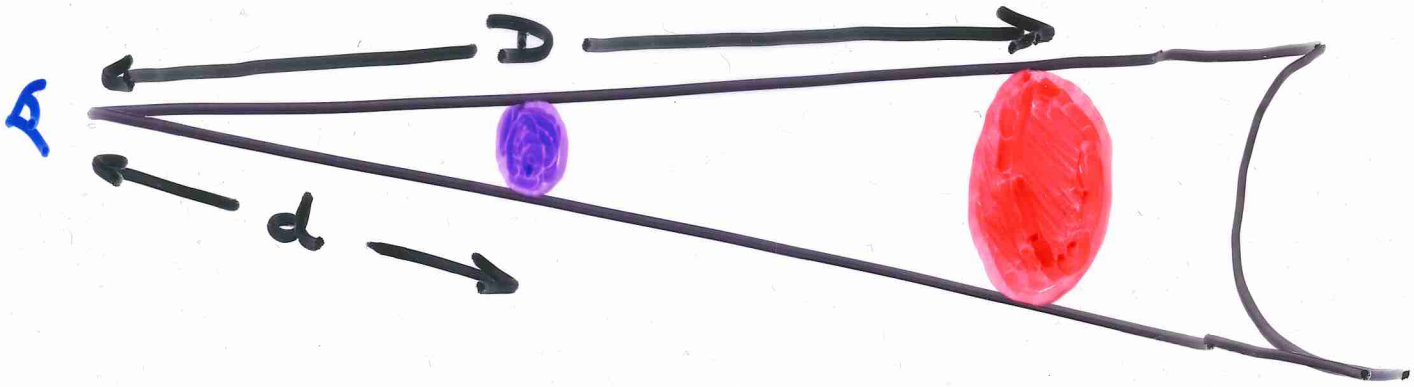
OLBERS' PARADOX

WHY IS THE SKY DARK AT NIGHT?

ASSUME UNIVERSE IS

- STATIC
- INFINITE
- ETERNAL
- HOMOGENEOUS

AS LONG AS LINE OF SIGHT ENDS ON A STAR, SKY WILL BE BRIGHT

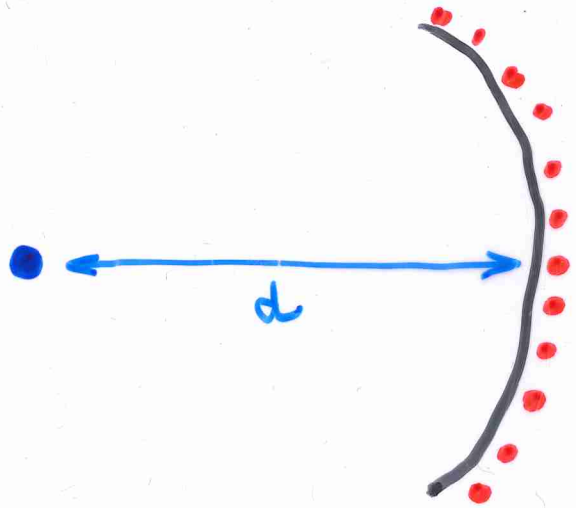


- EACH SQ CM OF SURFACE GIVES MORE LIGHT BEING CLOSER THAN

BUT IS SMALLER SO TOTAL CONTRIBUTION IS THE SAME

① CONTRIBUTION PER SQ CM ∝	$\frac{1}{d^2}$	$\frac{1}{D^2}$
② AREA OF STAR ∝	d^2	D^2
TOTAL ∝	1	1 = SAME!

ALTERNATIVE ARGUMENT



- BRIGHTNESS OF STAR $\propto \frac{L}{d^2}$
- NO. OF STARS AT DISTANCE d IS

$$N \times (\text{SURFACE AREA OF SPHERE})$$

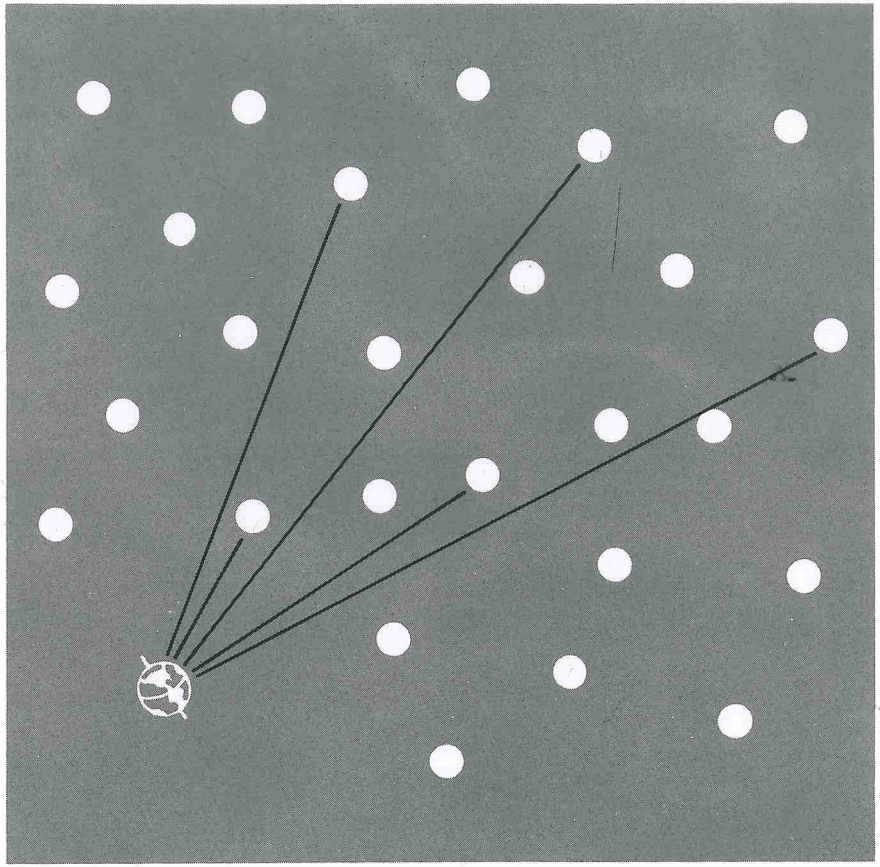
$$= N \times 4\pi d^2$$

- BRIGHTNESS OF SPHERE'S SURFACE

$$= 4\pi d^2 N \times \frac{L}{d^2}$$

$$= 4\pi N L \quad [d \text{ CANCELS}]$$

- BRIGHTNESS OF SKY $\rightarrow$ INFINITY



Olbers' paradox

Seeds: Horizons, 1995 ed., Fig. 15–1; Foundations of Astronomy, 1994 ed., Fig. 18–1

OLBER'S PARADOX

→ BRIGHT SKY AT NIGHT!

→ TEMPERATURE OF EARTH ~ 1000K!

NOT SO!!

WHICH ASSUMPTION(S) IS|ARE FALSE?

- UNIVERSE IS NOT INFINITE

  LIGHT TRAVELS AT SPEED OF LIGHT. IN UNIVERSE OF FINITE AGE, LIGHT REACHING US TODAY HAS COME FROM DISTANCES OUT TO t LIGHT-YEARS WHERE t IS AGE OF UNIVERSE.

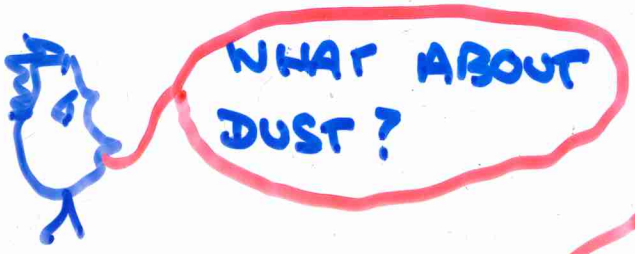
- UNIVERSE IS EXPANDING

PHOTONS GET RED-SHIFTED

AND FILL A LARGER VOLUME

FINITE AGE IS PRINCIPALLY RESPONSIBLE FOR RESOLVING OLBER'S PARADOX

AN EVERY'DAY' OBSERVATION HAS COSMOLOGICAL IMPLICATIONS



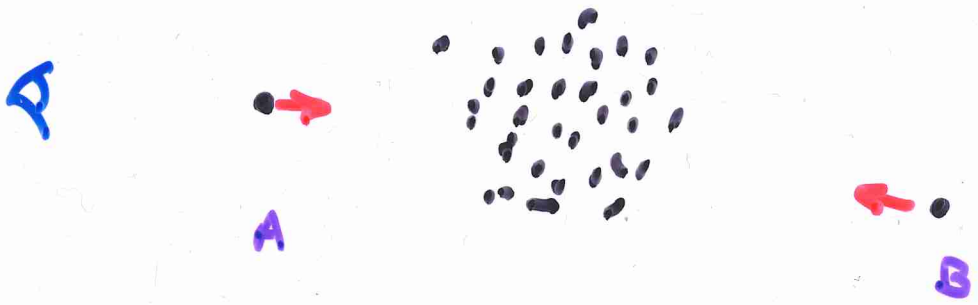
DUST WOULD BE HEATED BY ABSORBING *LIGHT AND EVAPORATED OR 'GLOW'

HUBBLE'S LAW AS A DISTANCE ESTIMATOR

- FIRST ESTABLISH $V = H_0 D$ FOR A SAMPLE OF NEARBY & DISTANT GALAXIES
  - SPECTRUM → V
  - DISTANCE from CEPHEIDS, SN, TULLY-FISHER etc.
- THEN USE LAW TO GET DISTANCES OF OTHER GALAXIES FROM OBSERVATION OF V AND FORMULA $D = \frac{V}{H_0}$

- EXPANSION ($V \propto D$) VERY UNIFORM (ISOTROPIC) EXCEPT FOR

- DEVIATIONS IN/NEAR GALAXY CLUSTERS, & especially SUPERCLUSTERS



A & B ARE 'FALLING IN' TO CLUSTER UNDER 'GRAVITY'

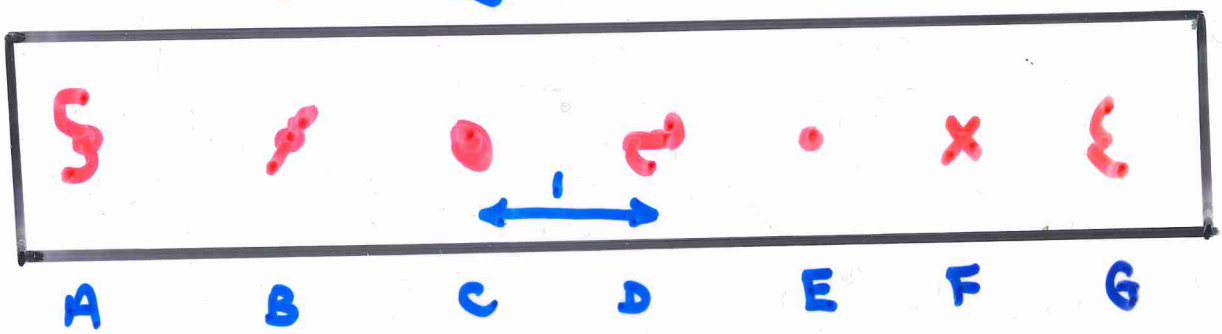
- AT VERY LARGE DISTANCES, WE MAY EXPECT $V \propto D$ TO FAIL

WE THEN SEEING GALAXIES EARLY IN LIFE OF UNIVERSE WHEN EXPANSION MAY HAVE BEEN DIFFERENT.

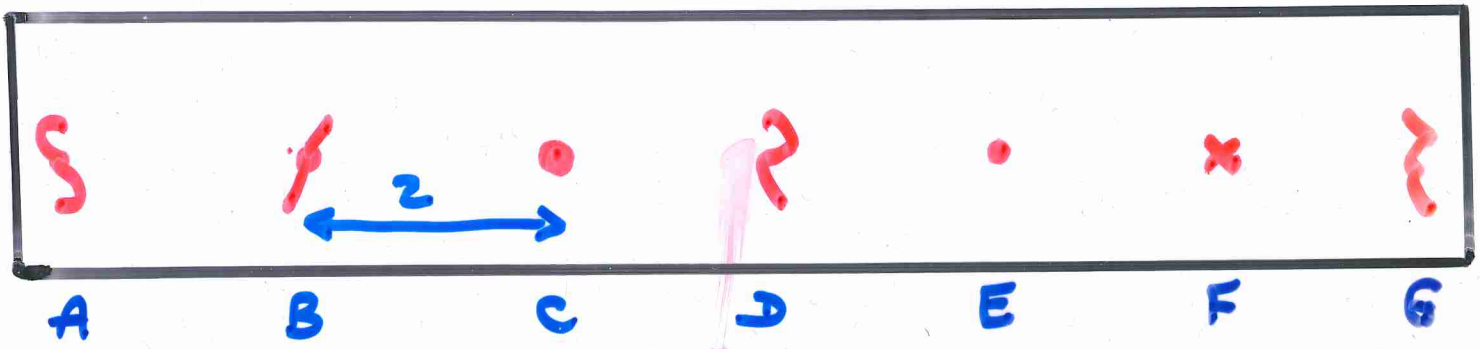
SIMPLE PROOF THAT UNIFORM EXPANSION RESULTS IN HUBBLE'S LAW : $V = H_0 D$

ONE DIMENSIONAL EXAMPLE

UNIVERSE contains galaxies in a line, equally spaced



UNIVERSE expands such that distances between galaxies doubles in 1 billion years



IS HUBBLE'S LAW OBEYED?

PICK A GALAXY : A

CALCULATE OBSERVED RECESSION VELOCITY OF THE OTHER GALAXIES AS VIEWED FROM A

B: $V = \frac{\text{DISTANCE CHANGE}}{\text{TIME INTERVAL}}$ INITIAL DISTANCE

$= \frac{2-1}{1} = 1$ 1

C: $V = \frac{4-2}{1} = 2$ 2

D: $V = \frac{6-3}{1} = 3$ 3

.....

G: $V = \frac{12-6}{1} = 6$ 6

$V \propto D$

OBSERVED
EXPANSION

$\cong$ ISOTROPIC

ARE WE THEN AT

CENTER OF UNIVERSE?

EXPANSION DOES NOT DEMAND US TO BE AT CENTER

- DOTS ON A BALLOON (2D)
- RAISINS IN A CAKE (3D)

EXPANSION DOES NOT IMPLY A CENTER

- INFINITE FLAT SPACE (2D)
- CURVED SPACE
  - SURFACE OF SPHERE (2D)
    finite area, no boundary, no center

SINCE COPERNICUS MAN
ROLLS FROM THE CENTRE
INTO X.

F. NIETZSCHE

THE WILL TO POWER

LOOK-BACK TIME

- LIGHT TRAVELS AT A FINITE SPEED (300,000 km/s)

∴ WE OBJECTS AS THEY WERE WHEN THE LIGHT WAS EMITTED

EXAMPLE

A GALAXY AT 2 BILLION LYrs IS SEEN AS IT WAS 2 BILLION YRS AGO

AND THERE IS A 'HORIZON' TO OUR UNIVERSE

DISTANCE TO HORIZON

$\approx$ c × AGE OF UNIVERSE

THIS HORIZON MAY OR MAY NOT INCLUDE ALL OR MOST OF THE UNIVERSE - DEPENDS ON THE MODEL OF UNIVERSE.

MODEL UNIVERSES

- COSMOLOGICAL PRINCIPLE
  AN OBSERVER ANYWHERE IN UNIVERSE SEES - AT A GIVEN TIME - ESSENTIALLY SAME PICTURE AS ALL OTHER OBSERVERS

  → HOMOGENEOUS, ISOTROPIC UNIVERSE

- LAWS OF NATURE, AS DETERMINED LOCALLY, APPLY ACROSS SPACE AND TIME.

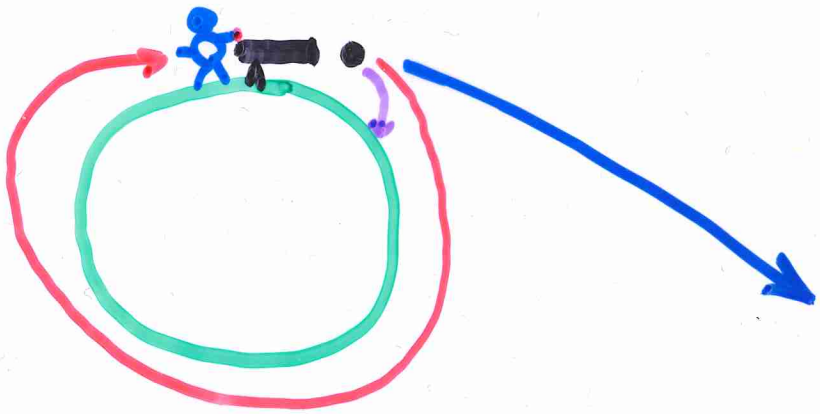
  THESE ARE ~~NOT~~ OBSERVATIONS BUT ASSUMPTIONS (CONSTRUCTION PRINCIPLES) TO BE CONFIRMED OR NOT BY COMPARISON OF MODEL'S PREDICTIONS WITH OBSERVATIONS

A FAMILY OF EXPANDING (EVOLUTIONARY) MODELS

ASSUMPTION: UNIVERSE BEGAN FROM A PRIMORDIAL FIREBALL - THE BIG BANG.

- DISCUSS EVIDENCE FOR THIS LATER

WHAT IS FUTURE OF EXPANDING UNIVERSES?



1. CLOSED UNIVERSE
2. FLAT UNIVERSE
3. OPEN UNIVERSE

1. CLOSED UNIVERSE

CURRENT EXPANSION SLOWS

CONTRACTION ENSUES

BIG CRUNCH!

2. FLAT UNIVERSE

EXPANSION SLOWS

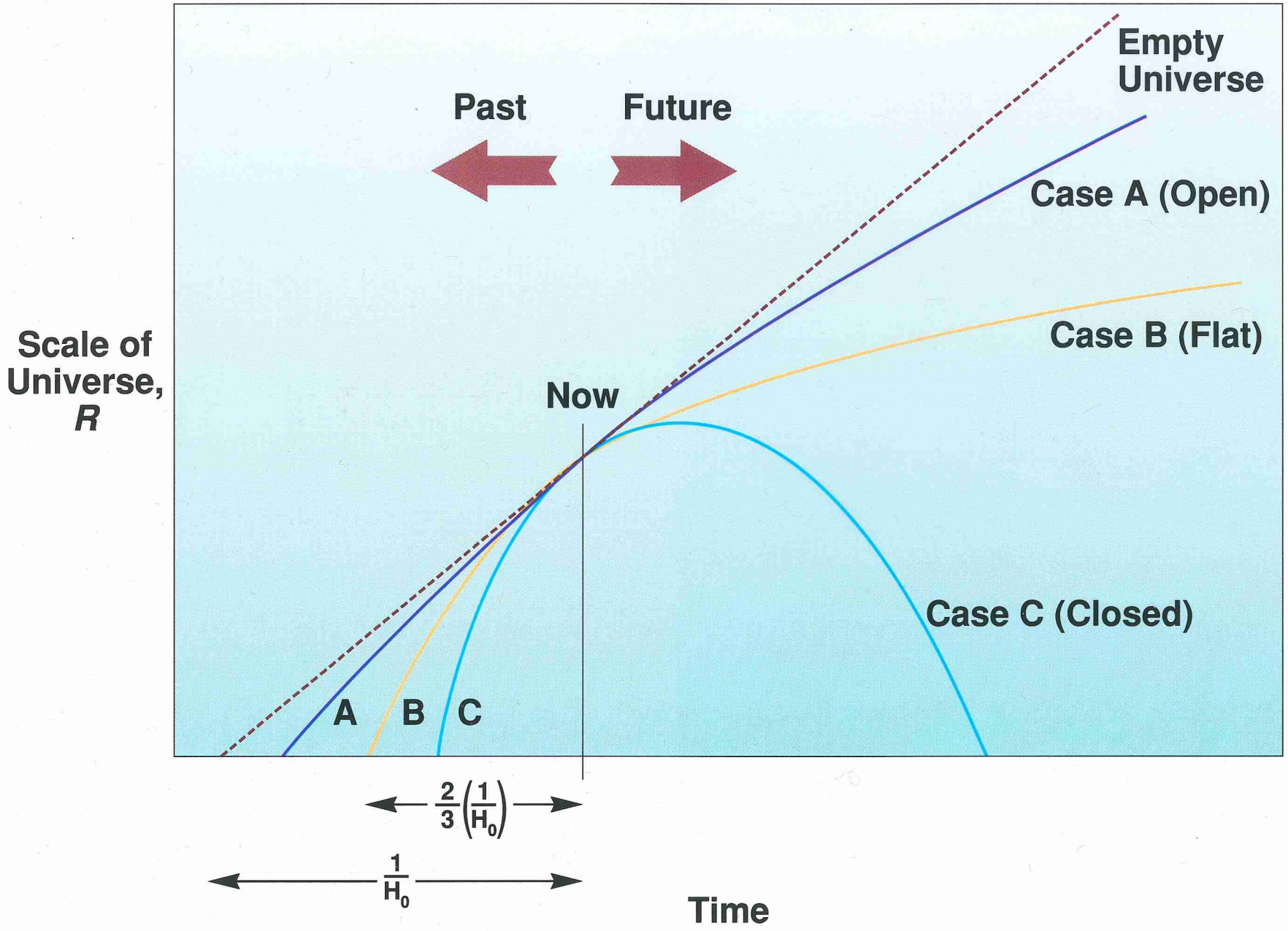
GALAXIES COAST TO A HALT

* BUT *

3. OPEN UNIVERSE

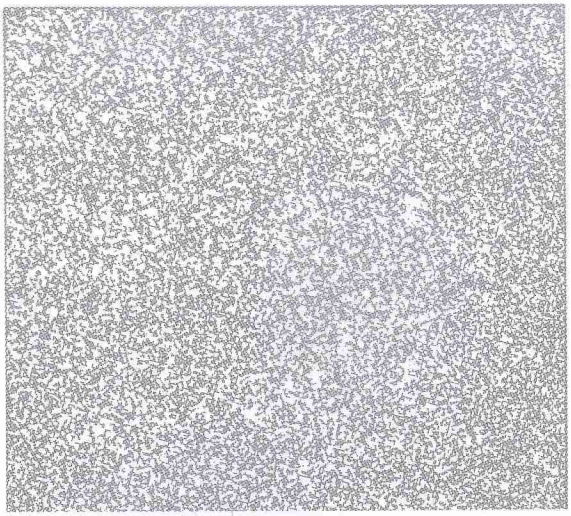
EXPANSION SLOWS BUT CONTINUES

THESE ARE BASED UPON EINSTEIN'S THEORY OF GENERAL RELATIVITY.

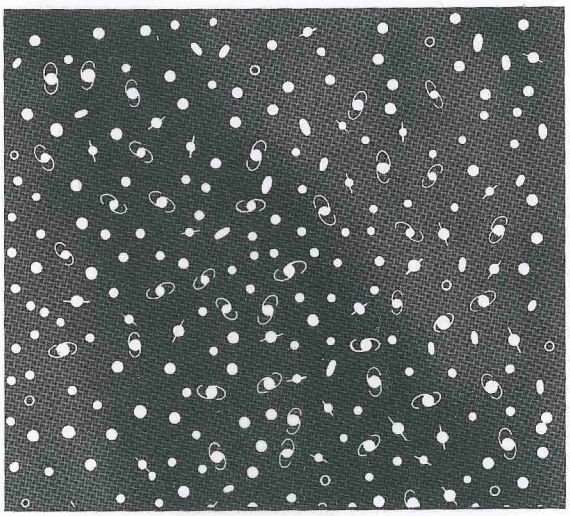


Changing scale of the universe

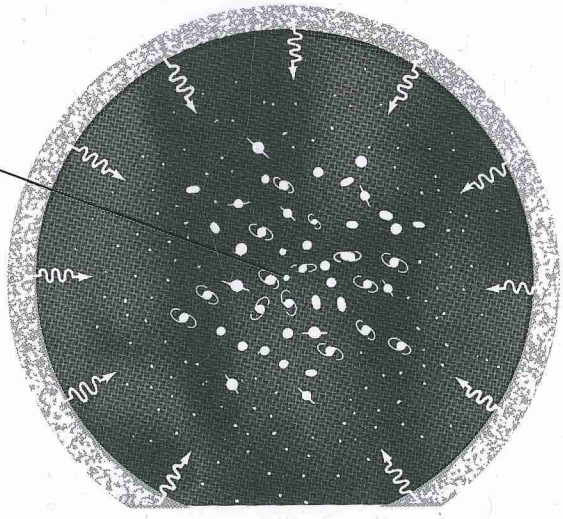
Hartmann/Impey: The Cosmic Journey, 5th ed., Fig. 26-10



A region of the universe during the big bang



A region of the universe now



The present universe as it appears from our galaxy

Three views—universe centered on our galaxy

Seeds: Horizons, 1995 ed., Fig. 15–7; Foundations of Astronomy, 1994 ed., Fig. 18–8

THE HUBBLE TIME

HUBBLE'S LAW IMPLIES EXPANSION OF UNIVERSE

IF WE ASSUME EXPANSION VELOCITIES HAVE BEEN CONSTANT, CAN READILY ESTIMATE WHEN EXPANSION BEGAN

CRUDE PICTURE:

EXPLOSION! FAST FRAGMENTS NOW FURTHER AWAY THAN SLOWLY MOVING FRAGMENTS

BUT

TIME (since explosion)

$$= \frac{\text{DISTANCE}}{\text{VELOCITY}}$$

$$= \frac{D}{V} = \frac{D}{H_0 D} = \frac{1}{H_0}$$

$V = H_0 D$

HUBBLE TIME $= \frac{1}{H_0}$

$\simeq \frac{1000}{H_0}$

for T in billion yrs &
H_0 in Km/s/Mpc

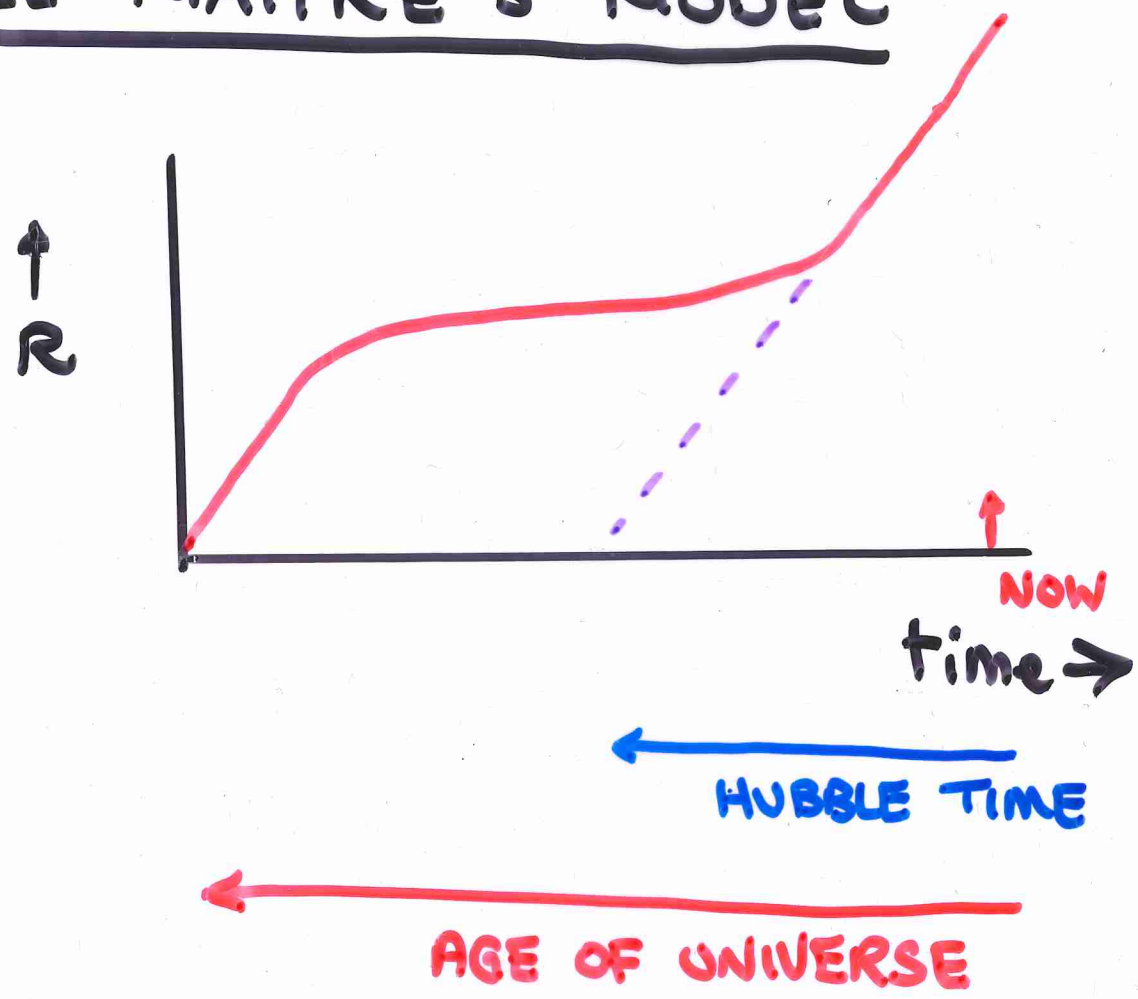
HIGH H_0 – large expansion velocity – young age

LOW H_0 – low exp. velocity
– older age of Universe.

HUBBLE's problem: $H_0 \approx 450$ Km/s/Mpc
→ $T \approx 2$ billion years, but
EARTH at 4½ billion years
is OLDER than the UNIVERSE
it belongs to!

OTHER MODELS HAVE BEEN PROPOSED:

- **LE MAÎTRE'S MODEL**



- BIG BANG
- EXPANSION HALTS
- COSMICAL REPULSION leads to CURRENT EXPANSION PHASE

- INTRODUCED IN 1930s TO RESOLVE THEN LARGE DISCREPANCY BETWEEN HUBBLE TIME (2½ Bill.yr) AND AGE OF EARTH (4½ Bill.yr).

• STEADY-STATE UNIVERSE

MOTIVATIONS

1. PHILOSOPHICAL to 'remove' the origin of universe. Replaced COSMOLOGICAL PRINCIPLE by PERFECT COSMOLOGICAL PRINCIPLE:

'AT A GIVEN TIME' IS REPLACED WITH 'AT ALL TIMES'.

EXPANSION IS A FACT. THEN, PCP DEMANDS THE CONTINUOUS CREATION OF MATTER

AT A RATE TOO LOW FOR LABORATORY TESTS!

2. AGE PROBLEM (of 1940s ≈ 1930s)

STEADY-STATE UNIVERSE allows some objects (e.g. EARTH, STARS) to be older than expansion age (HUBBLE TIME)

THE HOT BIG BANG

TIME	EVENTS etc.
0^s	$T > 10^{12}$ K

DENSE, ISOTROPIC, EXPANDING

PHOTONS, NEUTRINOS, ELECTRONS$^{\pm}$, QUARKS interact frequently ($e^+ + e^- \rightleftharpoons 2\gamma$, e.g.)

PARTICLE PHYSICS meets COSMOLOGY

EXPANSION DRIVEN BY RADIATION (PHOTON) PRESSURE

EINSTEIN'S THEORY OF GENERAL RELATIVITY ASSUMED

10^{-6} s $\quad T \simeq 10^{12}$ K

- EXPANSION, COOLING CONTINUE
- QUARKS ASSEMBLED INTO PROTONS AND NEUTRONS
- PARTICLES INTERACT FREQUENTLY, e.g.

$$n + e^+ \rightleftharpoons p + \bar{\nu}_e$$

$$n \rightleftharpoons p + e^- + \nu_e$$

$$p + e^- \rightleftharpoons n + \nu_e$$

Such that n/p ABUNDANCE RATIO fixed by T : more p than n because n is unstable

- FEW PARTICLES IN A BATH OF PHOTONS

$$\frac{\text{particles}}{\text{photons}} \sim 10^{-10}$$

[WHY?]

- MATTER $\gg$ ANTIMATTER [WHY?]

1 s $\quad T \simeq 10^{10}\,K \quad \left(T \approx \frac{10^{10}}{\sqrt{t_s}} \right)$

- DENSITY OF MATTER SO LOW THAT NEUTRINO-MATTER COLLISIONS CEASE.
- For $t > 1^s$ to TODAY, UNIVERSE TRANSPARENT TO ν's. WE ARE BATHED IN COSMOLOGICAL ν's - NOT YET DETECTED. POTENTIAL EXPLANATION FOR DARK MATTER
- RATIO OF n to p NOW FROZEN EXCEPT OF DECAY OF FREE neutrons

$$n \rightarrow p + e^- + \nu_e$$
$$p + e^- \rightarrow n + \nu_e$$

} REVERSE REACTIONS CEASE

- PHOTON ENERGIES (DECLINE AS T DROPS – WIEN'S LAW!) TOO LOW TO MAINTAIN e^-, e^+:

$$e^- + e^+ \rightarrow 2\gamma$$

BUT NOT REVERSE DIRECTION AS PREVIOUSLY