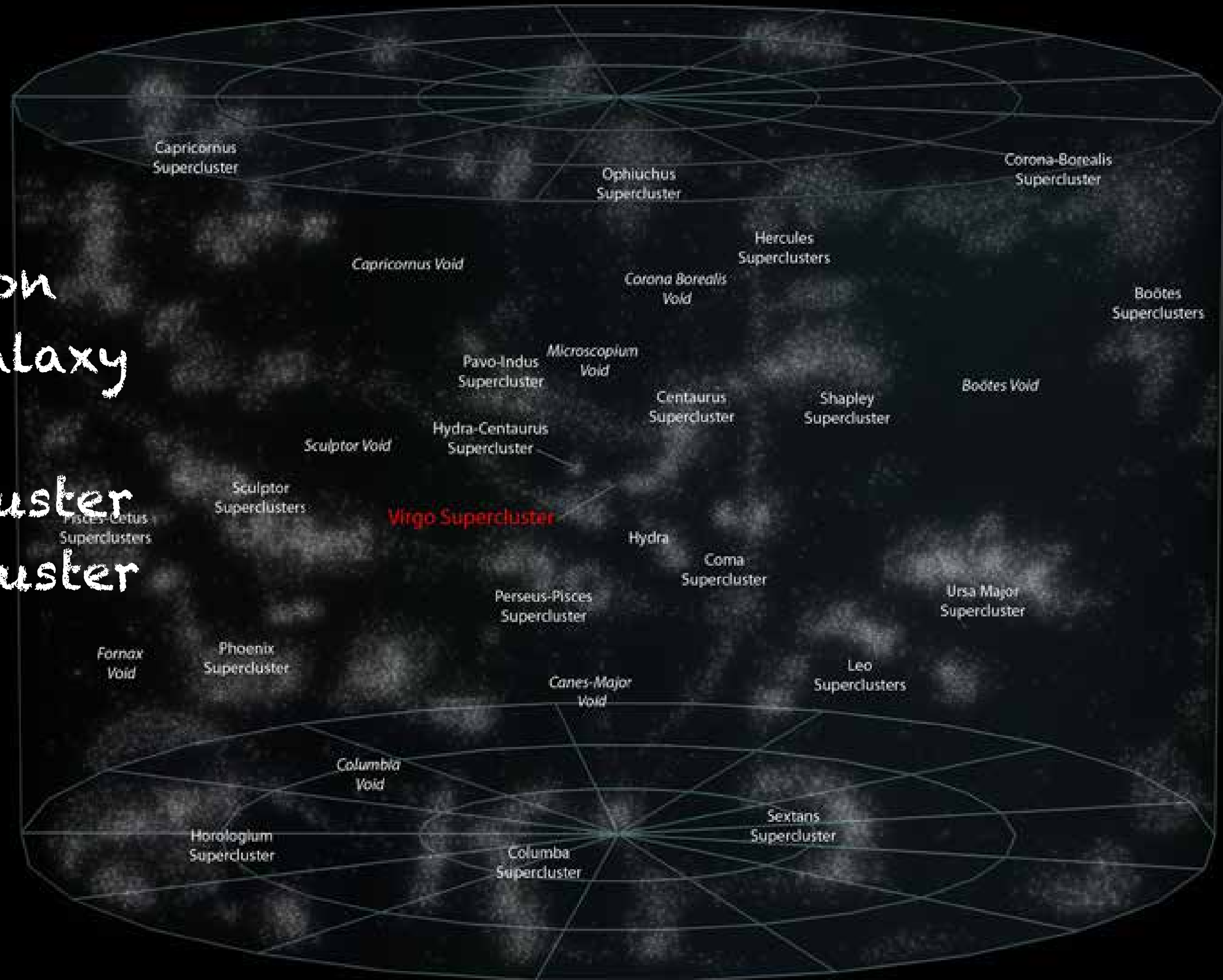
United Kingdom
Planet Earth
Solar System
Spiral Arm of Orion
The Milky Way Galaxy
The Local Group
near the Virgo Cluster
The Local Supercluster



Scale ~ 100 million light years

Our Place in the Universe

Rutherford Appleton Laboratory
Oxfordshire
United Kingdom
Planet Earth
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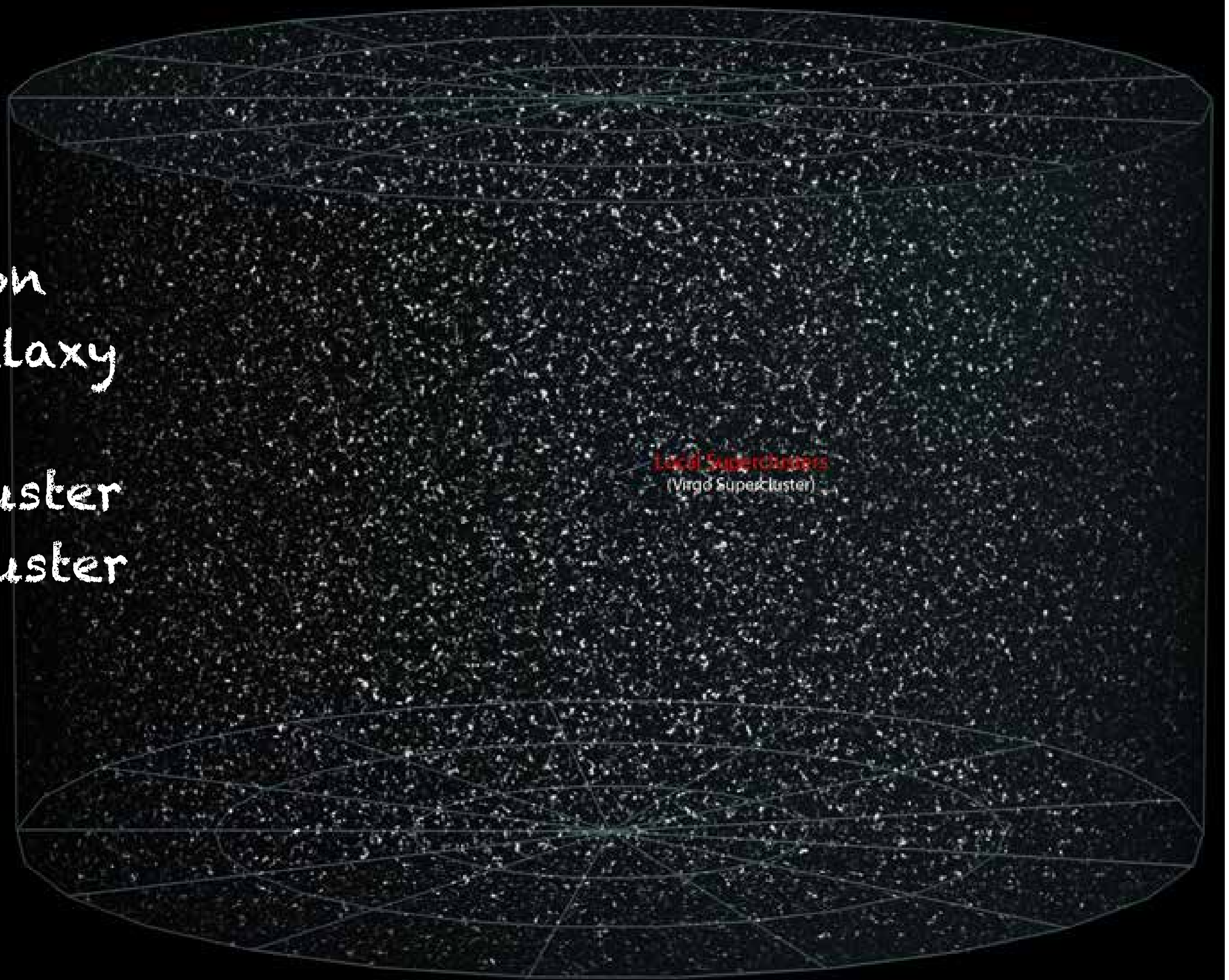
The Local Group
near the Virgo Cluster
The Local Supercluster
The Universe



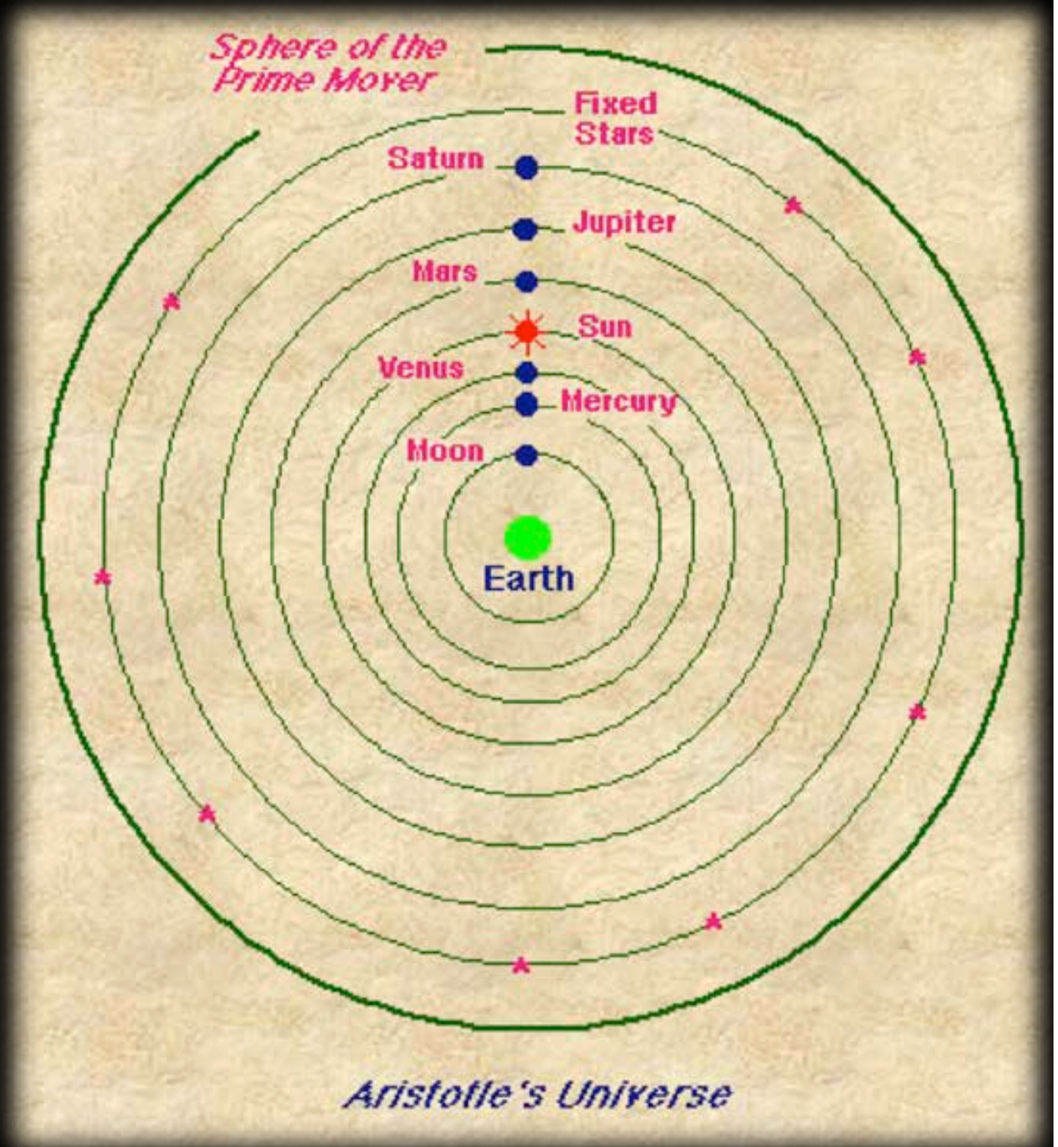
Scale ~ 90 billion light years ~ 28Gpc

The Birth of Cosmology

Ancient Greeks: The first cosmological model

Aristotle (384-322 B.C.)

Geocentric

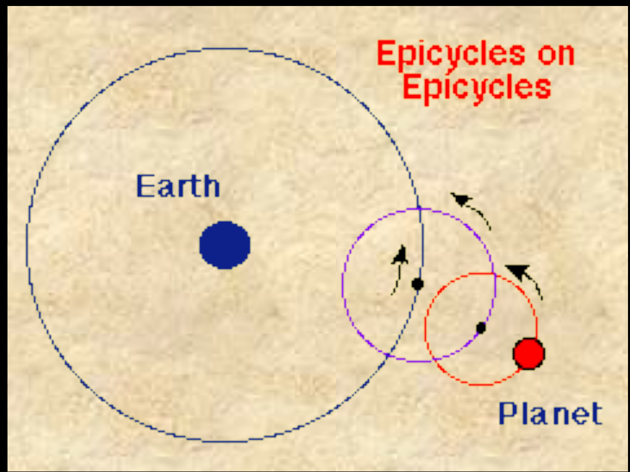


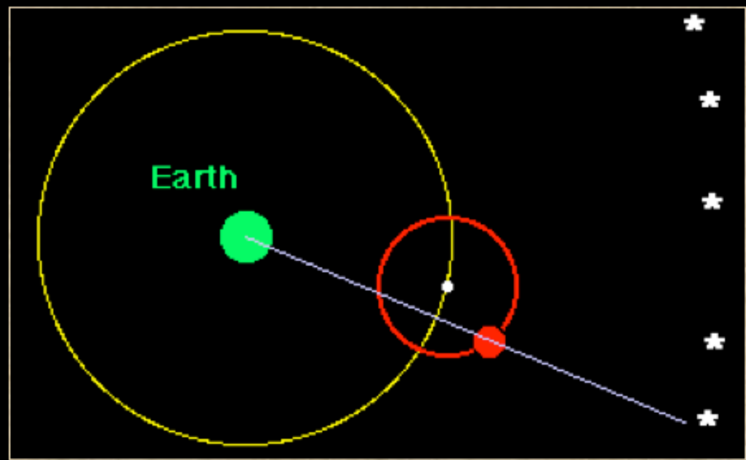
The Birth of Cosmology

Ptolemy (90-168 A.D.)

Geocentric

Perfect motion should be in circles, so the stars and planets, being heavenly objects, moved in circles.





The Birth of Cosmology

Copernicus (1473-1543)

Heliocentric

Copernican Cosmological Principle

The Earth does not occupy a special place in the Universe

The Birth of Cosmology

Olbers' Paradox: Why is the Sky so Dark ?

In an infinitely large and old Universe populated by stars of number density, *n*, average luminosity, *L*

Flux from star of Luminosity, *L*, at distance, *r* : $S(r) = \frac{L}{4\pi r^2}$

Intensity, *I*, from a shell of stars of thickness *dr*

$$dI(r) = \frac{L}{4\pi r^2} n r^2 dr = \frac{nL}{4\pi} dr \qquad \{Wm^{-2}sr^{-1}\}$$

Intensity from shell is independent of distance.
Integrating over all shells ➠ Total Intensity, *I*

$$I = \int_0^\infty dI(r)dr = \frac{nL}{4\pi}\int_0^\infty dr = \infty !!!!$$

The Sky should be infinitely bright !!!

The Birth of Cosmology

Olbers' Paradox: Why is the Sky so Dark ?

Solutions ?

1. Absorption by dust ?

   -Dust would be heated until it emitted at the same temperature as the stars ✗

2. Not all lines of sight intersect a star ?

   - Finite angular size of stars may block a line of sight ➡ Intensity = surface brightness of stars ✗

3. Number density and Luminosity not constant ($nL \neq constant$) ?

   - would require nL to decline faster than 1/r, $r \rightarrow \infty$ ✗

4. Universe is not infinitely large ?
   - For a finite universe, the average stellar background intensity, $I \sim (nL/4p)r_{max}$

5. Universe is not infinitely old ?
   - Not all light has reached us, the maximum intensity would be $I \sim (nL/4p)ct_o$

Primary Resolution to Olbers' Paradox - The Universe is NOT infinitely old
Not all the light from stars in the Universe has yet had time to reach us

Thermodynamic interpretation:
why is the Universe so cold ?- Stars have not had time to heat up Universe

Olbers' Paradox - Evidence for a finite age of our Universe

The Birth of Cosmology

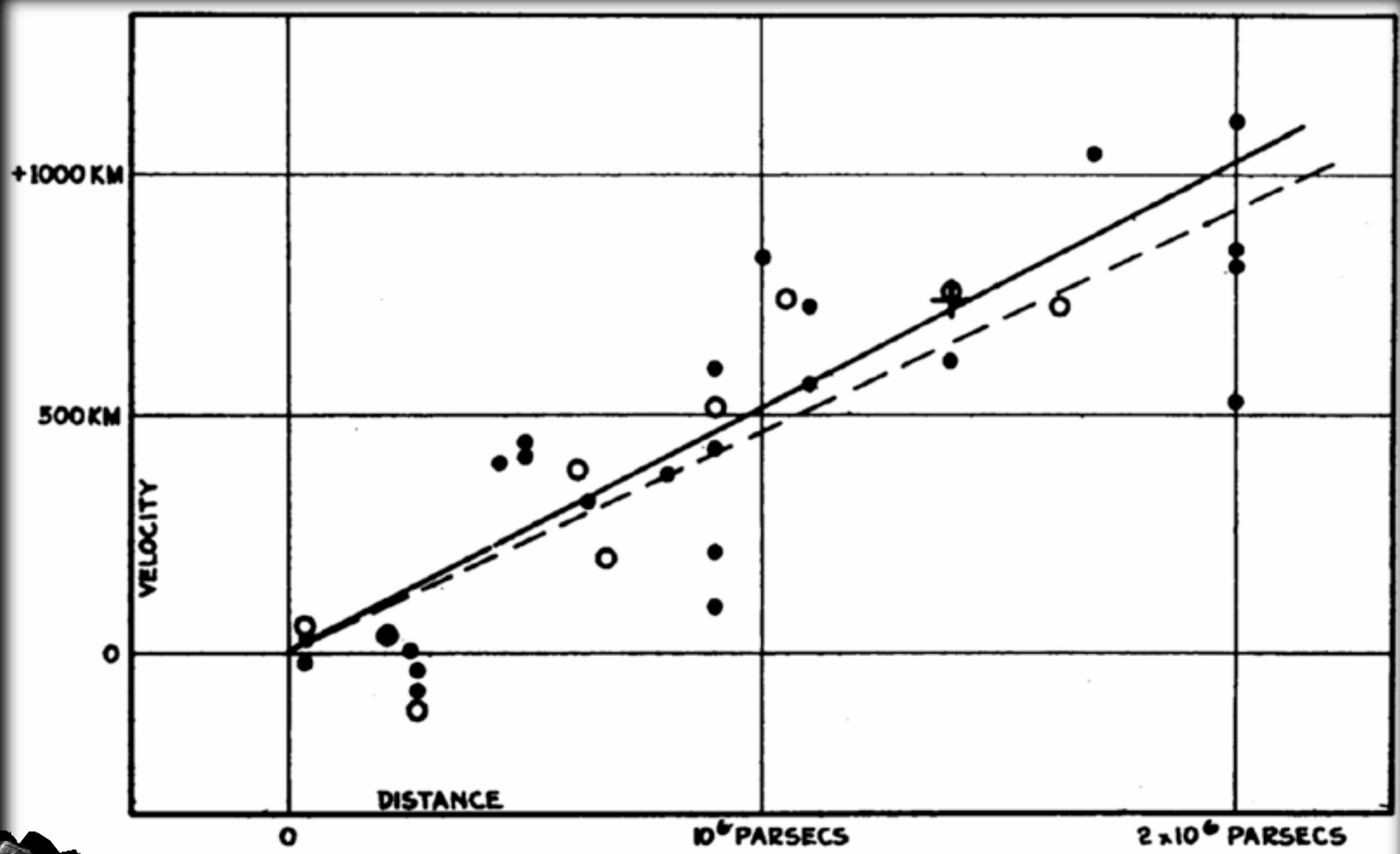
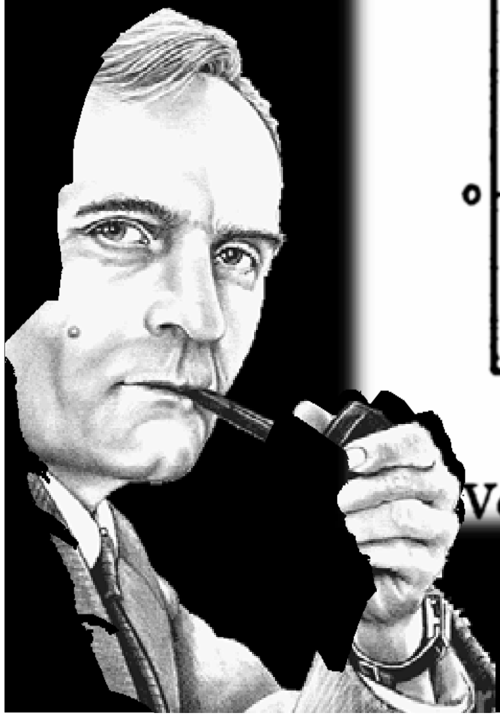


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.



Measure a Doppler shift in spectral lines $z = \frac{\lambda_o - \lambda_e}{\lambda_e}$

The Birth of Cosmology

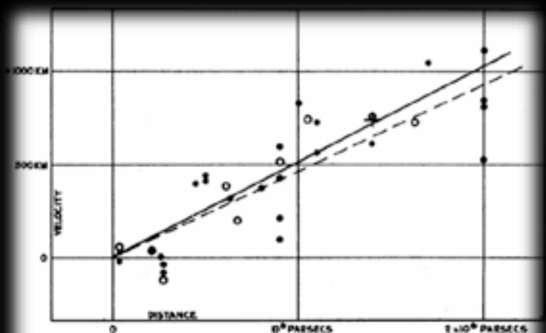


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

1) (almost) all galaxies are moving *away* from us

2) More distant galaxies are moving away *faster*

$$V \propto d \qquad V = H_0 d$$

H_0 : The Hubble Constant

The Cosmological Principle

***Fundamental Observer* :**

Someone at rest with respect to the rest of the Universe in their locality.

Universe ~ smooth fluid ~ substratum

Fundamental observers are co-moving with it.

***Homogeneity* :**

Same picture of Universe at any time seen by all *Fundamental Observers.*

No preferred locations

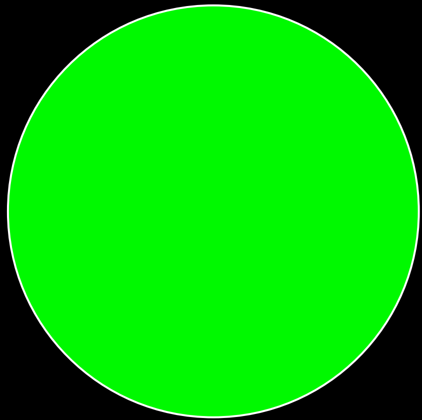
Isotropy :

The Universe looks the same in all directions to a *Fundamental Observer.*

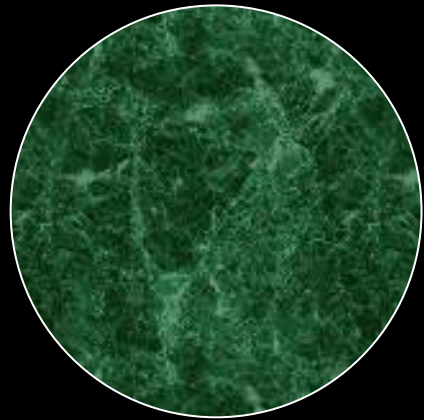
No preferred Directions

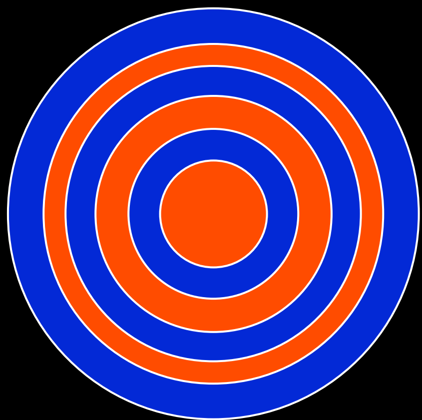
The Cosmological Principle

homogeneous

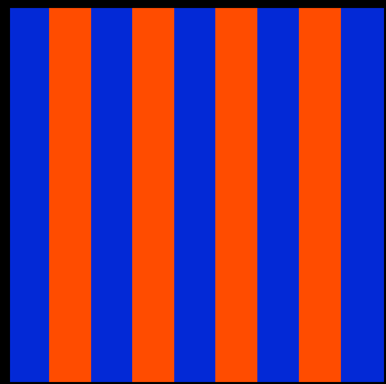


inhomogeneous





isotropic (about centre)



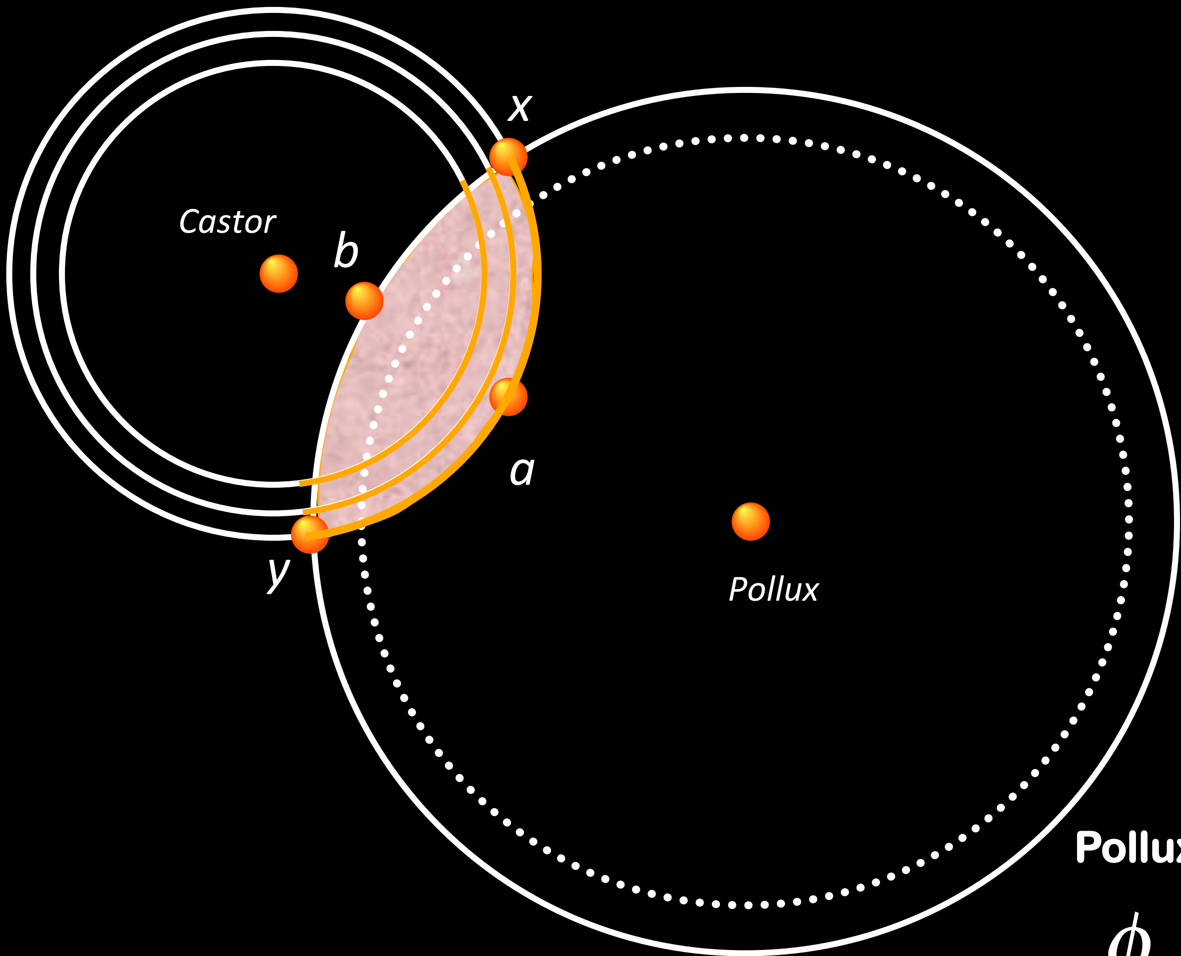
anisotropic

The Cosmological Principle

Isotropy + Copernican Principle implies Homogeneity

Castor *sees* Isotropic Universe

$$\phi_x = \phi_a = \phi_y$$



Pollux *sees* Isotropic Universe

$$\phi_x = \phi_b = \phi_y$$

The Cosmological Principle

Copernican Cosmological Principle
The Earth does not occupy a special place in the Universe

The Cosmological Principle
At any single epoch,
the Universe appears Homogeneous and Isotropic to all Fundamental Observers

Perfect Cosmological Principle
AT ALL TIMES
The Universe appears Homogeneous and Isotropic to all Fundamental Observers

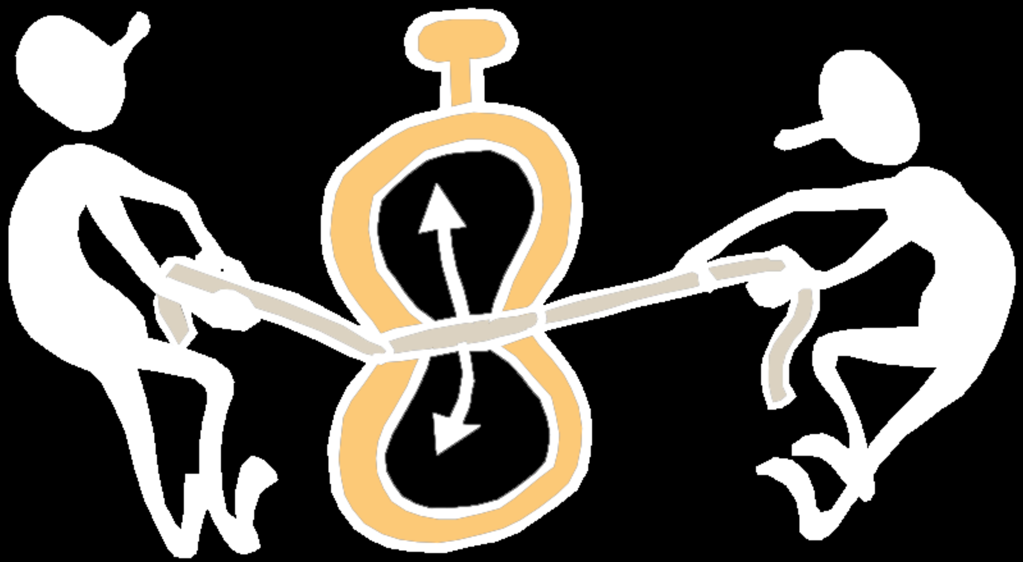
Anthropic Cosmological Principle
(WEAK) The conditions necessary for sentient life will only exist in a Universe where the laws of physics are the way they are as seen by us.

(STRONG) There could be many different universes, or regions in a single Universe, where the laws of physics are different.

The Cosmological Principle

Cosmological Principle (Homogeneity) implies a cosmic time

Since the Universe appears the same to all fundamental observers at any given time, All observers see the same sequence of events => they can all synchronize their watches to some event which occurs in the history of the Universe, thereafter all the watches measure the same cosmological time



The Cosmological Principle

Is the real Universe Isotropic and Homogeneous ?

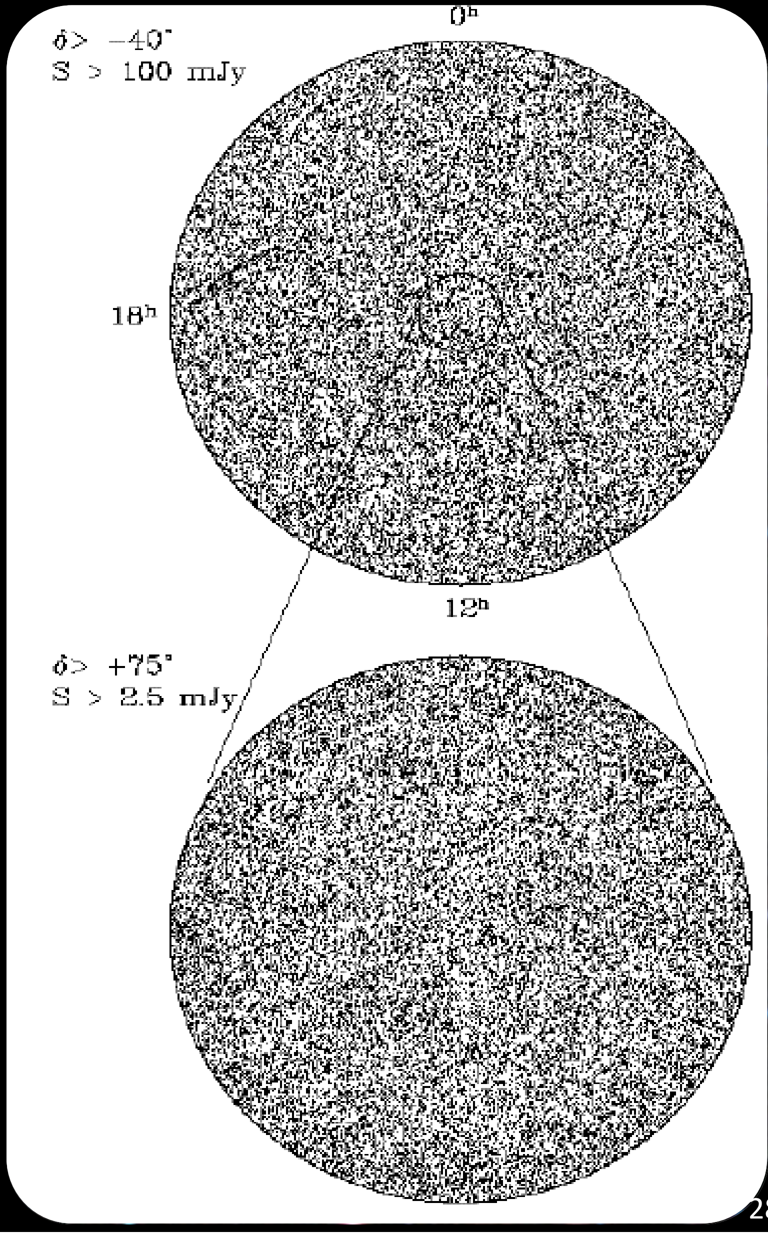
Matter

Small scales : Highly anisotropic

Large scales > 100Mpc

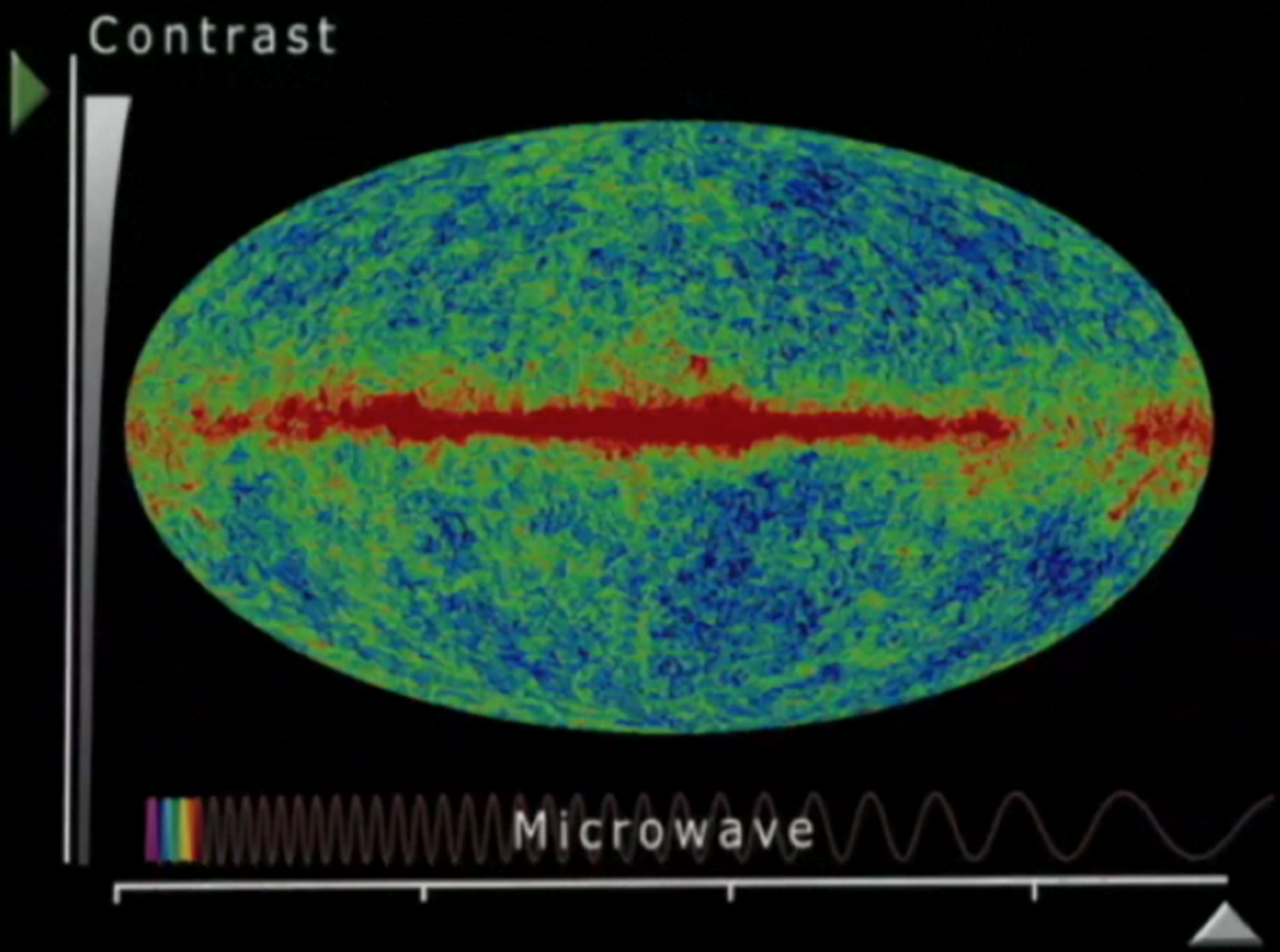
Clusters / Superclusters : fairly isotropic

Radio Sources: isotropic to a few percent



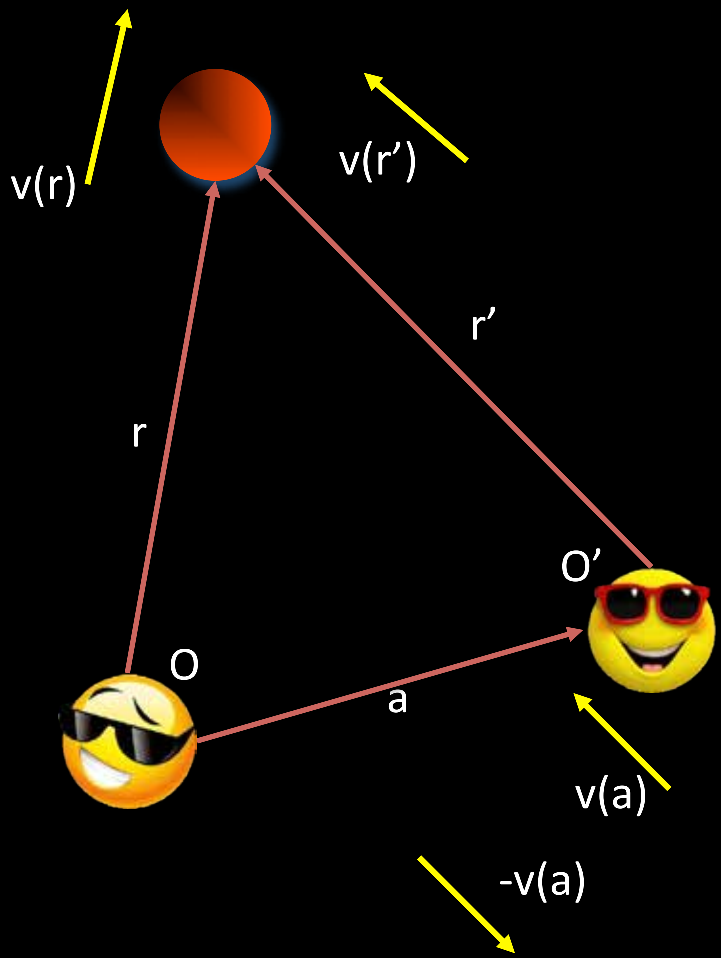
The Cosmological Principle

Radiation



The Cosmological Principle

Hubble's Law follows from the Cosmological Principle



$$r' = r - a \qquad (r, r', a = \text{vectors}) \quad (1)$$

$$v'(r') = v(r) - v(a) \quad (2)$$

$$(1) \Rightarrow v'(r') = v'(r - a) \quad (3)$$

Cosmological Principle

Homogeneity => O & O' see same events

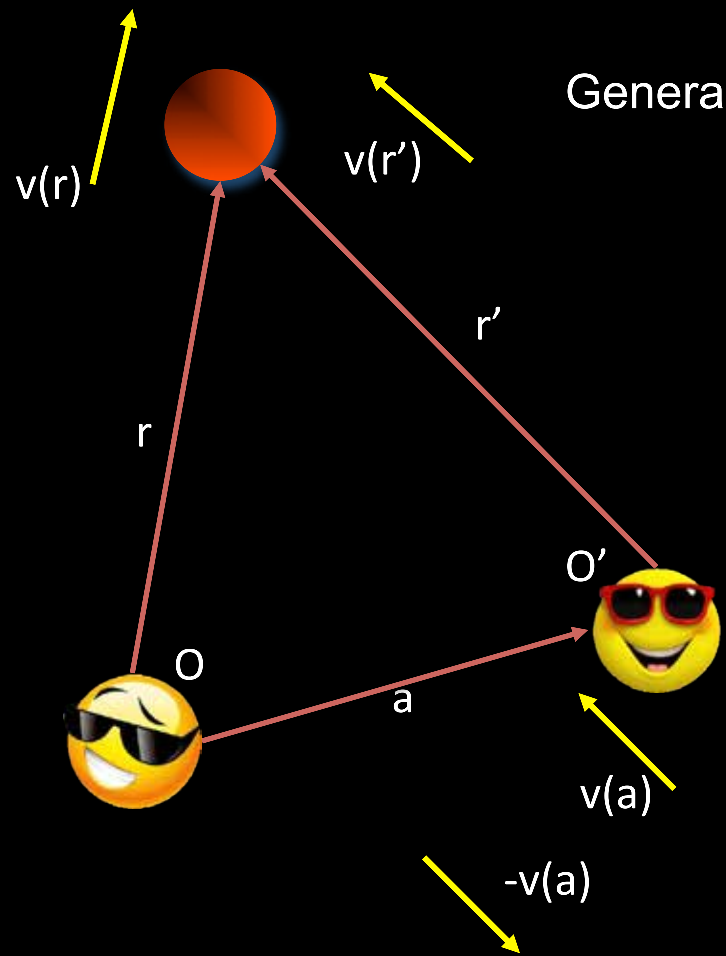
$$v'(r - a) = v(r - a) \quad (4)$$

$$(2)(3)(4) \Rightarrow v(r - a) = v(r) - v(a) \quad (5)$$

The Cosmological Principle

Hubble's Law follows from the Cosmological Principle

$$v(r - a) = v(r) - v(a) \quad (5)$$



General Solution

$$v_i(r) = \sum_{j=1}^{3} h_{ij} r_j \quad \text{or} \quad \begin{pmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{pmatrix} \begin{pmatrix} r_1 \\ r_2 \\ r_3 \end{pmatrix}$$

Can check by substituting $v_1 = h_{11}r_1 + h_{12}r_1 + h_{13}r_1$ into (5)

For all observers at all epochs h_{ij} *is fn(t) =* $h(t)_{ij}$

Cosmological Principle

Isotropy => matrix is rotationally invariant

$h_{ij} = 0$ *for* $i \neq j$

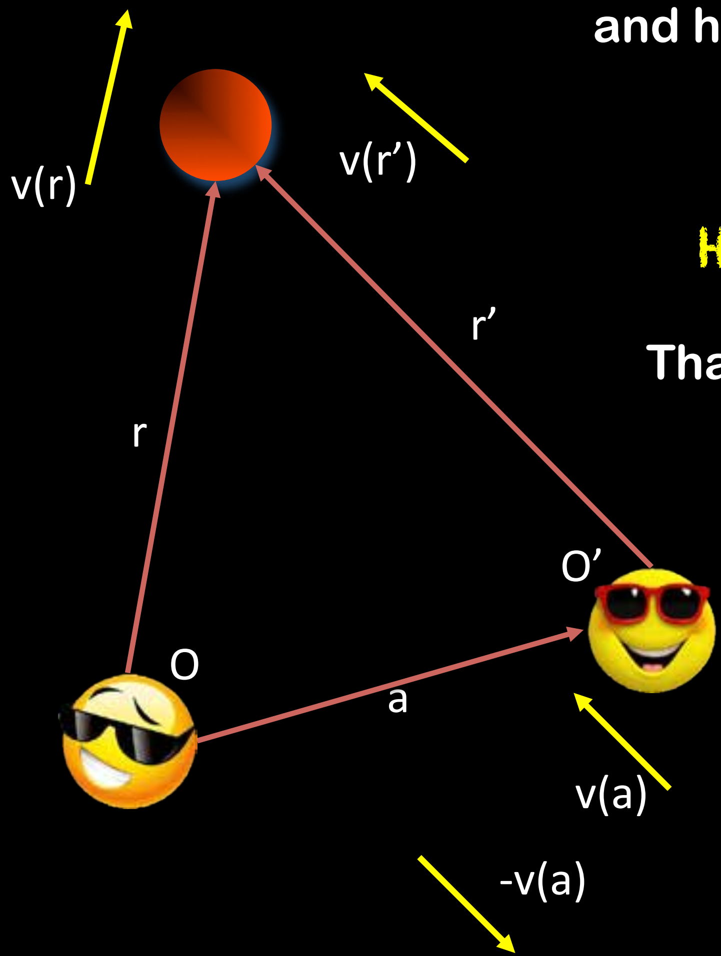
and $h_{11} = h_{22} = h_{33}$ = constant = $H(t)$

$v_1 = H(t)r_1$
$v_2 = H(t)r_2$
$v_{13} = H(t)r_3$

$$\Rightarrow \quad V = H(t)\, r$$

The Cosmological Principle

Hubble's Law follows from the Cosmological Principle



Assuming the Cosmological Principle of a isotropic and homogeneous has led us to Hubble's Law !

$$V = H(t)\ r$$

$H(t)$ **is the Hubble Parameter**

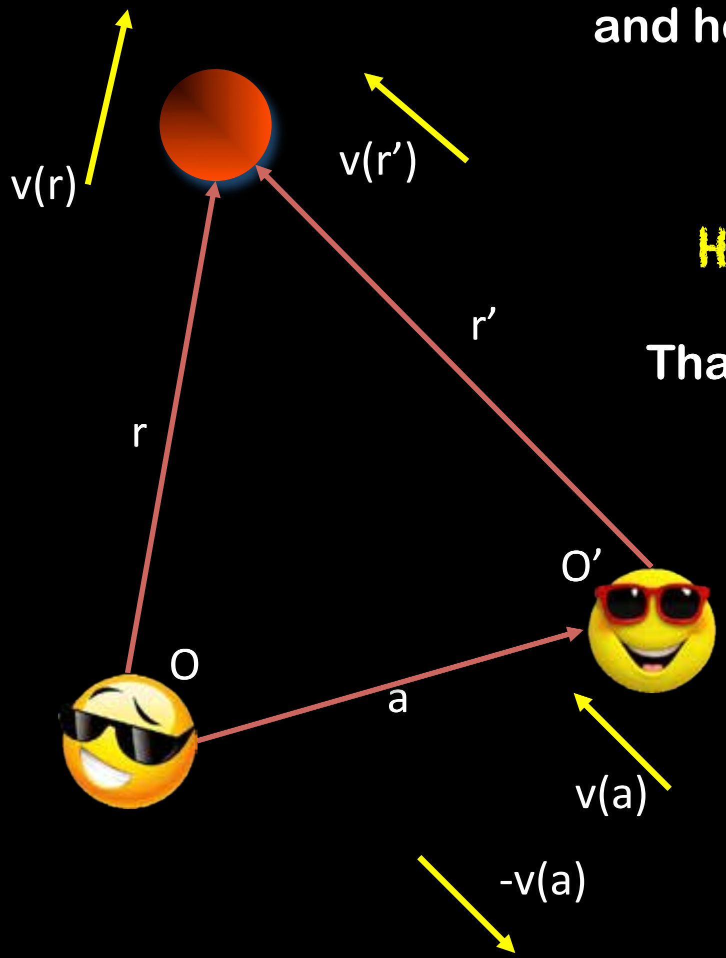
That the velocity of any co-moving particle is either;

- **zero (H=0)**
- **moving radially away (H>0)**
- **moving radially toward us (H<0)**

with a velocity proportional to the distance: i.e. HUBBLES LAW

The Cosmological Principle

Hubble's Law follows from the Cosmological Principle



Assuming the Cosmological Principle of a isotropic and homogeneous has led us to Hubble's Law !

$$V = H(t)\, r$$

$H(t)$ **is the Hubble Parameter**

That the Universe is either;

- **Static (H=0)**
- **uniformly expanding (H>0)**
- **uniformly contracting (H<0)**

with a velocity proportional to the distance: i.e. HUBBLES LAW

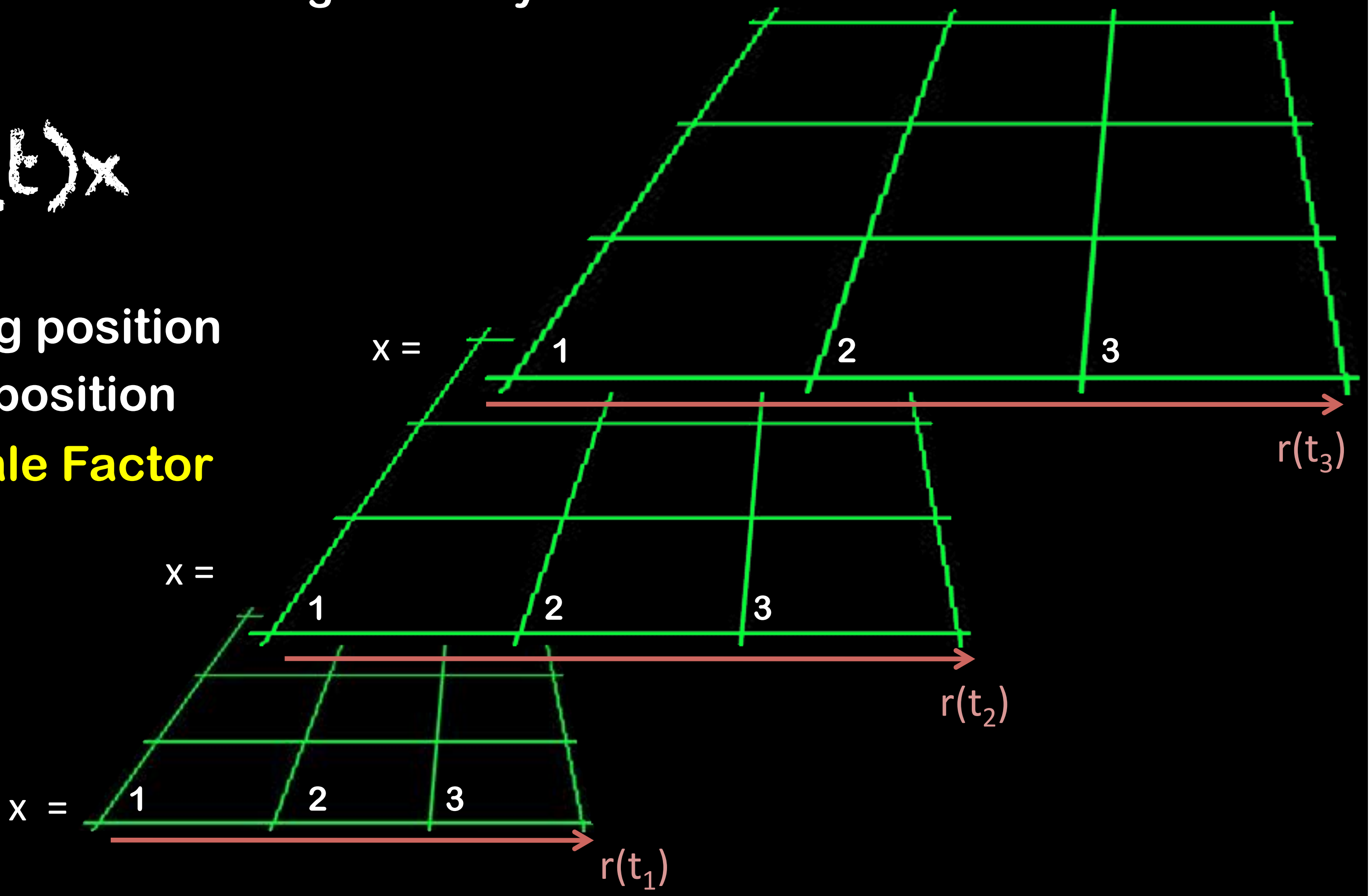
The Cosmological Principle

Hubble's Law follows from the Cosmological Principle

Cosmological Expansion:
Cosmic coordinates don't change but they are scaled with time

$$r(t) = R(t)x$$

x = co-moving position
r(t) = proper position
R(t) = the Scale Factor



All distances scaled by factor R(t) with time with isotropic expansion
Volumes also scale as $R(t)^3$

The Cosmological Principle

Hubble's Law follows from the Cosmological Principle

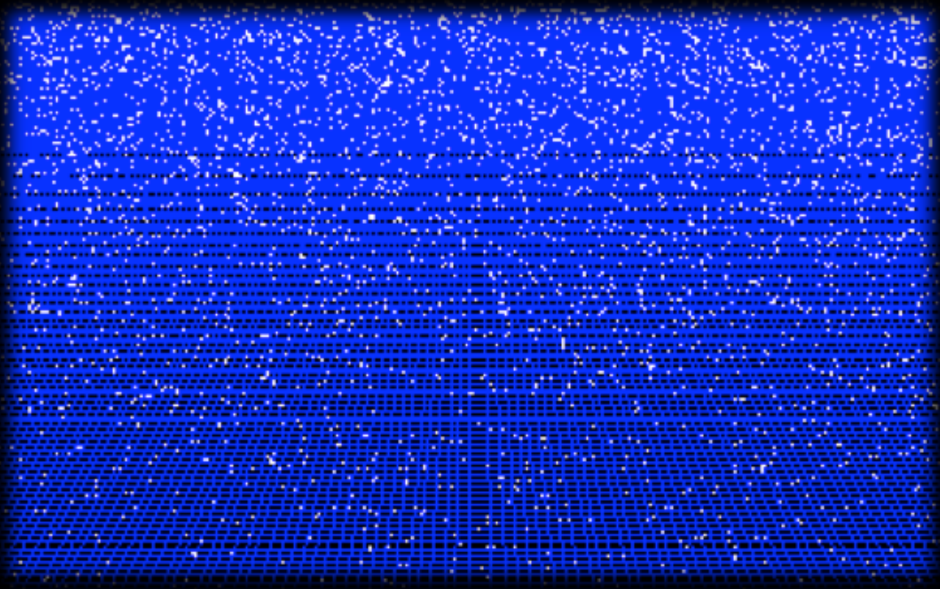
Cosmological Expansion:
Cosmic coordinates don't change but they are scaled with time

$$r(t) = R(t)x$$

$$\frac{dr}{dt} = \frac{dR(t)}{dt}x = \frac{\dot{R}}{R}r$$

$$v(r,t) = H(t)r(t)$$

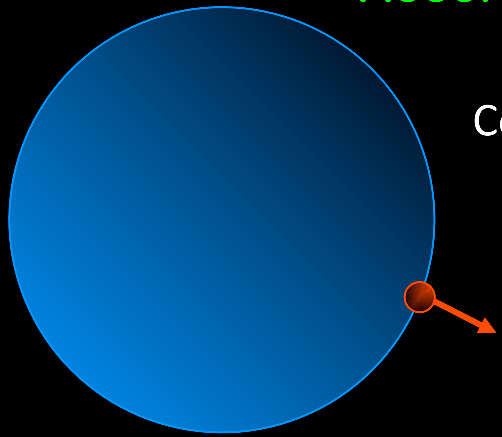
$$H(t) = \frac{\dot{R}(t)}{R(t)}$$



The Hubble parameter measures the expansion of the Universe

The Expanding Universe

According to Newton



Consider a particle P, on the edge of an isotropically expanding sphere

$$F = -\frac{GMm}{r^2} \qquad \ddot{r} = -\frac{GM}{r^2}$$

Multiply by $\dot{r}$ and integrate

$$\frac{1}{2}\dot{r}^2 = \frac{GM}{r} + U_{constant}$$

$$r = \frac{R(t)}{R_o} r_o$$

$$\dot{r} = \frac{\dot{R}(t)}{R_o} r_o$$

$$M = \frac{4\pi}{3}\rho r^3$$

$$\frac{1}{2}\dot{R}^2\left(\frac{r_o}{R_o}\right)^2 = \frac{4\pi G\rho}{3}R^2\left(\frac{r_o}{R_o}\right)^2 + U$$

$$\dot{R}^2 = \frac{8\pi G\rho}{3}R^2 + U$$

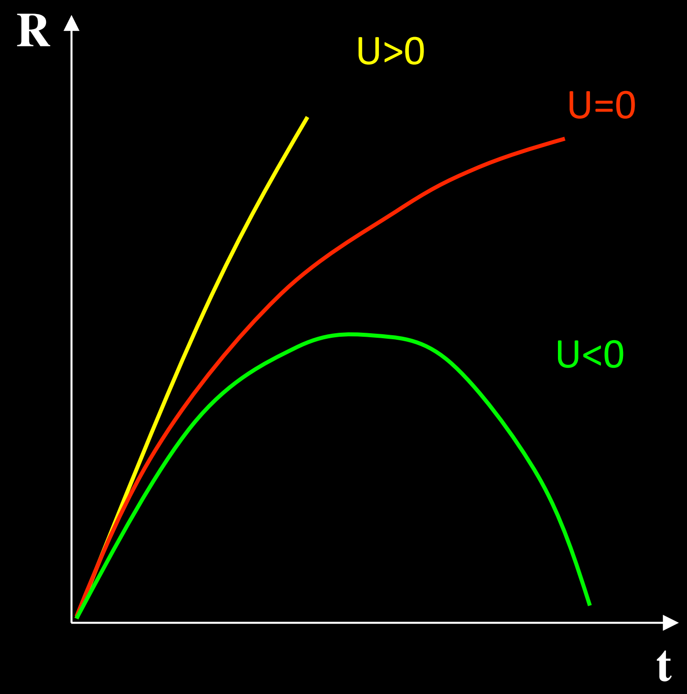
The Expanding Universe

According to Newton

$$\dot{R}^2 = \frac{8\pi G\rho}{3}R^2 + U$$

Friedmann Equation

Evolution of universes



U>0: RHS >0 for all time

U<0: RHS will become negative at some value of $R_{max} = \frac{2GM}{U}$

U=0: RHS >0 for all time $\dot{R} \to 0 \ (t \to \infty) \ \rho \to 0$

U ~ static potential of Universe (curvature)

Einstein's Universe

Einstein Tensor:
The Geometry of the Universe

$$G_{ik} = R_{kl} - \frac{1}{2} g_{ik} R$$

Energy Momentum Tensor:
The matter in the Universe

$$T^{ik} = (P + rc^2) u^i u^k - g^{ik} P$$

Einstein Equation:
Relates the Matter Energy to the Geometry of the Universe

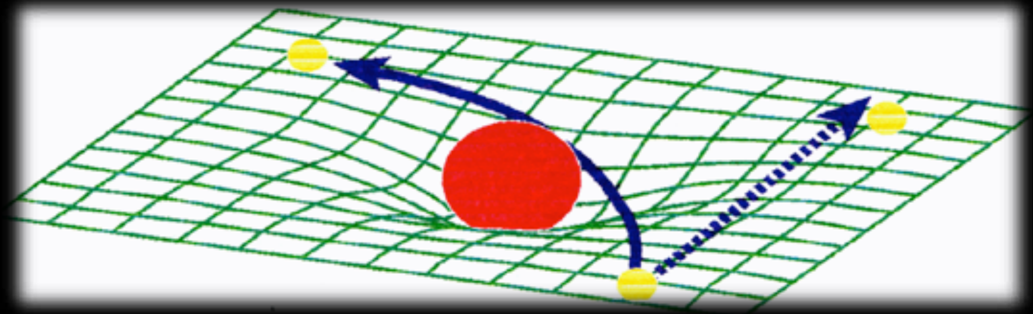
$$G_{ik} = R_{kl} - \frac{1}{2} g_{ik} R = \frac{8\pi G}{c^4} T^{ik}$$

geometry　　　　matter

Einstein's Universe

"Matter tells space how to curve. Space tells matter how to move."

Fabric of the Spacetime continuum and the energy of the matter within it are interwoven



$$G_{ik} = R_{kl} - \frac{1}{2} g_{ik} R = \frac{8\pi G}{c^4} T^{ik}$$

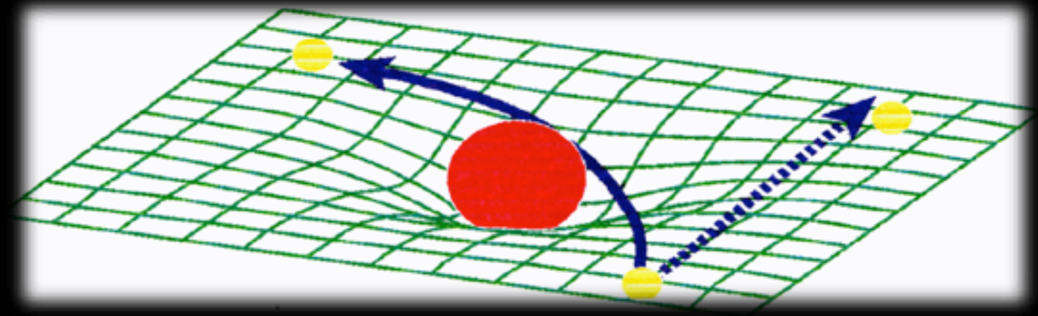
Einstein Equation does not give a static solution !

$$G_{ik} = R_{kl} - \frac{1}{2} g_{ik} R - \Lambda g_{ik} = \frac{8\pi G}{c^4} T^{ik}$$

Einstein's Universe

"Matter tells space how to curve. Space tells matter how to move."

Fabric of the Spacetime continuum and the energy of the matter within it are interwoven



$$G_{ik} = R_{kl} - \frac{1}{2} g_{ik} R - \Lambda g_{ik} = \frac{8\pi G}{c^4} T^{ik}$$

$$\dot{R}^2 = \frac{8\pi G \rho}{3} R^2 - kc^2 \quad \left(+ \frac{\Lambda R^2}{3} \right)$$

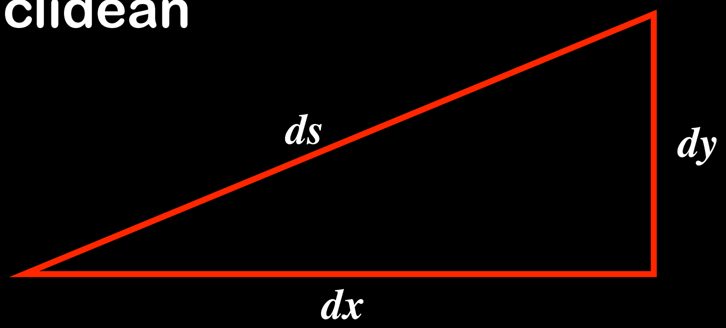
The Friedmann Equation

Where k is the curvature

Einstein's Universe

Events in Spacetime

Euclidean



2-D $$ds^2 = dx^2 + dy^2$$

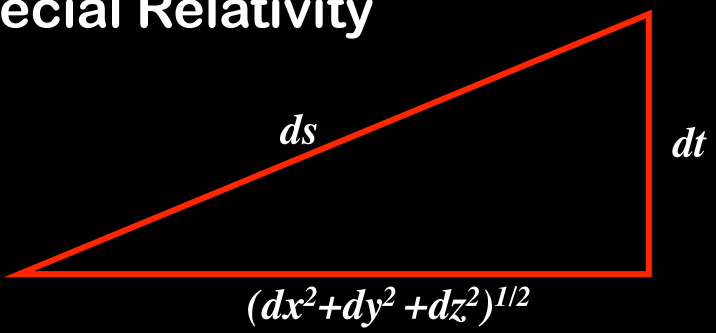
3-D $$ds^2 = dx^2 + dy^2 + dz^2$$

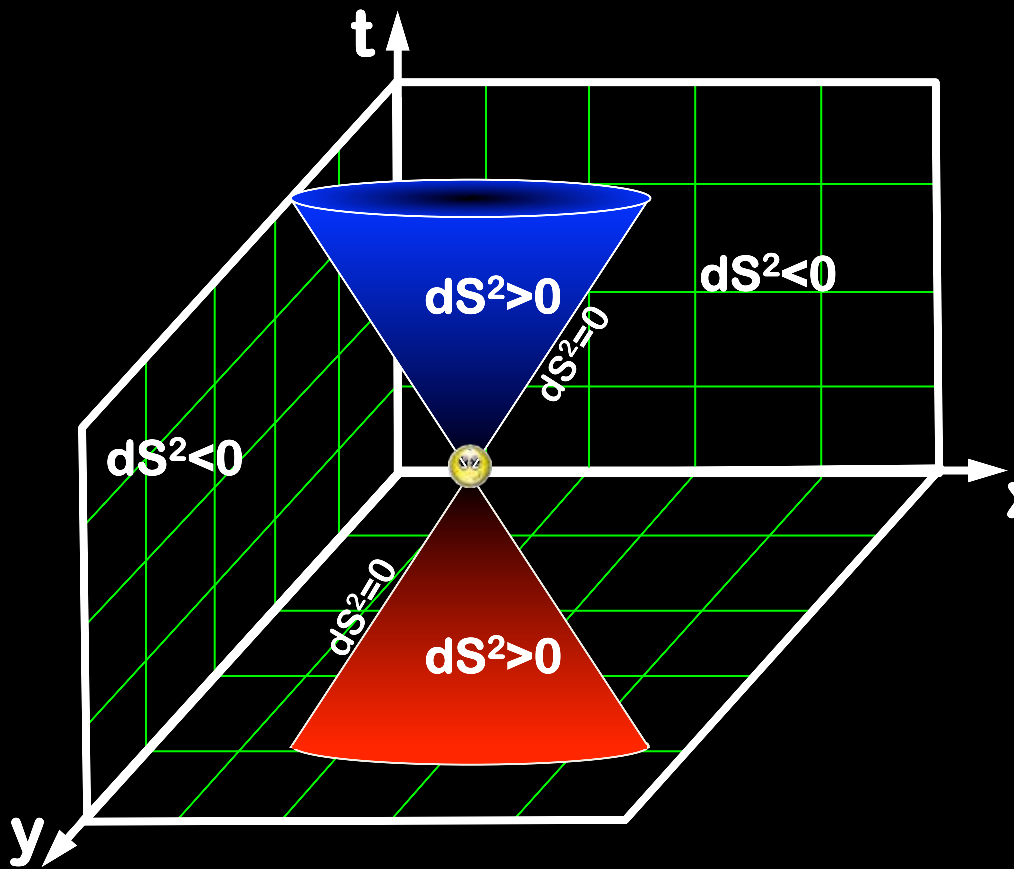
3-D $$ds^2 = dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta \, d\phi^2$$

Einstein's Universe

Events in Spacetime

Special Relativity





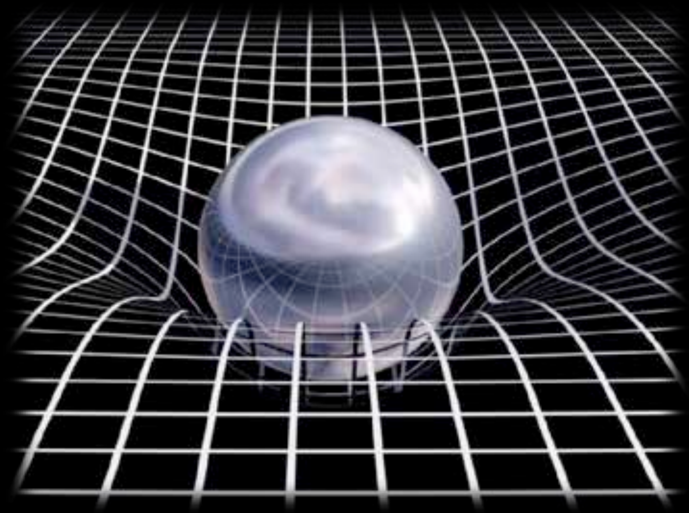
4-D $ds^2 = \left[dx^2 + dy^2 + dz^2\right] - c^2 dt^2$

4-D $ds^2 = \left[dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta\, d\phi^2\right] - cdt^2$

Einstein's Universe

Events in Spacetime

General Relativity



Curved Spacetime: $$ds^2 = \sum_{i,j=0}^{n} g_{ij}\,dx^i dx^j$$

$$ds^2 = c^2dt^2 - R^2(t)\left(\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta\, d\phi^2)\right)$$

The Robertson-Walker Metric

Einstein's Universe

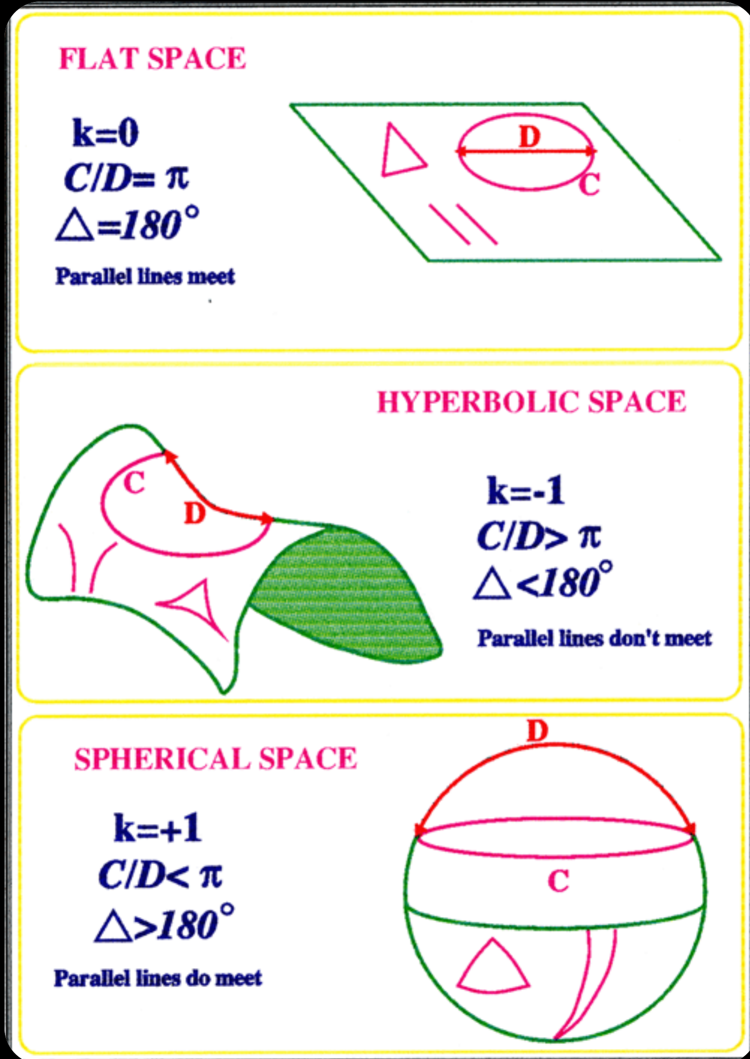
$$ds^2 = c^2 dt^2 - R^2(t)\left(\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta\, d\phi^2)\right)$$

- **The Robertson-Walker Metric and the Geometry of the Universe**

$k = 0$: Flat Space

$k = -1$: Hyperbolic Space

$k = +1$: Spherical Space



Cosmological World Models

matter tells spacetime how to **curve**

$$\frac{\dot{R}^2}{R^2} = \frac{8\pi G\rho}{3} - \frac{kc^2}{R^2} = H^2$$

for a flat (*k= 0*) universe define a critical density

$$\rho = \rho_c = \frac{3H^2}{8\pi G}$$

define

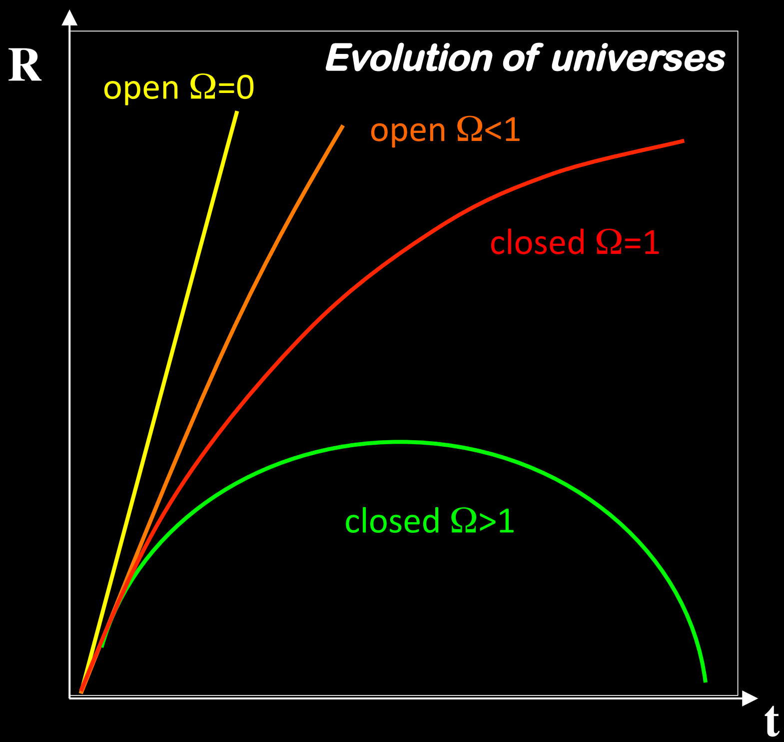
$$\Omega = \frac{\rho}{\rho_c} = \frac{8\pi G\rho}{3H^2}$$

Ω : The Density Parameter

$$\frac{kc^2}{H^2R^2} = \Omega - 1$$

- $\Omega > 1$ **then** $k>0$
- $\Omega < 1$ **then** $k<0$
- $\Omega = 1$ **then** $k=0$

Cosmological World Models



Ω : The Density Parameter

$$\frac{kc^2}{H^2R^2} = \Omega - 1$$

- $\Omega > 1$ **then** $k>0$
- $\Omega < 1$ **then** $k<0$
- $\Omega = 1$ **then** $k=0$

$\Omega < 1$: **low density, expands forever**

$\Omega = 0$: **no matter, expands forever**

$\Omega = 1$: **expands forever gradually slowing**

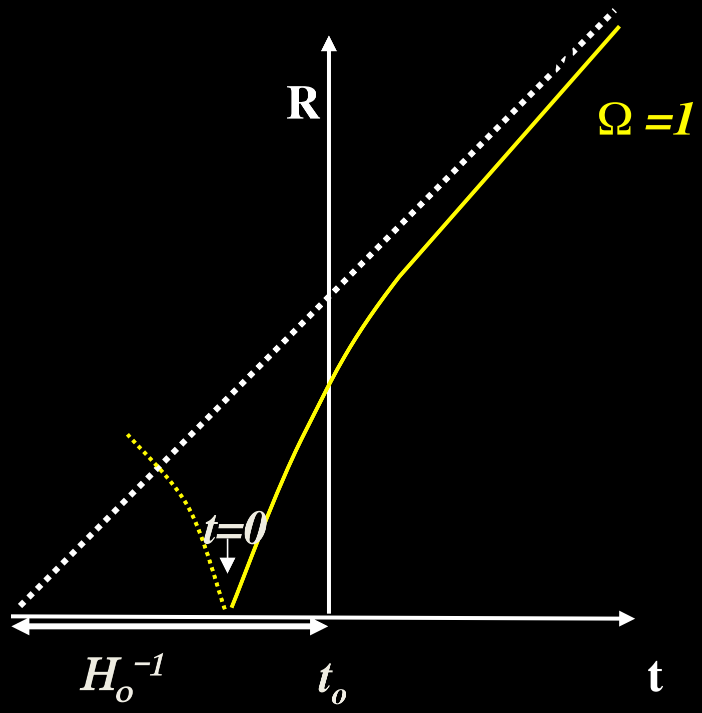
$\Omega > 1$: **expand to maximum and then re-contract**

Cosmological World Models

Einstein DeSitter Universe

Solution to the Friedmann equation for:

- Flat, k=0 universe
- Matter dominated $\rho = \rho_o (R_o/R)^3$
- No Cosmological Constant : $\Lambda=0$
- Density Parameter $\Omega = 1$



Universe expands uniformly and monotonically but at an ever decreasing rate:

$$R = \pm R_o \left(\frac{t}{t_o} \right)^{2/3} \propto t^{2/3}$$

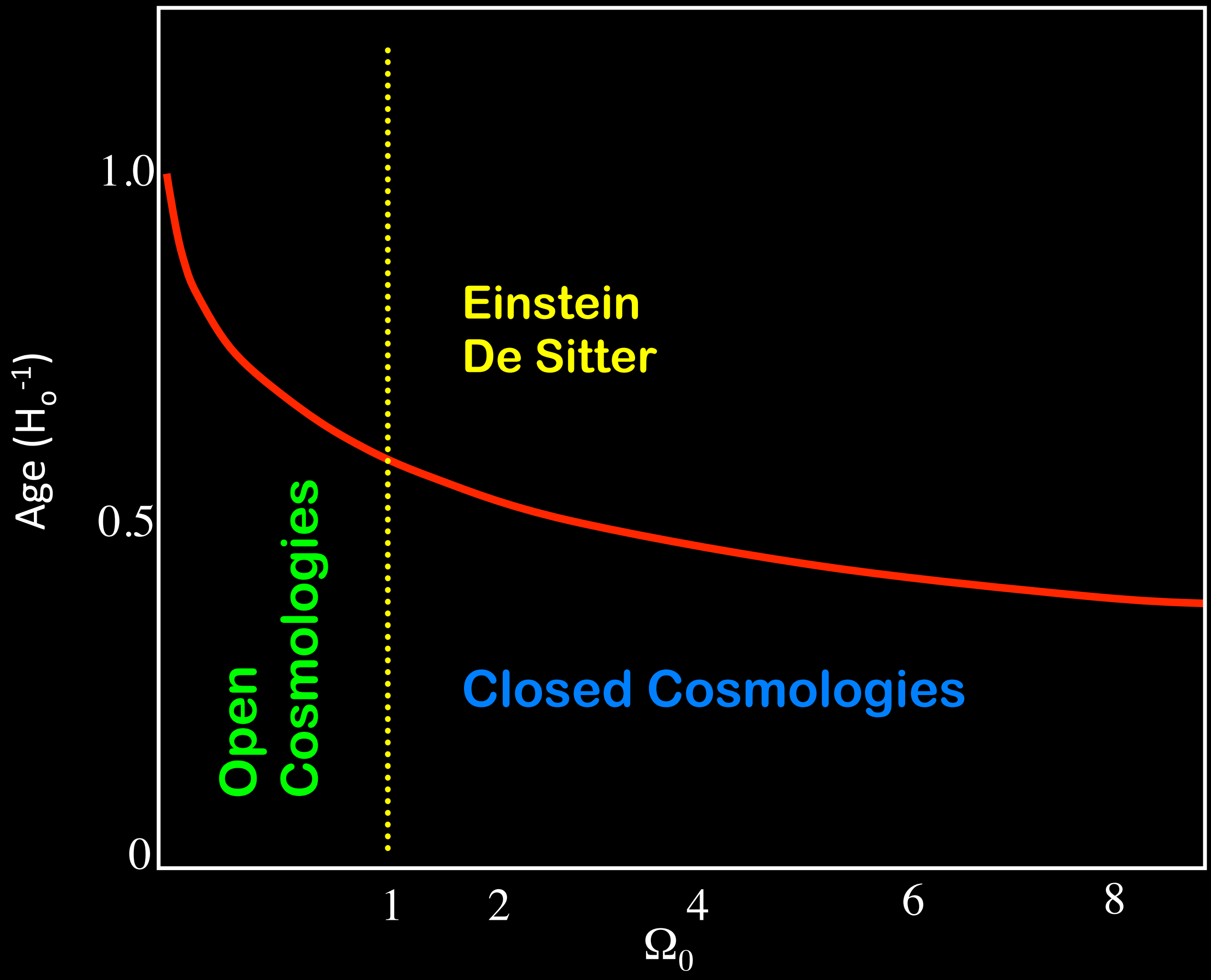
Age: $t_o = (2/3H_o)$

$$t \rightarrow \infty$$

$$R \rightarrow \infty$$

$$\dot{R} \rightarrow 0$$

Cosmological World Models



Cosmological Constant Universes

The Friedmann Equations
including Cosmological Constant

$$\dot{R}^2 = \frac{8\pi G\rho}{3}R^2 - kc^2 + \frac{\Lambda R^2}{3}$$

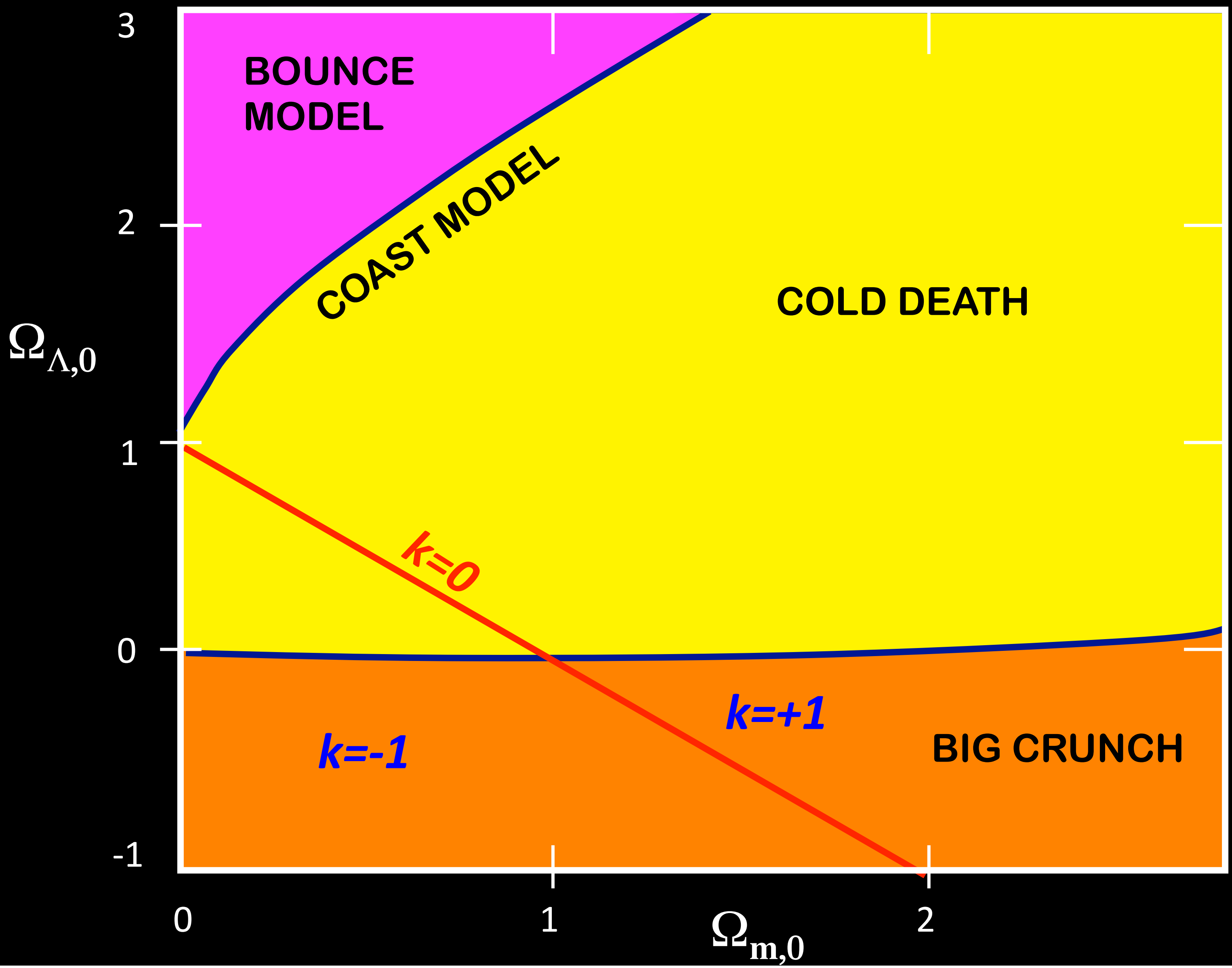
$$\ddot{R} = -\frac{4\pi G\rho}{3}R + \frac{\Lambda R}{3}$$

- **Modifies gravity at large distances**
- **Repulsive Force (Λ>0)**
- **Repulsion proportional to distance (from acceleration eqn.)**

Cosmological Constant Universes

Λ	k	Name	Dynamics	Evolution
<0	$\forall k$	Oscillatory (1st kind)	$\exists R_C \Rightarrow \dot{R}=0, \ddot{R}<0$	contract back to $R=0$ (oscillatory)
>0	≤ 0		$\dot{R}>0 \quad \forall \quad R$	monotomically expanding
>0	0	De Sitter	$\rho=0 \quad \dot{R}>0 \quad \forall \quad R$	monotomically expanding
Λ_C	1	Einstein Static	$\exists R_E(\Lambda_C) \Rightarrow \dot{R}=0, \ddot{R}=0$	Static $\forall\ t$ at $R=R_E$ with $\Lambda=\Lambda c$
$>\Lambda_C$	1		$\dot{R}>0 \quad \forall \quad R$	monotomically expanding
$\Lambda_C+\varepsilon$	1	Eddington Lemaitre (EL1)	$\dot{R}\to 0, \quad R\to R_E, \quad t\to\infty$	Big Bang → Einstein Static universe
$\Lambda_C+\varepsilon$	1	Eddington Lemaitre (EL2)	$R_E \to R, \quad t\to\infty$	expand from Einstein Static →∞
$\Lambda_C+\varepsilon$	1	Lemaitre	$R: 0\to R_E \to\infty$	Long coasting period at $R=R_E$
$0<\Lambda<\Lambda_C$	1	Oscillatory (1st kind)	$\exists R_{\max} \Rightarrow \dot{R}=0, \ddot{R}<0$	contract back to $R=0$ (oscillatory)
$0<\Lambda<\Lambda_C$	1	Oscillatory (2nd kind)	$(\dot{R}=0)\,R_B > R > R_B\,(\dot{R}>0)$	Universe bounces at R_B

Cosmological Constant Universes



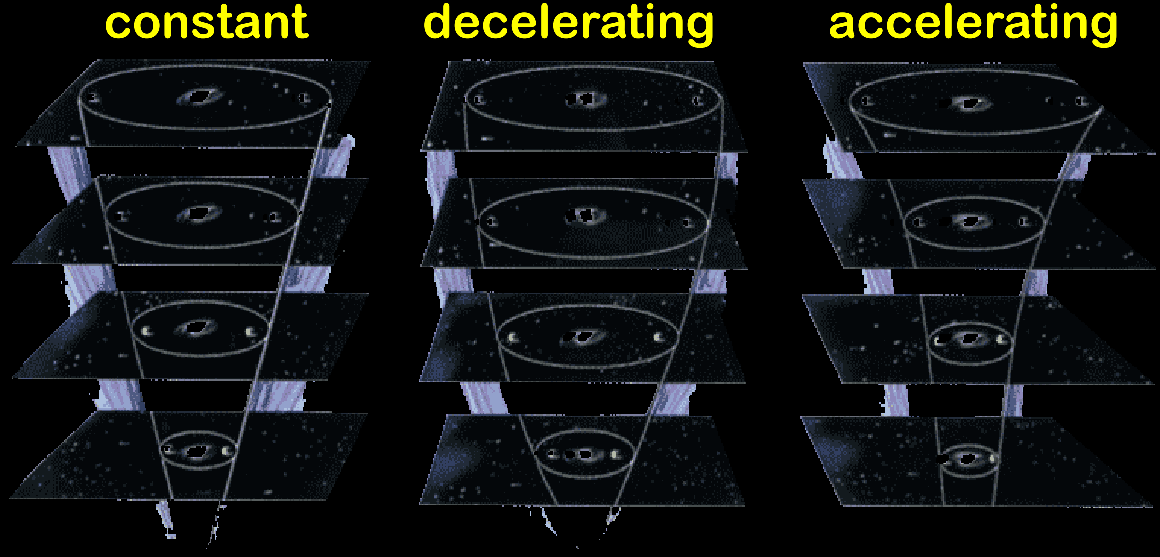
Our Universe

- What kind of Universe do we live in ?
- How can we measure it ?
- Would like to know;
  - Hubble Constant
  - Density Parameter
    - Ω_{total}
    - Ω_{matter}
    - Ω_{Λ}

Need to measure distances

Our Universe

Ω_Λ changes relationship between redshift, time and distance



For a population of objects of
- standard proper size (standard ruler)

or
- standard luminosity (standard candle)

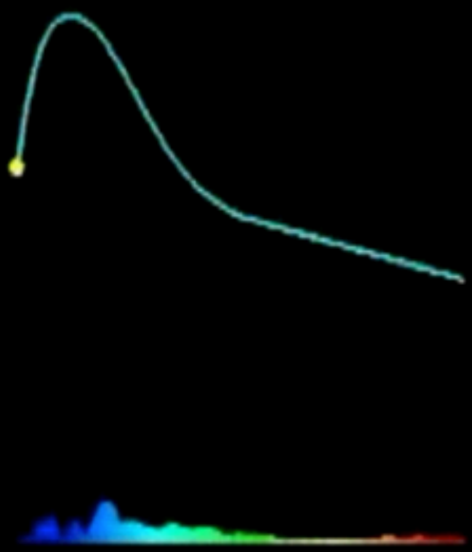
and
- high luminosity

can calculate
- Distance
- Measuring redshift ➠ cosmological parameters H_o $\Omega_{m,o}$ $\Omega_{\Lambda,o}$

Our Universe: Evidence from Supernova

Standard Candles: Type 1a Supernova

- After supernova occurs the light gradually fades.
- Peak brightness of supernovae depends on shape of light decay curve.
- Brighter Supernovae - slower climb and decay of light curve.
- Measure luminosity, observed flux ➟ DISTANCE !!!



Our Universe: Evidence from Supernova

Relationship between observed flux, intrinsic luminosity and distance

$$m - M = 5\lg d_{L,Mpc} + 25$$

$$m - M = 43 - 5\lg\left(\frac{H_o}{100h\ kms^{-1}Mpc^{-1}}\right) + 5\lg z + 1.086(1 - q_o)z$$

Expansion rate

Low z observations ➠ H_o

Acceleration

Higher z observations ➠ q_o

$q_o < 0$ ➠ **Universe is accelerating ➠standard candle of lower brightness**

$q_o > 0$ ➠ **Universe is decelerating ➠standard candle of higher brightness**

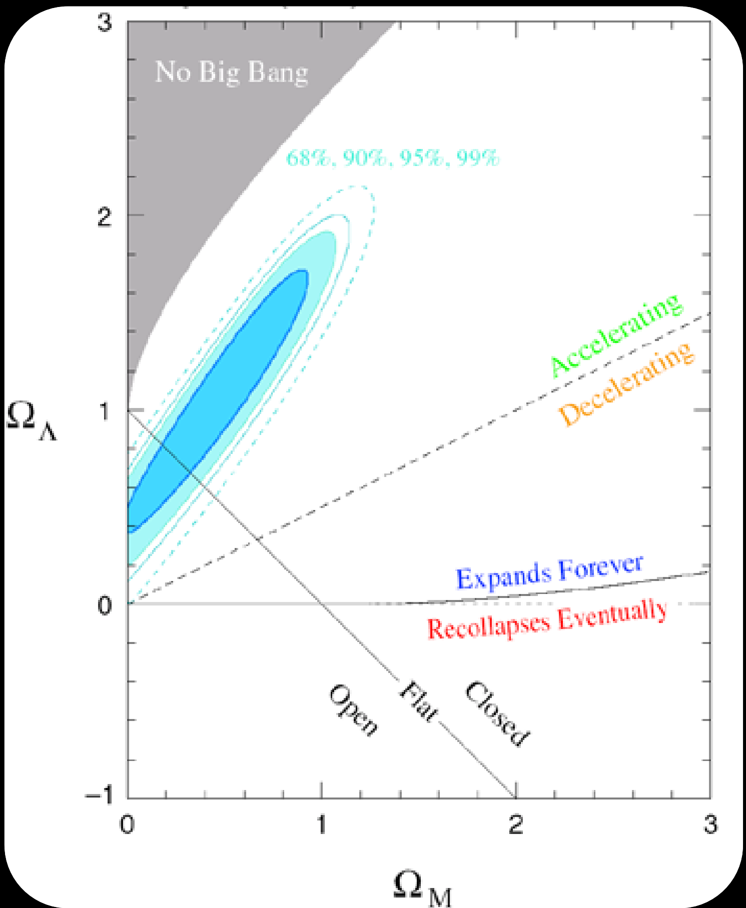
Our Universe: Evidence from Supernova

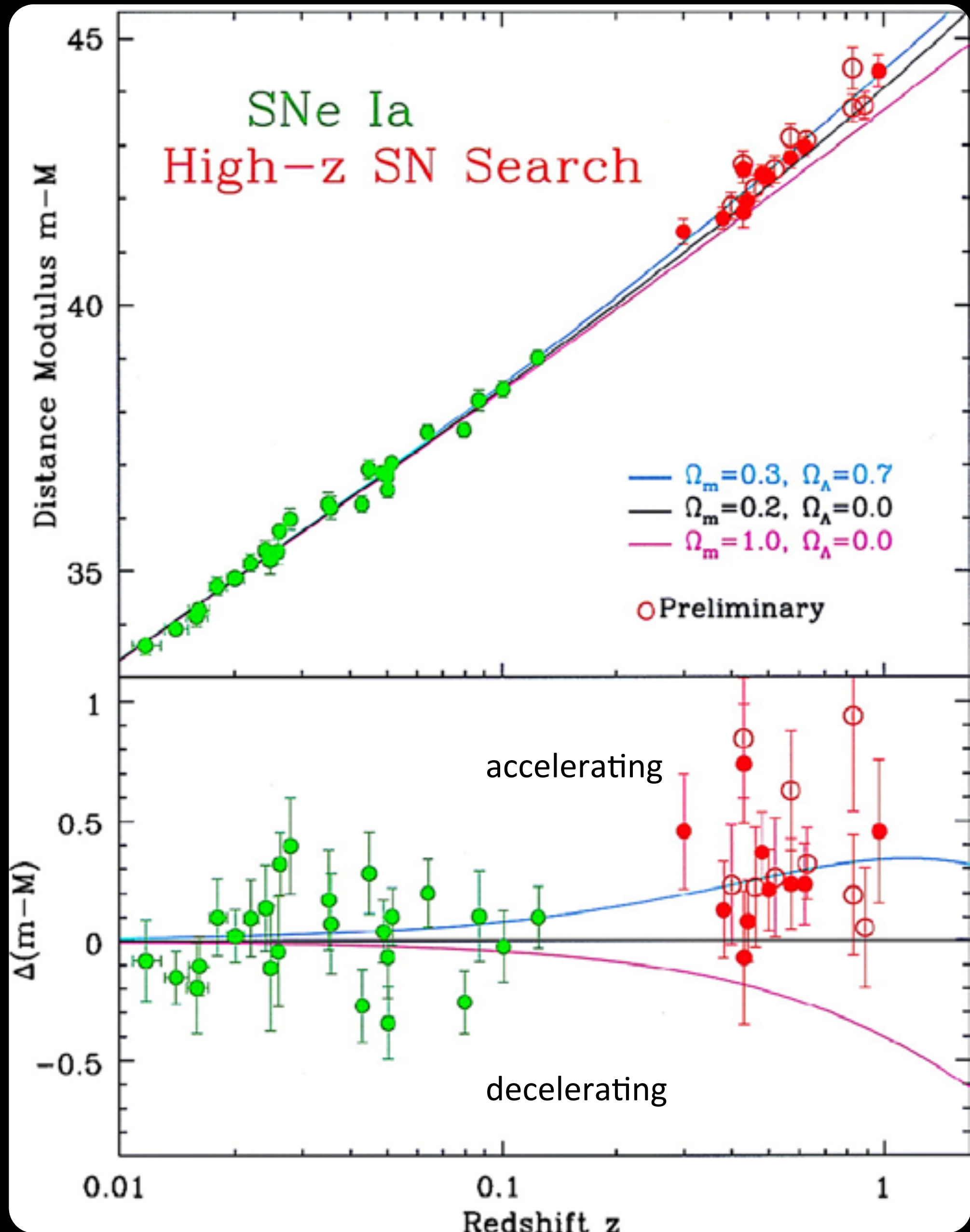
Best Fit

Ho = 72

$\Omega_{m,o} = 0.3$

$\Omega_{\Lambda,o} = 0.7$





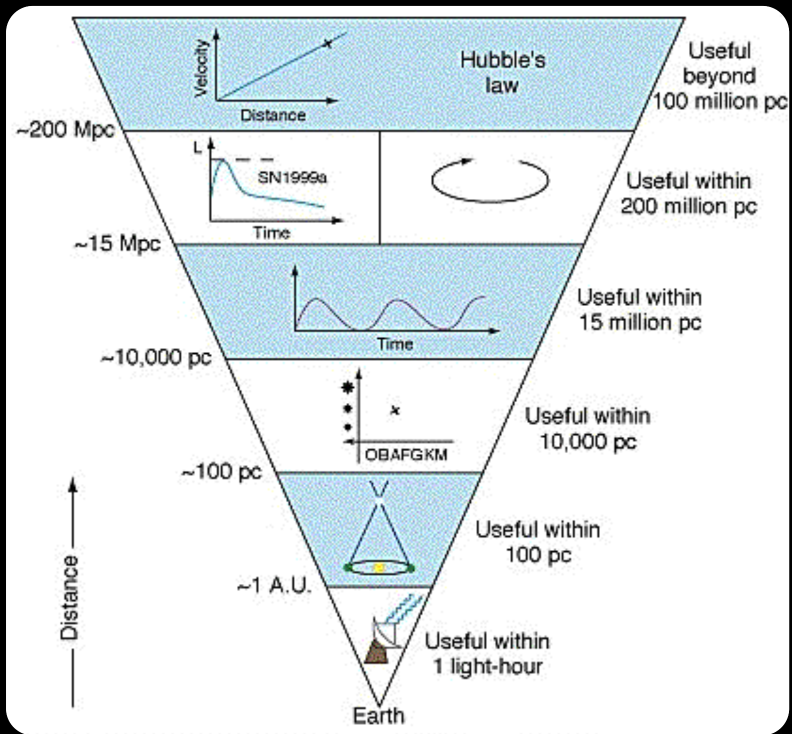
Our Universe: Evidence from Supernova

Our Universe is accelerating due to a repulsive force equivalent to $\Omega_{\Lambda,o}$ = 0.7

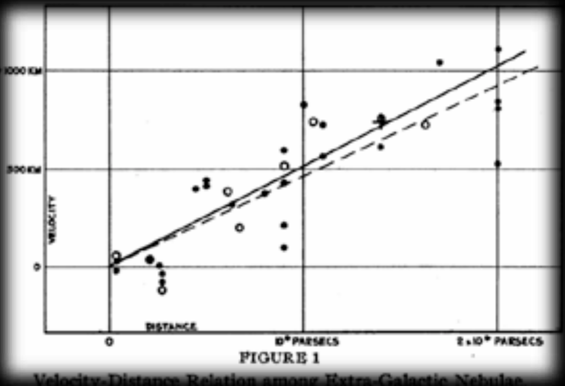
Our Universe: Evidence from Hubble

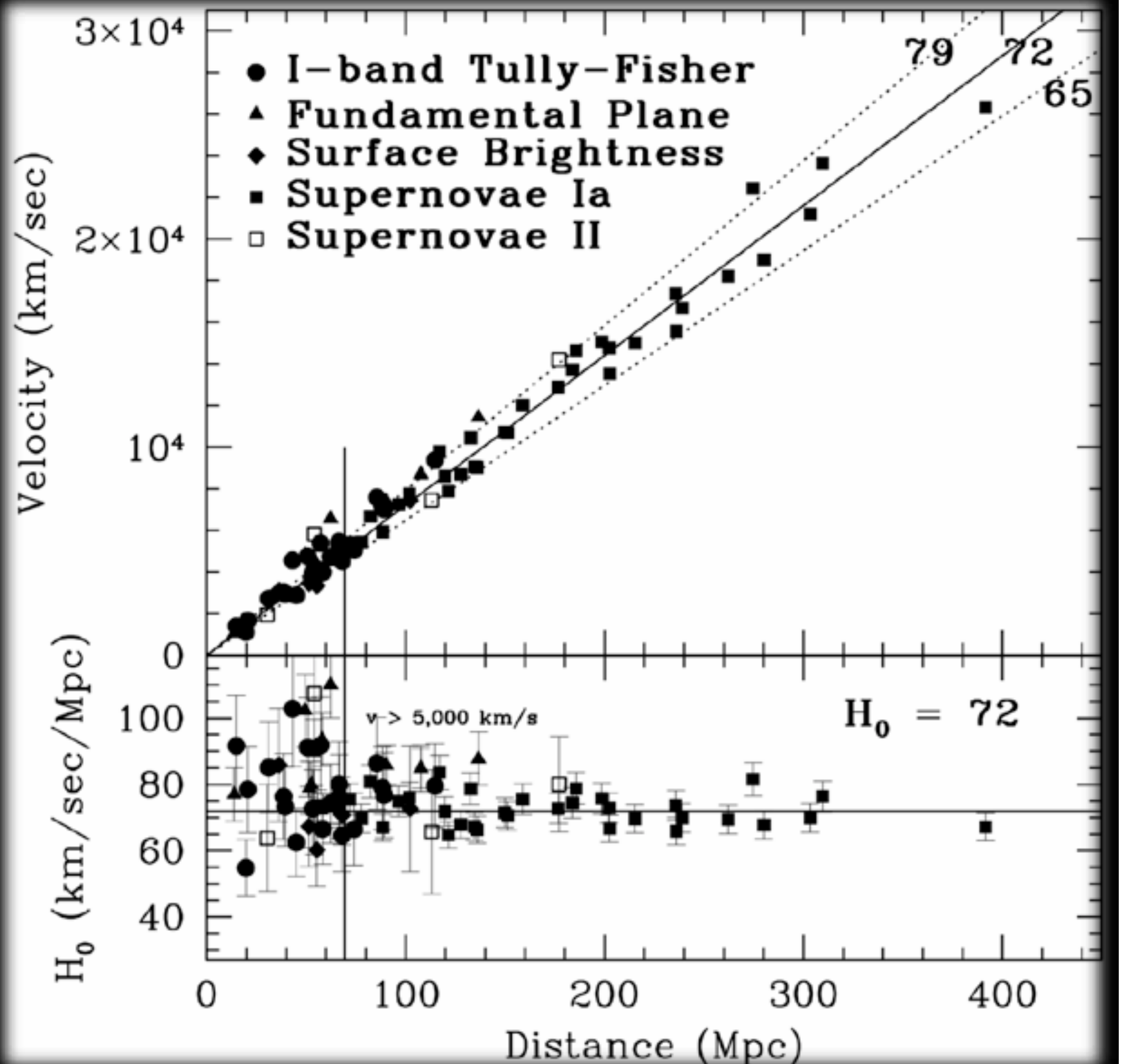
Hubble Key Project

- Discovery of distant Cepheids with the HST
- Comparison of many distance determination methods
- Comparison of systematic errors
- Determination of $H_o \pm 10\%$



Our Universe: Evidence from Hubble





$H_0 = 72 \pm 8$ km s^{-1} Mpc^{-1} $t_0 = 1.37 \times 10^{10}$ yr

Our Universe: Evidence from WMAP/Planck

Wilkinson Microwave Anisotropy Probe (2001)

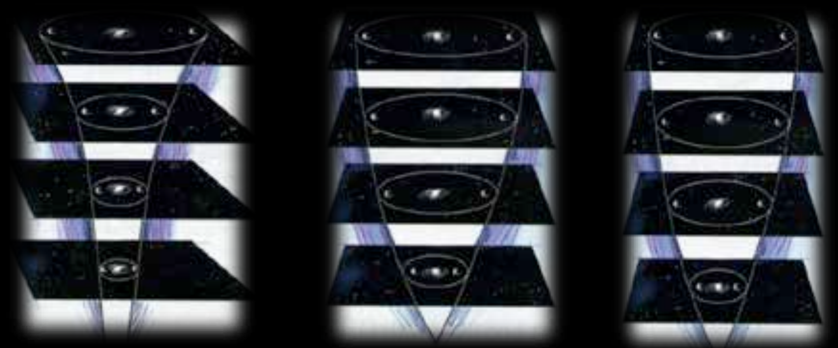
Planck Satellite (2009)

Detailed full-sky map of the oldest light in Universe.

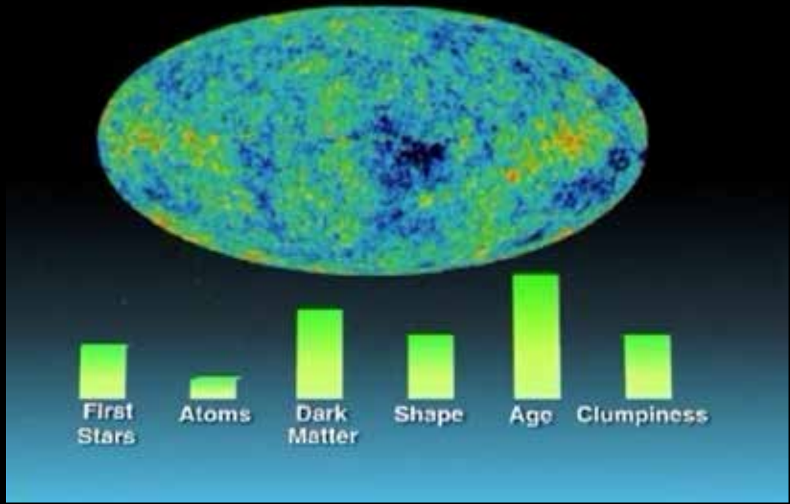
It is a "baby picture" of the 380,000yr old Universe

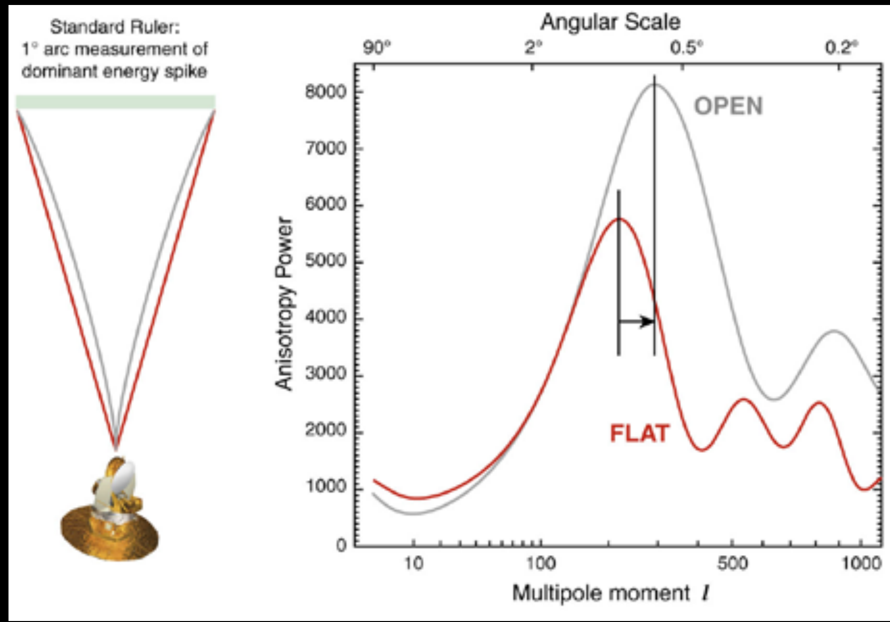
- **Temperature fluctuations imprinted on CMB at surface of last scattering**

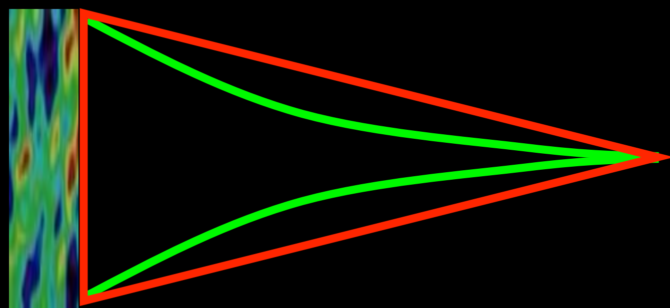
- **Temperature fluctuations over angular scales in CMB correspond to variations in matter/radiation density**



Our Universe: Evidence from WMAP/Planck

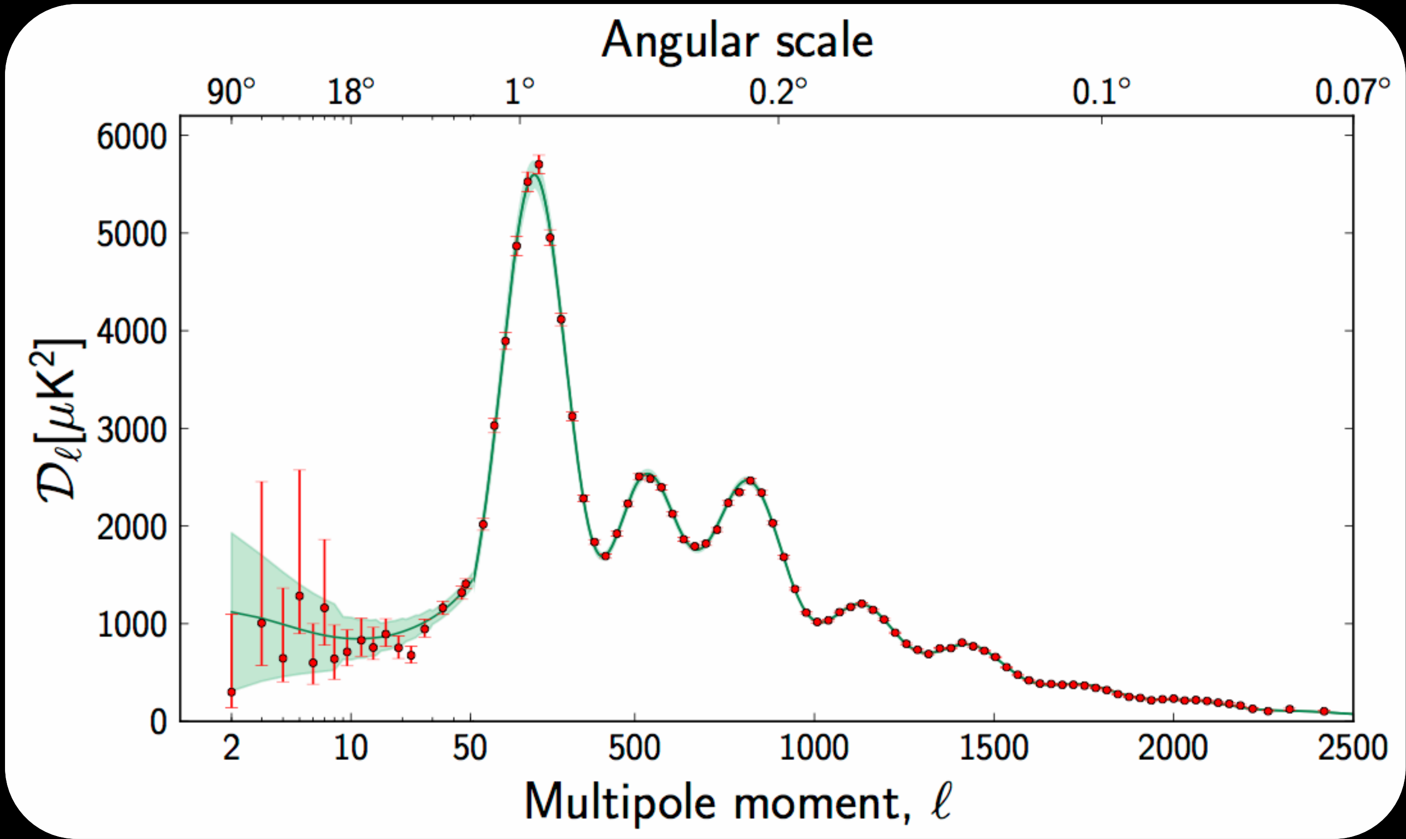






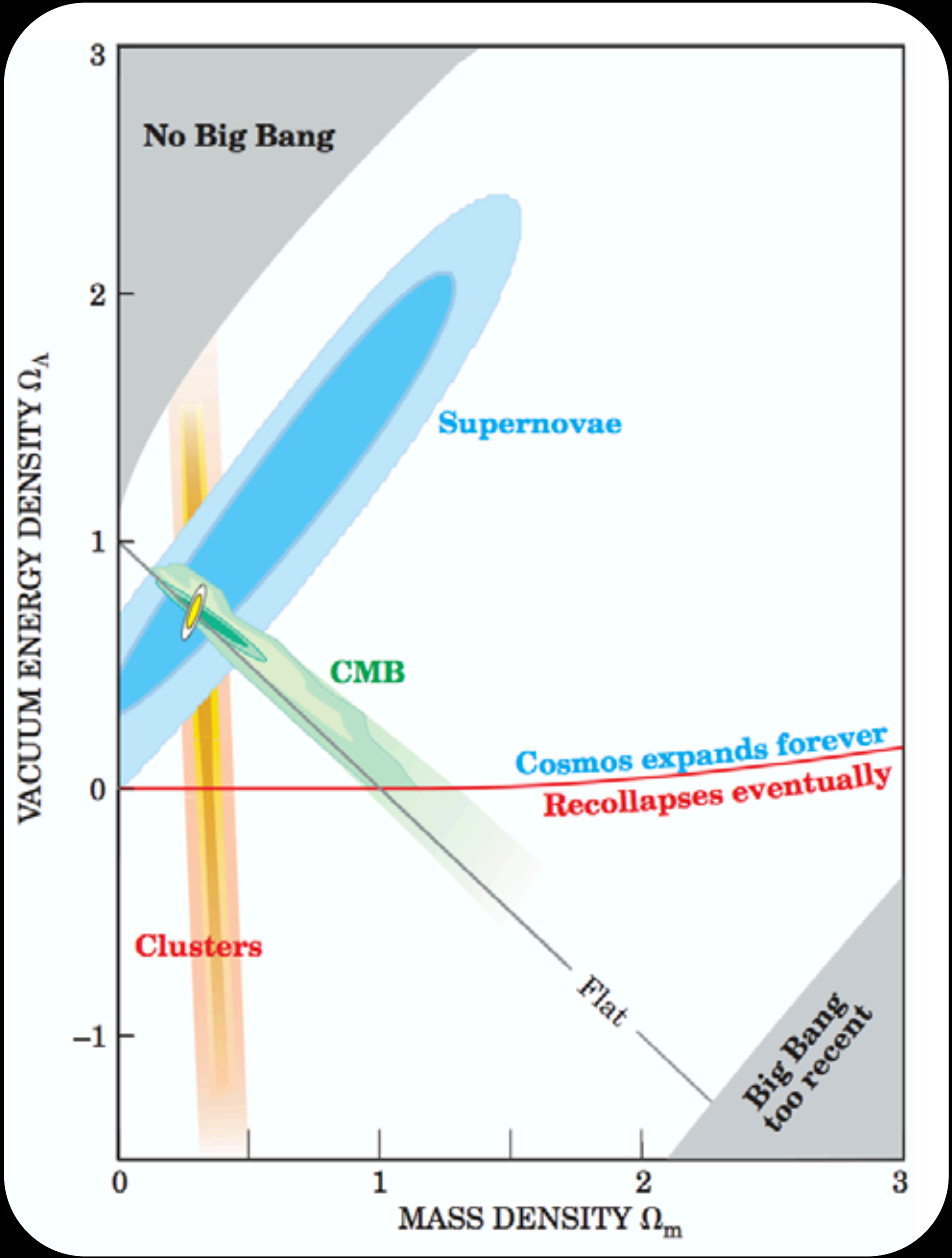
- WMAP / Planck - fingerprint of our Universe
- Flat Universe - sonic horizon ~ 1sq. Deg. ($l=180$)
- Open Universe - photons move on faster diverging pathes => angular scale is smaller for a given size
- Peak moves to smaller angular scales (larger values of l)

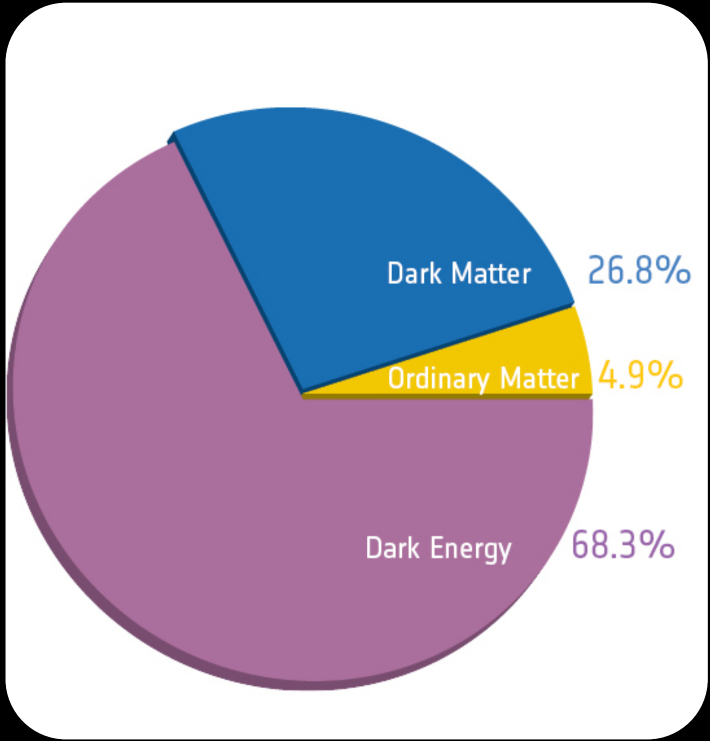
Our Universe: Evidence from WMAP/Planck



Consistent with $\Omega_{Total} = 1$

Our Universe





$H_o = 67.3$

$\Omega_{m,o} = 0.315$

$\Omega_{\Lambda,o} = 0.685$

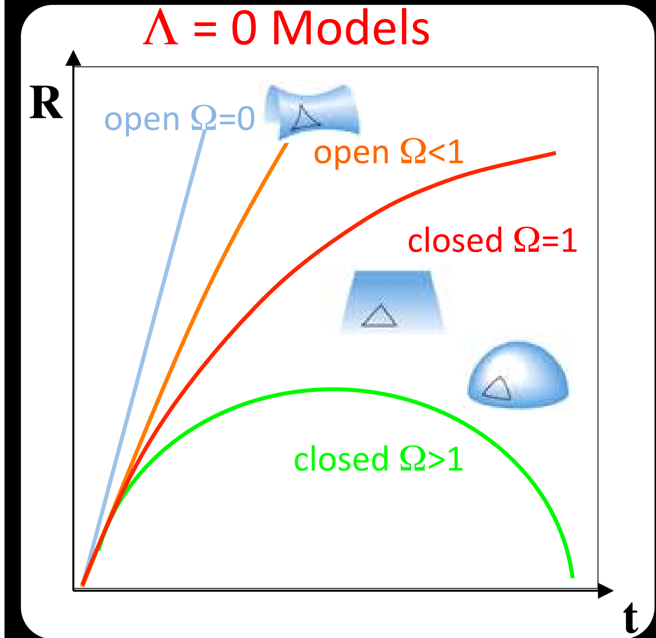
$\tau_{age} = 13.81$

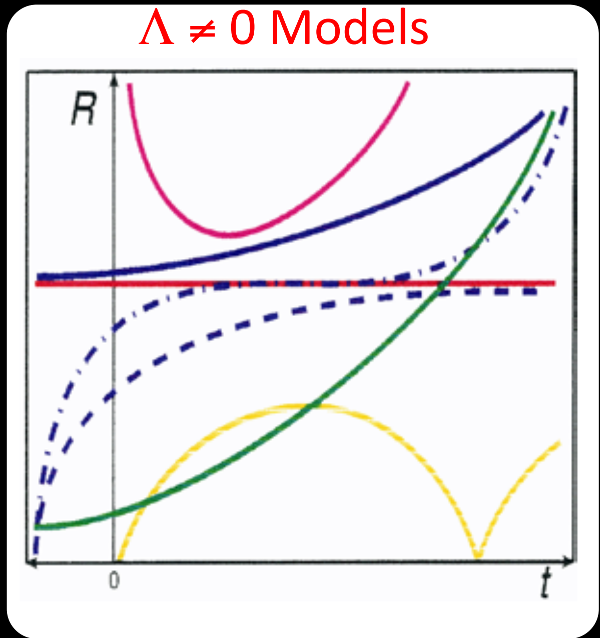
Our Universe

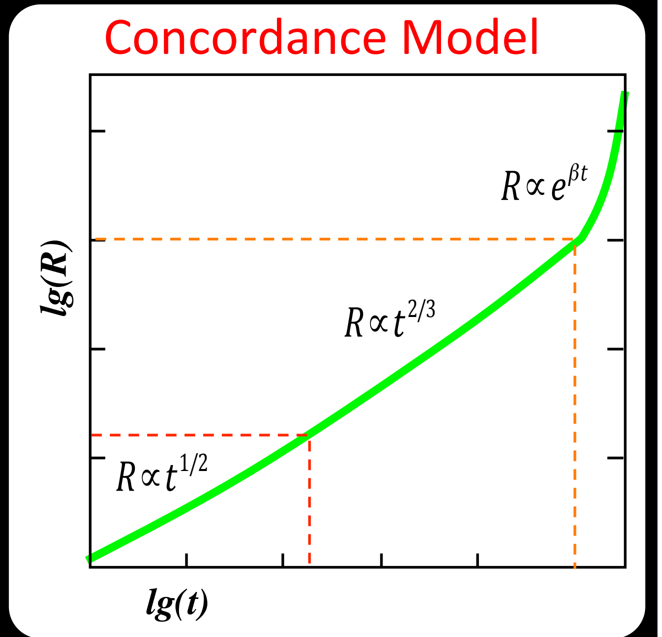
Friedmann Equations: Cosmological Models depending on the density Ω

Discovered a large family of cosmological World Models

Identified the most likely candidate for our own Universe







H_o = 67.3 ± 0.012 km/s/Mpc

$\Omega_{\Lambda,o}$ = 0.685 ± 0.017

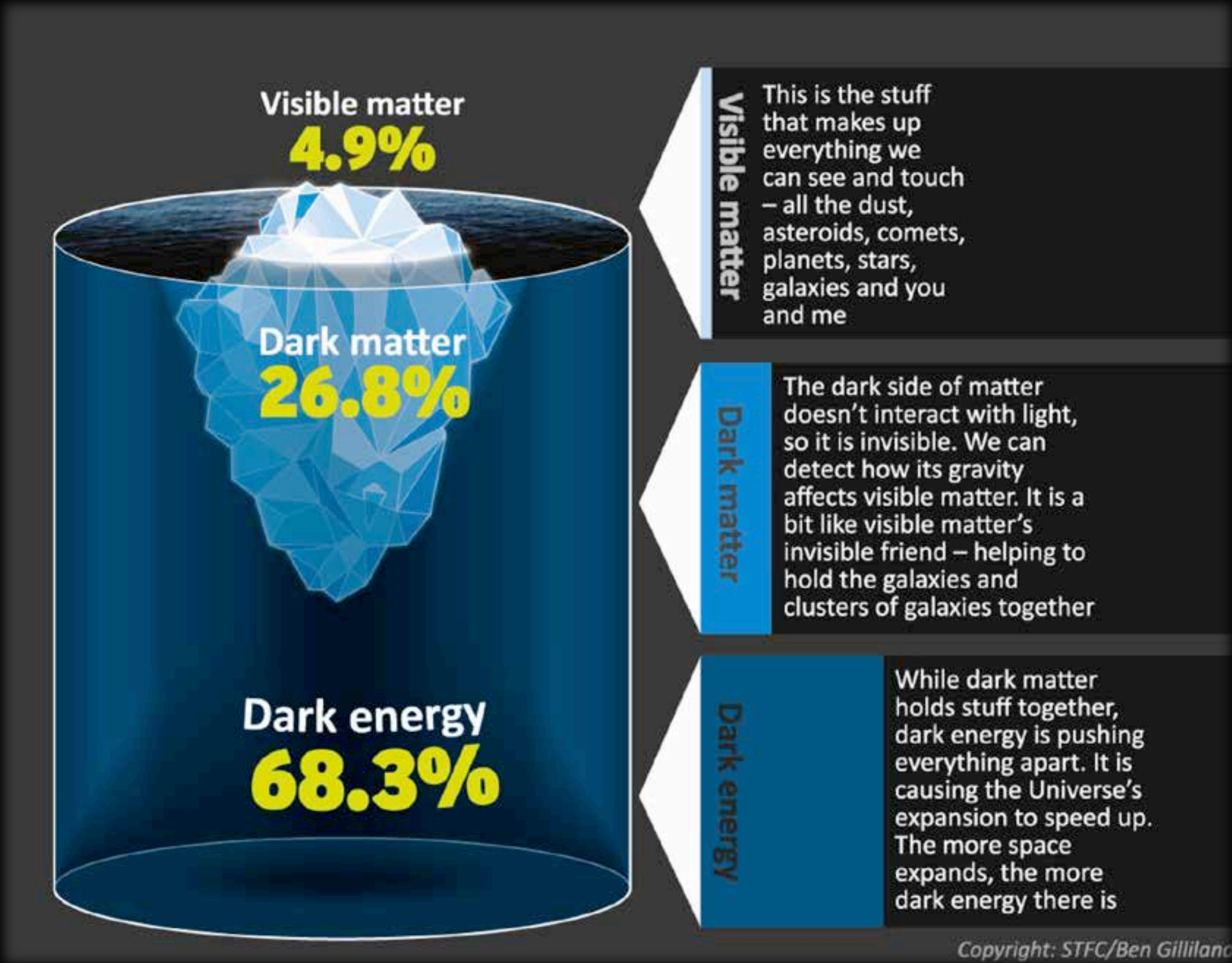
τ_{age} = 13.81 ± 0.05 Gyr

$\Omega_{m,o}$ = 0.315 ± 0.016

$\Omega_{DM,o}$ = 0.2662 ± 0.016

$\Omega_{b,o}$ = 0.0487 ± 0.00027

The End of the Story ?



The End of the Story ?

Not Likely ……