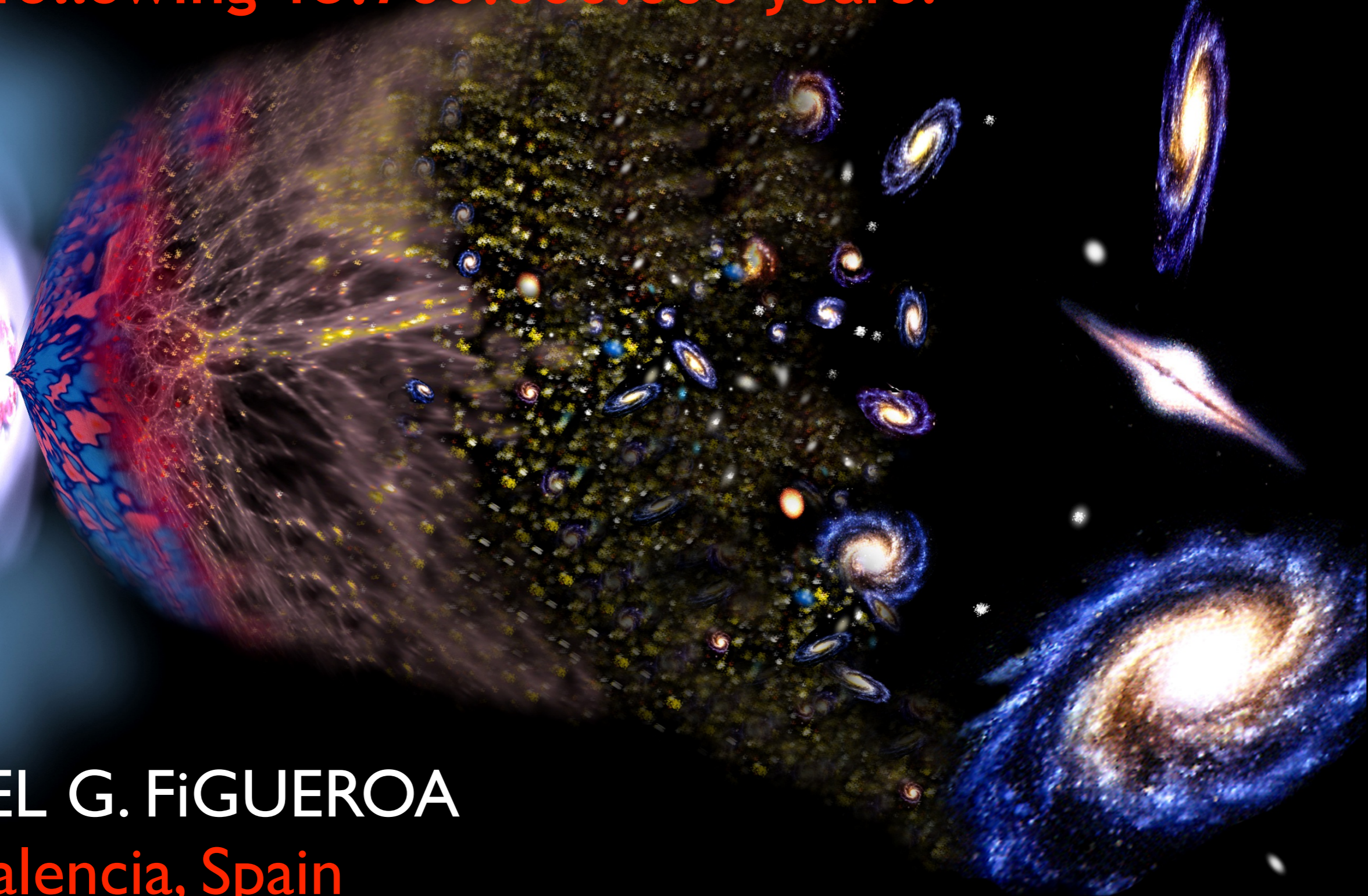


COSMOLOGY



DANIEL G. FIGUEROA
IFIC, Valencia, Spain

The first second of the Universe & the following 13.700.000.000 years!

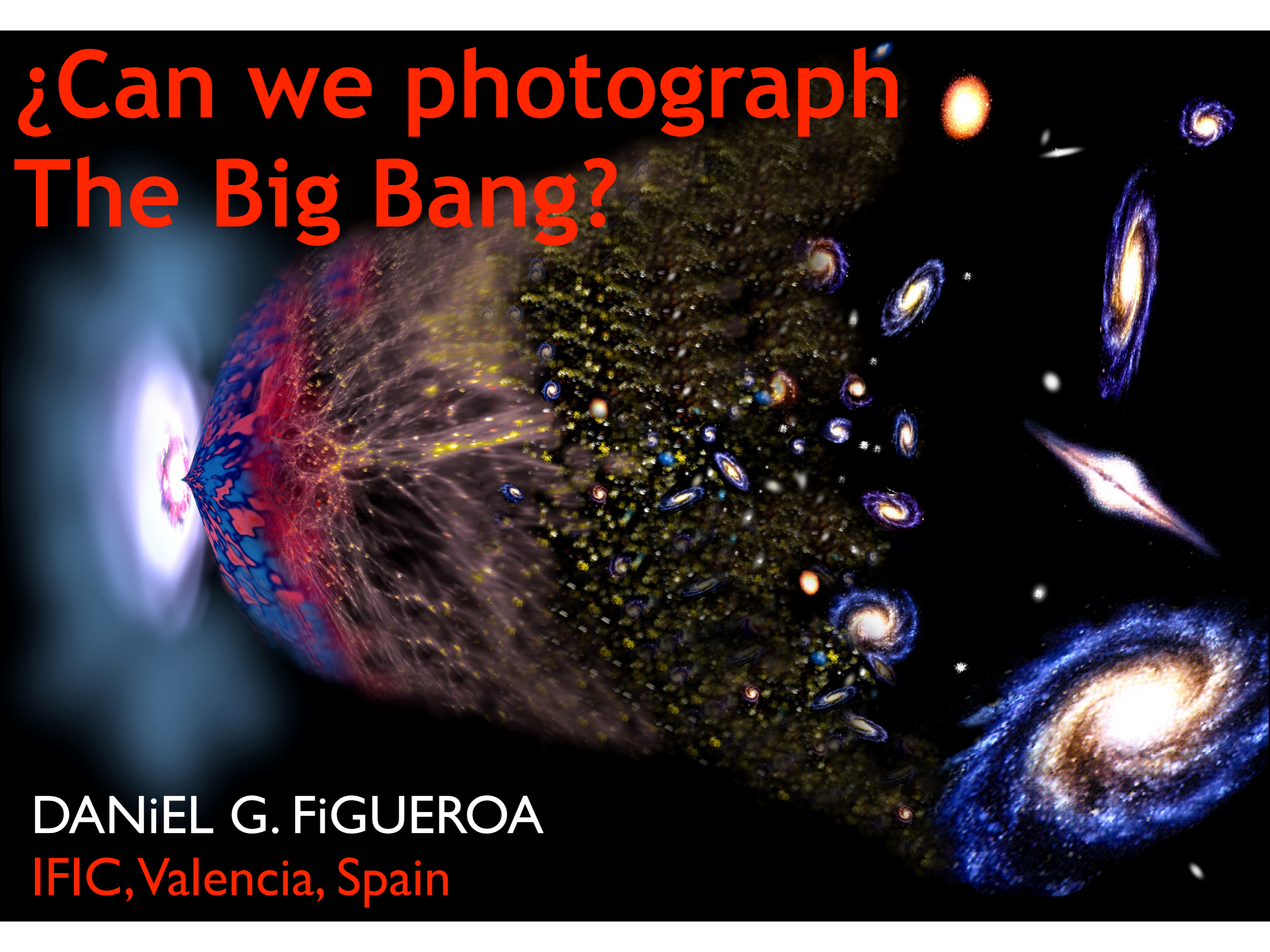


DANIEL G. FIGUEROA

IFIC, Valencia, Spain

¿Can we photograph The Big Bang?

DANIEL G. FIGUEROA
IFIC, Valencia, Spain



¿ Can we 'see'
the 'Big Bang' ?

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the 'Big Bang' ?

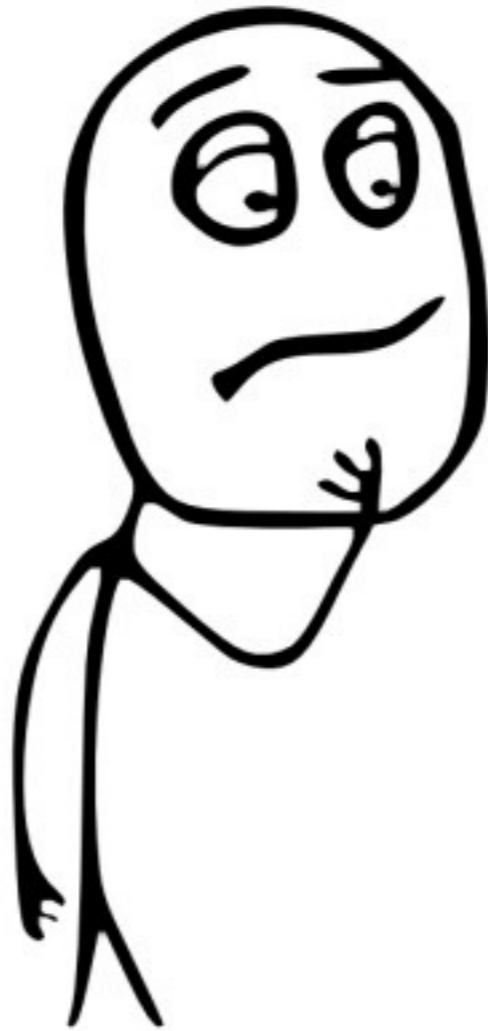


¿ Can we 'see'
the 'Big Bang' ?



Cosmology

... *mmm, Cosmology ?*



Cosmology = *Study* of the *Universe* as a **WHOLE**
(Evolution, Content,
"Birth", "Death",...)

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Scientific method:

Observe + Measure \longrightarrow Infer Laws

Laws \longrightarrow **Predict** new phenomena

Cosmology = *Study* of the *Universe* as a **WHOLE**
(Evolution, Content, "Birth", "Death",...)

Scientific method:

Observe + Measure → Infer Laws

Laws → **Predict** new phenomena

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

UNiVERSE



**'space'
CONTAINER**



**... of MATTER
(atoms, galaxies, ...
+ more exotic**

UNiVERSE



'space'

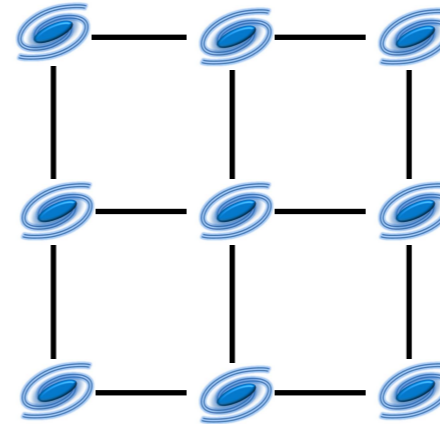
CONTAINER



... of MATTER

(atoms, galaxies, ...

+ more exotic



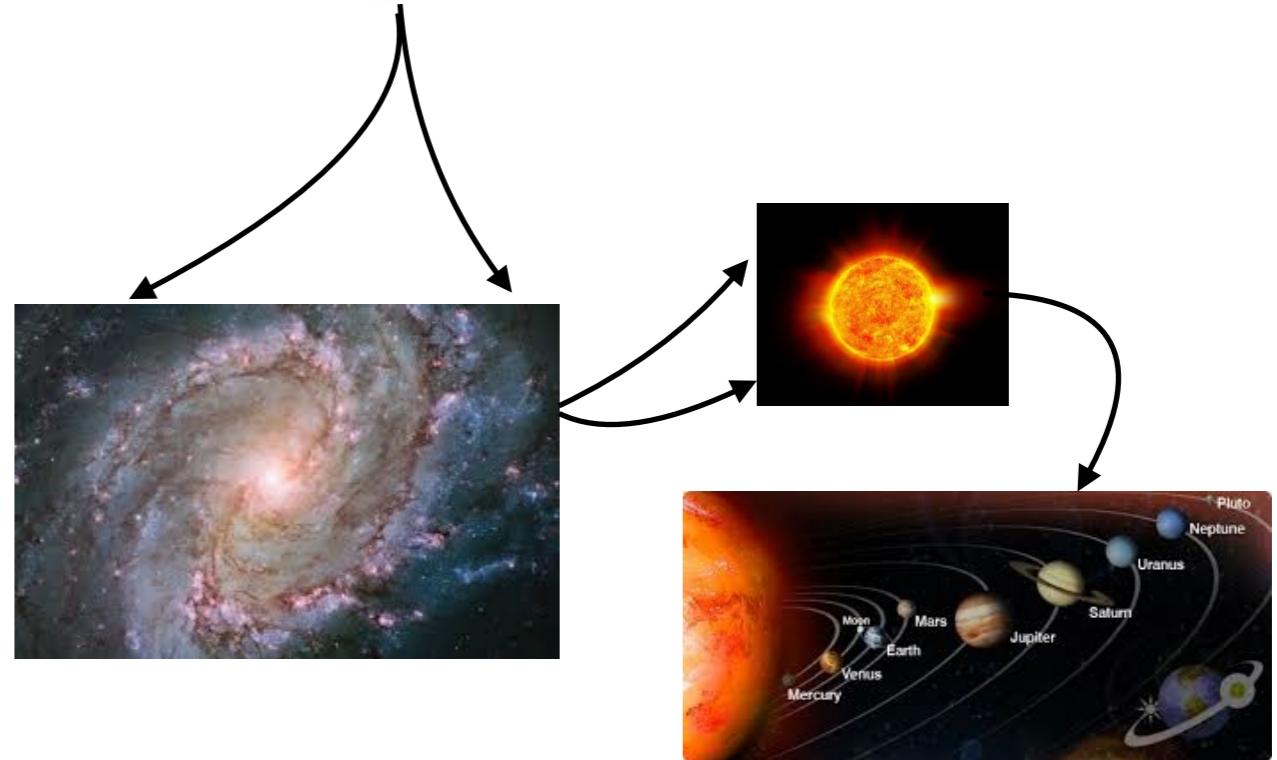
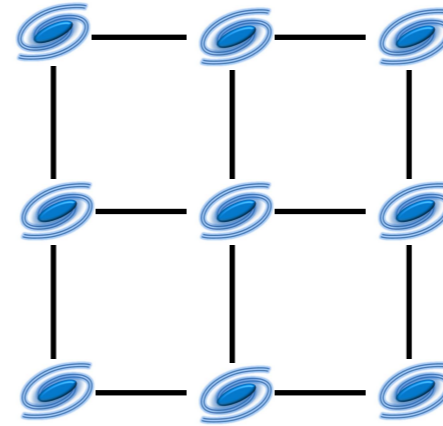
UNiVERSE



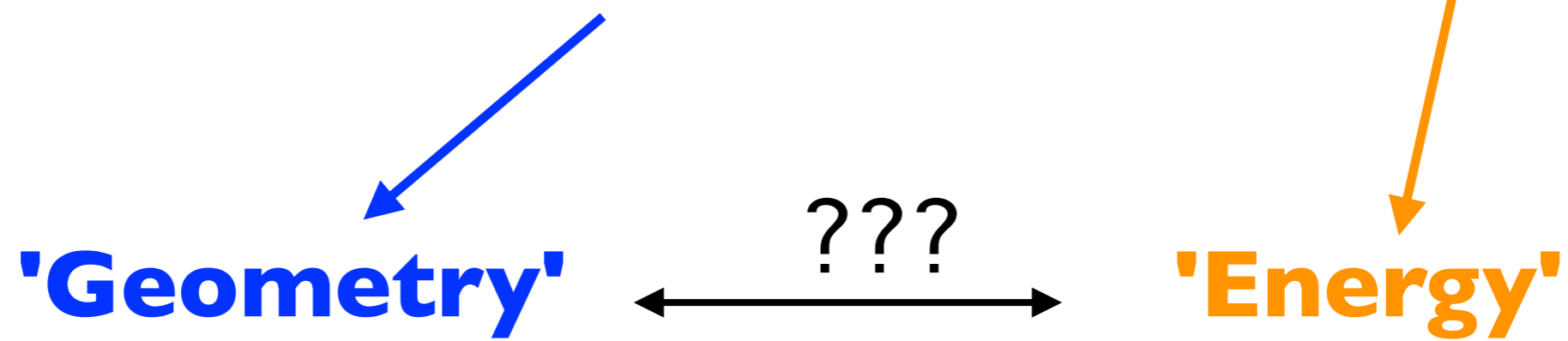
'space'
CONTAINER



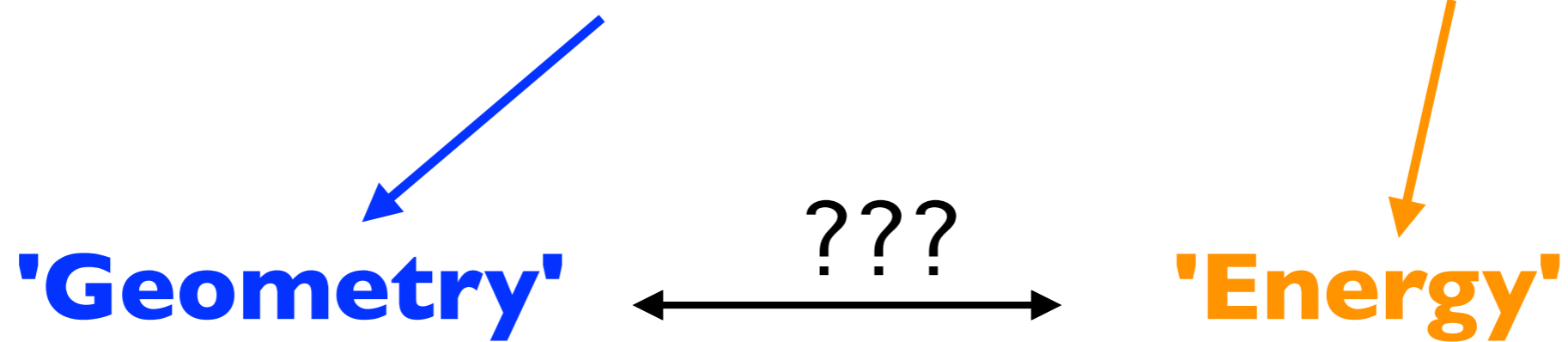
... of MATTER
(atoms, galaxies, ...
+ more exotic



UNiVERSE = Space Containing all Matter

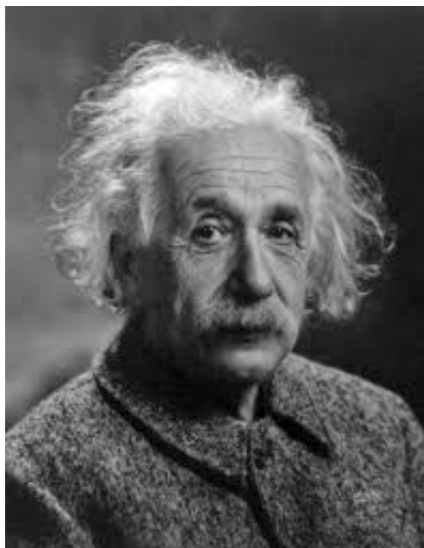


UNiVERSE = Space Containing all Matter

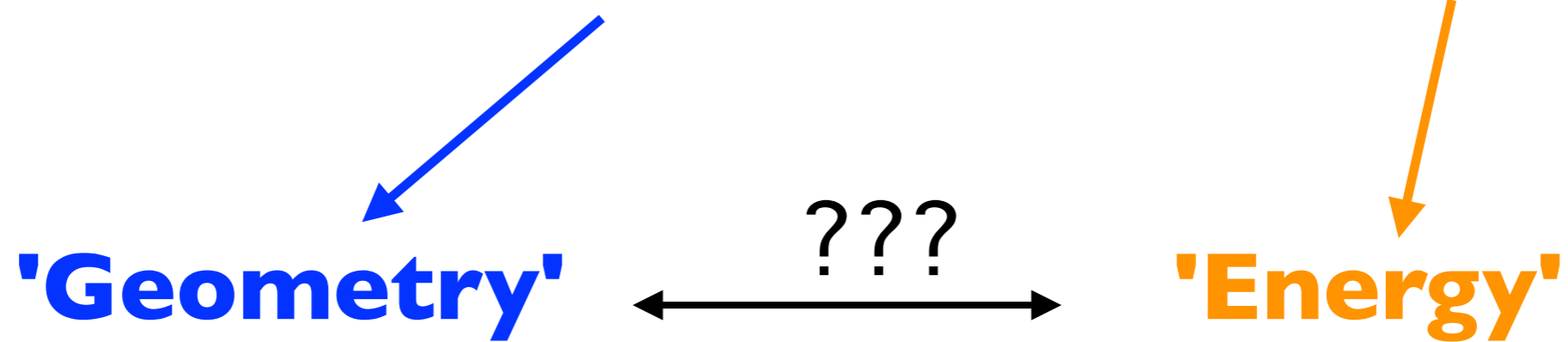


'Space-Time' Geometry
dictates **Movement of Matter**

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

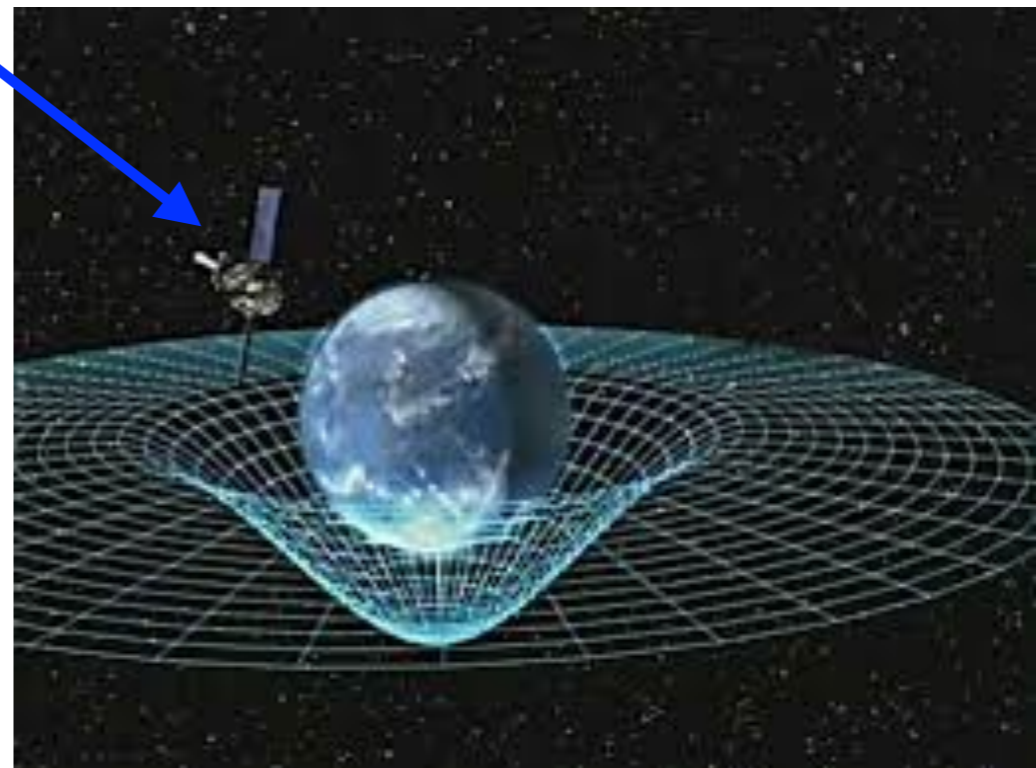
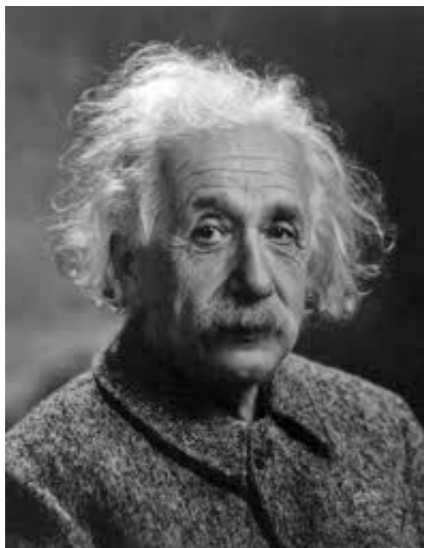


UNiVERSE = Space Containing all Matter

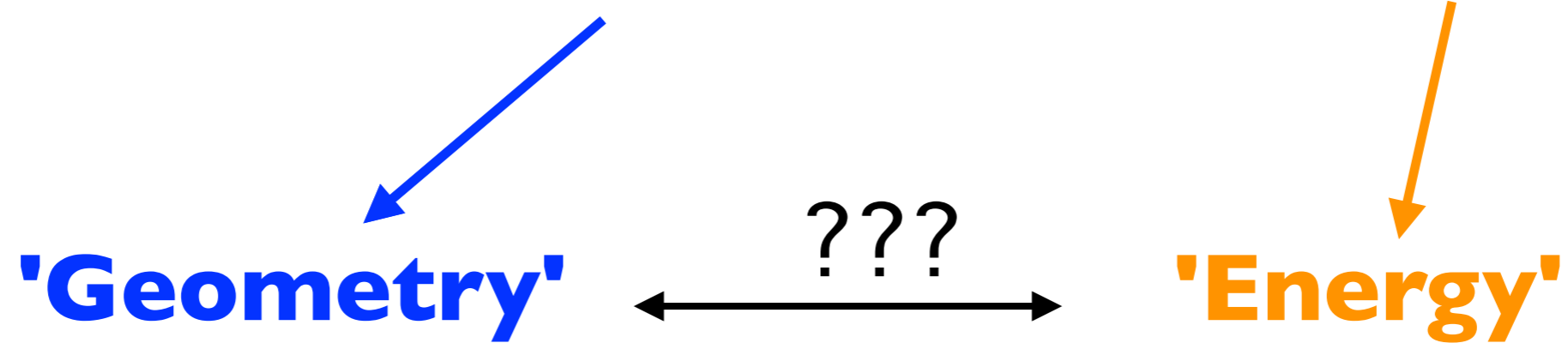


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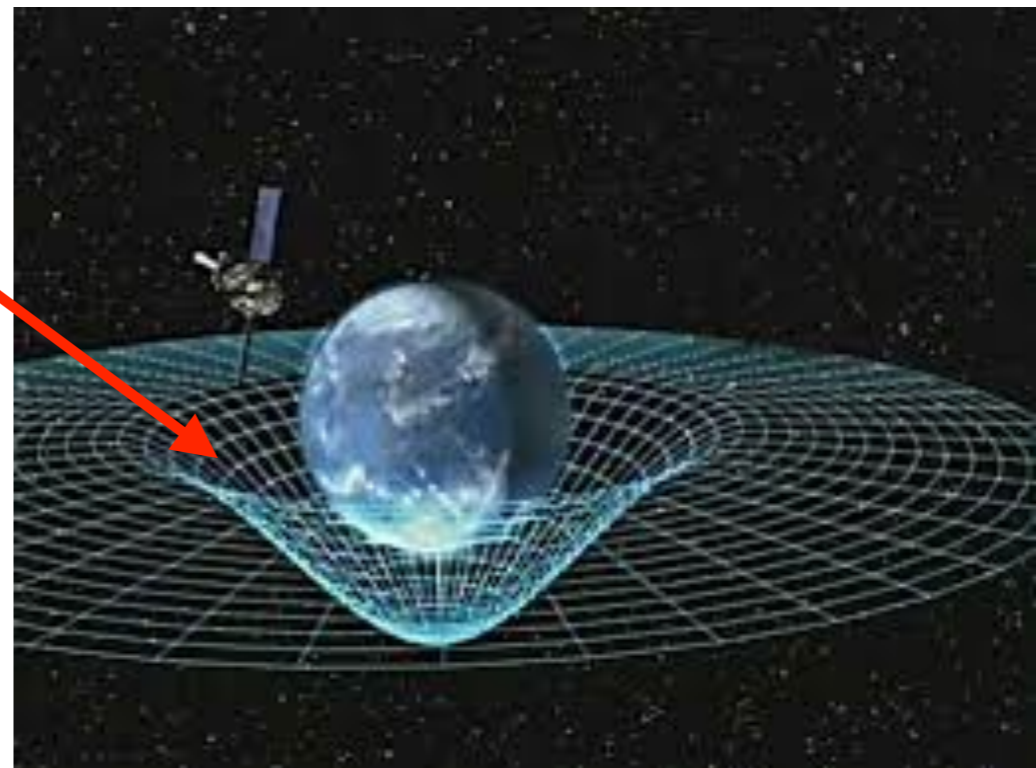
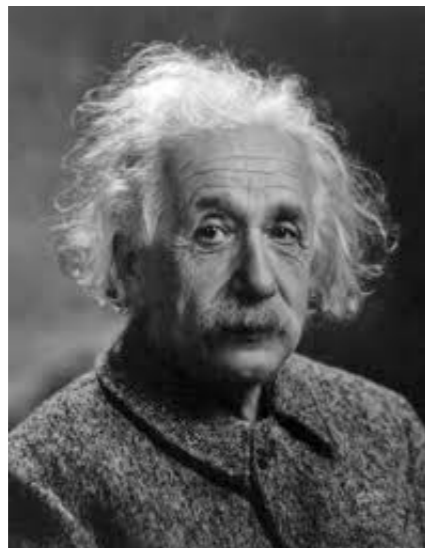


UNiVERSE = Space Containing all Matter



'Space-Time' Geometry
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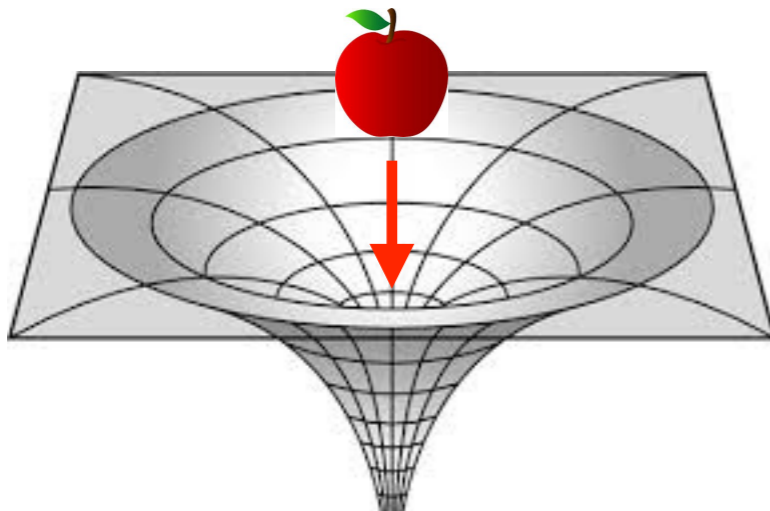
Presence of Matter (Energy)
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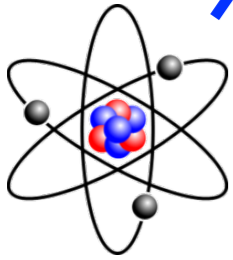
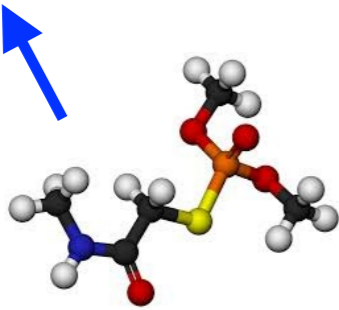
Space-Time ↔ **Matter**

Theory of GENERAL RELATIVITY (Einstein, 1915)

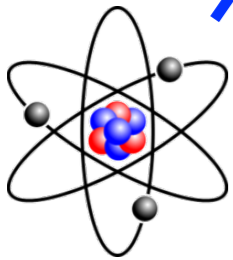
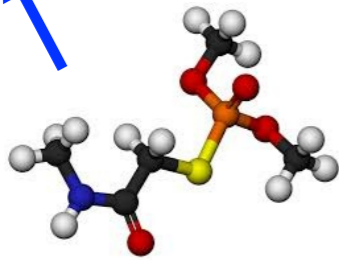
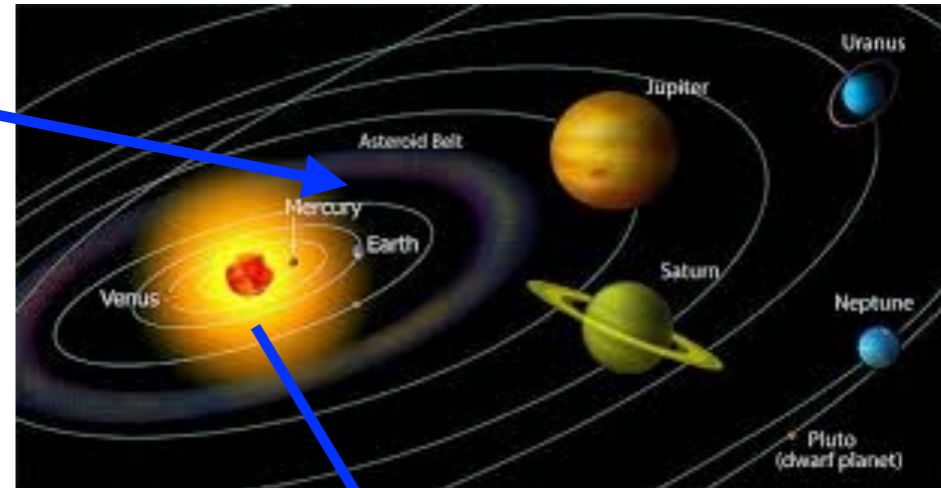
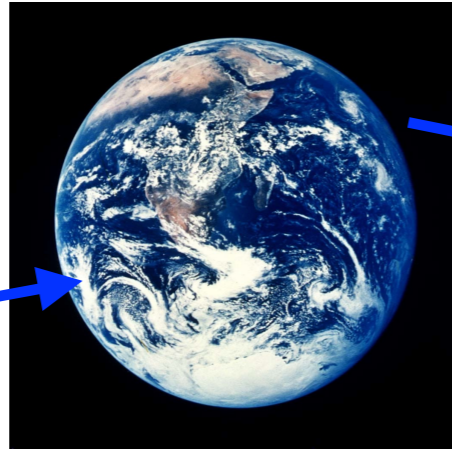
GENERAL RELATIVITY = THEORY of GRAVITY



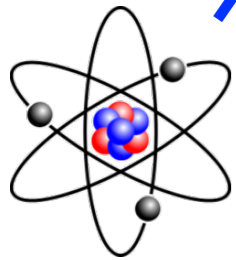
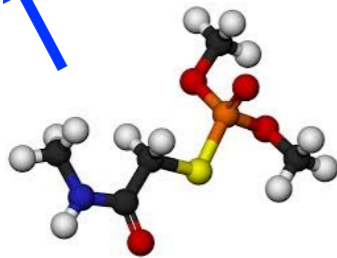
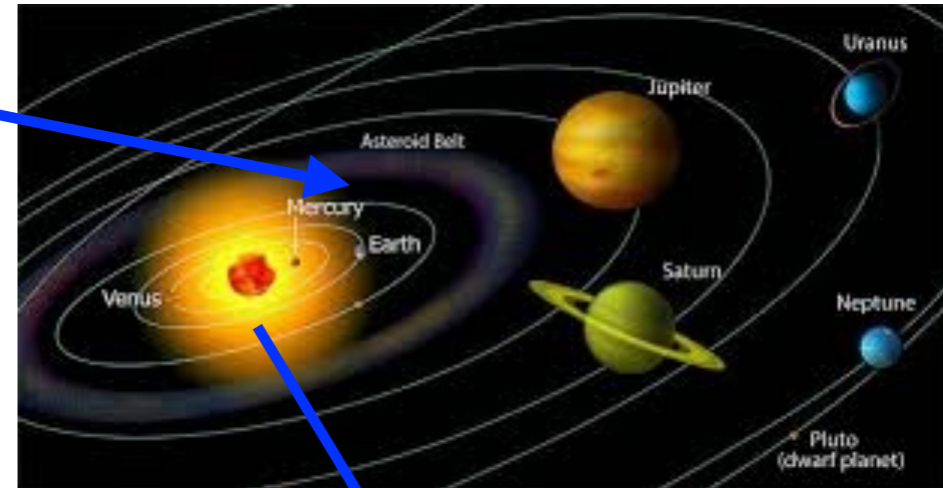
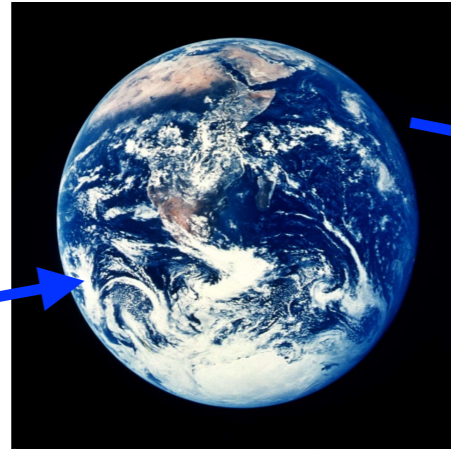
UNiVERSE = Space Containing all Matter



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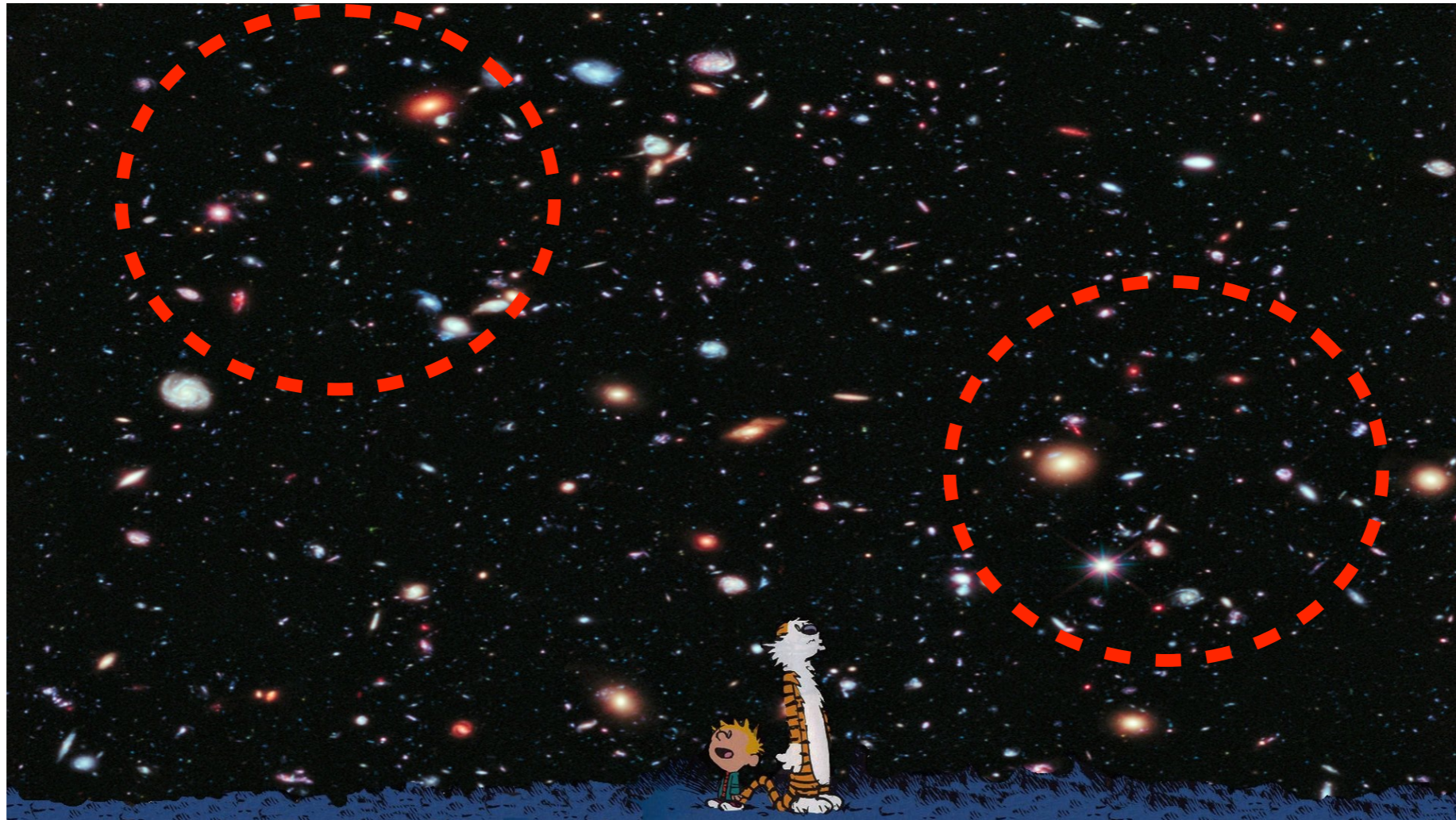
UNiVERSE = Space Containing all Matter



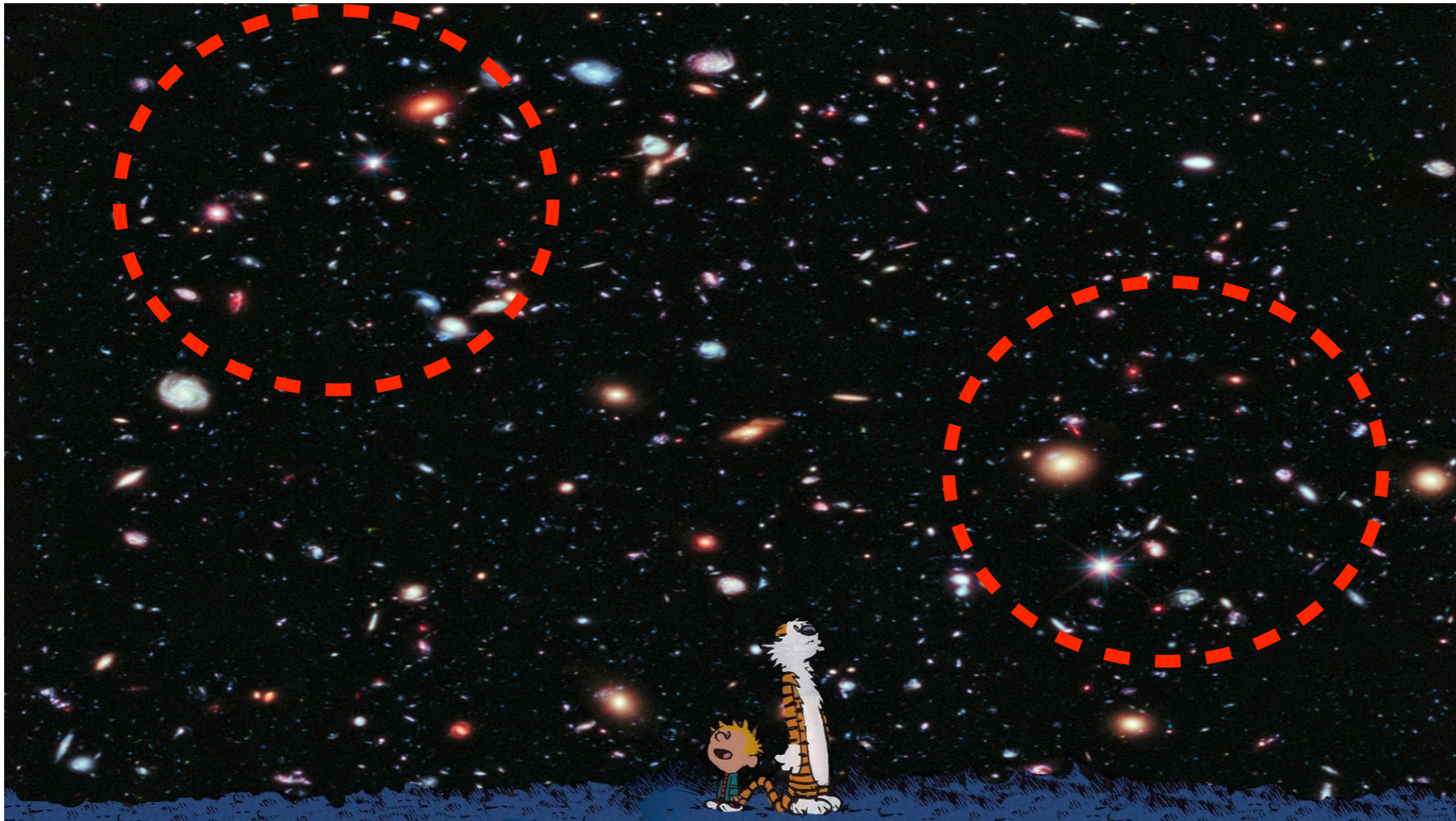
¿ UNiVERSE at LARGE SCALES ?



¿ UNiVERSE at LARGE SCALES ?

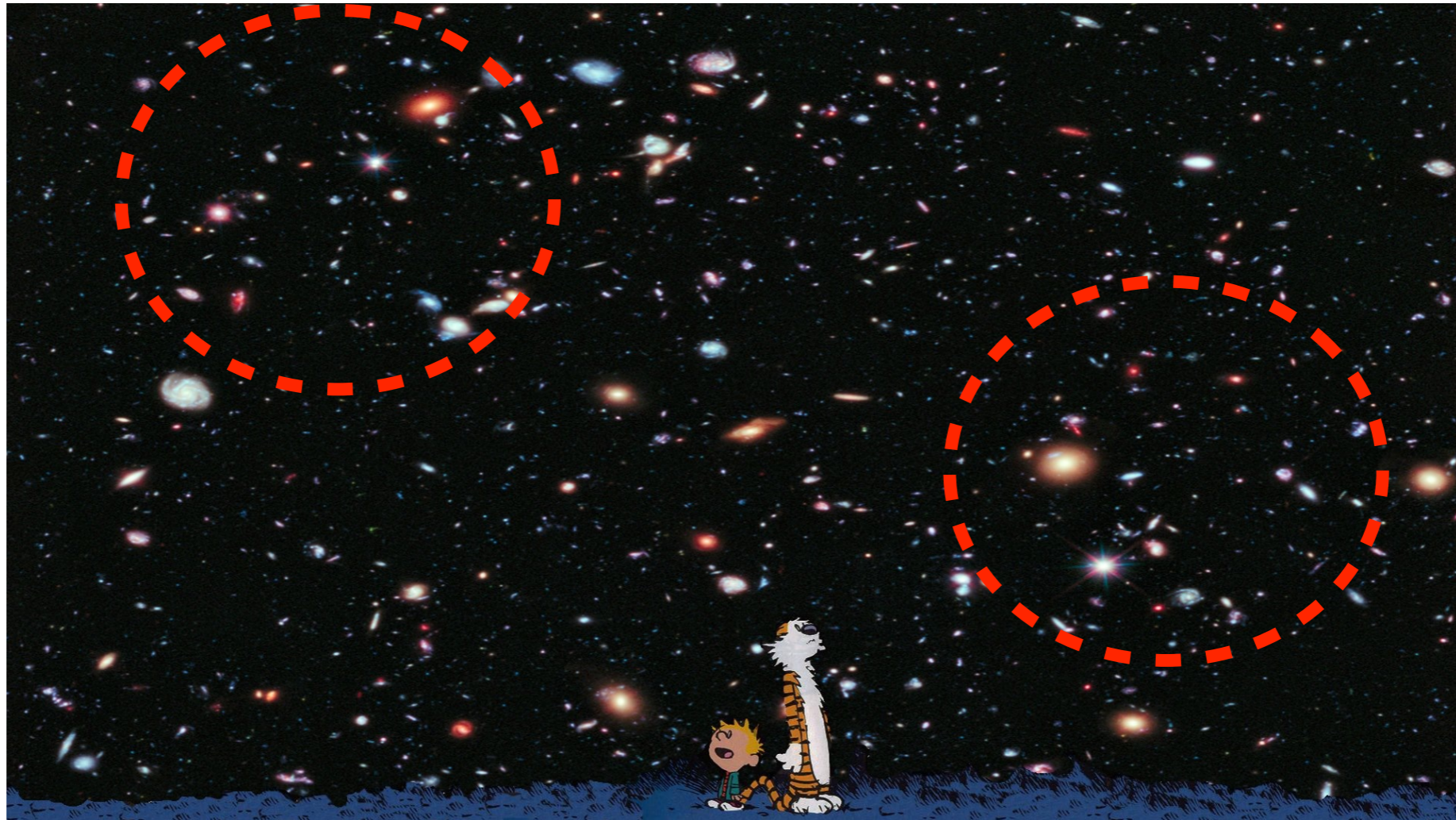


¿ UNiVERSE at LARGE SCALES ?



Cosmological Principle:
HOMOGENEOUS and ISOTROPIC

¿ UNiVERSE at LARGE SCALES ?

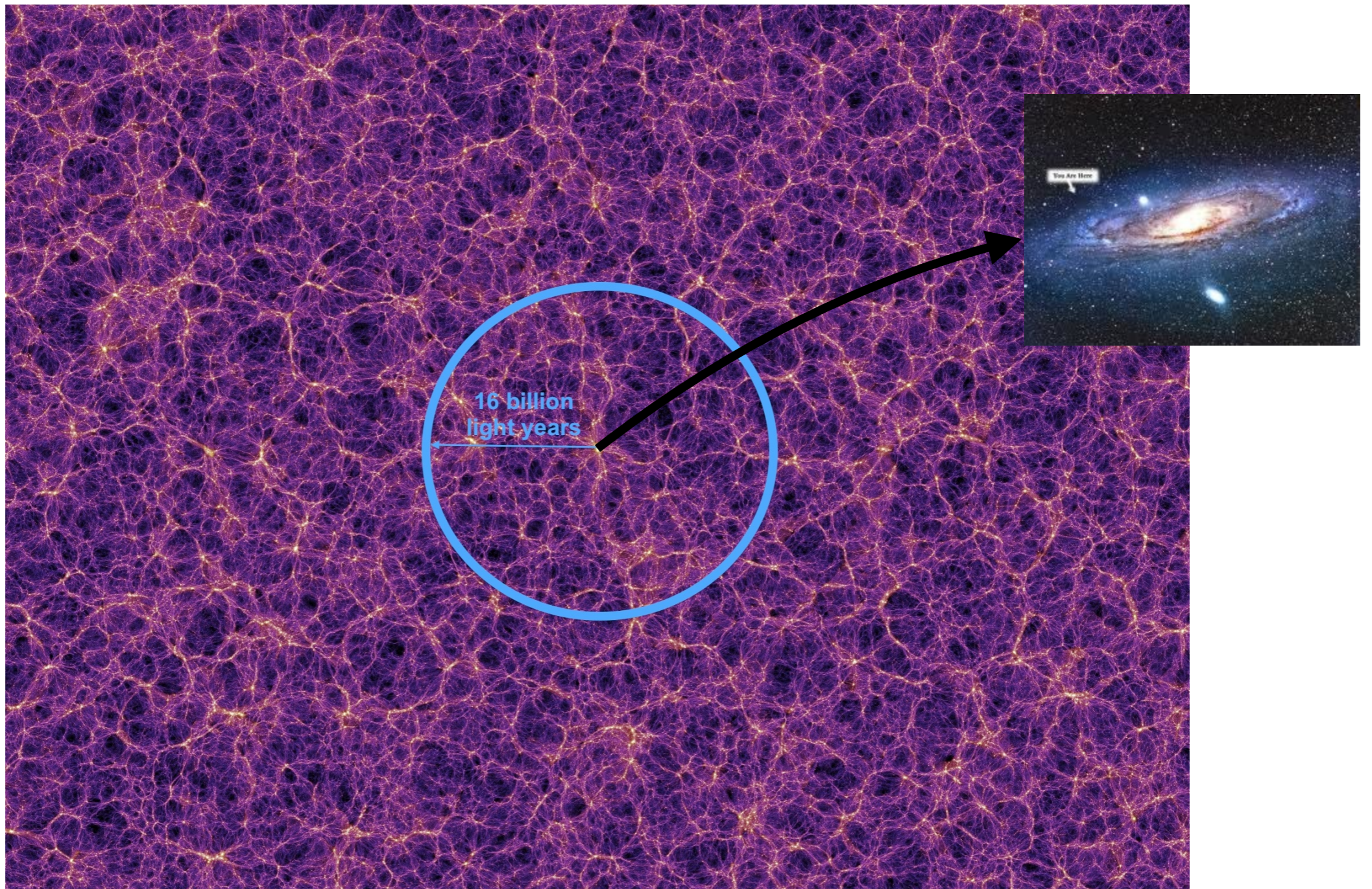


Cosmological Principle:
HOMOGENEOUS and ISOTROPIC

←
SAME EVERYWHERE !

←
SAME IN EVERY DIRECTION !

HOMOGENEOUS and ISOTROPIC

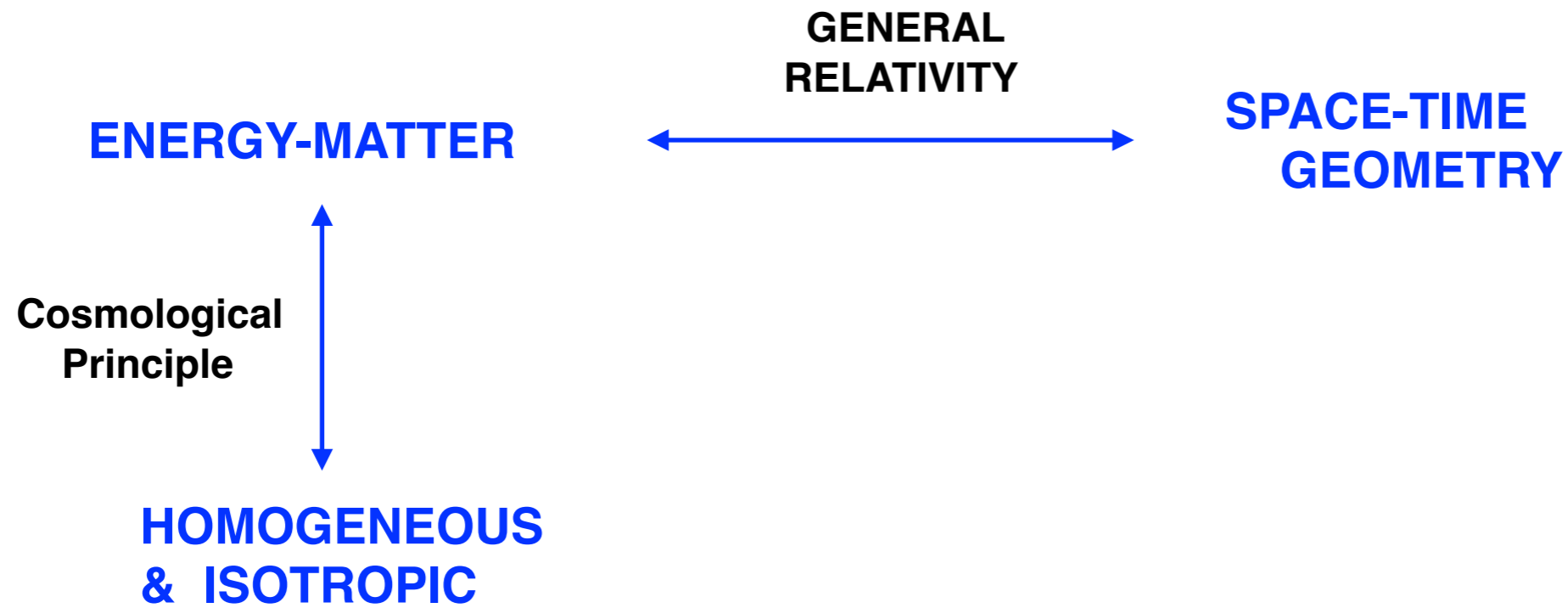


(Milkenium Simulation)

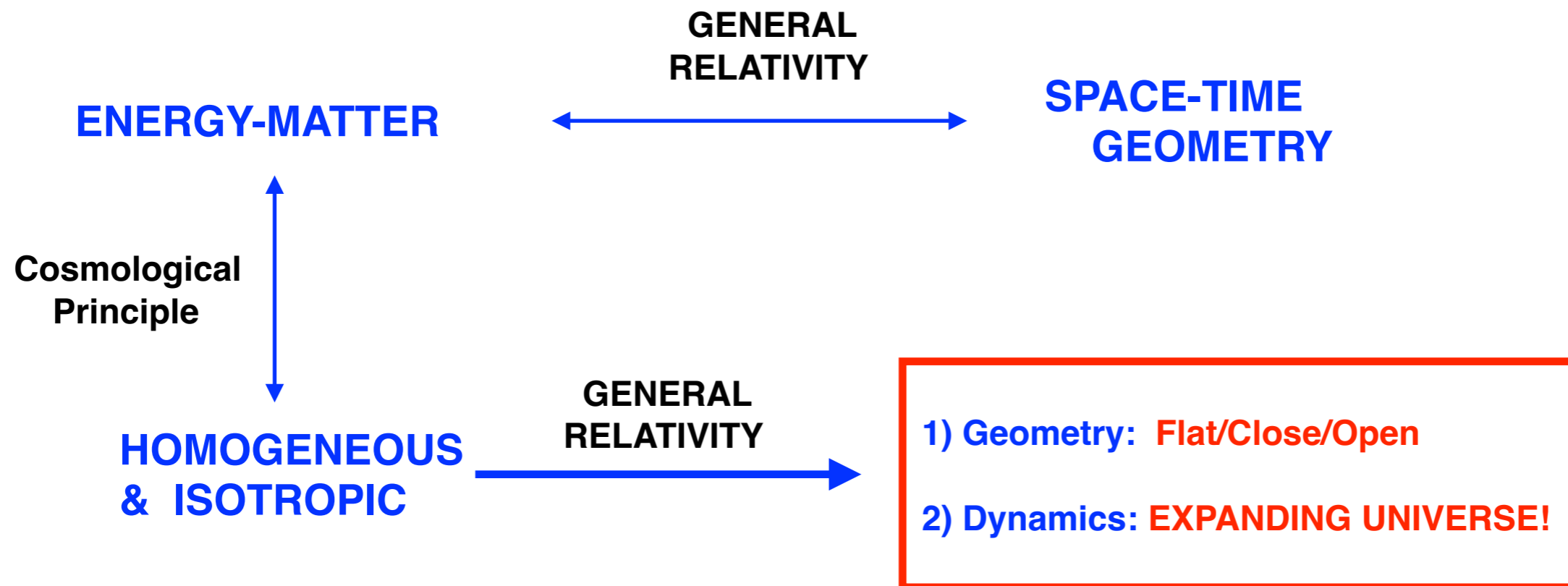
UNiVERSE: HOMOGENEOUS and iSOTROPiC



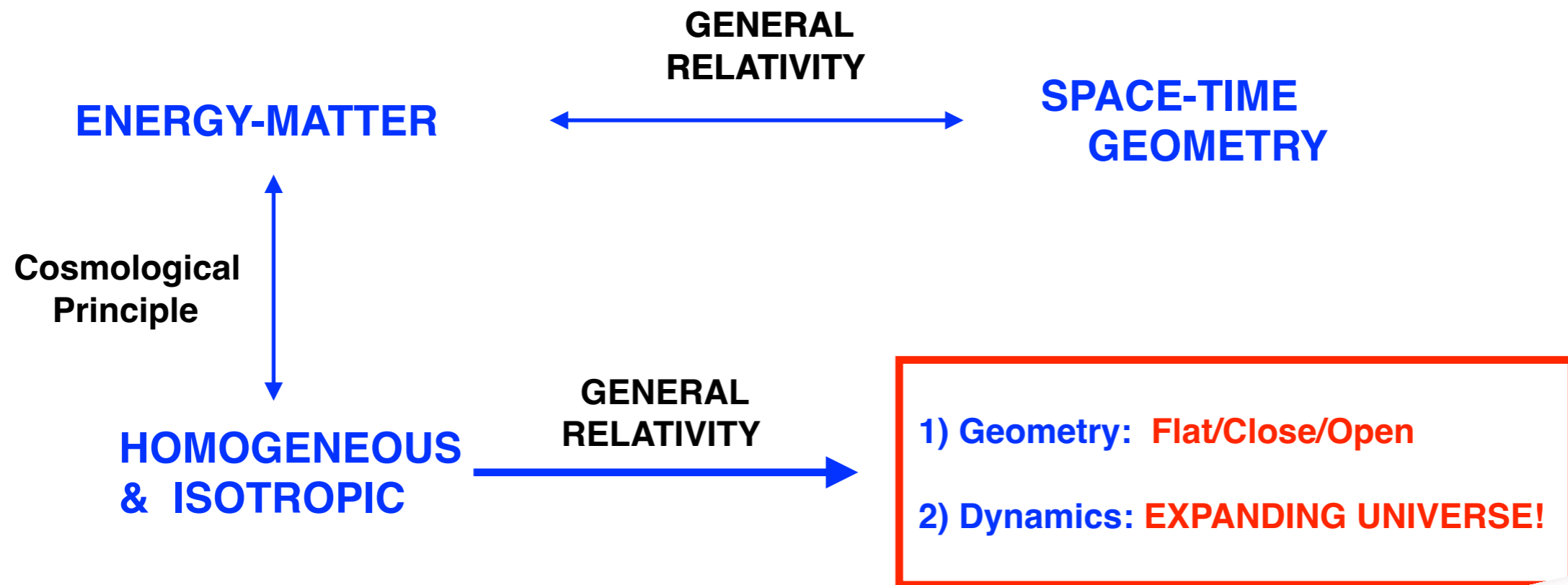
UNiVERSE: HOMOGENEOUS and iSOTROPiC



UNiVERSE: HOMOGENEOUS and iSOTROPiC



UNiVERSE: HOMOGENEOUS and iSOTROPiC



**Theoretical Basis for
BIG BANG theory!**

UNiVERSE: HOMOGENEOUS and iSOTROPiC

BIG BANG THEORY:

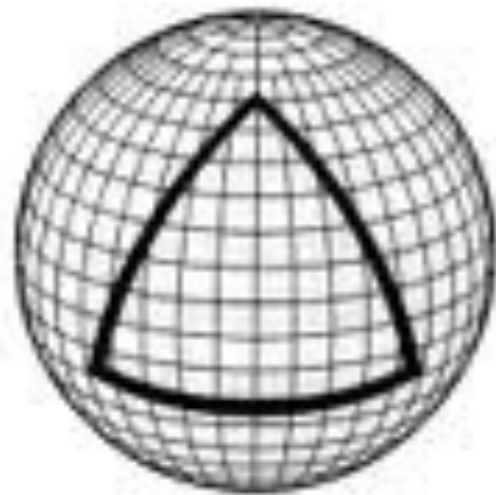
Geometry: Close/Open/Flat
Dynamics: EXPANDING Universe

UNiVERSE: HOMOGENEOUS and iSOTROPiC

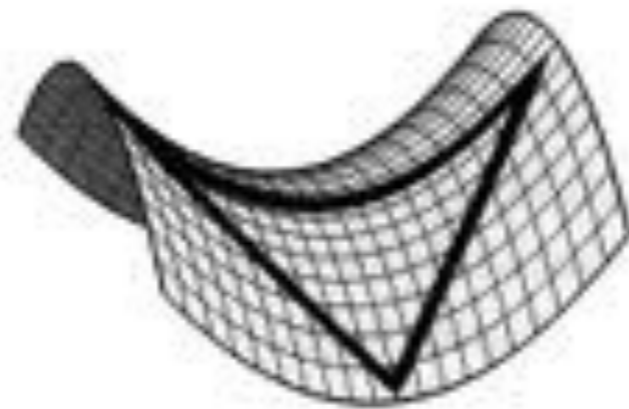
BIG BANG THEORY:

Geometry: Close/Open/Flat

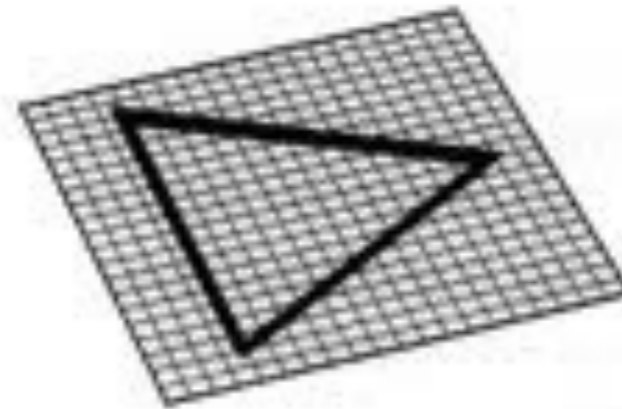
Dynamics: EXPANDING Universe



Positive Curvature



Negative Curvature



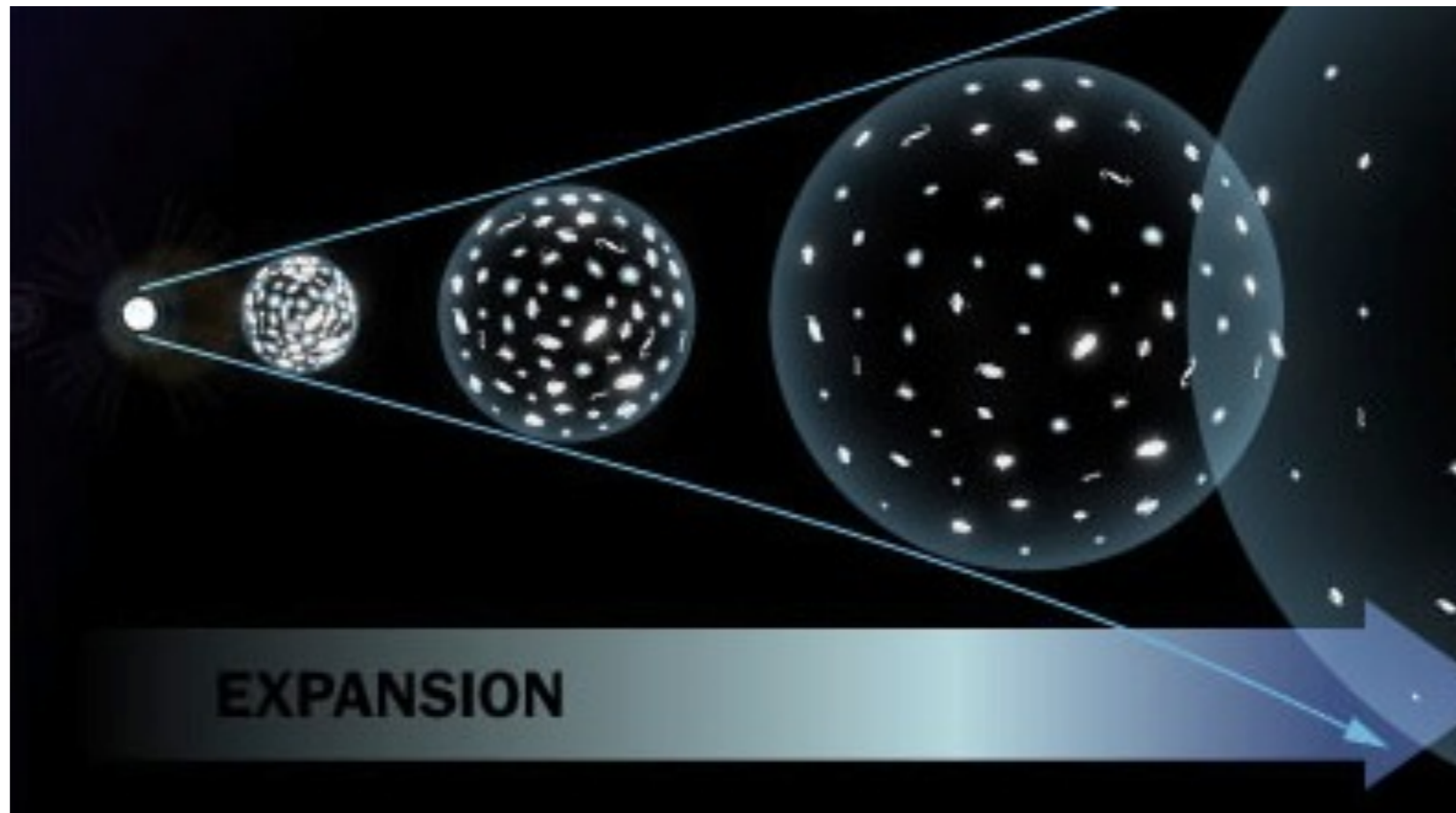
Flat Curvature

UNiVERSE: HOMOGENEOUS and iSOTROPiC

BIG BANG THEORY:

Geometry: Close/Open/Flat

Dynamics: EXPANDING Universe



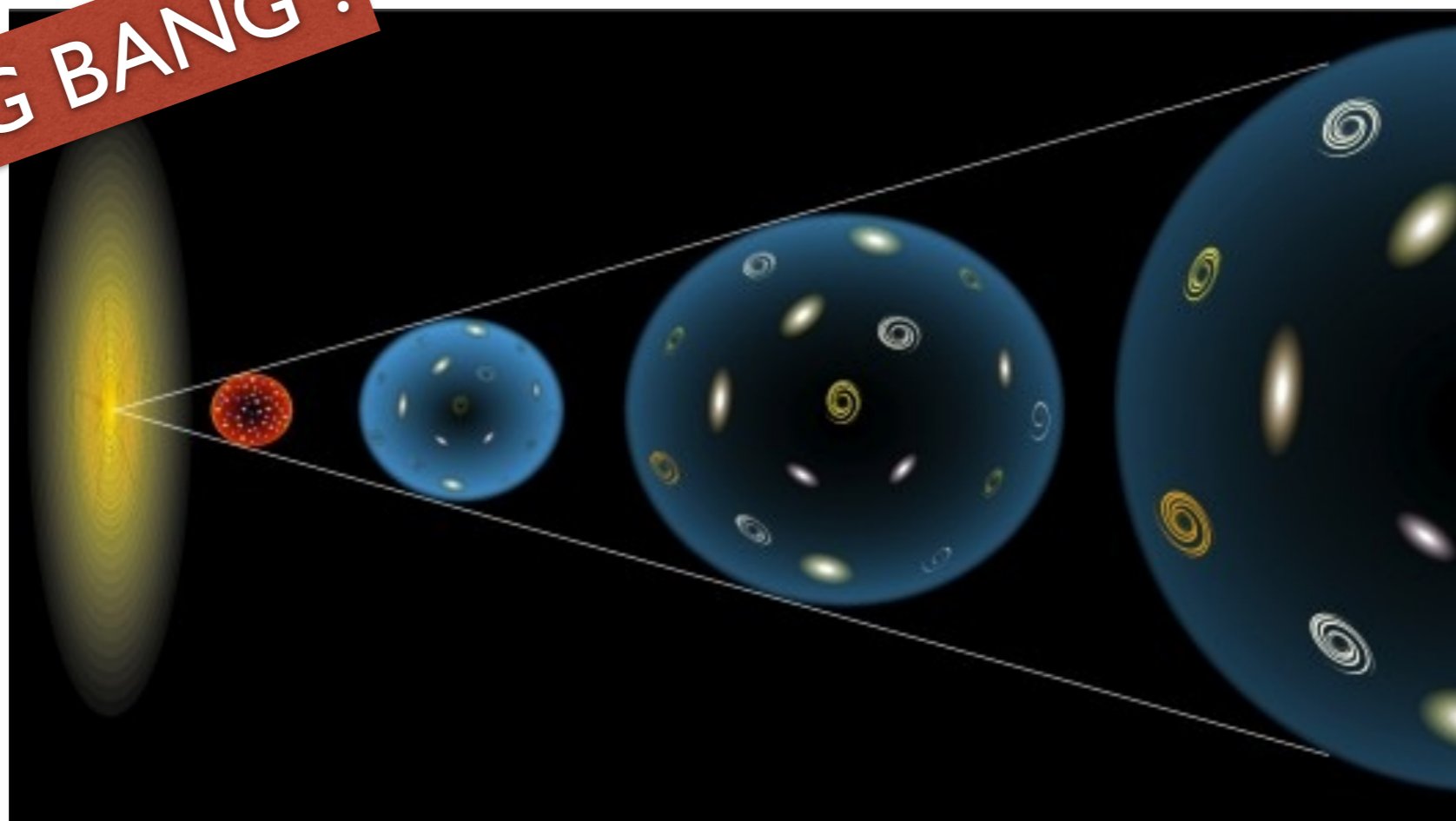
UNiVERSE: HOMOGENEOUS and iSOTROPiC

BIG BANG THEORY:

Geometry: Close/Open/Flat

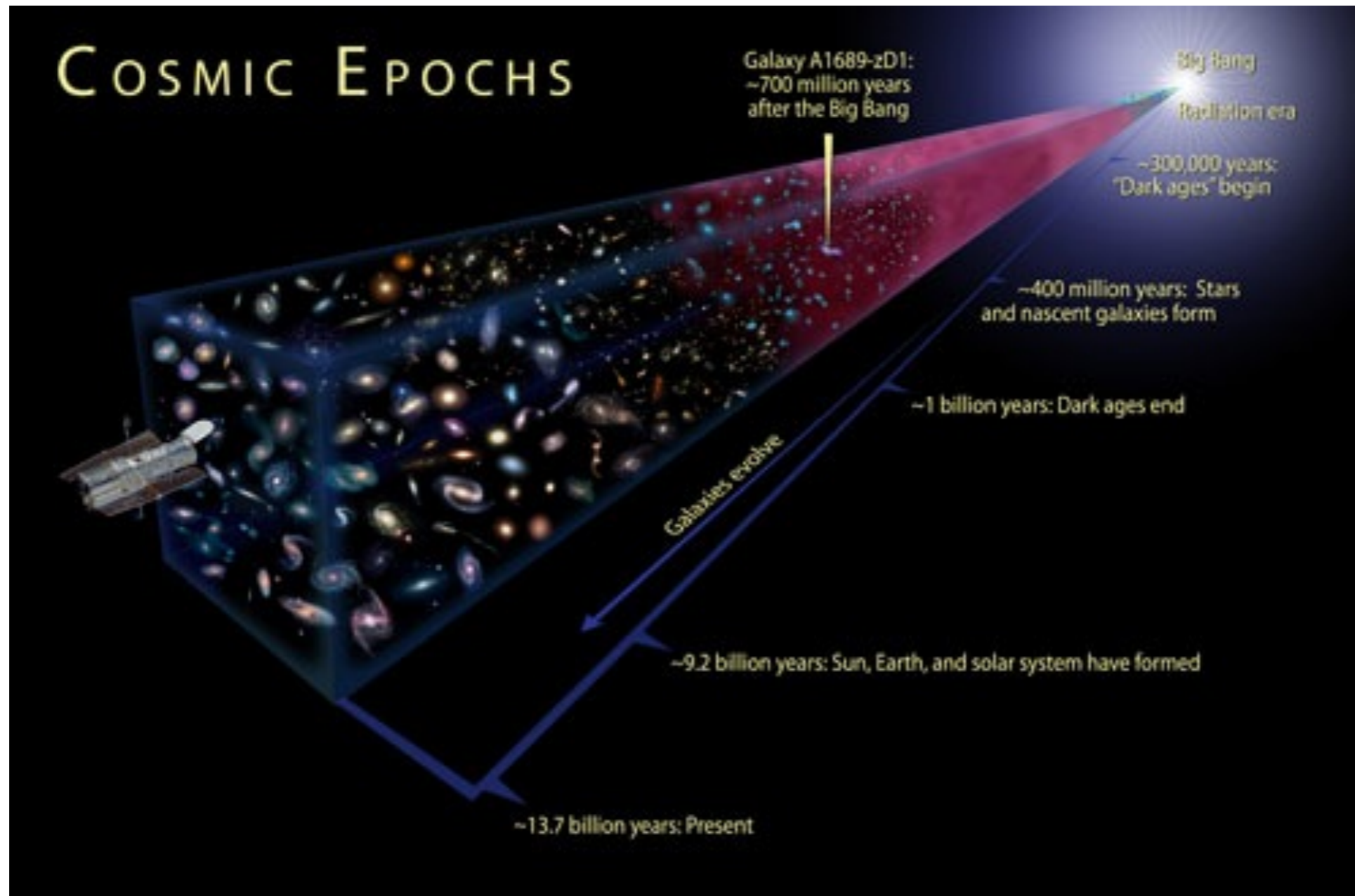
Dynamics: EXPANDING Universe

BIG BANG ?

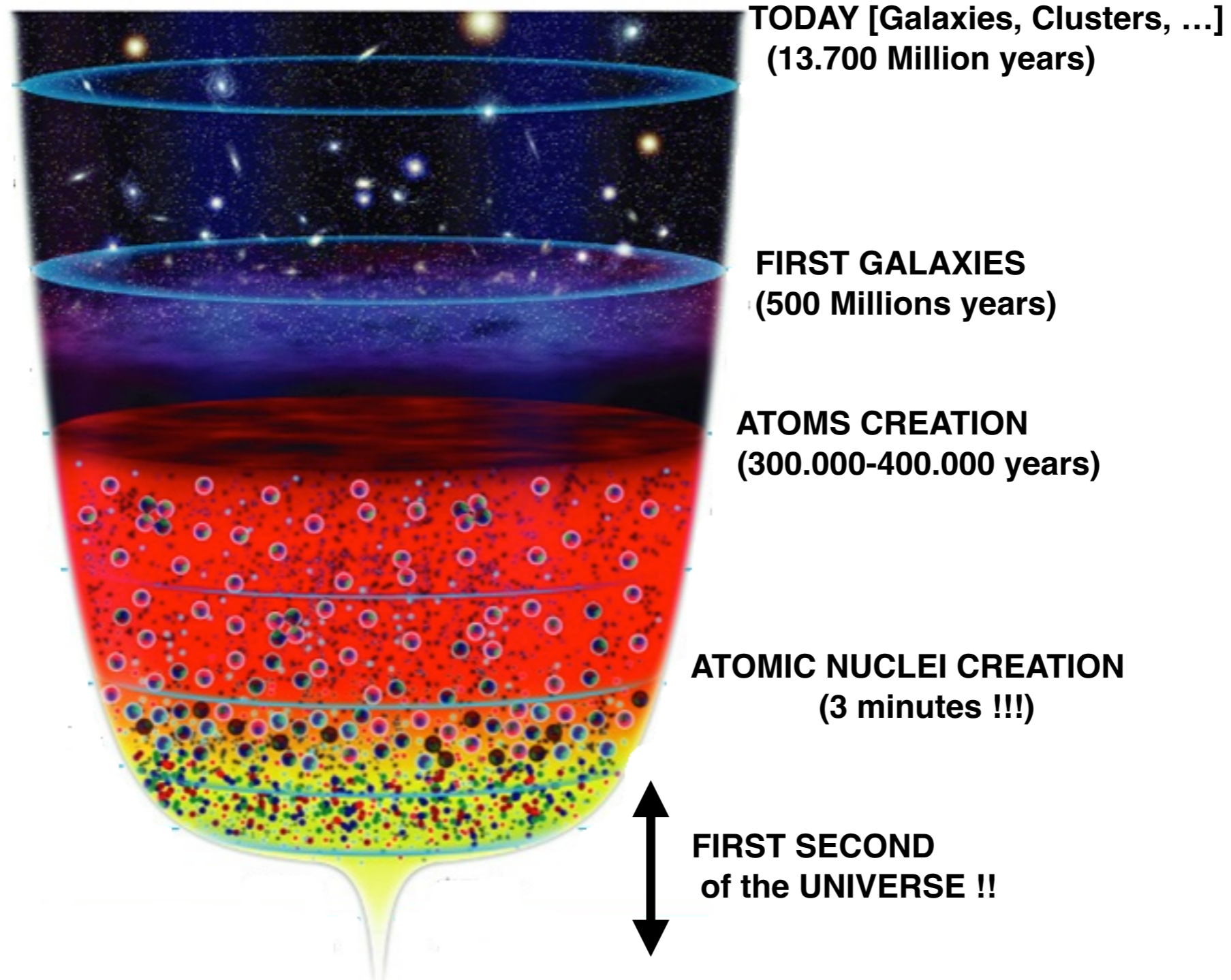


¿ $t = 0$?

COSMIC HISTORY of the UNiVERSE



COSMIC HISTORY of the UNiVERSE



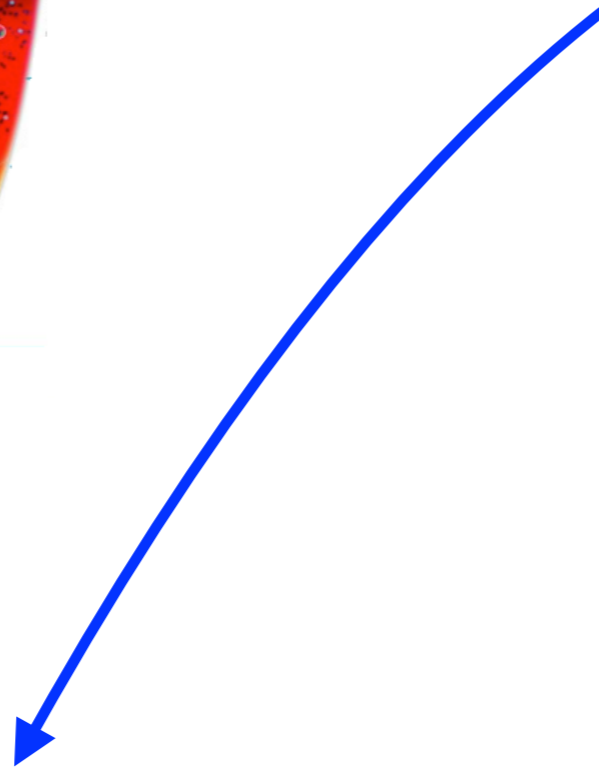
SUMMARY



**Universe
Homogeneous
&
Isotropic**



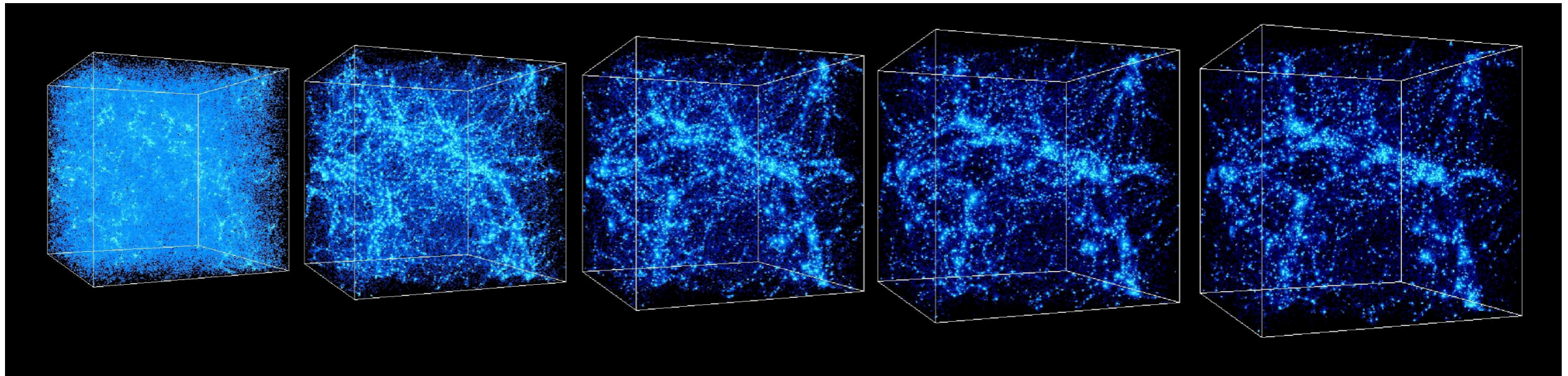
**Universe is
Expanding**
(Geom: Flat, Close,
Open)



Cosmic Epochs:

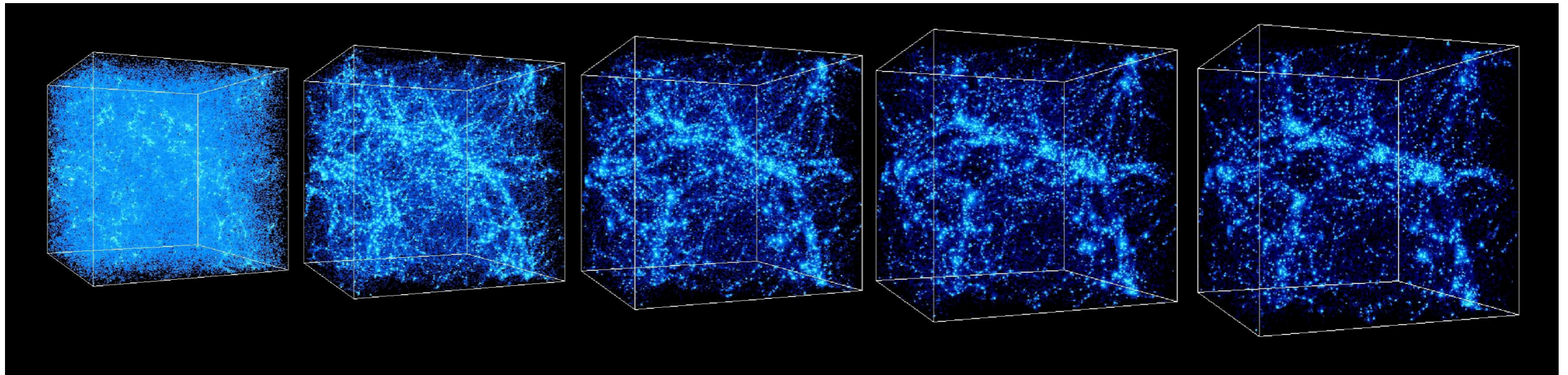
**Galaxy Formation,
Creation of Atoms,
Creation of atomic nuclei,
Creation of all elementary particles**

Cosmic Epochs: Galaxy Formation (500 Million



GAS of PARTICLES **Gravitational**
(homogeneous & isotropic) **Attraction** → **'Lumps'**

Cosmic Epochs: Galaxy Formation (500 Million



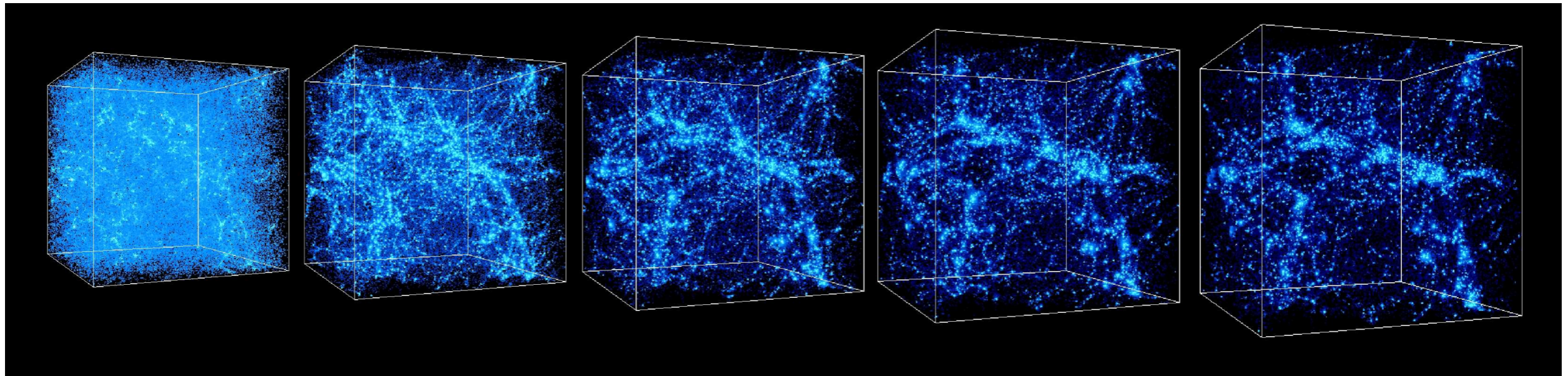
GAS of PARTICLES
(homogeneous & isotropic)

Gravitational
→
Attraction

'Lumps'

GALAXIES !

Cosmic Epochs: Galaxy Formation (500 Million



GAS of PARTICLES

~~homogeneous & isotropic~~

[not completely !]

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

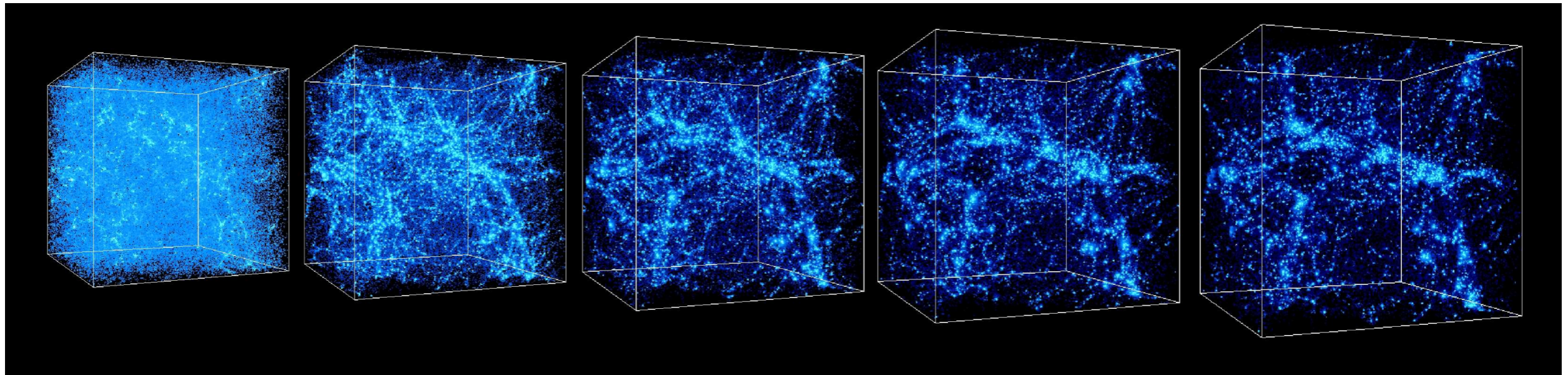
$$\delta\rho \sim \mathcal{O}(10^{-5})$$

**Gravitational
Attraction**

'Lumps'

GALAXIES !

Cosmic Epochs: Galaxy Formation (500 Million



GAS of PARTICLES

~~homogeneous & isotropic~~

[not completely !]

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

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

**Gravitational
Attraction**

'Lumps'

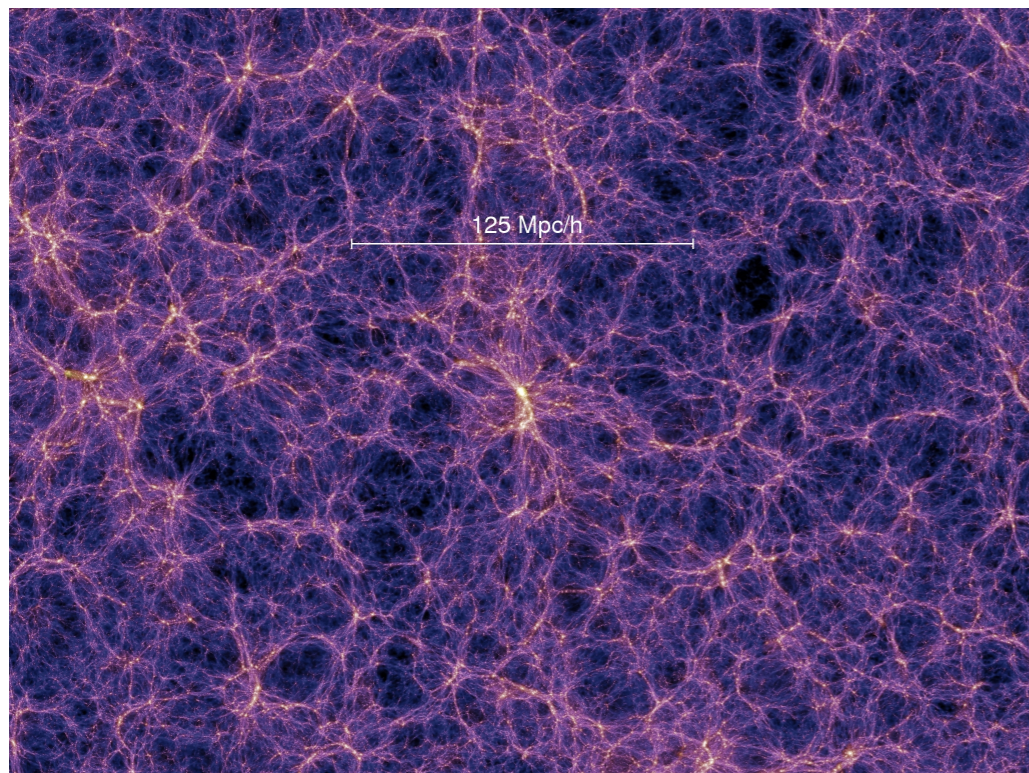
GALAXIES !

$$(\delta\rho \gg 1)$$

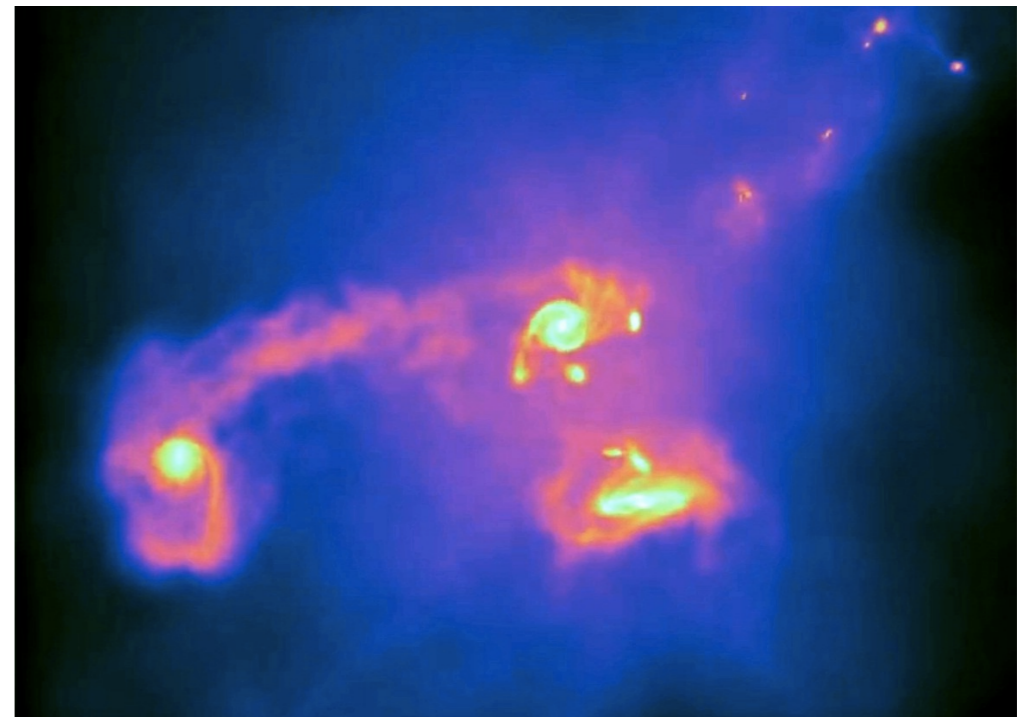
Gravitational Attraction

LARGE SCALE STRUCTURE of the UNIVERSE

MILLENNIUM Simulations

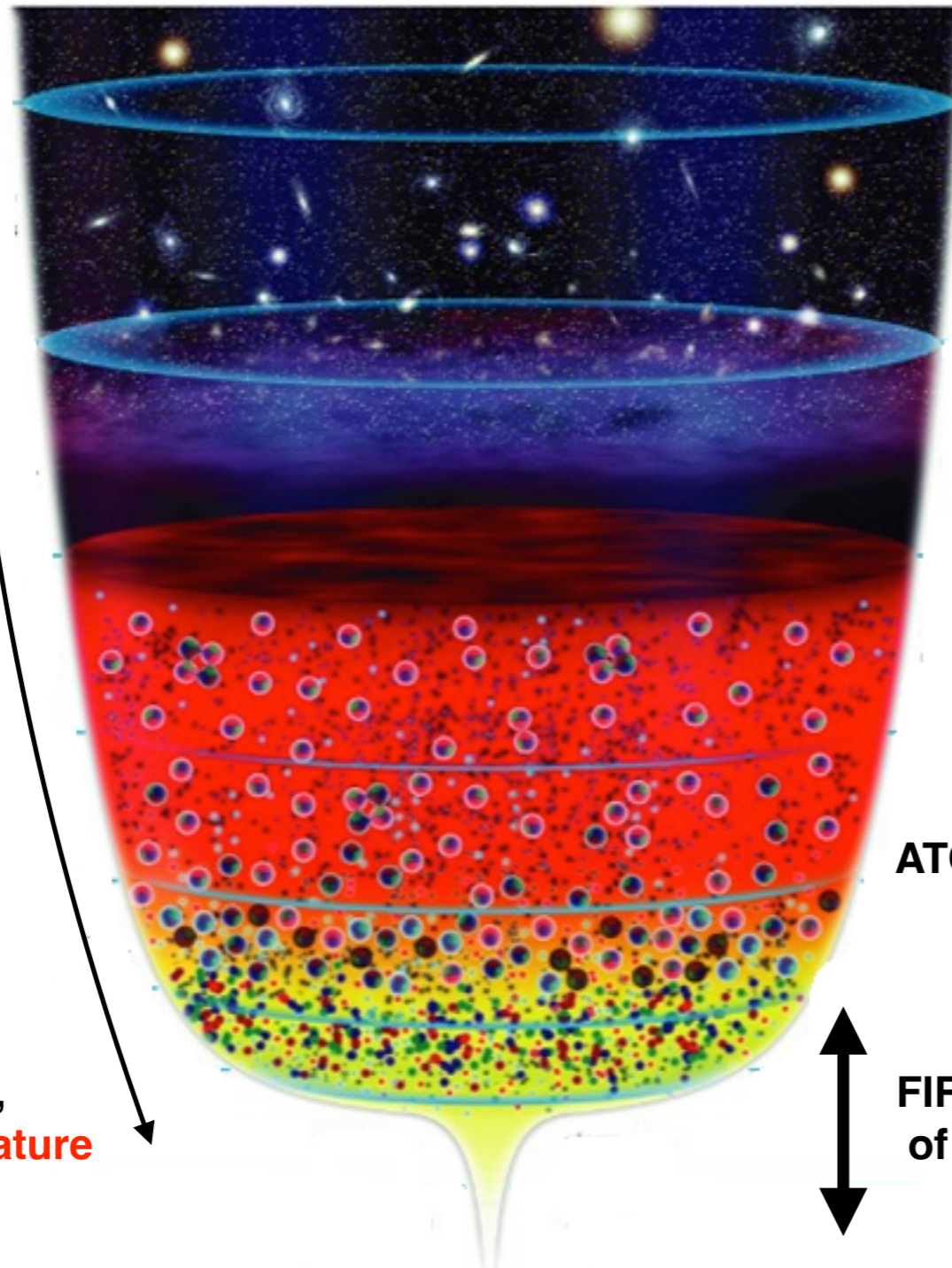


AREPO Simulations



COSMIC HISTORY of the UNiVERSE

BiGGER size,
SMALLER Temp



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

FIRST GALAXIES
(500 Millions years)

ATOMS CREATION
(300.000-400.000 years)

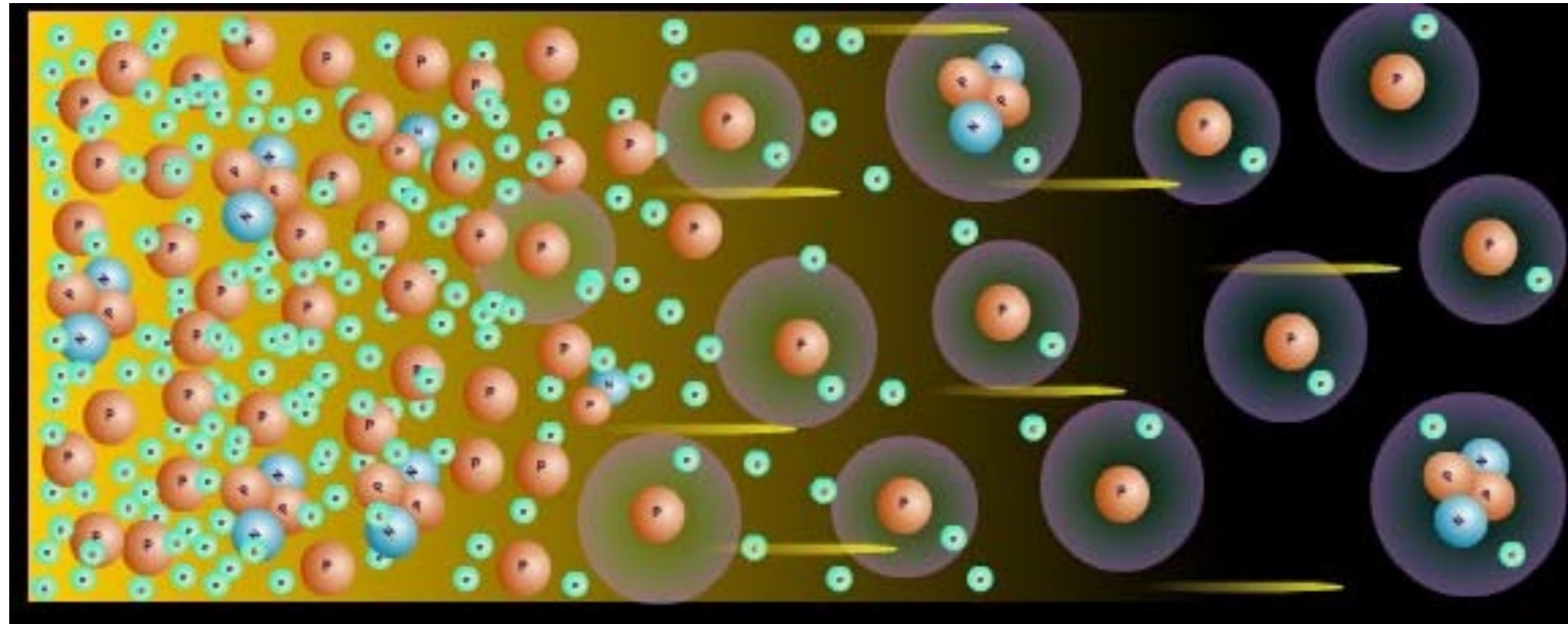
ATOMIC NUCLEI CREATION
(3 minutes !!!)

FIRST SECOND
of the UNIVERSE !!

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...

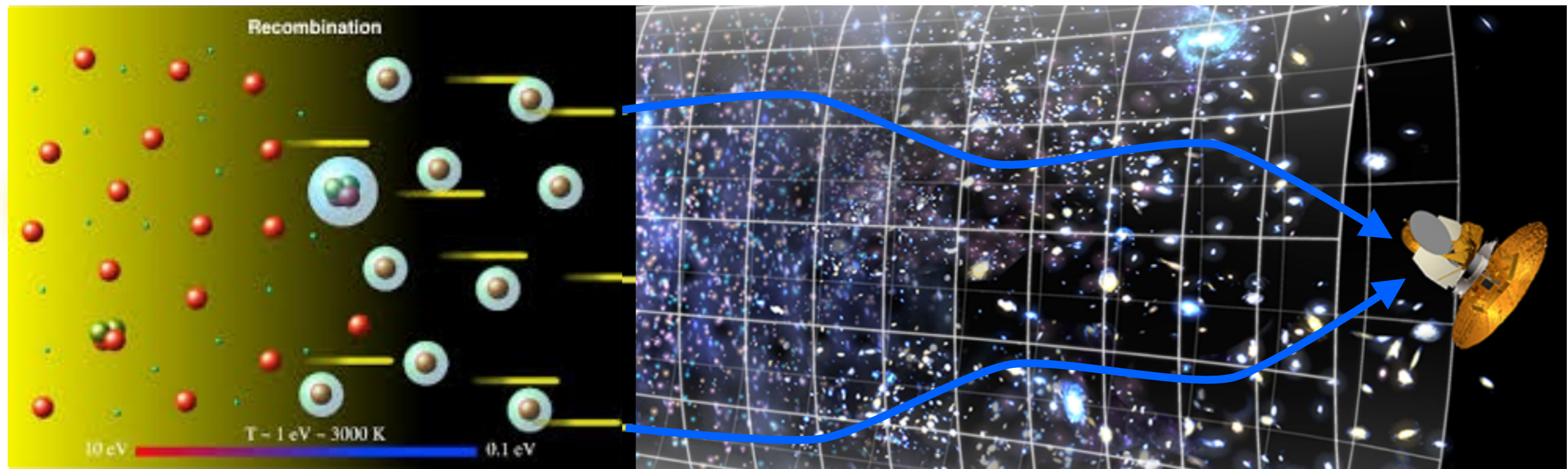
... Photons **do not** have enough
energy to break apart atoms,

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)

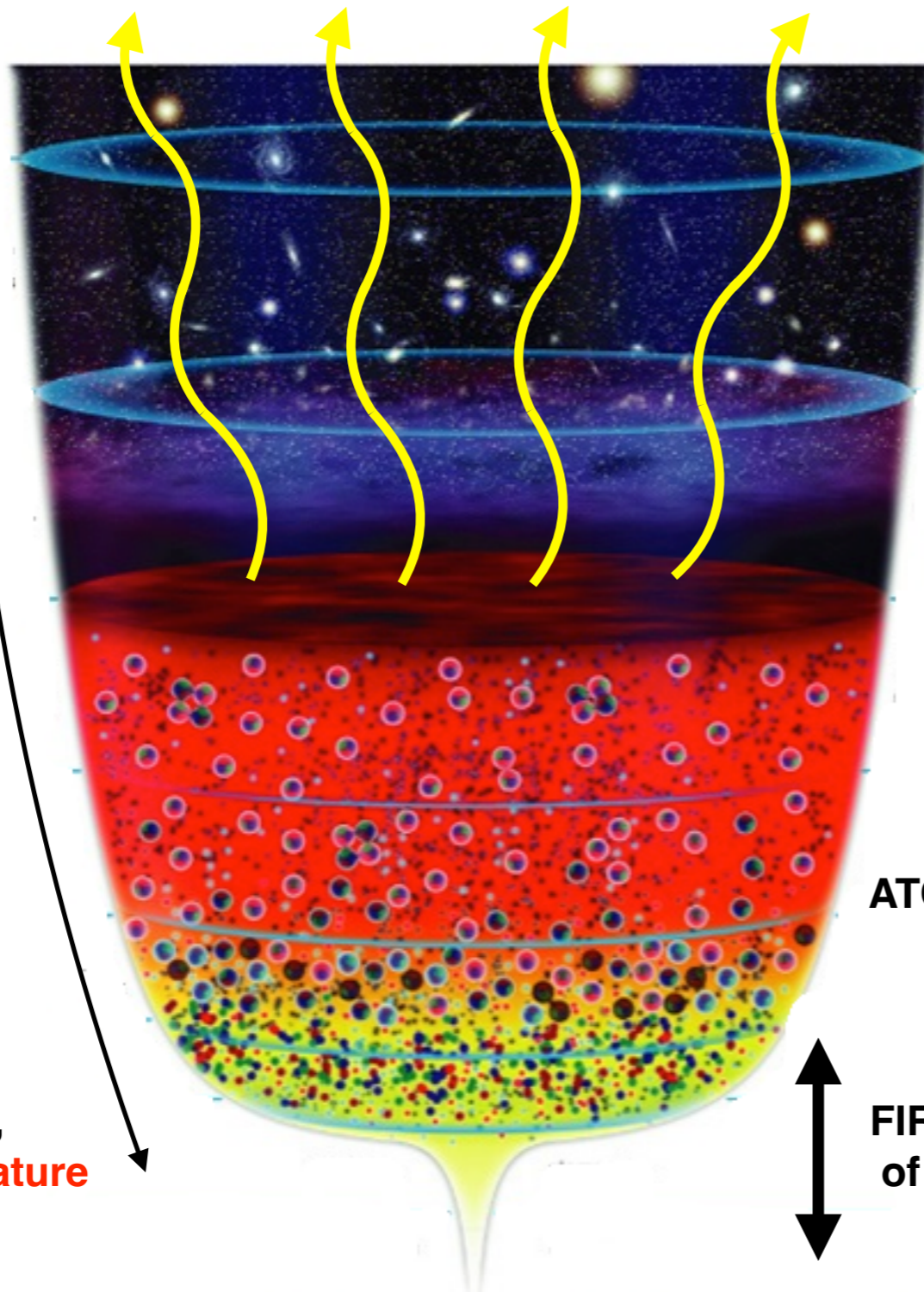


**Atom Formation: Free propagation of
(Recombination) light !!**

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

Where is that light?

BIGGER size,
SMALLER Temp



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

FIRST GALAXIES
(500 Millions years)

ATOMS FORMATION
(300.000-400.000 years)

ATOMIC NUCLEI FORMATION
(3 minutes !!!)

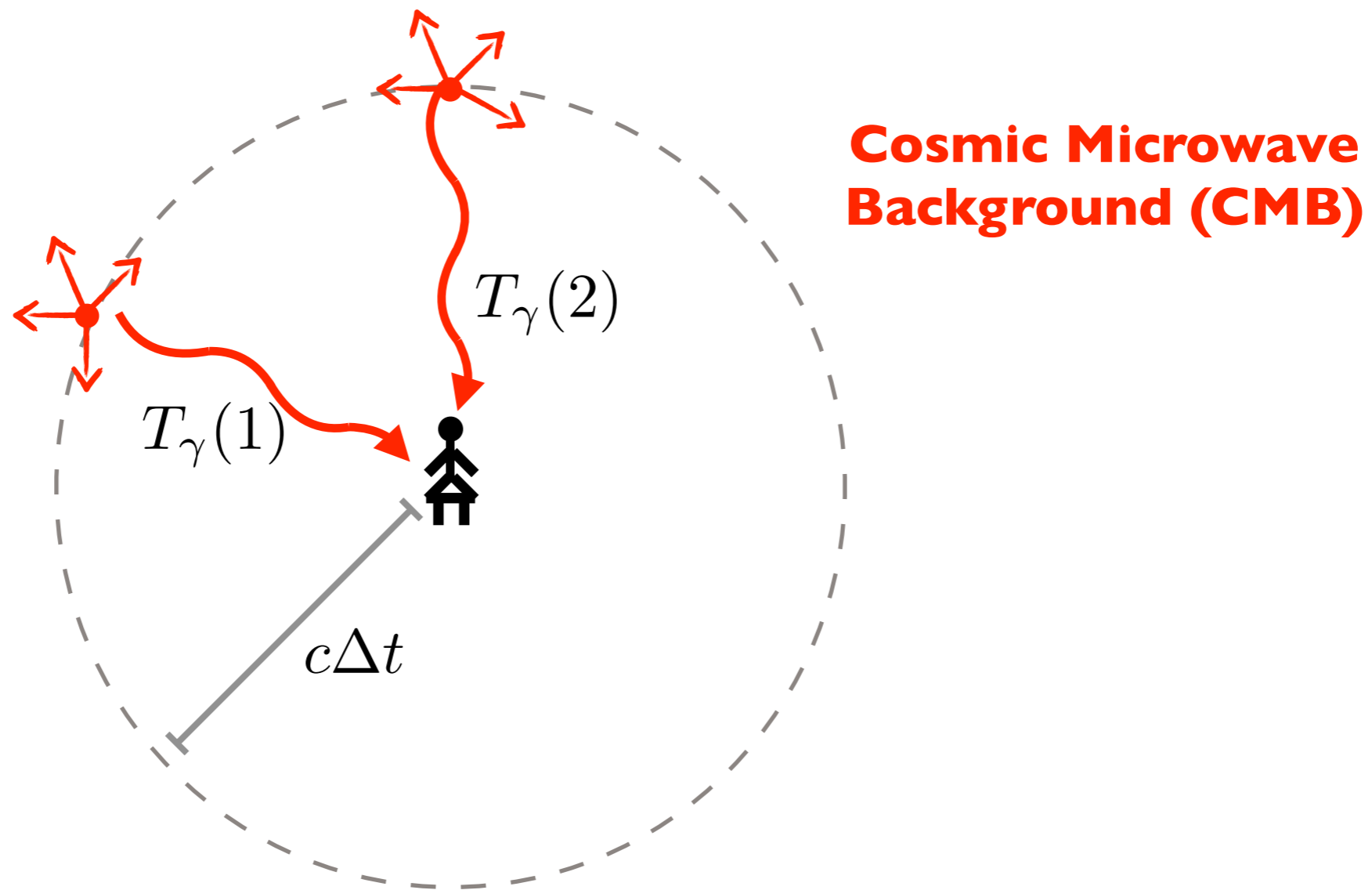
FIRST SECOND
of the UNIVERSE !!

**Emission of Cosmic
Microwave Radiation !**

SMALLER SIZE,
LARGER Temperature

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

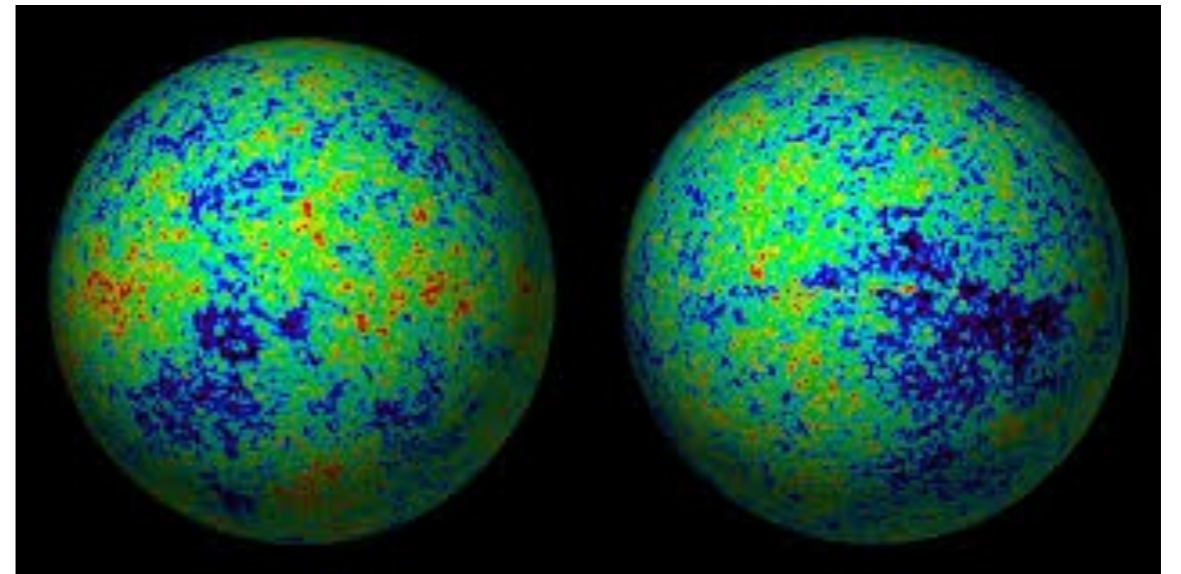
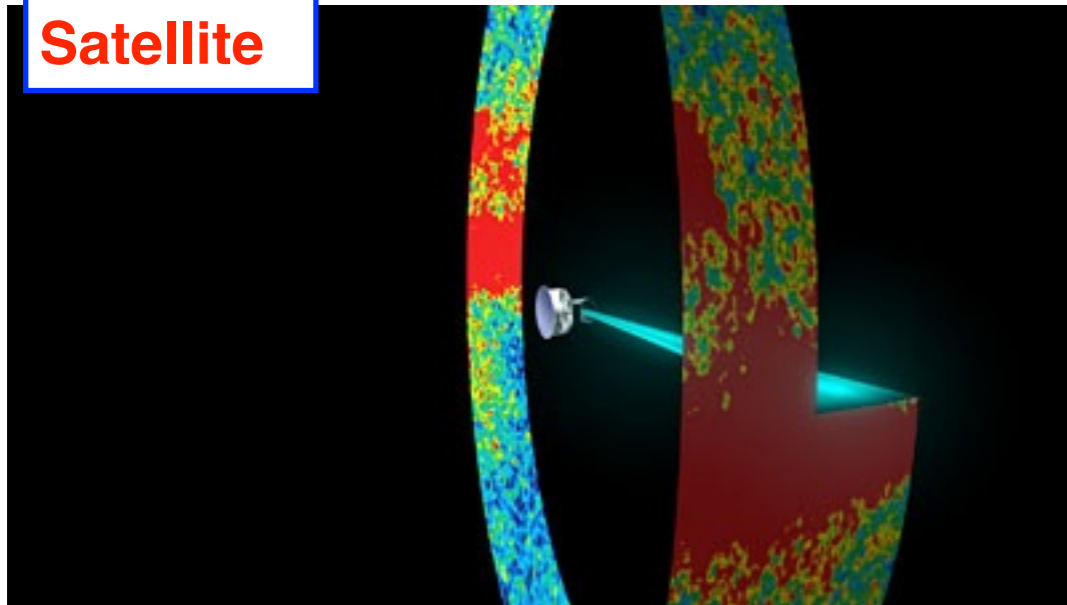
¿ Where is that light?



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

¿ Where is that light?

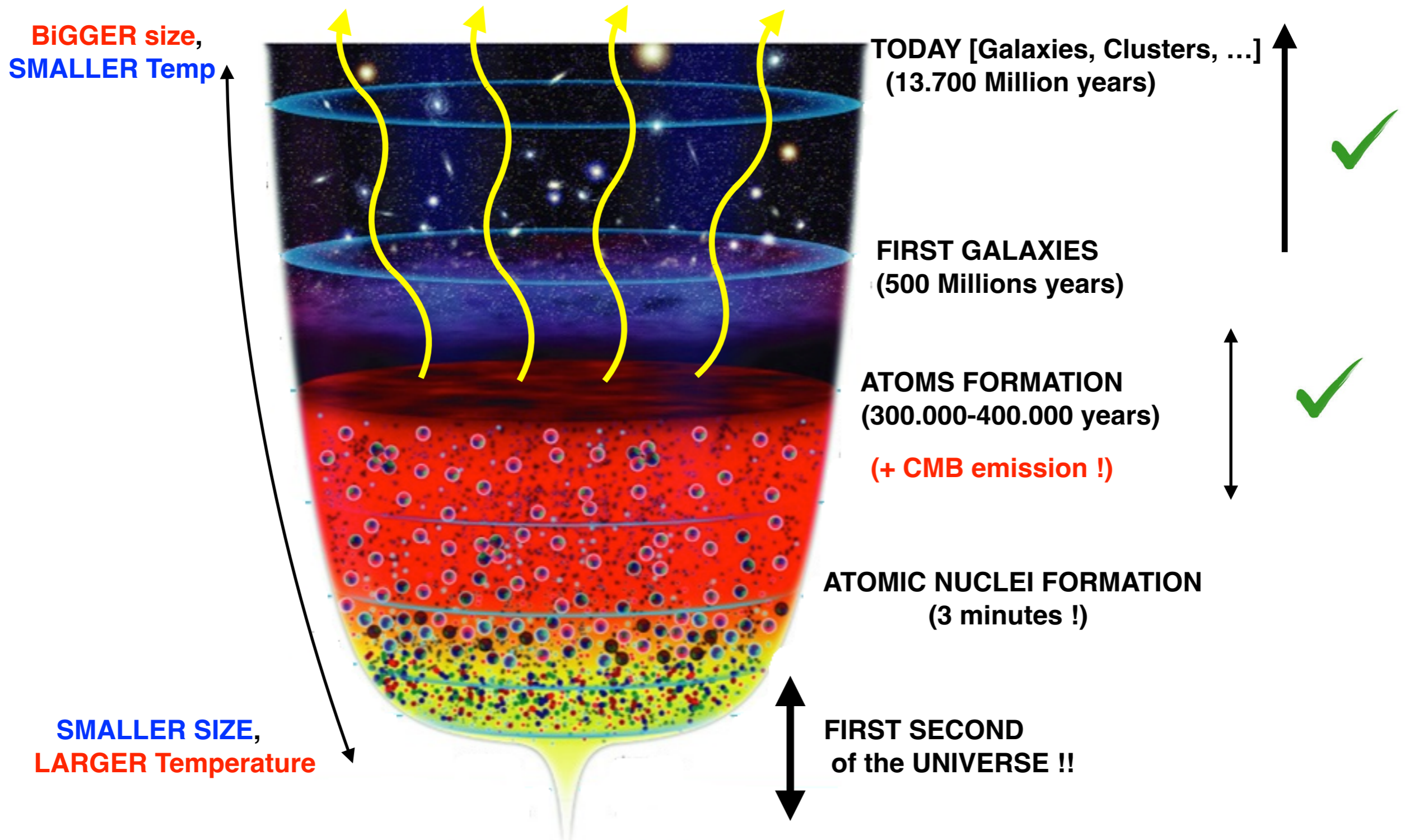
PLANCK
Satellite



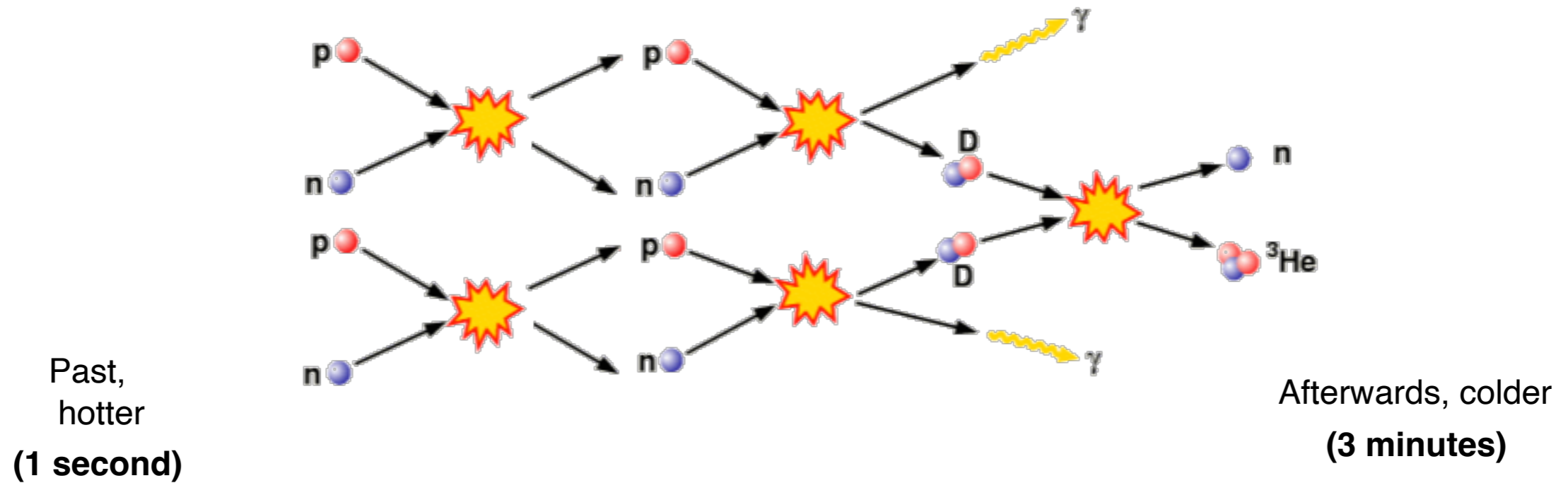
**Cosmic Microwave
Background (CMB)**

Definitive proof of
the Big Bang Theory!

COSMIC HISTORY of the UNiVERSE



Cosmic Epochs: Formation of atomic nuclei (3 mins)



**Protons,
Neutrons**

**Interact
strongly**

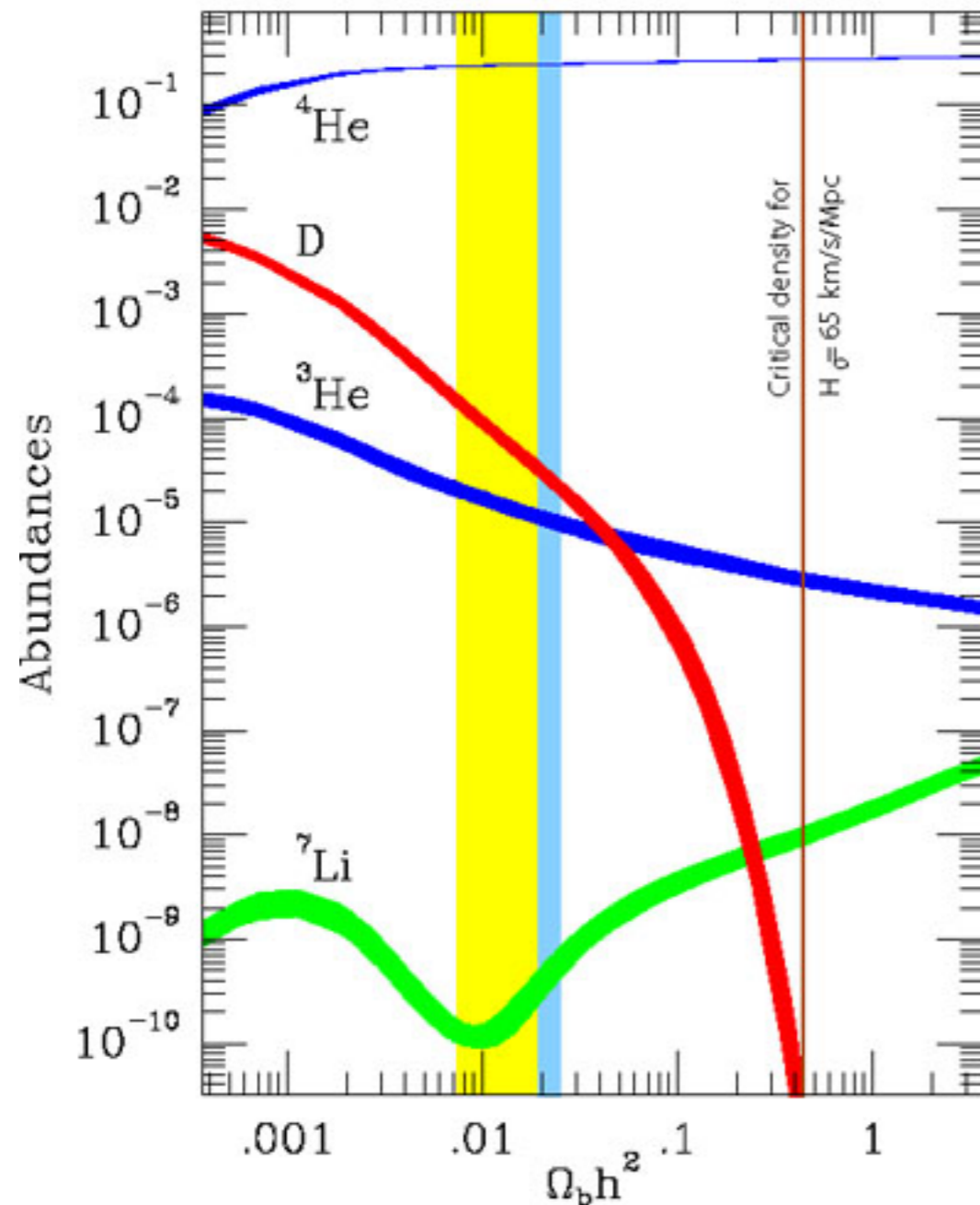
Universe cools down...

... 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)



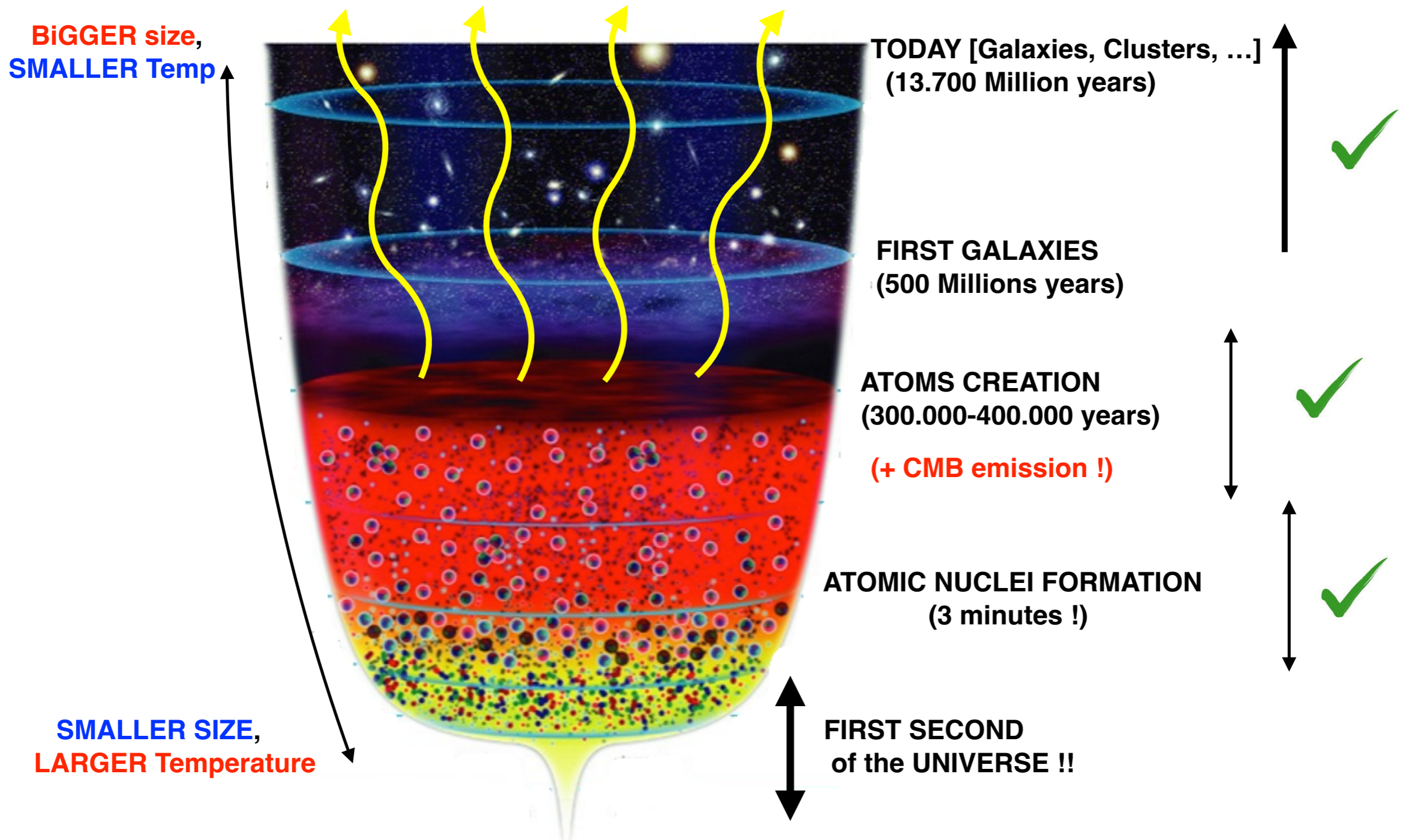
NUCLEAR PHYSICS
(measured in the lab)

Lets to predict abundances
of

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

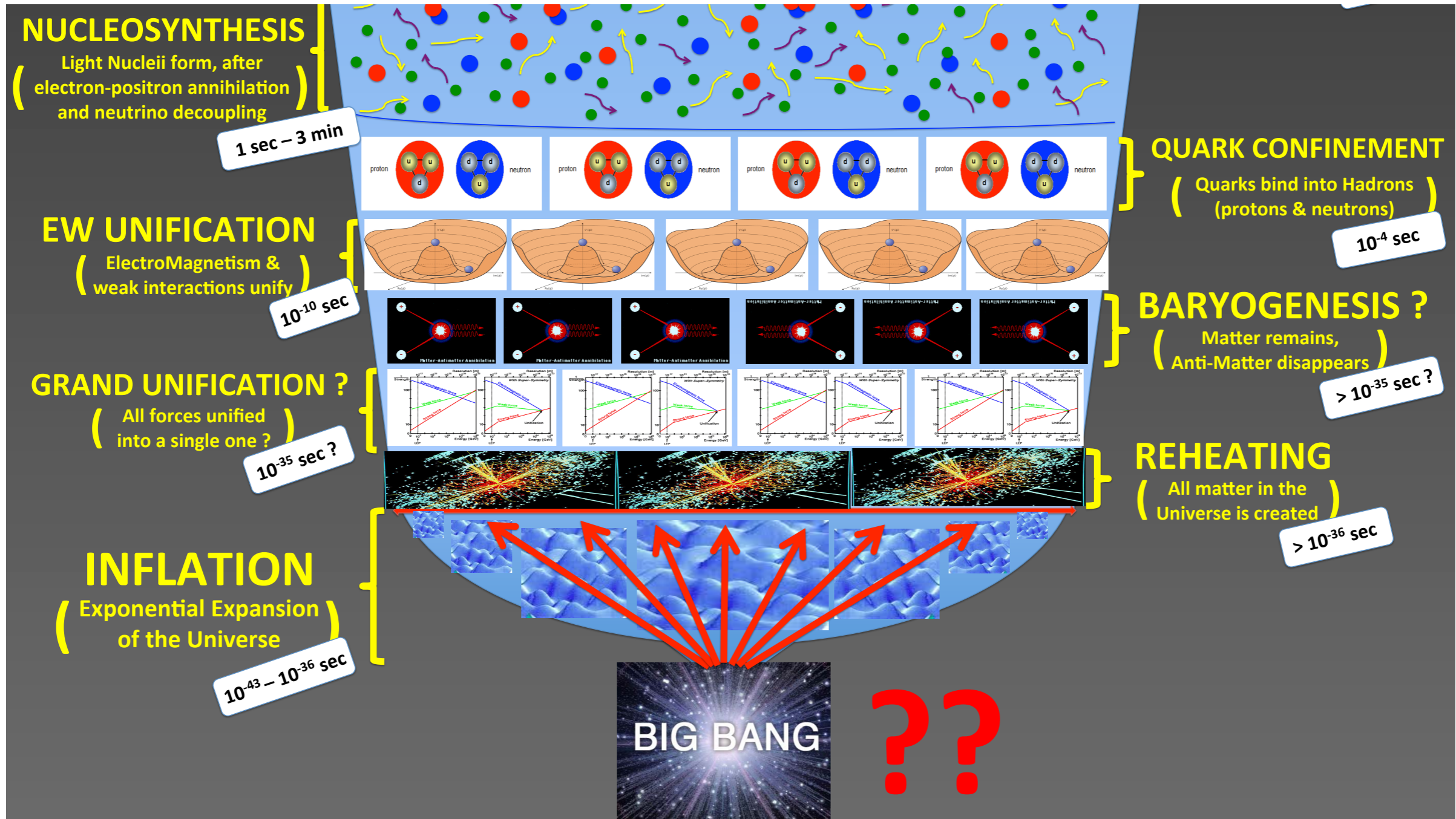
Another definitive proof
of the Big Bang theory !

COSMIC HISTORY of the UNiVERSE



Cosmic Epochs: The first Second of the Universe !

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



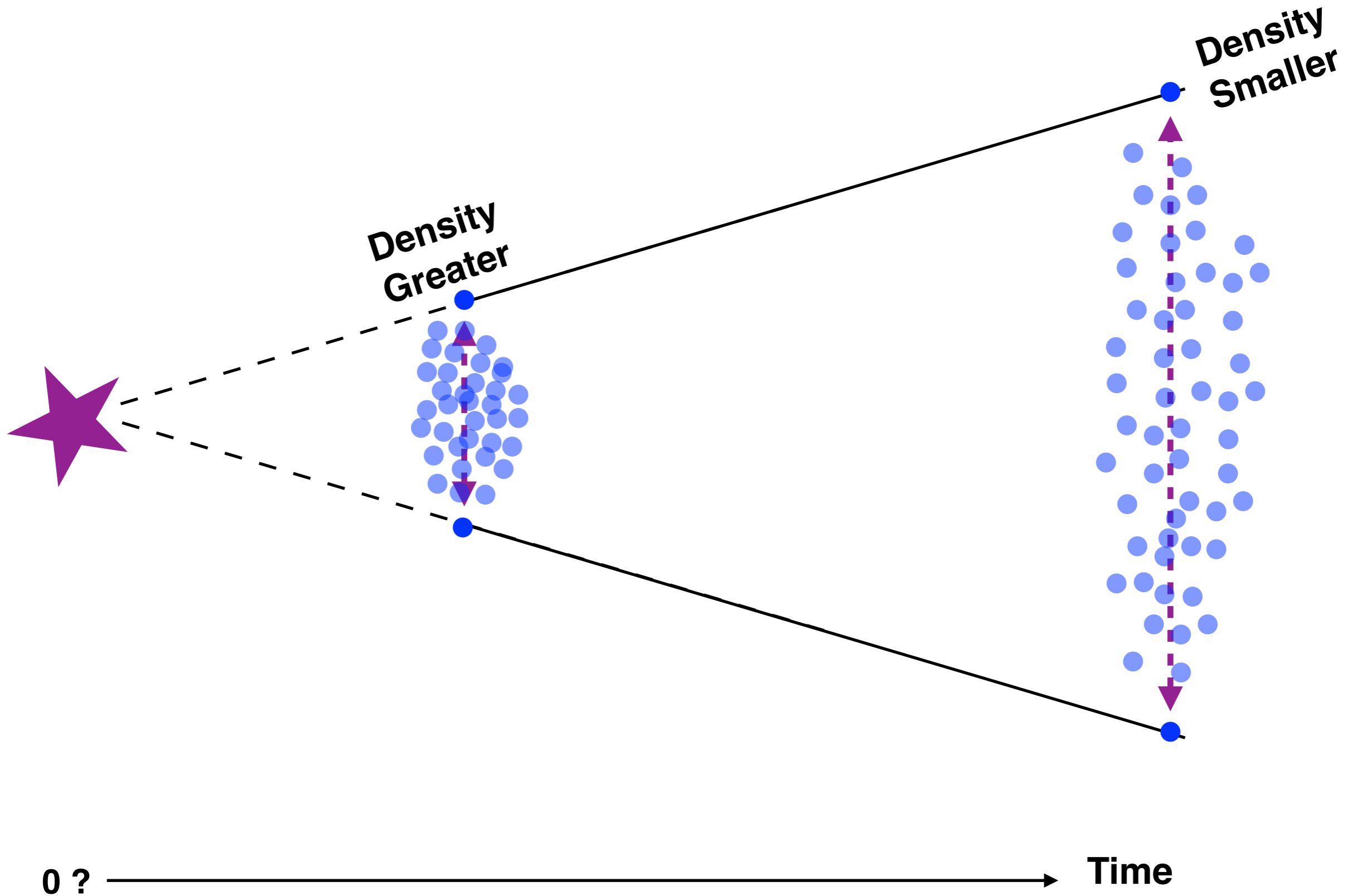
Particle Accelerators (LHC): Reach up to 10^{-10} sec

Cosmic Epochs:

Was there really a Big Bang ?

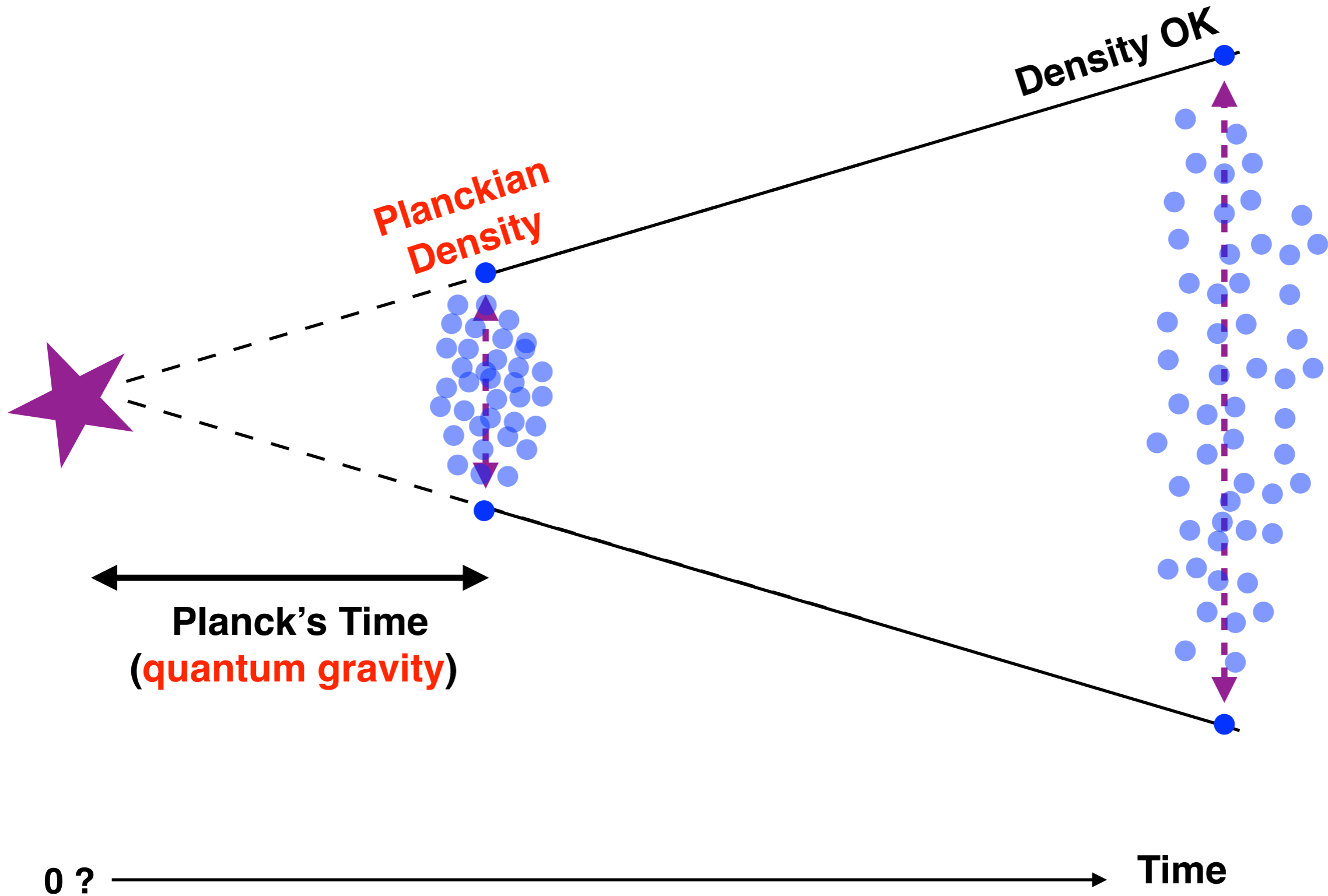
Cosmic Epochs:

Was there really a Big Bang ?



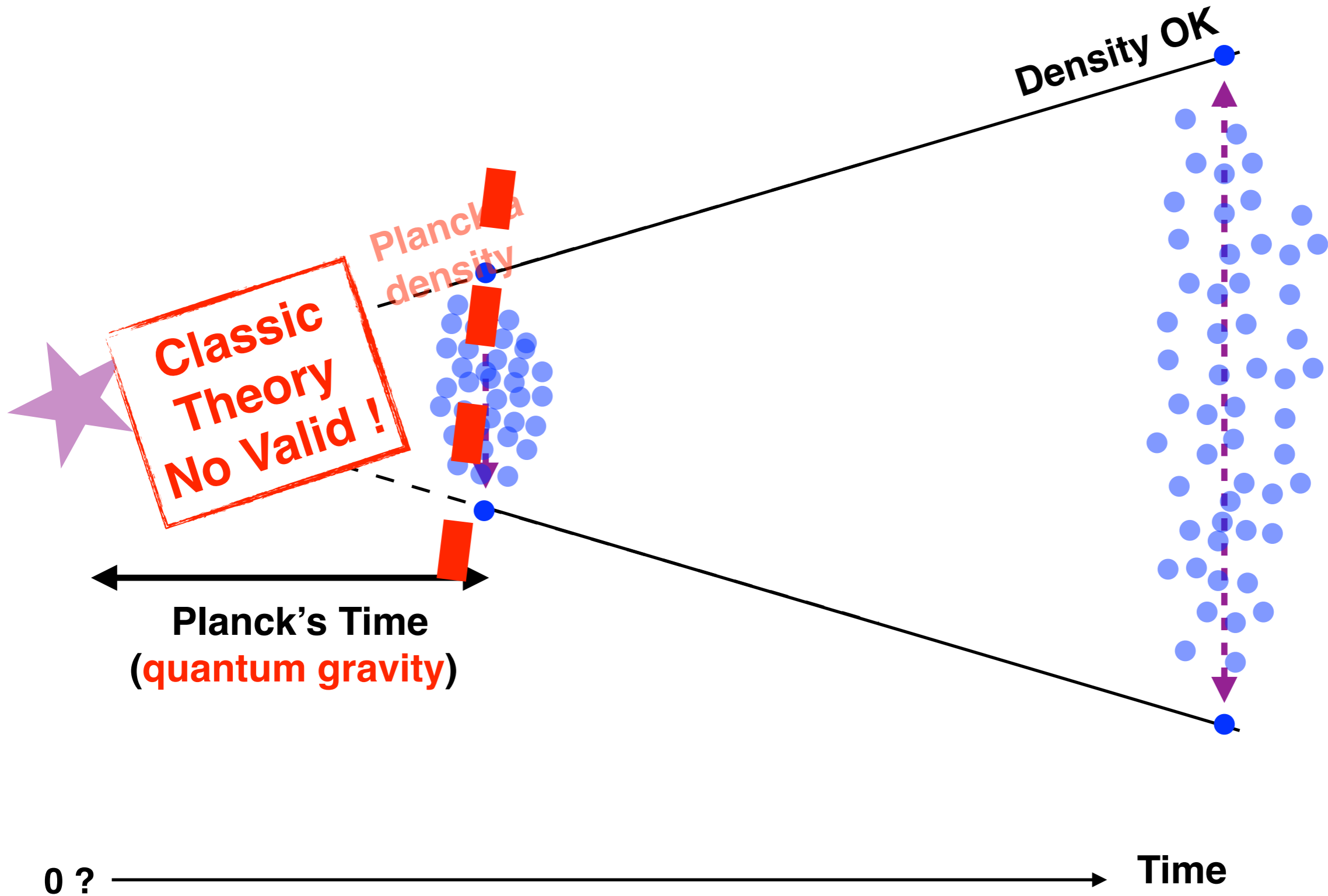
Cosmic Epochs:

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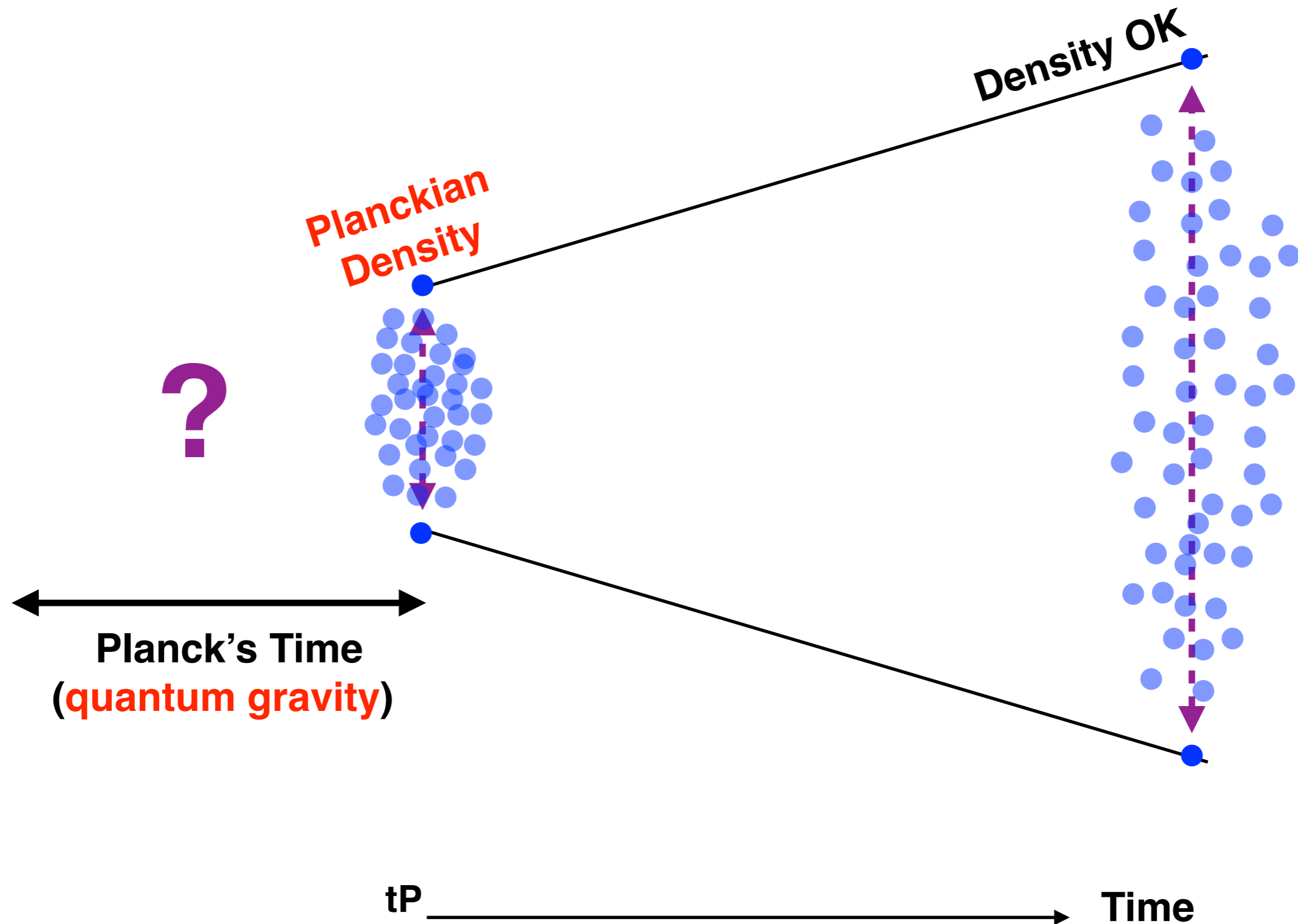
Cosmic Epochs:

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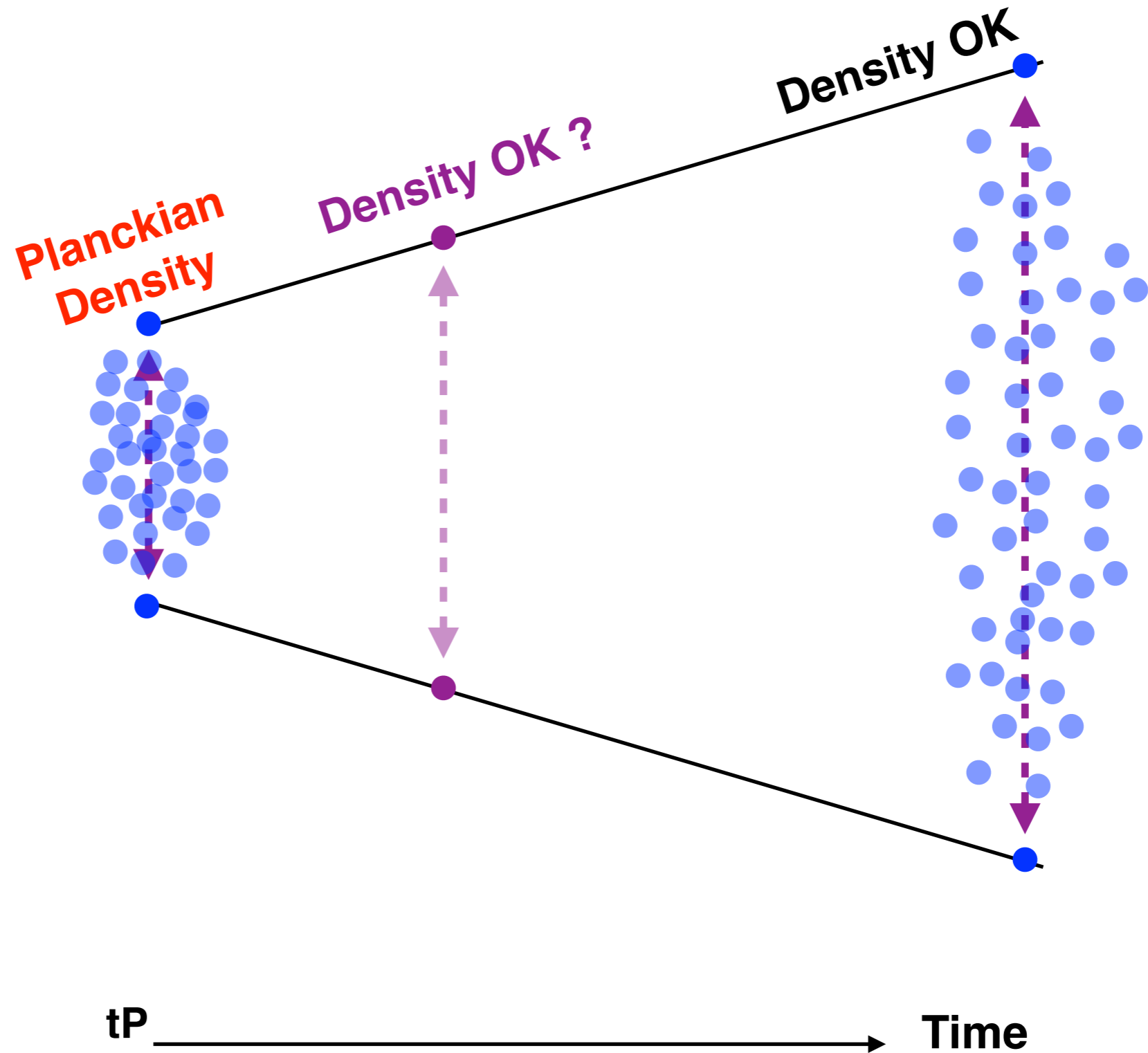
Cosmic Epochs:

Was there really a Big Bang ?



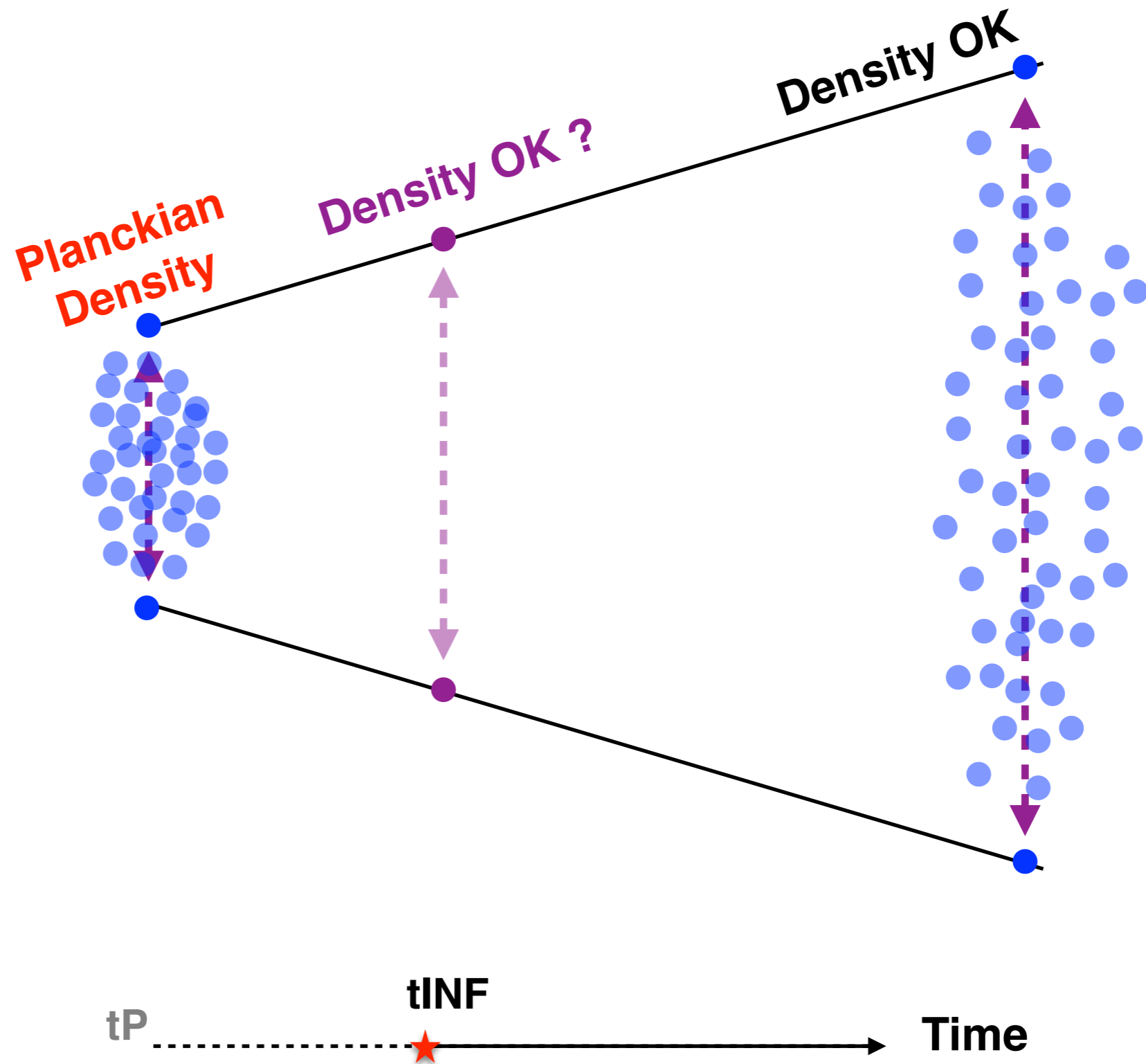
Cosmic Epochs:

Was there really a Big Bang ?



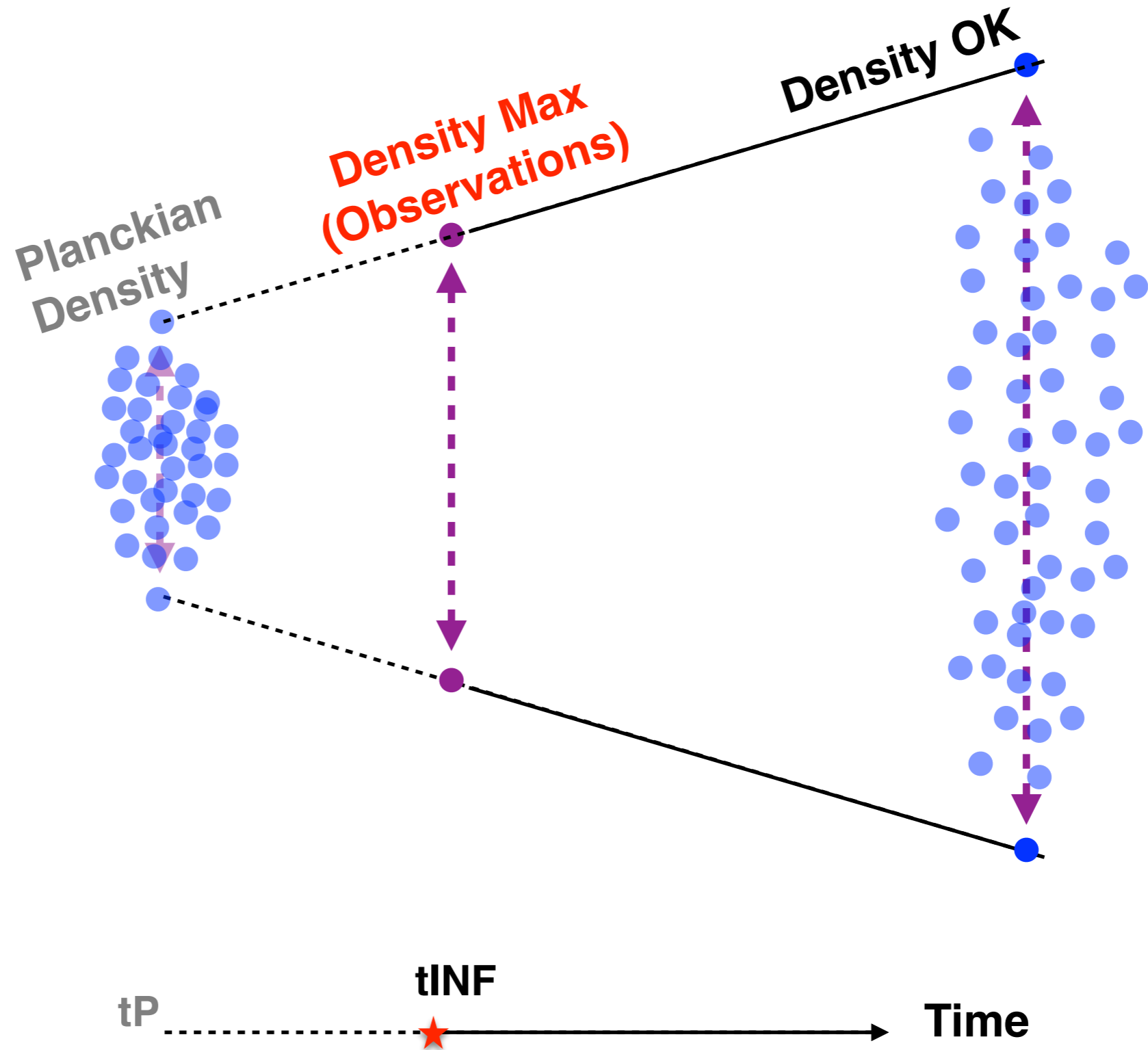
Cosmic Epochs:

Was there really a Big Bang ?



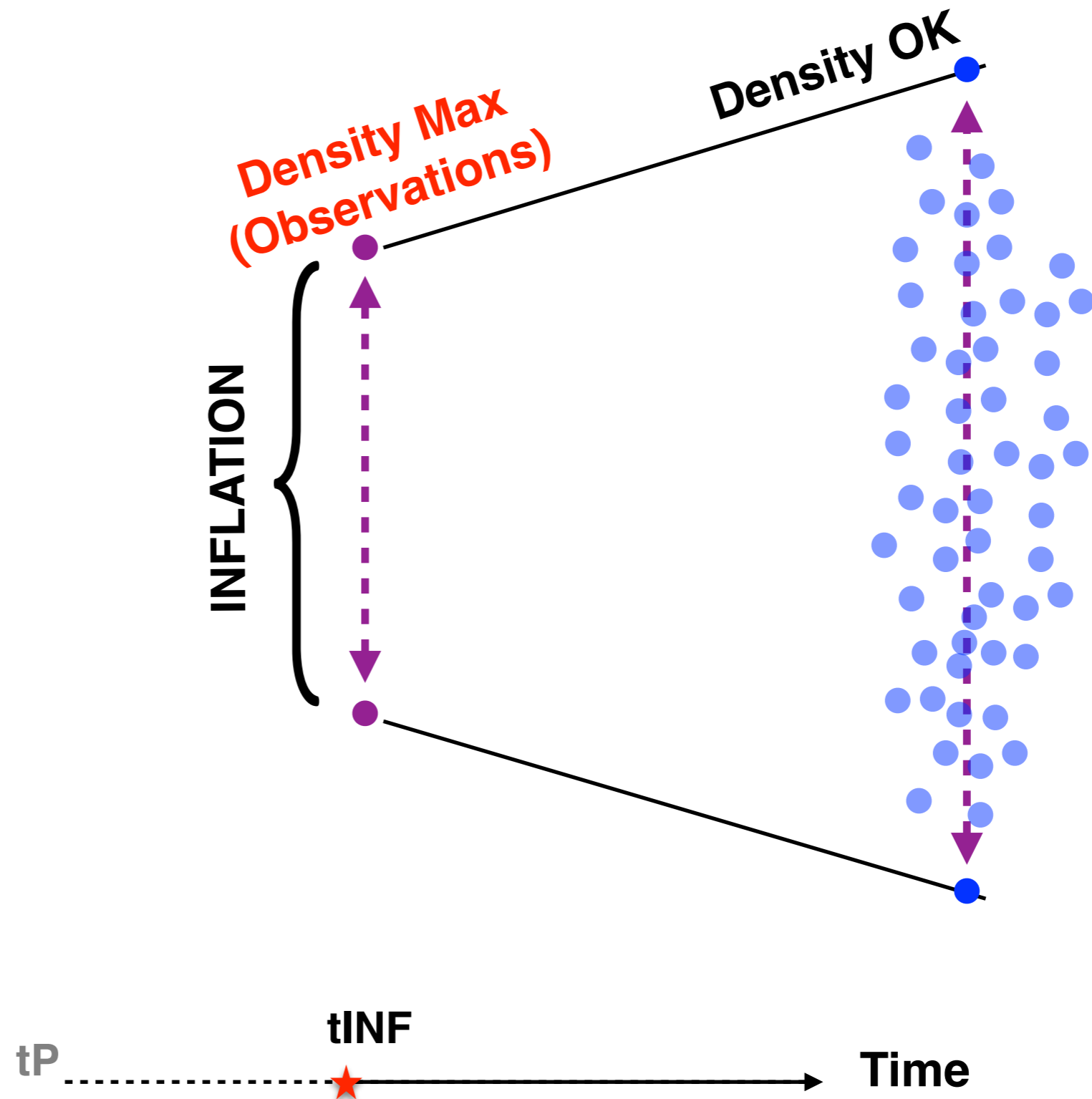
Cosmic Epochs:

Was there really a Big Bang ?



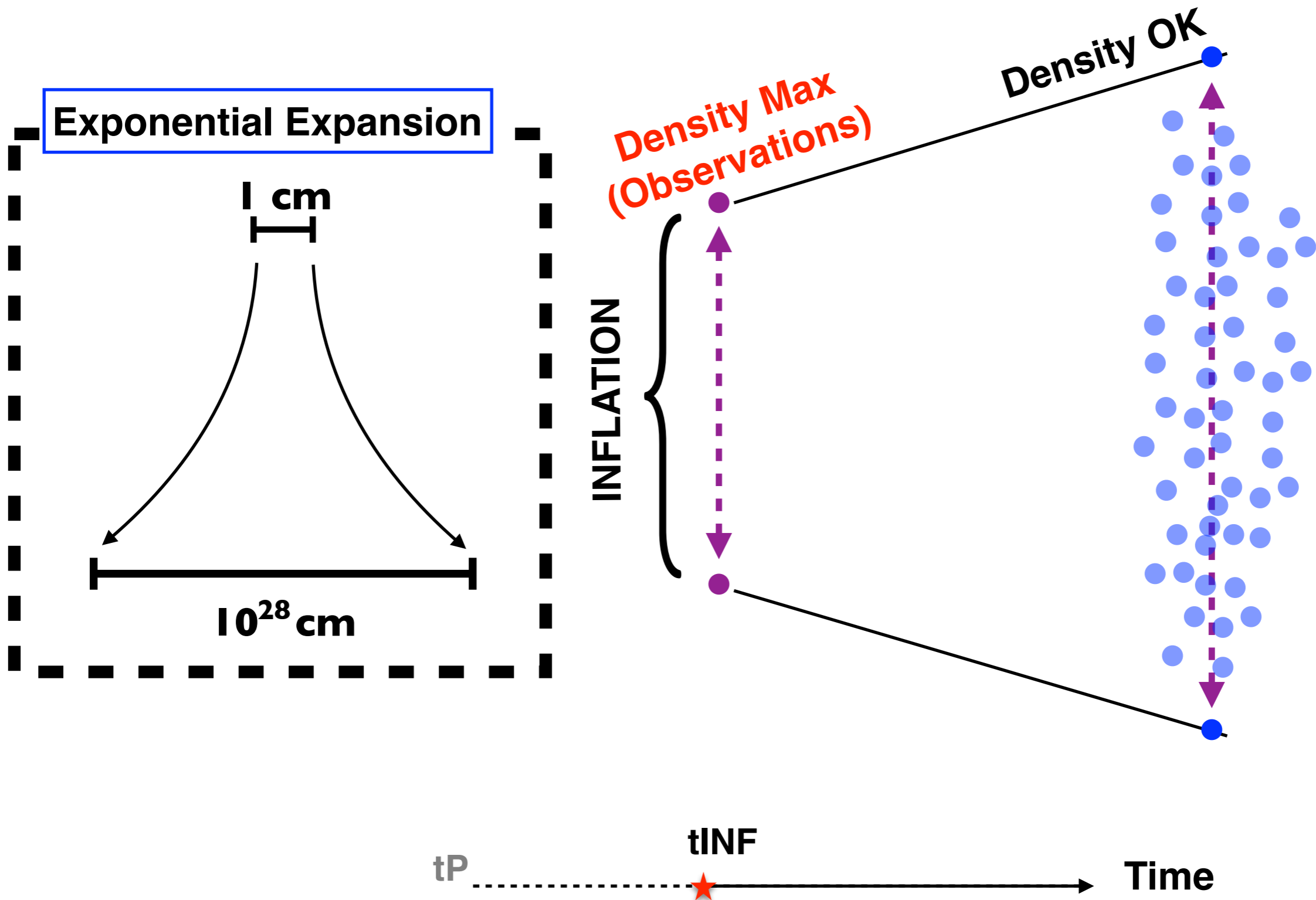
Cosmic Epochs:

Was there really a Big Bang ?



Cosmic Epochs:

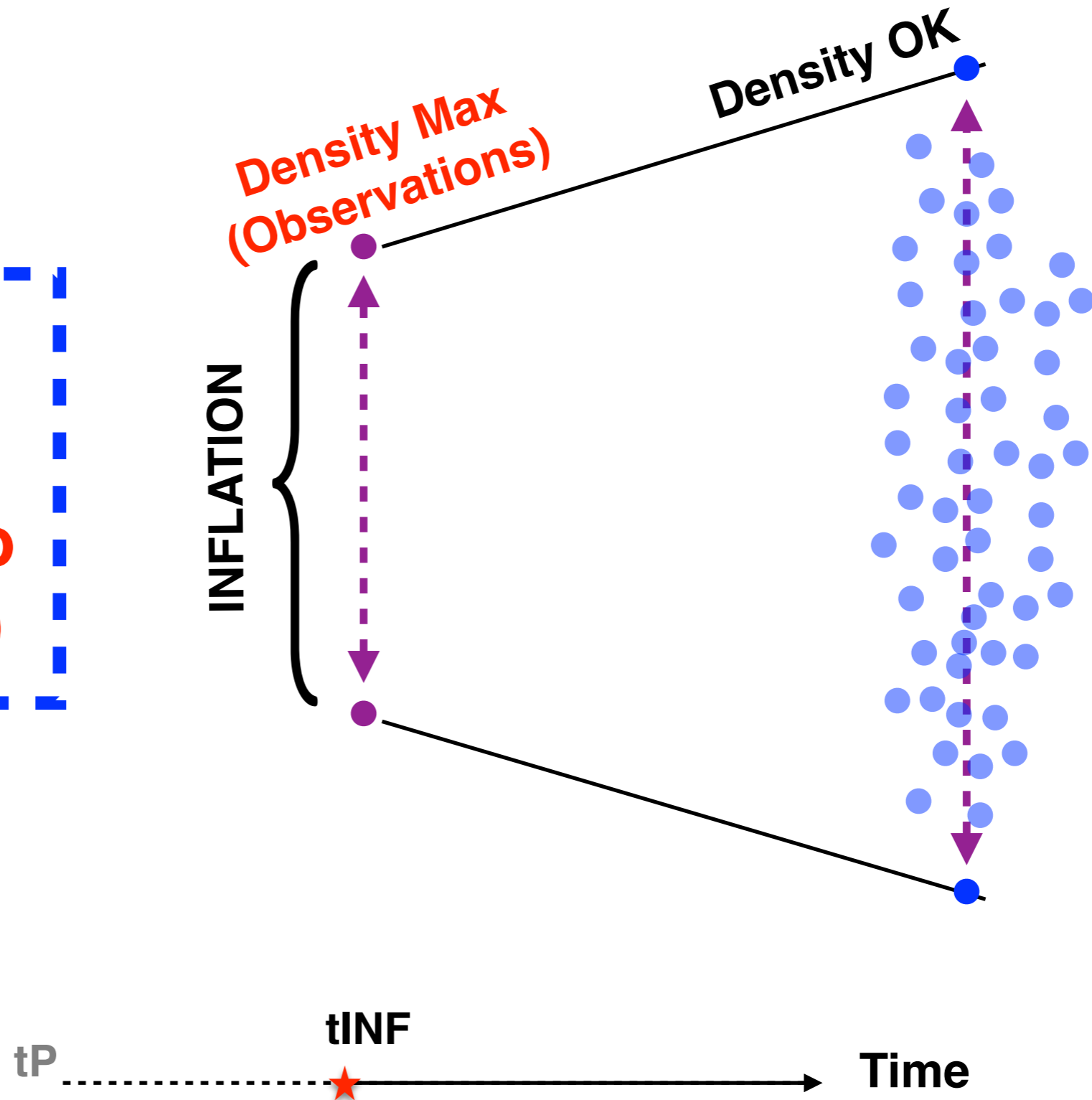
Was there really a Big Bang ?



Cosmic Epochs:

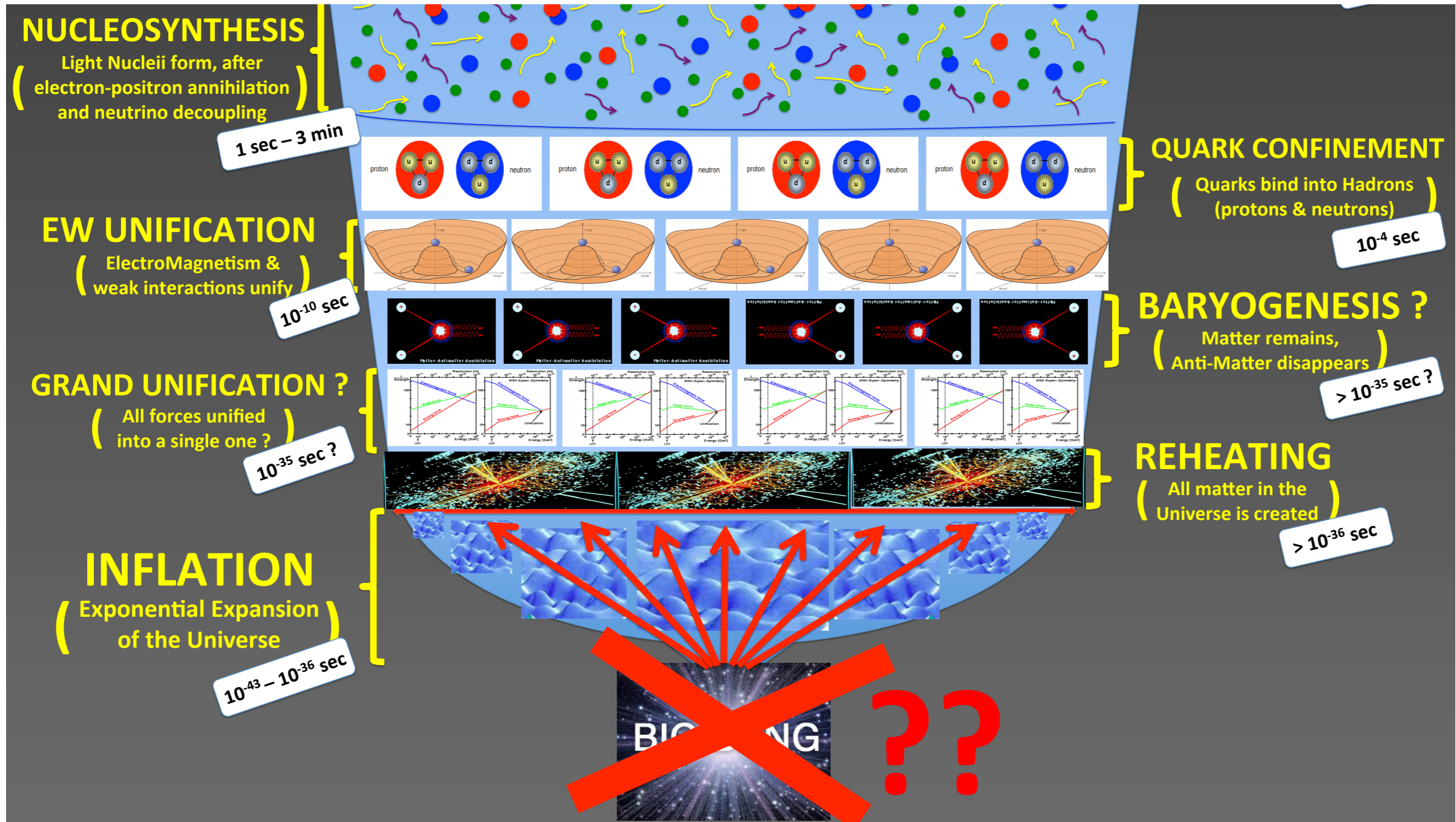
Was there really a Big Bang ?

INFLATION
ExponenTial
ExpansiON
(There is No
Big Bang !)



Cosmic Epochs: The first Second of the Universe !

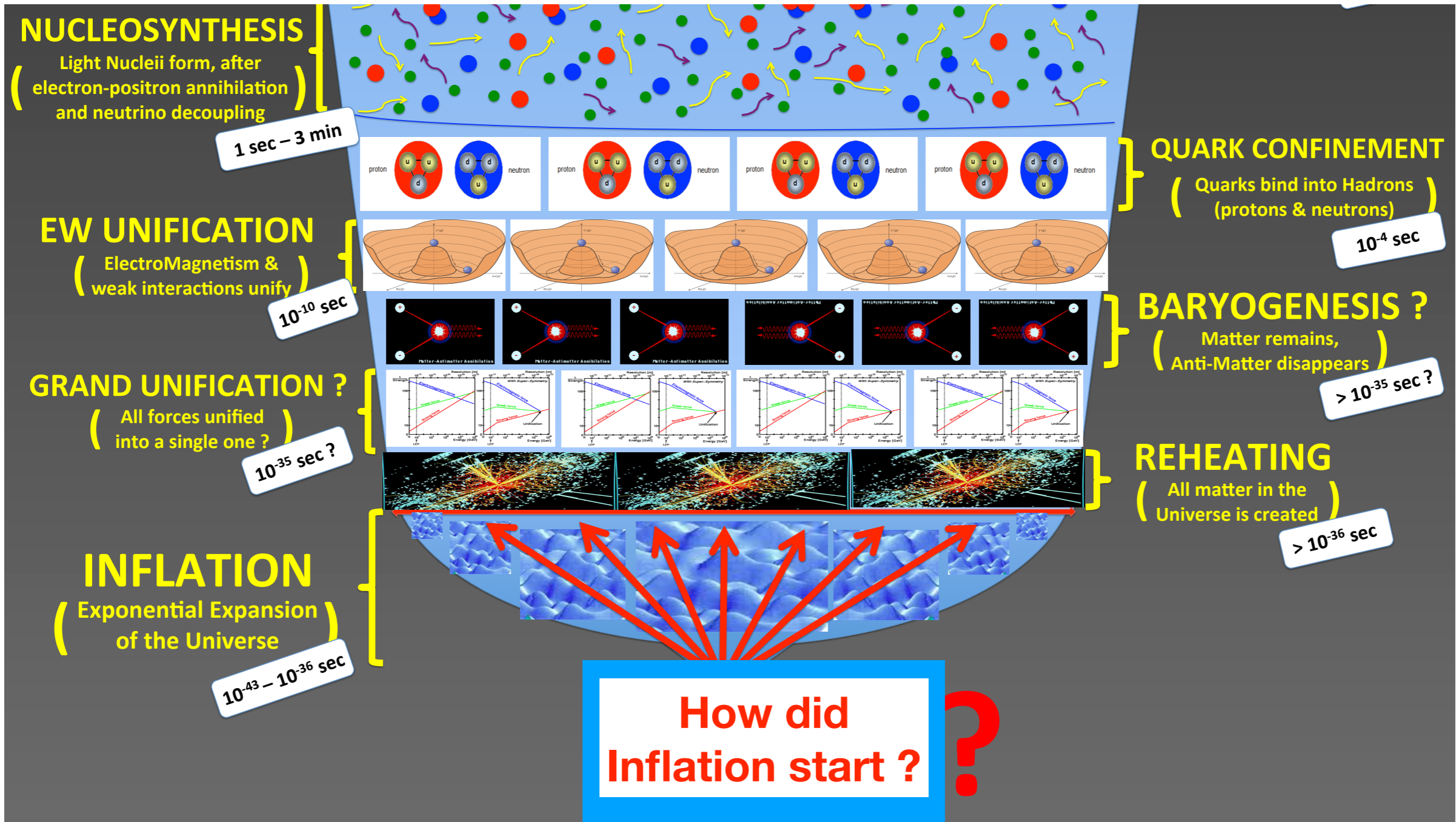
Notation : 10^{-n} seg = 0.00....001 seg



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

Cosmic Epochs: The first Second of the Universe !

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

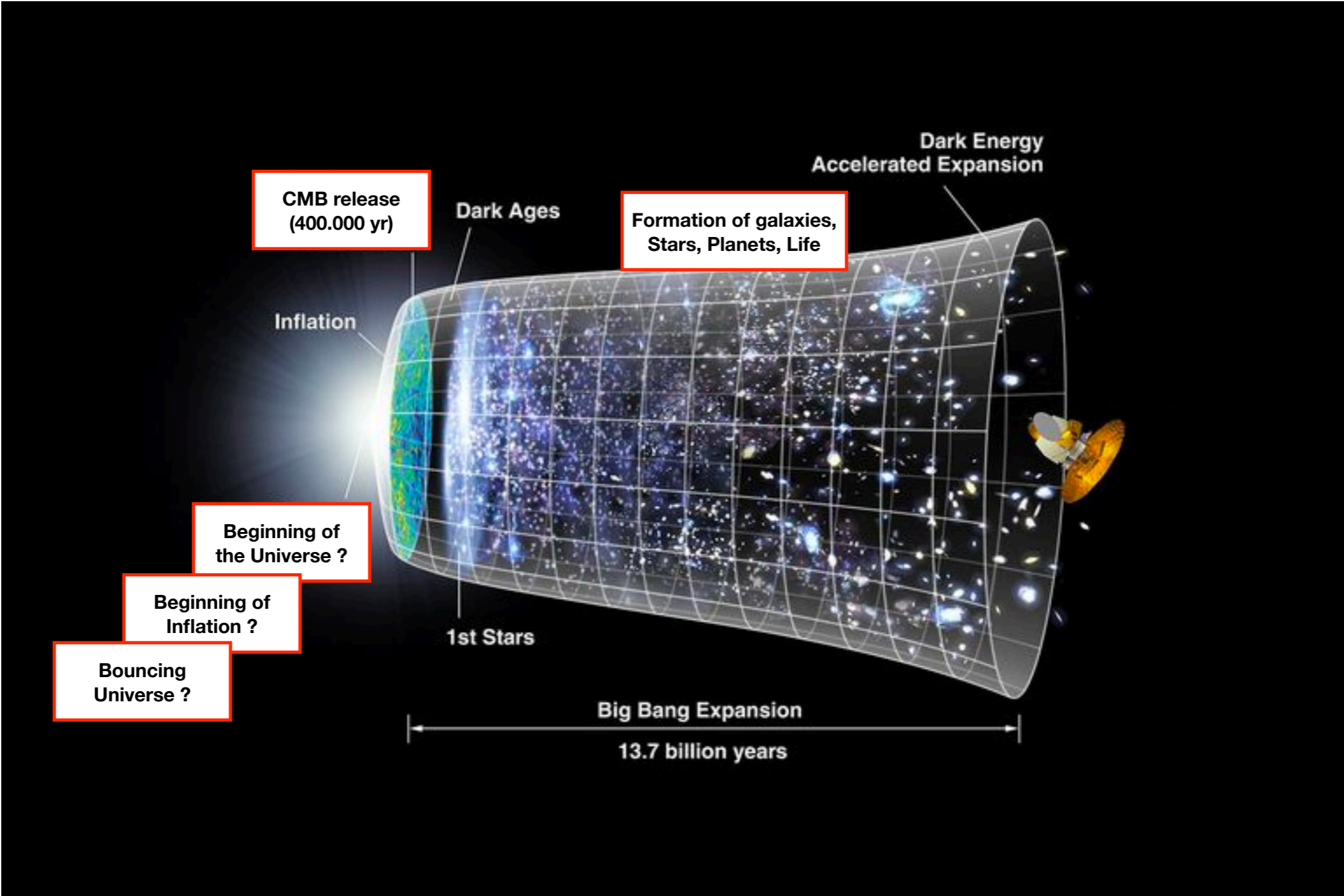


How did Inflation start ?
 (Universe State?)

Particle Accelerator up to 10^{-10} sec

Cosmic Epochs: The first Second of the Universe !

Current Understanding



Cosmic Epochs: The first Second of the Universe !

Can we photograph the Big Bang ?



Cosmic Epochs: The first Second of the Universe !

Can we photograph the ~~Big Bang~~ ?



Cosmic Epochs: The first Second of the Universe !

Can we photograph the Primordial Universe ?



Cosmic Epochs: The first Second of the Universe !

Can we photograph **Inflation, or afterwards** ?



Cosmic Epochs: The first Second of the Universe !

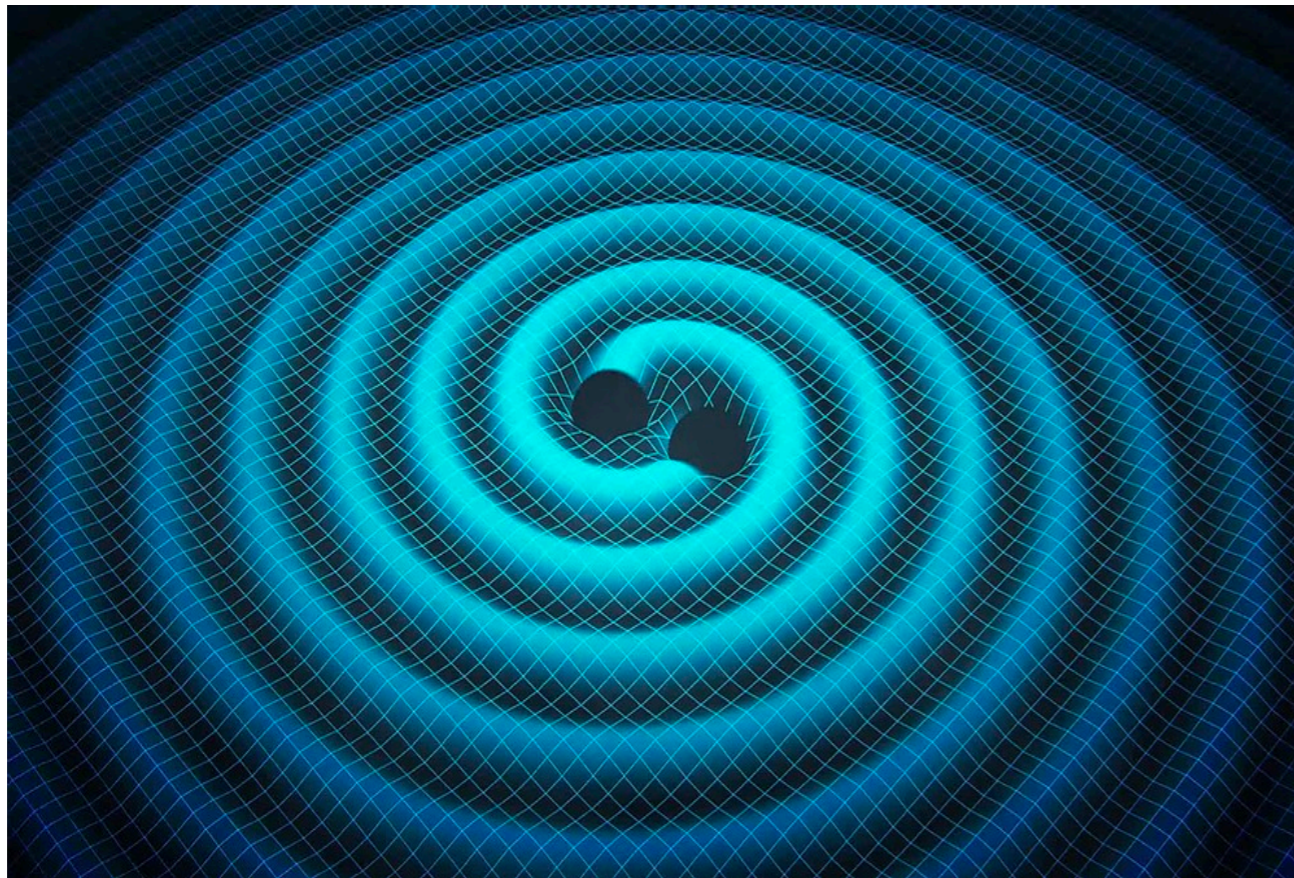
Can we photograph **Inflation, or afterwards ?**
↓
'Image'



**We need
to see
something
that is not
visible**

Cosmic Epochs: The first Second of the Universe !

Can we photograph **Inflation, or afterwards ?**
↓
'Image'



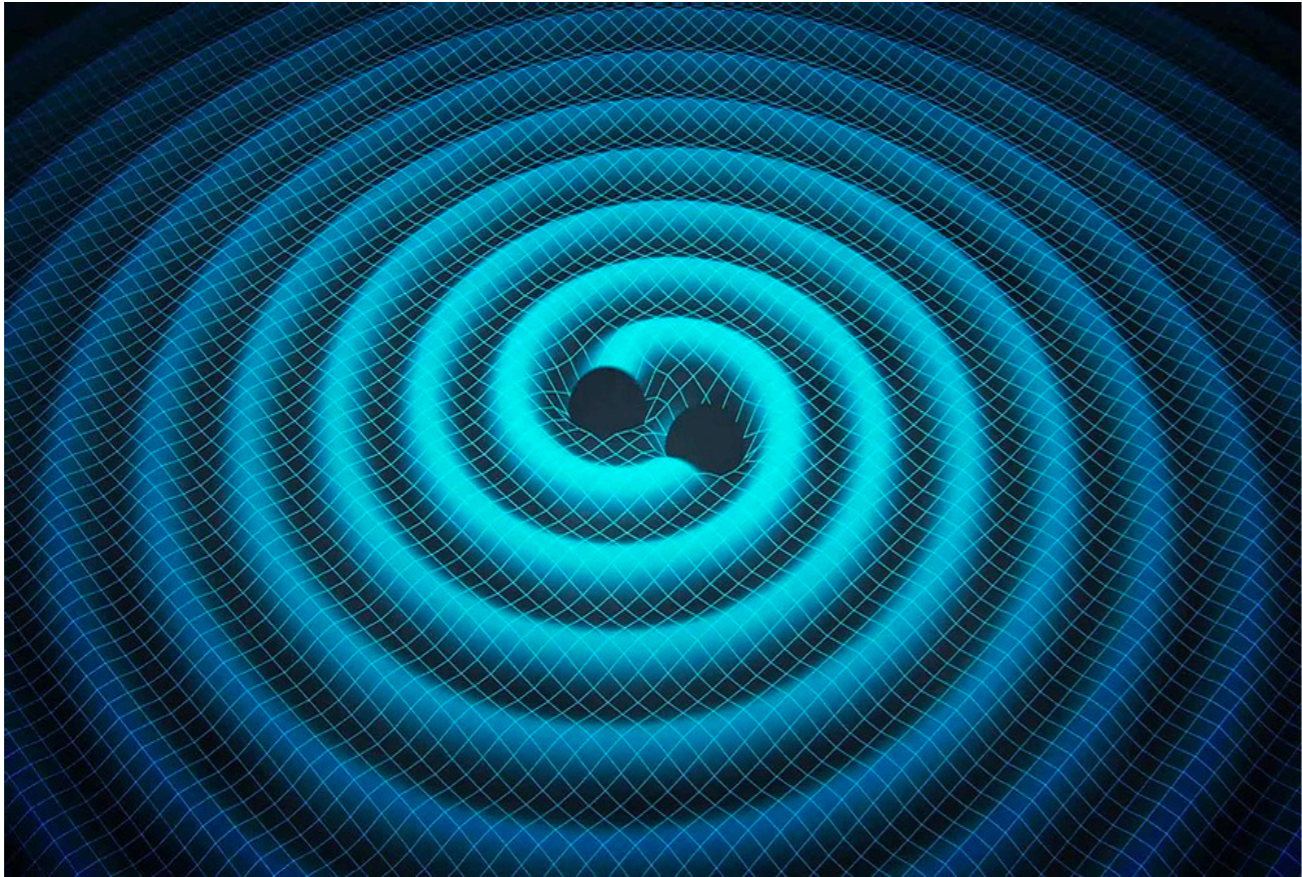
~~Electromagnetic
Waves~~

**Gravitational
Waves**

Cosmic Epochs: The first Second of the Universe !

Can we photograph **Inflation, or afterwards ?**

'gravitational photograph'

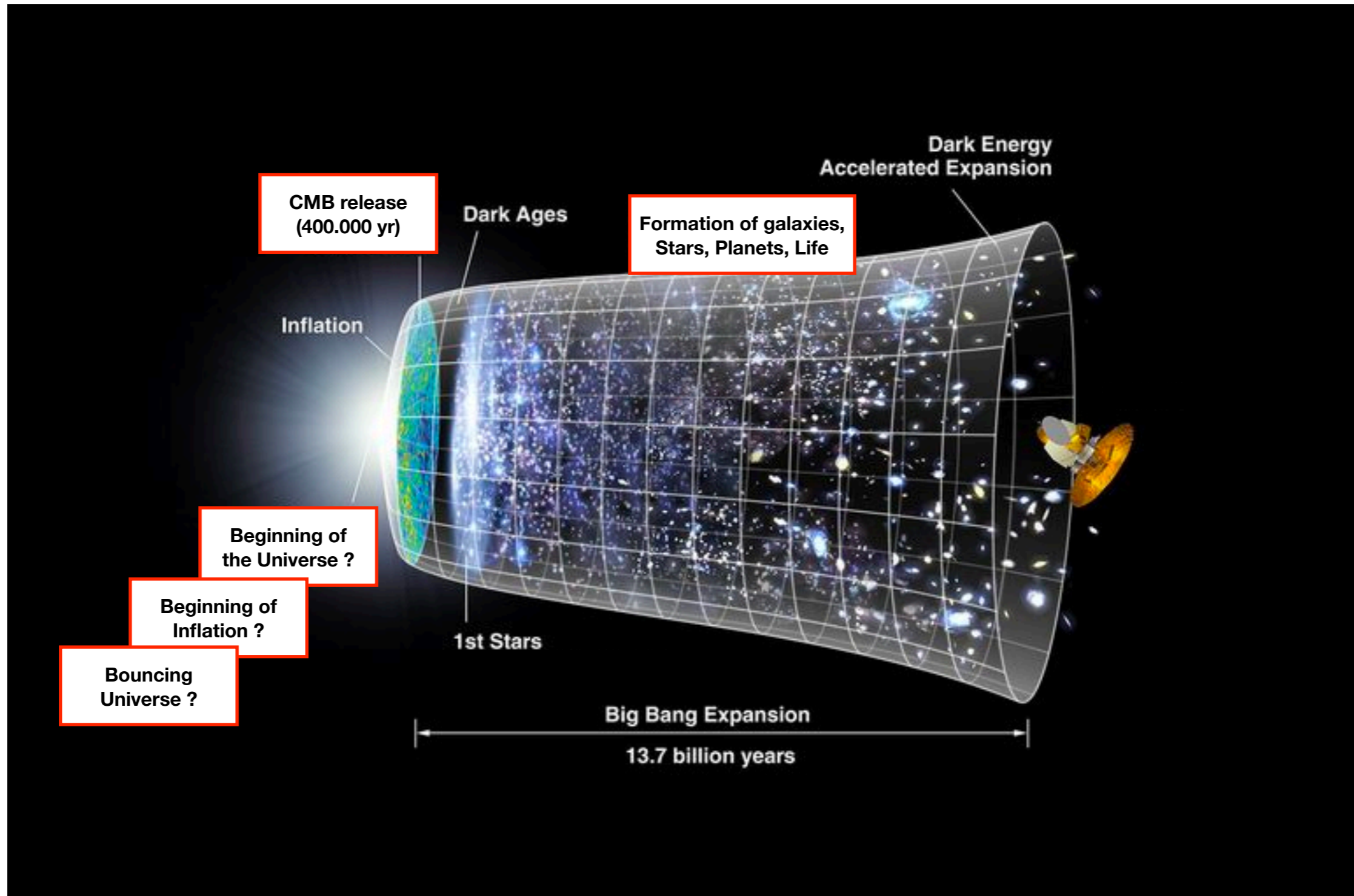


~~Electromagnetic Waves~~

Gravitational Waves

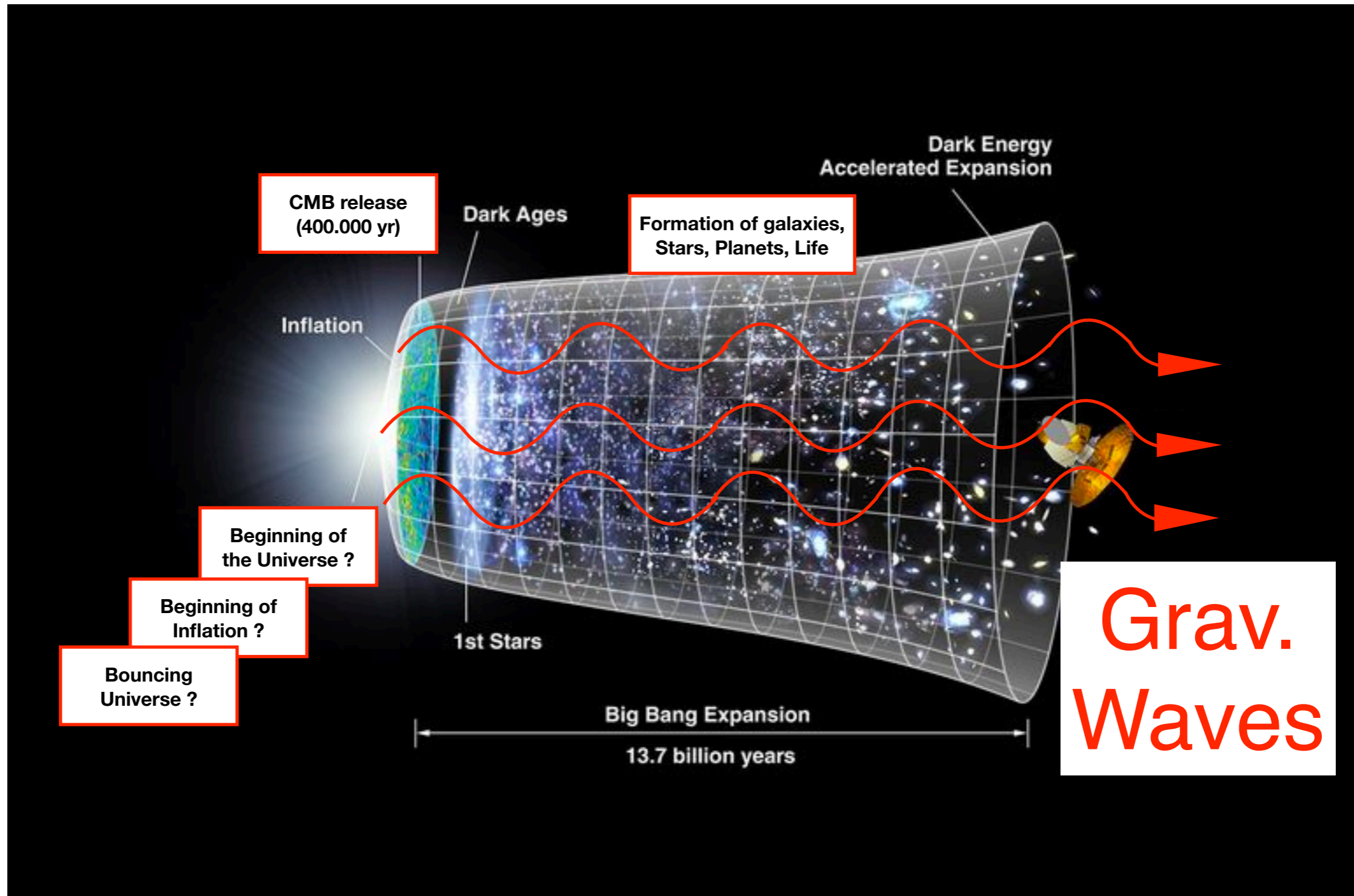
Cosmic Epochs: The first Second of the Universe !

Can we photograph **'gravitational photograph'** Inflation, or afterwards ?



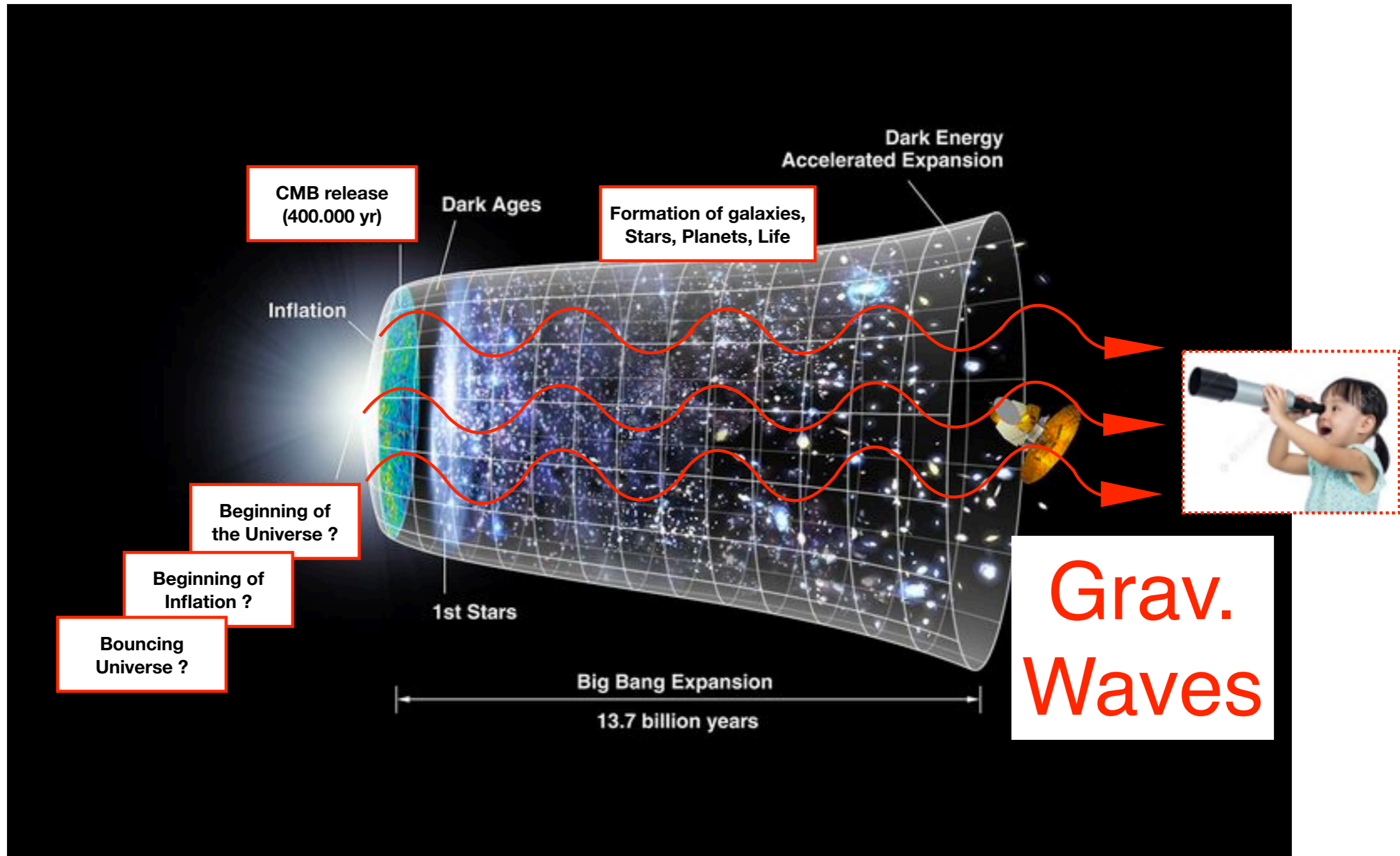
Cosmic Epochs: The first Second of the Universe !

Can we photograph **'gravitational photograph'** Inflation, or afterwards ?



Cosmic Epochs: The first Second of the Universe !

Can we photograph **'gravitational photograph'** Inflation, or afterwards ?



Cosmic Epochs: The first Second of the Universe !

Can we photograph **Inflation, or afterwards** ?

'gravitational photograph'

Primordial Backgrounds of Gravitational Waves



Beginning of Inflation ?
Bouncing Universe ?

13.7 billion years

grav. Waves

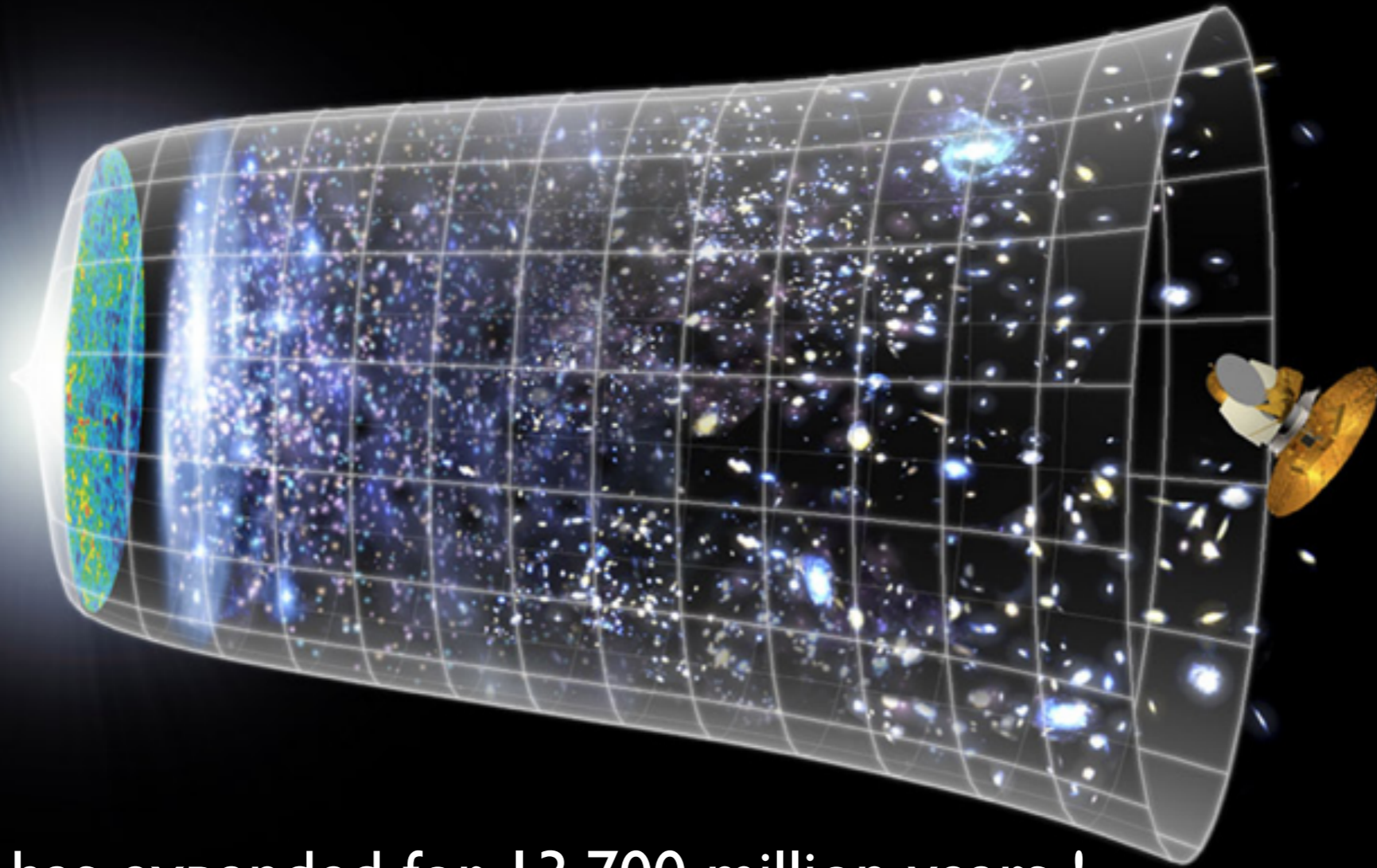
**Many thanks
for your
attention !**

To know more (books)

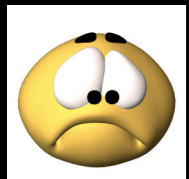
- The first three minutes of the Universe (S. Weinberg) **Big Bang Theory**
- Black Holes and warped space-time (K. Thorne) **Gravity**
- The charm of physics (S. L. Glashow) **Particle Physics**
- The Elegant Universe (B. Green) **String Theory**
- The Inflationary Universe (A. Guth) **Inflationary Theory**

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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



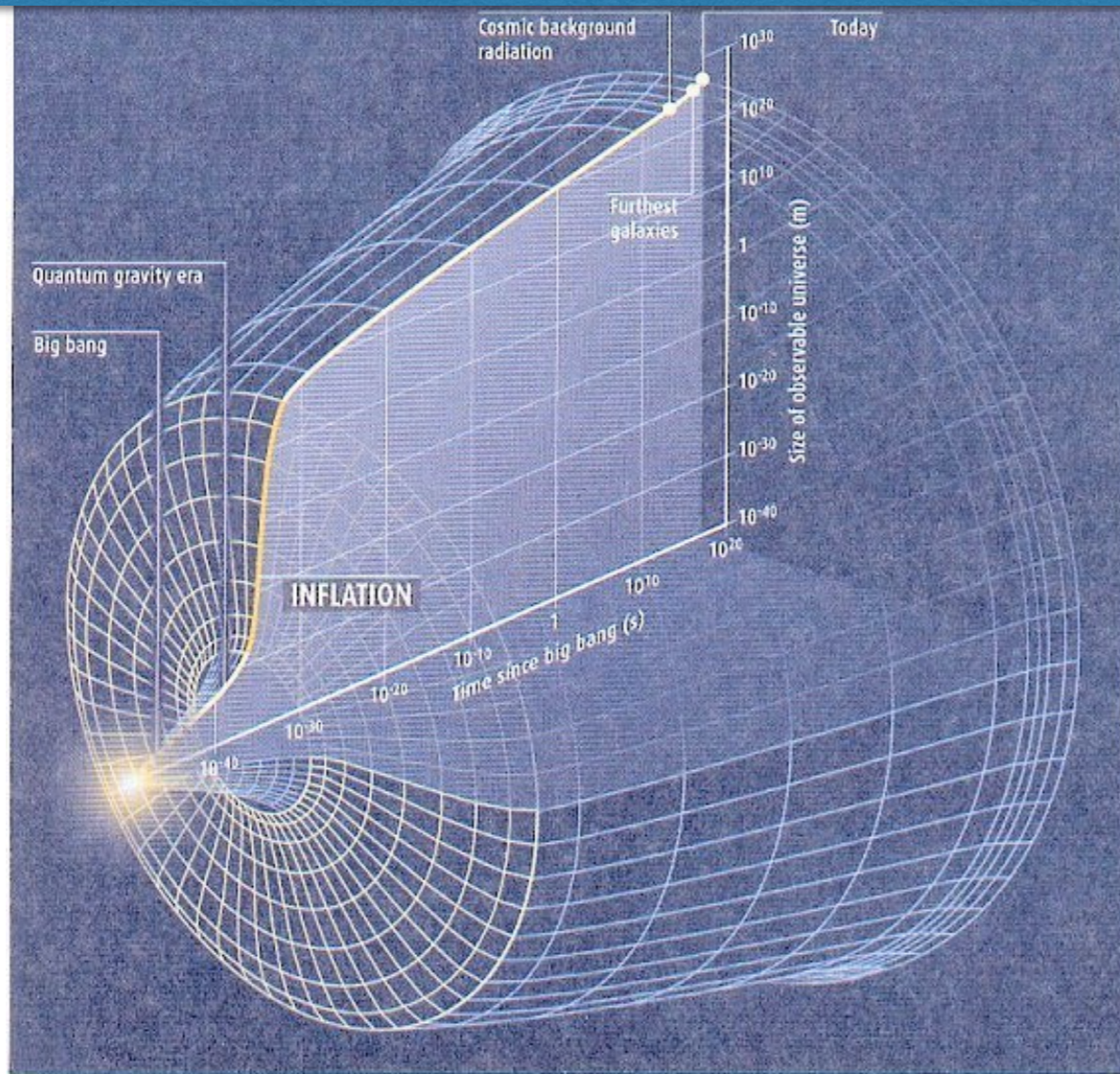
But yet we DON'T UNDERSTAND that First Second !

WHAT DID I NOT TELL YOU ?

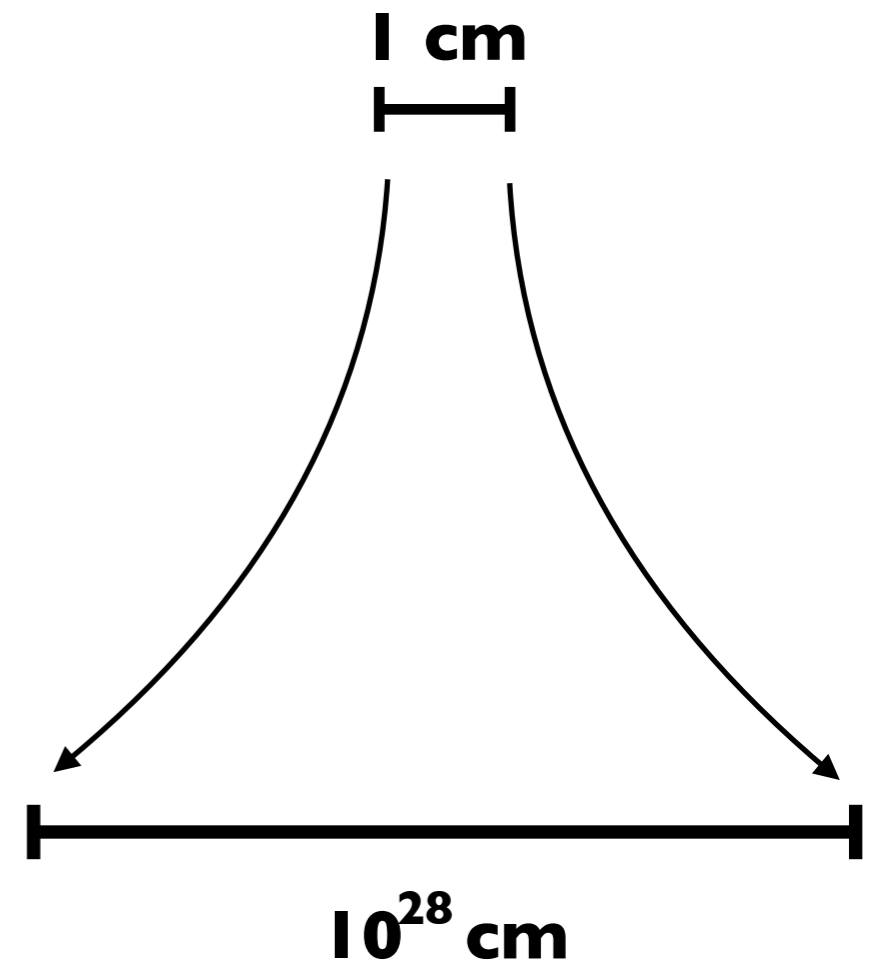
MANY THINGS !

WHAT DID I NOT TELL YOU ?

COSMIC INFLATION !

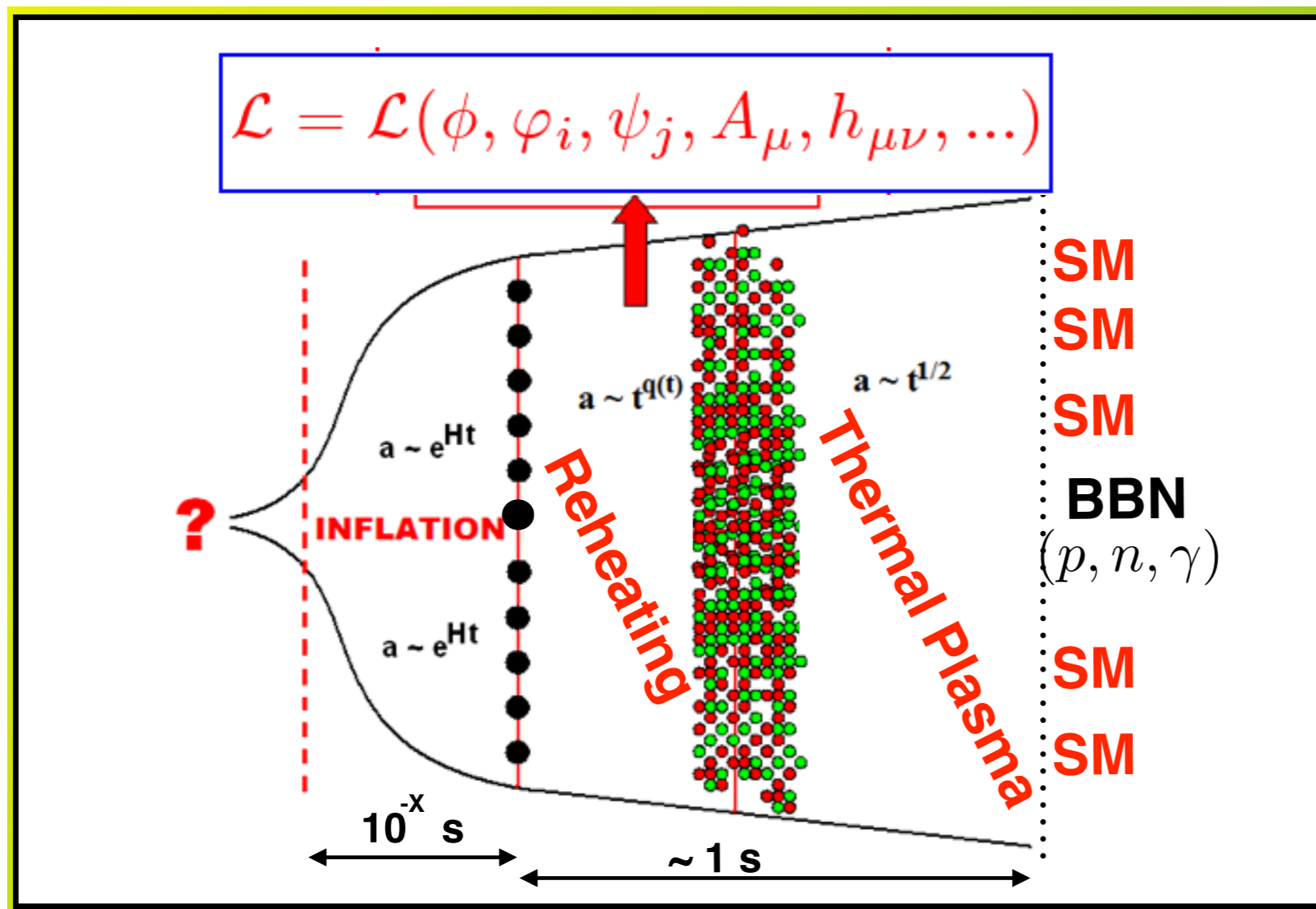


Needed for **Consistency** of the **Big Bang theory** !



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 ?

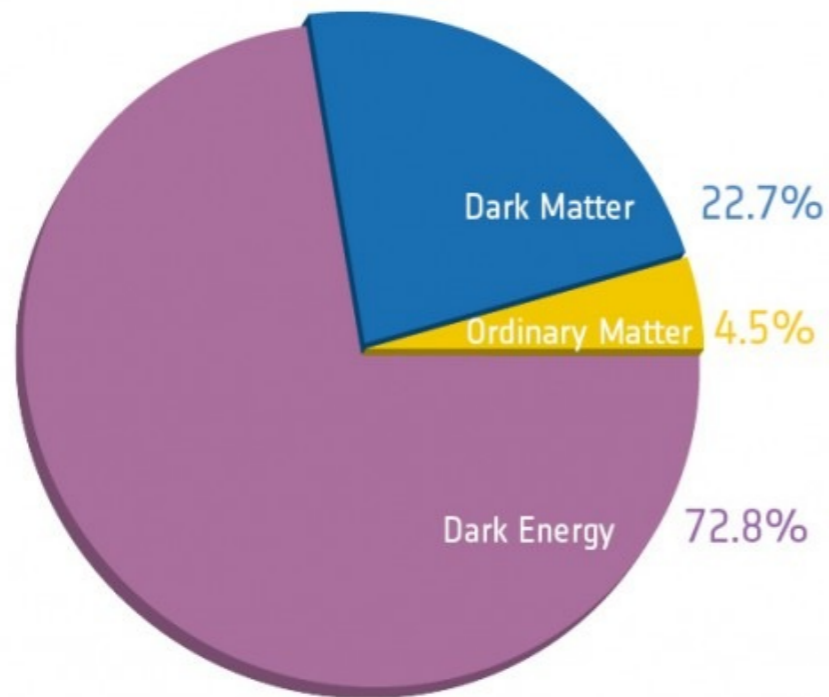


DARK ENERGY !
(Accelerated Expansion)

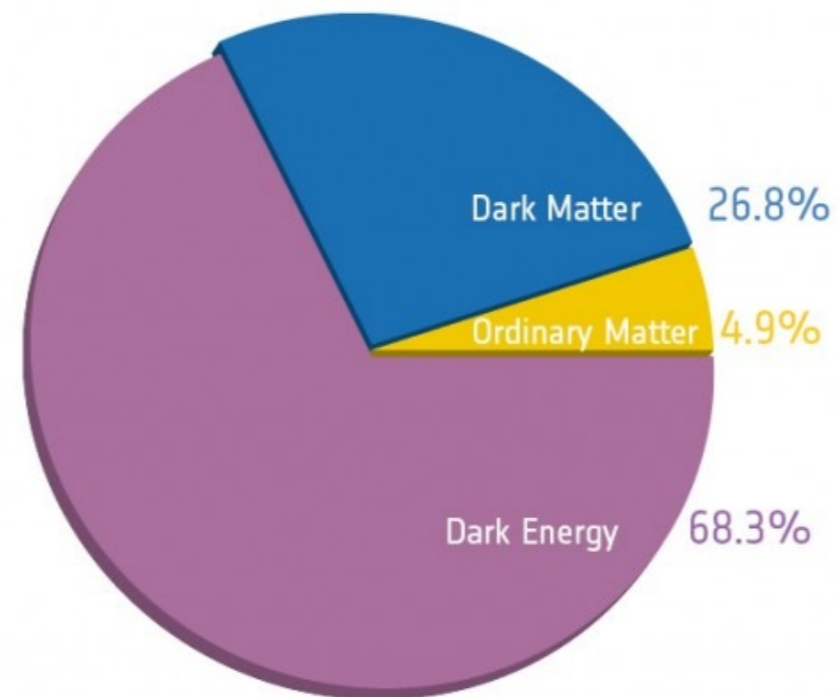
DARK MATTER !

WHAT DID I NOT TELL YOU ?

Matter content within the Universe



Before Planck



After Planck

WHAT ELSE DID I NOT TELL

WHAT ELSE DID I NOT TELL

**THANKS FOR
YOUR
ATTENTION !!**

To know more

- 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?

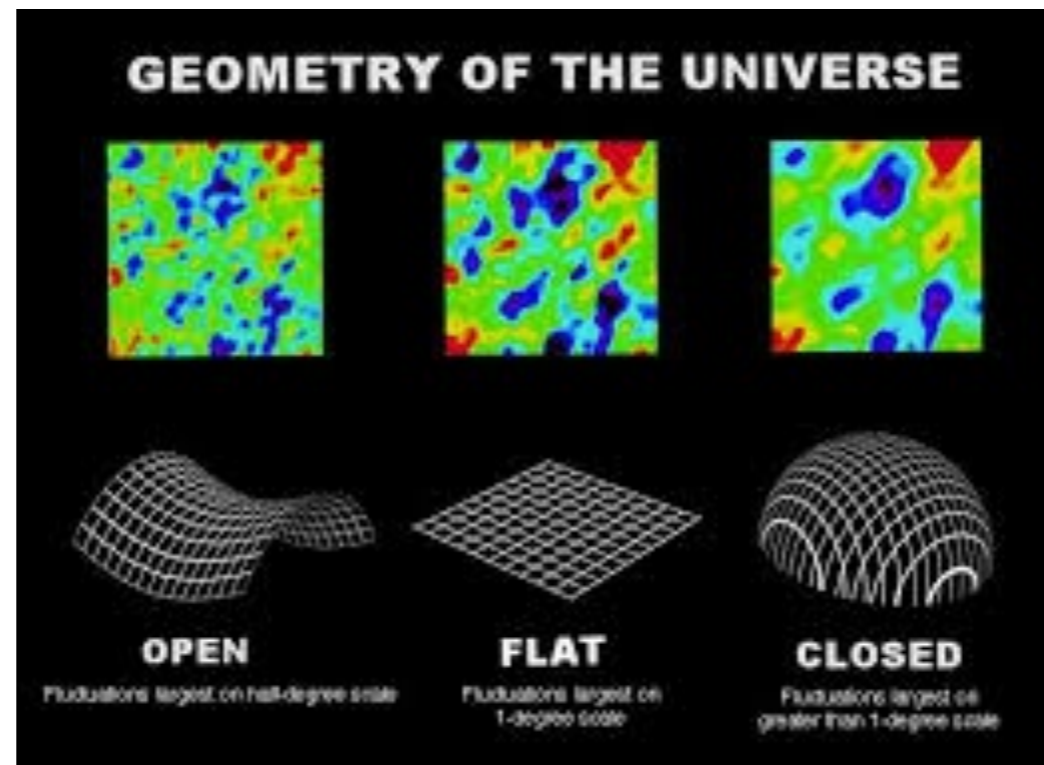
¿How did the Universe appeared?

¿Did Inflation really occurred?

...

Cosmic Epochs Formation of atoms (300.000-400.000 yrs)

Properties of the Cosmic Microwave



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

The UNIVERSE has FLAT GEOMETRY !