The first second of the Universe
(and the following 13.700.000.000 years!)

Daniel G. Figueroa
CERN, Theory Division

Cosmology = *Study* *of the* *Universe* *as a* *WHOLE*

(Evolution, Content,
"Birth", "Death",…)

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Observe + Measure → Infer Laws

Laws → **Predict** new phenomena

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CAREFUL! : We cannot manipulate the Universe, we can only observe it!

UNiVERSE

‘space'

CONTAINER

… of MATTER

(atoms, galaxies, …

+ more exotic ‘objects')

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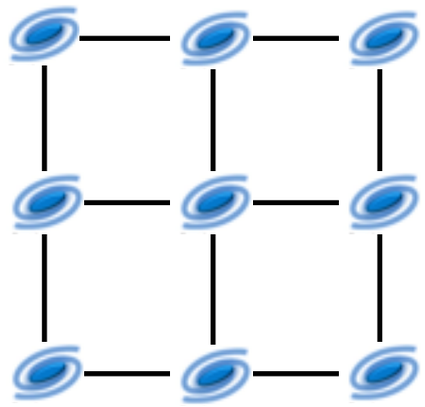

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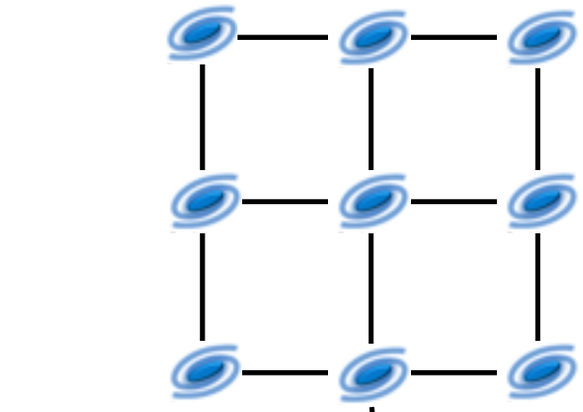
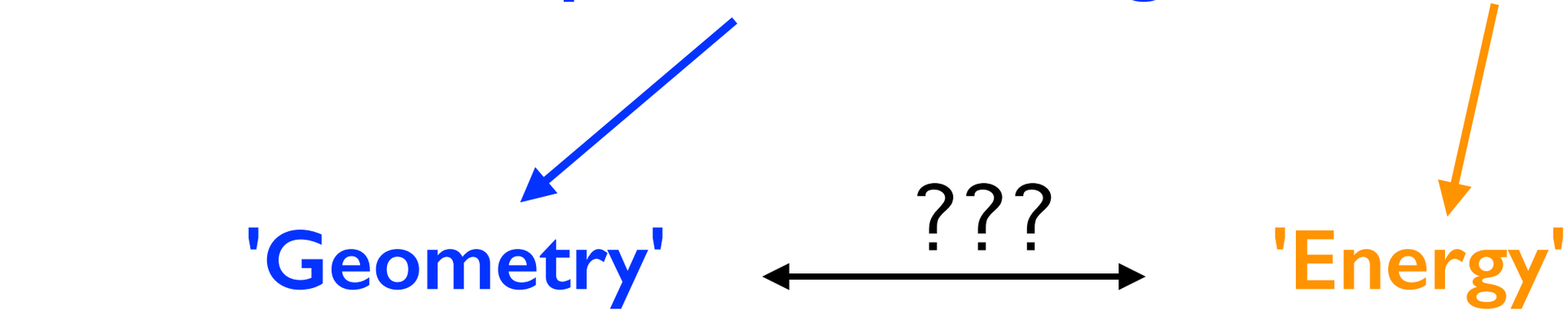


UNiVERSE = Space Containing all Matter



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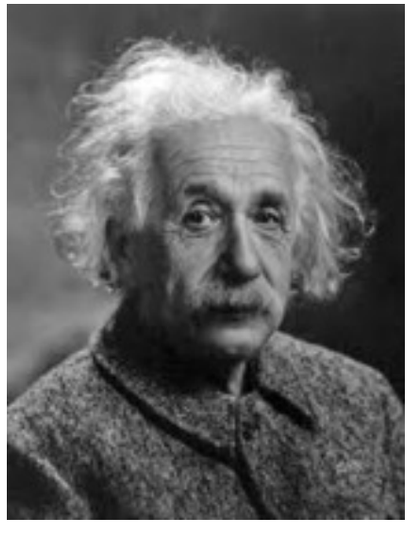
'Geometry' ??? 'Energy'

'Space-Time' Geometry
dictates Movement of Matter

Presence of Matter (Energy)
dictates 'Space-Time' Geometry



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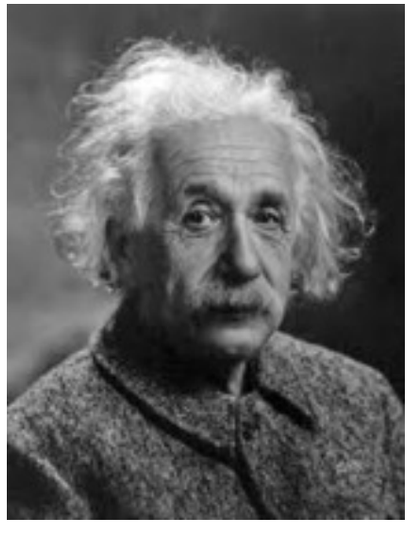

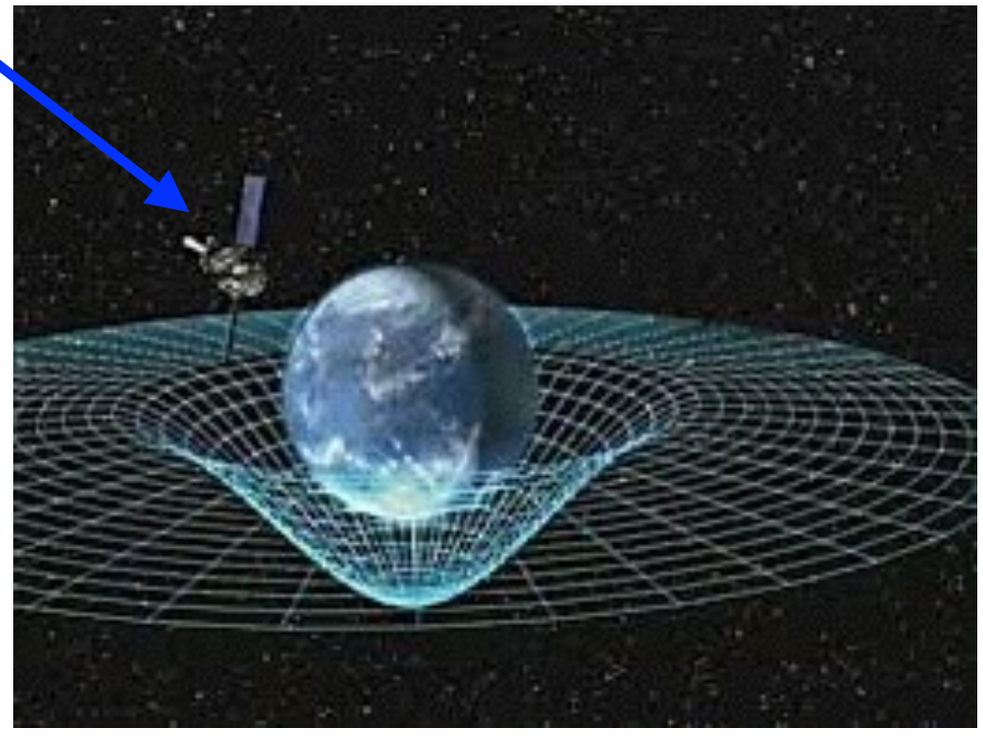

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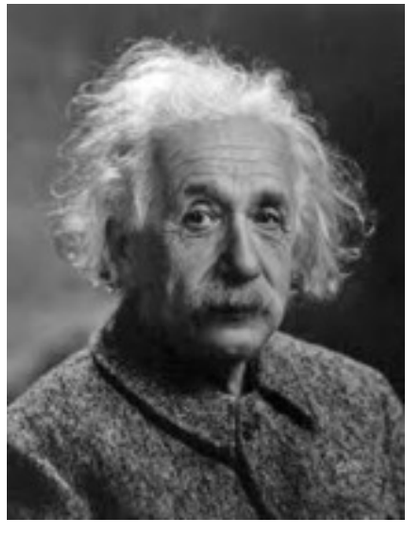
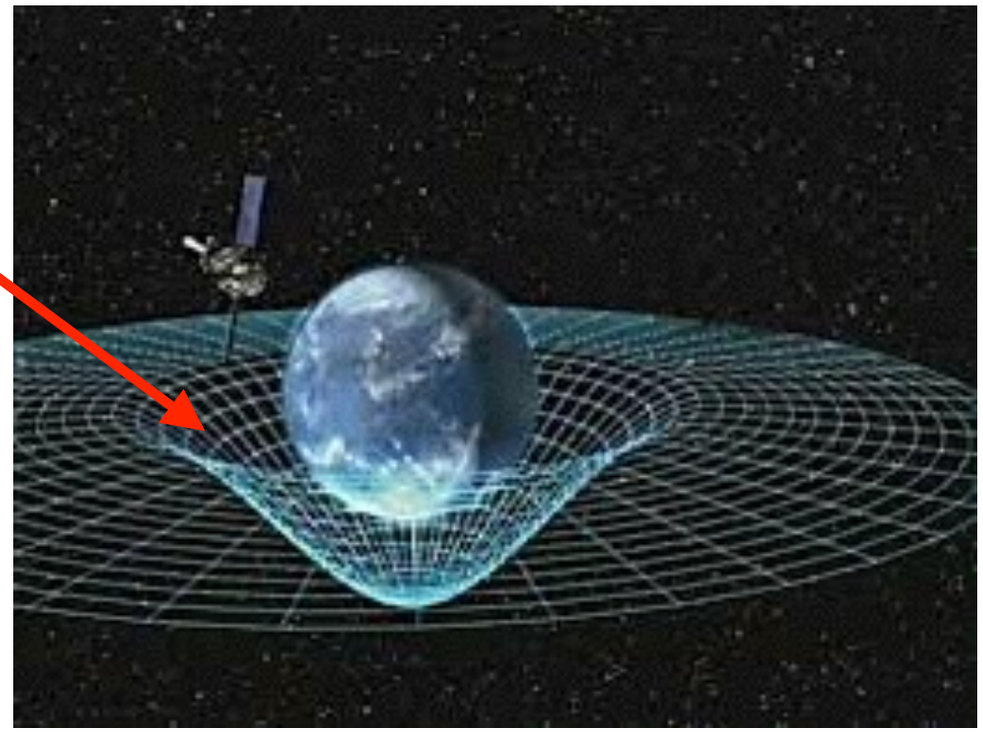
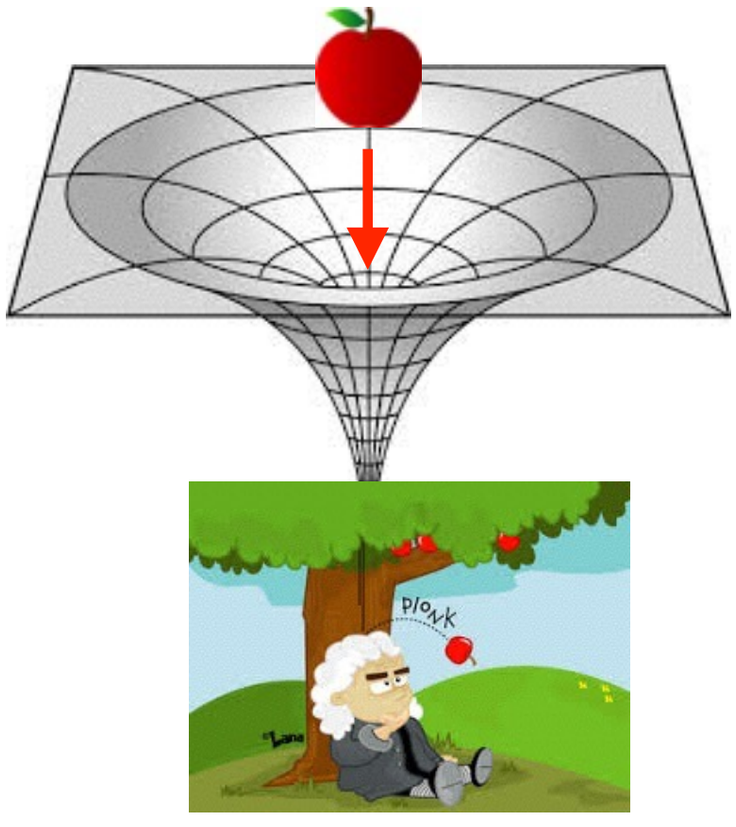




Space-Time ⟷ **Matter**

Theory of GENERAL RELATIVITY (Einstein,1915)

GENERAL RELATIVITY = THEORY of GRAVITY



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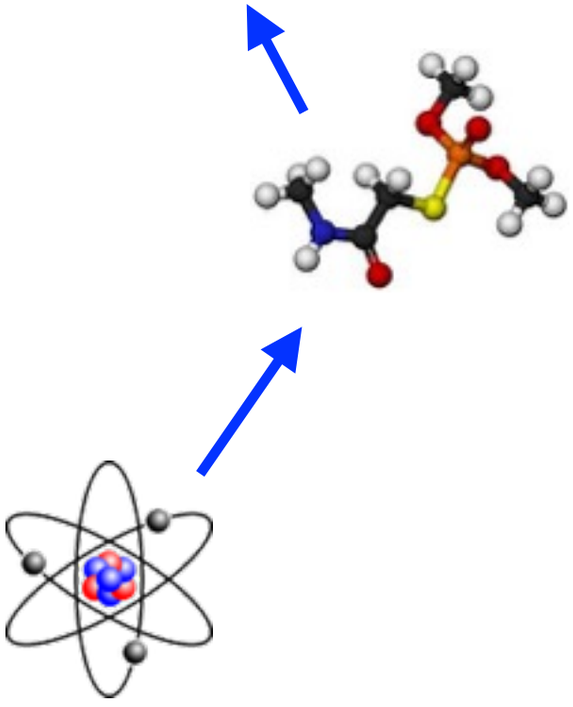

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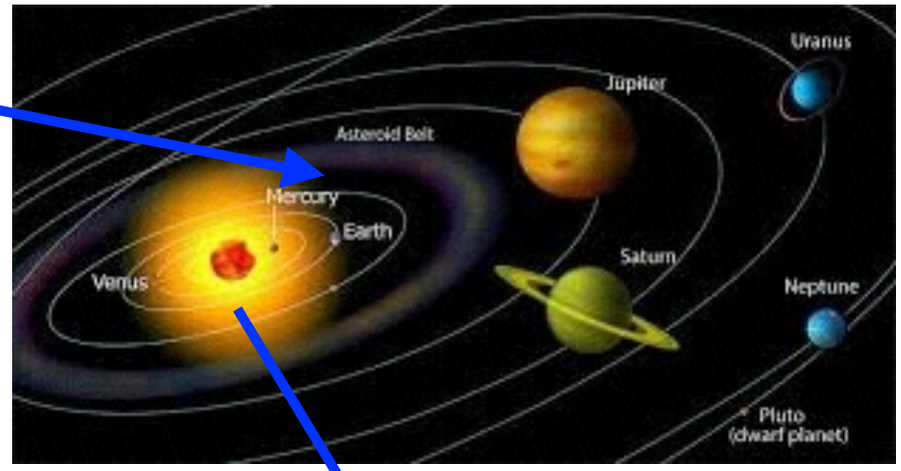

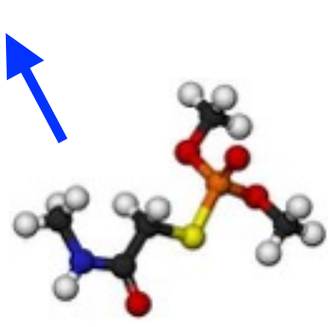

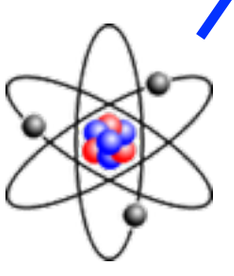

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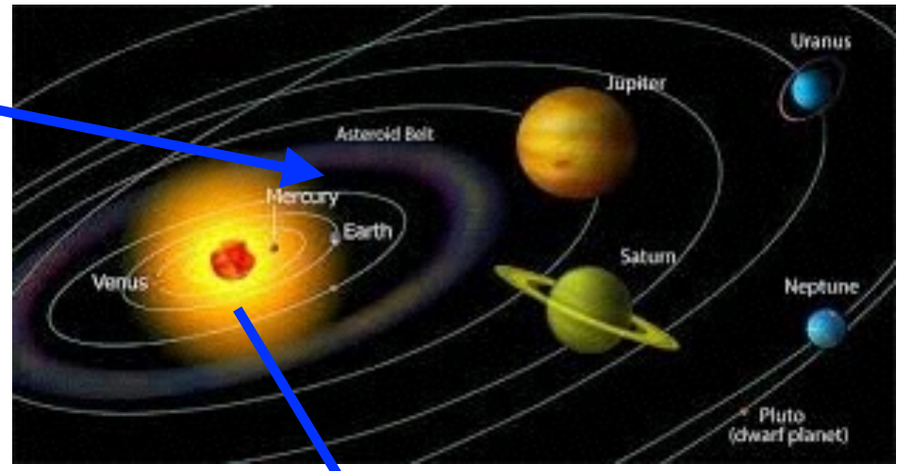

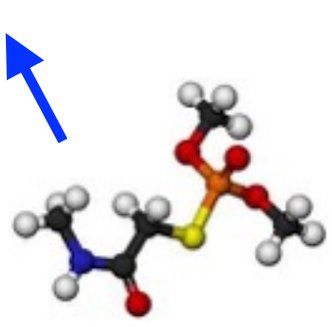

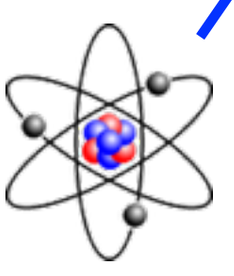

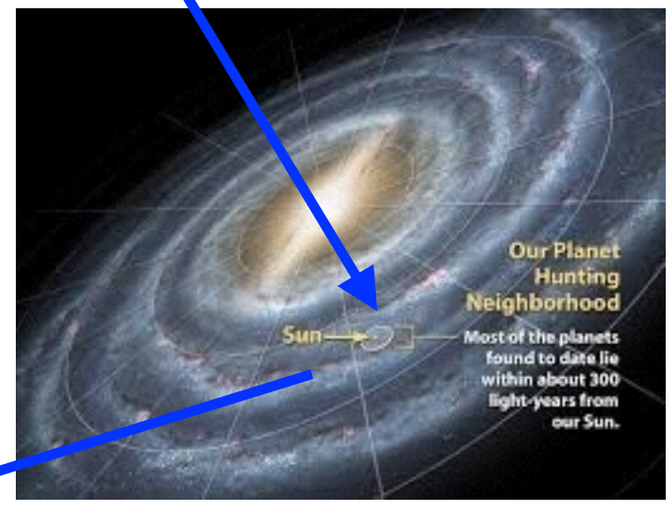

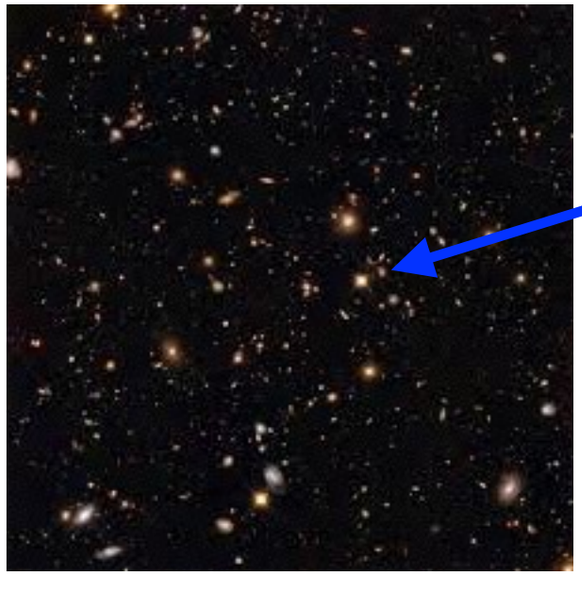

¿ UNiVERSE at LARGE SCALES ?

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Cosmological Principle:
HOMOGENEOUS and ISOTROPIC

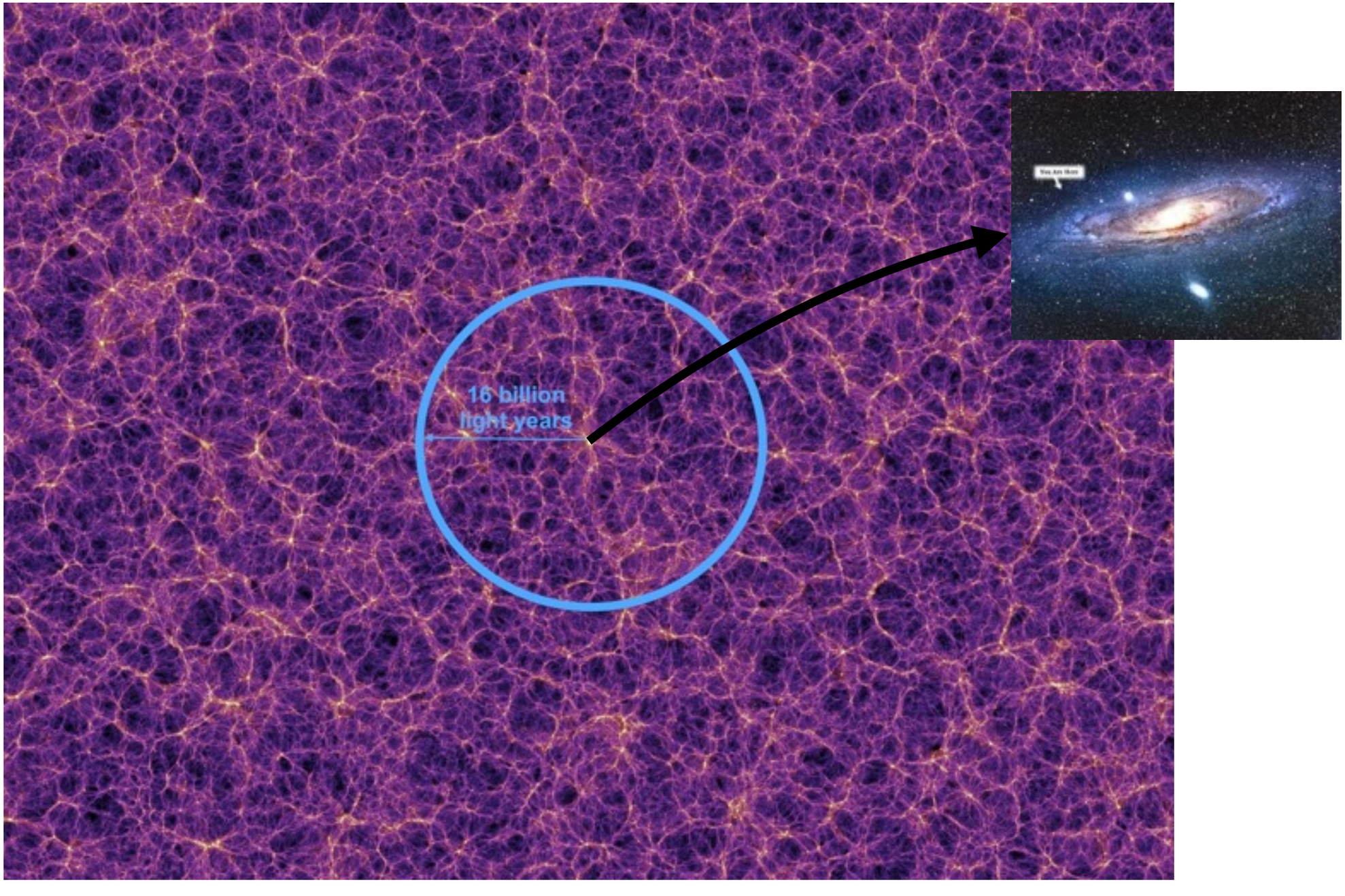
¿ UNiVERSE at LARGE SCALES ?

Cosmological Principle:
HOMOGENEOUS and ISOTROPIC

SAME EVERYWHERE !

SAME IN EVERY DIRECTION !

HOMOGENEOUS and ISOTROPIC



(Millenium Simulation)

UNiVERSE: HOMOGENEOUS and iSOTROPiC

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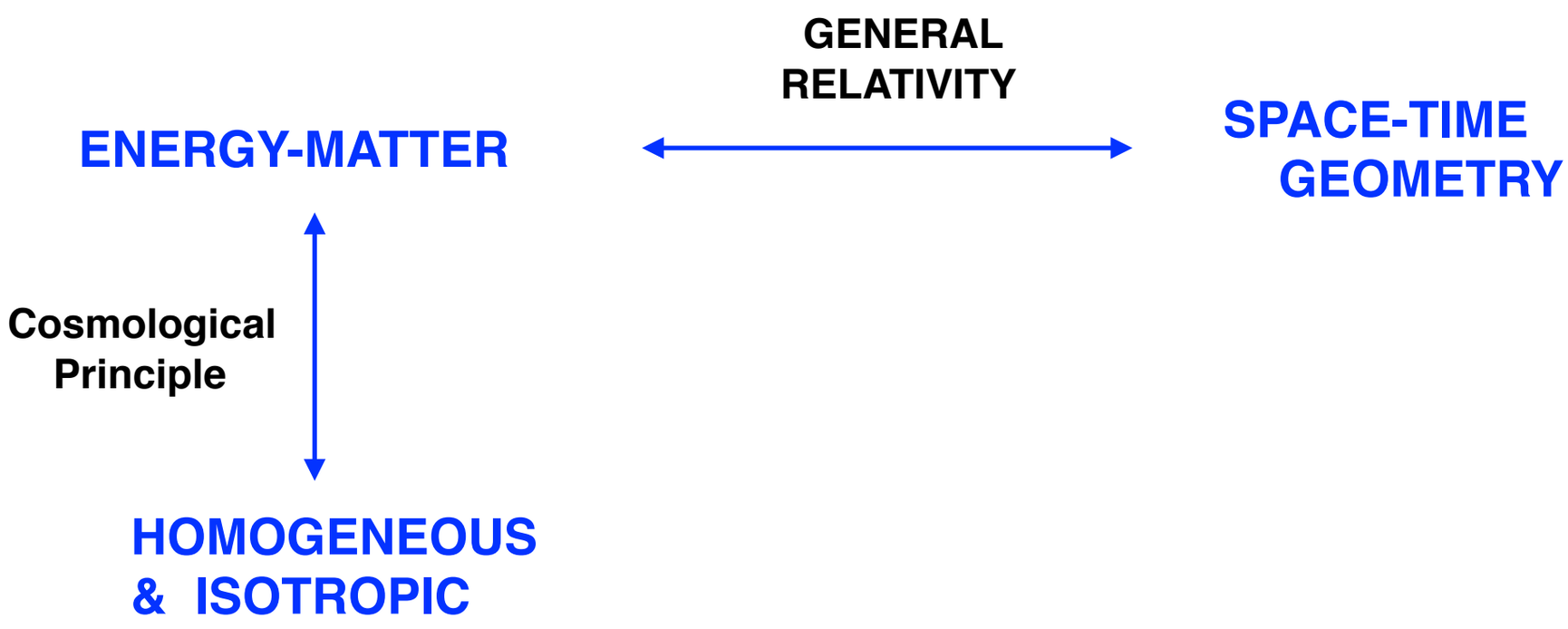

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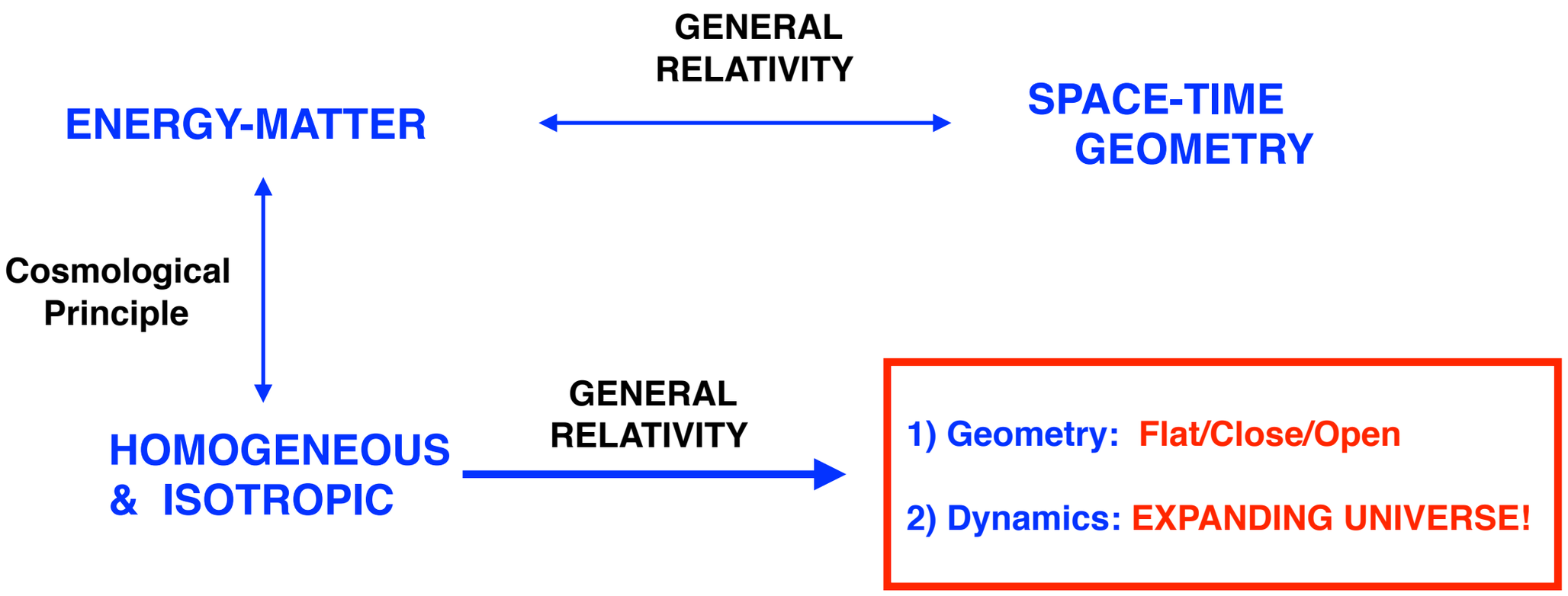

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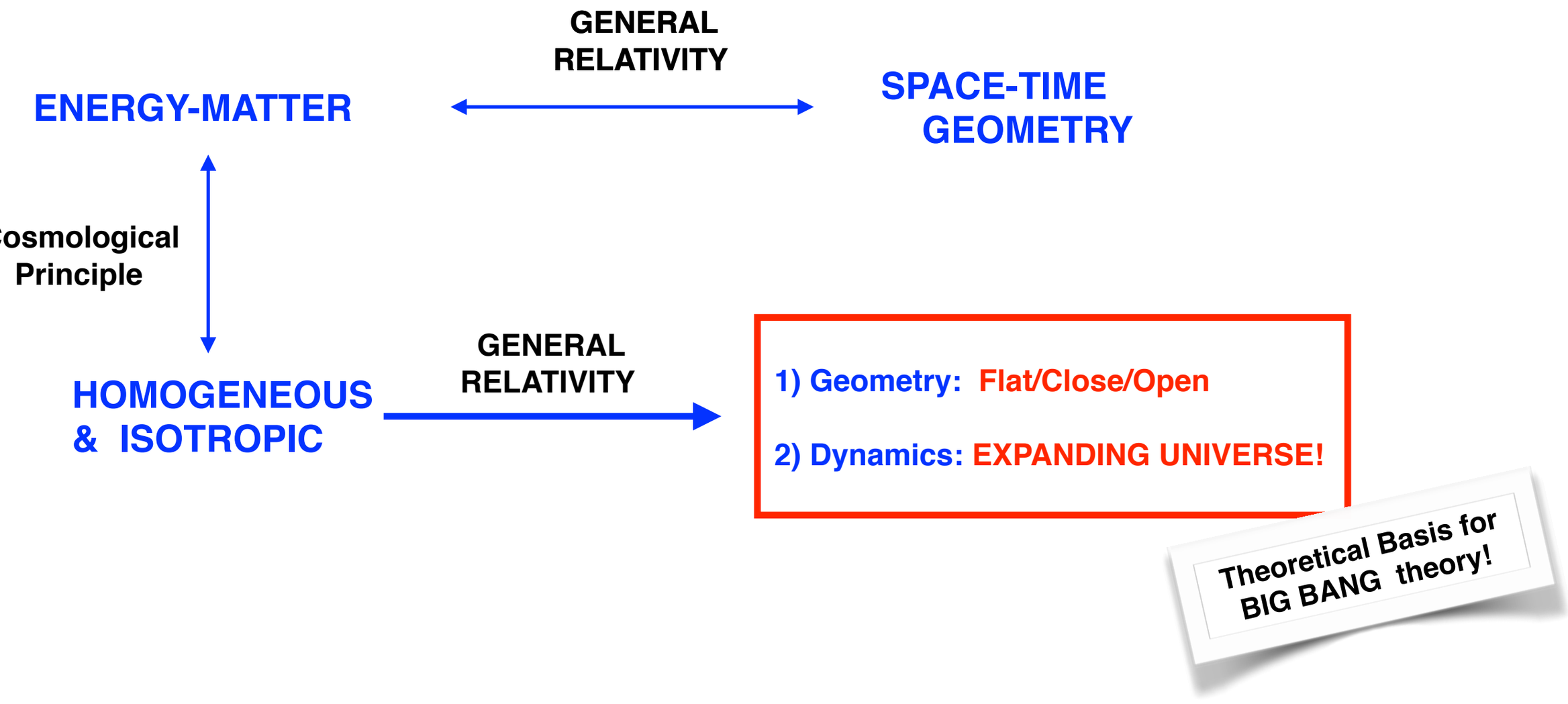

UNiVERSE: HOMOGENEOUS and iSOTROPiC

BIG BANG THEORY: { **Geometry: Close/Open/Flat**

Dynamics: EXPANDING Universe

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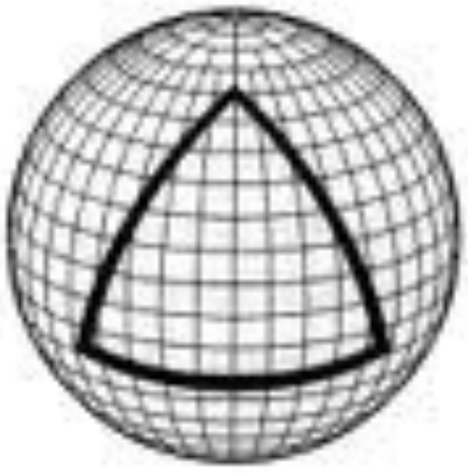
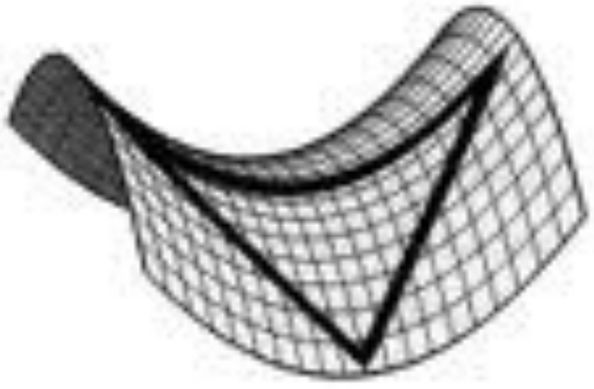
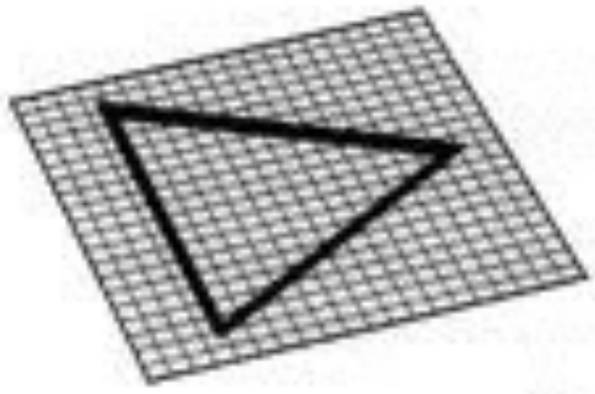


Positive Curvature



Negative Curvature



Flat Curvature

UNiVERSE: HOMOGENEOUS and iSOTROPiC

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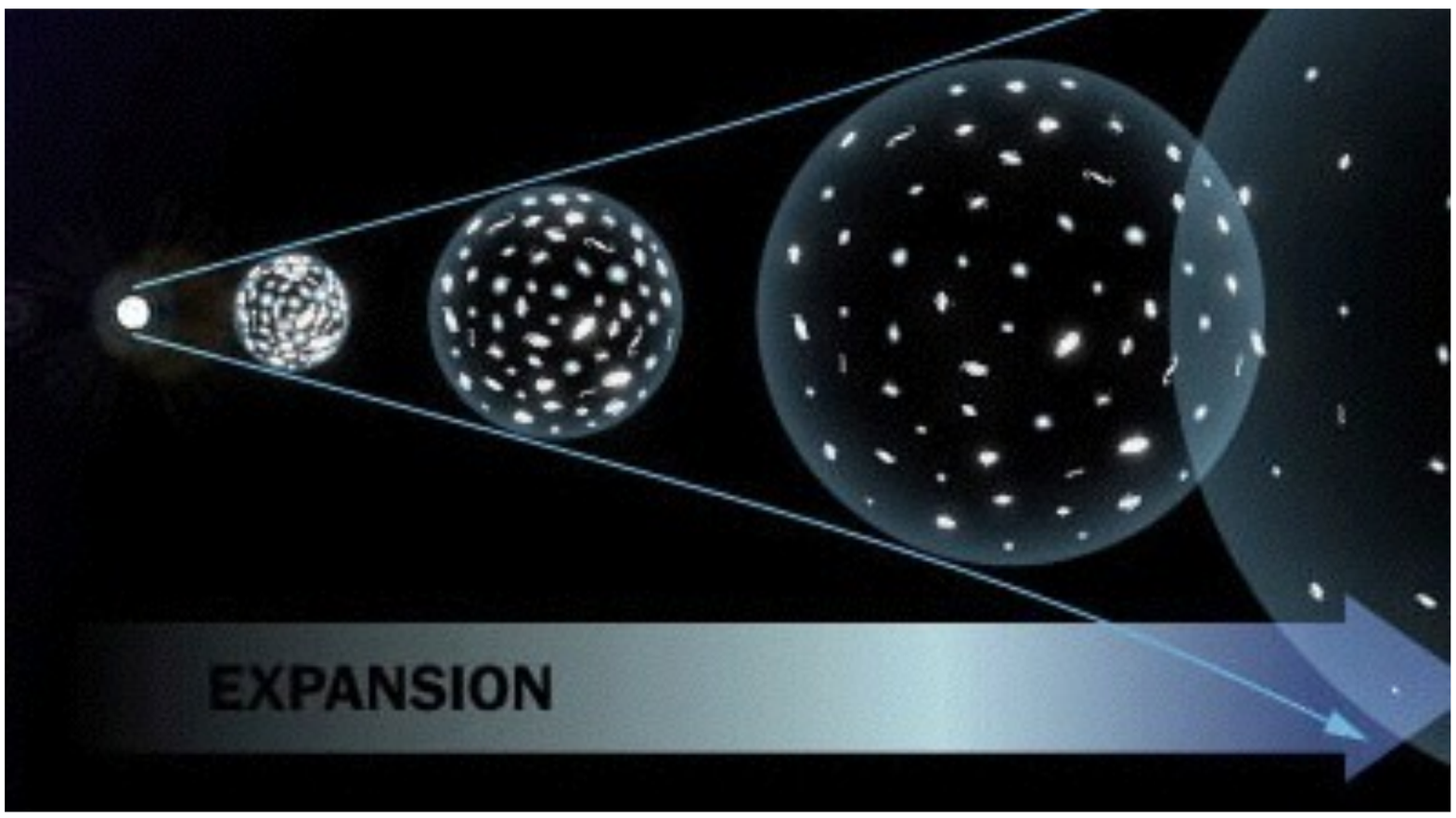

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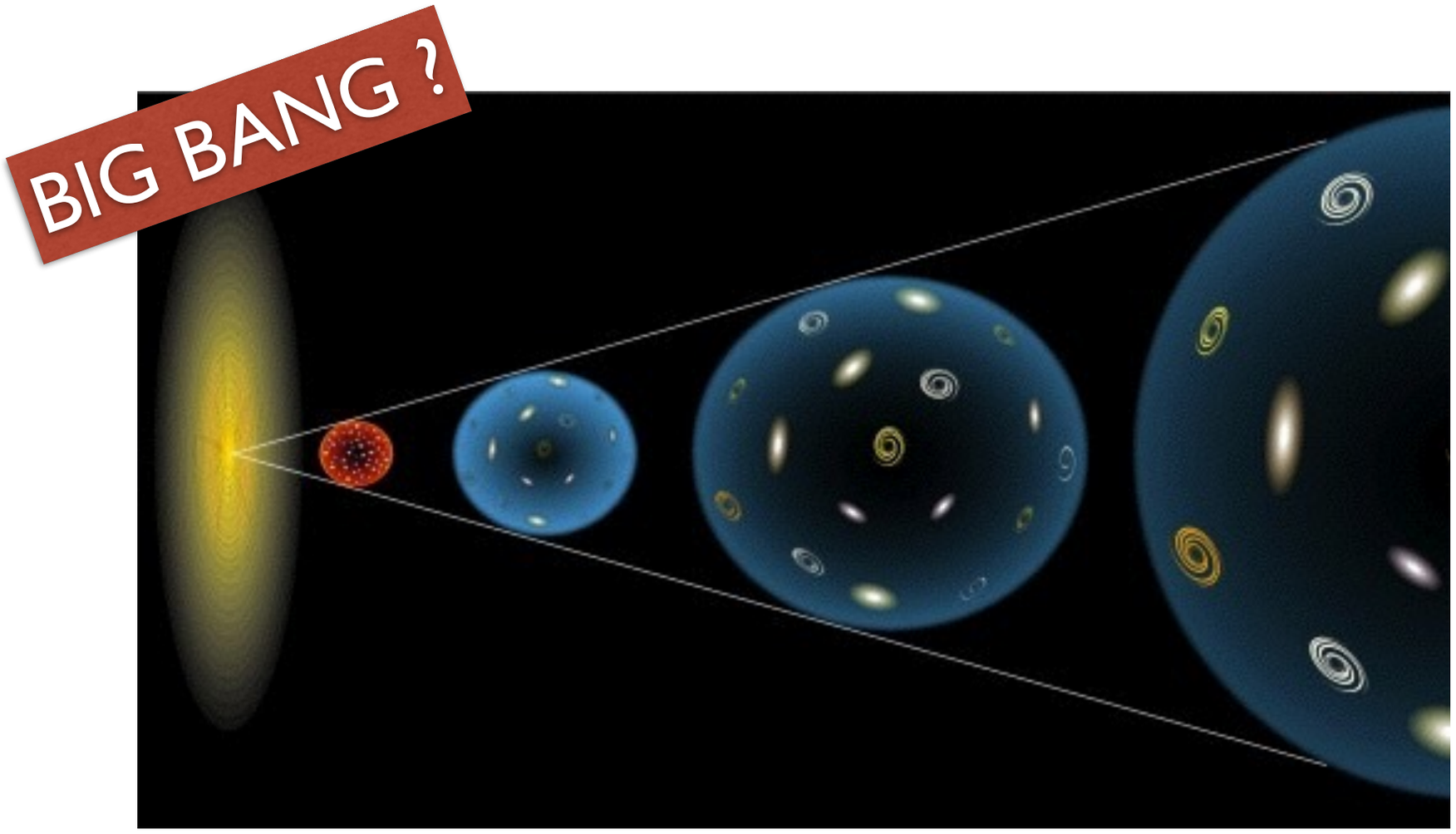
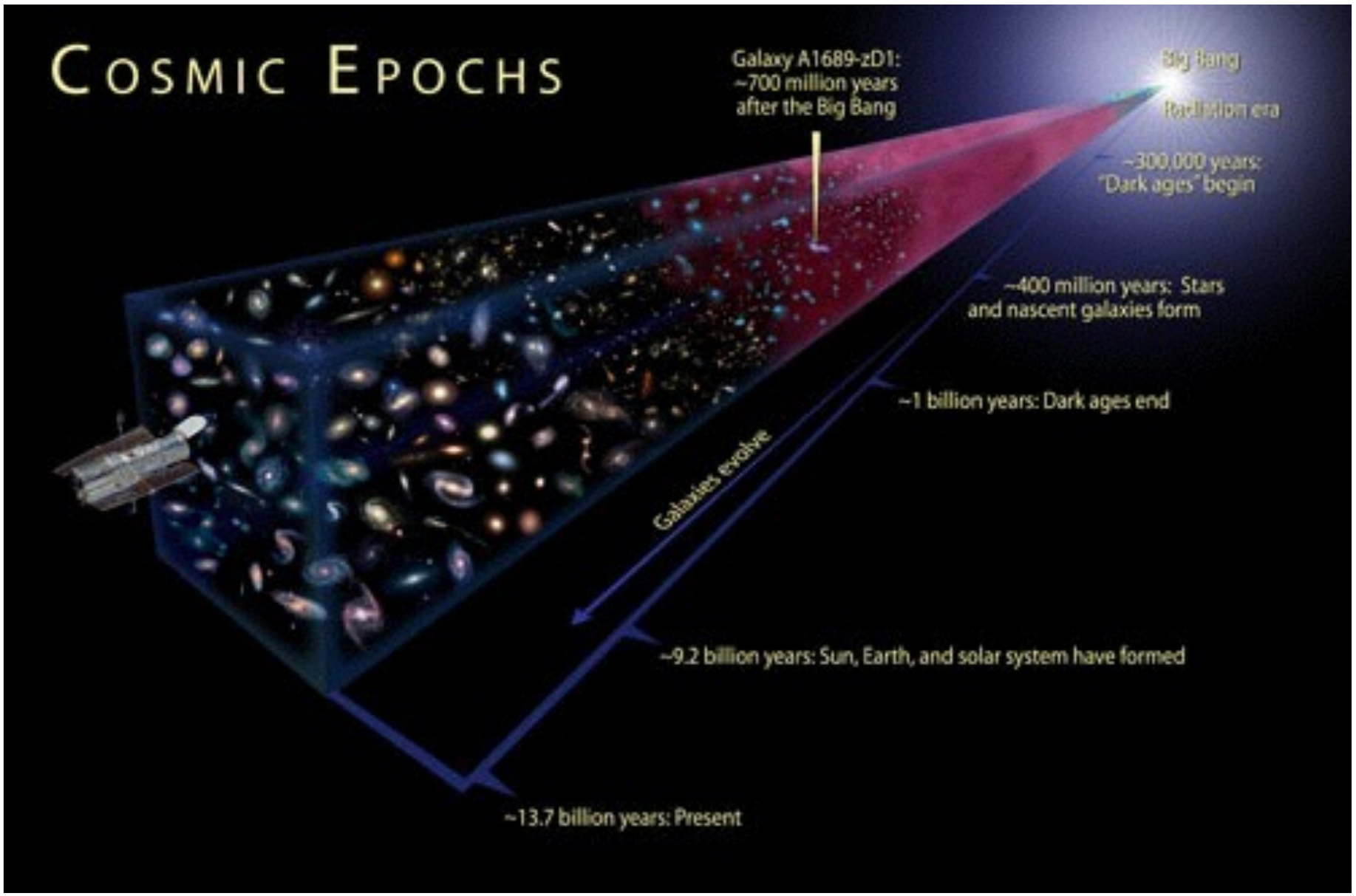
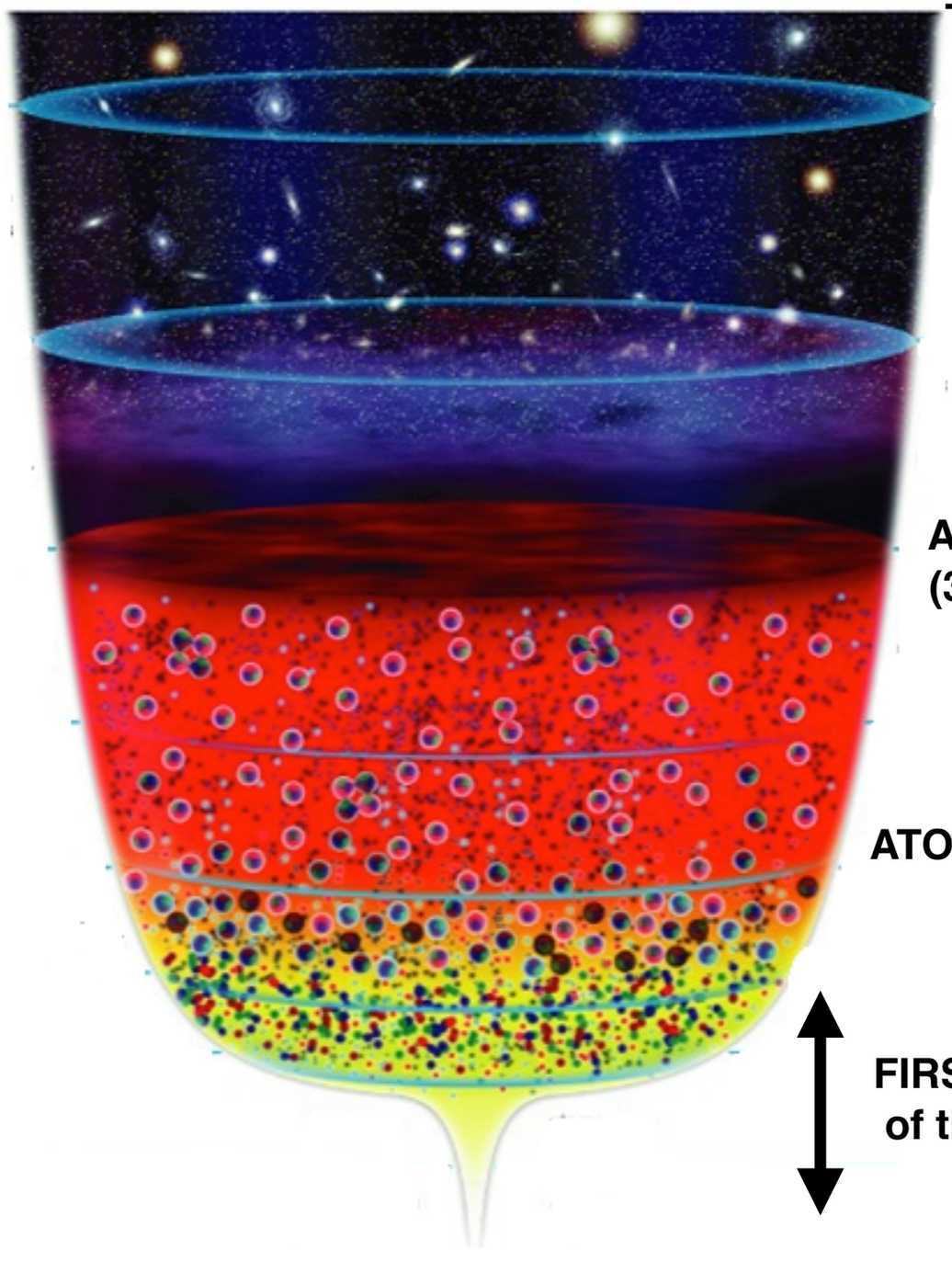


¿ t = 0 ?

COSMIC HISTORY of the UNiVERSE



COSMIC HISTORY of the UNiVERSE



TODAY [Galaxies, Clusters, …]
(13.700 Million years)

FIRST GALAXIES
(500 Millions years)

ATOMS CREATION
(300.000-400.000 years)

ATOMIC NUCLEI CREATION
(3 minutes !!!)

FIRST SECOND
of the UNIVERSE !!

SUMMARY

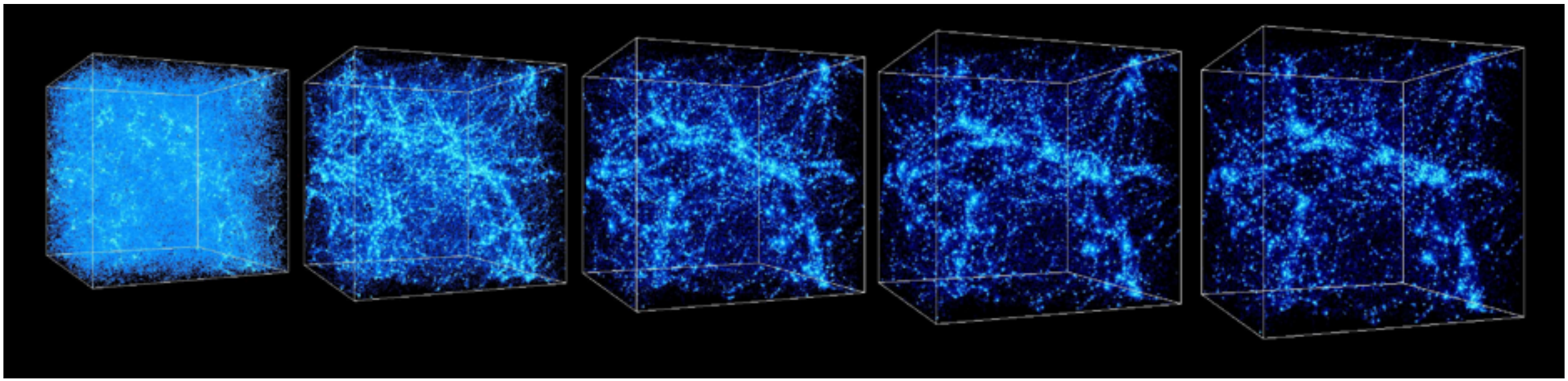
Universe
Homogeneous
& Isotropic

Universe is
Expanding
(Geom: Flat, Close, Open)

Cosmic Epochs:

Galaxy Formation,
Creation of Atoms,
Creation of atomic nuclei,
Creation of all elementary particles

Cosmic Epochs: Galaxy Formation (500 Million years)

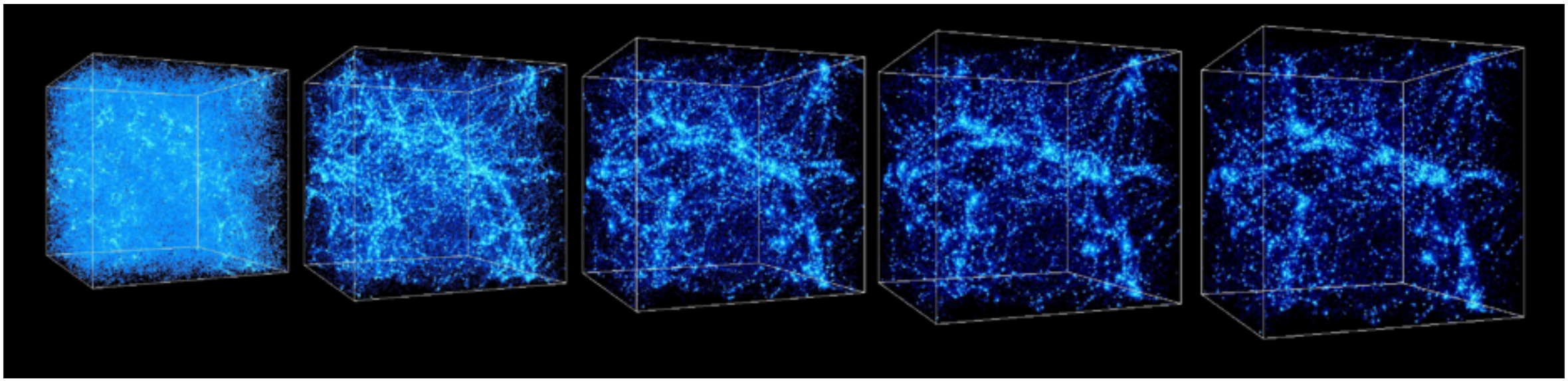


GAS of PARTiCLES
(homogeneous & isotropic)

Gravitational
Attraction

'Lumps‘

Cosmic Epochs: Galaxy Formation (500 Million years)



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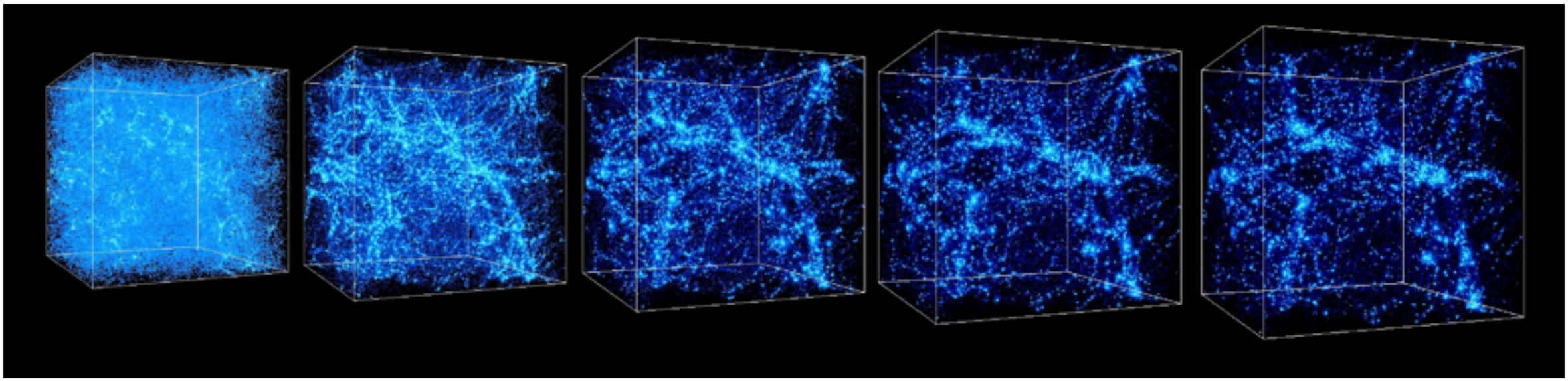

GAS of PARTiCLES

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[not completely !]

$$\rho = \bar{\rho}(1 \pm \delta\rho)$$

$$\delta\rho \sim \mathcal{O}(10^{-5})$$

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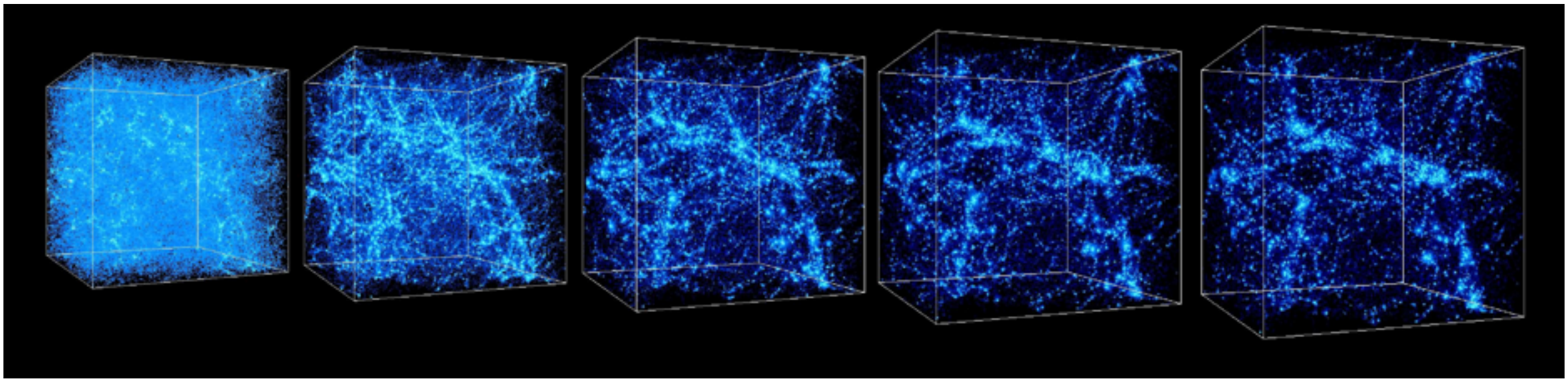

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Gravitational Attraction

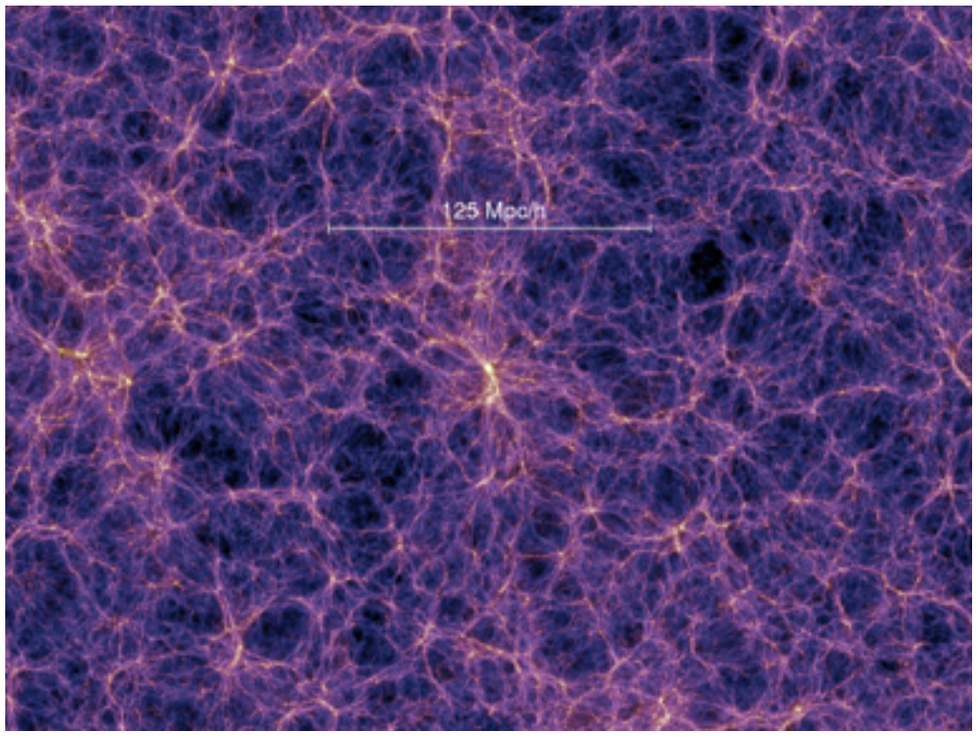
'Lumps'

GALAXIES !

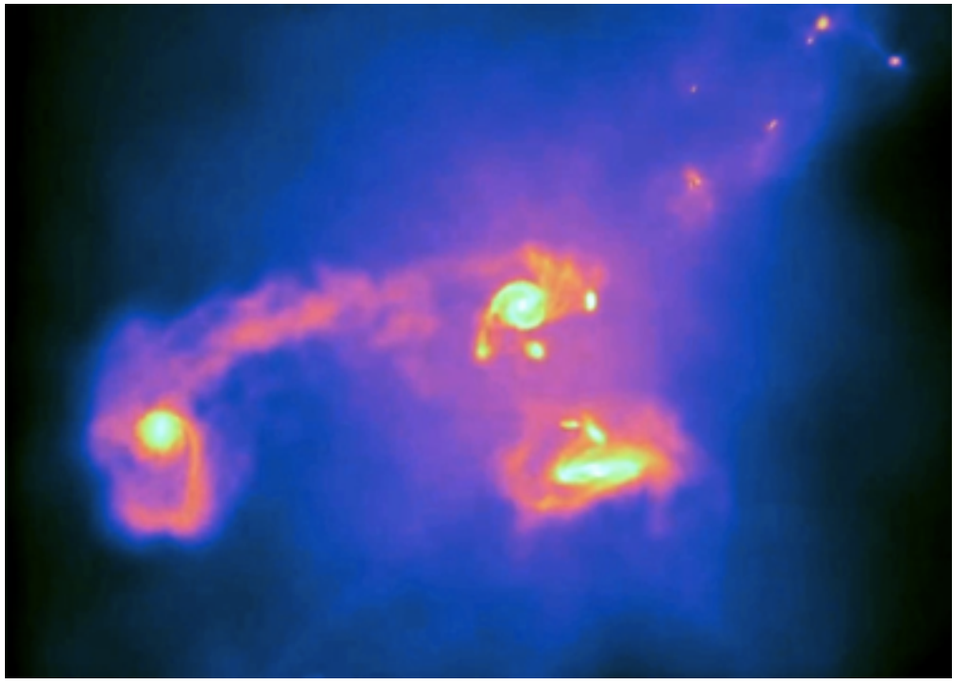
$(\delta\rho \gg 1)$

LARGE SCALE STRUCTURE
of the UNIVERSE

MILLENNIUM Simulations

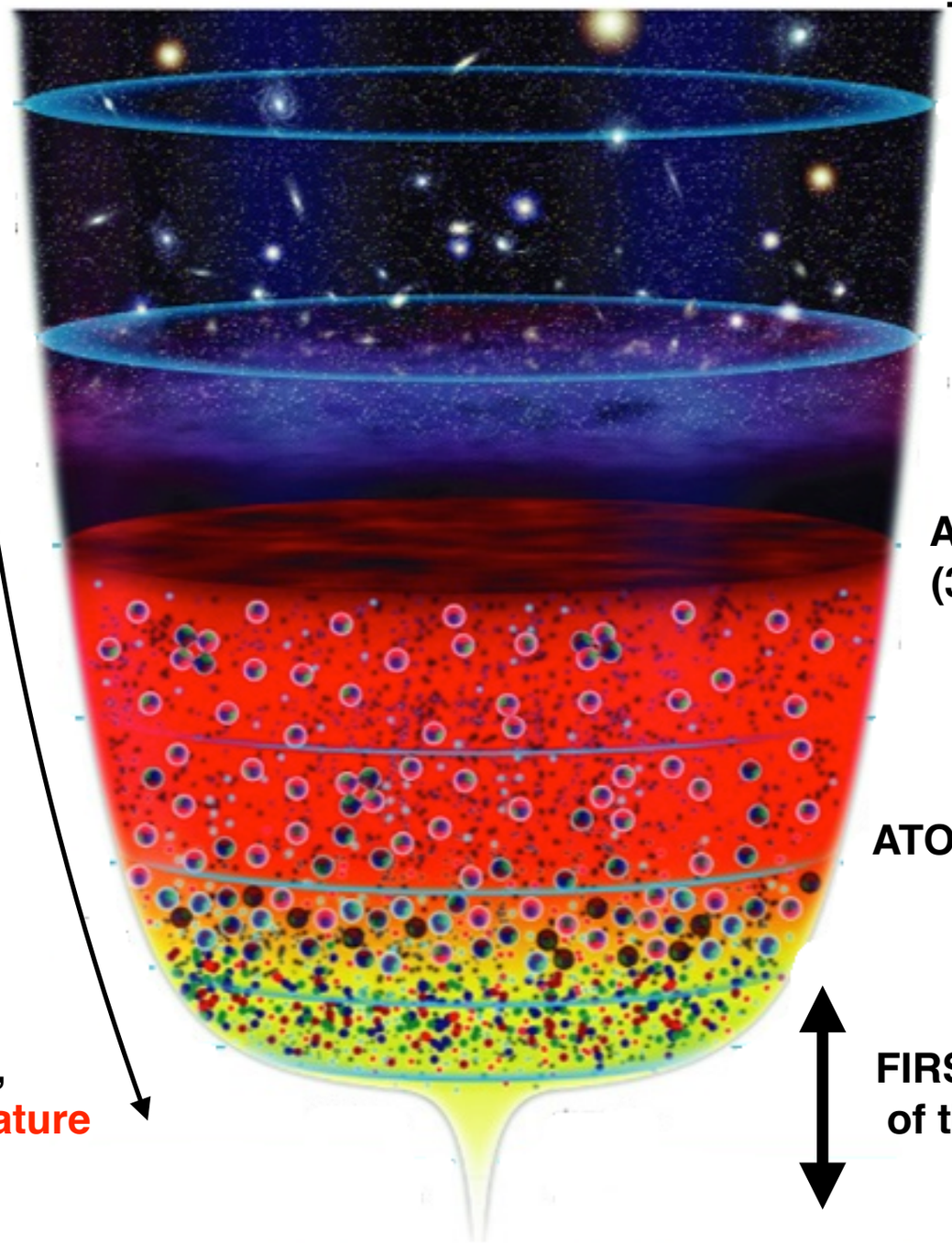


AREPO Simulations



COSMIC HISTORY of the UNiVERSE

BiGGER size,
SMALLER Temp



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ATOMIC NUCLEI CREATION
(3 minutes !!!)

FIRST SECOND
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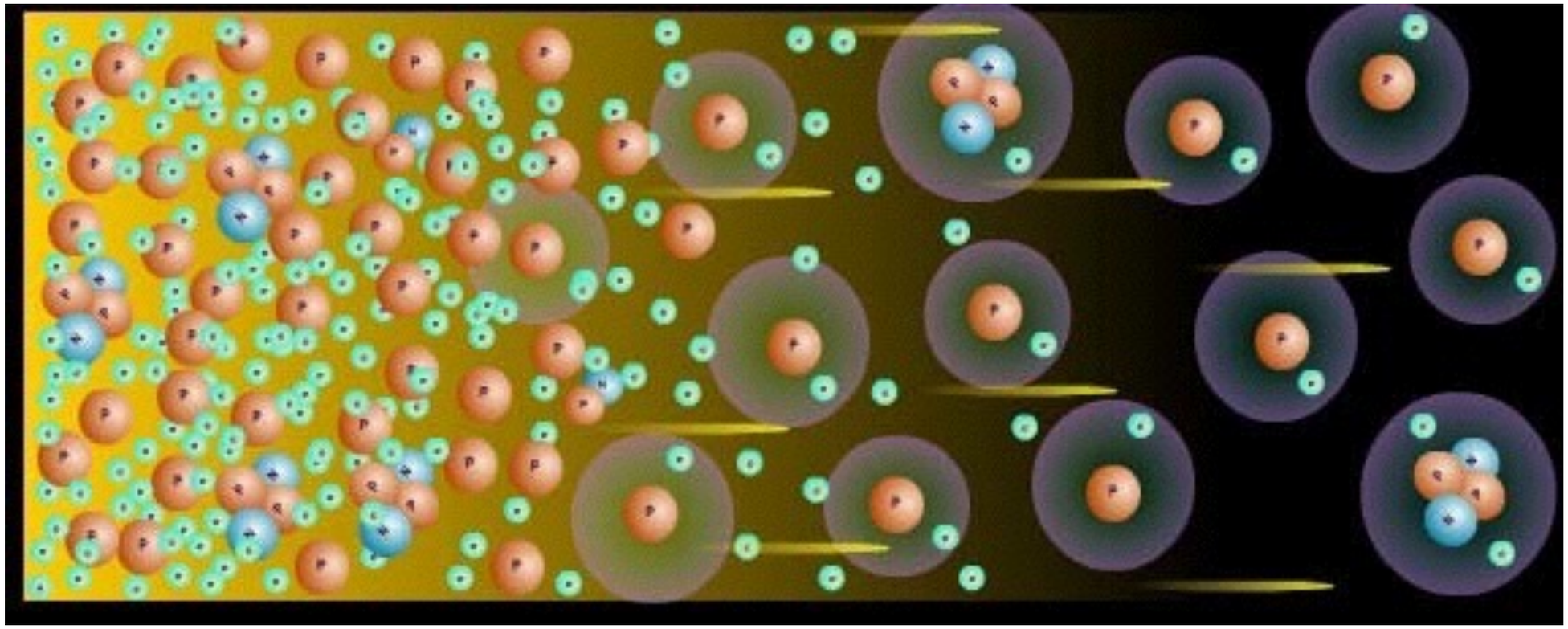
SMALLER SIZE,
LARGER Temperature

Cosmic Epochs: Formation of atoms (300.000-400.000 yrs)



Past, hotter

Later, colder

Protons, Electrons, Photons

Interact electro-magnetically

Universe cools down…

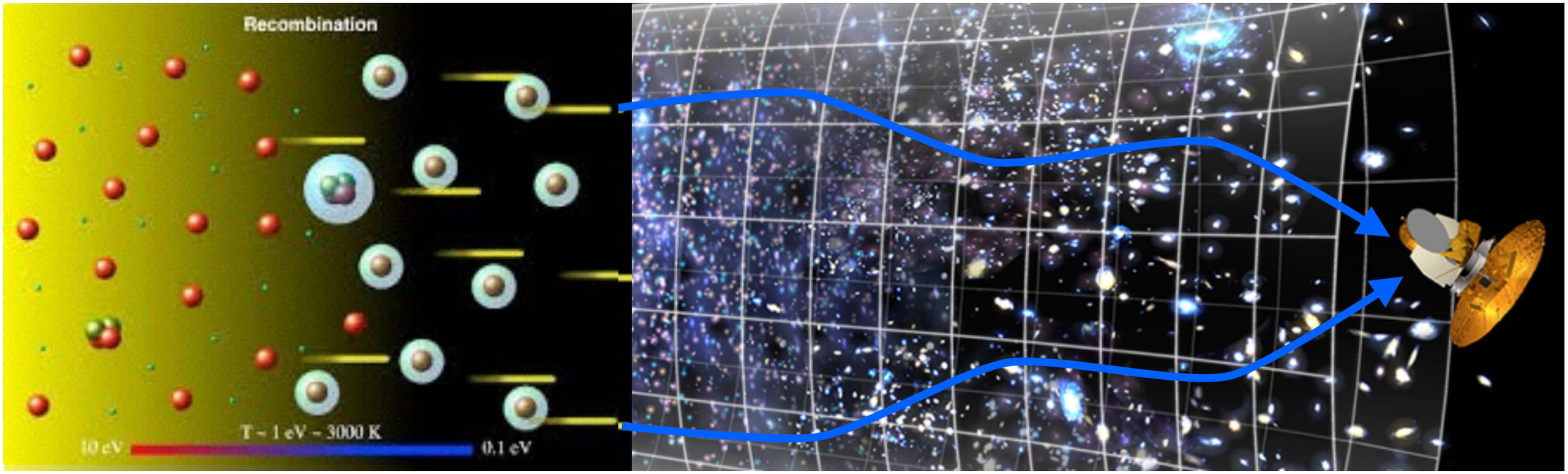
… Photons **do not have enough energy** to break apart atoms,

Then **electrons join to the atomic nuclei**: Atoms formed!!!

Atoms formed !

Light (electromagnetic radiation) set free !

Cosmic Epochs: Formation of atoms (300.000-400.000 yrs)

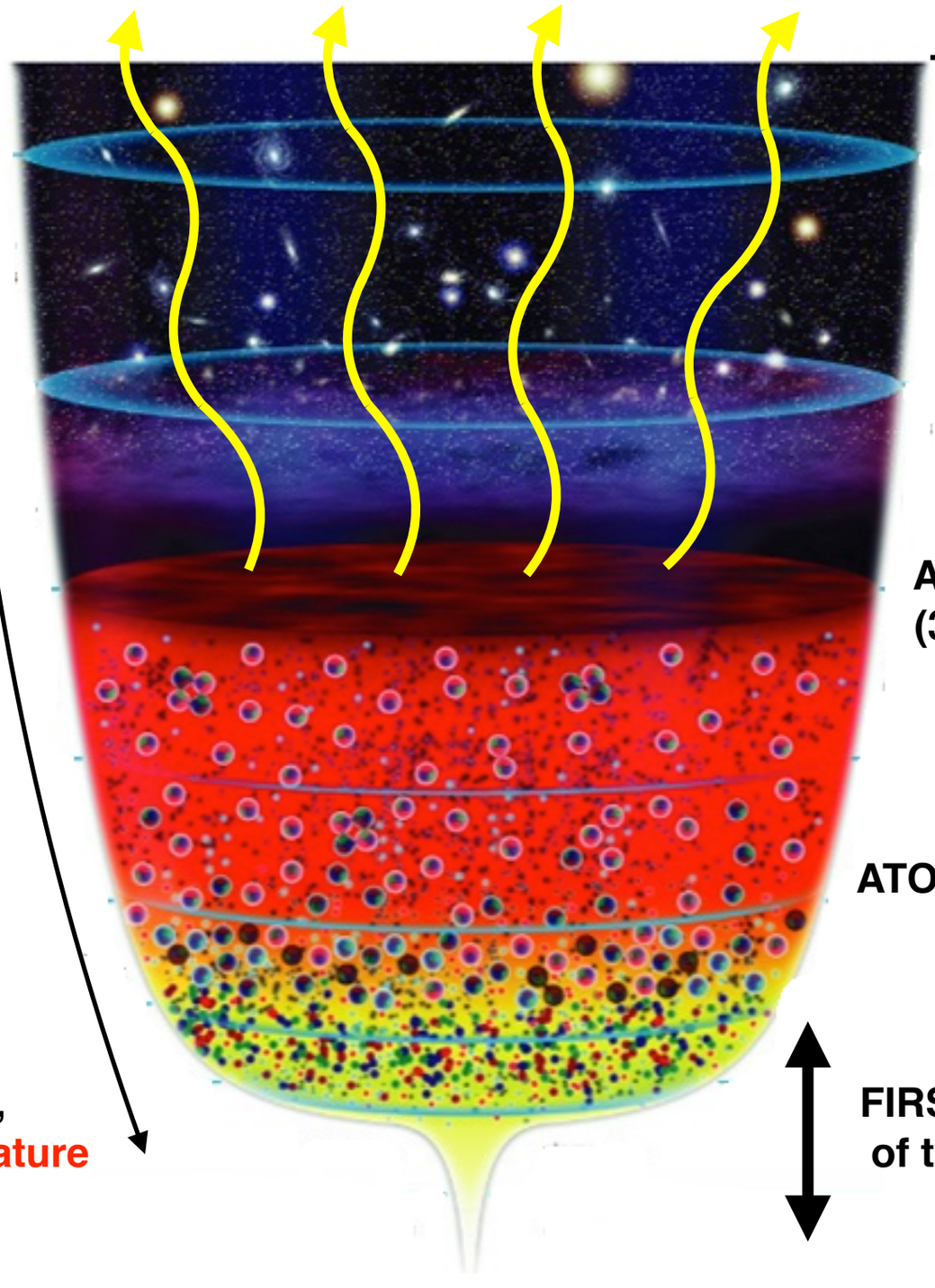


Atom Formation: Free propagation of light !!
(Recombination)

Cosmic Epochs: Formation of atoms (300.000-400.000 yrs)

¿Where is that light? Everywhere!

BiGGER size,
SMALLER Temp



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ATOMS FORMATION
(300.000-400.000 years)

Emission of Cosmic Microwave Radiation !

ATOMIC NUCLEI FORMATION
(3 minutes !!!)

FIRST SECOND
of the UNIVERSE !!

SMALLER SIZE,
LARGER Temperature

Cosmic Epochs: Formation of atoms (300.000-400.000 yrs)

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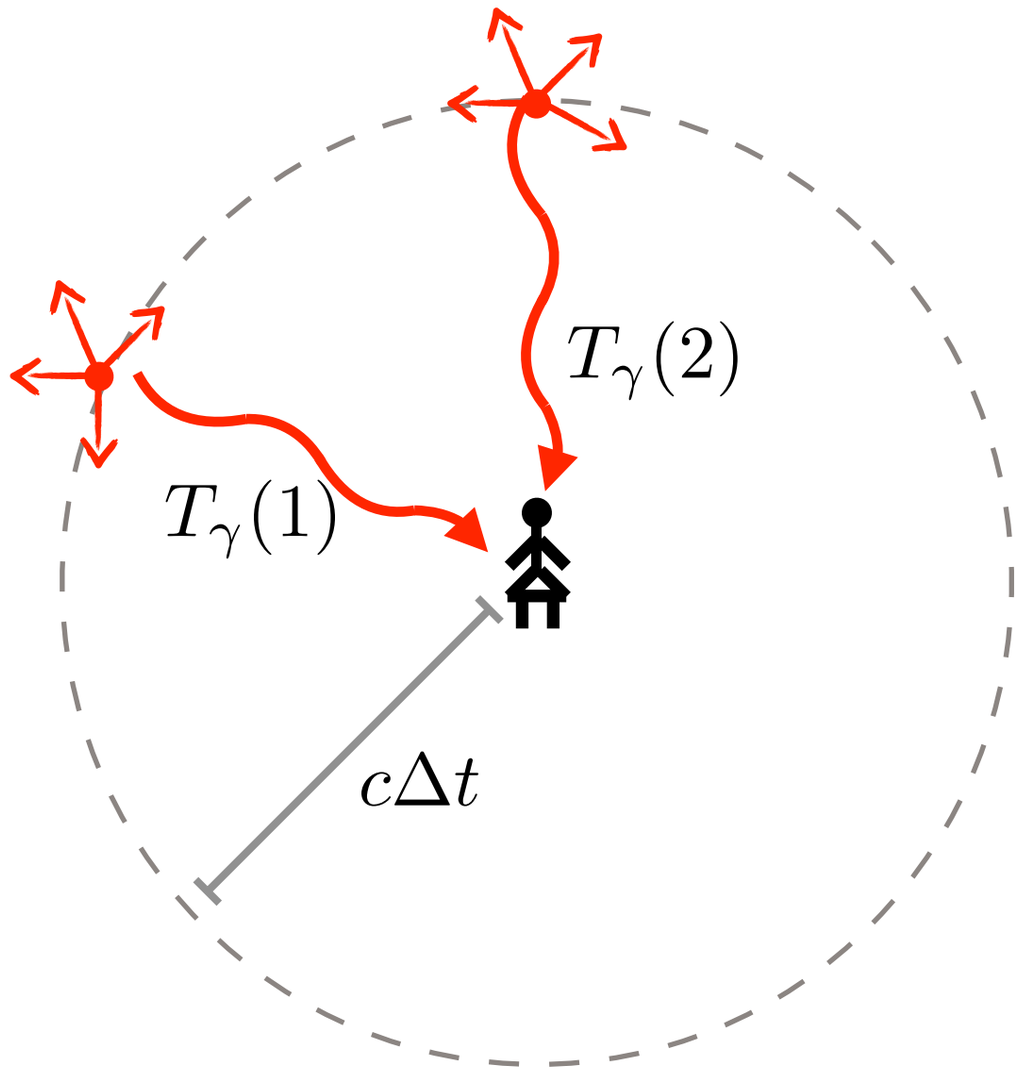

Cosmic Microwave Background (CMB)

Cosmic Epochs: Formation of atoms (300.000-400.000 yrs)

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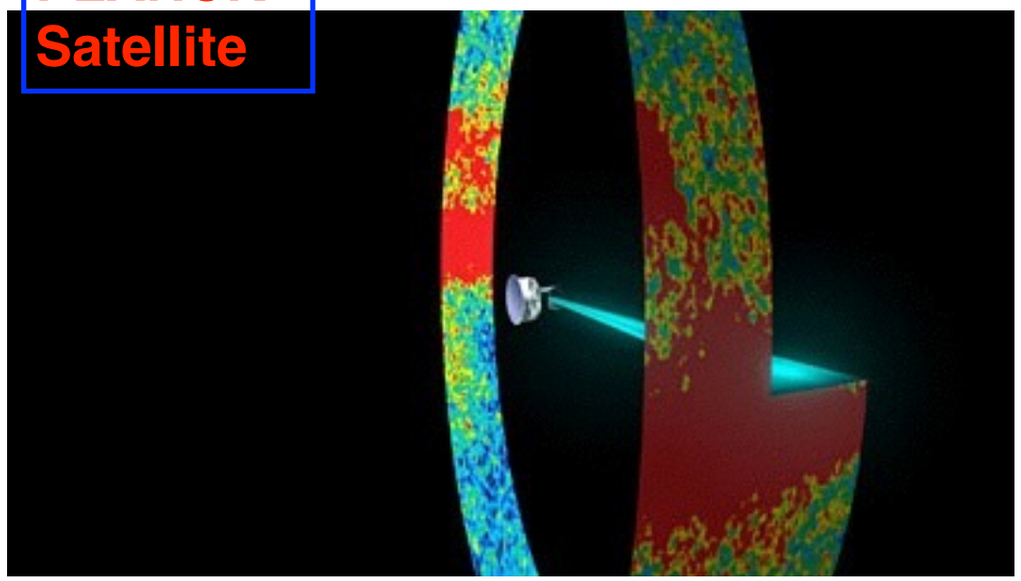
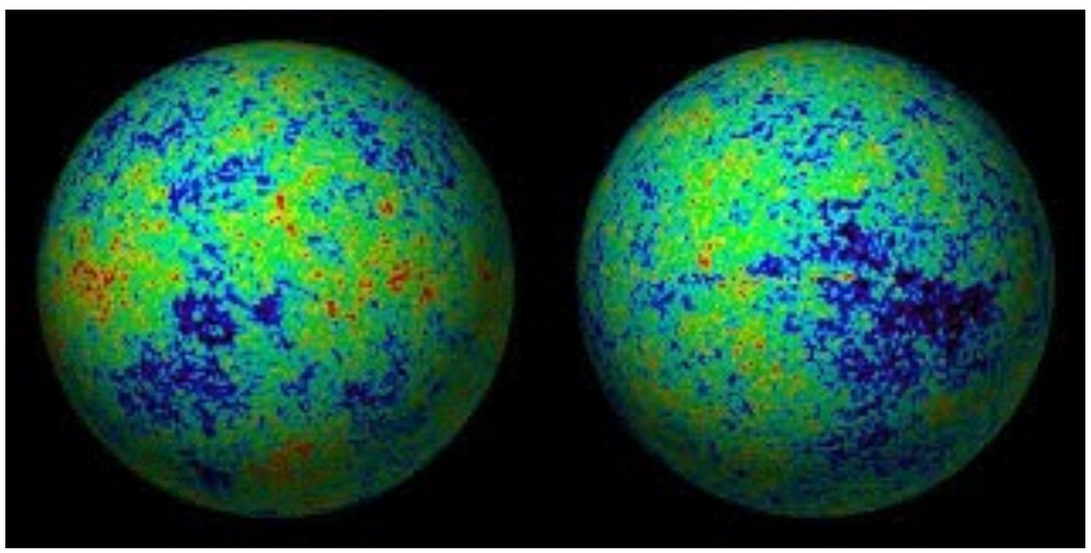
PLANCK Satellite



Cosmic Microwave Background (CMB)

Definitive proof of the Big Bang Theory!



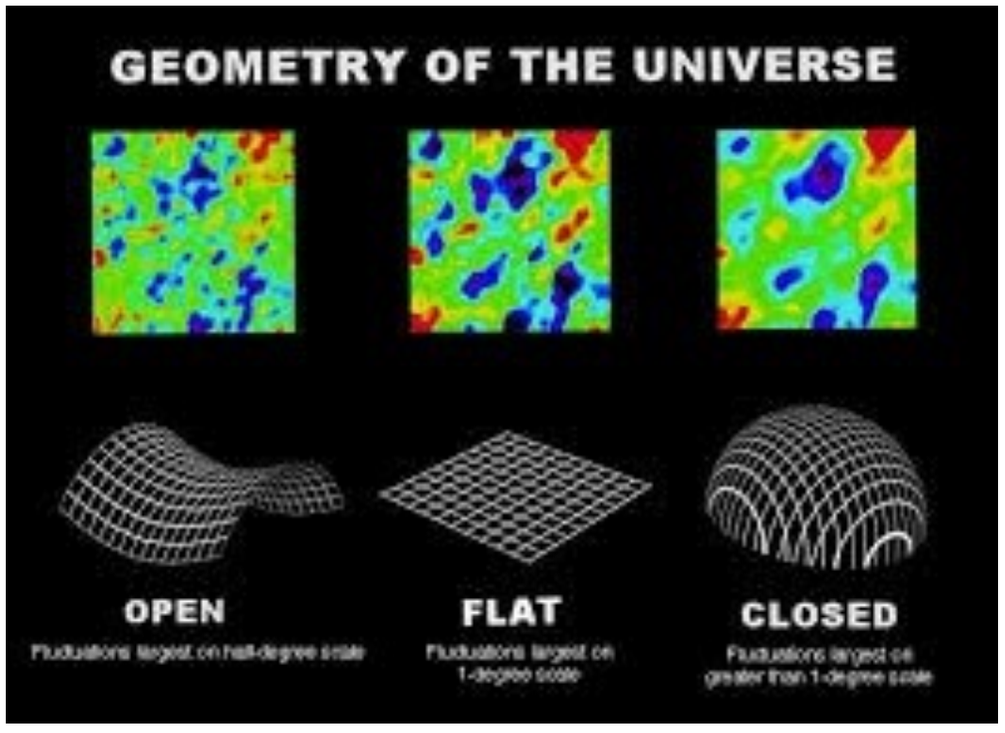
(almost-)ISOTROPIC

But ….

There are small 'Inhomogeneities' !!!
(variations of 1/100.000)

Cosmic Epochs: Formation of atoms (300.000-400.000 yrs)

Properties of the Cosmic Microwave Background

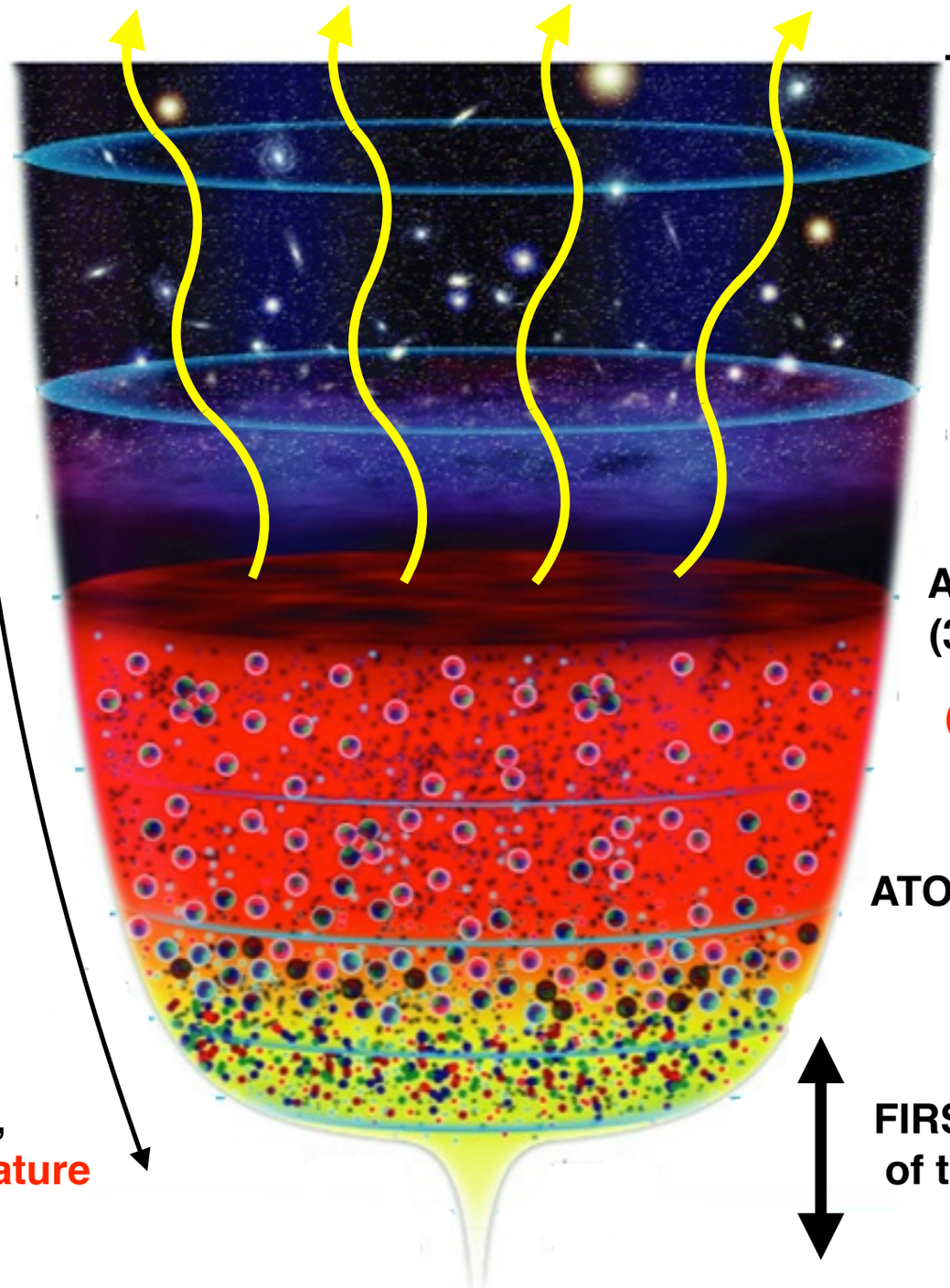


Properties of the Anisotropies then …. Geometry of the Universe !

The UNIVERSE has FLAT GEOMETRY !

COSMIC HISTORY of the UNiVERSE

BiGGER size,
SMALLER Temp



TODAY [Galaxies, Clusters, …]
(13.700 Million years)

FIRST GALAXIES
(500 Millions years)

ATOMS FORMATION
(300.000-400.000 years)

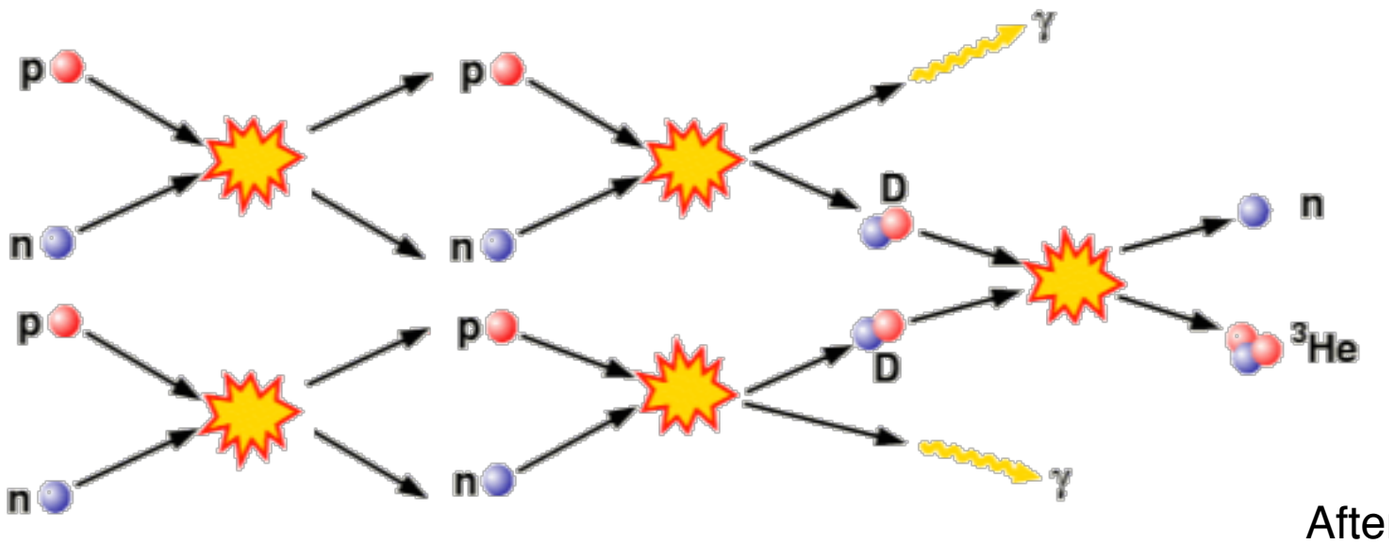
(+ CMB emission !)

ATOMIC NUCLEI FORMATION
(3 minutes !)

FIRST SECOND
of the UNIVERSE !!

SMALLER SIZE,
LARGER Temperature

Cosmic Epochs: Formation of atomic nuclei (3 mins)



Past, hotter (1 second)

Afterwards, colder (3 minutes)

Protons, Neutrons

Interact strongly

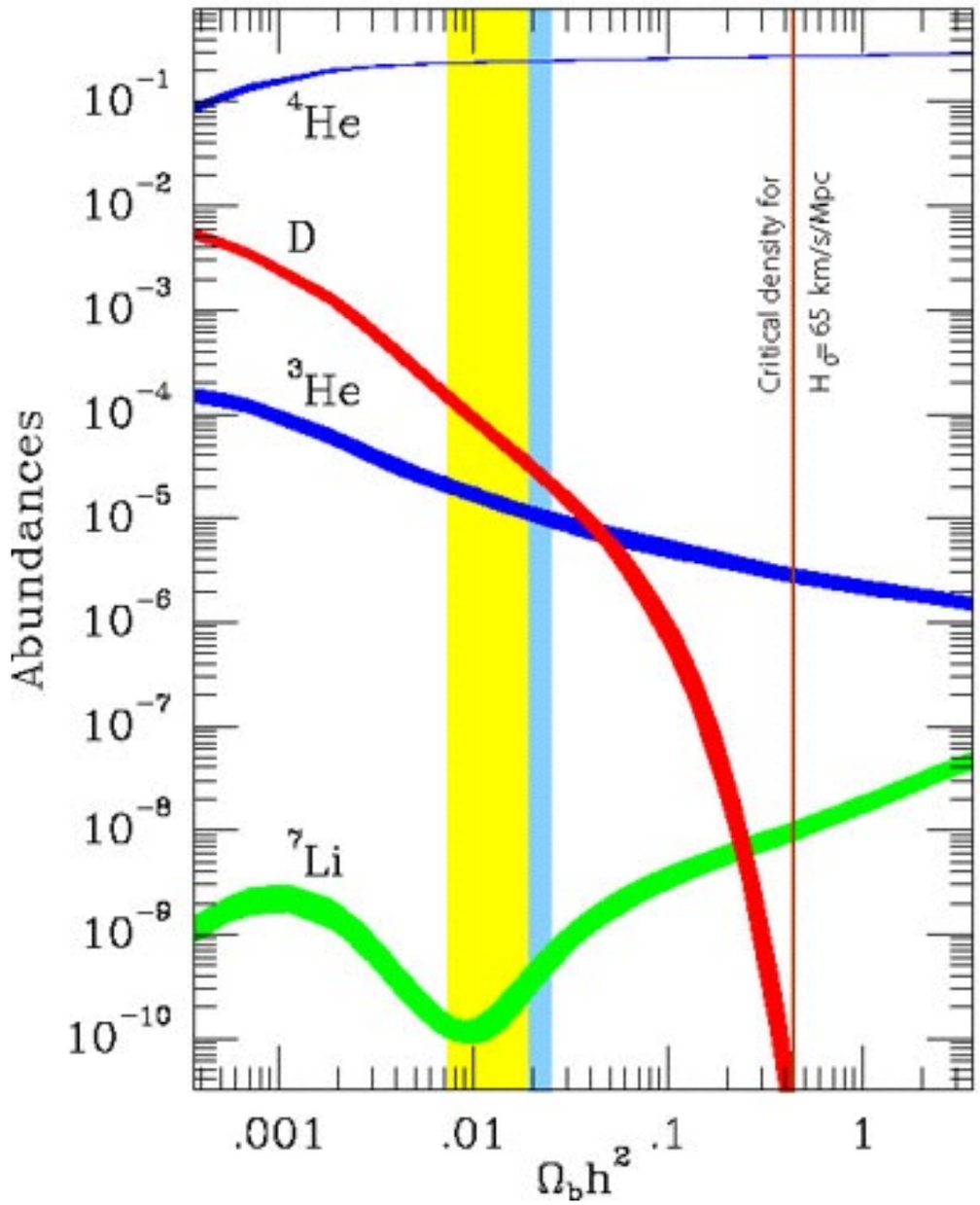
Universe cools down…

… protons and neutrons **don't have sufficient energy anymore**

Then **they join together forming atomic nuclei**: Nuclear Physics!

Atomic Nuclei created !

Cosmic Epochs: Formation of atomic nuclei (3 mins)



NUCLEAR PHYSICS
(measured in the lab)

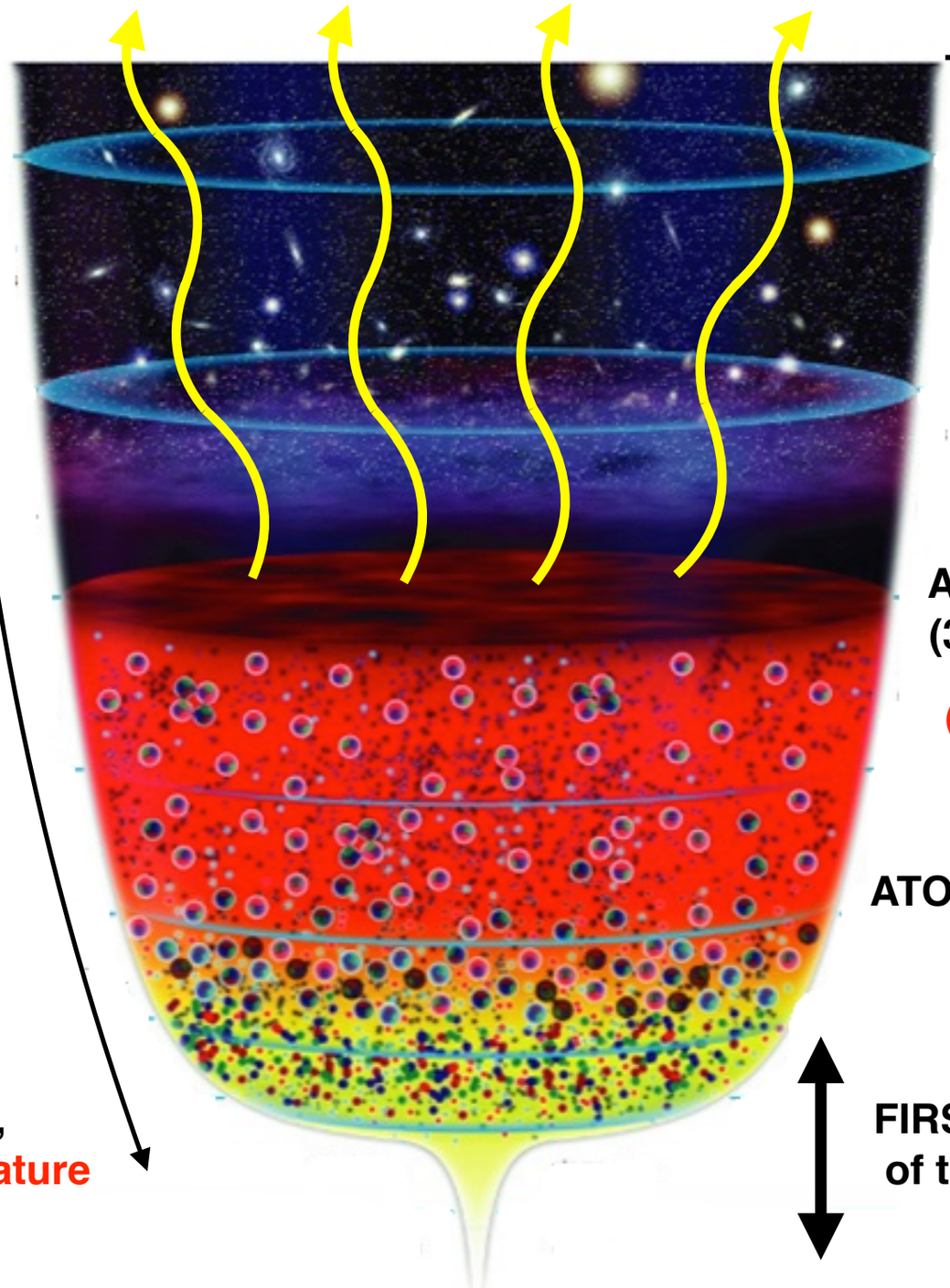
Lets to predict abundances of

$$H,\ {}^4He,\ D,\ {}^3He,\ {}^7Li, \ldots$$

Another definitive proof of the Big Bang theory !

COSMIC HISTORY of the UNiVERSE

BiGGER size,
SMALLER Temp



TODAY [Galaxies, Clusters, …]
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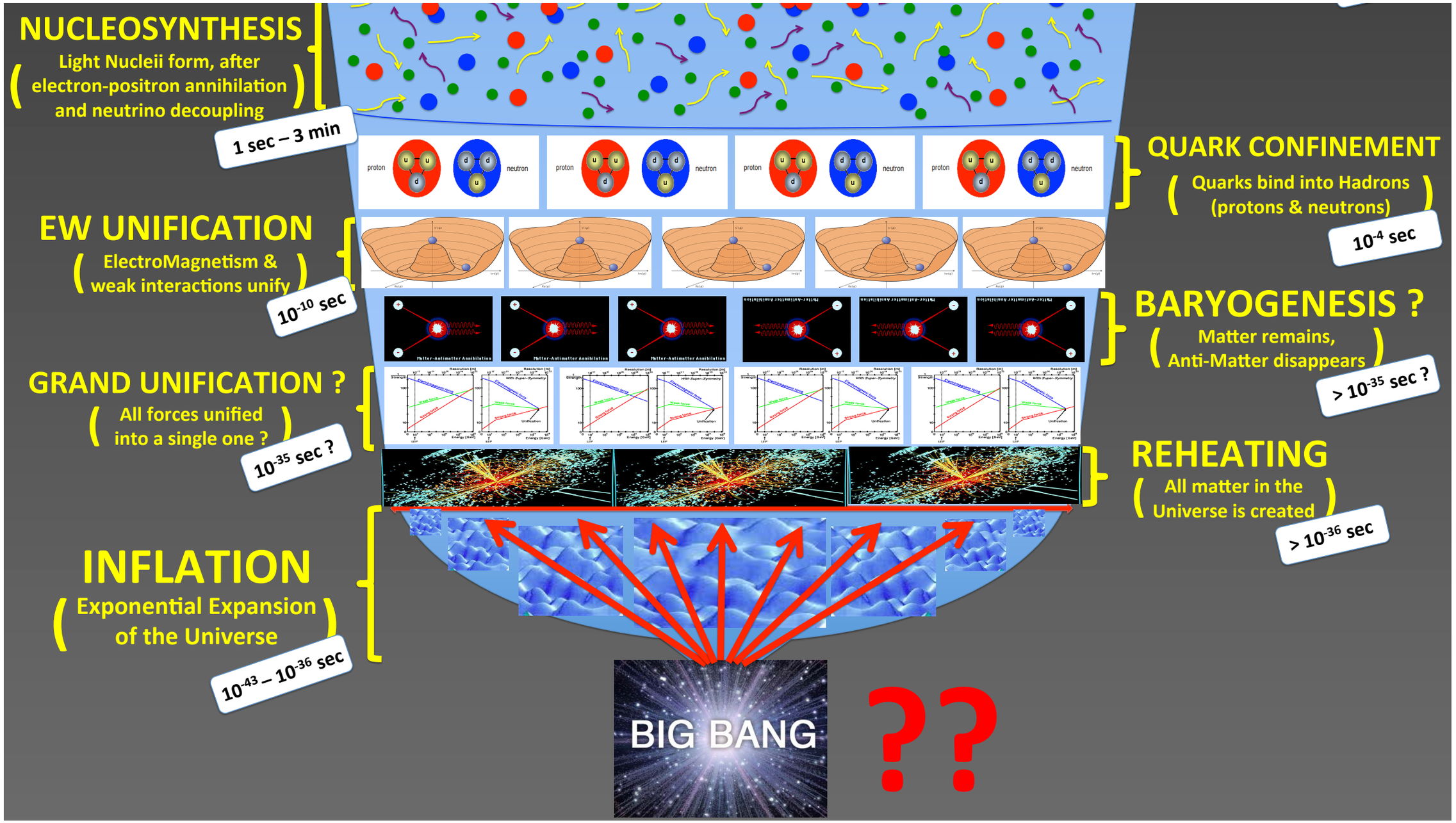
ATOMIC NUCLEI FORMATION
(3 minutes !)

FIRST SECOND
of the UNIVERSE !!

SMALLER SIZE,
LARGER Temperature

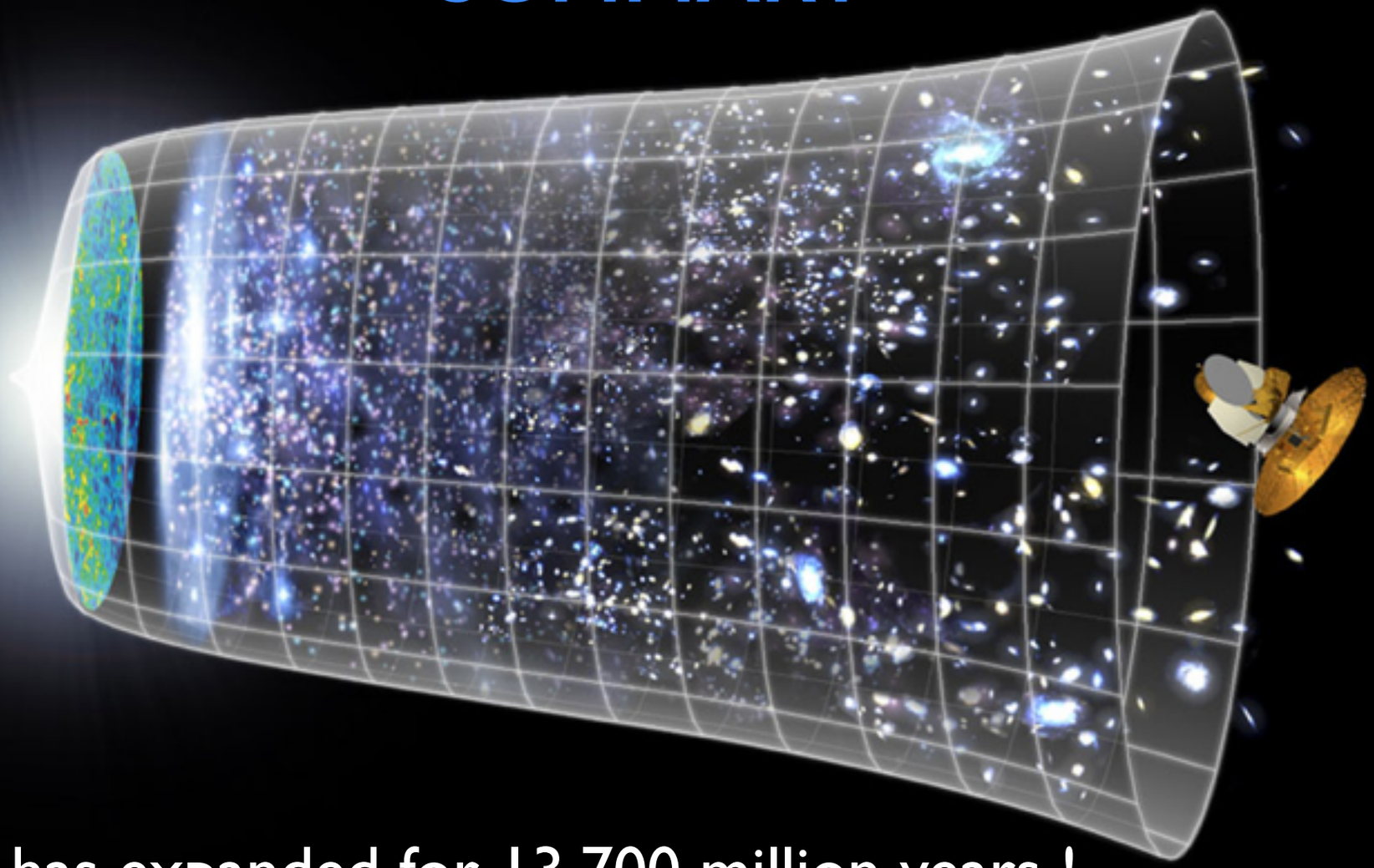
Cosmic Epochs: The first Second of the Universe !

Notation : 10^{-n} seg $= 0.00....001$ seg



Particle Accelerators (LHC): Reach up to 10^{-10} sec

SUMMARY



- ✓ Universe has expanded for 13.700 million years !
- ✓ Several Epochs have been crucial in the evolution of the Universe
- ✓ The first second is crucial to understand the evolution afterwards

But yet we DON'T UNDERSTAND that First Second !

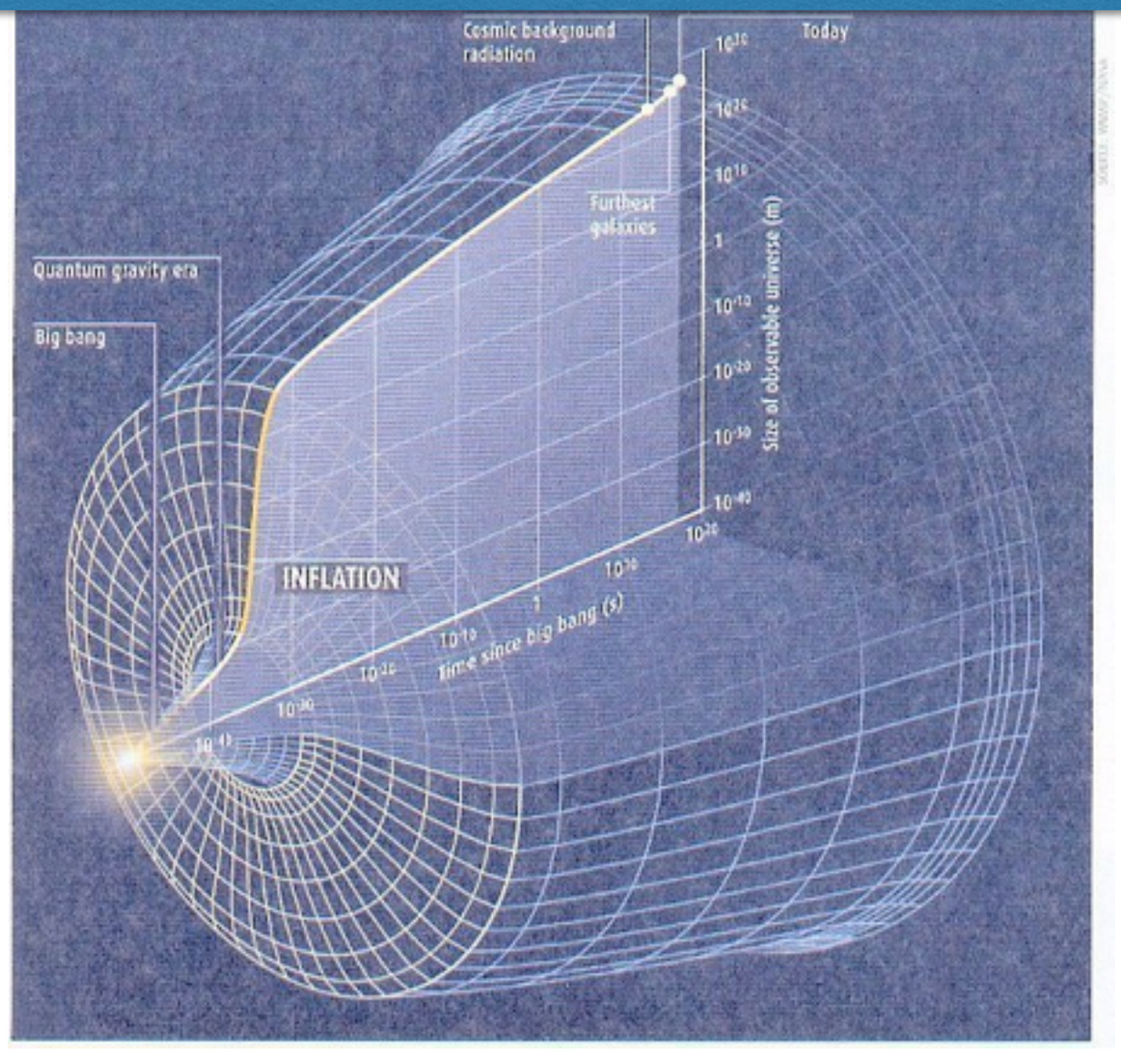
WHAT DID I NOT TELL YOU ?

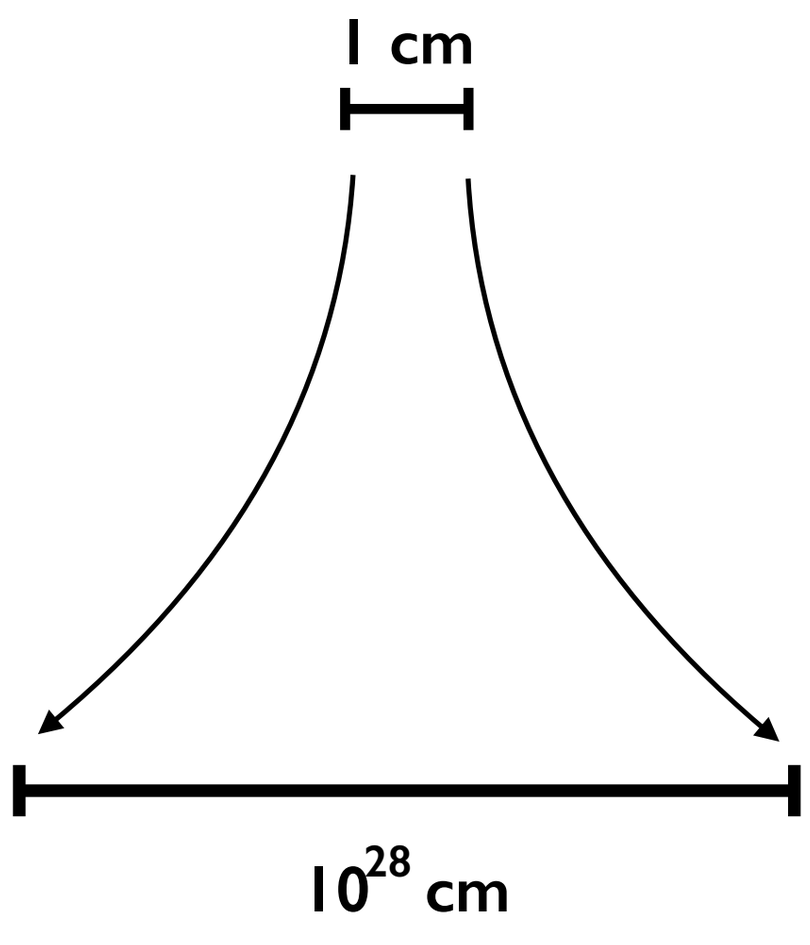
MANY THINGS !

WHAT DID I NOT TELL YOU ?

COSMIC INFLATION !

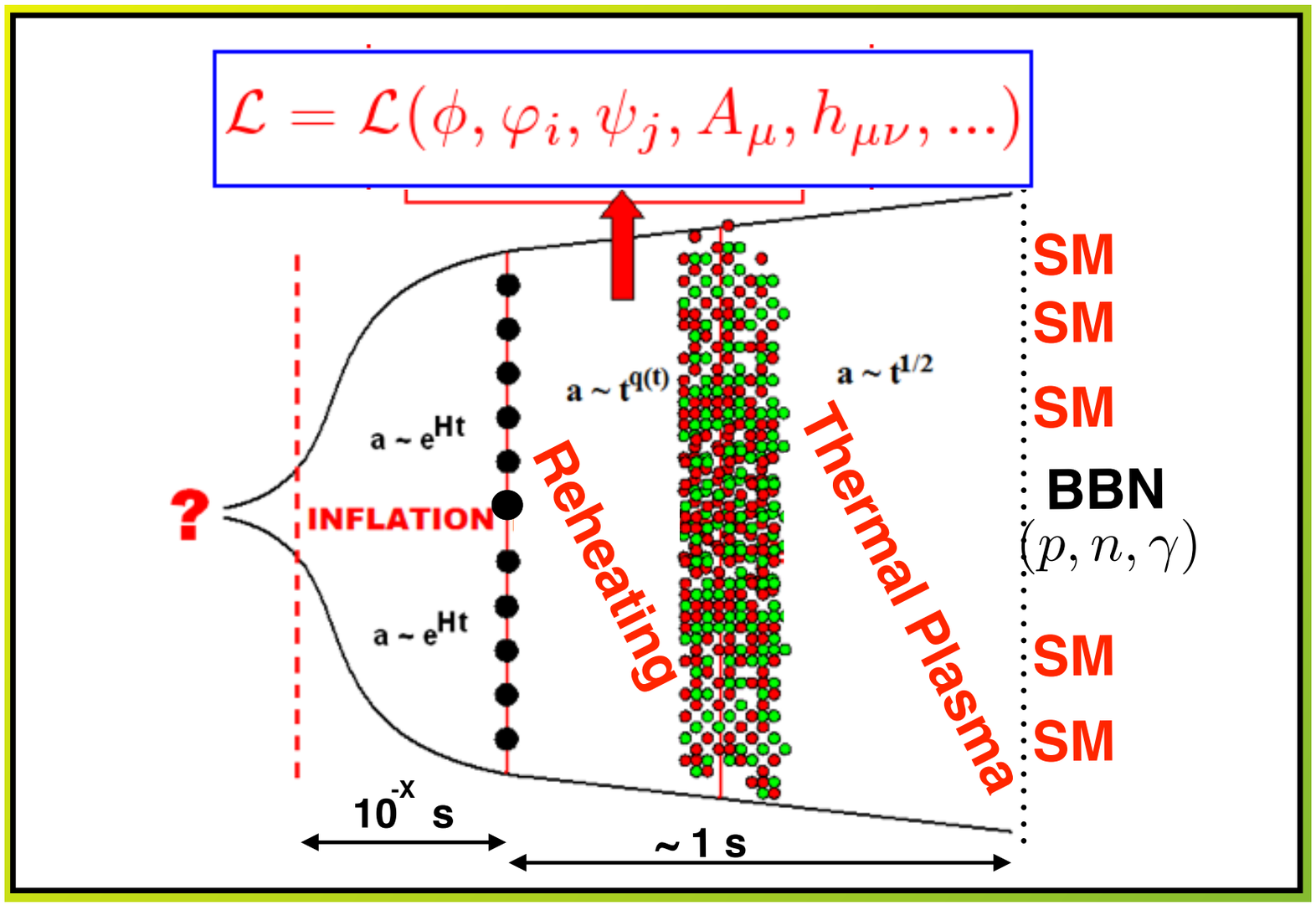
Needed for Consistency of the Big Bang theory !





WHAT DID I NOT TELL YOU ?

Reheating: **Production of all the particles in the Universe (after Inflation)**



*** Higgs: only Spin = 0 particle in Standard Model !**

*** How to connect Inflation with the Standard Model: Possibly through the Higgs!**
(but we don't know)

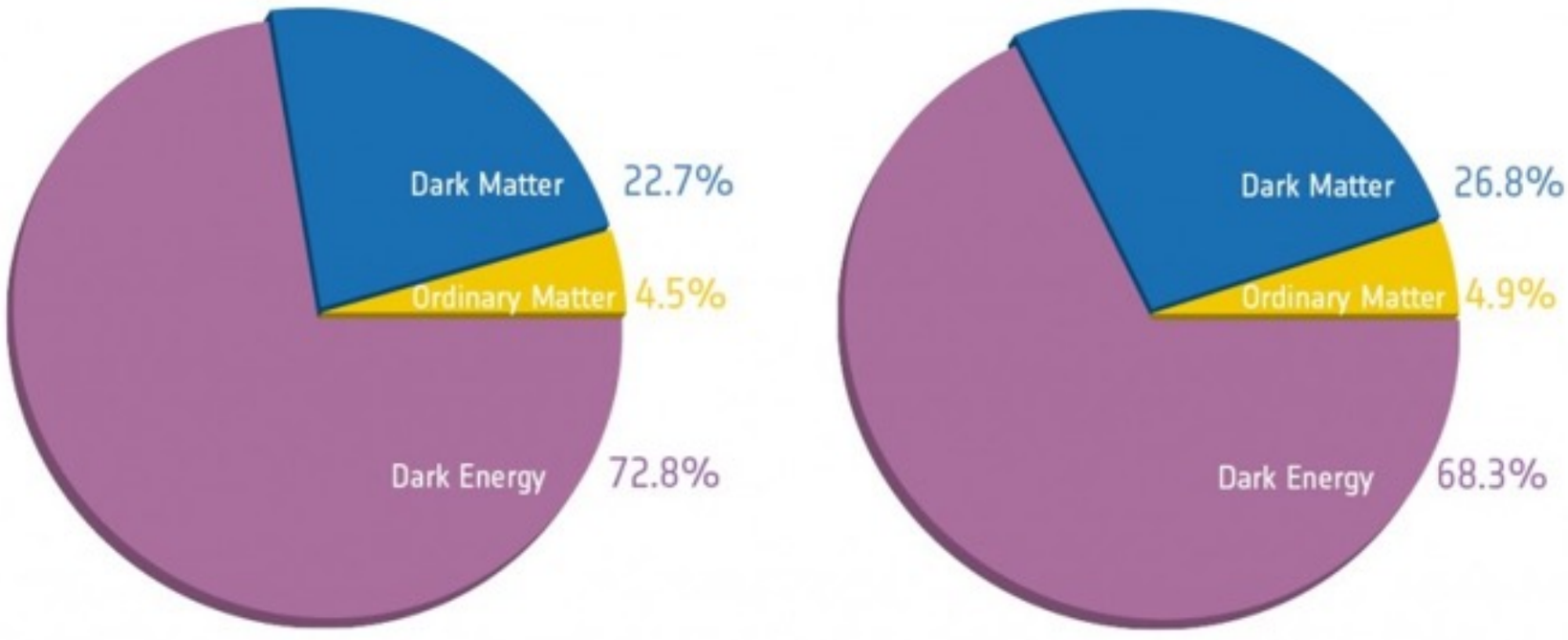
WHAT DID I NOT TELL YOU ?

DARK ENERGY !
(Accelerated Expansion)

DARK MATTER !

WHAT DID I NOT TELL YOU ?

Matter content within the Universe



Before Planck

After Planck

WHAT ELSE DID I NOT TELL YOU ?

WHAT ELSE DID I NOT TELL YOU ?

THANKS FOR
YOUR
ATTENTION !!

To know more (books)

- The first three minutes (S. Weinberg) **Big Bang Theory**
- Black holes and warped spacetime (K. Thorne) **Gravity**
- The Charm of Physics (S. L. Glashow) **Particle Physics**
- The Elegant Universe (B. Green) **String Theory**
- El Inflationary Universe (A. Guth) **Inflationary Paradigm**

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Open Questions …

¿What is Dark Matter made of?

¿What is Dark Energy?

¿Is there a "before" the Big Bang?

¿Is the Universe Infinite?

¿How did the anti-matter disappear?

¿How did the Universe appeared?

¿Did Inflation really occurred?

…