What’s the Matter?

Joseph Silk
Gresham College
28 February 2018

Matter

physical substance in general, as distinct from mind and spirit; (in physics) that which occupies space and possesses rest mass, especially as distinct from energy.

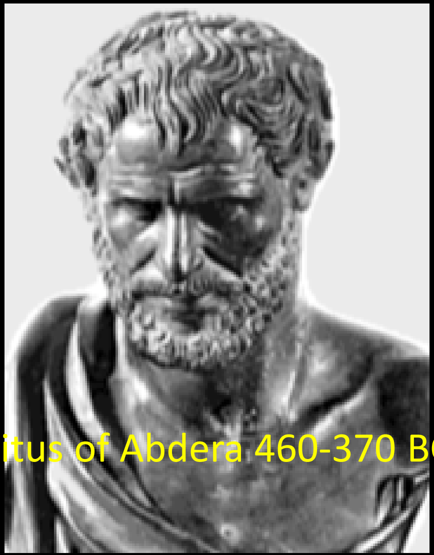
Oxford English Dictionary

By convention, sweet is sweet, bitter is bitter, hot is hot, cold is cold, color is color; but in truth there are only atoms and the void.

Democritus of Abdera, 5th century BC

All things are made of atoms--little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another.

Richard Feynman, The Feyman Lectures on Physics, Vol. 1, 1964



Democritus of Abdera 460-370 BC

Richard Feynman 1918-1988

- Protons
- Electrons
- Neutrons
- Neutrinos
- Nuclear reactors

PROTONS

Protons must decay

That's what the unified theory of physics requires.

Because it unifies protons with electrons at sufficiently high energy

Life-time of a proton

- We would be dropping dead of cancer if proton life-time was less than 10000 times age of the universe

- 1000 rads or ~ 10^5 erg/gm is lethal dose, in a day

or 1000 watt-sec/person or 10^{-14} gamma/atom/yr

How do you do better? You monitor a lot more atoms than in the human body,

50000 tons of ultra-purified water and you look continuously for years

can improve precision by a huge factor

Super-Kamiokande, Japan
in an abandoned zinc mine

No proton decay events seen!

proton lifetime is

$>1.6 \times 10^{34}$ yrs

cf. age of the universe

1.4×10^{10} yrs

- Quarks are fundamental particles

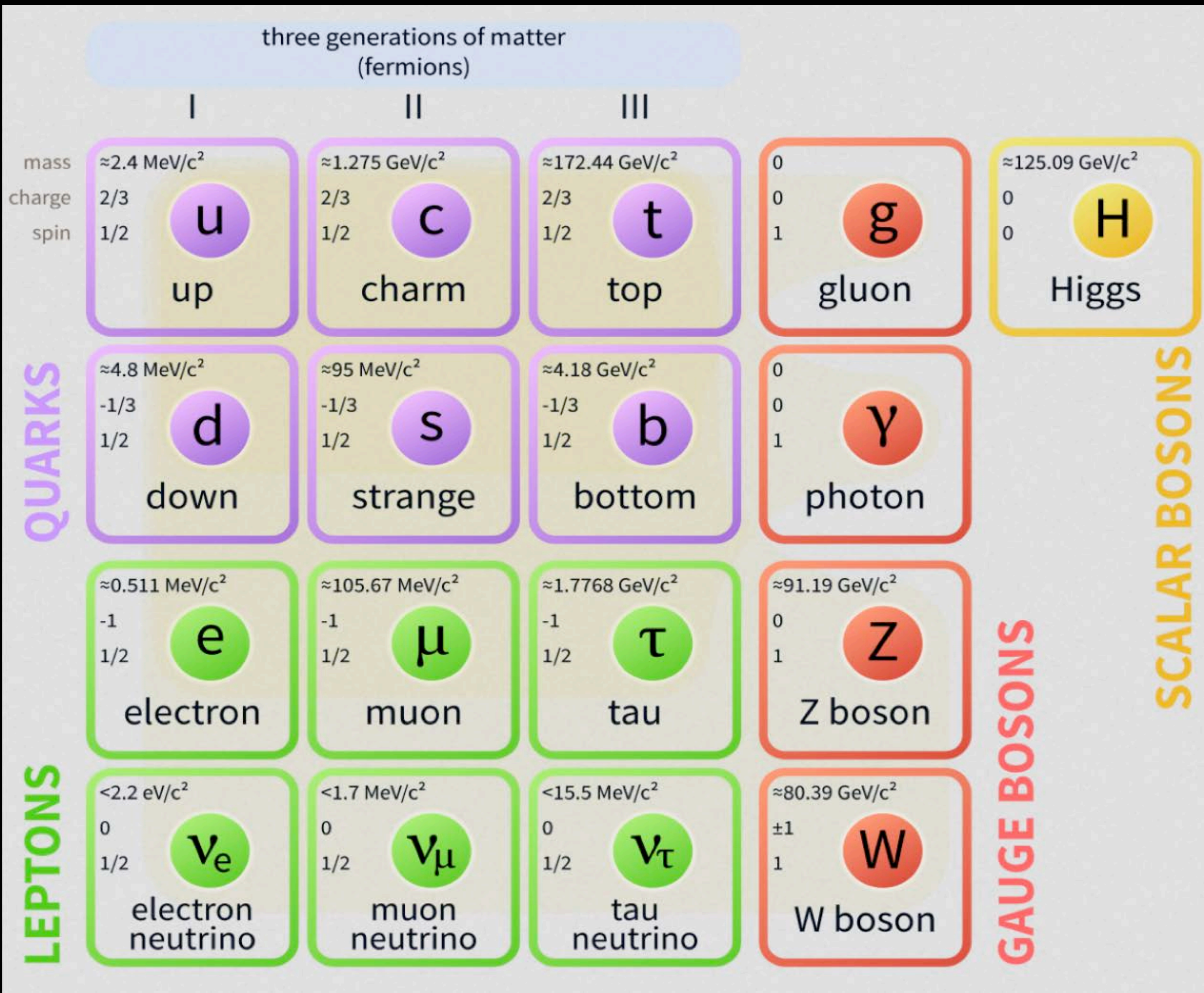
less than 1000th of a proton in size (or < 10^{-16}cm)

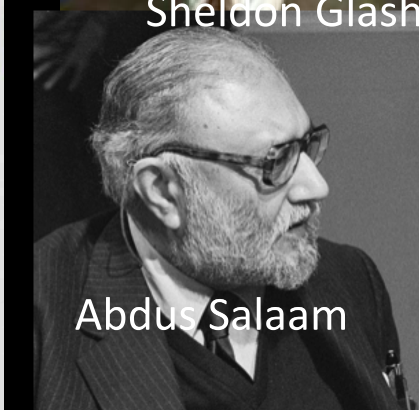
- Electrons are fundamental particles, they are point-like.

- Clouds of electrons surround positively charged nuclei, and are responsible for all of chemistry

The standard model

of elementary particles





Why are quarks undetectable directly?

In nuclei, quarks are held together by gluons

Nuclei are stable (protons and neutrons)

Forces between quarks are weak in nuclei

Outside nuclei, gluons don’t exist

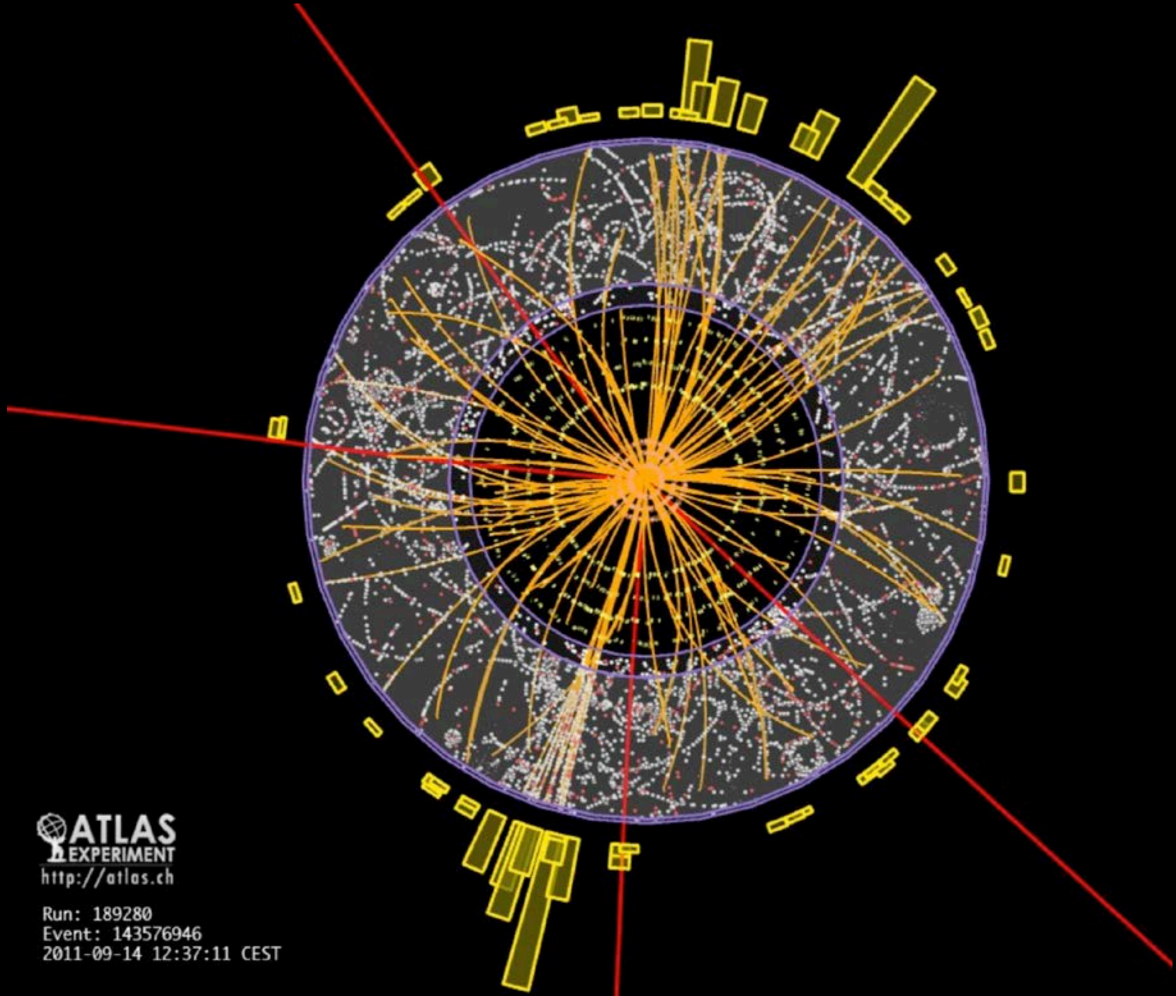
Forces between quarks are strong

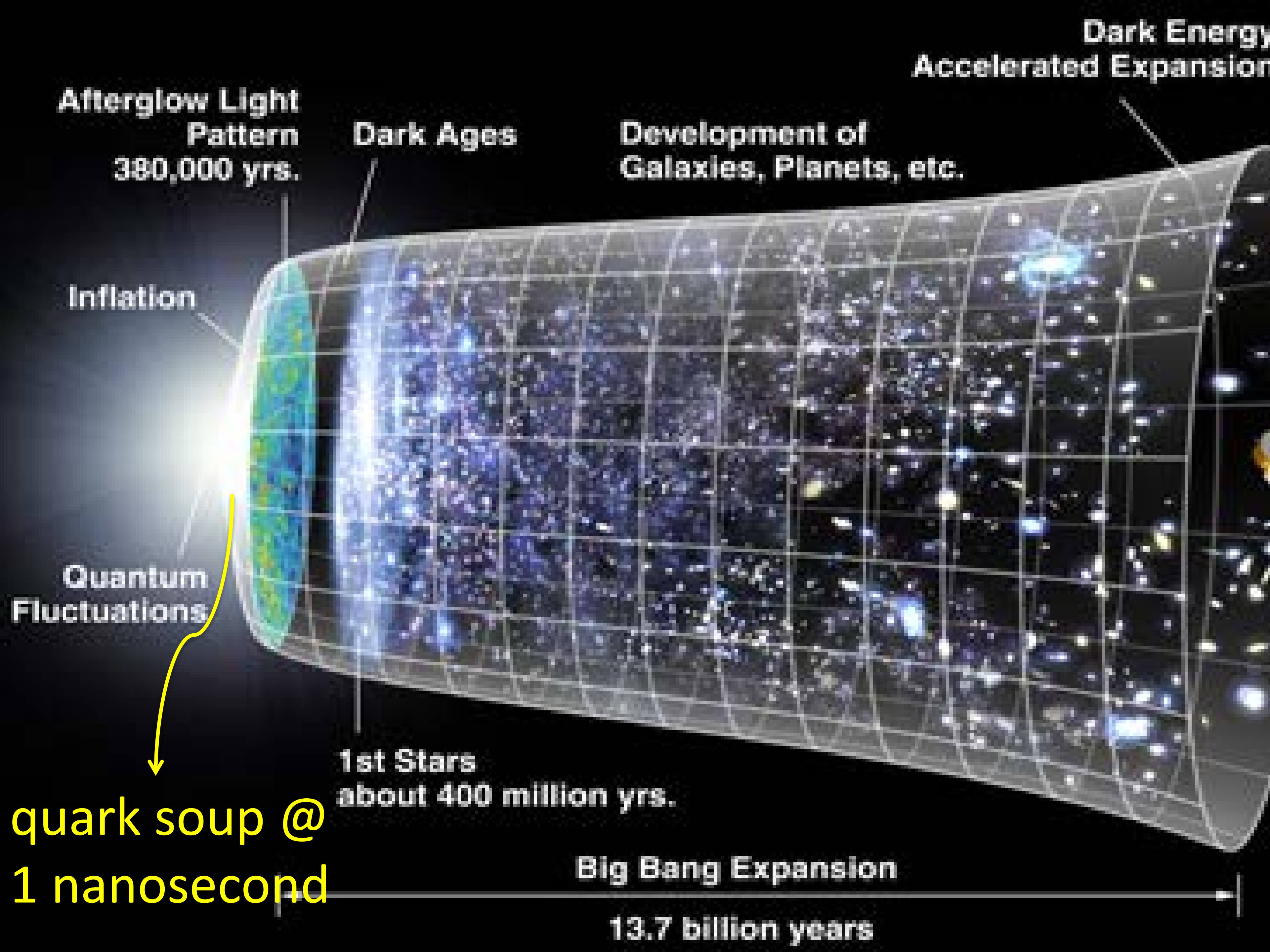
Quarks can’t exist in free space

We detect quarks indirectly

Protons are made of quarks

- We can never detect quarks directly!
- Colliders create them, we see their decays





Dark Energy
Accelerated Expansion
Afterglow Light Pattern 380,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Inflation
Quantum Fluctuations
1st Stars about 400 million yrs.
quark soup @ 1 nanosecond
Big Bang Expansion
13.7 billion years

Where is the antimatter?

- Cosmic microwave background: fossil radiation from the Big Bang
- There are 1.6 billion photons per proton
- Matter and antimatter annihilate to photons
- At high enough energy photons create matter and antimatter
- The ratio of matter to matter + antimatter was only

  6.2×10^{-10} during the first nanosecond of the universe

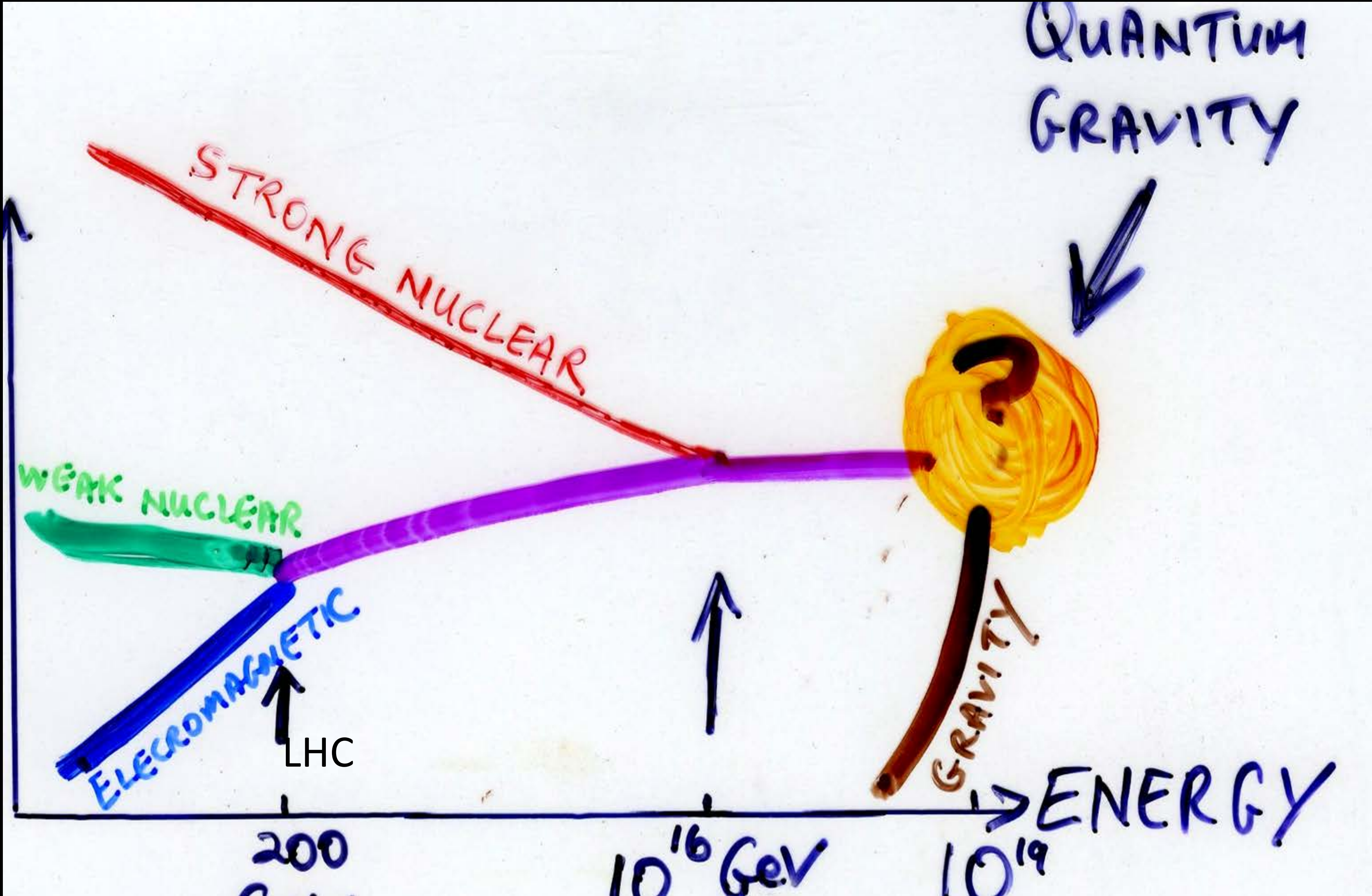
Today, matter overwhelms antimatter!

EARLY UNIVERSE WAS A TEST BED FOR HIGH ENERGY PHYSICS

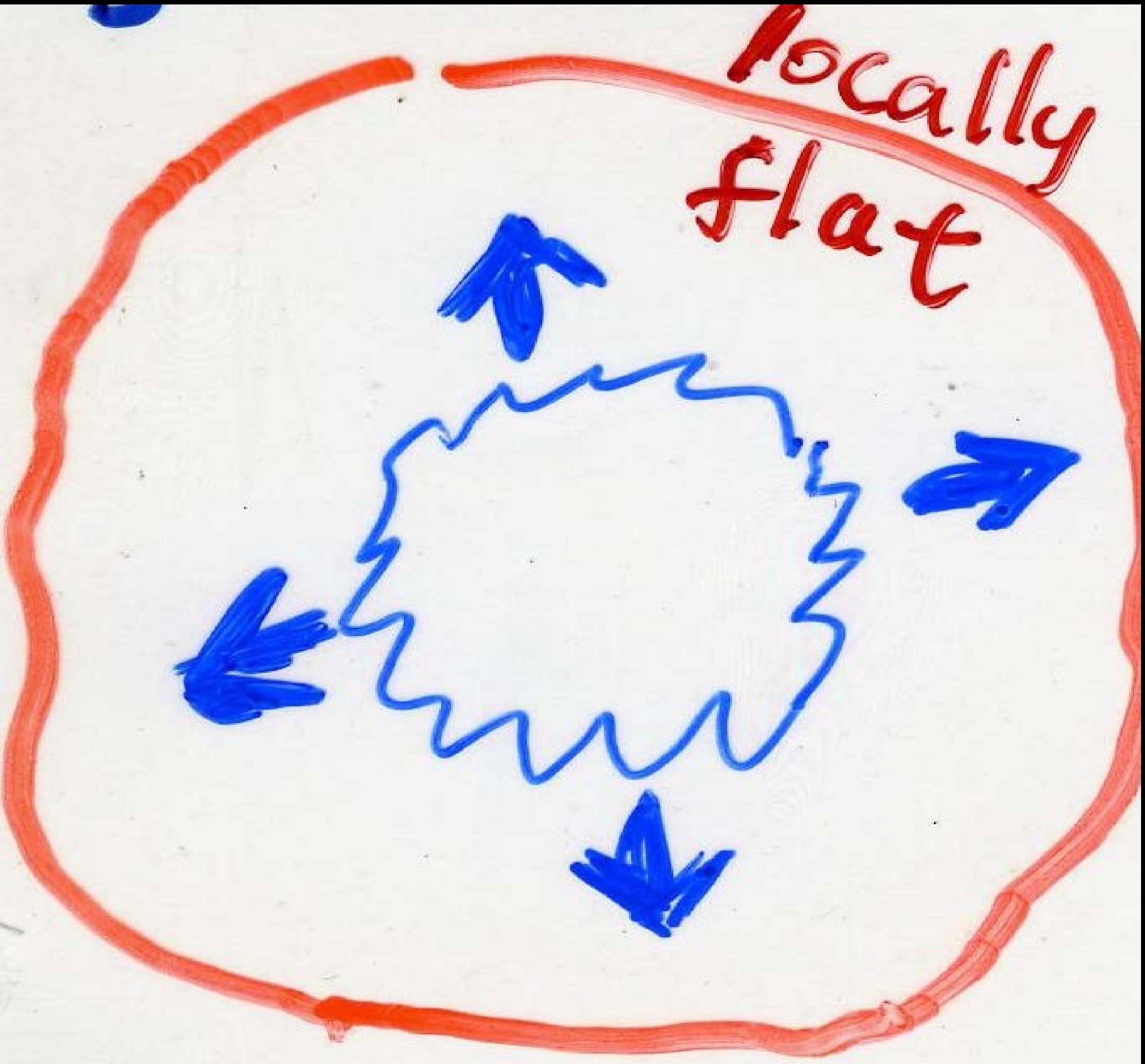
replicating these energies today requires an accelerator stretching halfway to the Moon

- A phase transition from unification of the fundamental forces when quarks and electrons were interchangeable
- To separation of strong from weak forces
- Like ice melting, this released energy
- For a brief moment, the universe inflated

Unification of the fundamental forces



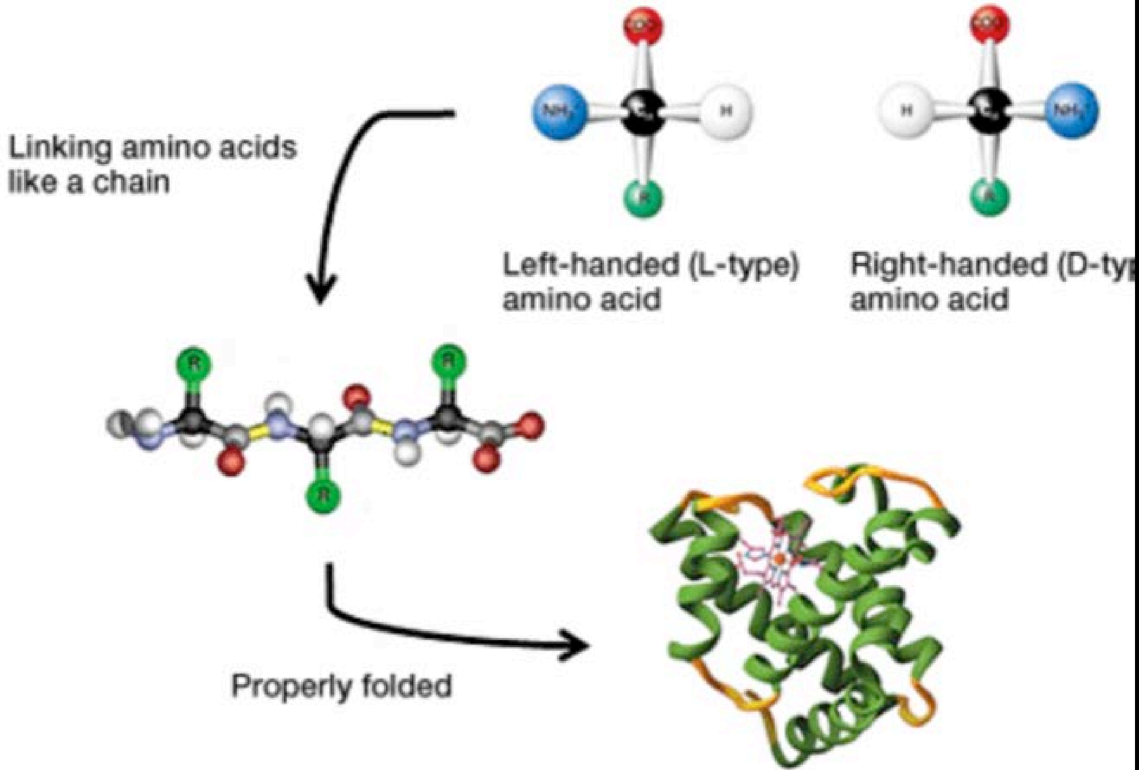
Inflation

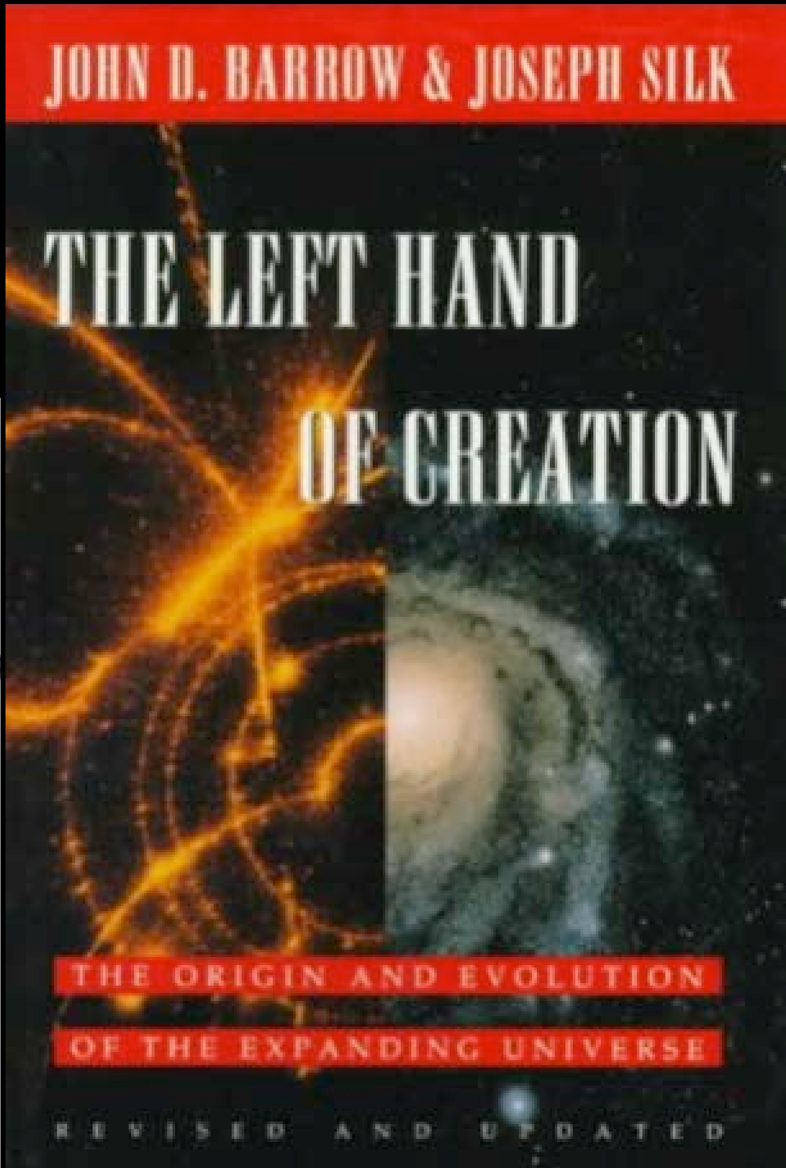


Why matter rather than antimatter?

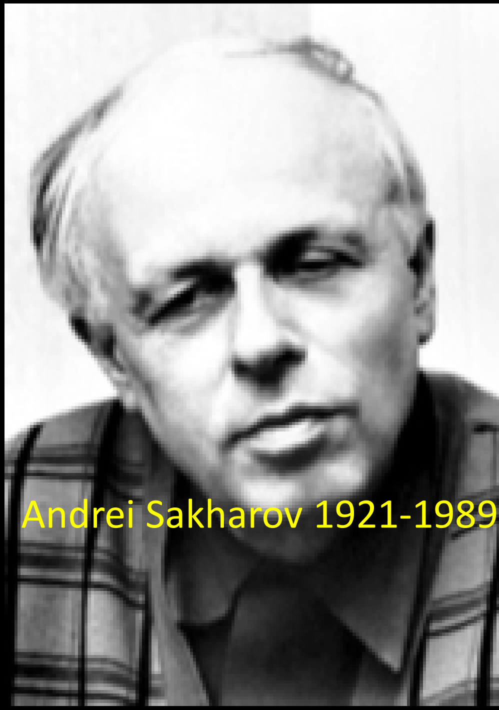
- Back to the Big Bang
- Need an asymmetry in Nature

eg, amino acids are left-handed





Andrei Sakharov



Father of Soviet H-bomb

Nobel peace prize 1975

1967:

Preponderance of matter over antimatter

arose from baryon number violation, embodied in the theory of “grand unification”: all forces are unified at very high energy, only achievable in the Big Bang

plus the requirement that decay of baryons into leptons has to proceed asymmetrically.

We are still seeking to prove this, along with the prediction that protons decay

ELECTRONS

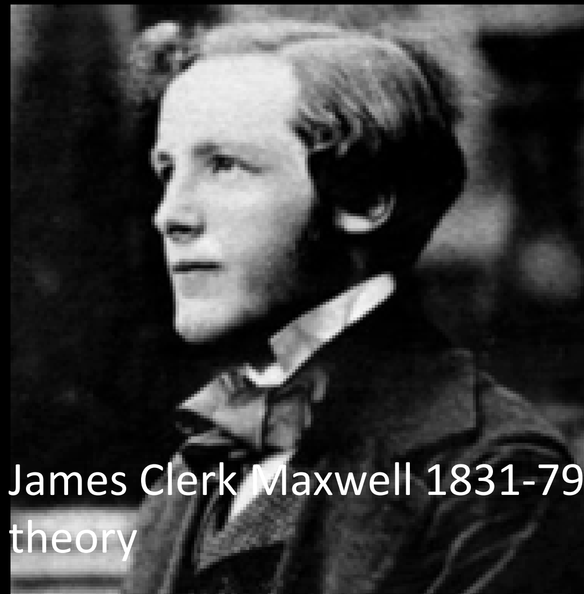
first subatomic particle to be discovered

carrier of electricity

Joseph Thomson 1856-1940
Discoverer of electron in 1897

- when accelerated, electrons produces waves

Heinrich Hertz 1857-94
discovery



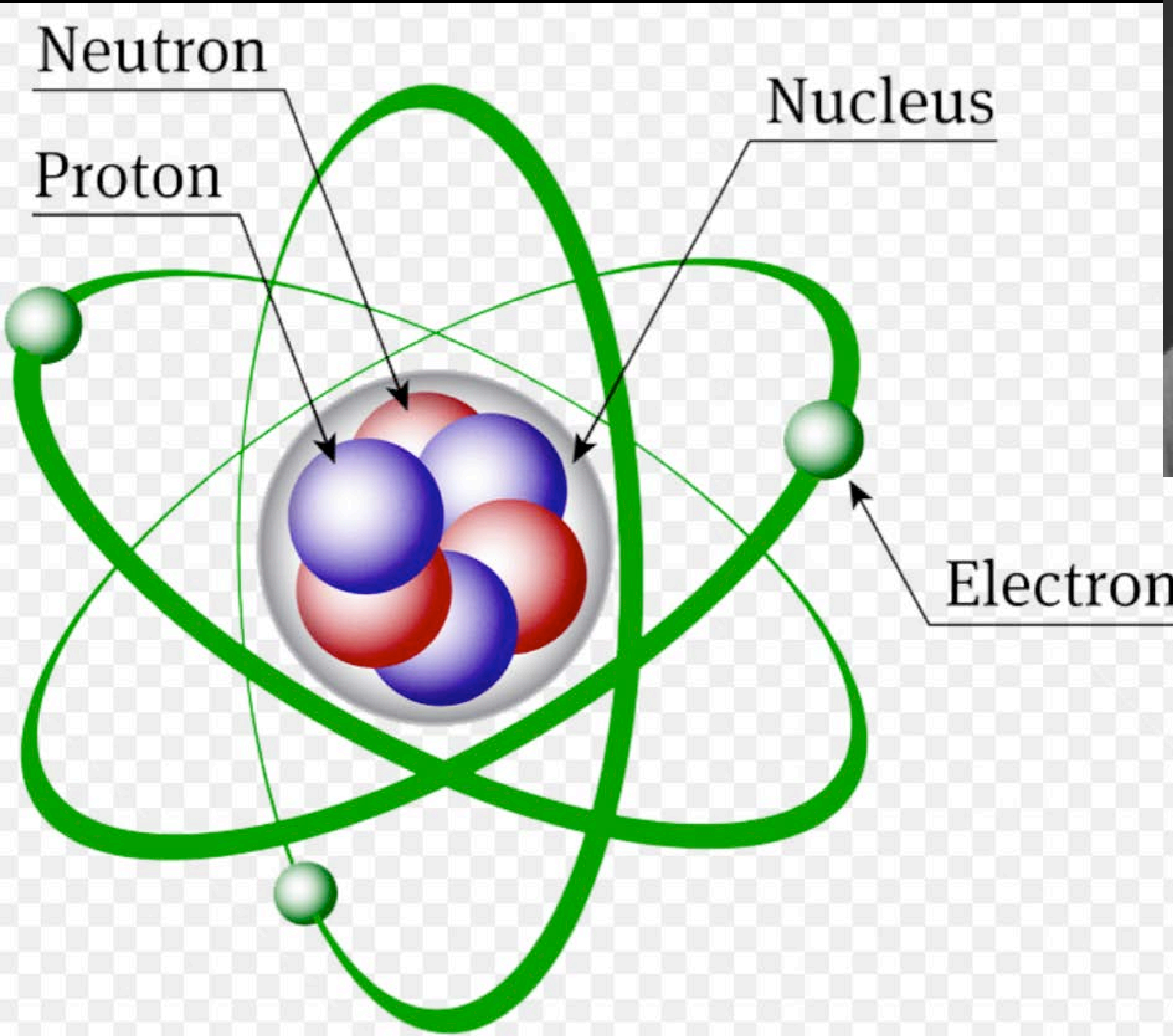
James Clerk Maxwell 1831-79
theory

Alexander Graham Bell 1847-1922
telephone

Guglielmo Marconi 1874-1937
radio

waves are particles (quanta)

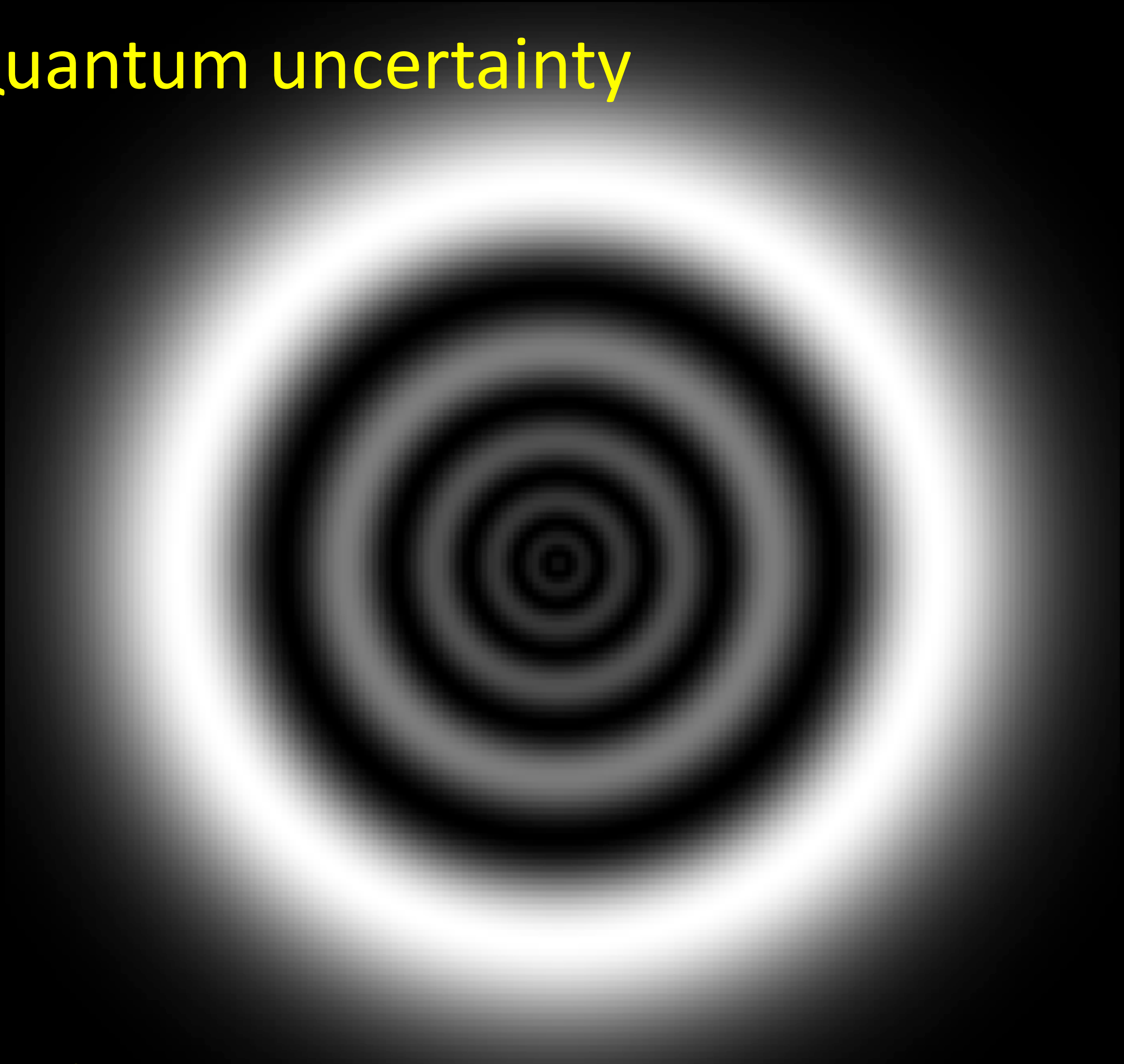
particles are waves



Neils Bohr 1885-1962

$m_e = m_p/1836$

Quantum uncertainty

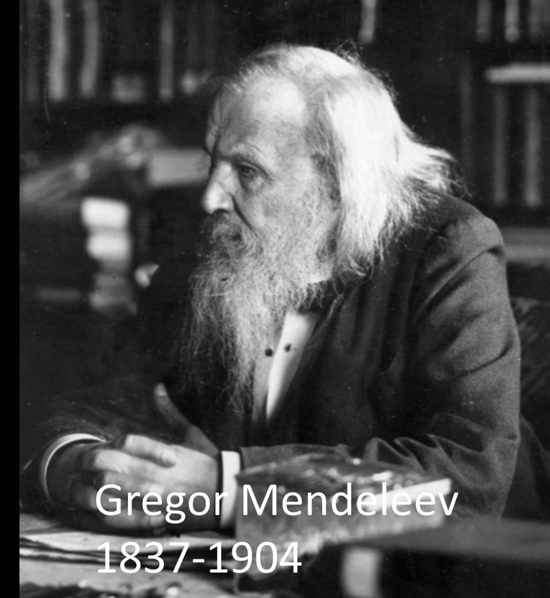


Probability of observing an electron

NEUTRONS

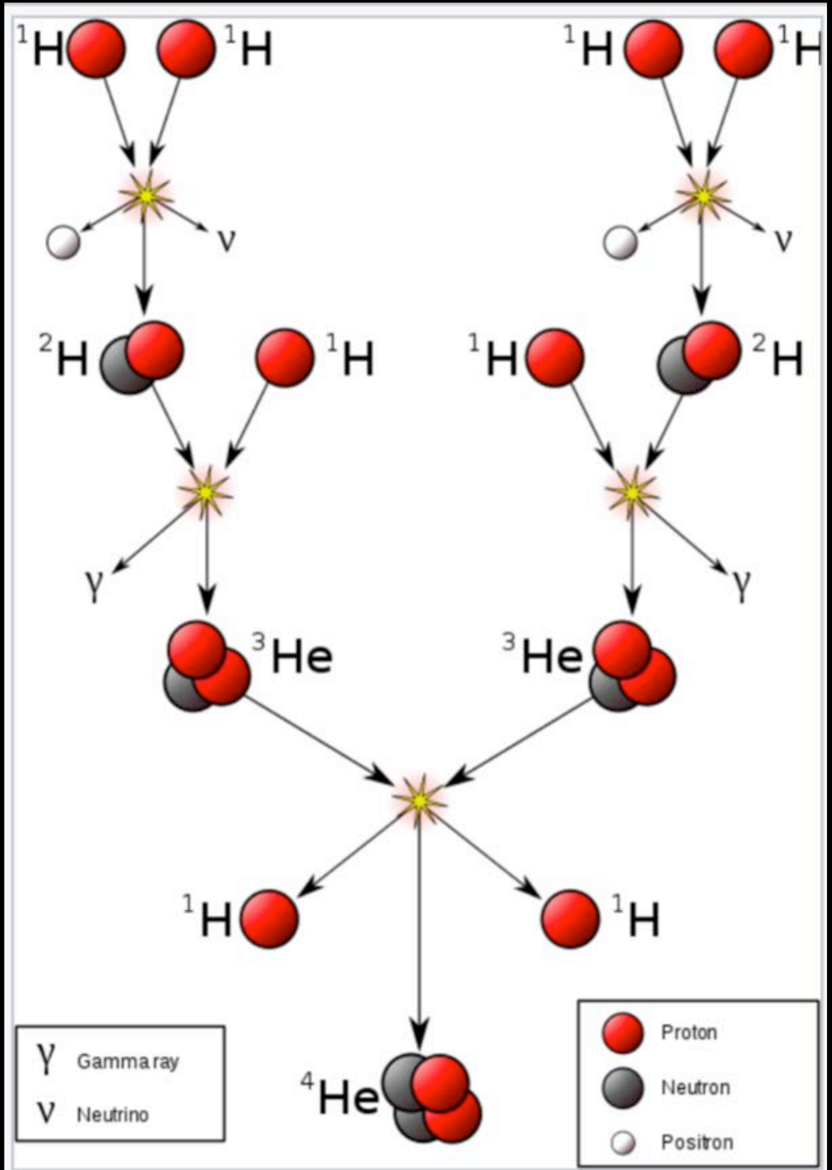
- Mass of neutron = 938.2723 MeV
- Mass of electron = 0.5110 MeV
- Mass of proton = 939.5656 MeV
- $E=mc^2$

- Electrons and protons + neutrons make atoms → periodic table



1 H																		2 He
3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc		22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y		40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
			*	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
			**	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

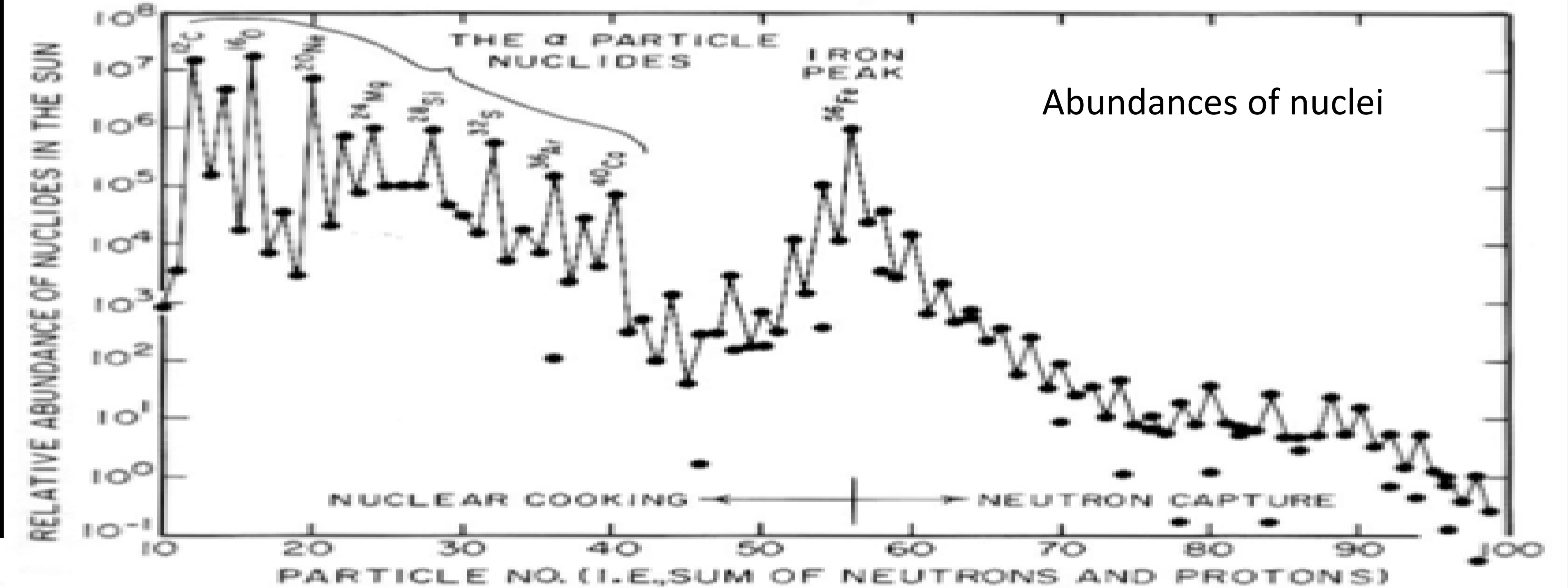
Neutrons and stellar nuclear reactions

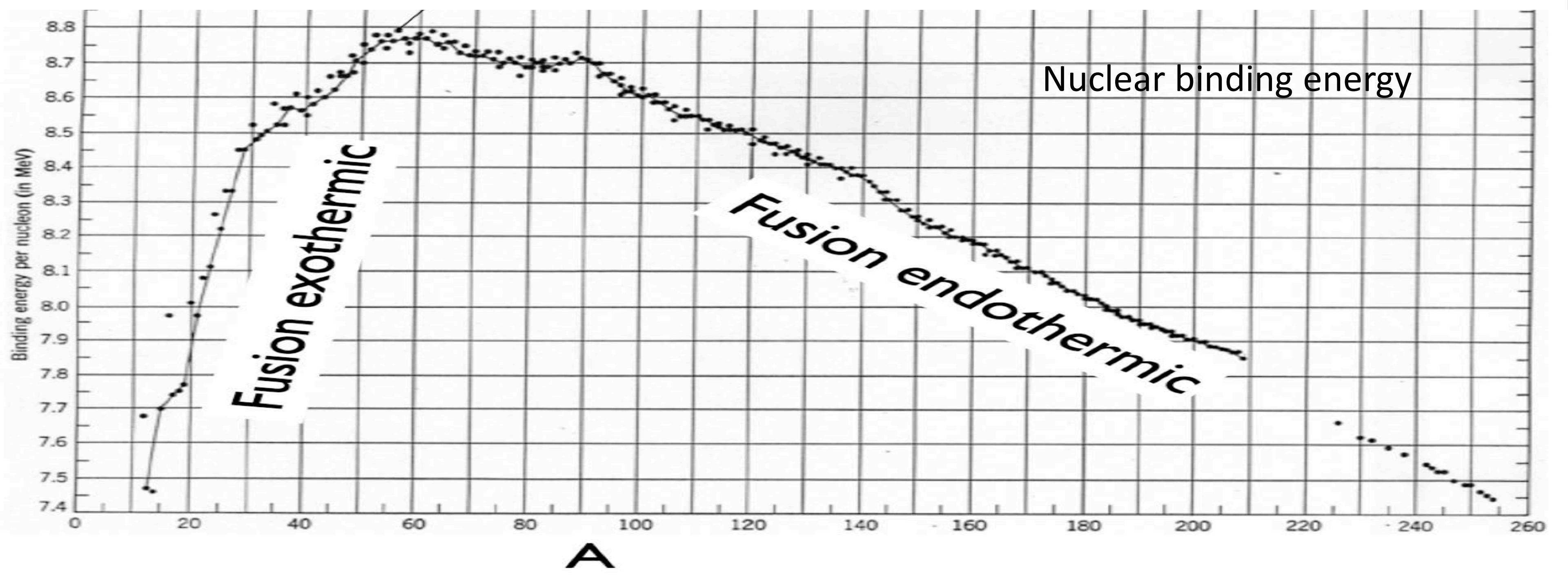


proton-proton cycle powers the sun

Stars are powered by thermonuclear fusion

All elements up to iron are made by fusion


THE α PARTICLE NUCLIDES
IRON PEAK
Abundances of nuclei
RELATIVE ABUNDANCE OF NUCLIDES IN THE SUN
NUCLEAR COOKING
NEUTRON CAPTURE
PARTICLE NO. (I.E., SUM OF NEUTRONS AND PROTONS)


Nuclear binding energy
Binding energy per nucleon (in MeV)
Fusion exothermic
Fusion endothermic
A

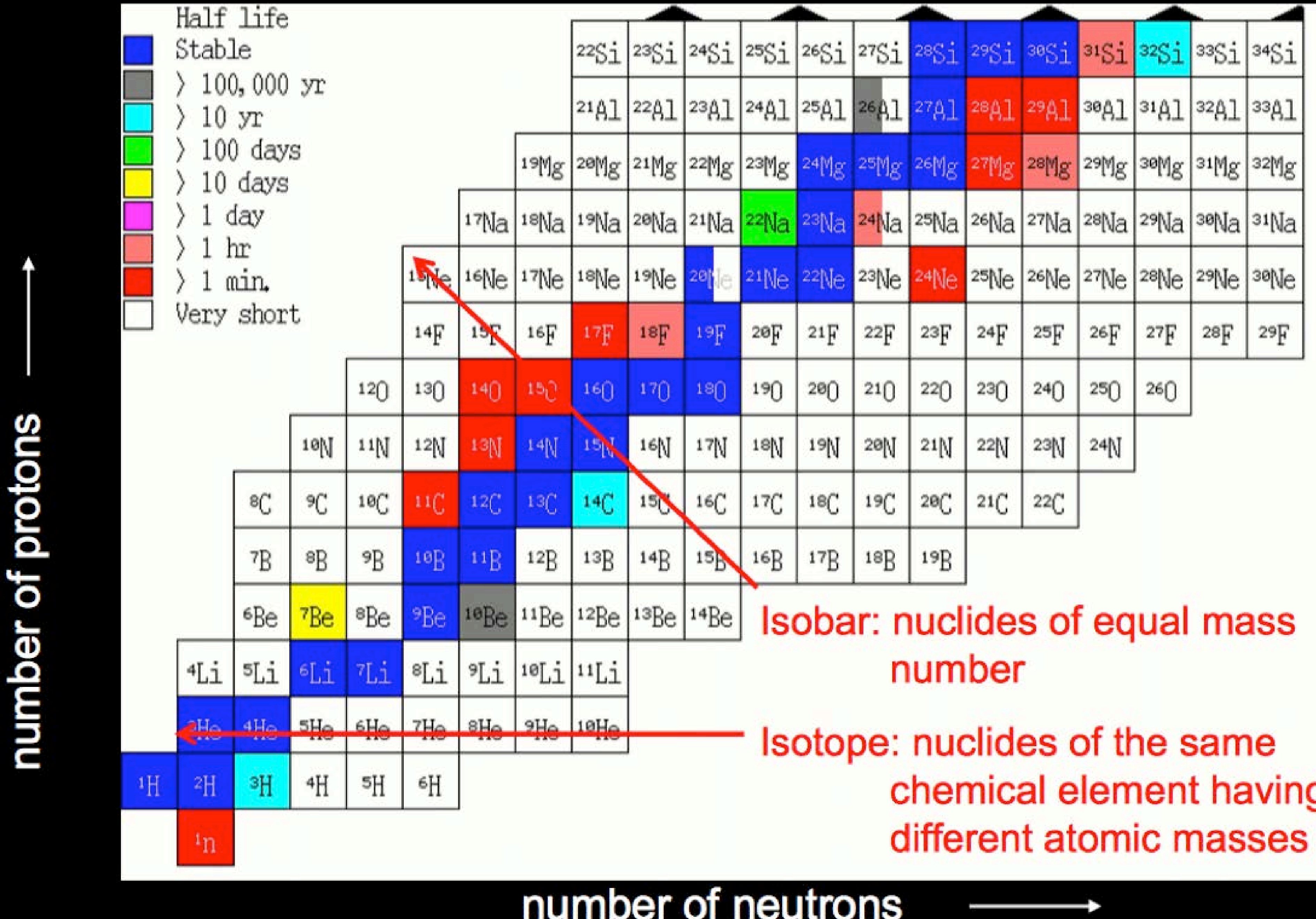
Thermonuclear fission

Elements with right balance of n/p are stable

All others are radioactive and undergo fission

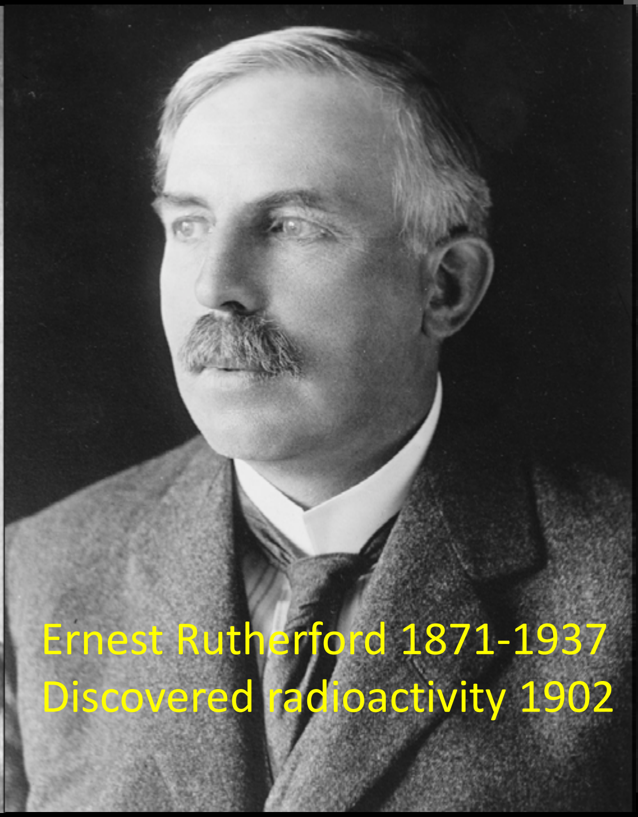
Too few n: beta decay converts p to n + e^+ + ν

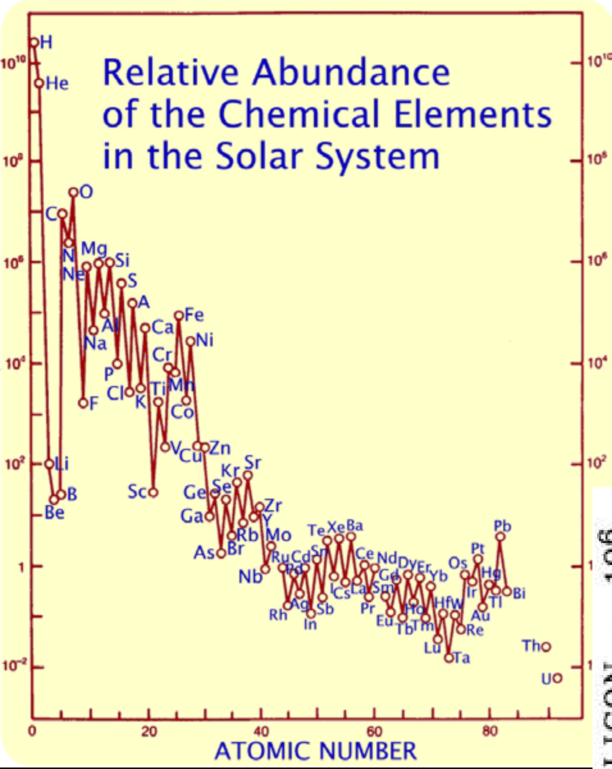
Too many n: beta decay converts n to p + e + ν


Half life
Stable
› 100,000 yr
› 10 yr
› 100 days
› 10 days
› 1 day
› 1 hr
› 1 min.
Very short
22Si 23Si 24Si 25Si 26Si 27Si 28Si 29Si 30Si 31Si 32Si 33Si 34Si
21Al 22Al 23Al 24Al 25Al 26Al 27Al 28Al 29Al 30Al 31Al 32Al 33Al
19Mg 20Mg 21Mg 22Mg 23Mg 24Mg 25Mg 26Mg 27Mg 28Mg 29Mg 30Mg 31Mg 32Mg
17Na 18Na 19Na 20Na 21Na 22Na 23Na 24Na 25Na 26Na 27Na 28Na 29Na 30Na 31Na
15Ne 16Ne 17Ne 18Ne 19Ne 20Ne 21Ne 22Ne 23Ne 24Ne 25Ne 26Ne 27Ne 28Ne 29Ne 30Ne
14F 15F 16F 17F 18F 19F 20F 21F 22F 23F 24F 25F 26F 27F 28F 29F
12O 13O 14O 15O 16O 17O 18O 19O 20O 21O 22O 23O 24O 25O 26O
10N 11N 12N 13N 14N 15N 16N 17N 18N 19N 20N 21N 22N 23N 24N
8C 9C 10C 11C 12C 13C 14C 15C 16C 17C 18C 19C 20C 21C 22C
7B 8B 9B 10B 11B 12B 13B 14B 15B 16B 17B 18B 19B
6Be 7Be 8Be 9Be 10Be 11Be 12Be 13Be 14Be
4Li 5Li 6Li 7Li 8Li 9Li 10Li 11Li
3He 4He 5He 6He 7He 8He 9He 10He
1H 2H 3H 4H 5H 6H
1n
Isobar: nuclides of equal mass number
Isotope: nuclides of the same chemical element having different atomic masses
number of protons
number of neutrons

Neutrons and radioactivity

- One proton plus a neutron is a stable configuration
- More neutrons leads to radioactive decay

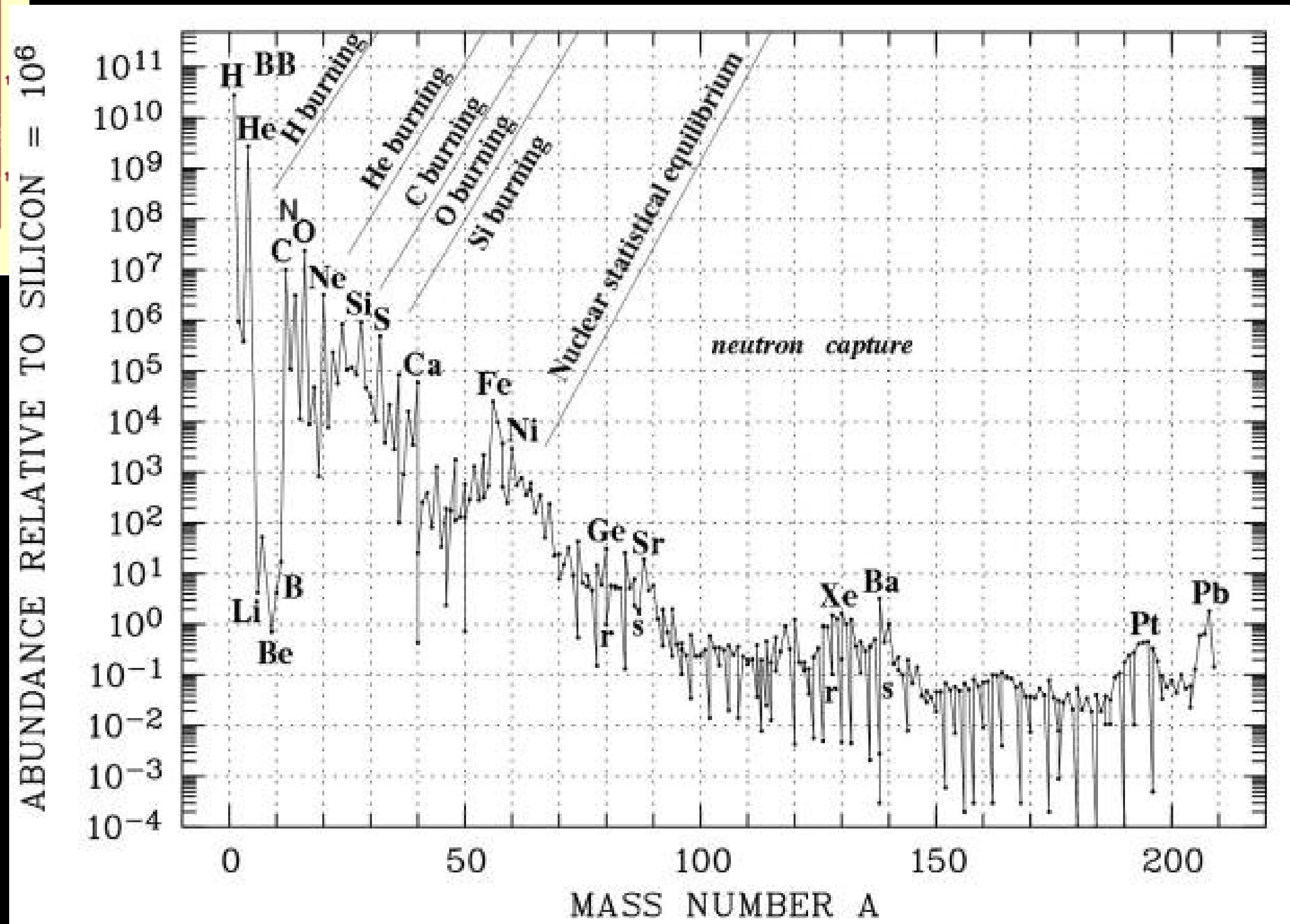




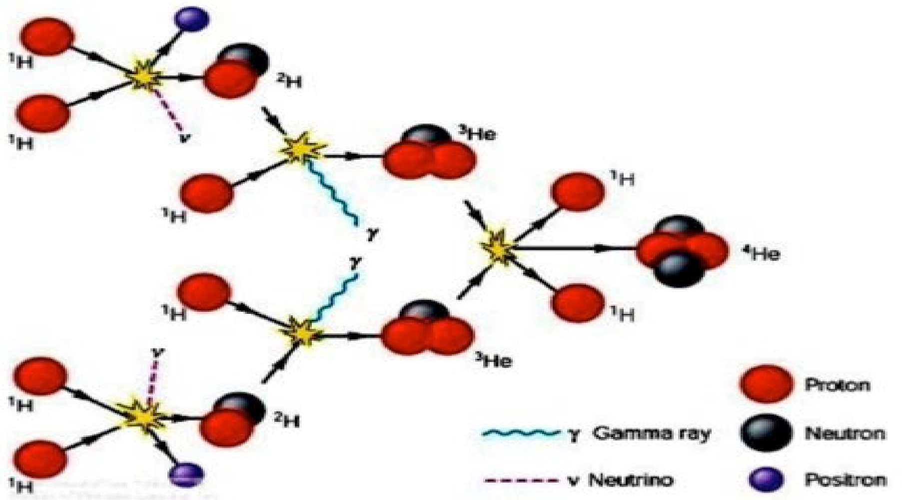
Big Bang

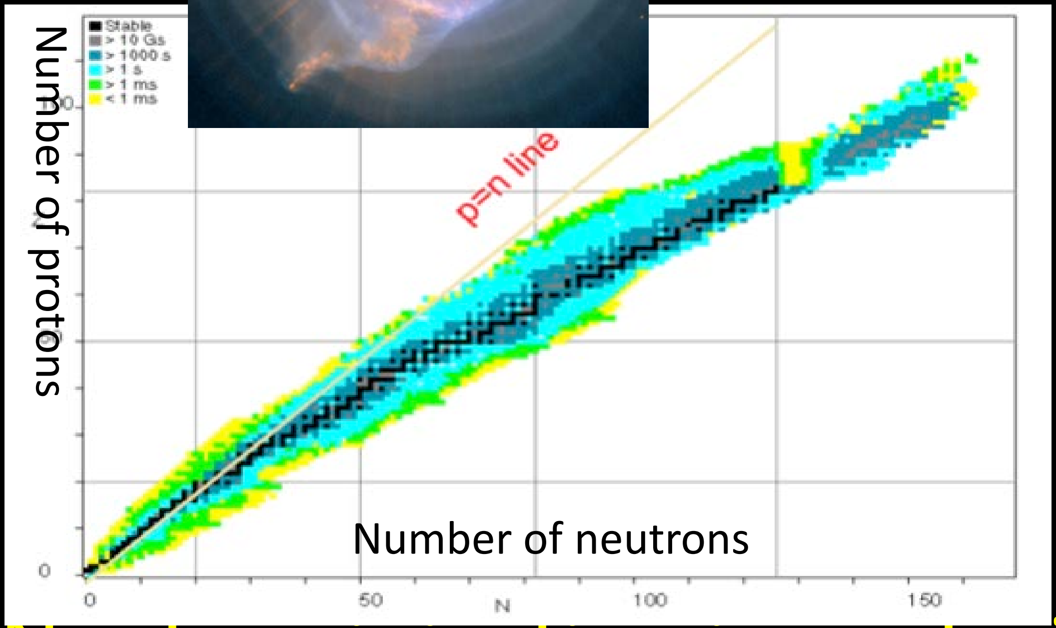
Low mass stars

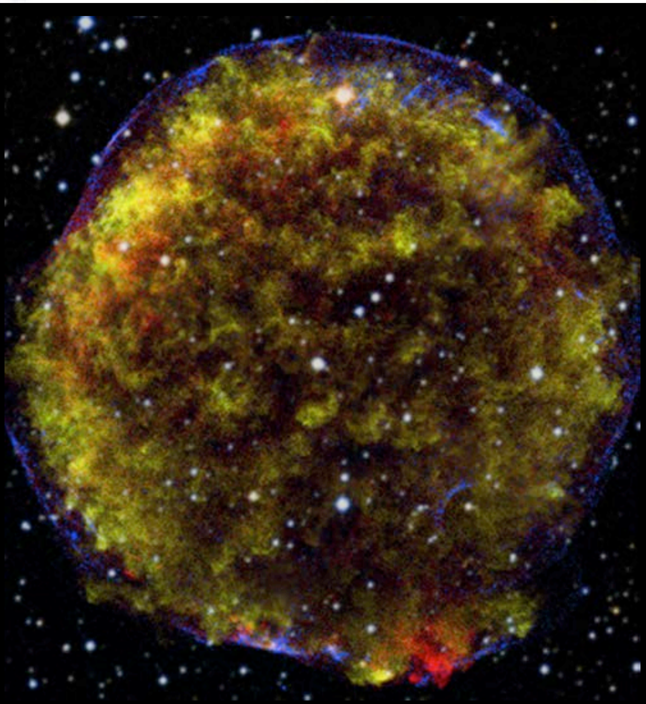
Massive stars



Cooking in low mass stars that die as white dwarfs



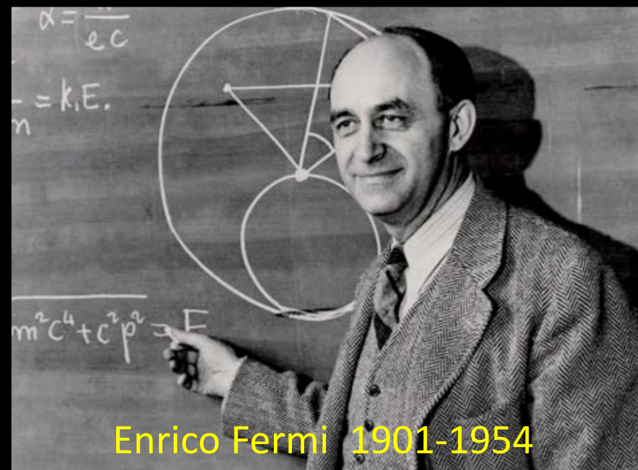




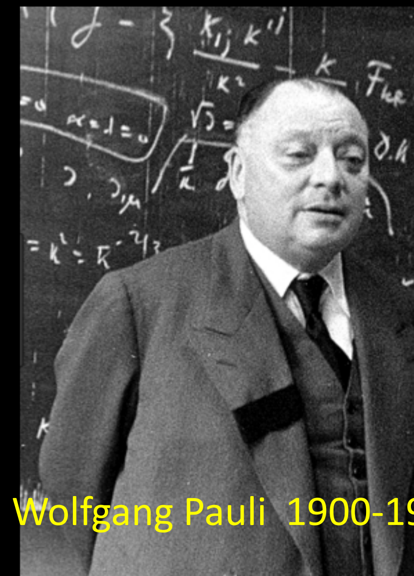
Neutron injection in explosions of massive stars that form neutron stars (or black holes)

NEUTRINOS

”the little neutron”



Enrico Fermi 1901-1954



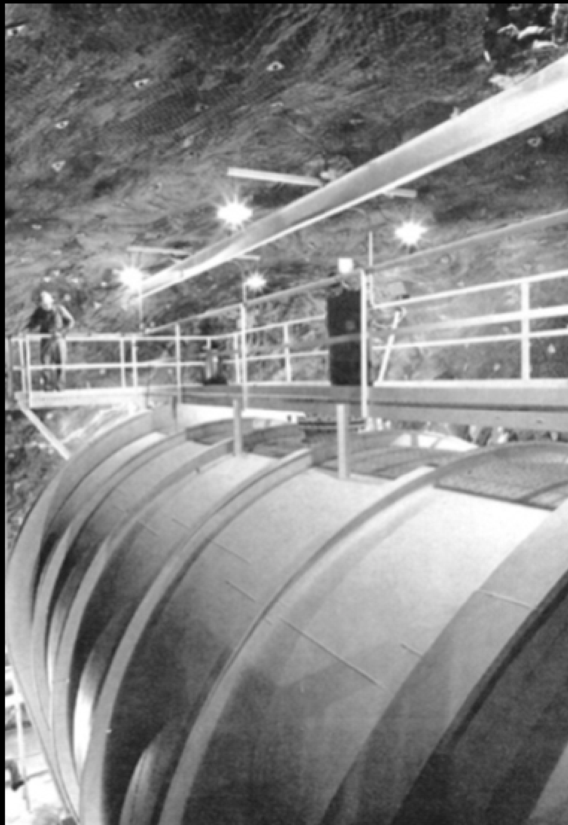
Wolfgang Pauli 1900-1958

Invented to account for beta decay in radioactivity:
when protons or neutrons inside atomic nuclei decay, they spit out electrons or positrons.
These   “beta rays” carry extra energy but negigible mass: hence the neutrino was discovered

Neutrinos are very weakly interacting, they pass through anything!

1968-72   Homestake mine in Lead, S. Dakota: tank filled with 100,000 gallons of cleaning fluid.
1 chlorine atom/day   absorbs a neutrino, ejects an electron, and becomes radioactive argon

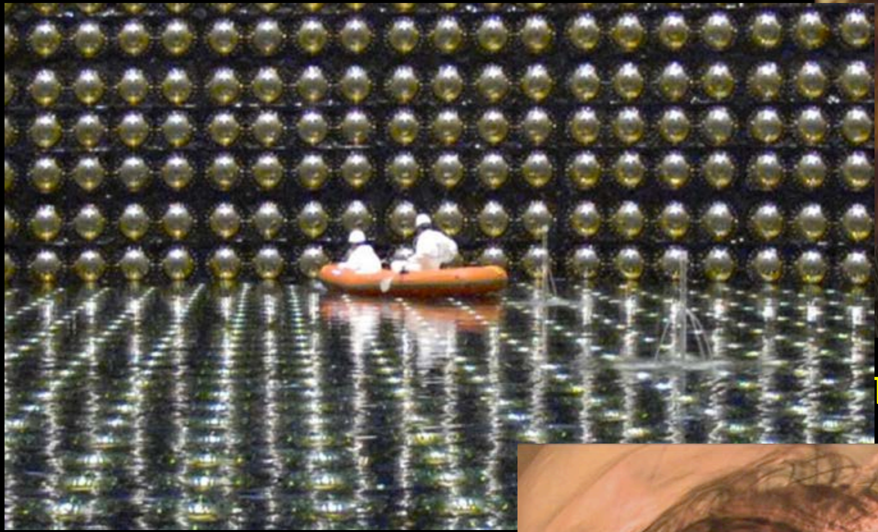
Ray Davis 1914-2006



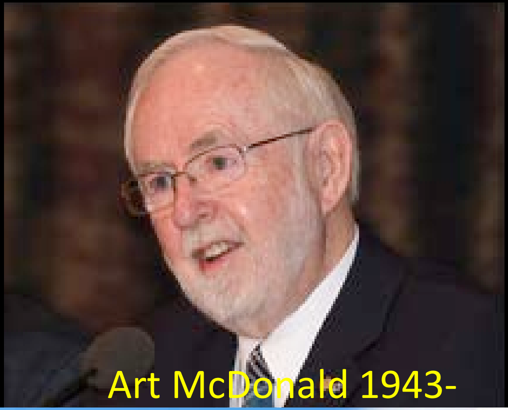
Detect neutrinos from the centre of the sun

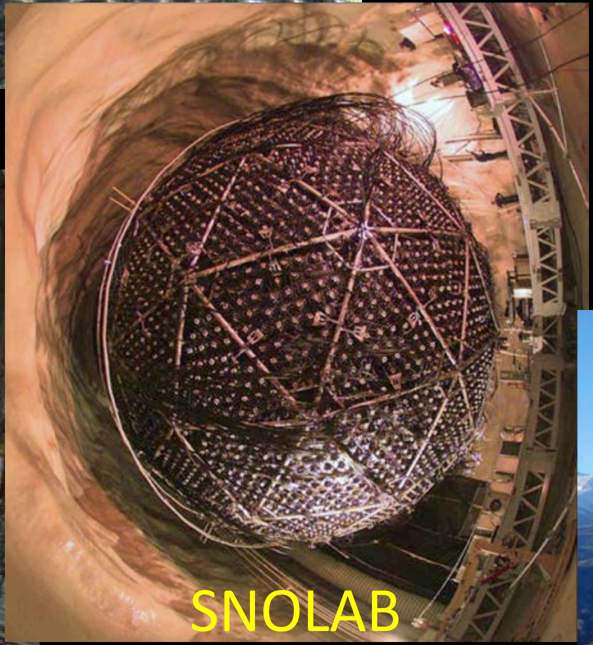
SuperKamiokande

Solar neutrino oscillations

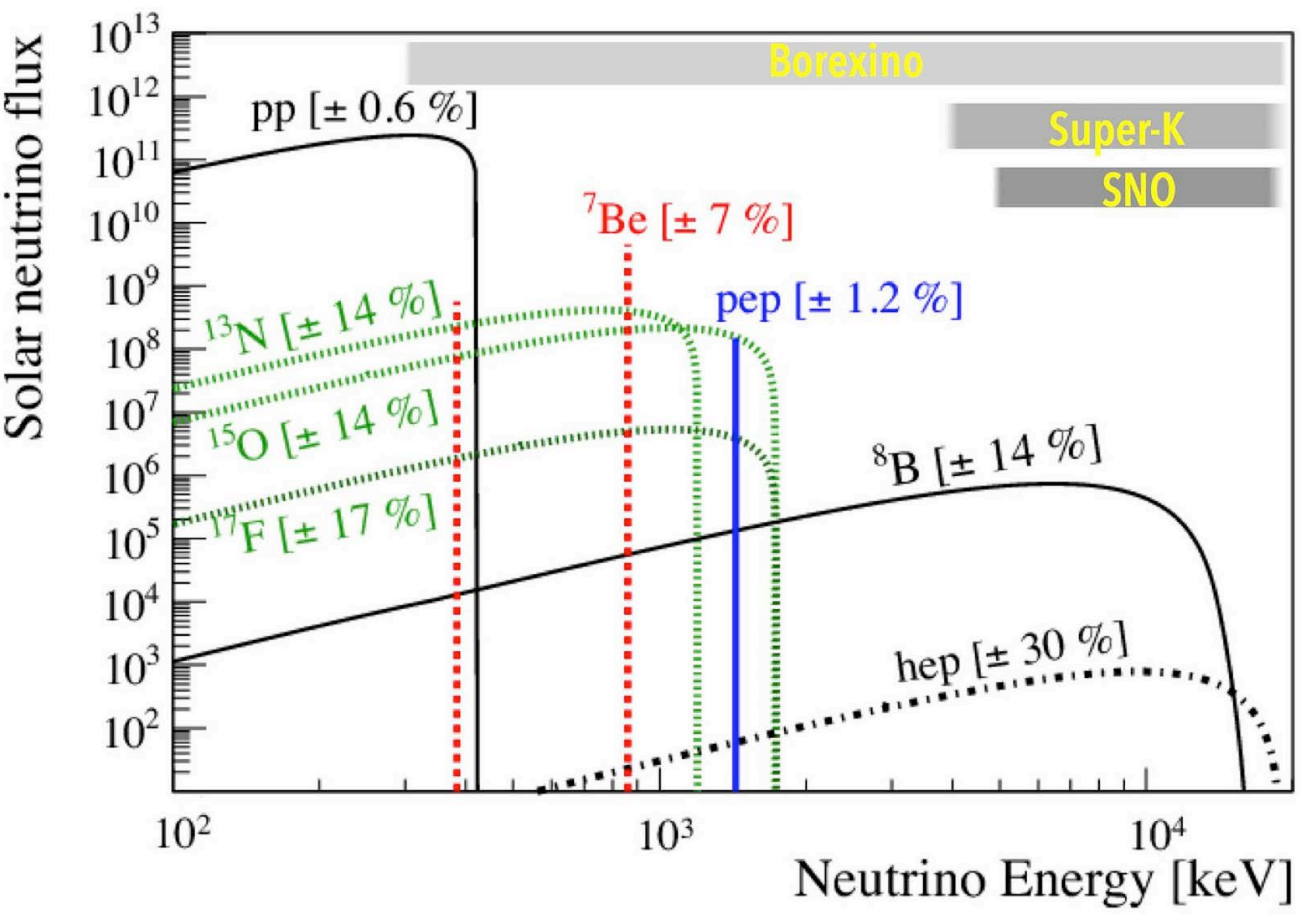


Takaaji Najita 1959-



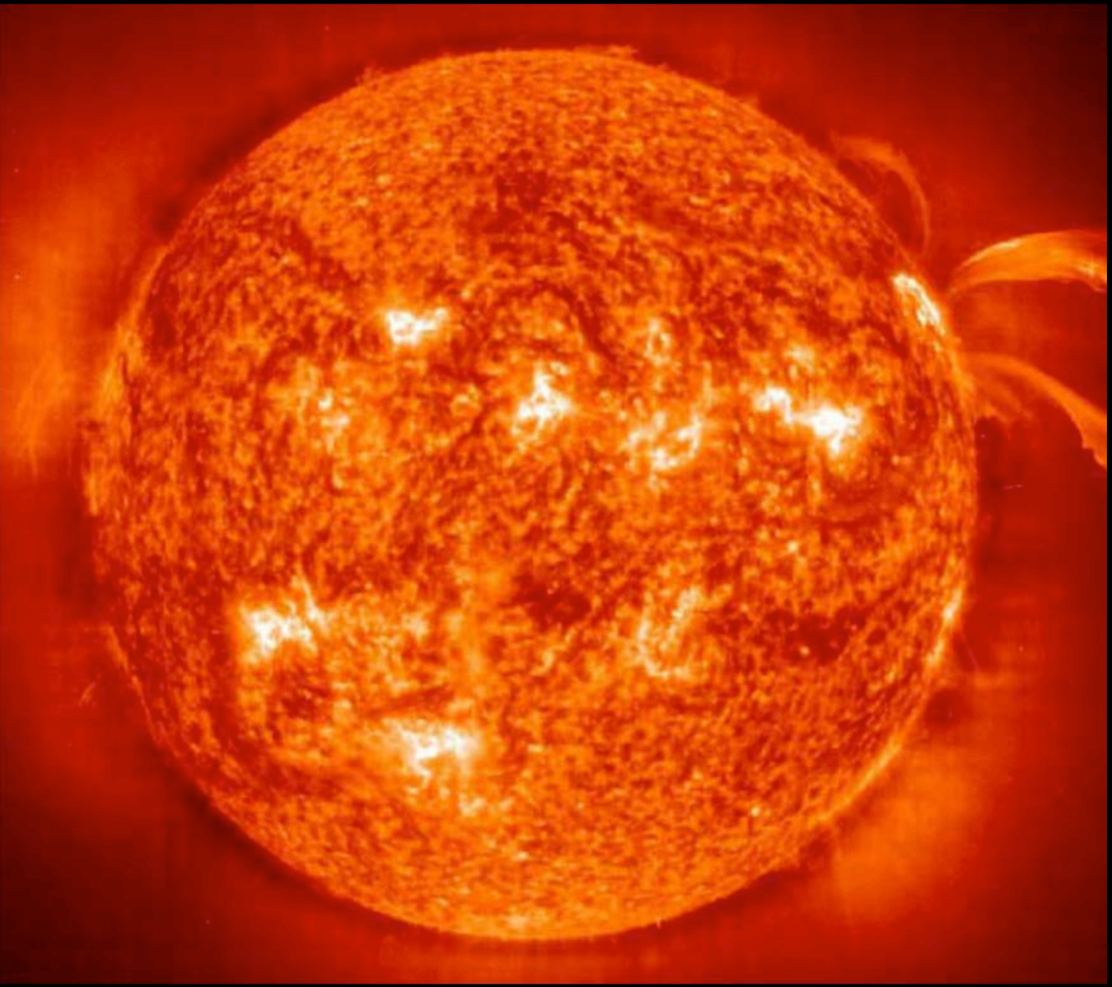


THE NEAR FUTURE OF ν EXPERIMENTS



NUCLEAR REACTORS

A fusion reactor that creates and sustains life

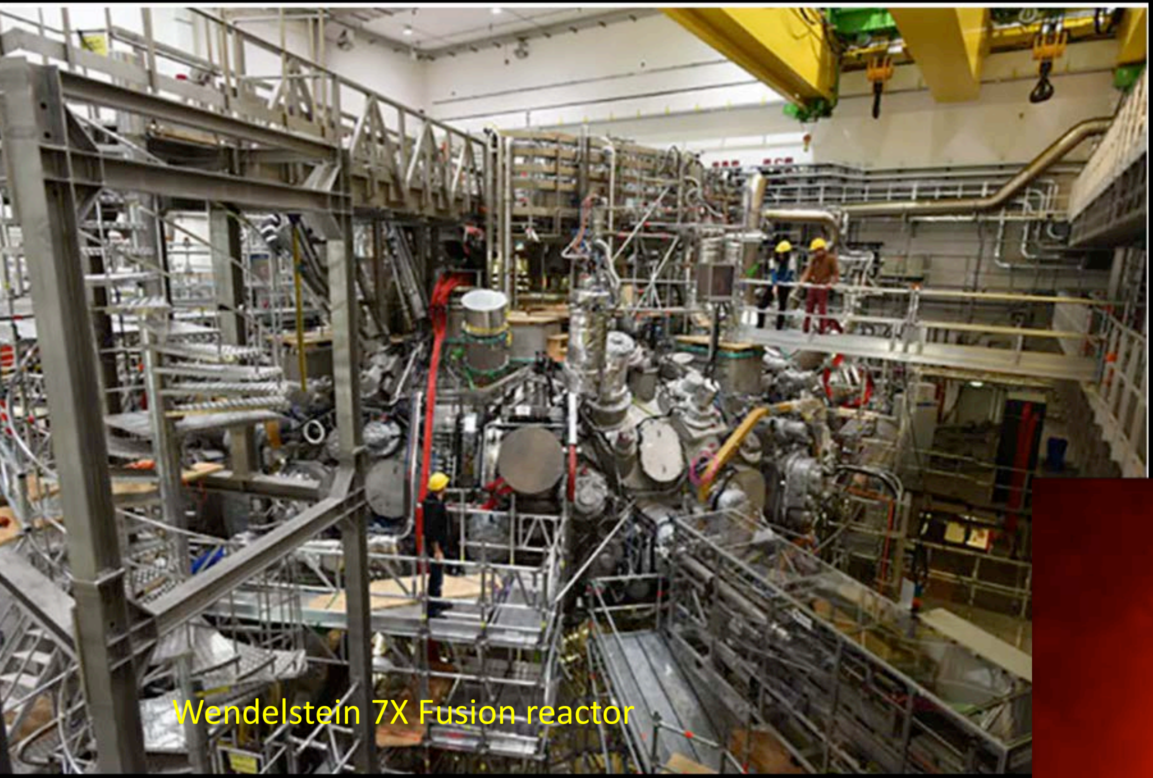


22 gigawatts

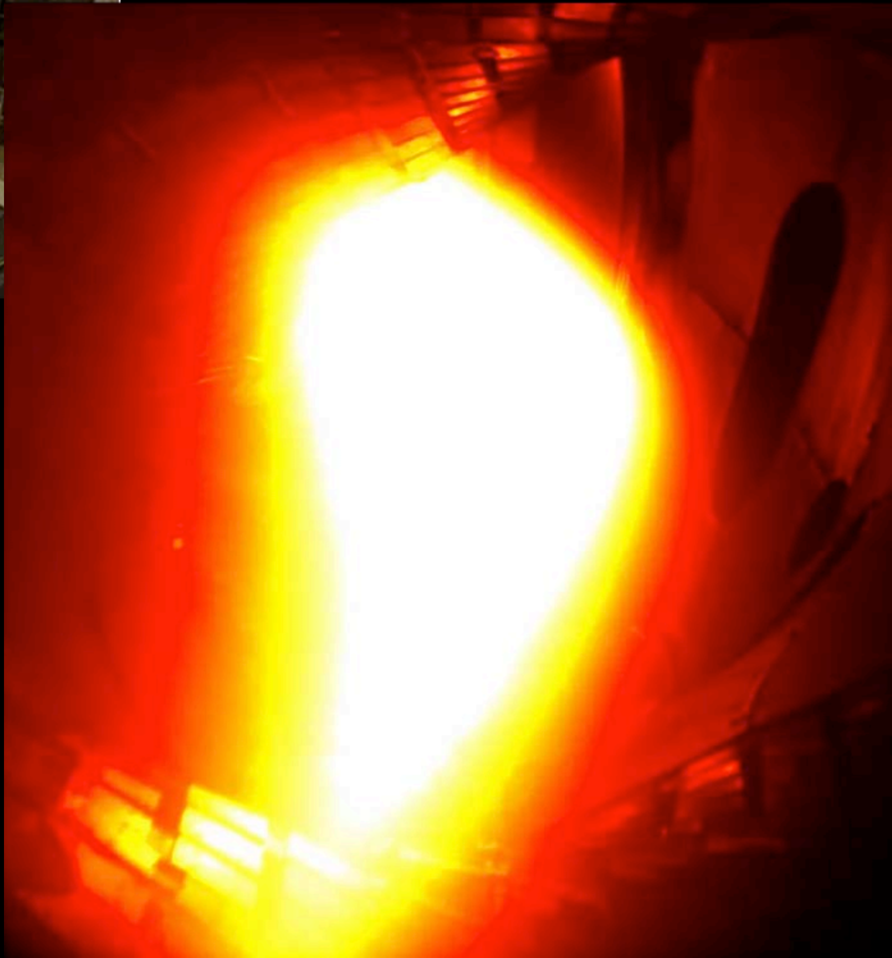
3 Gorges dam, China

4.10^{33} ergs/s or 4.10^{17}gigawatts

The earth captures 2.10^{8} gigawatts



Stellarator



First steps to controlled thermonuclear fusion

Germany, 2016


Bikini atoll 1946 23 kton


Hiroshima 15ktons 1945


French Indonesia 1Mton 1970


Bikini atoll 4Mton 1954

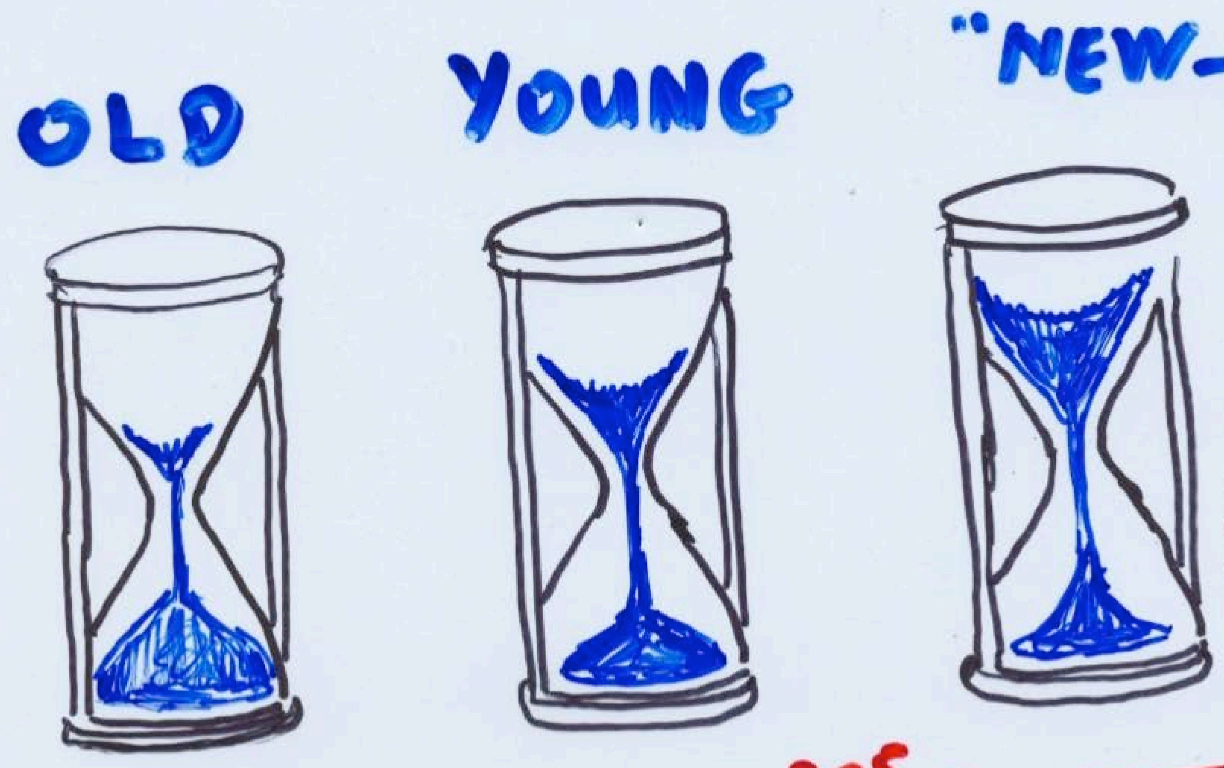

Russia 140kTon
lake & dam 1965

- Big Bang nucleosynthesis makes only isotopes with atomic masses 2, 3, 4 and 7,
  - because masses 5 and 8 are not stable
- Stellar fusion makes helium, and elements from carbon to iron
- Supernova fusion makes the “iron peak”
- Neutron capture makes elements heavier than iron

Oklo uranium mine,
Gabon

AGE OF THE CHEMICAL ELEMENTS

VIA RADIOACTIVE DATING OF ROCKS



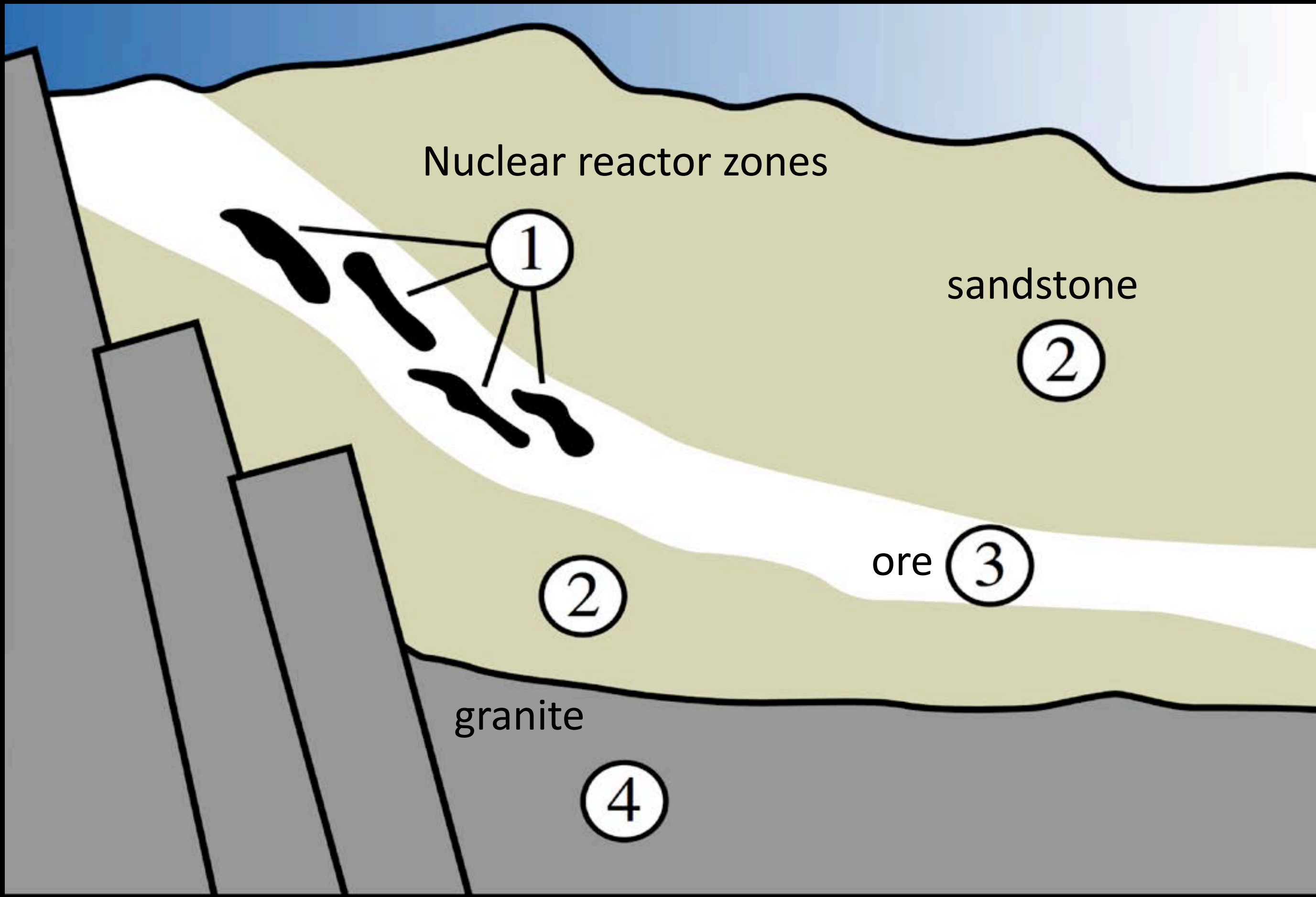
U^{238} decays with half life 4×10^{9} yr

Pb^{205} ←

A natural nuclear reactor

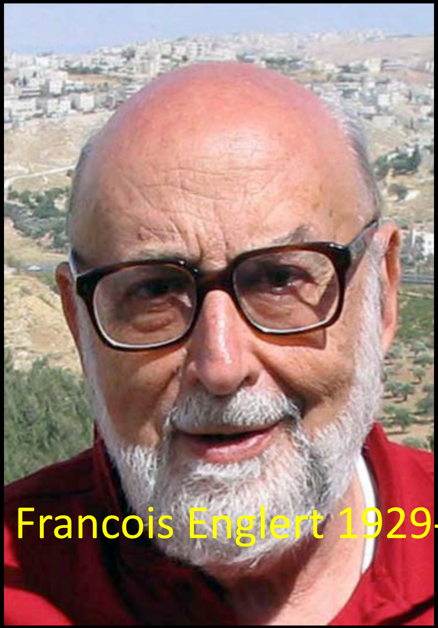
A tiny deficiency of uranium -235 was noticed by French scientists in the 1970s

nuclear chain reaction occurred deep underground, 1.7 billion years ago, thanks to locally enhanced uranium + water seepage



Oklo uranium mine, Gabon

What's wrong with the standard model of particles?


Francois Englert 1929-

electroweak theory requires a new particle to account for masses of quarks and electrons, predicted in 1964

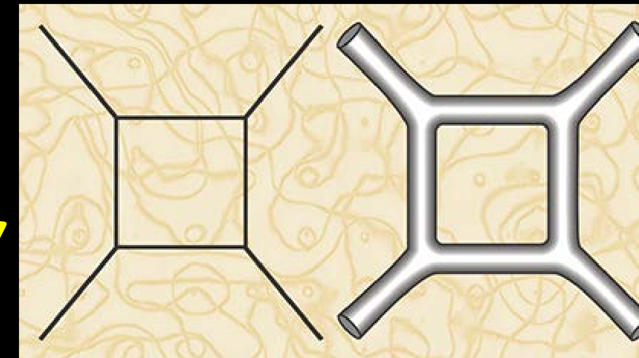
the Higgs boson was detected in 2012: standard model confirmed

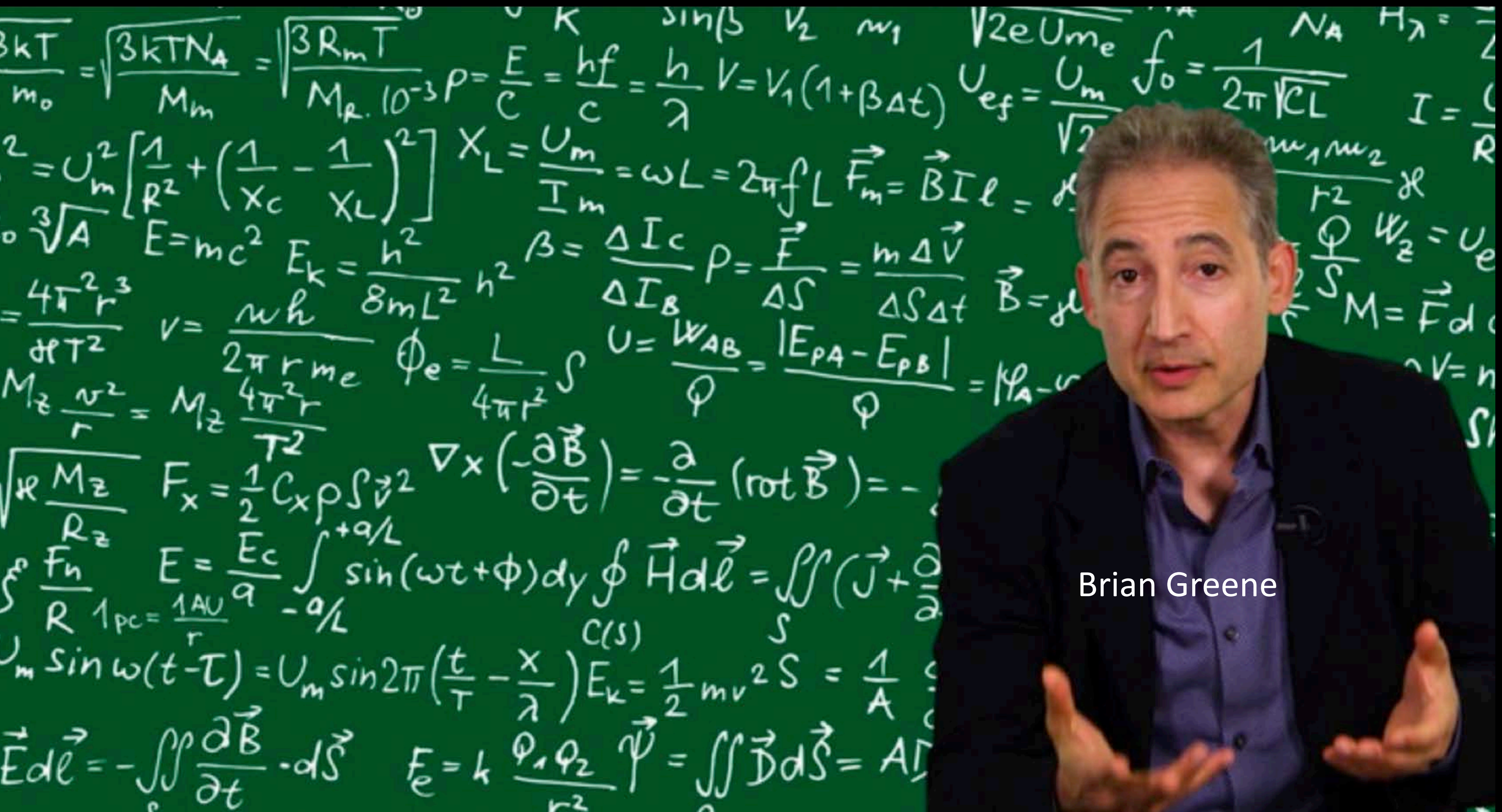

Peter Higgs 1932-

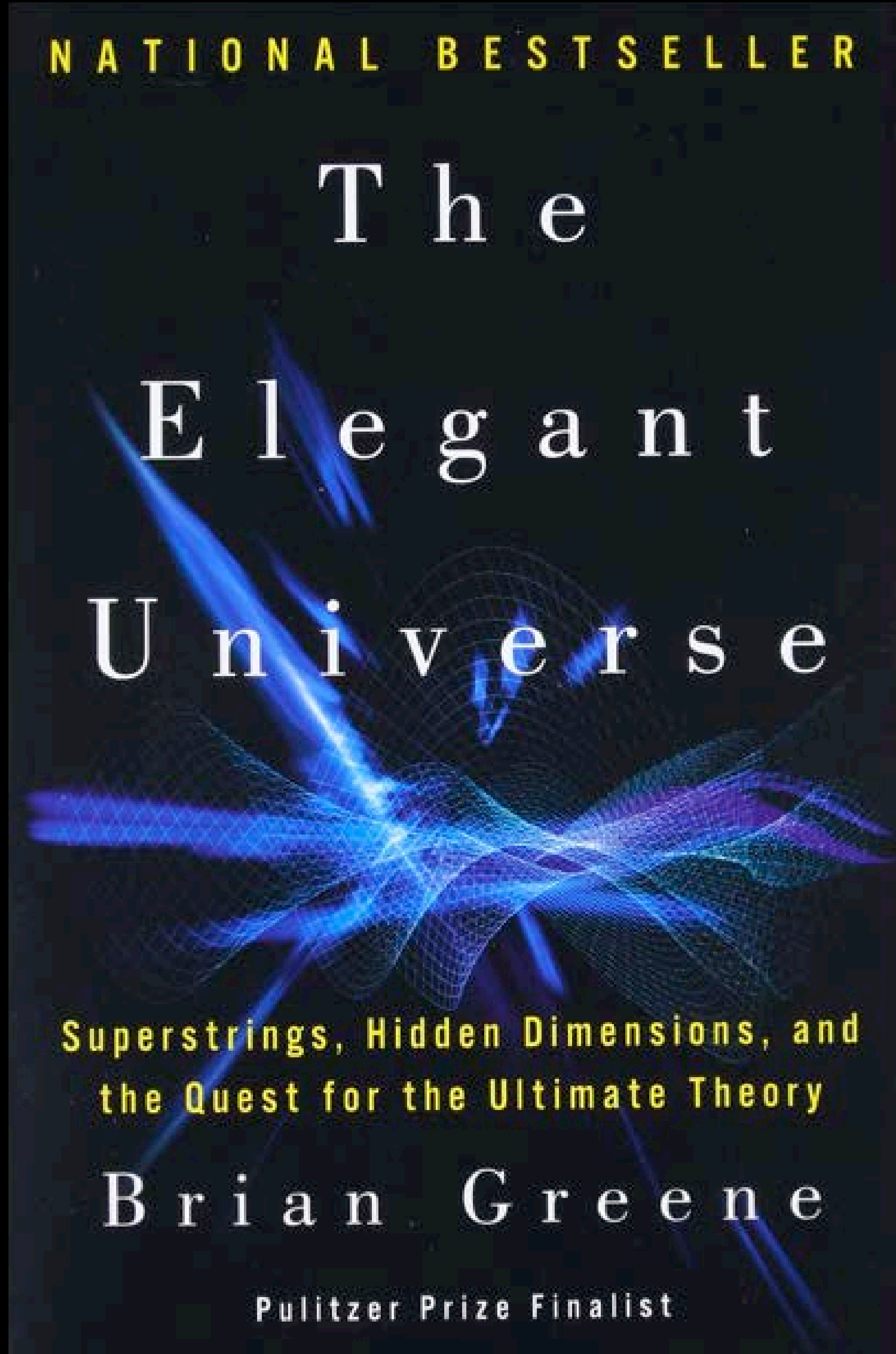
But the standard model still does not:
1) account for neutrino mass
2) include gravity
3) account for dark matter particles

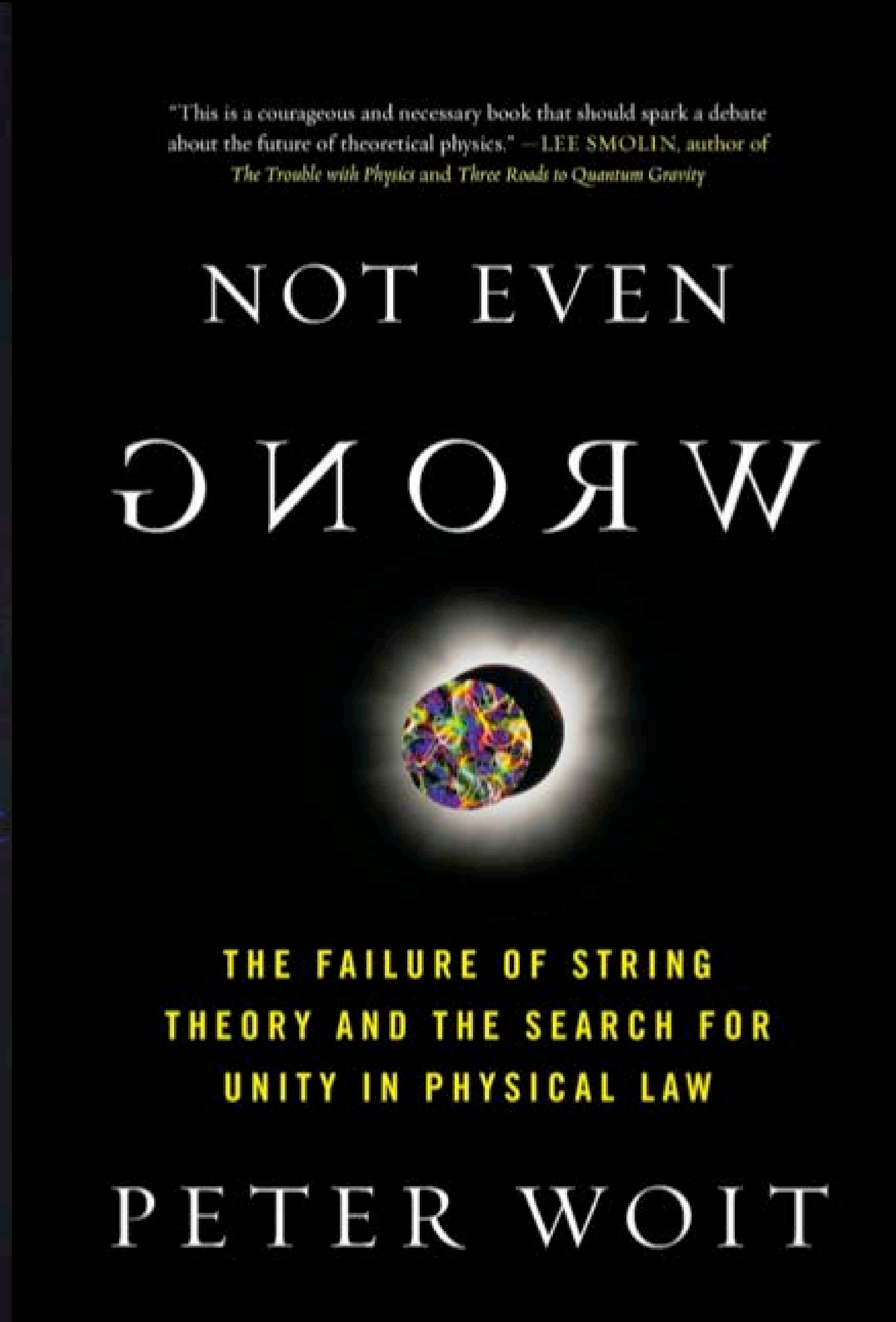
Something new is needed

STRING THEORY






NATIONAL BESTSELLER
The Elegant Universe
Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory
Brian Greene
Pulitzer Prize Finalist


"This is a courageous and necessary book that should spark a debate about the future of theoretical physics." — LEE SMOLIN, author of The Trouble with Physics and Three Roads to Quantum Gravity
NOT EVEN WRONG
THE FAILURE OF STRING THEORY AND THE SEARCH FOR UNITY IN PHYSICAL LAW
PETER WOIT

We have made enormous advances
But the ultimate theory eludes us

how to proceed? give us more funding for ever larger telescopes or particle colliders? Or are we reaching the limit?

WFIRST (100 X Hubble) is approximately the cost of half an aircraft carrier
and just cancelled by DJT