100 s

$T = 10^9$ K [ERA OF NUCLEOSYNTHESIS]

- GAS CONSISTS OF p, n, e^-, ν, γ AT START
- DEUTERIUM BOTTLENECK!

$p + p \rightarrow d + e^+ + \nu$ (VERY SLOW/WEAK INT.)

$p + n \rightarrow d + \gamma$ ($d \equiv (n+p) \equiv$ heavy hydrogen)

A FASTER REACTION BUT PRIOR TO 100 s 'HOT' PHOTONS DESTROY d AS FAST AS IT IS MADE

AFTER $t \sim 100$ s, FEW ENERGETIC PHOTONS AND A TRACE OF d SURVIVES

- NUCLEAR REACTIONS SWIFTLY CONVERT ALL NEUTRONS TO ^4He ($\equiv 2p + 2n$)

  - RECALL n/p RATIO FROZEN WHEN ν's CEASED TO INTERACT AT $t \sim 1^s$.

    PREDICT $^4He/H \sim 10\%$ by number AND A TRACE OF DEUTERIUM AND ^3He AND ^7Li:

  - BOTTLENECKS AT MASS = 5 AND 8:

    ALL NUCLEI OF MASS 5 AND 8 ARE HIGHLY UNSTABLE (NUCLEAR FORCES vs ELECTROSTATIC REPULSION).

    GAS IS p AND ^4He $\therefore$ ONLY POSSIBILITIES ARE 1+1, 1+4, AND 4+4 !

- PREDICTIONS depend on ratio of matter to photons

BUT APPROXIMATELY

$$\frac{^4He}{H} \sim 10\%$$

$$\frac{D}{H} \sim 10^{-4}$$

$$\frac{^3He}{^4He} \sim 10^{-4}$$

$$\frac{^7Li}{H} \sim 10^{-10}$$

AND NO OTHER ELEMENTS IN SIGNIFICANT AMOUNTS

NEED ELEMENT SYNTHESIS BY STARS

TESTS OF BIG BANG MODELS

① NUCLEOSYNTHESIS

PREDICTIONS:

$He/H \sim 5\text{-}7\%$ by number

D/H, $^3He/H$ } v. little DEPENDS ON MATTER/PHOTON RATIO

^7Li:

NOTHING ELSE!

OBSERVATIONS: HELIUM

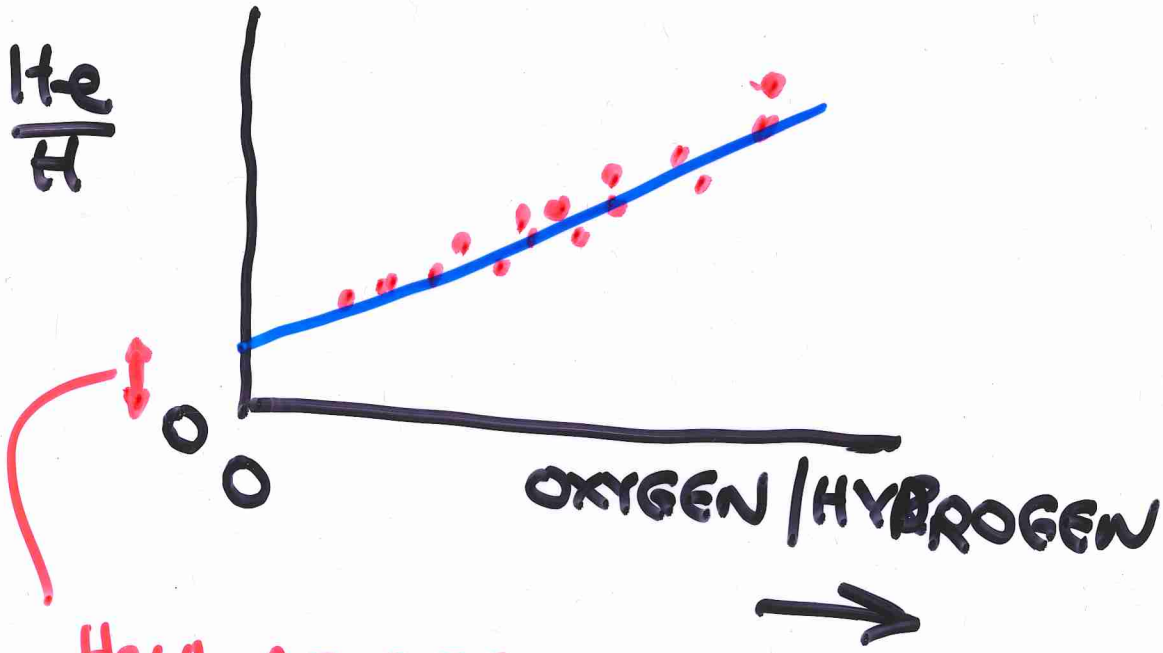
PROBLEM – HELIUM IS ALSO MADE BY STARS

SOLUTION – OBSERVE HELIUM IN OBJECTS CONTAMINATED DIFFERENTLY BY EJECTA FROM ★

EXAMPLE : H II REGIONS IN GALAXIES OF DIFFERENT OXYGEN CONTENTS

↓ FROM STARS

[WHY NOT OBSERVE STARS?]



HeIH AT ZERO OXYGEN (BIG BANG YIELD)

IRONY - 1.

ALL STARS CONVERT H to He ON MAIN SEQUENCE (AND LATER)

BUT He IS NOT PRINCIPALLY A PRODUCT OF STARS BUT OF THE BIG BANG.

LUMINOSITY OF GALAXY
AGE of GALAXY
ASSUME ALL LUMINOSITY From H → He FUSION

→ $He/H \sim 1\%$ IF ALL He RELEASED BY STARS, BUT LOTS → WD, BH, NS

BUT $He/H \sim 10\%$ IS OBSERVED

∴ UNLIKELY He IS PRIMARILY PRODUCT OF STARS

IRONY-2.

THIS CONCLUSION WAS REACHED IN 1964 BY FRED HOYLE, STEADY-STATE UNIVERSE CO-FOUNDER, WHO CONSIDERED ALL ELEMENTS TO BE MADE BY STARS. NO HOT BIG BANG IN HIS UNIVERSE

HOW DID HE WRIGGLE OUT?

SUPERMASSIVE OBJECTS ($10^6 M_\odot$)! ($\approx$ MINI-BIG BANGS)

AND HE COINED TERM 'BIG BANG', AS A PEJORATIVE.

CONCLUSION

OBSERVED He/H, D/H, $(^3He/H)$, & Li/H OF PRIMORDIAL GAS IS CONSISTENT WITH A HOT BIG BANG WITH A PARTICULAR MATTER/PHOTON RATIO

THIS CONFIRMS BIG BANG MODEL AT A FEW MINUTES AFTER ORIGIN

TEXAS IS HELIUM CAPITAL OF 'UNIVERSE'. IS THIS BIG BANG He ?

700,000 YRS $T \sim 3000\ K$

- PROTONS + ELECTRONS COMBINE TO FORM H ATOMS : PHOTONS NO LONGER ENERGETIC ENOUGH TO BREAK H ATOMS UP

$$p + e \rightarrow H + \gamma$$

BUT NOT

$$\gamma + H \rightarrow p + \gamma$$, AS BEFORE 10^5 yrs.

- NOW, PHOTONS FIND UNIVERSE TRANSPARENT WHERE PREVIOUSLY THEY FOUND IN OPAQUE (SCATTERED OFF FREE ELECTRONS)

RADIATION DECOUPLED FROM MATTER

700,000 YRS
TO PRESENT

T continues to drop

GALAXIES, QUASARS form
& evolve

OBSERVE EVOLUTION, IF NOT
YET FULLY UNDERSTOOD!

NOW

~15 BILLION YRS

GALAXIES have formed and evolved.

PHOTONS from 700,000 YRS FILL THE UNIVERSE

LARGER VOLUME & REDSHIFTED

PHOTON TEMPERATURE DROPPED FROM 3000K TO ABOUT 3K

COSMIC MICROWAVE BACKGROUND RADIATION

② COSMIC MICROWAVE BACKGROUND RADIATION (3°K)

RECALL $t \sim 700{,}000$ YRS WHEN $e + p \rightarrow H$ AND UNIVERSE TRANSPARENT TO PHOTONS of 3000 K.

DISCOVERY - FASCINATING TALE

1964 : PENZIAS & WILSON (BELL LABS)

TESTING COMMUNICATIONS ANTENNA

FOUND EXCESS INCOMING SIGNALS EQUIVALENT TO

$T \sim 3°K$, SAME IN ALL DIRECTIONS

DICKE & PEEBLES (PRINCETON)

PREDICTED BIG BANG RADIATION, SCOOPED!

~1990 COBE SATELLITE

- 3°K IS TRULY A BLACK BODY ($T = 2.733$ K)

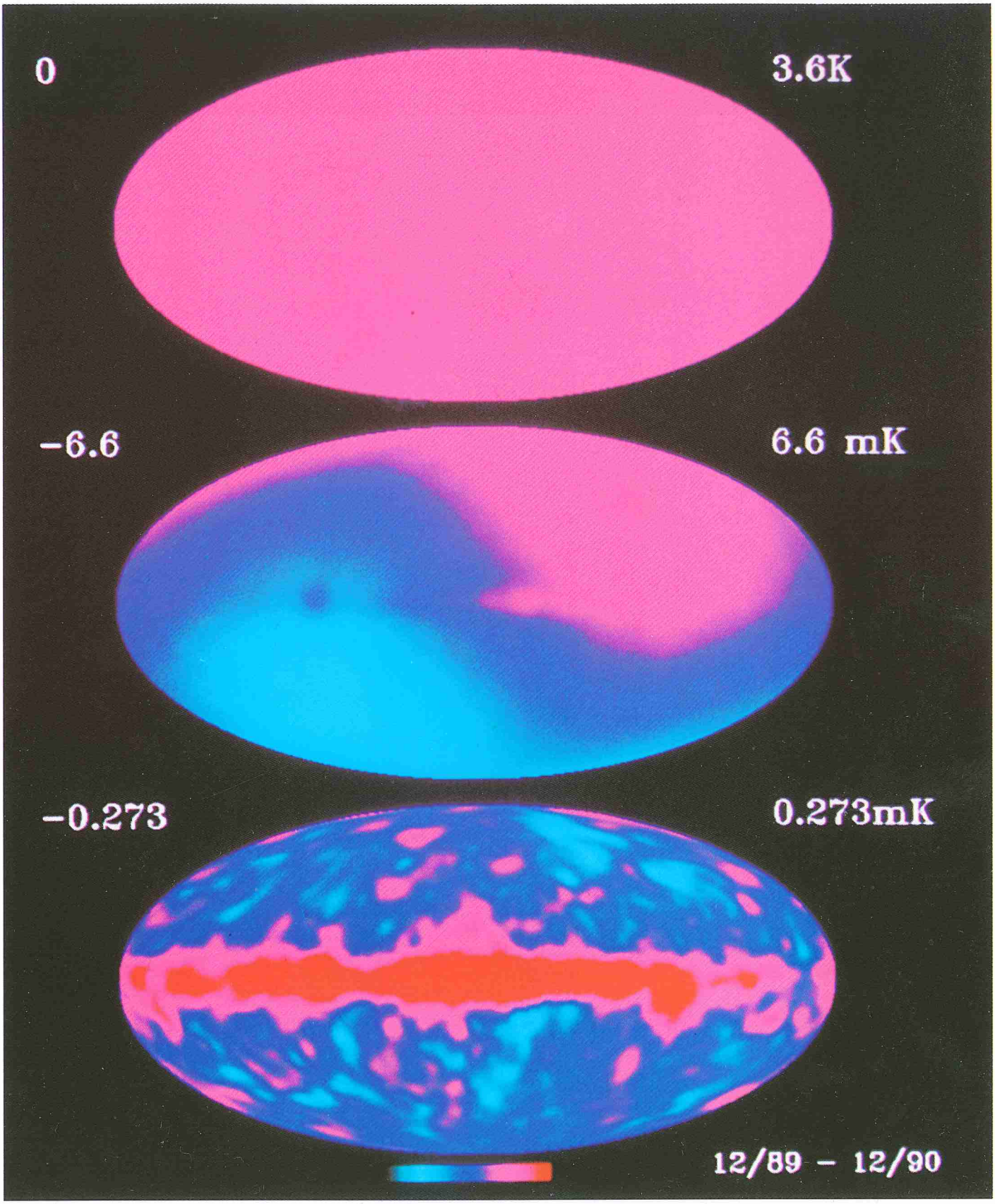
- DETECTED DOPPLER SHIFT OF EARTH/SUN MOVING REL. TO 3°K RADIATION

AFTER KNOWN MOTIONS CONSIDERED, MOTION IS ~ 400 KM/S TOWARDS 'GREAT ATTRACTOR')

[0.003 K effect]

- HIGHLY ISOTROPIC. DIFFERENCE DETECTED AS FEW PARTS IN 100,000

[WHY WAS UNIVERSE SO UNIFORM AT 700,000 YEARS AND HIGHLY NON-UNIFORM (GALAXIES) NOT LONG AFTERWARDS.]



Microwave background radiation measured by COBE

Hartmann/Impey: The Cosmic Journey, 5th ed., Fig. 26-9

STEADY-STATE vs EVOLUTIONARY MODELS

"THE 1950-1960s DEBATE"

- OBSERVATIONAL EVIDENCE STRONGLY FAVORS EVOLUTIONARY MODELS
  NOW
  - 3°K BACKGROUND RADIATION
  - GALAXIES, QUASARS, ... EVOLVE WITH LOOK-BACK TIME
  - HOT BIG-BANG NEEDED TO ACCOUNT FOR HELIUM CONTENT
- DEBATE WAS A SPUR
  - OBSERVATIONAL ASTRONOMY DEVELOPED FASTER, eg. RADIO ASTRONOMY
  - IDEAS ABOUT STELLAR NUCLEOSYNTHESIS GREW
    DO STARS OR FIREBALL (BIG BANG) MAKE THE CHEMICAL ELEMENTS?

A PUZZLING UNIVERSE?

< 1998

GRAVITY MUST SLOW HUBBLE EXPANSION

> 1998

OBSERVATIONS [Ia SN]

SHOW EXPANSION IS NOW ACCELERATING

CMB RIPPLES SHOW UNIVERSE IS FLAT

– VERY FLAT

MASS + ENERGY BUDGET - TODAY

(SEEDS p. 415)

4.5% NORMAL [BARYONIC] MATTER

22.7% DARK [NON-BARYONIC] MATTER

72.8% DARK ENERGY (REPULSIVE)

$H_0 = 70$ km/s/Mpc

WHAT GRADE WOULD YOU GIVE ASTRONOMERS?

EXTRA-SOLAR PLANETS (EXOPLANETS)

DETECTION

- RADIAL VELOCITY
- TRANSITS
- IMAGING { VISIBLE / INFRA-RED

HOT JUPITERS

NOT ALWAYS COPLANAR

INHABITED WORLDS ?

SEEDS p438+ DRAKE EQUATION

$$N_c = N_* \cdot f_p \cdot n_{HZ} \cdot f_L \cdot f_I \cdot f_S$$

TABLE 19-1 The Number of Technological Civilizations per Galaxy

Estimates	Variables	Pessimistic	Optimistic
N_*	Number of stars in a typical large galaxy	2×10^{11}	2×10^{11}
f_P	Fraction of stars with planets	0.1	0.5
n_{HZ}	Number of planets per star that orbit in the habitable zone for longer than 4 billion years	0.01	1
f_L	Fraction of habitable zone planets on which life begins	0.01	1
f_I	Fraction of planets with life on which some species evolves to intelligence	0.01	1
f_S	Fraction of star's existence during which a technological civilization survives	10^{-8}	10^{-3}
N_c	Current number of communicative civilizations per galaxy	2×10^{-4}	1×10^{8}

ONLY US IN THE GALAXY

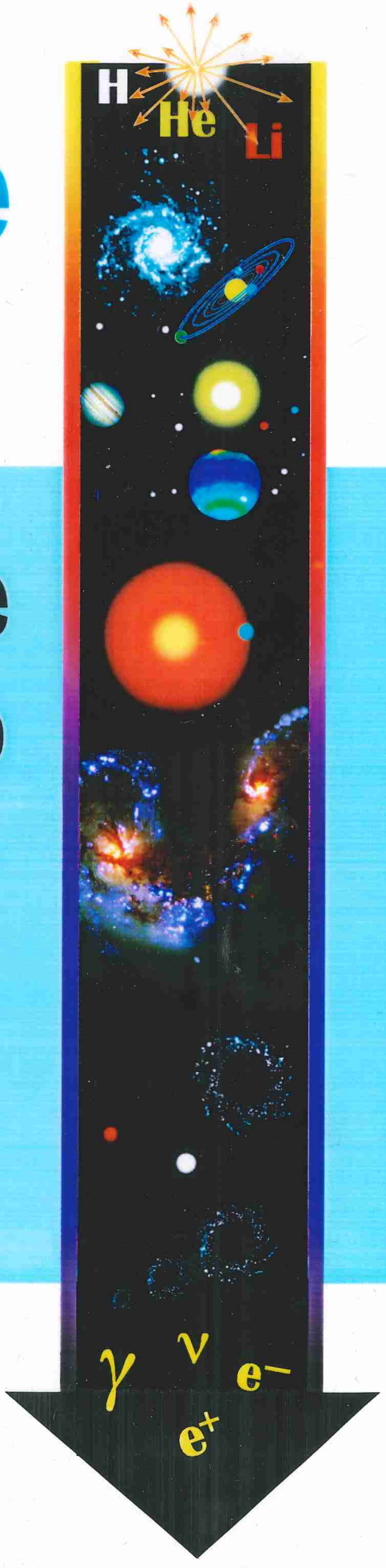
THEY ARE FEW LYRS AWAY

Eras of the Universe

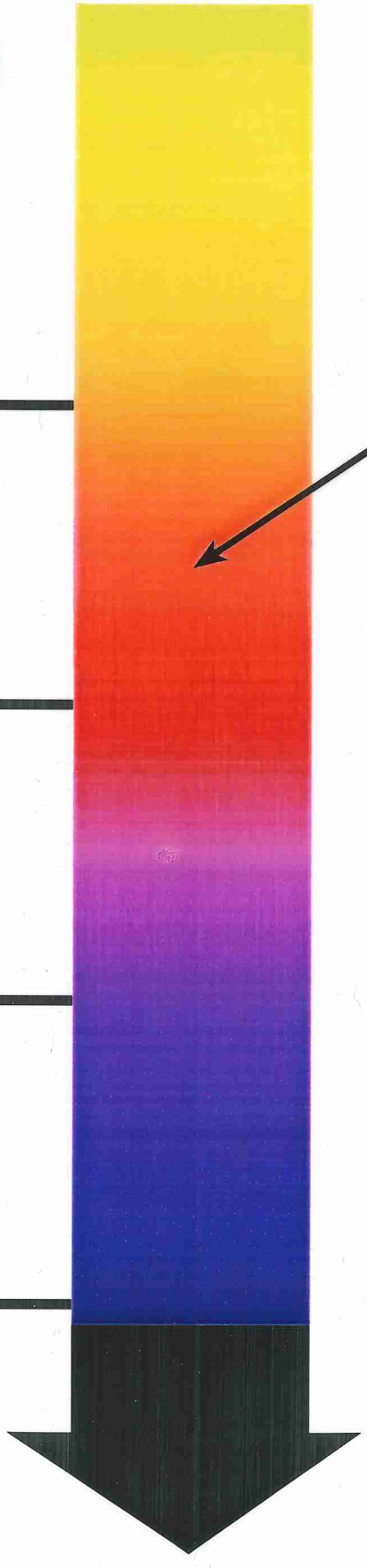
The Universe Beginning to End

Age = 10^{η} years

$\eta = -\infty$ to > 100



Eras of the Universe



Radiation-dominated Era

$\eta = -\infty$ to 4

you are here

Stelliferous Era

$\eta = 6$ to 14

Degenerate Era

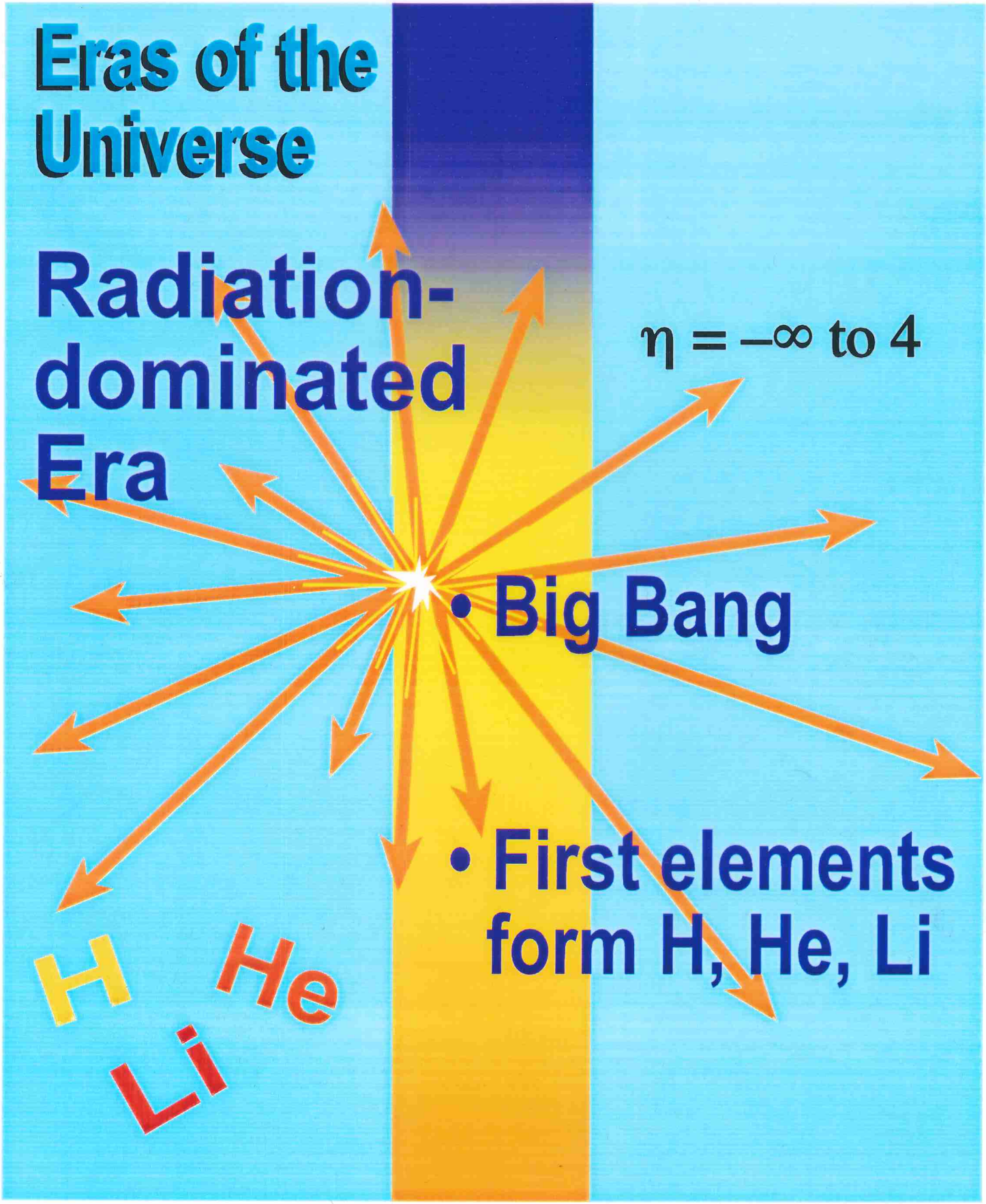
$\eta = 15$ to 37

Black Hole Era

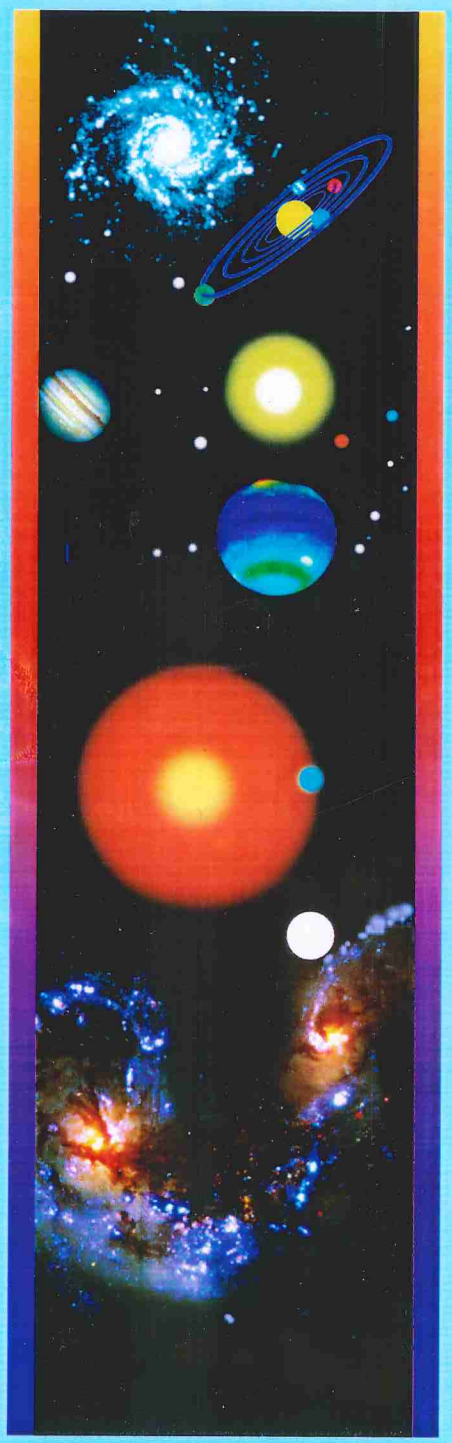
$\eta = 38$ to 100

Dark Era

$\eta > 100$


Eras of the Universe
Radiation-dominated Era
$\eta = -\infty$ to 4
• Big Bang
• First elements form H, He, Li
H
He
Li

Eras of the Universe



Stelliferous Era

$\eta = 6$ to 14

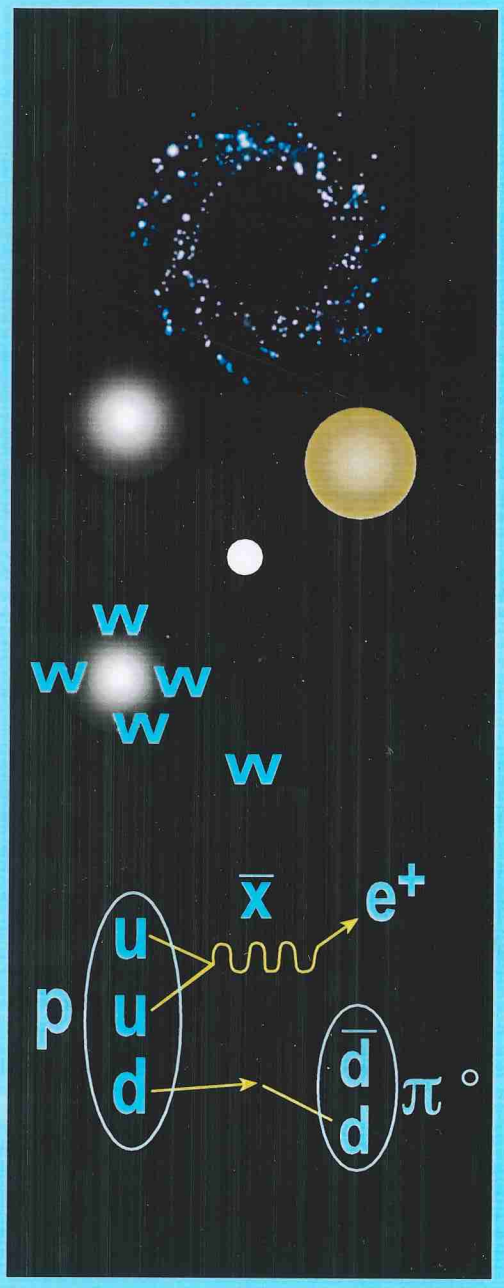
- Galaxy formation
- Solar System forms
- You are here
- Earth enveloped by Sun
- Sun becomes a white dwarf
- Galaxies collide

Eras of the Universe

Degenerate Era

$\eta = 15$ to 37

- Universe consists of:
  Black holes
  White dwarfs
  Neutron stars
  Brown dwarfs
- White dwarfs capture WIMPS
- Proton decay destroys white dwarfs, planets and brown dwarfs



Eras of the Universe

Black Hole Era

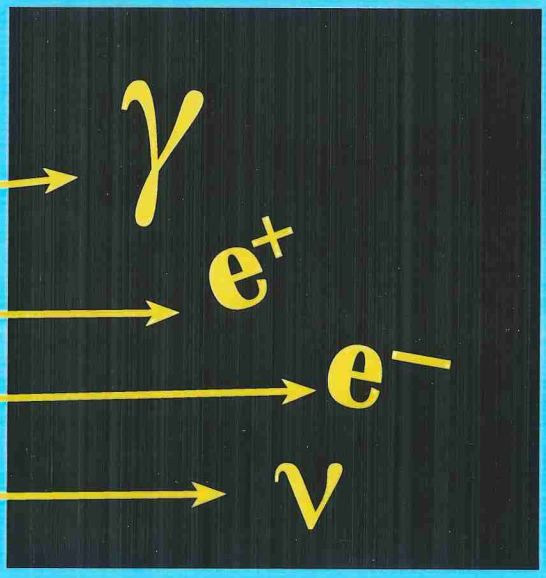
$\eta = 38$ to 100

- Black holes evaporate

Dark Era

$\eta > 100$

photons
positrons
electrons
neutrinos



There is something fascinating about science. One gets such a wholesale return of conjecture out of such a trifling investment of fact.

Mark Twain
Life on the Mississippi
1883

ONE THING ABOUT THE PAST.

IT'S LIKELY TO LAST.

OGDEN NASH

NOW MY SUSPICION IS THAT THE UNIVERSE IS NOT ONLY QUEERER THAN WE SUPPOSE, BUT QUEERER THAN WE CAN SUPPOSE.

J. B. S. HALDANE
POSSIBLE WORLDS, 1927.

Thus the explorations of space end on a note of uncertainty. And necessarily so. We are, by definition, in the very center of the observable region. We know our immediate neighborhood rather intimately. With increasing distance, our knowledge fades, and fades rapidly. Eventually, we reach the dim boundary -- the utmost limits of our telescopes. There, we measure shadows, and we search among ghostly errors of measurement for landmarks that are scarcely more substantial.

The search will continue. Not until the empirical resources are exhausted need we pass on to the dreamy realms of speculation.

Edwin P. Hubble
The Realm of the Nebulae
1936