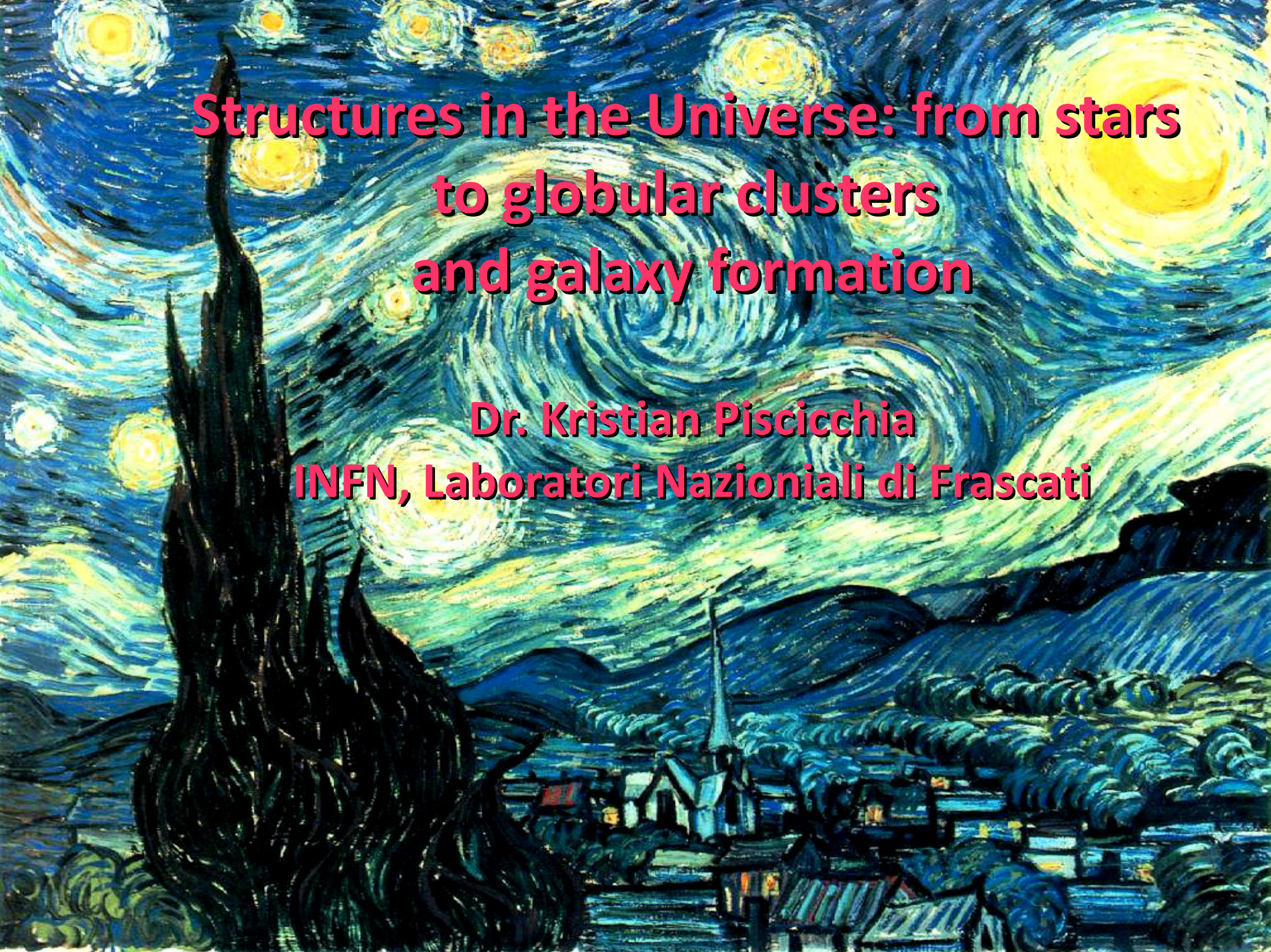


Structures in the Universe: from stars to globular clusters and galaxy formation

Dr. Kristian Piscicchia
INFN, Laboratori Nazionali di Frascati

- Gravitational interaction among two particles

$(m_1\ m_2)/r^2$

Principia of Newton (1687)

- Gravitational interaction is long range: any particle of the system influences the motion of any other!

- Gravitational interaction diverges when $r \rightarrow 0$ serious problem when you use computers!

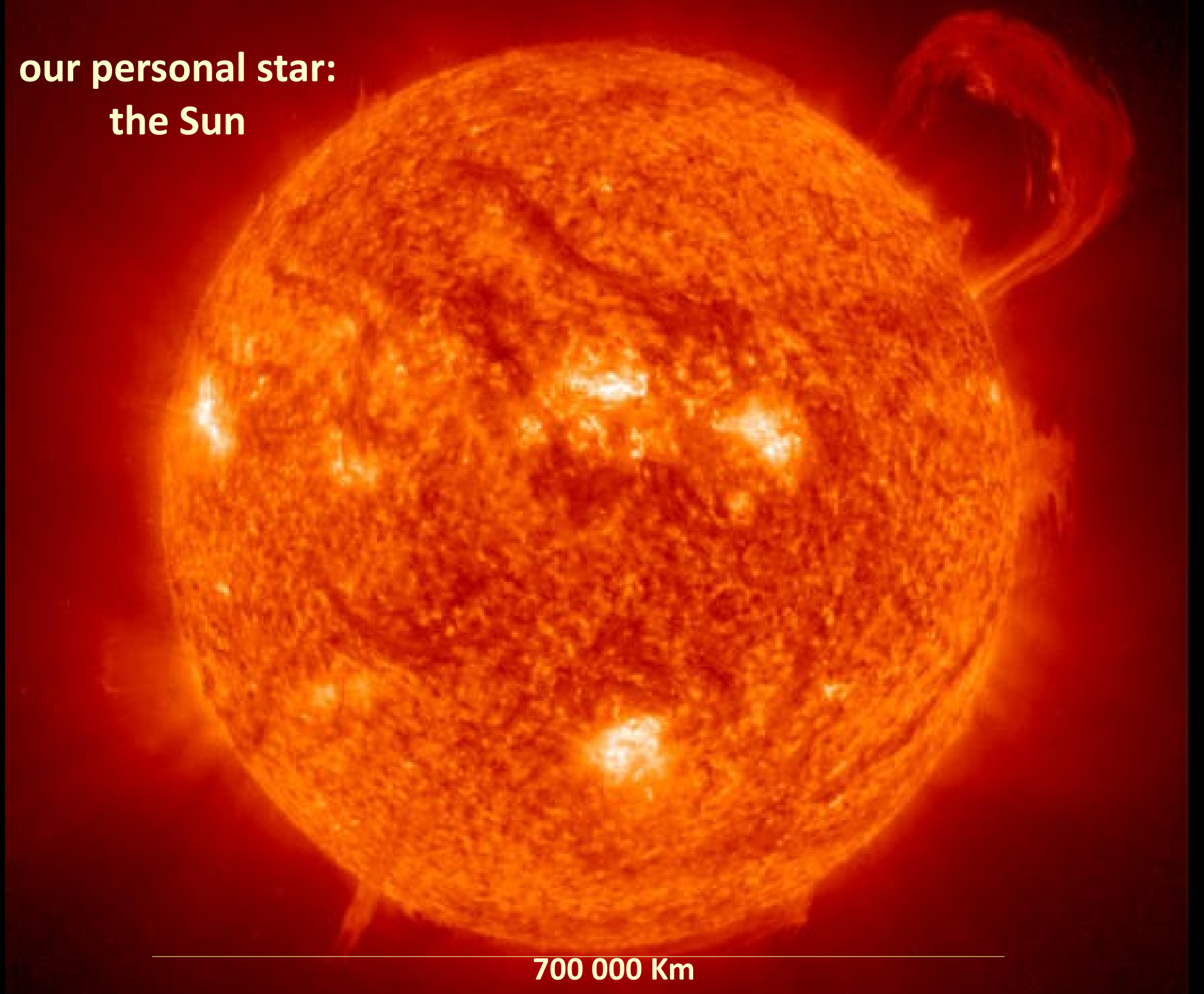
Our image of the univers began to be clear only 50-60 years ago:

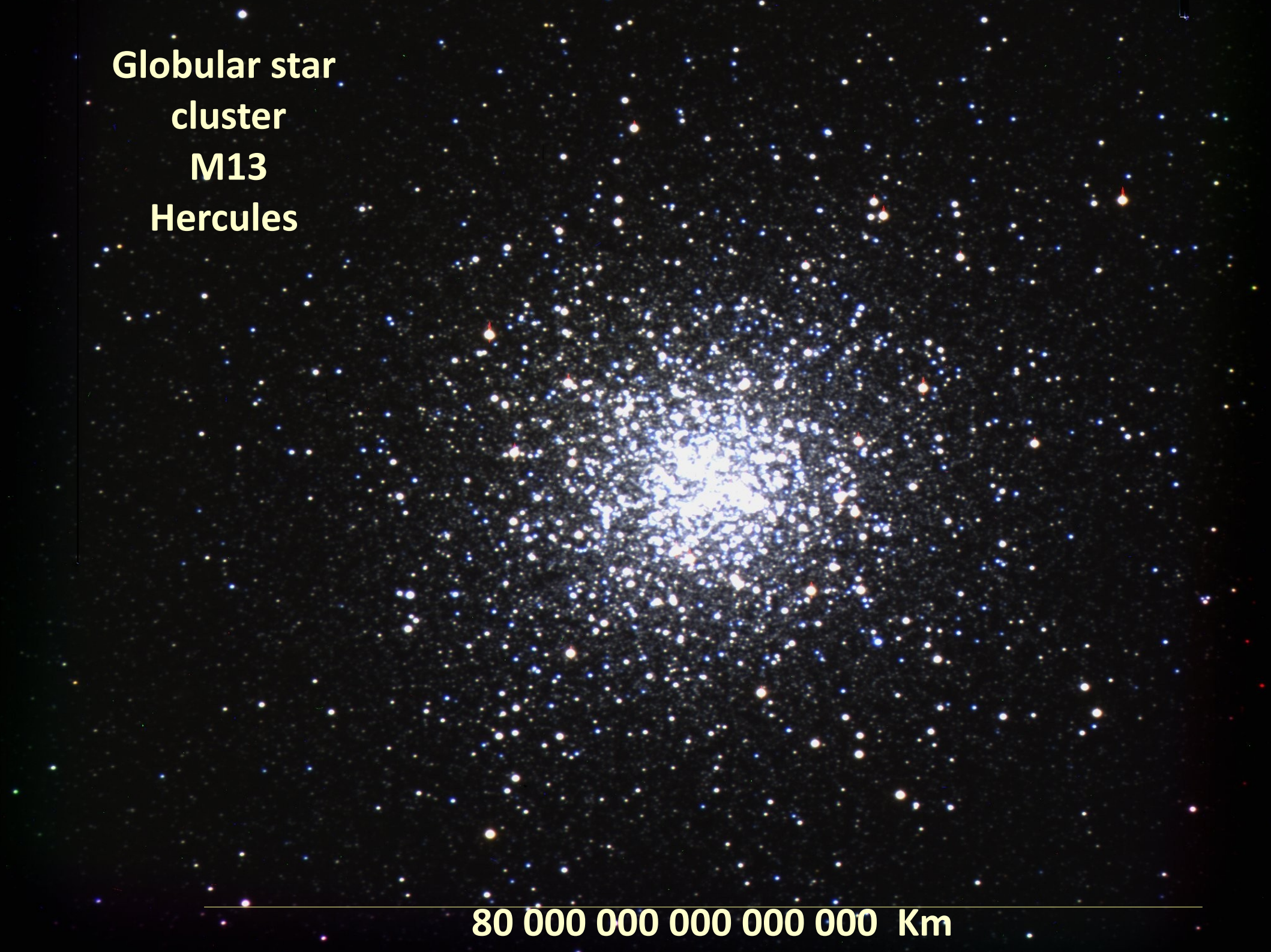
- **Galileo was the first to resolve in the "*celestial fluid*" single stars similar to our Sun**

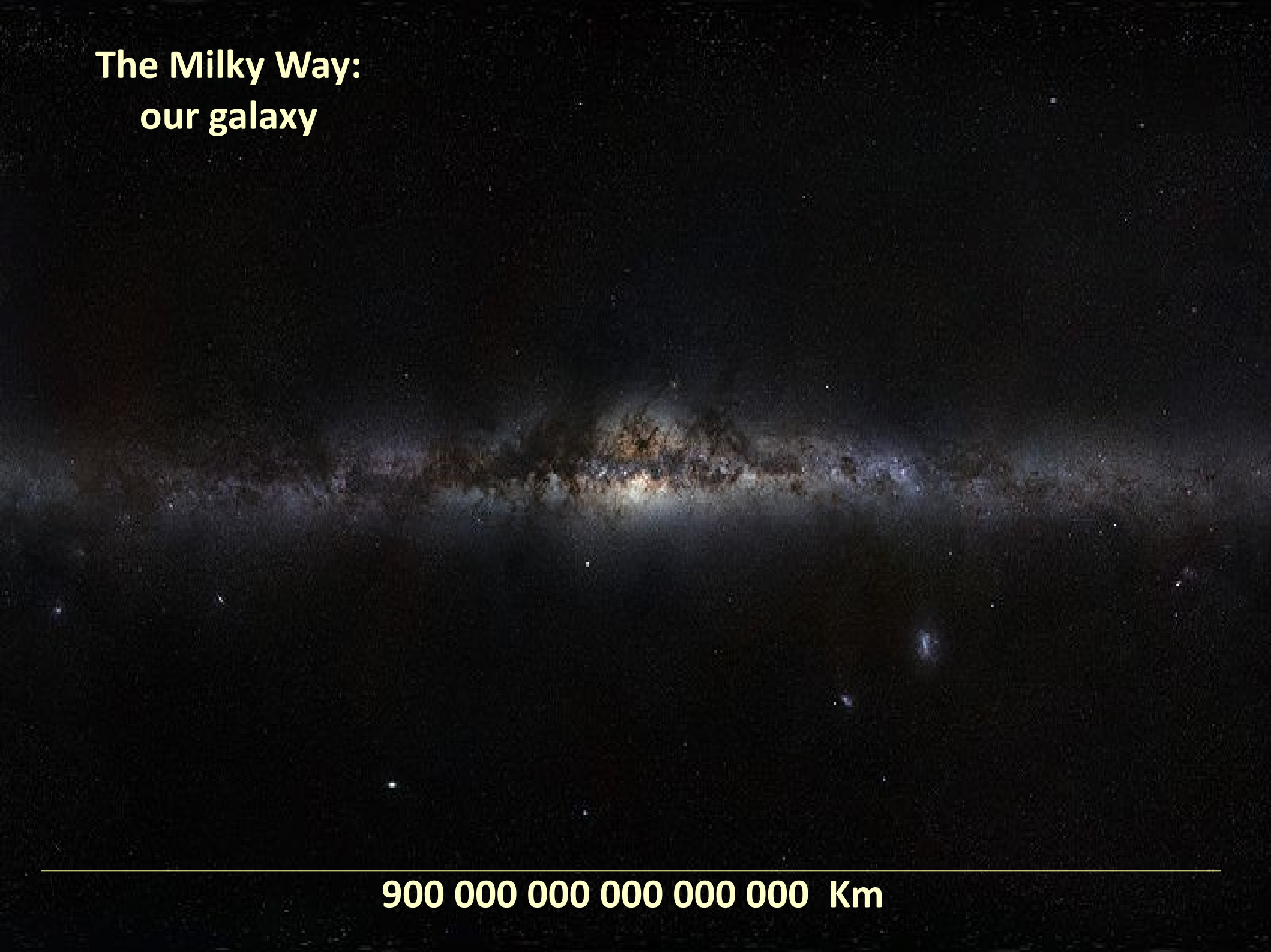
- **Immanuel Kant: the galaxy could be a disk. And why not other similar objects, "universe islands"?**

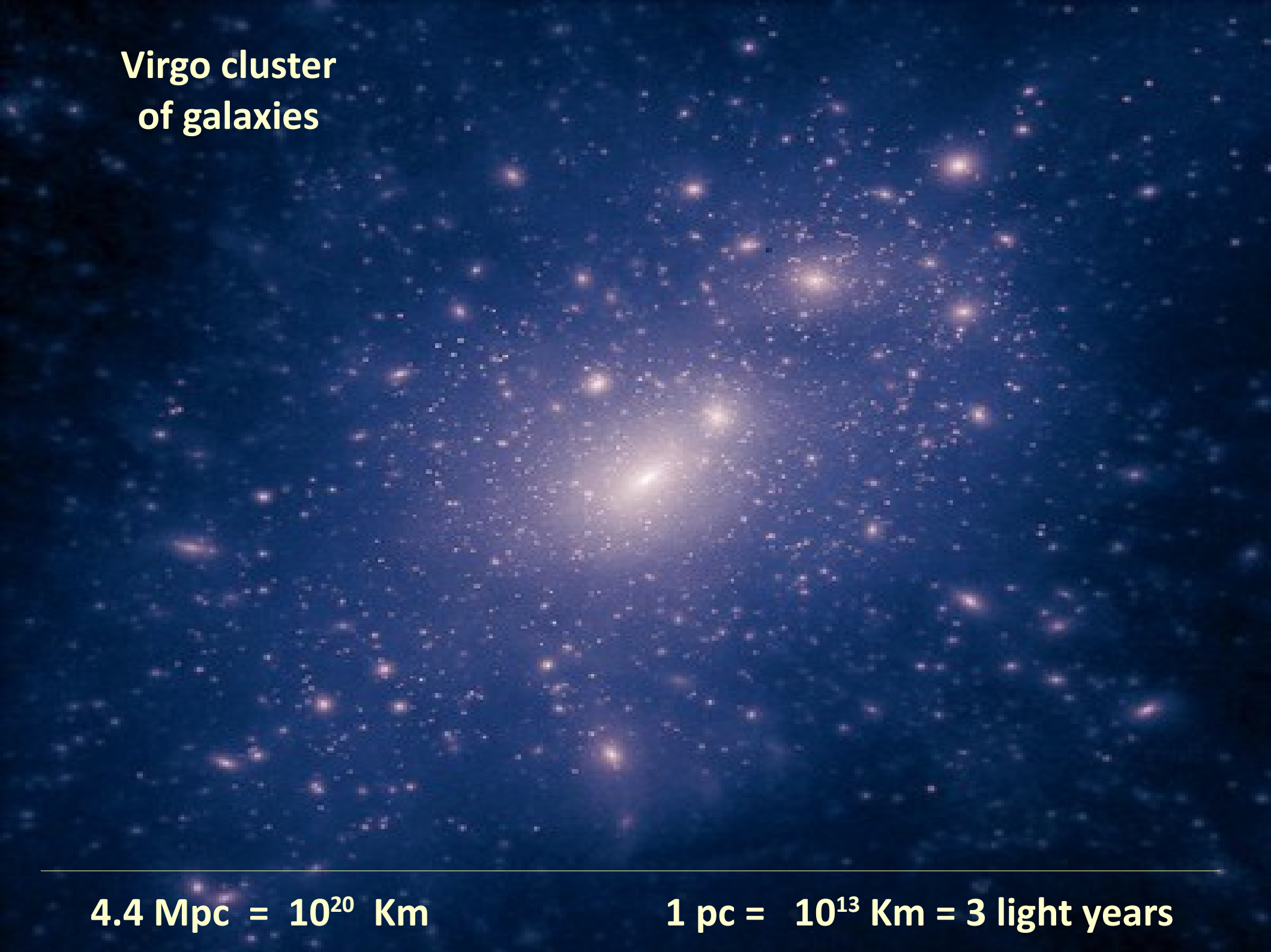
- **construction of greater telescopes.. discovery of the interstellar medium.. birth of spectroscopy..**

- ***finally Hubble resolves single stars in external galaxies. Dymension and structure of our galaxy are established.***


our personal star:
the Sun
700 000 Km


Globular star
cluster
M13
Hercules
80 000 000 000 000 000 Km

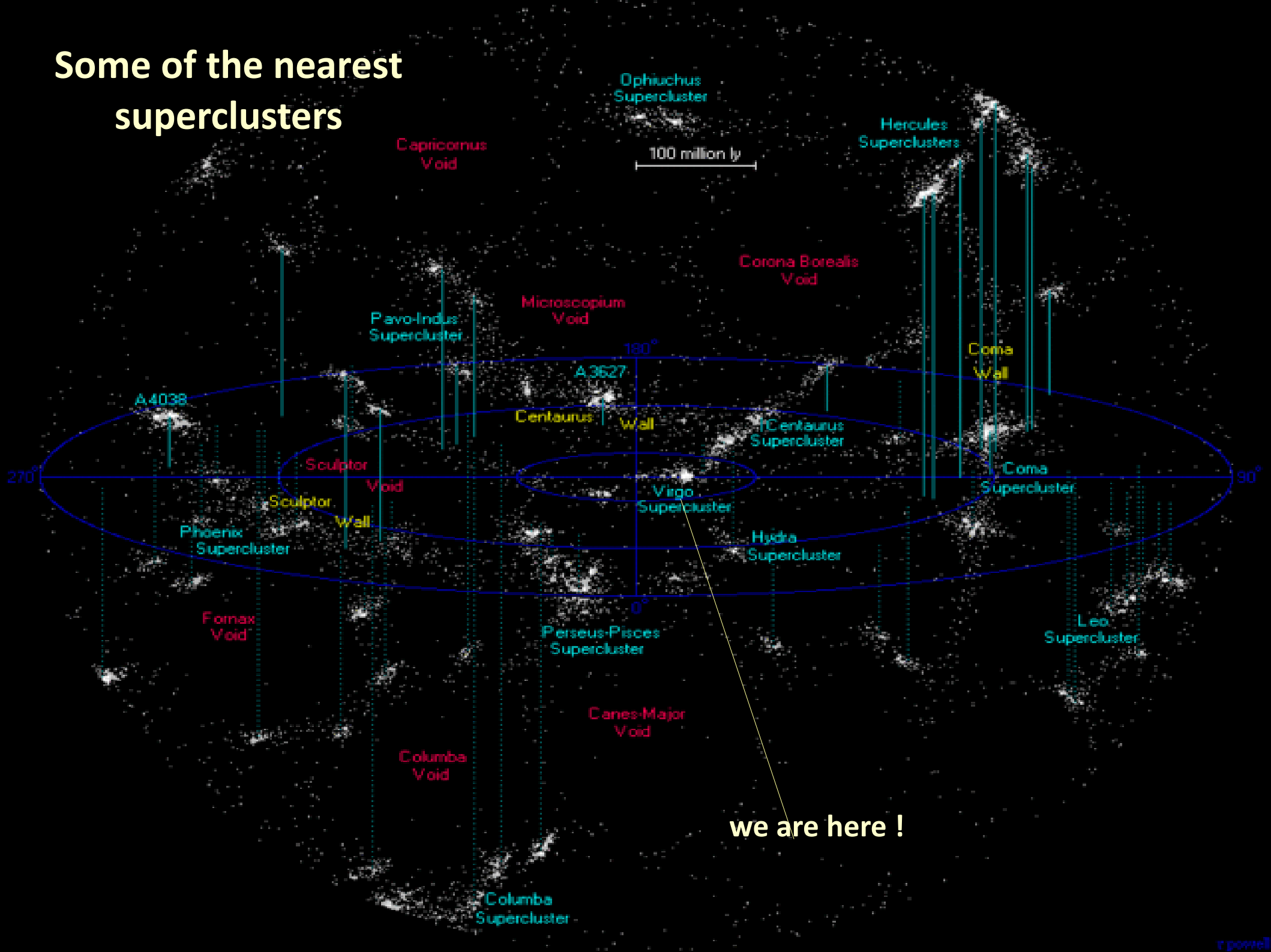

The Milky Way:
our galaxy
900 000 000 000 000 000 Km



4.4 Mpc = 10^{20} Km

1 pc = 10^{13} Km = 3 light years

Some of the nearest superclusters



What we learned?

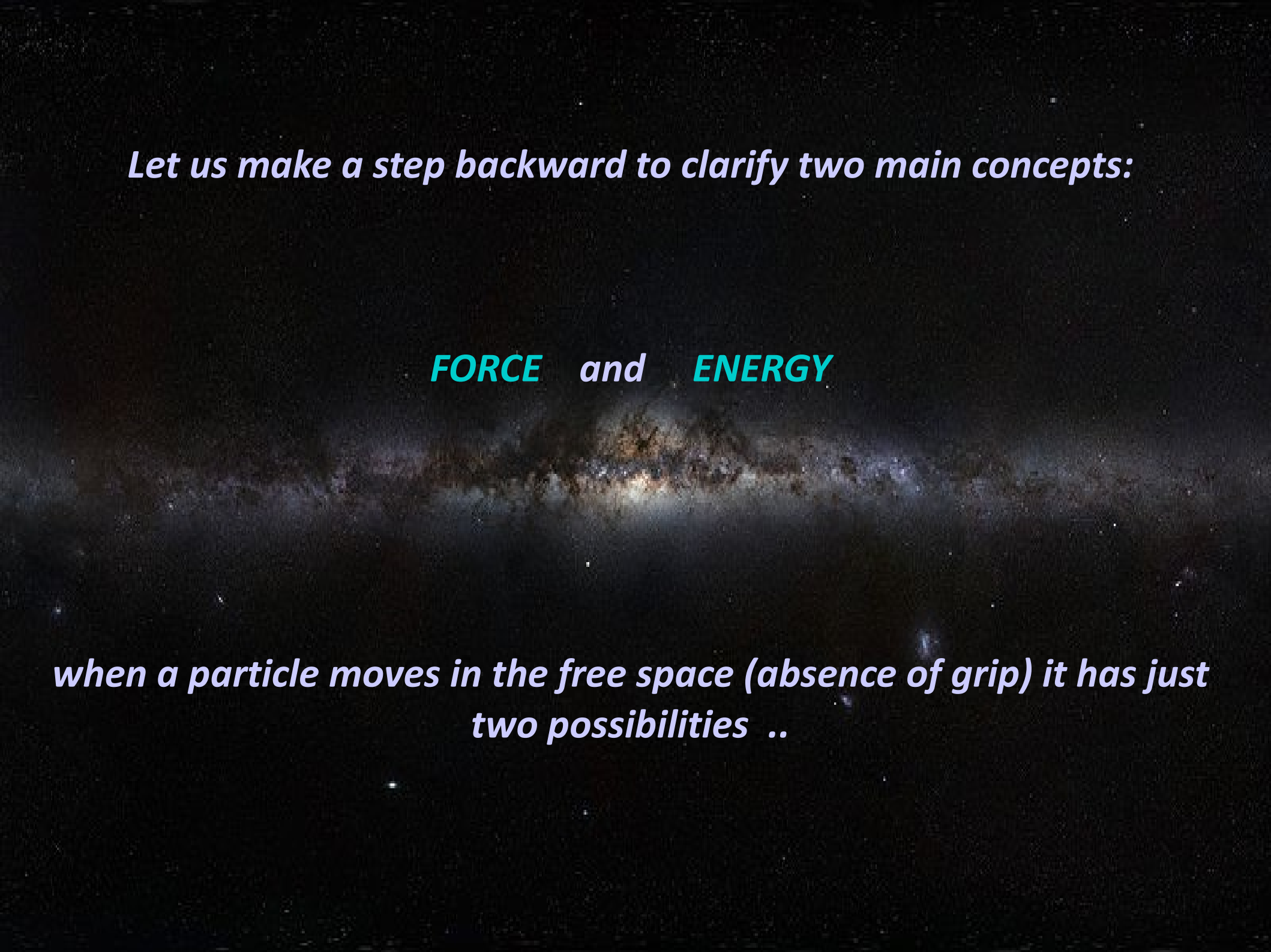
Gravitational force extends to **all the scales** of the universe!!

Gravitation is the force **responsible for the formation of structures** in the universe
it shapes the matter giving rise to complex entirety of particles

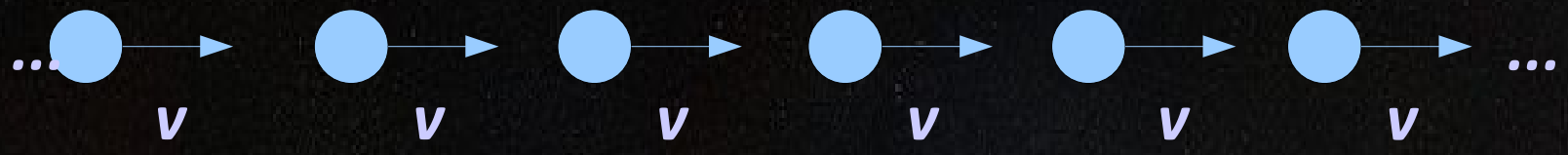
planets, stars, solar systems, clusters of stars,
galaxies, clusters of galaxies, superclusters of galaxies ...

...and so on

*but **WHY GRAVITY ??***


Let us make a step backward to clarify two main concepts:
FORCE and ENERGY
when a particle moves in the free space (absence of grip) it has just two possibilities ..

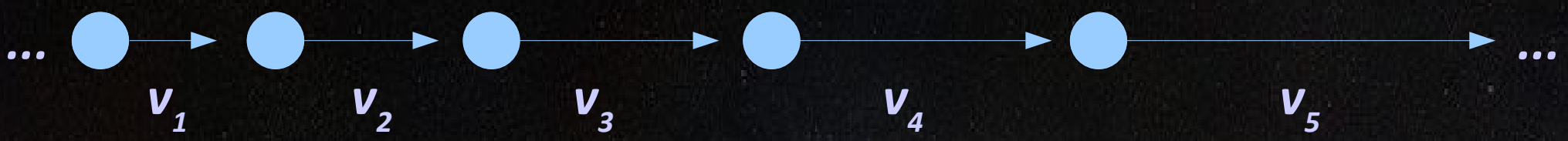
.. ***FIRST POSSIBILITY*** *the particle moves with* ***constant velocity*** *(which could be zero, that is the particle is at rest)*



This means that ***NO FORCE*** *is acting on our particle!! Or the particle is* ***NOT INTERACTING*** *with any other body.*

This case the particle is endowed with an energy due to the simple fact it is moving with a certain CONSTANT velocity, named ***KINETIC ENERGY***

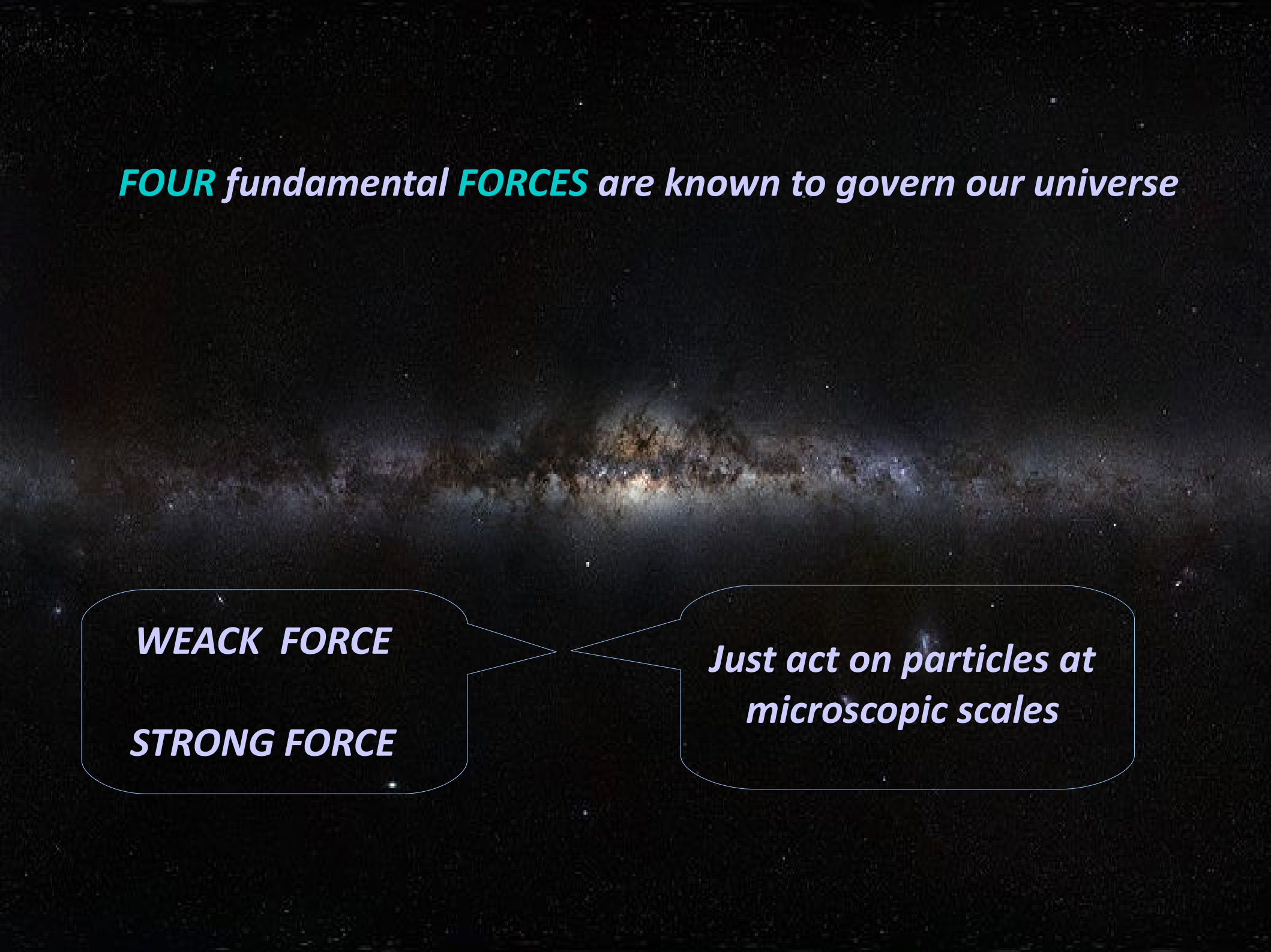
.. SECOND POSSIBILITY the particle moves with a velocity which changes at any instant of time



This means that SOME FORCE is acting on our particle!! Or the particle is INTERACTING with another body.

This case the particle has of course KINETIC ENERGY (just becouse the fact it has a velocity)

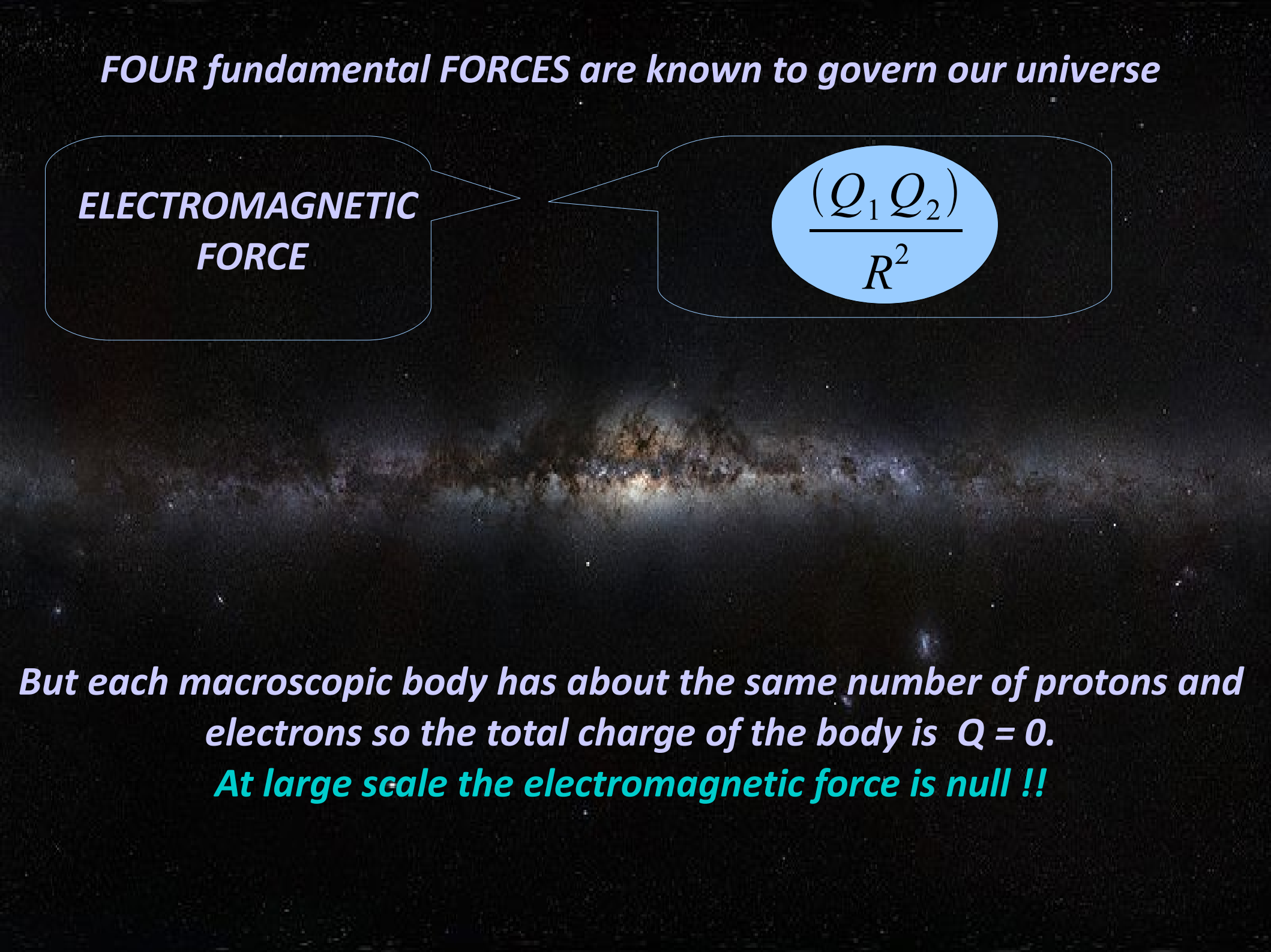
BUT it also has an energy caused by the fact that something external is impressing a force on her..
..this is known as POTENTIAL ENERGY


FOUR fundamental FORCES are known to govern our universe
WEACK FORCE
STRONG FORCE
Just act on particles at microscopic scales

FOUR fundamental FORCES are known to govern our universe

ELECTROMAGNETIC FORCE

$$\frac{(Q_1 Q_2)}{R^2}$$



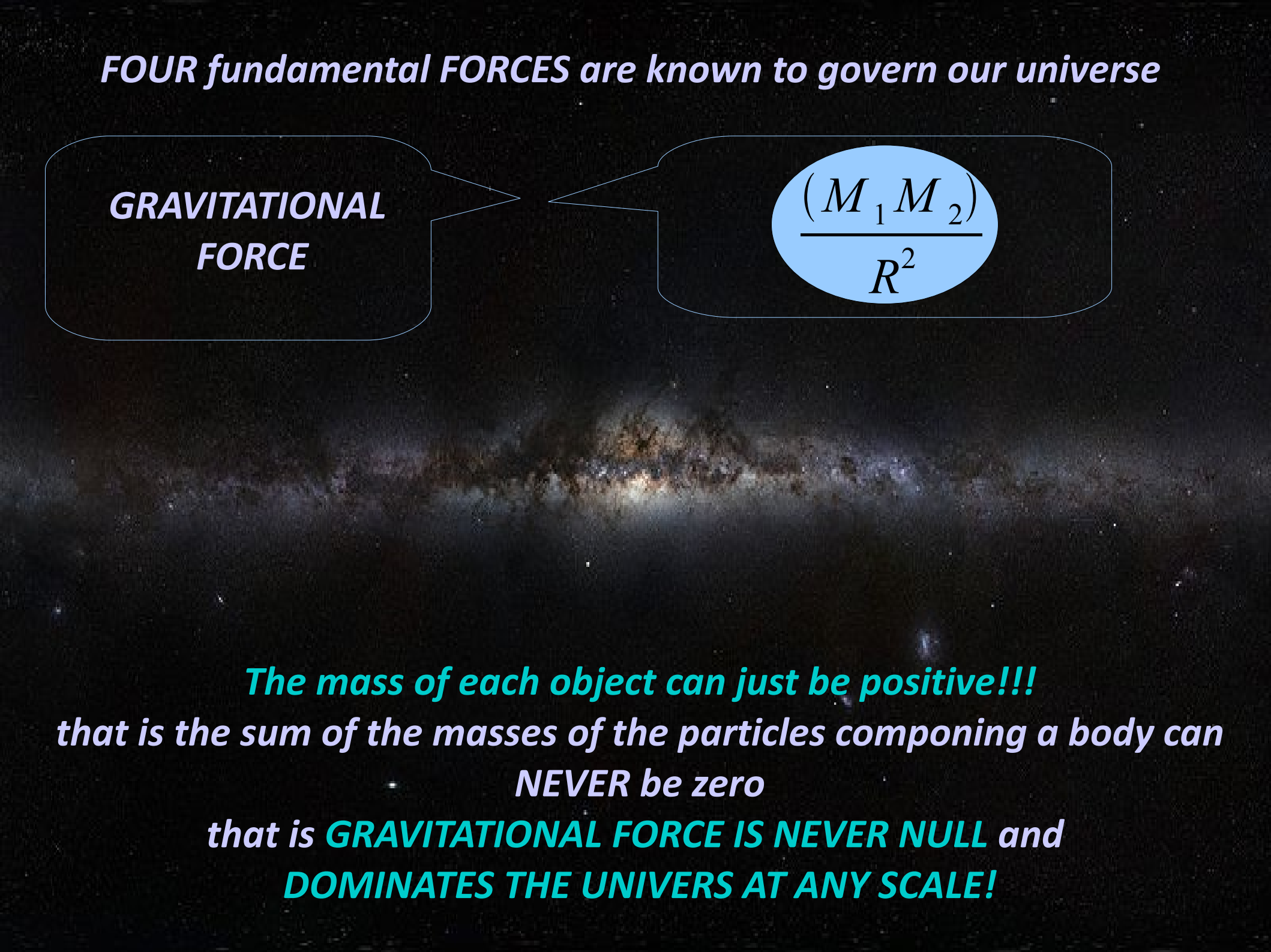
But each macroscopic body has about the same number of protons and electrons so the total charge of the body is Q = 0.

At large scale the electromagnetic force is null !!

FOUR fundamental FORCES are known to govern our universe

GRAVITATIONAL FORCE

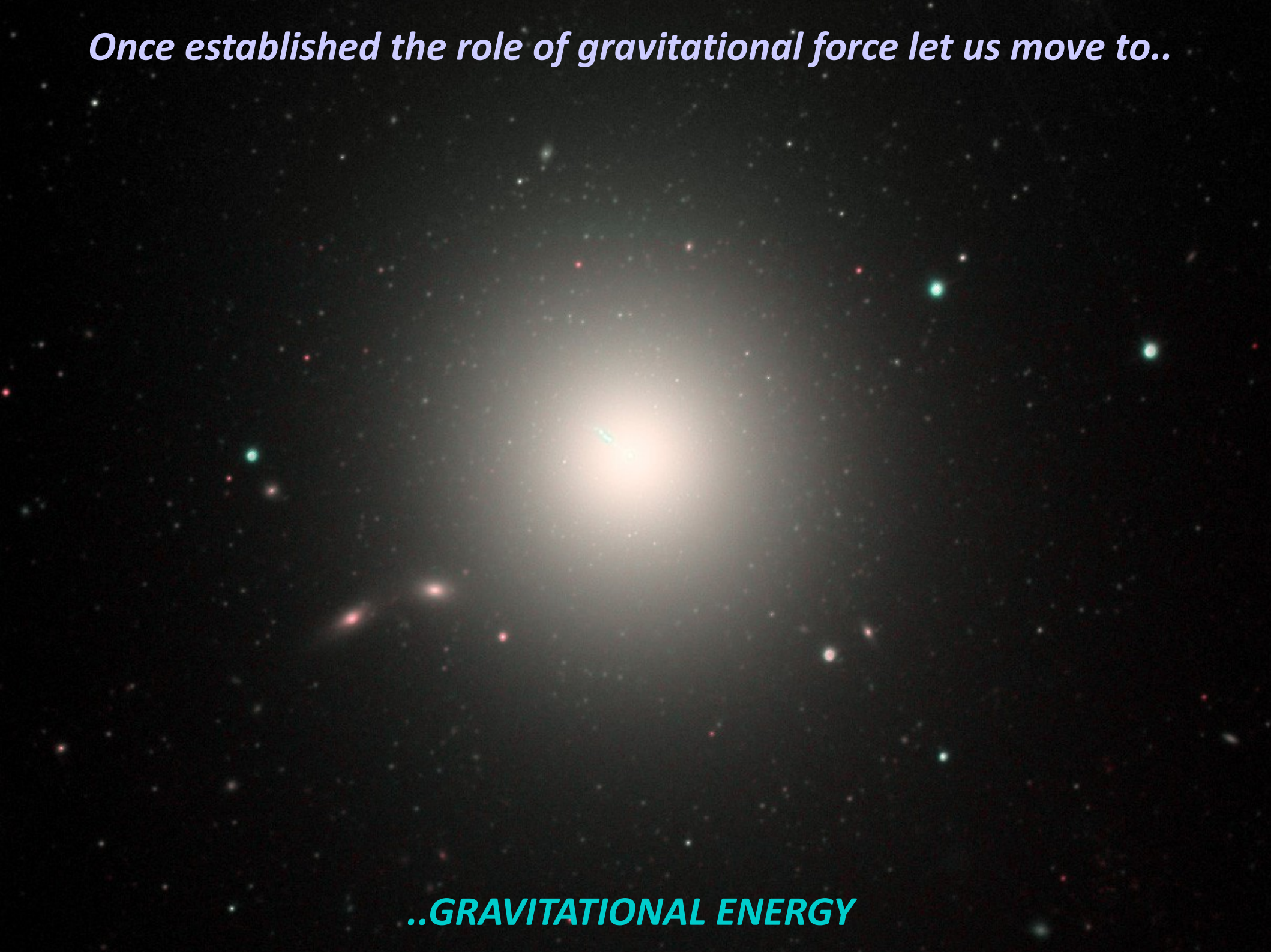
$$\frac{(M_1 M_2)}{R^2}$$

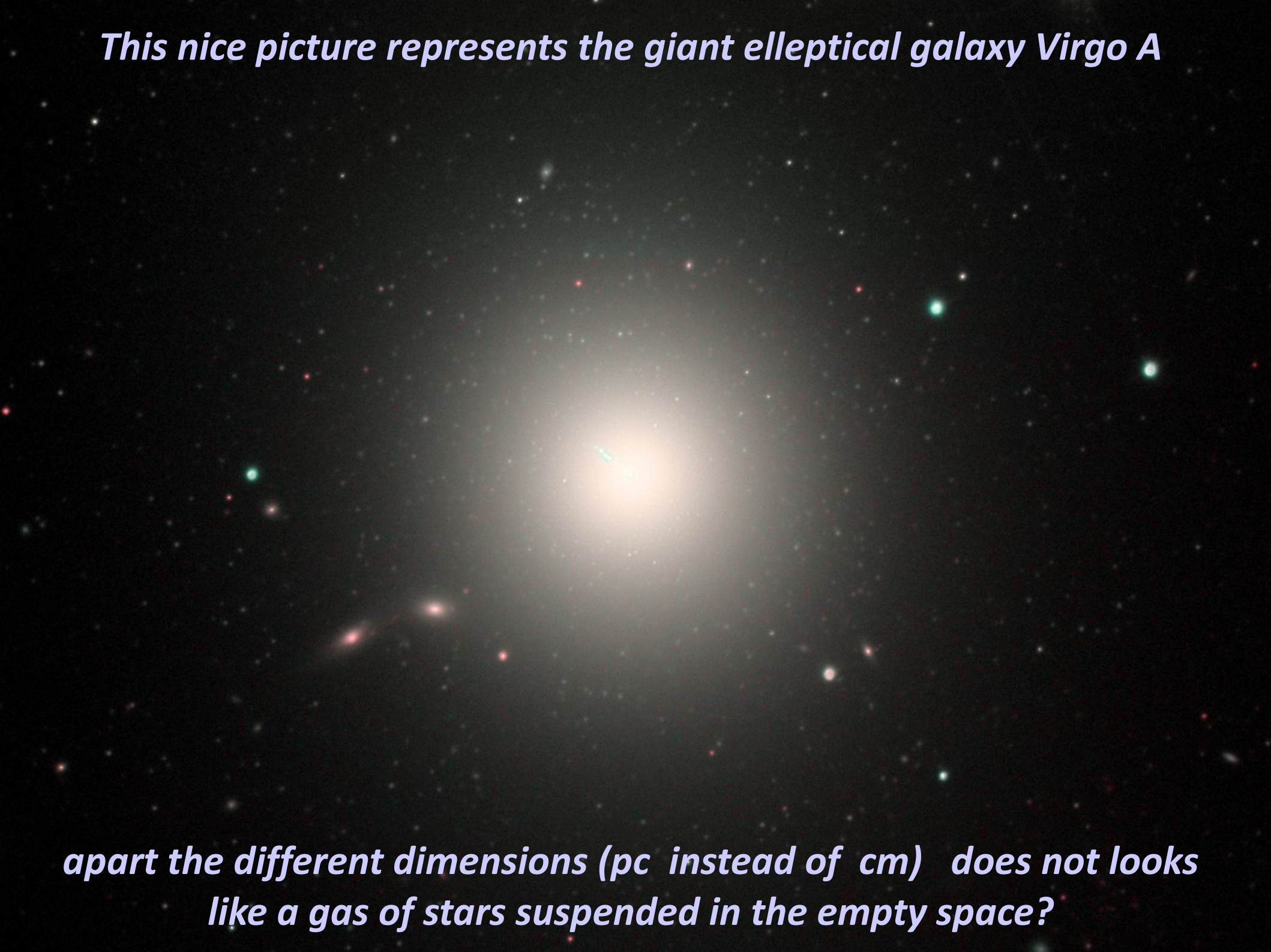


The mass of each object can just be positive!!!

that is the sum of the masses of the particles componing a body can NEVER be zero

that is GRAVITATIONAL FORCE IS NEVER NULL and DOMINATES THE UNIVERS AT ANY SCALE!

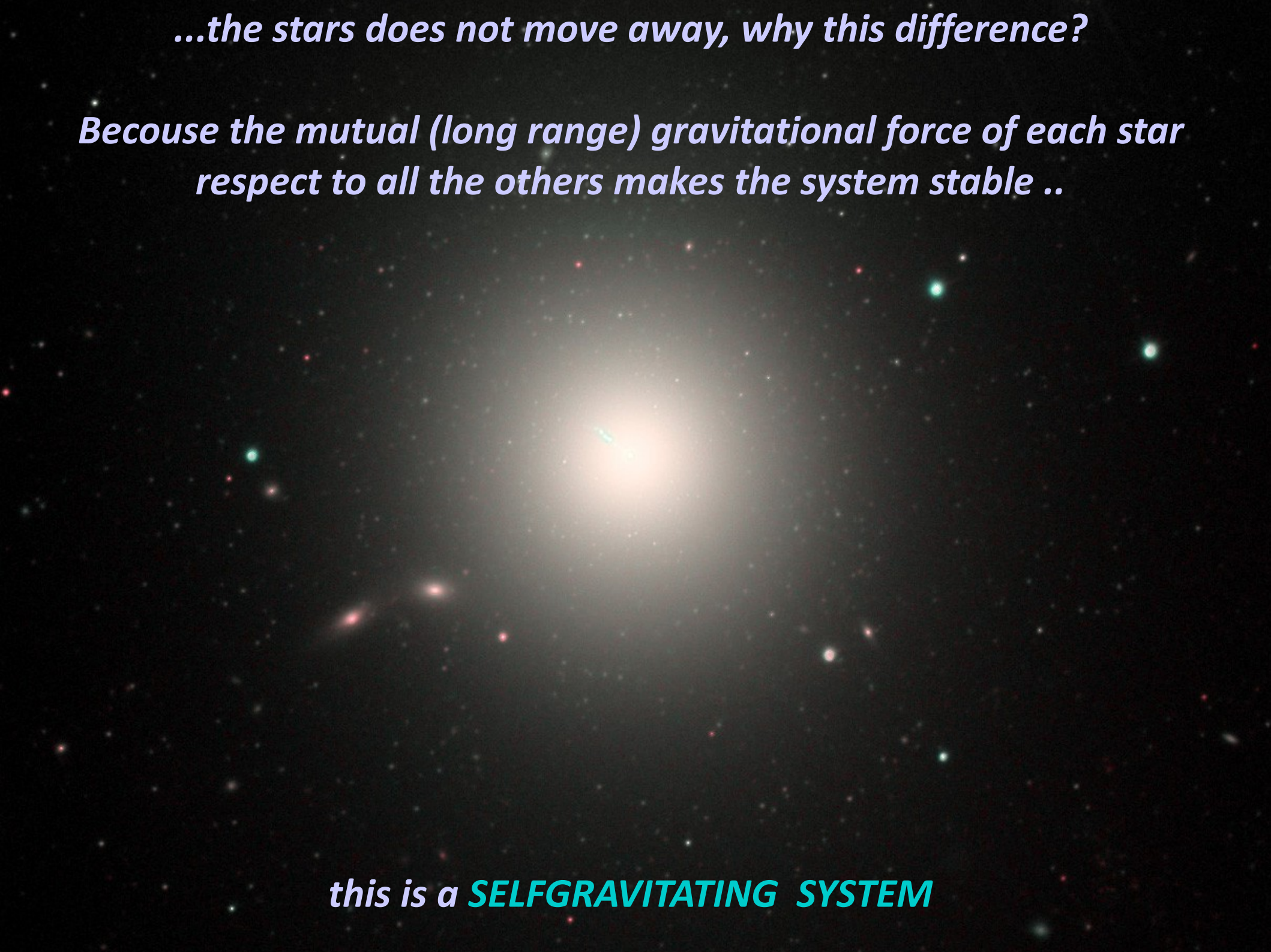

Once established the role of gravitational force let us move to..
..GRAVITATIONAL ENERGY

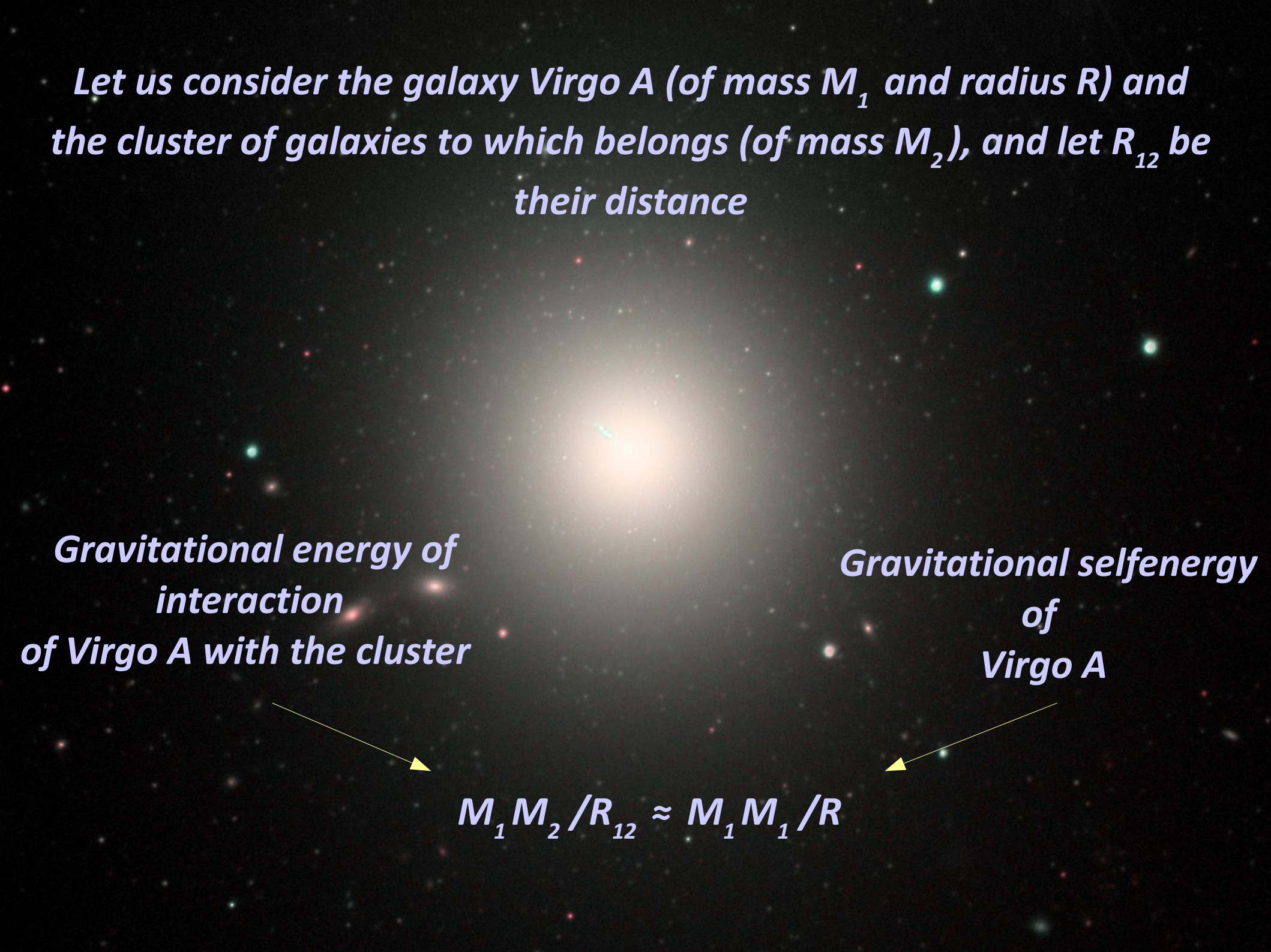

This nice picture represents the giant elleptical galaxy Virgo A
apart the different dimensions (pc instead of cm) does not looks like a gas of stars suspended in the empty space?

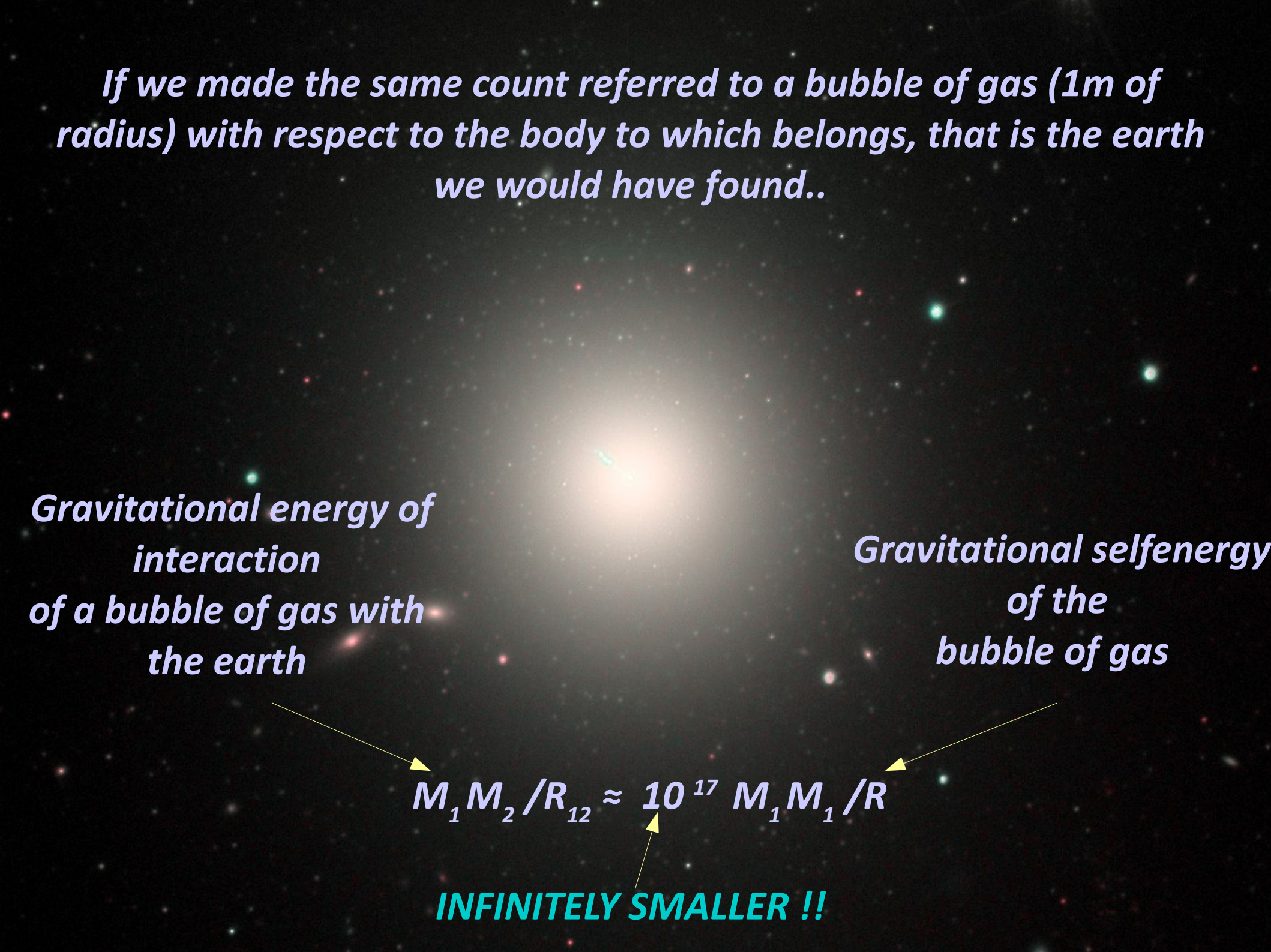
A big difference is immediate:

if you remove the container which encloses the particles of a common gas, this will move away pushed by pressure expanding in all the space at their disposal

while if we remove the bubble surrounding Virgo A ?

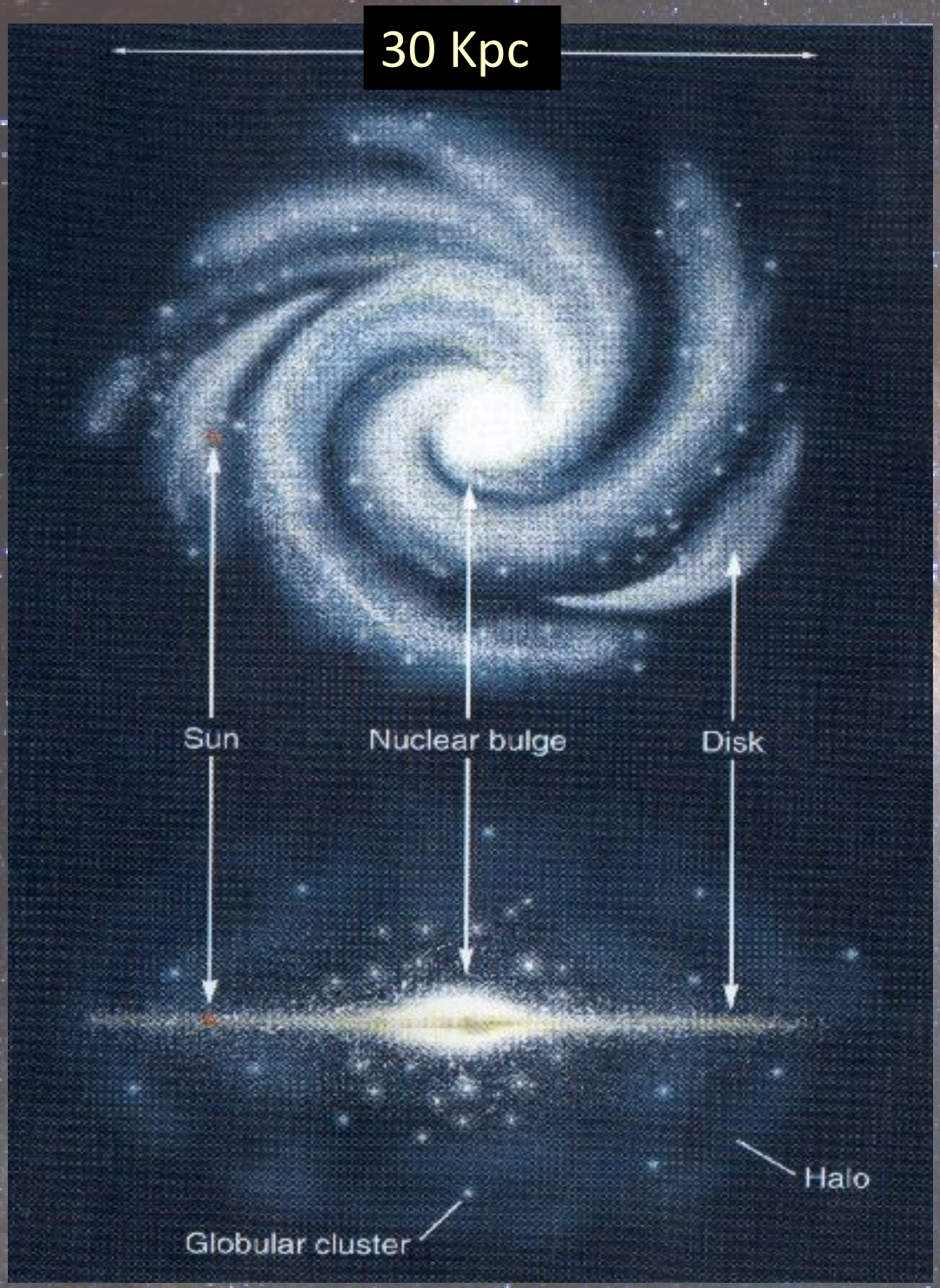

...the stars does not move away, why this difference?
Becouse the mutual (long range) gravitational force of each star respect to all the others makes the system stable ..
this is a SELFGRAVITATING SYSTEM


Let us consider the galaxy Virgo A (of mass M_1 and radius R) and the cluster of galaxies to which belongs (of mass M_2), and let R_{12} be their distance
Gravitational energy of interaction of Virgo A with the cluster
Gravitational selfenergy of Virgo A
$M_1 M_2 / R_{12} \approx M_1 M_1 / R$


If we made the same count referred to a bubble of gas (1m of radius) with respect to the body to which belongs, that is the earth we would have found..
Gravitational energy of interaction of a bubble of gas with the earth
Gravitational selfenergy of the bubble of gas
$M_1 M_2 / R_{12} \approx 10^{17} M_1 M_1 / R$
INFINITELY SMALLER !!


...this is why galaxies, stars etc.. are selfgravitating systems
while common gases are not.

Structure of our galaxy



Main components:

disk **(30 Kpc)**

bulge **(5 Kpc)**

spiral arms

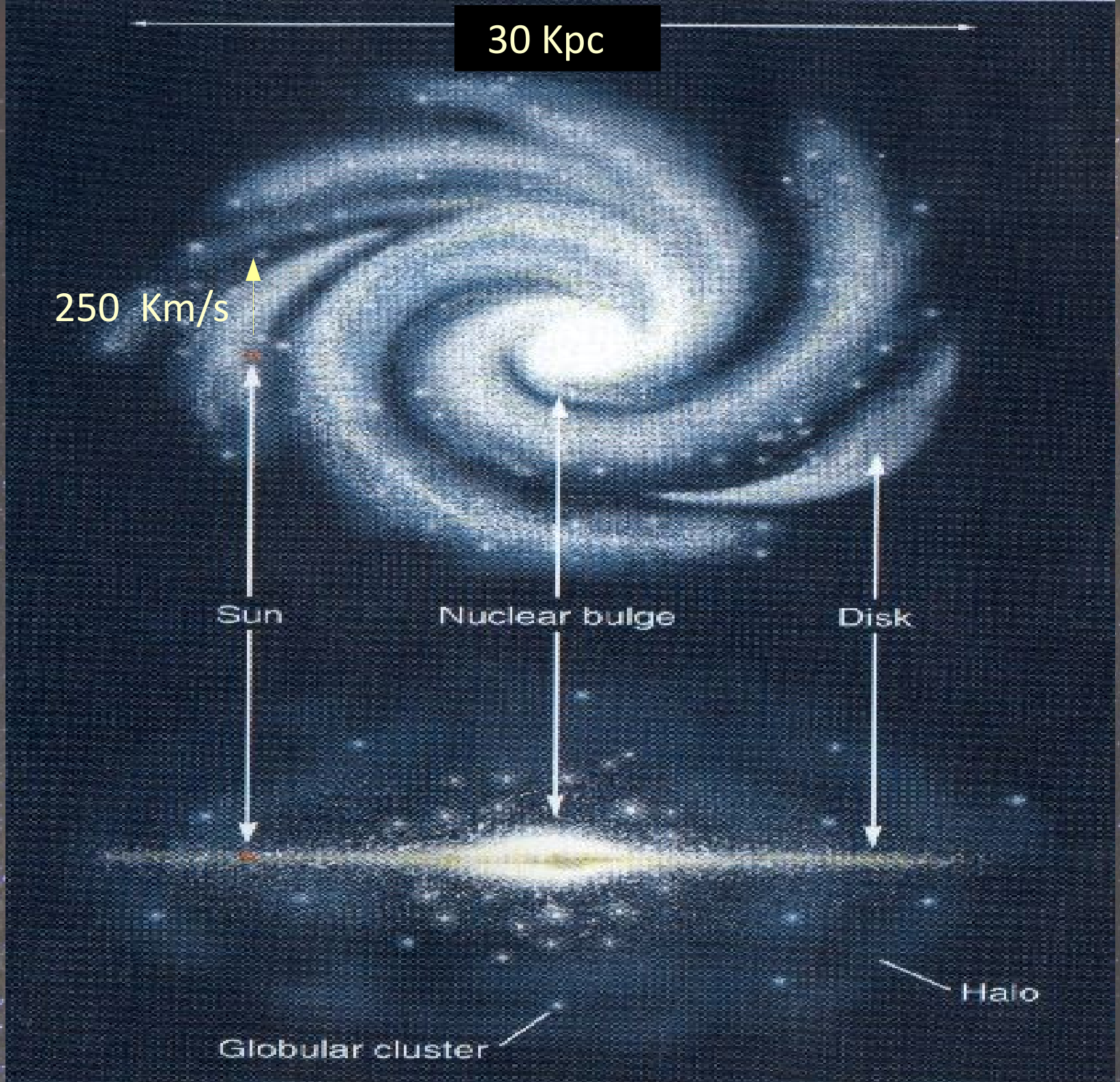
all surrounded by..

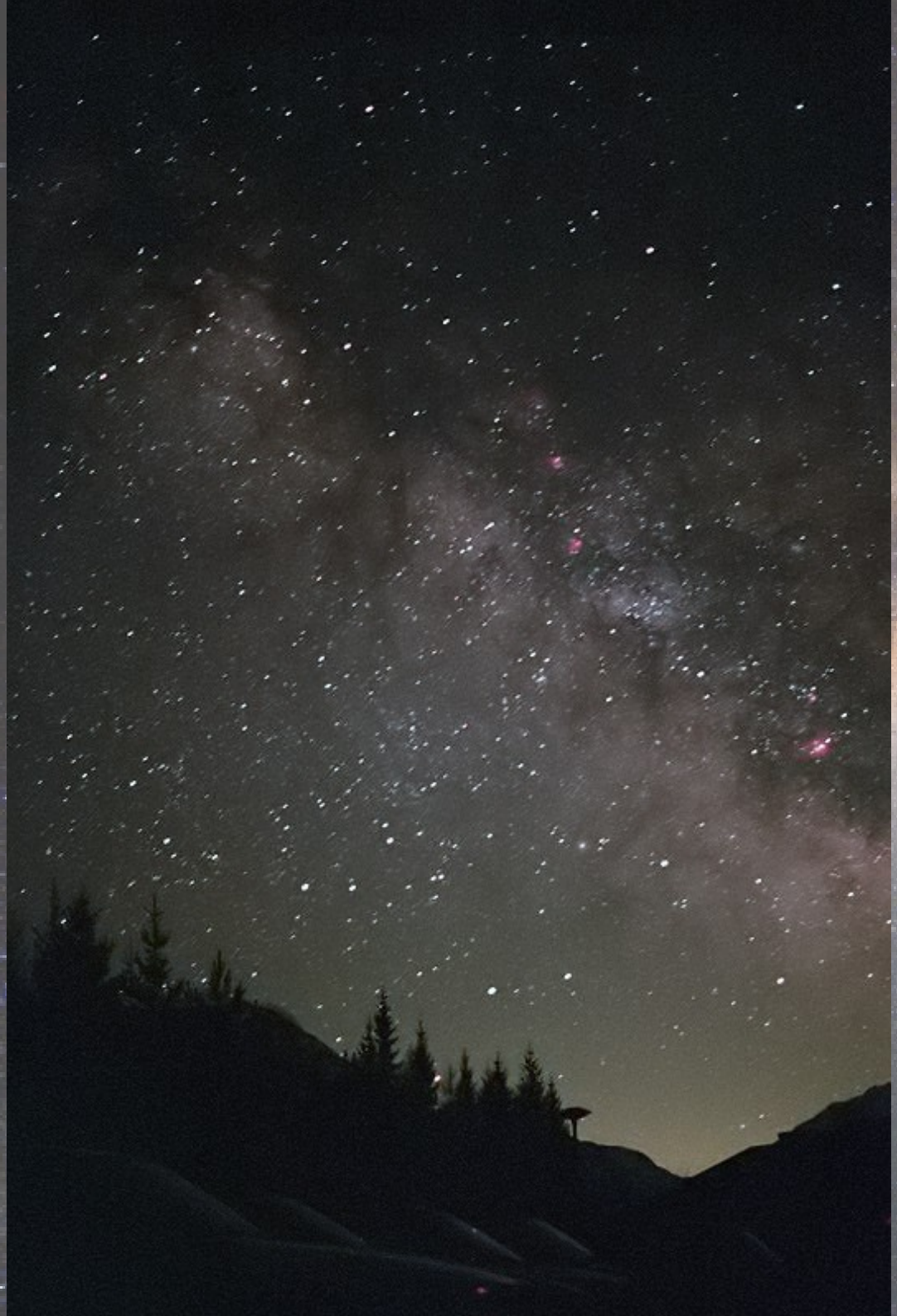
halo **(30 Kpc)**

spherical crown **(100 Kpc)**

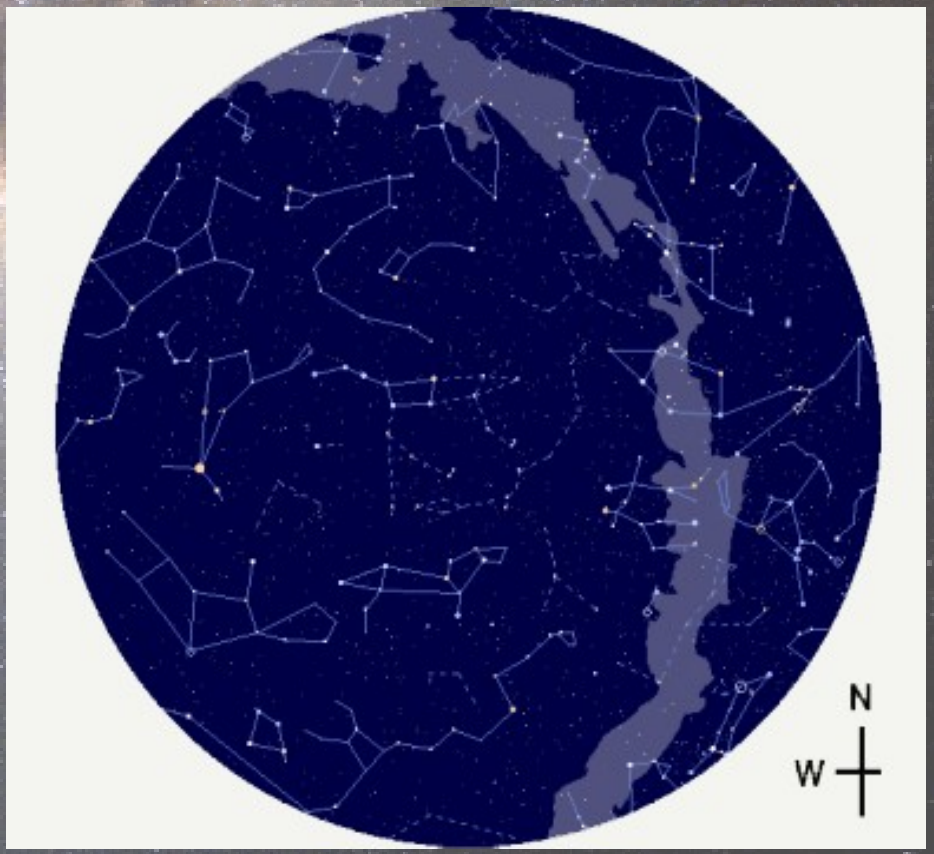
containing about 150

globular clusters


30 Kpc
250 Km/s
Sun
Nuclear bulge
Disk
Halo
Globular cluster



stars and nebulae surrounding us appear projected on the celestial sphere as a luminous maximum circle



The situation looks complicated..

but it's even MORE COMPLICATED

the Galaxy is just one of billions galaxies which populates the universe. These looked to first observers as diffuse nebulae..

10% of matter in our Galaxy is in the form of diffused matter.
Cluods of matter in our galaxy (75% H 25% He)
(expelled by supernova explosions as we will see..)
illuminated by near stars can appear as galaxies.

Finally more powerful telescopes resolved in stars or globular clusters the periphery of nearest galaxies which gained a clear identity: Kant was right!!

The first classification of galaxies is due to Hubble, also known

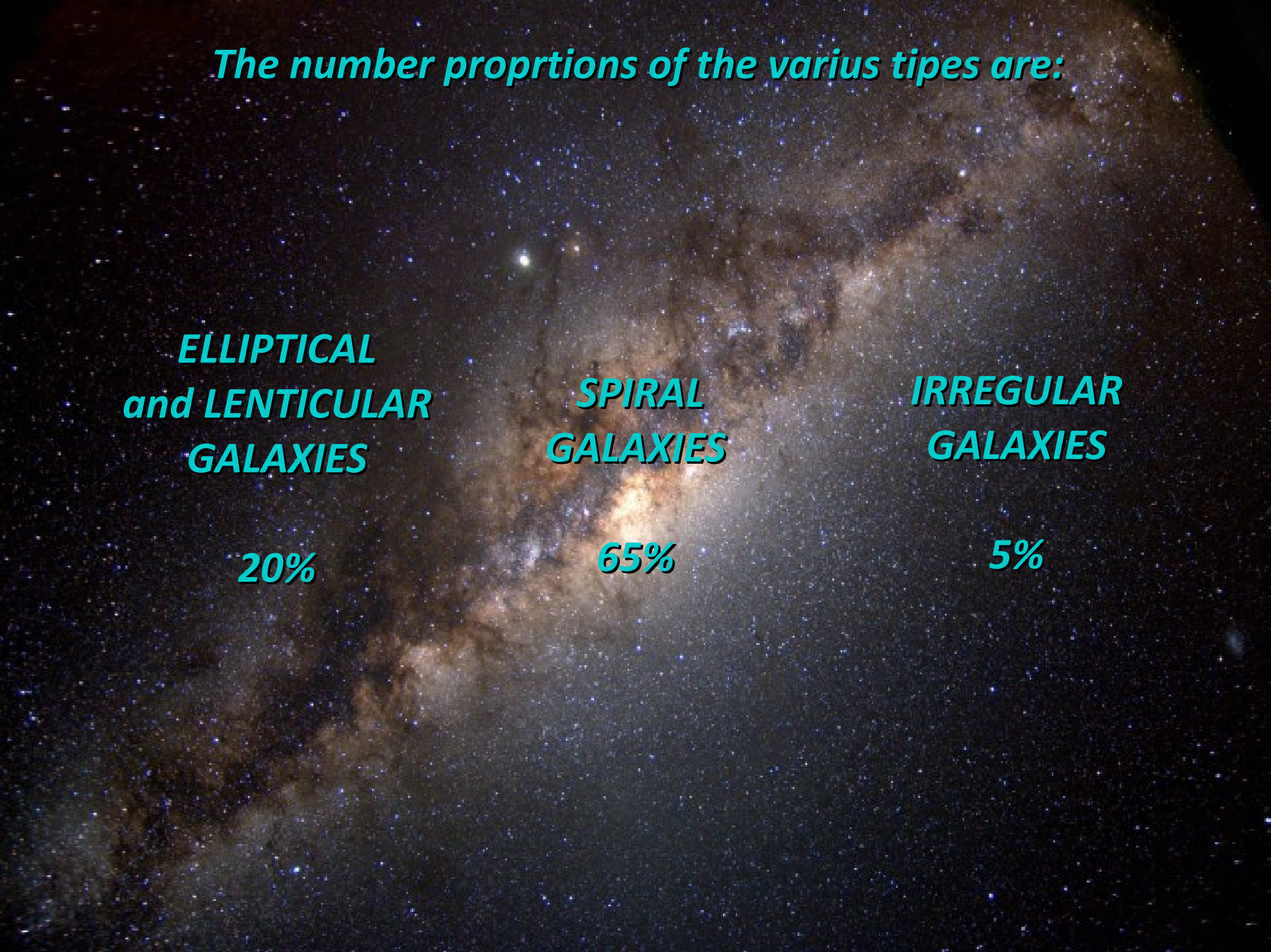
DIAPASON

NORMAL SPIRAL GALAXIES

ELLIPTICAL and LENTICULAR GALAXIES

IRREGULAR GALAXIES

BARRED SPIRAL GALAXIES


The number proprtions of the varius tipes are:
ELLIPTICAL and LENTICULAR GALAXIES
20%
SPIRAL GALAXIES
65%
IRREGULAR GALAXIES
5%

MAIN DIFFERENCES:

ELLIPTICAL GALAXIES

elliptical galaxies show almost spherical simmetry.
They are caracterized by older, smaller, and more red stars.

SPIRAL GALAXIES

their bulge is similar to an elliptical galaxy.
The disc is reach of joung, massive, and more blu stars.

All the galaxies has the same age: 10^{10} years

Searching for a model of galaxy formation
gravitational instability

The first physician who faced the problem of the formation of gravitational structures was Jeans at the beginning of ninetienth century.

He imagined an infinite, uniform, homogeneus and static gas of particles which self-interact via gravitational force.

The prototipe for this gas are interstellar medium (75% H, 25% He) very low density (about 100 particles per cm^3) or HII regions, formed by ionized hydrogen

Searching for a model of galaxy formation

gravitational instability

Let us now imagine that something causes in this gas a small local perturbation, which modifies density, pressure and velocity of the particles

Jeans discovered that such perturbation will evolve like an exponentially growing spherical wave if the mass of the gas exceedes the critical value:

$$M_J \alpha 1/\rho^{0,5}$$

this give srise to the shrinking of the matter inside a radius λ_J and it's density grows and grows up..

Searching for a model of galaxy formation

gravitational instability

The critical mass for a static interstellar medium, or an HII region is of the order of $10^6 M_o$

one million times greater than the mass of the sun !!

but becomes much greater for a rotationg gas such as the medium in which spiral protogalaxies form.

To conclude the formation of a spiral galaxy follows these steps:

1) a protogalactic rotating cloud, of spherical shape undergoes gravitational instability

2) angular momentum conservation makes the contraction follow a disk shape and not spherical

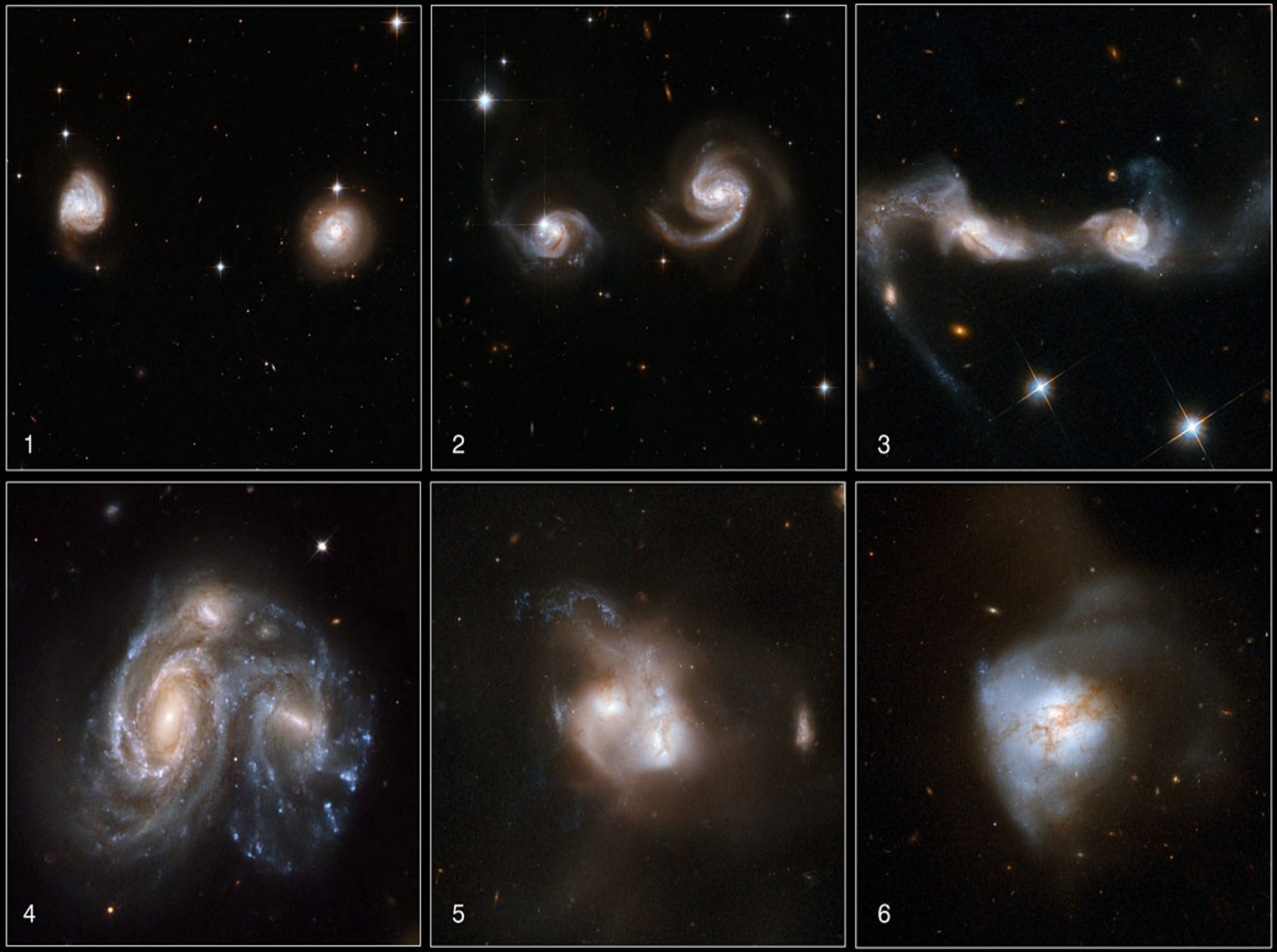
3) fragments of the protogalactic cluod, shot from the central body, contract to form globular clusters

4) friction in turbolent motions gives rise to a bulge

5) perturbations in the disk originates the spiral arms.


AND FOR WHAT REGARDS ELLIPTICAL (LENTICULAR) GALAXIES ?
The hypotesis is that colossal galaxy collisions,
in the central parts of galaxy cluters where the density is higher
gives origin to these huge “spherical” structures

The phases of a colossal galaxy collision



Formation and evolution of stars

(one of the main achievements of human mind)

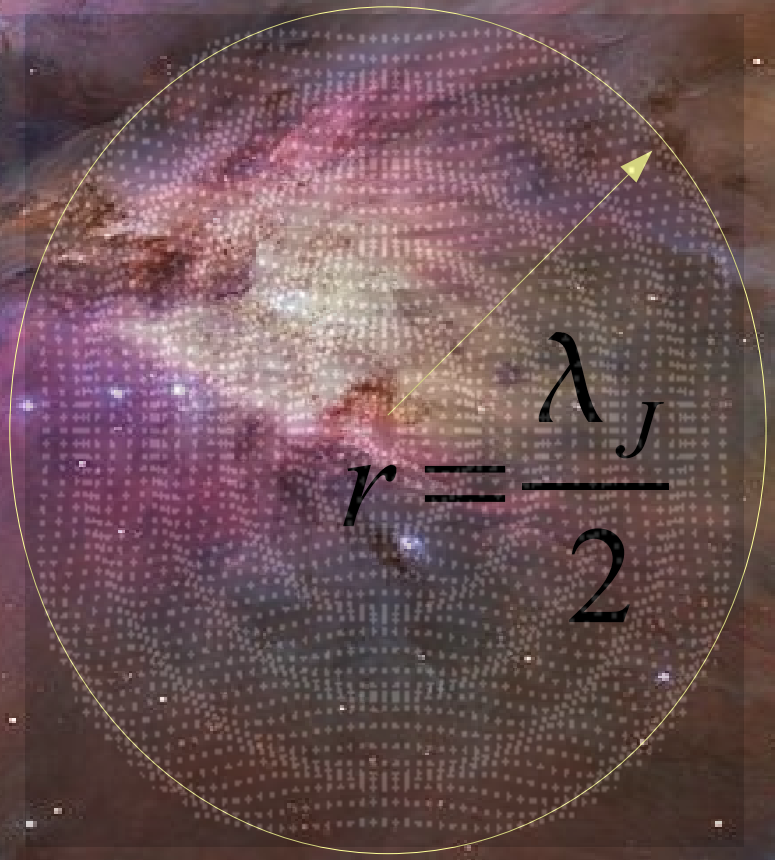
- *Theory of stellar structure: selfconsinstent theory based on balance between pressure and gravity*
  balance between generated energy and emitted energy
  energy transportation across the star

- *Totally confirmed by the study of the Sun, and star populations in globular clusters (globular clusters are the consequence of one single formation impulse, all has the SAME AGE but DIFFERENT INITIAL MASSES!!!) REPRESENT A SNAPSHOT OF ALL POSSIBLE CONFIGURATIONS*

- *Explains the origin of ALL the chemical known elements*
  BIG BANG just created H and He

Orion nebula

interstellar medium becomes instable respect to the propagation of a density perturbation, if the radius exceeds a critical value: the JEANS RADIUS

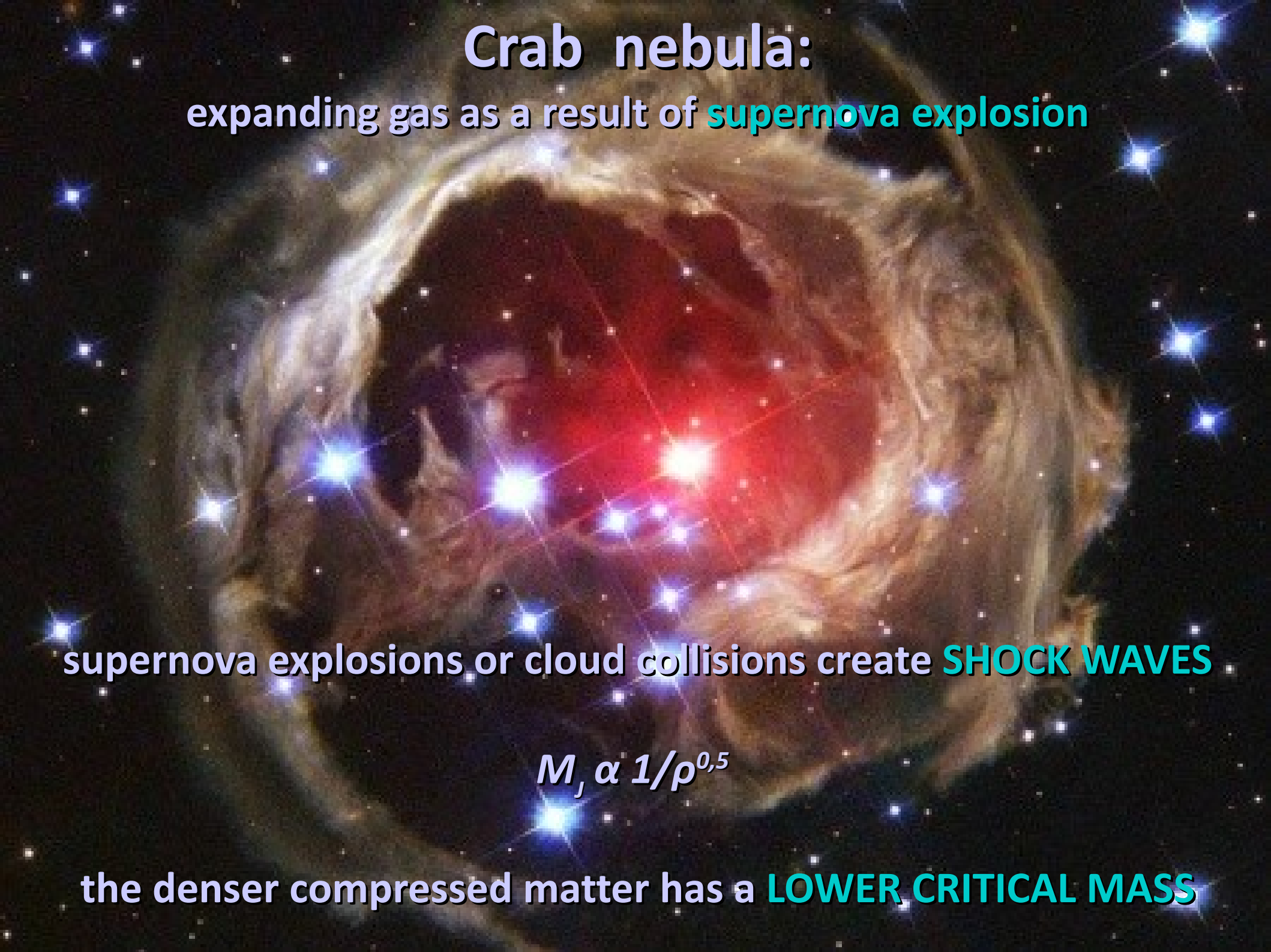


this corresponds to a mass of 10^6 M_o

1 MILLION TIMES THE SUN

*This explains **globular clusters**.. but not the formation of single stars like the Sun!*

What is the solution to the paradox??


Crab nebula:
expanding gas as a result of supernova explosion
supernova explosions or cloud collisions create SHOCK WAVES
$M_J \alpha 1/\rho^{0,5}$
the denser compressed matter has a LOWER CRITICAL MASS


Young bright stars clearly visible at the border of spiral arms
consequence of shock waves which compresses the matter

..the cloud collapses, radius decreases
gravitational energy grows

$$W = -\tfrac{1}{2} GM^2/r$$

kinetic energy $K = \tfrac{1}{2} GM^2/2r$ gravitational energy

BUT energy does not disappear, it transforms in kinetic energy
that is heat..

$K = 3/2\ k\ T$ kinetic energy is temperature
the temperature begins to grow

equilibrium between gravity and pressure
begins to enstablish indeed..

$$P\ V = N\ k\ T$$

The protostar develops a dense and hot nucleus ($M_{nuc} = ½ M_{star}$) and reaches a stage named ***zero age sequence***

the time passed from the beginning is
$\tau_k = 10^7$ *years*

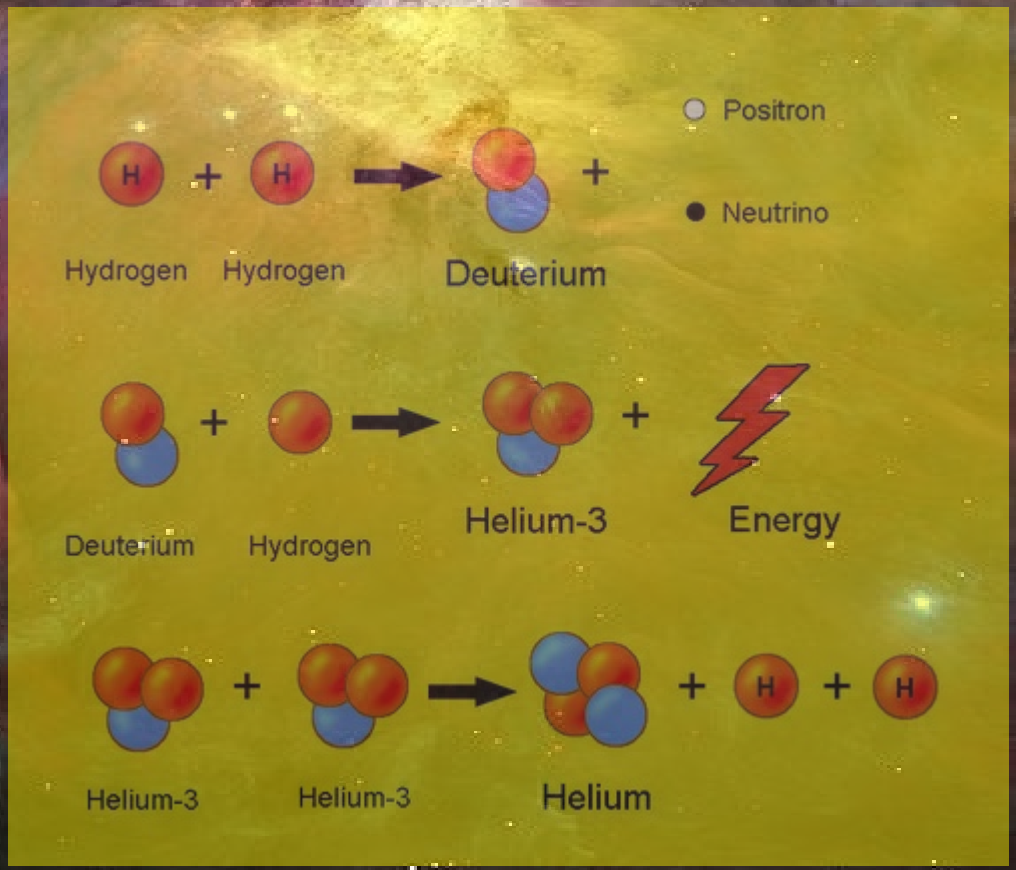
if the star mass is M > 1/10 M_o somthing extraordinary happens that represents the ***birth of the star ...***

When the nucleus temperature reaches 10^7 °K
nuclear fusion of hydrogen in helium begins

ENERGY

$$4H \rightarrow He + 2e^{+} + 2\nu + photons$$

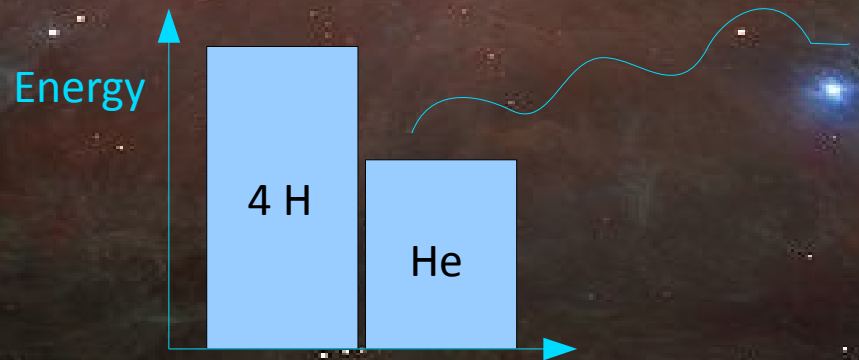
this can happen trough varius reactions, one of this is *p-p* chain



Each system of interacting objects in the universe naturally evolves towards the condition of minimum energy

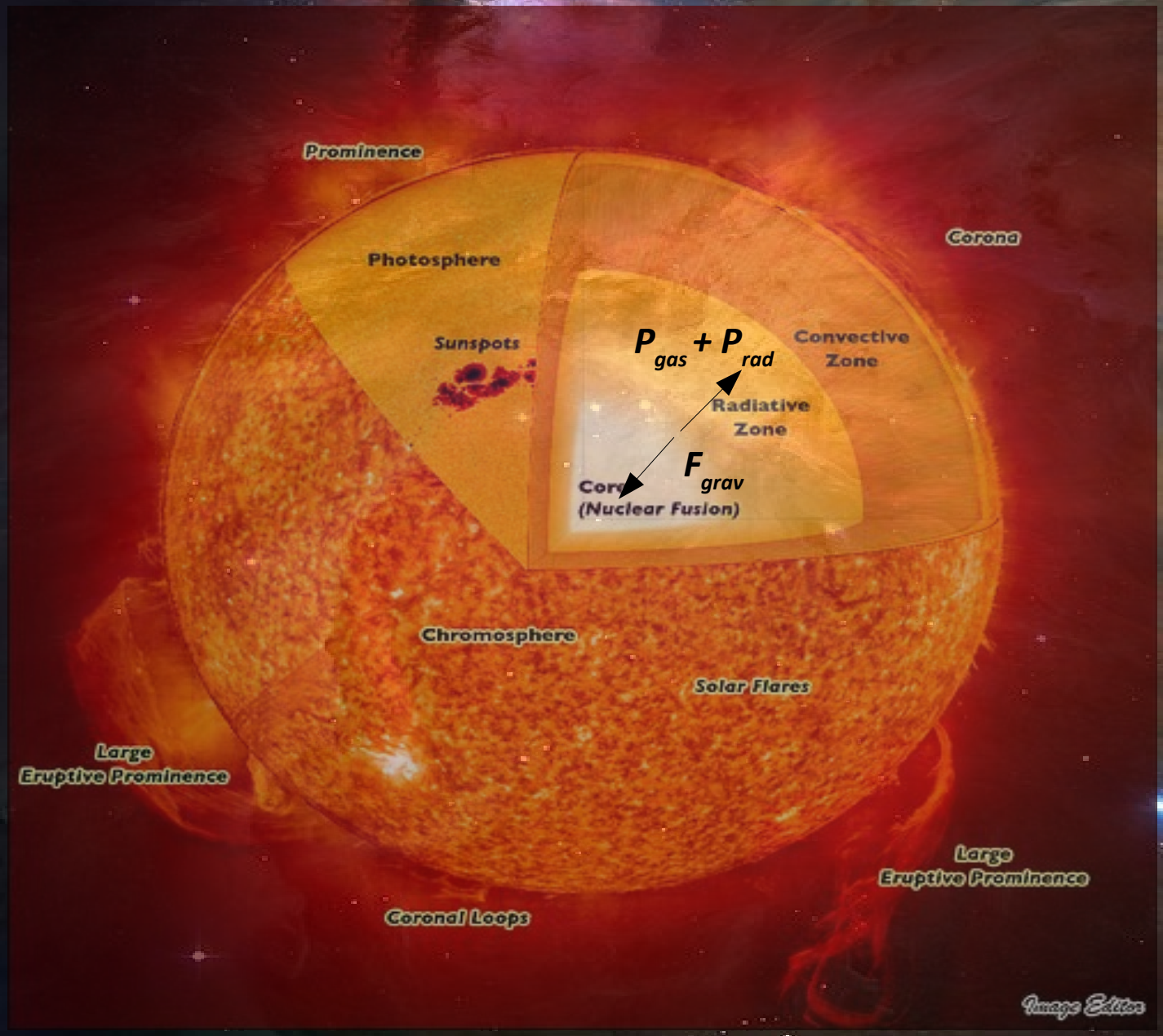
the total energy of four separated hydrogen atoms is greater then the total energy of the helium nucleus

the energy difference is emitted in the form of particles and mainly photons



The protostar evolution is finished!

nuclear contraction stops becouse the balance of gravity and pressure



NUCLEUS: where nuclear fusion takes place

ATMOSPHERE: responible for the radiation emitted

T, P and ρ decrease from the center to the edge

The time spended by the star in this stage is the time needed to transform all the H present in the nucleus in He

$t_H \alpha M/L = 10^{10}$ *years for the sun*

the main sequence life is as short as big is the mass!!
huge stars rapidly burn their fuel

massive stars has greater temperatures
high temperature means brighter colours
from white to blue

If instead the mass of the protostar is too small

$M < 0.1\ M_{\odot}$

the temperature reached by the nucleus is not sufficient ..
the star continues to contract
it's temperature decreases
the star ends it's life as a ***black dwarf***

When all the H present in the core is converted into He
H fusion shifts in a shell surrounding the He nucleus

the central engine is turn off → gravity is not substained

the nucleus collapses and the central temperature rises to

$T = 10^8\ ^oK$ *!!*

the fusion of He in C begins

trigger of He will coincide with a violent FLASH!

The transformation of a star with a mass similar to Sun will be magnificent and catastrofic..

..as shown by this nice picture of a star in the fase of GIANT

The transformation of a star with a mass similar to Sun will be magnificent and catastrofic..
the contraction of the nucleus will cause the expansion of the envelop and the atmosphere

Mercury, and Venus will be completely destroyed ...

The transformation of a star with a mass similar to Sun will be magnificent and catastrofic..
as the nucleus expands the envelop and the atmosphere expand

the Earth itself will not survive

The same processes characterizes the subsequent evolution in stars of greater and greater mass:

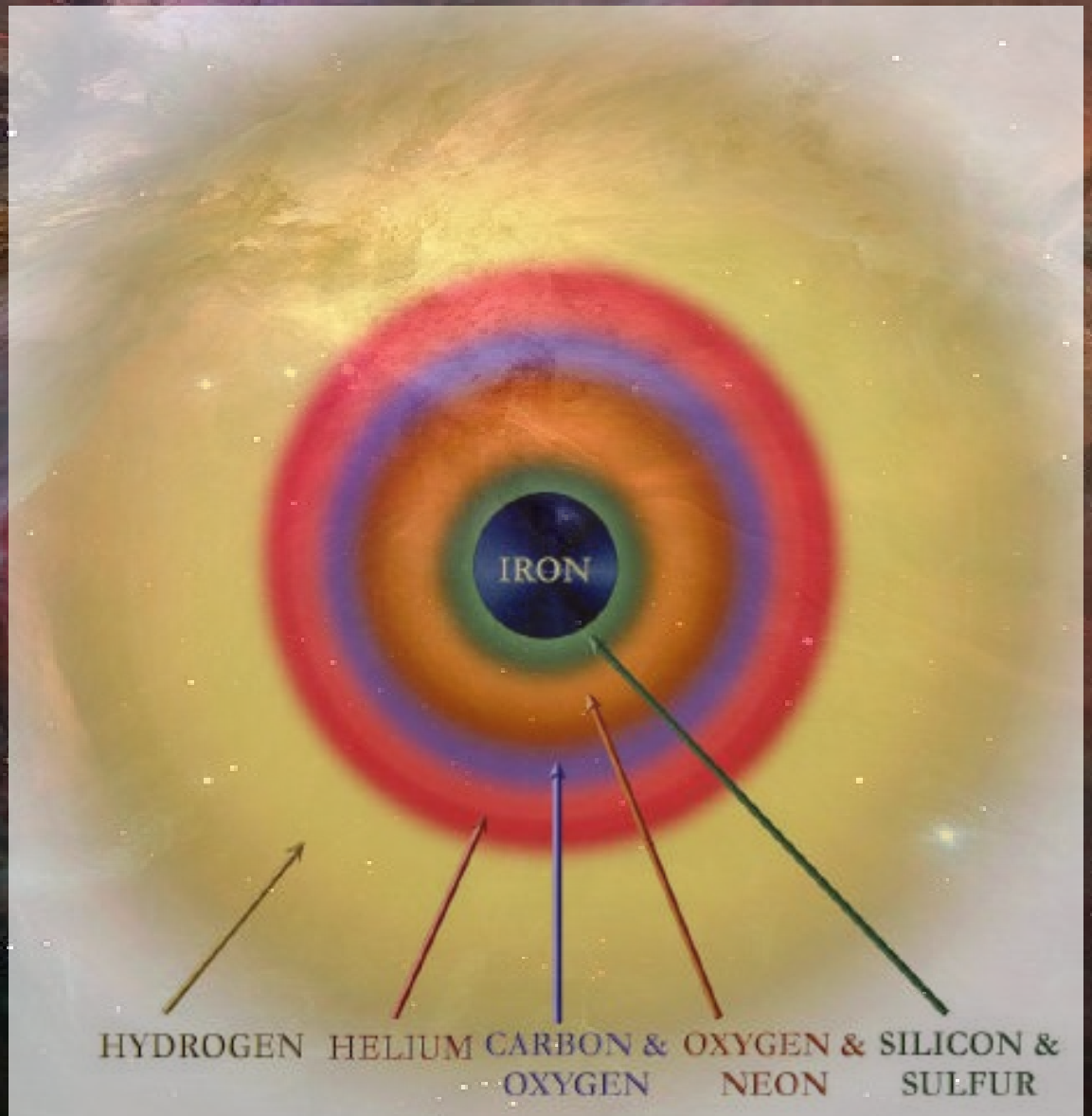
1) THE BURNING STOPS WHEN THE NUCLEUS IS DEPLETED
2) NEW CONTRACTION
3) INCREASE OF TEMPERATURE
4) TURN ON OF THE SUBSEQUENT NUCLEAR REACTION WITH FORMATION OF HAVIER ELEMENTS

this gives origin to the elements from He to Fe

Structure of a heavy star at the end of the process:

1) a core of iron

2) concentrical layers with nuclear reactions of ligter elements



If the star has a mass greater than 12 M_o it's final fate is really violent:

THE INTERNAL PRESSURE IS NOT ENOUGH TO SUBSTAIN THE WEIGH OF SUPERFICIAL LAYERS

A CATASTROPHIC IMPLOSION CONDENSES THE MATTER TO 10^{14} g/cm^3

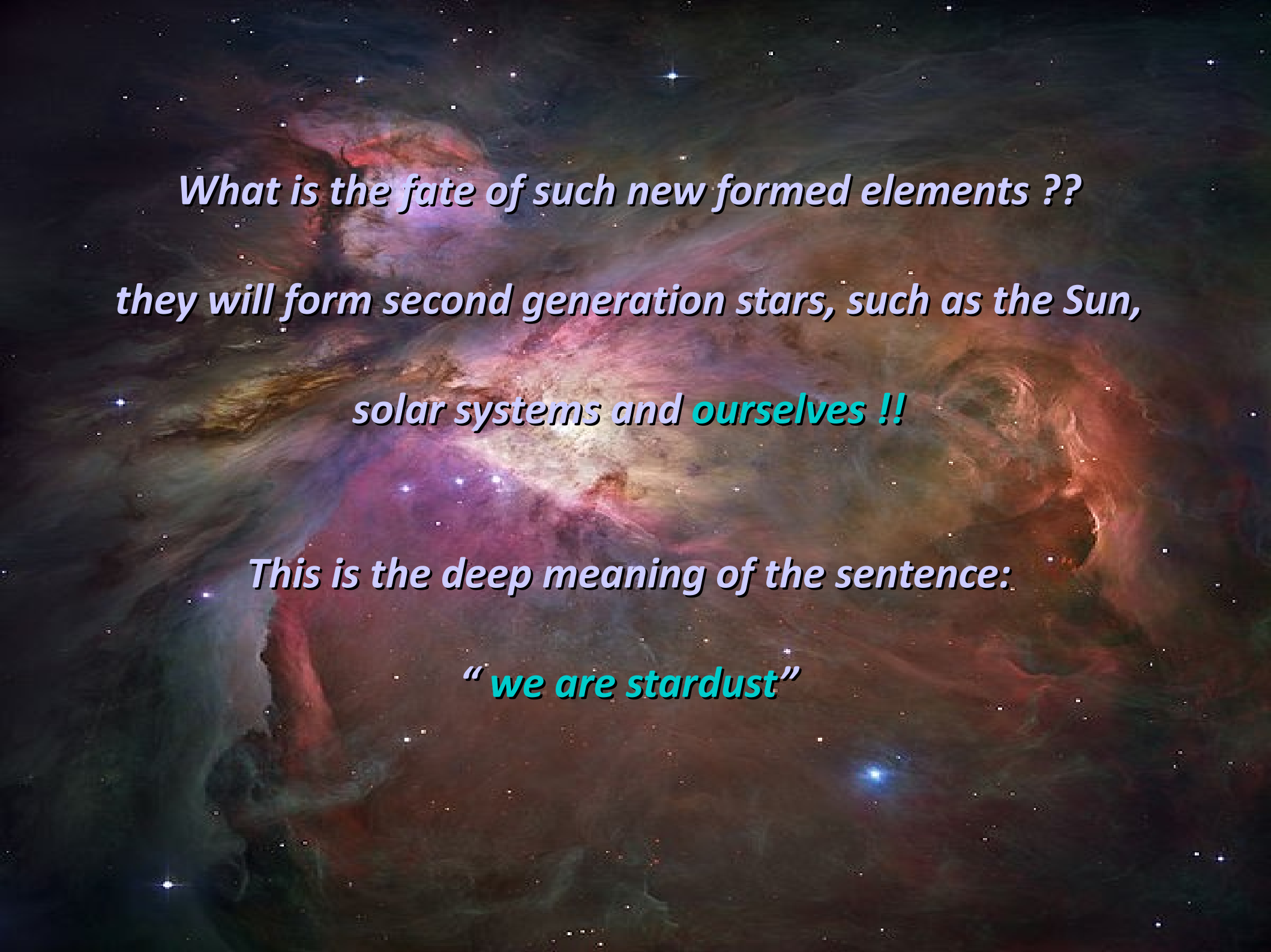
(the same density you could obtain shrinking the moon in this room)

The free falling matter bounches on this compressed core producing a shock wave which destroys the star

SUPERNOVA EXPLOSION

During the deflagration the elements havier than iron are produced

this concludes the nucleosyntesis of ALL the KNOWN ELEMENTS!


What is the fate of such new formed elements ??
they will form second generation stars, such as the Sun,
solar systems and ourselves !!
This is the deep meaning of the sentence:
“ we are stardust”

The central object which survives the supernova explosion can be..

1) a NEUTRON STAR if $M < 2\ M_{\odot}$: an extremely compact object (radius of 10 Km !!!) in rapid rotation about it's axis.

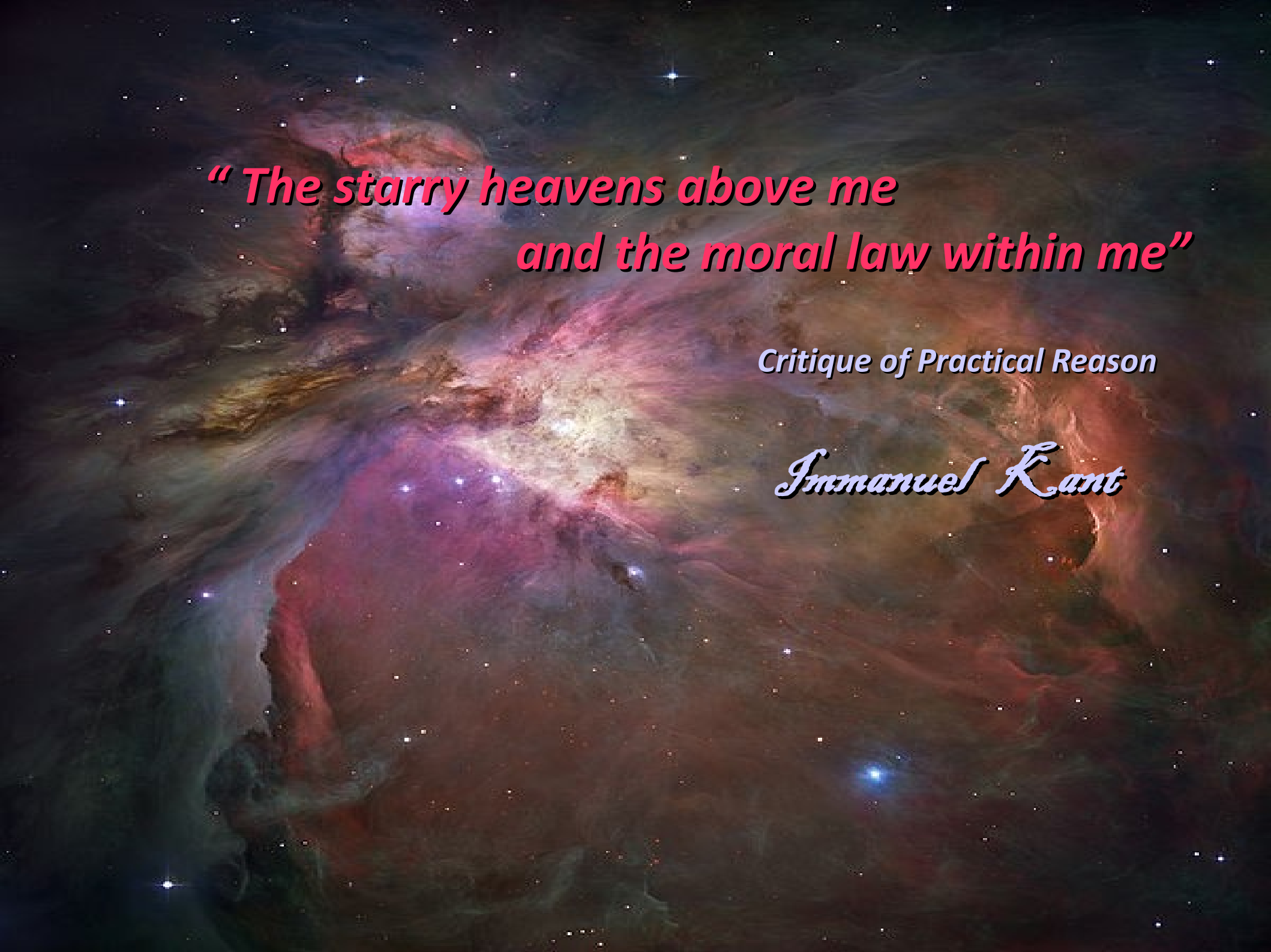
Such objects are too faint in the visible light

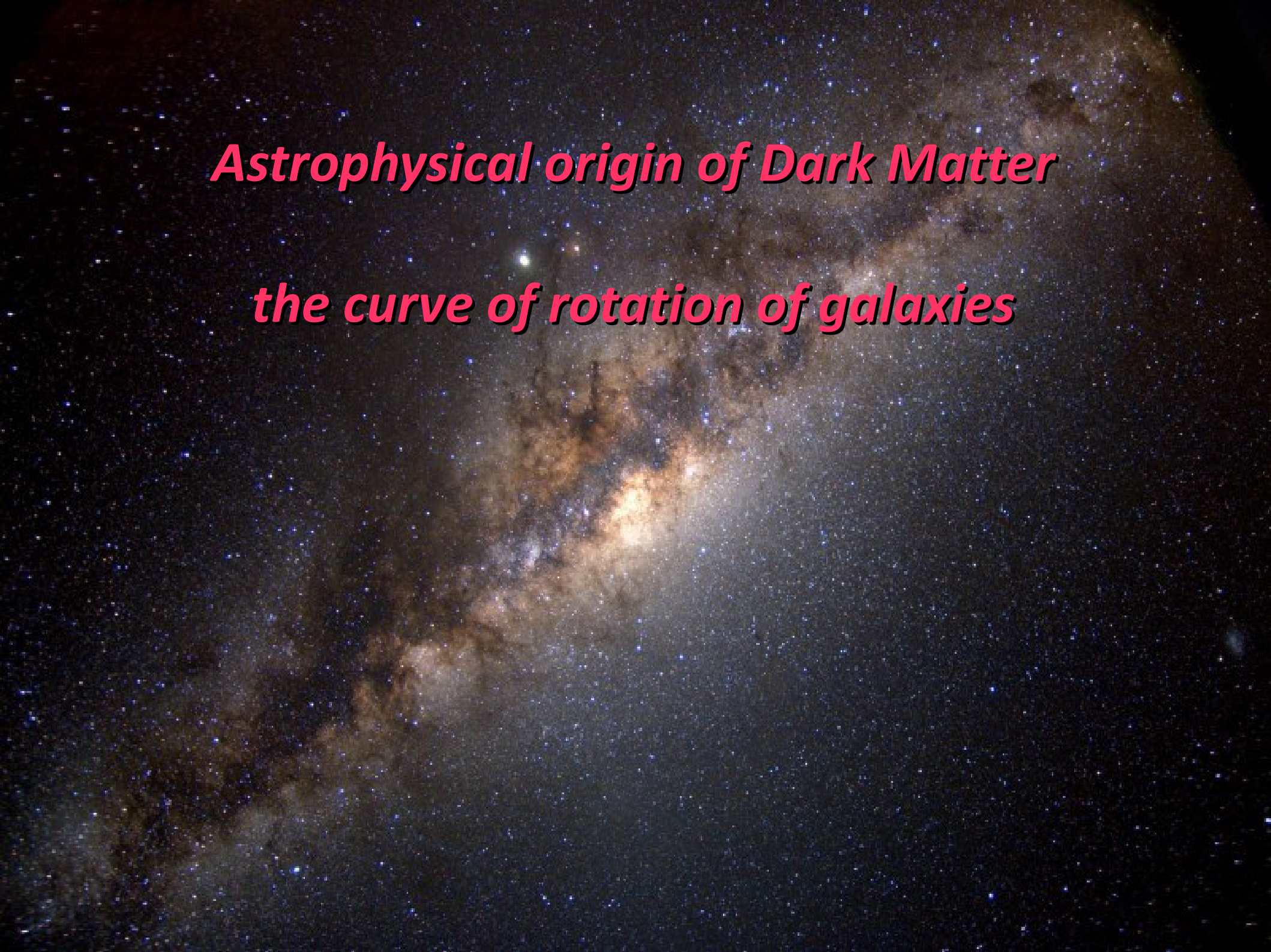
but are powerful X ray sources

2) a **BLACK HOLE** if $M > 2\,M_o$: if the mass exceedes this limit the **gravitational collapse can not be stopped** at all !!

The intensity of the gravitational fild becomes so huge that **even light can not excape.**

Inside the radius of this object (**the horizon of events**) the density is such extreme that space and time loose significance.

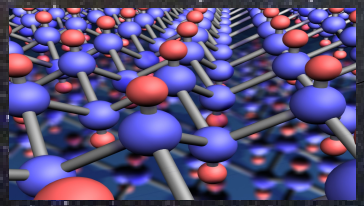

“ The starry heavens above me
and the moral law within me”
Critique of Practical Reason
Immanuel Kant

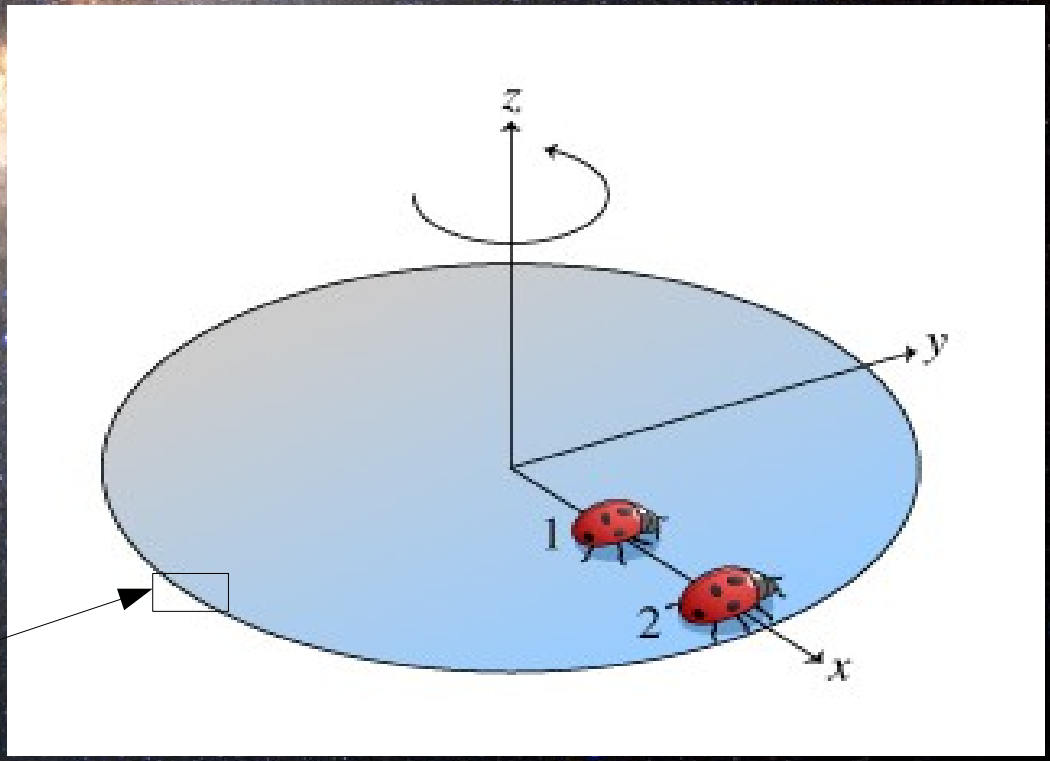

Astrophysical origin of Dark Matter
the curve of rotation of galaxies

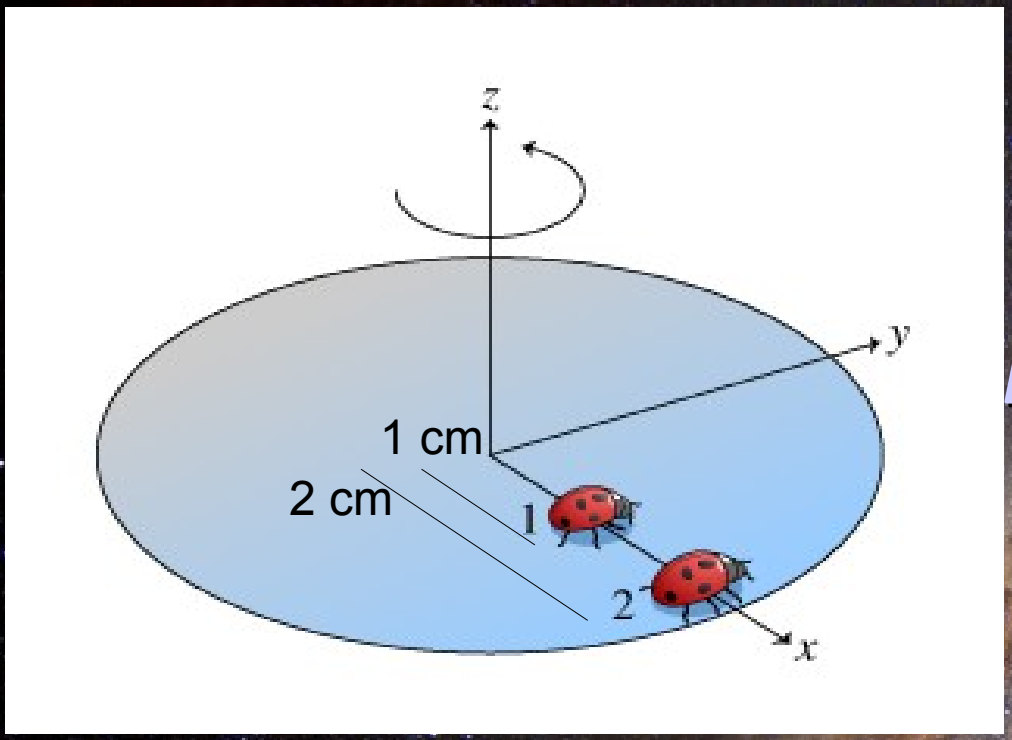
the disc rotates around the center, the velocity of the circular motion of stars depends on the distance from the center..

..but why?

let us consider a rigid disk (for example a CD) whose atoms mantain FIX positions in a cristal



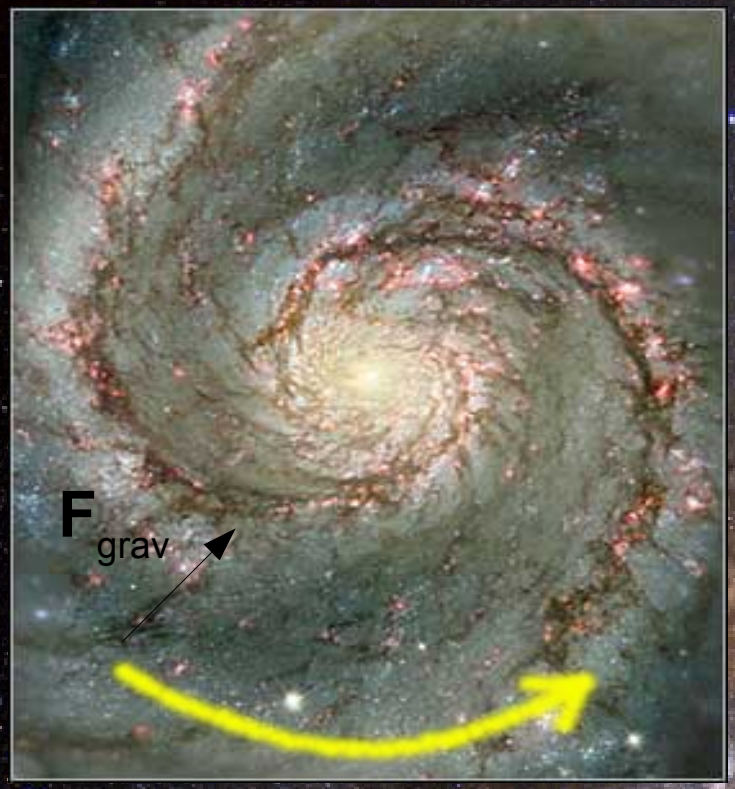




Ladybug 1 covers 2π x 1cm ≈ 6 cm
in a time t
Ladybug 2 covers 2π x 2cm ≈ 12 cm
in the SAME TIME t

velocity of ladybug 1 v_1 = 6cm/t
in a time t

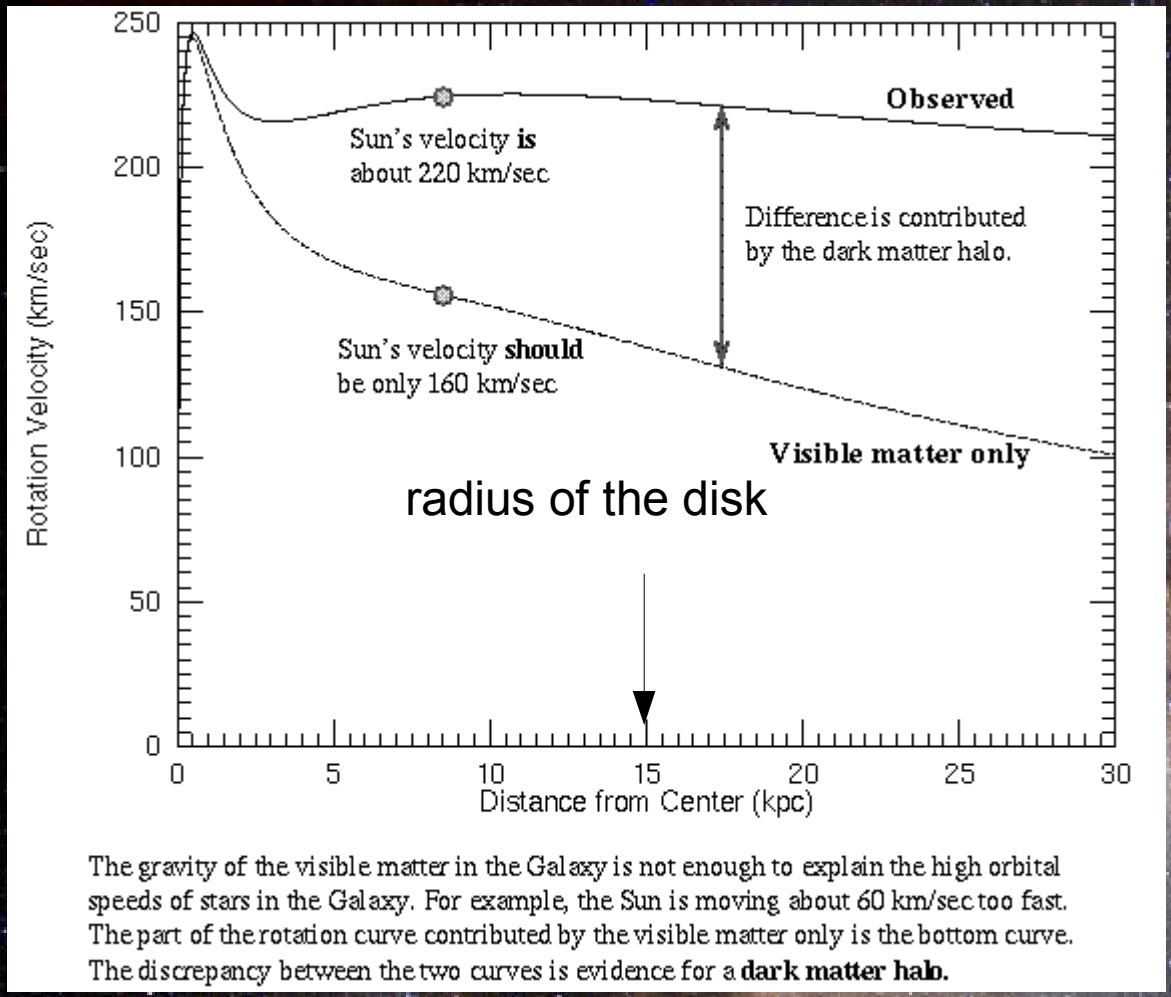
velocity of ladybug 2 v_2 = 12cm/t = 2 x v_1



but the disk of the Galaxy is not rigid..
stars does not form a crystal they are held together by the mutual gravitational interaction!!

the velocity of a star at distance r from the center is caused by the gravitational force acting on the star:

$$v = \sqrt{(r\, Fgrav)}$$



The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two curves is evidence for a **dark matter halo.**

The velocity far away the center is TOO HIGH!!

the mass of the observed matter is not enough to explain the observed velocity

the Galaxy is surrounded by a spherical crown of matter which does not emit light: DARK MATTER

(small stars, planetoids or new exotic particles?)