The Evolution of Chemical Elements in Galaxies

Dr. Benoit Côté

ThaiPass School
October 17th, 2018

The Plan for Today

Lecture #1

- Introduction to astronomical scales
- Evolution of the Universe

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- Introduction to chemical evolution
- Observing the evolution of the elements
- Simulating the evolution of the elements

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Hands-on activity
- Run simple galaxy models
- Look into stellar abundances data
- Run chemical evolution models
- Learn where the elements come from

Introduction to Cosmic Scales

Zoom Out from the Earth to the Cosmos

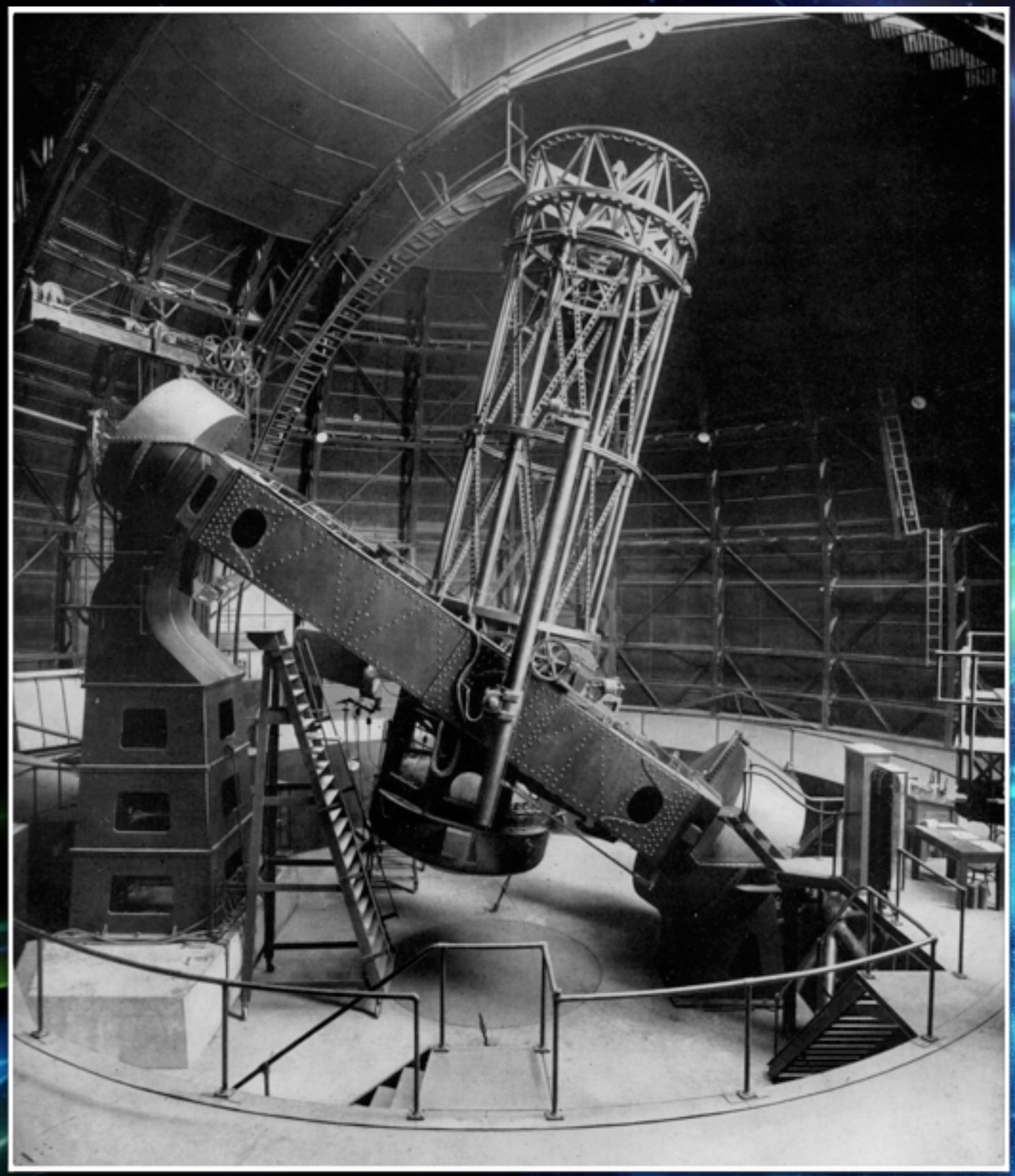
Scene from the 1997 « Contact » movie from Warner Bros

The Night Sky

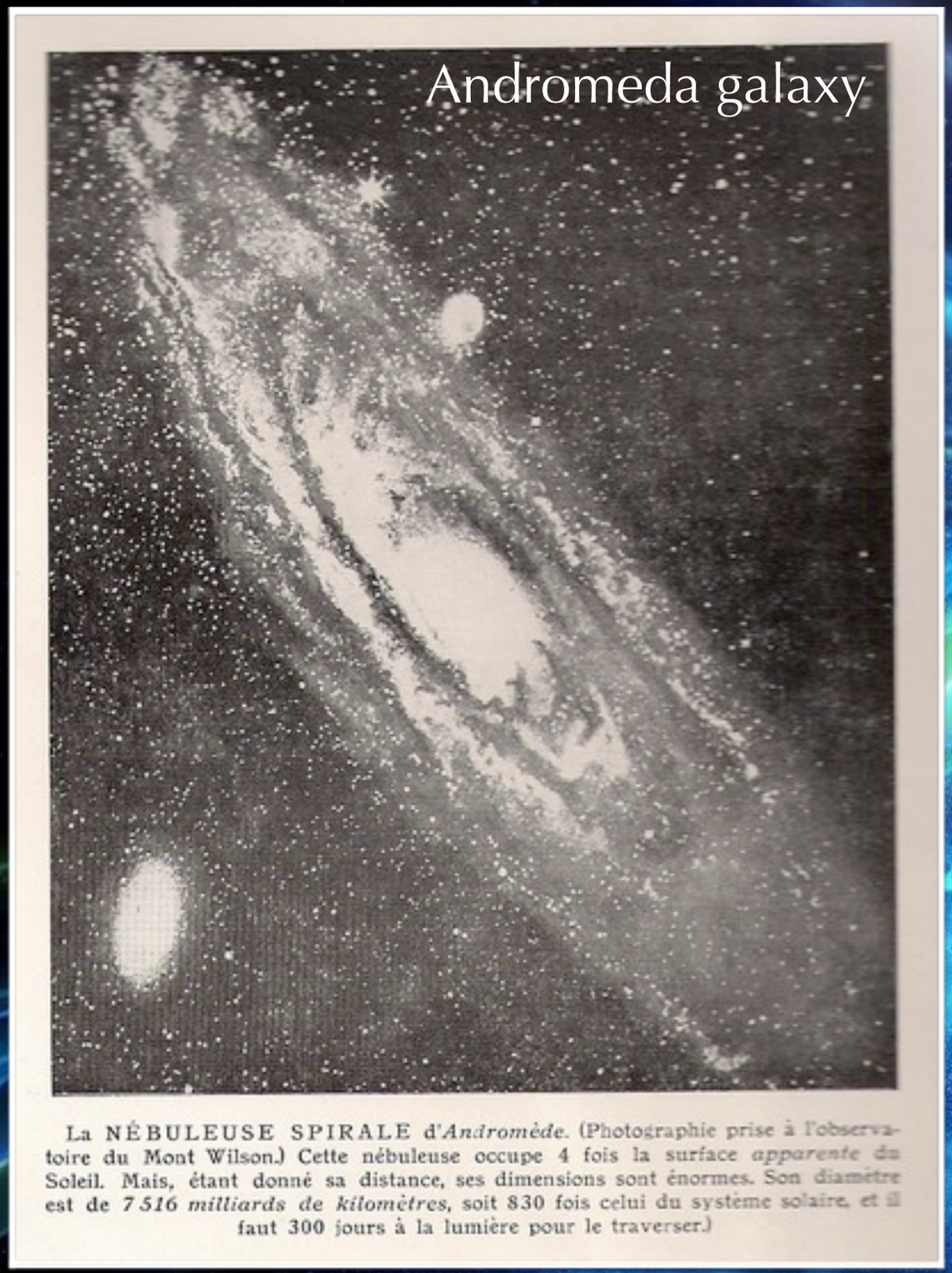
The Vision of the Universe in 1920

The Vision of the Universe in 1920

Mont Wilson telescope



The Observation of Galaxies



Edwin Hubble's observations

The Observation of Galaxies

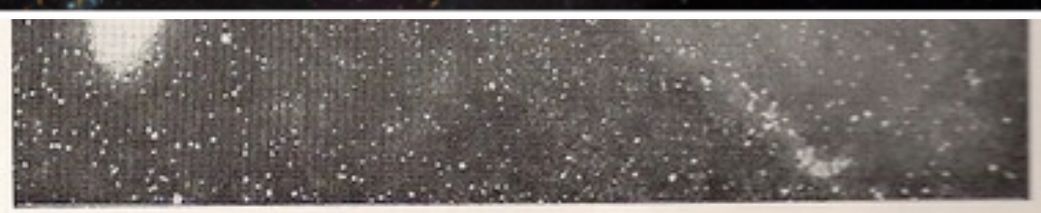
buleuses spirales contraste sera des plus féconde

M101 galaxy

La nébuleuse SPIRALE (M. 101) de la *Grande Ourse* (Photogr. prise à l'observatoire du Mont Wilson).

es traînées de matière absor- pôles, et quelques-unes av

@Hubble Image: NASA, ESA

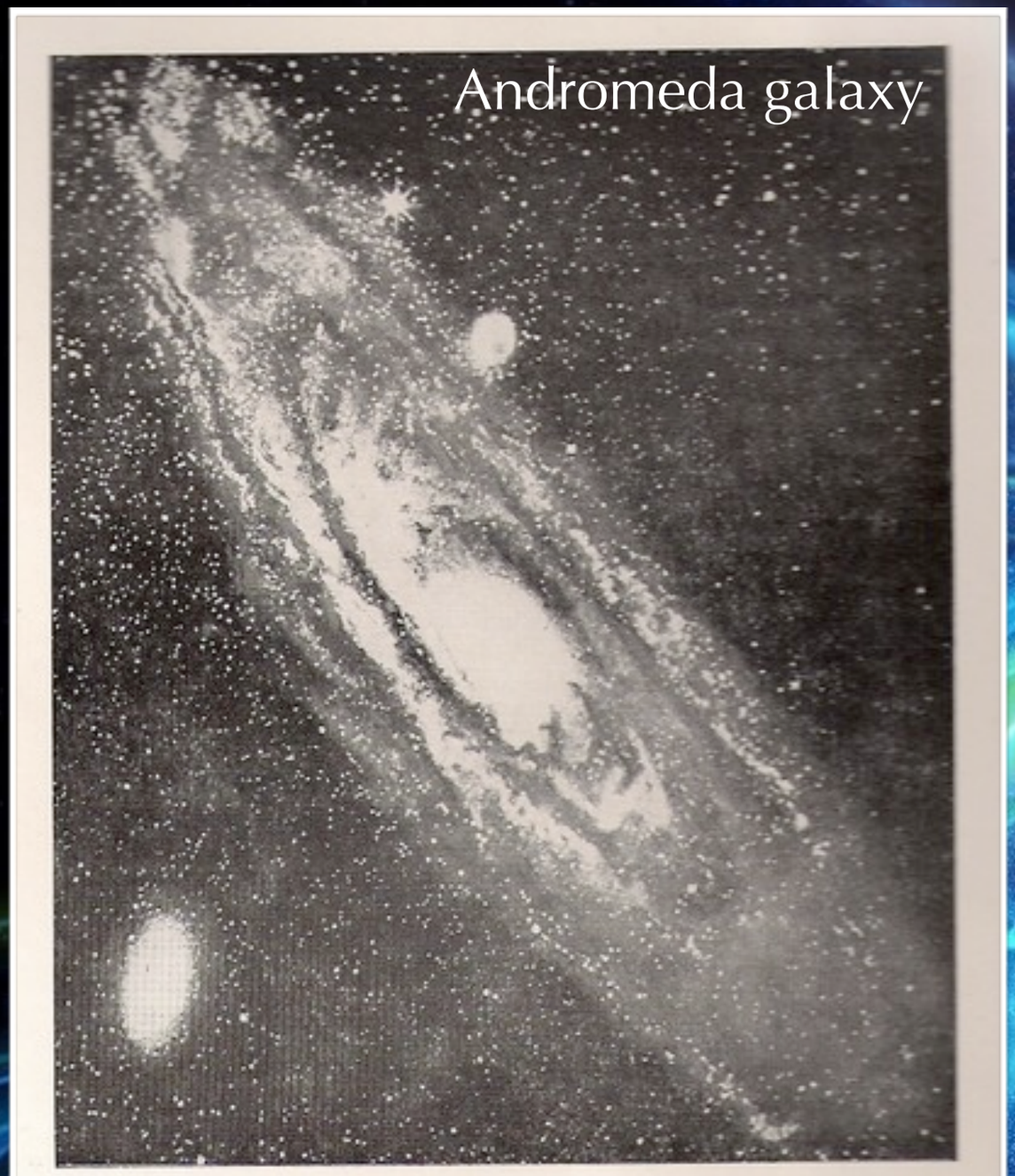


La NÉBULEUSE SPIRALE d'*Andromède*. (Photographie prise à l'observatoire du Mont Wilson.) Cette nébuleuse occupe 4 fois la surface *apparente* du Soleil. Mais, étant donné sa distance, ses dimensions sont énormes. Son diamètre est de *7 516 milliards de kilomètres*, soit 830 fois celui du système solaire, et il faut 300 jours à la lumière pour le traverser.)

Edwin Hubble's observations

The Observation of Galaxies

@http://www.outters.fr/galaxie%20d%20andromede%20tec-fli.htm



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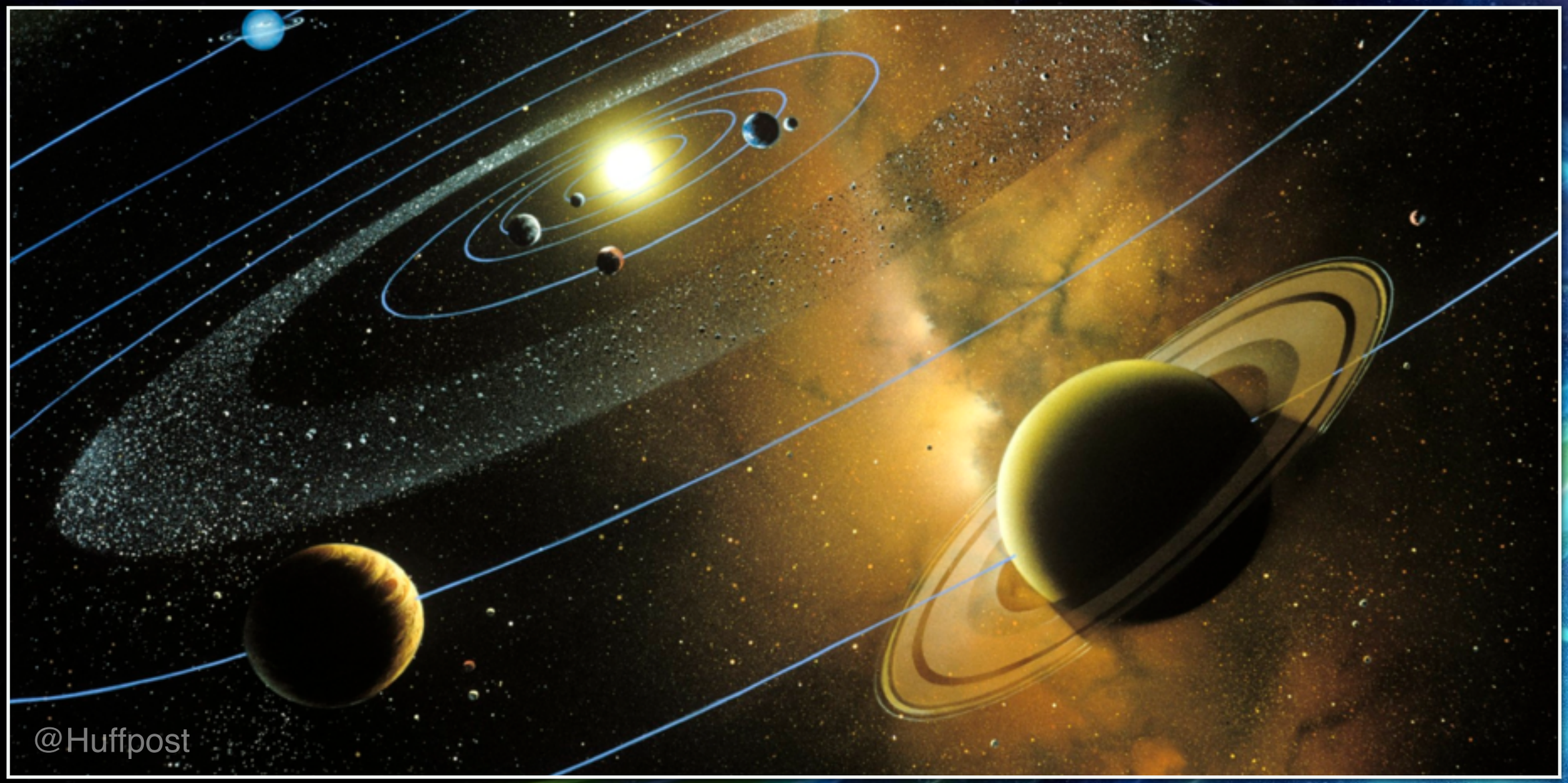
Edwin Hubble's observations

Our Solar System



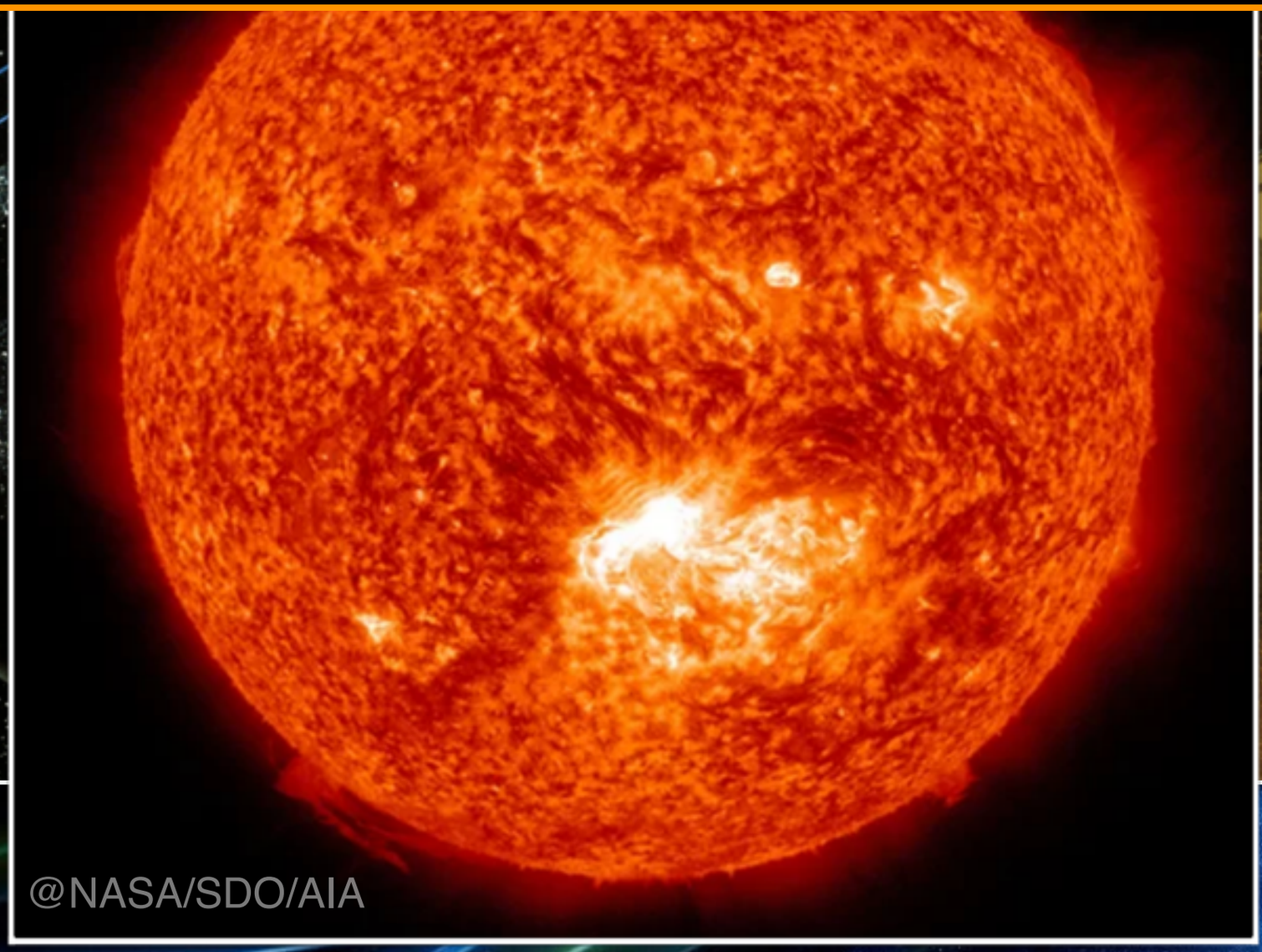
Our Solar System

2 000 000 000 000 000 000 000 000 000 000 kg

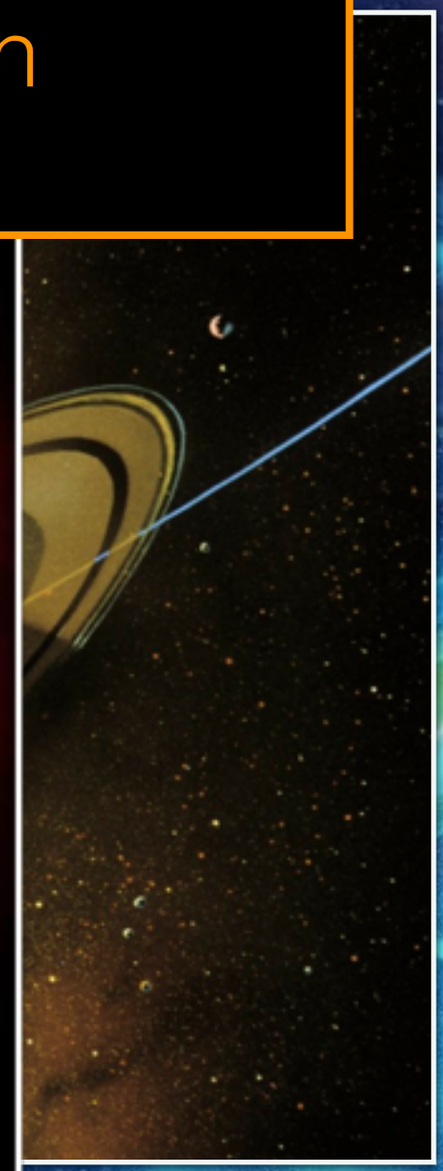
333 333 times the mass of the Earth

1 Solar Mass

@Huffpost



@NASA/SDO/AIA



How Big Are Planets and Stars?

https://www.youtube.com/watch?v=octRYMsiLX0

What is the Size of Our Solar System?

Relative size in this image is ok
. . . but the distances are NOT ok

@ESA/Hubble (M. Kornmesser & L. Calçada)

@Wikipedia

What is the Size of Our Solar System?

This is the Earth - Moon system at correct scale.

380 000 km

@Bob Singer

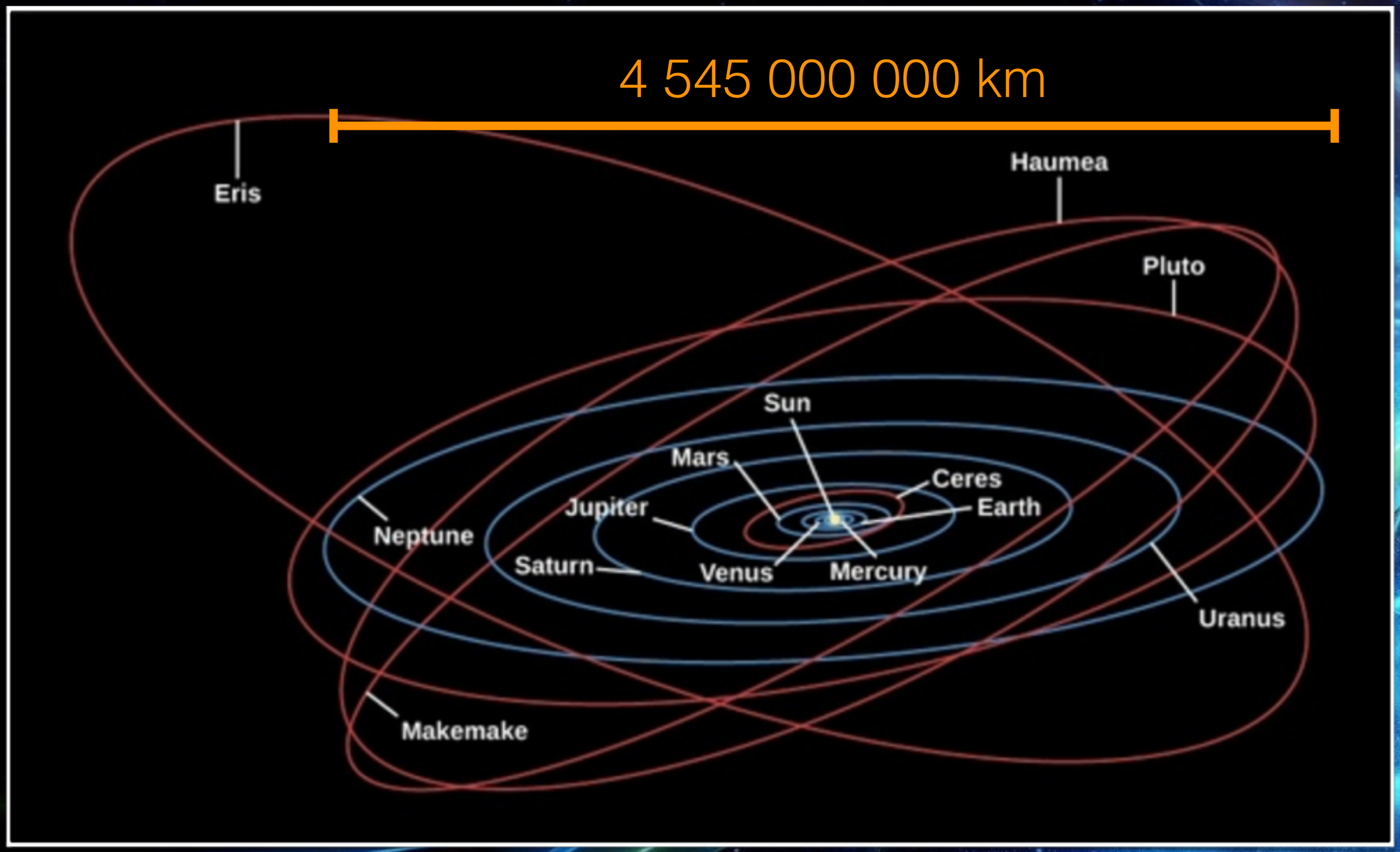
~ 160 days by car

Sun - Earth

150 000 000 km

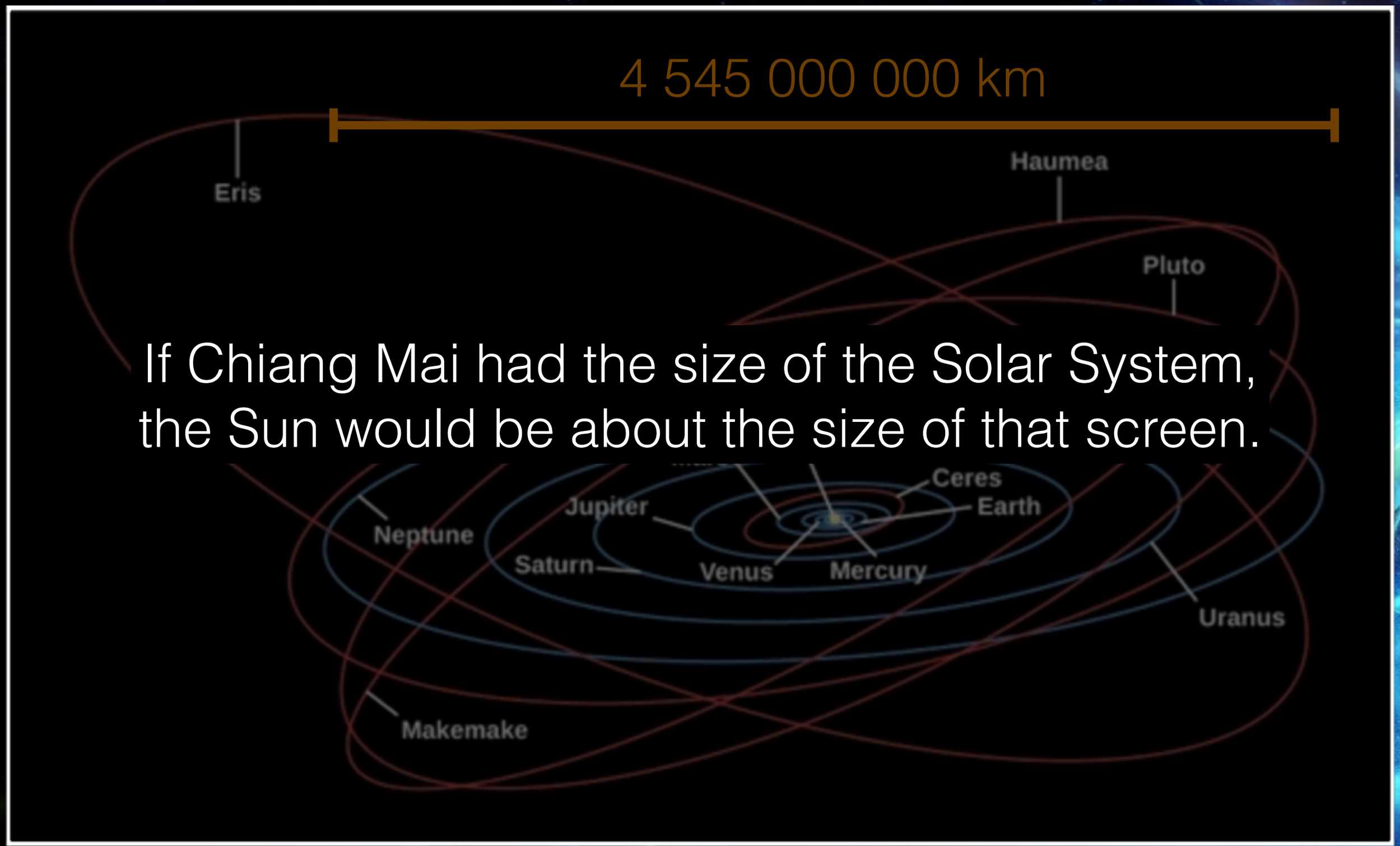
~ 170 years by car

What is the Size of Our Solar System?



https://www.quora.com/Do-all-planetary-systems-orbit-their-stars-in-the-same-plane-or-is-it-just-to-make-life-easier-for-illustrators-when-creating-artist-impressions

What is the Size of Our Solar System?



If Chiang Mai had the size of the Solar System, the Sun would be about the size of that screen.

https://www.quora.com/Do-all-planetary-systems-orbit-their-stars-in-the-same-plane-or-is-it-just-to-make-life-easier-for-illustrators-when-creating-artist-impressions

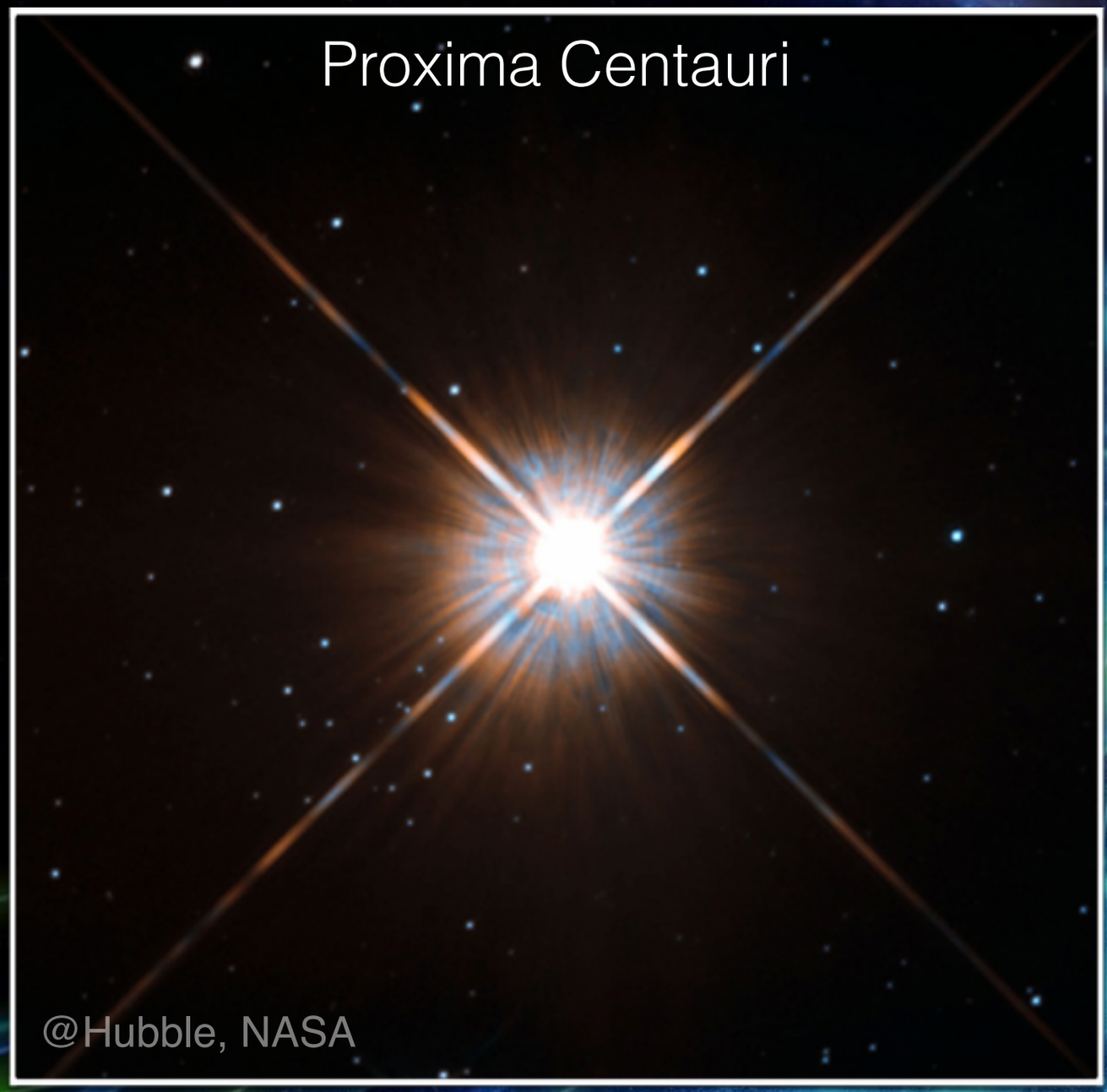
Distance to the Closest Star

4.24 light-years away

speed of light
300 000 000 meters per second

Light travels around the world
7.5 times in one second!

31 536 000 seconds in a year



Proxima Centauri is at 40 113 000 000 000 km away from us
(.. or 4.24 light-years)

Distance to the Closest Star

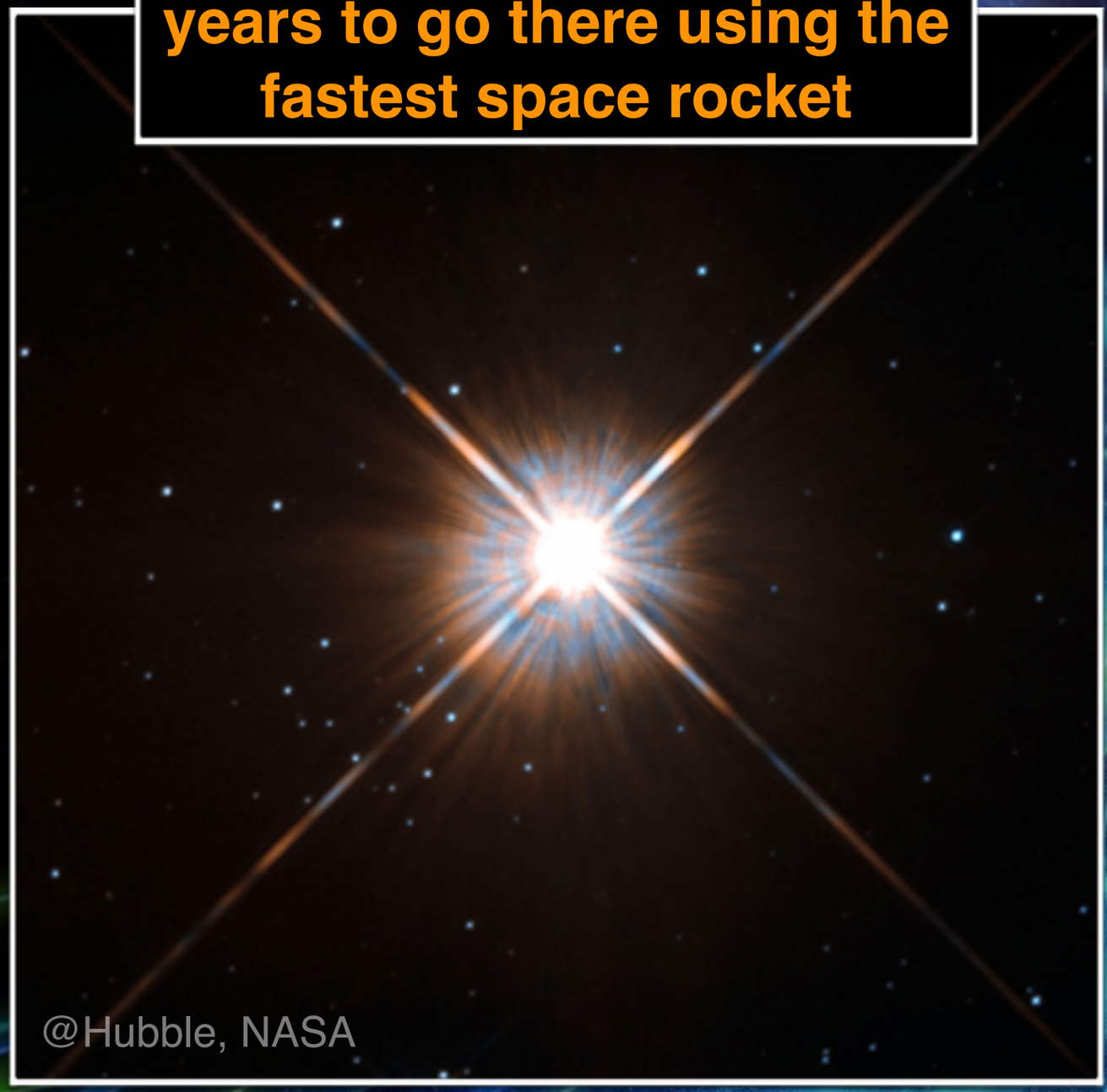
4.24 light-years away

speed of light
300 000 000 meters per second

Light travels around the world
7.5 times in one second!

31 536 000 seconds in a year

Would take about 7000 years to go there using the fastest space rocket

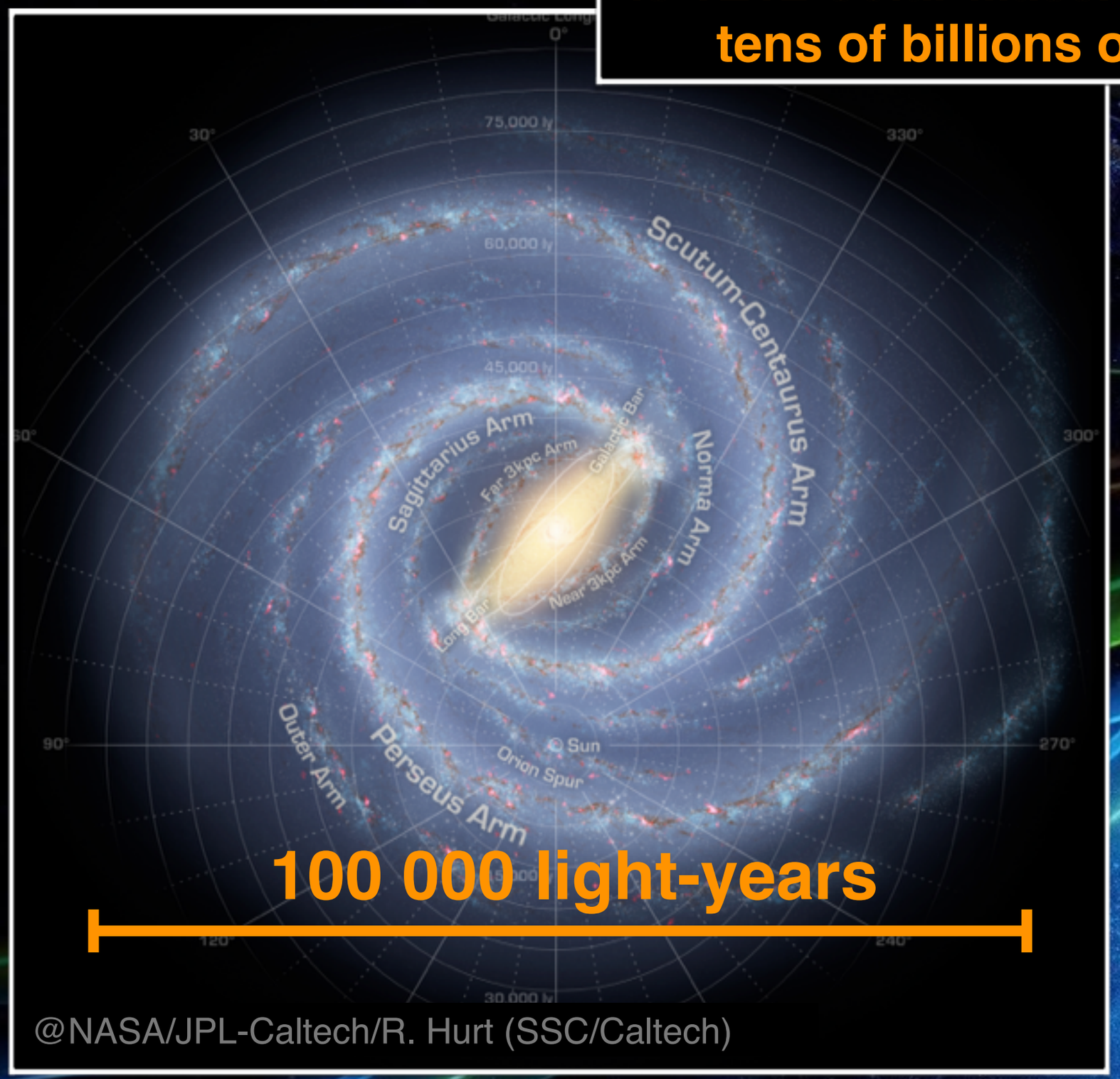


@Hubble, NASA

Proxima Centauri is at 40 113 000 000 000 km away from us
(.. or 4.24 light-years)

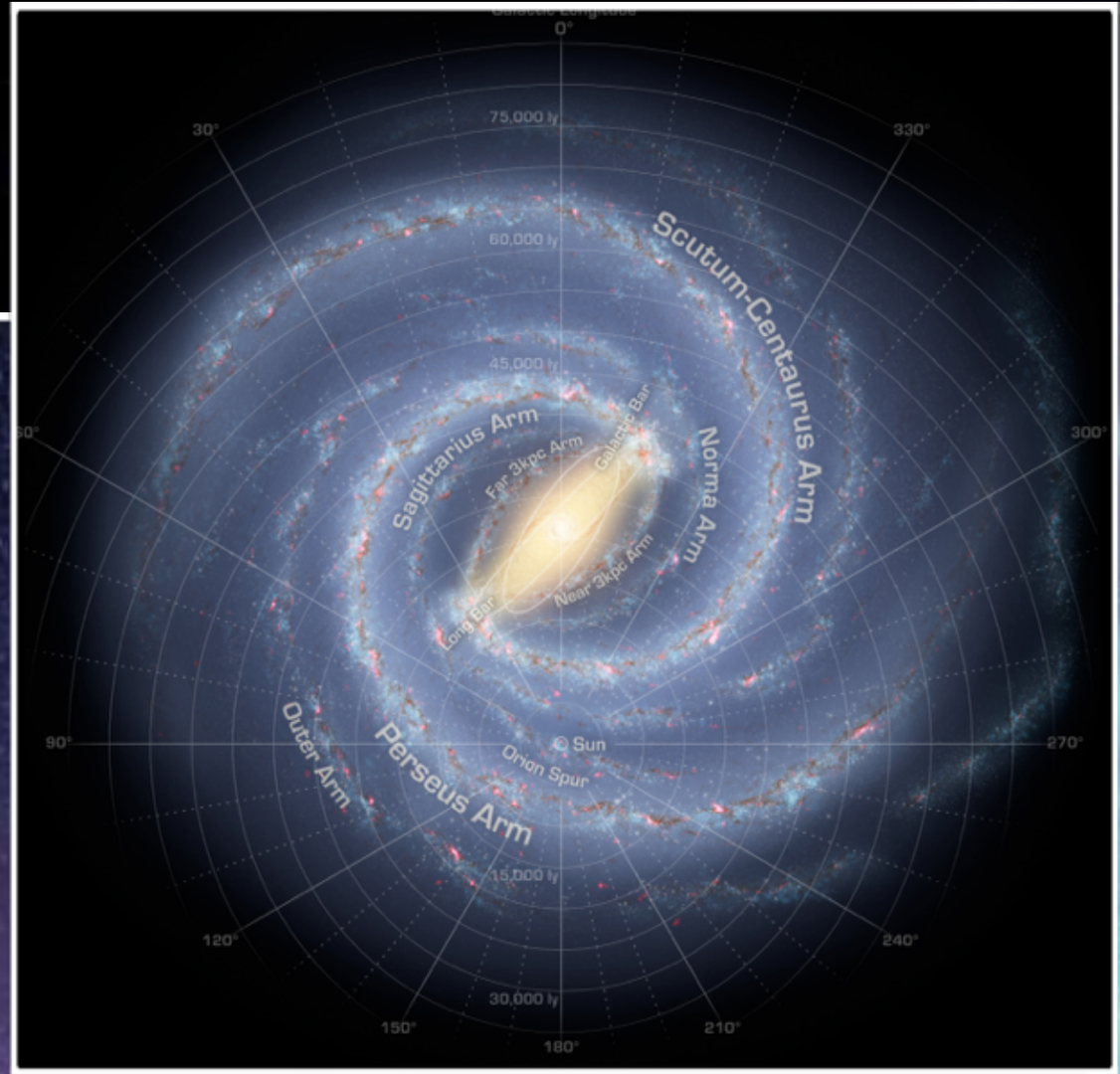
Our Galaxy, the Milky Way

The total mass of the Milky Way is 1E12 Solar Mass. It contains tens of billions of stars.



@NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

Our Galaxy, the Milky Way



@Hubble telescope

NGC 6357

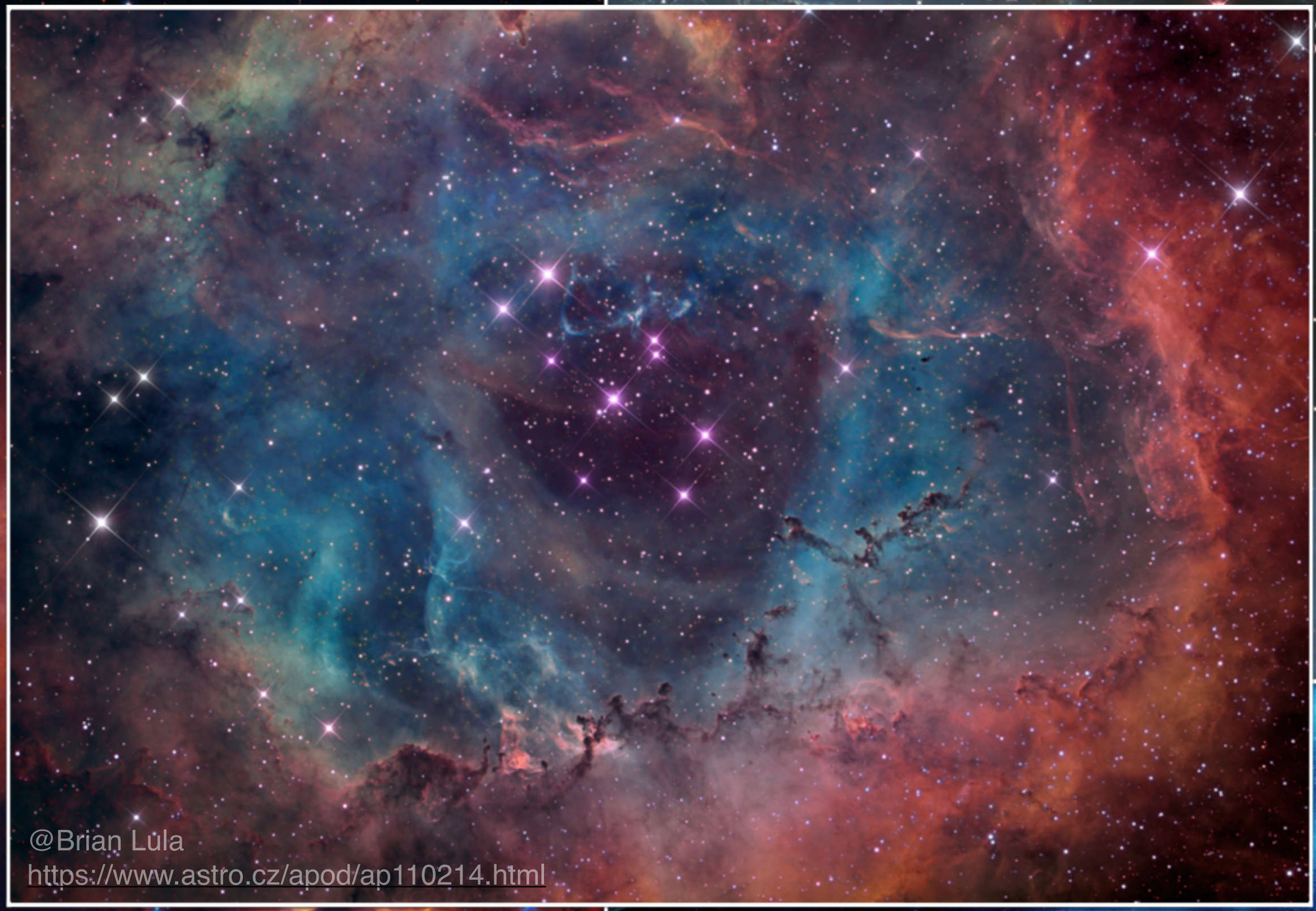
Part of Orion nebula

@NASA, ESA, and the Hubble Heritage Team (STScI/AURA)

@Hubble telescope

NGC 6357

Part of Orion nebula

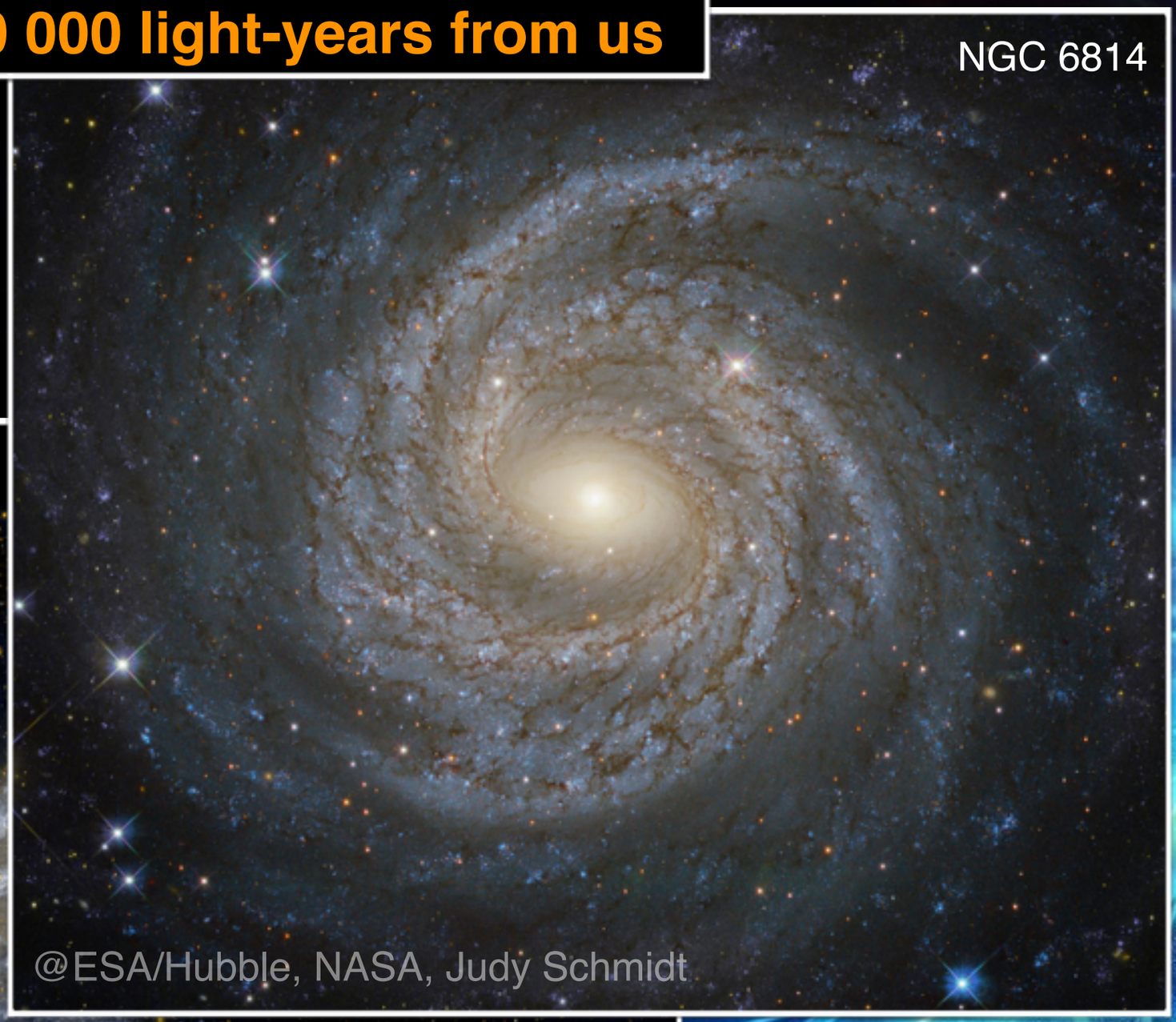


@Brian Lula
https://www.astro.cz/apod/ap110214.html

What is Inside our Galaxy?

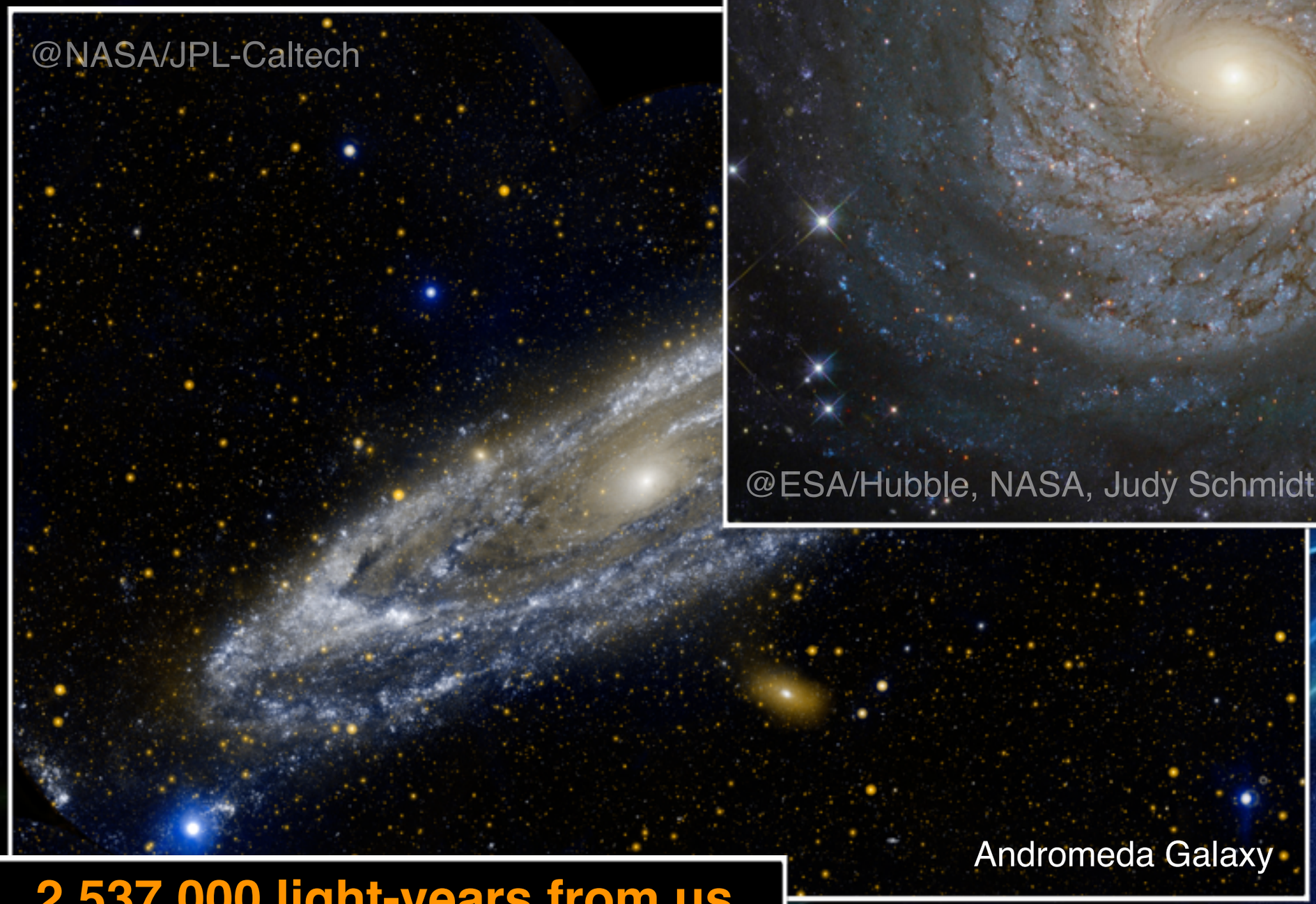
Other Galaxies

70 000 000 light-years from us



NGC 6814

@ESA/Hubble, NASA, Judy Schmidt



@NASA/JPL-Caltech

Andromeda Galaxy

2 537 000 light-years from us

Hubble Deep Field Image

Summary

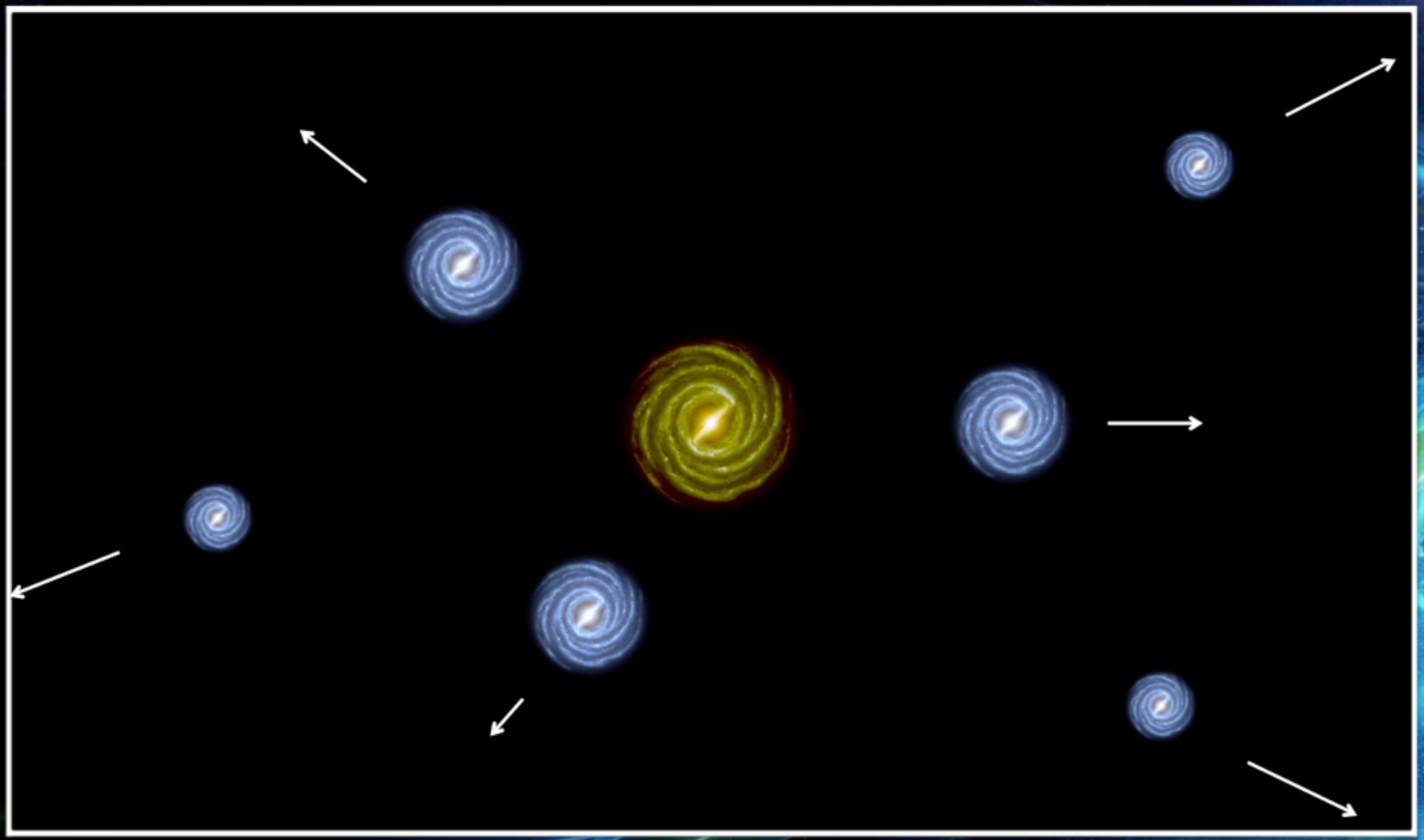
Things are big, massive, and very far apart

A galaxy is composed of gas, dust, and billions of stars (and even more planets)

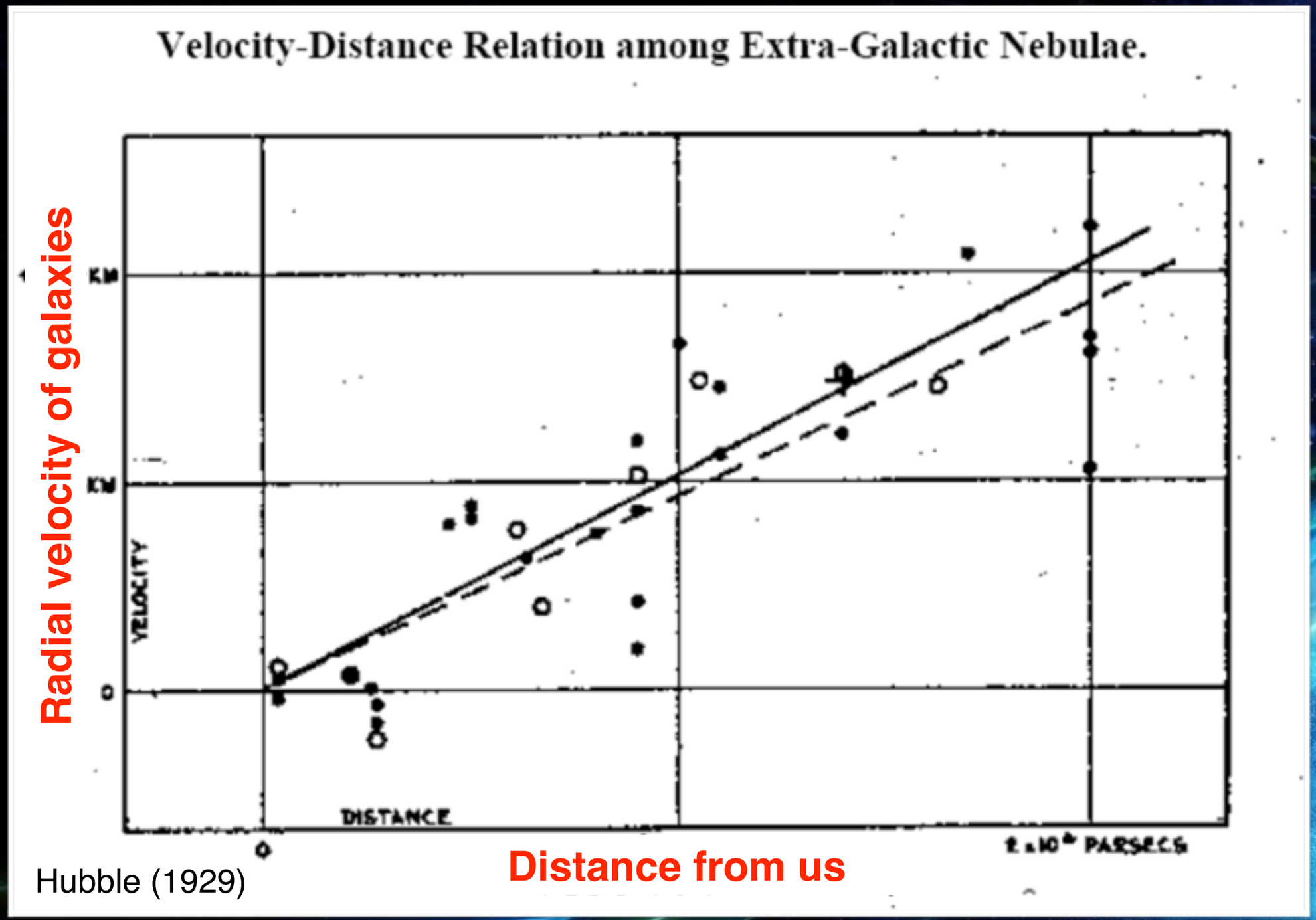
In the Universe we know of, there are billions of galaxies.

Evolution of the Universe

Motion of Galaxies Around Us



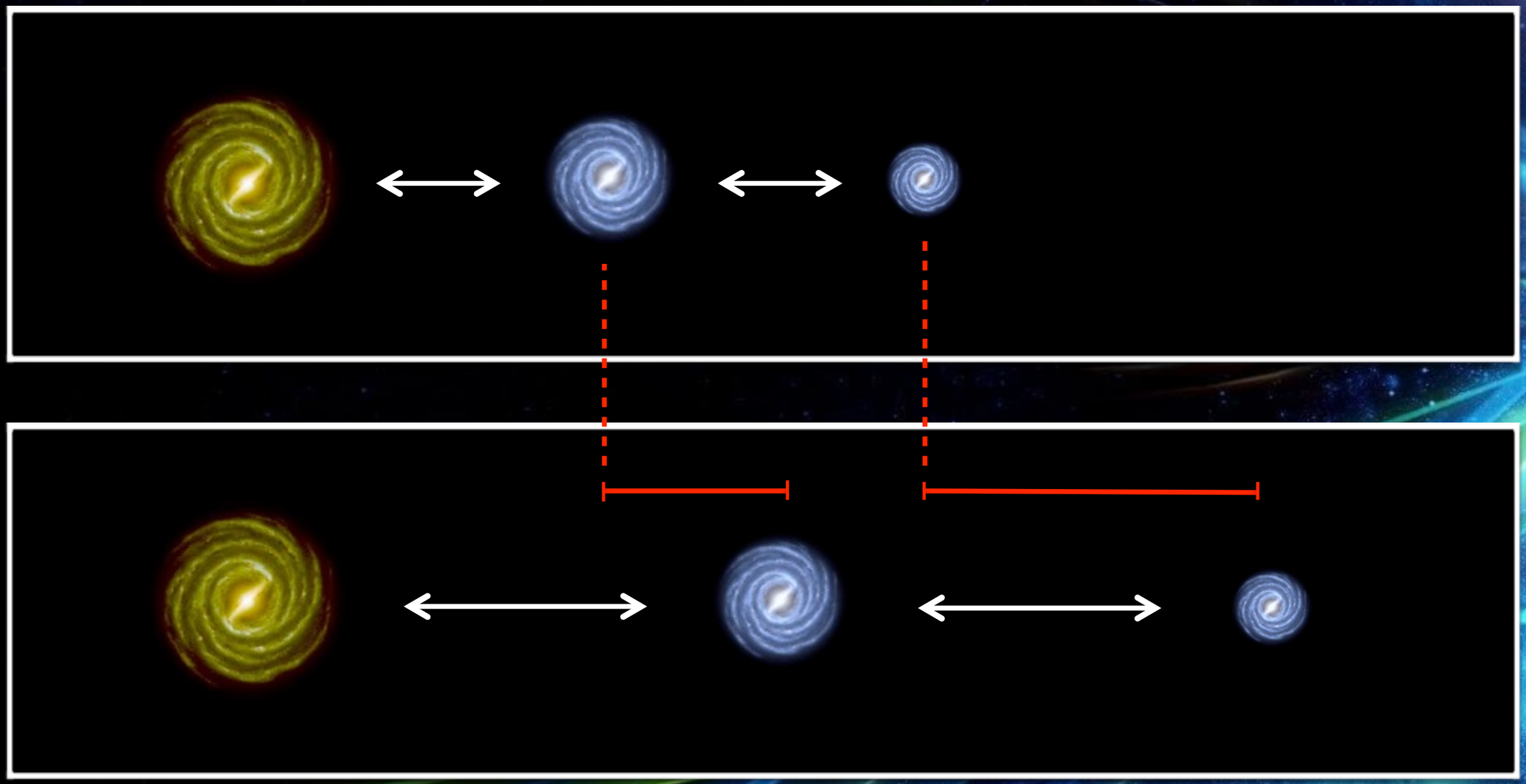
Motion of Galaxies Around Us



Hubble (1929)

The Expansion of the Universe

The Expansion of the Universe



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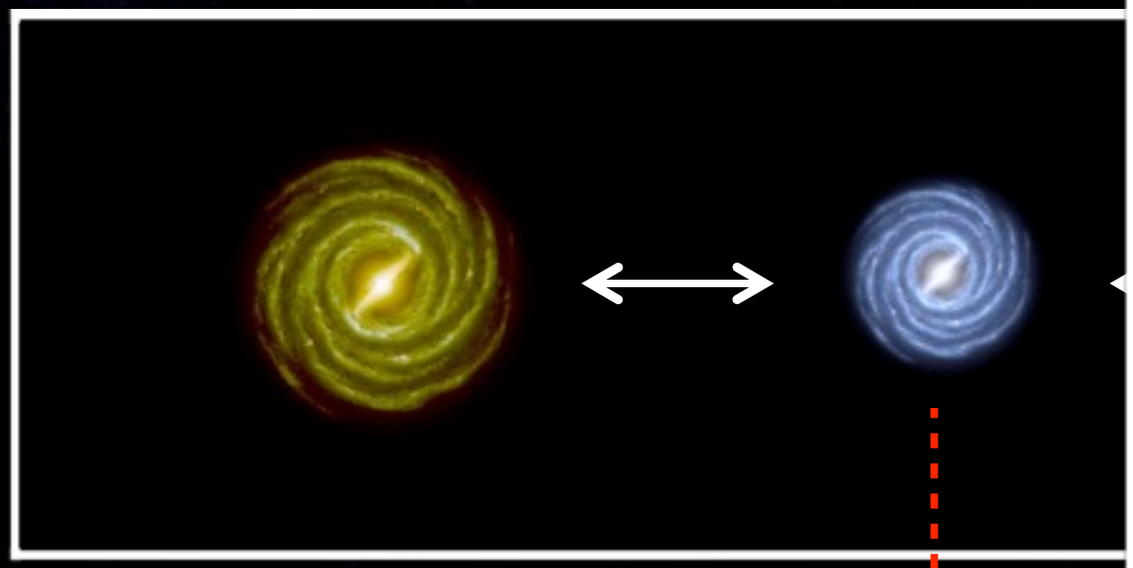
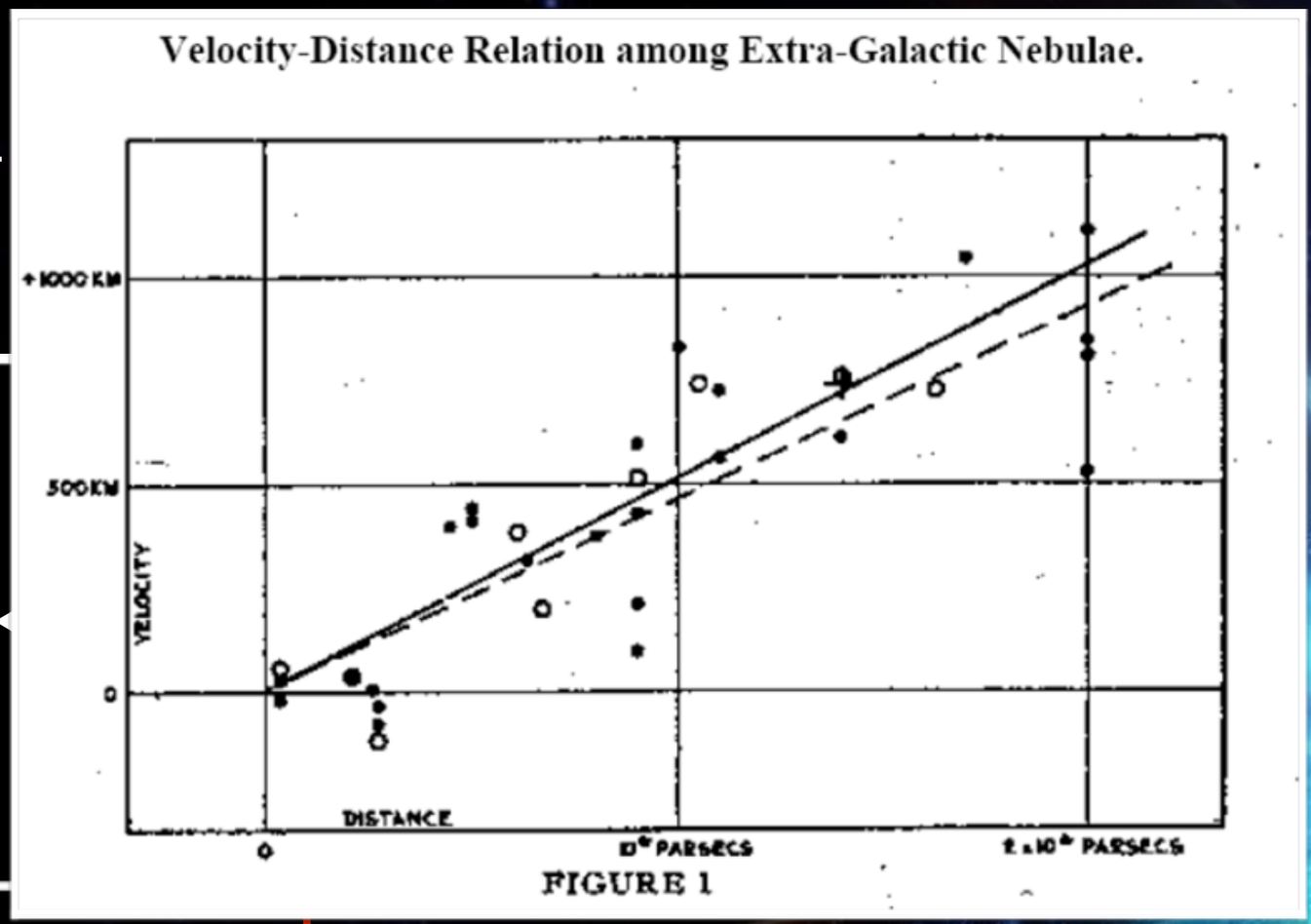
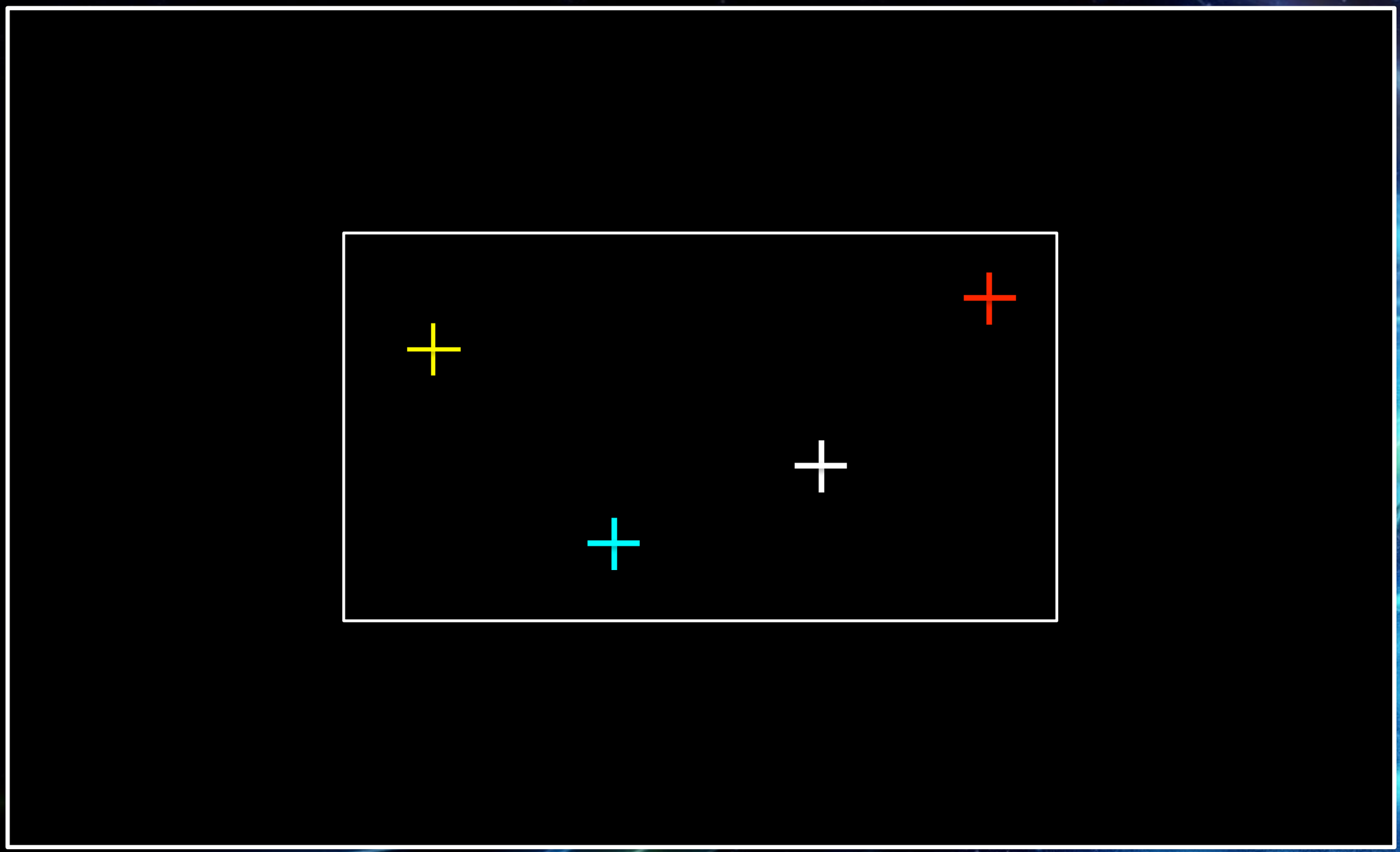
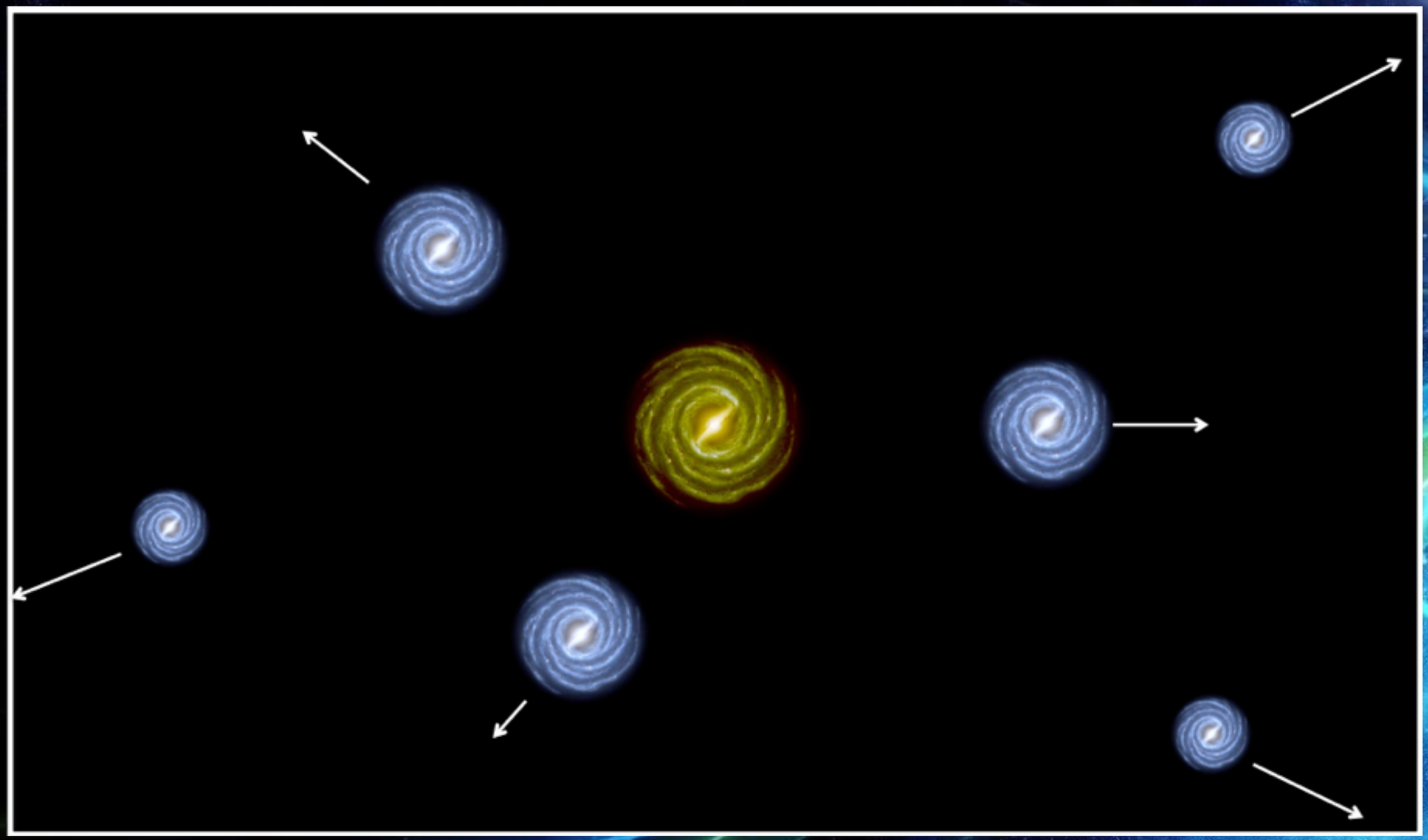




Are We the Center of the Universe?



What Happens if we Go Back in Time?



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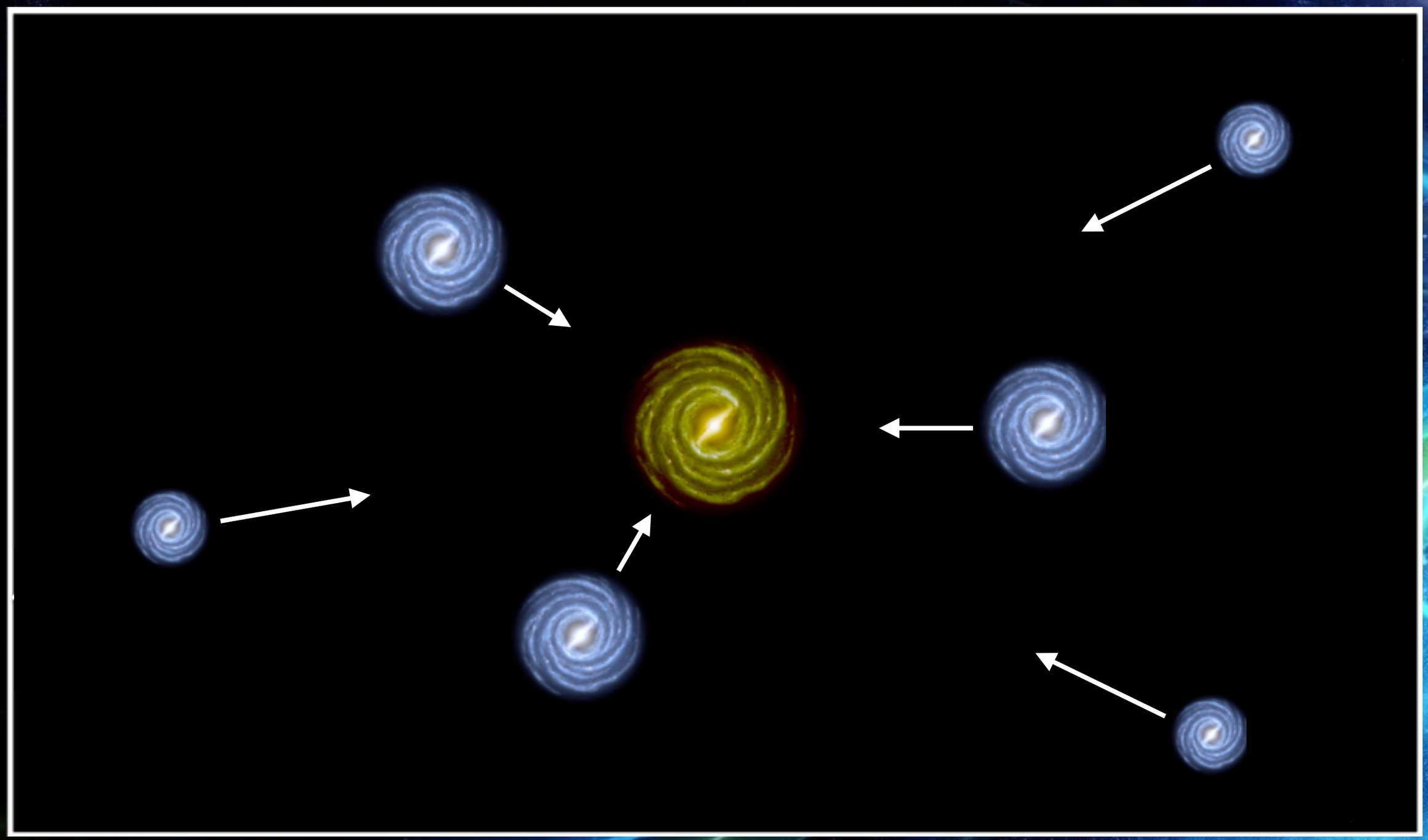
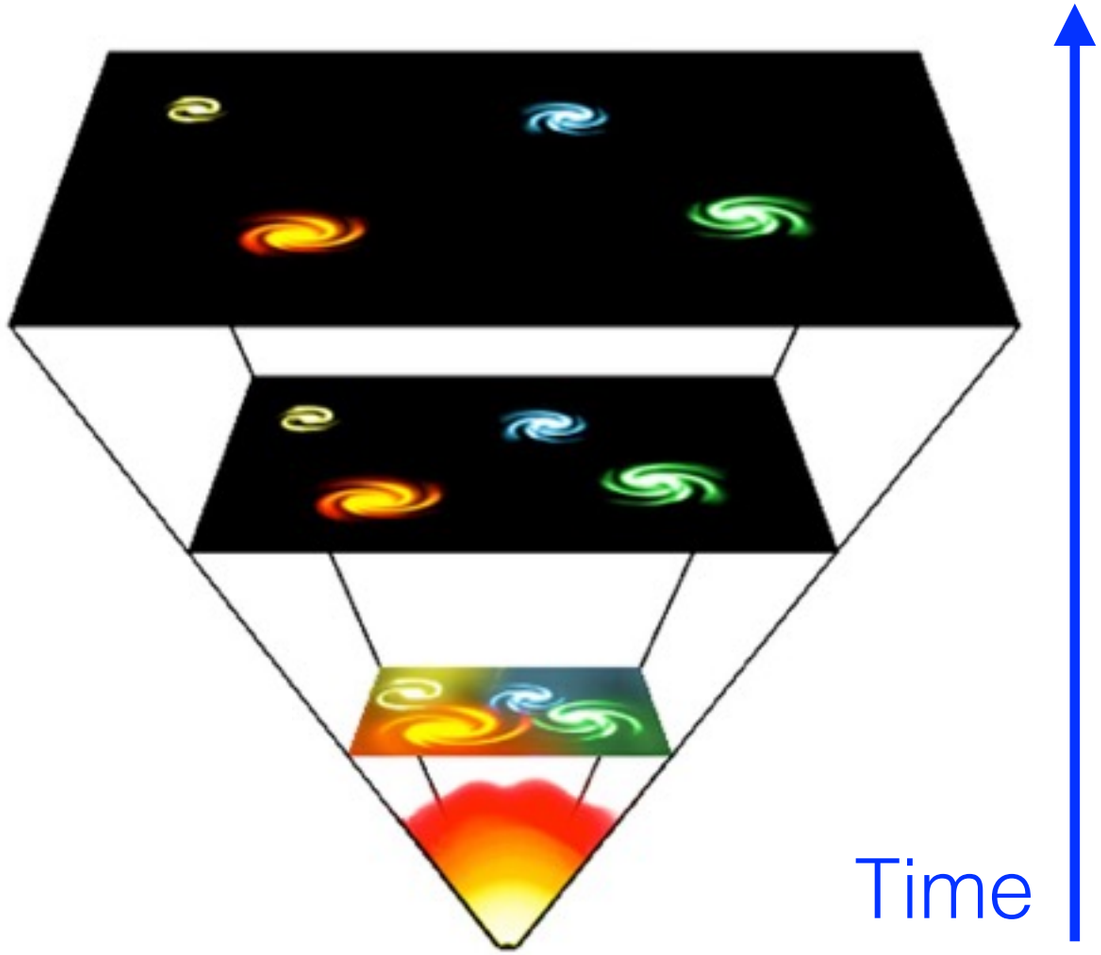


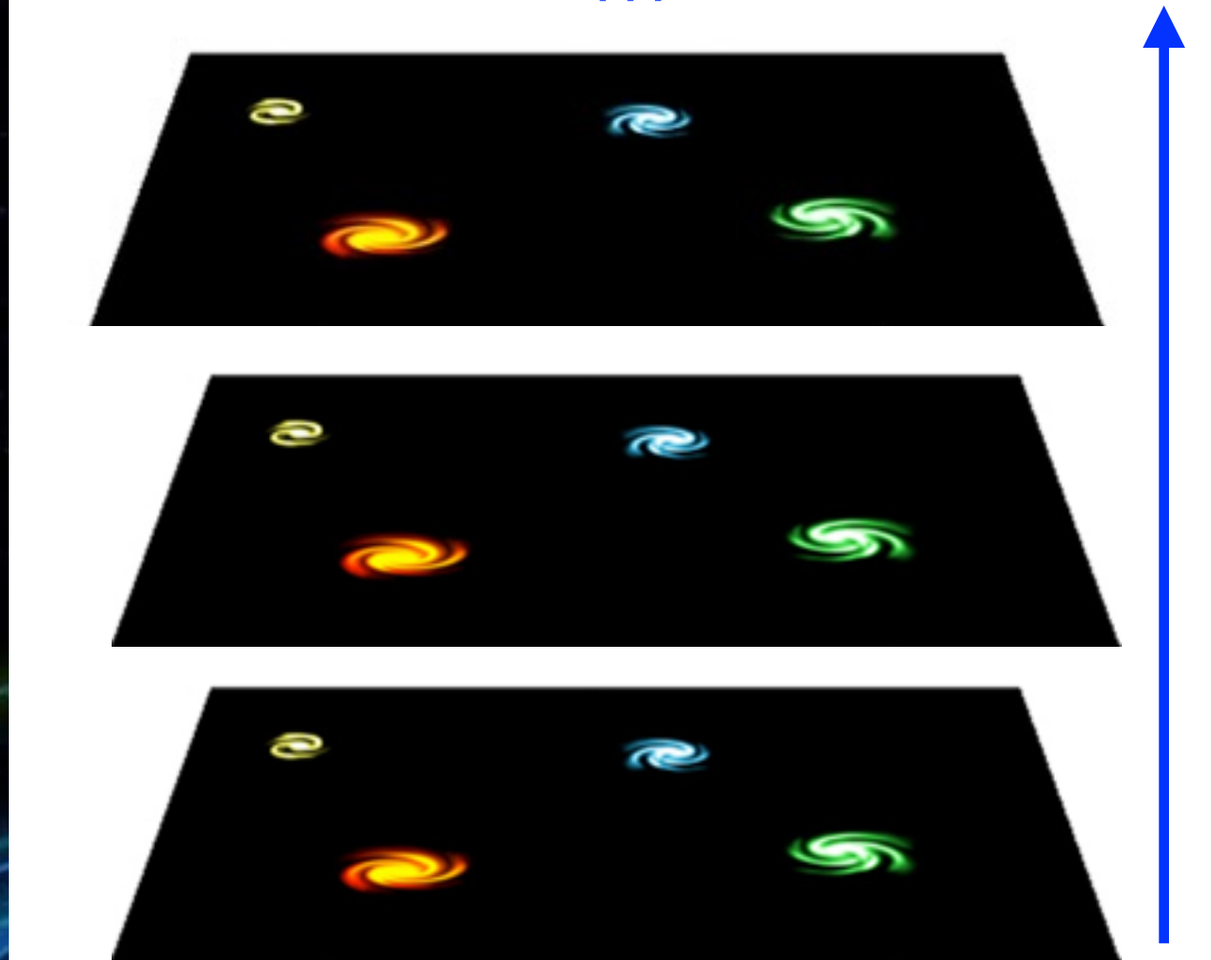
The Big Bang

The density of matter **changes**



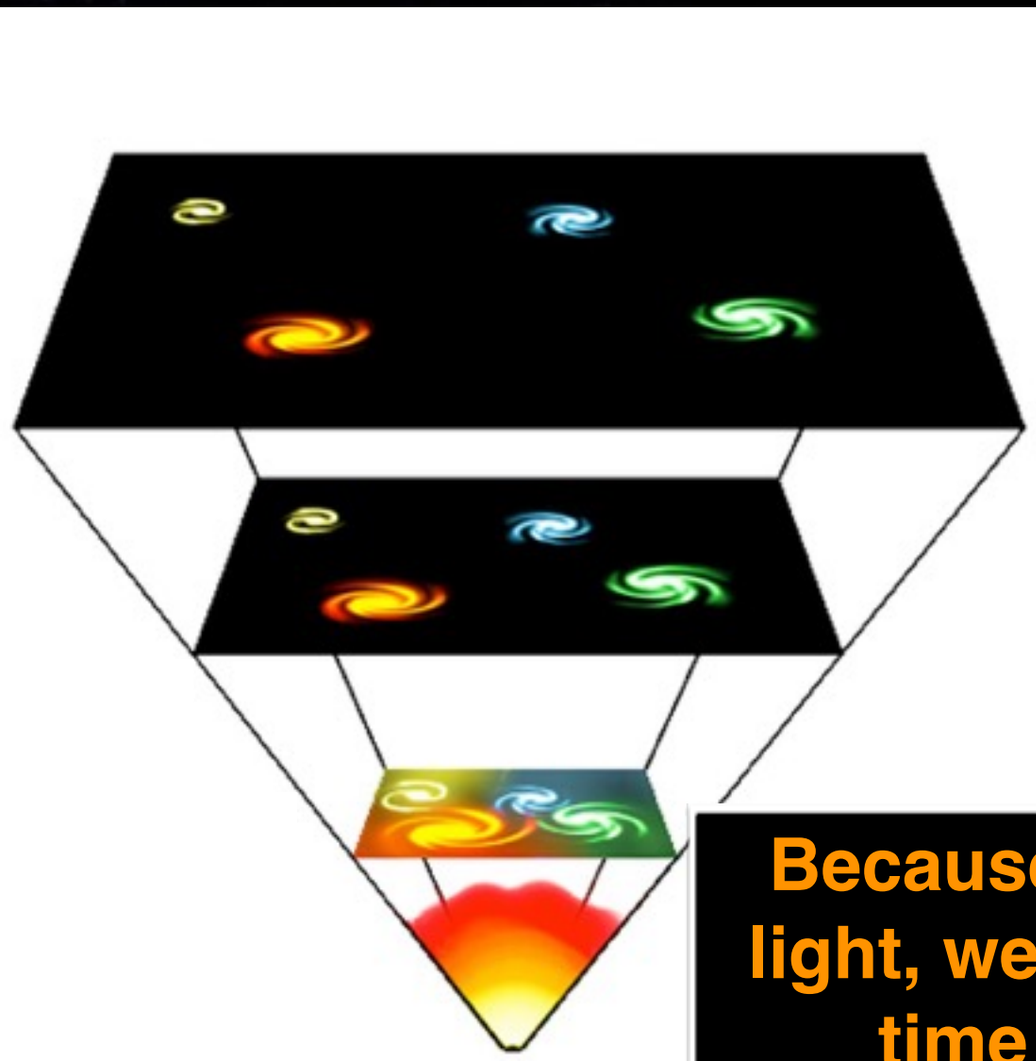
The Stationary Universe

The density of matter **never changes**



The Big Bang

The density of matter **changes**



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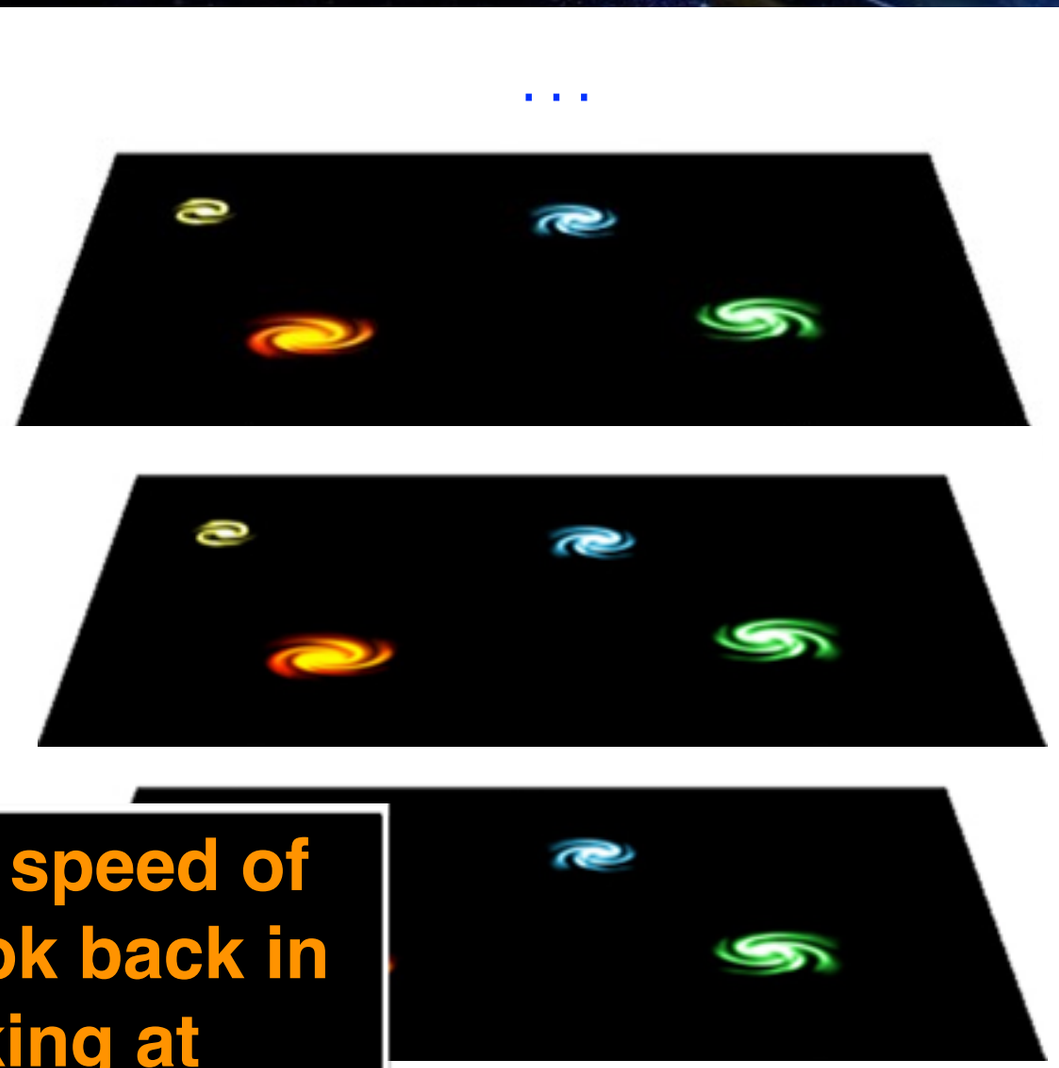
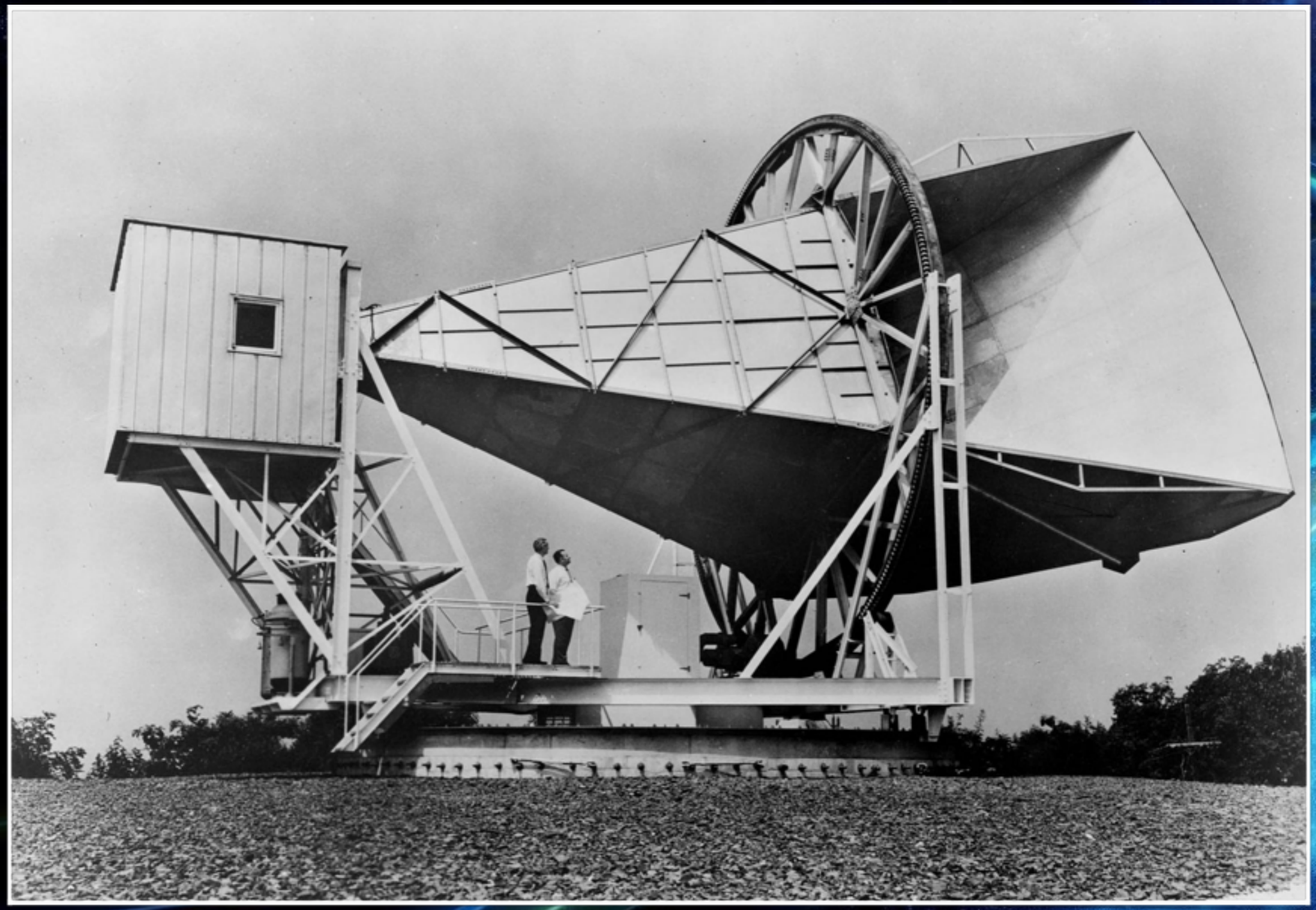


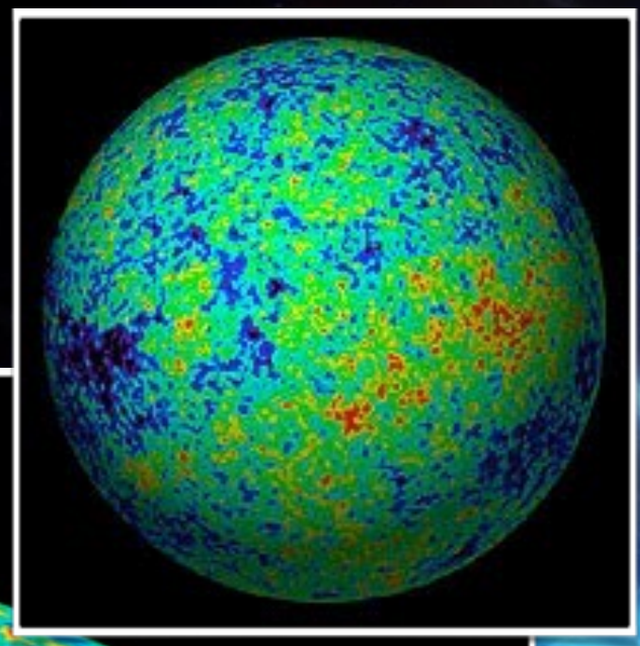
Because of the speed of light, we can look back in time by looking at something far away

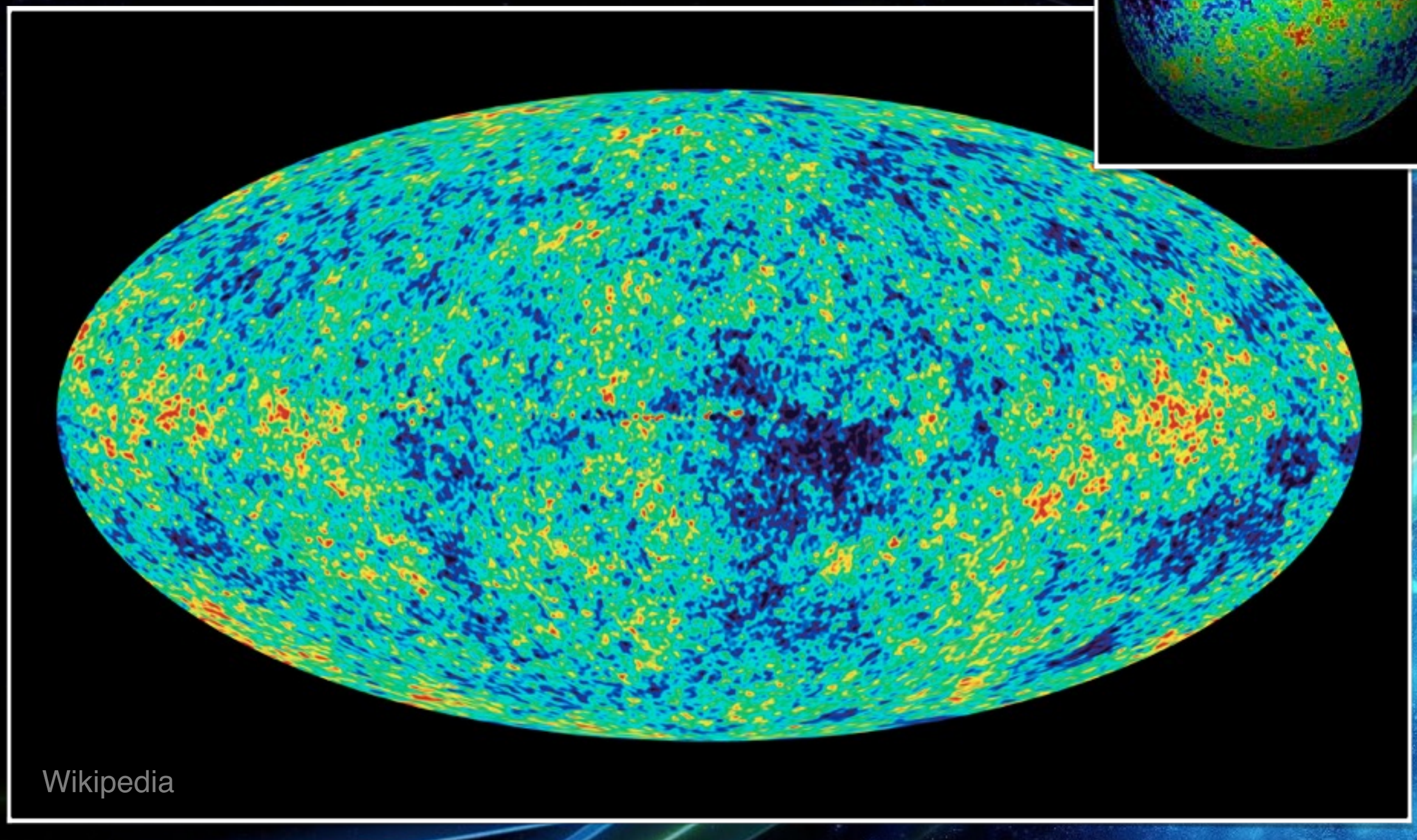
Detection of the Cosmic Microwave Background



Wikipedia - Horn Antenna-in Holmdel, New Jersey

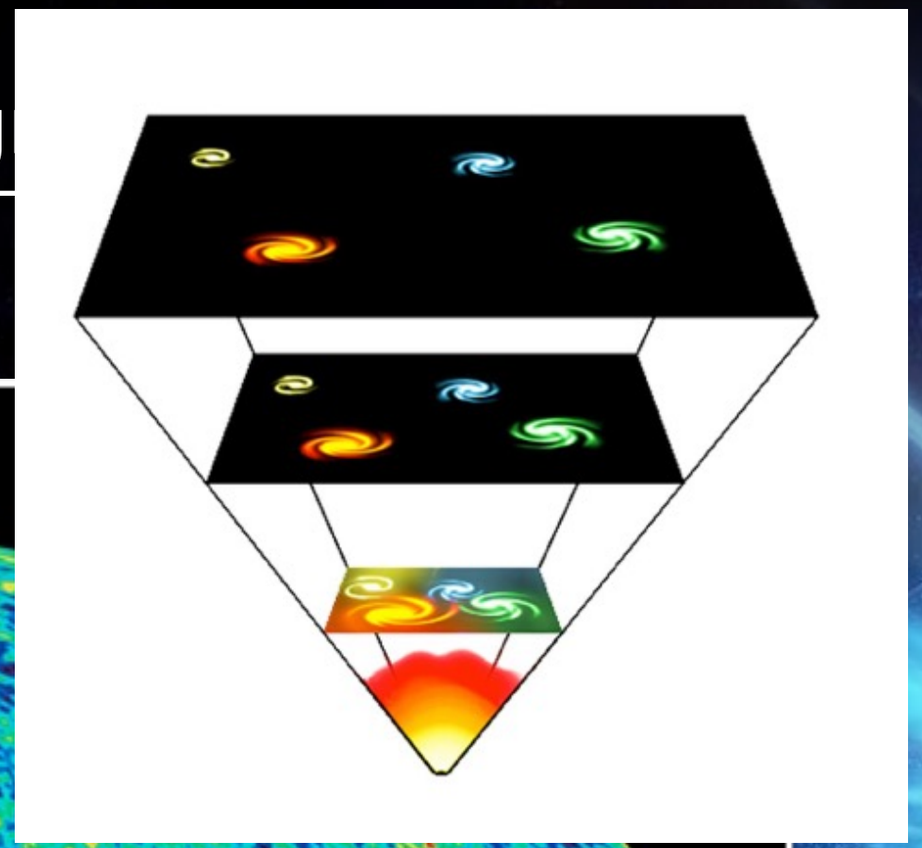
Detection of the Cosmic Microwave Background





Wikipedia

Detection of the Cosmic Microwave Backg

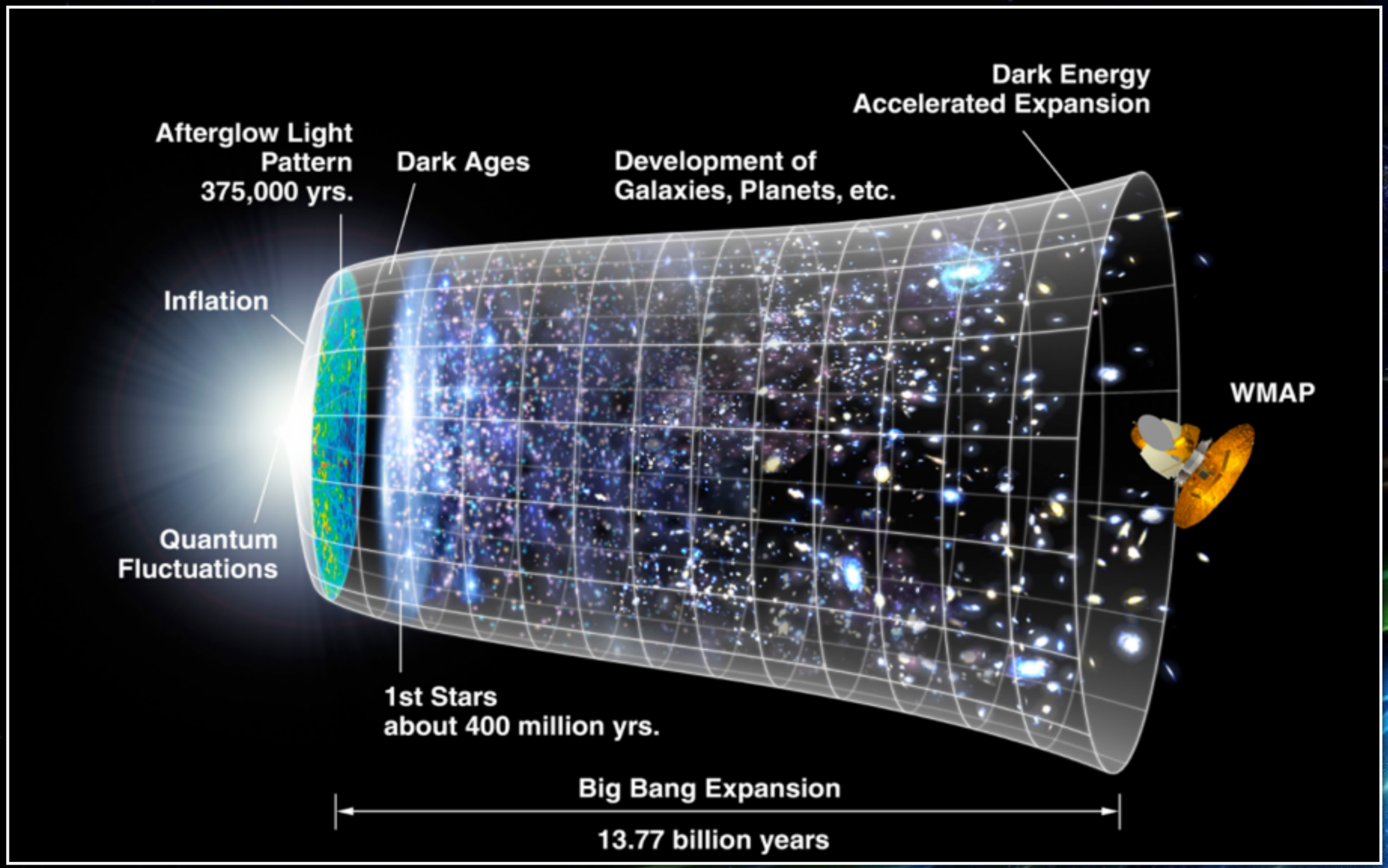


This light is 13.7 billions light-years away from us, which means this light was emitted 13.7 billions ago.

Wikipedia

This is the oldest picture in the Universe

The Evolution of the Universe



Summary

The space of the Universe is expanding,
and it is accelerating.

The detection of the cosmic microwave background
proves that the Universe had a beginning.

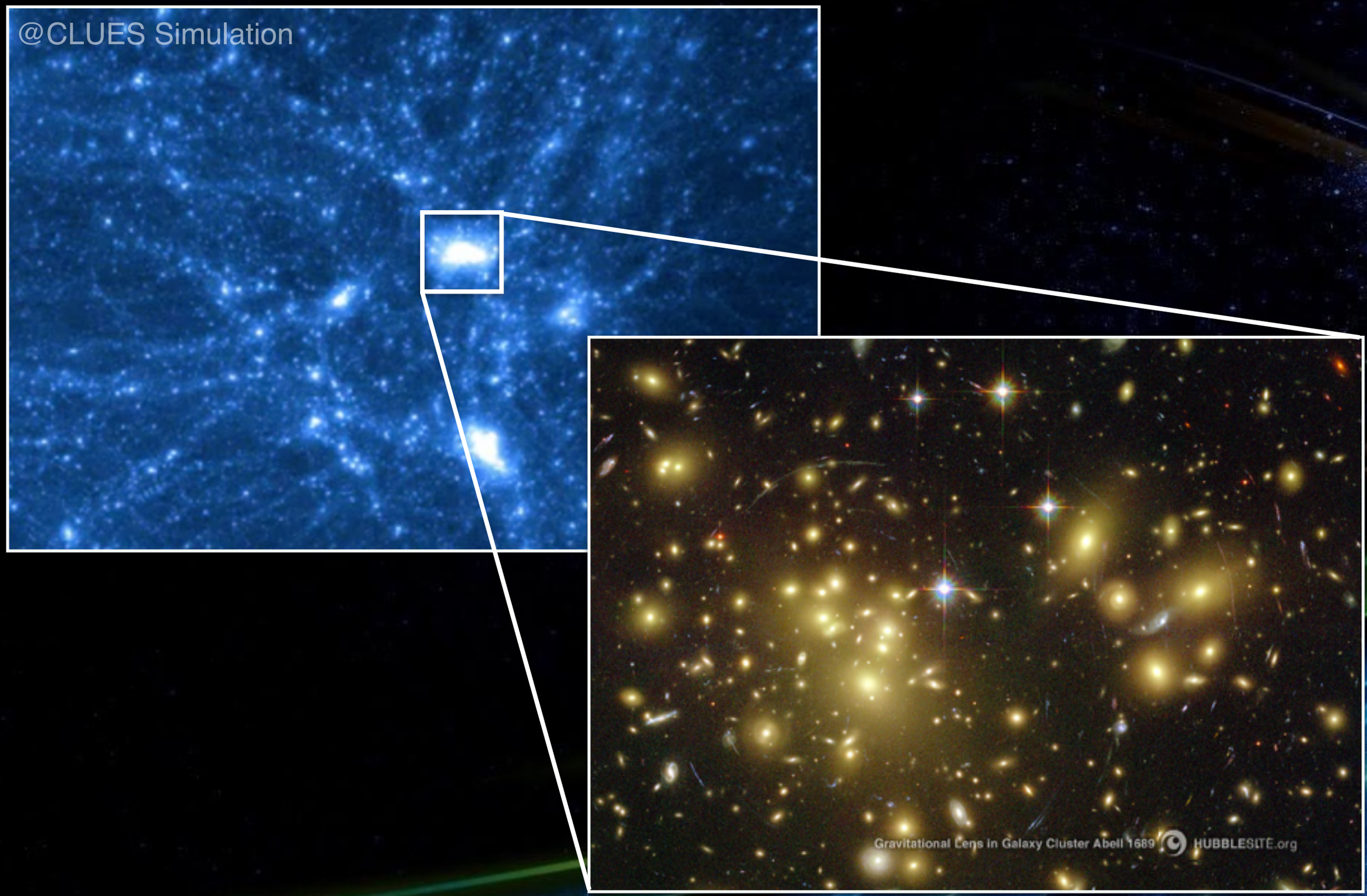
There was a time, 13.7 billions of years ago where
there was no galaxy, no star, no planet, no life.

The Formation and Evolution of Galaxies

Video

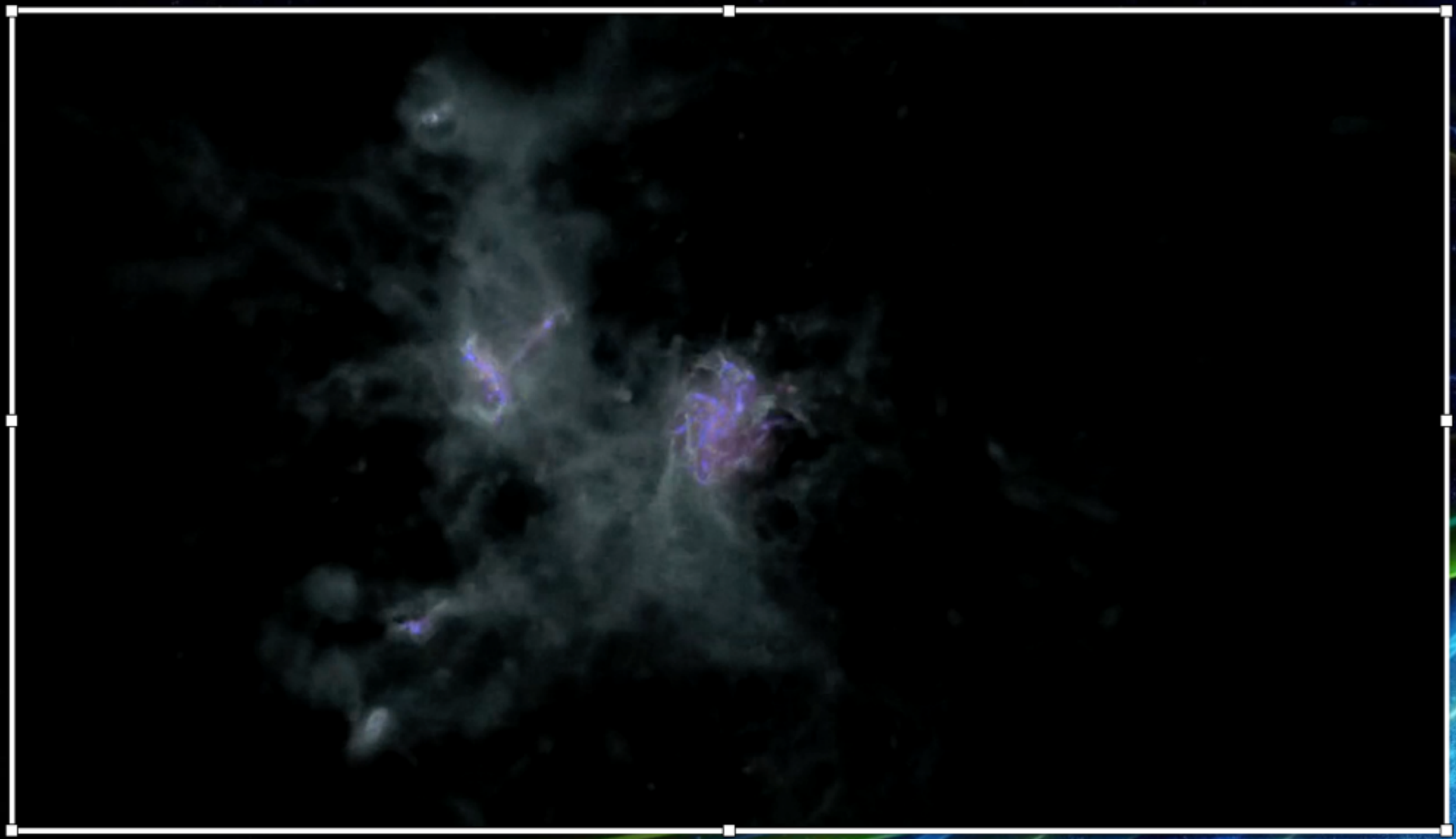
@CLUES Simulation

The Formation of Galaxies



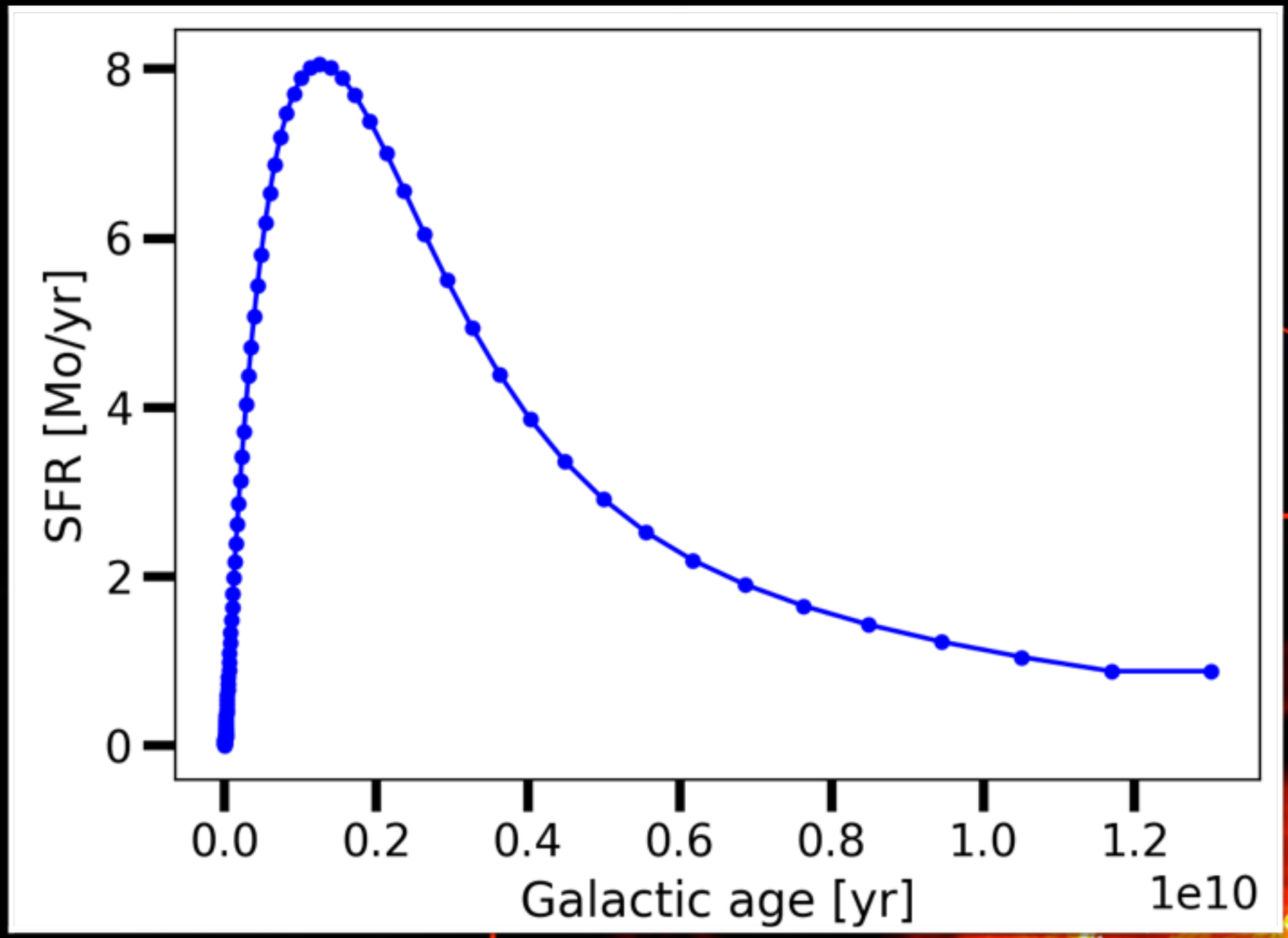
The Formation of Galaxies

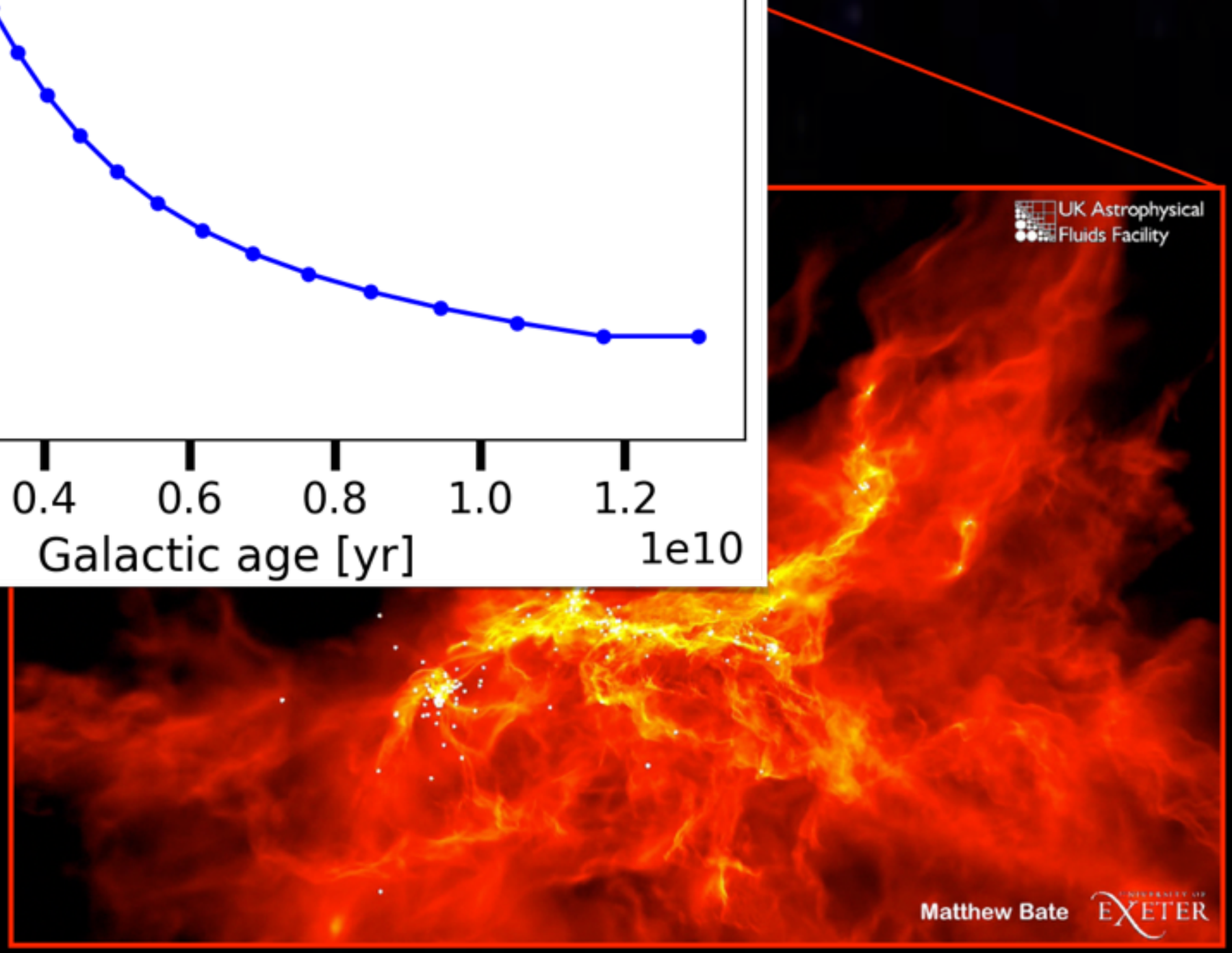
@F. Governato and T. Quinn (Univ. of Washington), A. Brooks (Univ. of Wisconsin, Madison), and J. Wadsley (McMaster Univ.), NASA's Ames Research Center



https://www.youtube.com/watch?v=_Ssc1GsqHds

The Formation of Stars

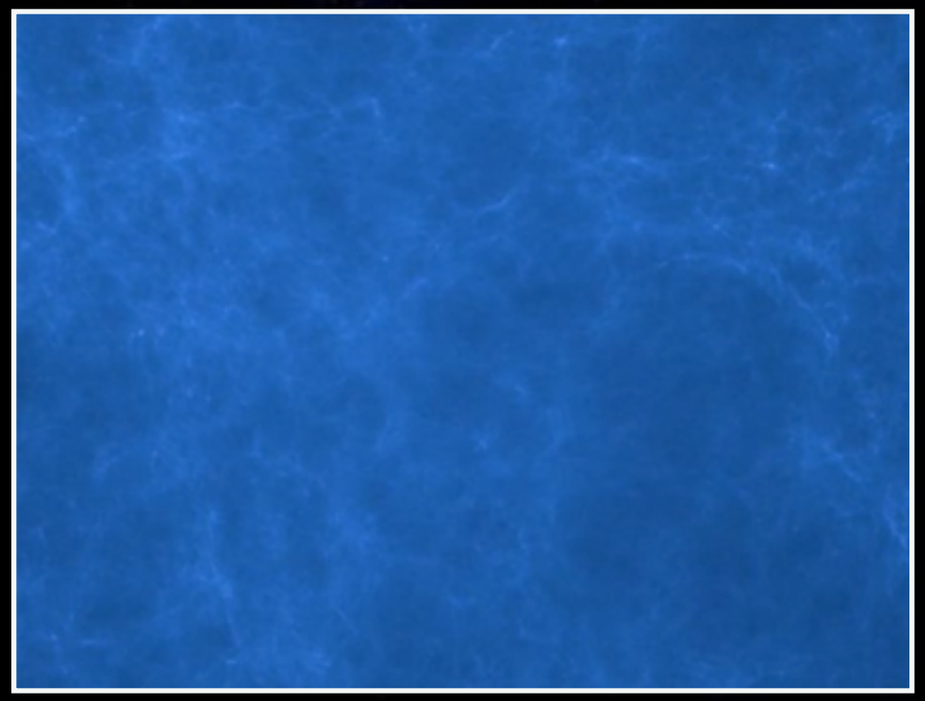

SFR [Mo/yr]
0
2
4
6
8
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1e10
Galactic age [yr]


UK Astrophysical Fluids Facility
Matthew Bate
University of Exeter

The Evolution of Chemical Elements in Galaxies

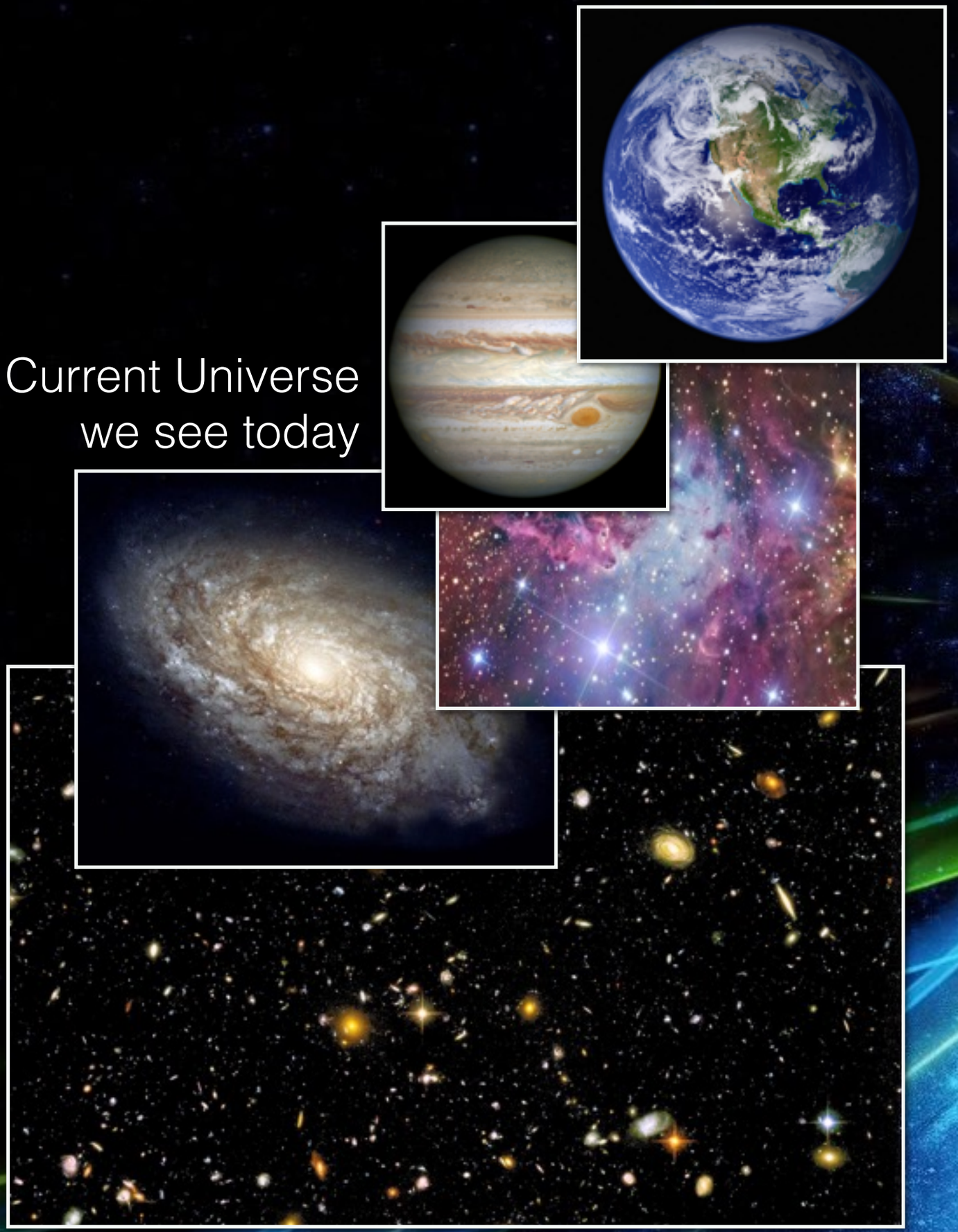
Chemical Evolution

Universe at early time



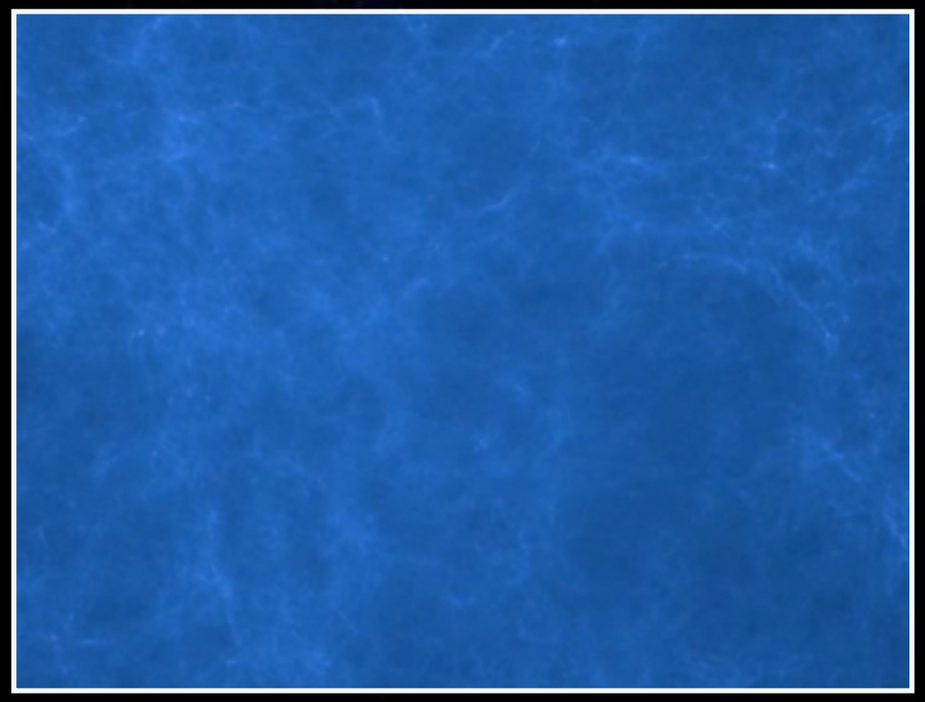
After 13.7 Gyr of evolution

Current Universe
we see today



Chemical Evolution

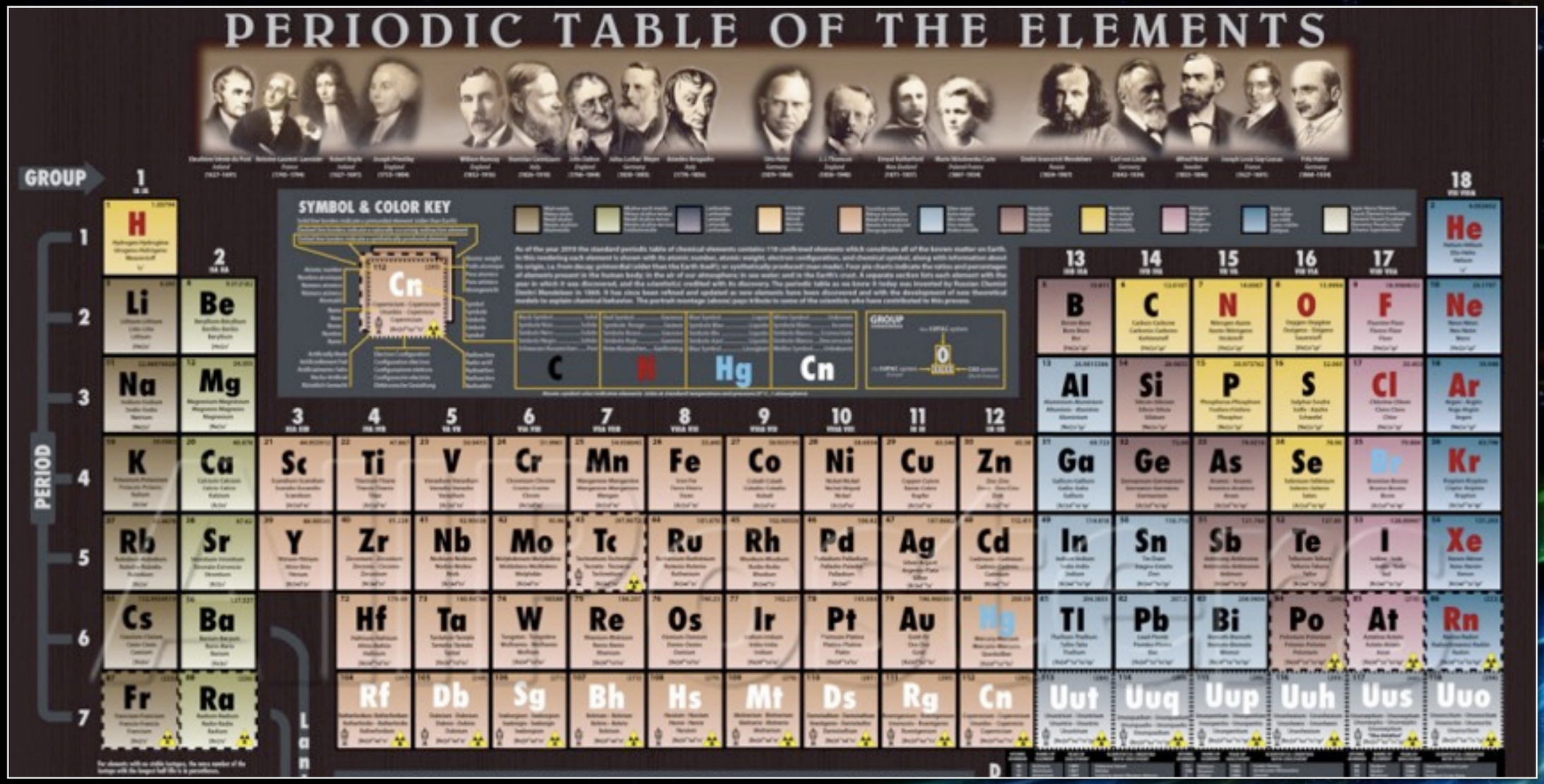
Only composed of Hydrogen (**H**) and Helium (**He**)



After 13.7 Gyr of evolution

C, N, O, Ca, Mg, Fe, Ni, Ag, Au, ..

Neutrons, Protons, and Atoms



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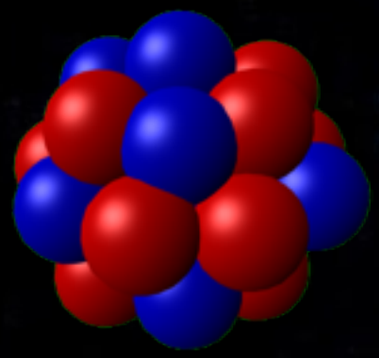
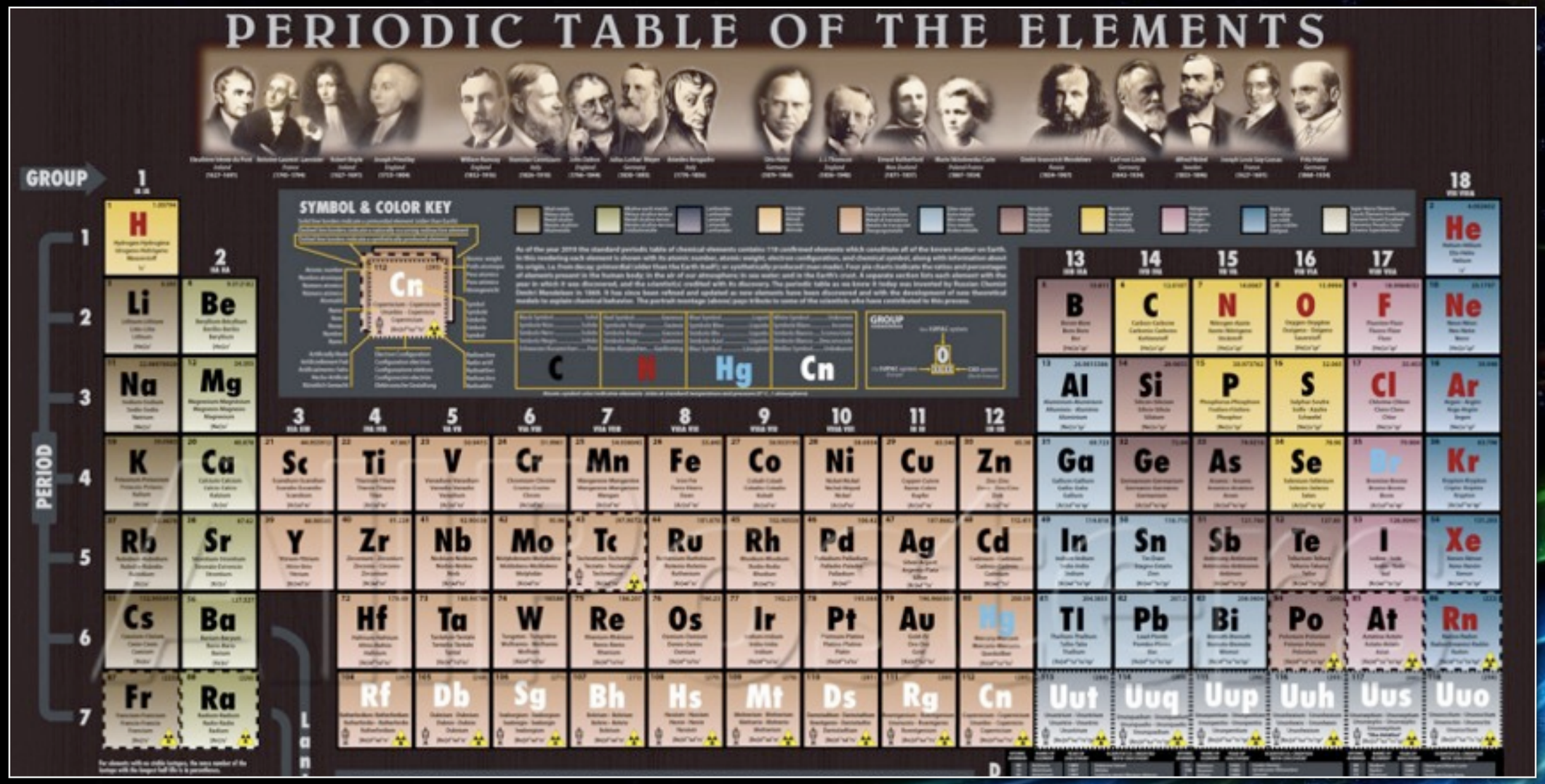
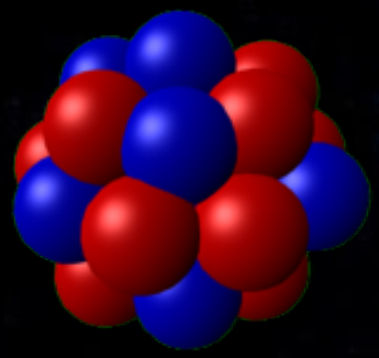


Proton

Neutron

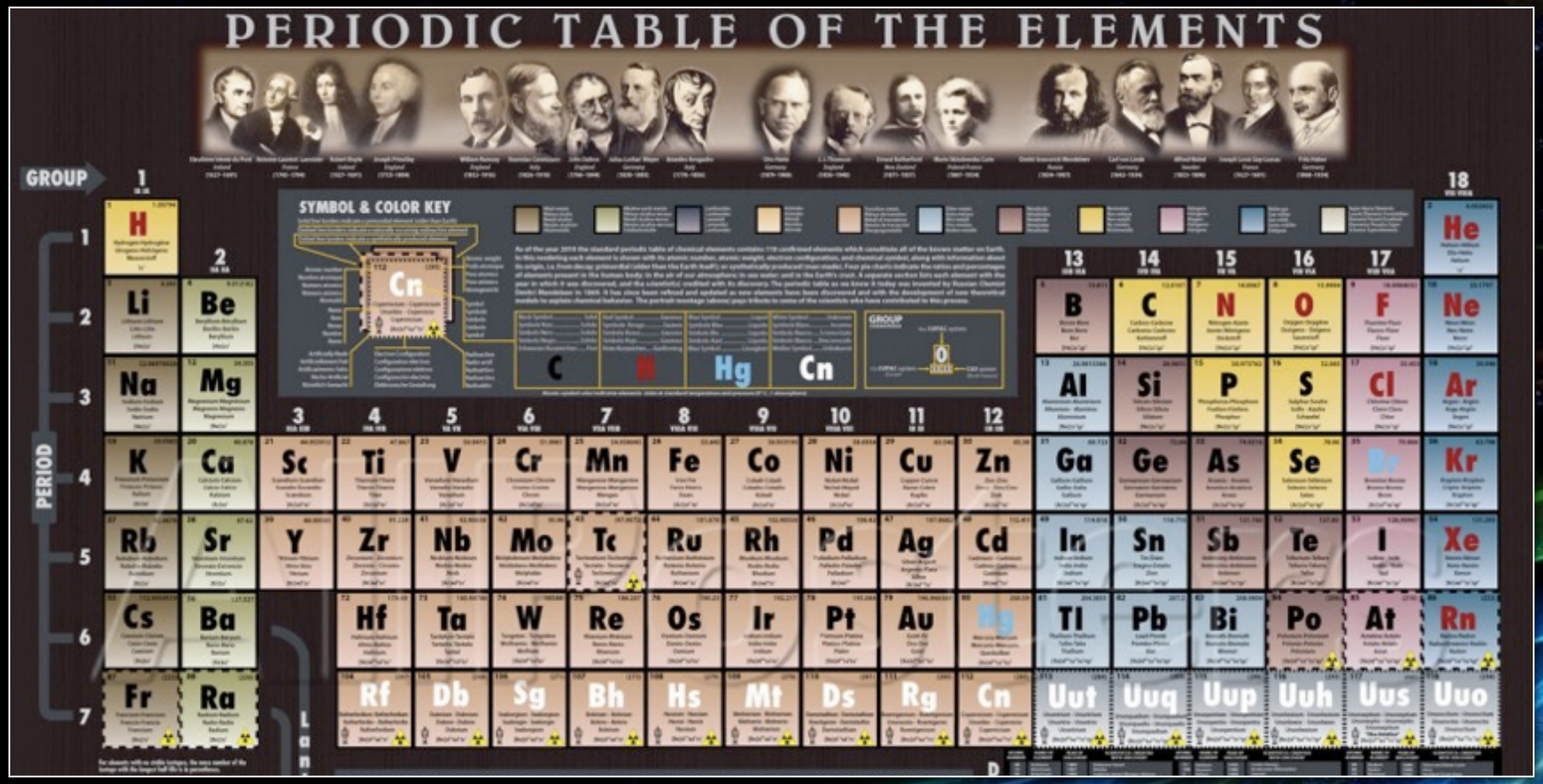


Neutrons, Protons, and Atoms



Proton

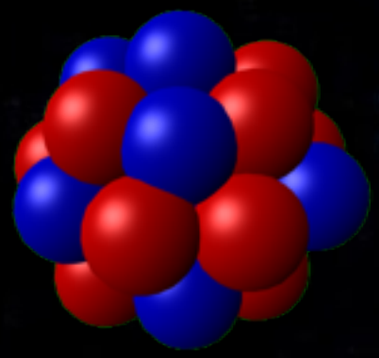
Neutron



The number of protons determine what is the element

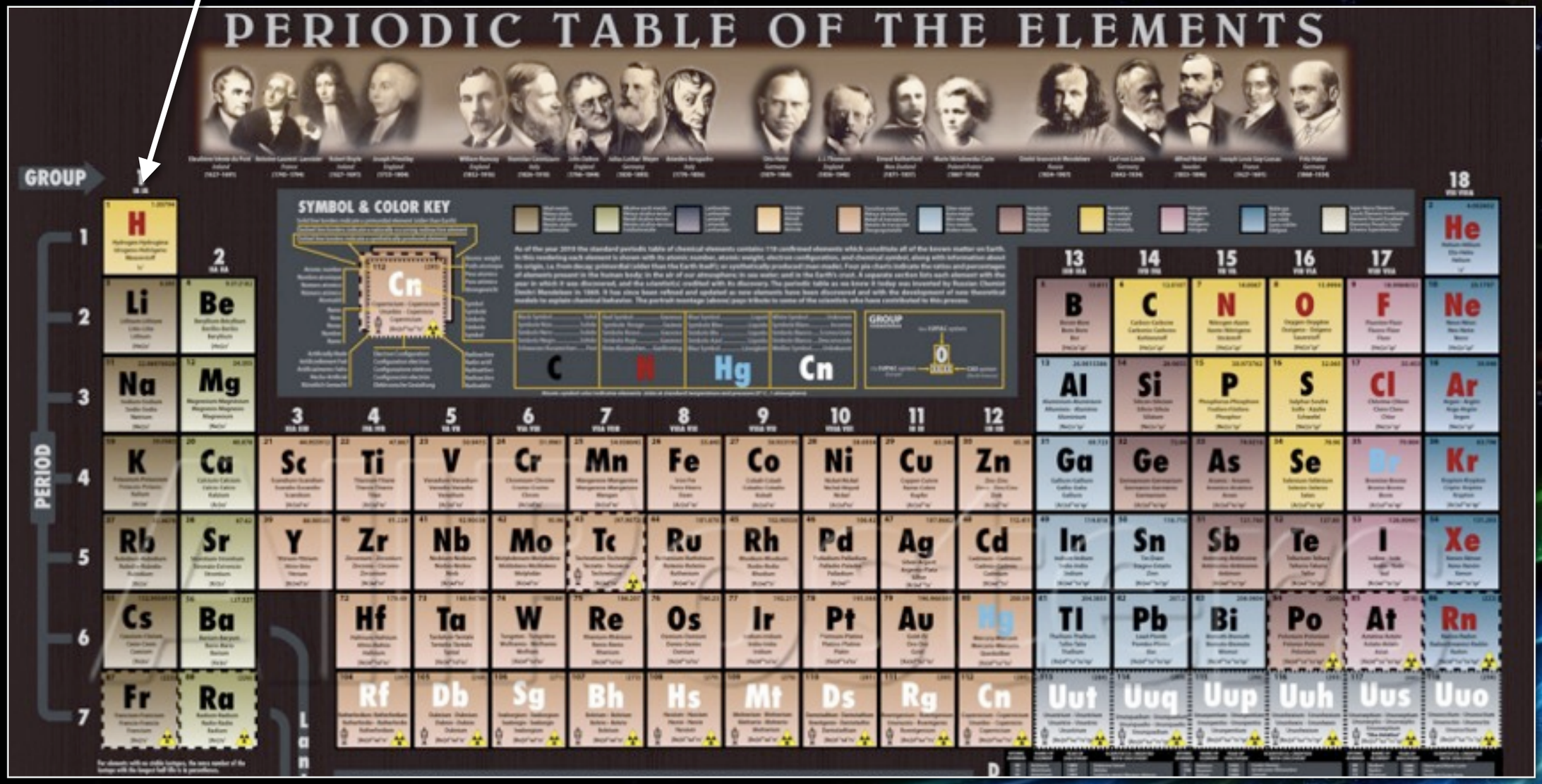
Neutrons, Protons, and Atoms

Hydrogen



Proton

Neutron

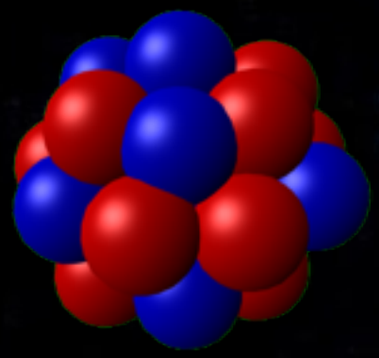


The number of protons determine what is the element

Neutrons, Protons, and Atoms

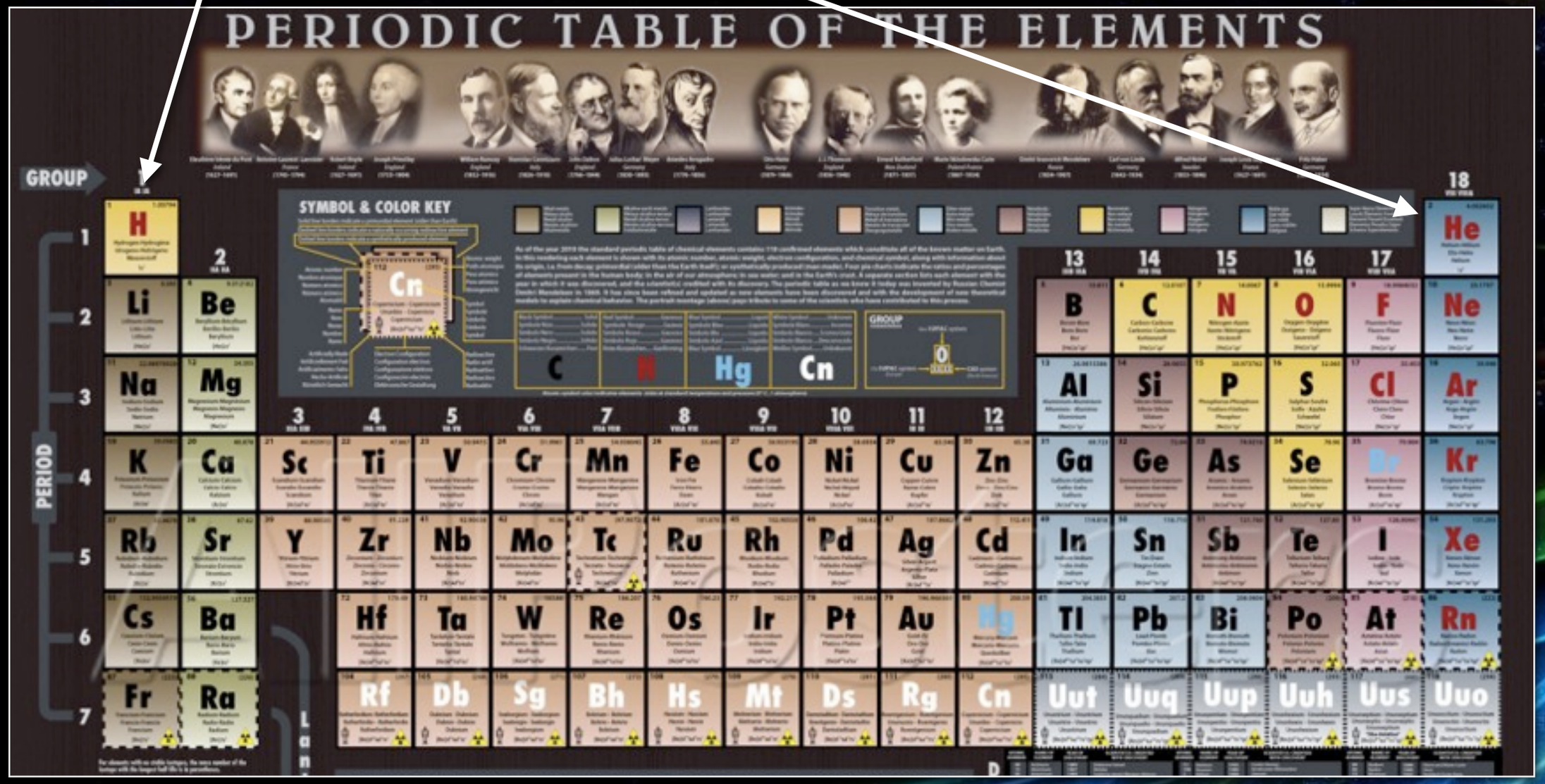
Hydrogen

Helium



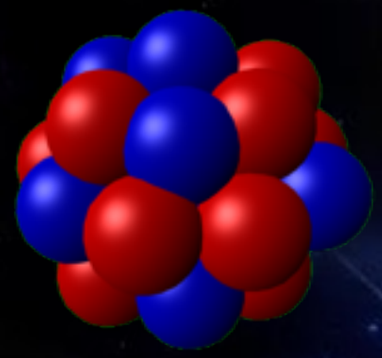
Proton

Neutron

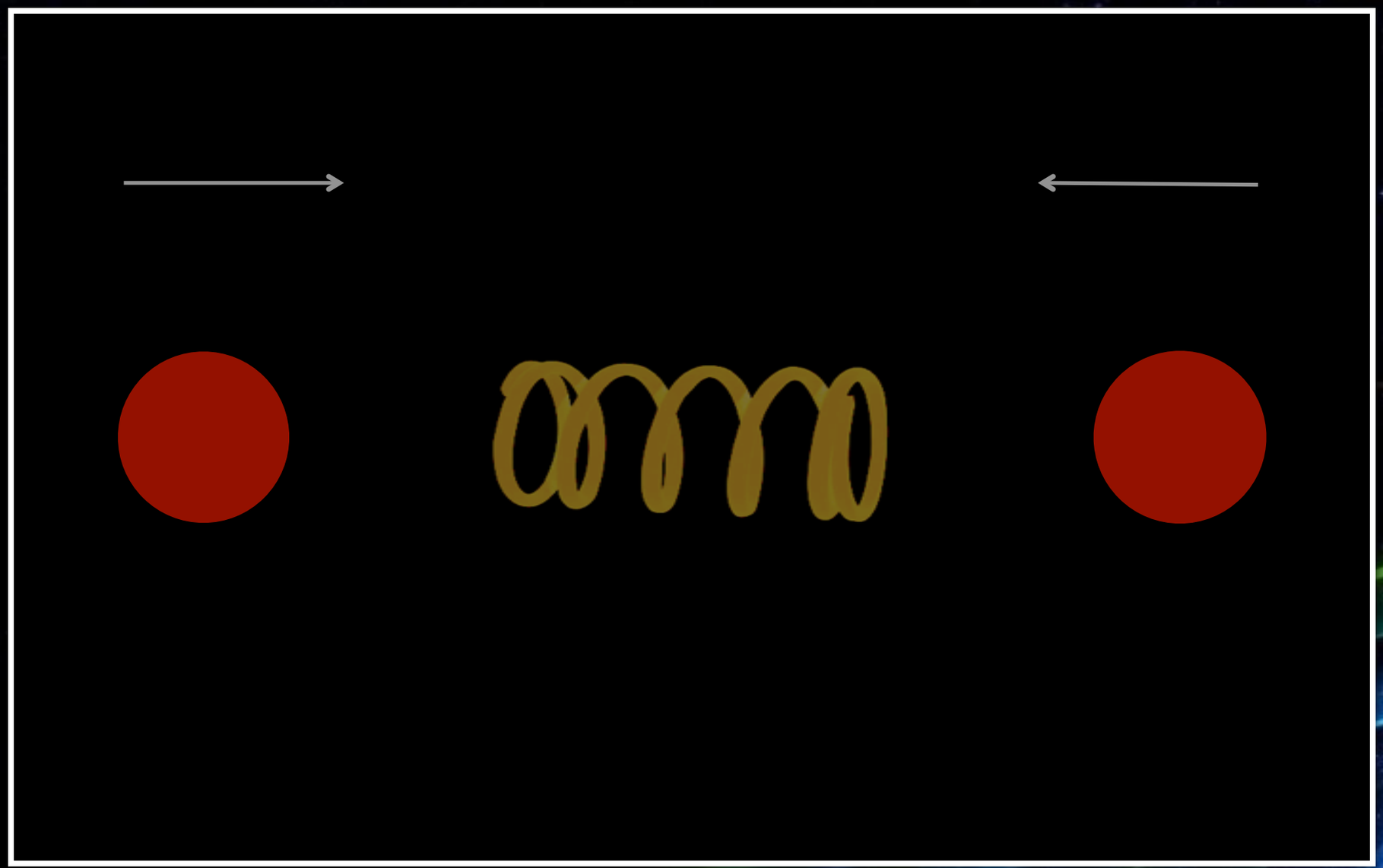


The number of protons determine what is the element

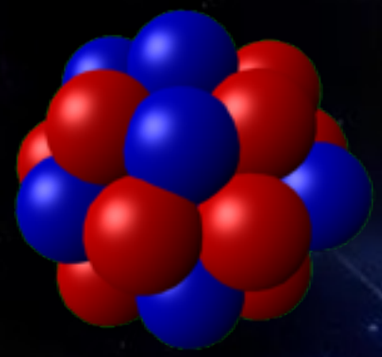
The Process of Nuclear Fusion



Electric force (repulsion)

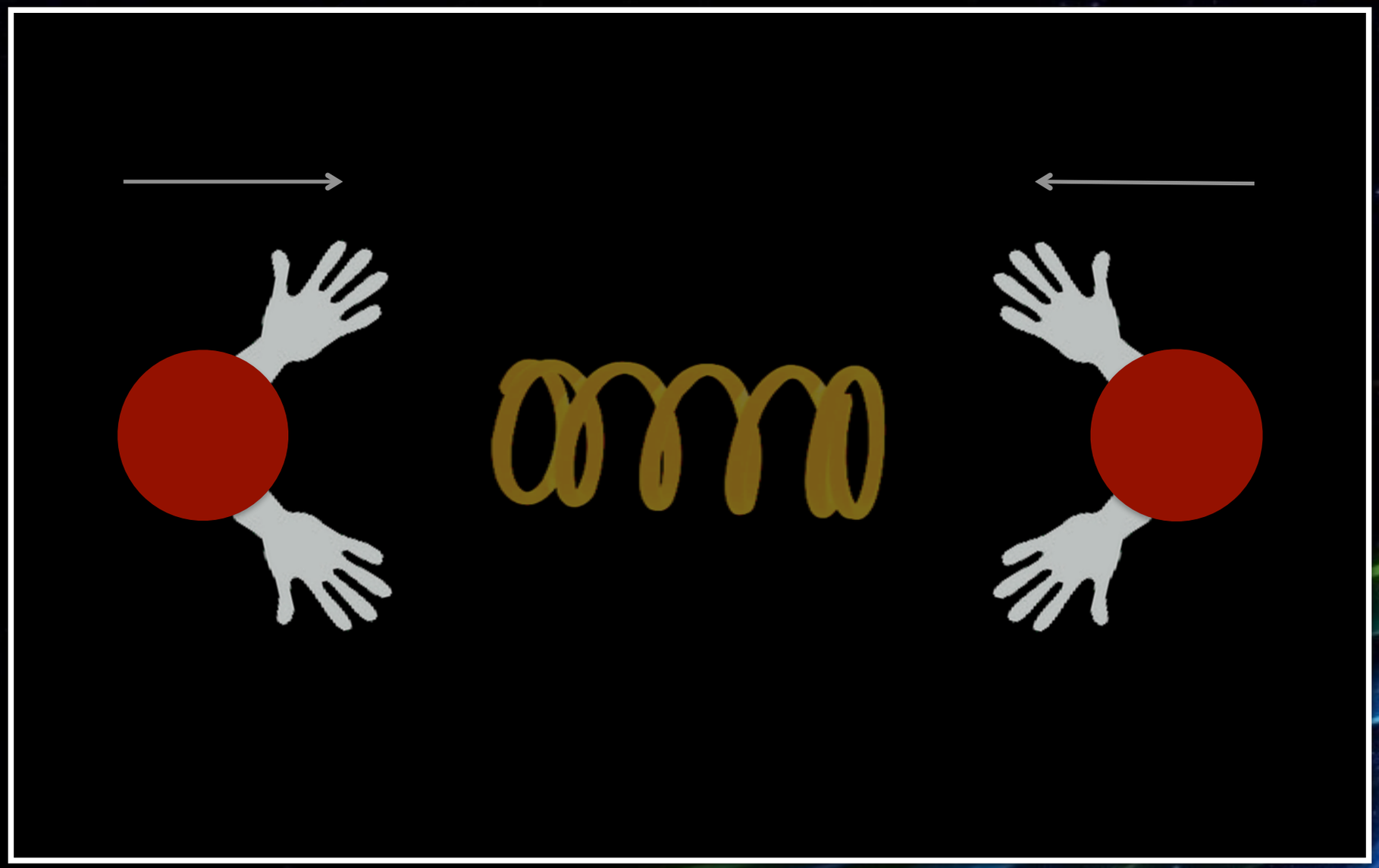


The Process of Nuclear Fusion



Electric force (repulsion)

Nuclear force (attraction)



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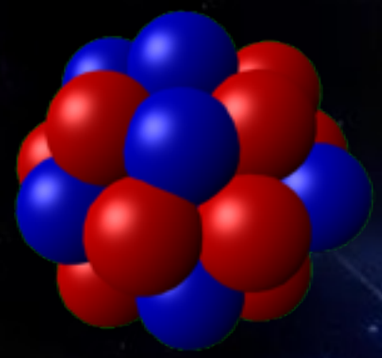

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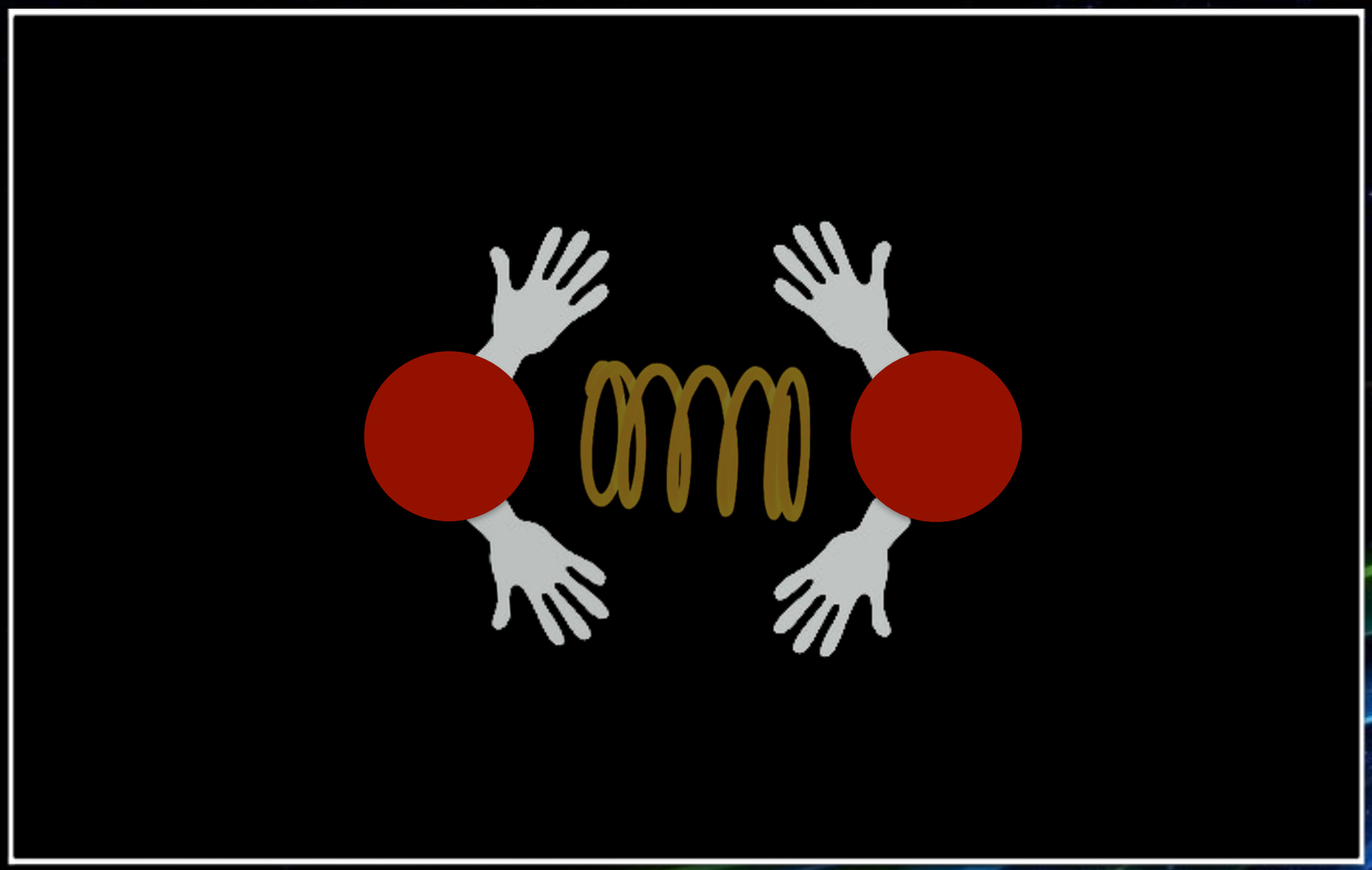

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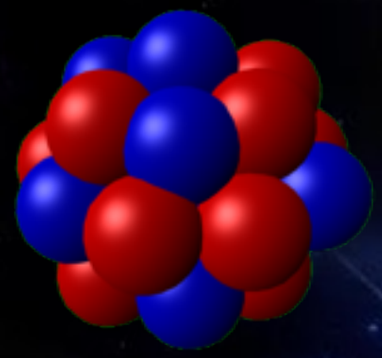

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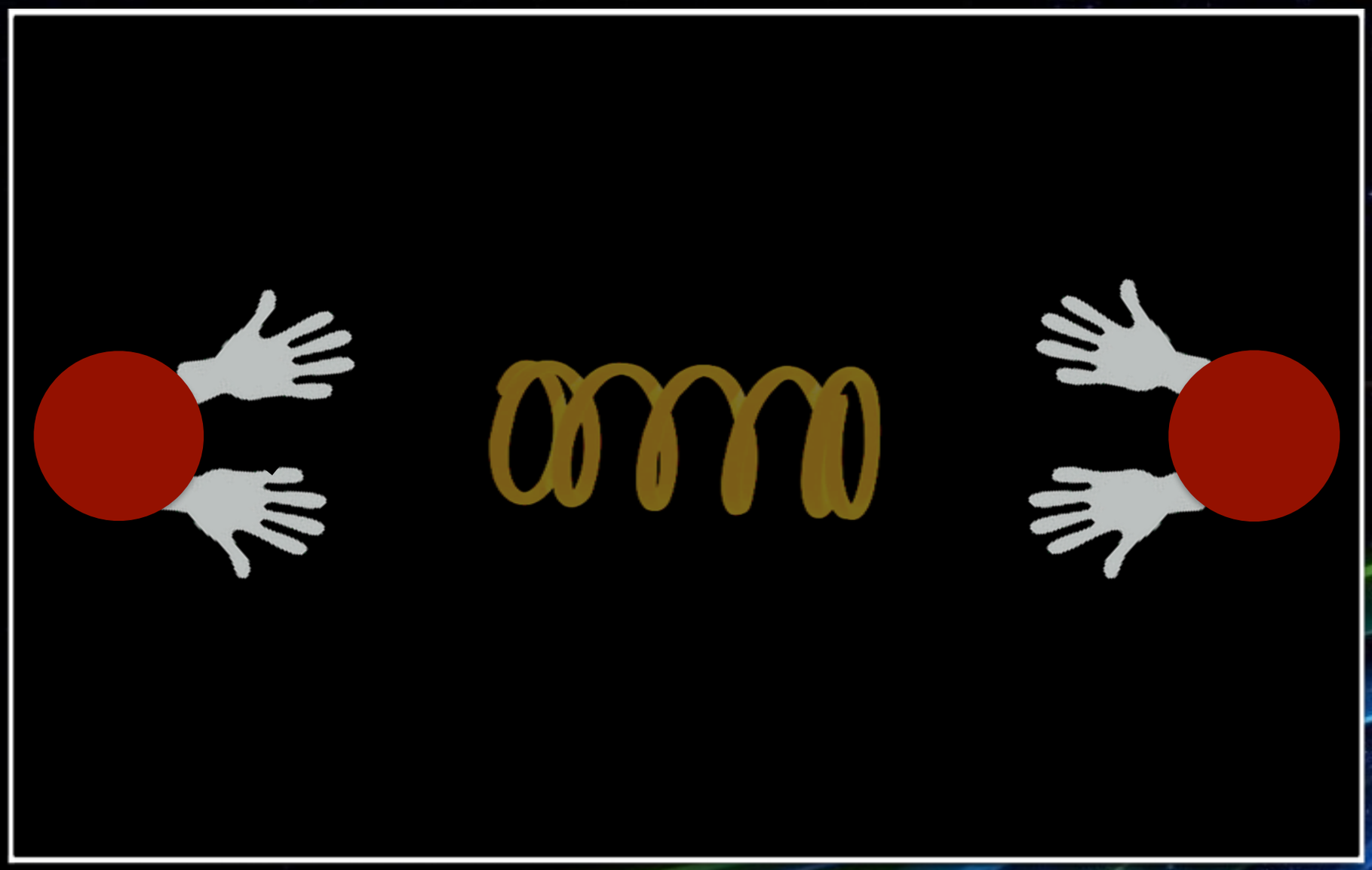
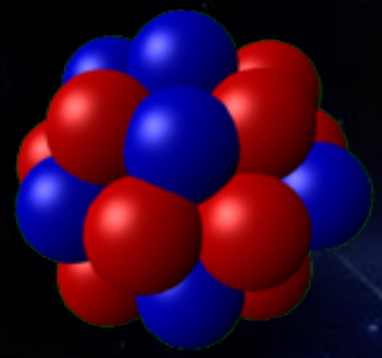


The Process of Nuclear Fusion



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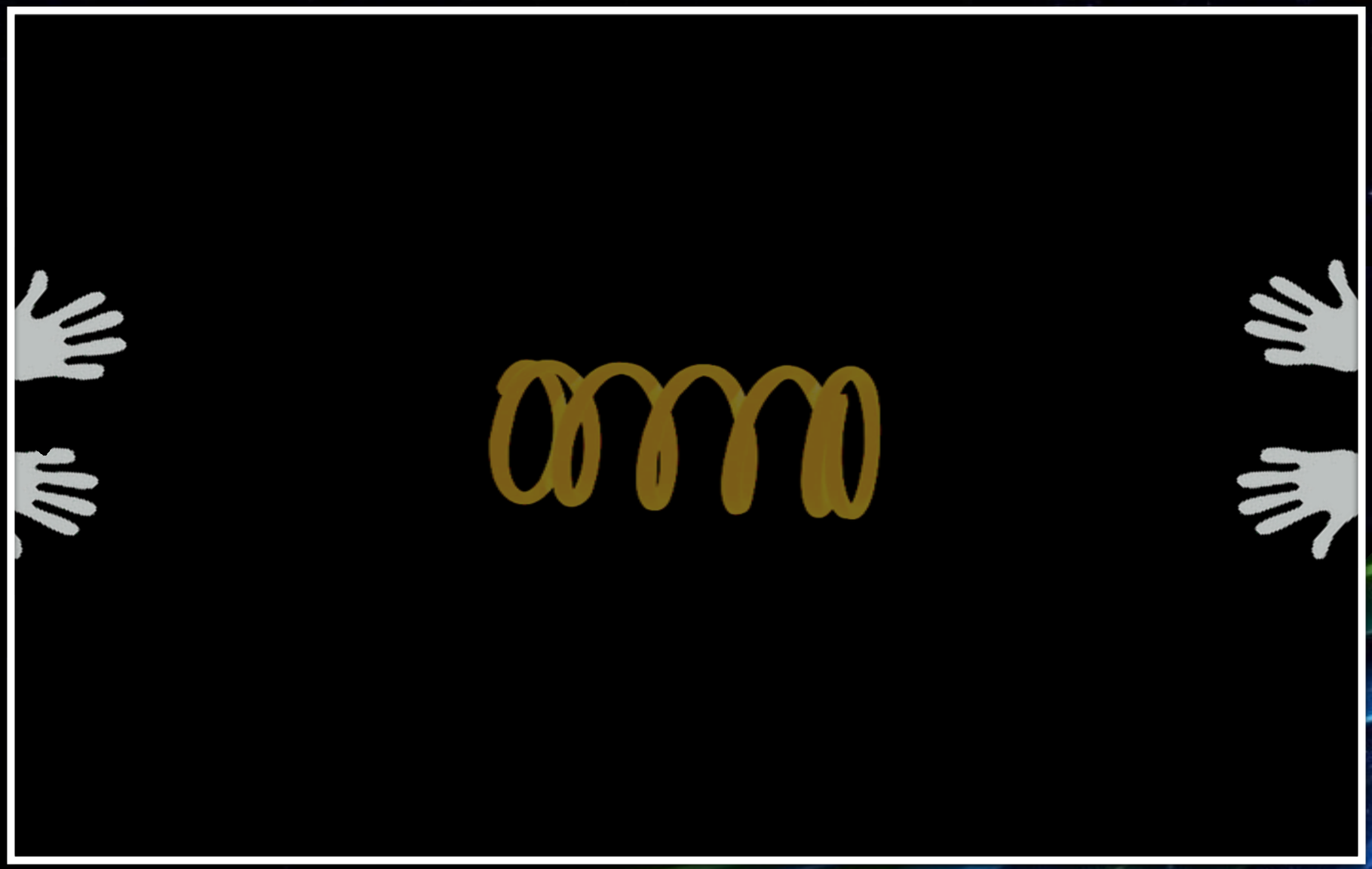
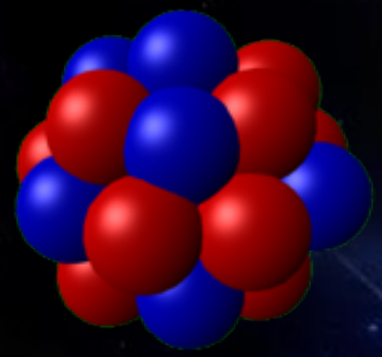


The Process of Nuclear Fusion



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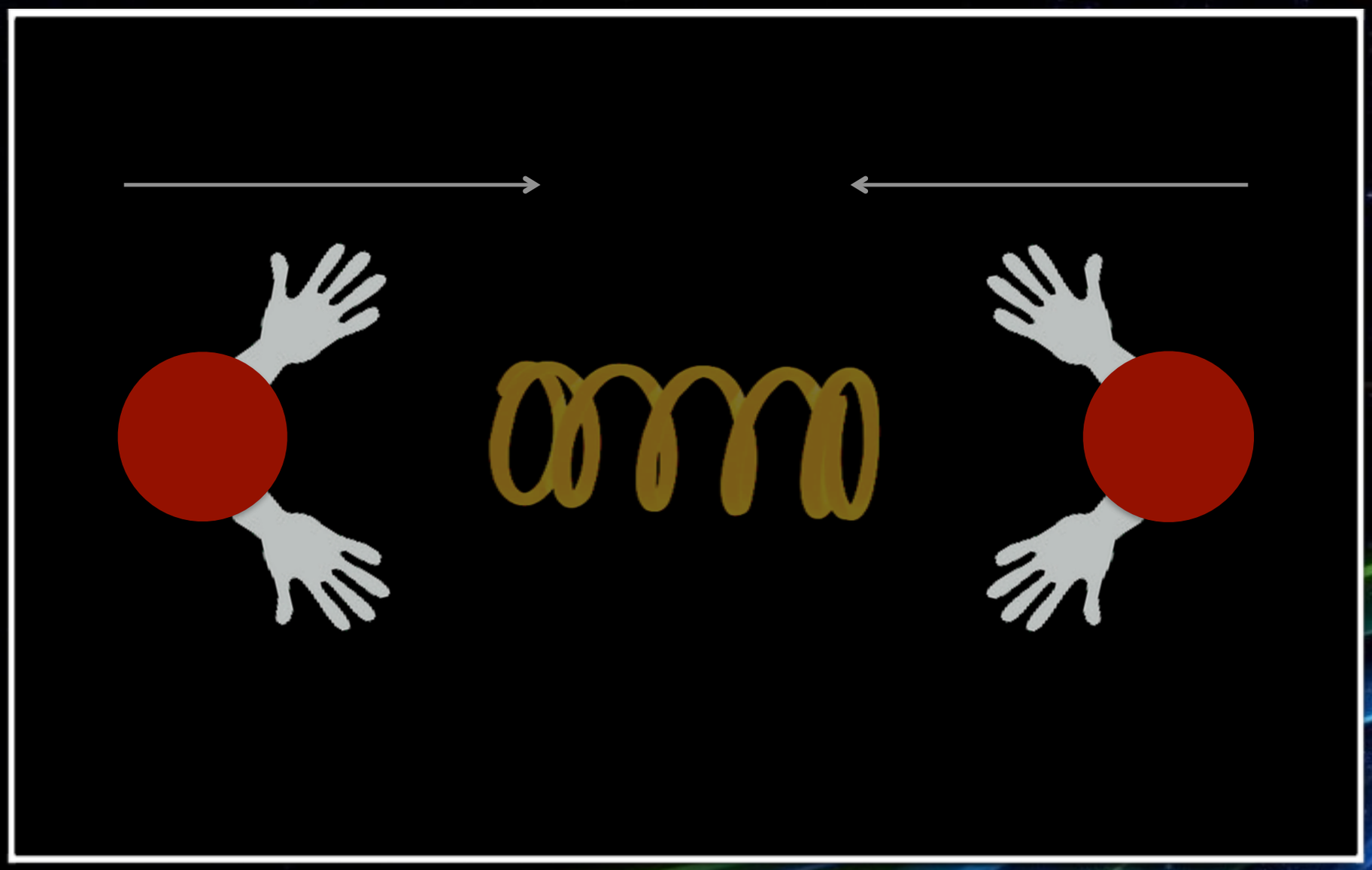
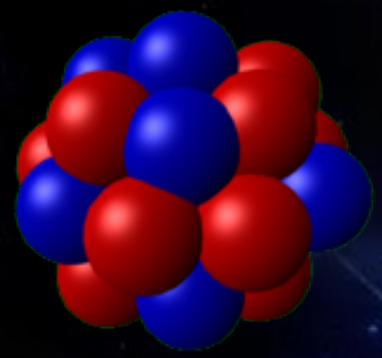


The Process of Nuclear Fusion



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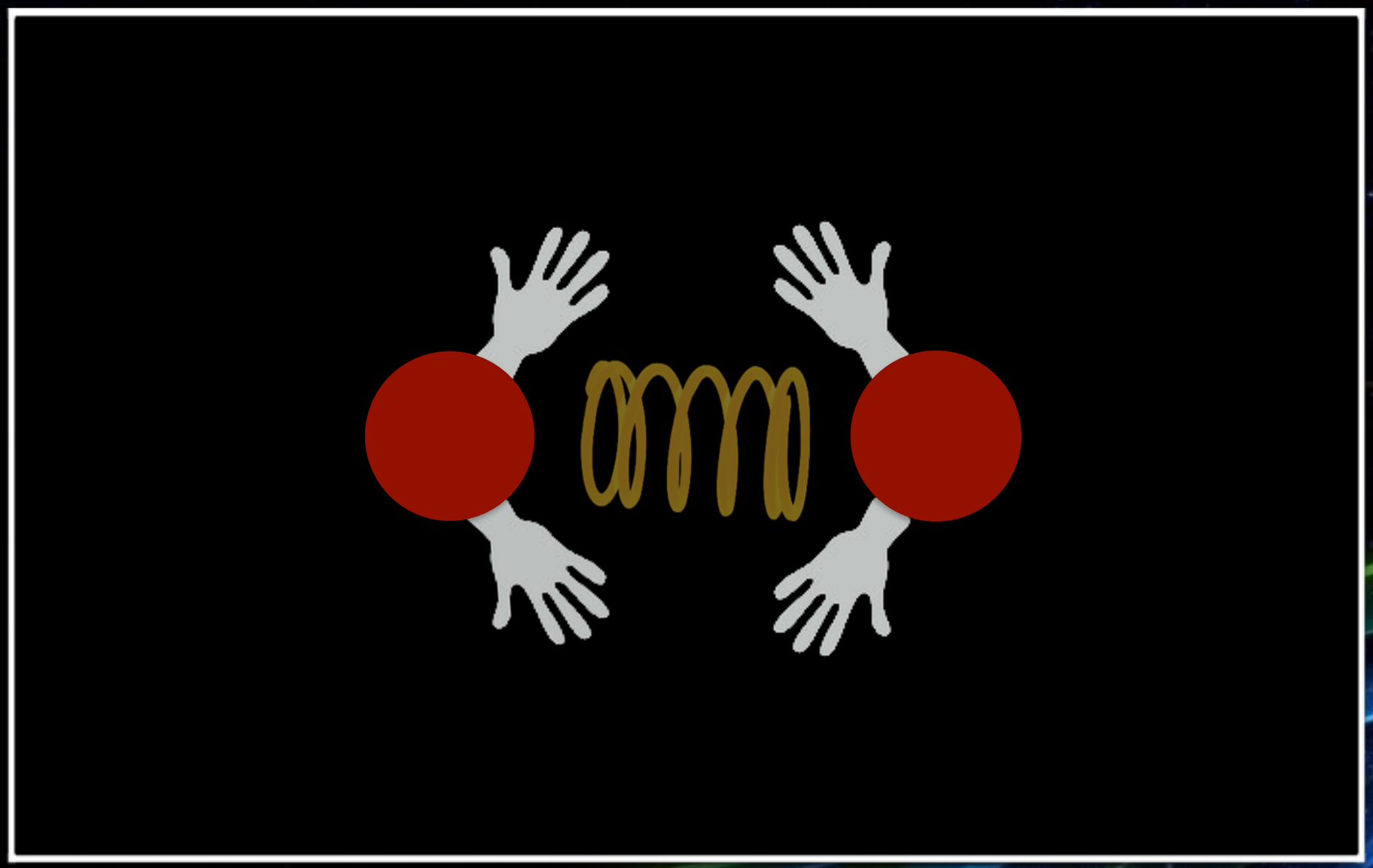
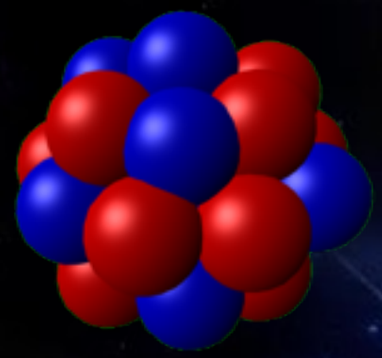


The Process of Nuclear Fusion



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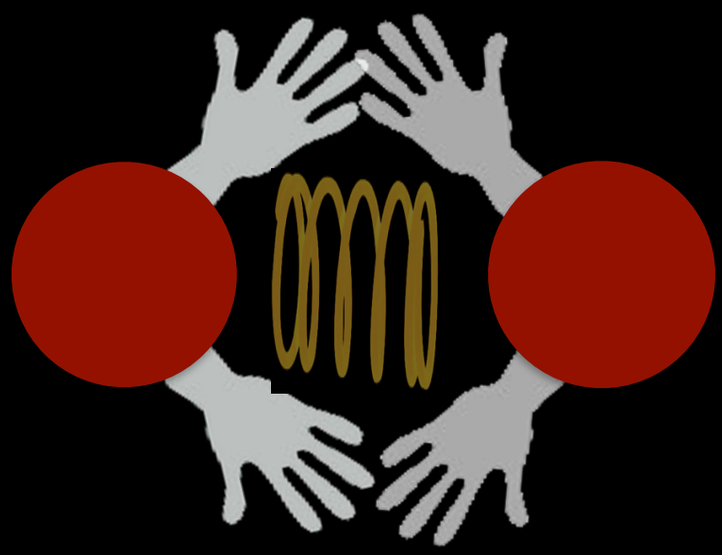
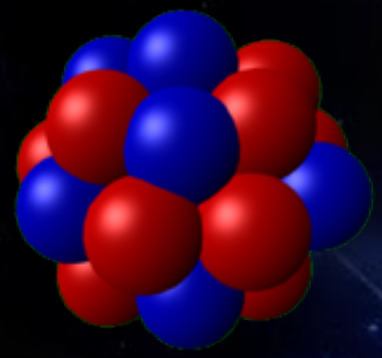


The Process of Nuclear Fusion



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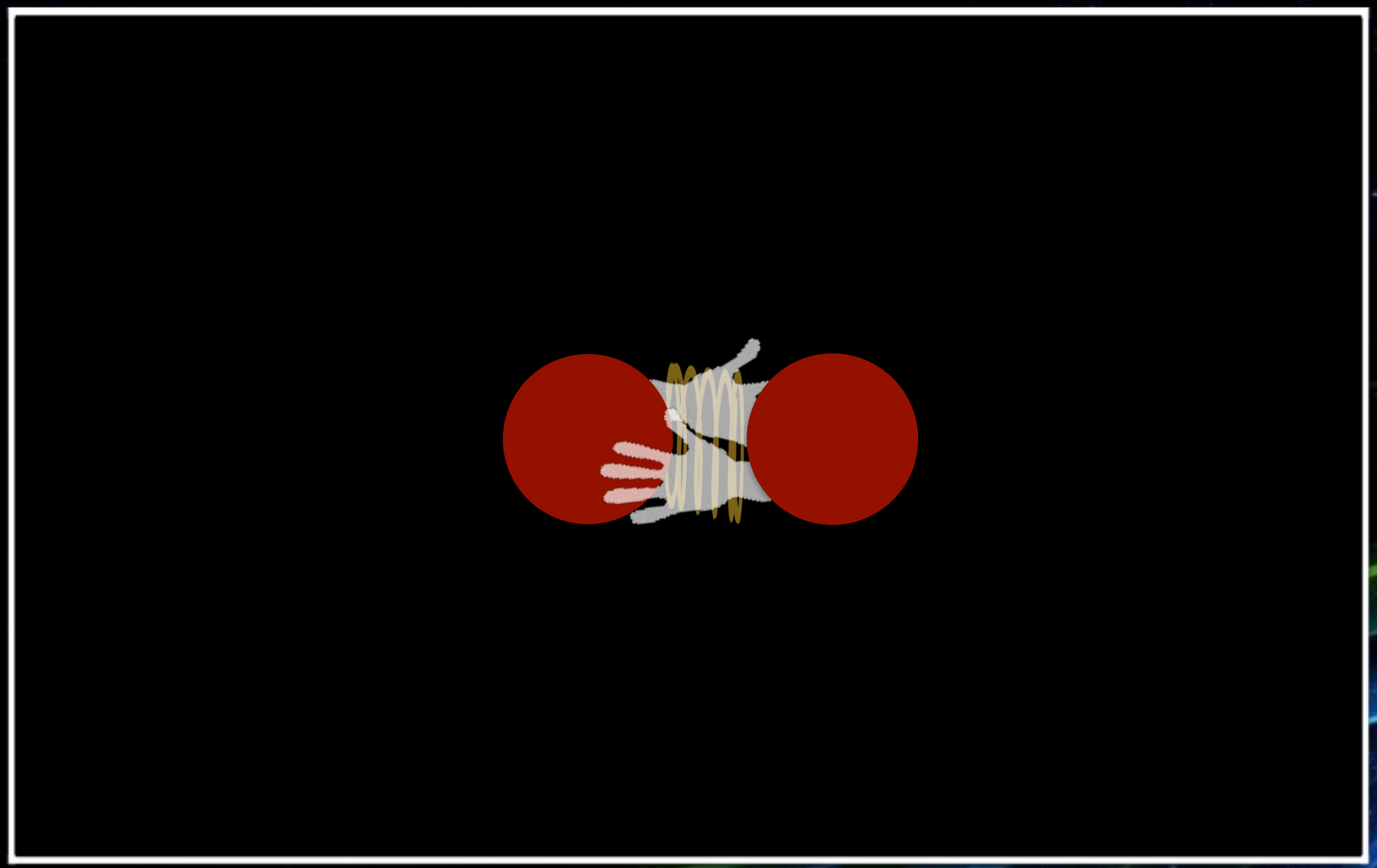
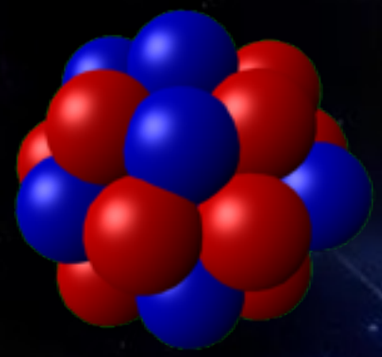


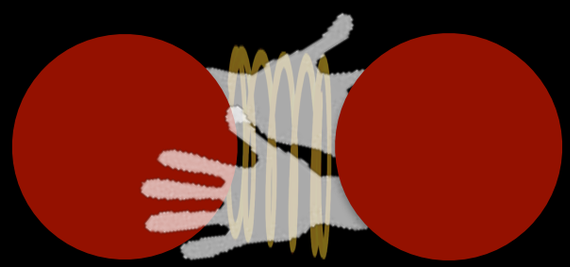
The Process of Nuclear Fusion



Electric force (repulsion)

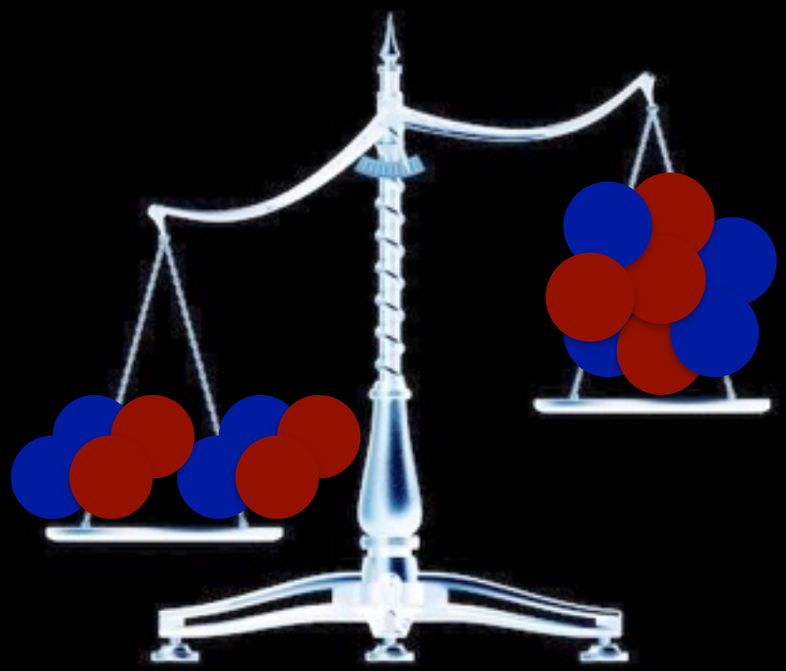
Nuclear force (attraction)

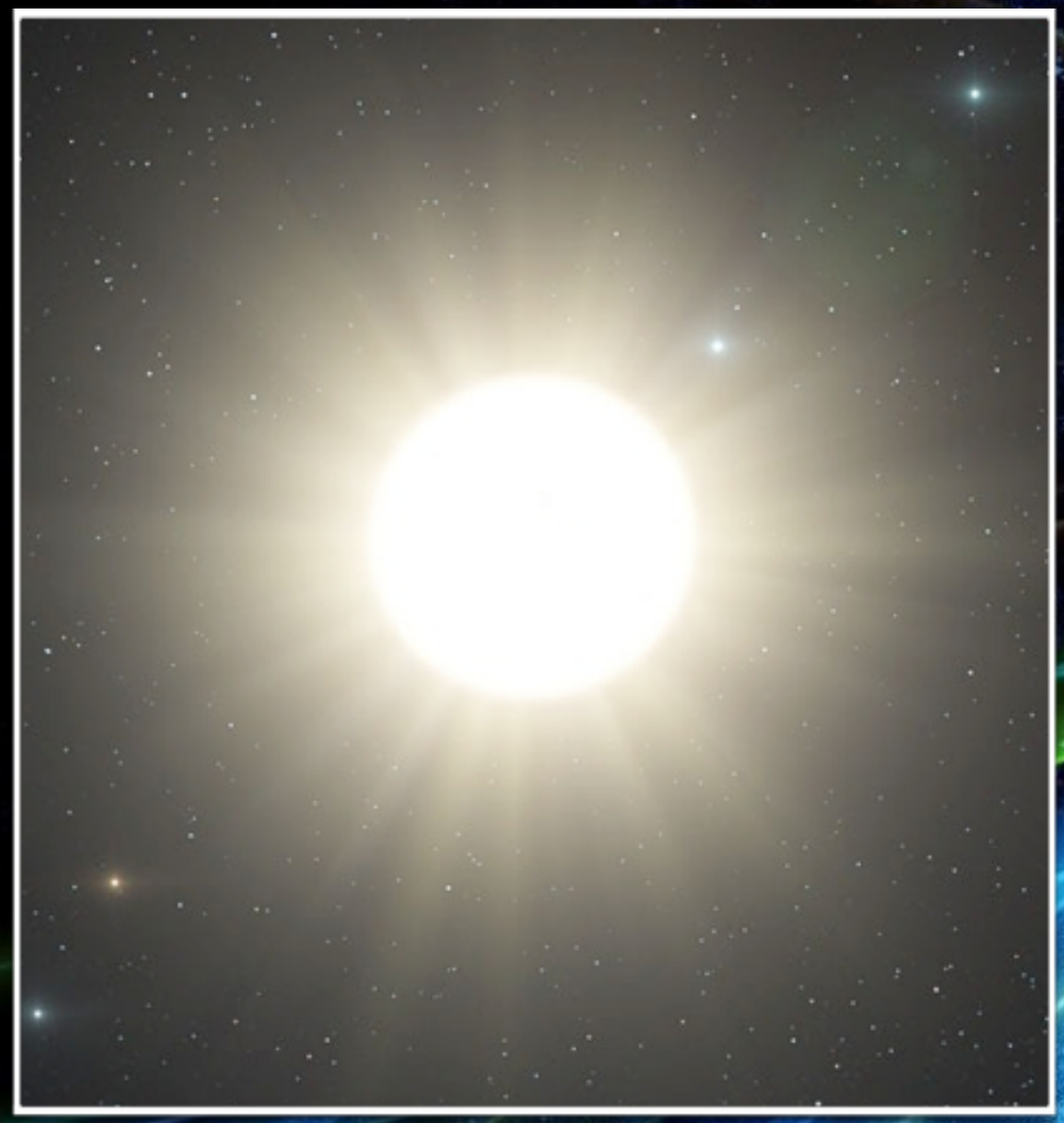
The nuclear force is stronger than the electric force



The Process of Nuclear Fusion

$E = mc^2$

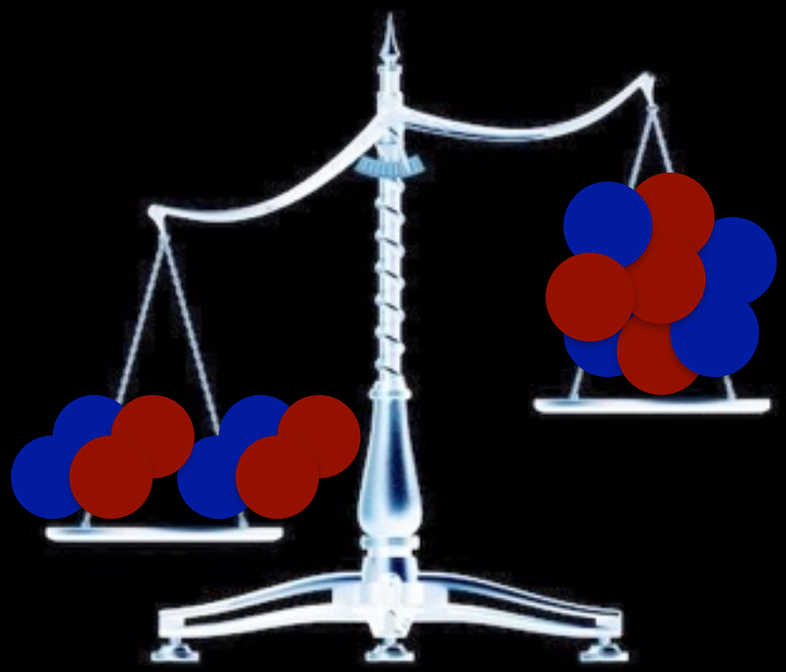


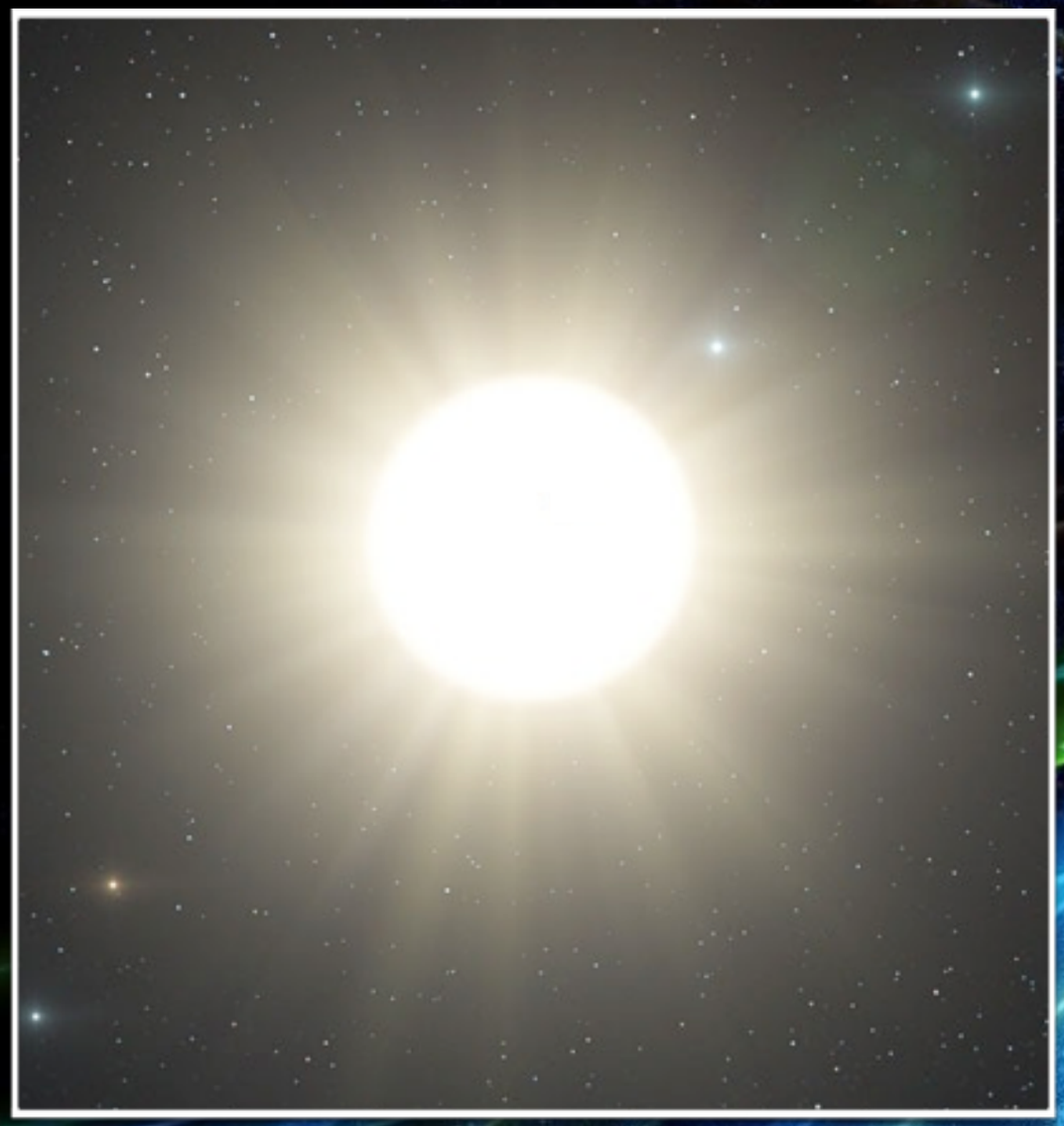


The Process of Nuclear Fusion

Each year, the Sun produce 25 millions of millions more energy than what humanity consumes in a year.

$$E = mc^2$$



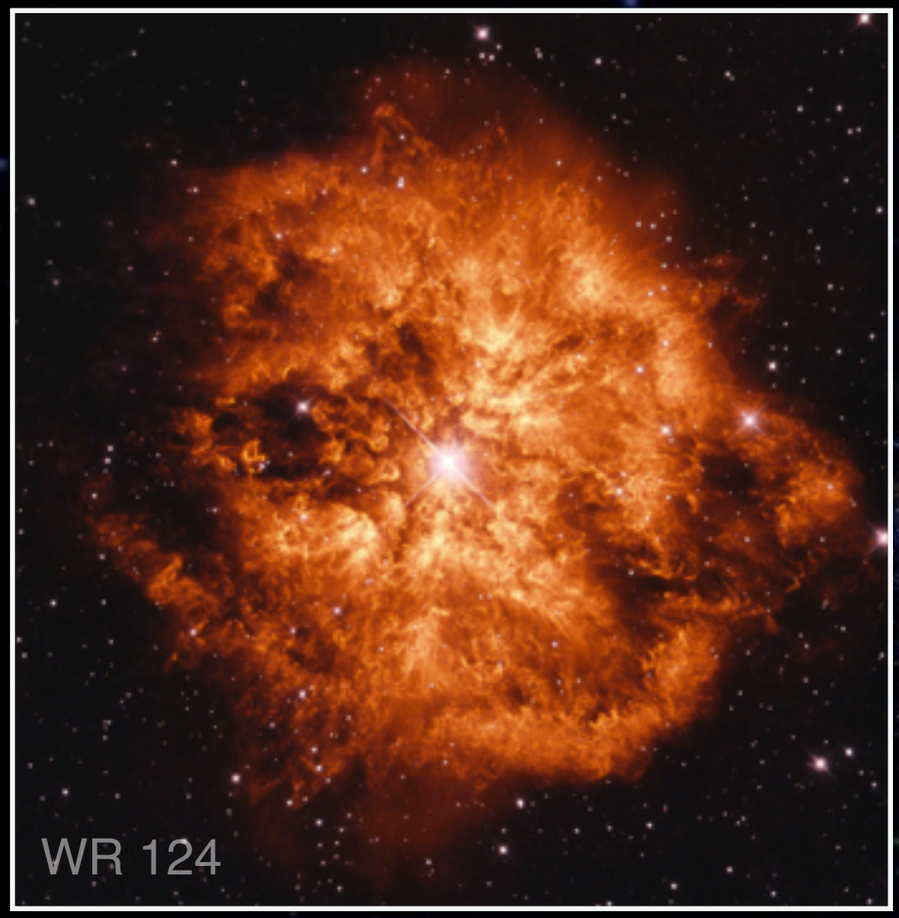


New Elements Ejected in Space

Core-collapse supernovae

Type Ia supernovae

Stellar winds from massive stars



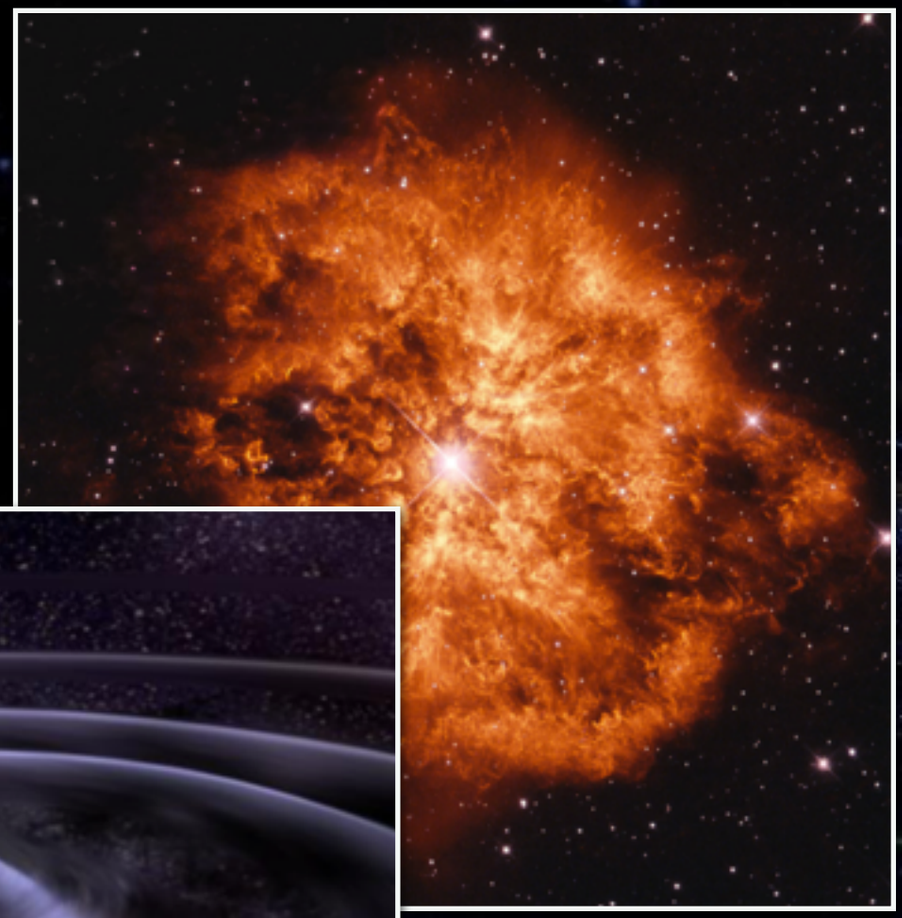
Stellar winds from low-mass stars

New Elements Ejected in Space

Core-collapse supernovae

Crab nebula

Stellar winds from massive stars

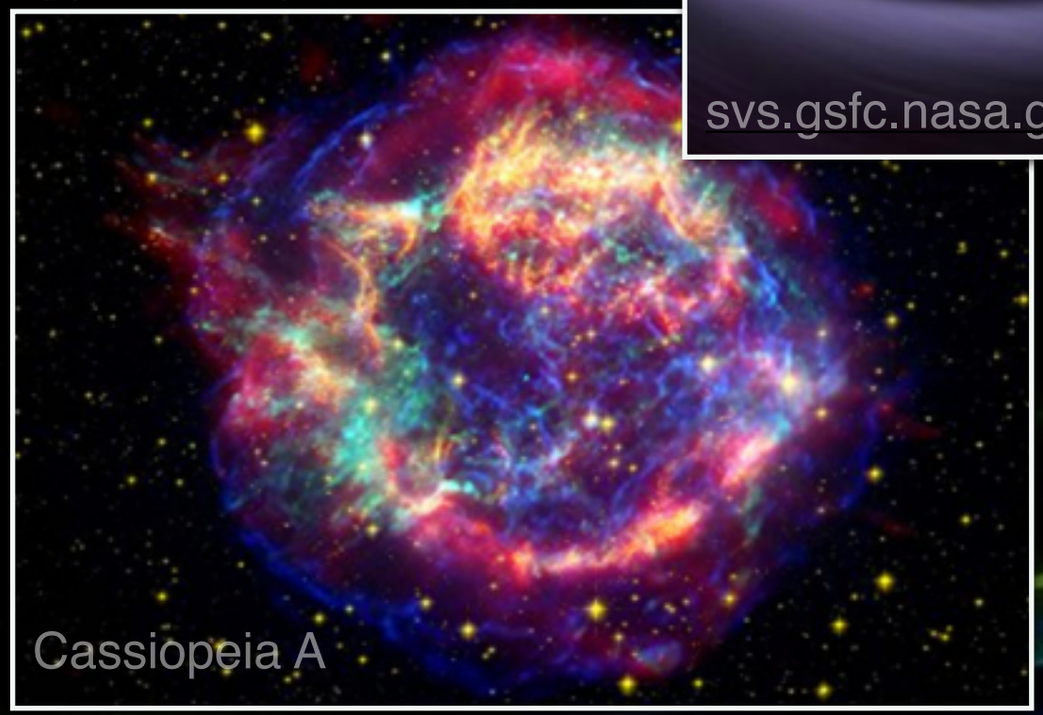


Neutron star mergers

svs.gsfc.nasa.gov

mass stars

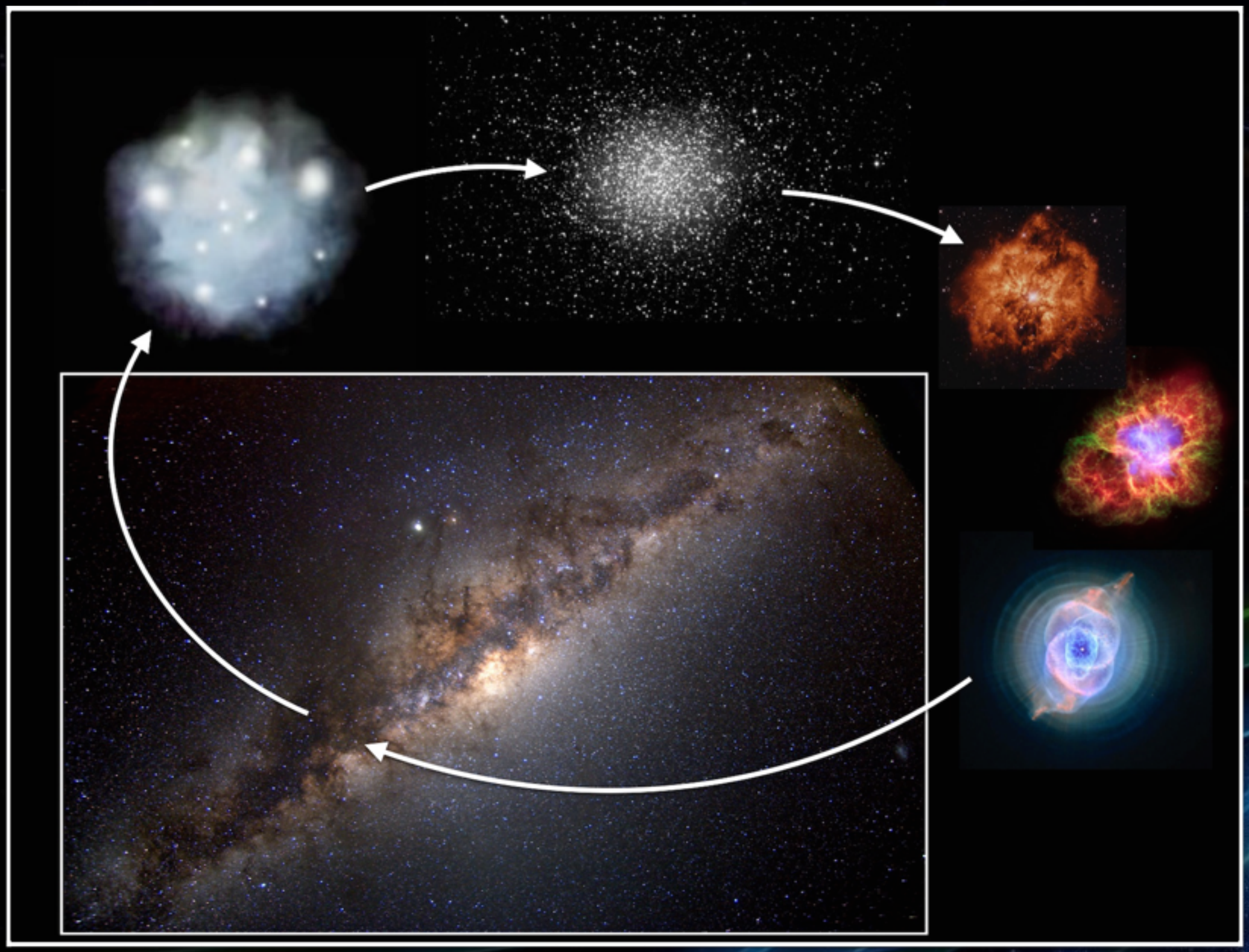
Type Ia supernovae



Cassiopeia A

Cat eye nebula

The Life Cycle of Stars



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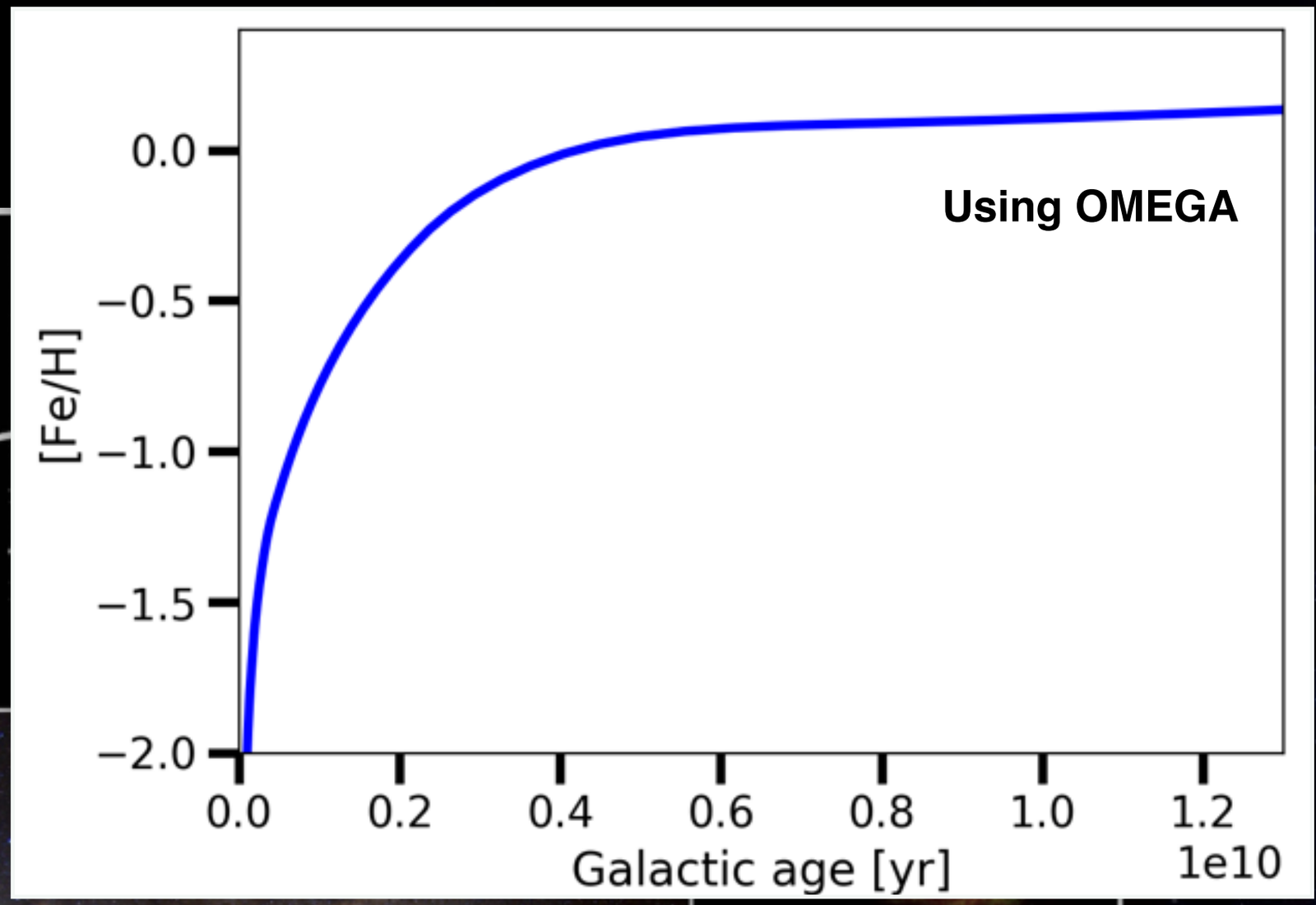
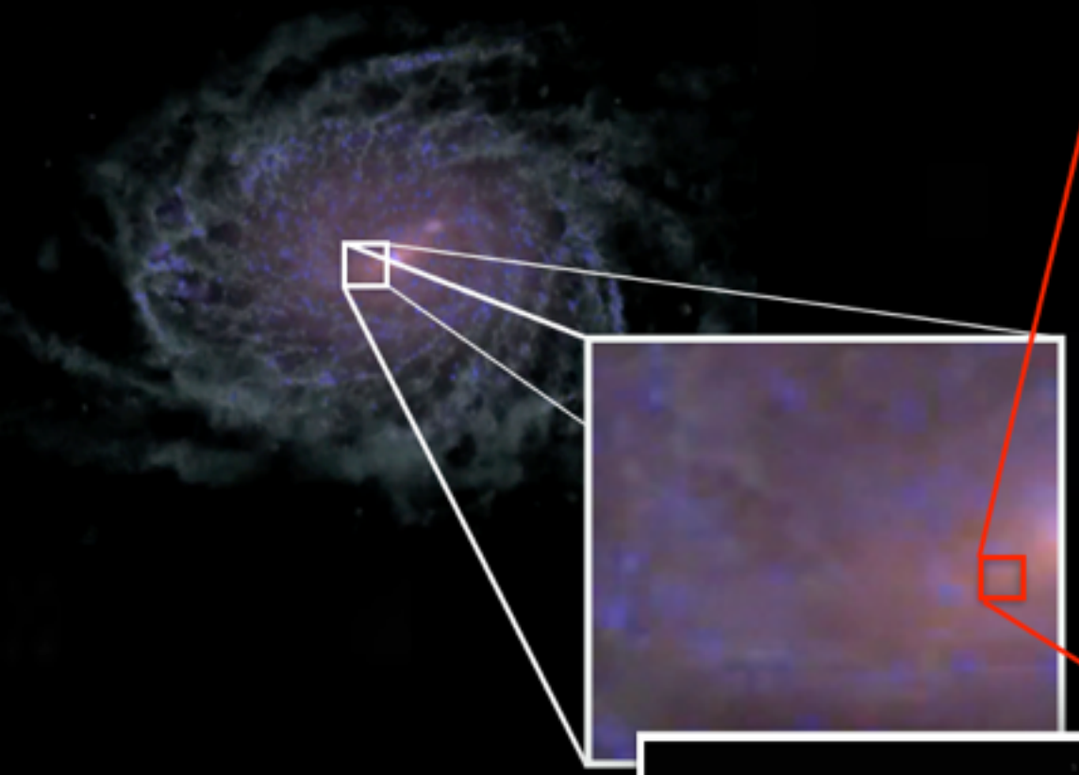
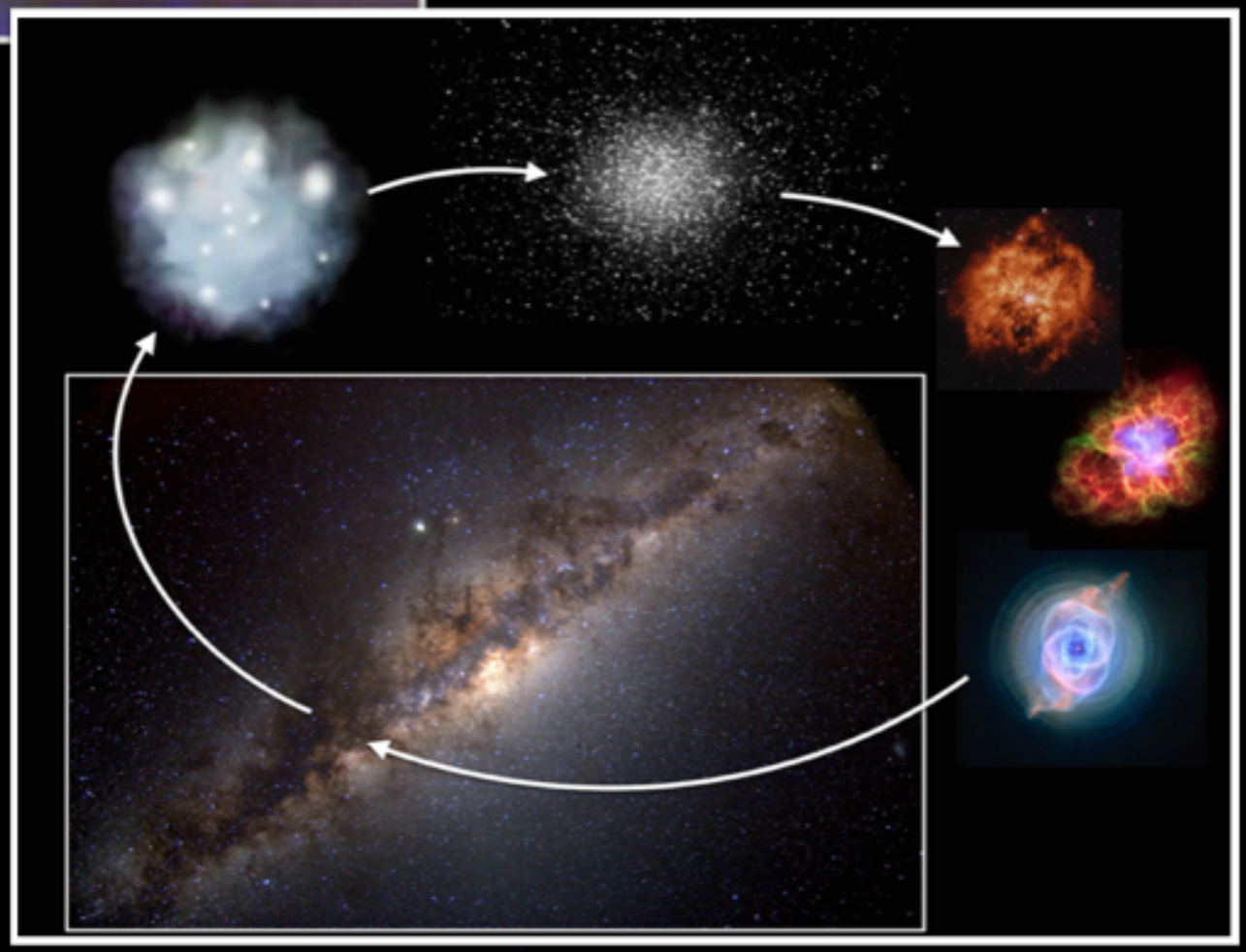


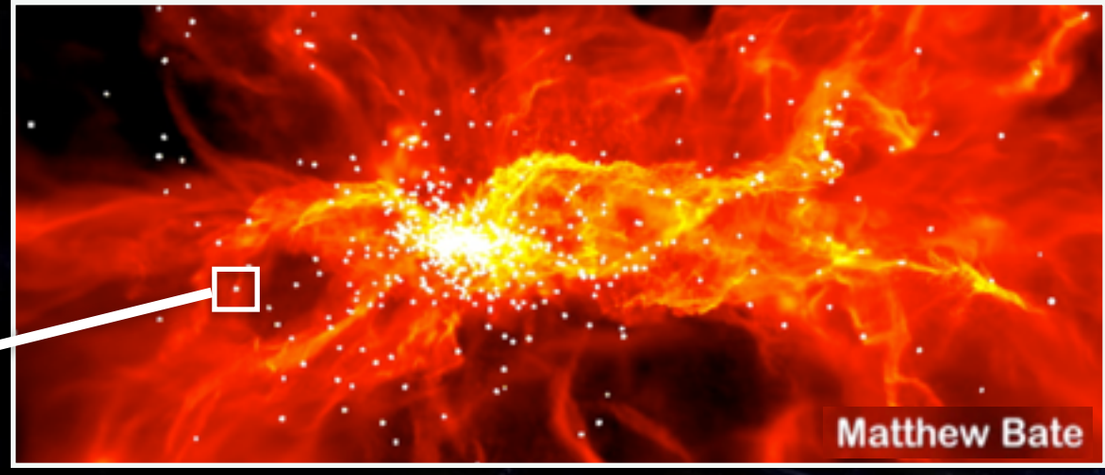
Chemical Evolution





The Formation of our Solar System

wallstreetotc.com



Helmut Wimmer

The Formation of our Solar System

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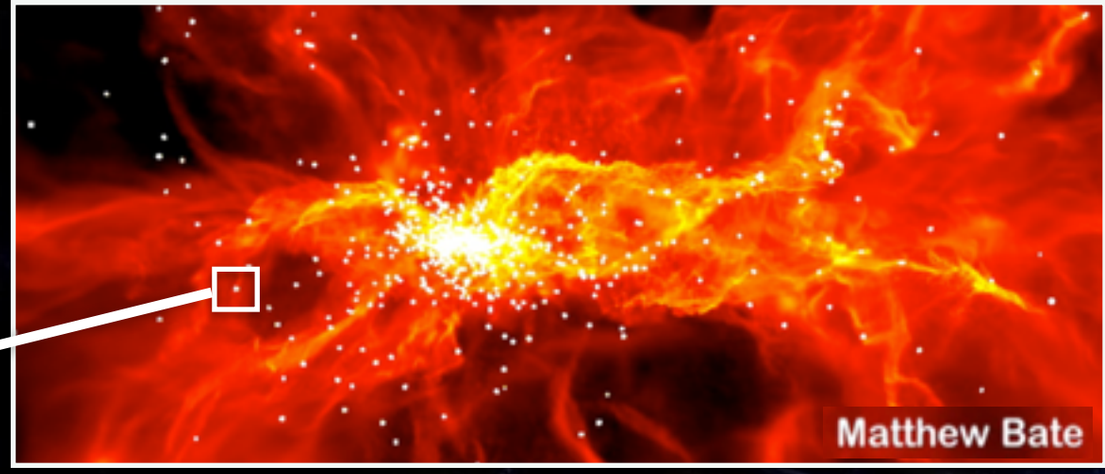

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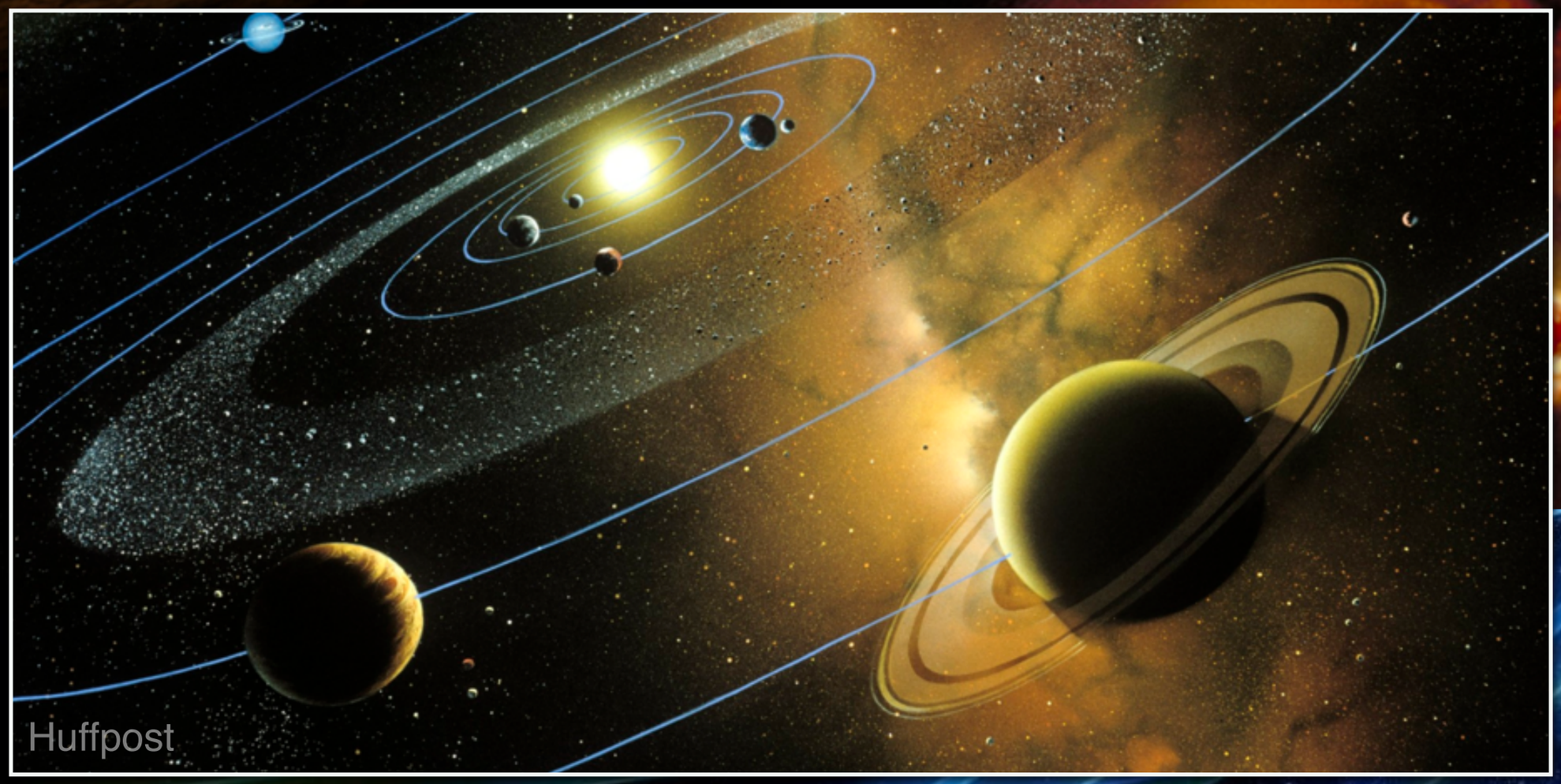

Huffpost

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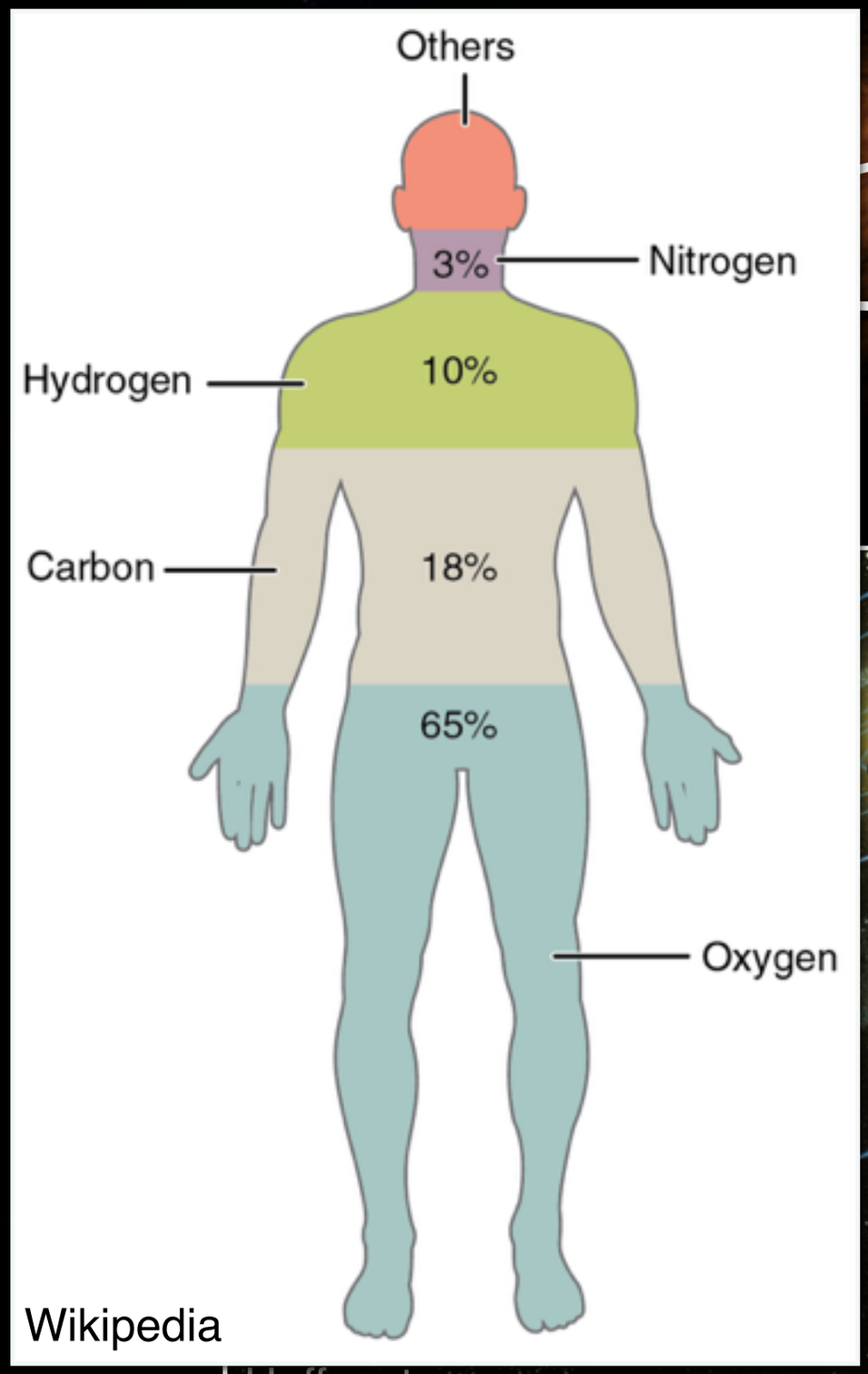
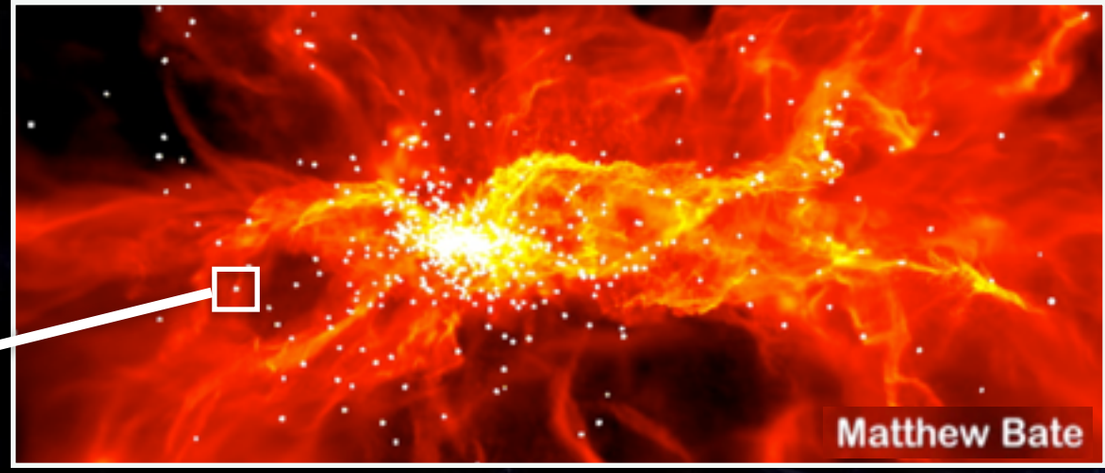


Wikipedia

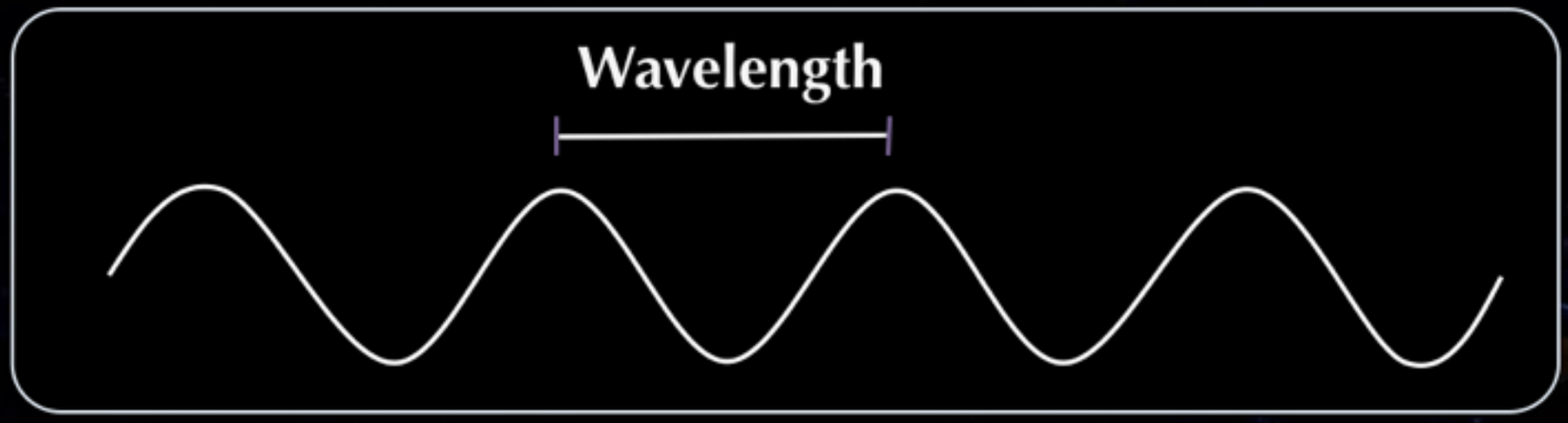


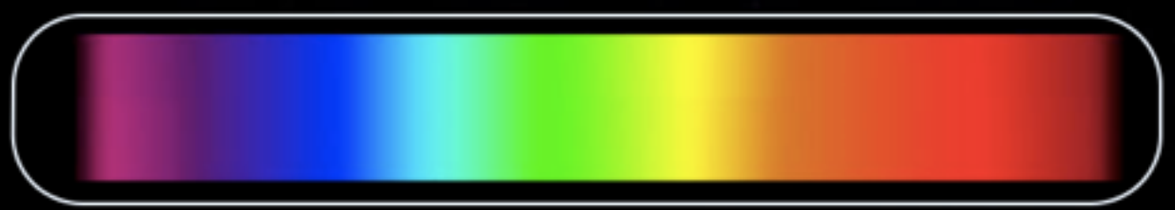
Helmut Wimmer

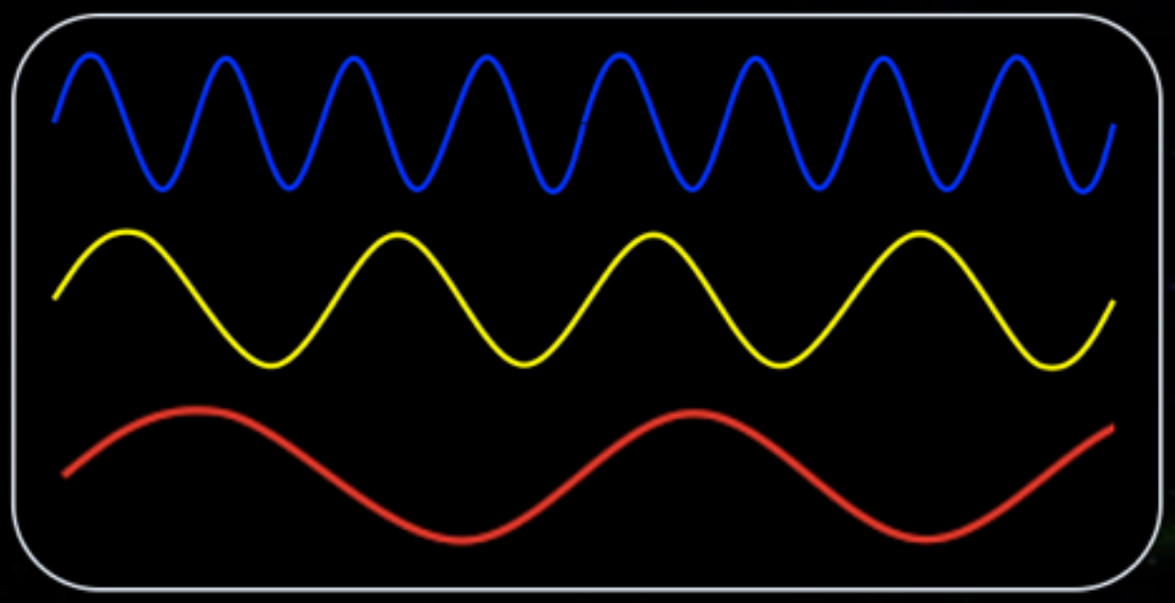
Huffpost

Observing the Evolution of Chemical Elements

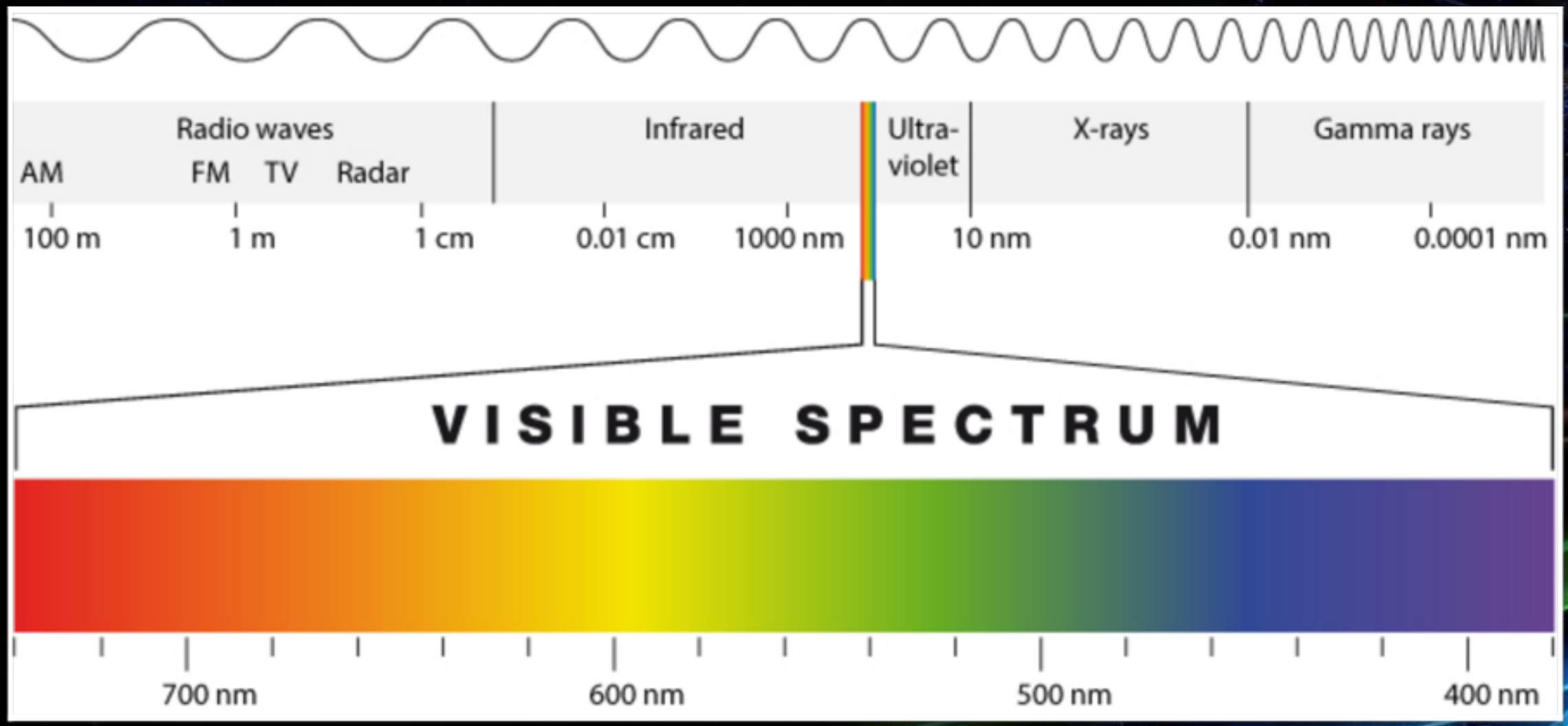
Light







Light



https://www.extremetech.com/extreme/252295-layered-solar-cell-can-capture-wavelengths-solar-spectrum

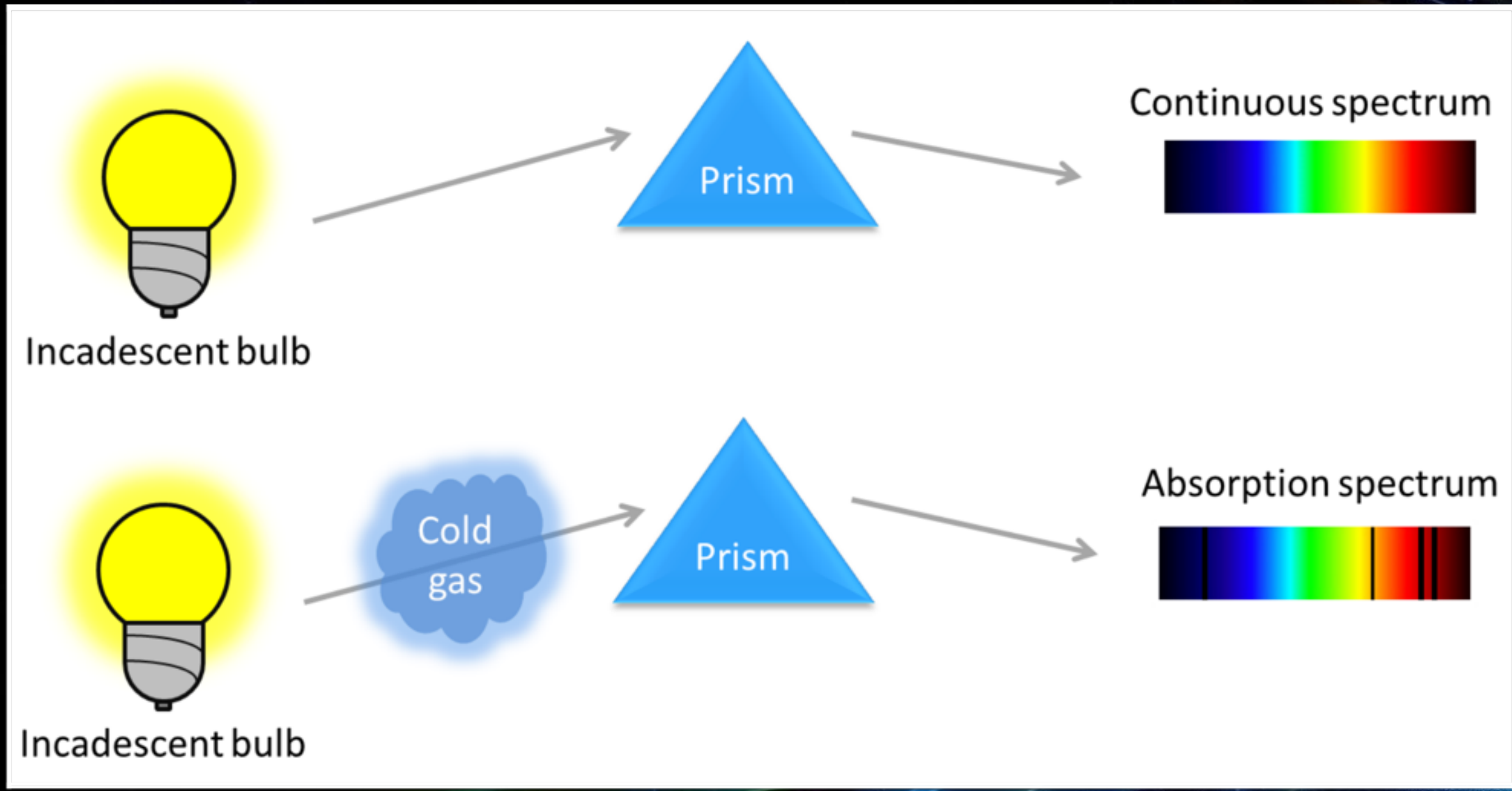
Decomposing Light Into Colors

https://www.quora.com/Which-color-deviates-the-least-when-a-light-passes-through-a-prism-Why

Spectroscopy

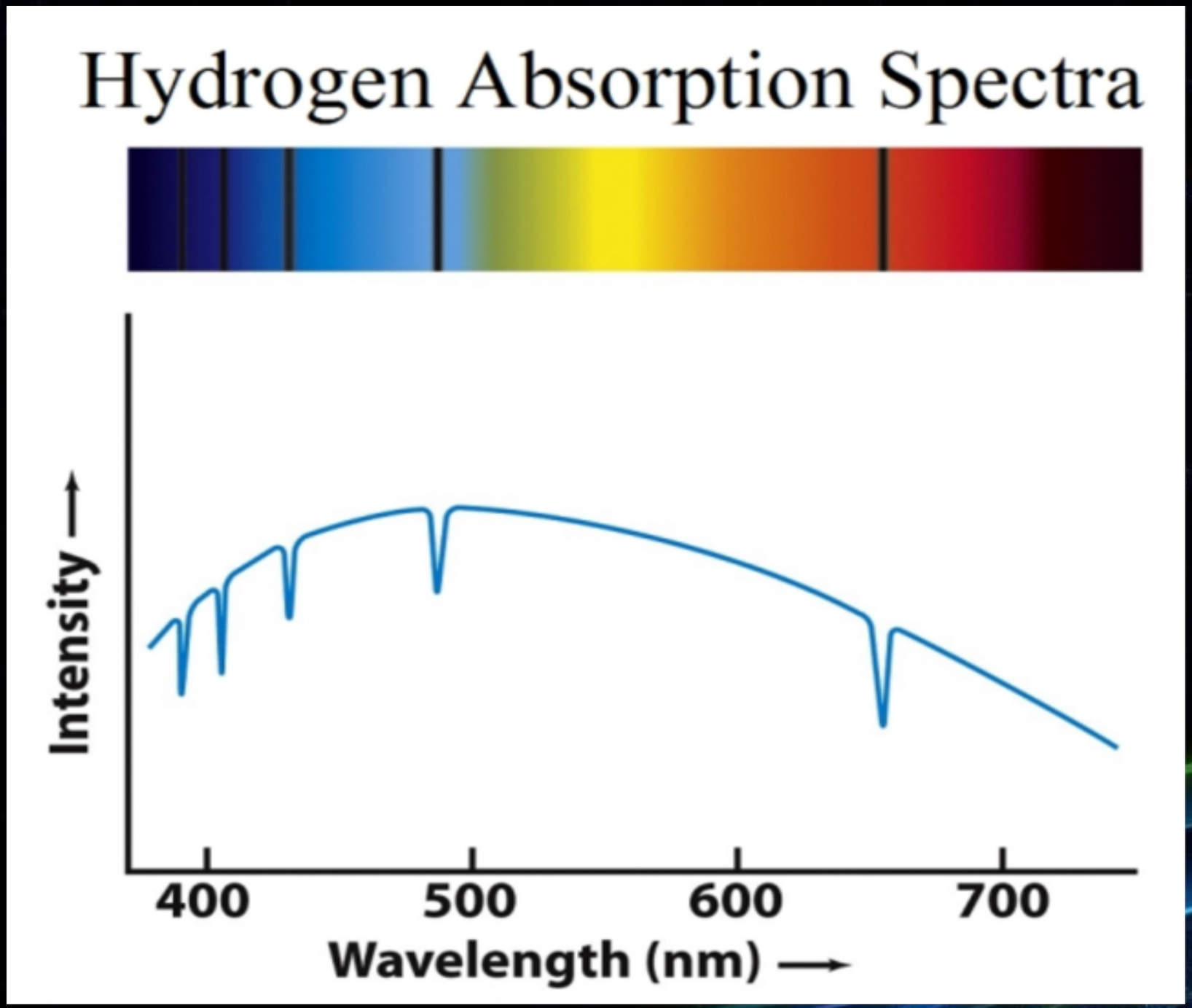
Each element will absorb specific colors.

Different elements do not absorb the same colors.



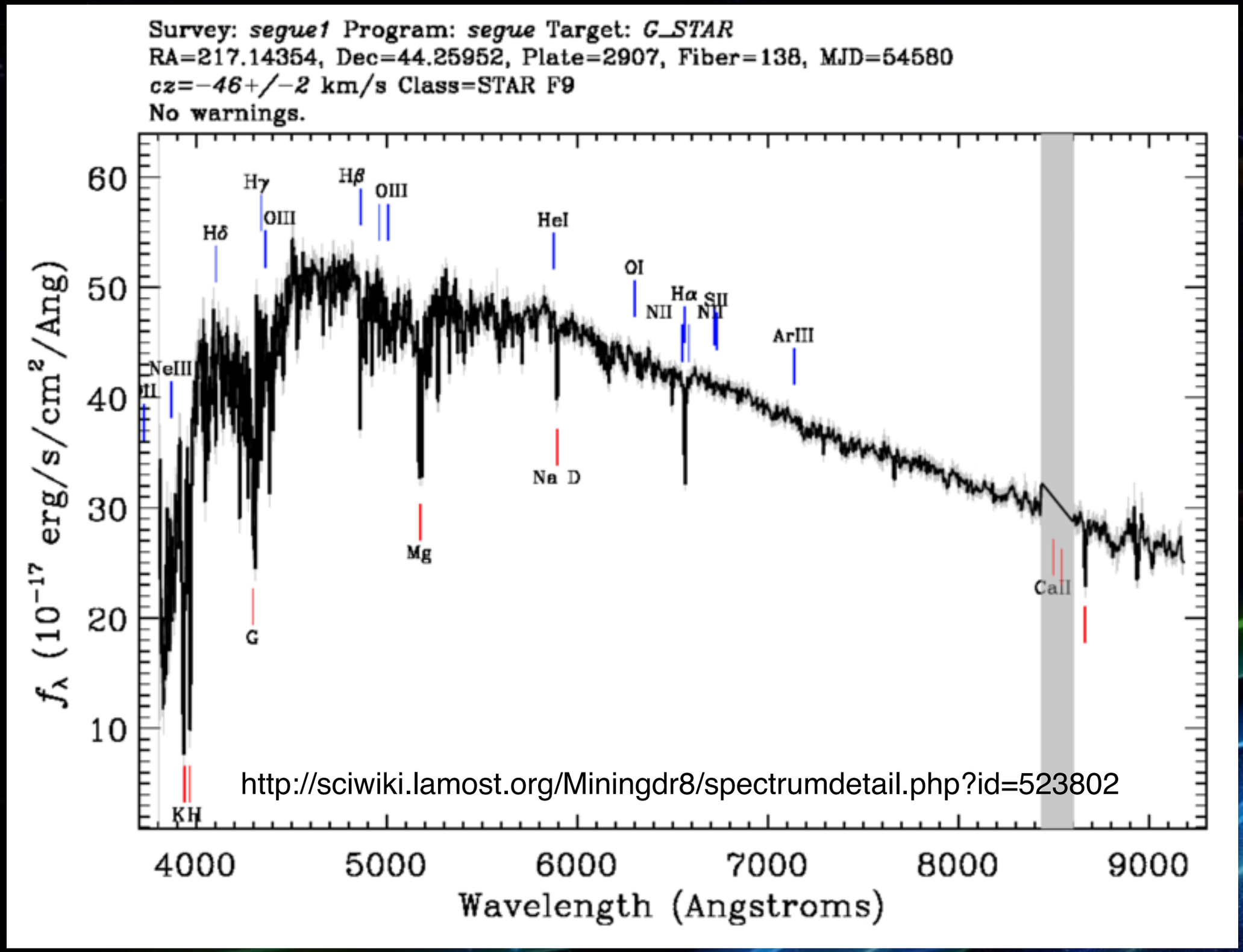
https://matyasmolnar.com/spectroscopy/

Spectroscopy



https://www.harding.edu/lmurray/113_files/html/c_light%20and%20telescopes/sld008.htm

Spectroscopy



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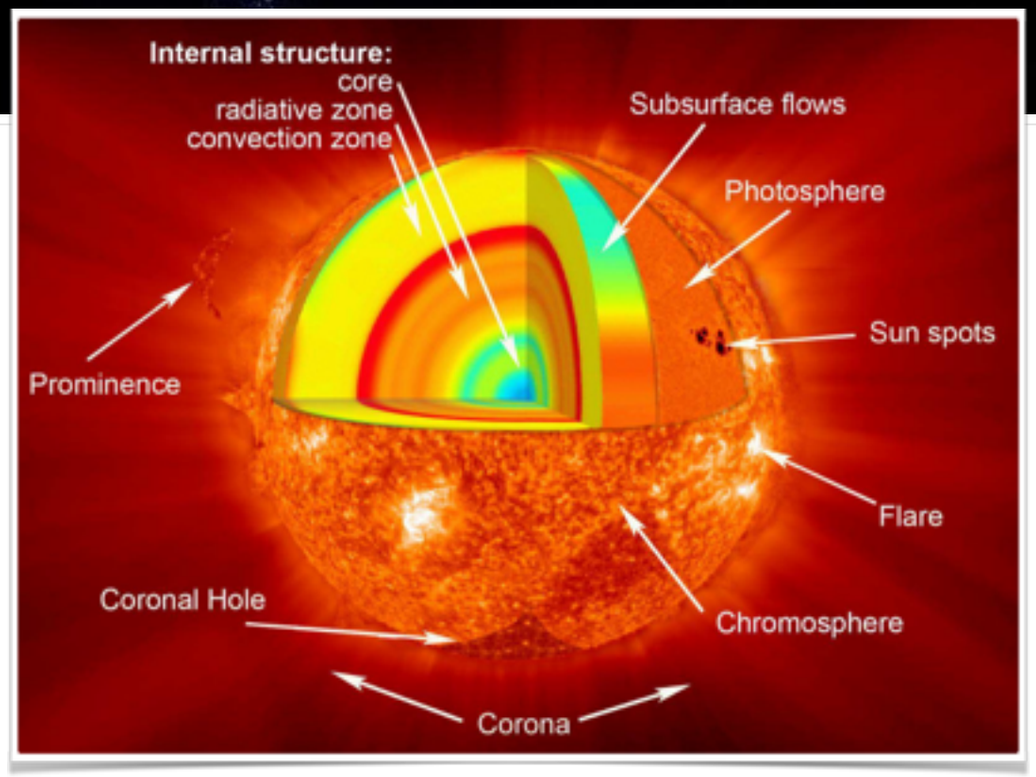
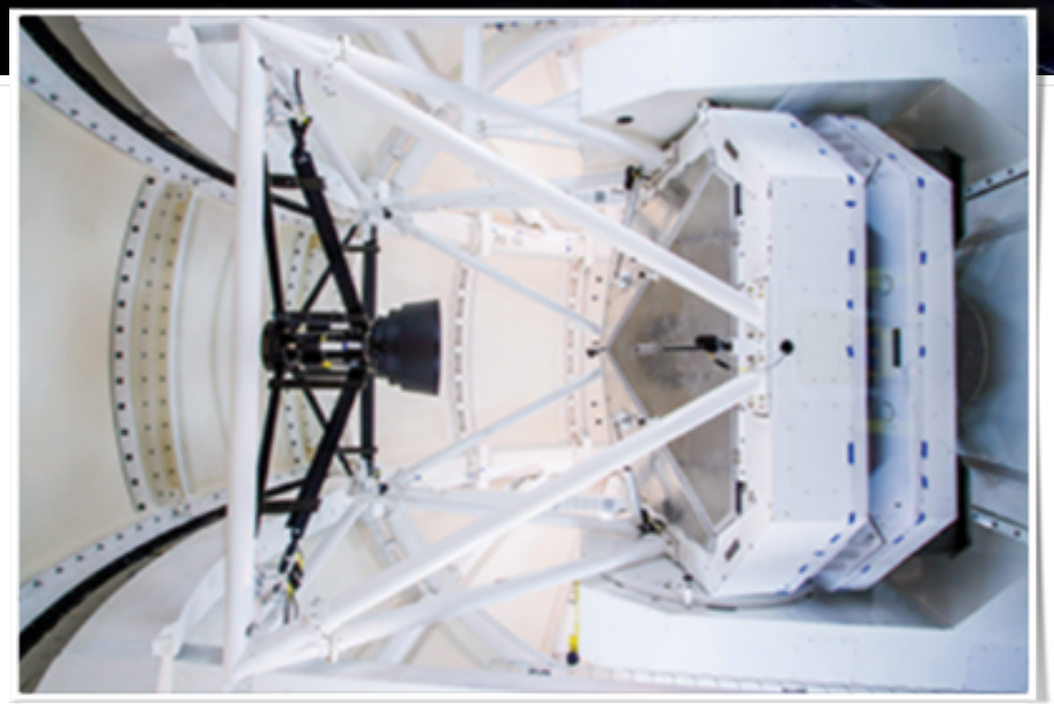
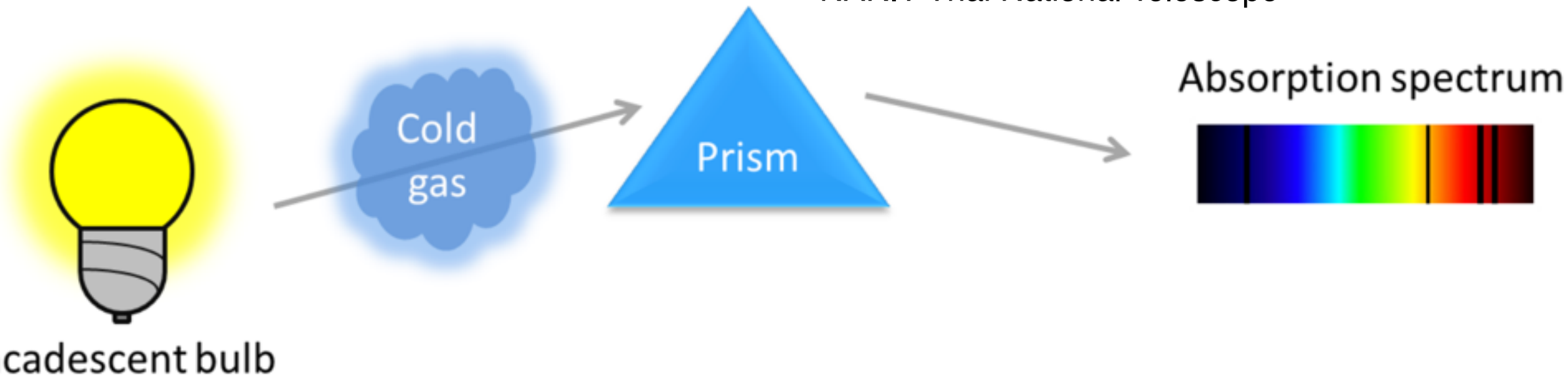




NARIT Thai National Telescope



https://matyasmolnar.com/spectroscopy/

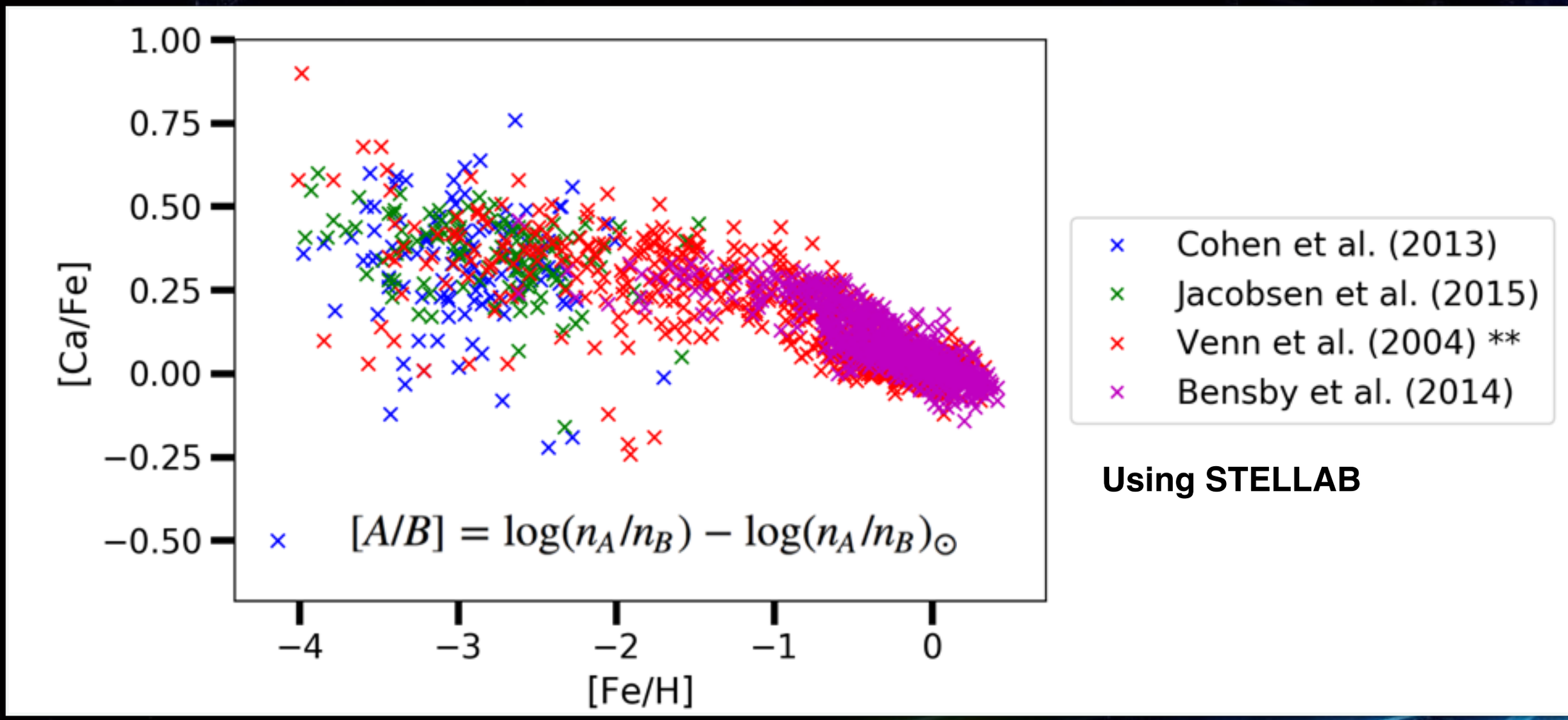
Observing Chemical Evolution using Spectroscopy

When stars form, they lock the chemical composition of the gas on their surface

Looking at the surface of a 10 Gyr old star tells us about the composition of the galactic gas 10 Gyr ago

M31 Wikipedia @Adan Evans

Observing Chemical Evolution using Spectroscopy

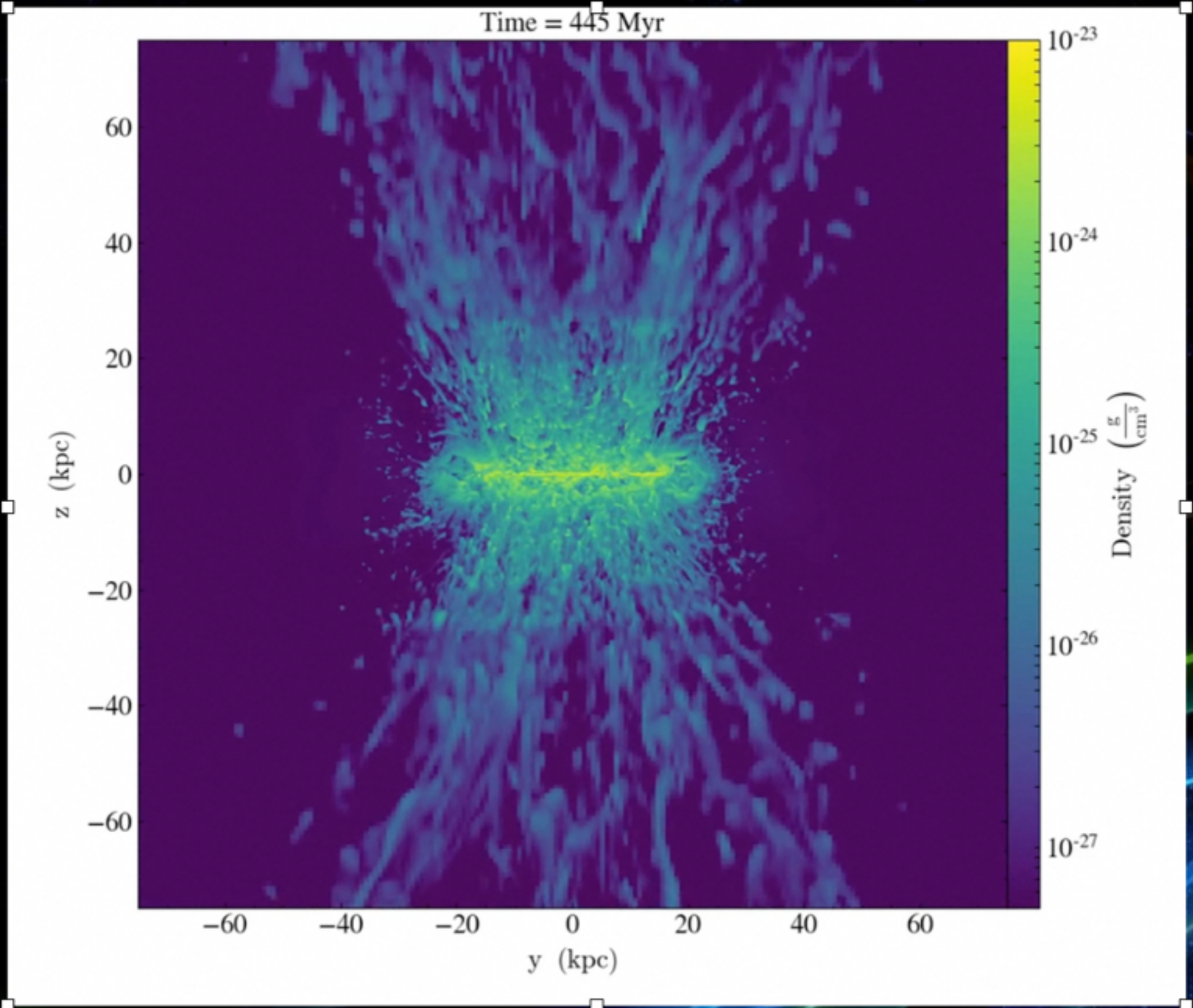


Using STELLAB

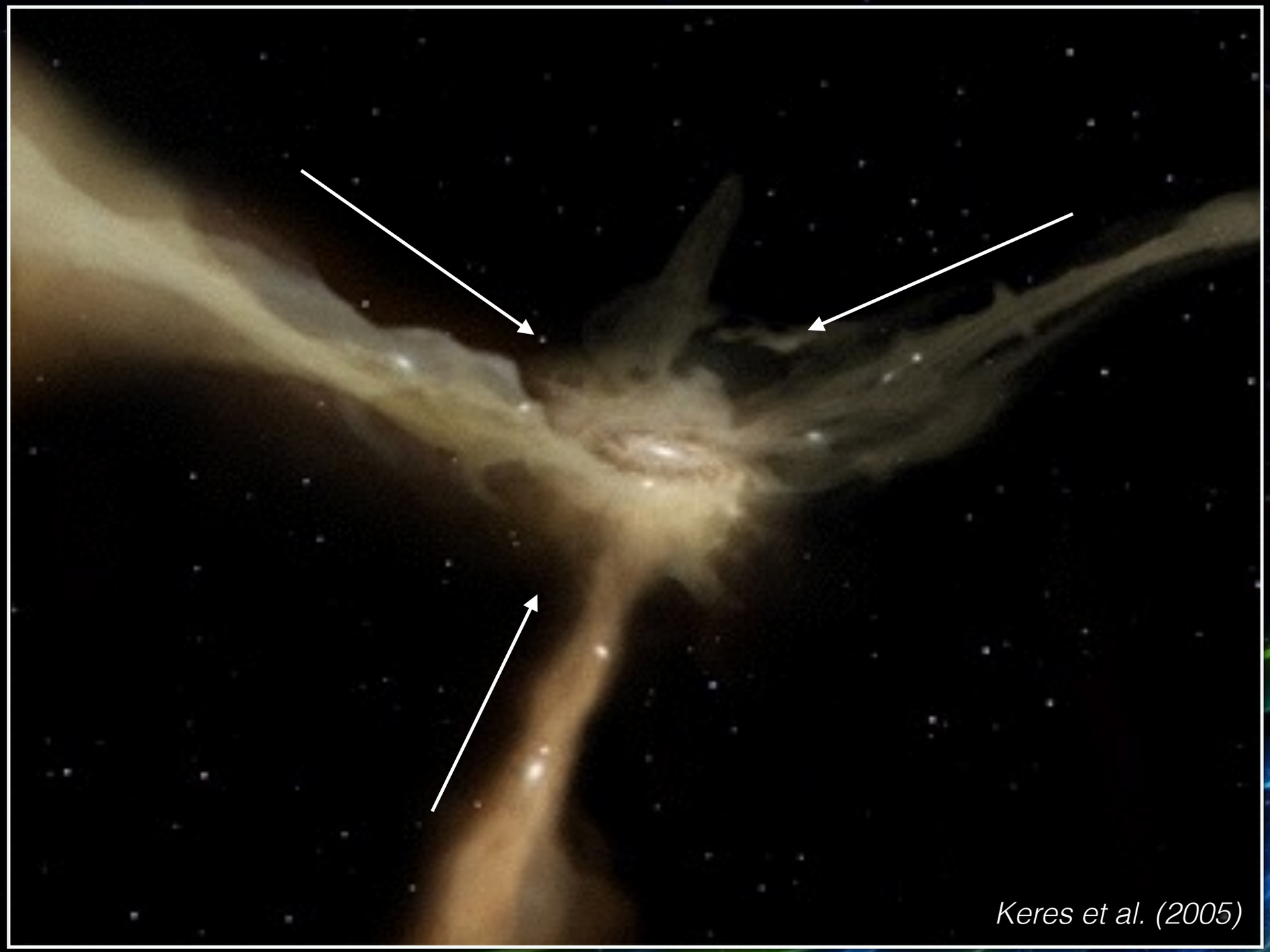
Past → **Present**

Galactic Outflows

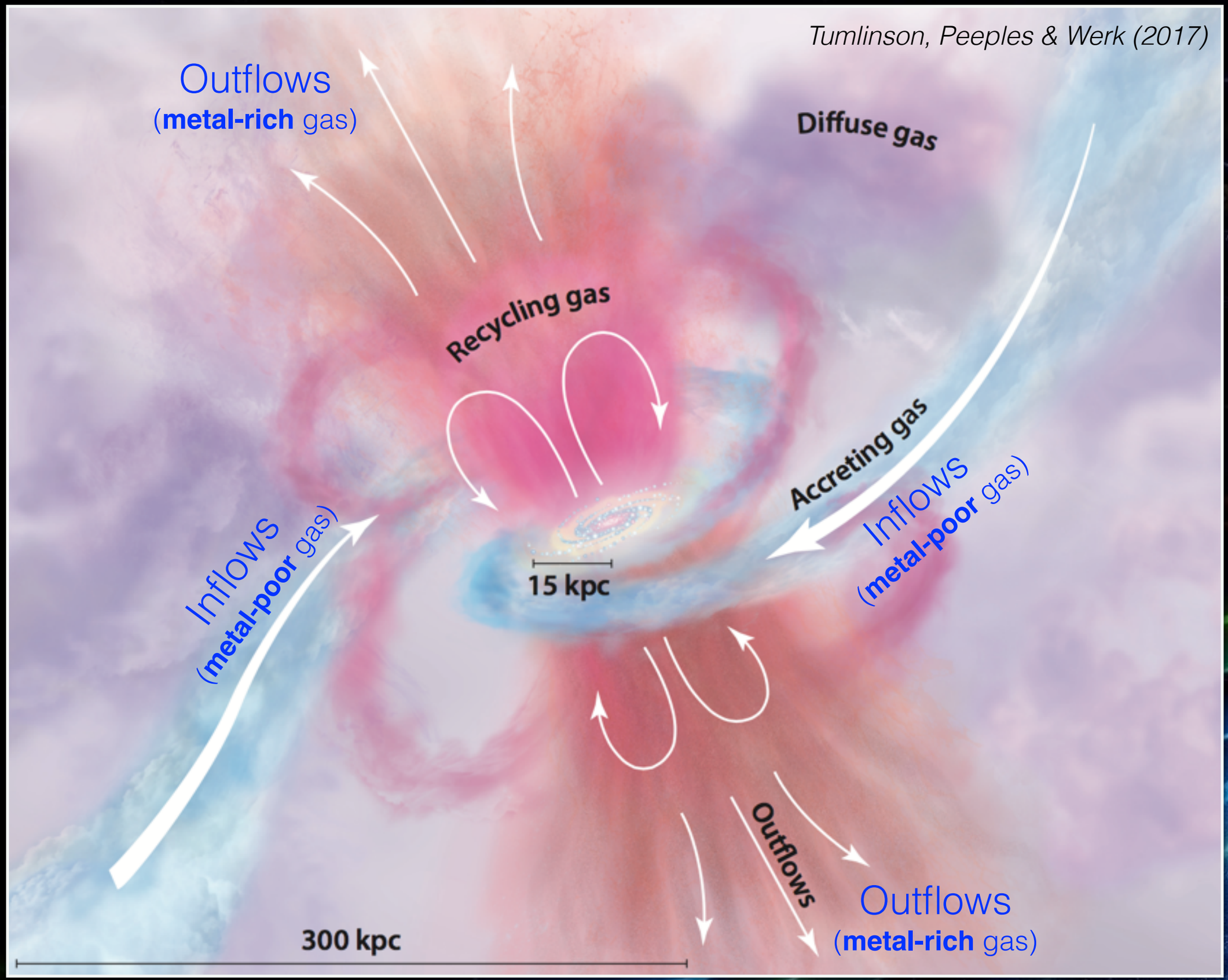
@Dr. Devin Silvia



Galactic Inflows



Galactic Inflows and Outflows



Modeling Chemical Evolution

Inflows Star formation

$$M_{\rm gas}(t+\Delta t) = M_{\rm gas}(t) + \left[\dot{M}_{\rm in}(t) + \dot{M}_{\rm ej}(t) - \dot{M}_{\star}(t) - \dot{M}_{\rm out}(t)\right]\Delta t$$

Stellar ejecta Outflows

Modeling Chemical Evolution

Inflows

Star formation

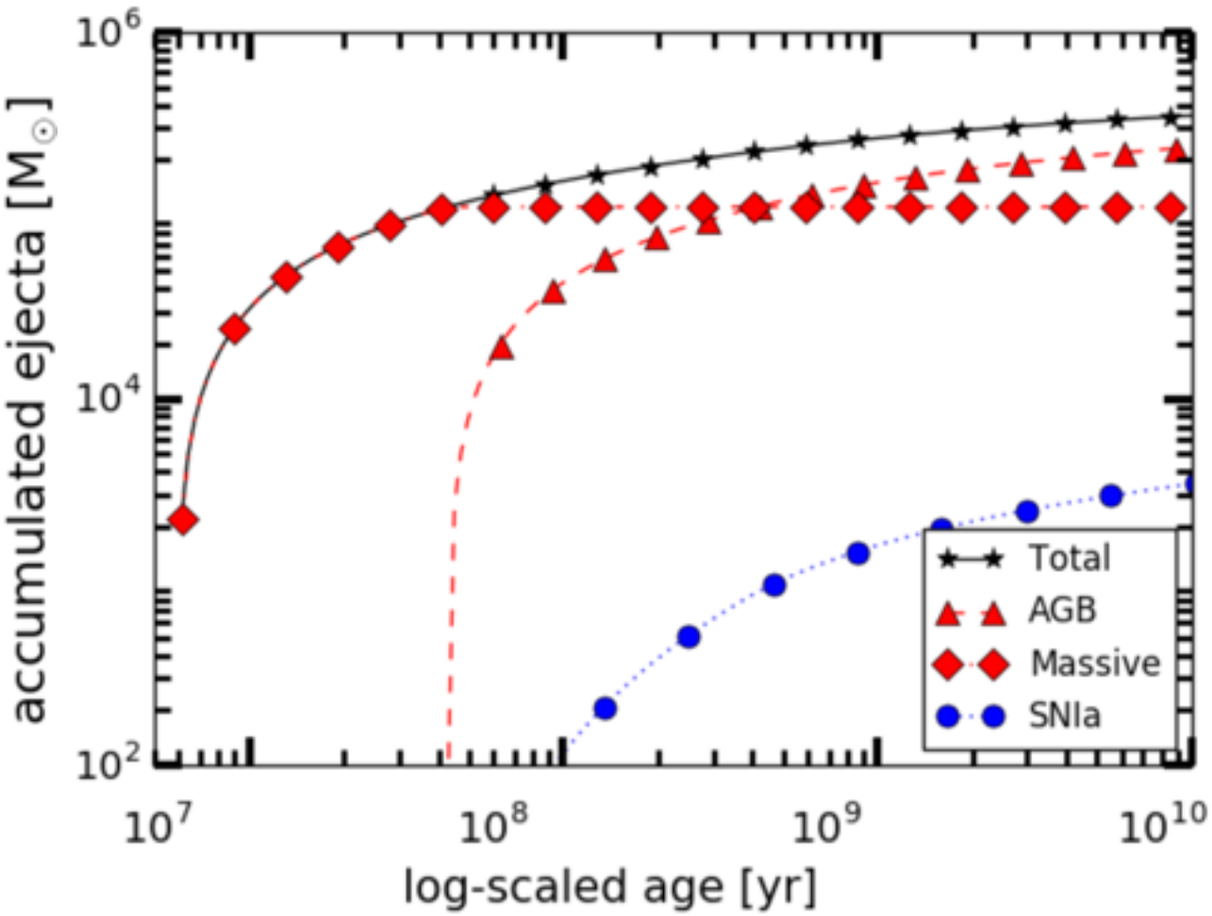
$$M_{\rm gas}(t+\Delta t) = M_{\rm gas}(t) + \left[\dot{M}_{\rm in}(t) + \dot{M}_{\rm ej}(t) - \dot{M}_{\star}(t) - \dot{M}_{\rm out}(t)\right]\Delta t$$

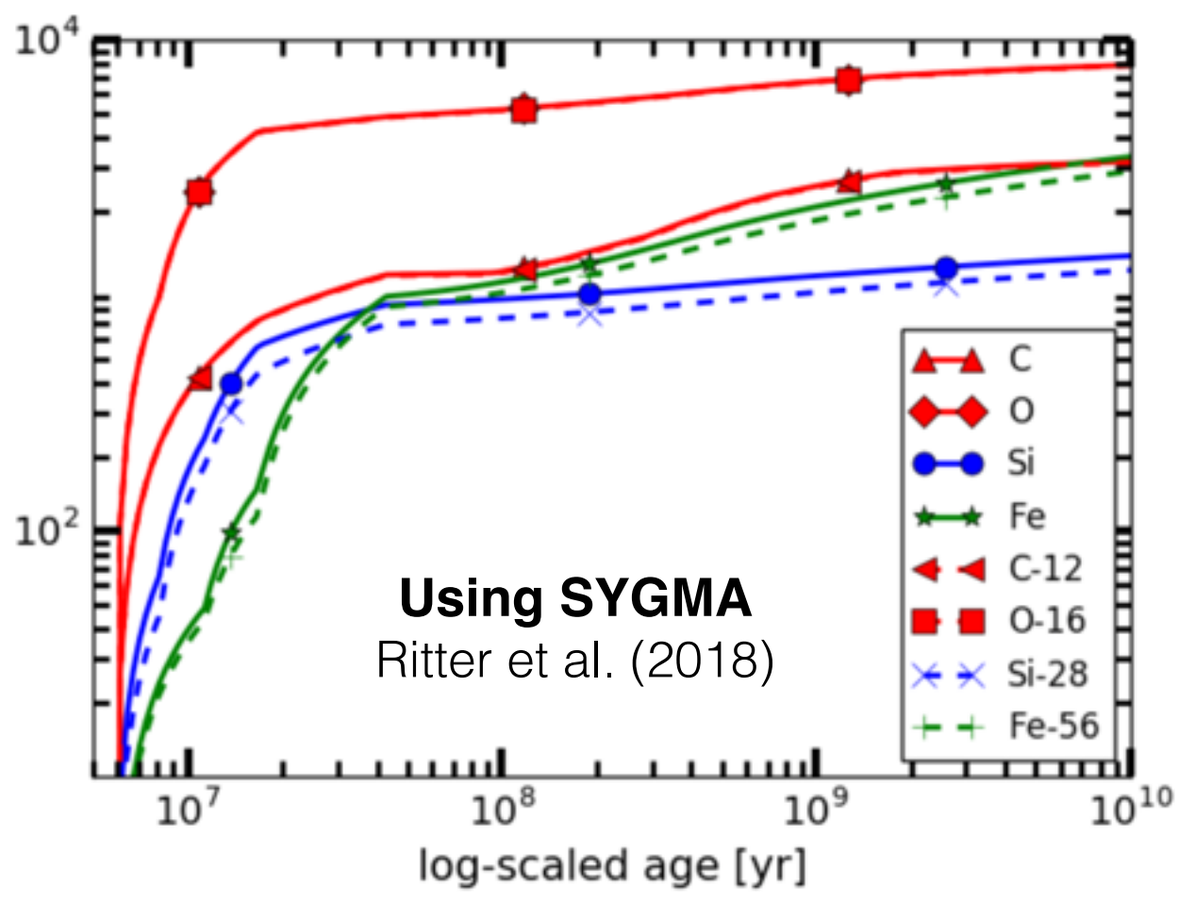
Stellar ejecta

Outflows

Modeling Chemical Evolution

One stellar population

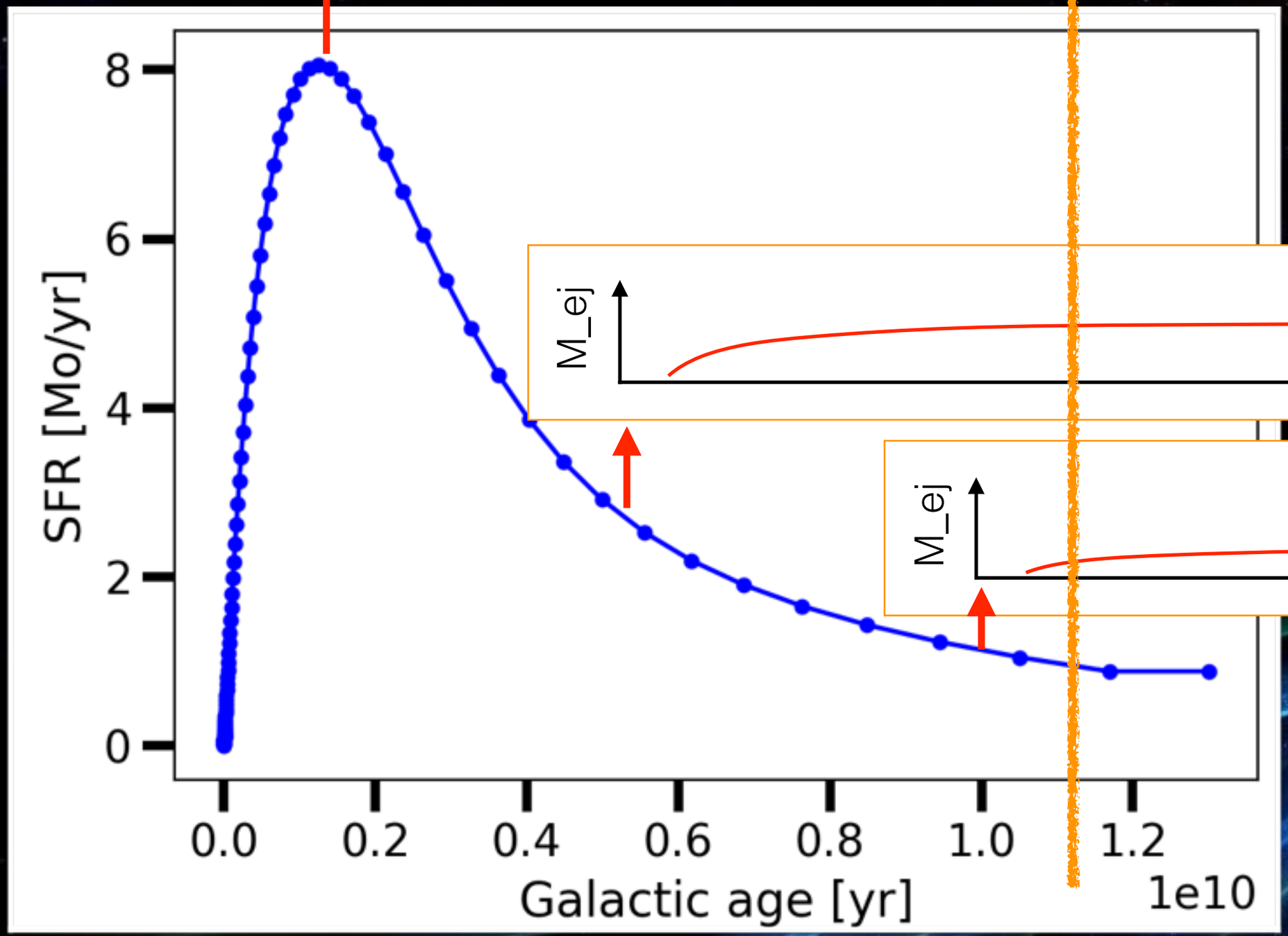




Using SYGMA
Ritter et al. (2018)

Modeling Chemical Evolution

Many stellar populations



Modeling Chemical Evolution

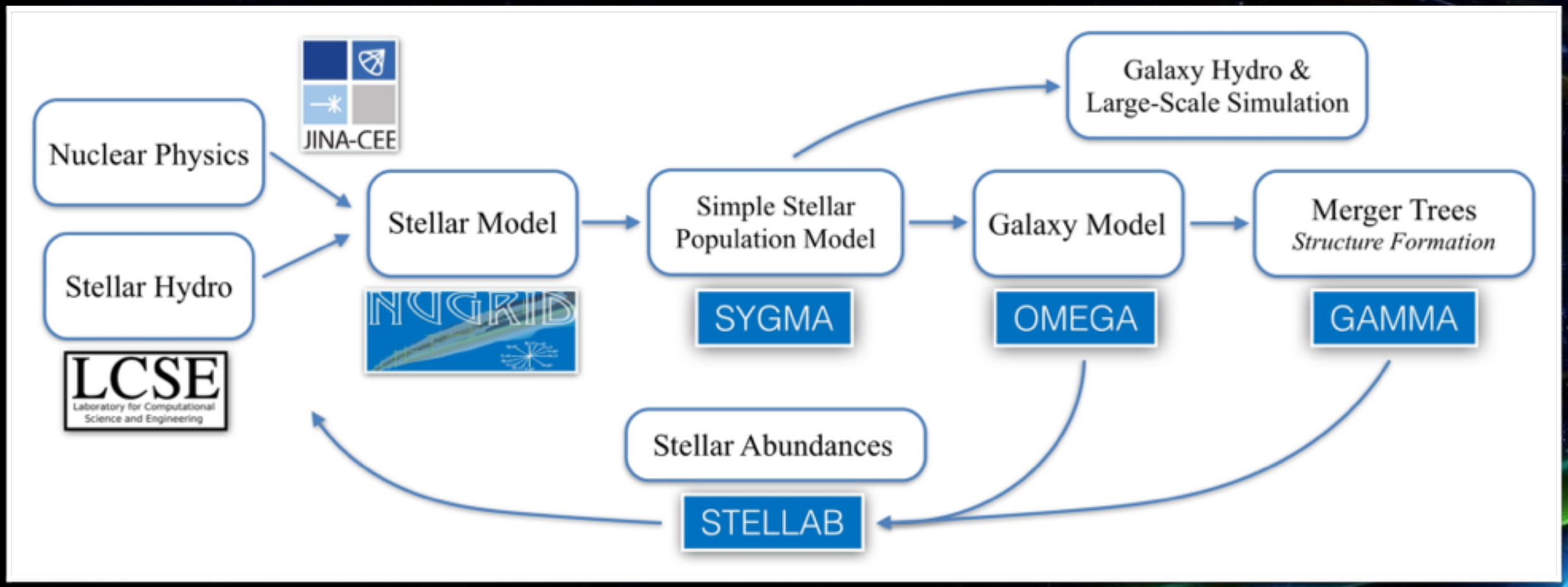
Inflows Star formation

$$M_{\rm gas}(t+\Delta t) = M_{\rm gas}(t) + \left[\dot{M}_{\rm in}(t) + \dot{M}_{\rm ej}(t) - \dot{M}_{\star}(t) - \dot{M}_{\rm out}(t)\right]\Delta t$$

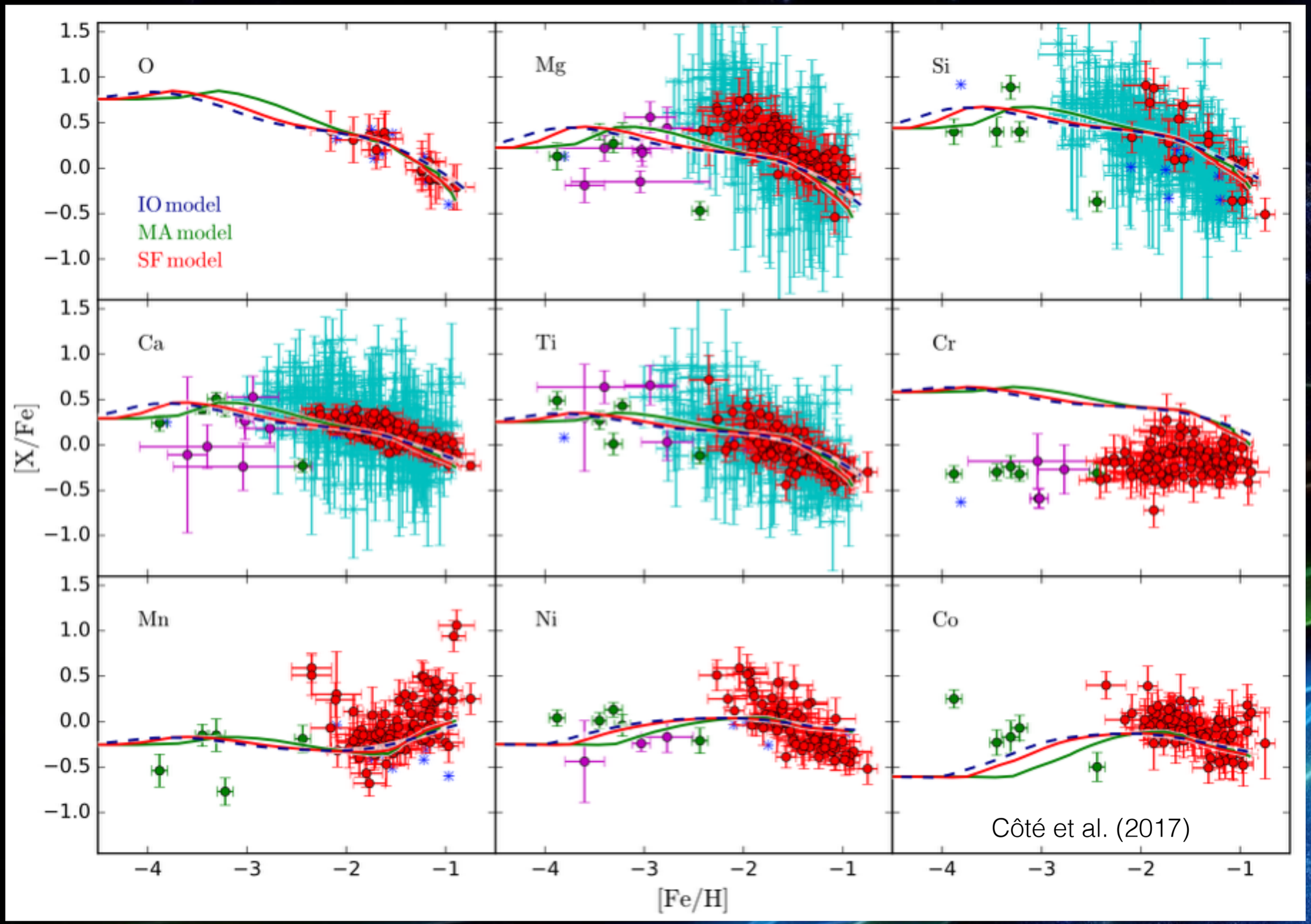
Stellar ejecta Outflows

$$\dot{M}_{\rm ej}(t)\,\Delta t = \sum_{i=1}^{N_{\rm SSP}} \sum_{\rm X=1}^{N_X} \dot{M}_{{\rm ej}_X}(M_i,\, Z_i,\, \tau_i)\,\Delta t$$

Modeling Chemical Evolution



Modeling Chemical Evolution



Côté et al. (2017)