Physics 2D Lecture Slides
Oct 13

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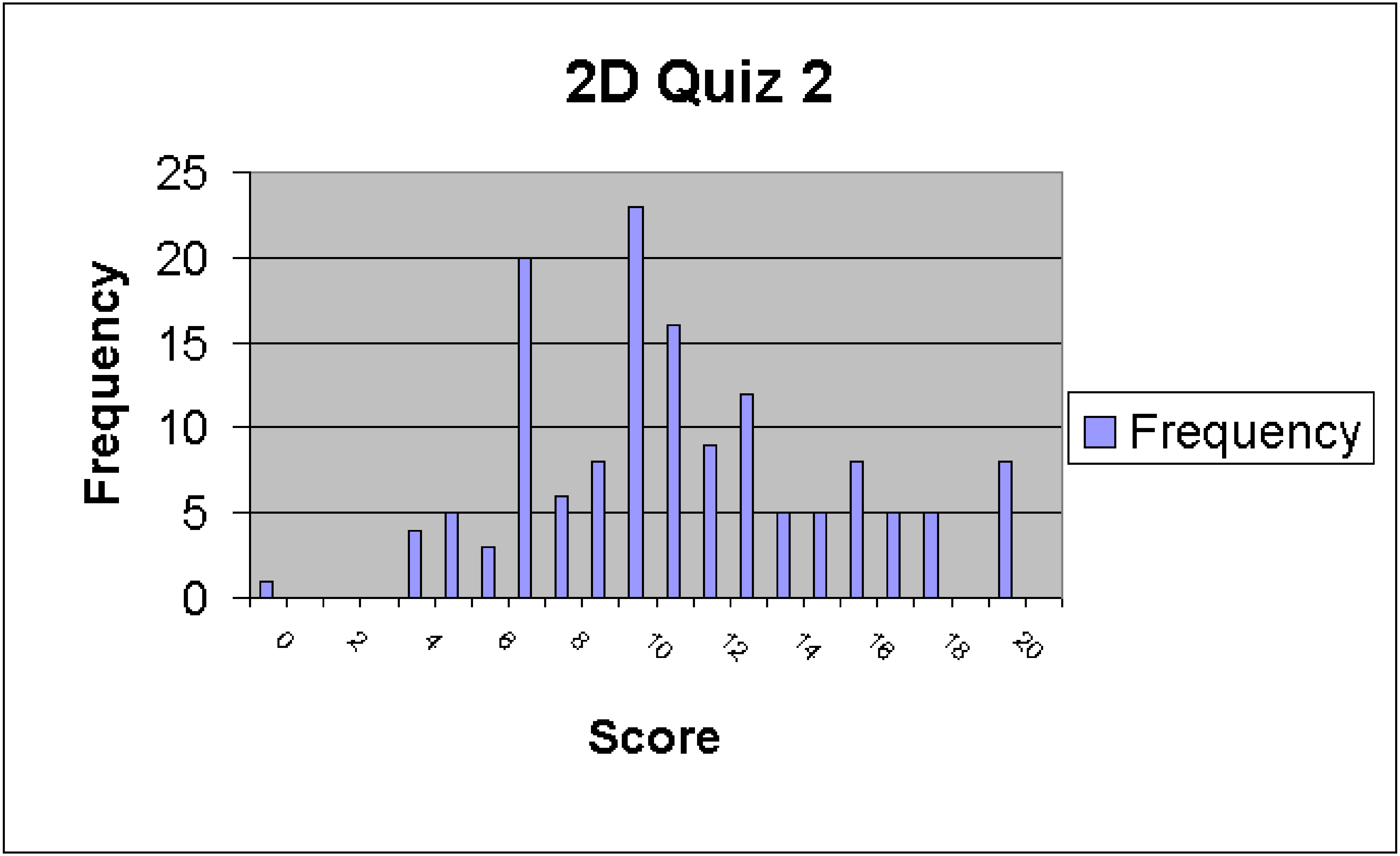
2D Quiz 2
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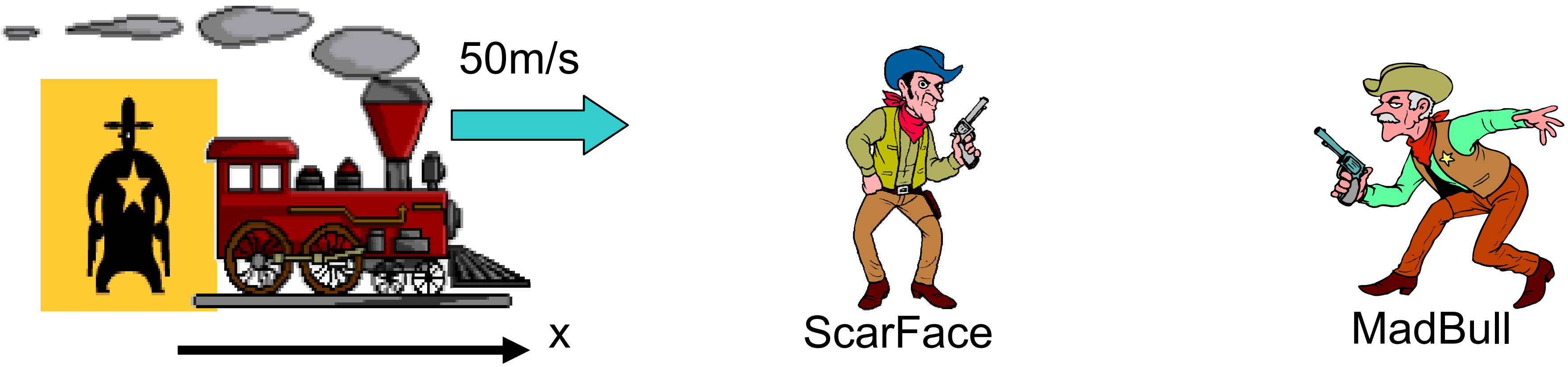
Quiz 2 : Wild Wild West got a Bit too wild



In the old west, a sheriff riding on a train traveling 50m/s sees a shootout between two bandits standing on the earth 50m apart parallel to the train. The sheriff's instruments indicate that in his reference frame the two men fired simultaneously.

(a) Which of the two bandits, the first one the train passes from the left (ScarFace) or the second one (MadBull) sould be arrested for firing the first shot?

(b) how much earlier did he fire? (c) who was struck first?

Hint: Deduce your answers from the Lorentz transformation rules.

Relativistic Kinetic Energy & Newtonian Physics

Relativistic KE = $\gamma mc^2 - mc^2$

When $u \ll c$, $\left[1-\frac{u^2}{c^2}\right]^{-\frac{1}{2}} \cong 1+\frac{1}{2}\frac{u^2}{c^2}+\ldots$smaller terms

so $K \cong mc^2[1+\frac{1}{2}\frac{u^2}{c^2}]-mc^2 = \frac{1}{2}mu^2$ (classical form recovered)

Total Energy of a Particle

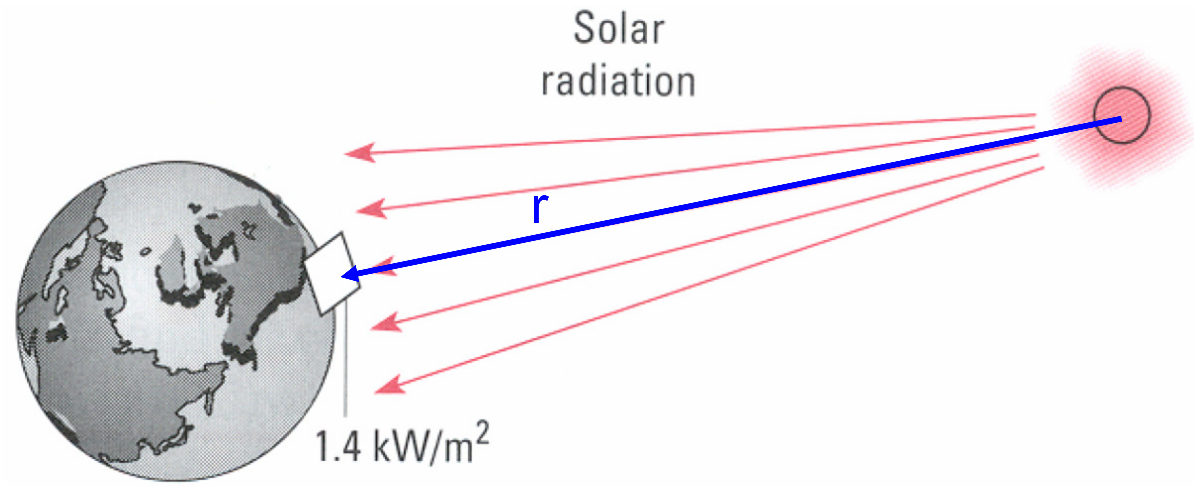
$$E = \gamma mc^2 = KE + mc^2$$

For a particle at rest, u = 0

$\Rightarrow$ Total Energy E= mc^2

Sunshine Won't Be Forever

Q: Solar Energy reaches earth at rate of 1.4kW per square meter of surface perpendicular to the direction of the sun. by how much does the mass of sun decrease per second owing to energy loss? The mean radius of the Earth's orbit is 1.5 x 10^{11}m.



- Surface area of a sphere of radius r is $A = 4\pi r^2$
- Total Power radiated by Sun = power received by a sphere whose radius is equal to earth's orbit radius

$$P = \frac{P}{A}A = \frac{P}{A}4\pi r^2 = (1.4\times10^3 W/m^2)(4\pi)(1.5\times10^{11})^2$$

$$P = 4.0\times10^{26} W$$

So Sun loses E=4.0×10^{26} J of rest energy per second

Its mass decreases by $m=\frac{E}{c^2} = \frac{4.0\times10^{26}\text{ J}}{(3.0\times10^8)^2} = 4.4\times10^9 kg$!!

If the Sun's Mass = $2.0\times10^{30} kg$ So how long with the Sun last ?

Relationship between P and E

$$E = \gamma mc^2 \Rightarrow E^2 = \gamma^2 m^2 c^4$$

$$p = \gamma mu \Rightarrow p^2 c^2 = \gamma^2 m^2 u^2 c^2$$

$$\Rightarrow E^2 - p^2 c^2 = \gamma^2 m^2 c^4 - \gamma^2 m^2 u^2 c^2 = \gamma^2 m^2 c^2 (c^2 - u^2)$$

$$= \frac{m^2 c^2}{1 - \frac{u^2}{c^2}} (c^2 - u^2) = \frac{m^2 c^4}{c^2 - u^2} (c^2 - u^2) = m^2 c^4$$

$$E^2 = p^2 c^2 + (mc^2)^2$$ ....important relation

For particles with zero rest mass like photon (EM waves)

$$E = pc \text{ or } p = \frac{E}{c}$$ (light has momentum!)

Relativistic Invariance : $E^2 - p^2 c^2 = m^2 c^4$: In all Ref Frames

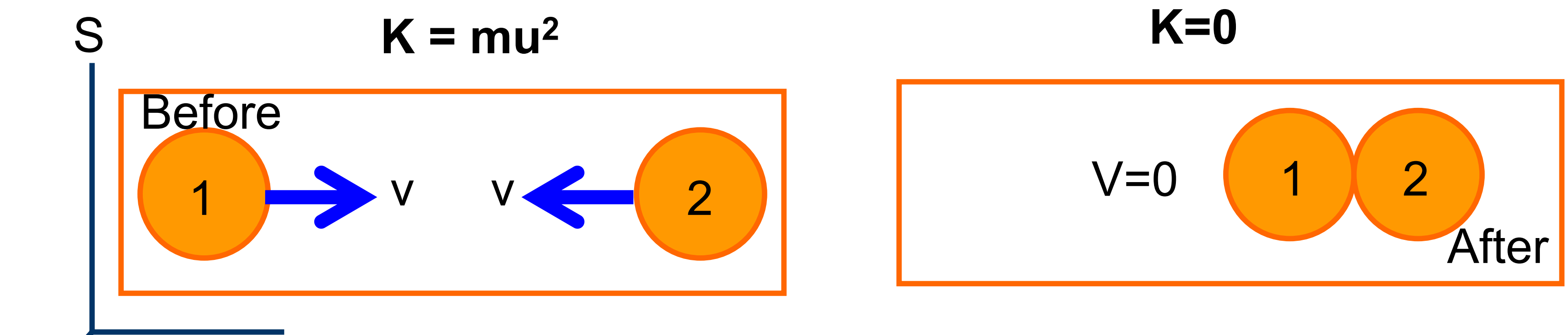
Rest Mass is a "finger print" of the particle

Mass Can “Morph” into Energy & Vice Verca

- Unlike in Newtonian mechanics
- In relativistic physics : Mass and Energy are the same thing
- New word/concept : Mass-Energy , just like spacetime
- It is the mass-energy that is always conserved in every reaction : Before & After a reaction has happened
- Like squeezing a balloon :
  - **If you squeeze mass, it becomes (kinetic) energy & vice verca !**
    - **CONVERSION FACTOR = C^2**
    - **This exchange rate never changes !**

Mass is Energy, Energy is Mass : Mass-Energy Conservation

Examine Kinetic energy Before and After Inelastic Collision: Conserved?



Mass-Energy Conservation: sum of mass-energy of a system of particles before interaction must equal sum of mass-energy after interaction

$$E_{before} = E_{after}$$

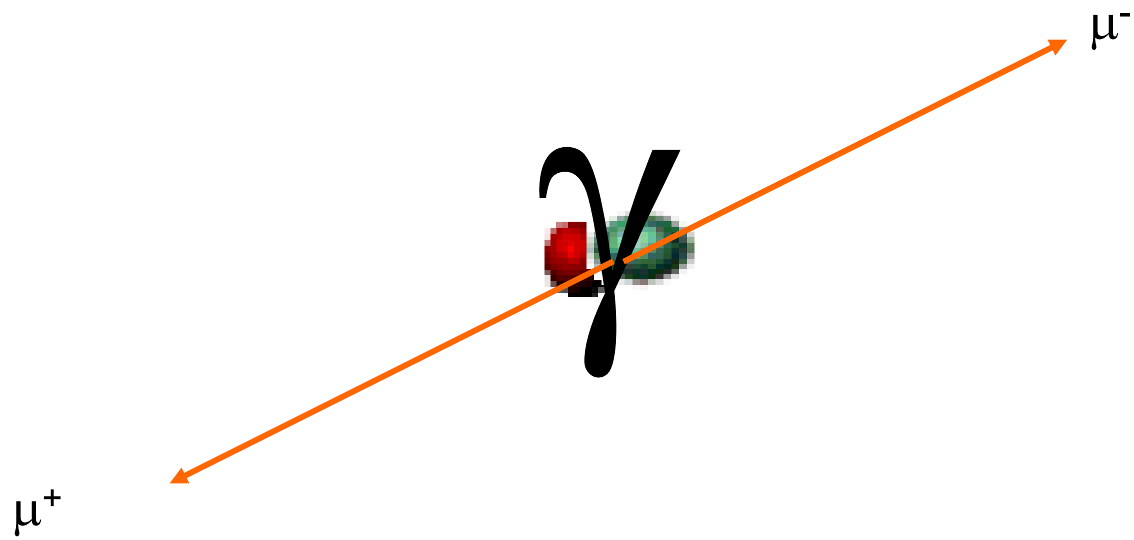
$$\frac{mc^2}{\sqrt{1-\frac{u^2}{c^2}}} + \frac{mc^2}{\sqrt{1-\frac{u^2}{c^2}}} = Mc^2 \Rightarrow M = \frac{2m}{\sqrt{1-\frac{u^2}{c^2}}} > 2m$$

Kinetic energy has been transformed into mass increase

$$\Delta M = M - 2m = \frac{2K}{c^2} = \frac{2}{c^2}\left(\frac{mc^2}{\sqrt{1-\frac{u^2}{c^2}}} - mc^2\right)$$

Kinetic energy is not lost, its transformed into more mass in final state

Creation and Annihilation of Particles

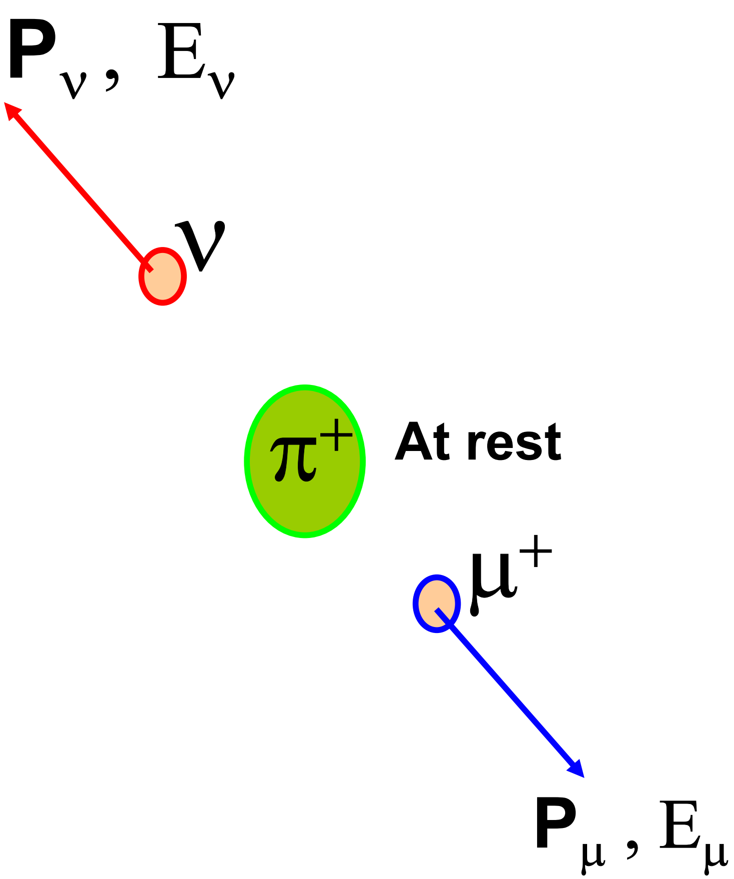


Sequence of events in a matter-antimatter collision:

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

Relativistic Kinematics of Subatomic Particles

Reconstructing Decay of a π Meson



The decay of a stationary $\pi^+ \to \mu^+ \upsilon$ happens quickly,

υ is invisible, has m $\cong 0$; μ^+ leaves a trace in a B field

μ^+ mass=106 MeV/c^2, KE = 4.6 MeV

What was mass of the fleeting π^+?

Energy Conservation:

$$\mathrm{E}_\pi = E_\mu + E_\nu \;\Rightarrow\; \mathrm{m}_\pi c^2 = \sqrt{(m_\mu c^2)^2 + p_\mu^2 c^2} + p_\upsilon c$$

Momentum Conservation : $p_\mu = p_\nu$

$$\Rightarrow m_\pi c^2 = \sqrt{(m_\mu c^2)^2 + p_\mu^2 c^2} + p_\mu c$$

$$also\; p_\mu^2 c^2 = E_\mu^2 - (m_\mu c^2)^2 = (K_\mu + m_\mu c^2)^2 - (m_\mu c^2)^2$$

$$= K_\mu^2 + 2K_\mu m_\mu c^2$$

Substituting for $p_\mu^2 c^2 \Rightarrow$

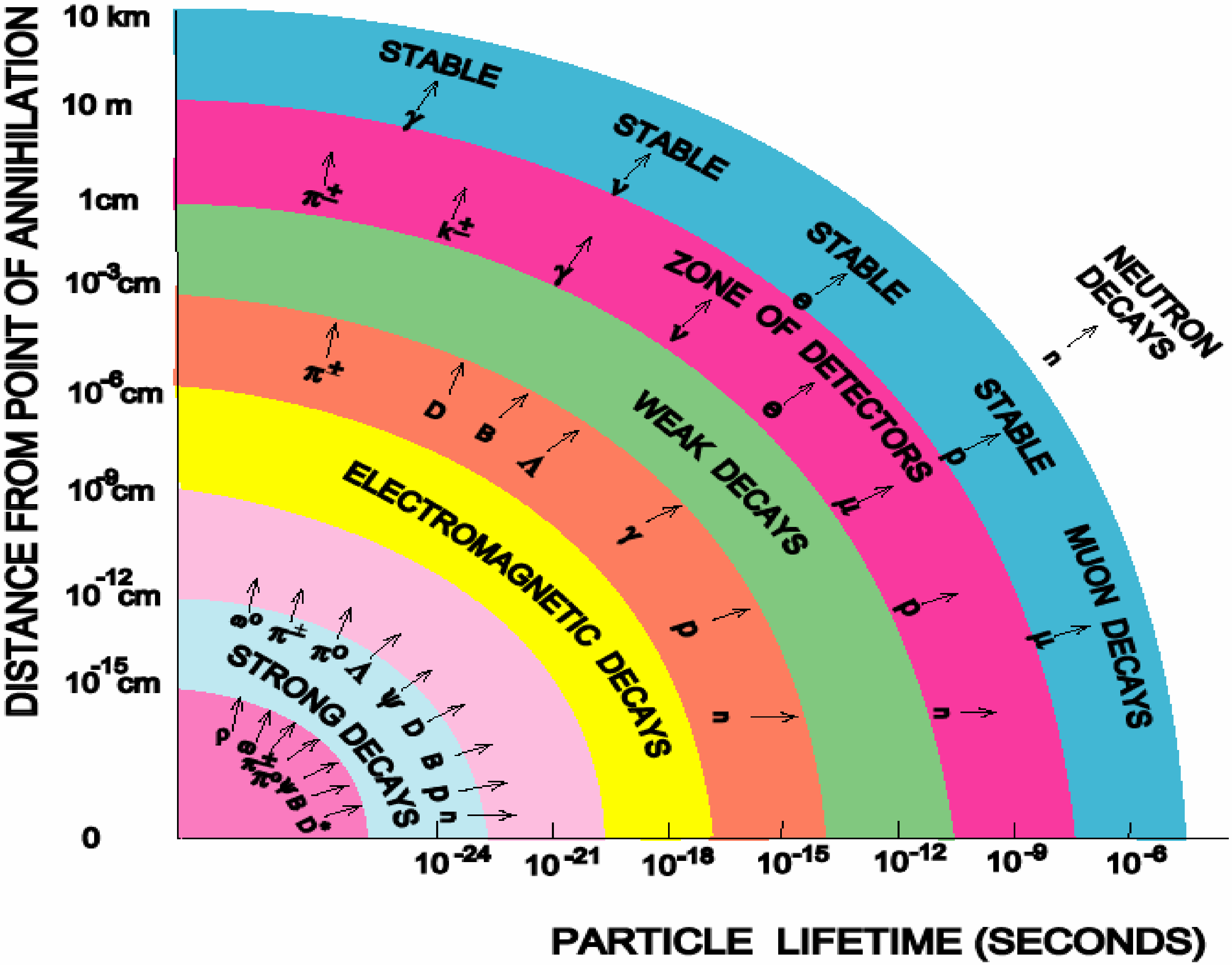
$$\mathrm{m}_\pi c^2 = \sqrt{m_\mu^2 c^4 + K_\mu^2 + 2K_\mu m_\mu c^2} + \sqrt{K_\mu^2 + 2K_\mu m_\mu c^2}$$

Put in all the known #s

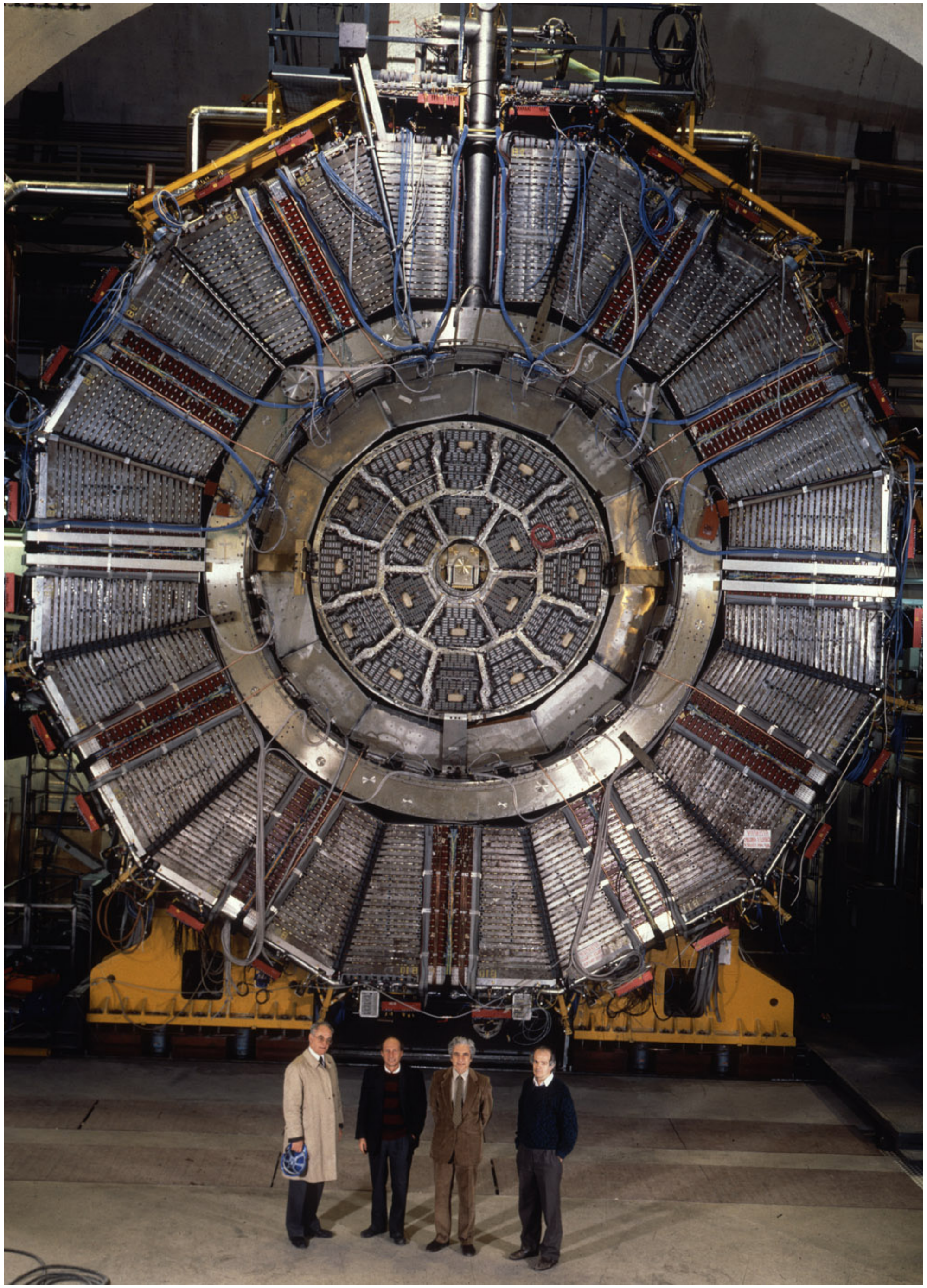
$$\Rightarrow m_\pi c^2 = 111 MeV + 31 MeV = 141 MeV$$

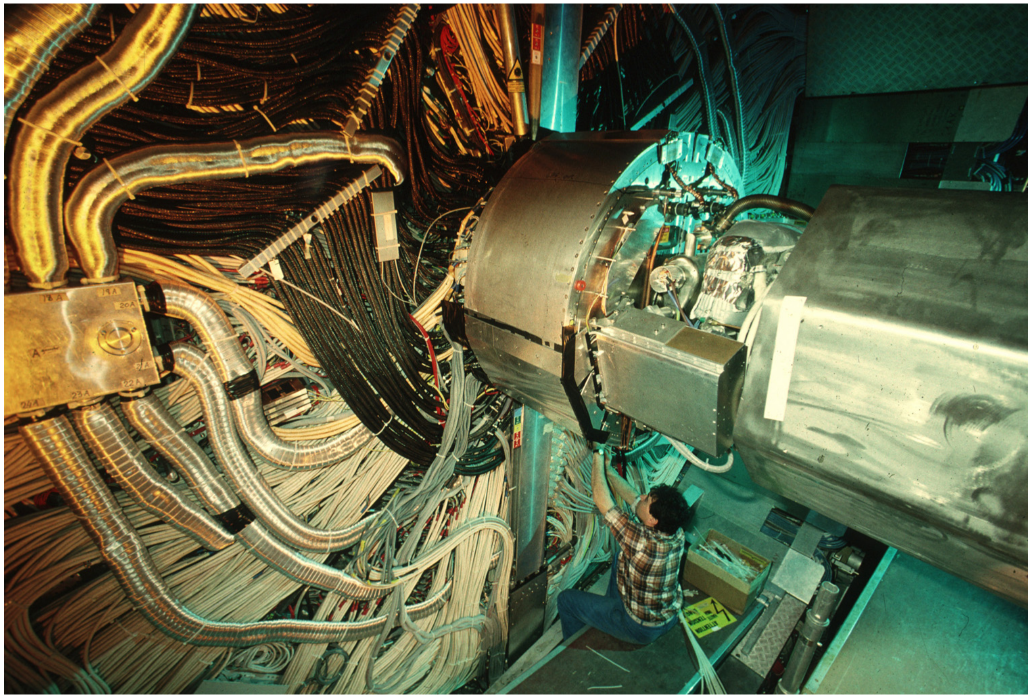
$$\Rightarrow m_\pi = 141 MeV / c^2$$

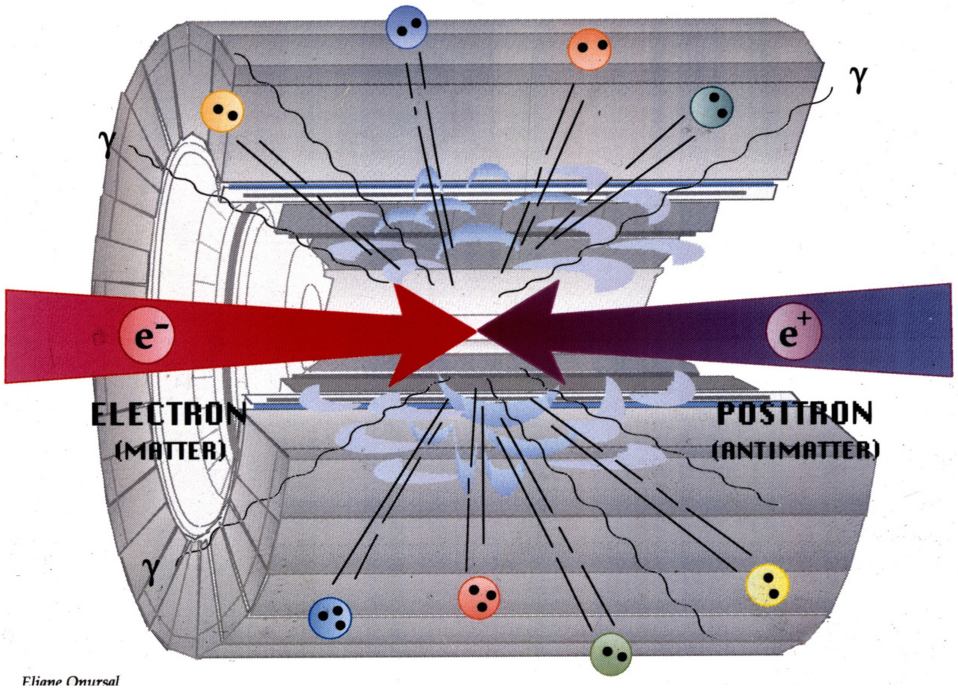
THE SEQUENCE OF PARTICLE DECAY FOLLOWING e^+e^- ANNIHILATION



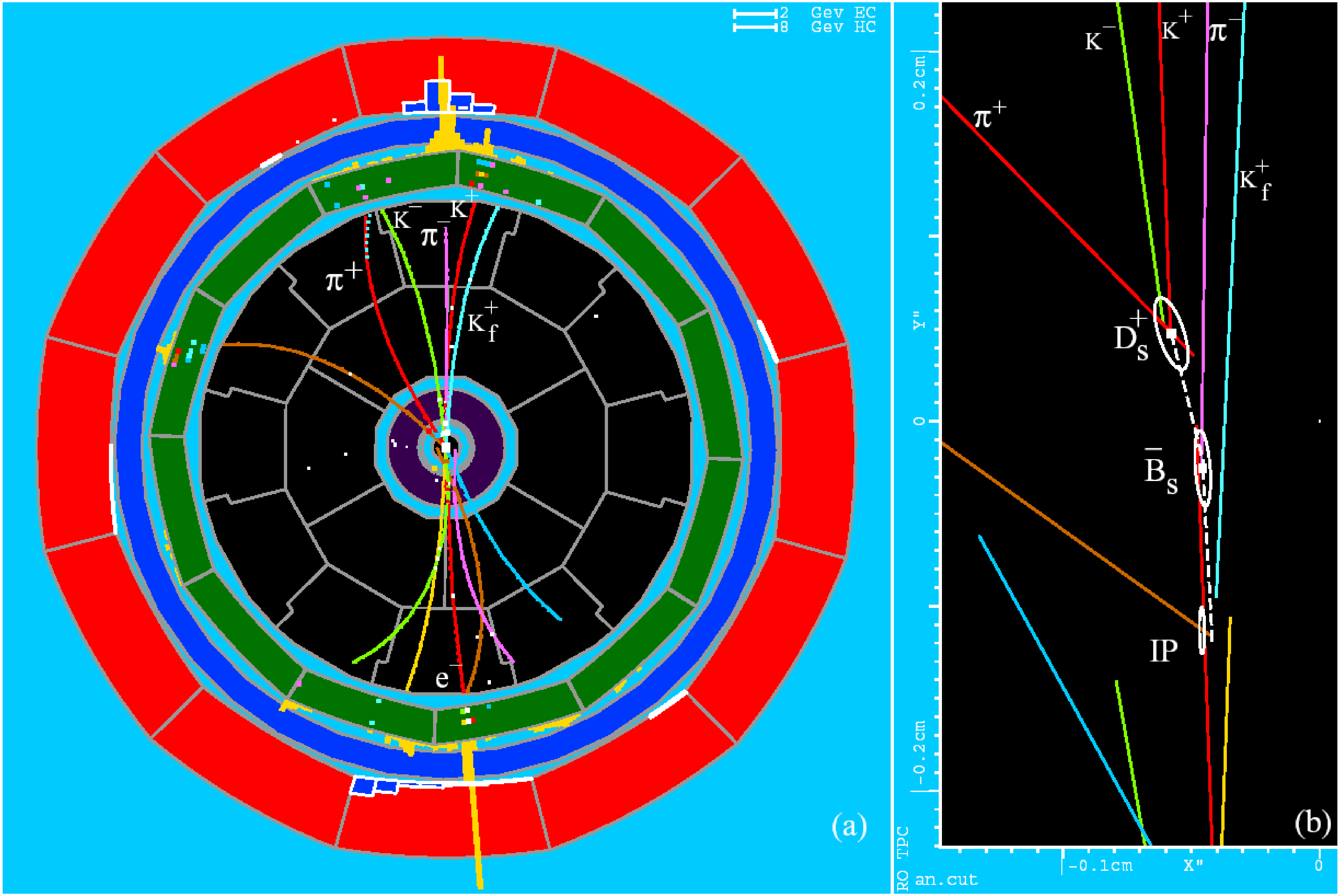
Detecting Baby Universes : Need a "Camera"







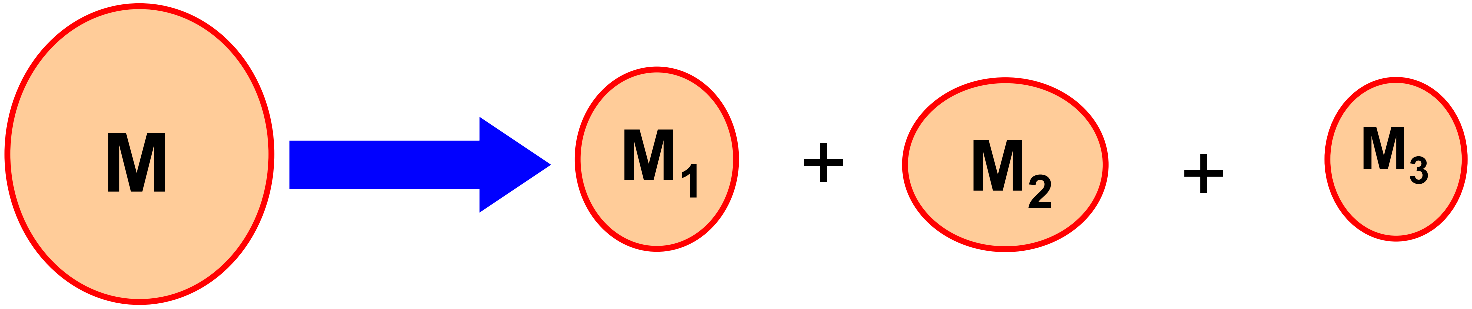
My Discovery (1993): Beauty With Strangeness



Two Faced Particle : Beauty With Strangeness (Bs)

Sometimes Matter
Sometimes Antimatter

Conservation of Mass-Energy: Nuclear Fission



Nuclear Fission

$$Mc^2 = \frac{M_1 c^2}{\underbrace{\sqrt{1-\frac{u_1^2}{c^2}}}_{<1}} + \frac{M_2 c^2}{\underbrace{\sqrt{1-\frac{u_2^2}{c^2}}}_{<1}} + \frac{M_3 c^2}{\underbrace{\sqrt{1-\frac{u_3^2}{c^2}}}_{<1}} \Rightarrow M > M_1 + M_2 + M_3$$

Loss of mass shows up as kinetic energy of final state particles

Disintegration energy per fission $Q=(M-(M_1+M_2+M_3))c^2 = \Delta Mc^2$

$^{236}_{92}U \rightarrow {}^{143}_{55}Cs + {}^{90}_{92}Rb + 3\,{}^{1}_{0}n$ $\quad$ (1 AMU$= 1.6605402\times 10^{-27} kg = 931.49$ MeV)

$\Delta m = 0.177537u = 2.9471\times 10^{-28} kg = 165.4$ MeV= energy release/fission =peanuts

What makes it explosive is 1 mole of Uranium = 6.023 x 10^{23} Nuclei !!

Energy Released by 1 Kg of Fissionable Uranium

1 Mole of Uranium = 236 gm,   Avagadro"s # = 6.023×10^{23} Nuclei

So in 1 kg $N = \dfrac{6.023\times10^{23}}{236g/mole}\times1000g = 2.55\times10^{24}$ nuclei

1 Nuclear fission = 165.4 MeV $\therefore\ 10^3\ g = 2.55\times10^{24}\times165.4$ MeV

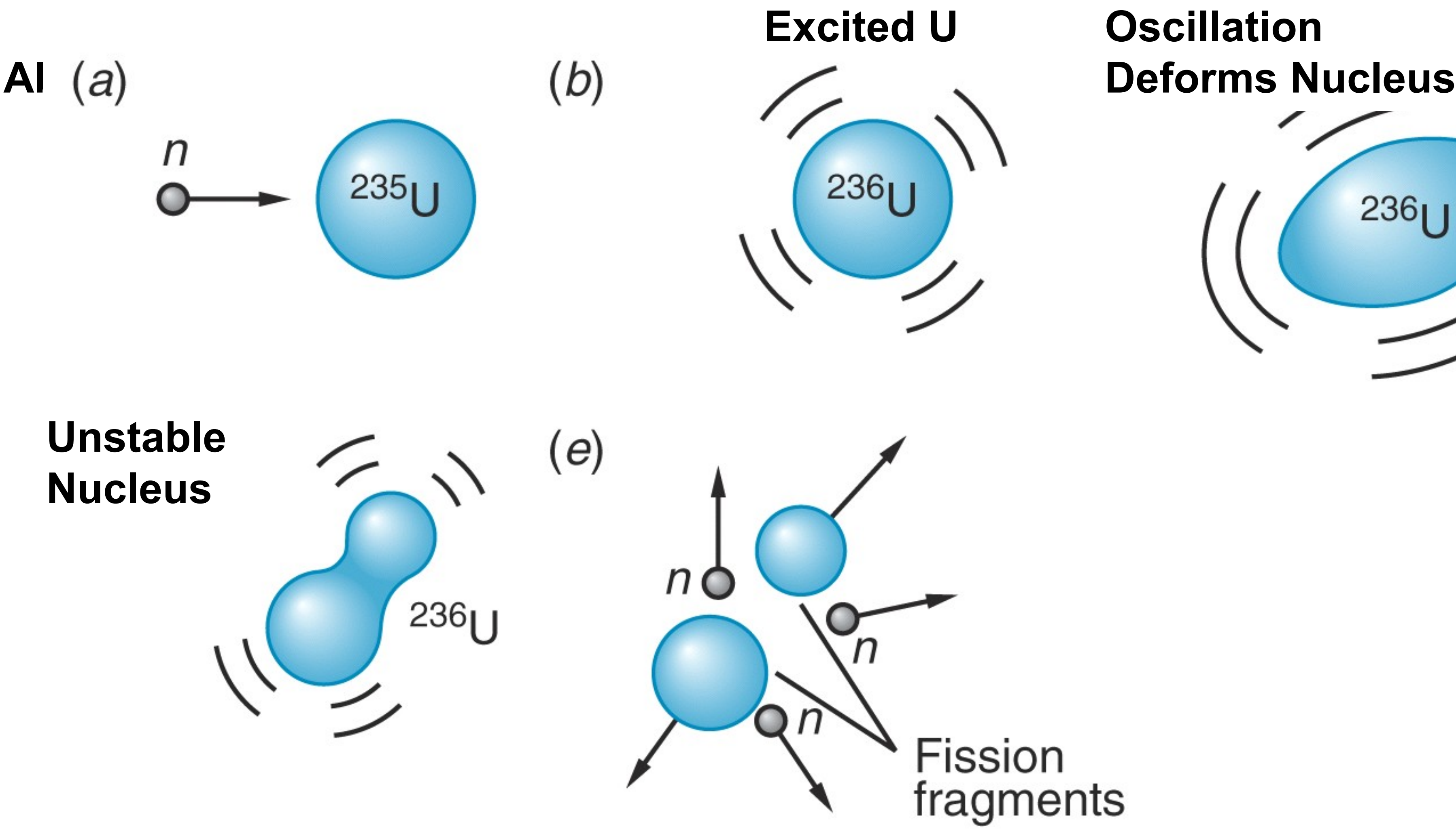
Note 1 MeV = $4.45\times10^{-20}\ kWh$

If the power plant has conversion efficiency = 40%

Energy Transformed = $748\times10^{6}\ kWh$

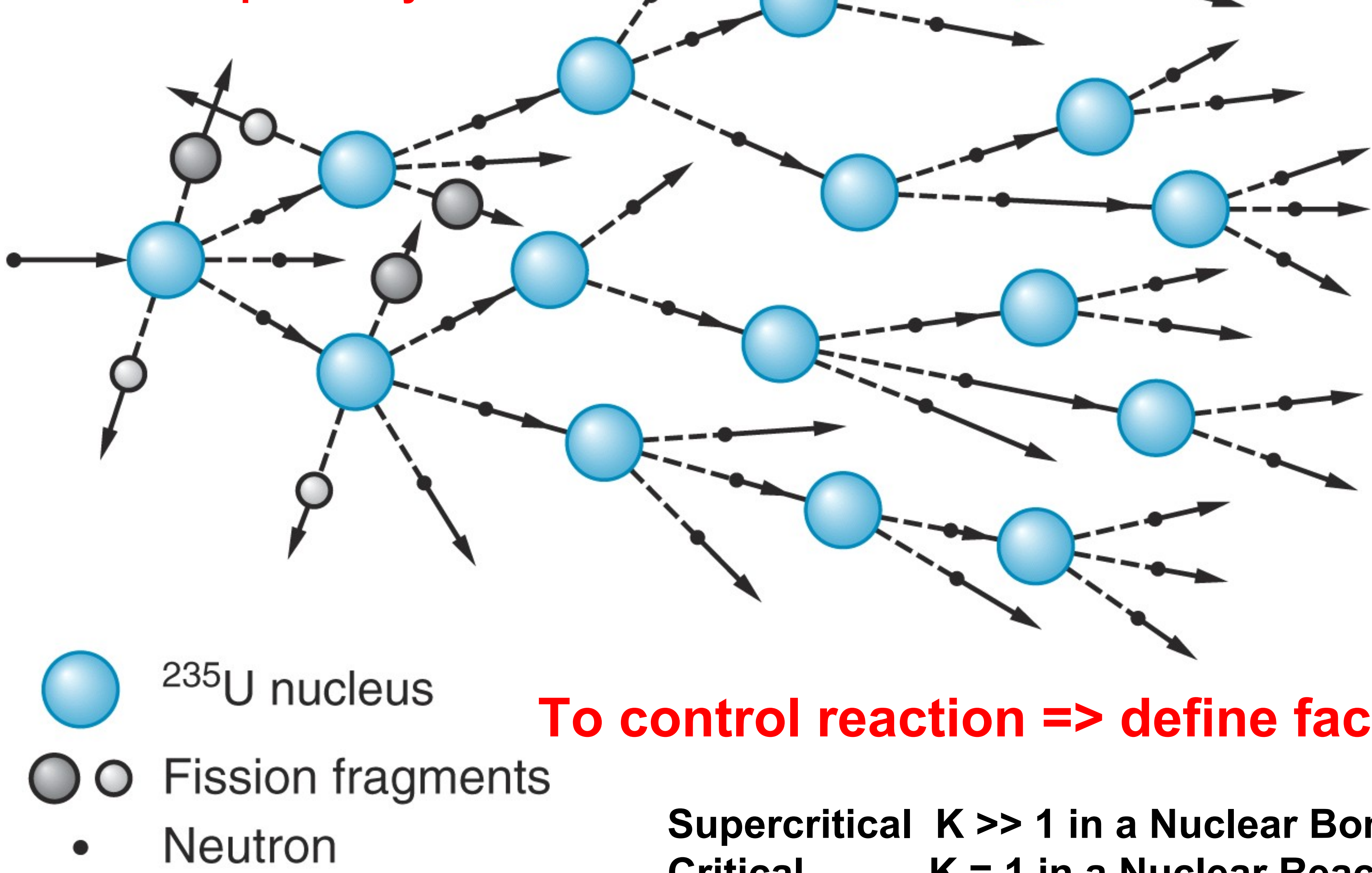
$\Rightarrow$ 1 100W lamp can be lit for 8500 years !

Nuclear Fission Schematic



Sustaining Chain Reaction: 1^{st} three Fissions

Average # of Neutrons/Fission = 2.5
Neutron emitted in fission of one U
Needs to be captured by another

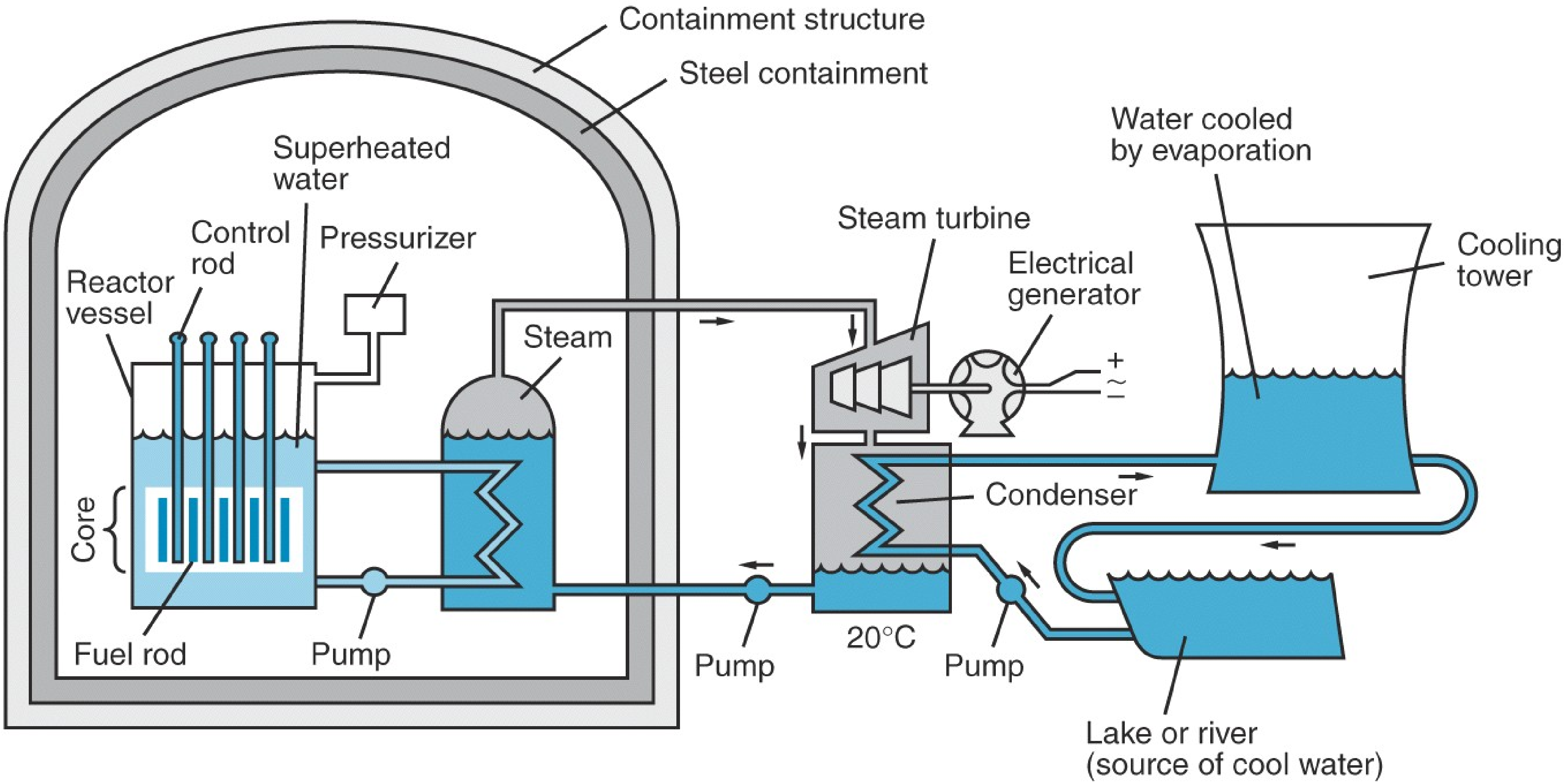


To control reaction => define factor K

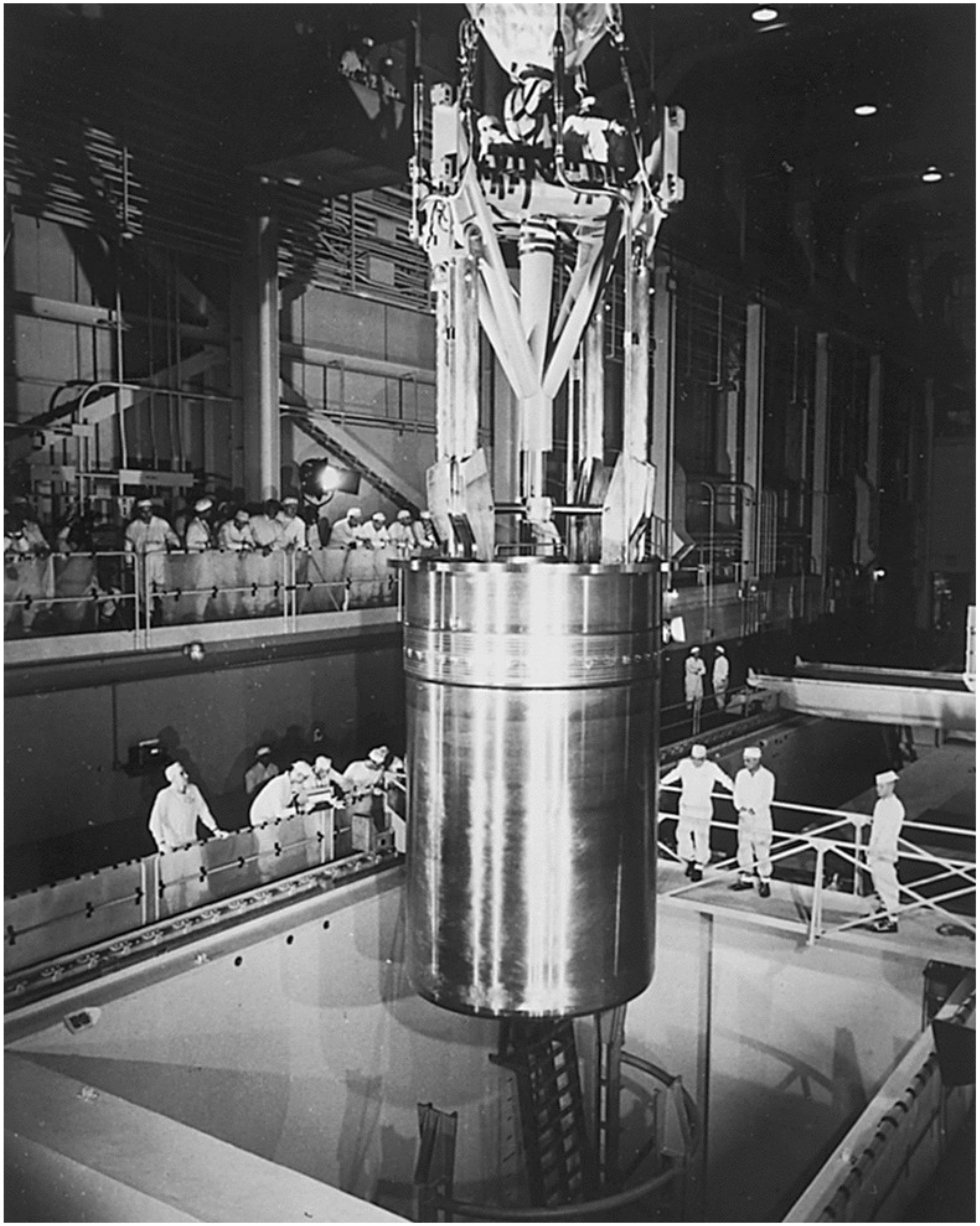
Supercritical K >> 1 in a Nuclear Bomb
Critical K = 1 in a Nuclear Reactor

Schematic of a Pressurized-Water Reactor

Water in contact with reactor core serves as a moderator and heat transfer Medium. Heat produced in fission drives turbine



Lowering Fuel Core in a Nuclear Reactor



First Nuke Reactor :Pennsylvania 1957

Pressure Vessel contains :
14 Tons of Natural Uranium
+ 165 lb of enriched Uranium

Power plant rated at 90MW, Retired (82)

Pressure vessel packed with Concrete now sits in Nuclear Waste Facility in Hanford, Washington

Nuclear Fusion : What Powers the Sun

Opposite of Fission

Mass of a Nucleus $<$ mass of its component protons+Neutrons

Nuclei are stable, bound by an attractive "Strong Force"

Think of Nuclei as molecules and proton/neutron as atoms making it

Binding Energy: Work/Energy required to pull a bound system (M) apart leaving its components (m) free of the attractive force and at rest:

$$Mc^2 + BE = \sum_{i=1}^{n} m_i c^2$$

$${}^4_2He \quad + \quad 23.9\ MeV \quad = \quad {}^2_1H \quad + \quad {}^2_1H$$

Helium — Deuterium — Deuterium

Think of energy released in Fusion as Dissociation energy in Chem

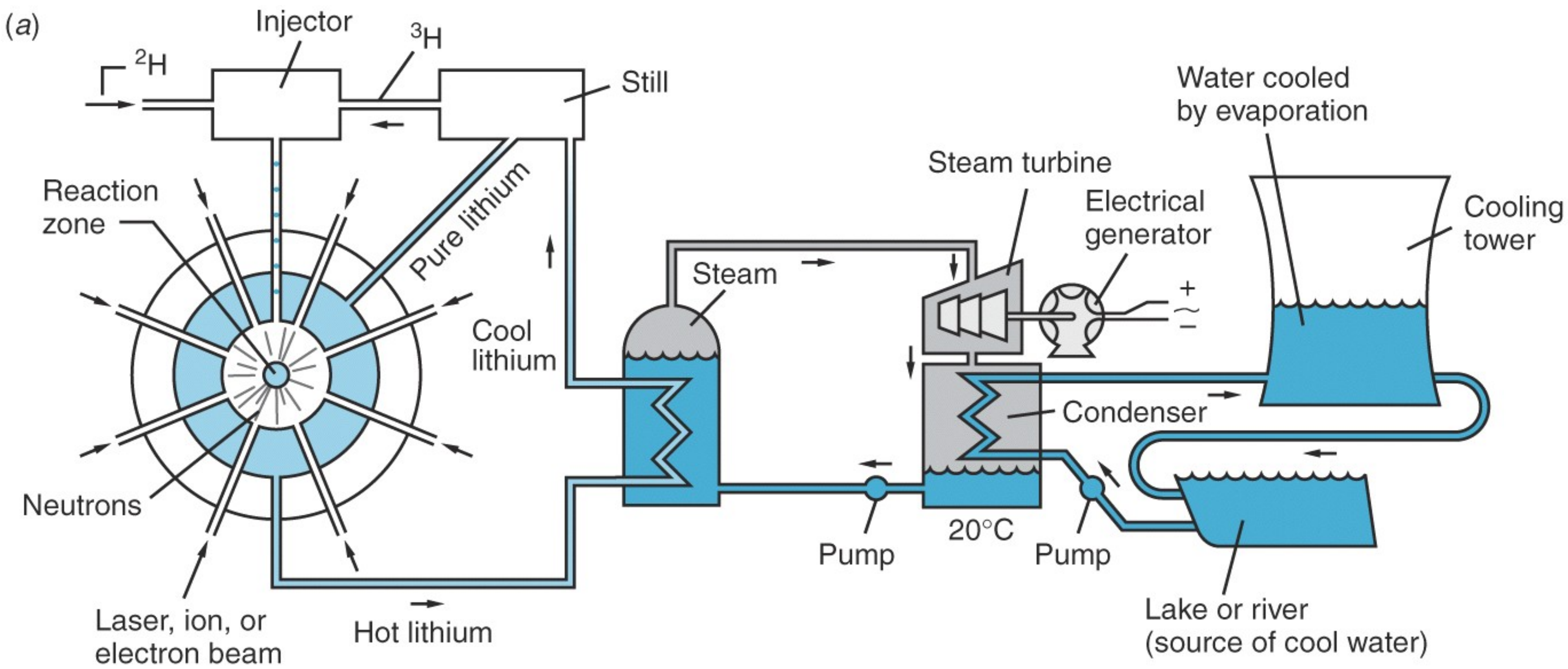
Sun's Power Output $= 4\times10^{26}$ Watts $\Rightarrow 10^{38}$ Fusion/Second

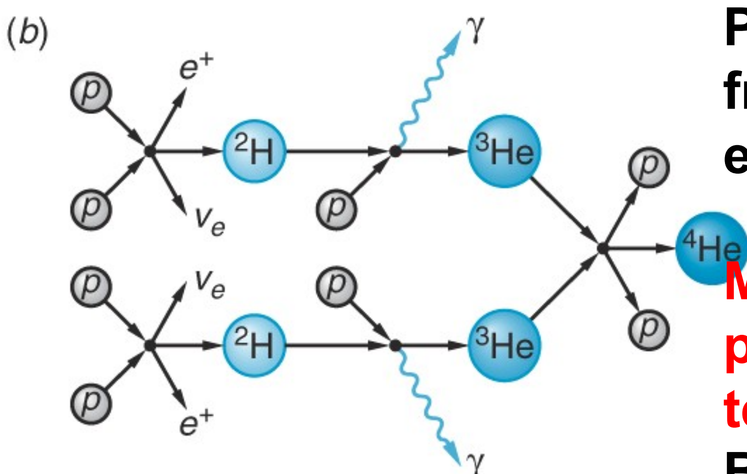
No wonder Sun is considered a God in many cultures !

Nuclear Fusion: Wishing For The Star

- Fusion is eminently desirable because
  - More Energy/Nucleon
    - (3.52 MeV in fusion Vs 1 MeV in fission)
    - $^{2}H + {}^{3}H \rightarrow {}^{4}He + n + 17.6$ MeV
  - Relatively abundant fuel supply
  - No danger like nuclear reactor going supercritical
- Unfortunately technology not commercially available
  - What's inside nuclei => protons and Neutrons
  - Need Large KE to overcome Coulomb repulsion between nuclei
    - About 1 MeV needed to bring nuclei close enough together for Strong Nuclear Attraction →fusion
    - Need to
      - heat particle to high temp such that $kT \approx 10$keV ➔ tunneling
      - High density plasma at high temp $T \approx 10^{8}$ K like in stars
      - Confine Plasma (± ions) long enough for fusion
        - » In stars, enormous gravitational field confines plasma

Inertial Fusion Reactor : Schematic





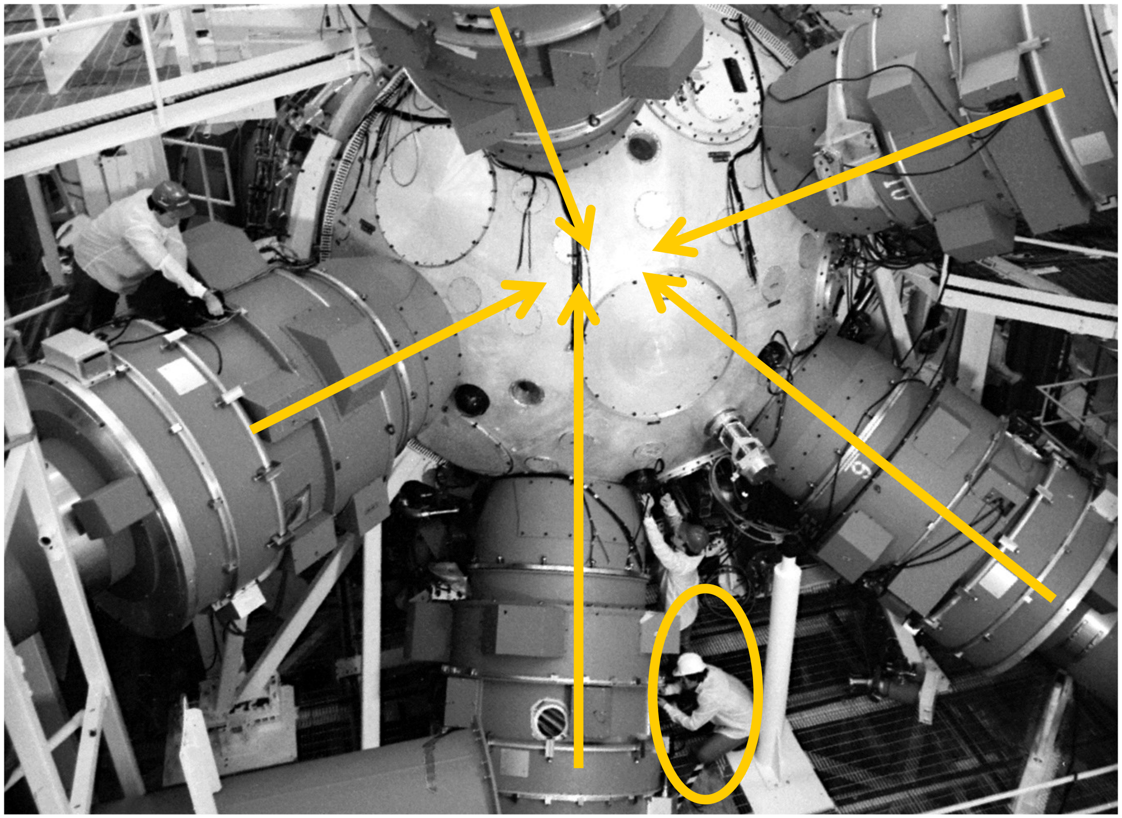
Pellet of frozen-solid Deuterium & tritium bombarded from all sides with intense pulsed laser beam with energy ≈10^6 Joules lasting 10^{-8} S

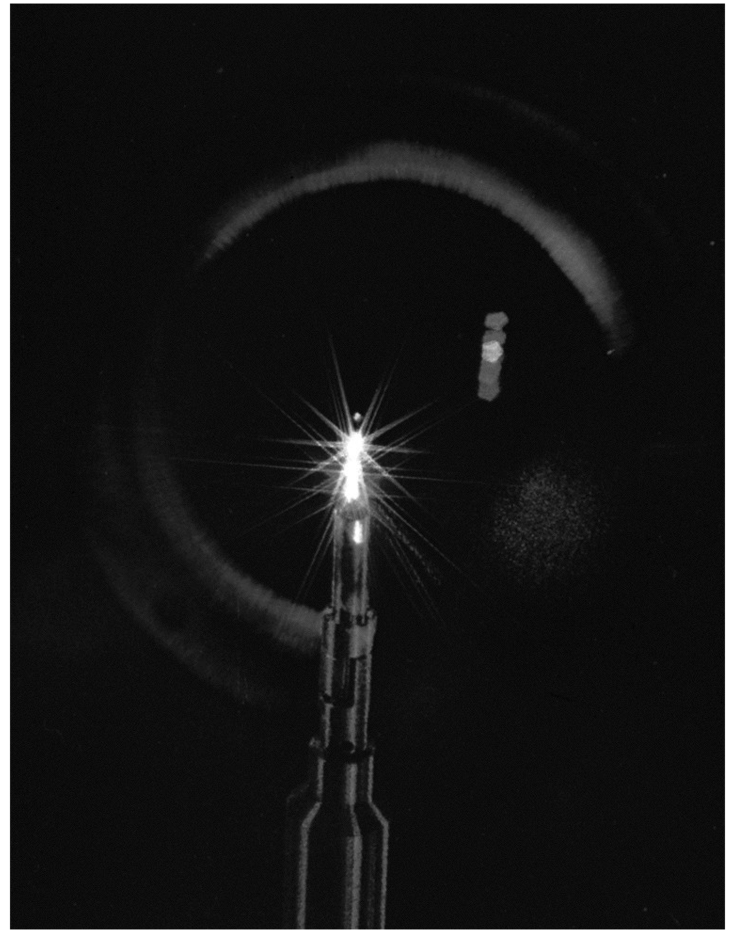
Momentum imparted by laser beam compresses pellet by 1/10000 of normal density and heats it to temp T ≈ 10^8 K for 10^{-10} S
Burst of fusion energy transported away by liquid Li

World's Most Powerful Laser : NOVA @ LLNL

Size of football field, 3 stories tall

Generates 1.0 x 10^{14} watts (100 terawatts)





10 laser beams converge onto H pellet (0.5mm diam)

Fusion reaction is visible as a starlight lasting 10^{-10} S
Releasing 10^{13} neutrons