The SM of Astrophysics & Cosmology

النموذج القياسي للفيزياء الفلكية وعلم الكونيات

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AFS2024 Marrakech, Astrophysics & Cosmology July 2024

Welcome to the Universe

1. **Welcome to Large Scale Physics**

   Aesthetics and other stuff…

2. **An Inventory of the Cosmos**
   – **The stellar world …and the realm of the galaxies**
   – ***Quasars, AGN's, GRB's, XRB's, Kilonova, FRB's***

3. **Stellar Physics?**
   - **The stellar mess and more *:***
     - ***Black holes, neutron stars, pulsars, white and brown dwarfs***
   - **How does a star work? Deriving the stellar structure equations**

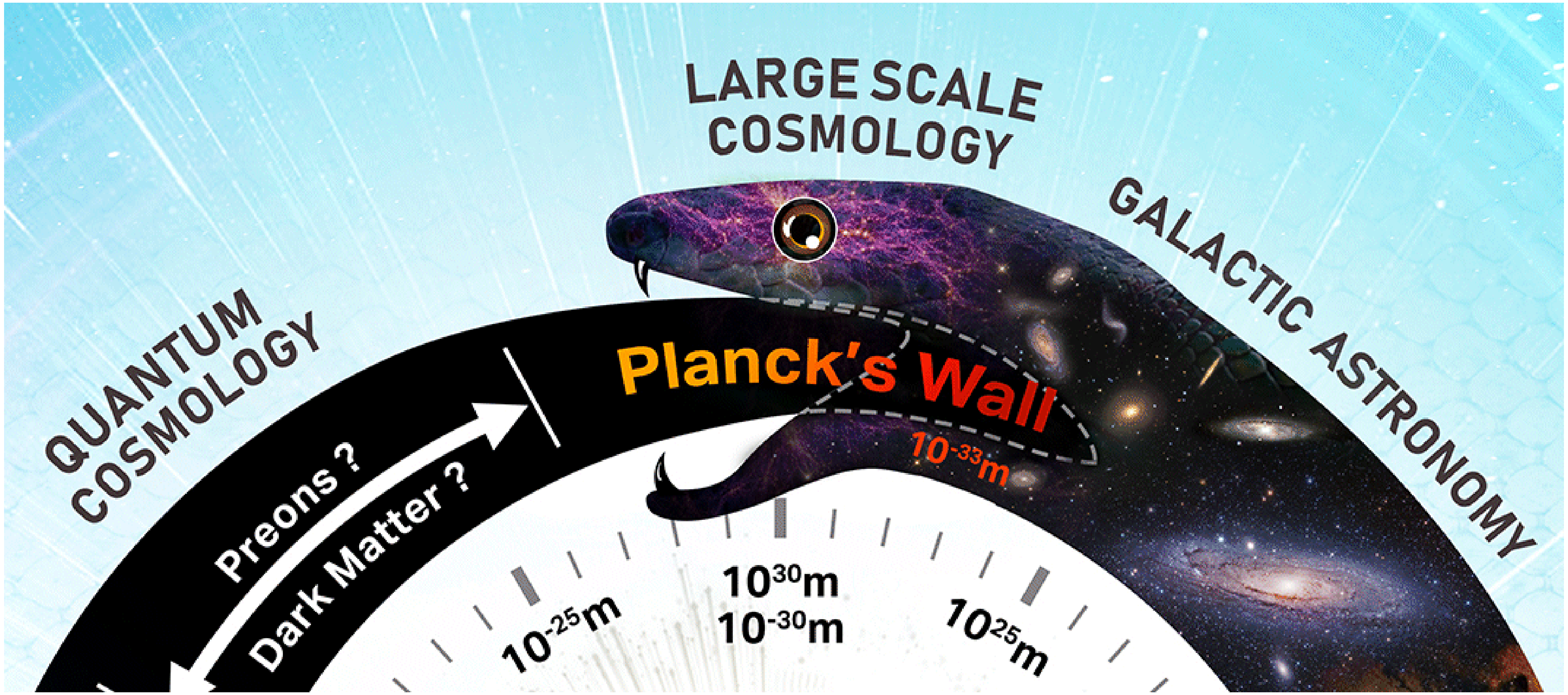
4. **Cosmology**
   - **Big Bang Cosmology: ΛCDM**
   - **The Thermal History of the Universe & Particle decoupling…**
   - **The « ordinary matter » and its Dark Complications …**

What is Physics ?

What is
the most basic science of all?

It is the science which deals with all things at all scales !

LARGE SCALE COSMOLOGY
GALACTIC ASTRONOMY
STELLAR ASTRONOMY
SOLAR SYSTEM ASTRONOMY
EARTH SCIENCES
BIOLOGY
CHEMISTRY
ATOMIC PHYSICS
ATOM
NUCLEAR PHYSICS
NUCLEUS
PARTICLE PHYSICS
QUARKS INSIDE NUCLEON
QUANTUM COSMOLOGY
Preons ?
Dark Matter ?
Planck's Wall
10^{-33}m
10^{30}m
10^{-30}m
10^{25}m
10^{20}m
10^{15}m
10^{10}m
10^{5}m
1 m
10^{-5}m
10^{-10}m
10^{-15}m
10^{-20}m
10^{-25}m
GLASHOW's SNAKE
حيّة غلاشو
THE COSMIC UROBOROS
THE SNAKE THAT BITES IN ITS OWN TAIL



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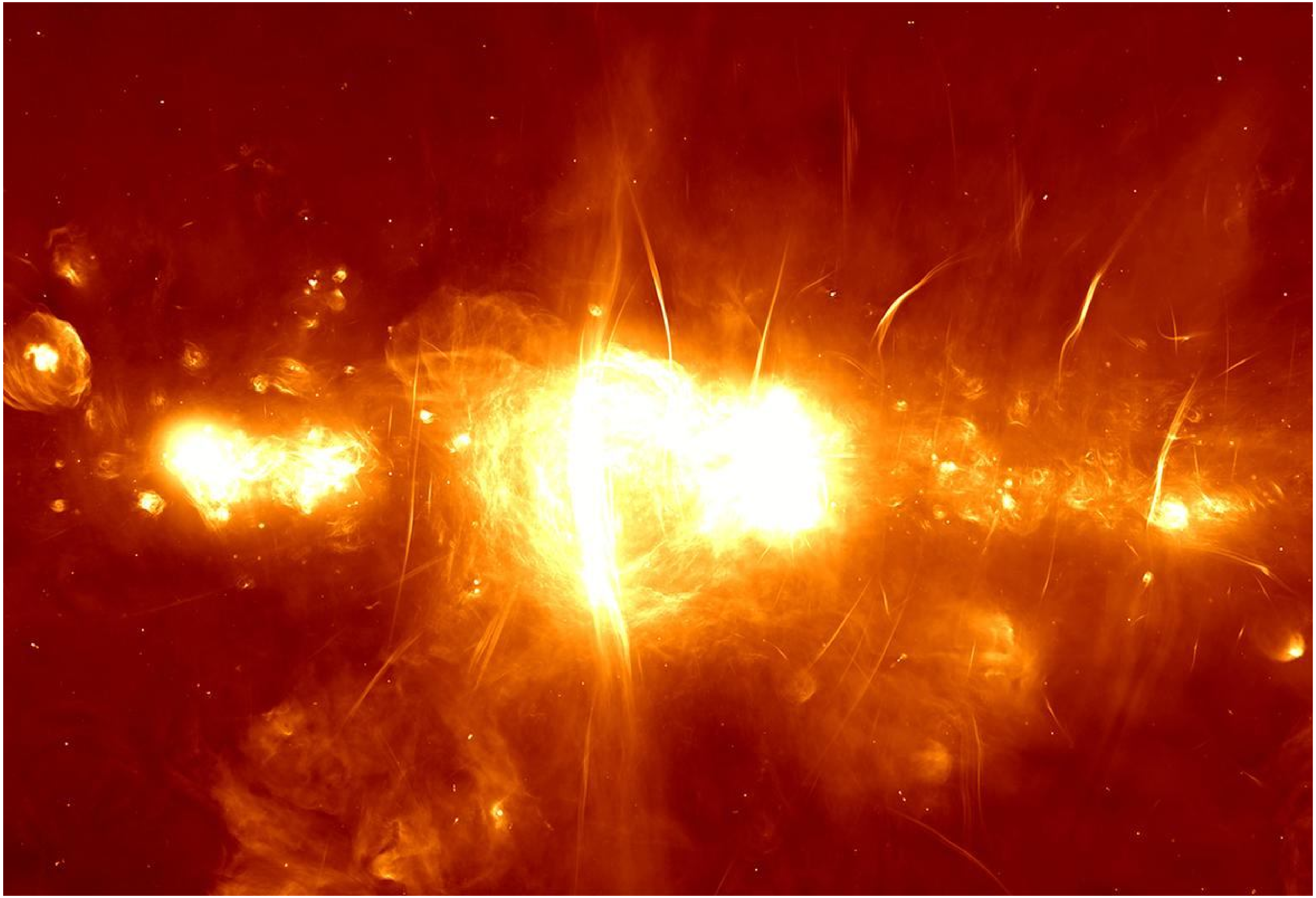
The Realm of Physics

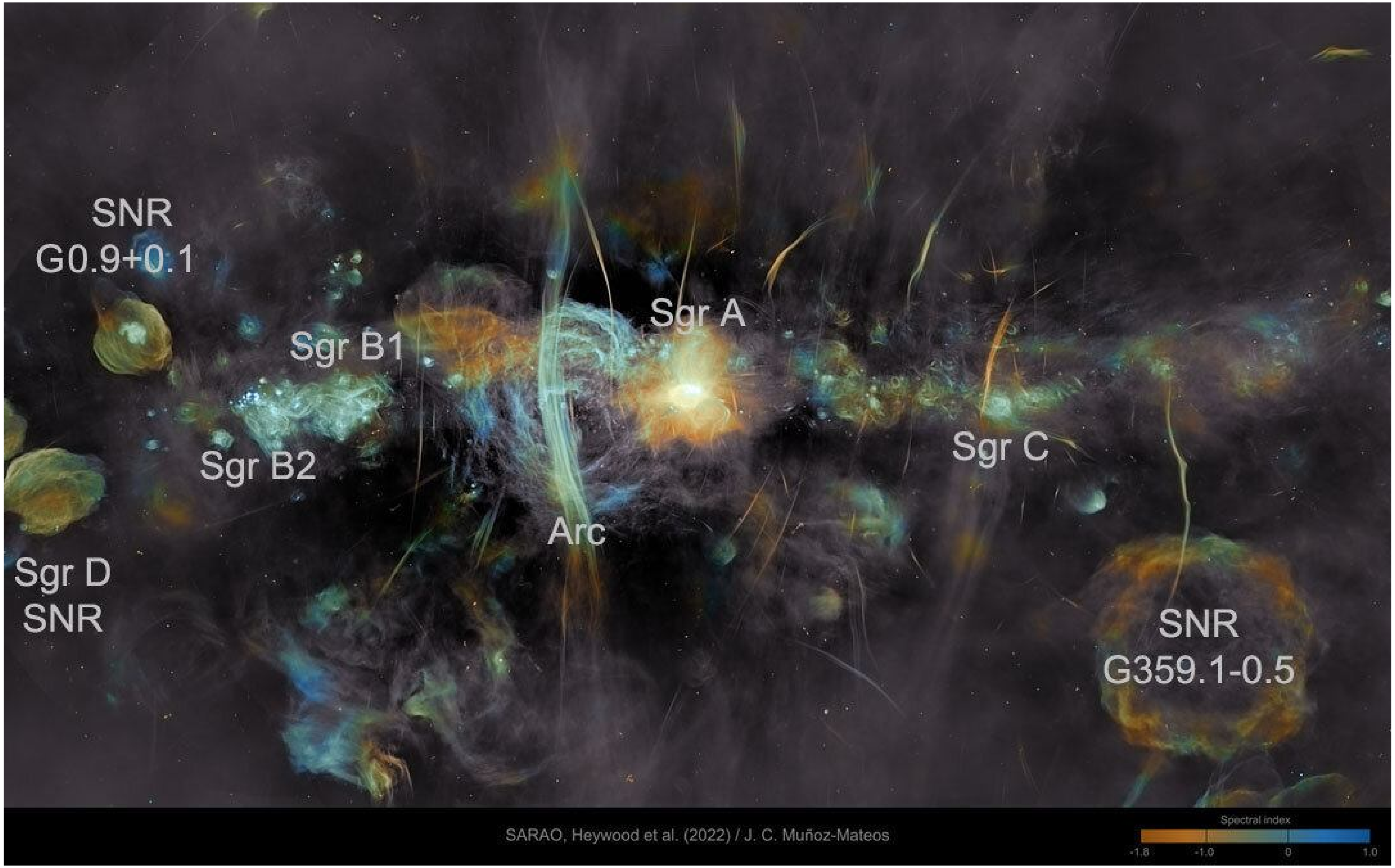
Each scale its physics!

Domain	Scale
Sub-nuclear physics	$<10^{-15}$m
Nuclear physics	Fermi, $\sim10^{-15}$m
Atomic physics	Angstrom, $<10^{-10}$m
Femto physics	10^{-12}m, femtometer
Nano physics	10^{-9}m, nanometer
Micro physics	10^{-6}m, « optical » physics
Small scale (Macro) physics	~1m human scale objects
Medium Scale	Planets
Large scale	Stars
Very large scale physics	Galaxies & clusters of galaxies

The Fundamental Problem of Astronomy
المعضلة الأساسية في علم الفلك

MeerKAT: The center of our Galaxy in radio…





MeerKAT's observations in many wavelengths: an incredible panorama ***spanning an area of about 1,000 light-years by 500.*** Notice the ***magnetized "filament" structures that shine bright as radio signals***.

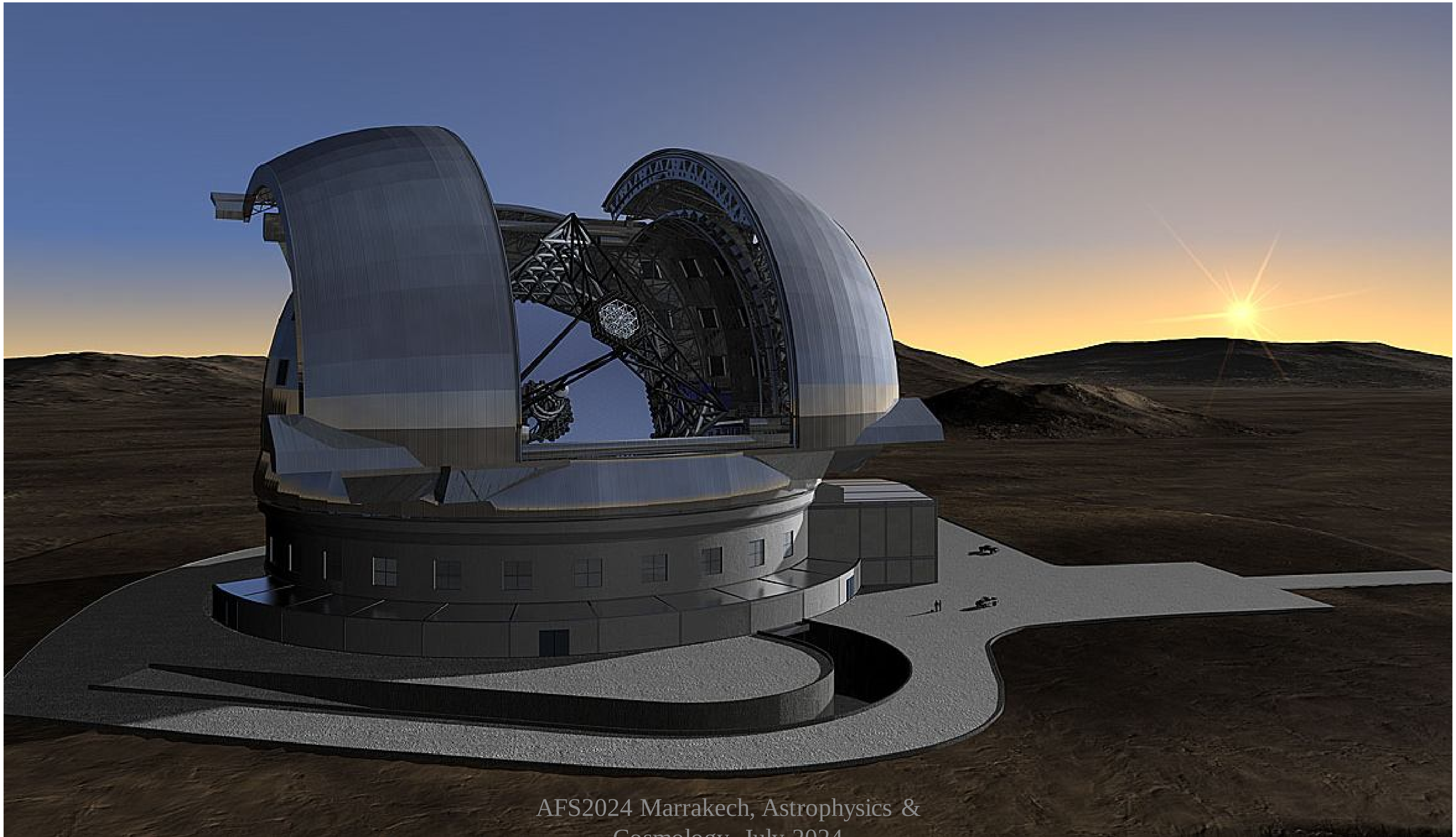
1- Large Scale Physics is: Astronomy!

It is :

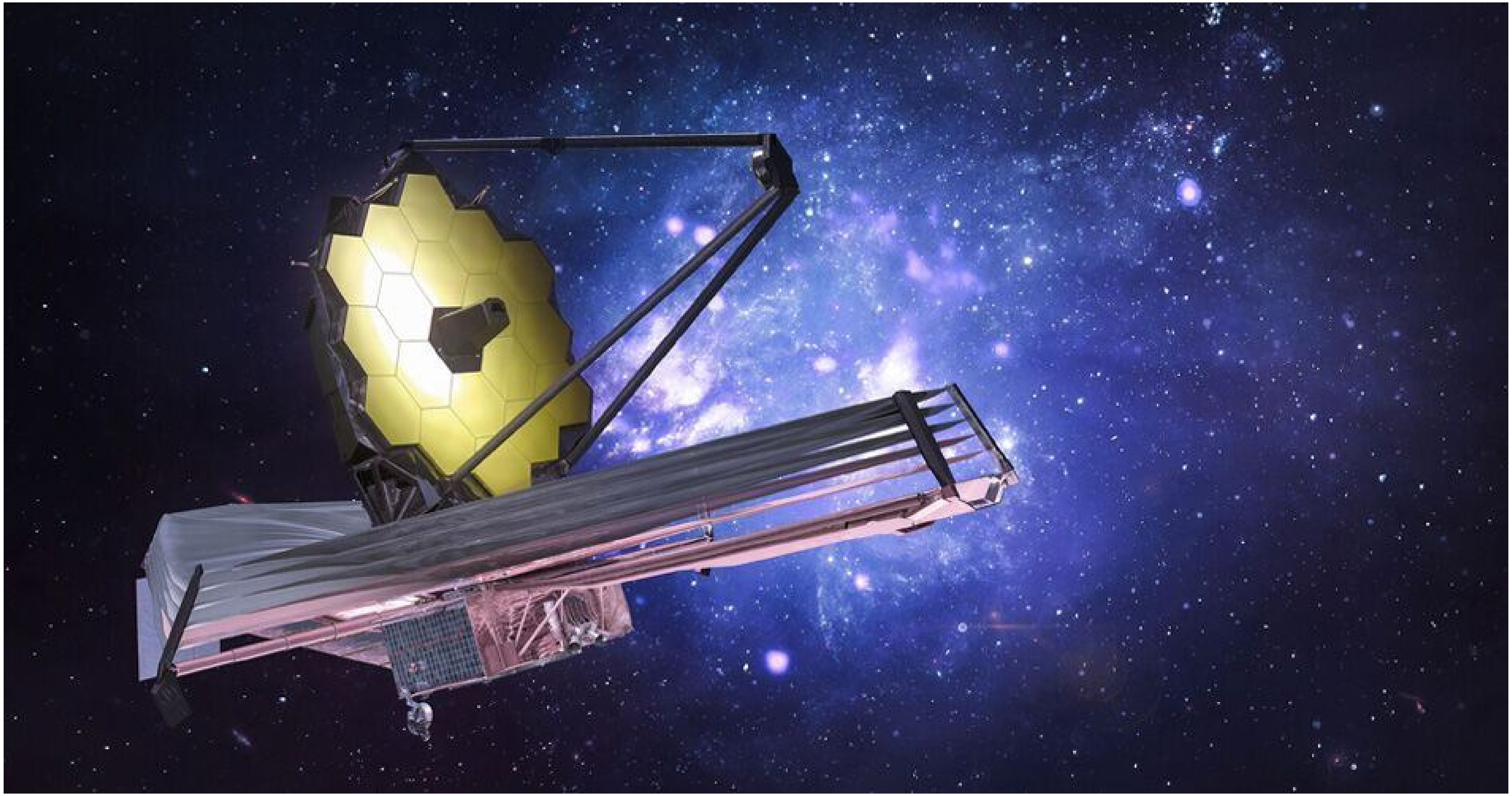
- **Generalized physics… *(almost) by definition***
- **Generalized geography: *cosmic geography (cosmography!)***
- **Generalized geology: *planetology***

Observing the Large Scale Physics

ELT: The European Extremely Large Telescope



The James Webb Space Telescope



Gamma-Ray Telescopes

The HESS Telescope in Namibia

SALT South Africa
The big optical telescope

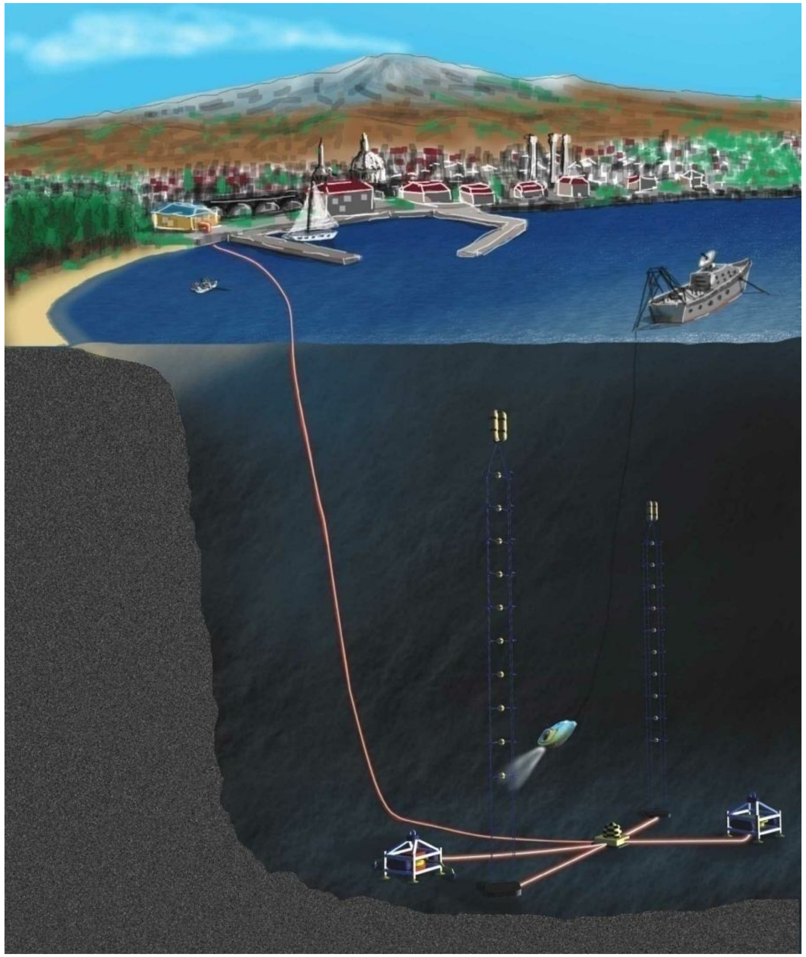
Radiotelescope
Meerkat’s 64 antennae (SA)

FAST, the Chinese's largest Radiotelescope in the World : 500m of diameter

The νeutrino Telescope

Fishing and Ice-fishing for Neutrinos

=



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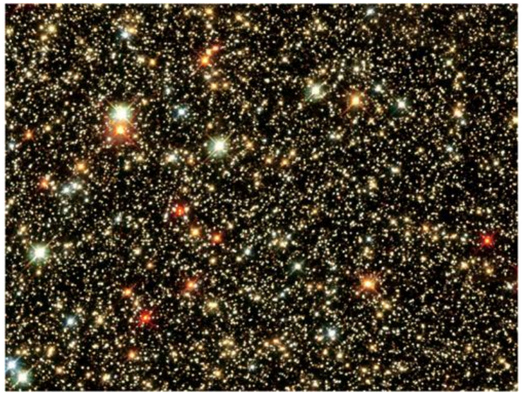
The Gravitational Wave Telescope

LIGO – Hanford, Wa, USA

2- The Universe :
An Inventory circa-2024



1- Planets and small bodies

2- Stars and their bestiary

3- Nebulae and Galaxies

3- Clusters and Super-clusters of galaxies

4- Exotic objects

- Black holes, neutron stars, pulsars, white and brown dwarfs

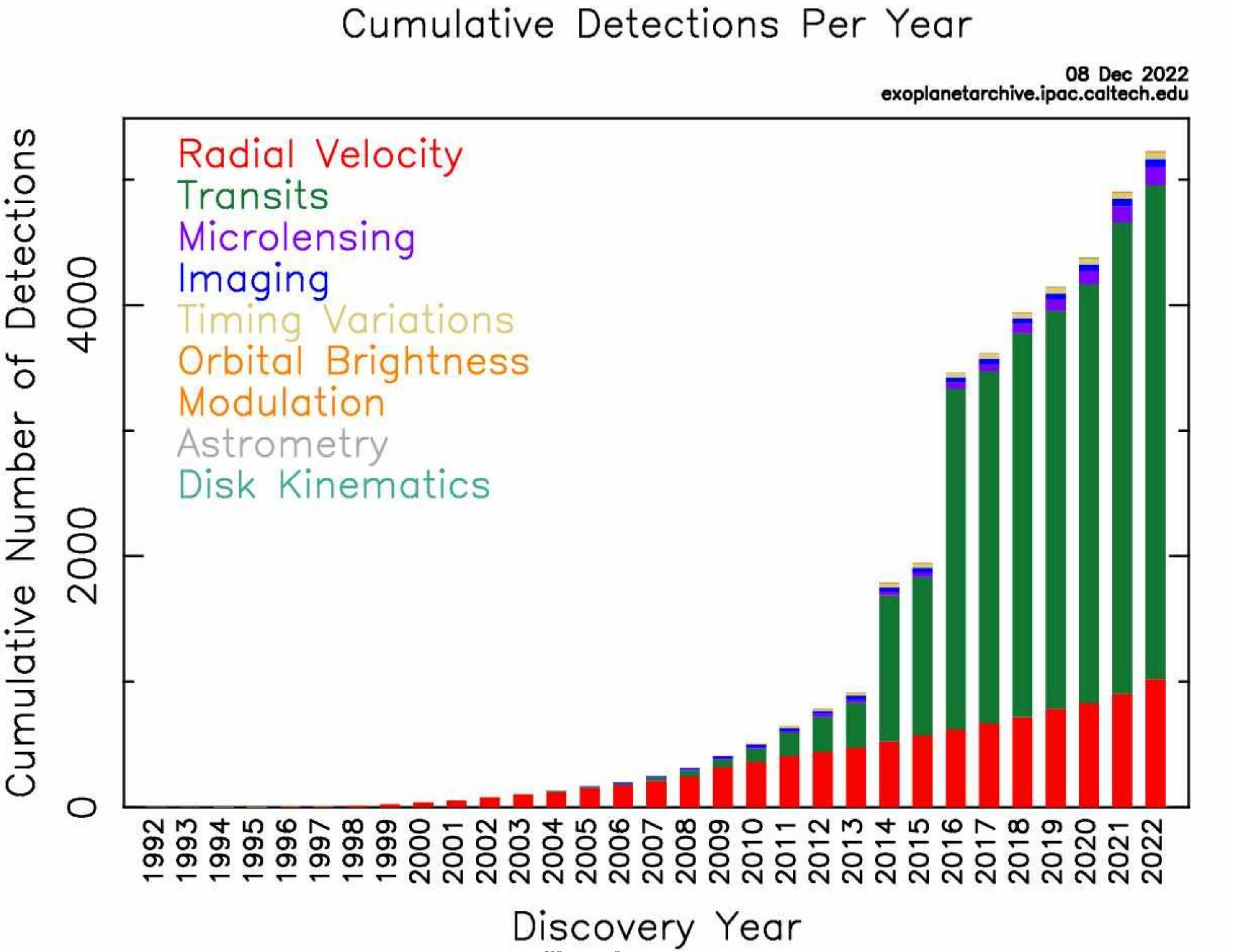
- Quasars, AGN's, GRB's, XRB's, Kilonovae, FRB's

New Worlds... Planetology
Systematic geology!

What are Exoplanets? : An extrasolar planet orbiting a star other than the sun. As of 27 June 2024, there are 5,678 confirmed exoplanets in 4,231 planetary systems, with 952 systems having more than one planet.

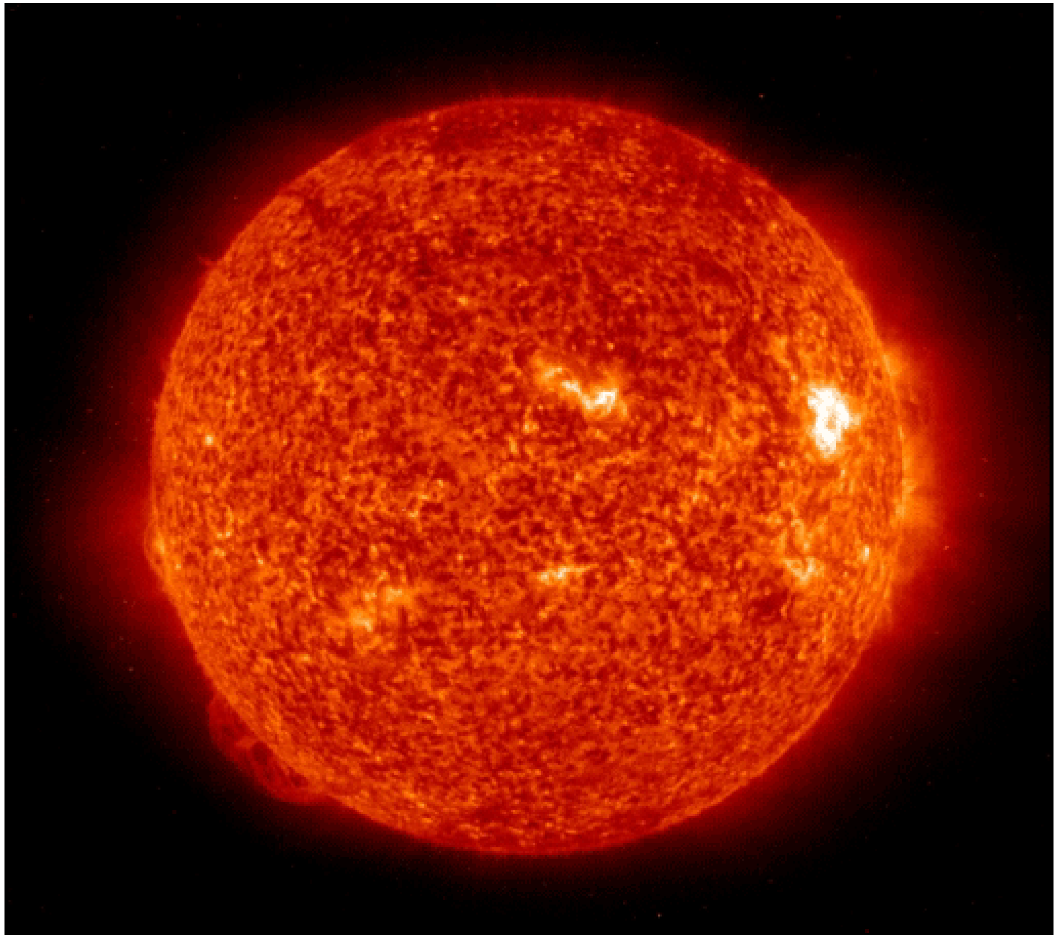
Artist's Impression of "Hot Jupiter" Exoplanets
NASA and ESA ▪ STScI-PRC15-44a

… rapid growth



3- The Stellar World

Talking of Stars... ... speaking of our Sun



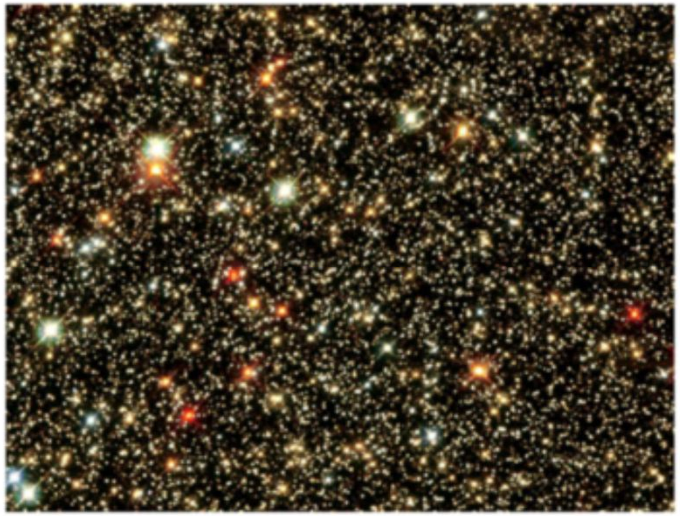
The Stellar World...
... speaking of our Sun

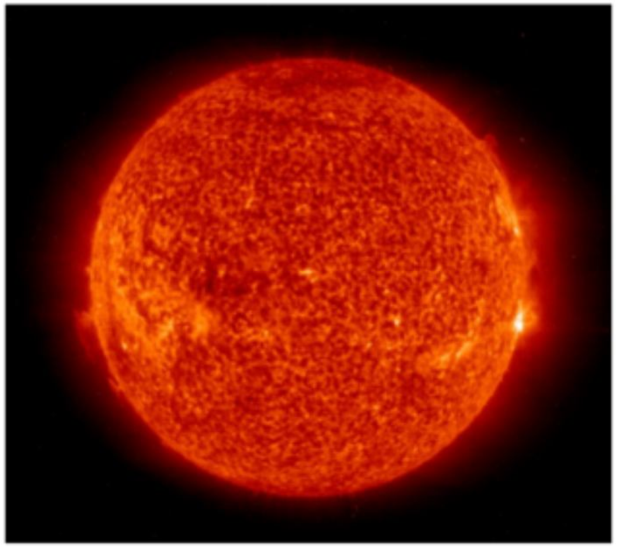
Very different composition than that of Earth, yet…

- Overall Sun's composition: that of the Cosmos!
- Its « heavy elements » composition: It is that of the planets

From Point-like Objects ...
...to Power houses

- **Stars: Romantic /« un-informed » vision of tiny far away dots shinning at night.**
- **Then, they realized that they are mere Sun-like objects**





Our « Quiet » Sun

1- One of the simplest objects…

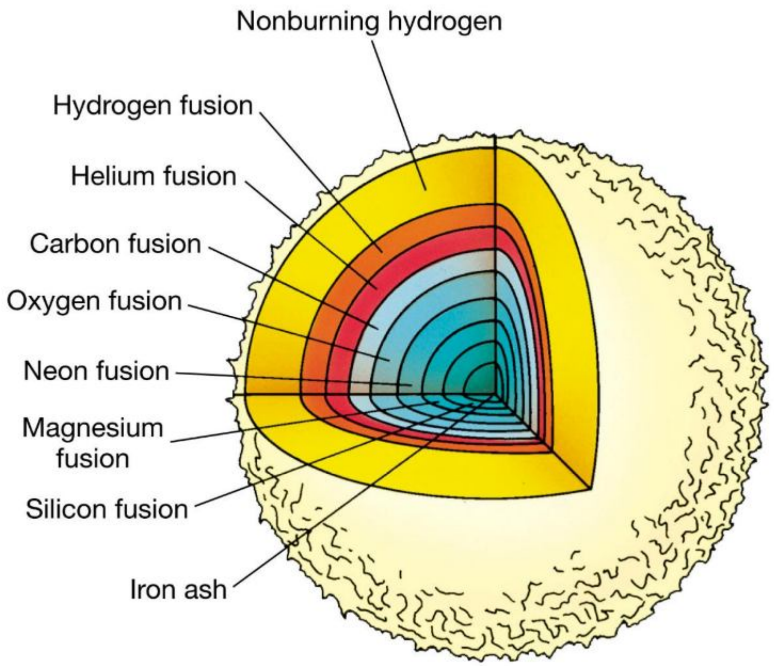
- Mass and intial chemical composition determine it all.
- Layers of ideal gases in a plasmic state
- A simple thermodynamic machine powered by nuclear fusion energy
- Stars from point-like objects… now to be understood as true powerhouse machines.

From our « Quiet » Sun, to…

2… to heavy stars

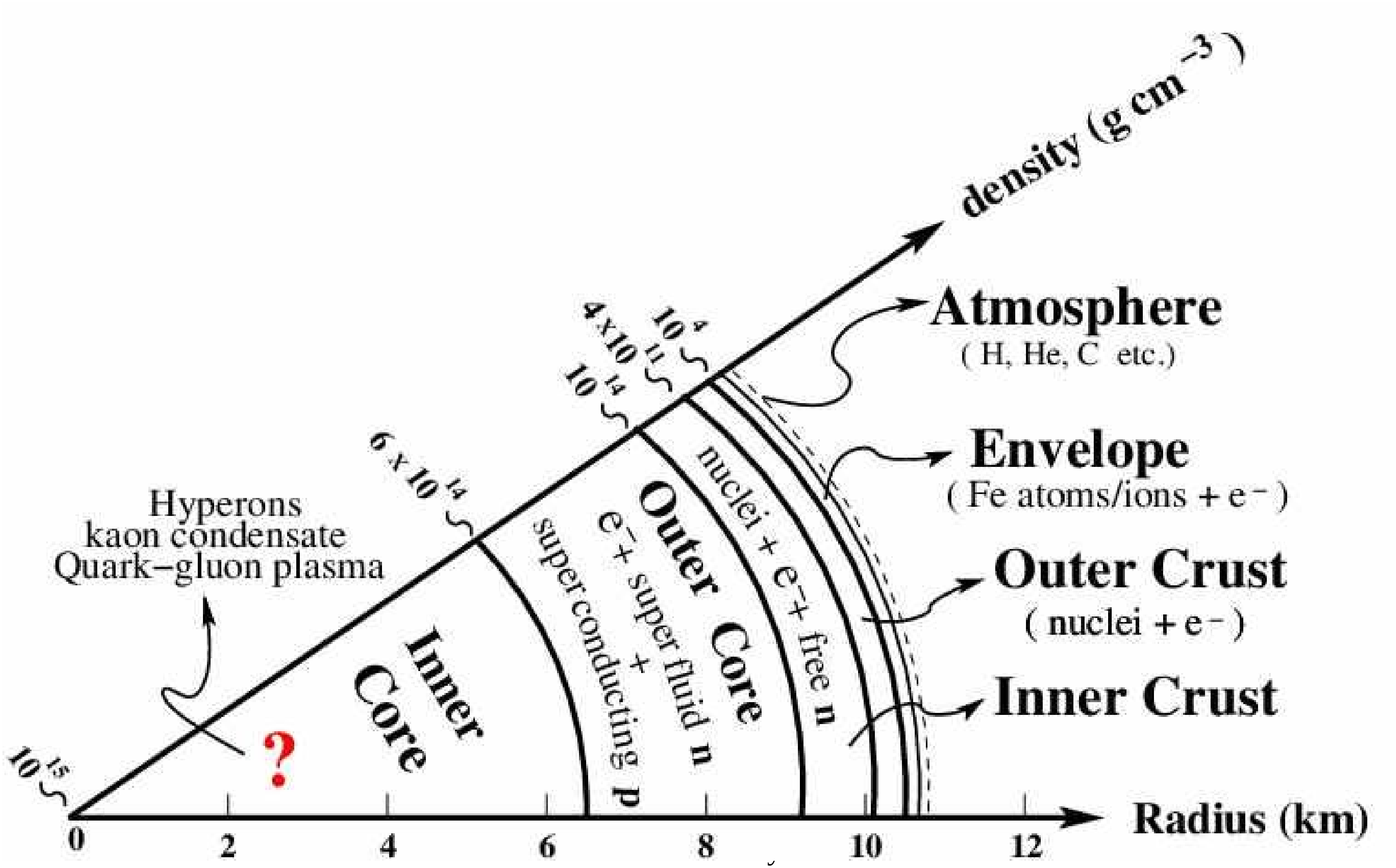
For a mass ~ $8M_{Sun}$ or more, we get a messy mash of periodic table of elements, each element burning at a given depth and cooking temperature and pressure.

- No complicated physics; just standard coupled non-linear diff. equations on a non-coarse space and time optimized meshing.



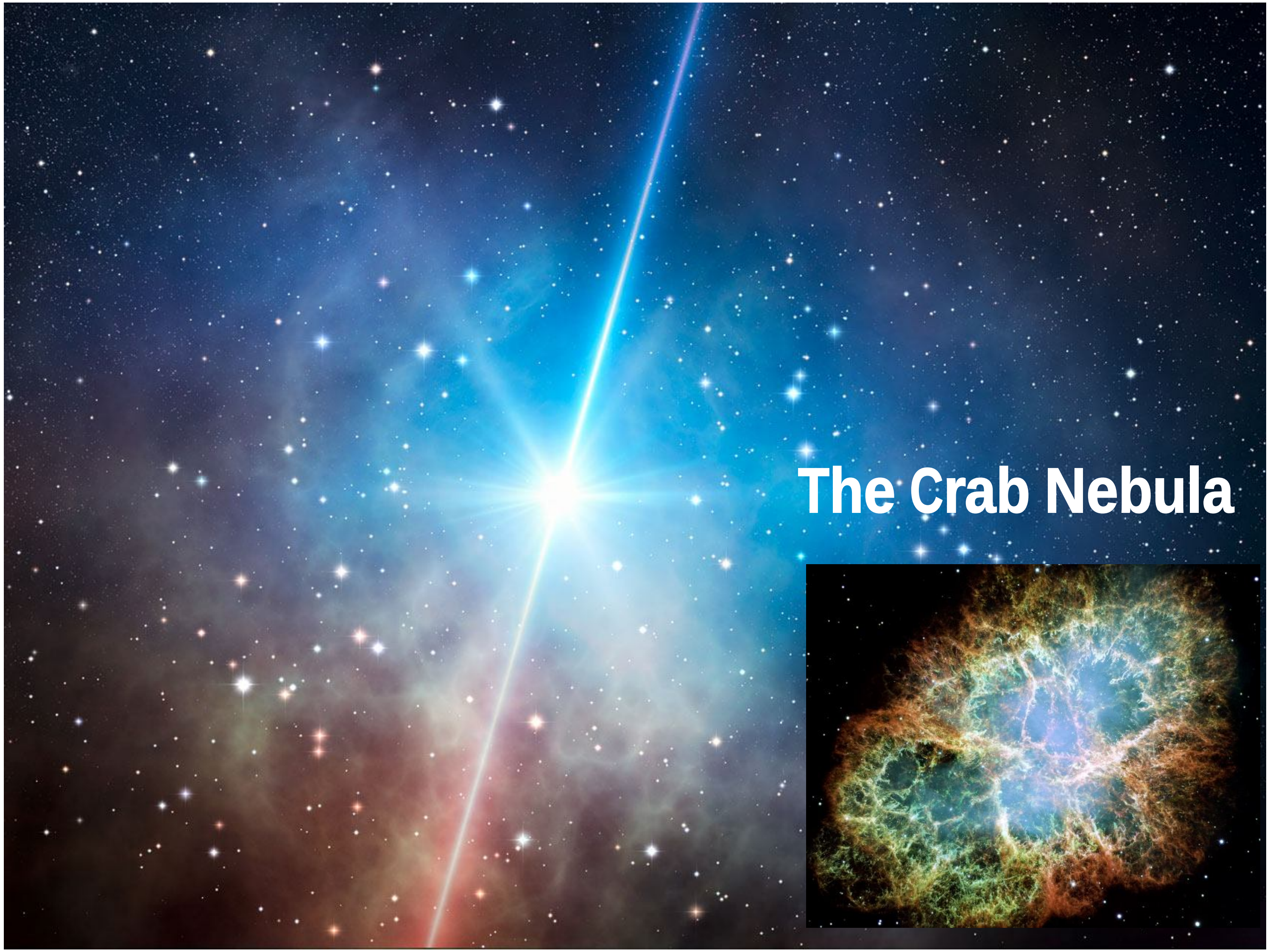
Messy Stellar World

3- Neutron stars and Black Holes:

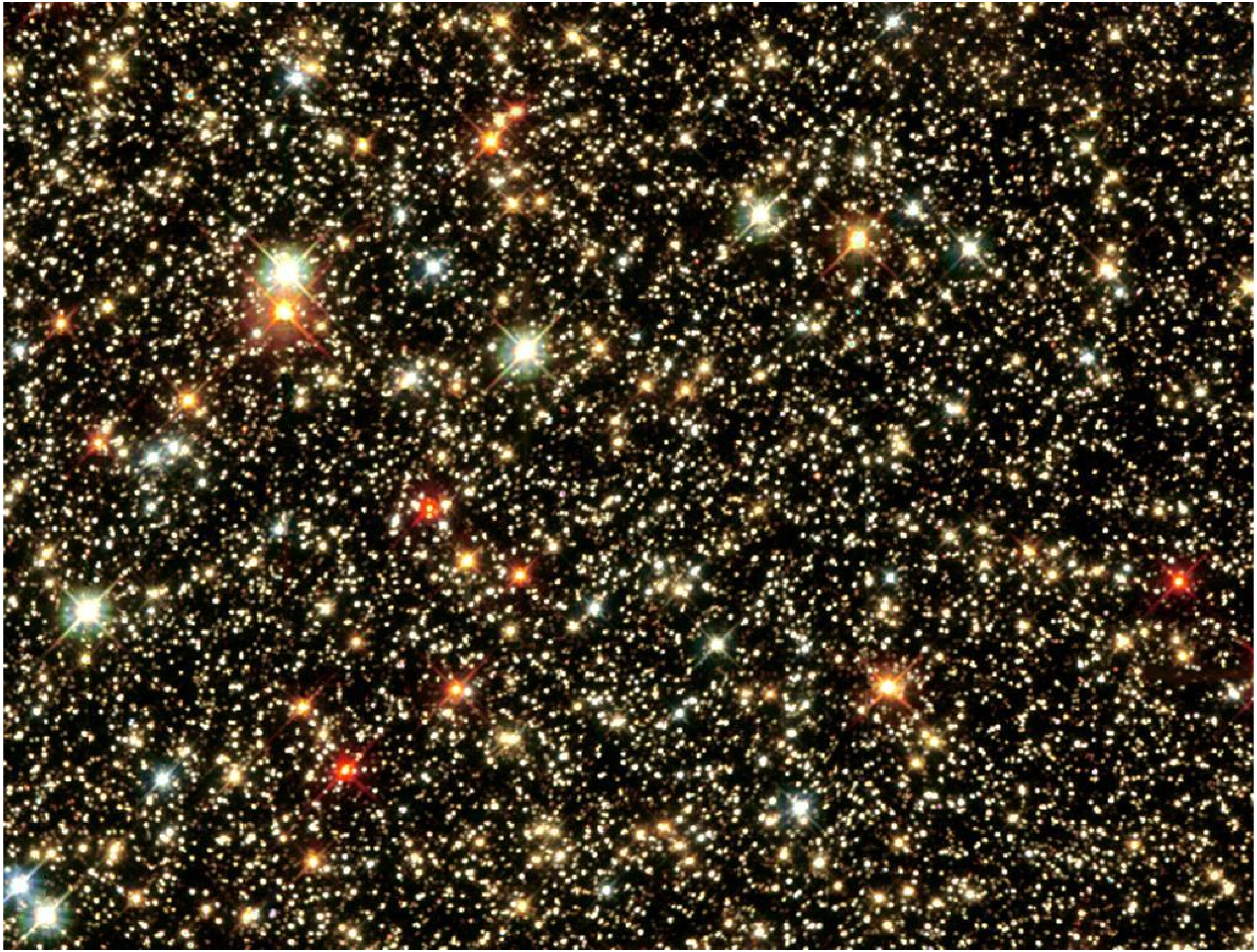


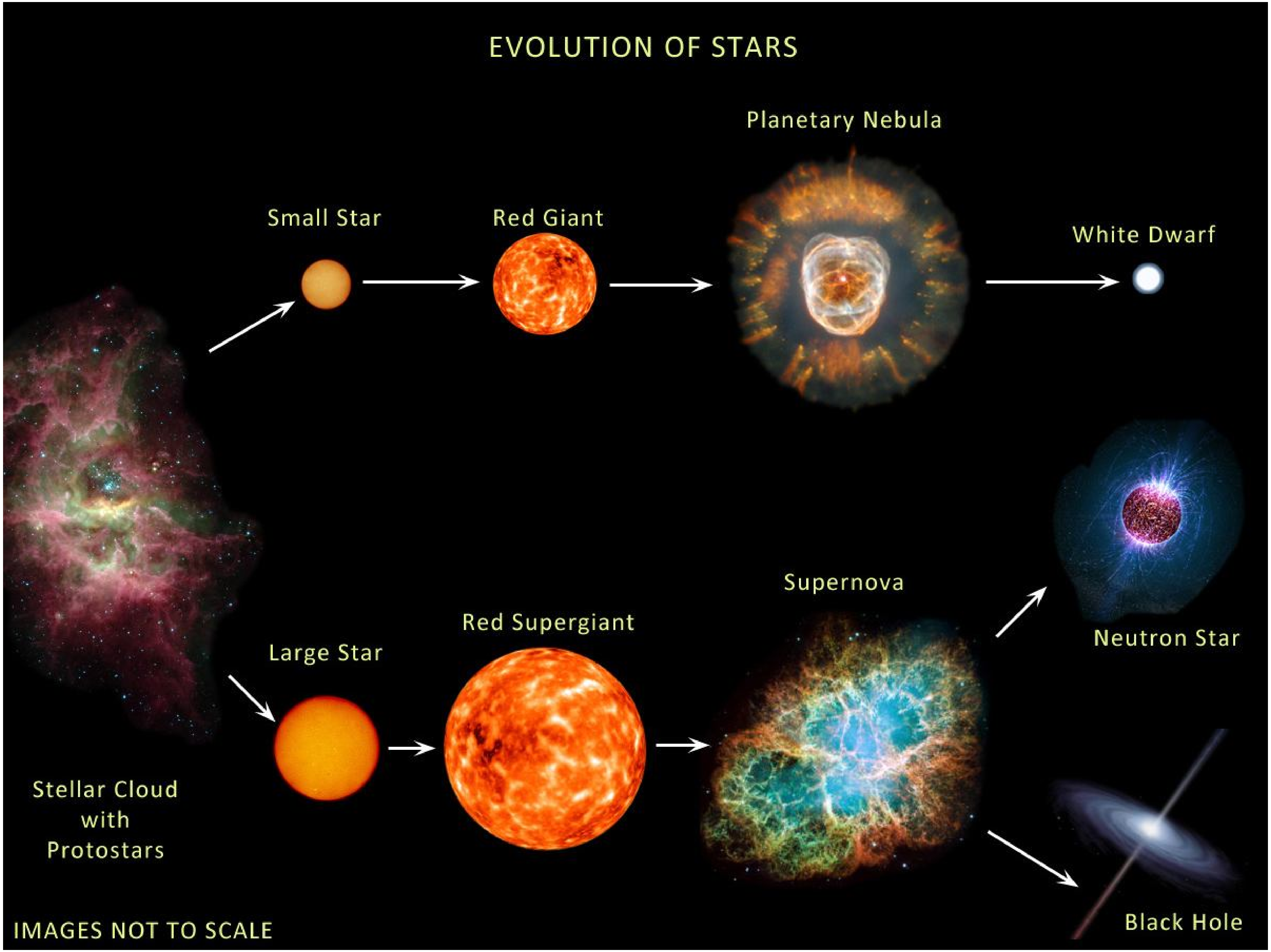
The Role of Supernovae:

Seeding the Cosmos with heavy elements



Stellar mess…

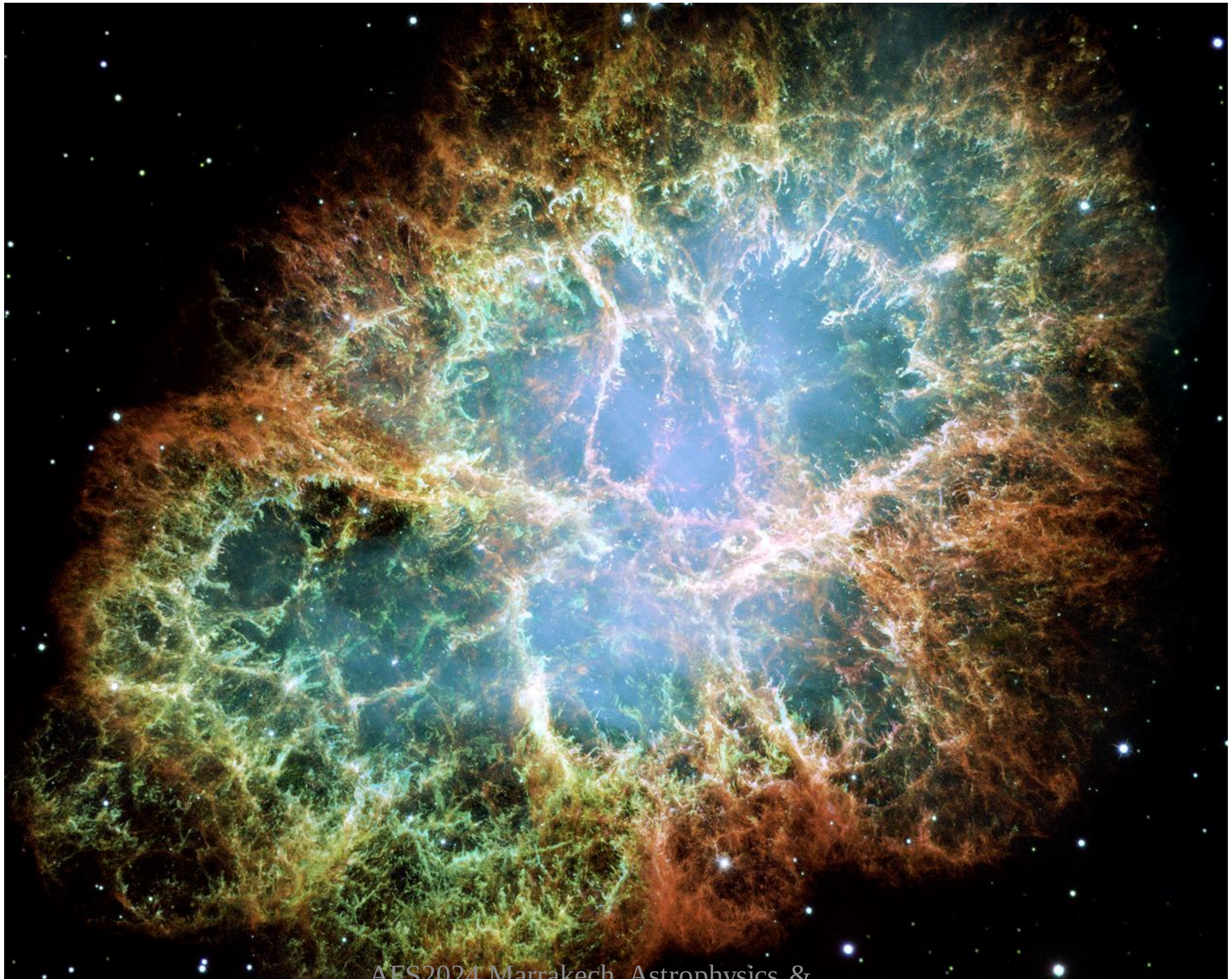


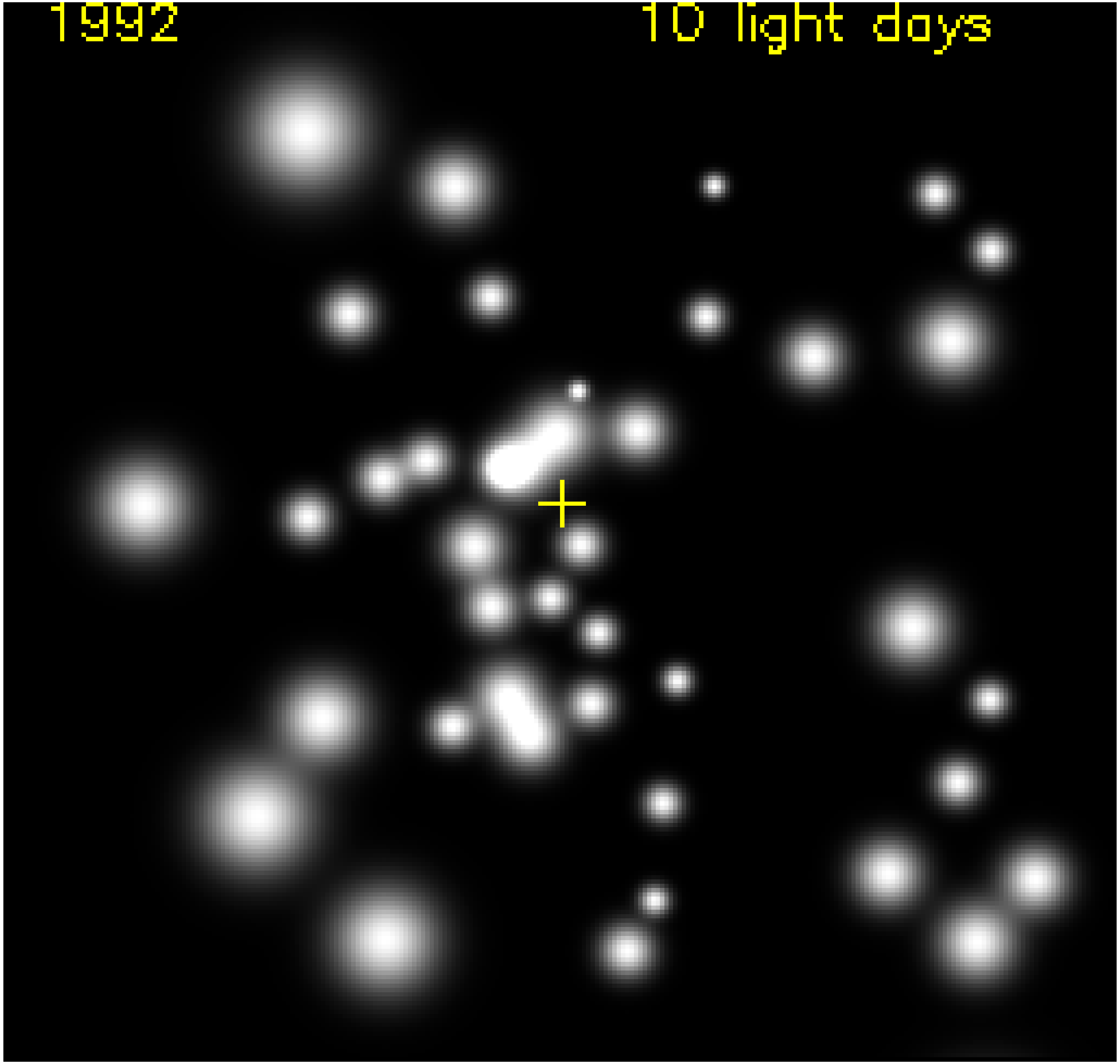

EVOLUTION OF STARS
Planetary Nebula
Small Star
Red Giant
White Dwarf
Supernova
Neutron Star
Red Supergiant
Large Star
Stellar Cloud
with
Protostars
Black Hole
IMAGES NOT TO SCALE

Nebula: Stars Nurseries

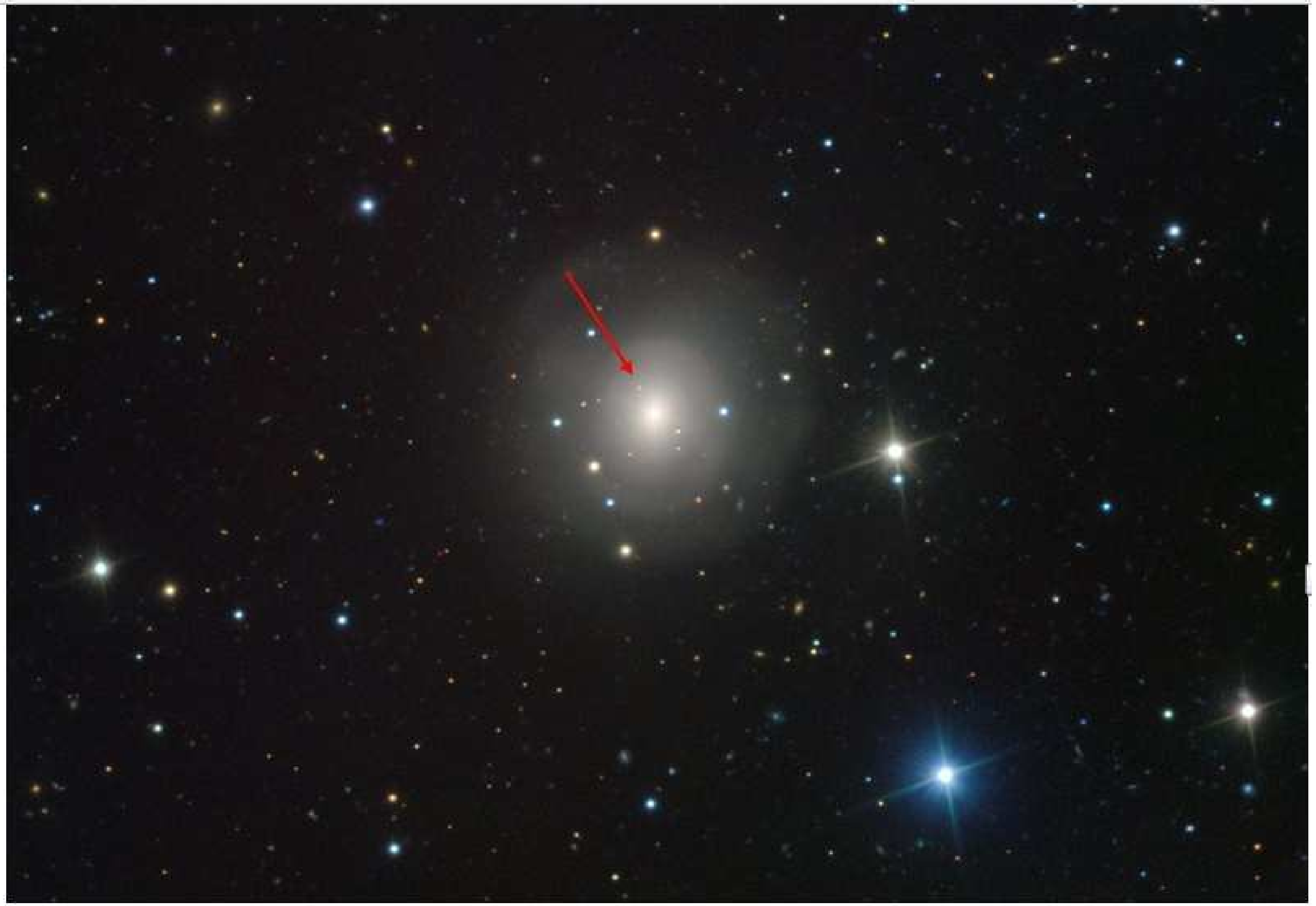
SNe Remnants

The Crab Nebula



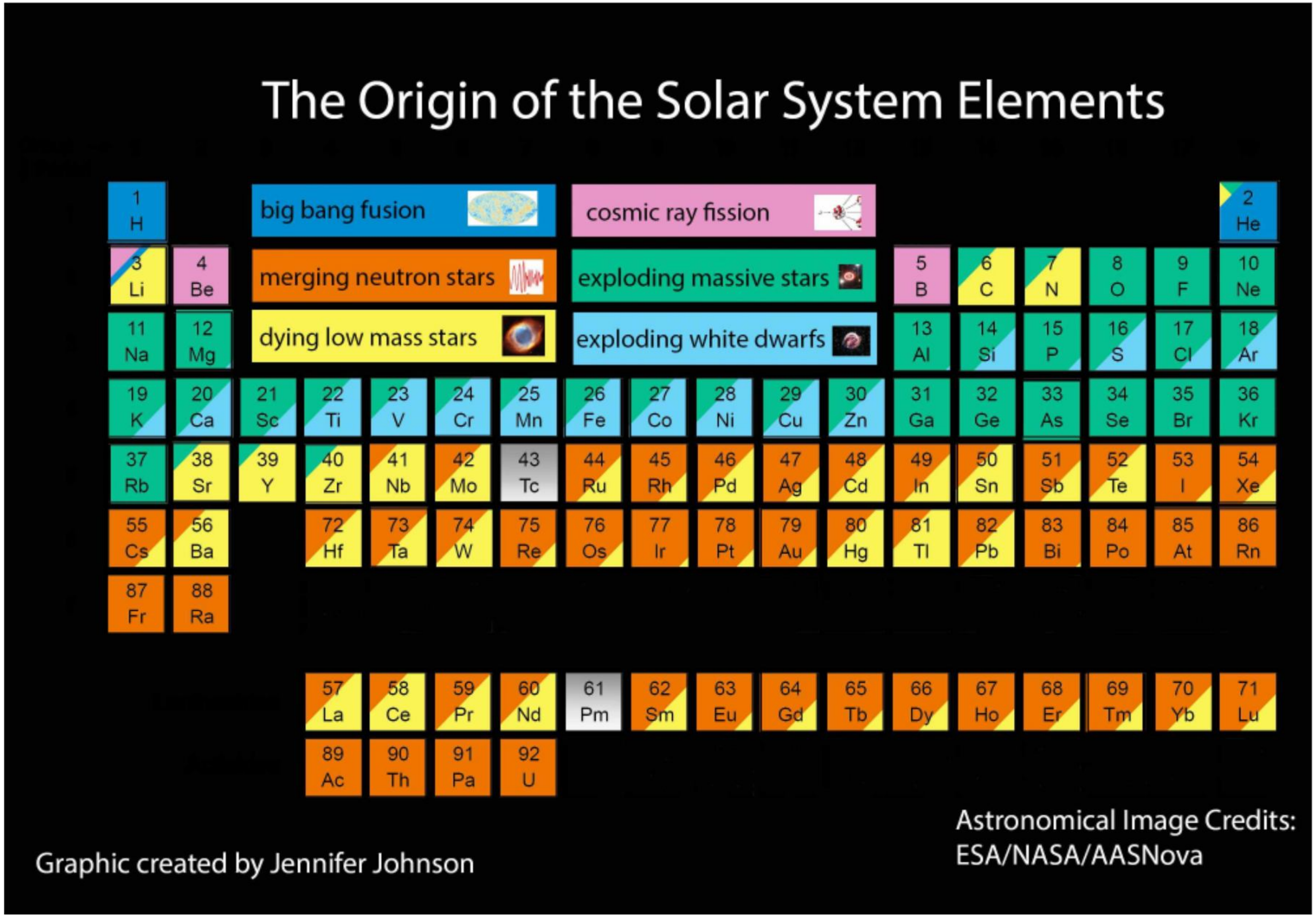

1992
10 light days

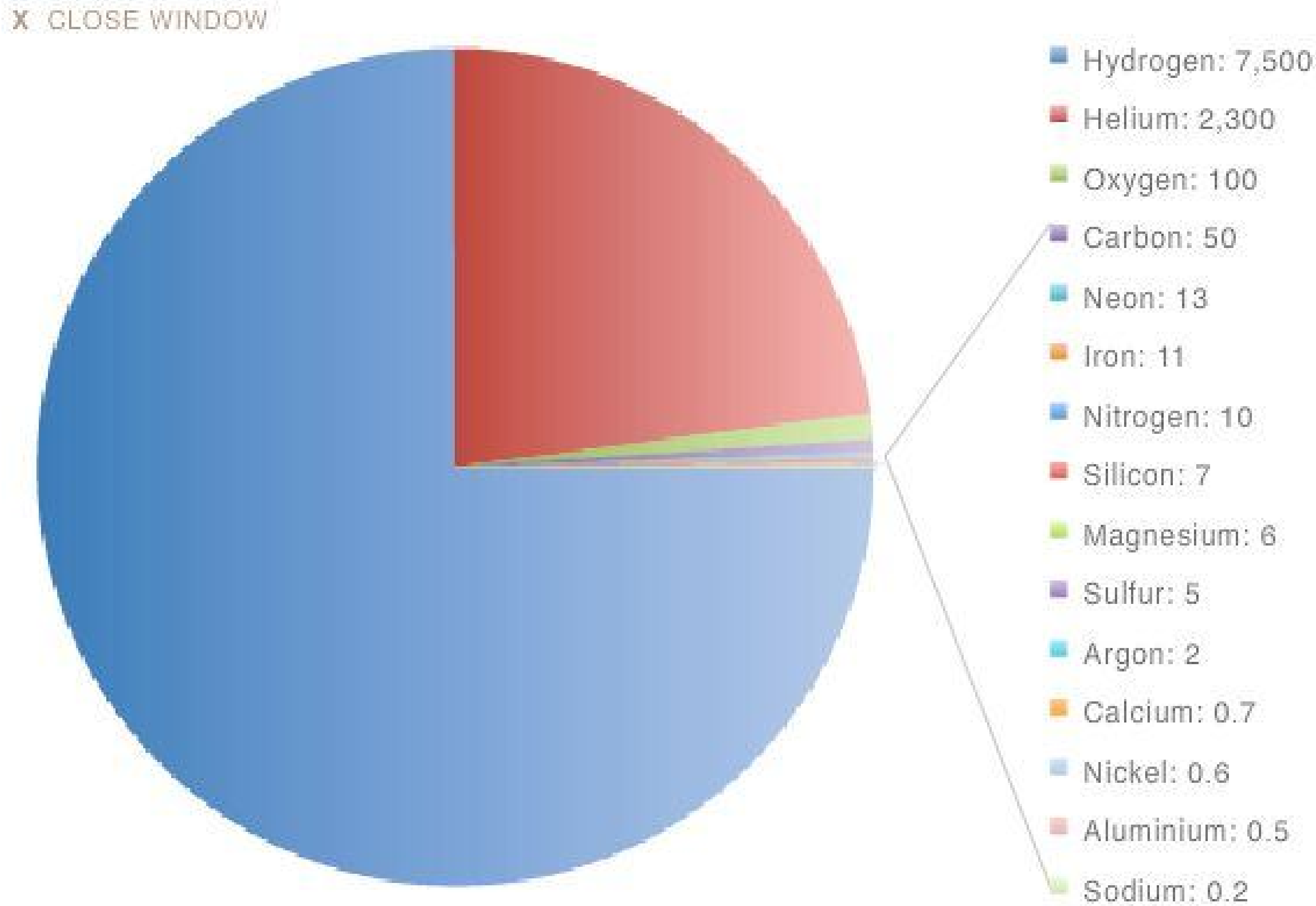
Kilonova: The merging of two neutron stars



Chemical aspects of stellar evolution

And Man-Made elements





X CLOSE WINDOW
Hydrogen: 7,500
Helium: 2,300
Oxygen: 100
Carbon: 50
Neon: 13
Iron: 11
Nitrogen: 10
Silicon: 7
Magnesium: 6
Sulfur: 5
Argon: 2
Calcium: 0.7
Nickel: 0.6
Aluminium: 0.5
Sodium: 0.2

Solving the Equations of a Star

Spherically symmetric quasi-static model

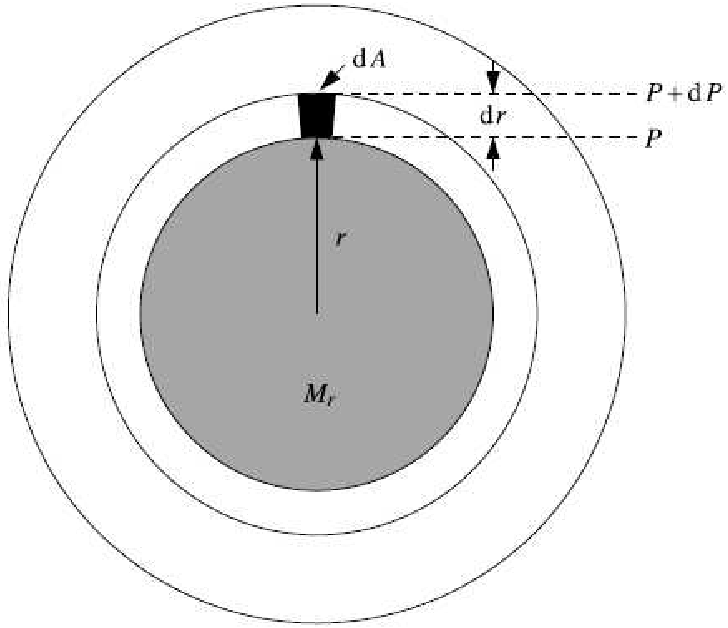
- a star is in a steady state
- it is spherically symmetric.

Four basic first-order differential equations:

- two represent how matter and pressure vary with radius
- two represent how temperature and luminosity vary with radius.

Solving the Equations of a Star

1- Equation of hydrostatic equilibrium



$$dF_g = -\frac{GM_r\,dm}{r^2} = -\frac{GM_r\rho}{r^2}\,dA\,dr,$$

$$dF_p = P\,dA - (P + dP)\,dA$$

$$= -dP\,dA.$$

$$0 = dF_g + dF_p$$

$$= -\frac{GM_r\rho}{r^2}\,dA\,dr - dP\,dA$$

$$\frac{dP}{dr} = -\frac{GM_r\rho}{r^2}.$$

Solving the Equations of a Star

2- Mass Distribution

$$\mathrm{d}M_r = 4\pi r^2 \rho \, \mathrm{d}r,$$

3- Energy Production

$$\mathrm{d}L_r = L_{r+\mathrm{d}r} - L_r = \varepsilon \, \mathrm{d}M_r = 4\pi r^2 \rho \varepsilon \, \mathrm{d}r.$$

$$\frac{\mathrm{d}L_r}{\mathrm{d}r} = 4\pi r^2 \rho \varepsilon.$$

4- Heat transfert

- Conduction ,
- Radiation,
- Convection

For radiative equilibrium :

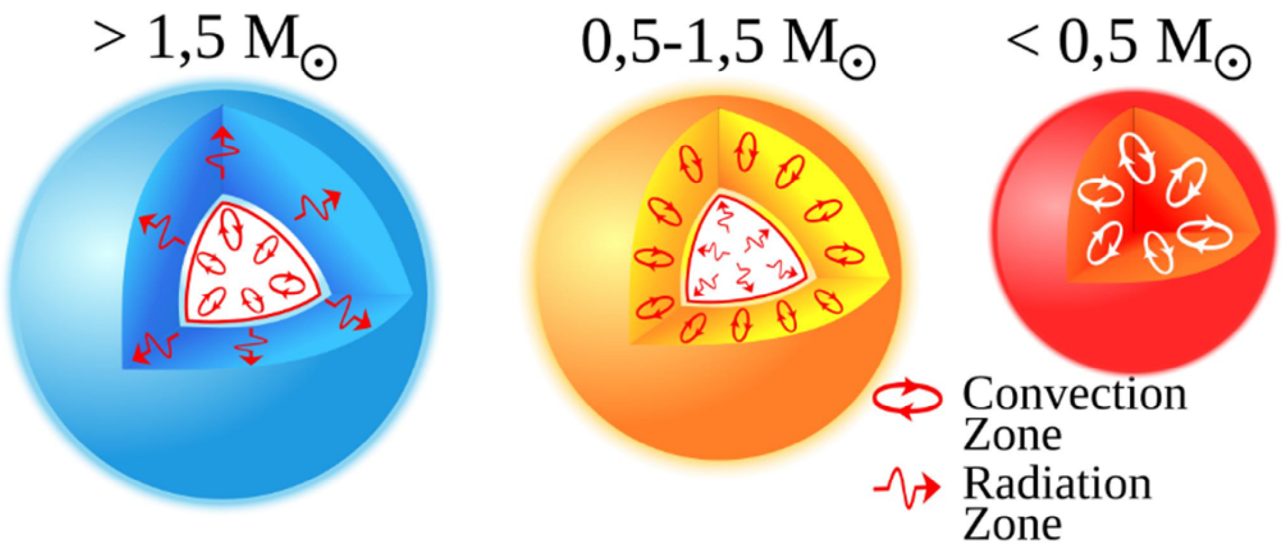
κ mass absorption coefficient

$$\frac{\mathrm{d}T}{\mathrm{d}r} = \left(-\frac{3}{4ac}\right)\left(\frac{\kappa\rho}{T^3}\right)\left(\frac{L_r}{4\pi r^2}\right),$$

$$a = 4\sigma/c = 7.564 \times 10^{-16} \ \mathrm{J\,m^{-3}\,K^{-4}}$$

Solving the Equations of a Star

- Between convective and radiative heat transfert in ordinary stars
- Conductive heat transfert in white dwarves...



Solving the Equations of a Star

5- Equation of State

$$P = \frac{k}{\mu m_{\rm H}} \rho T,$$

Mean molecular weight : μ

$$\mu = \frac{1}{2X + \frac{3}{4} Y + \frac{1}{2} Z}. \qquad X + Y + Z = 1.$$

The sources of pressure:

- Radiation pressure: heavy stars

$$P = \frac{k}{\mu m_{\rm H}} \rho T + \frac{1}{3} a T^4.$$

- Pauli principle: at very high density, the matter is degenerate!

$$P \approx hc \left(\frac{N}{V}\right)^{4/3} = hc \left(\frac{\rho}{\mu_e m_{\rm H}}\right)^{4/3}.$$

$$P = P(T, \rho, X, Y, Z),$$

Solving the Equations of a Star

System of 4 differential equations + Constraints:

M, T, L, P, ρ, κ, ε, μ -> 4 structure equations + EOS + ε(T, ρ, X,Y,Z)+ $\mu + \kappa$

All in fonction of the radius r

Boundary conditions:

- No sources of energy or mass at the center inside the radius r = 0; thus M(0) = 0 and L(0) = 0.

– The total mass within the radius R of the star is fixed, M(r=R) =M.

– Temperature and pressure at surface small:T(r=R) = 0 and P(r=R) = 0.

Vogt Russel thm:

Knowing mass M, and chemical composition X, Y, Z enough to « solve » a star

Solving the Equations of a Star

Evolution:

- Till now, quasi-static case

- In practise there is an evolution driven by μ changing:

Stellar modeling !

Start at Zero Age Main Sequence (ZAMS) with a given chemical compostion (older meteorites),

X=0,71, Y= 0,28, Z= 002

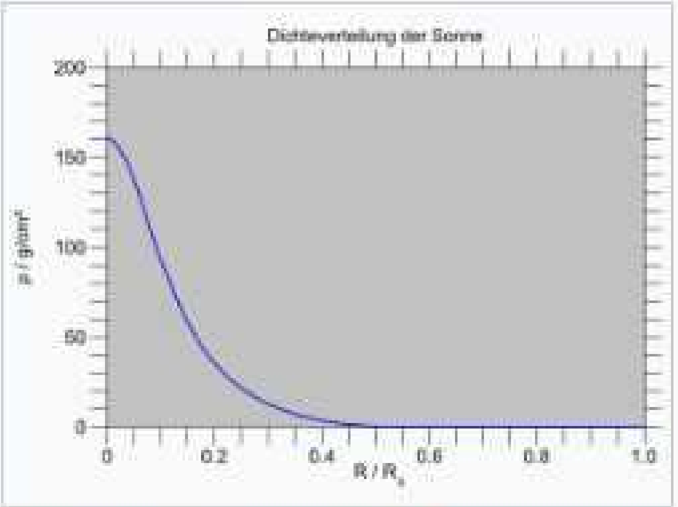
Let the system evolve in time…

Solving the Equations of a Star

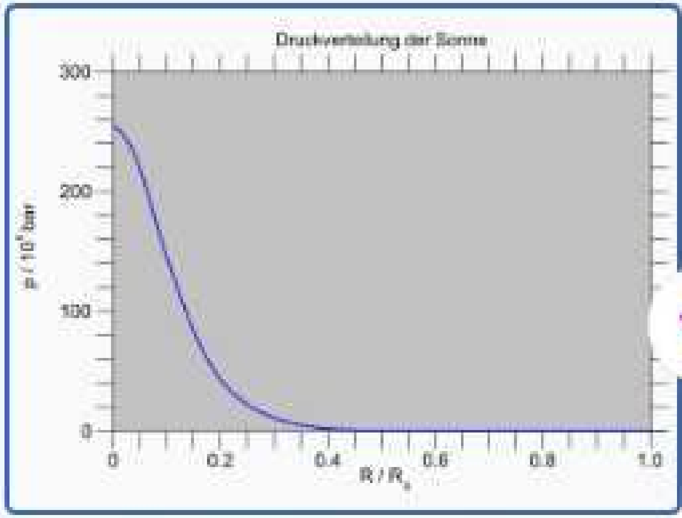
M [$M_\odot$]	R [$R_\odot$]	L [$L_\odot$]	T_e [K]	T_c [10^6 K]	ρ_c [kg/m^3]	M_{ci} [M]	M_{ce} [M]
30	6.6	140,000	44,000	36	3000	0.60	0
15	4.7	21,000	32,000	34	6200	0.39	0
9	3.5	4500	26,000	31	7900	0.26	0
5	2.2	630	20,000	27	26,000	0.22	0
3	1.7	93	14,000	24	42,000	0.18	0
1.5	1.2	5.4	8100	19	95,000	0.06	0
1.0	0.87	0.74	5800	14	89,000	0	0.01
0.5	0.44	0.038	3900	9.1	78,000	0	0.41

Properties of zero age main sequence stars. (T_c = central temperature; ρ_c = central density; M_{ci} = relative mass of convective interior; M_{ce} = relative mass of convective envelope)

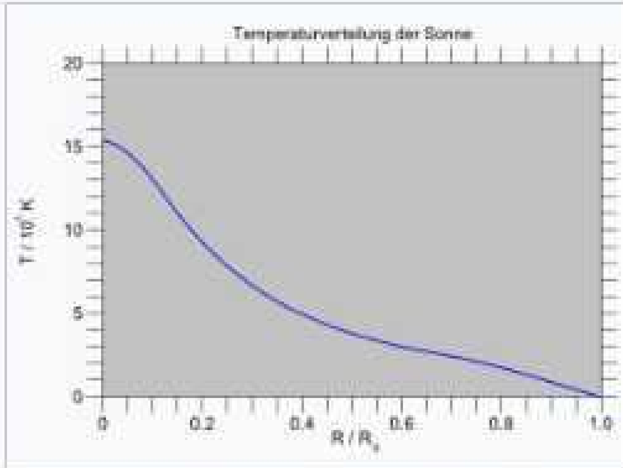
Solutions in graphic form



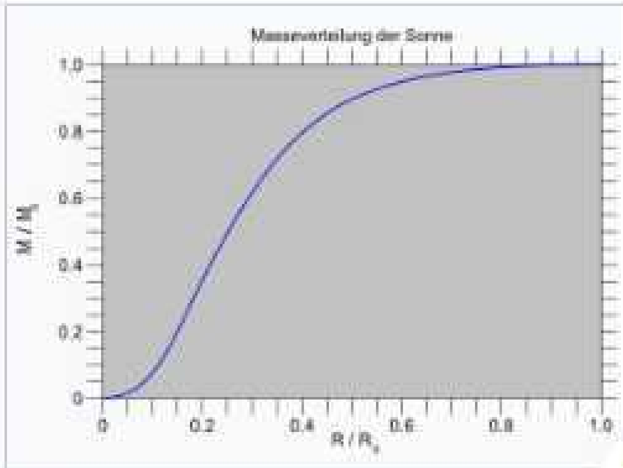
Density profile in the Sun



Pressure profile in the Sun



Temperature profile in the Sun



Mass inside a given radius in the Sun

How is the Sun Shining ?

Thermonuclear fusion reactions:

Proton-proton Chain (pp chain) (Mostly in the Sun)

$$\begin{array}{lll} \text{ppI:} \quad (1) & {}^1\text{H} + {}^1\text{H} & \rightarrow {}^2\text{H} + e^+ + \nu_e, \\ & {}^1\text{H} + {}^1\text{H} + e^- & \rightarrow {}^2\text{H} + \nu_e, \\ (2) & {}^2\text{H} + {}^1\text{H} & \rightarrow {}^3\text{He} + \gamma, \\ (3) & {}^3\text{He} + {}^3\text{He} & \rightarrow {}^4\text{He} + 2\,{}^1\text{H}. \end{array}$$

CNO cycle :

Mostly in heavy stars M<1,5

Msun, T< 20,10^{6}K

$$\begin{array}{lll} (1) & {}^{12}\text{C} + {}^1\text{H} & \rightarrow {}^{13}\text{N} + \gamma, \\ (2) & {}^{13}\text{N} & \rightarrow {}^{13}\text{C} + e^+ + \nu_e, \\ (3) & {}^{13}\text{C} + {}^1\text{H} & \rightarrow {}^{14}\text{N} + \gamma, \\ (4) & {}^{14}\text{N} + {}^1\text{H} & \rightarrow {}^{15}\text{O} + \gamma, \\ (5) & {}^{15}\text{O} & \rightarrow {}^{15}\text{N} + \gamma + \nu_e, \\ (6) & {}^{15}\text{N} + {}^1\text{H} & \rightarrow {}^{12}\text{C} + {}^4\text{He}. \end{array}$$

How is the Sun Shining ?

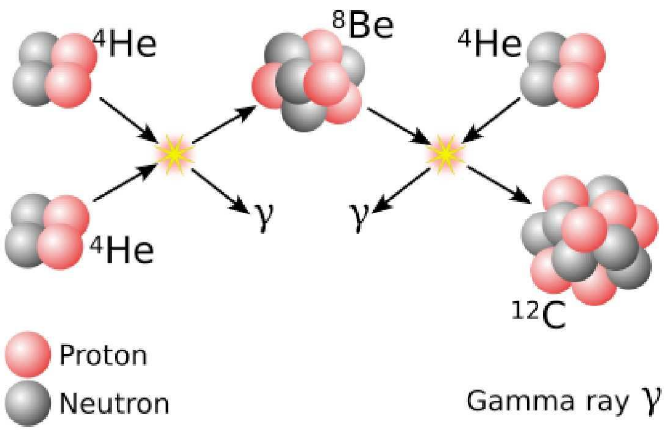
The Triple alpha reaction bottleneck:

When a star runs out of hydrogen to fuse in its core, it begins to contract and heat up, At a temperature above 10^8 K, the helium can be transformed into carbon in the triple alpha reaction:

(1) $^4He + {}^4He \leftrightarrow {}^8Be$,

(2) $^8Be + {}^4He \rightarrow {}^{12}C + \gamma$.

But ^8Be unstable and decays into two ^4He nuclei or alpha particles in 2.6×10^{-16} seconds.



Three-body collision !

Hoyle resonance (1954)

That is: $3\ {}^4He \rightarrow {}^{12}C + \gamma$

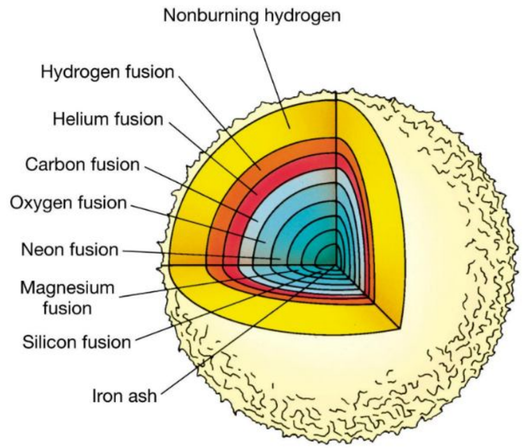
How is the Sun Shining ?

The Triple alpha bottleneck II

Other reactions can now proceed:

Alpha reactions

$$^{12}C + {}^{4}He \rightarrow {}^{16}O + \gamma,$$
$$^{16}O + {}^{4}He \rightarrow {}^{20}Ne + \gamma,$$
$$^{20}Ne + {}^{4}He \rightarrow {}^{24}Mg + \gamma.$$



Carbon burning reactions

$$\begin{aligned} ^{12}C + {}^{12}C &\rightarrow {}^{24}Mg + \gamma \\ &\rightarrow {}^{23}Na + {}^{1}H \\ &\rightarrow {}^{20}Ne + {}^{4}He \\ &\rightarrow {}^{23}Mg + n \\ &\rightarrow {}^{16}O + 2\,{}^{4}He. \end{aligned}$$

... up to Iron

In Conclusion about Stars

Most **fundamental objects** in the Universe, and possibly the **most interesting ones** from the physics standpoint.

A quick summary of some basic star stuff:

1. Sun-like stars*: just thermodyn. and good nuclear and atomic physics*
2. Heavy stars: … *add complicated « chemical » evolution.*
3. Compact stars: physics of the extreme: *White dwarf, Neutron stars*
4. Exotic stars : exotic matter or conditions of matter: *axion stars, strange matter stars, …, magnetars…*
5. More types of stars will be found in the future as **our physics « evolves ».**

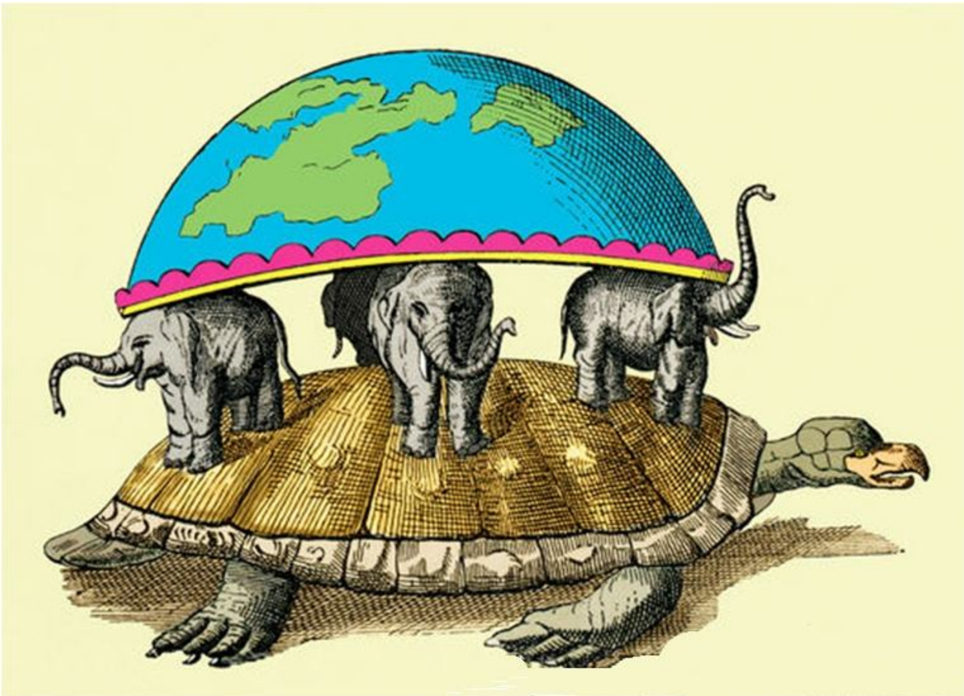
4- Big Bang Cosmology:
Λ–CDM

“Cosmologists are often wrong but never in doubt”

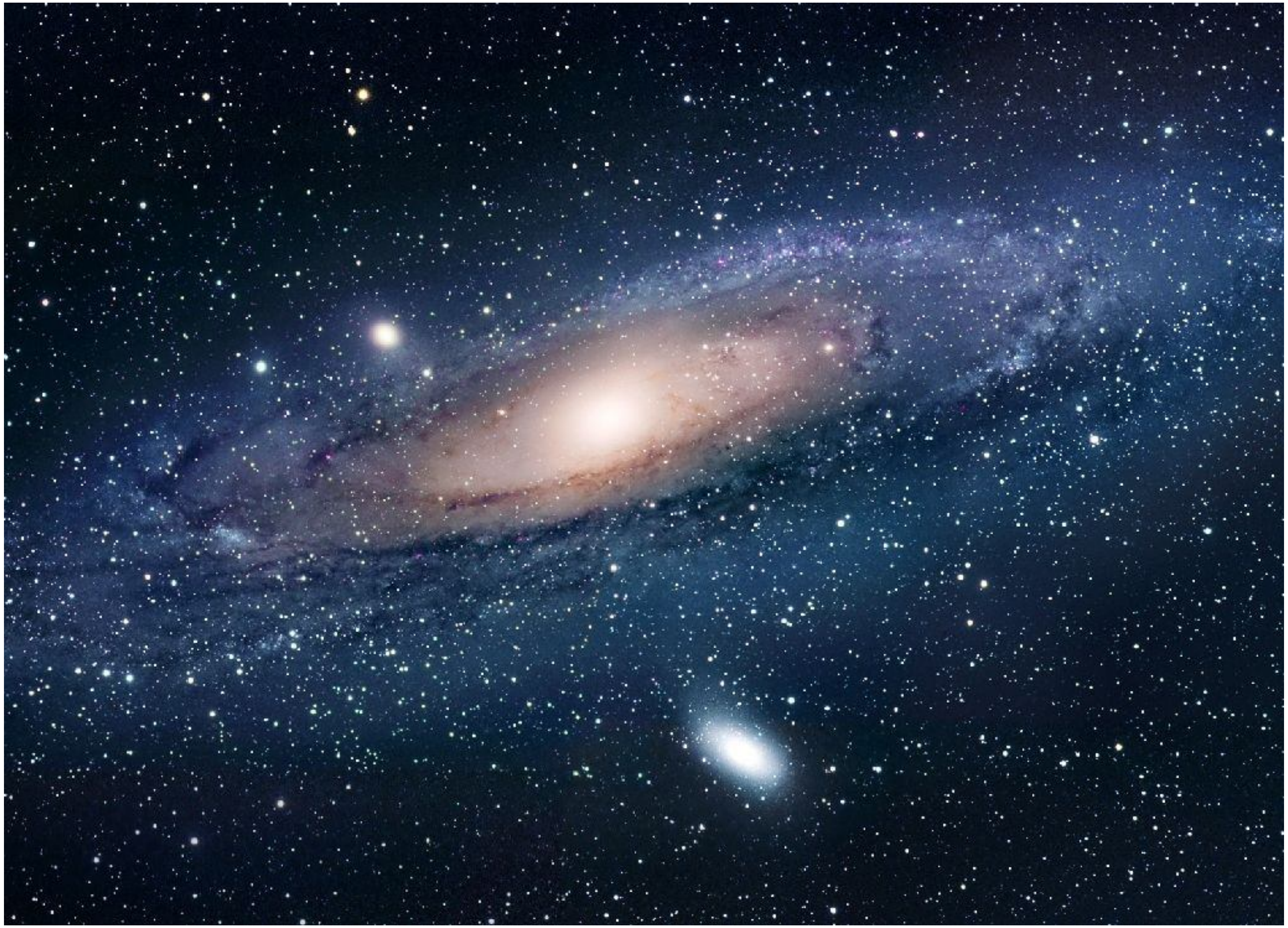
- Lev Landau

“The history of cosmology shows that in every age devout people believe that they have at last discovered the true nature of the Universe.”

– E. R. Harrison (1981)



The Realm of the Galaxies

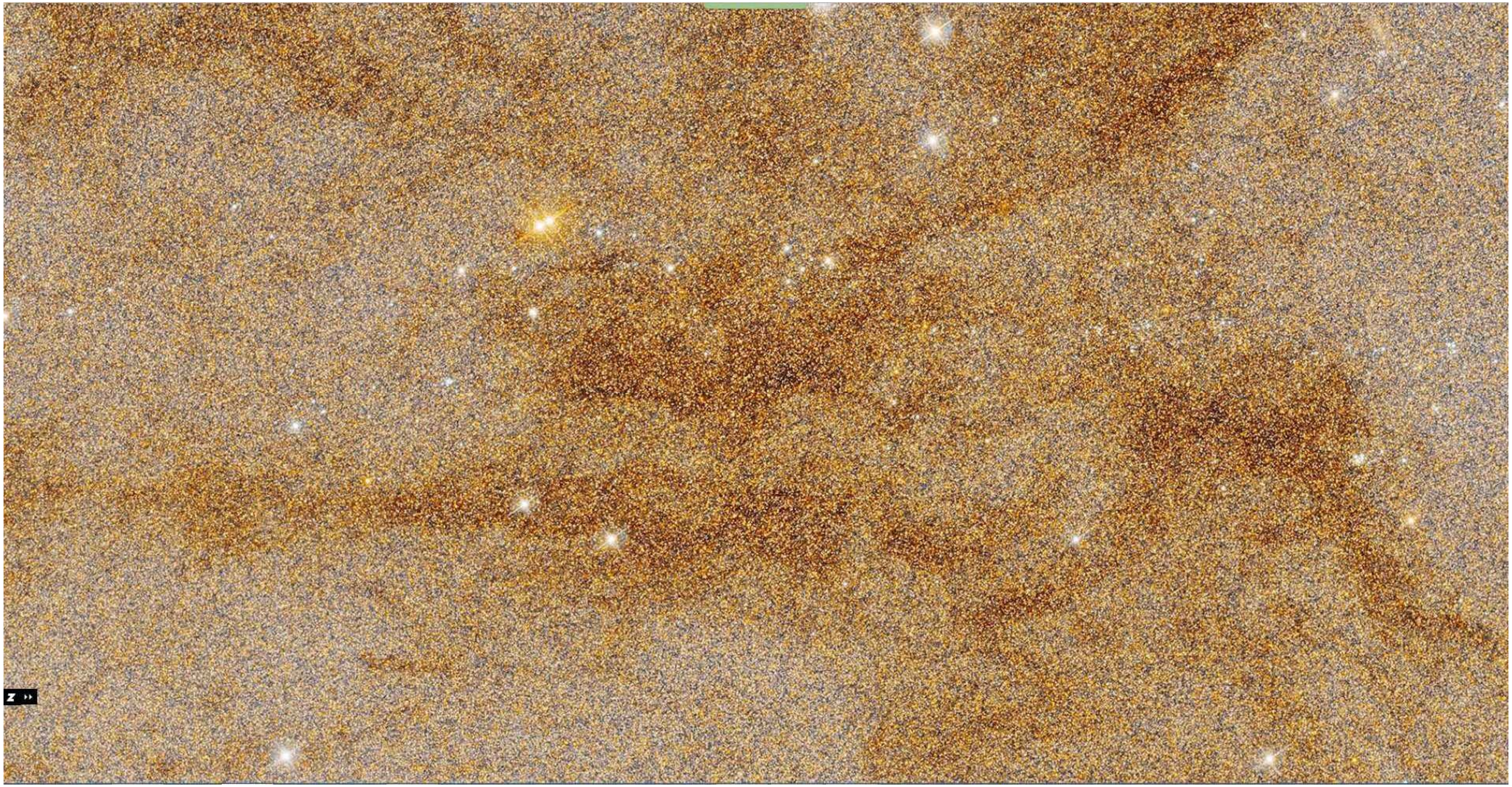


- **The Andromeda Galaxy in visible light**

Understanding at last why the Andromeda galaxy is not a nebula

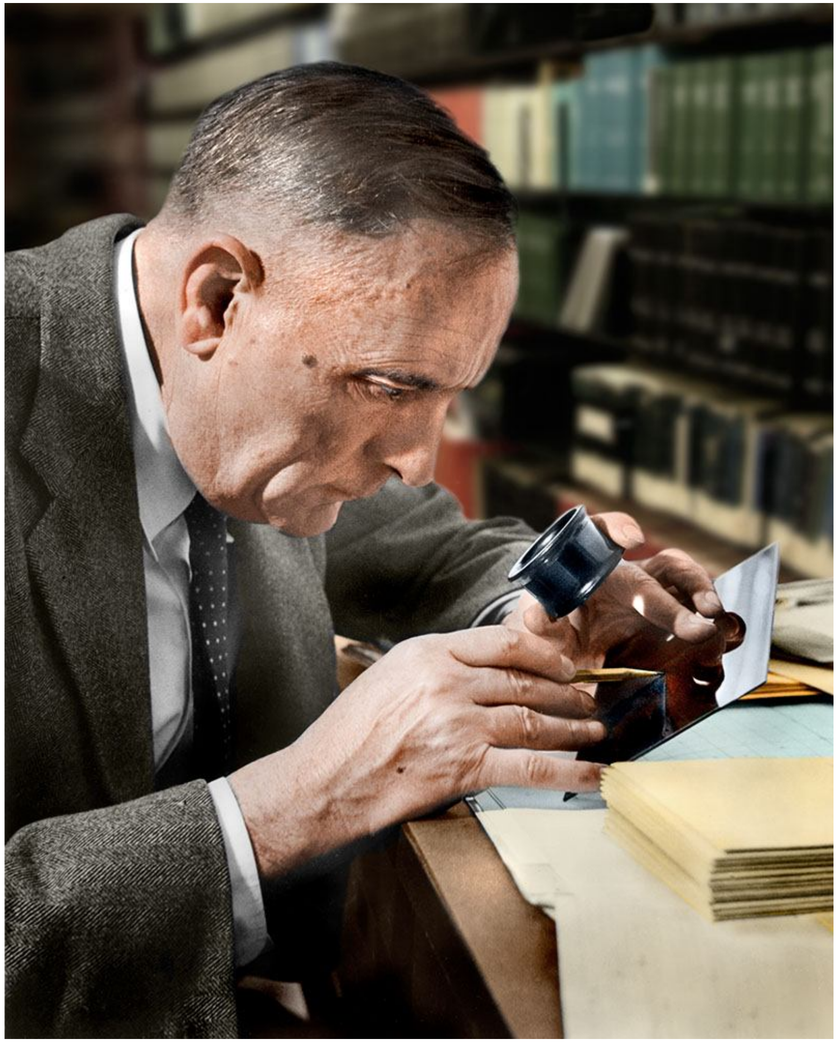
Hubble 1923 (Using HST pictures!)

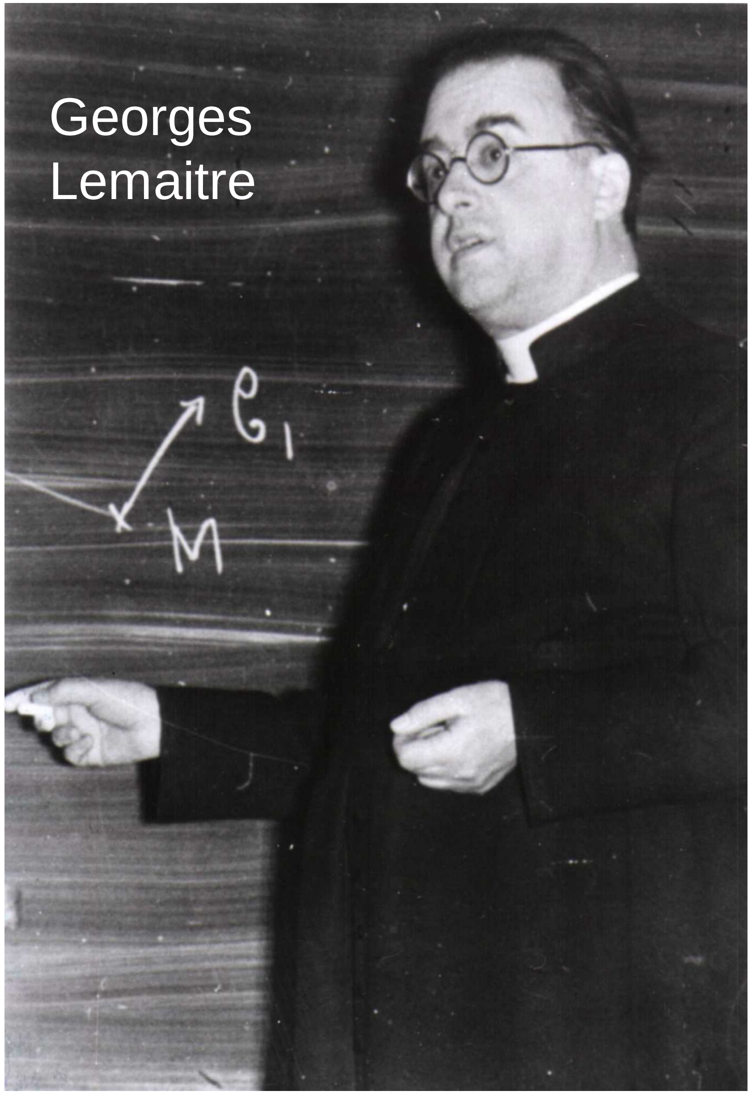
Zooming in:
From « smooth » to « grainy »



« Classical » Cosmology

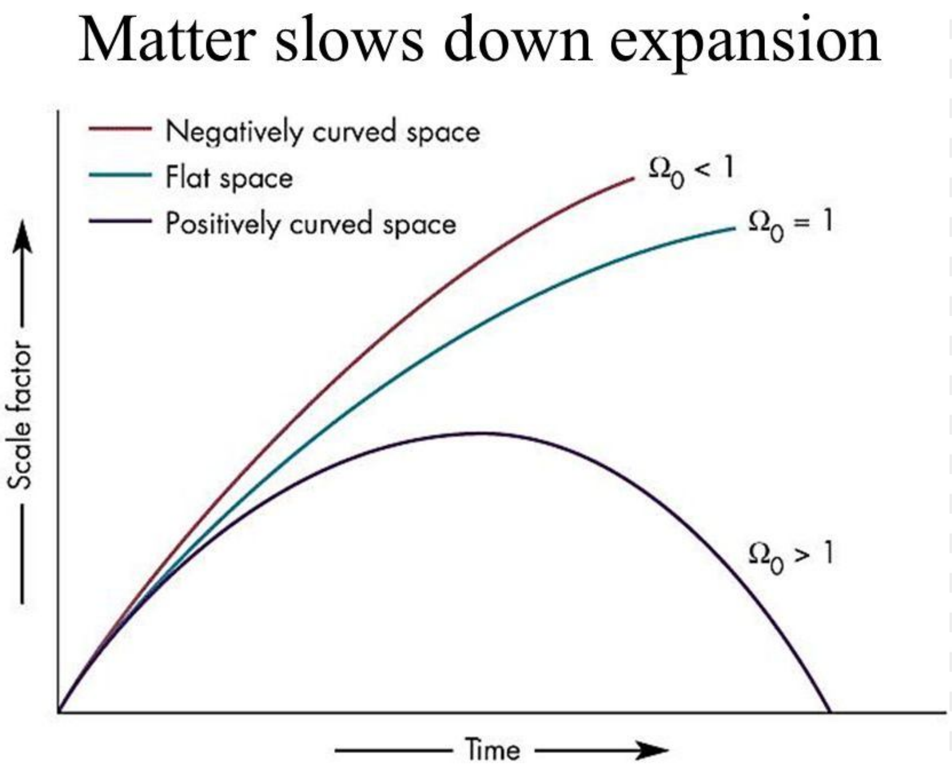
The Tale of Two Giants…

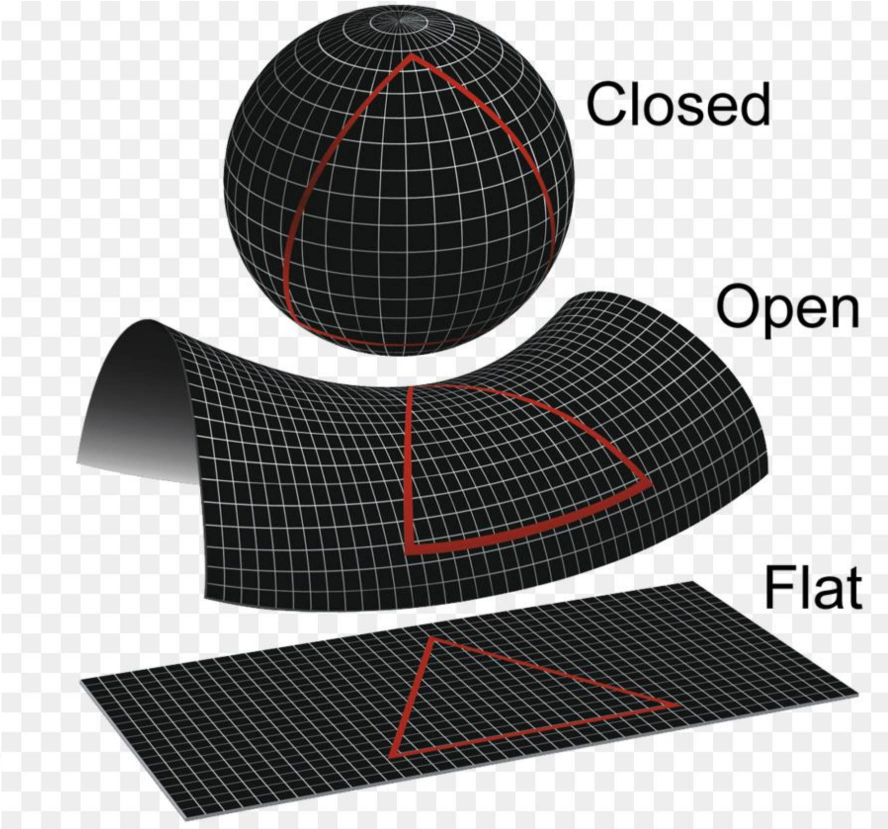




There was a time when ...

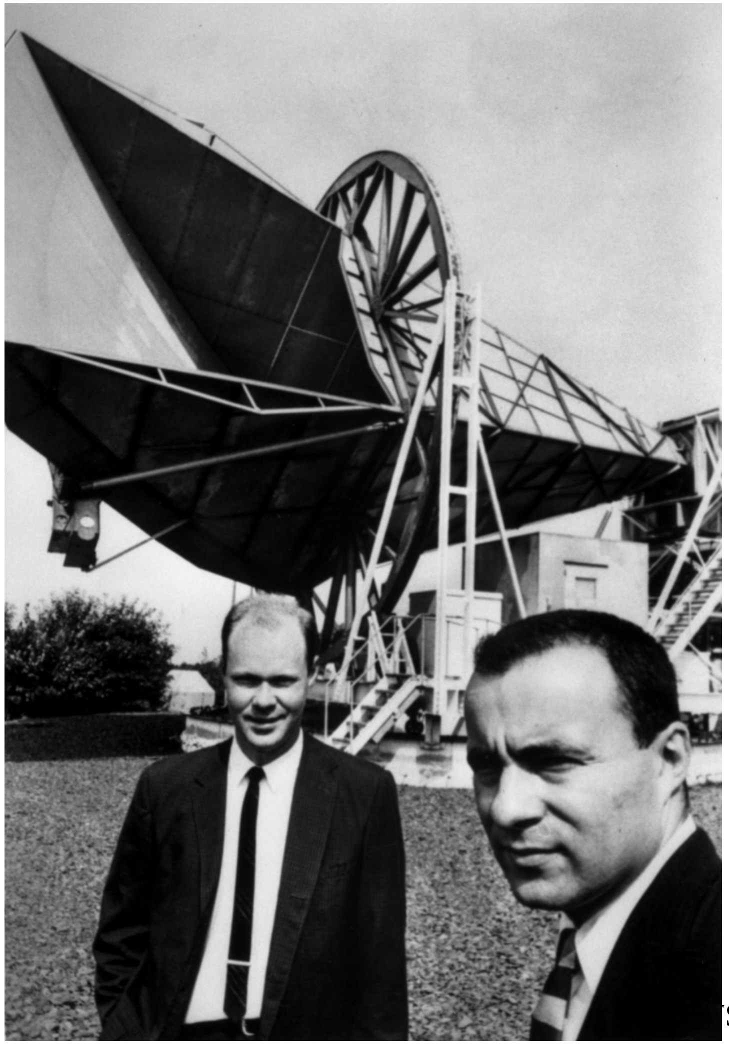
… «one constant» Cosmology

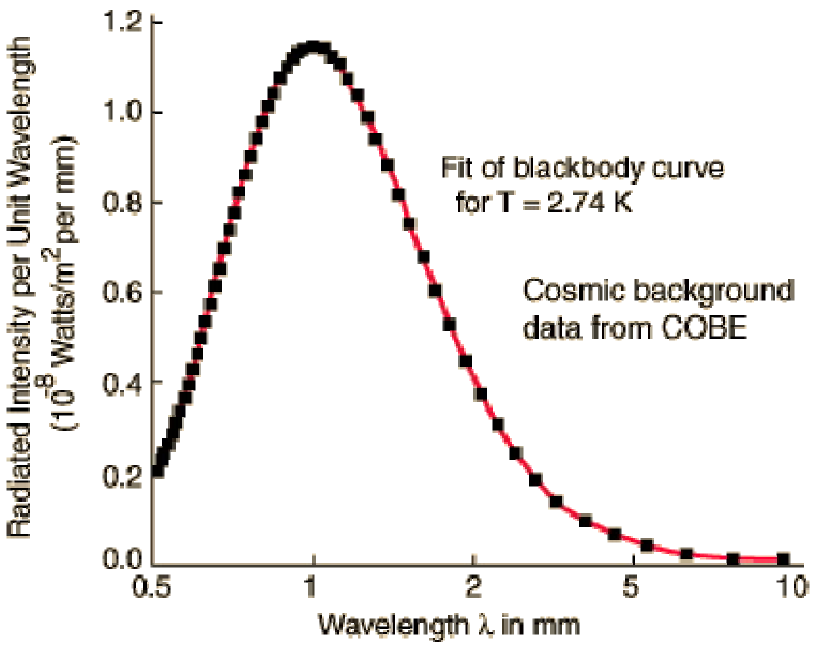




The Discovery of the CMB:

The Founding Act
of the Hot Big bang Theory

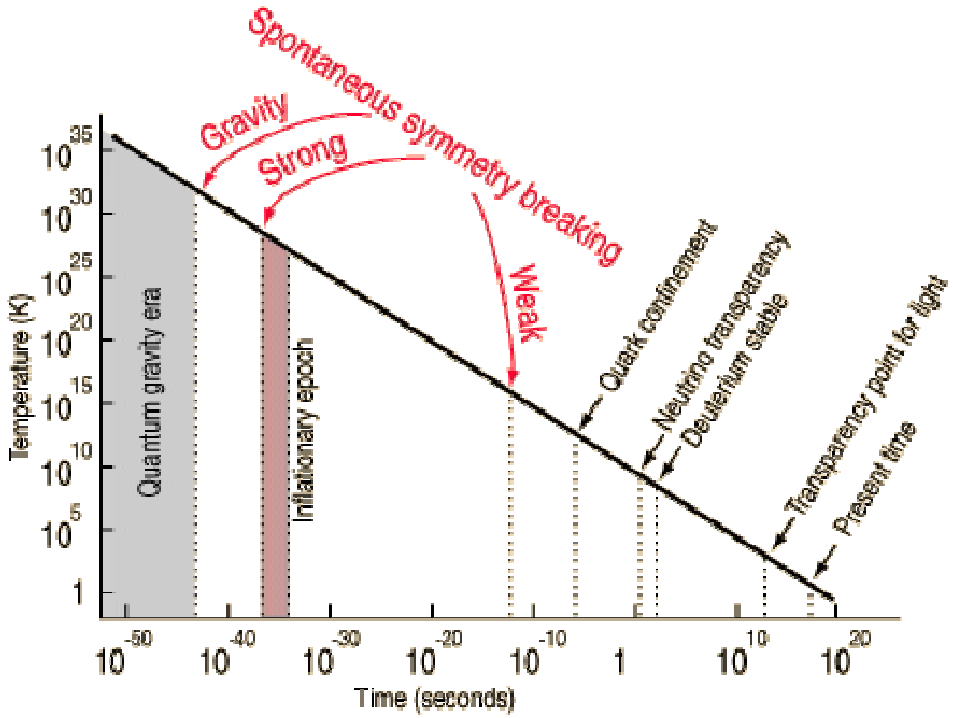


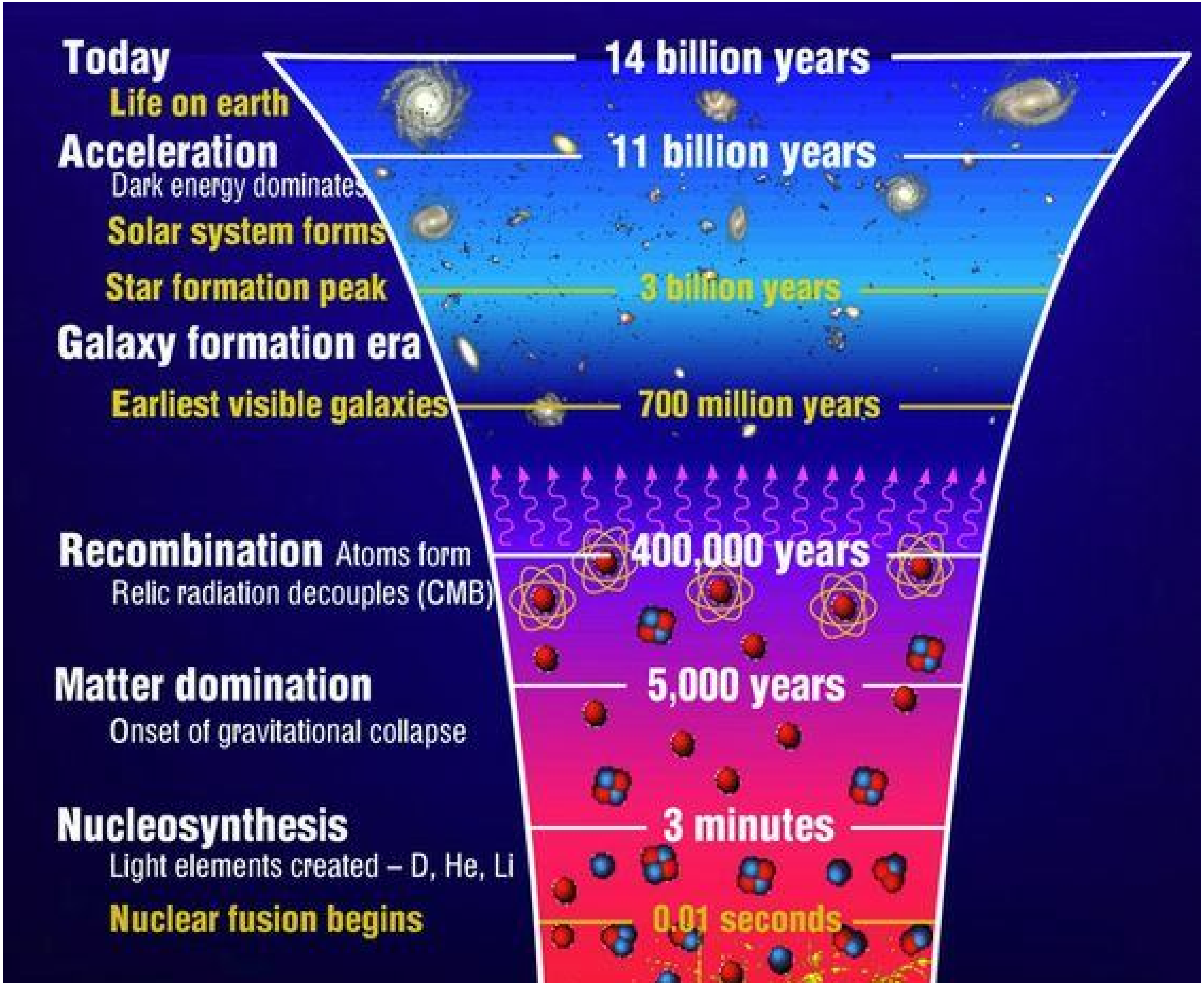


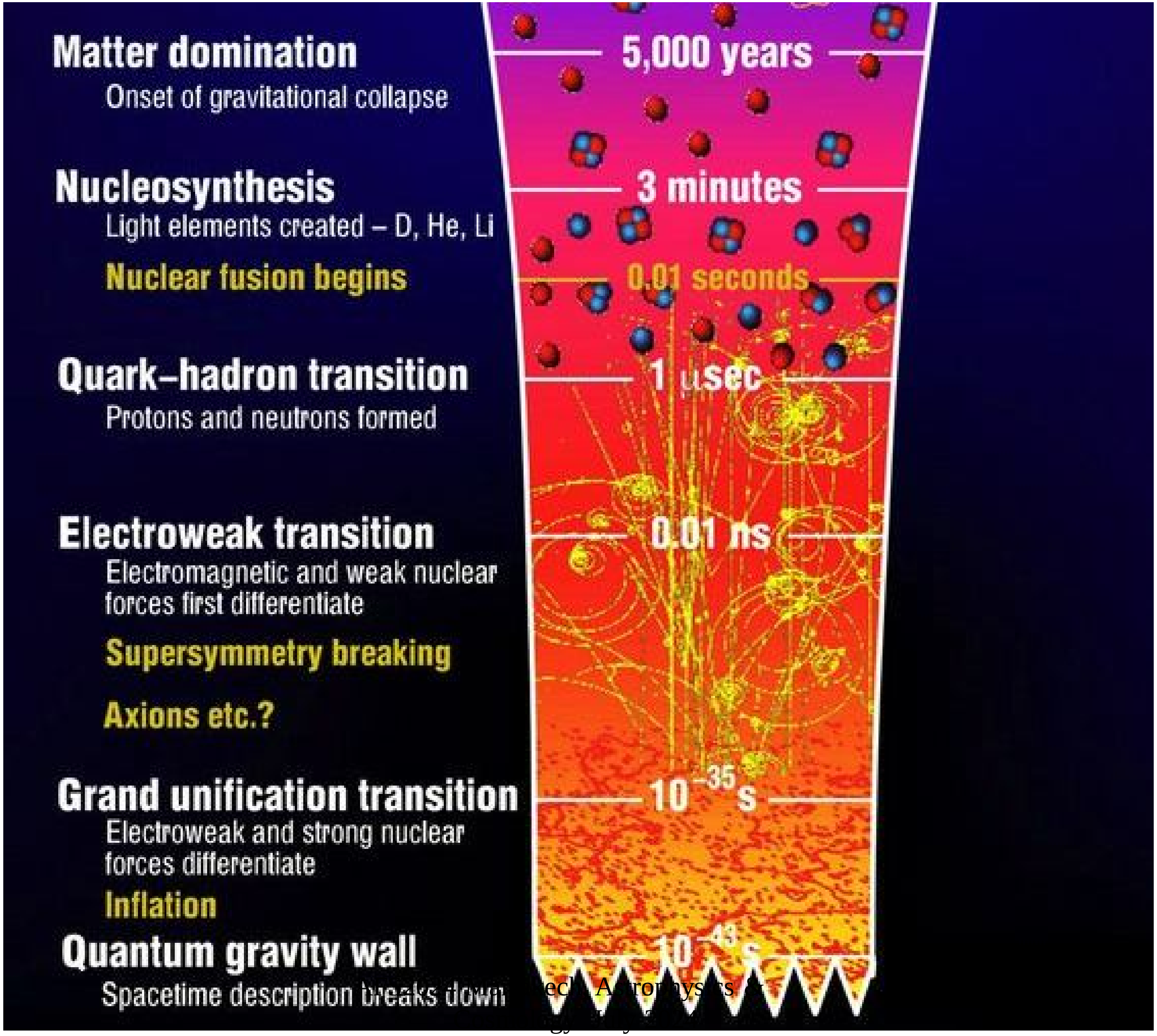
Wilson & Penzias:
Discoverers of the CMB

The Thermal History of the Universe

Warning: The treatment will be a bit patchy as a more advanced course will be given later during the second week… Mostly flashes



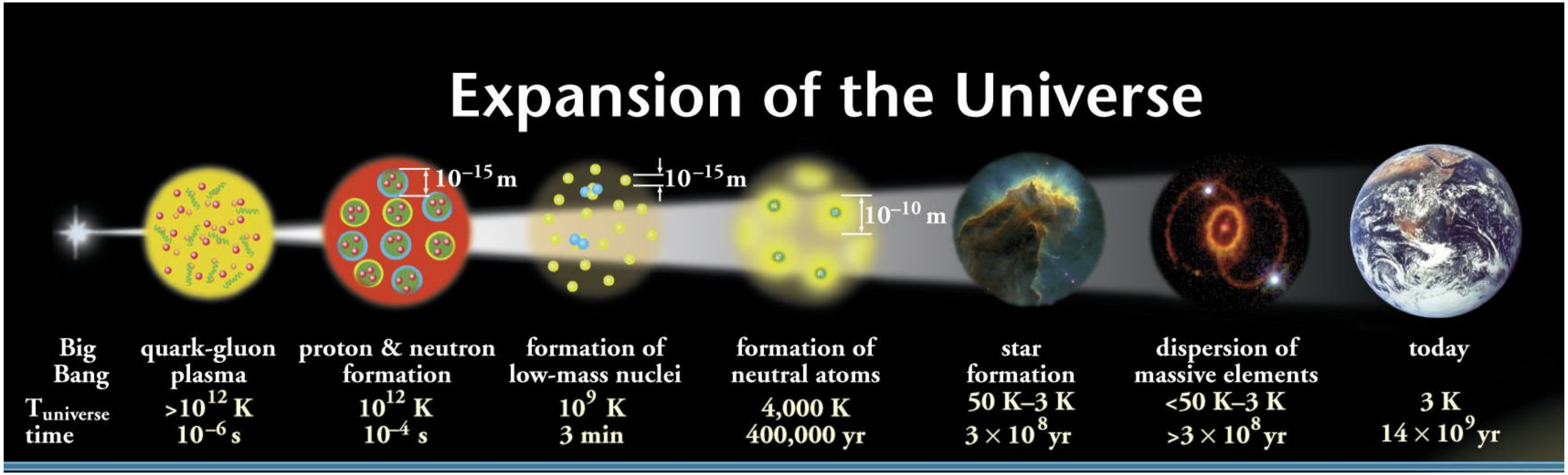

Today
Life on earth
Acceleration
Dark energy dominates
Solar system forms
Star formation peak
Galaxy formation era
Earliest visible galaxies
Recombination Atoms form
Relic radiation decouples (CMB)
Matter domination
Onset of gravitational collapse
Nucleosynthesis
Light elements created – D, He, Li
Nuclear fusion begins
14 billion years
11 billion years
3 billion years
700 million years
400,000 years
5,000 years
3 minutes
0.01 seconds



Matter domination
Onset of gravitational collapse
5,000 years
Nucleosynthesis
Light elements created – D, He, Li
3 minutes
Nuclear fusion begins
0.01 seconds
Quark–hadron transition
Protons and neutrons formed
1 μsec
Electroweak transition
Electromagnetic and weak nuclear forces first differentiate
0.01 ns
Supersymmetry breaking
Axions etc.?
Grand unification transition
Electroweak and strong nuclear forces differentiate
10^-35 s
Inflation
Quantum gravity wall
Spacetime description breaks down
10^-43 s

HE physics is more & more relevant

as we go up in energy i.e. get closer to the Big Bang



The Thermal History of the Universe

from the Big Bang to the present

- We will discuss in a general and « rough » way, one key concept in the thermal history of the Universe, namely that of particle decoupling…

- Then we will present few general synthetic slides which contain a lot of physics, but we unfortunately we can't go into it in this overview…

Key assumptions :

- the Big Bang theory accurately describes the universe's origin; the universe has been expanding and cooling over time
- general relativity and quantum mechanics govern the behavior of matter
- physical laws have remained constant
- the universe is homogeneous and isotropic on large scales;

The Thermodynamics of the Early Universe

- The Universe starts in a hot, dense state dominated by high-energy particles and radiation.
- Assume it has gone through a rapid inflationary phase that sets the IC for its subsequent thermal evolution.
- Particle physics and temperature Evolution:

  as the Universe expands, it cools down.

The Early Universe's different eras

Phases of the Universe:

- radiation-dominated era
- matter-dominated era
- dark energy-dominated era (late-time evolution)

Focus on the radiation-dominated era (Where all the action is):

Energy density is dominated by relativistic particles: photons, neutrinos, and others...

The Early Universe's different eras

'Law of the jungle applied to particle physics':

- the strongest (Interaction wise)
- The more numerous

Due to Stat. mechanics, only relativistic particles (So called relativistic d.o.f) matter as their energy dominate:

Particle decoupling in Early Universe

- How particle interactions and their energy thresholds regulate the temperature of the Universe.
- Particles freeze out or decouple from thermal equilibrium as the temperature drops below their respective masses or interaction rates.
- The dual between the cooling particle's interaction rate with that of the expansion rate of the Universe given by $H \sim 1/t$ (t being the age of the Universe)

Interaction rate : Γ --> partic. inequil.: $\Gamma >> H$

Expansion rate : H --> partic. decoupled: $\Gamma << H$

Phase Transitions
Particle decoupling

The relevant metric from Friedmann equations is:

$(a/a)2=8\pi G\rho/3\ -ka^2$

where a is the scale factor, ρ is the energy density, k is the curvature parameter.

while the equations of motion for the matter in the Universe are:

$$T^{\alpha\beta}{}_{;\beta} = 0$$

Phase Transitions
Particle decoupling

Giving $$\frac{d}{dt}(\rho a^3) = -p\frac{d}{dt}a^3$$

which can be rewritten as: $$a^3\frac{dp}{dt} = \frac{d}{dt}[a^3(\rho + p)]$$

1- For radiation, where p = ρ/3, it gives $\rho \sim a^{-4}$ while for the matter $\rho \sim a^{-3}$

- Note that all particle species which are light enough such that their average thermal kinetic energies at a certain temperature are larger than the rest mass have the equation of state of radiation,

2- For matter domination, where p = 0, $\rho \sim a^{-3}$.

In both cases, in the early Universe (... for small a) the curvature term $\sim k/a^2$ was much less important than

Particle decoupling

- We will discuss in a general and « rough » way, one key concept, namely that of particle decoupling…

- Then we will present few general slides which contain a lot of physics, ut taht we unfortuantely can't go into in this overview

The number density of particles decreases faster with temperature (Thus time) than the Hubble parameter. => at certain epochs, some particles will leave equilibrium and their number density will "freeze", to be only diluted afterwards by the expansion.

Particle decoupling

Radiation-Dominated Era

- Energy Density of Radiation: $\rho_{\text{rad}} = (\pi^2/30) g_* T^4$ where g_* is the effective number of relativistic degrees of freedom.

- Statistical Mechanics and Particle Interactions Boltzmann Distribution:

$n_i \propto g_i (m_i T/2\pi)^{3/2} e^{-mi/T}$

Matter-Radiation Equality and Transition

Equality Epoch: $\rho_m = \rho_r$ when $a$eq∼Ωr−1/4Ωm−1/3ρ m =ρ r whena eq ∼Ω r−1/4 Ω m−1/3

Particle decoupling

Compare the cooling particle's interaction rate with the expansion rate of the Universe given by **H ~ 1 / t** (t being the age of the Universe)

Interaction rate : Γ --> partic. inequil.: Γ >> H

Expansion rate : H --> partic. decoupled: Γ << H

For constituents with number density n, relative velocities v, and interaction with cross-section σ, the interaction rate per particle Γ is given by:

$$\Gamma = n\sigma v$$

Example of computation

Neutrino decoupling

Let us compute the decoupling temperature for neutrinos in the early Universe using the standard WS cross section (In fact in Fermi theory) for neutrino scattering, and writting the Hubble constant in fonction of the temperature through the density equation during the radiation era:

$$\Gamma(T) = n(T)\langle \sigma v \rangle_T \quad \sigma_F \simeq G_F^2 E^2 \simeq G_F^2 T^2 \quad \Gamma_F \sim G_F^2 T^5$$

$$H(T) = \sqrt{\frac{8\pi G}{3}}\sqrt{\rho_R} \simeq \frac{5.44}{m_P} T^2 \qquad g_* = 2 + \frac{7}{8}(3 \times 2 + 2 \times 2)$$

$$\Rightarrow \boxed{\frac{\Gamma_F}{H(T)} \simeq 0.24 T^3 G_F^2 m_P \simeq \left(\frac{T}{1\mathrm{MeV}}\right)^3}$$

The neutrinos decouple when their temperature become ~ 1 MeV due to the weakness of their interactions.

Recall that : 11.000K ~1eV

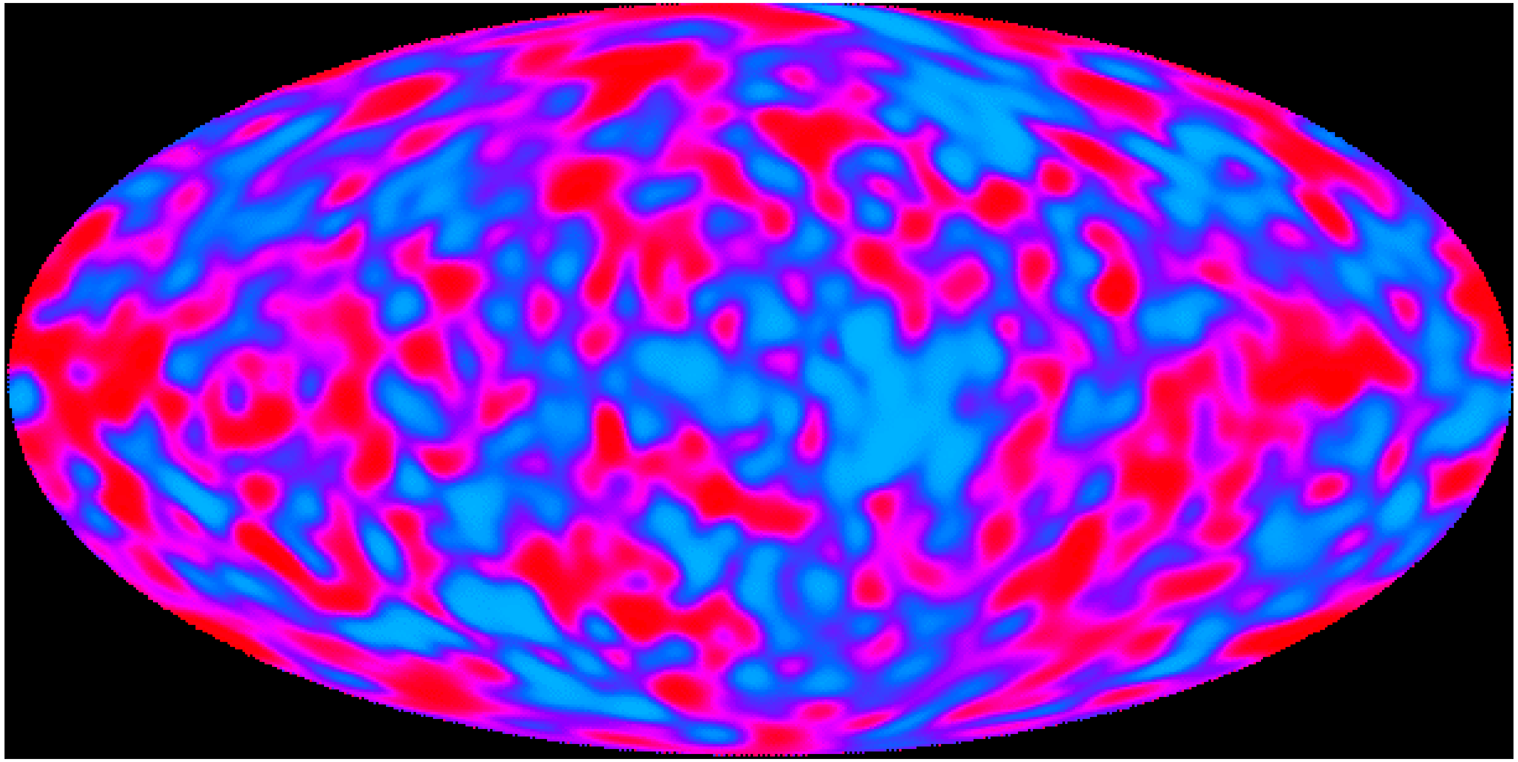
The Cosmic Microwave Background (CMB) Today

The CMB radiation results *from the decoupling of radiation from matter: the Universe became transparent to radiation* (by becoming neutral) which is now free streaming!

- It provides a snapshot of the Universe when it was around 380,000 years old.
- Its discovery in 1965 confirmed the hot, dense early state of the Universe.
- The temperature of the CMB today is equal to its temperature at decoupling time divided by the scale factor : $T_{CMB}=T_{dec} \cdot a_{dec}/a_0$ that is ~3000K

The CMB today

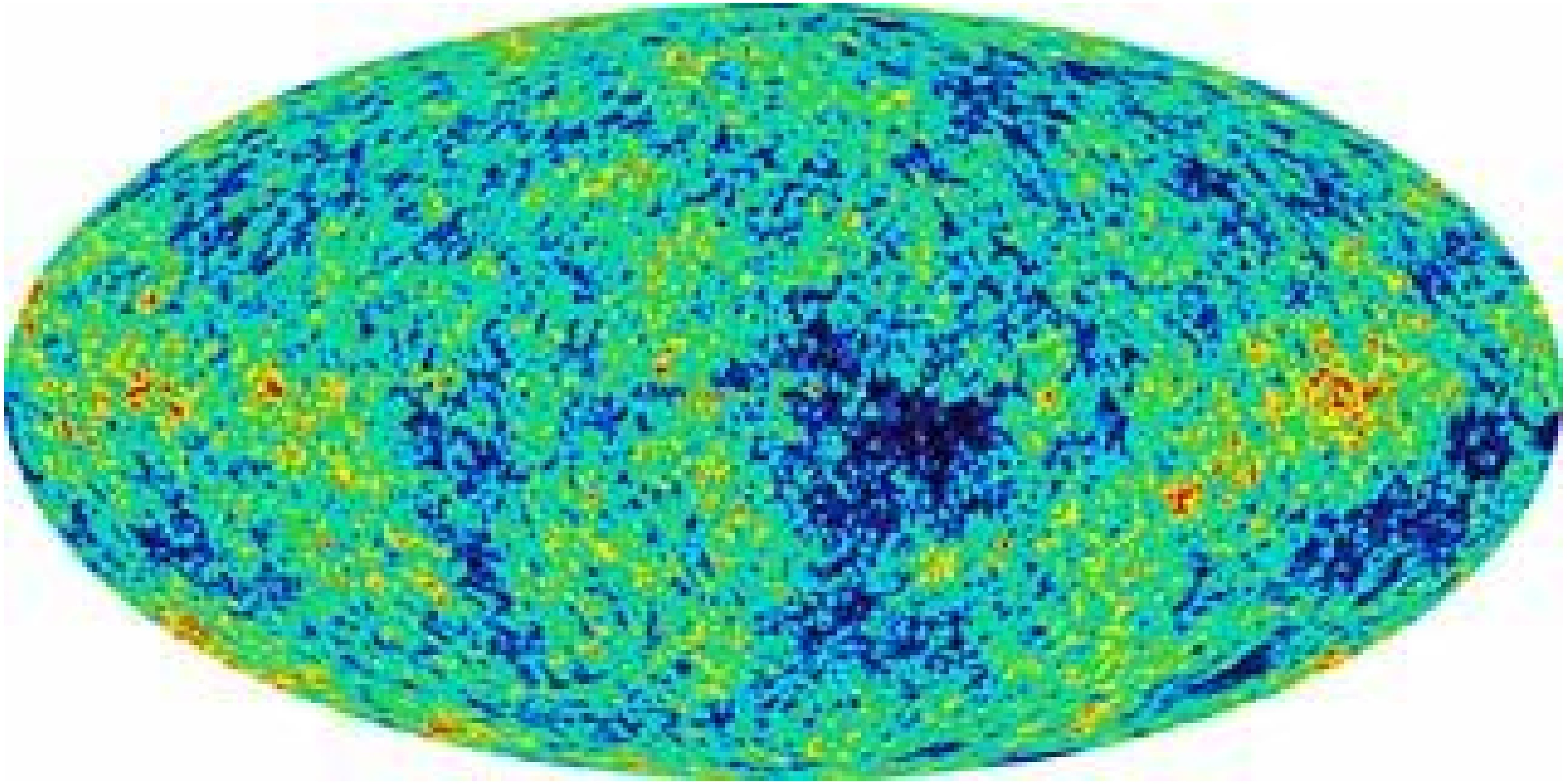
From COBE to Planck



A view of the universe 99.997% of the way back toward the Big Bang - and much more.

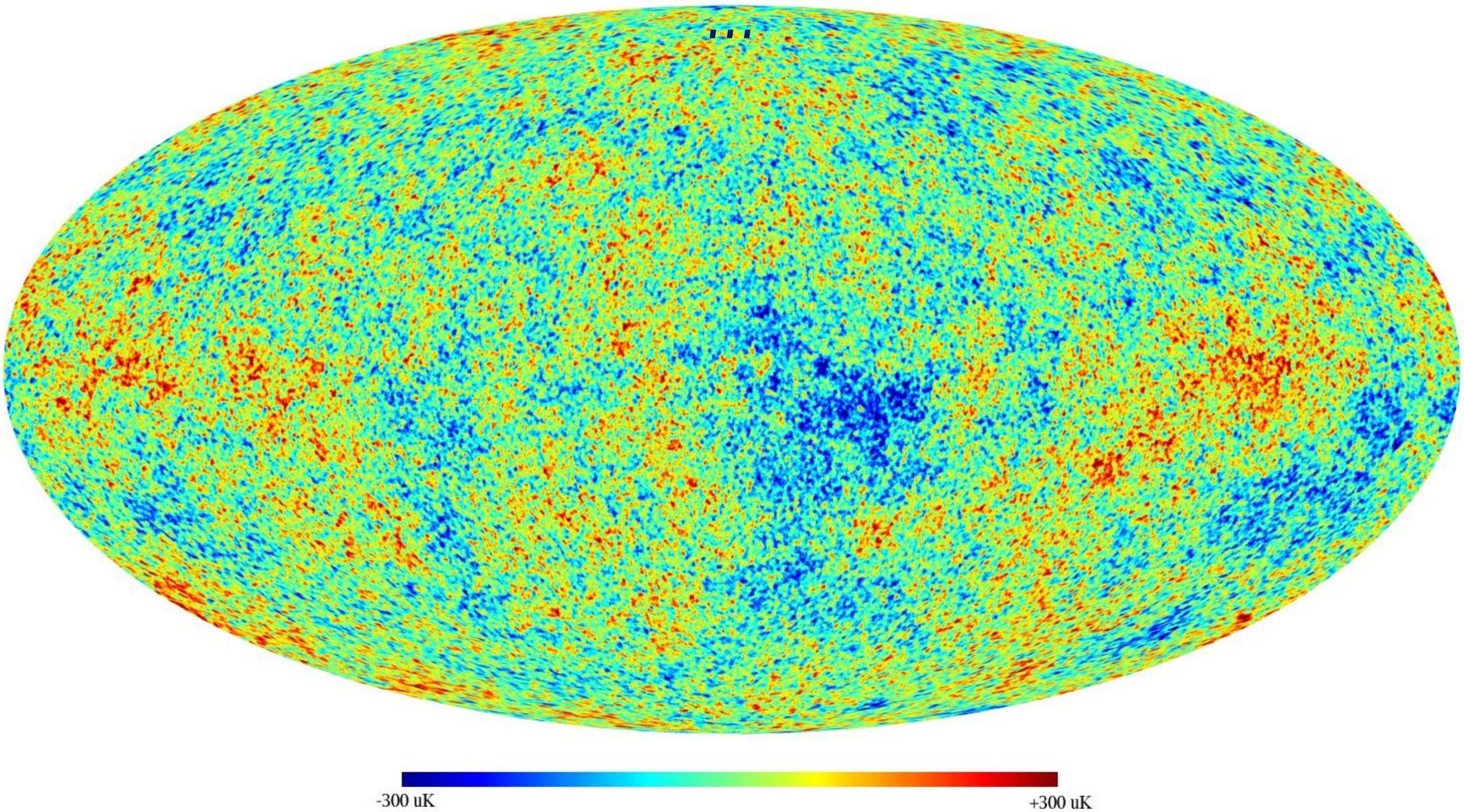
The CMB today

…



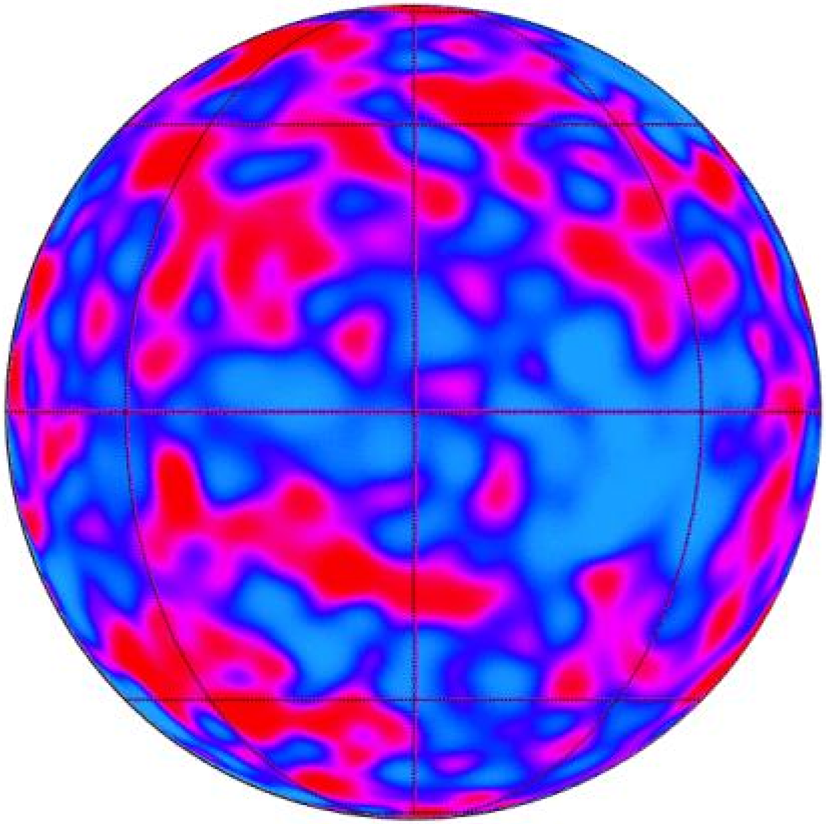
A view of the universe 99.997% of the way back toward the Big Bang - and much more.

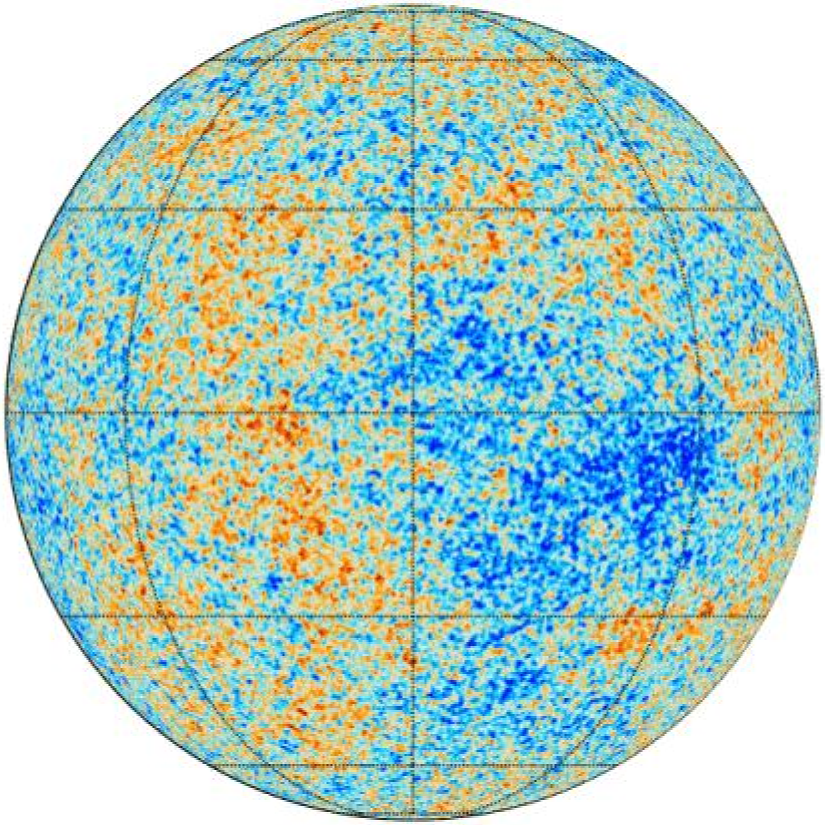
The CMB today



A view of the universe 99.997% of the way back toward the Big Bang - and much more.

Improvement on the Thermal Fluctuation Map…
…from COBE to Planck





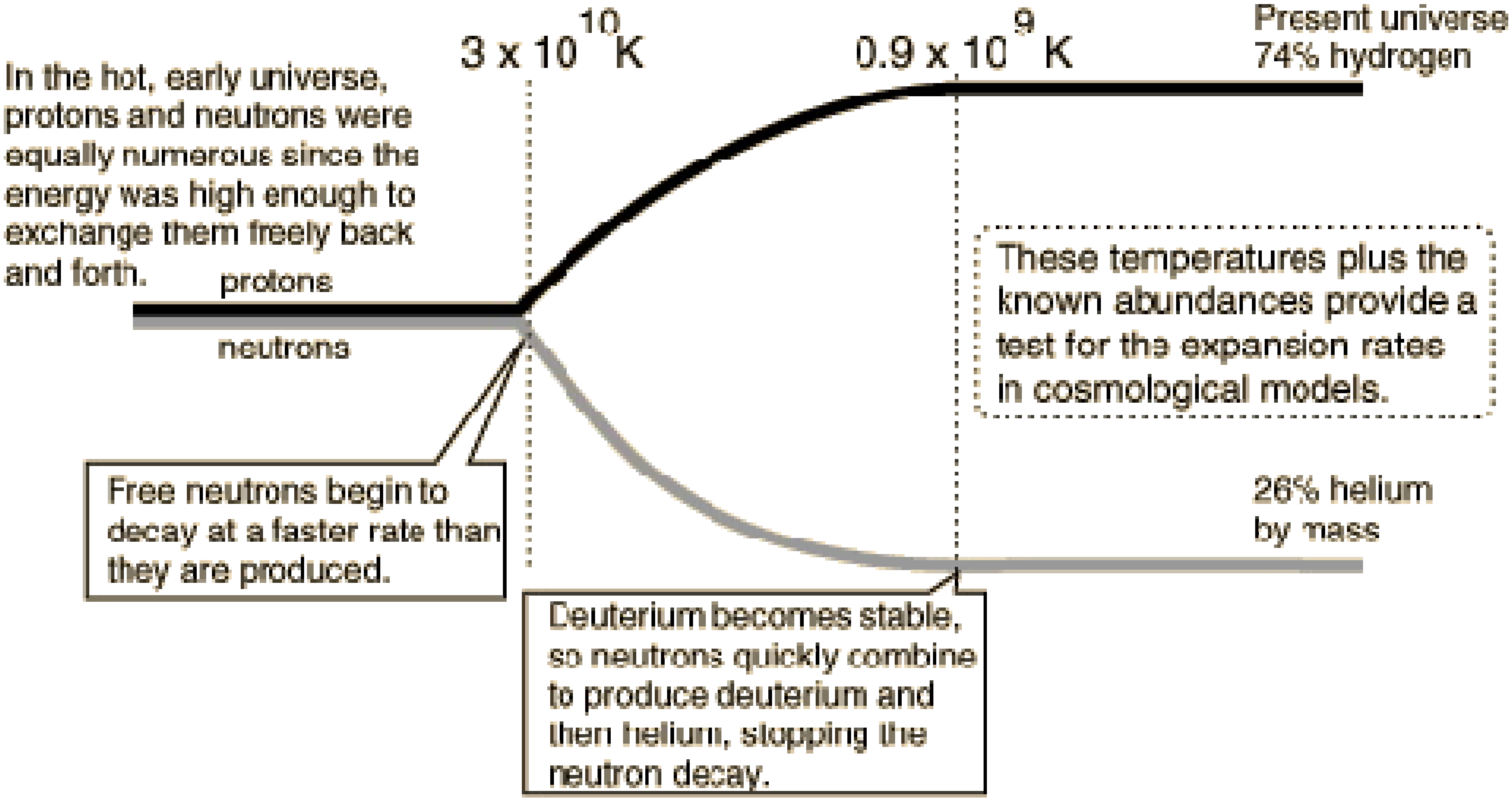
Nucleosynthesis and Formation of Light Elements

- During the first few minutes light elements like hydrogen, helium, and trace amounts of lithium are formed
- Neutron-proton ratios and nuclear reactions is determining the abundances of these elements.

- The Ionization equilibrium during recombination can be obtained through the Saha Equation:

$$\mathrm{n}_e n_p / n_H \sim (2\pi m_e kT/h^2)^{3/2} e^{-Ei/kT}$$

Big Bang Nucleosynthesis (BBN) in few words



Structure formation & Future Evolution

Formation of Structure:

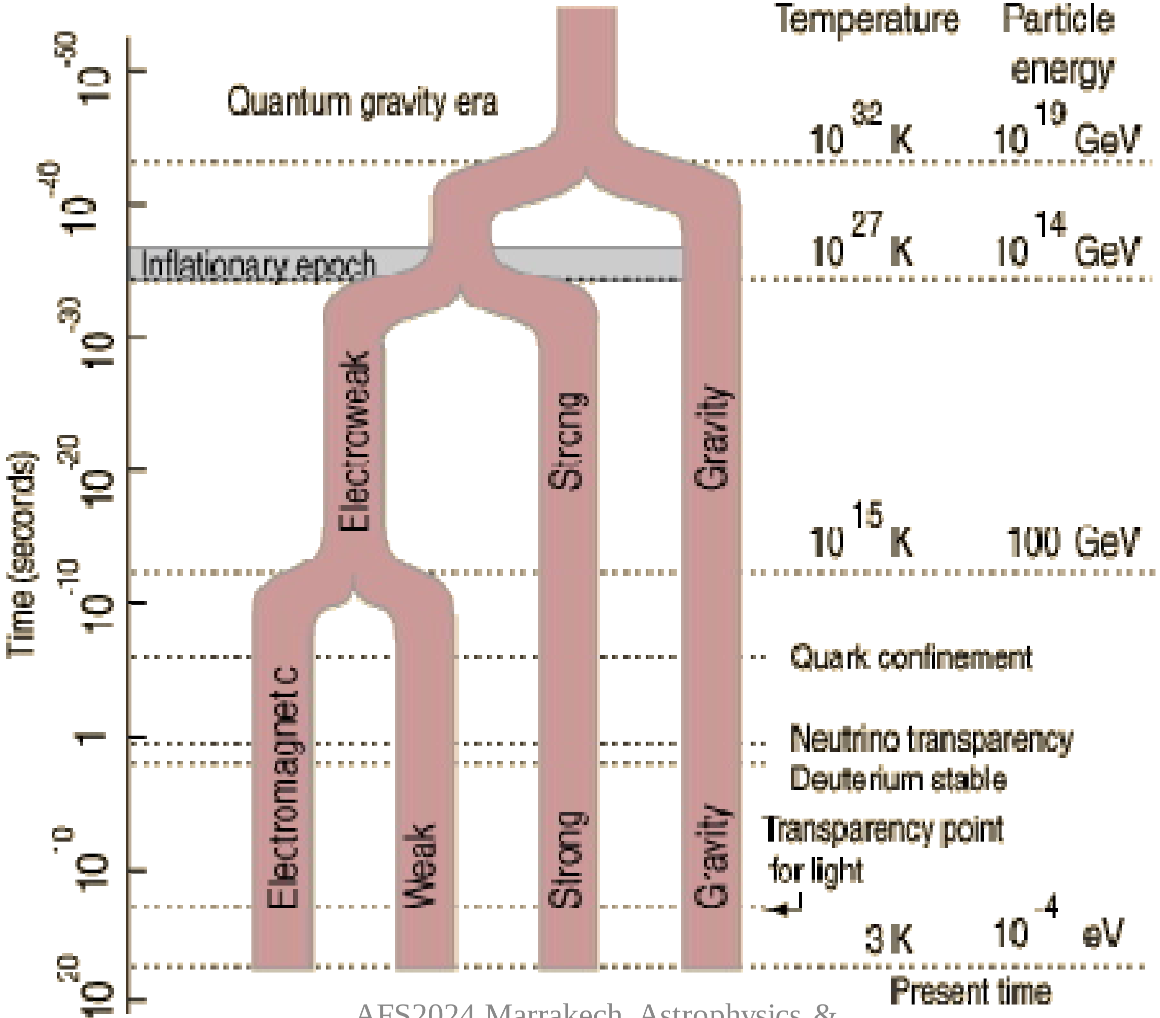
- Small fluctuations in the density of the early Universe led to the formation of structures like galaxies and clusters of galaxies over billions of years.

- The current state of the Universe is dominated by dark energy, which accelerates its expansion.
- Two ratios enable are us to trace the amount of those exotic componants :

$\Omega_m = \rho_m/\rho_{crit}$ and $\Omega_\Lambda = \rho_\Lambda/\rho_{crit}$ where $\rho_{crit} = 3H^2/8\pi G$ is the critical density of the Universe.

The Early Universe Chronology

From a phase transition point of view



Timeline Summary

Energy (γ)	Time	Event
1 MeV	7s	neutrino freeze-out
0.5 MeV	10s	e^+/e^- annihilation, $T_\gamma \sim 1.4\ T_\nu$
70 keV	3 minutes	BBN (Big Bang nucleosynthesis), light elements formed
0.77 eV	70.000 yr	onset of matter domination
0.31 eV	300.000 yr	recombination
0.26 eV	380.000 yr	photon decoupling, origin of CMB
0.2 meV	14 Gyr	today

Exo:
Verify the values above by using the « Master » formula (correct during the radiation dominated era) : $\mathbf{T(MeV).(t)^{1/2} = 1}$
where T is the temperature, and t is the time en seconds since the Big Bang

The Horizon, Isotropy and Flatness problems…

Three major cosmological puzzles

- **The Horizon and Isotropy problem**:
- The observed uniformity of the CMB across the universe, suggests that distant regions shouldn't be the same temperature due to the limit of light speed and the expansion of the universe.

Furthermore, regions of the universe that are now vastly separated were in thermal equilibrium at some point in the past. However, these regions should not have had enough time since the Big Bang to exchange information (light or any other signal) and thus achieve such uniformity.

- **The third one is the “flatness problem**:

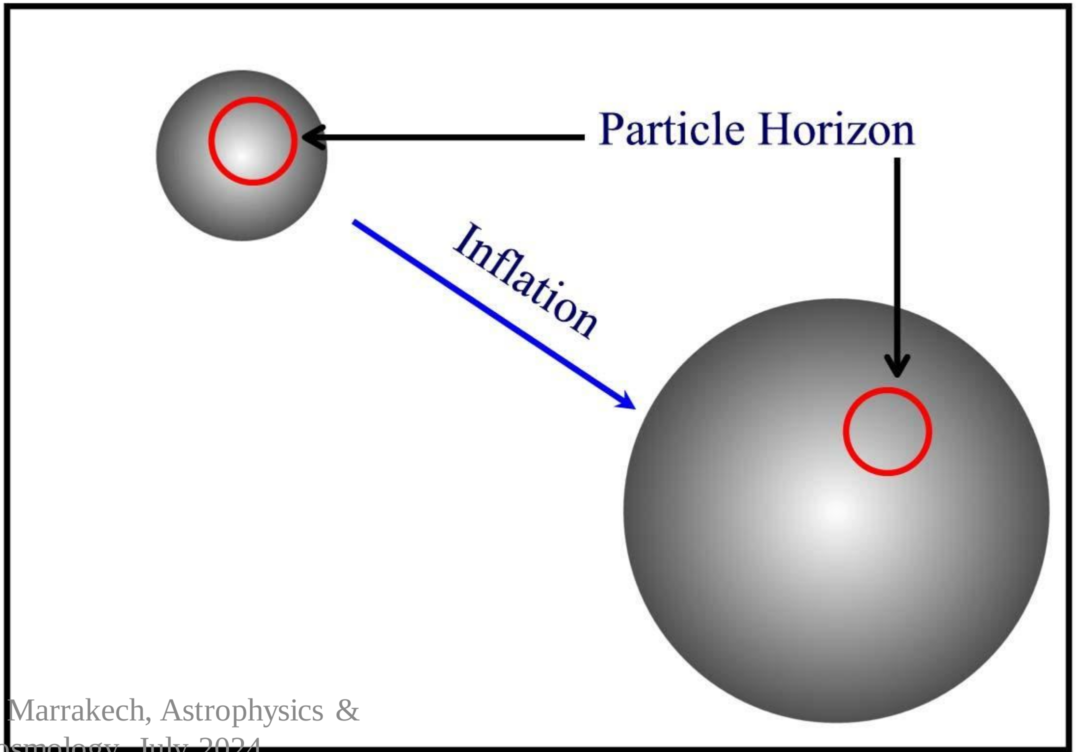
It arises from the observation that the universe appears to be very flat on large scales, meaning its spatial curvature parameter Ω_k is extremely close to zero. In the context of general relativity, the curvature of the universe is determined by the total energy density and the critical density:

$$\Omega k=(\rho-\rho_{crit})/\rho_{crit}$$

where ρ is the actual energy density of the universe and ρ_{crit} is the critical density at which the universe is exactly flat.

.. and a Fourth Cosmological Puzzle…

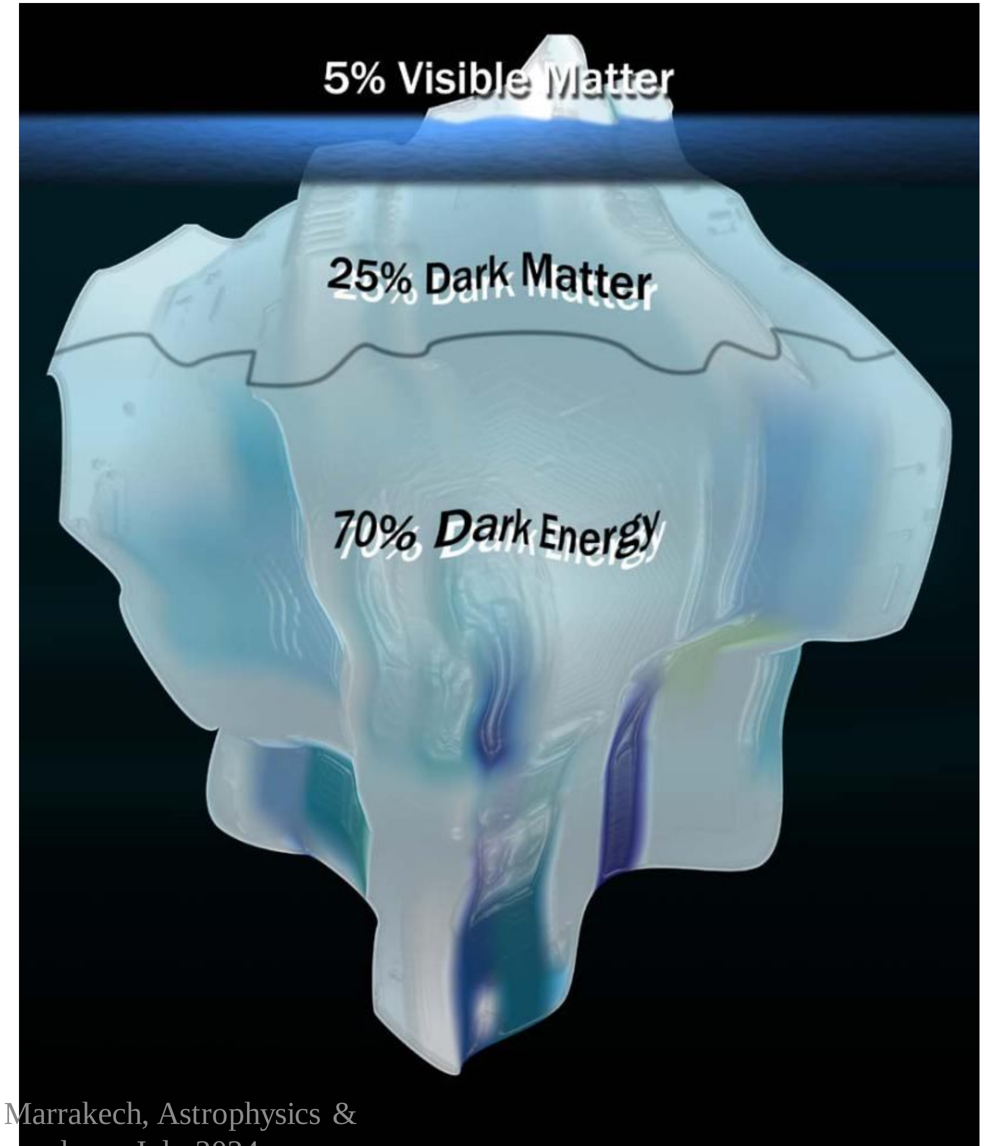
There is actually a fourth cosmological puzzle, namely the Magnetic Monopole Problem... According to the standard Big Bang model, regions of the universe that are now vastly separated were in thermal equilibrium at some point in the past. However, these regions should not have had enough time since the Big Bang to exchange information (light or any other signal) and thus achieve such uniformity.



XXth Century's Complications

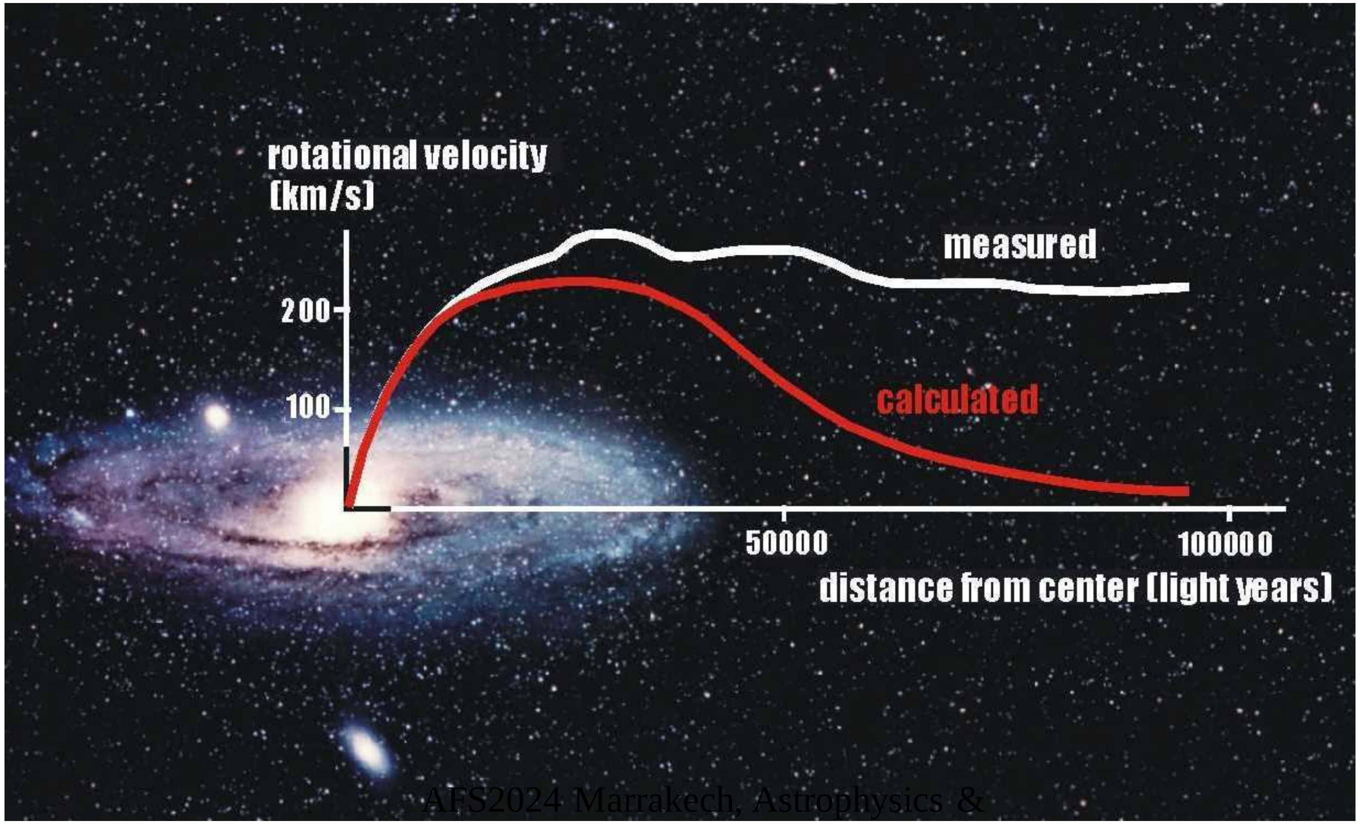
- **Dark Matter & Dark Energy**

- **Average density of ordinary matter is not enough**



The Necessity of Dark Matter

- Rotation curves of stars in galaxies: 1933
- The dynamics of galactic clusters: 1970's
- Large-scale gravitational lensing: 1980's

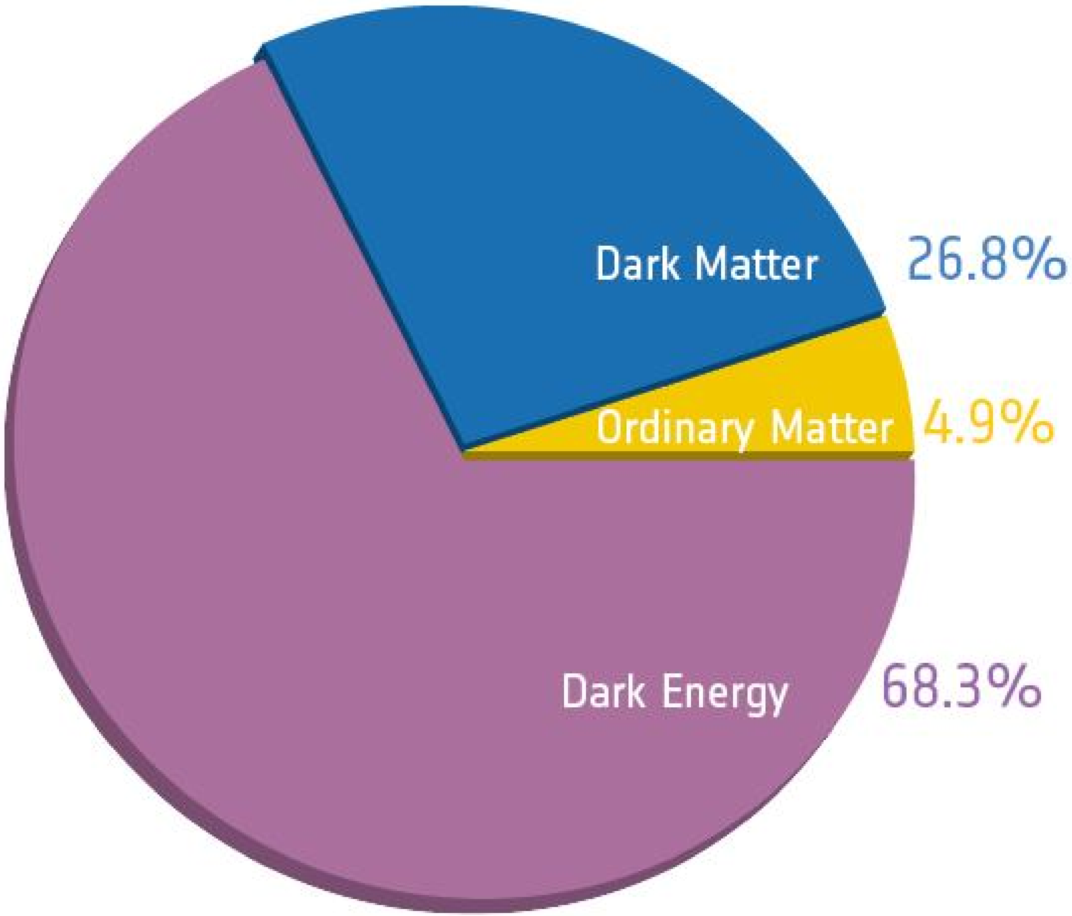


The Material Content of the Universe

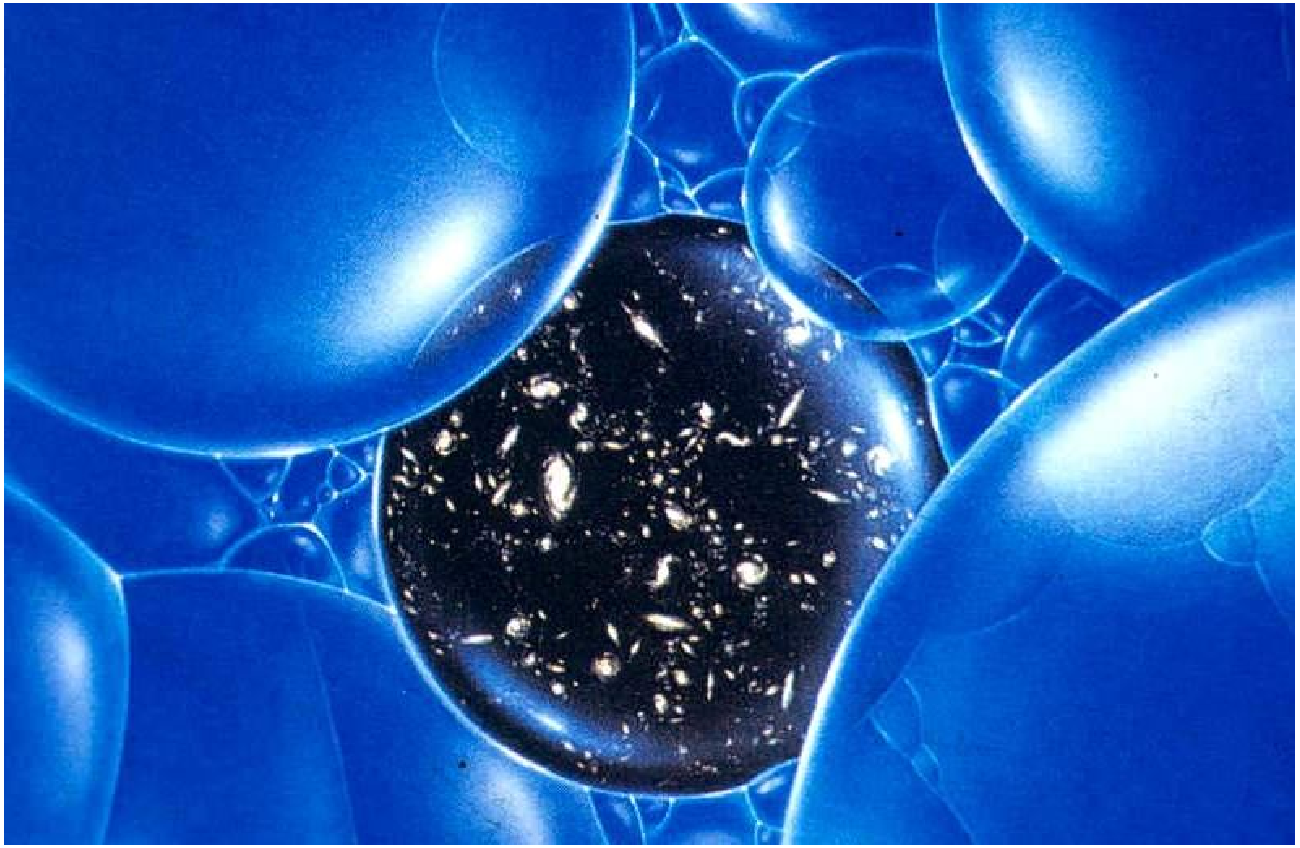
المحتوى المادي للكون

- **68% :** dark energy
- **27%** dark matter

- 5% : Normal matter**:**
Everything on Earth, or that can ever be observed



Fantastic Cosmologies
...or Monster Universes



- **Multiverse**, pre Big Bang cosmologies, cyclic bouncing universes,...


merci ...
The End