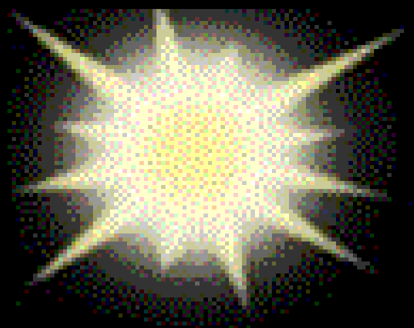
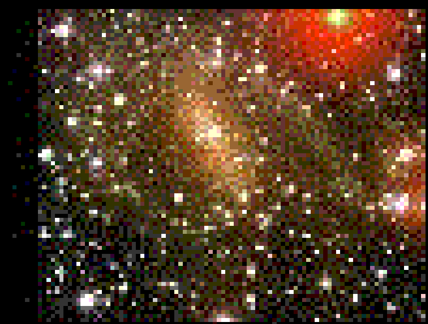
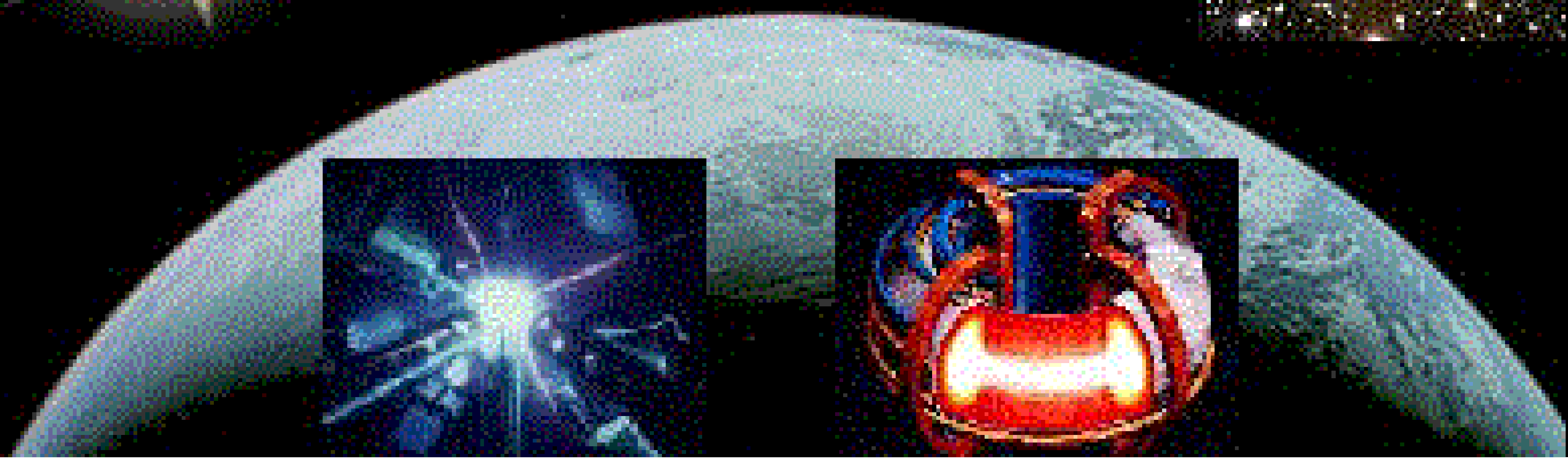
TÓPICOS EM FÍSICA DE PLASMAS

Curso de Verão do IFUSP

Alvaro Vannucci - janeiro 2002

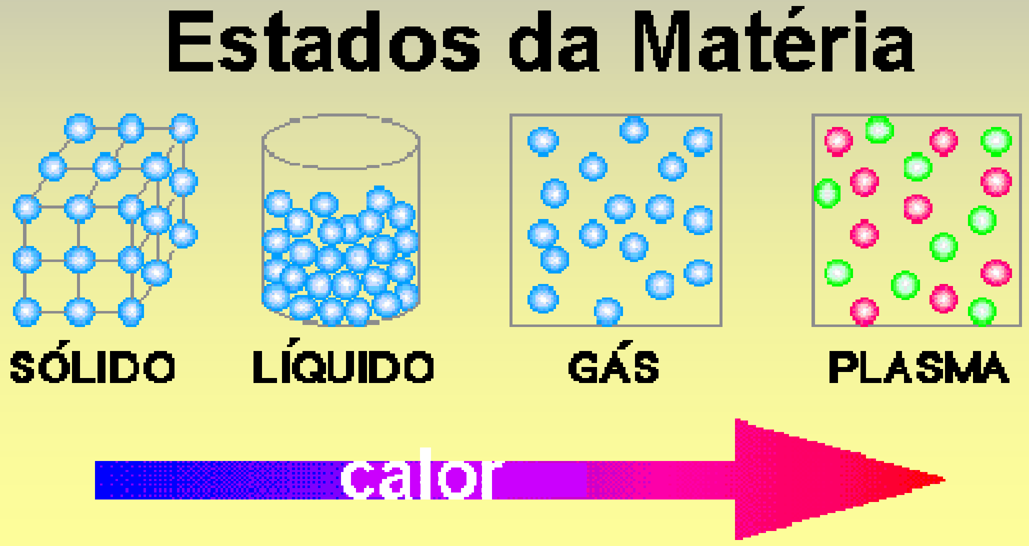




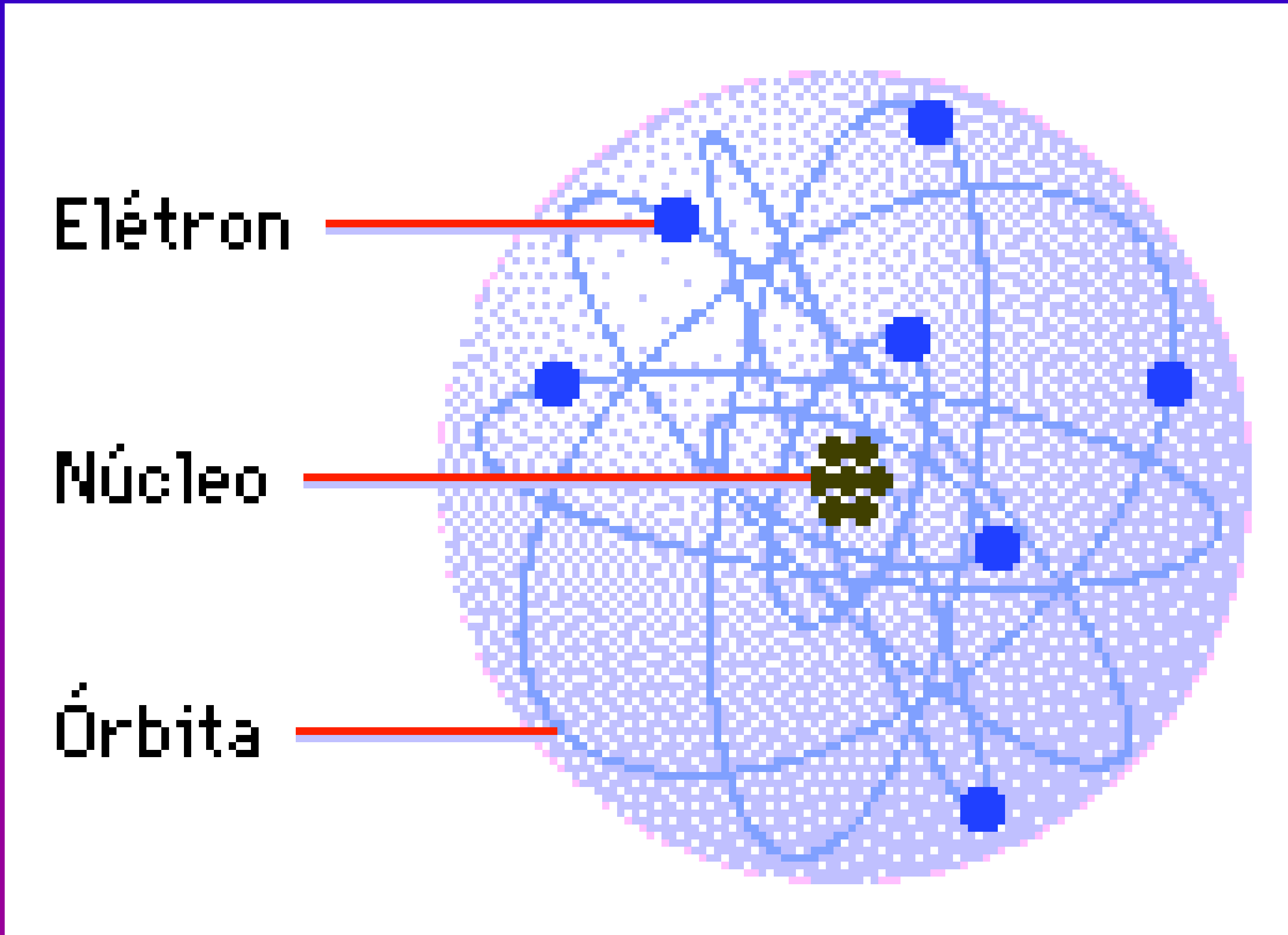


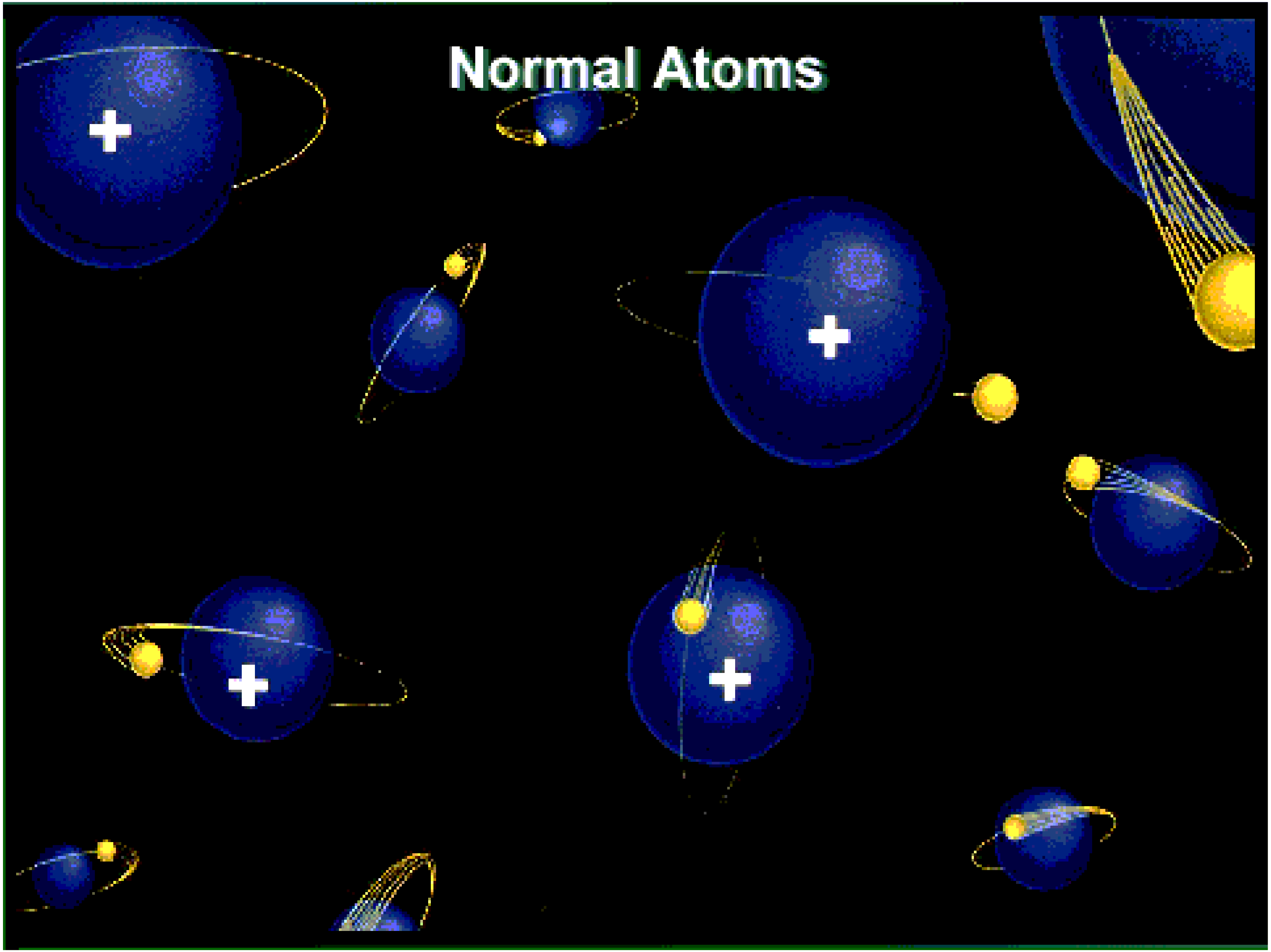
O que é Plasma?

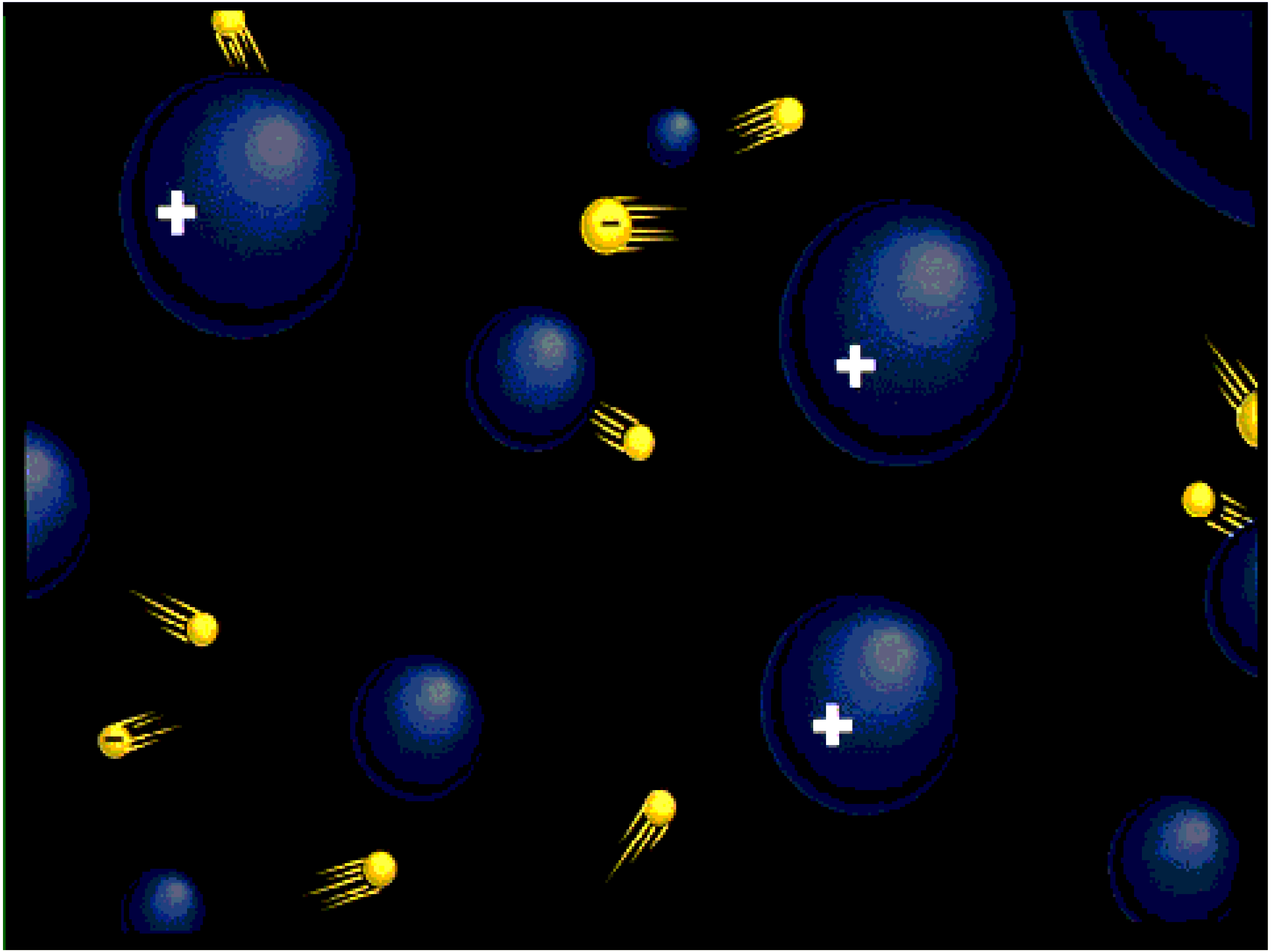
- Gás a altíssimas temperaturas (átomos ionizados)
- Número de cargas + e – aproximadamente o mesmo
- É usualmente denominado o 4º Estado da Matéria



Modelo nuclear **(clássico)**




Normal Atoms



Motivação

- Estima-se que 99% da matéria conhecida no Universo encontra-se na forma de Plasma

Lembrando que a Velocidade da Luz:

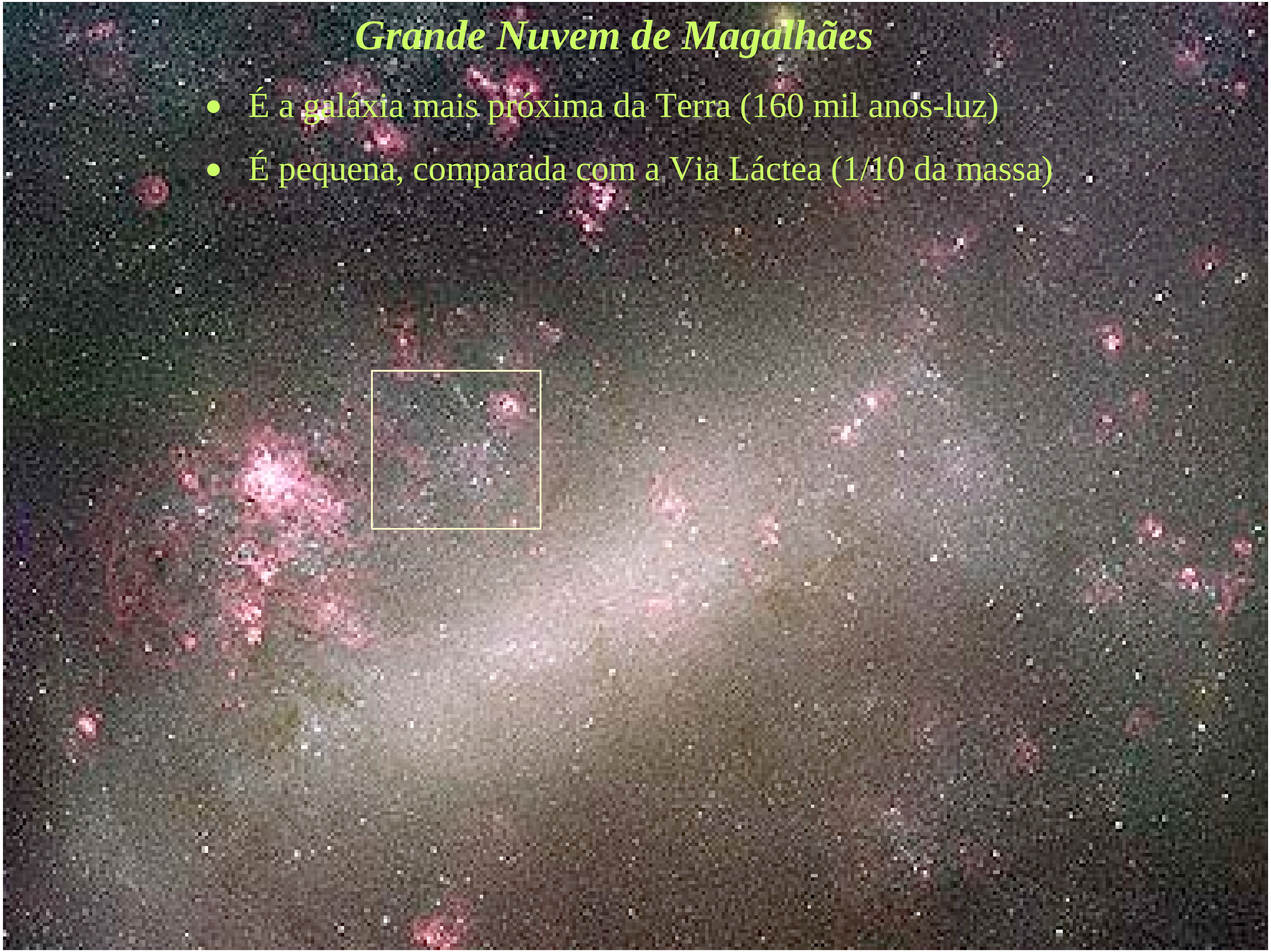
c = 300.000 km/s

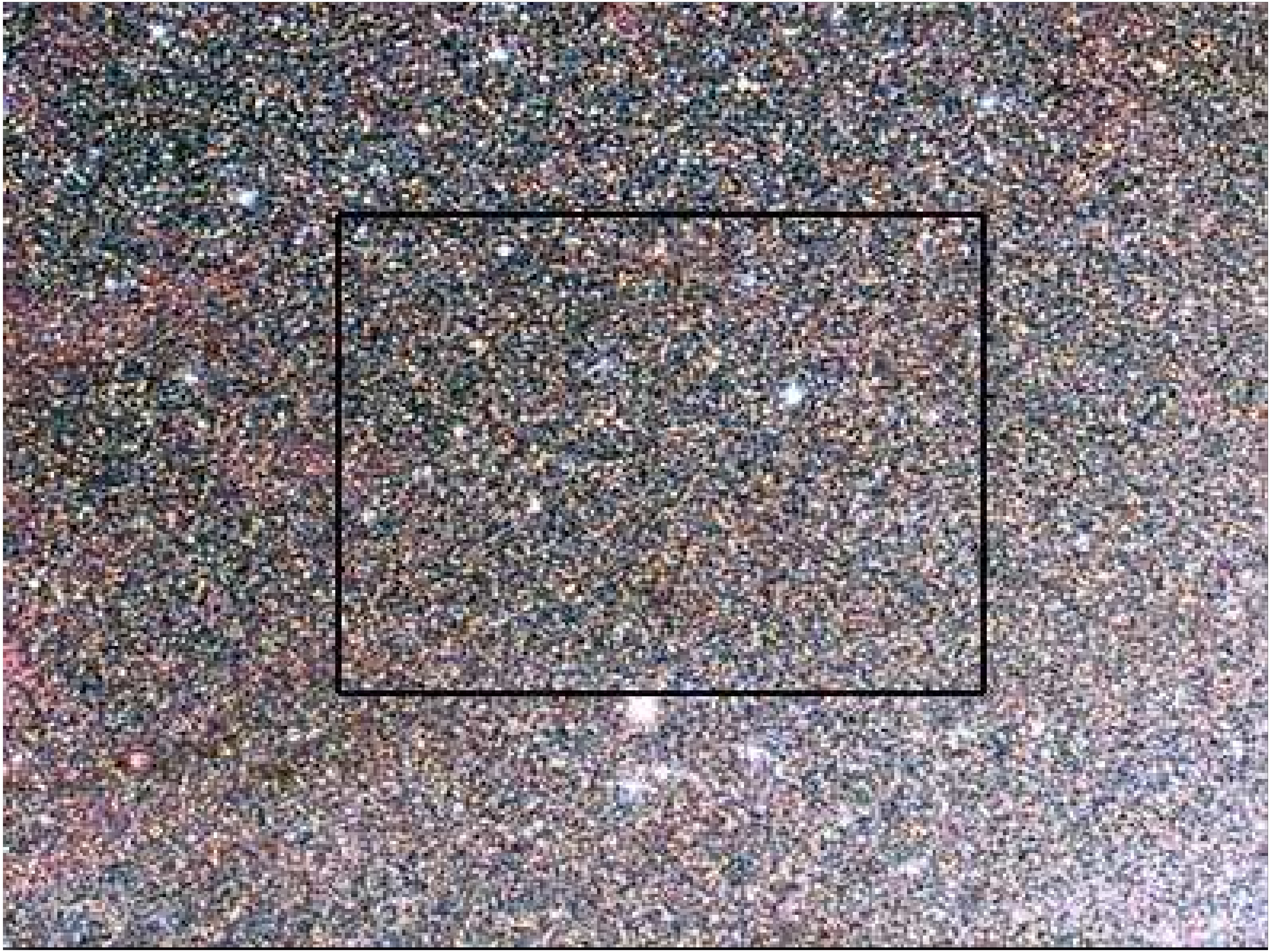
Via Láctea:

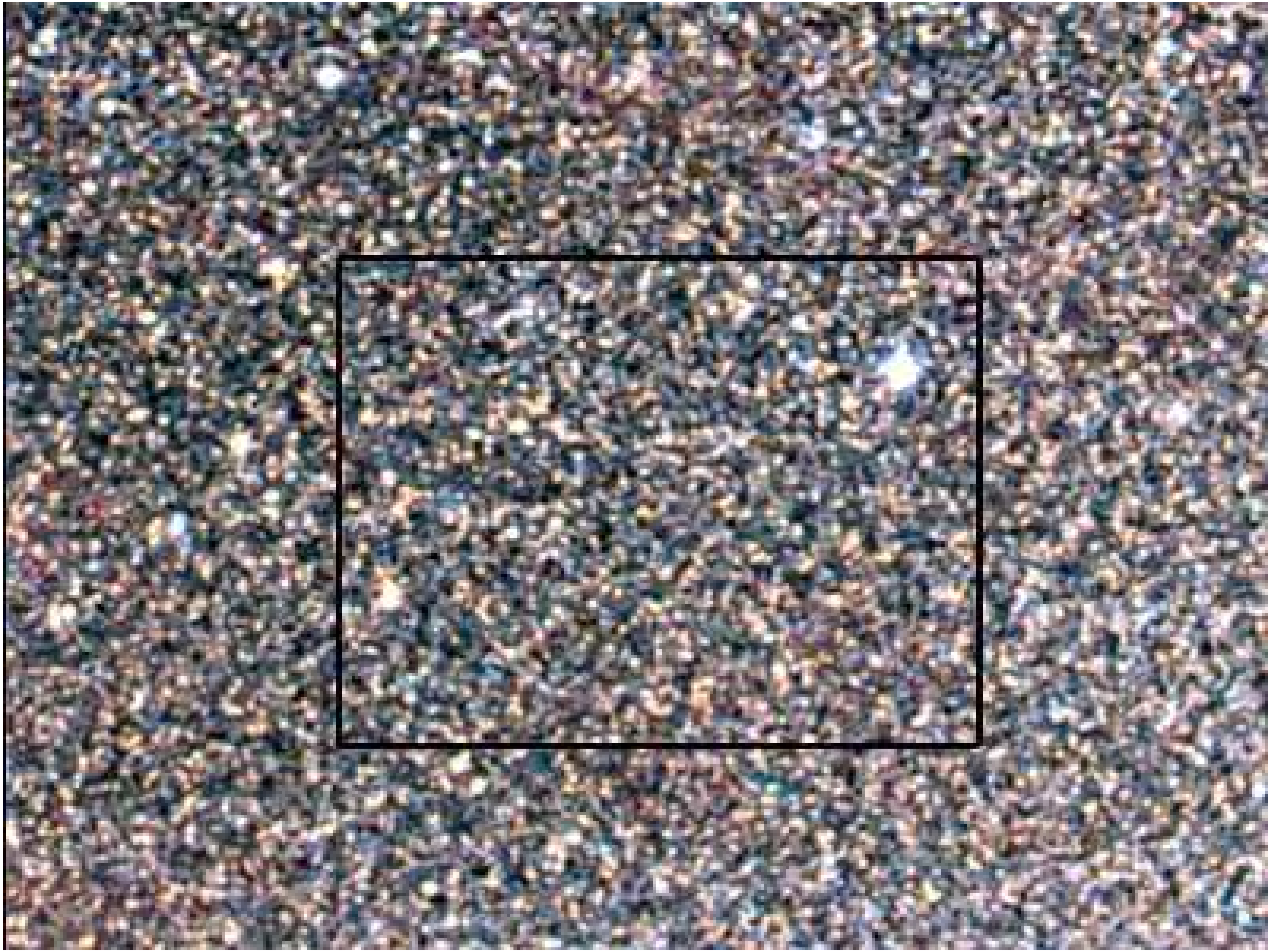
* 200 bilhões de Estrelas! - *Ainda existem?*
* 100.000 anos-luz de diâmetro.
* Sol encontra-se a 30.000 anos-luz do centro.
* Período de translação do Sol: 200 milhões de anos.

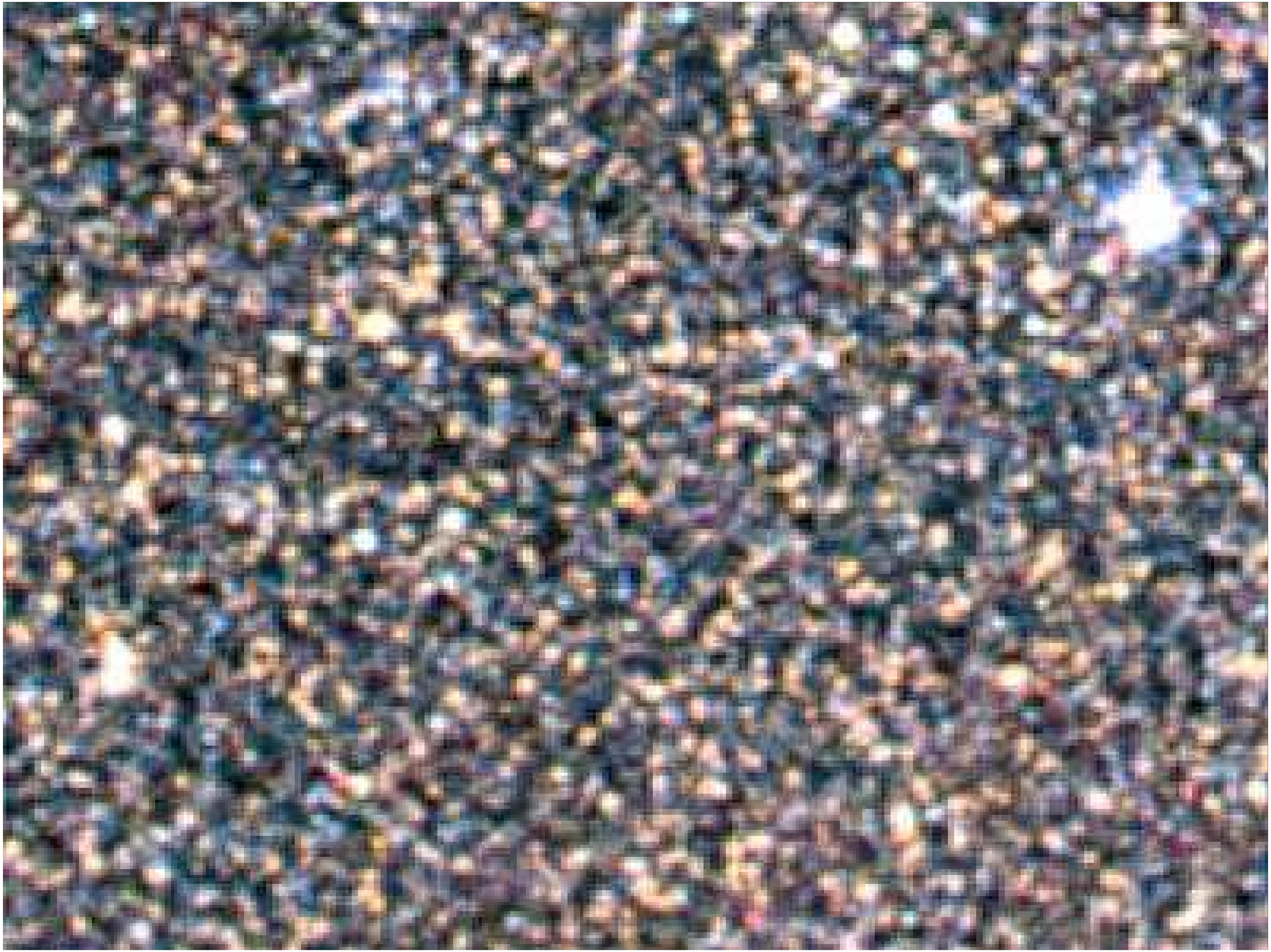
Grande Nuvem de Magalhães

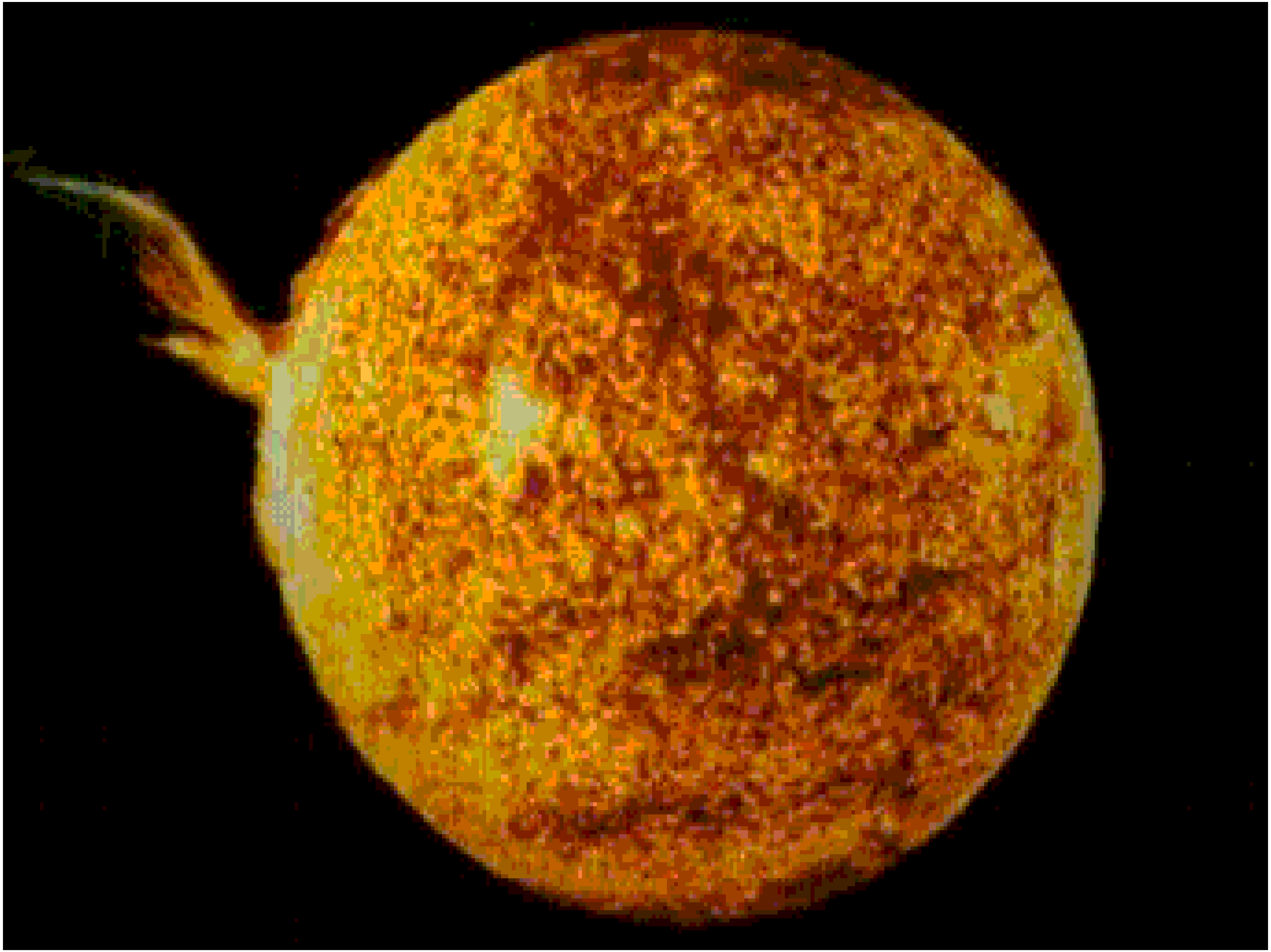
- É a galáxia mais próxima da Terra (160 mil anos-luz)
- É pequena, comparada com a Via Láctea (1/10 da massa)

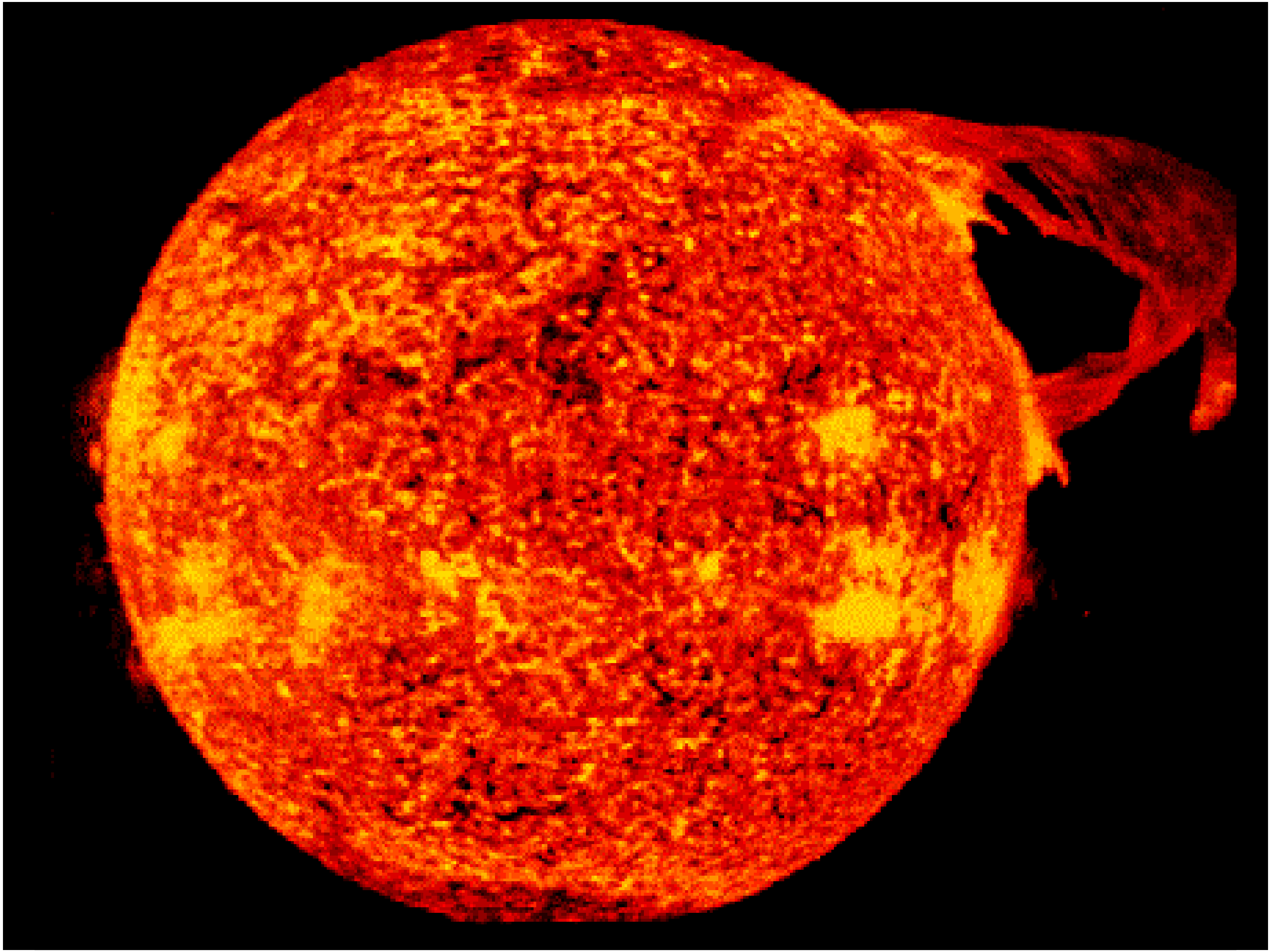


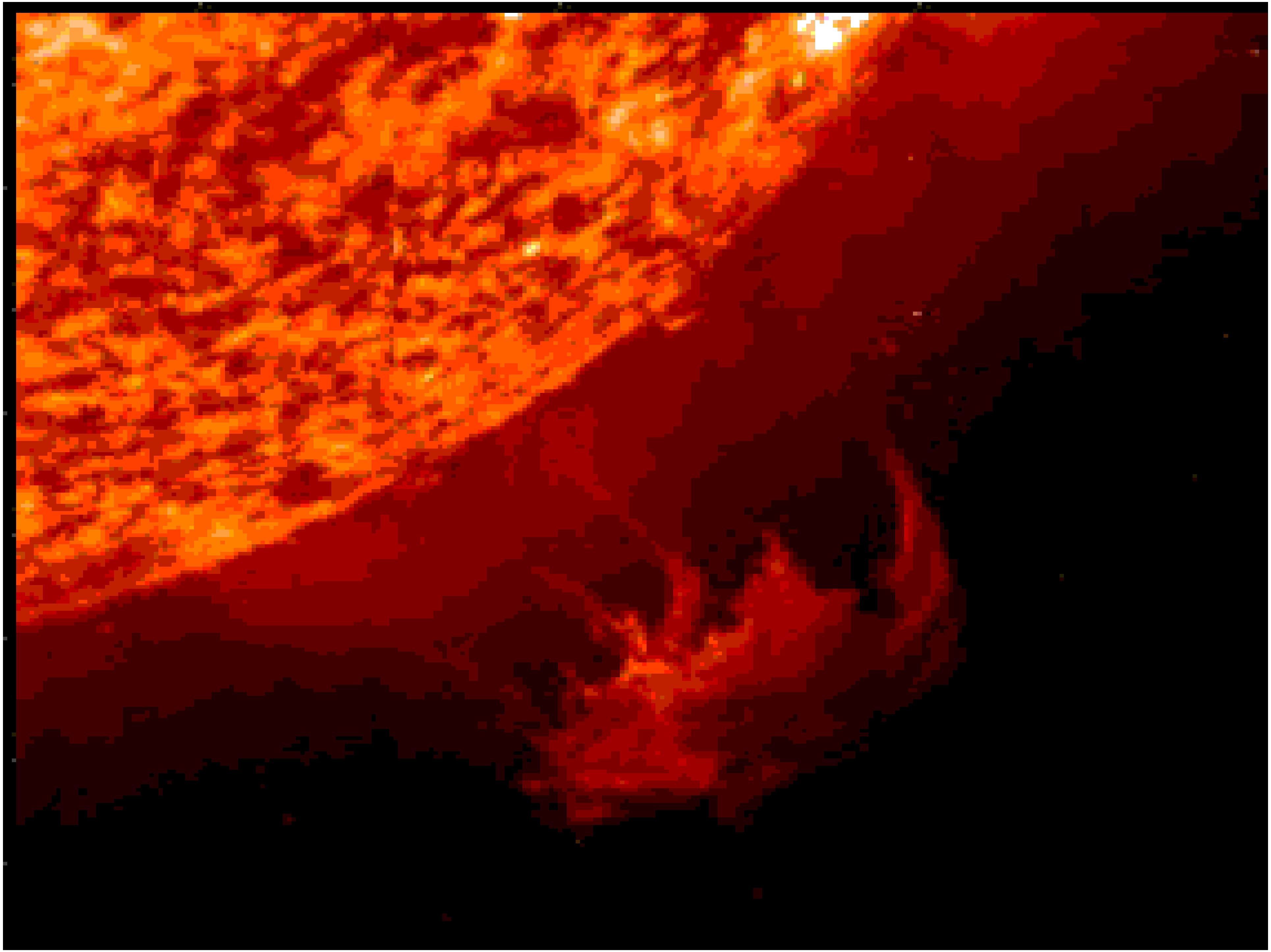


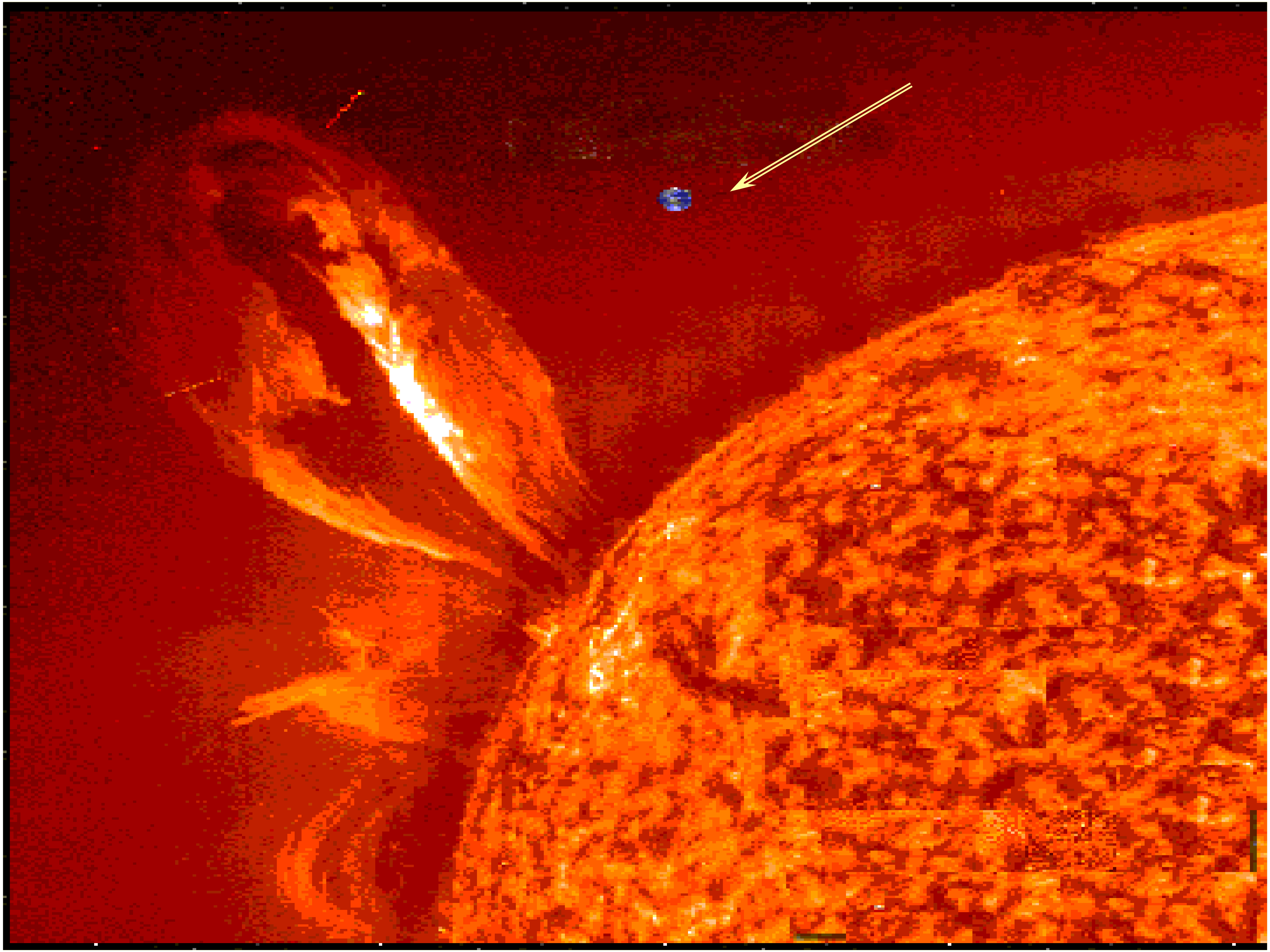


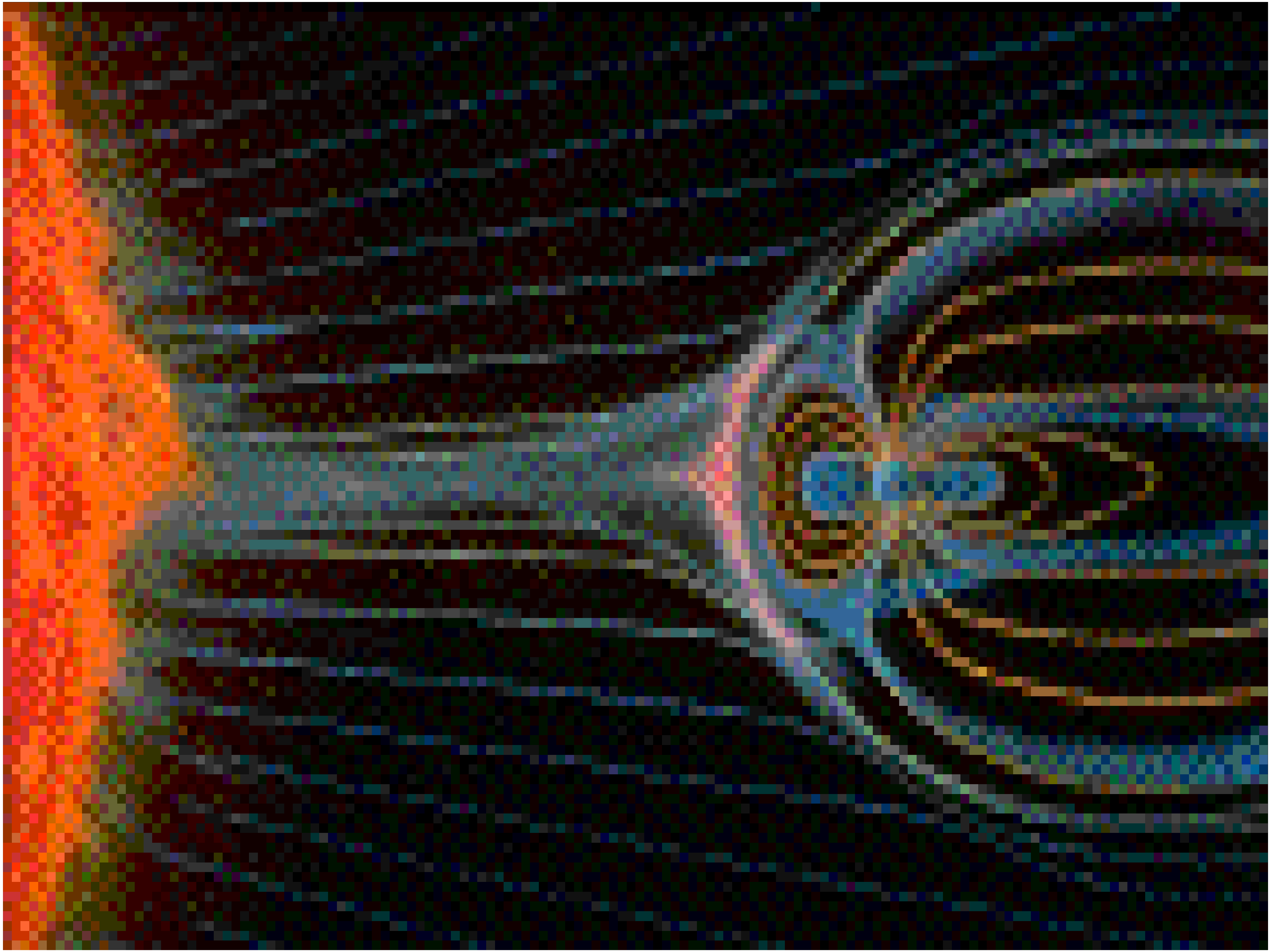






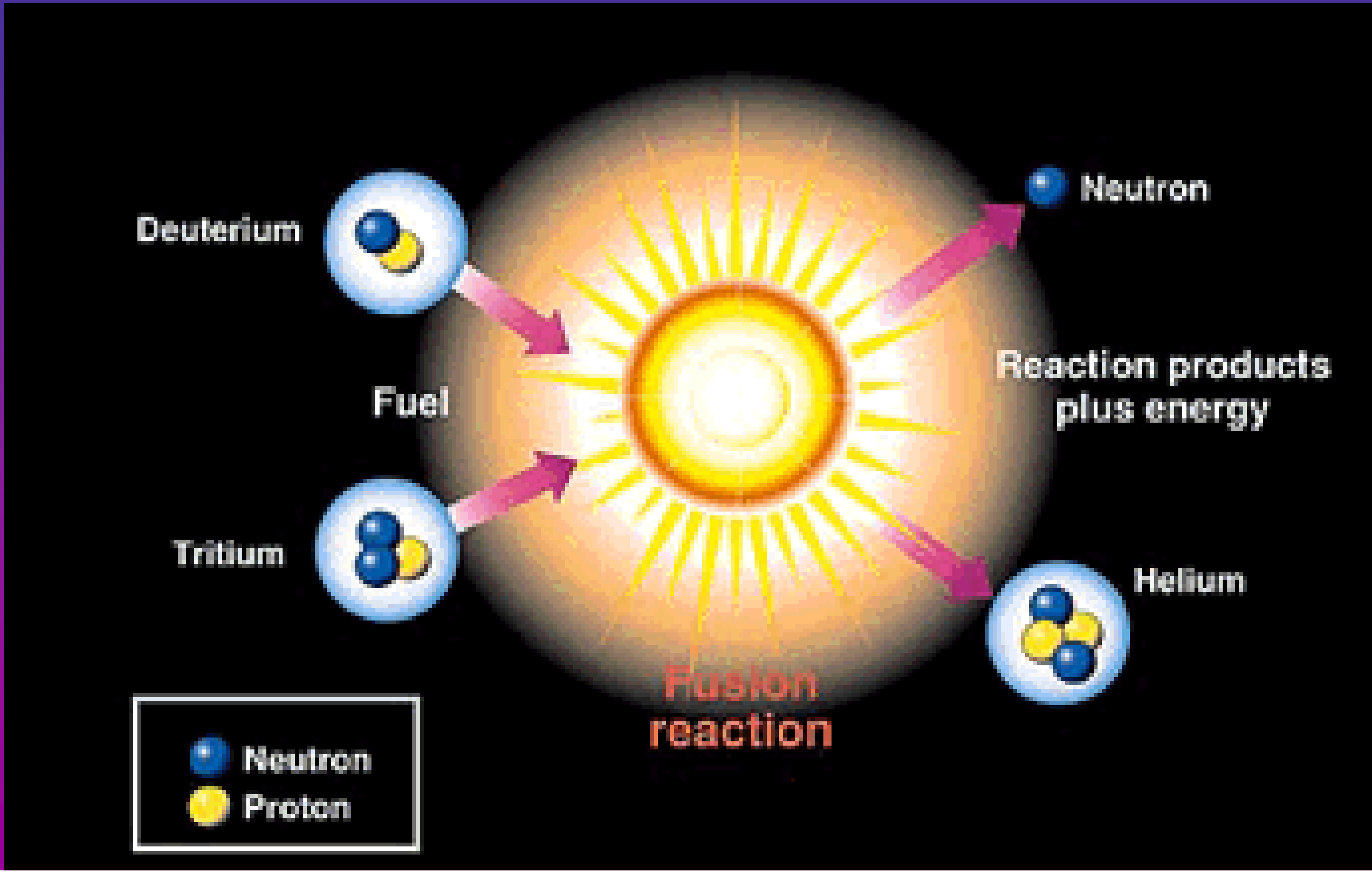




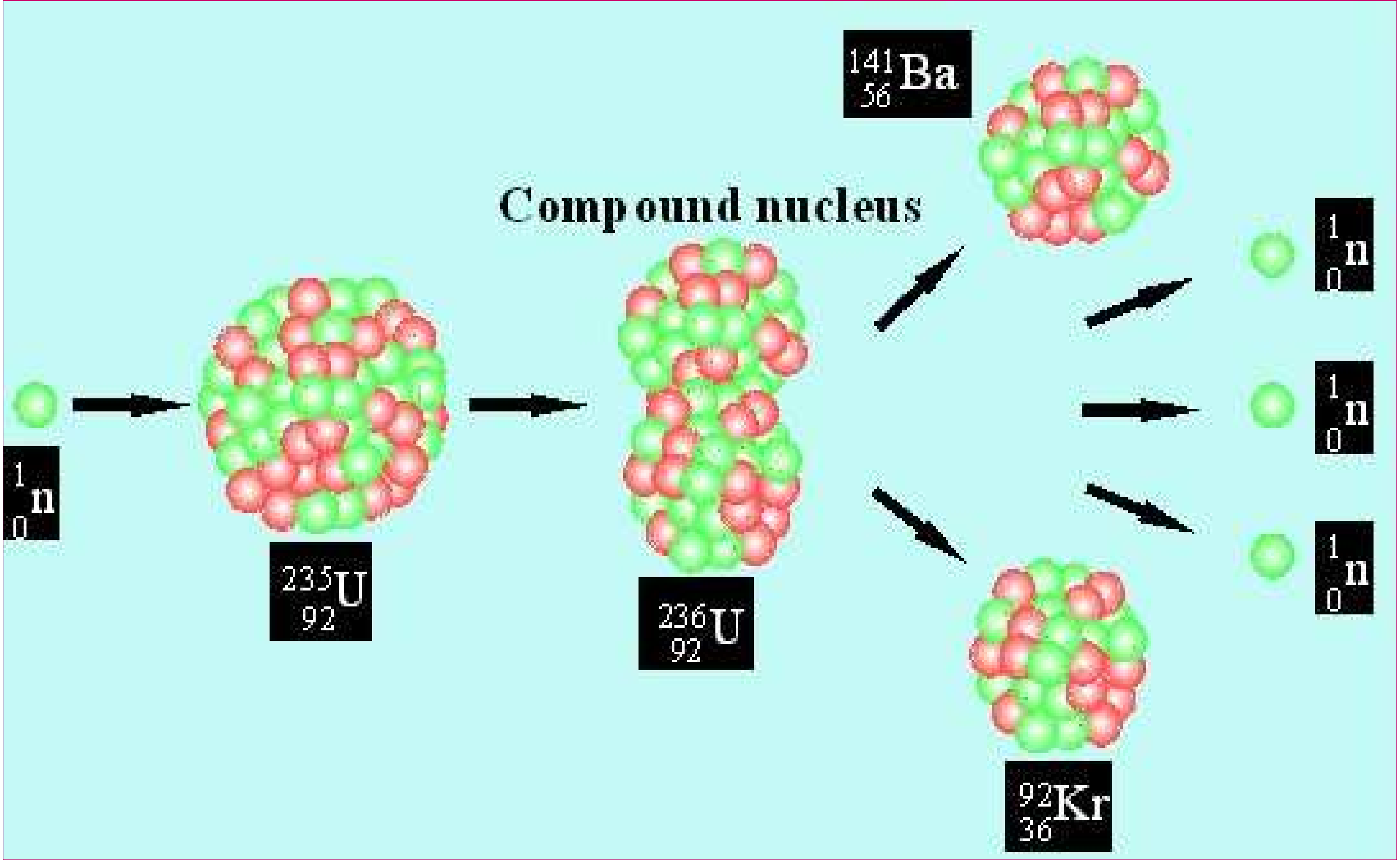


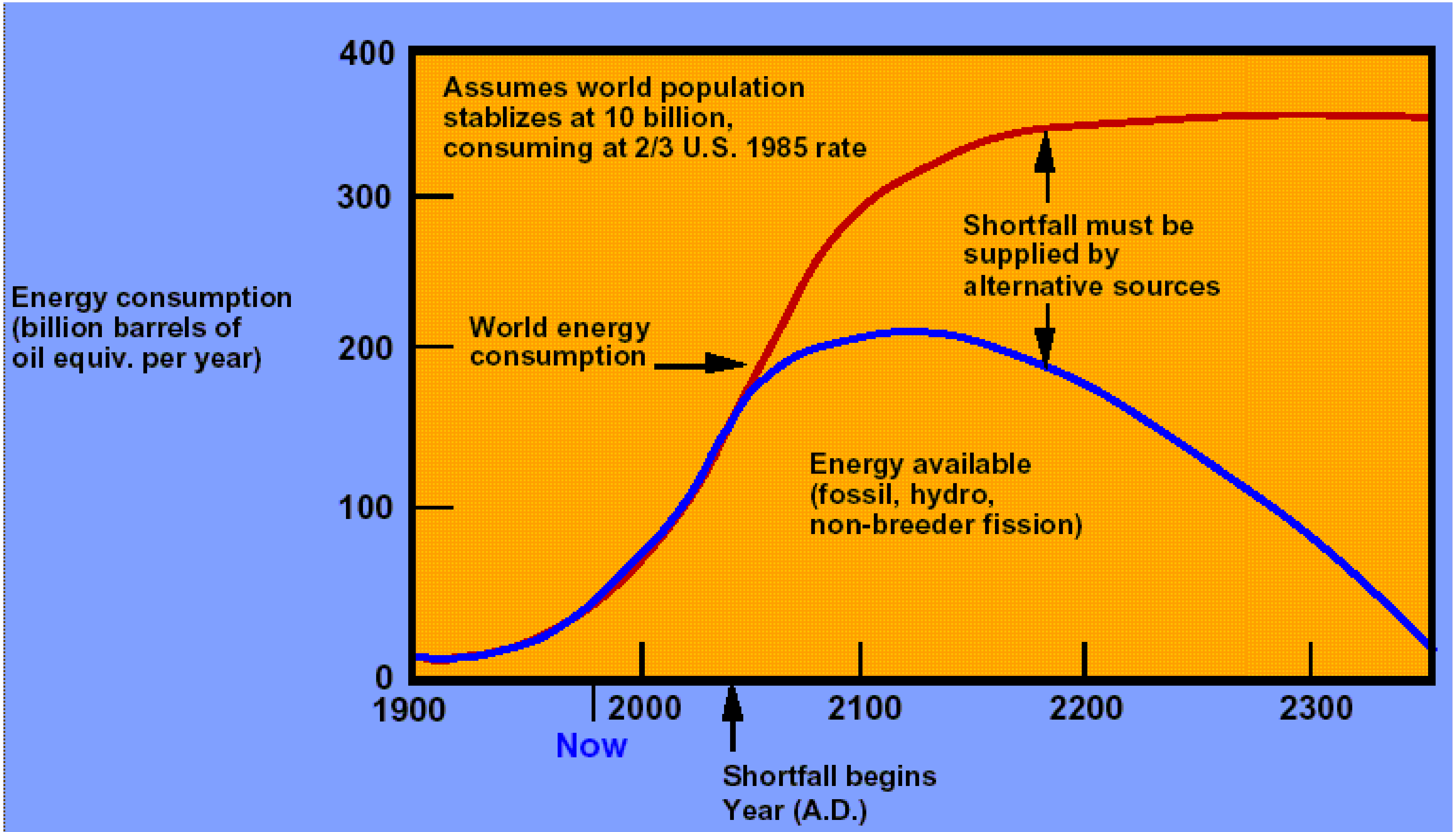
Principal Objetivo

- **Obtenção da** ***Fusão Termonuclear Controlada***

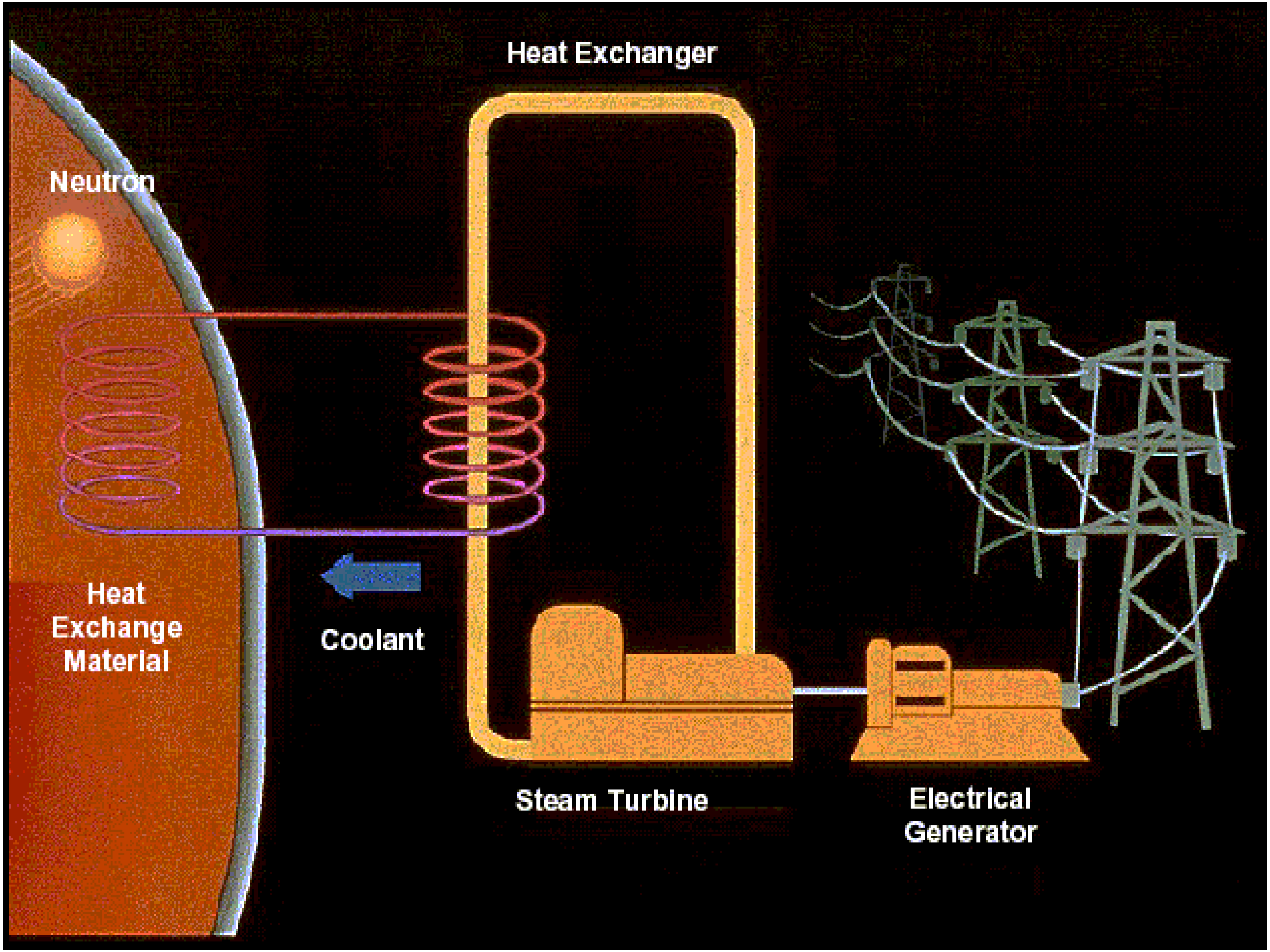


Fissão Nuclear

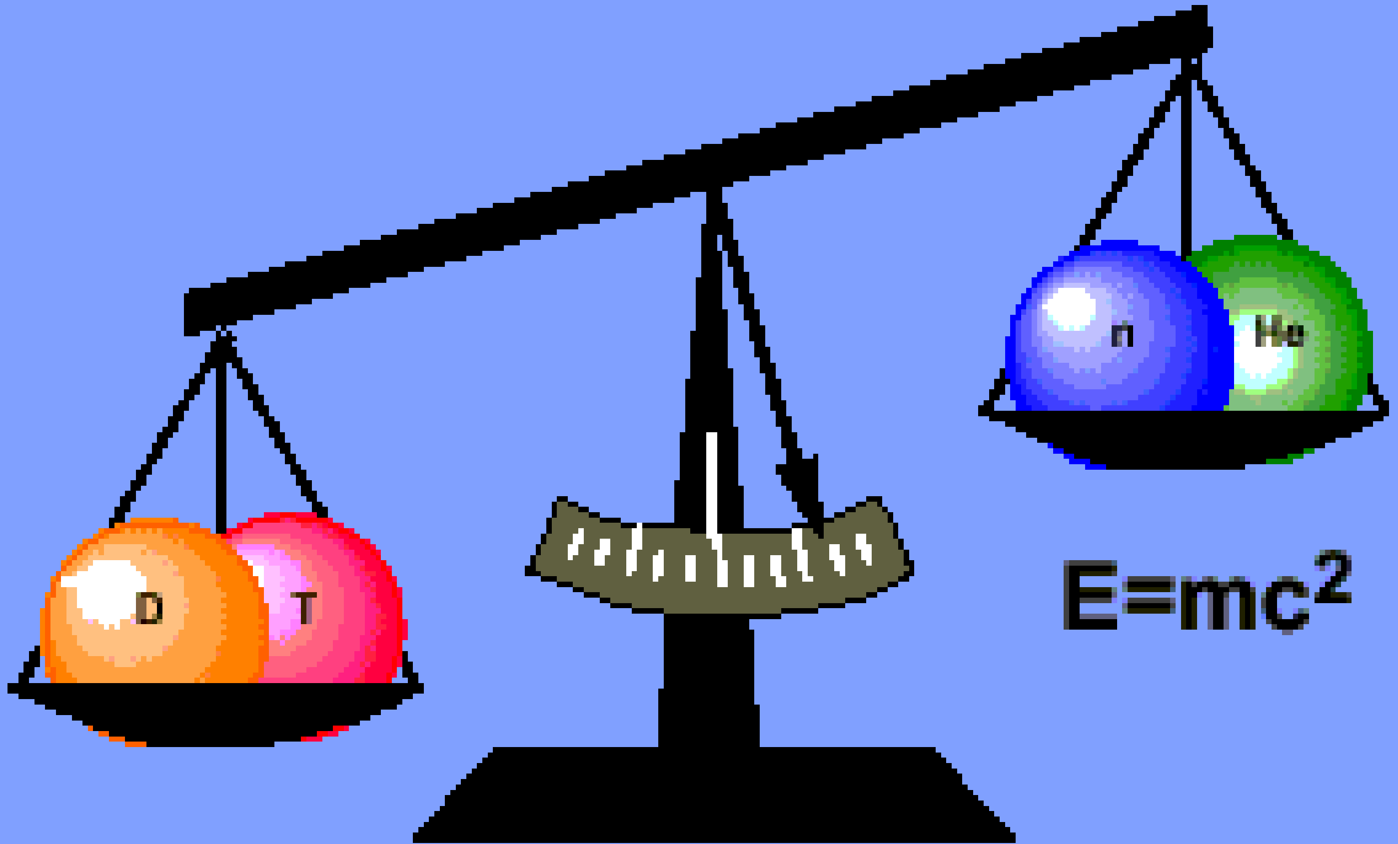




- **Energia liberada na fusão de uma grama de DT equivale à obtida com a queima de 10.000 L de óleo**


Heat Exchanger
Neutron
Heat
Exchange
Material
Coolant
Steam Turbine
Electrical
Generator

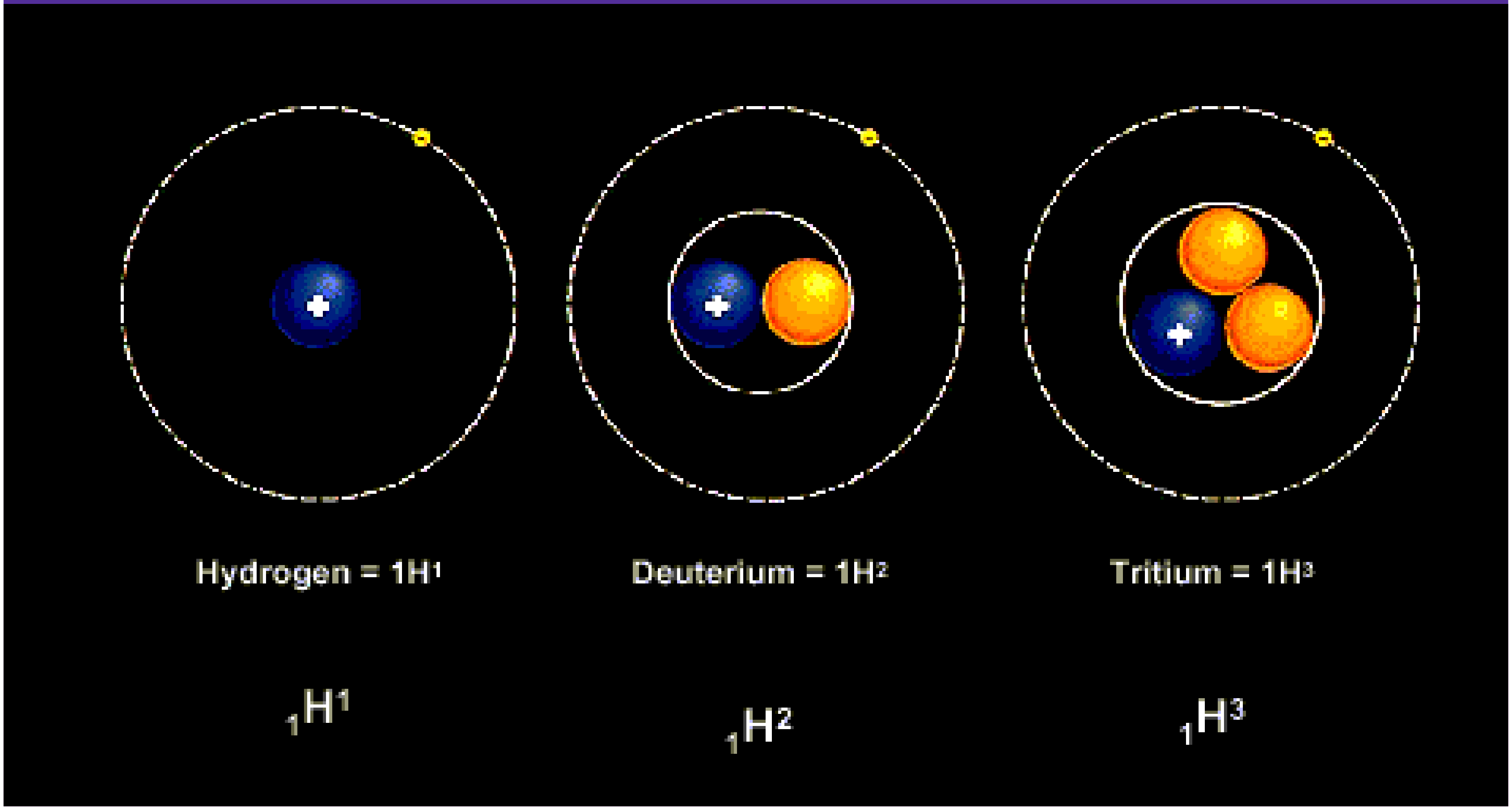
Princípio físico básico: $E = mc^2$



Vantagens da Fusão Nuclear sobre a Fissão

- É uma fonte de energia razoavelmente "limpa": não produz lixo radiativo
- É praticamente nula a probabilidade de acidentes
- A água do mar praticamente corresponde a uma fonte inesgotável de deutério!

Isótopos do Hidrogênio



Reações de fusão mais significativas

Reaction: Fuel	Reaction: Product	Ignition Temperature (millions of °C)	Ignition Temperature (keV)	Output Energy (keV)
D + T	^{4}He + n	45	4	17,600
D + ^{3}He	^{4}He + p	350	30	18,300
D + D	^{3}He + n	400	35	~4,000
	T + p	400	35	~4,000

Elétron-Volt

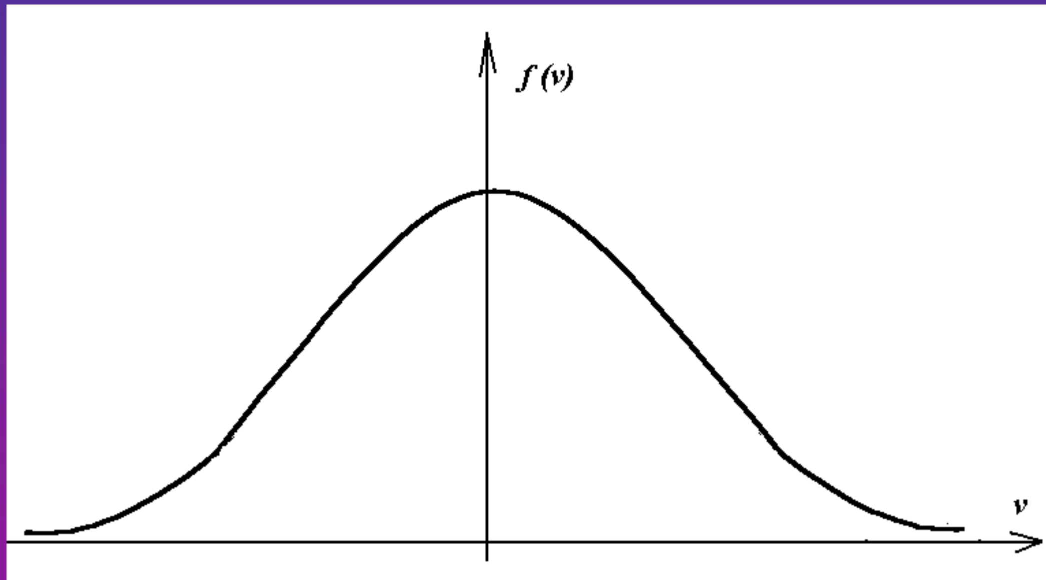
- É a energia adquirida por um elétron quando acelerado por uma ddp de 1 Volt ($W = \Delta E_{cin} = q\,\Delta V$)

Energia ganha = (carga) x (tensão)

$$1\ eV = 1{,}6 \times 10^{-19}\ C \times 1V = 1{,}6 \times 10^{-19}\ J$$

Ampliando o conceito de Temperatura

- Um gás, em equilíbrio térmico, tem partículas com uma distribuição Maxwelliana de velocidades



$$f(v) = f_0 \exp\left(- \tfrac{1}{2}\, m\, v^2 / KT\right) \qquad \text{(1D)}$$

Sendo $f_0 = n\,(m / 2\pi\, KT)^{1/2}$ ($n \equiv$ densidade e K a constante de Boltzmann)

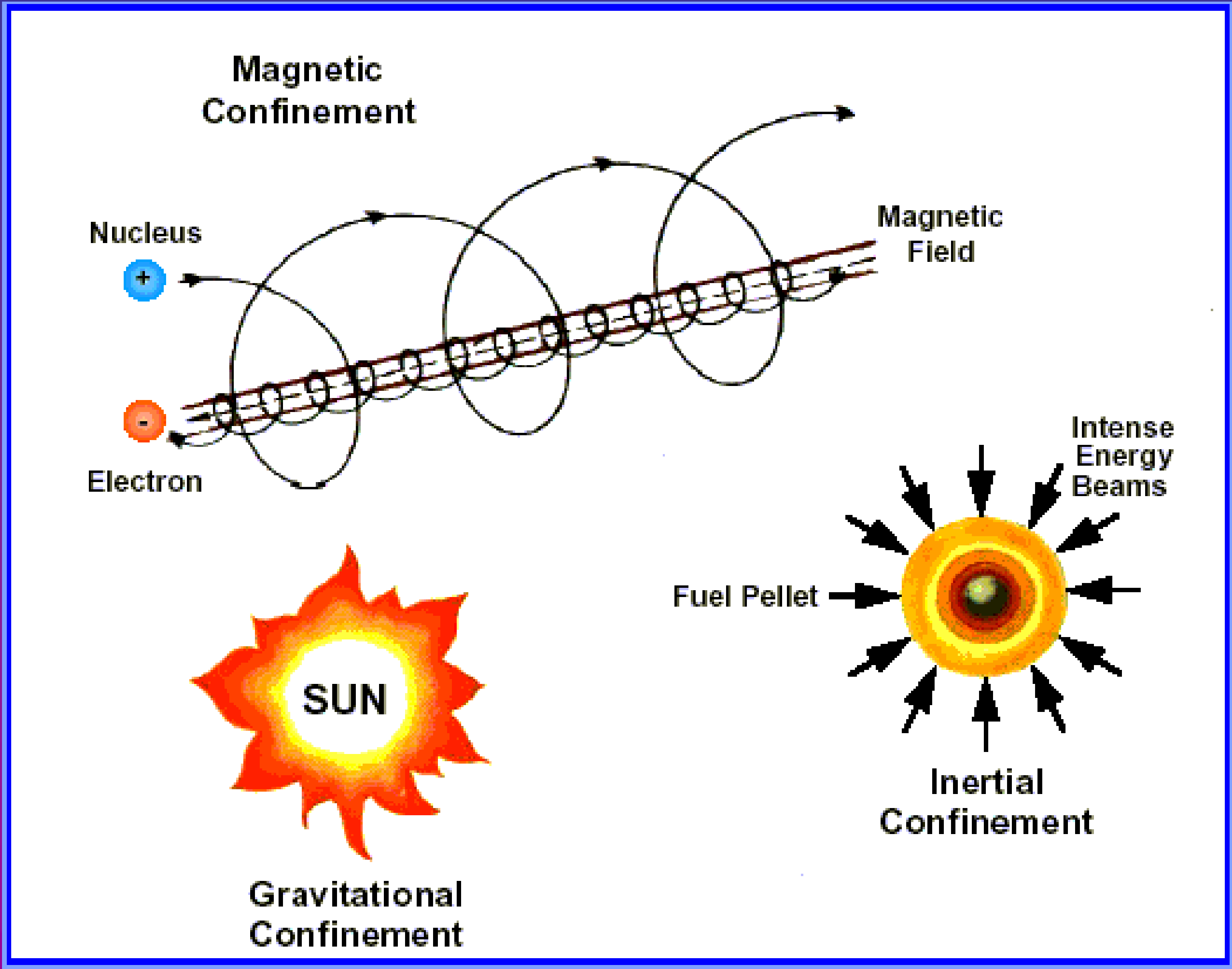
- **A Temperatura T está relacionada com a largura da distribuição**

- Para **KT = 1 eV = 1,6 x 10^{-19} J , tem-se:**

$$T = \frac{1{,}6x10^{-19}}{1{,}38x10^{-23}} \approx 11.600K$$

Ou seja: **1 eV ≡ 11.600 K**

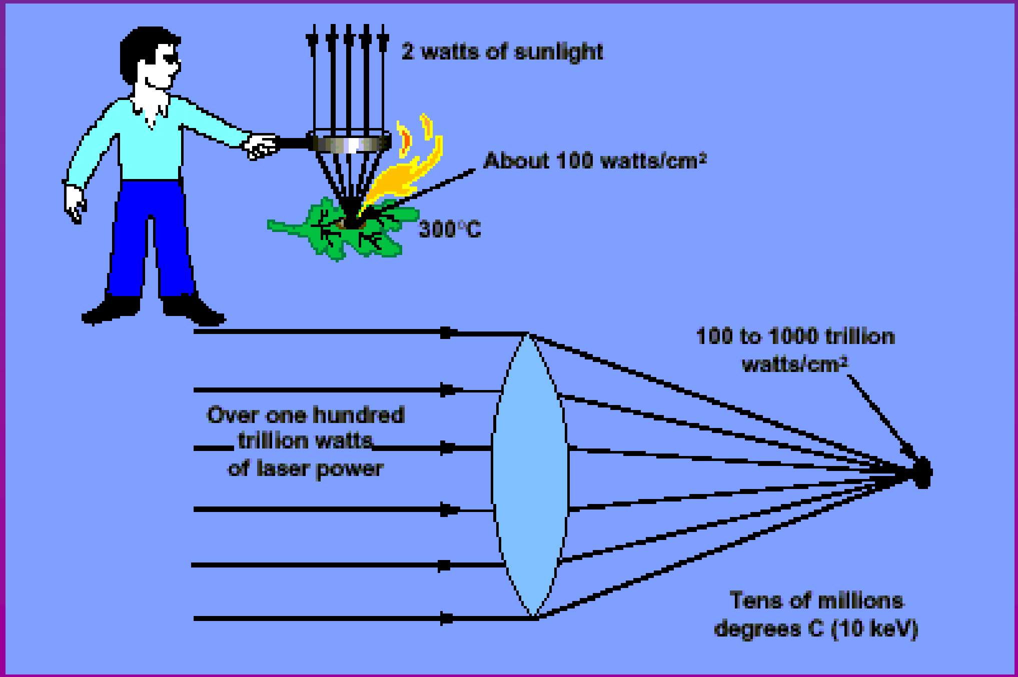
- **A fusão pode ser obtida de 3 maneiras diferentes**



Confinamento Inercial

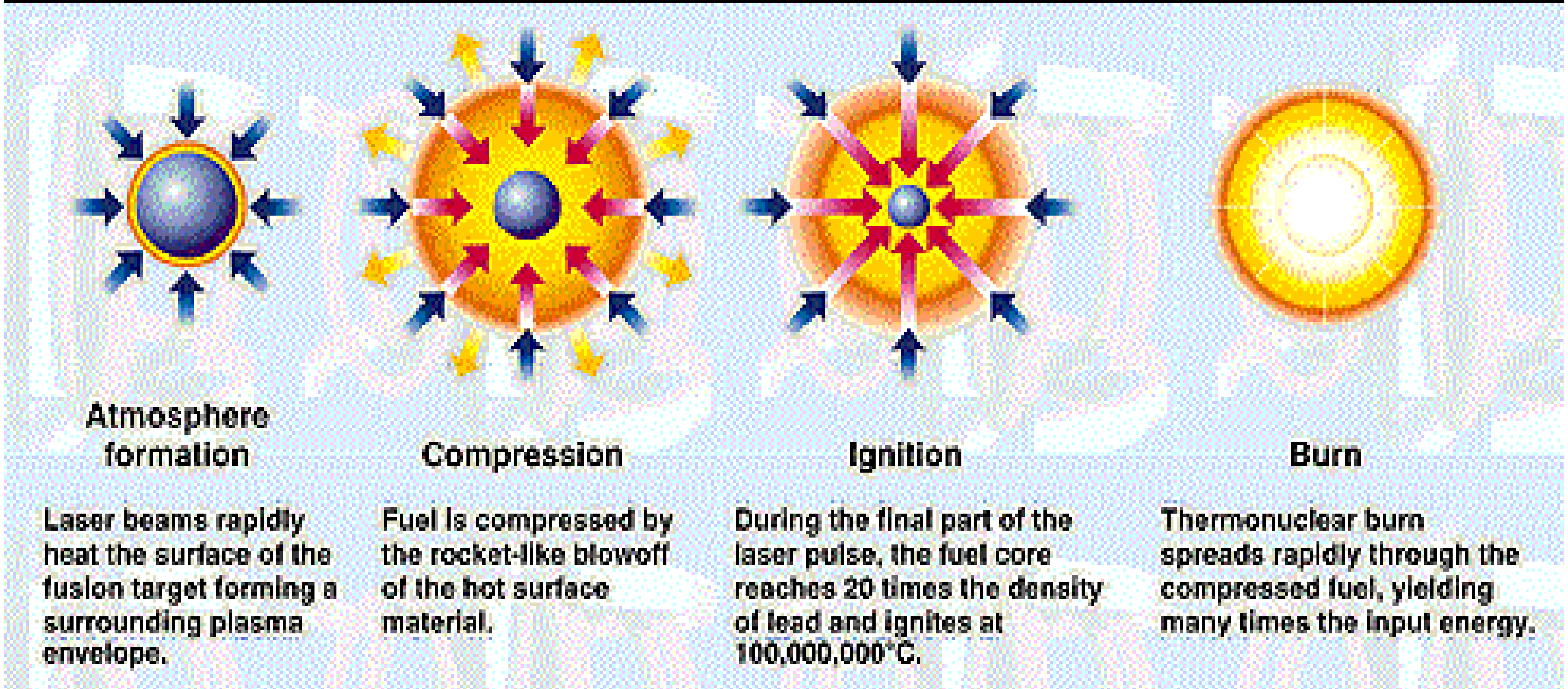
- Feixes de laser de altíssimas potências (centenas de Tera Watts) incidem simultânea e simetricamente.

- A pastilha de deutério-trítio congelada é aquecida e comprimida a altíssimas temperatura e densidade, provocando sua ignição.

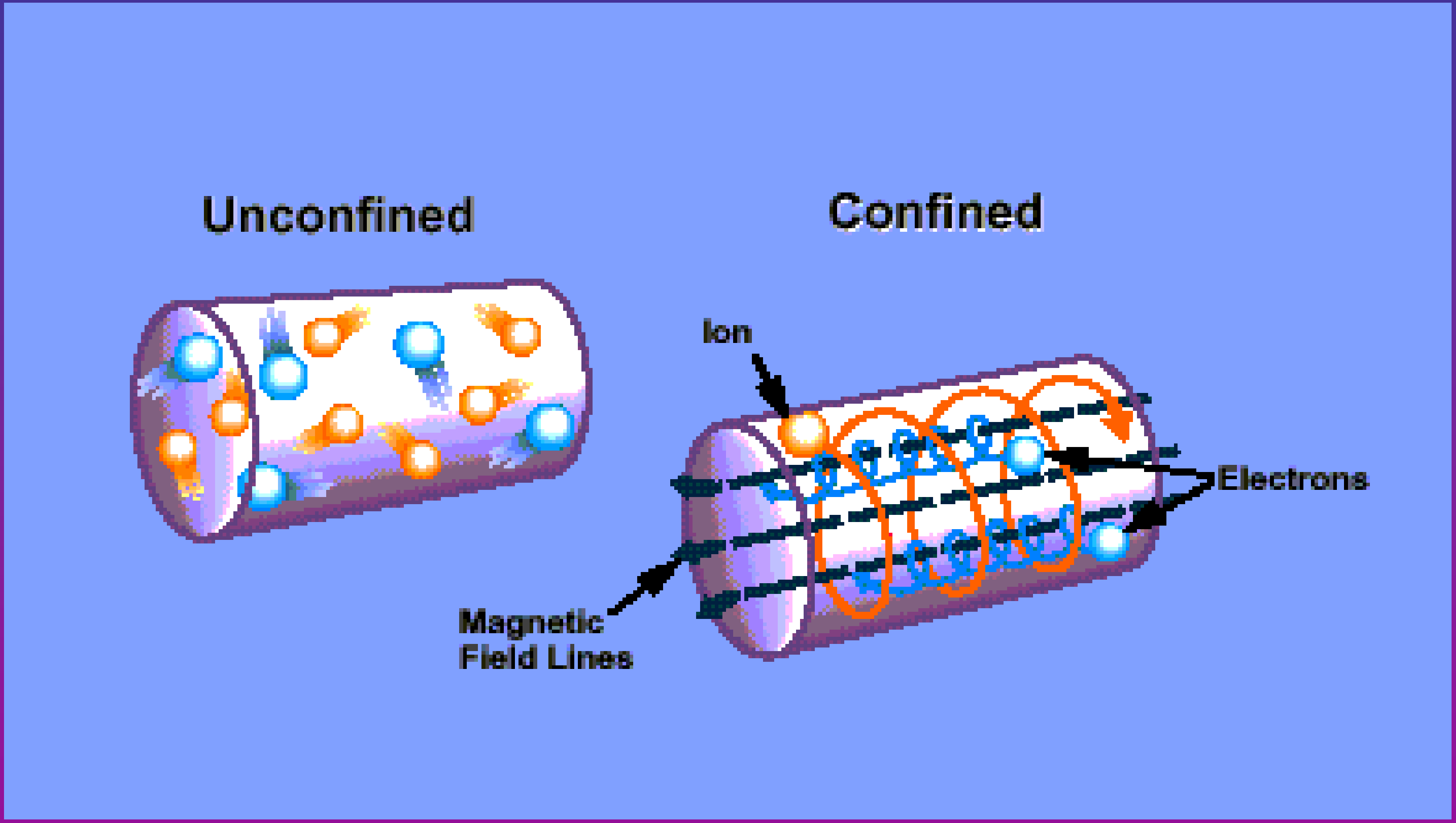


NOVA Machine Used Inertial Confinement

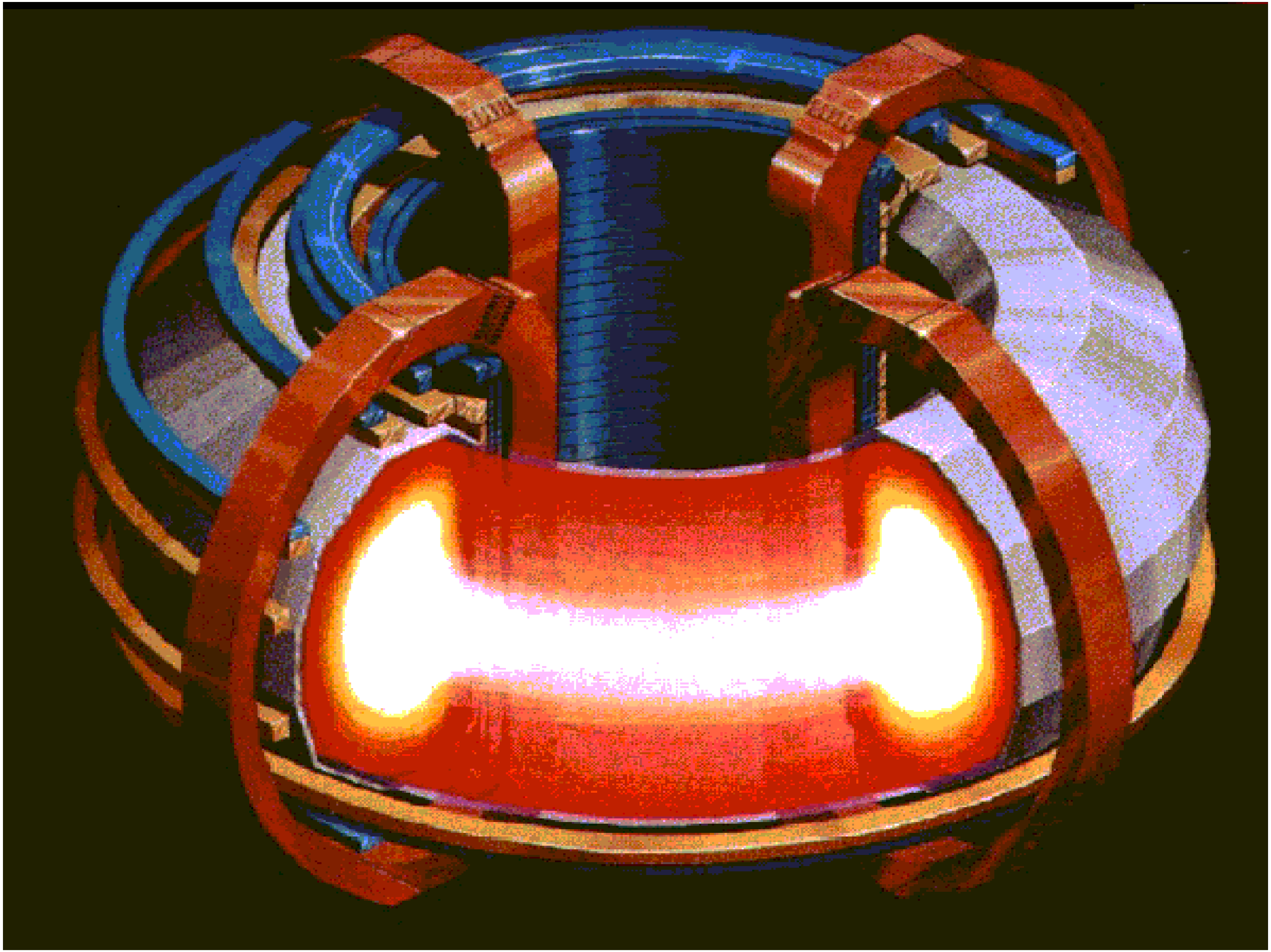
(Has Not Proved as Successful as Magnetic Confinement)

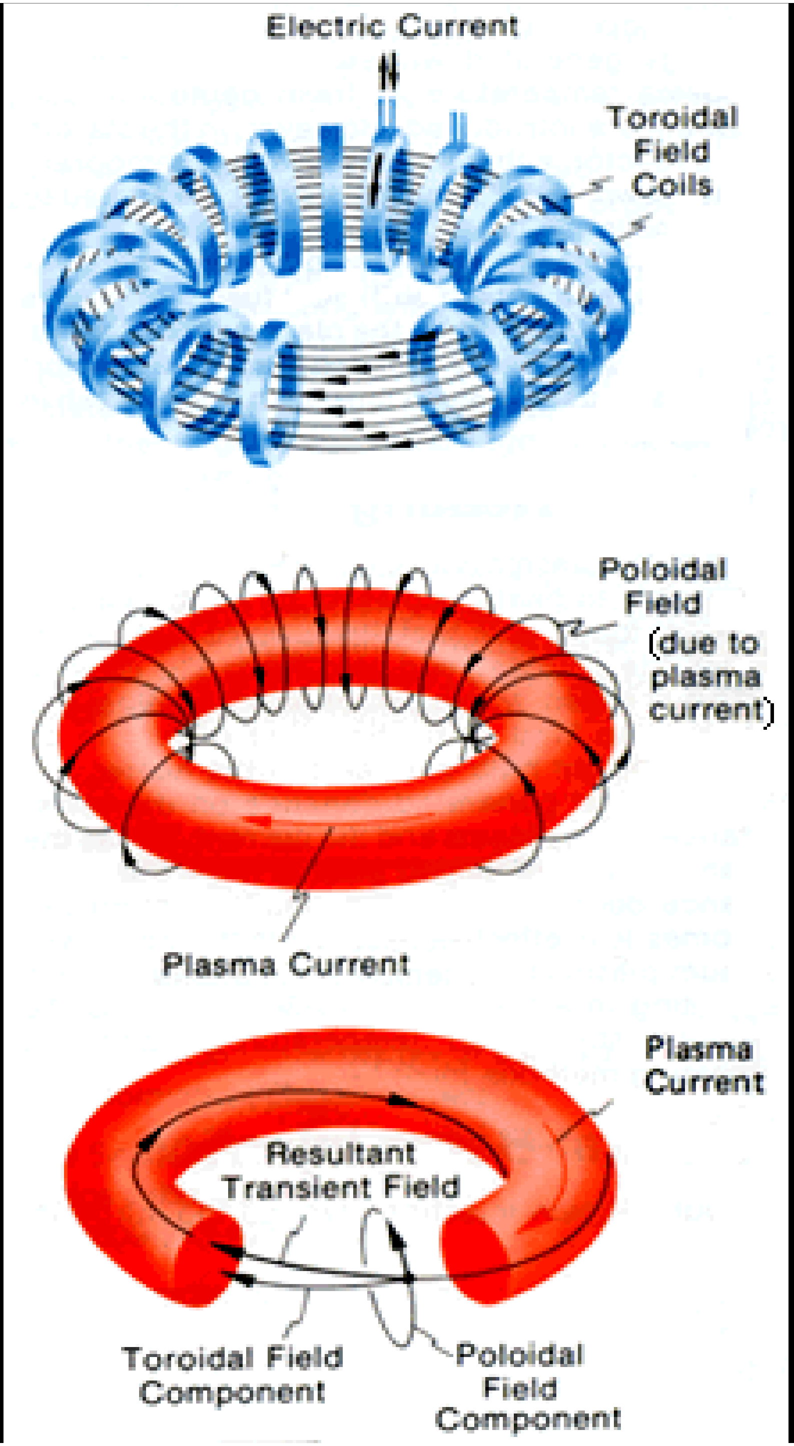

Atmosphere formation
Compression
Ignition
Burn
Laser beams rapidly heat the surface of the fusion target forming a surrounding plasma envelope.
Fuel is compressed by the rocket-like blowoff of the hot surface material.
During the final part of the laser pulse, the fuel core reaches 20 times the density of lead and ignites at 100,000,000°C.
Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.

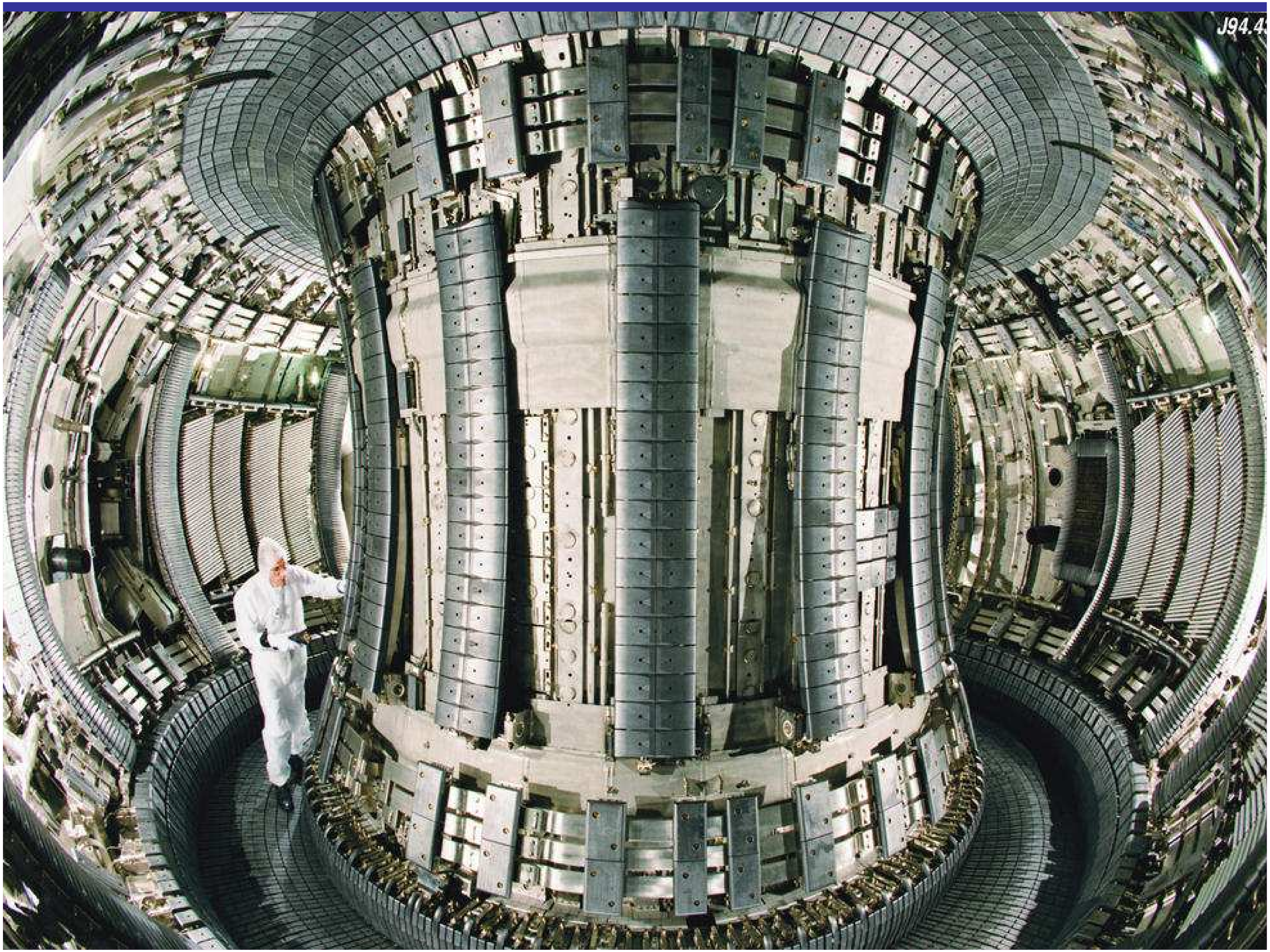
Confinamento Magnético

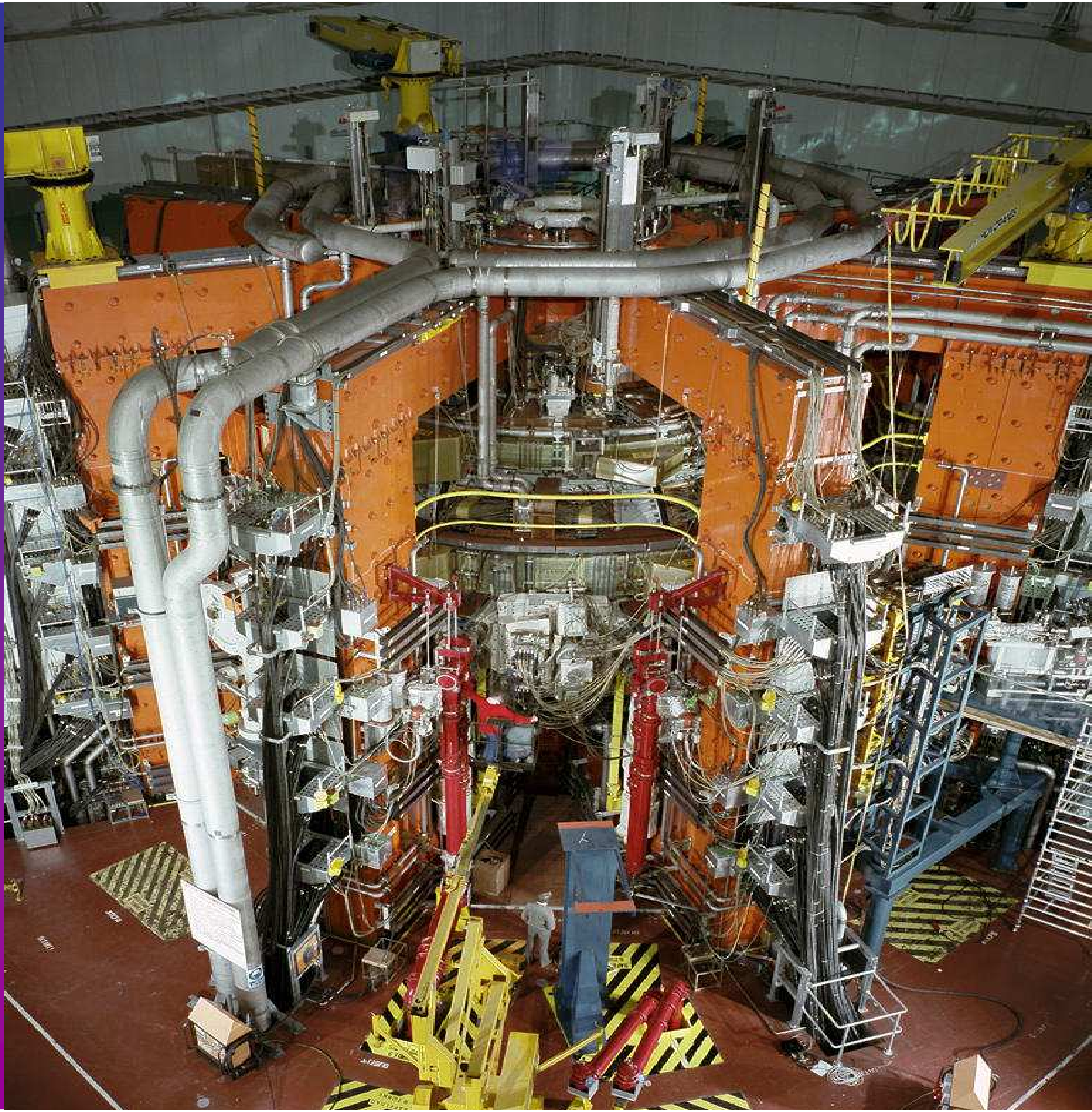


- O tokamak tem apresentado os melhores resultados

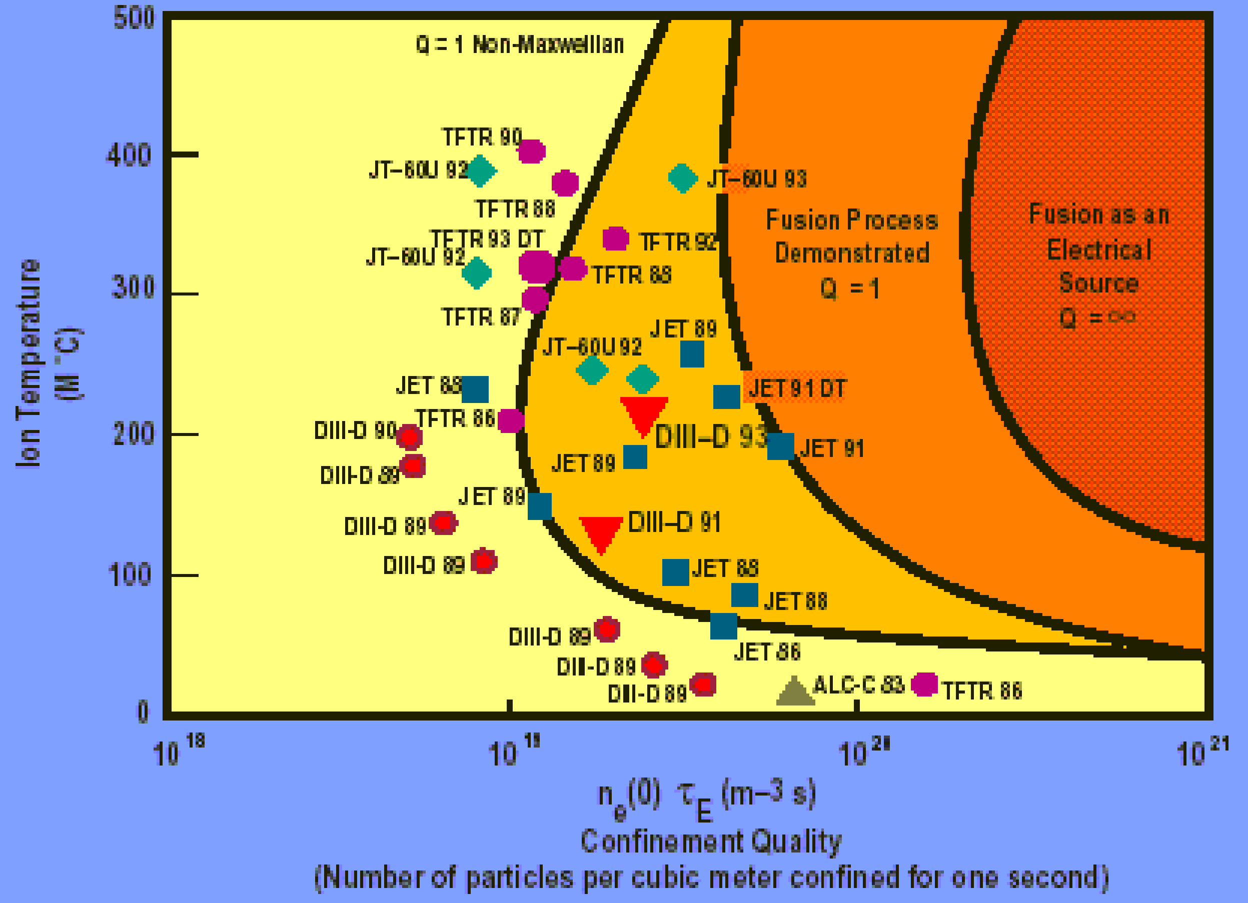


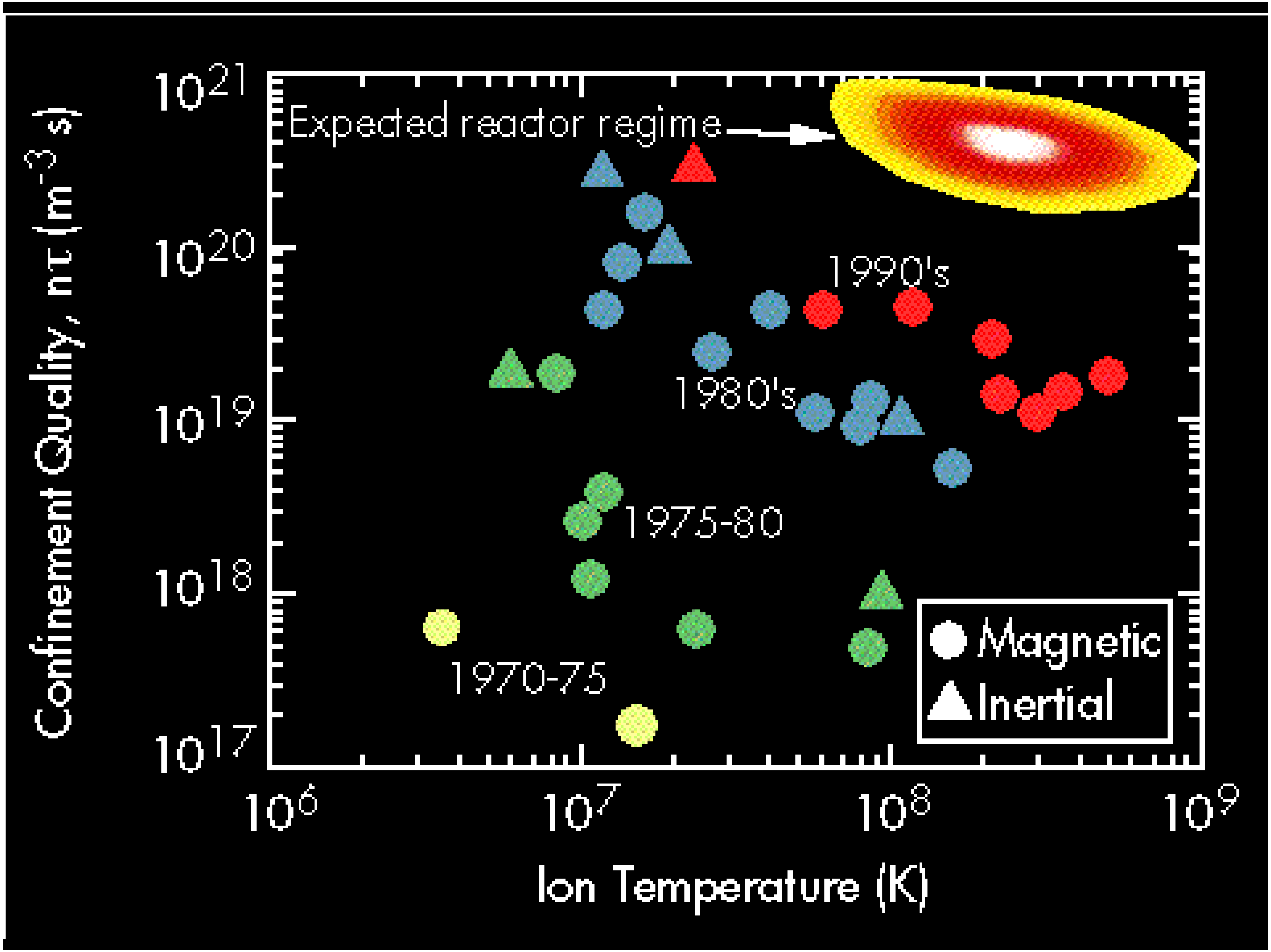

Electric Current
Toroidal
Field
Coils
Poloidal
Field
(due to
plasma
current)
Plasma Current
Plasma
Current
Resultant
Transient Field
Toroidal Field
Component
Poloidal
Field
Component



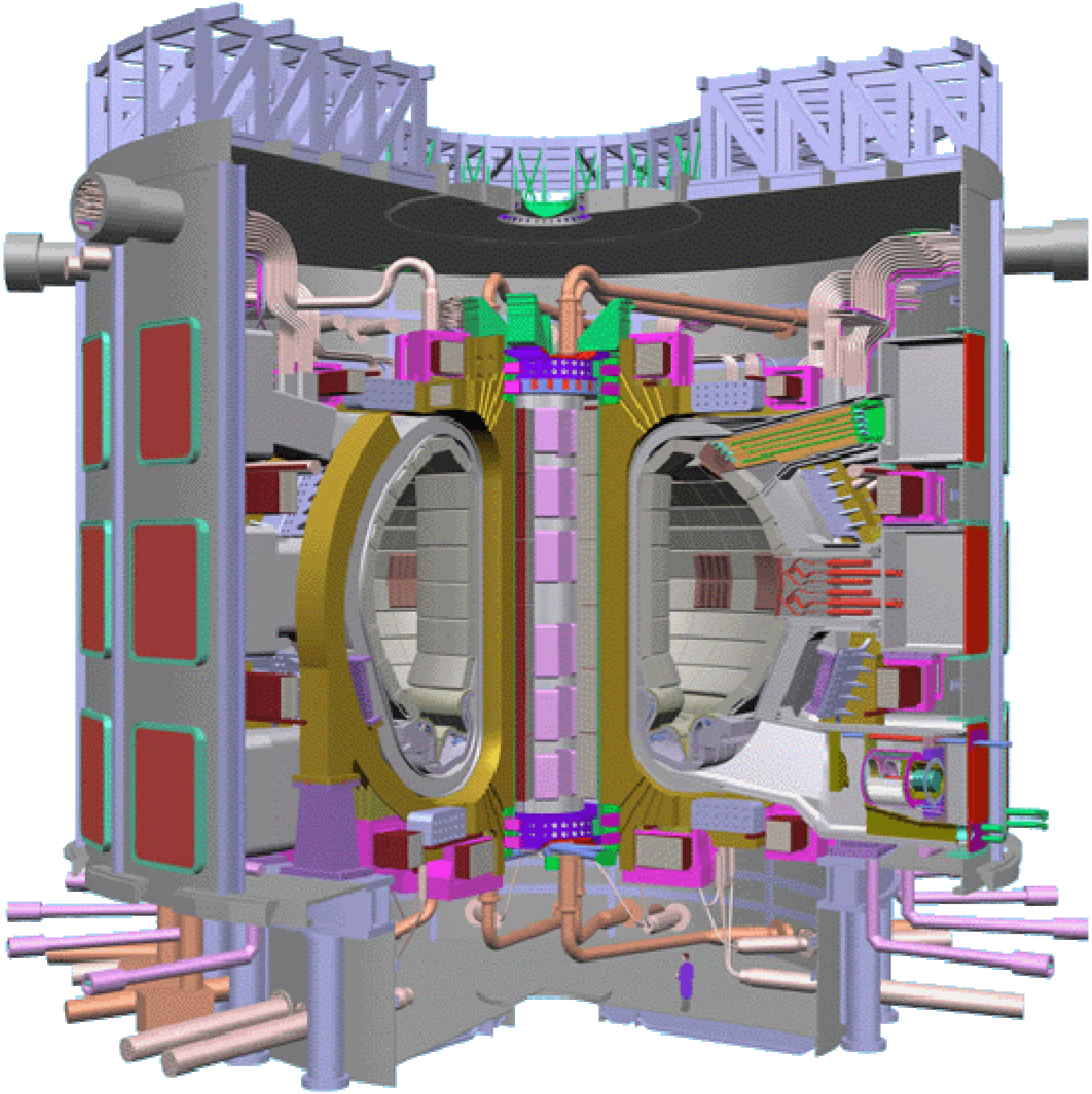


Fusion Experiments Now Approach Ignition Conditions





10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
Confinement Quality, $n\tau$ (m^{-3} s)
Expected reactor regime
1990's
1980's
1975-80
1970-75
Magnetic
Inertial
10^6
10^7
10^8
10^9
Ion Temperature (K)

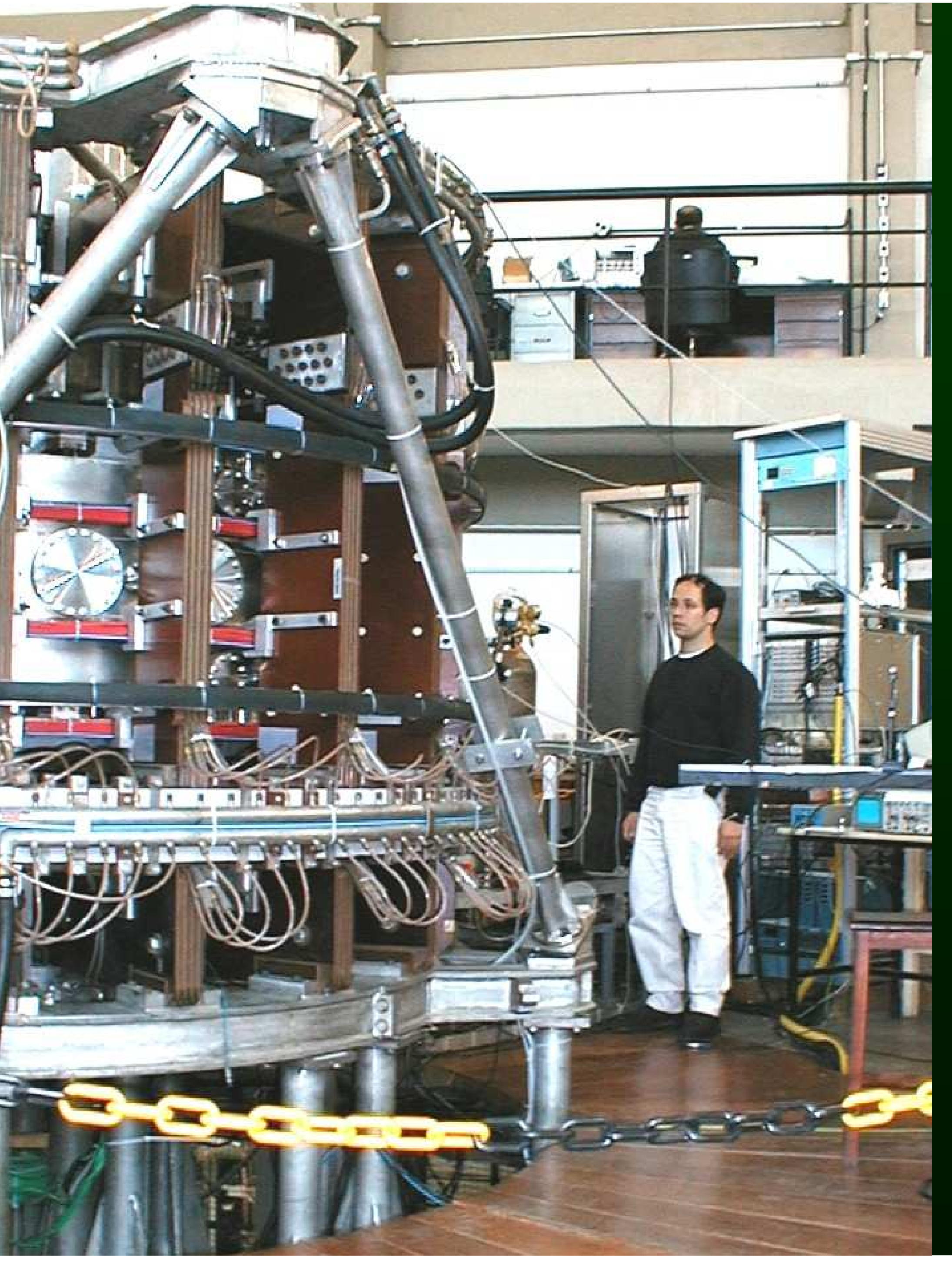


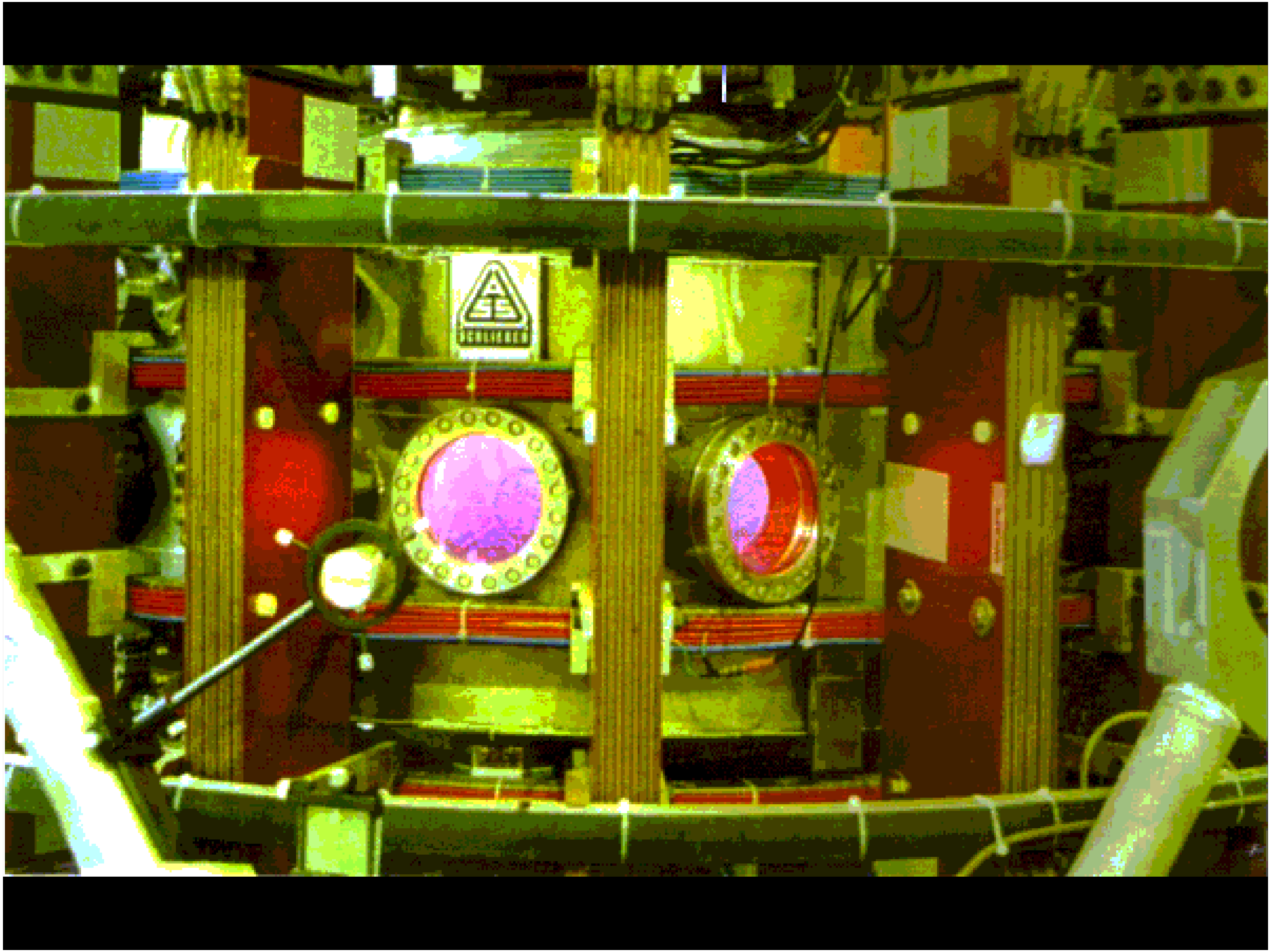
Main Plasma Parameters and Dimensions

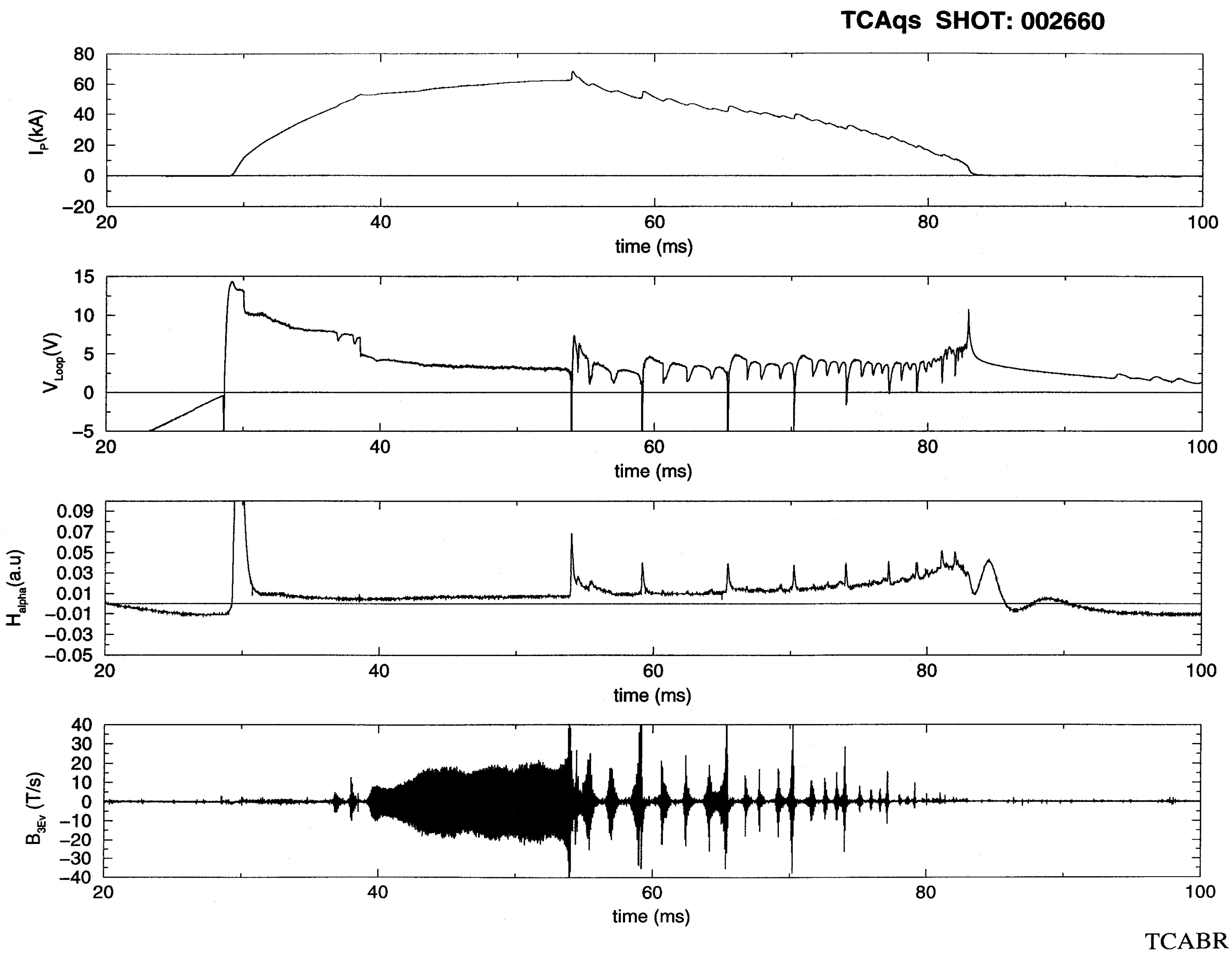
Total fusion power	500 MW *(700MW)*
Q = fusion power/auxiliary heating power	≥ 10
Average neutron wall loading	0.57 MW/m^2 *(0.8 MW/m^2)*
Plasma inductive burn time	≥ 300 s
Plasma major radius	6.2 m
Plasma minor radius	2.0 m
Plasma current (I_p)	15 MA *(17.4 MA)*
Vertical elongation @95% flux surface/separatrix	1.70/1.85
Triangularity @95% flux surface/separatrix	0.33/0.49
Safety factor @95% flux surface	3.0
Toroidal field @6.2 m radius	5.3 T
Plasma volume	837 m^3
Plasma surface	678 m^2
Installed auxiliary heating/current drive power	73 MW *(100 MW)*

O tokamak TCABR do IFUSP

- Máquina de médio porte, trazido da Suiça
- Substituiu o pequeno tokamak TBR-1
- Projeto de pesquisa principal: Aquecimento do plasma por ondas de Alfvèn
- Principais parâmetros:
  - I_p ~ 100 kA
  - τ_p ~ 150 ms
  - B_t ~ 1,1 T
  - R_0 = 61 cm
  - a = 18 cm






TCAqs SHOT: 002660
I_P(kA)
V_Loop(V)
H_alpha(a.u)
B_3Ev (T/s)
time (ms)
TCABR