
Perspectives on Origin of
Chemical Elements and the Origin of Lif
in the Universe
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MULTI-MESSENGER ASTRONOMY

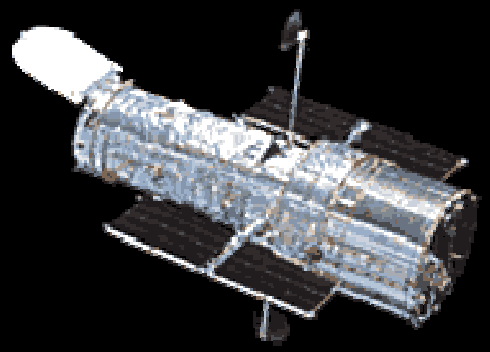
Astronomy has always been driven by technologic advancements.

Some landmarks:

- 1610 [Galileo]
- 1910 - 1930 [Harlow Shapley, Edwin Hubble]
- 1950 – 1970 [Martin Ryle, Bernard Lowell, B. Y. Mills, G. Swarup]
- 1965 – 1980 [Rossi, Giacconi,…….]
- 1988 - [COBE, GMRT, HST,CROMPTON GRO, CHANDRA, SPITZER, LIGO]

WINDOWS ON THE UNIVERSE

Optical
Radio
Microwave
Infrared
X-ray
γ-ray
Cosmic rays
Neutrinos
Gravitational Waves



[Balloons, Rockets, Satellites]

Astronomy has over the ages been a testing ground for theories of gravity.

Kepler: Motions of Planets under Sun's Gravitational Fiel

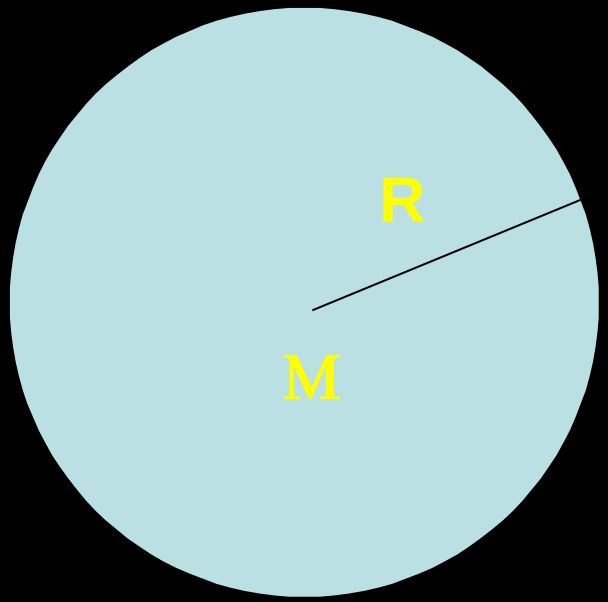
Newton: Mechanics of Planetary Motions & precessi of elliptical orbits under inverse square law

Einstein: Binary compact objects (neutron stars, blac holes) when they merge, serve as powerful transmitters of gravitational waves.

MILESTONES in ASTROPHYSICS & COSMOLOGY
in the 20th and 21st century

1930-1970:	Stellar Structure
1950-1980:	Thermonuclear evolution stars & Synthesis of elements
1960-2000:	Collapsed Objects: White Dwarfs, Neutron Stars, Black Holes
1990-2010:	Cosmic Microwave Background Radiation. Origin & Growth of Galaxies & Large-Scale Structure of the Universe . Accelerating Universe. Dark Matter & Dark Energy.
2010:	Exoplanets. Gravitational Waves

QUASI – EQUILIBRIUM OF STARS



$$\rho \sim M / R^3$$

$$kT \sim \frac{GM}{R} m_p$$

$T_c(^0K)$	10^7	10^8	10^9	10^{10}
	H ⟶	He ⟶	C, O ⟶	Si, Mg ⟶ Fe, Ni
$\rho_c(gm/cm^3)$	$\sim 10^2$	$\sim 10^6$	$\sim 10^9$	$\sim 10^{14}$

ENERGY SOURCES FOR STARS

- GRAVITATIONAL

$E_{grav} = - GM^2 / R \sim -4 \times 10^{48}$ erg

- THERMAL

$E_{thm} = (3k T/2 m_H) M \sim 2 \times 10^{48}$ erg

- NUCLEAR

$E_{nuc} = 0.008 Mc^2 \sim 10^{52}$ **erg**

- CAPTURE OF MATTER (ACCRETION)

COSMIC KITCHEN

Ve are all made of star stuff" – Carl Sagan

ucleosynthesis describes the process by which atomic nuclei are
ansformed from one species to another in the cosmos.

hus, the lighter elements like hydrogen (^{1}H), deuterium(^{2}H),
tium(^{3}H), helium(^{4}He) and lithium(^{7}Li) are manufactured in the h
ense initial phase during the first there minutes after birth of the
niverse (S, Weinberg).

ow elements lighter and heavier than iron which bear directly on
xistence, are formed?

Observed abundances nuclei are determined from the ashes of previous nuclear processes

TABLE 1. *Cosmic abundance of Chemical elements*

Name	*Chemical Symbol*	*Cosmic Abundance*
Hydrogen	H	9.18×10^{4}
Helium	He	2.21×10^{3}
Oxygen	O	2.14×10
Carbon	C	1.18×10
Nitrogen	N	3.64
Neon	Ne	3.44
Magnesium	Mg	1.06
Silicon	Si	1
Aluminium	Al	8.5×10^{-1}
Iron	Fe	8.3×10^{-1}
Sulfur	S	5.0×10^{-1}
Argon	A	1.2×10^{-1}
Calcium	Ca	7.2×10^{-2}
Nickel	Ni	4.8×10^{-2}
Phosphorus	P	9.6×10^{-3}
Manganese	Mn	9.3×10^{-3}

Note that all the abundances are relative, with 10^{6} forsilicon taken as standard of reference.

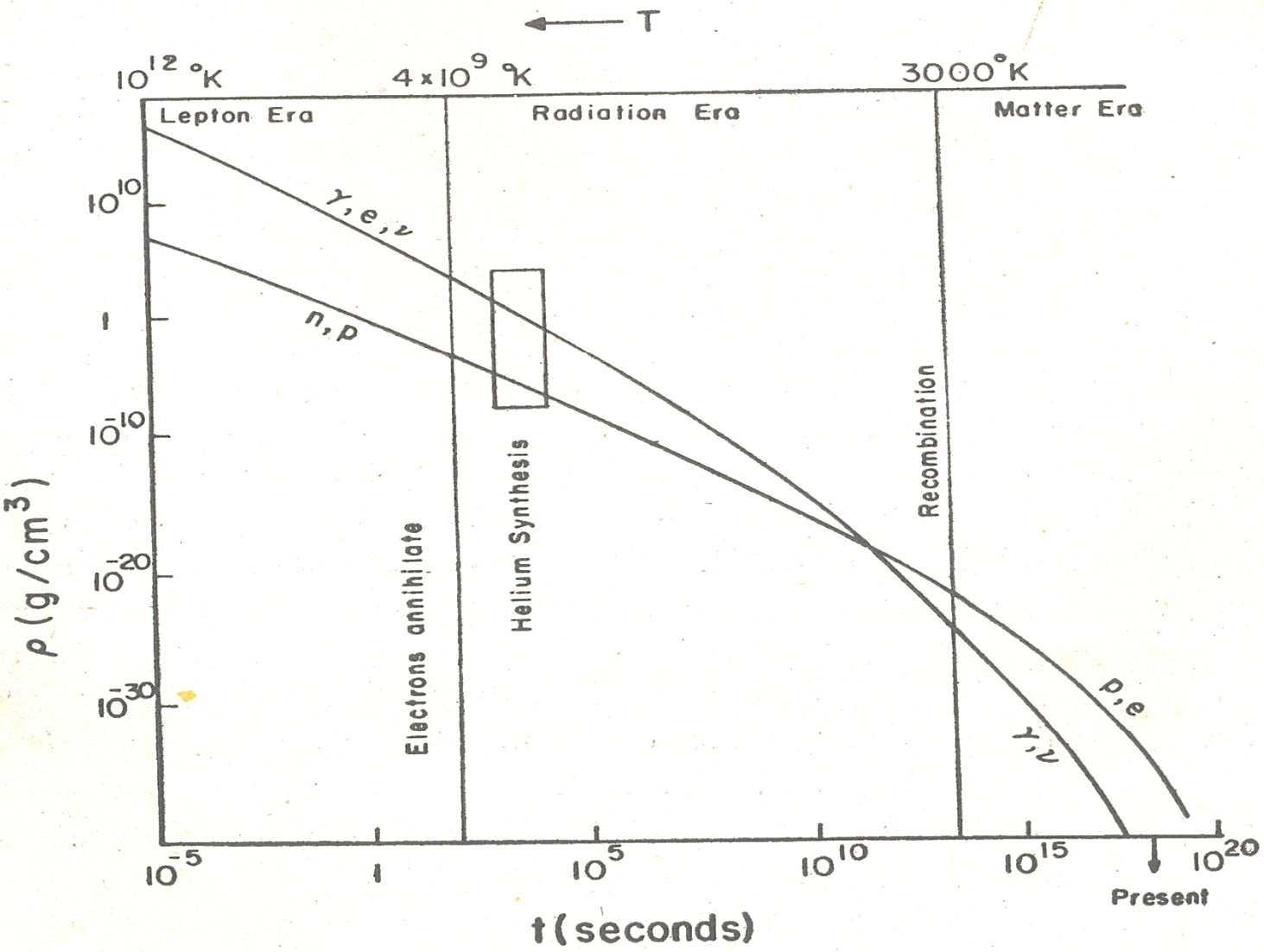


Fig.—1 Thermal history of early universe

he early Universe there is a plethora of neutrons and protons. During first three minutes, after birth of the Universe the following reactions ur.

p $\longrightarrow$ $^{2}H + \gamma$

p $\longrightarrow$ $^{3}He + \gamma$

$^{3}He \longrightarrow {}^{4}He + 2p + \gamma$

$^{4}He \longrightarrow {}^{7}Be + \gamma$

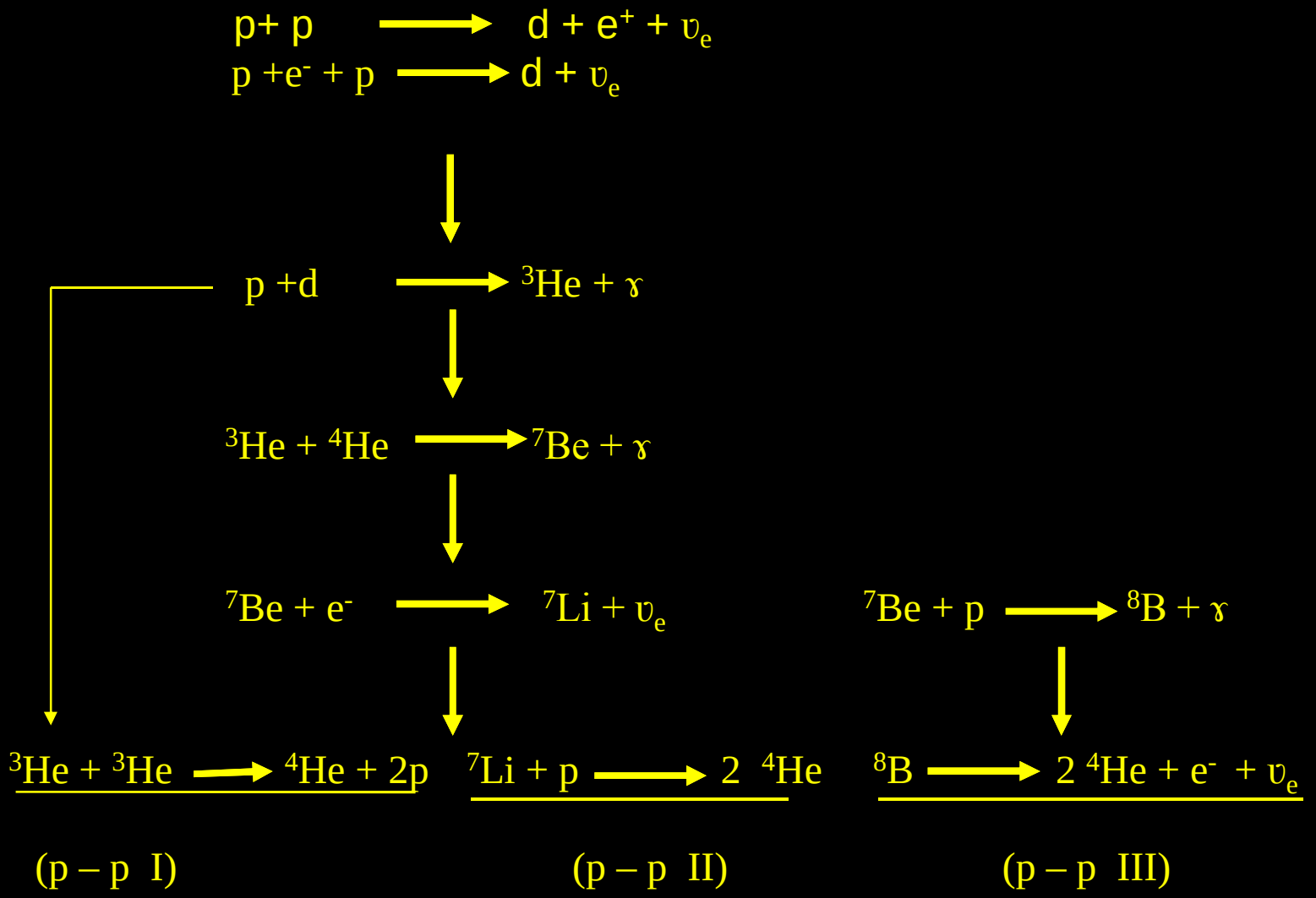
$- e^{-} \longrightarrow {}^{7}Li + \upsilon_{e}$

p $\longrightarrow$ $^{4}He + {}^{4}He$

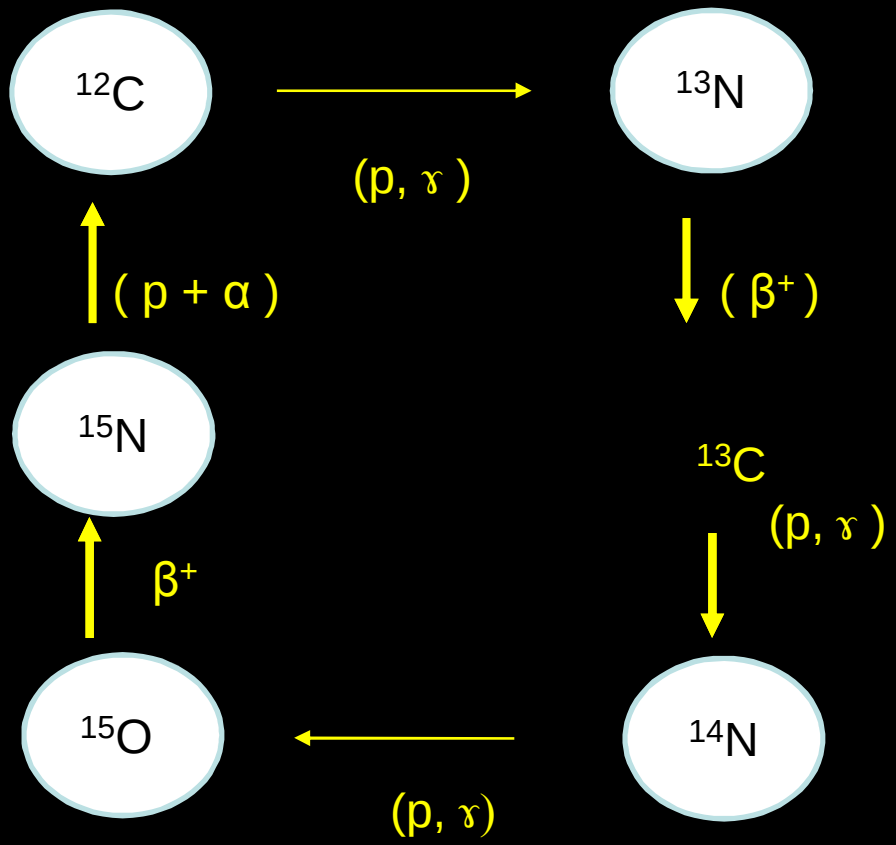
The only nuclear species which are produce during the epoch of big bang are:

^{2}H, ^{3}He,^{4}He, ^{7}Li

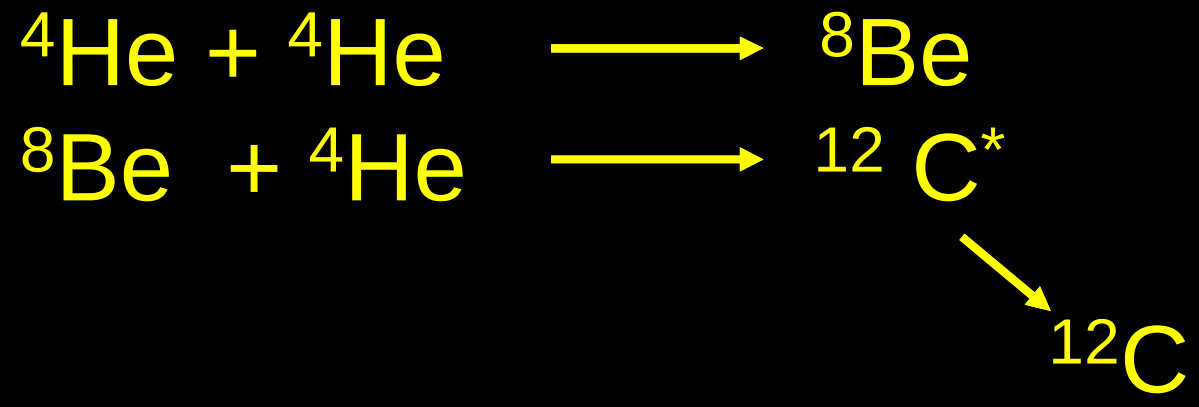
p-p Chain


p+ p → d + e+ + υe
p +e- + p → d + υe
p +d → 3He + ɤ
3He + 4He → 7Be + ɤ
7Be + e- → 7Li + υe
7Be + p → 8B + ɤ
3He + 3He → 4He + 2p
7Li + p → 2 4He
8B → 2 4He + e- + υe
(p – p I)
(p – p II)
(p – p III)

CNO Cycle



Triple Alpha Reaction



ALPHA PARTICLE REACTIONS

$^{12}C + {}^{4}He \longrightarrow {}^{16}O + \gamma$

$^{16}O + {}^{4}He \longrightarrow {}^{20}Ne + \gamma$

$^{20}Ne + {}^{4}He \longrightarrow {}^{24}Mg + \gamma$

$^{24}Mg + {}^{4}He \longrightarrow {}^{28}Si + \gamma$

$^{13}C + {}^{4}He \longrightarrow {}^{16}O + n$

$^{17}O + {}^{4}He \longrightarrow {}^{20}Ne + n$

$^{21}Ne + {}^{4}He \longrightarrow {}^{24}Mg + n$

$^{22}Ne + {}^{4}He \longrightarrow {}^{25}Mg + n$

$^{18}O + {}^{4}He \longrightarrow {}^{21}Ne + n$

$^{26}Mg + {}^{4}He \longrightarrow {}^{29}Si + n$

ADDITIONAL ALPHA PARTICLE REACTIONS (p- capture)

$^{12}C + p \longrightarrow {}^{13}N + \gamma$

$^{13}N \longrightarrow {}^{13}C + e^{+} + \upsilon_e$

$^{15}N + p \longrightarrow {}^{16}O + \gamma$

$^{16}O + p \longrightarrow {}^{17}F + \gamma$

$^{17}F \longrightarrow {}^{17}O + e^{+} + \upsilon_e$

$^{17}O + p \longrightarrow {}^{14}N + {}^{4}He$

$^{20}Ne + p \longrightarrow {}^{21}Na + \gamma$

$^{21}Na \longrightarrow {}^{21}Ne + e^{+} + 2_e$

$^{21}Ne + p \longrightarrow {}^{22}Na + \gamma$

$^{23}Na + p \longrightarrow {}^{20}Ne + {}^{4}He$

Most of the elements lighter than iron (^{56}Fe) can be formed via thermonuclear fusion in the central regions of stars. In fact, iron cannot fuse with other particles to from heavier elements due to the Coulomb repulsion and the fact that iron has the highest nuclear binding energy.

Actually, stars can not manufacture by thermonuclear fusion heavier elements beyond iron in their cores. Most of the element heavier than iron are formed in one or two types of processes.

Slow neutron capture (s-process) and rapid neutron capture (r-proces

n the former reaction the rate at which neutrons are captured is slow compared to the average rate of decay of unstable nuclei. The s-process which operates in the atmosphere of stars with masses $\geq$ 2-3 M_0 during the asymptotic giant branch stage, can produce stable nuclei upto lead and bismuth. Beyond this no nuclei are stable enough to permit the slow neutron capture process since they undergo radioactive decay before any additiona neutrons can be captured. Note that in the AGB stage the degenerate carbon-oxygen cores of these stars are surrounded by a helium burning she n which certain nuclear reaction release neutrons that can be captured by successive nuclei. Once the s-process elements have been formed they are transported via convection to the outer layers of the star which are ejected i the surrounding space via powerful stellar winds or by a subsequent supernova explosion in the more massive stars. It turns out the contribution s-process elements to the interstellar medium from massive stars is fairly small. Actually, the low-mass stars are largely responsible for must of the elements with atomic masses around 90 or more.

n the formation of r-process elements the rate of the beta
lecay reaction is longer than that of neutron capture. The
-process occurs so rapidly that it permits the formation of
neutron-rich species and operates when there is large
abundance of free neutrons available (for example, in the
supernova explosion environment, or neutron- star
mergers) which can produce substantial quantities of r-
process elements. The r-process is mainly responsible in
manufacturing elements from carbon to thorium, uranium
europium and plutonium.

Note: Elements produced exclusively via the r-process are present in essentially the same abundance ratio as those observed in the Solar System; while the s-process element abundance is 1000 times less compared to the Solar System abundance.

BORN OUT OF THE ASHES OF DEAD STARS

In Summery

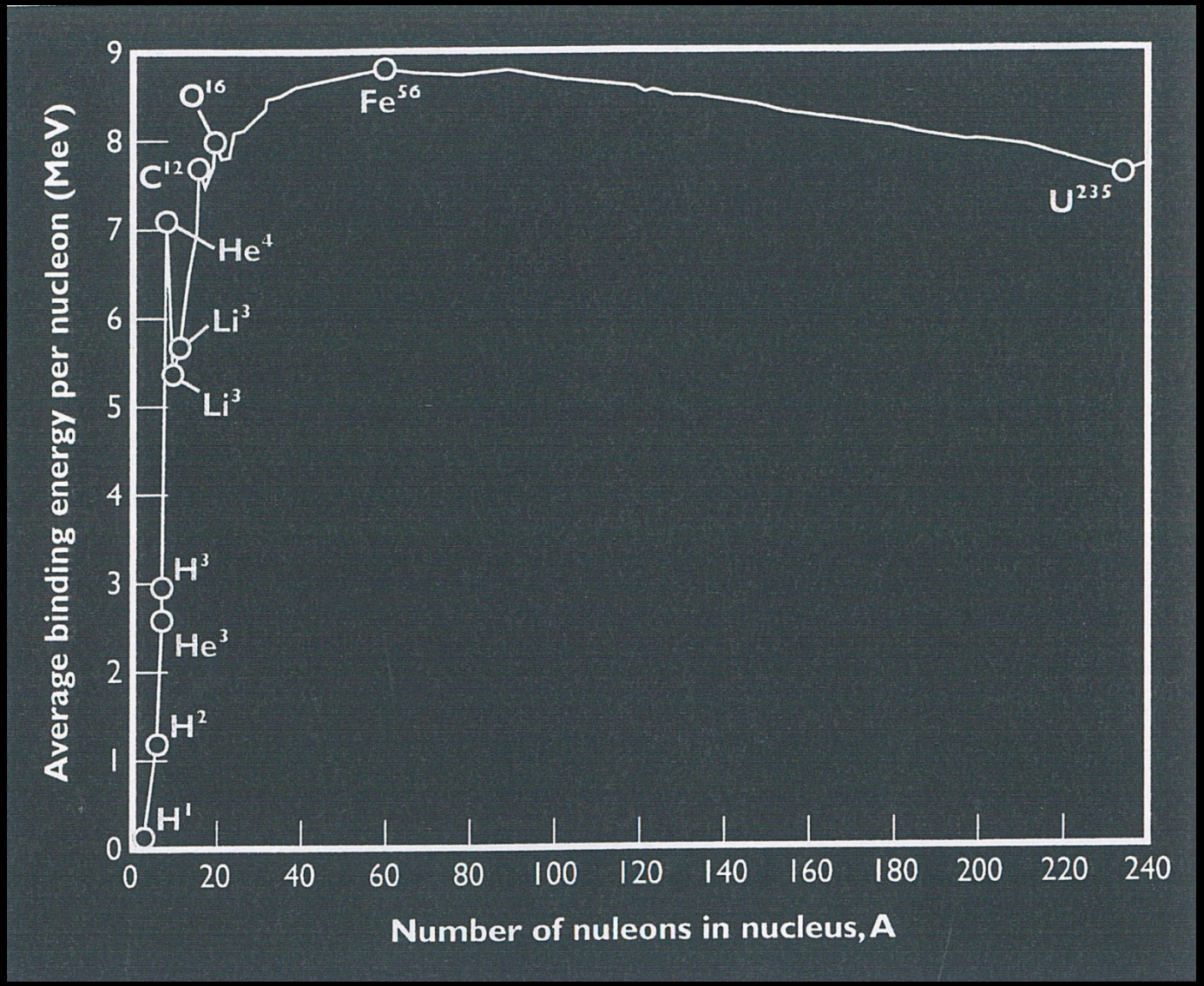
- Light elements like Hydrogen, Deuterium, Tritium, Helium, Beryllium and Lithium are manufactured within first three minutes after the birth of the universe.

- Life history of a star is characterized by continued contraction of its central regions with halts caused by a succession of Nuclear Energy generation

H → He → C, O → Ne, Si, Mg → Fe, Ni,…

- Most of the elements lighter than iron c be formed via thermonuclear fusion in th central reasons of stars

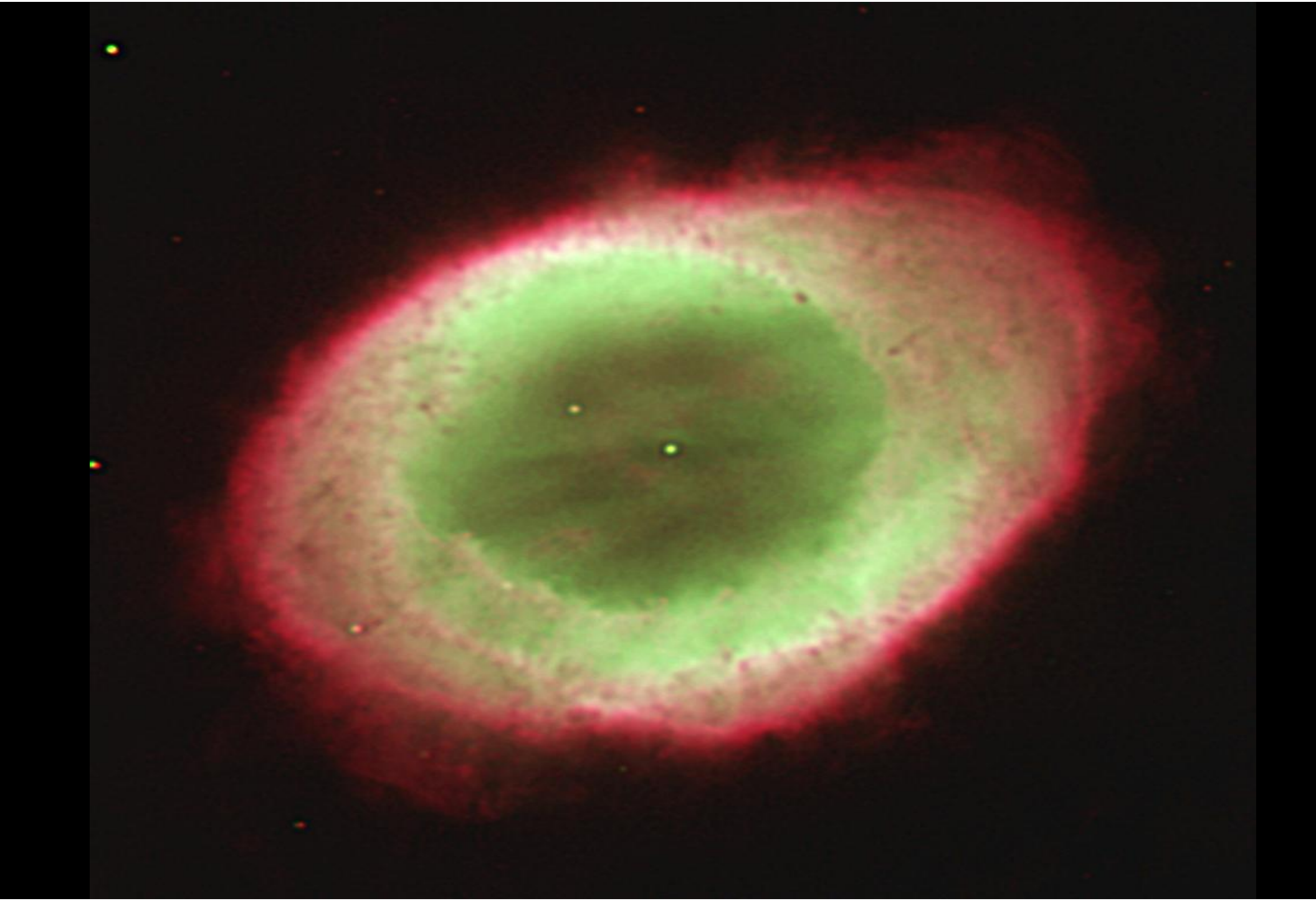
- Stars cannot generate by thermonuclea fusion elements heavier than iron



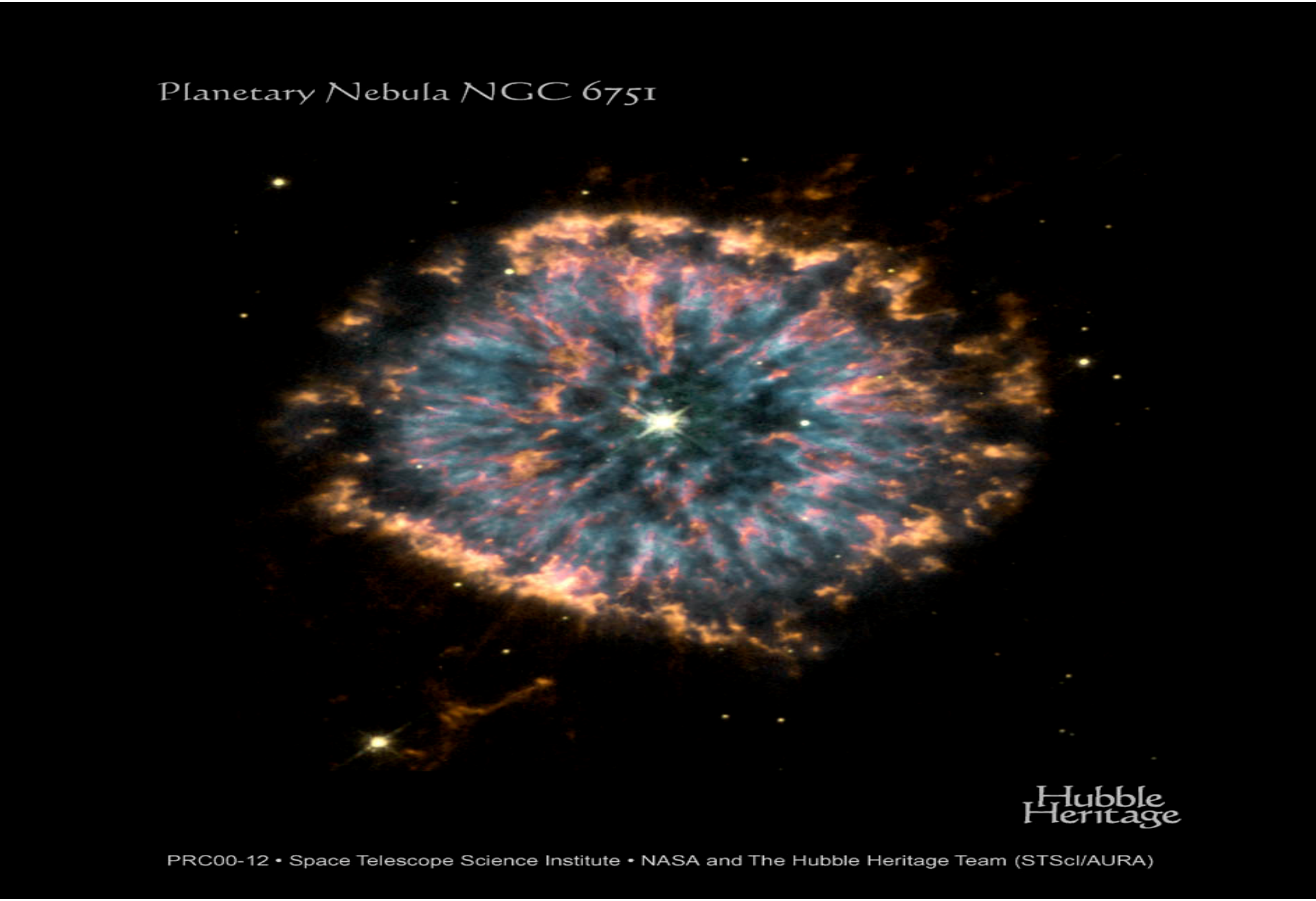
Average binding energy per nucleon as a function of number of nucleons in the atomic nucleus

or very light nuclei upto ^{4}He the average binding
nergy per nucleon increases very sharply. This rise
ontinues until ^{56}Fe after which the average binding
nergy per nucleon decreases slightly due to the
ncreasing number of protons feeding the repulsive
oulomb force which eventfully overcomes the
ttractive nuclear force.

Note the average binding energy per nucleon
s a function of A for stable nuclei. For very lig
nuclei (up to ^{4}He the average binding energy
per nucleon increases sharply which continue
up to ^{56}Fe. After A= 56 the average binding
energy per nucleon decreases slightly due to
ncreasing number of protons feeding the
repulsive Coulomb force which eventfully
overcome the attractive nuclear force.

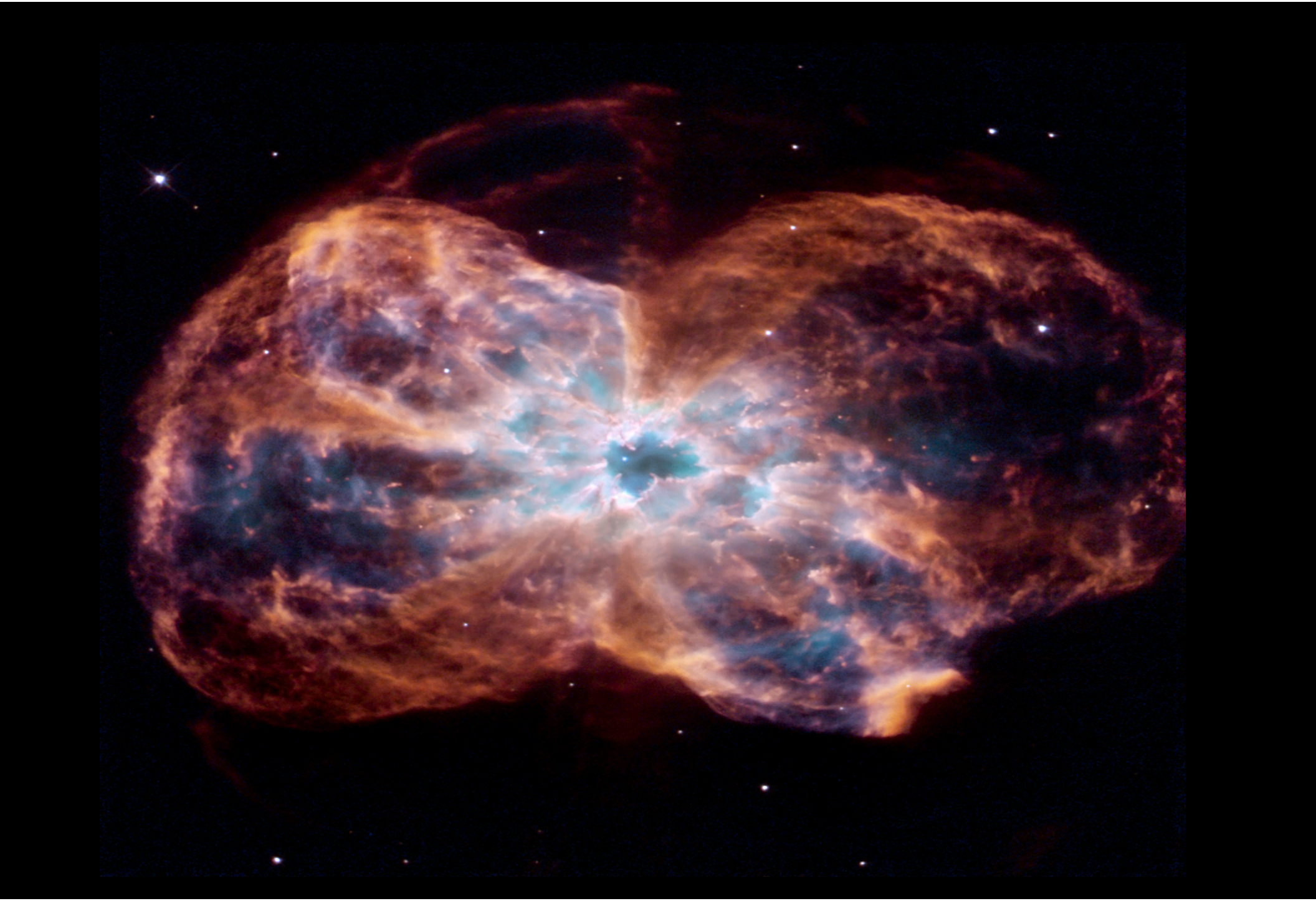


Planetary Nebula NGC 6751

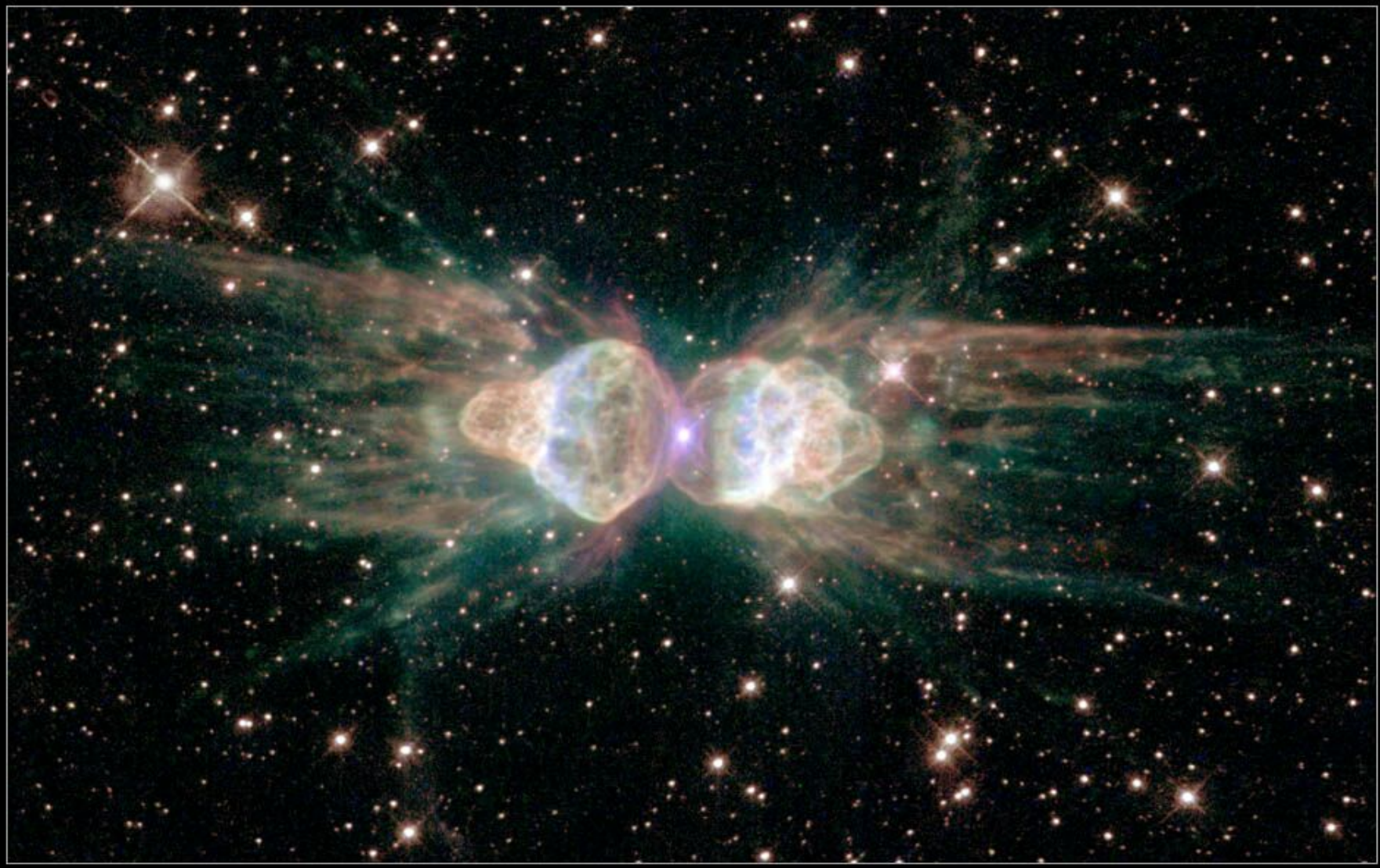


Hubble Heritage

PRC00-12 • Space Telescope Science Institute • NASA and The Hubble Heritage Team (STScI/AURA)

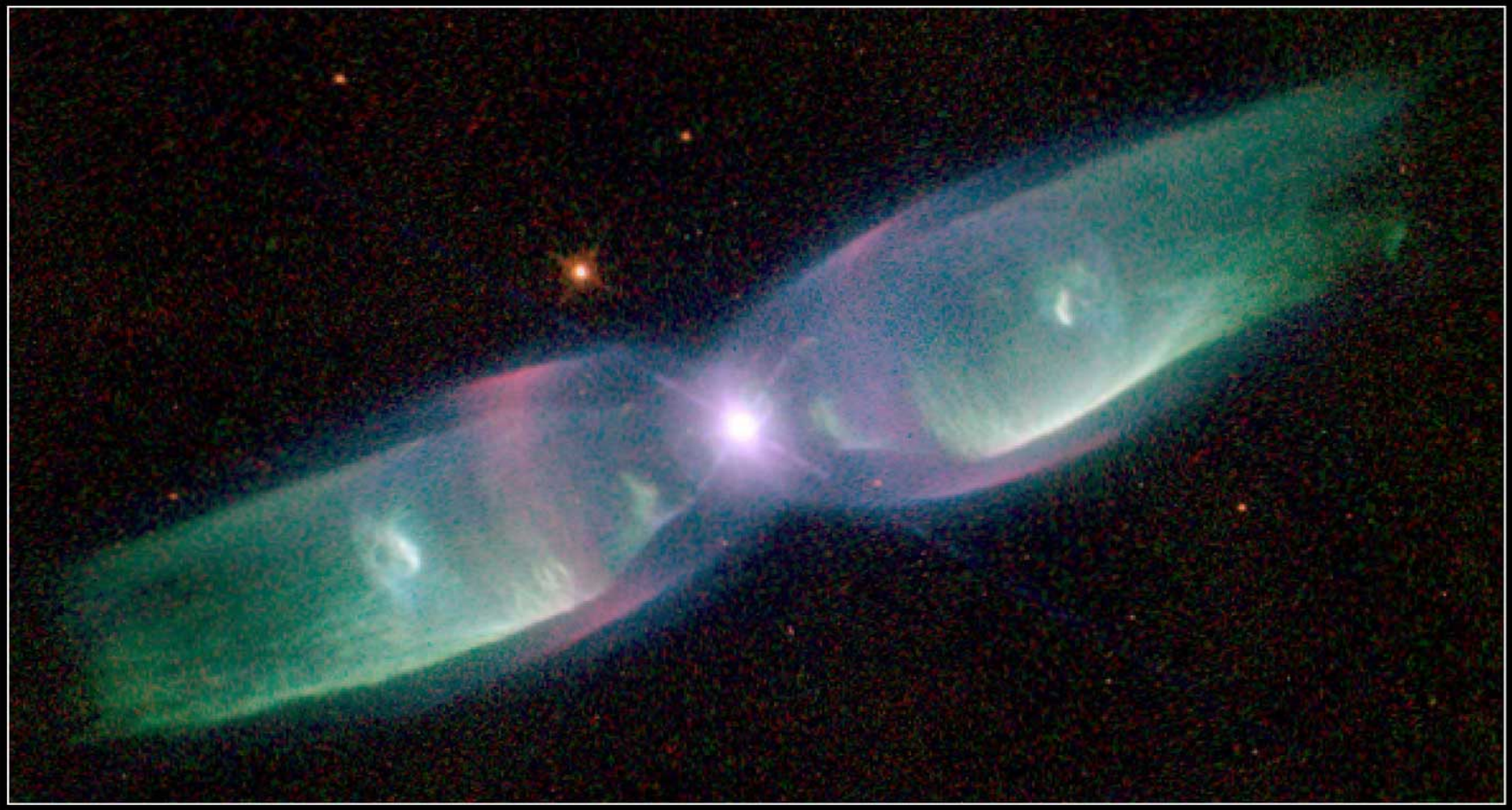


Planetary Nebula Mz 3



Hubble Heritage

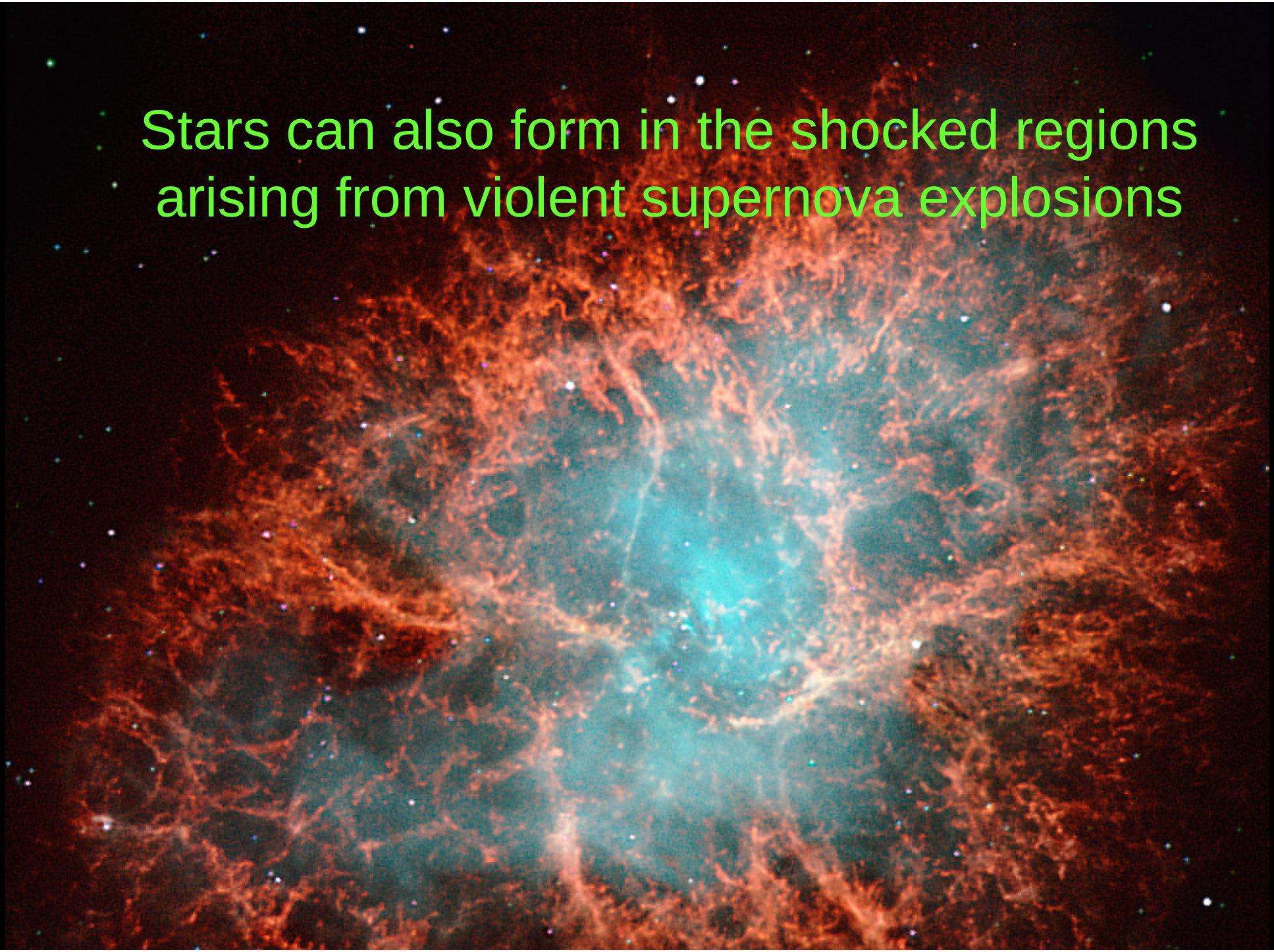
NASA, ESA, and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope WFPC2 • STScI-PRC01-05

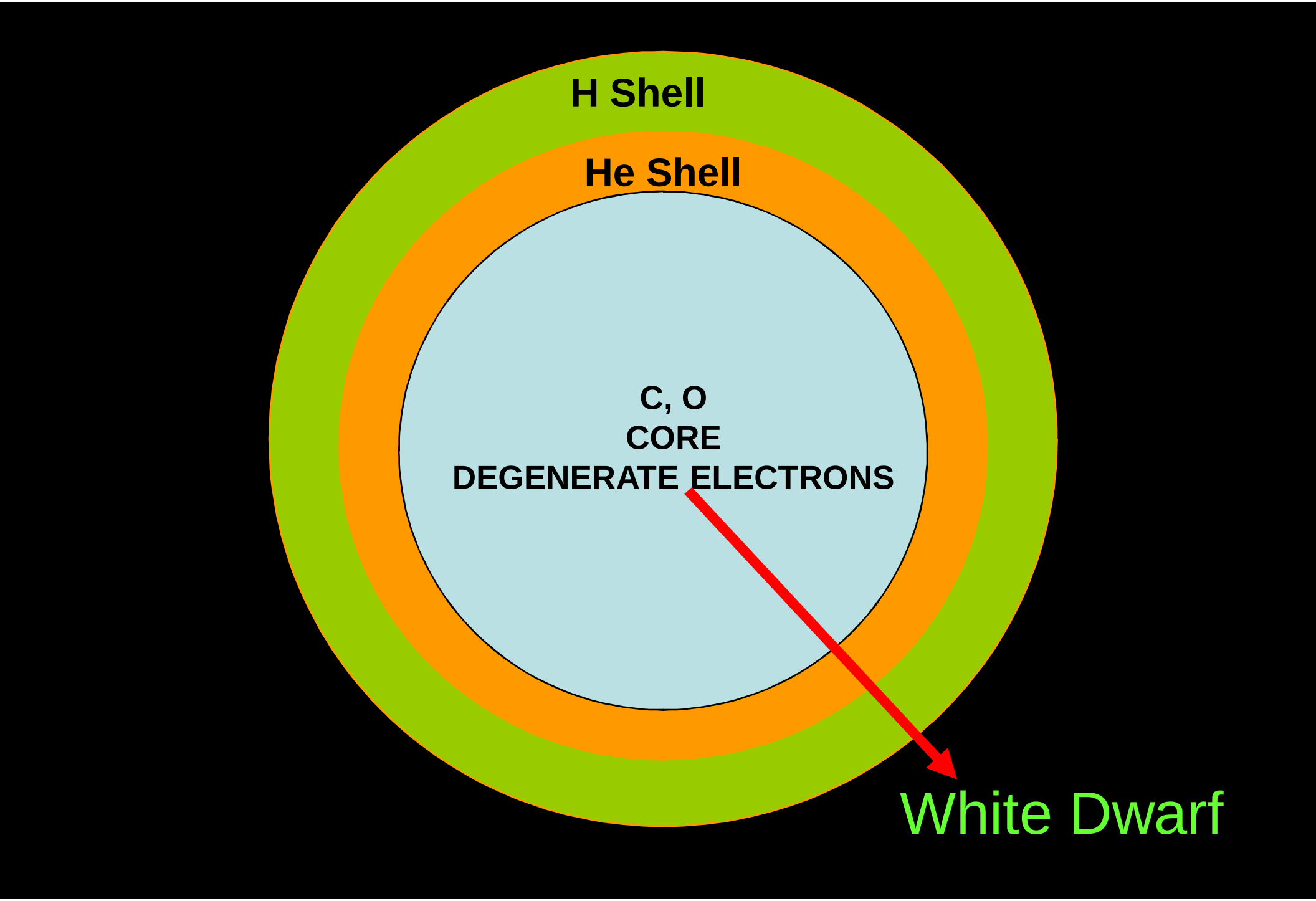


Planetary Nebula M2-9
Hubble Space Telescope • WFPC2

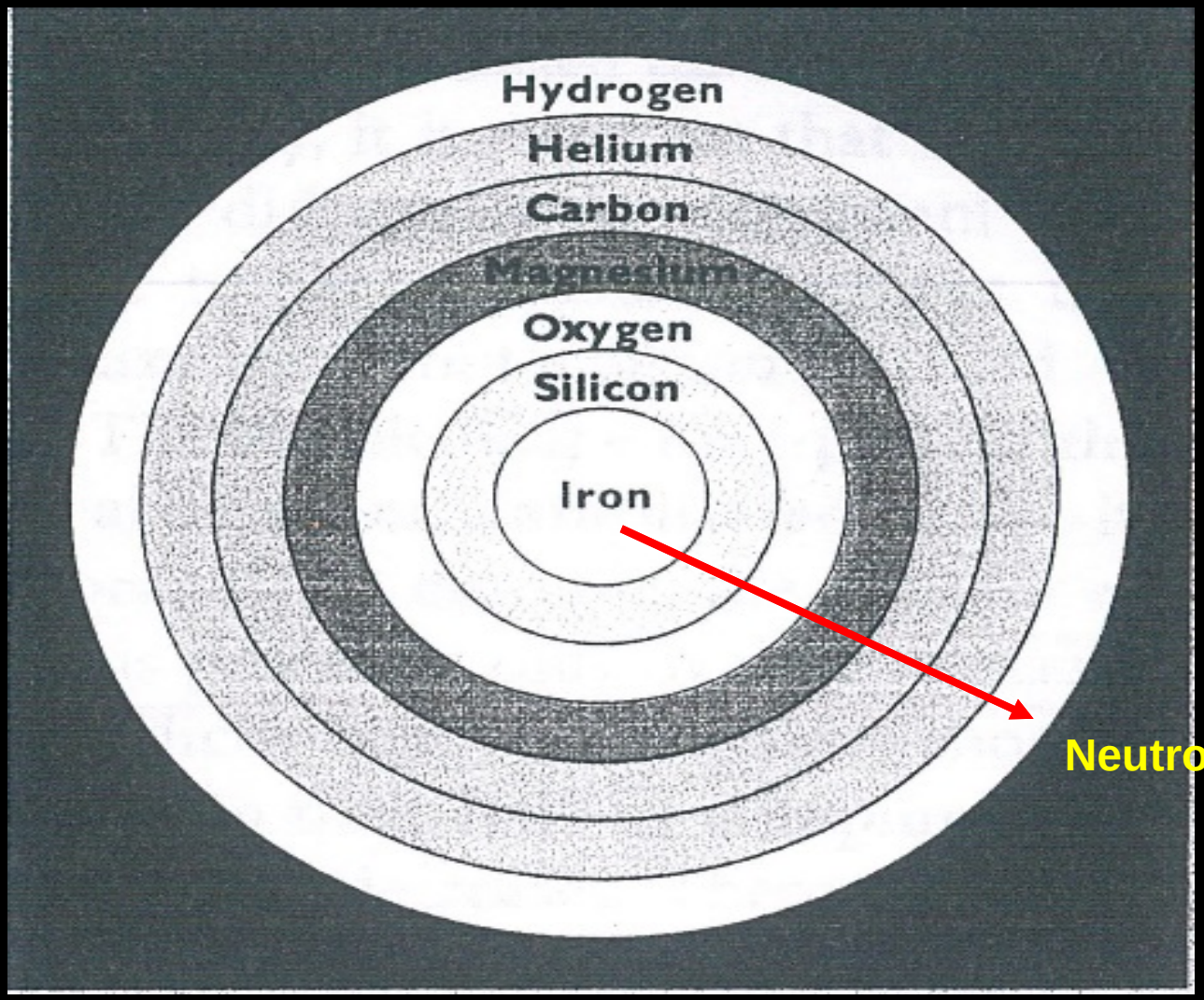
PRC97-38a • ST ScI OPO • December 17, 1997 • B. Balick (University of Washington) and NASA

Creation of stars at tips of the pillars in the Eagle Nebula


Stars can also form in the shocked regions
arising from violent supernova explosions


H Shell
He Shell
C, O
CORE
DEGENERATE ELECTRONS
White Dwarf

Neutron Star formation from onion-skin structure of a massive star



PHOTODISSOCIATION

$$^{56}Fe + \gamma \longrightarrow {}^{13}\,{}^{4}He + \gamma$$

$$^{4}He + \gamma \longrightarrow 2n + 2p$$

$$p + e^{-} \longrightarrow n + \upsilon_e$$

CONNECTION BETWEEN DEATH AND BIRTH OF STARS

- Birth of our Sun in the aftermath of a spectacular supernova explosion close to the site of proto-solar nebula

"We living beings are a late outgrowth of the metabolism of our Galaxy."

- *George Wald*

LIMITING MASS FOR WHITE DWARFS

(CHANDRASEKHAR LIMIT)

$M_{Ch} \simeq (hc/Gm_p^2)^{3/2}\, m_p \simeq 1.4\, M_\odot$

h= Planck constant

G= Gravitational constant

c = Speed of light

m_p= Mass of proton

Chandrasekhar's limiting mass for white dwarfs elegantly combined Special Relativity with Quantum Physics.

Limiting mass of a neutron star is comparable to that of a white dwarf (~ Chandrasekhar limiting mass)

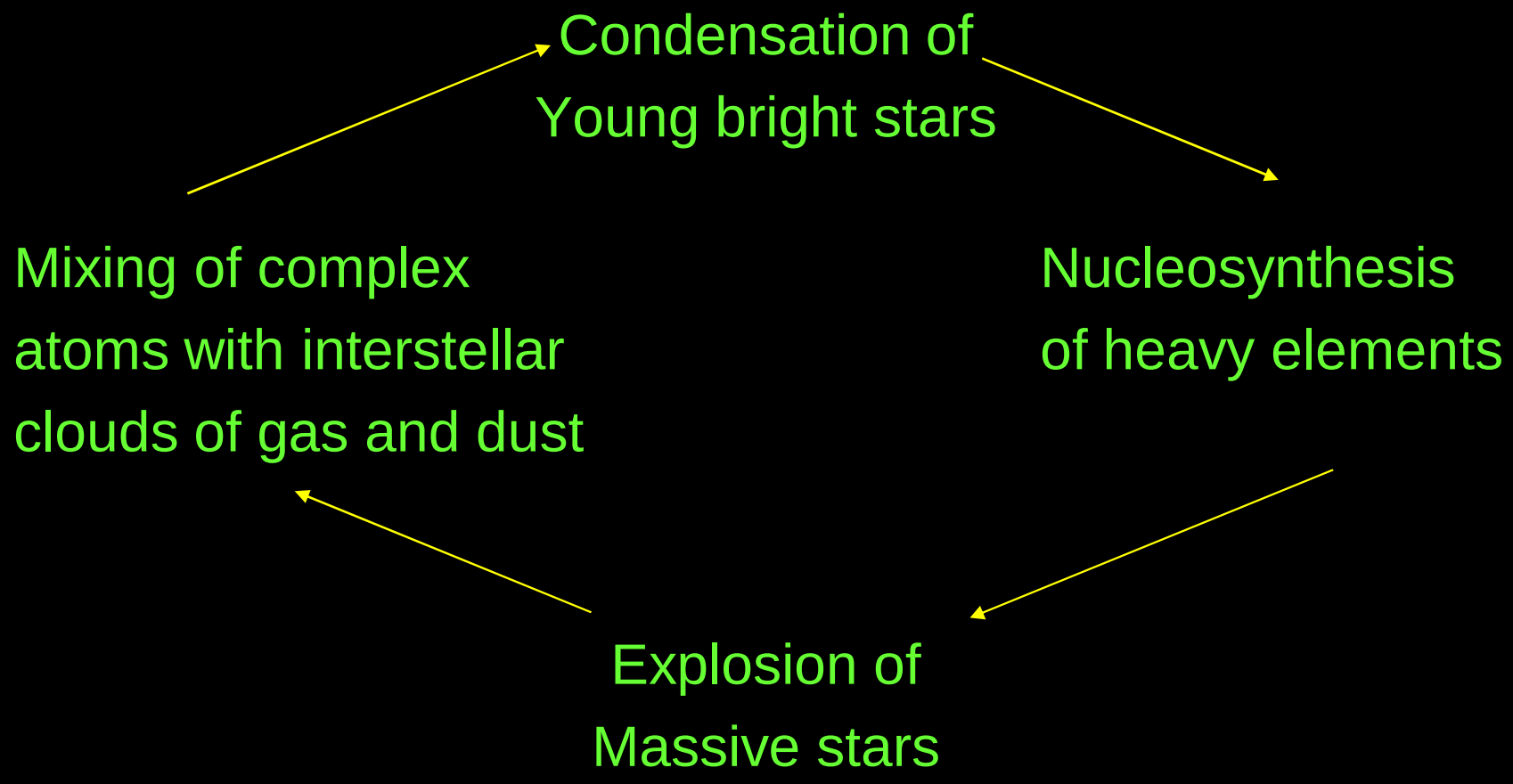
FORMATION OF COMPACT OBJECTS

MASS RANGE	LIFETIME (years)	REMNANT
$M / M_\odot > 07$	$\sim 10^{10}$	BROWN DWARFS
$0.07 \lesssim M / M_\odot \lesssim 8$	$\sim 10^{9}$	WHITE DWARFS
$8 \lesssim M / M_\odot \lesssim 20$	$\sim 10^{7.5}$	NEUTRON STARS
$20 \lesssim M / M_\odot$	$\sim 10^{7}$	BLACK HOLES

VITAL STATISTICS

High Energy Astrophysics

	Sun	White Dwarf	Neutron Star	Black Hole
Radius (km)	700,000	7,000	10	3
Mean density (gm/cm^3)	1	10^{7}	10^{14}	$2x10^{16}$
Rot. Speed (radians/sec)	$3 x10^{-6}$	$3 x10^{-2}$	$2 x 10^{2}$-10^{4}	-
Magnetic field (Gauss)	1	10^{7}	10^{12}-10^{16}	-
Efficien. of Grav. Energy Release (= GM / Rc^2) (Gravitation Parameter)	10^{-6}	10^{-4}	10^{-2} -10^{-1}	$6x10^{-2}$-$4x10^{-1}$



Stars have to die for us to inherit the elements like Carbon, Nitrogen, Oxygen, Phosphorus, Calcium, Iron…… that are vital for life processes

Binary Pulsar PSR 1913+16

Period (P)	59.03 ms
Eccentricity (e)	0.617± 0.010
Orbital Period (T)	~7 hrs
Mass of Pulsar (M_p)	1.44 $M_\odot$
Mass of companion (M_c)	1.39 $M_\odot$

Double PULSAR PSR J0737-3039

Period (P)	22.7 ms
Eccentricity (e)	0.088
Orbital Period (T)	~2.4 hrs
Mass of Pulsar (M_p)	1.34 $M_\odot$
Mass of companion (M_c)	1.25 $M_\odot$

Rate of energy radiated in the form of gravitational waves

$$L = \frac{32\, G^4 M_p^5 (M_c/M_p)^7}{5\, c^5 a^5 (1+M_c/M_p)^4} (1+73/24\, e^2+37/96\, e^4)(1-e^2)^{-7/2} \quad \text{erg / s}$$

(a = semi major axis, e = eccentricity)

COLLAPSED OBJECTS & ASTROPHYSICAL PHENOMENA

- RADIO PULSARS : ROTATI NG NEUTRON STAR PROVIDING THE STABLE CLOCK MECHANISM
- BINARY / DOUBLE PULSARS : PAIR OF NEUTRON STARS ACTING AS GARAVITATIONAL RADIATION TRANSMITTER
- X-RAY BINARIES : NEUTRON STAR / BLACKHOLE WITH MASS LOSING COMPANION
- GAMMA RAY BURSTERS : MERGING NEUTRON STARS / BLACKHOLES

  HYPERNOVAE
- AGNs / QUASARS : POWERED BY DISK ACCRETION OF GAS ONTO SUPERMASSIVE BLACKHOLES IN NUCLEI OF GALAXIES

GOLDEN AGE OF ASTRONOMY
(ASTRONOMY on the CUSP)

ACTIVE GALACTIC NUCLEI [QUASARS] (1963)

COSMIC MICROWAVE BACKGROUND RADIATION (1965)

BINARY X-RAY SOURCES (1962)

SOLAR NEUTRINO EXPERIMENT (1966)

PUSARS (1967)

GAMMA RAY BURSTS (1973)

TRANSIENT SOURCES (2000)

GRAVITATIONAL WAVES (2016)

SOLAR SYSTEM

Sun with its planetary system and minor bodies (Asteroids, Comets)

ORIGIN OF THE SOLAR SYSTEM

- Nebular Hypothesis (Kant 1755, Laplace 1796)
- Glancing collision with a passing star and tidal capture of material (Jeans 1922)
- Birth of our Sun in the aftermath of a spectacular supernova explosion close to the site of proto-solar nebula

Birth of stars and planets in the Orion Nebula

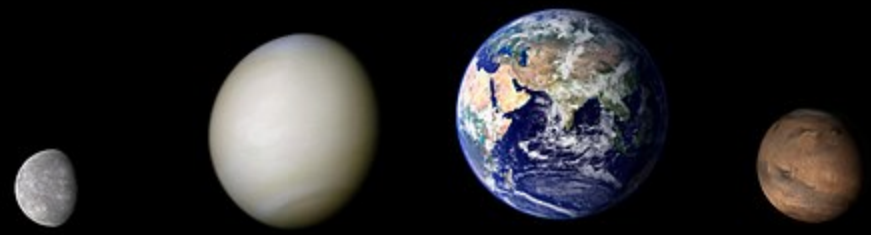
EXOPLANETS

- **1000 Stars are known to have planetary systems**
- **Over 1500 planets have been deducted**
- **18 are multiple planet systems**
- **Very few (~3) Earth-like planets have been detected while most are Jupiter- like**

Illustrations

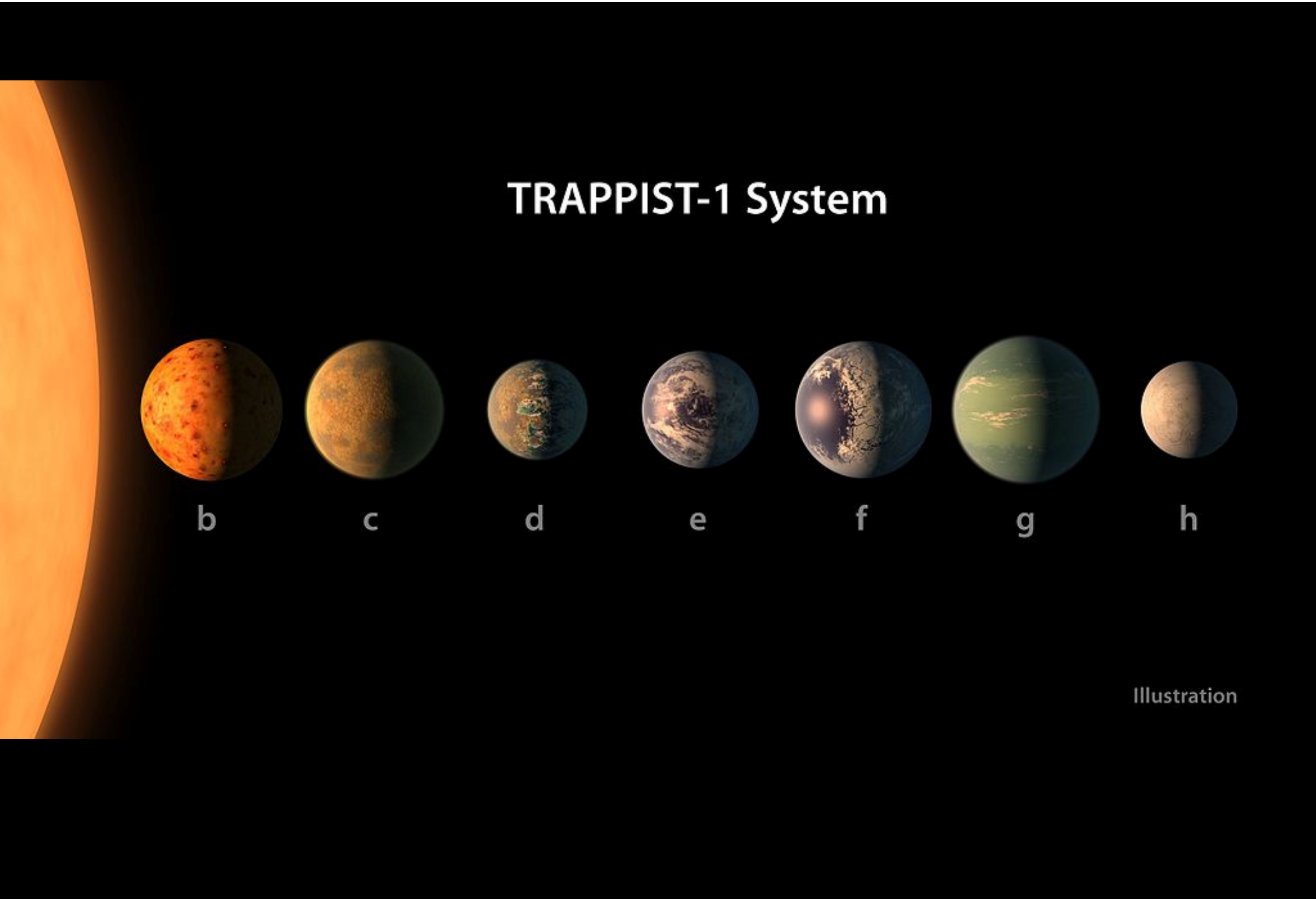
TRAPPIST-1 System

	b	c	d	e	f	g	h
Orbital Period *days*	1.51 *days*	2.42 *days*	4.05 *days*	6.10 *days*	9.21 *days*	12.35 *days*	~20 *days*
Distance to Star *Astronomical Units (AU)*	0.011 *AU*	0.015 *AU*	0.021 *AU*	0.028 *AU*	0.037 *AU*	0.045 *AU*	~0.06 *AU*
Planet Radius *relative to Earth*	1.09 R_{earth}	1.06 R_{earth}	0.77 R_{earth}	0.92 R_{earth}	1.04 R_{earth}	1.13 R_{earth}	0.76 R_{earth}
Planet Mass *relative to Earth*	0.85 M_{earth}	1.38 M_{earth}	0.41 M_{earth}	0.62 M_{earth}	0.68 M_{earth}	1.34 $_{earth}$	–



Solar System
Rocky Planets

	Mercury	Venus	Earth	Mars
Orbital Period *days*	87.97 *days*	224.70 *days*	365.26 *days*	686.98 *days*
Distance to Star *Astronomical Units (AU)*	0.387 *AU*	0.723 *AU*	1.000 *AU*	1.524 *AU*
Planet Radius *relative to Earth*	0.38 R_{earth}	0.95 R_{earth}	1.00 R_{earth}	0.53 R_{earth}
Planet Mass *relative to Earth*	0.06 M_{earth}	0.82 M_{earth}	1.00 M_{earth}	0.11 M_{earth}


TRAPPIST-1 System
b
c
d
e
f
g
h
Illustration

WHAT IS LIFE?

- Animate and inanimate world essentially made of the same basic stuff
- Biodiversity of life on Earth: Large variety of living organisms of different sizes and shapes from snails, ants, termites to elephants
- Living beings have a complex physical and chemical interaction with the environment, they consume energy, grow and self replicate
- Life is basically composed of elements such as carbon, nitrogen, oxygen, molecular hydrogen… which are commonly present in the universe
- Life may be based on carbon chemistry, silicon or sulphur chemistry in the process directing matter essentially from Disorder to Order, while in natural phenomena the arrow is from Order to Disorder

ORIGIN OF LIFE

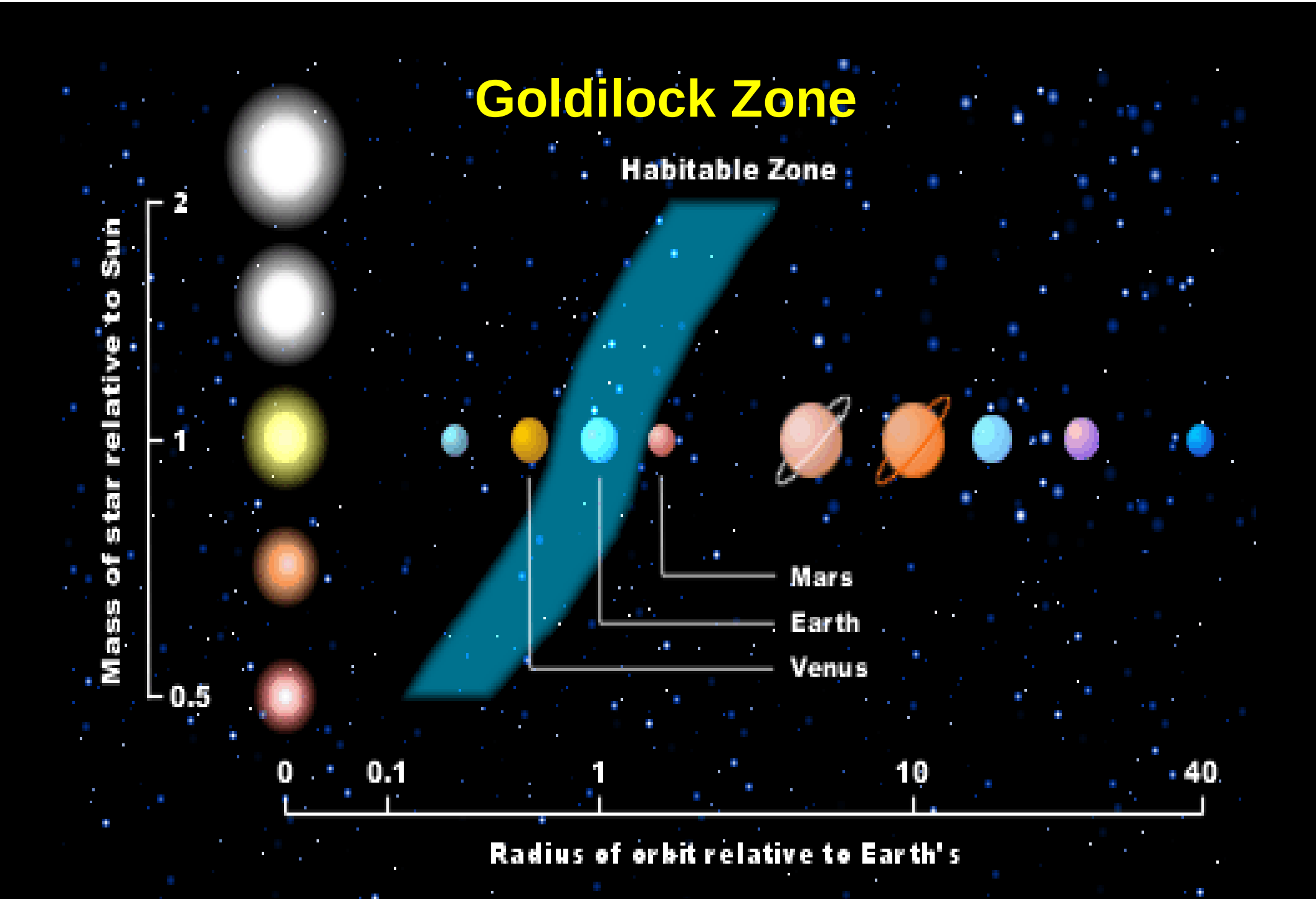
INTELLIGENT DESIGN: Created by Divine Intervention

PRIMORDIAL SOUP of Ammonia, Phosphoric Salts, Heat, Light, Electricity
Dream of the chemical evolutionist (cf. laboratory experiment of Stanley Miller and Harold Urey) to recreate Darwin's Warm Little Pond

PANSPERMIA: Extraterrestrial origin, with asteroids, meteorites and comet as carriers

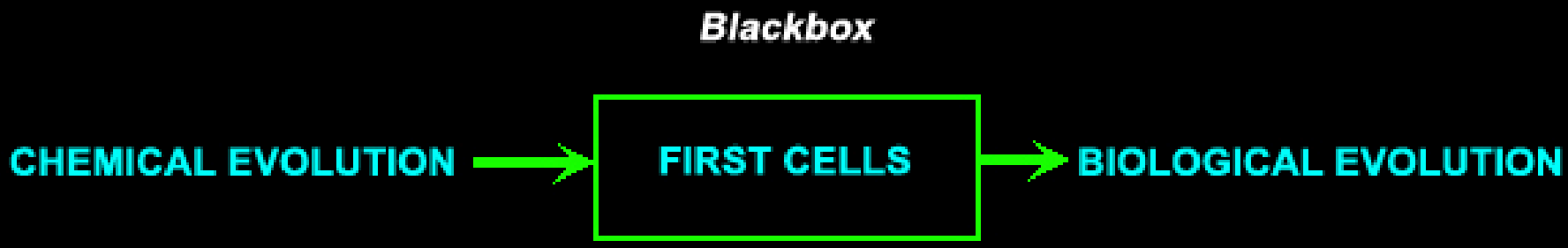
ZOO HYPOTHESIS: Seeding of microbes launched into space accidentally or specially planted by external intelligent civilization

ANTHROPIC PRINCIPLE: Only those universes exist which have conscious observers


Goldilock Zone
Habitable Zone
Mass of star relative to Sun
2
1
0.5
Mars
Earth
Venus
0
0.1
1
10
40
Radius of orbit relative to Earth's

FORMATION OF THE FIRST LIVING CELLS

Huge leap from primordial organic soup to membrane-moderated, self-replicating, DNA – based structures:



SEARCH FOR INTELLIGENT LIFE ON HOSPITABLE PLANETARY SITES

mber of intelligent civilizations capable of interstellar communication :

Total number of stars in the Galaxy: Rate of star formation

Fraction of stars that have planetary companions

Fraction of stars with habitable zones around them

Fraction of planets with hospitable conditions for the development of life forms

Fraction of sites where intelligent life has evolved during the life of the pare star

Average lifetime of the technically advanced civilization after reaching the communicative pha

Drake’s Equation

MODES OF COMMUNICATION WITH EXTRATERRESTRIALS

- **ACTUAL PHYSICAL CONTACT**
  - LANDING OF ALIEN ASTRONAUTS
  - CHANCE ENCOUNTER WITH ALIENS
  - VISITS OF ALIEN ROBOTS

- **GALACTIC CLUB OF ADVANCED CIVILIZATIONS**

- **GALACTIC LIBRARY**

MAY BE WE ARE ALONE IN THIS UNIVERSE!

- ACCORDING TO TIPLER, WE HAVE NOT HAD VISITS FROM INTERSTELLAR TRAVELLERS THUS FAR, SO EXTRATERRESTRIAL INTELLIGENT BEINGS DO NOT EXIST! BUT THE ABSENCE OF EVIDENCE DOES NOT MEAN EVIDENCE FOR ABSENCE!! PERHAPS, SOME TECHNOLOGICAL AND BIOLOGICAL OBSTACLES MAKE SPACE TRAVEL INFEASIBLE FOR EXTRA TERRESTRIALS OVER INTERSTELLAR DISTANCES.

EARTHLINGS MAY NOT BE ALL THAT INTERESTING SPECIES FROM THEIR VIEWPOINT

MAY BE WE DID HAVE VISITATIONS IN THE PAST WHEN OUR SOCIETY WAS NOT SUFFICIENTLY ADVANCED OR RECEPTIVE TO BE WORTHY OF ANY ATTENTION.

VERY LIKELY EXTRATERRESTRIALS DO NOT SUBSCRIBE TO THE ANTHROPOMORPHIC VIEW AND ARE QUITE SELF-SUFFICIENT AND MAY NOT BE ALL THAT KEEN ON INTERESTELLAR EXPLORATION.

HUMAN BEINGS ARE PROBABLY INEVITABLE PRODUCTS OF A GRAND COSMIC EVOLUTIONARY SCHEME, SET INTO MOTION WITH THE BIRTH OF THE UNIVERSE. WE MAY BE MEMBERS OF A MUCH LARGER FAMILY OF LIVING BEINGS SOME OF WHOM MAY HAVE UNIMAGINABLE CAPABILITIES.

- SUCH SOCIETIES MIGHT SURVIVE ONLY MOMENTARILY IN TIME COMPARED TO LIFE-SPAN OF THE UNIVERSE AND AS INDIVIDUALS WE MAY BE INCONSPICUOS AND INSIGNIFICANT SPECKS OF DUST PARTICIPATING IN A CONTINUOUSLY EVOLVING SYSTEM THAT VASTLY TRANSCENDS US.

VERTHLESS, COLLECTIVELY WE PROVIDE NECESSARY LINKS

TWEEN THE COSMIC PAST AND UNCHARTED FUTURE. AS HUMAN

INGS OUR PRIME RESPONSIBILITY IS TO NURTURE THE LIVING

STEM THAT HAS ARISEN ON THIS PLANET AND MAINTAIN THE

ONTINUTY IN TRANSMITTING KNOWLEDGE THAT WE HAVE

CUMULATED, NOT MERELY TO SUCCESSIVE GENERATIONS OF

UMANS BUT TO A MUCH LARGER BROTHERHOOD.

- In the beginning love arose
  Which was the primal germ cell of the mind.
  The seers, searching in their hearts with wisdom
  discovered the connection of being with non-being

- Who really knows? Who can presume to tell it?
  Whence was it born? Whence issued this creation?
  Even the gods came after its emergence
  Then who can tell from whence it came to be

- That out of which creation has arisen,
  whether it held it firm or it did not
  HE who surveys it in highest heaven,
  HE surely knows – or may be HE does not!

- RIGVEDA X, 129
(Reproduced from the 'VEDIC EXPERIENCE'
commentary by R. Panikar)

In conclusion, over the course of the star life depending on its mass the star fuses successively higher mass nucleus. Thus, hydrogen is fused to produce helium and subsequently, when the central temperature rises to 10 ^{8}ək, helium fuses to manufacture carbon and oxygen. The massive stars can fuse nuclei upto iron which has the highest binding energy per nucleon.

Fusing further iron nuclei requires additional mass to compensate for the decrease in biding energy for the production of higher nuclei – in other words, fusing iron requires more energy than it produces.

Metallicity of a star is indicated by the abundance ratio of iron to hydrogen [Fe/ HJ].

GAMMA RAY BURSTS (GRBs)

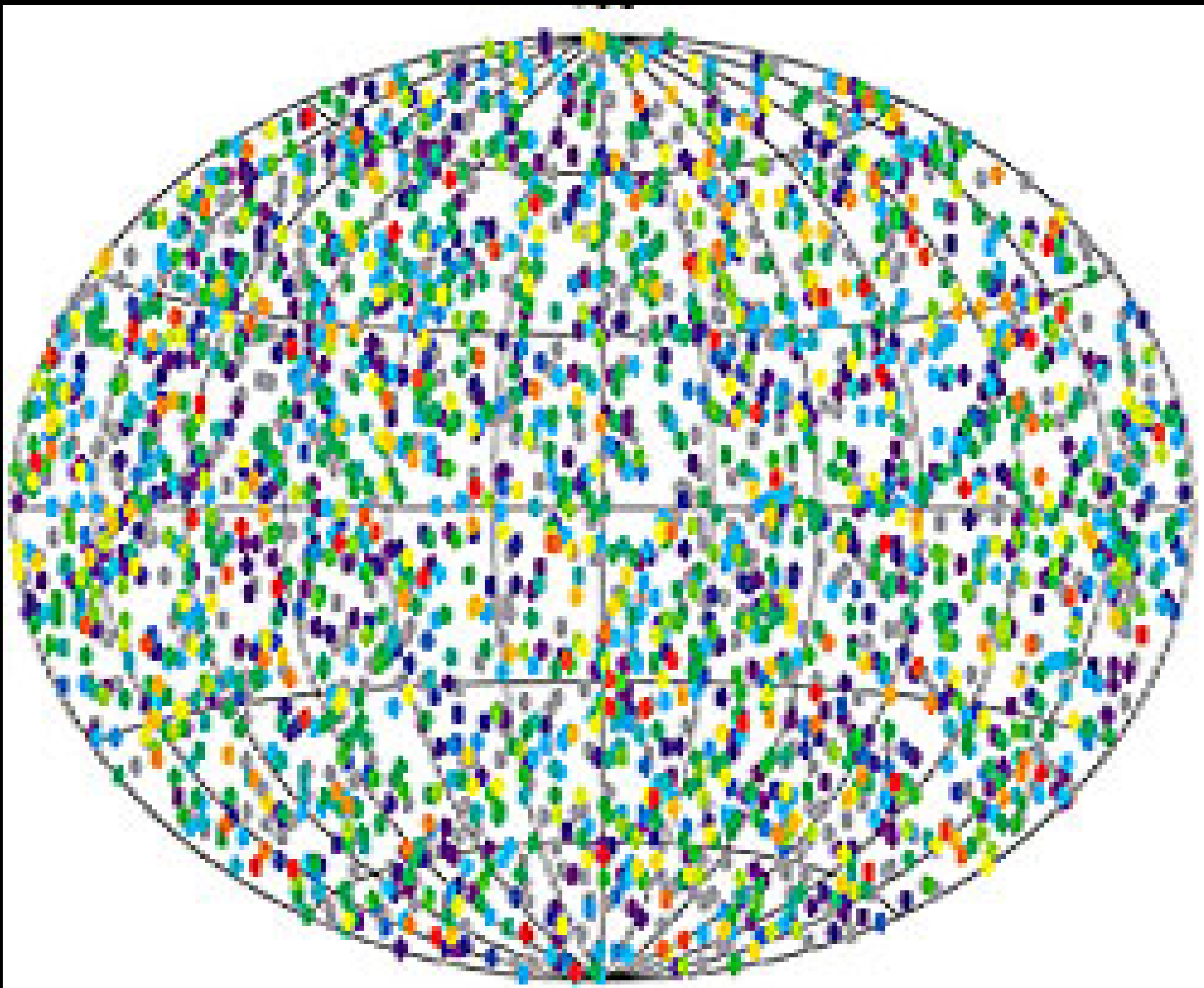
GRBs accidentally discovered in late 1960s military VELA satellites monitoring atmospheric nuclear explosions.
(BATSE, COMPTON GRO, BeppoSAX)

Cosmological origin of GRBs with energy
~ 10^{52} – 10^{53} erg.

For a few seconds GRBs are the most dazzling objects in the sky outshining rest of the universe with intense burst emission in KeV – MeV range, lasting for ~ 30 microsec to hundreds of seconds and occurring at the rate of ~ 1000 per year.

Afterglow discovered in radio, optical, X-ray bands.
Steller mans compact objects are the central engines driving GRBs.

Merging neutron stars / black holes
Hypernovae resulting from collapsed massive stars.



THANK YOU