

# The Evolution of Chemical Elements in Galaxies

Dr. Benoit Côté

# The Plan for Today

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## Lecture #1

- Introduction to astronomical scales
- Evolution of the Universe

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## Lecture #2

- Introduction to galaxy evolution
- 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

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Scene from the 1997 « Contact » movie from Warner Bros

A scene from the movie Contact showing a zoom out from Earth to the cosmos. The image starts with a close-up of Earth's horizon, showing clouds and landmasses. As the camera zooms out, the planet becomes smaller, and the vastness of space is revealed. A bright star or celestial body is visible in the upper right. The background is filled with distant stars and galaxies, creating a sense of infinite space.

Video

# The Night Sky



[pixabay.com](https://pixabay.com)  
[pexels.com](https://pexels.com)

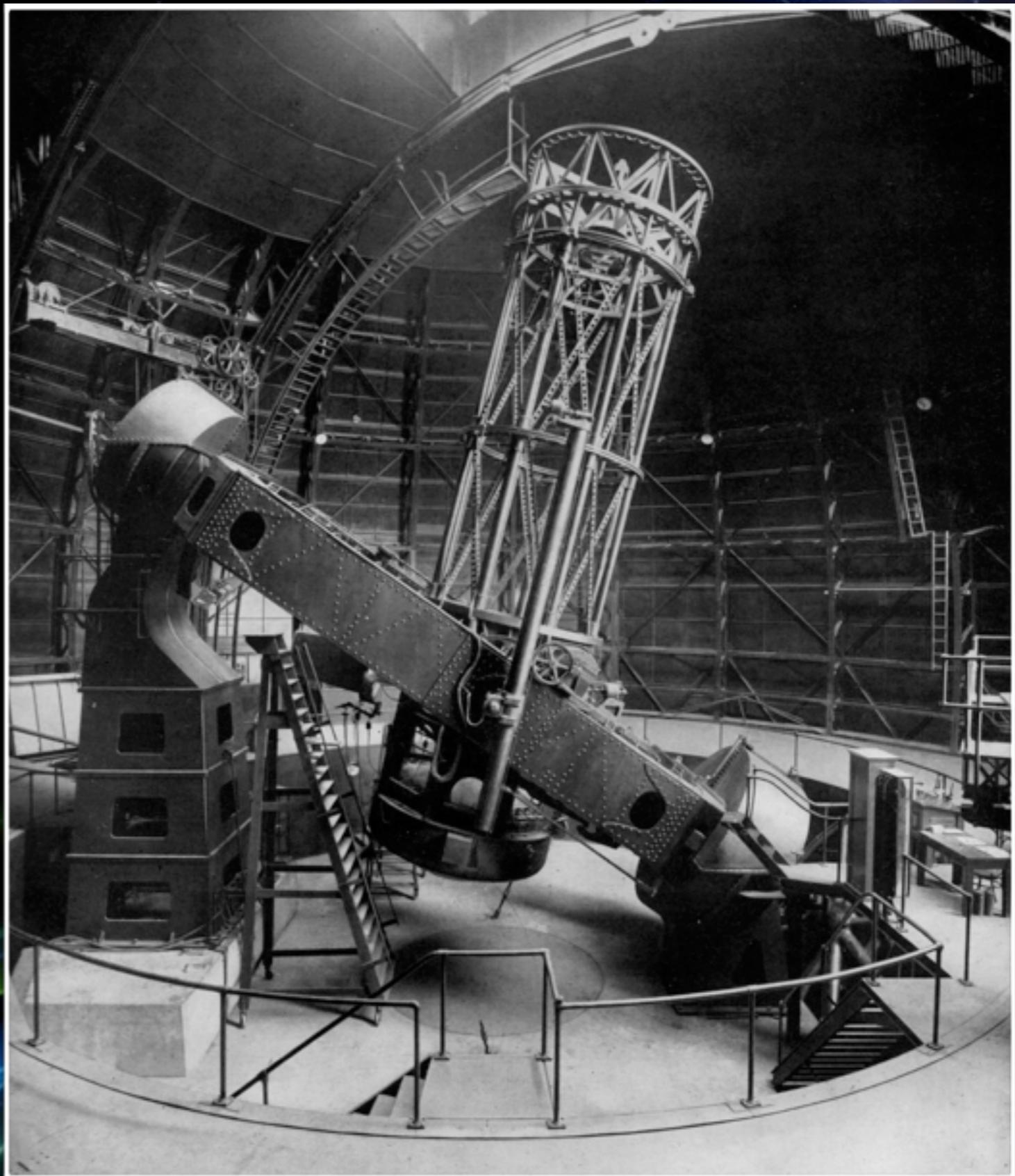
# The Vision of the Universe in 1920

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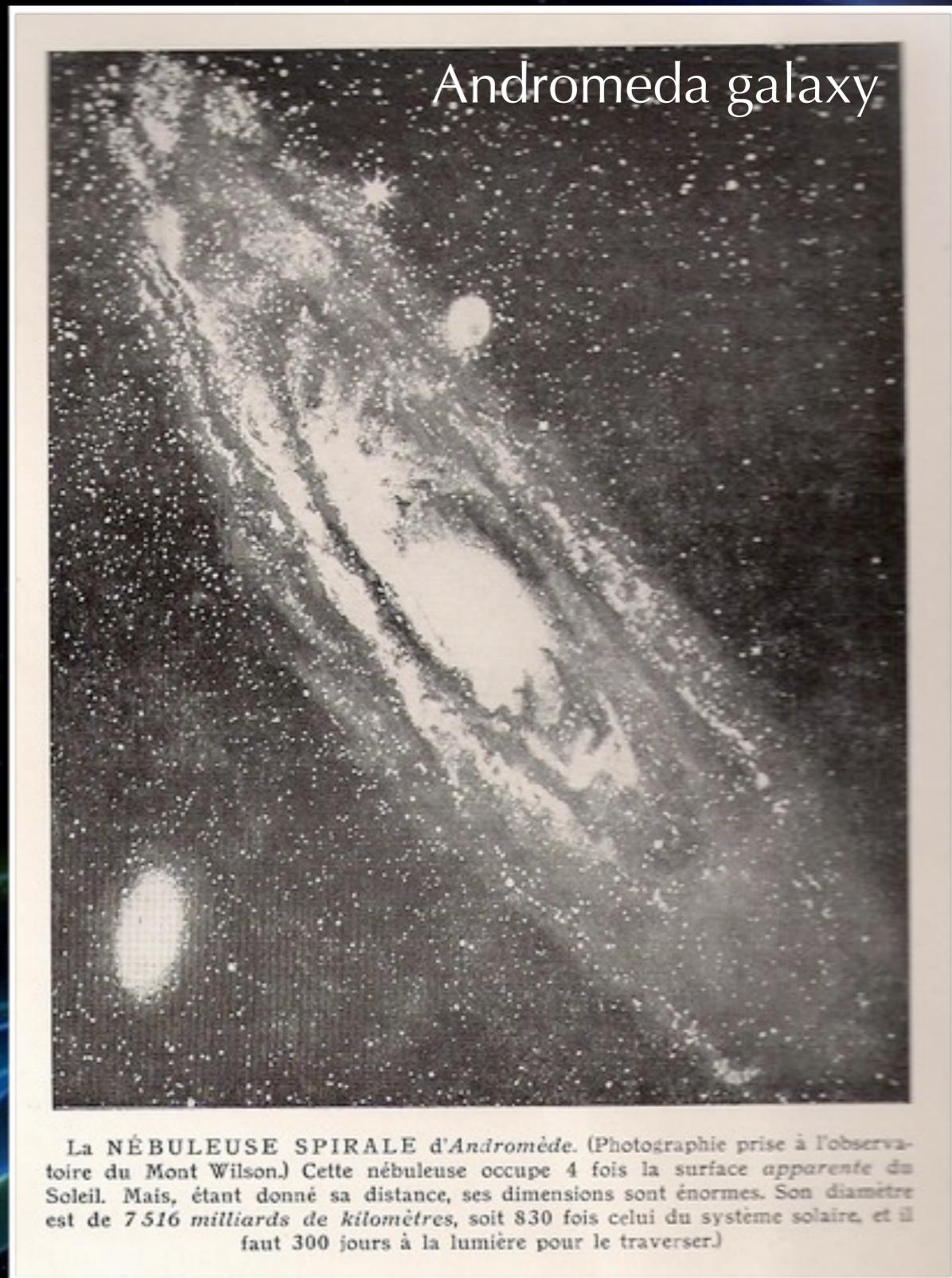


# The Vision of the Universe in 1920

Mont Wilson telescope



# The Observation of Galaxies



Edwin Hubble's observations

# The Observation of Galaxies



Edwin Hubble's observations

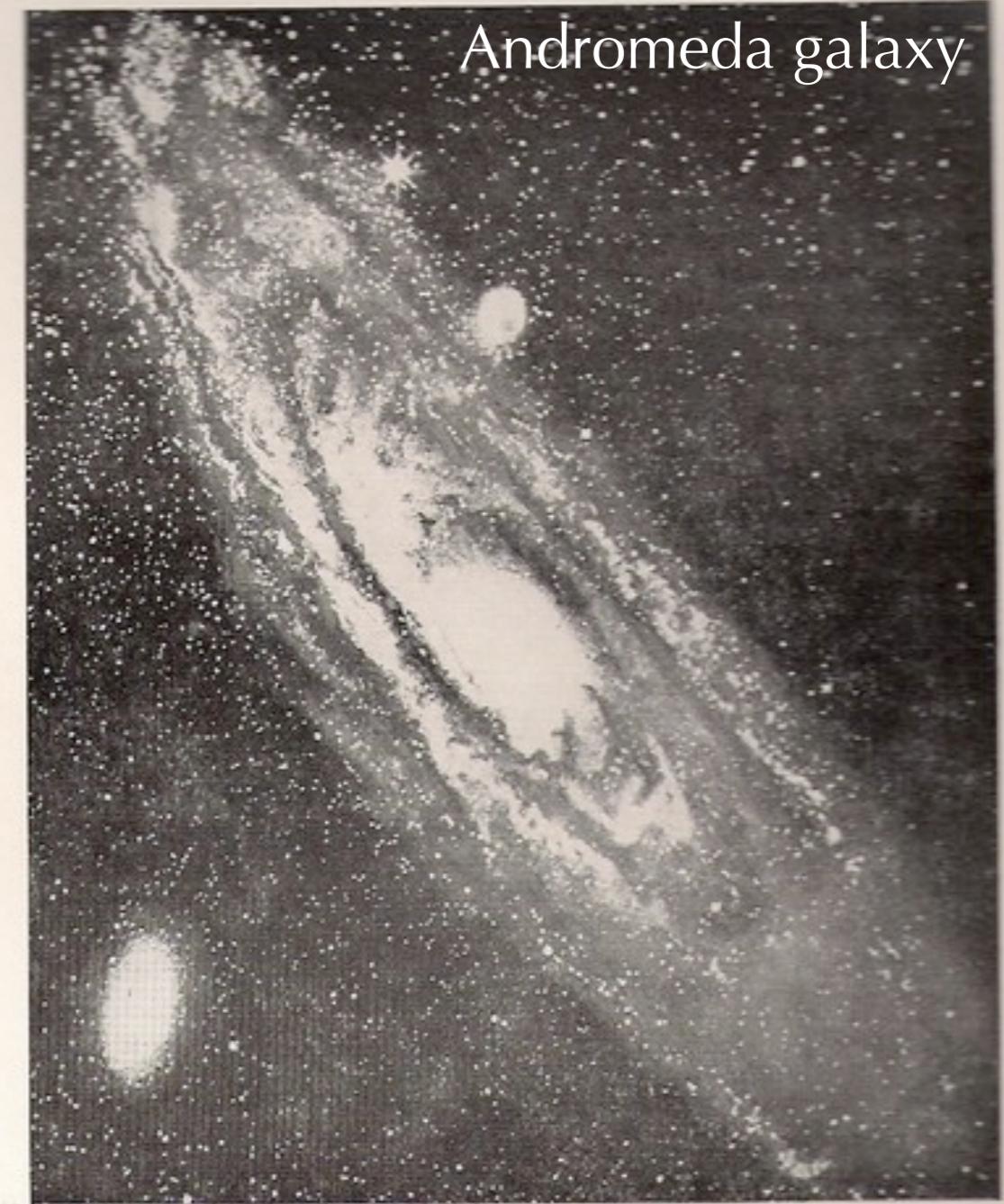
# The Observation of Galaxies



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



# Andromeda galaxy

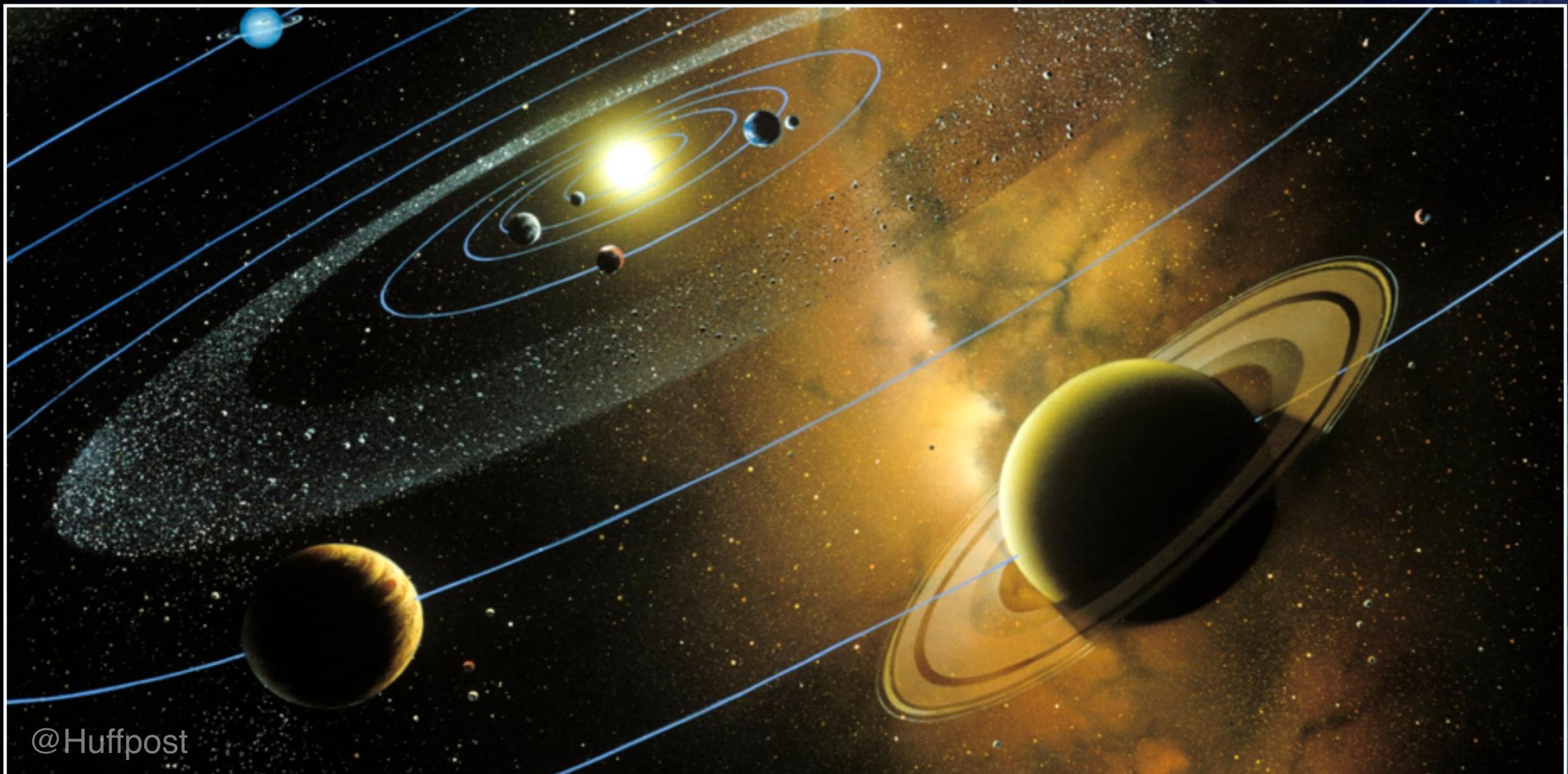


La NÉBULEUSE SPIRALE d'*Andromède*. (Photographie prise à l'observatoire du Mont Wilson.) Cette nébuleuse occupe 4 fois la surface apparente du Soleil. Mais, étant donné sa distance, ses dimensions sont énormes. Son diamètre est de 7 516 milliards de kilomètres, soit 830 fois celui du système solaire,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

# Edwin Hubble's observations

# Our Solar System

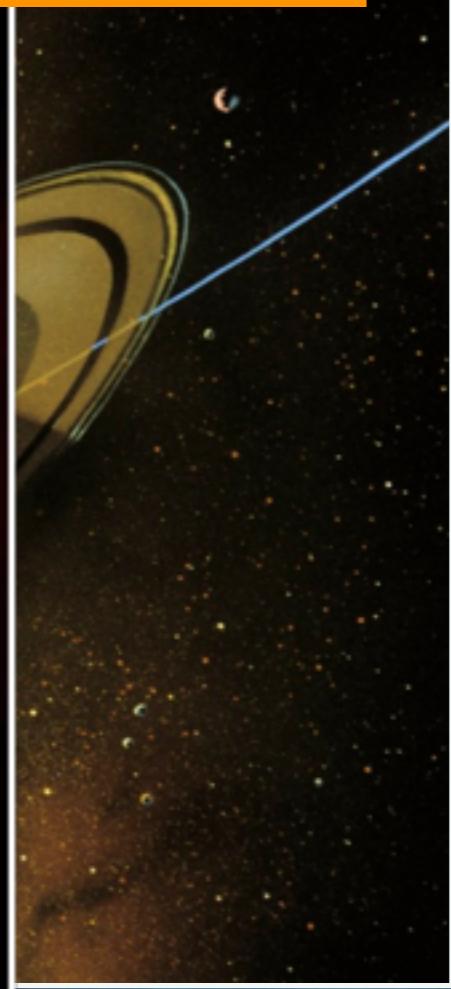
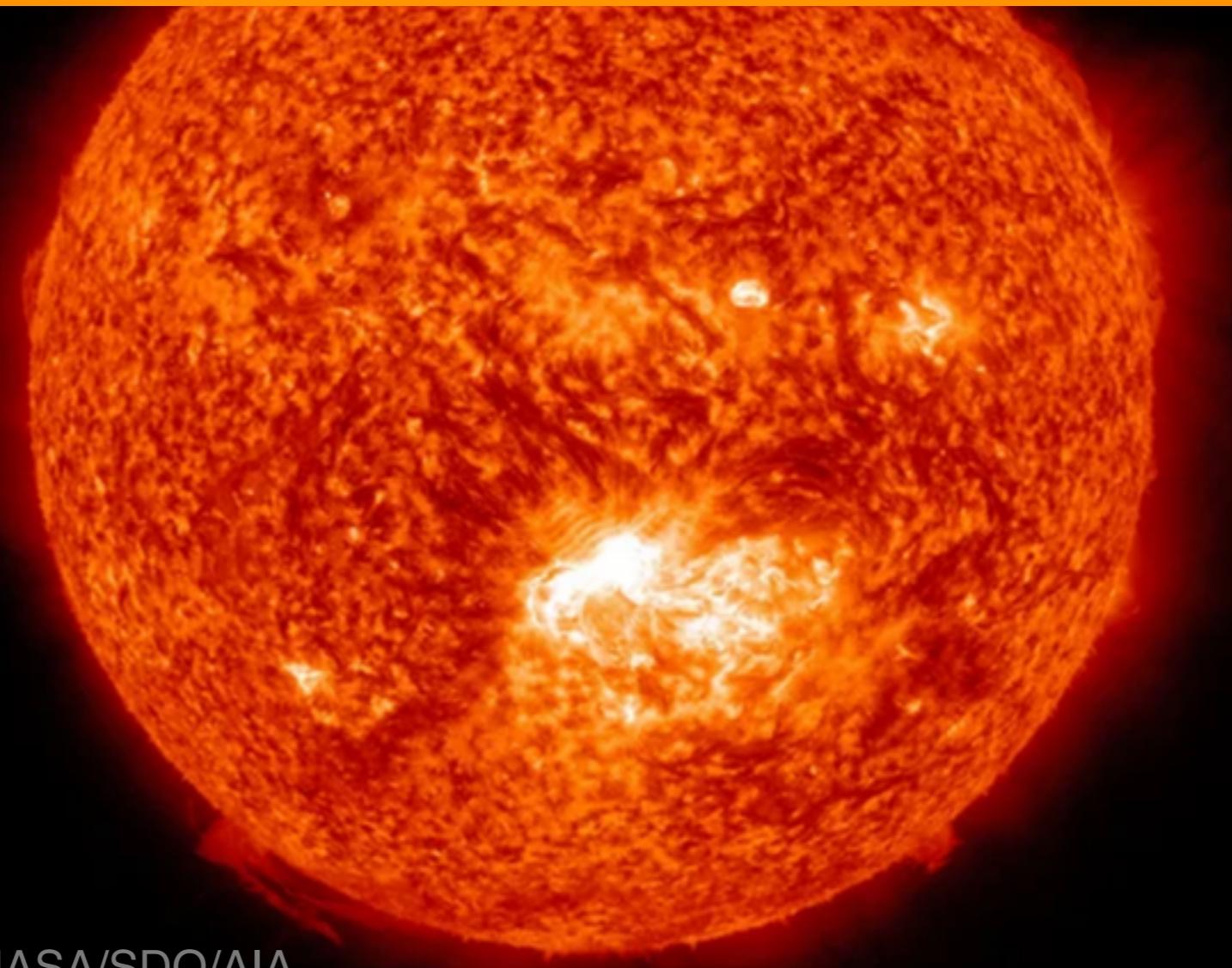
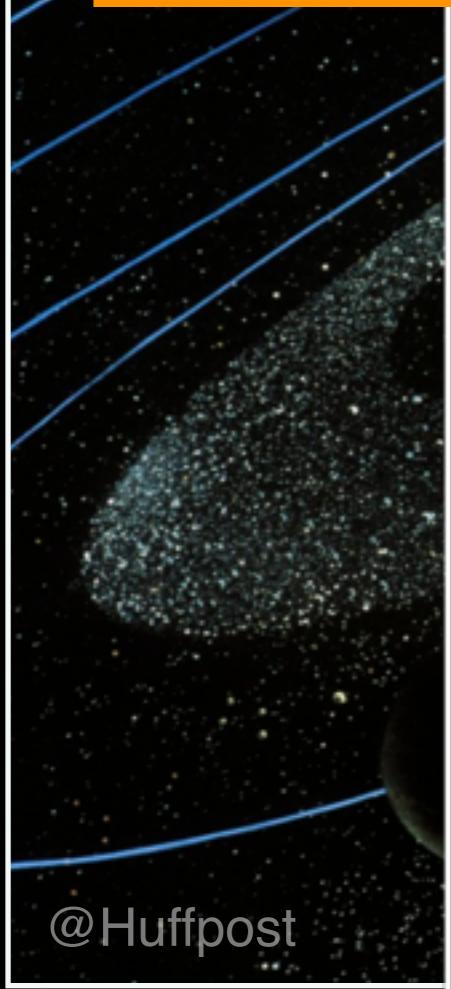
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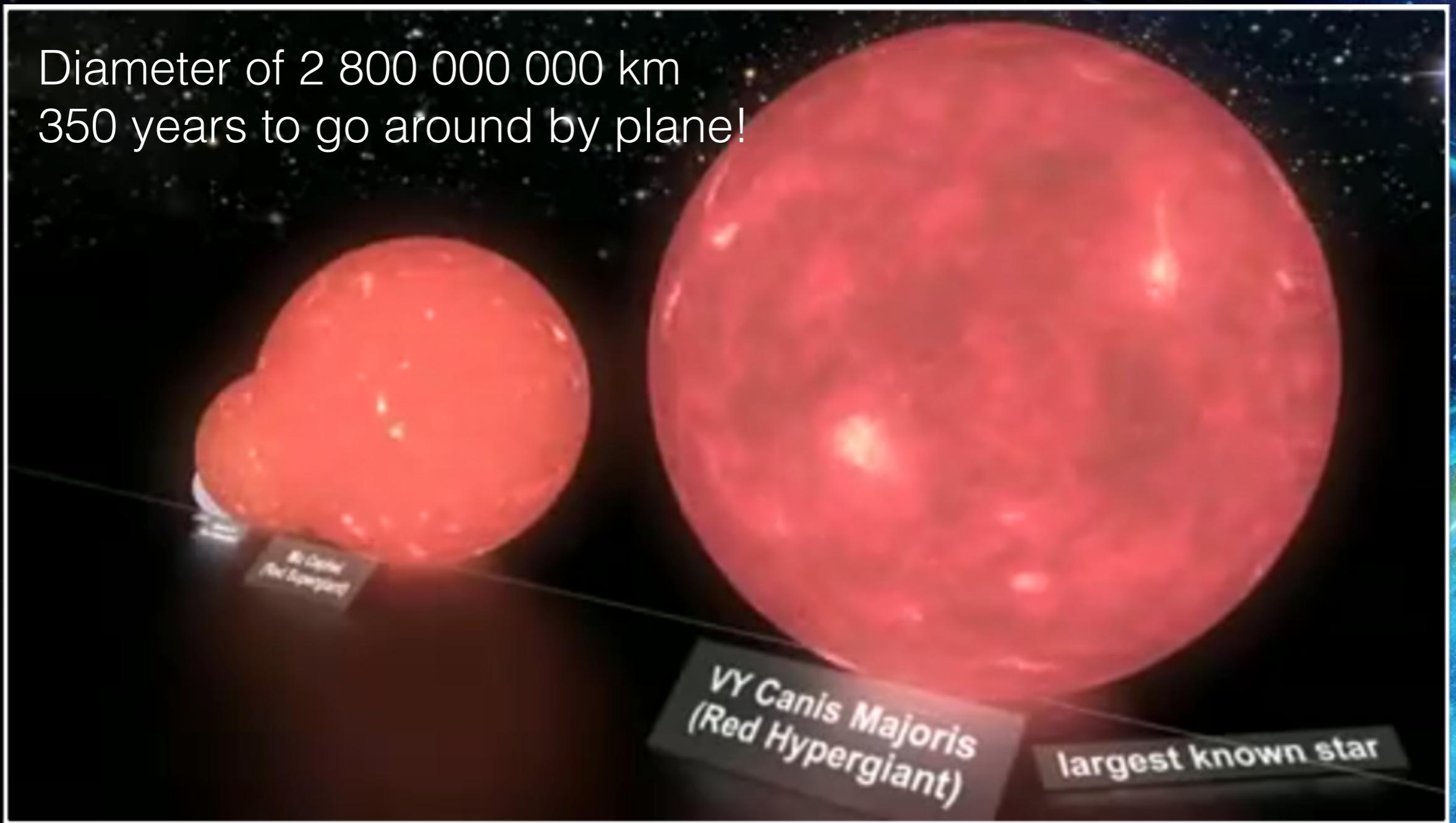
# Our Solar System

**2 000 000 000 000 000 000 000 000 000 kg**

333 333 times the mass of the Earth  
1 Solar Mass



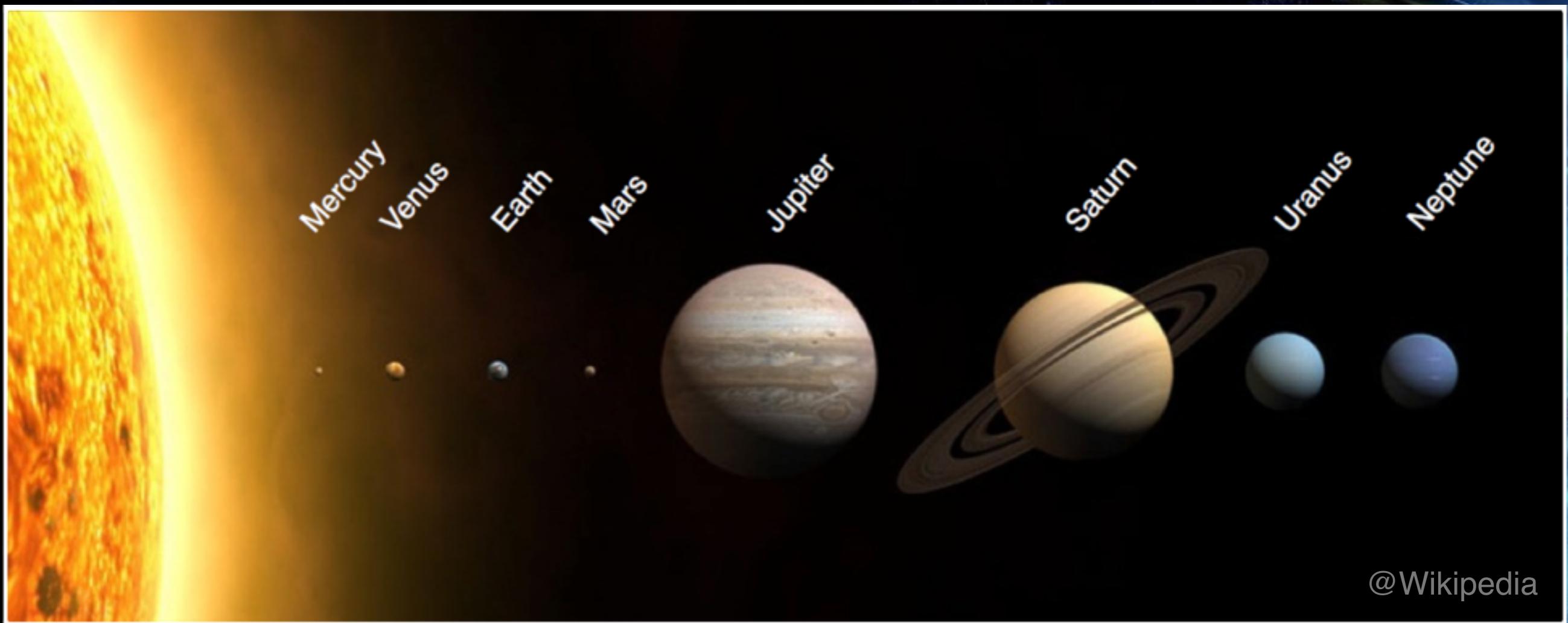
# How Big Are Planets and Stars?



<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





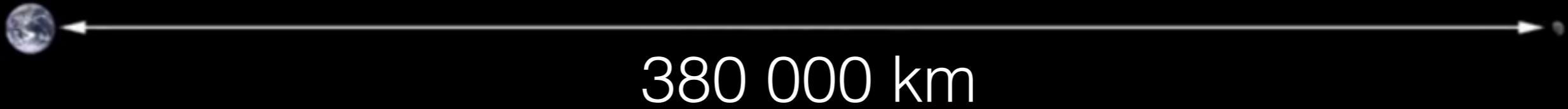
@ESA/Hubble (M. Kornmesser & L. Calçada)



@Wikipedia

# What is the Size of Our Solar System?

This is the Earth - Moon system at correct scale.



@Bob Singer

~ 160 days by car

Sun - Earth

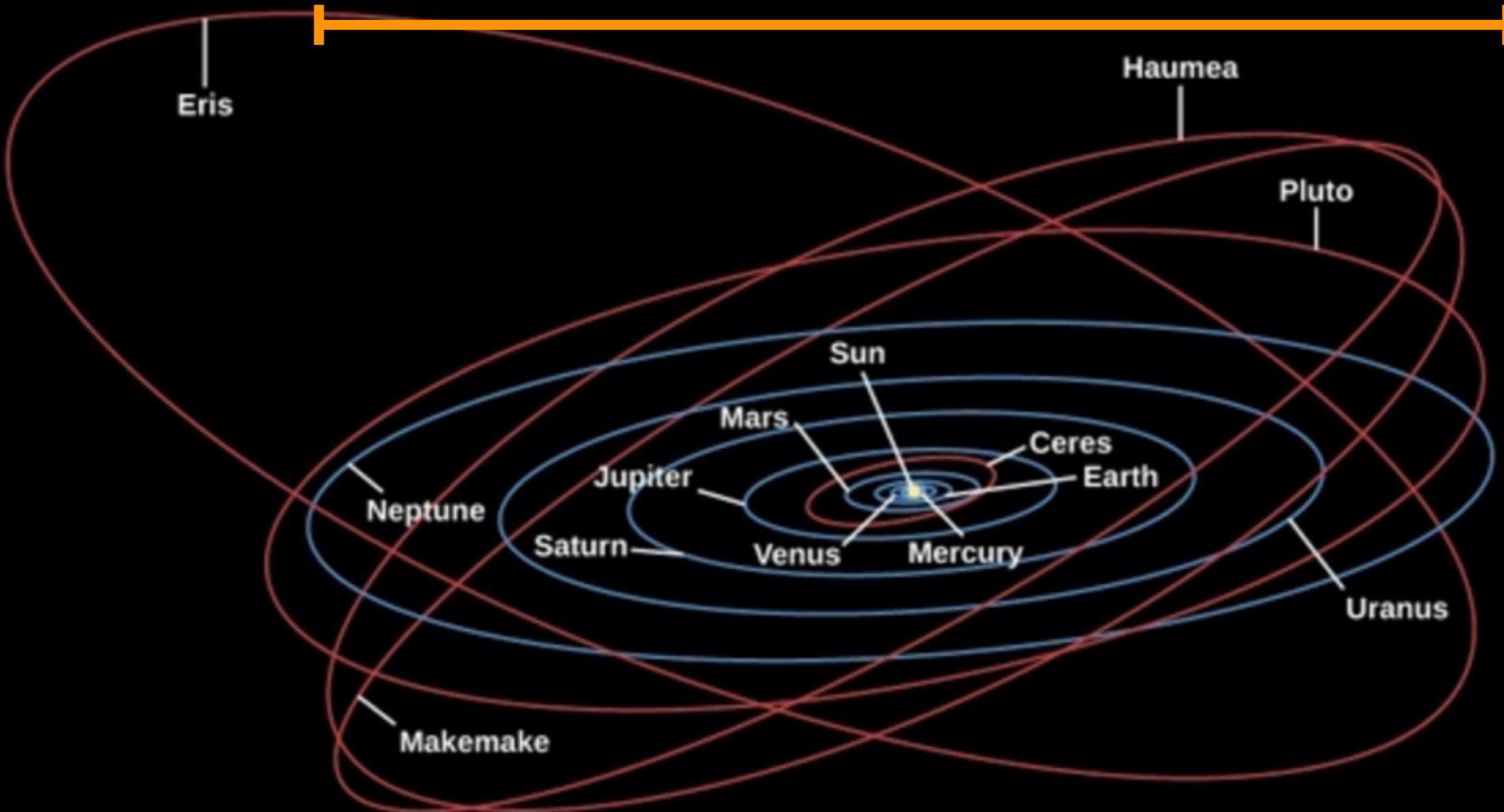


150 000 000 km

~ 170 years by car

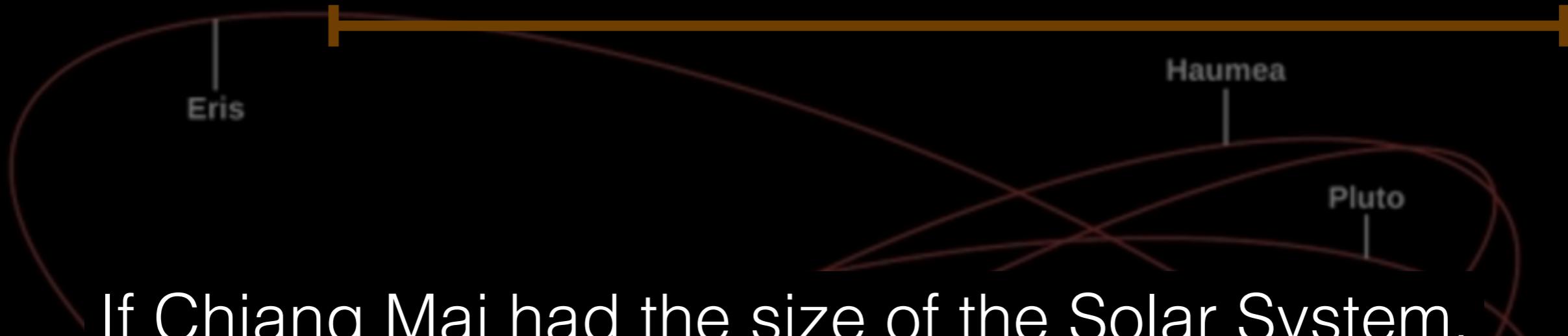
# What is the Size of Our Solar System?

4 545 000 000 km

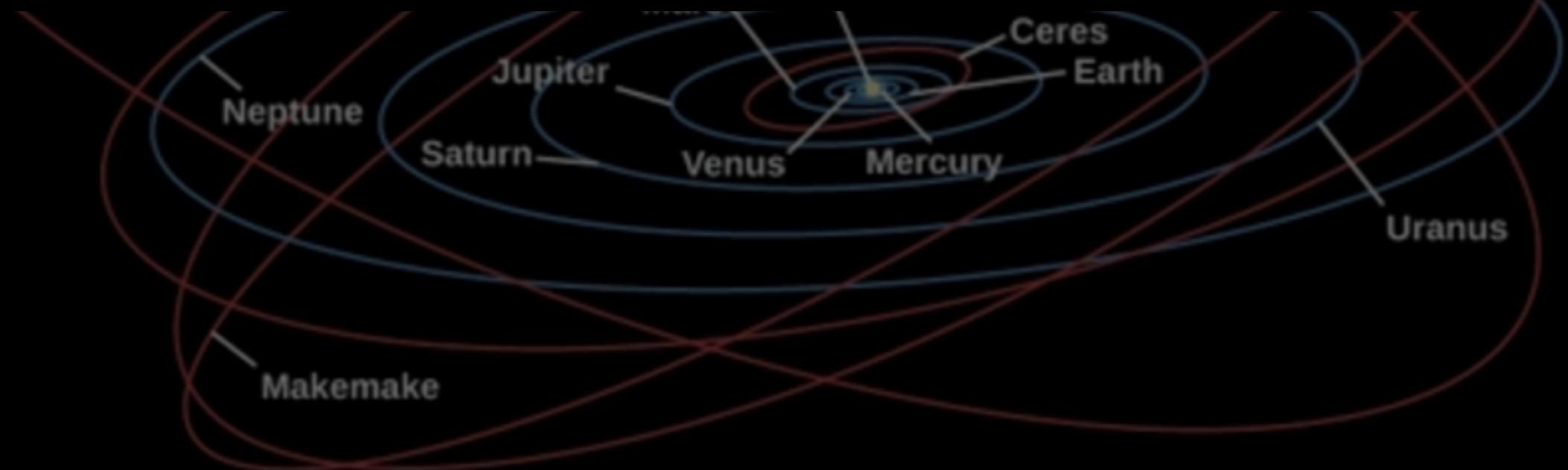


# What is the Size of Our Solar System?

4 545 000 000 km



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



# 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

@Hubble, NASA

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

# Distance to the Closest Star

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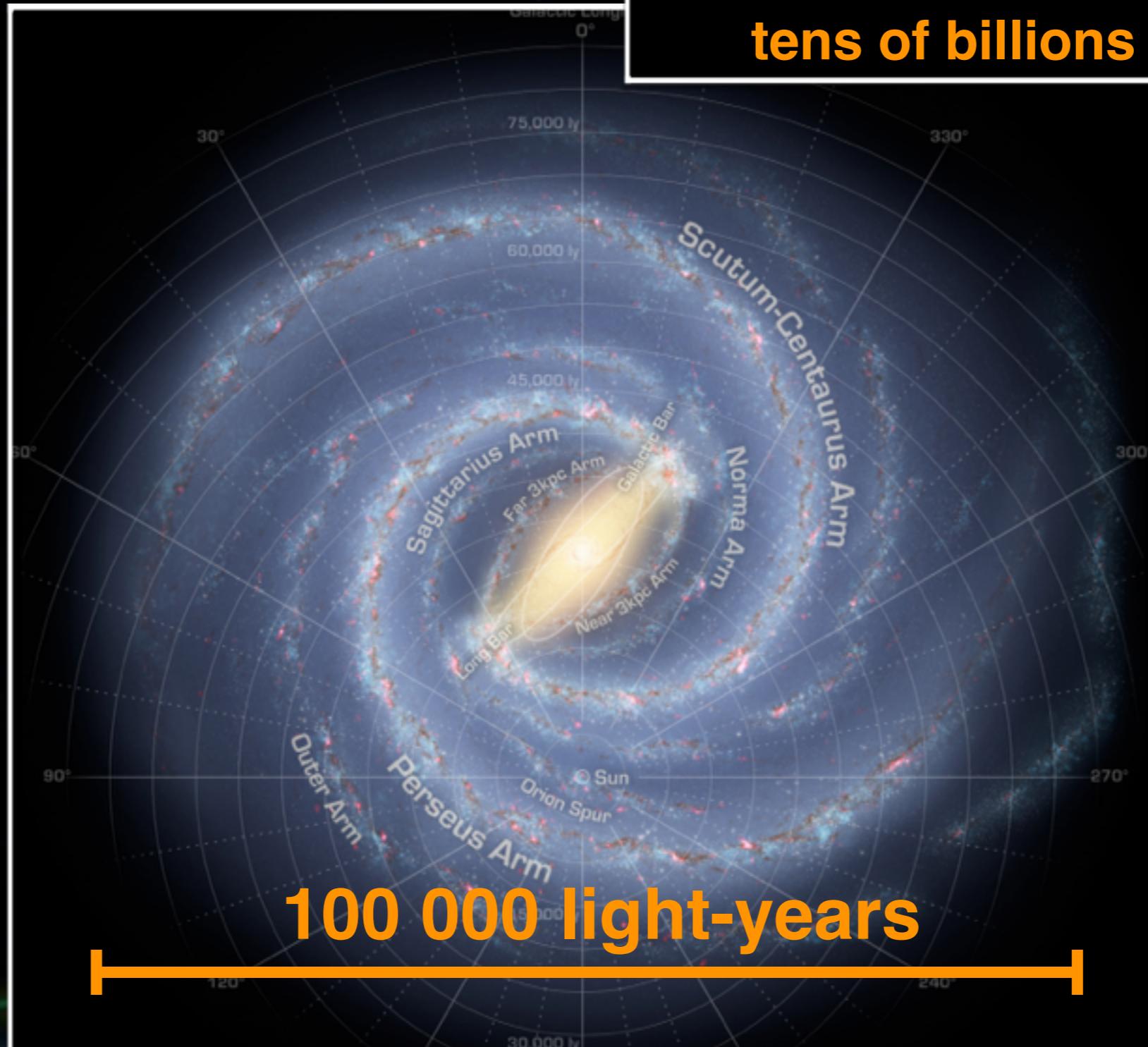
**Would take about 7000  
years to go there using the  
fastest space rocket**

@Hubble, NASA

Proxima Centauri is at 40 113 000 000 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



@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

@NASA/JPL-Caltech

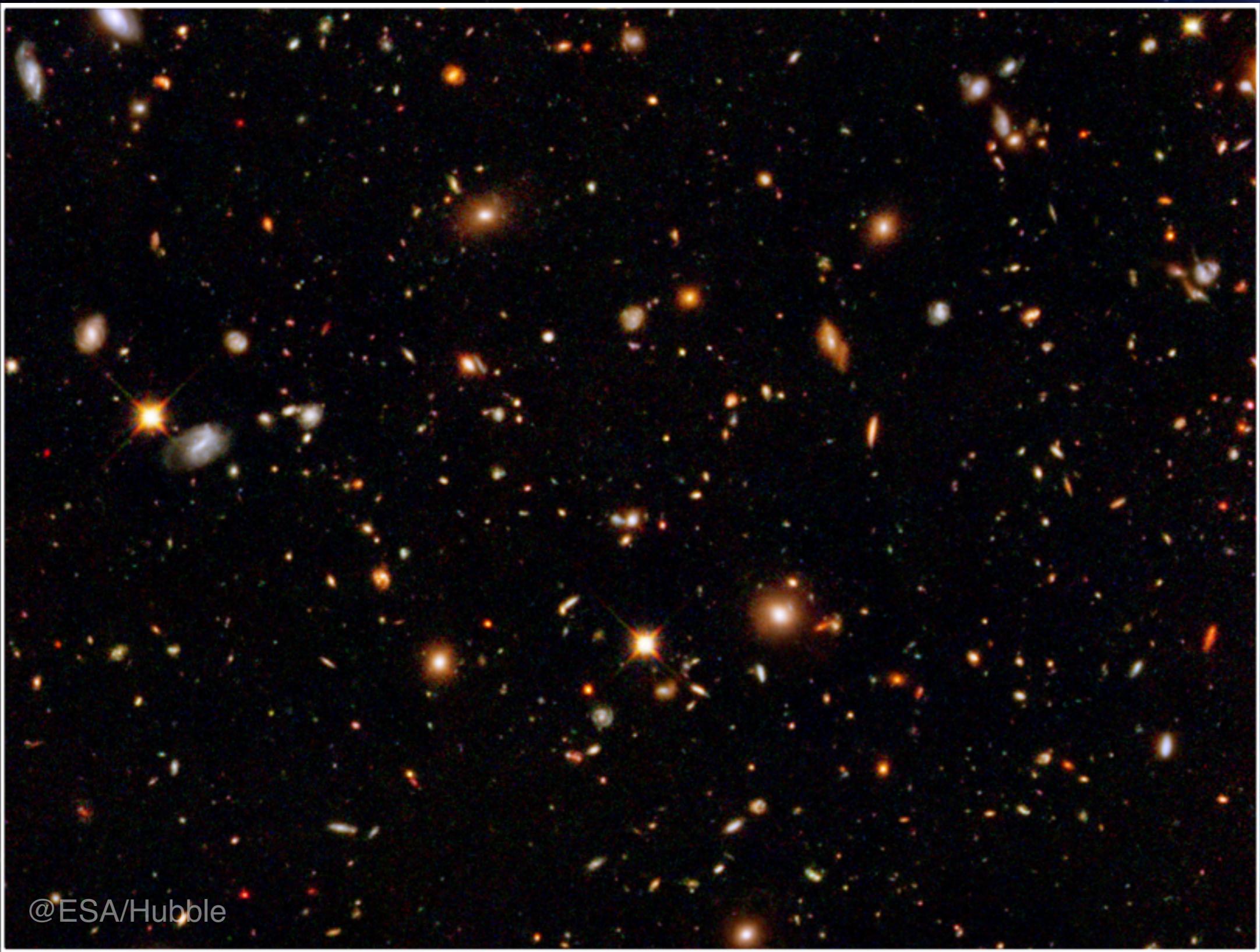
@ESA/Hubble, NASA, Judy Schmidt

2 537 000 light-years from us

Andromeda Galaxy

# Hubble Deep Field Image

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@ESA/Hubble

## Summary

Things are big, massive, and very far apart

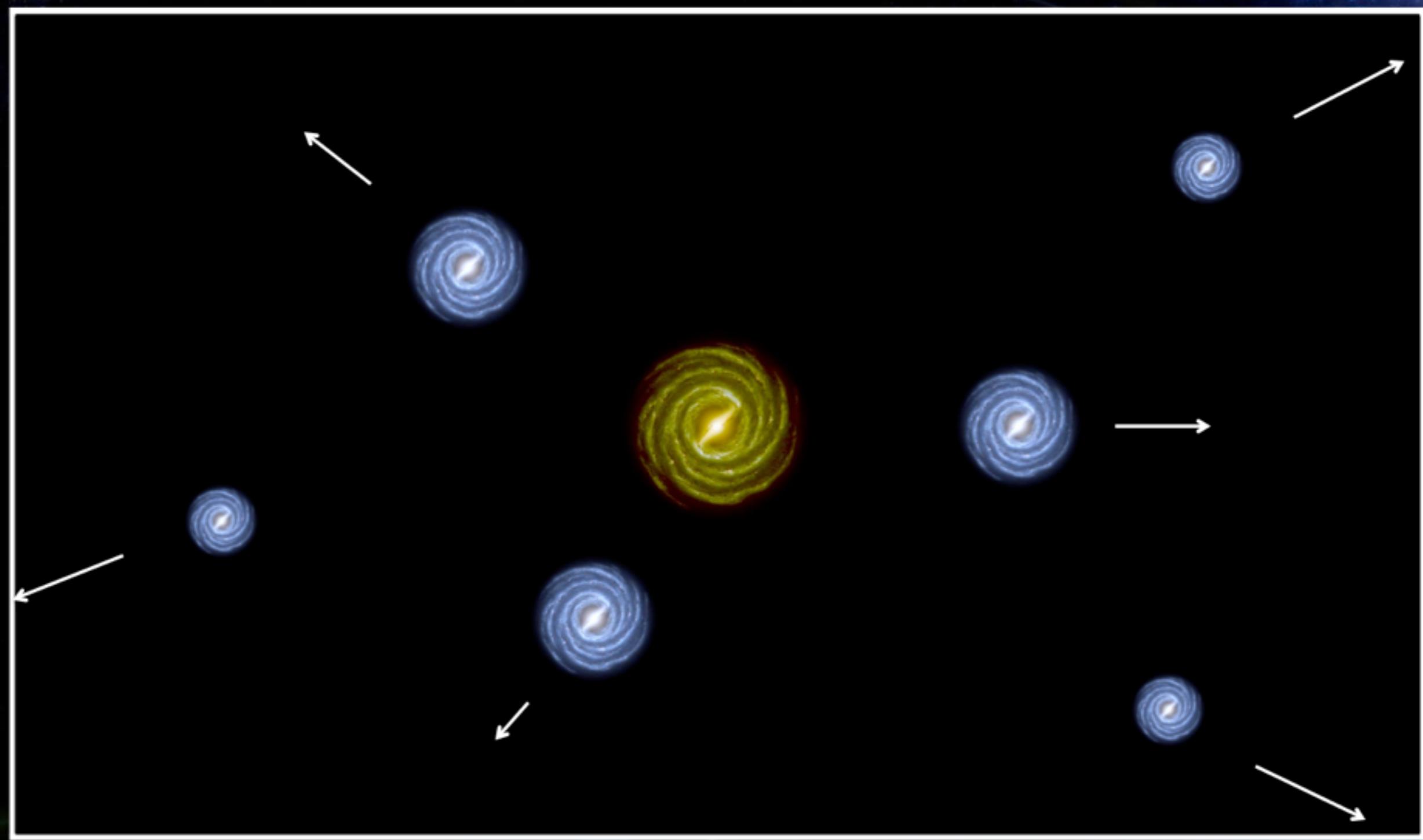
A galaxy is composed of gas, dust, and billions of stars (and even more planets)

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

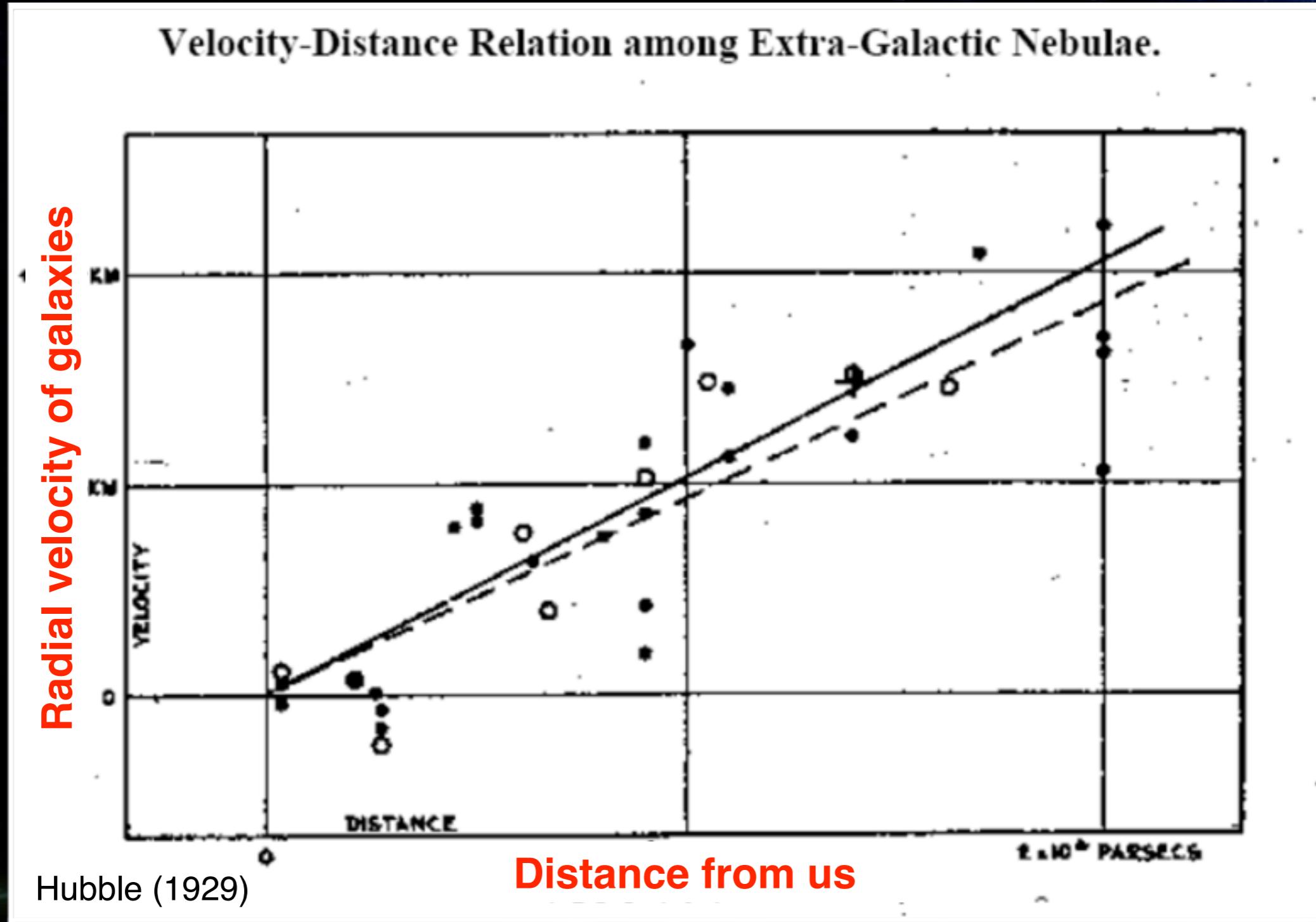
# Evolution of the Universe



# Motion of Galaxies Around Us



# Motion of Galaxies Around Us

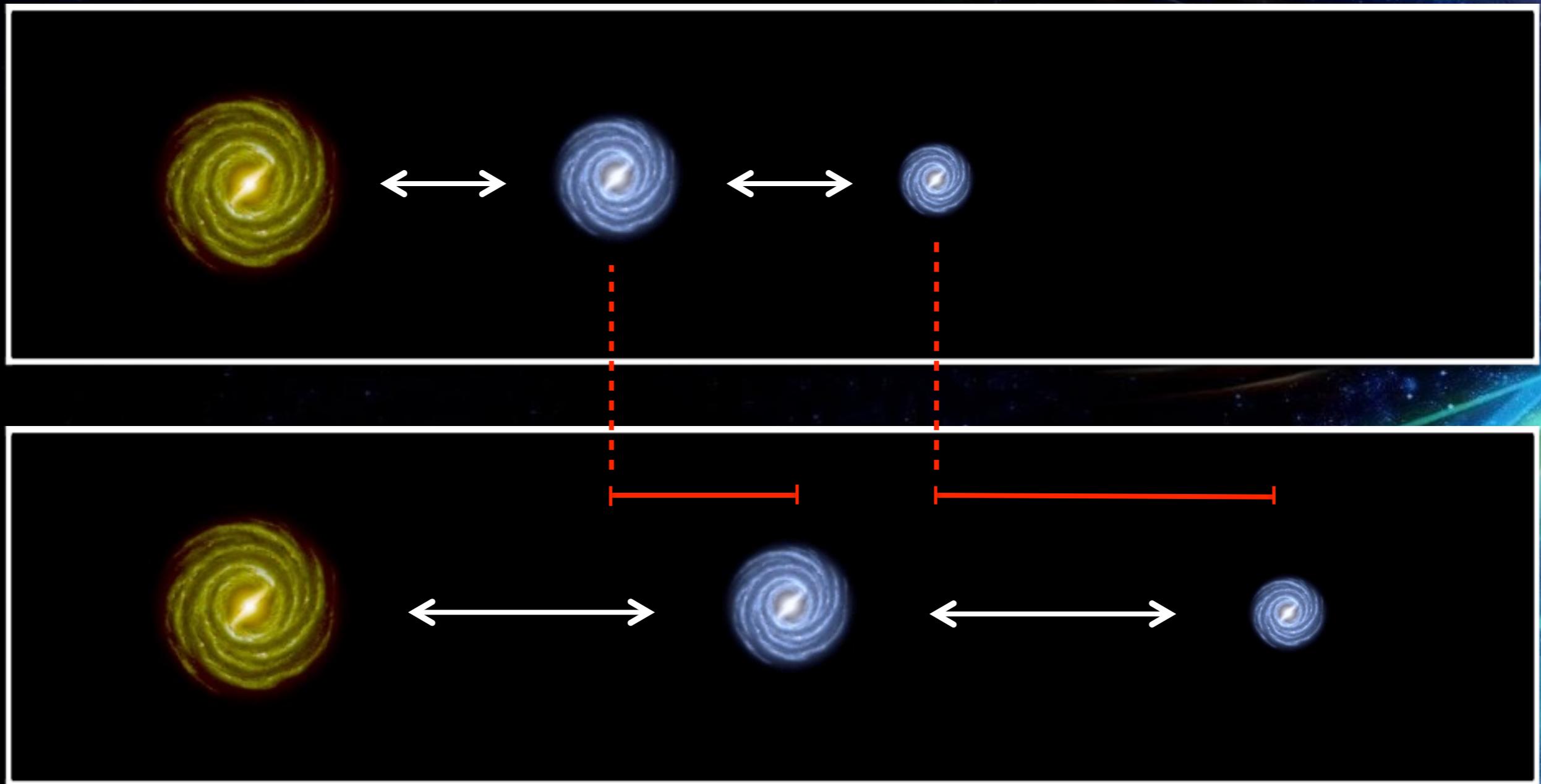


# The Expansion of the Universe

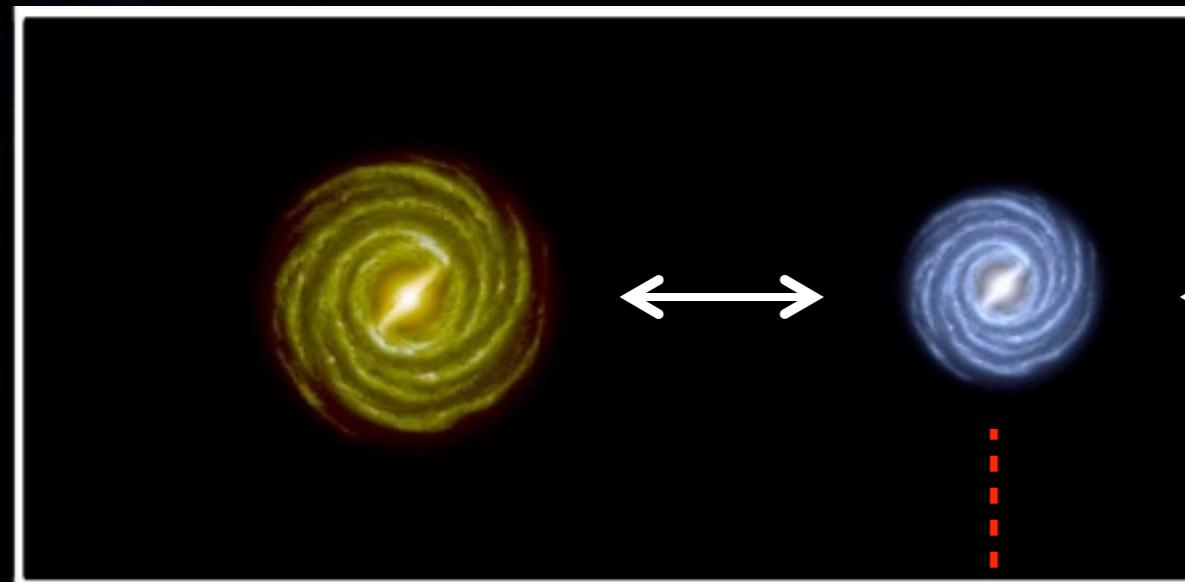
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# The Expansion of the Universe



# The Expansion of the Universe



Velocity-Distance Relation among Extra-Galactic Nebulae.

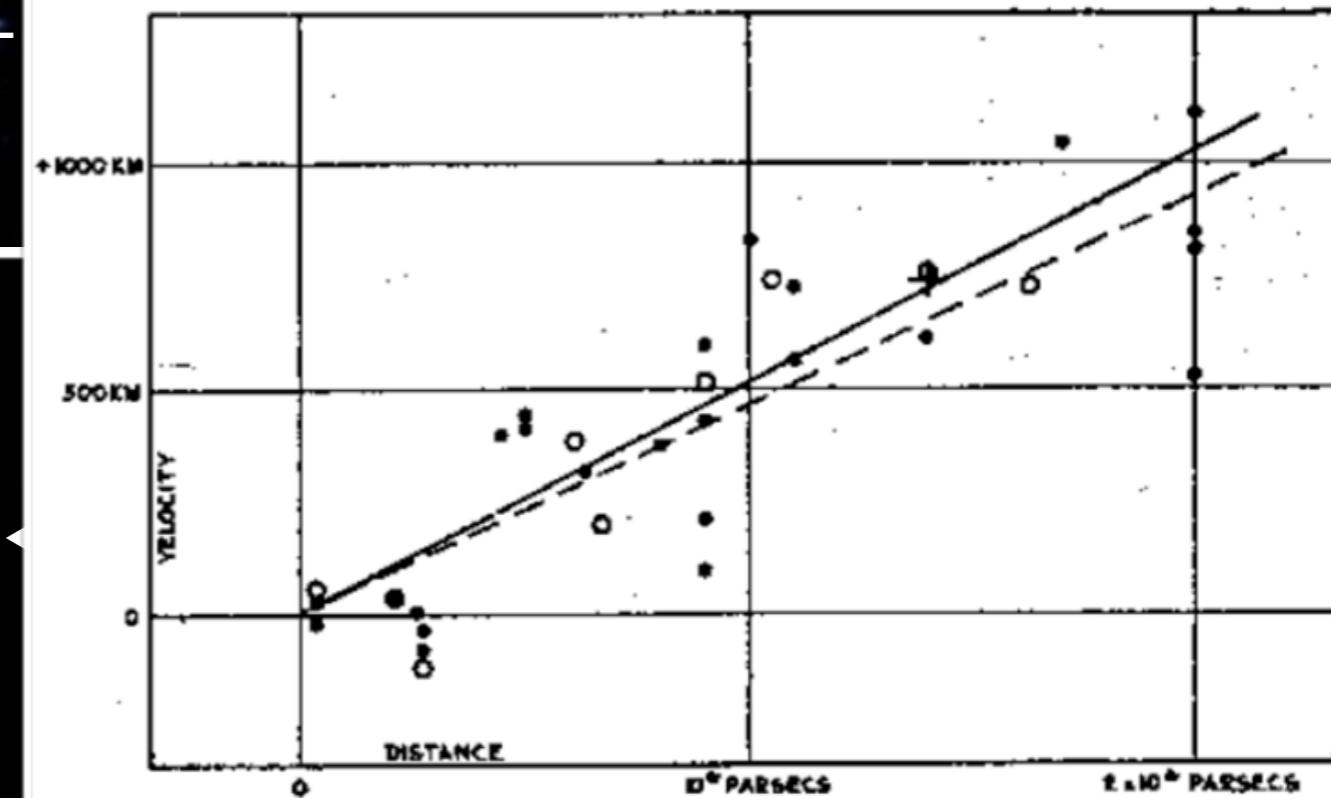
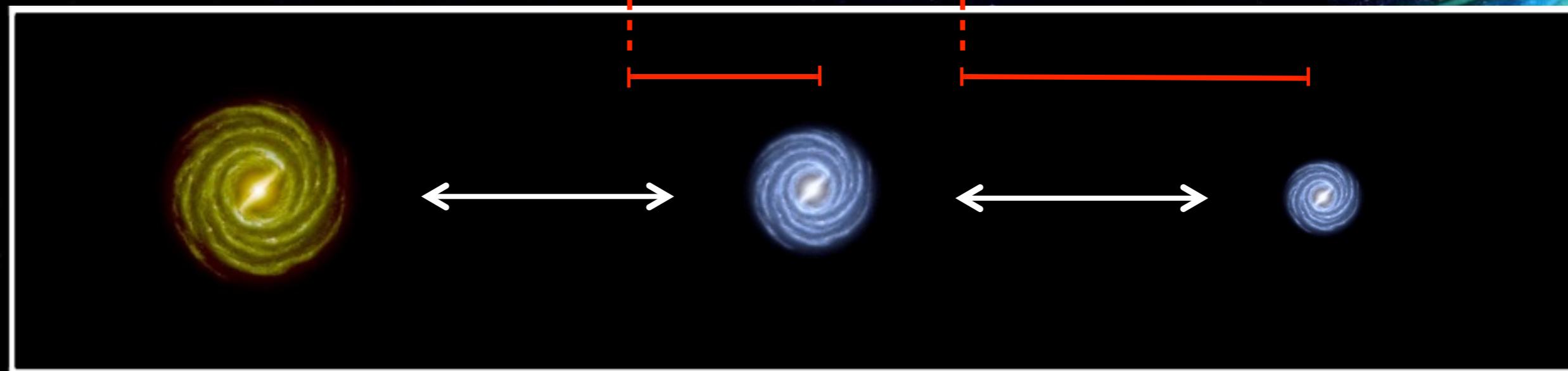
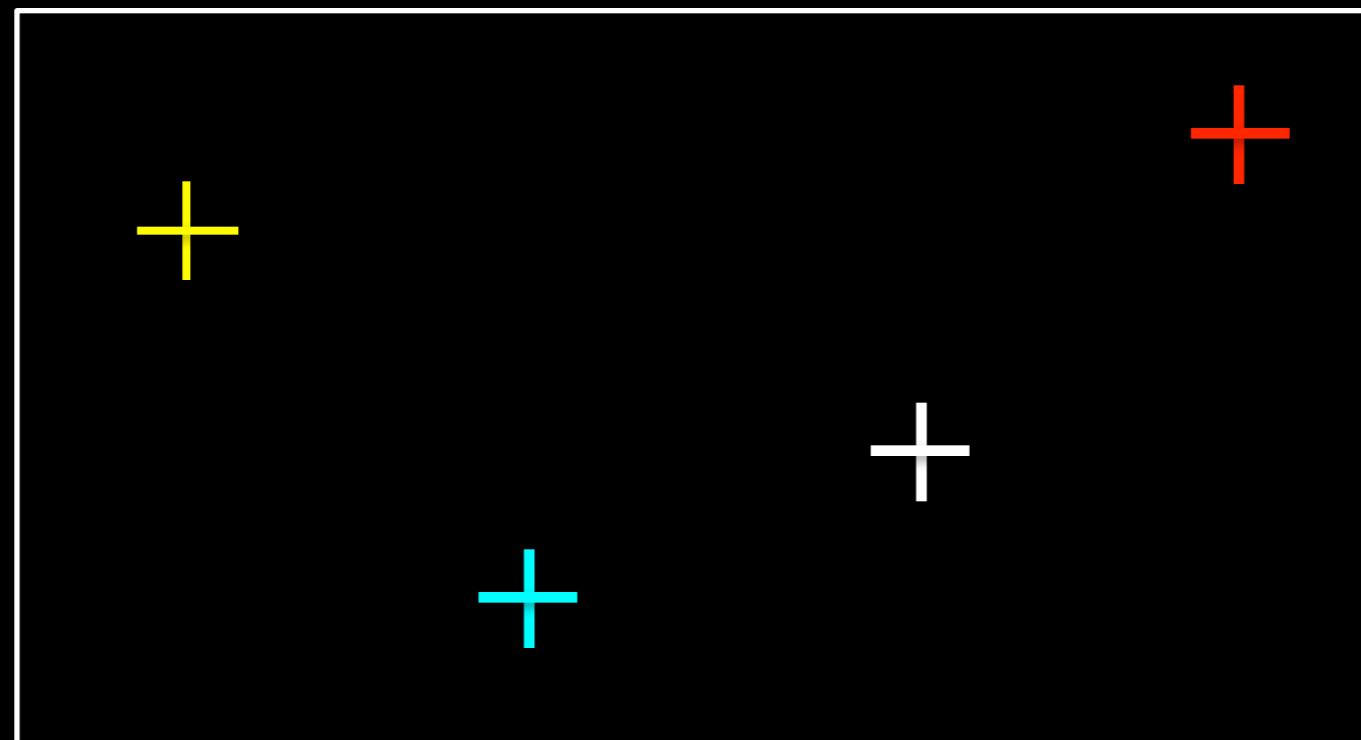


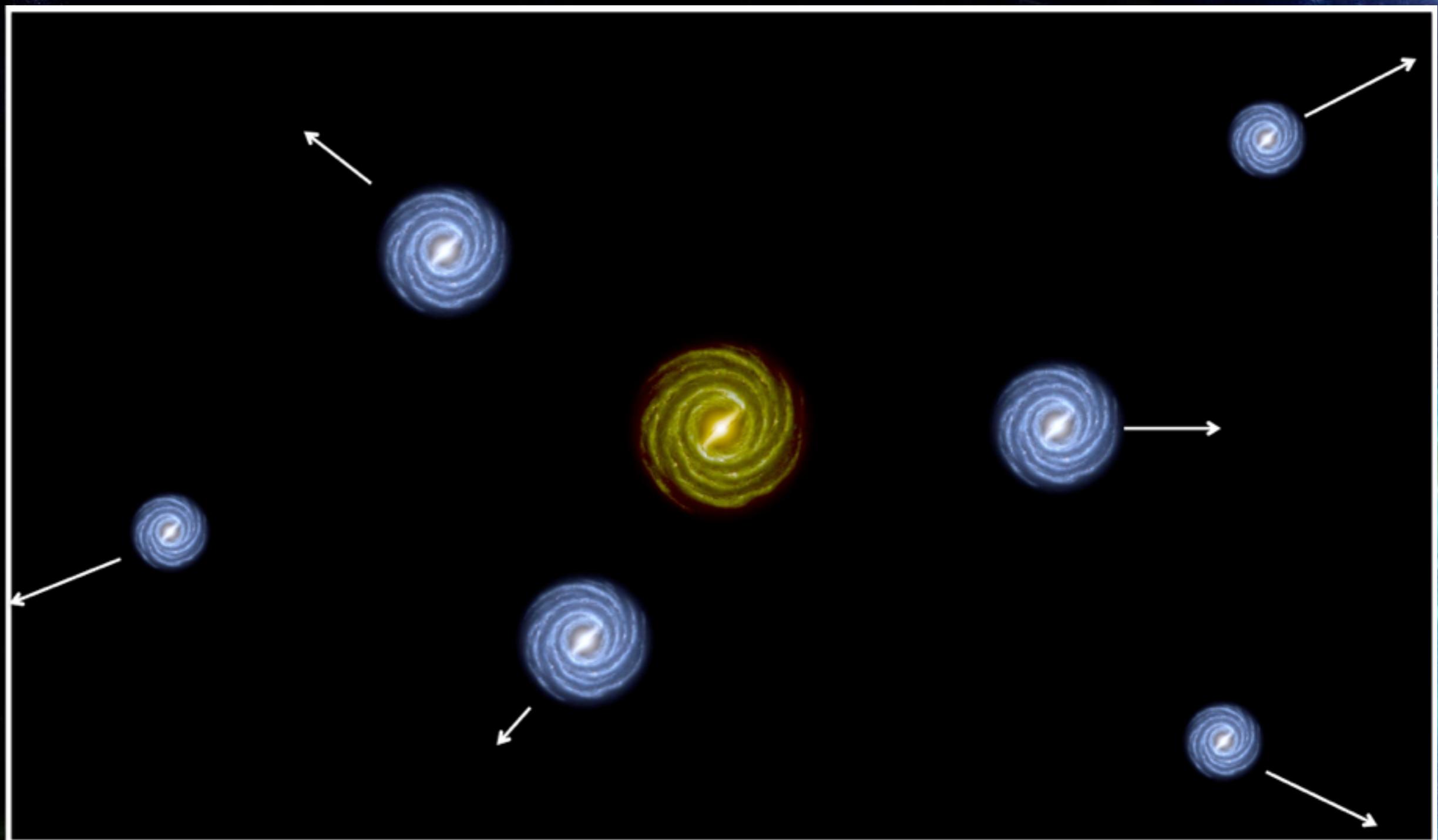
FIGURE 1



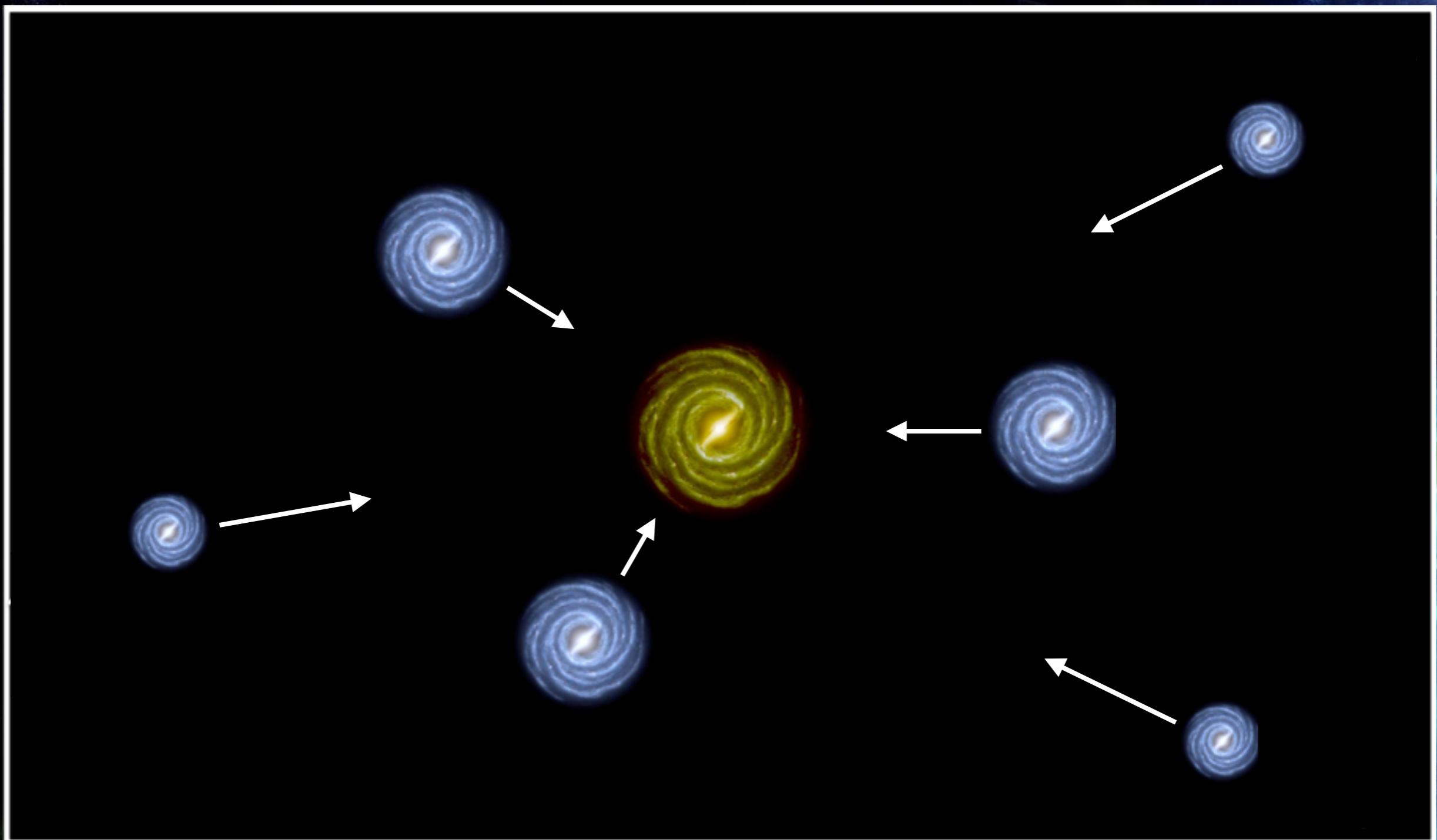
# Are We the Center of the Universe?



# What Happens if we Go Back in Time?

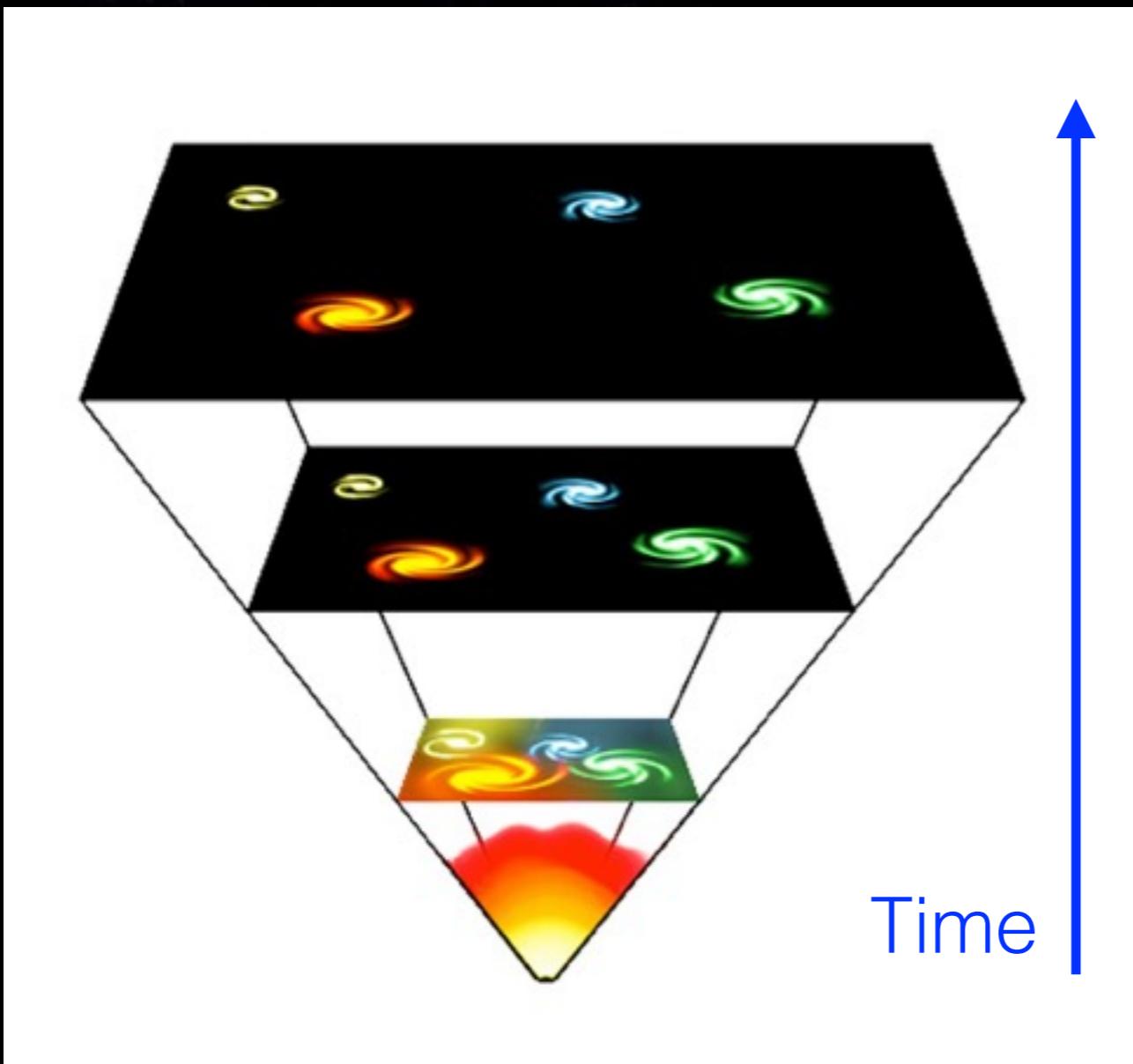


# What Happens if we Go Back in Time?



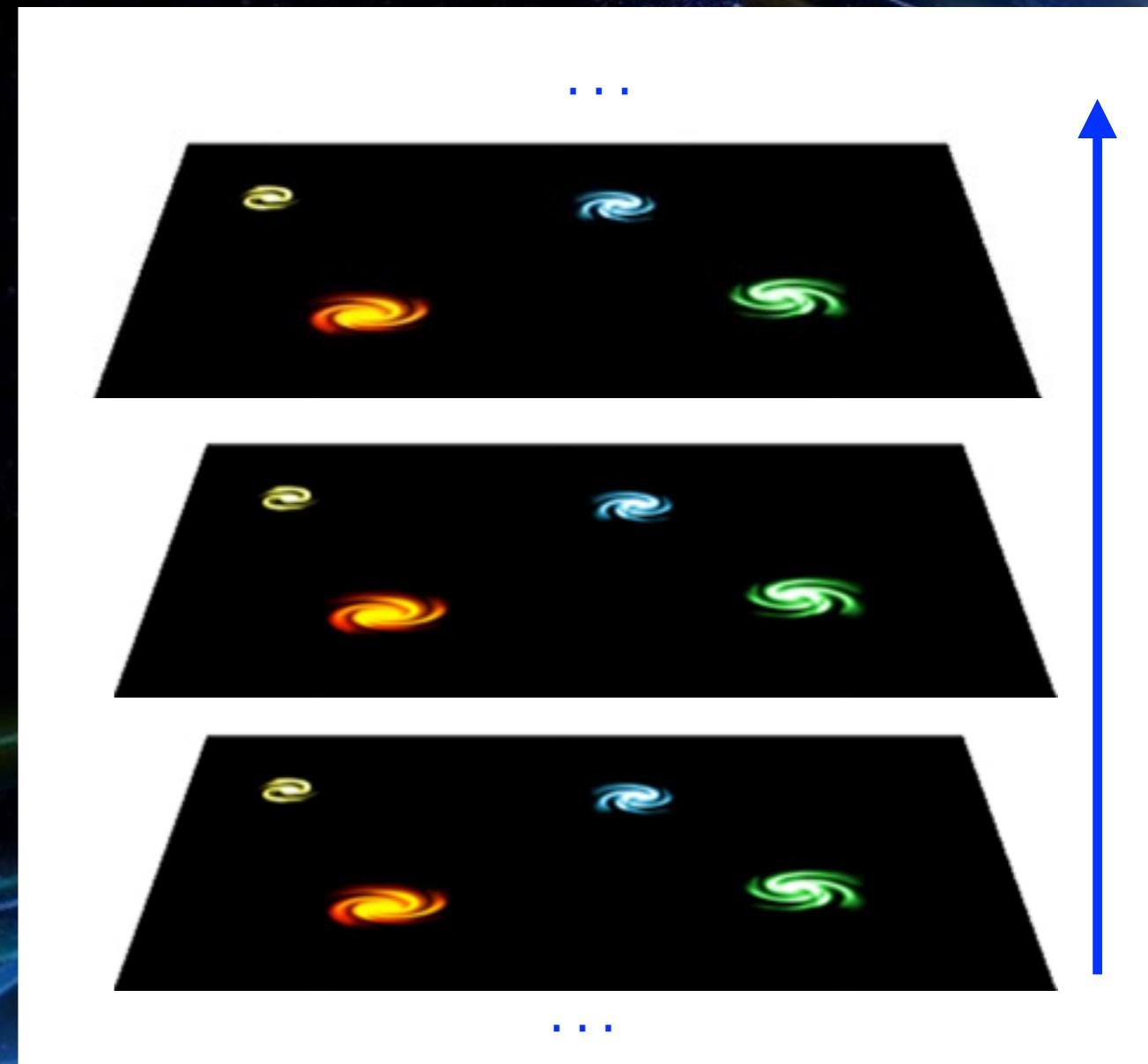
# The Big Bang

The density of matter **changes**



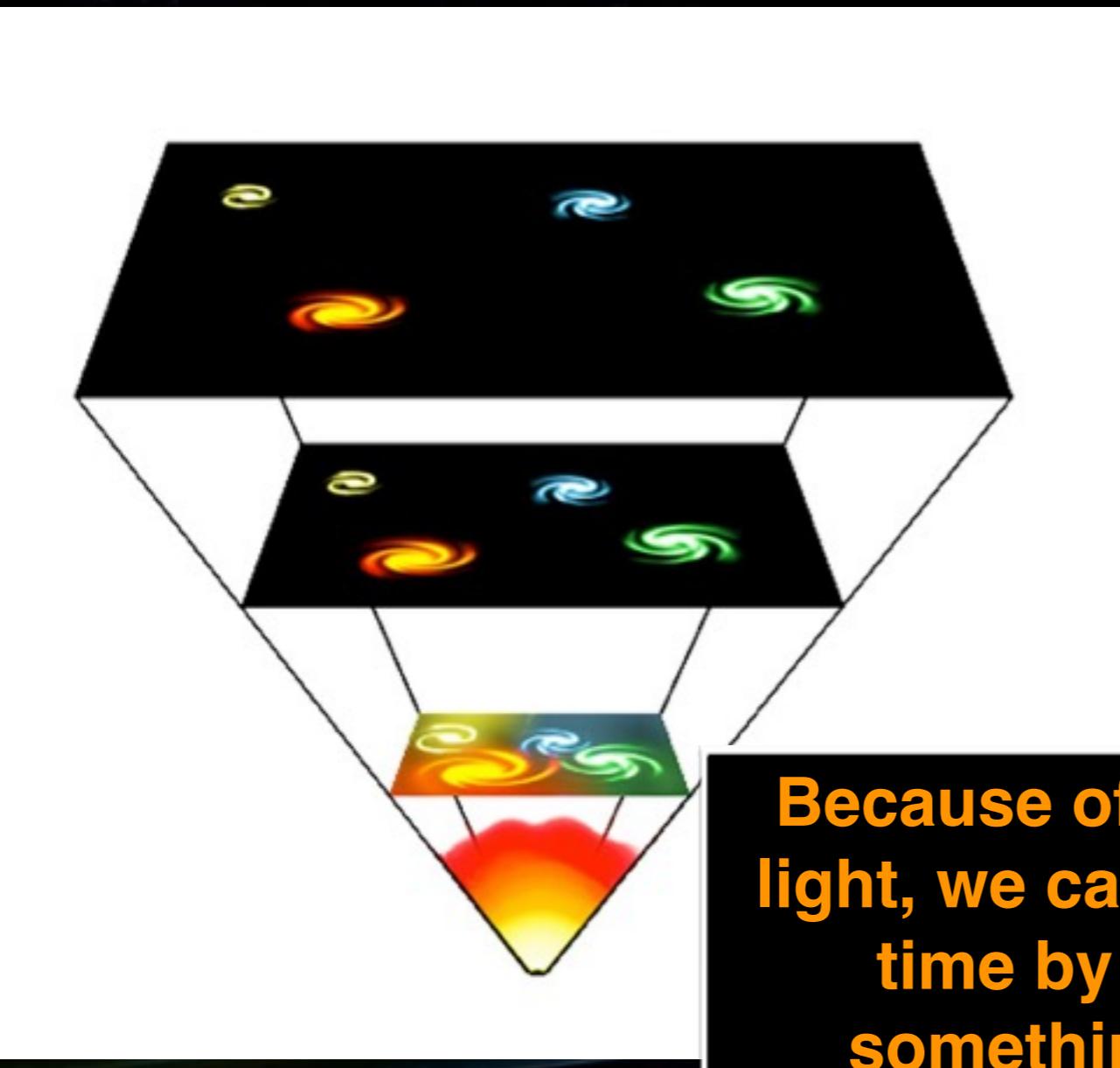
# The Stationary Universe

The density of matter **never changes**



# The Big Bang

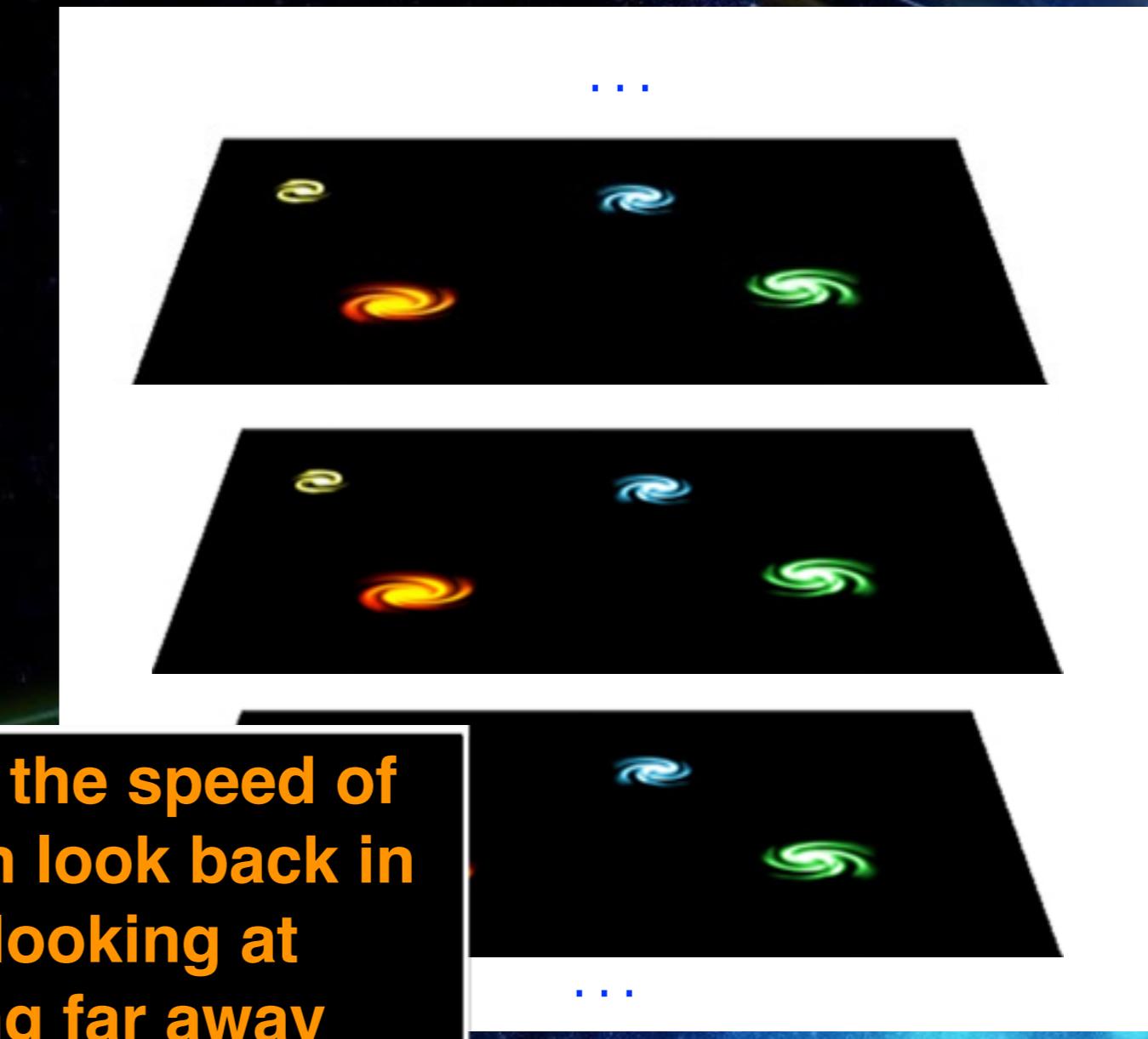
The density of matter **changes**



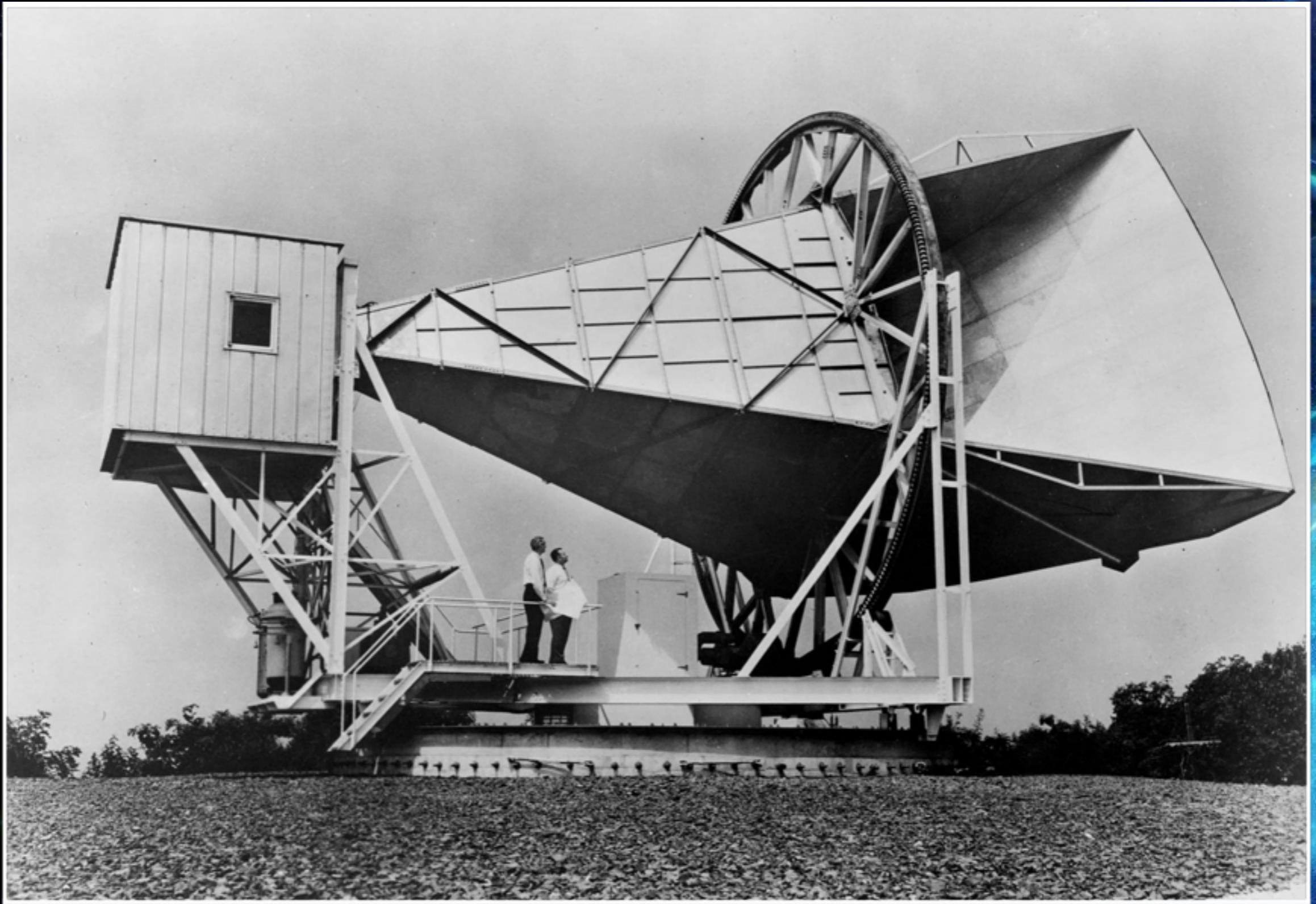
**Because of the speed of light, we can look back in time by looking at something far away**

# The Stationary Universe

The density of matter **never changes**

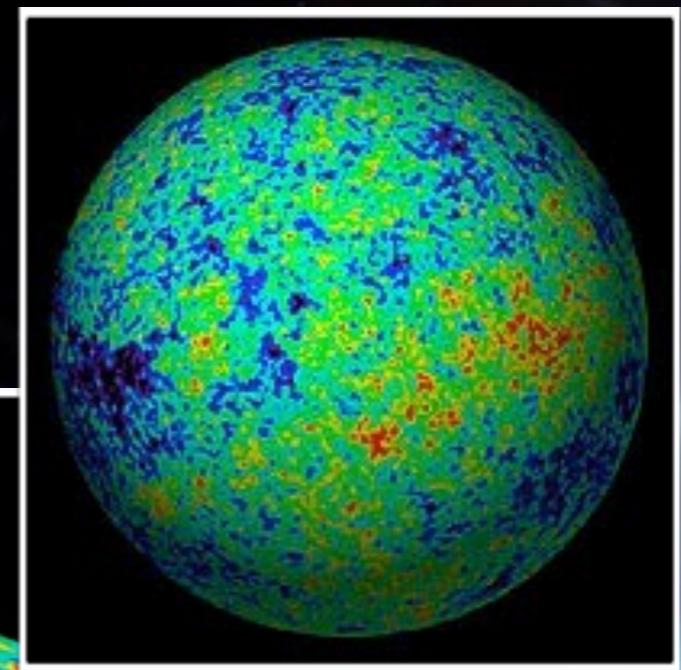
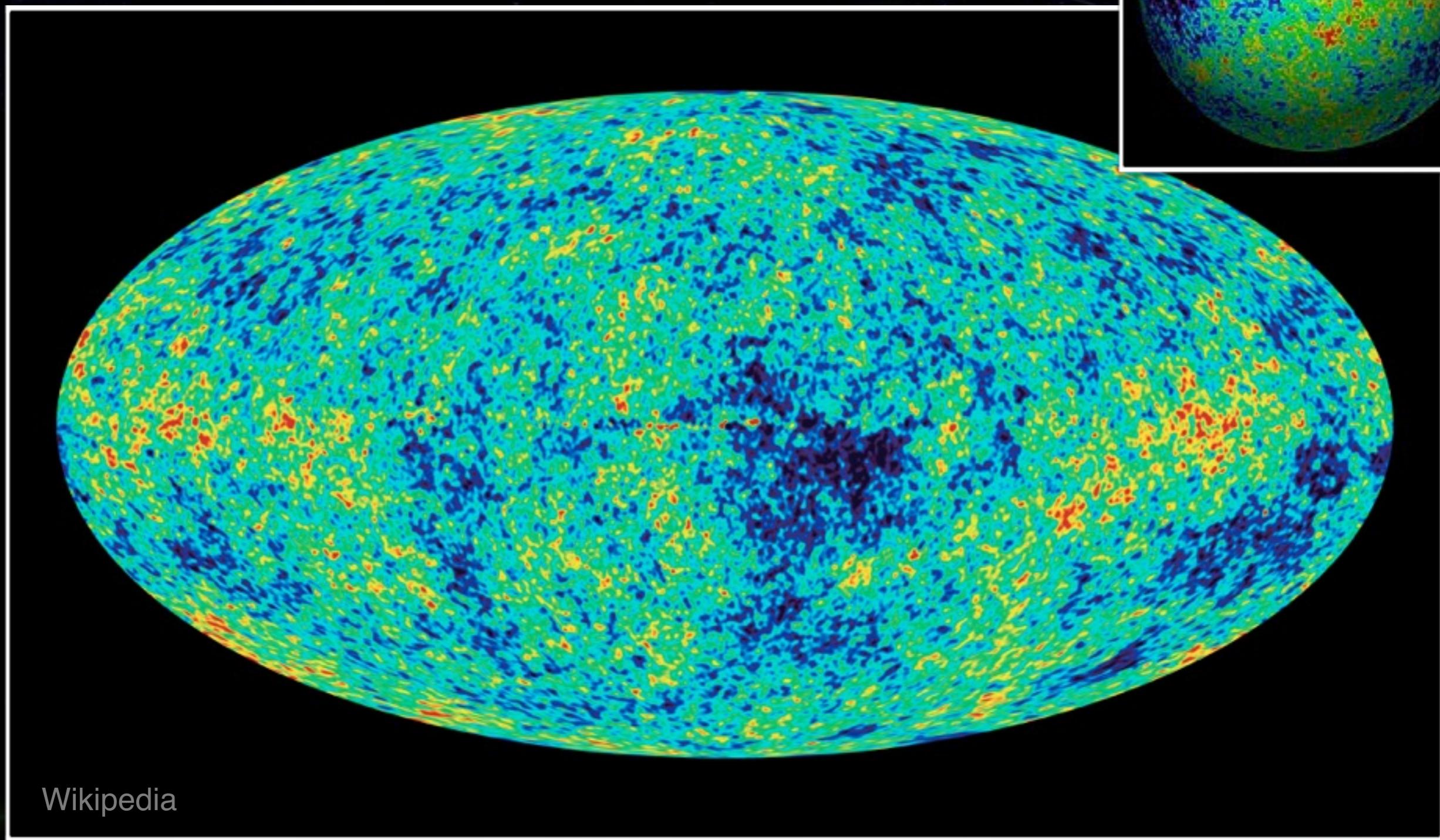


# Detection of the Cosmic Microwave Background



Wikipedia - Horn Antenna-in Holmdel, New Jersey

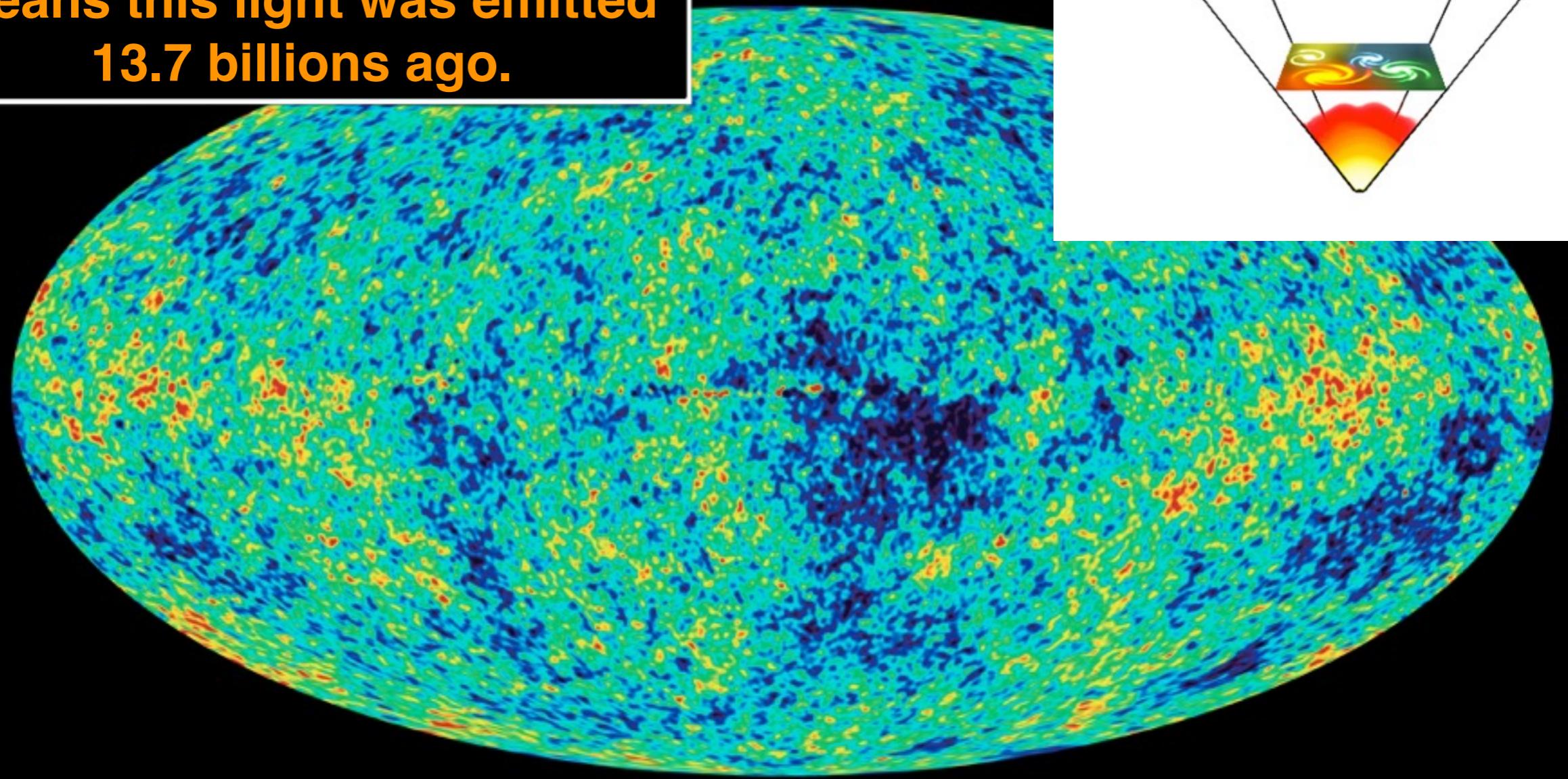
# Detection of the Cosmic Microwave Background



Wikipedia

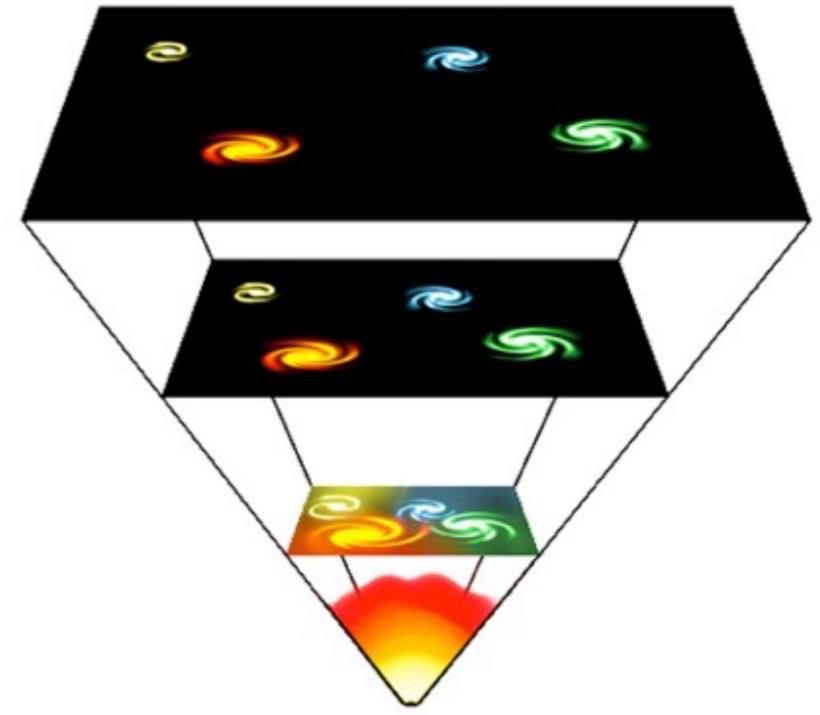
# Detection of the Cosmic Microwave Backg

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

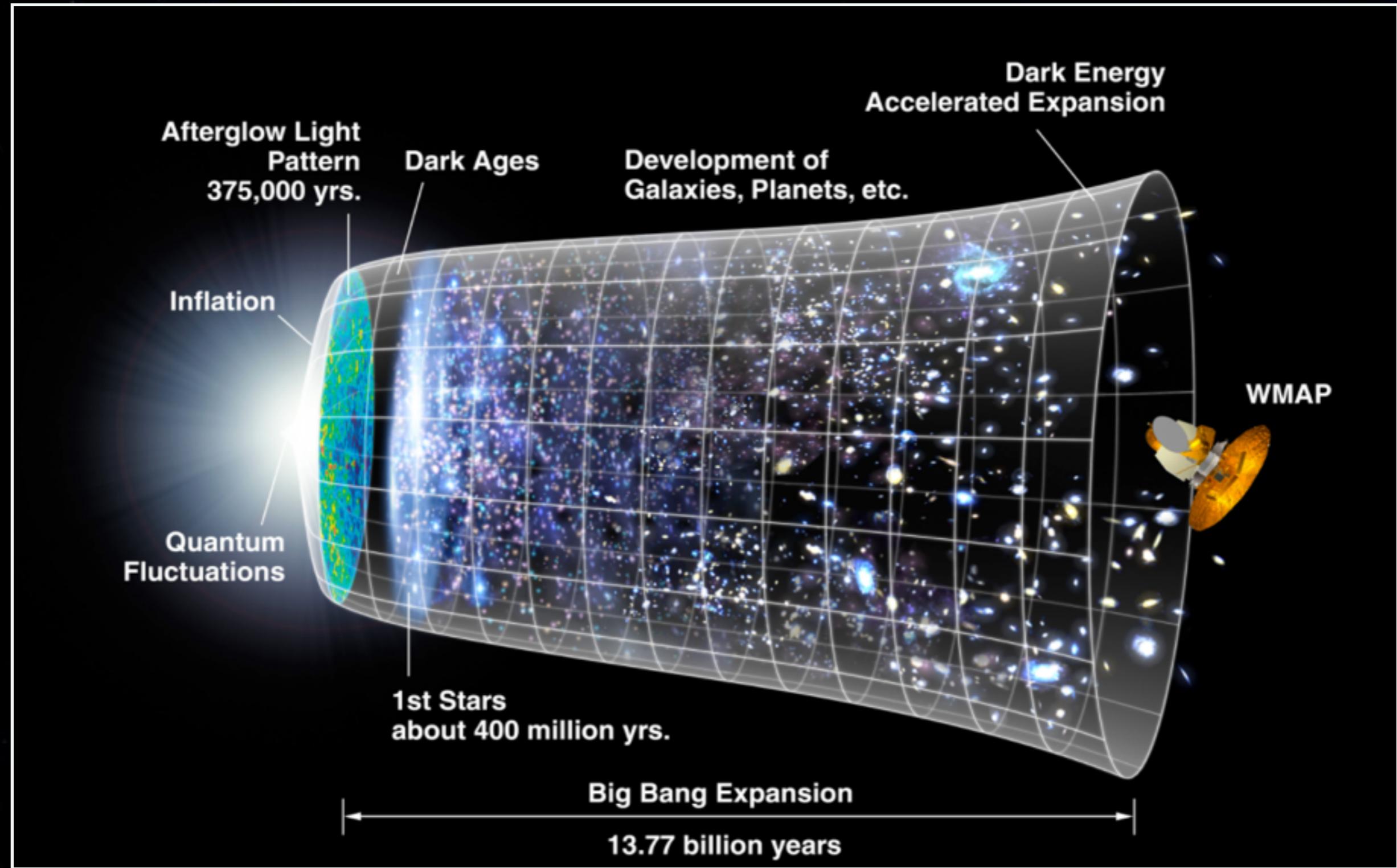


Wikipedia

This is the oldest picture in the Universe



# The Evolution of the Universe



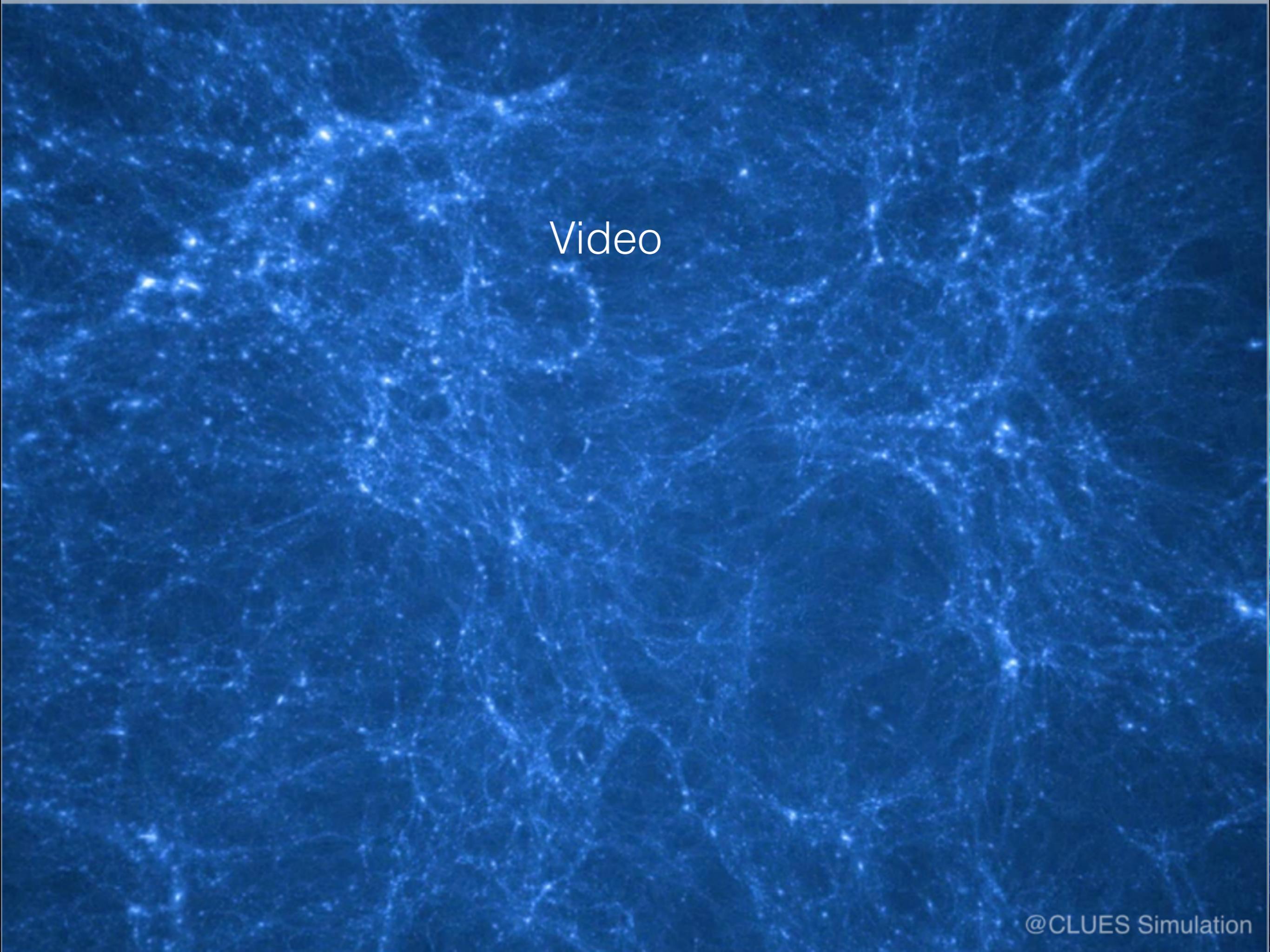
## Summary

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

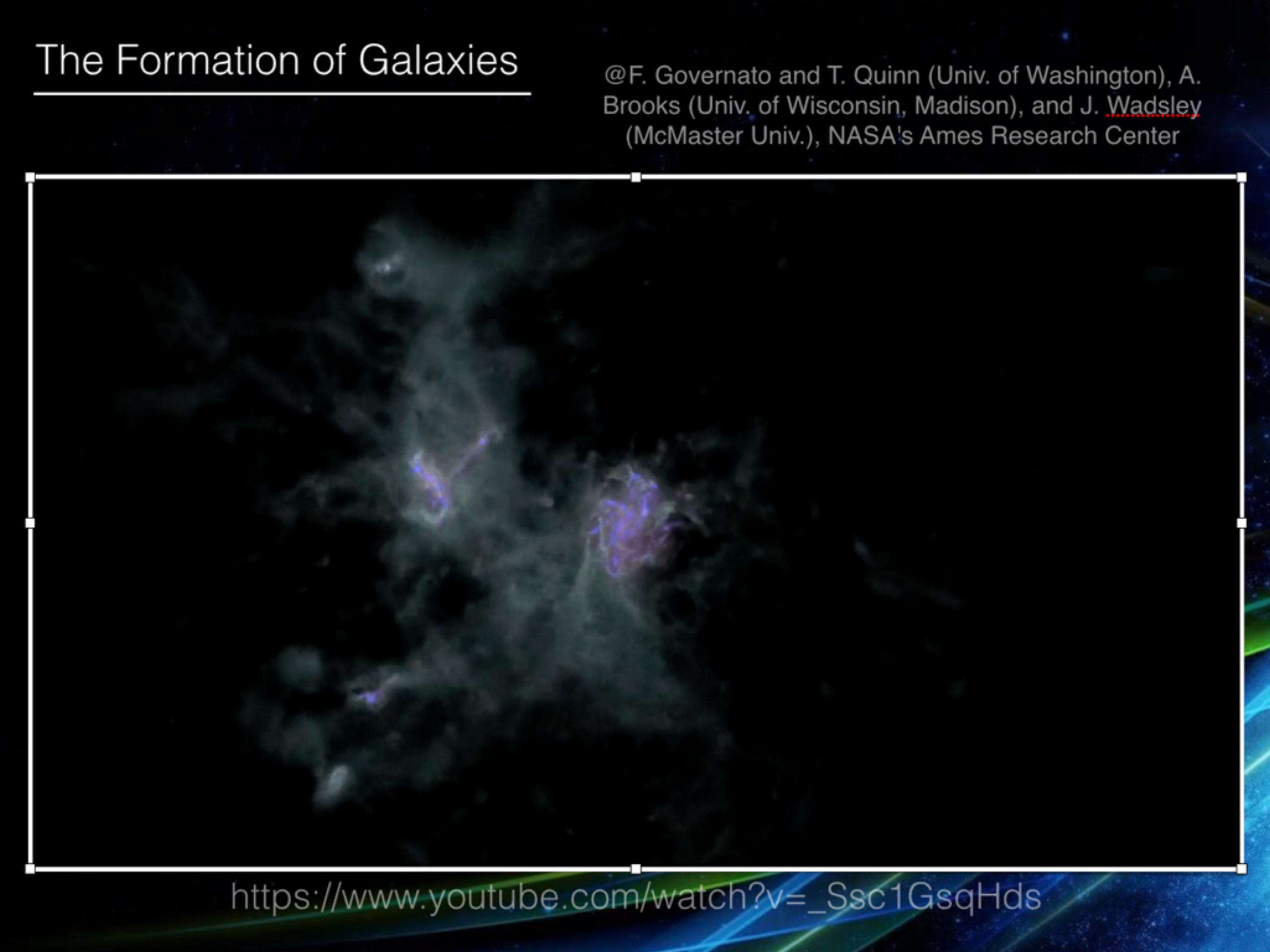
# The Formation of Galaxies

@CLUES Simulation



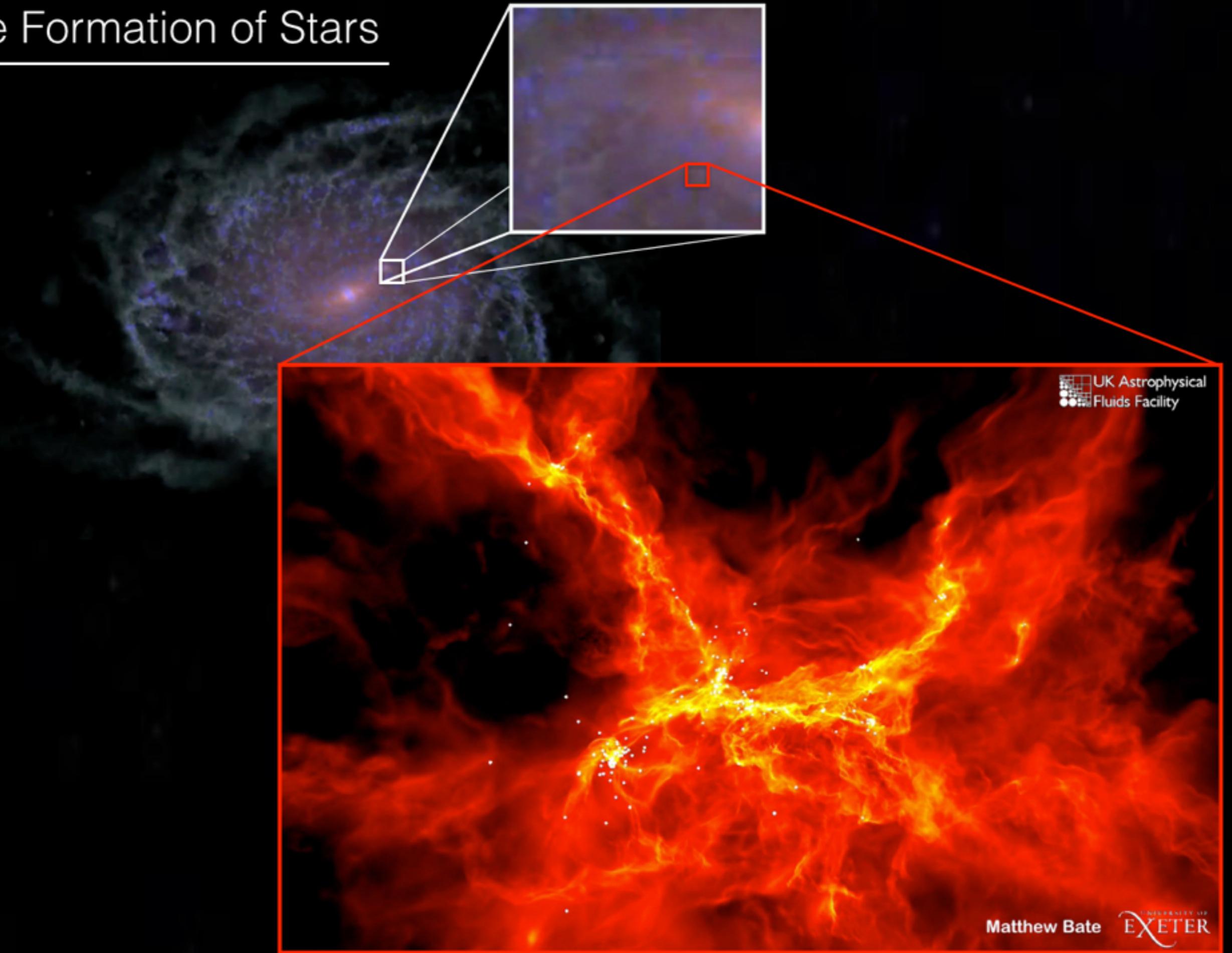
# The Formation of Galaxies

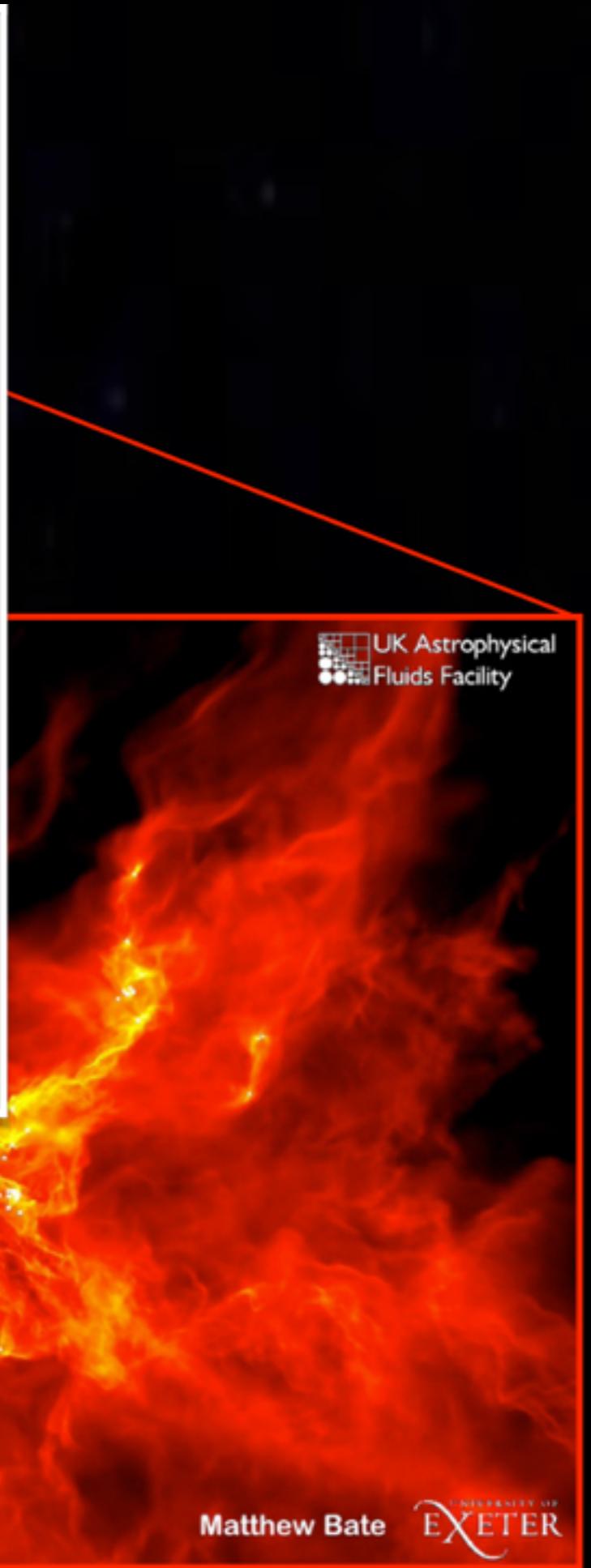
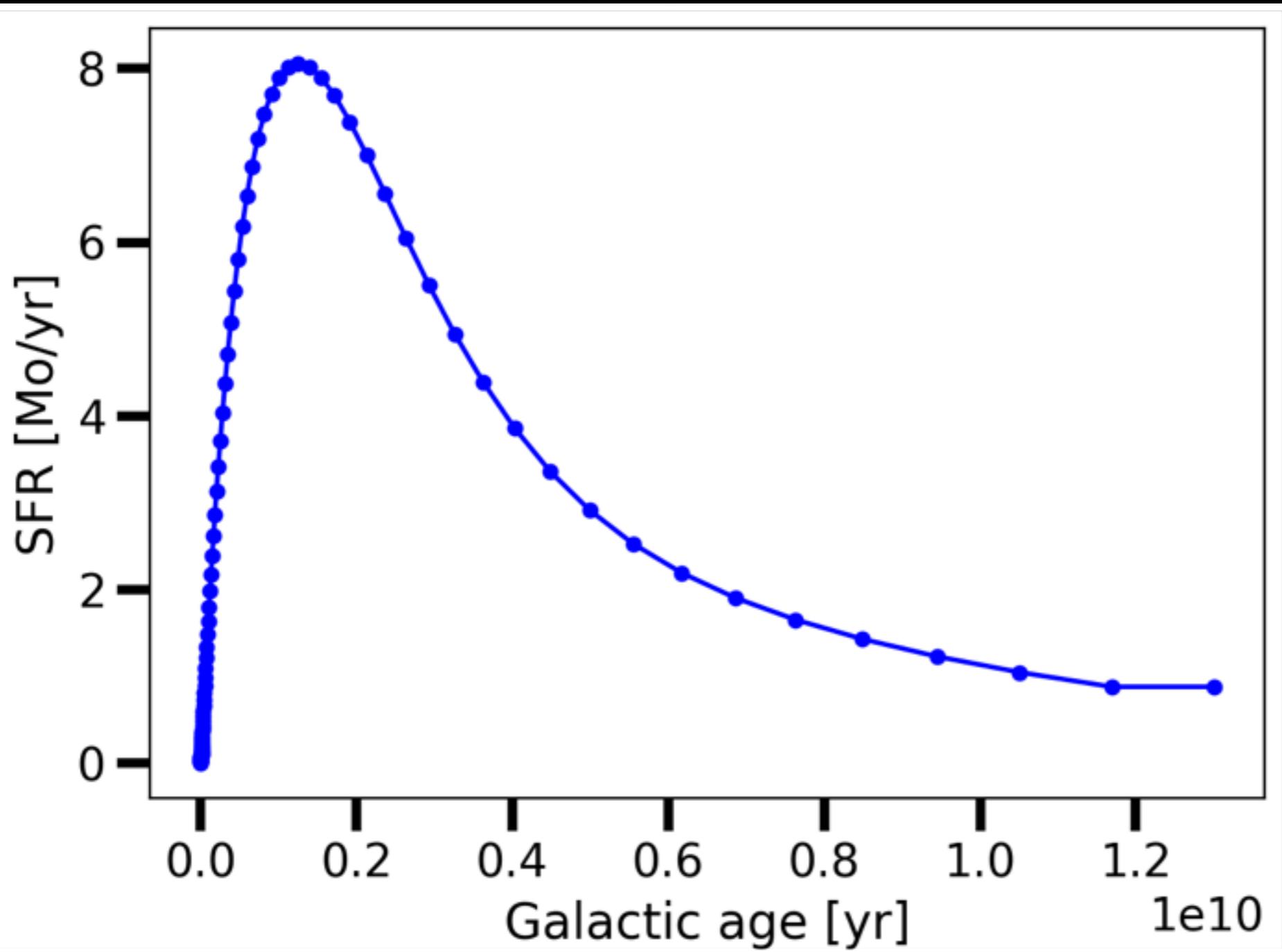
@F. Governato and T. Quinn (Univ. of Washington), A. Brooks (Univ. of Wisconsin, Madison), and J. Wadsley (McMaster Univ.), NASA's Ames Research Center



[https://www.youtube.com/watch?v=\\_Ssc1GsqHds](https://www.youtube.com/watch?v=_Ssc1GsqHds)

# The Formation of Stars





# The Evolution of Chemical Elements in Galaxies

# Chemical Evolution

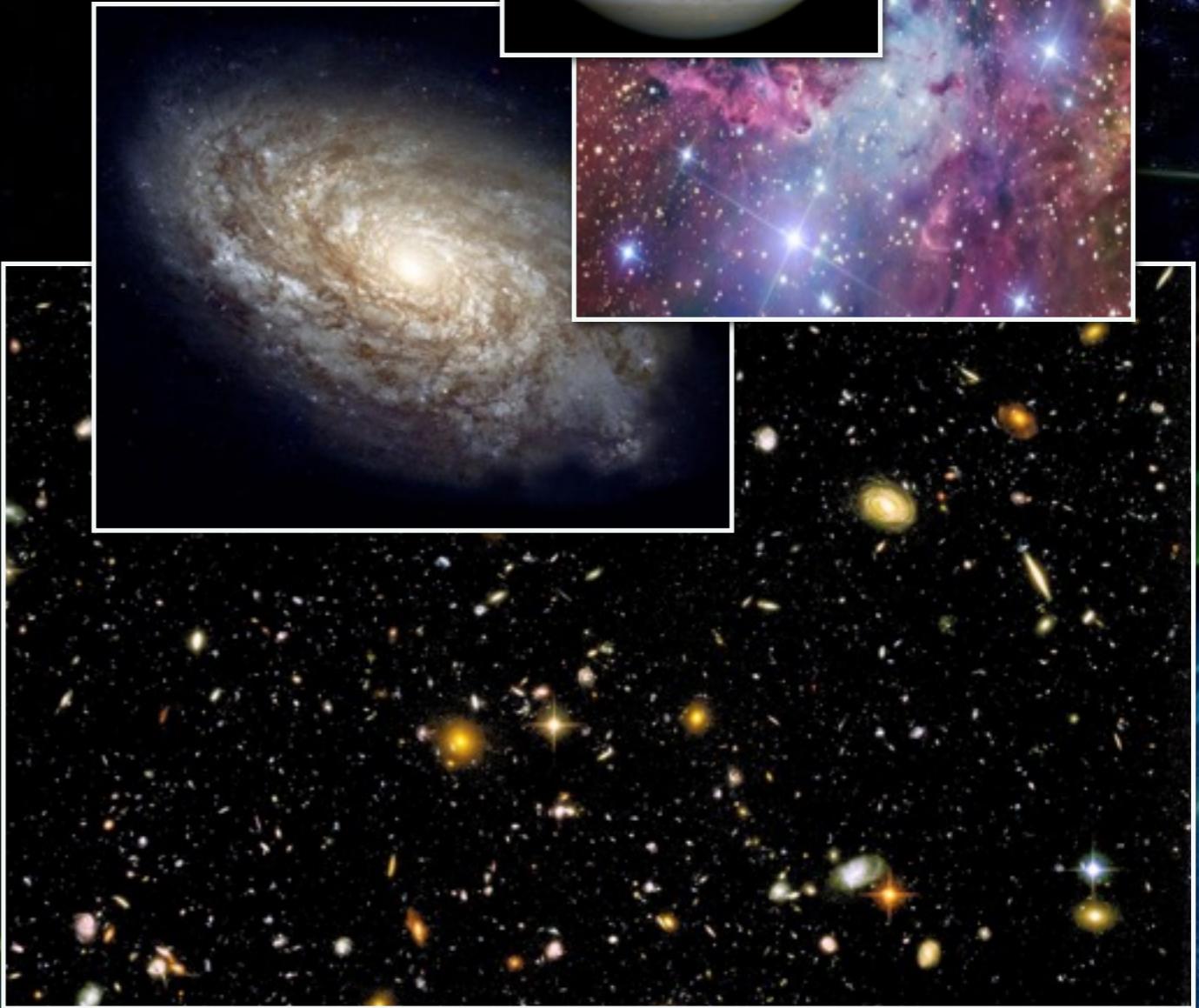
Universe at early time



After 13.7 Gyr of evolution

An orange curved arrow points from the "Universe at early time" image towards the "Current Universe we see today" image.

Current Universe  
we see today



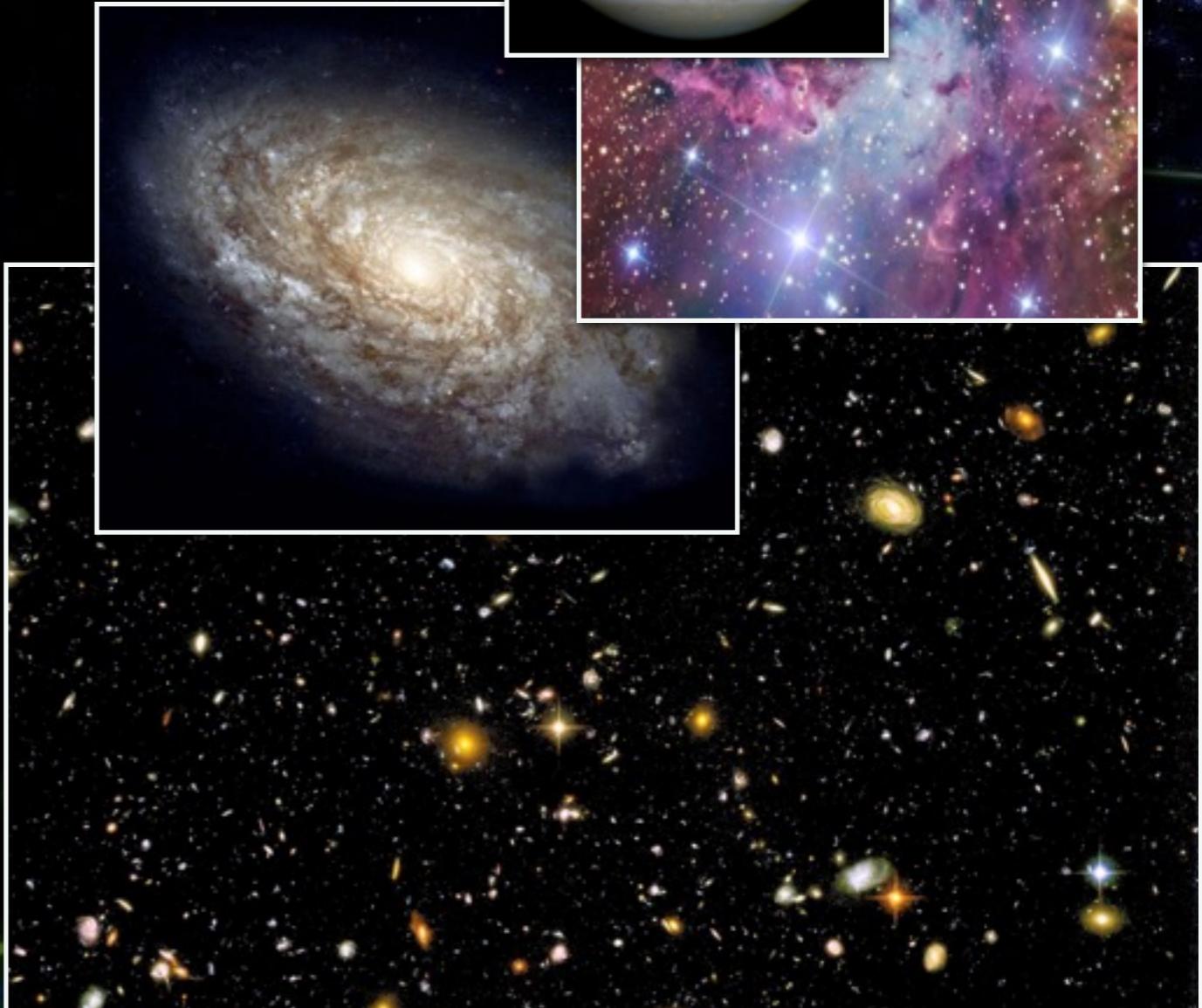
# Chemical Evolution

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

**PERIODIC TABLE OF THE ELEMENTS**

The Periodic Table of the Elements is a tabular arrangement of all known chemical elements. It consists of 18 groups and 7 periods. The table is color-coded according to the element's category:

- Metals:** Yellow (Groups 1-2), Orange (Groups 3-12), and Red (Groups 13-18).
- Non-metals:** Green (Groups 1-2), Blue (Groups 3-12), and Purple (Groups 13-18).
- Post-transition metals:** Light blue (Groups 3-12).
- Actinides:** Light purple (Groups 13-18).
- Hydrogen:** Light yellow (Group 1).
- Helium:** Light orange (Group 18).

**Symbol & Color Key:**

As of the year 2019 the standard periodic table of chemical elements contains 119 confirmed elements which constitute all of the known matter on Earth, including every living organism, every rock, every plant, animal, mineral, metal, liquid, gas, solid, and plasma, along with all matter ever made or destroyed since the Big Bang, including every star and planet, every galaxy, and every element that has ever existed since the beginning of time. All of these elements are represented in its periodic table, along with their atomic number, symbol, name, and various properties, such as density, melting point, boiling point, and electrical conductivity. These properties are used to group the elements into categories, such as metals, non-metals, and post-transition metals. Each group contains elements with similar properties, such as the same number of valence electrons. The periodic table is a useful tool for predicting the behavior of elements based on their position in the table. It also helps in understanding the periodic trends in properties of elements, such as atomic radius, ionization energy, and electron affinity. The periodic table is a fundamental concept in chemistry and is used in many applications, such as medicine, engineering, and technology.

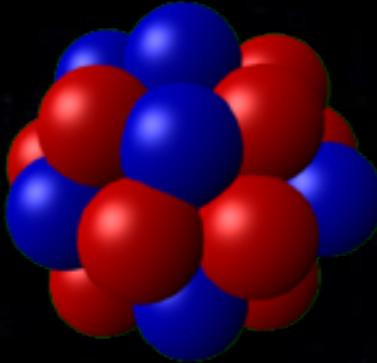
**Notable features:**

- Artificial Elements:** Elements 94 and higher are synthetic and have not been found in nature.
- Transactinides:** Elements 104 and higher are predicted to exist but have not yet been synthesized.
- Actinides:** Elements 57-71 are actinides, which are radioactive and have unique properties.
- Post-transition Metals:** Elements 31-36 are post-transition metals, which are transition metals with some additional properties.
- Hydrogen and Helium:** Hydrogen (H) and Helium (He) are the first two elements in the periodic table and have unique properties.

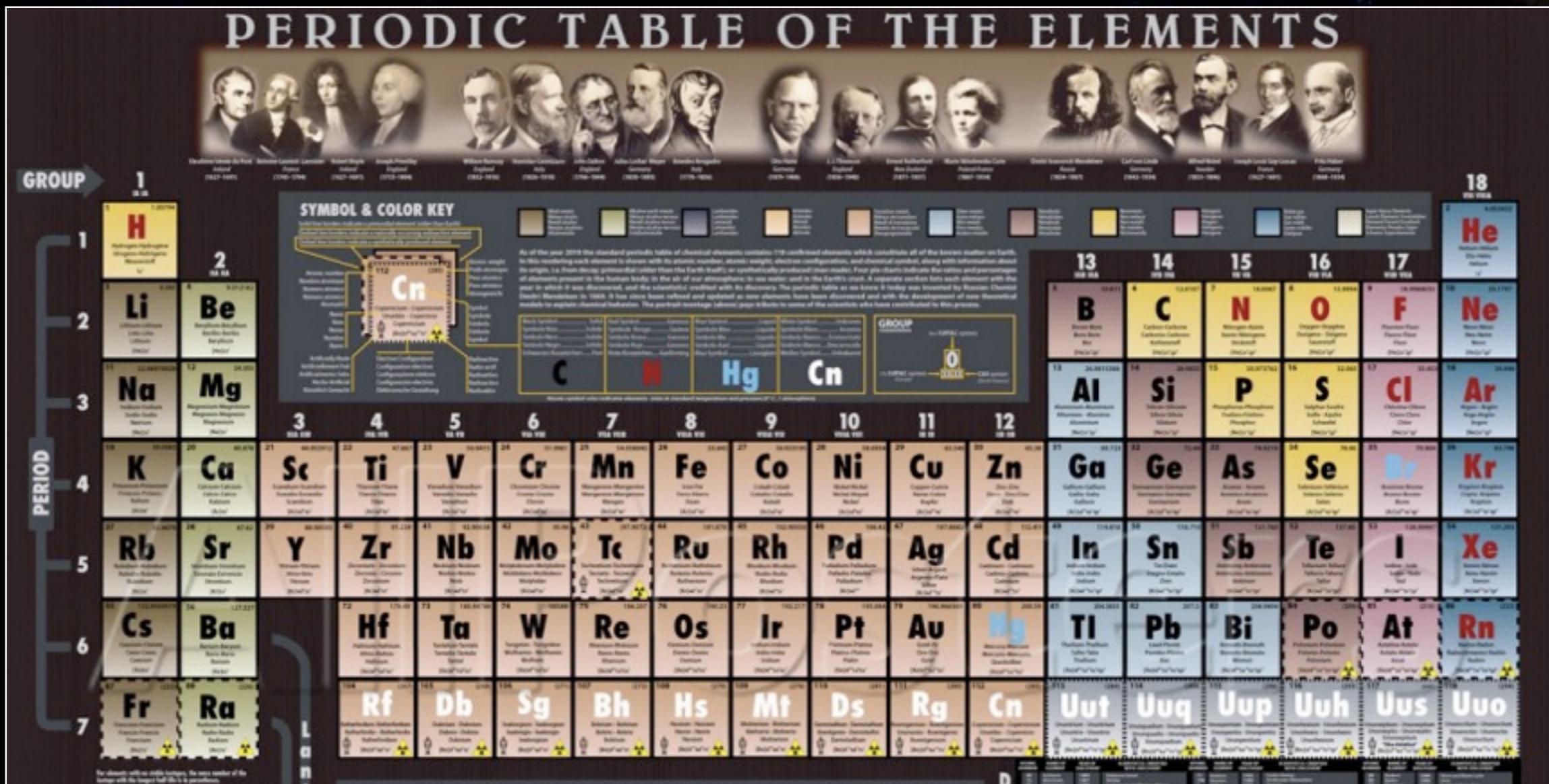
**Portrait Row:** A row of portraits of famous chemists and physicists who have contributed to the development of the periodic table.

GROUP	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H	He																
2	Li	Be																
3	Na	Mg																
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Al	Si	P	S	Cl	Ar
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs	Ba	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn	
7	Fr	Ra	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Uup	Uuh	Uus	Uuo		

# Neutrons, Protons, and Atoms



Proton  
Neutron



# Neutrons, Protons, and Atoms

# Proton

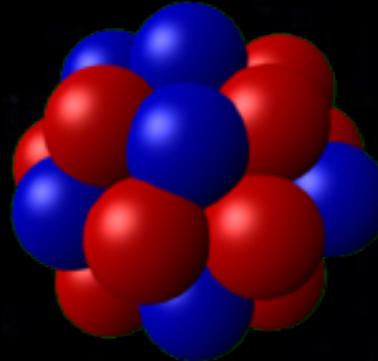
# Neutron

The Periodic Table of Elements poster is a comprehensive educational tool. It features a grid of elements from Hydrogen (H) to Oganesson (Ouo), organized by group (1-18) and period (1-7). Each element box contains its symbol, atomic number, name, atomic weight, and a detailed description of its properties and uses. A central 'Symbol & Color Key' provides a legend for the colors used in the boxes, which correspond to different physical states (Solid, Liquid, Gas) and other characteristics. The poster also includes a timeline at the top showing portraits of 18 scientists who have contributed significantly to the discovery and understanding of elements. A large 'E' graphic on the left side serves as a decorative element.

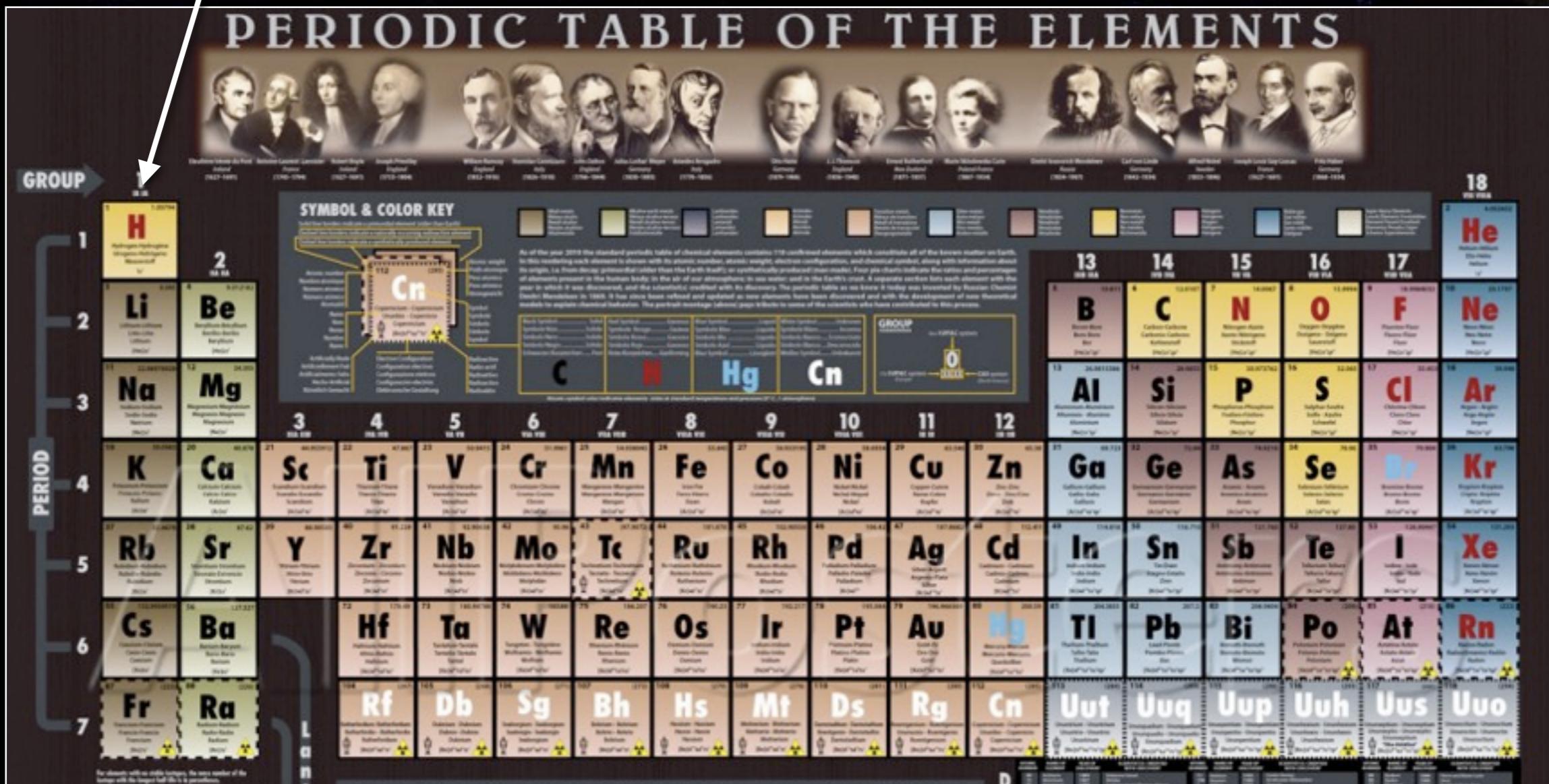
## The number of protons determine what is the element

# Neutrons, Protons, and Atoms

Hydrogen



- Proton
- Neutron



The number of protons determine what is the element

# Neutrons, Protons, and Atoms

Hydrogen

Helium

Proton

Neutron

**PERIODIC TABLE OF THE ELEMENTS**

**SYMBOL & COLOR KEY**

The standard periodic table of chemical elements contains 118 confirmed elements which constitute all of the known matter on Earth, including every living organism, every rock you can touch, and every star in the sky. As of the year 2019 the standard periodic table of chemical elements contains 118 confirmed elements which constitute all of the known matter on Earth, including every living organism, every rock you can touch, and every star in the sky. All of the elements in the periodic table are color-coded according to their properties, i.e., which chemical and physical properties they share with other elements. For example, the noble gases (He, Ne, Ar, Kr, Xe, Rn) are color-coded light blue, while the alkali metals (Li, Na, K, Rb, Cs, Fr) are color-coded yellow. The periodic table also includes a separate section for the lanthanides and actinides, which are color-coded pink. The periodic table also includes a separate section for the lanthanides and actinides, which are color-coded pink. The periodic table also includes a separate section for the lanthanides and actinides, which are color-coded pink.

**GROUP**

**PERIOD**

**Lanthanides**

**Actinides**

**18** **18**

**He**

**Hydrogen**

**Li**

**Be**

**Na**

**Mg**

**K**

**Ca**

**Sc**

**Ti**

**V**

**Cr**

**Mn**

**Fe**

**Co**

**Ni**

**Cu**

**Zn**

**Ga**

**Ge**

**As**

**Se**

**Br**

**Kr**

**Rb**

**Sr**

**Y**

**Zr**

**Nb**

**Mo**

**Tc**

**Ru**

**Rh**

**Pd**

**Ag**

**Cd**

**In**

**Sn**

**Sb**

**Te**

**I**

**Xe**

**Cs**

**Ba**

**Hf**

**Ta**

**W**

**Re**

**Os**

**Ir**

**Pt**

**Au**

**Hg**

**Tl**

**Pb**

**Bi**

**Po**

**At**

**Rn**

**Fr**

**Ra**

**Rf**

**Db**

**Sg**

**Bh**

**Hs**

**Mt**

**Ds**

**Rg**

**Cn**

**Uut**

**Uup**

**Uuh**

**Uus**

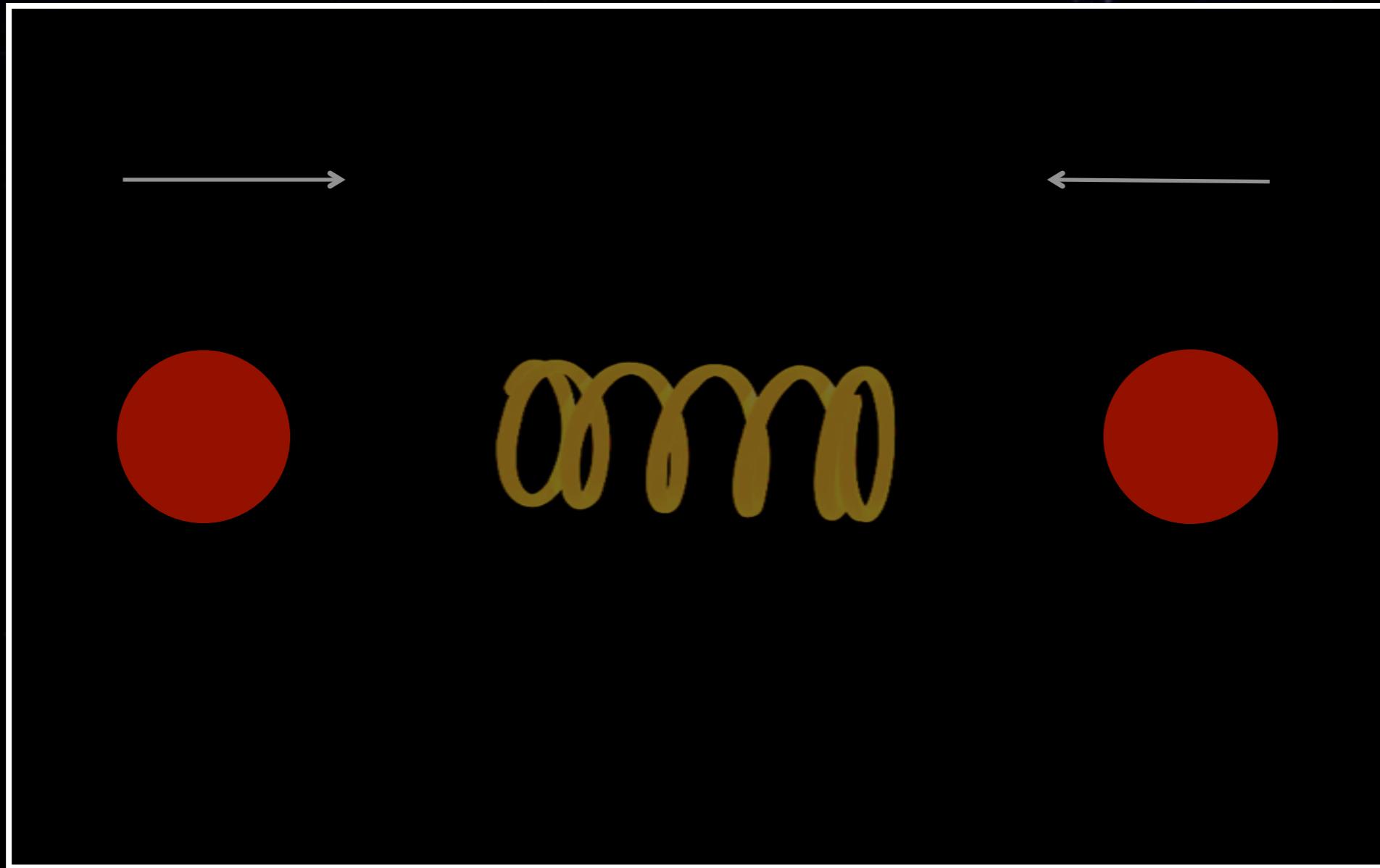
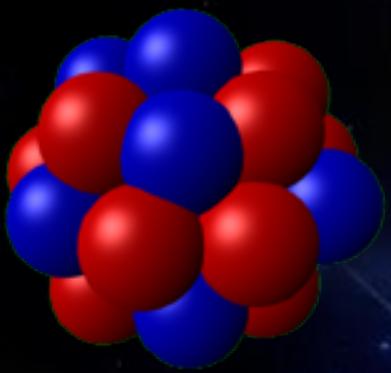
**Uuo**

The number of protons determine what is the element

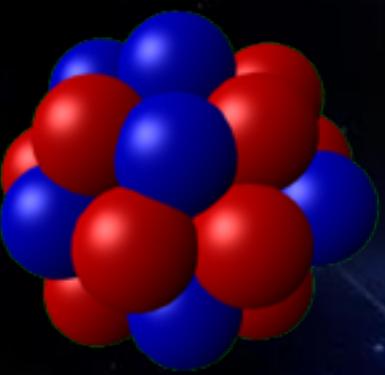
# The Process of Nuclear Fusion



Electric force (repulsion)



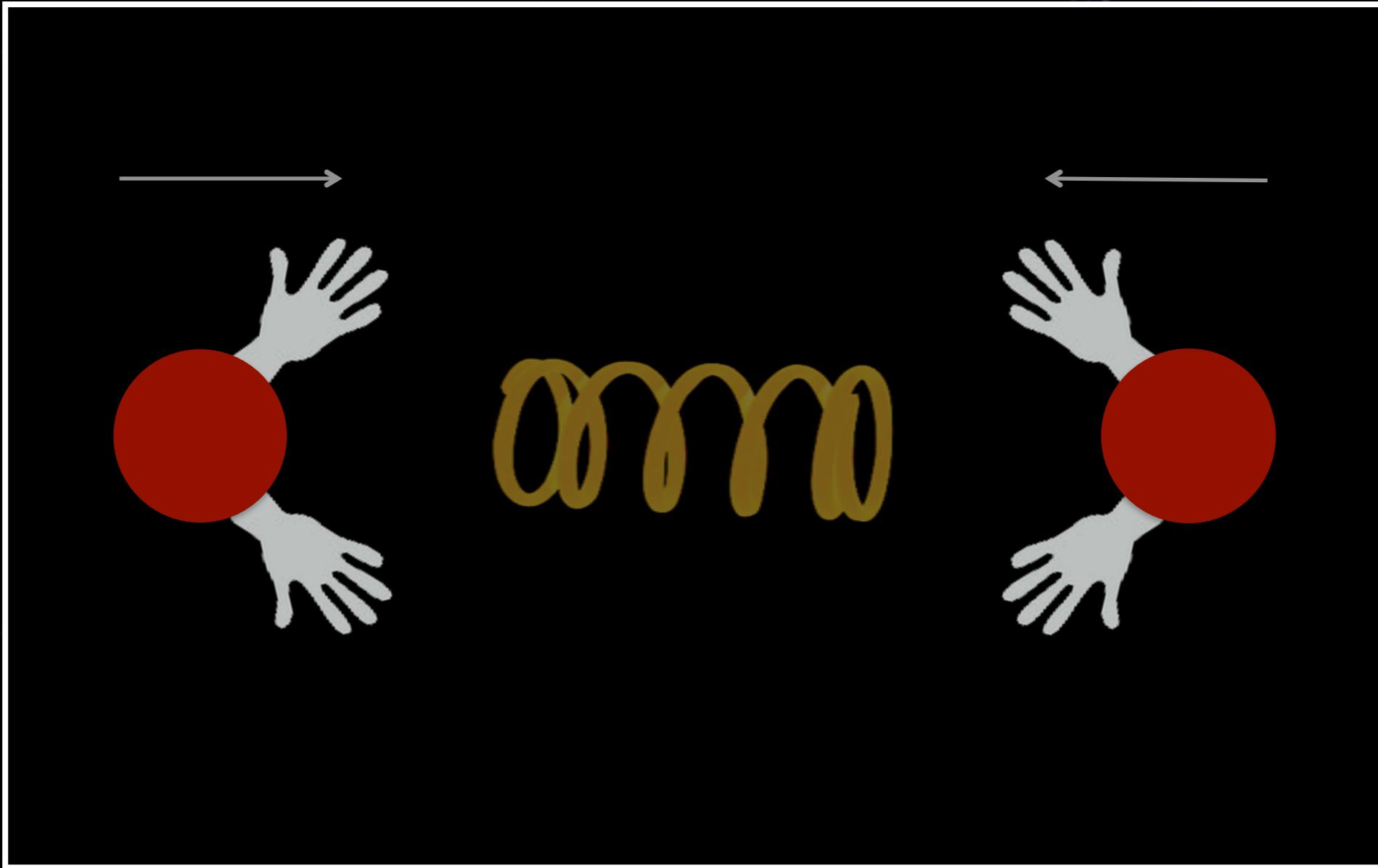
# The Process of Nuclear Fusion



Electric force (repulsion)



Nuclear force (attraction)



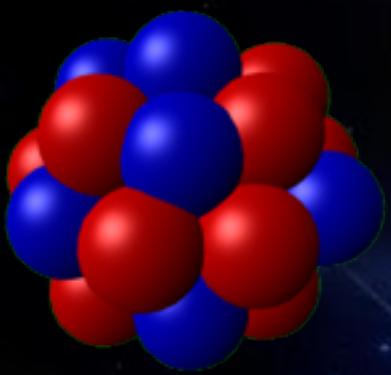
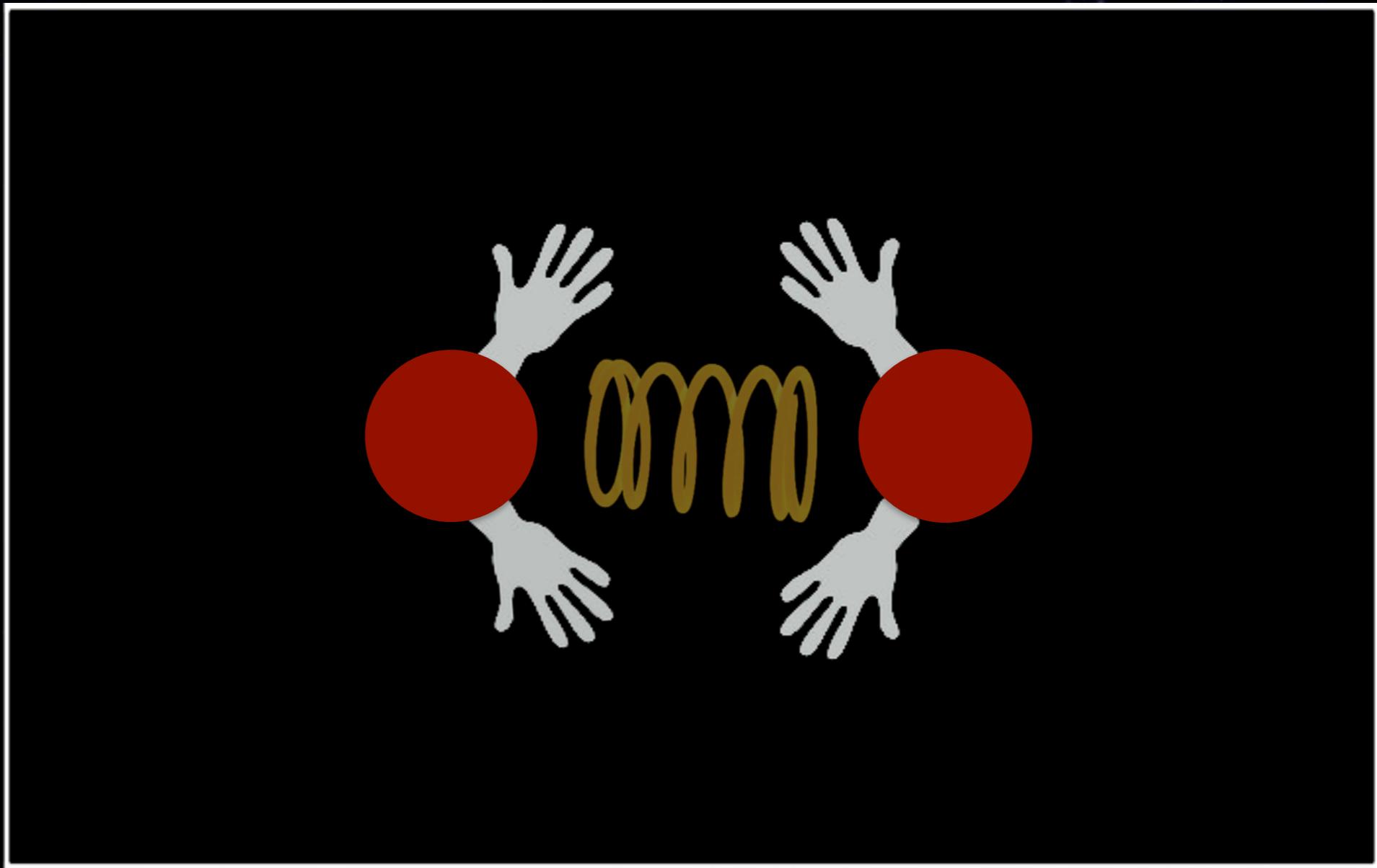
# The Process of Nuclear Fusion



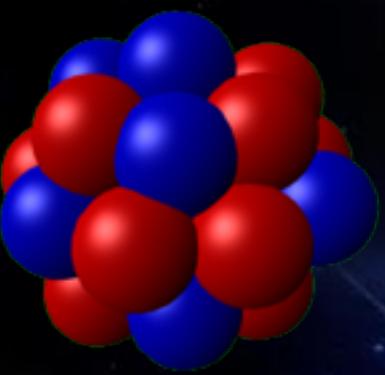
Electric force (repulsion)



Nuclear force (attraction)



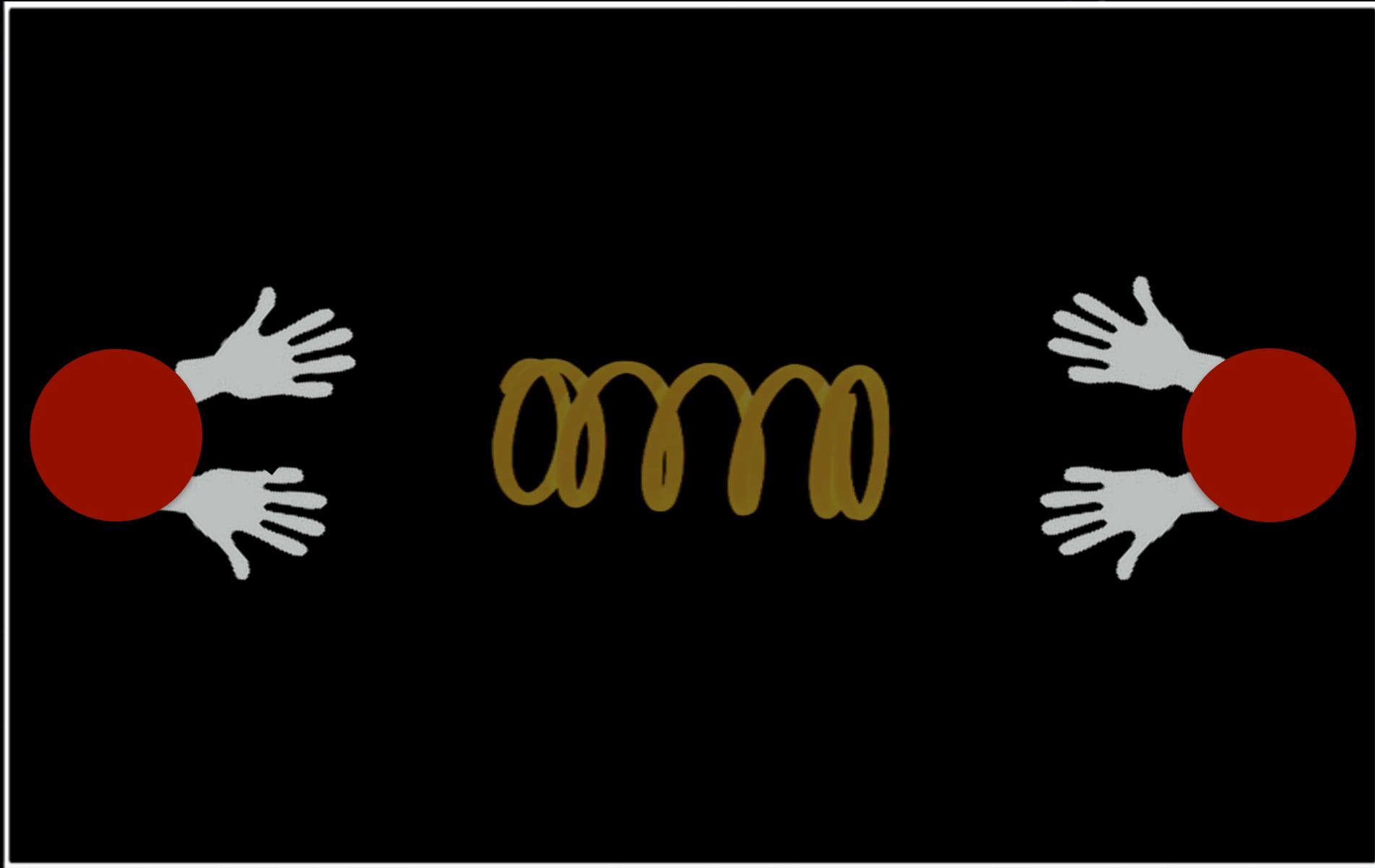
# The Process of Nuclear Fusion



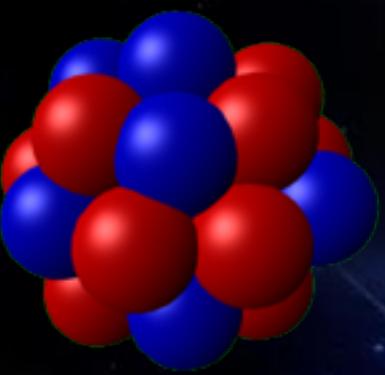
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Nuclear force (attraction)



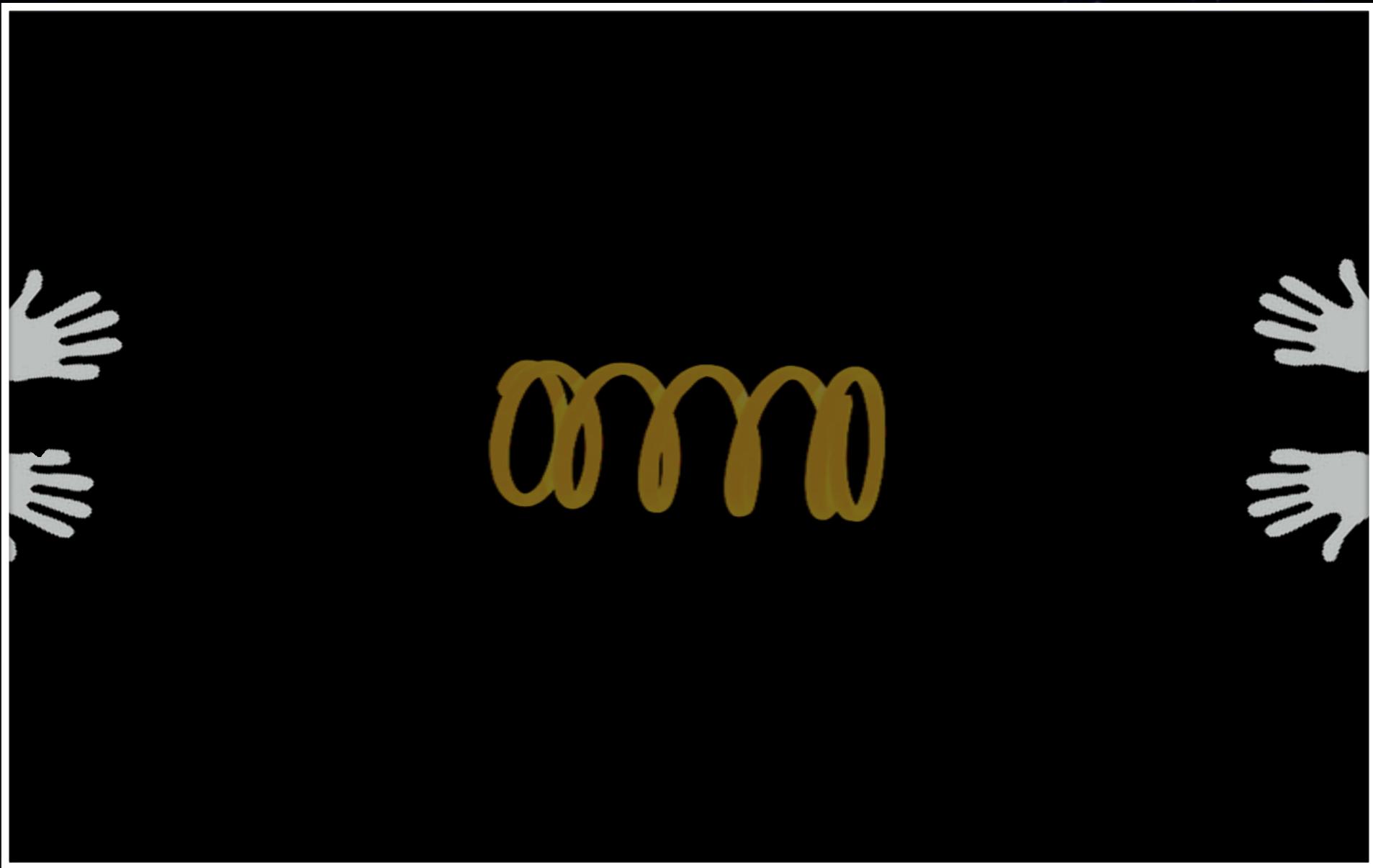
# The Process of Nuclear Fusion



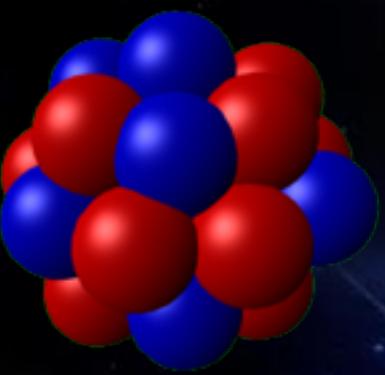
Electric force (repulsion)



Nuclear force (attraction)



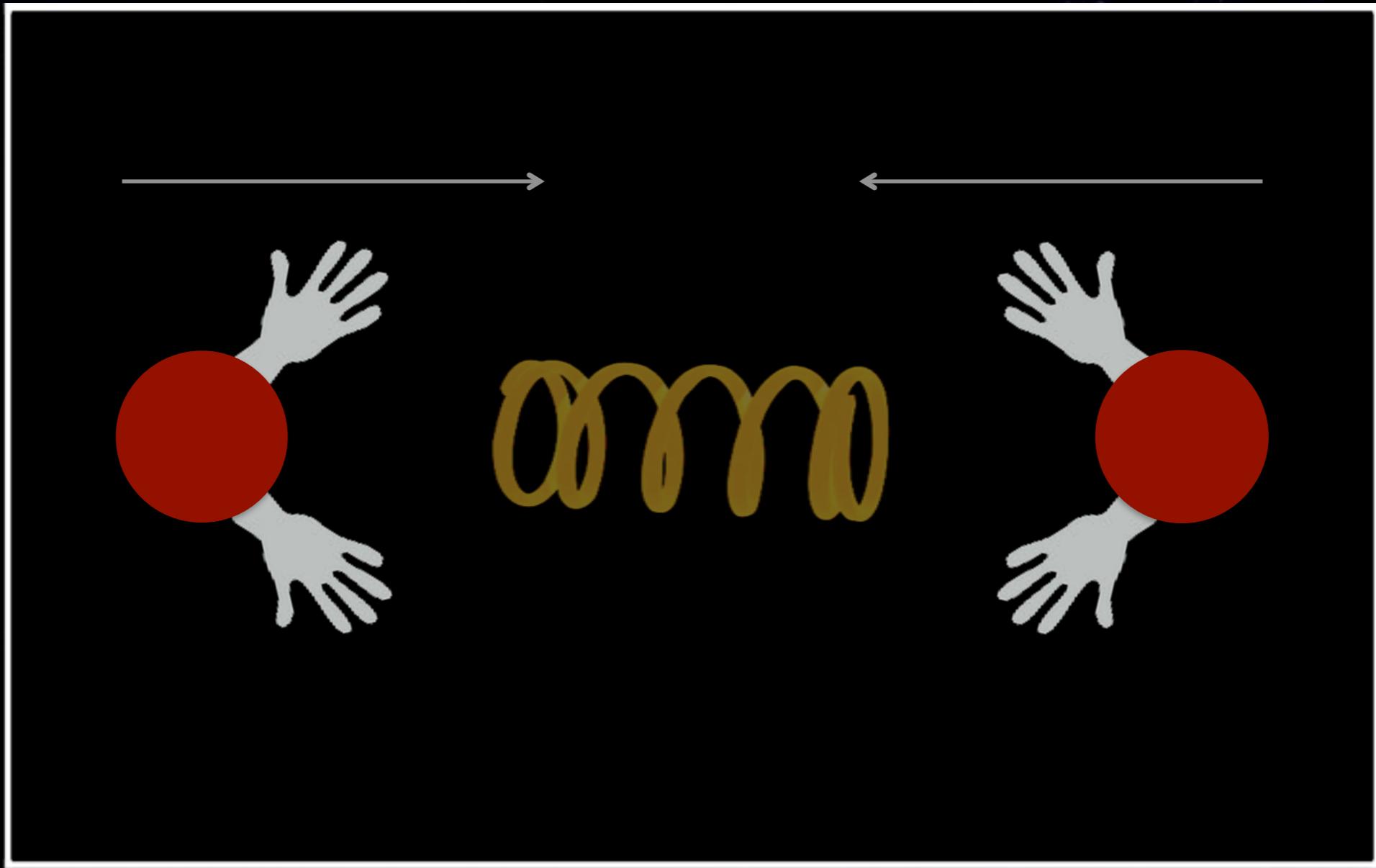
# The Process of Nuclear Fusion



Electric force (repulsion)



Nuclear force (attraction)



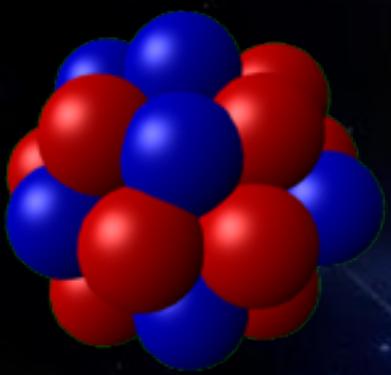
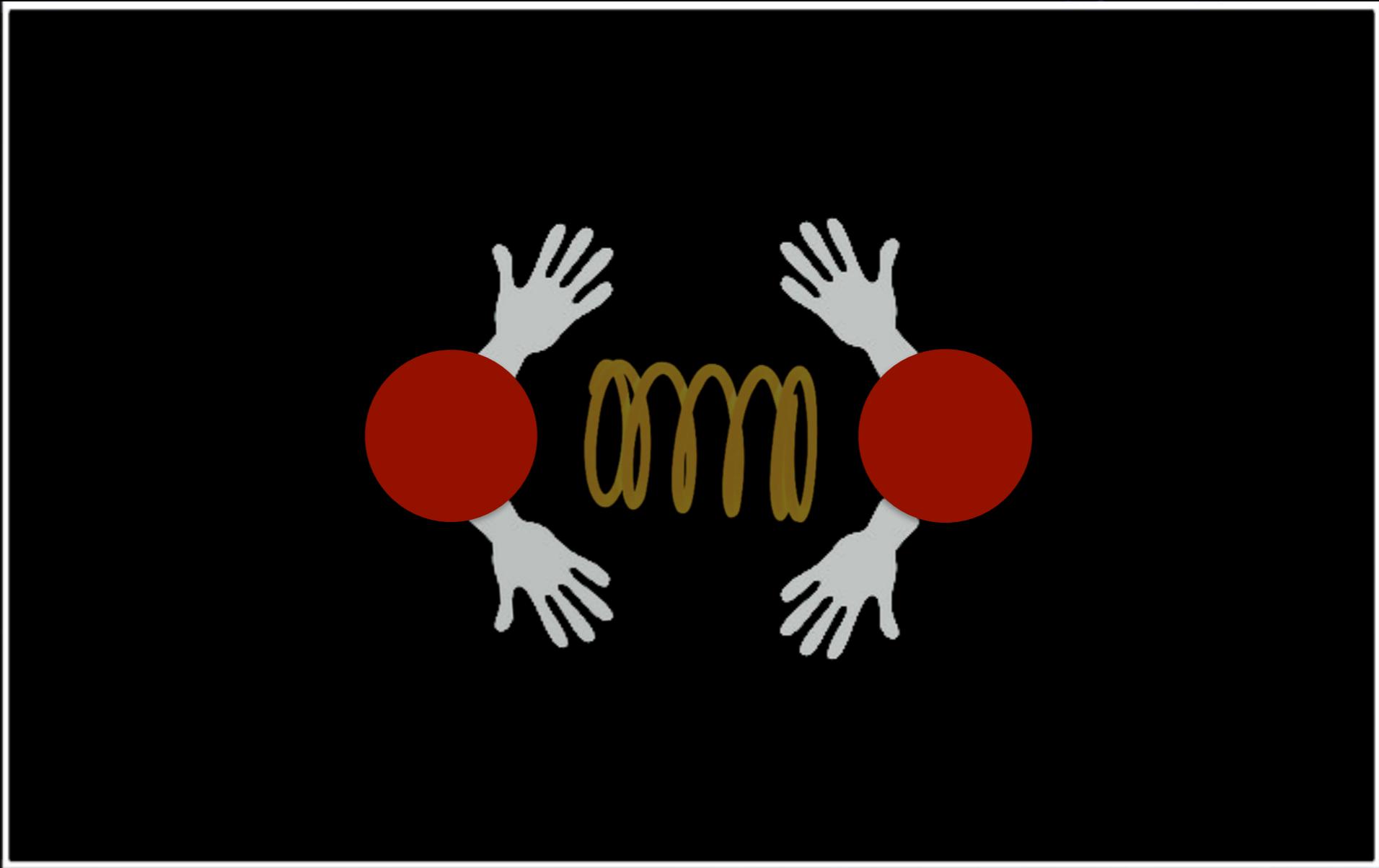
# The Process of Nuclear Fusion



Electric force (repulsion)



Nuclear force (attraction)



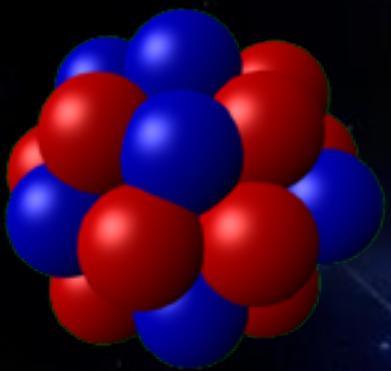
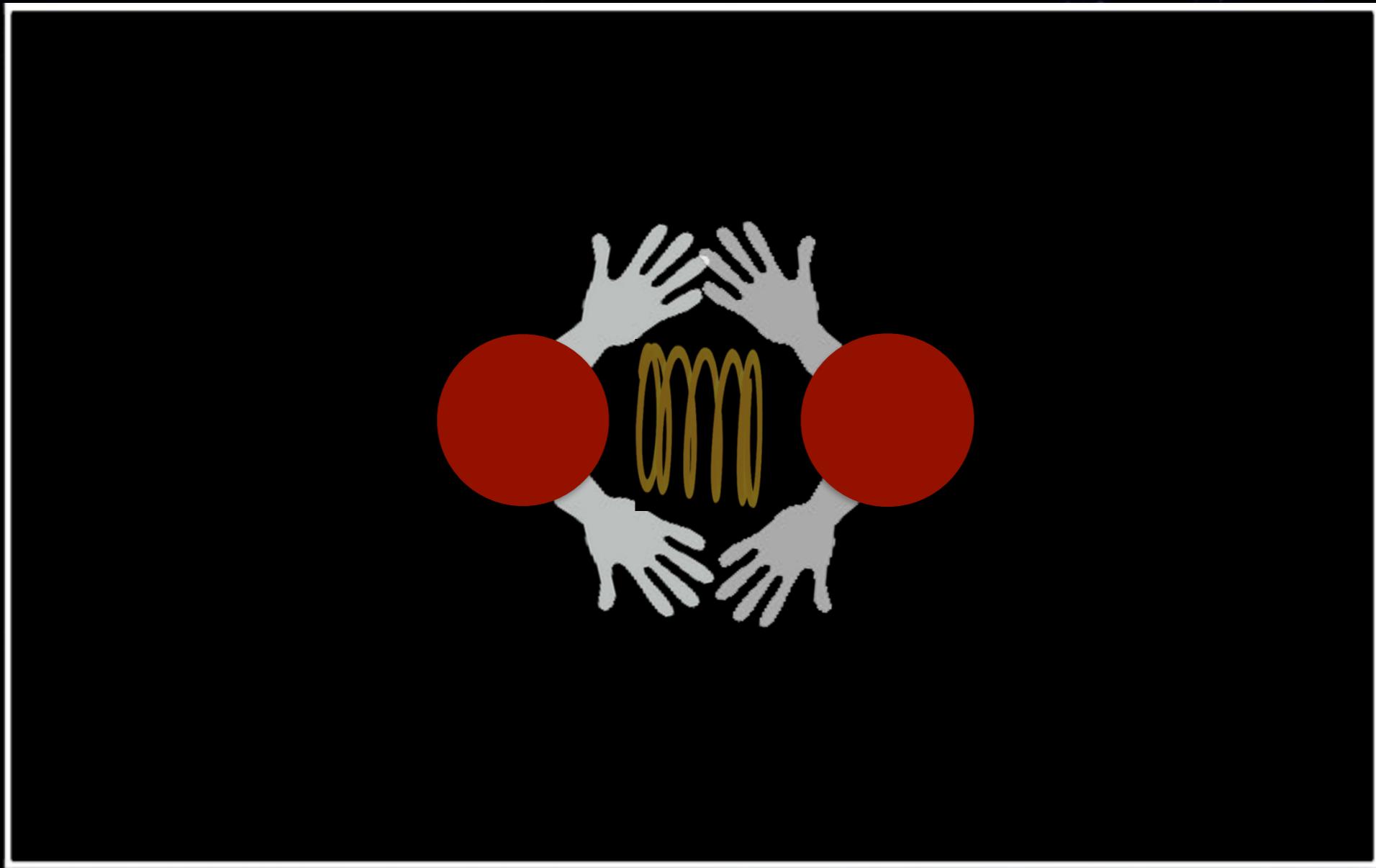
# The Process of Nuclear Fusion



Electric force (repulsion)



Nuclear force (attraction)



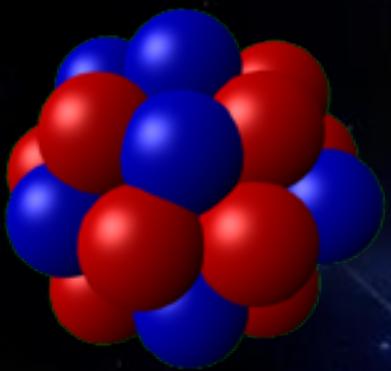
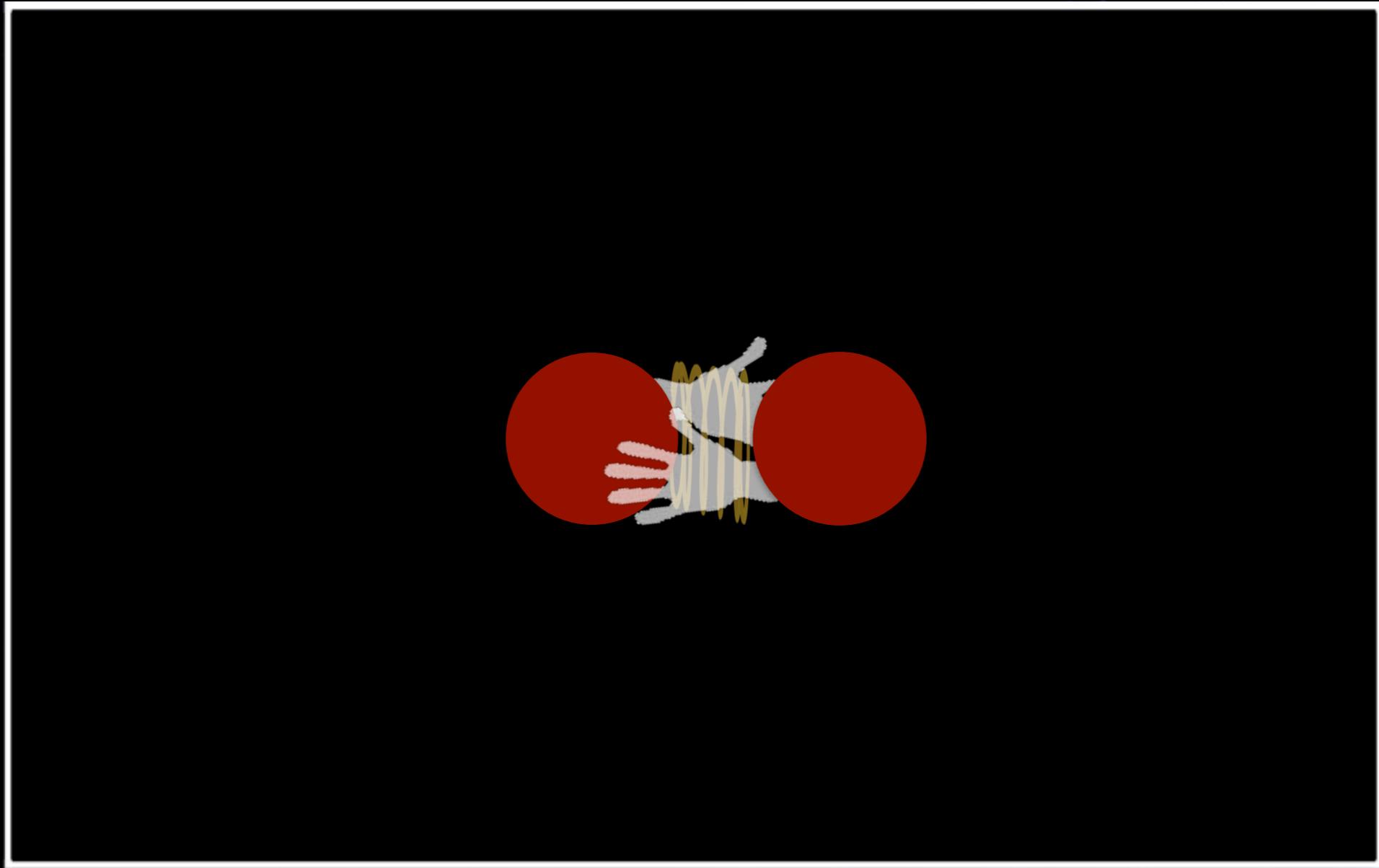
# The Process of Nuclear Fusion



Electric force (repulsion)



Nuclear force (attraction)



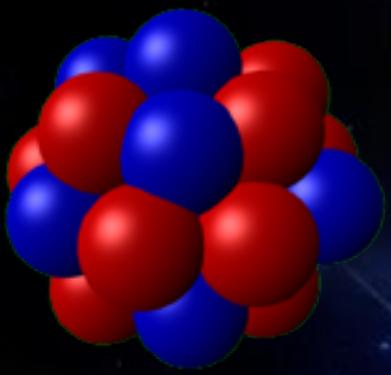
# The Process of Nuclear Fusion



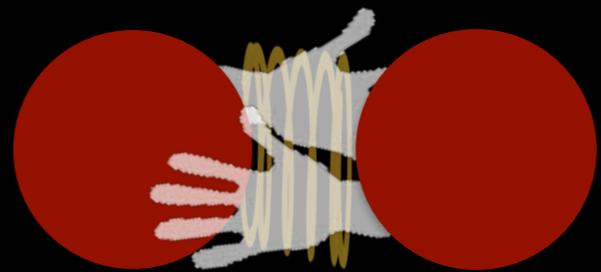
Electric force (repulsion)



Nuclear force (attraction)



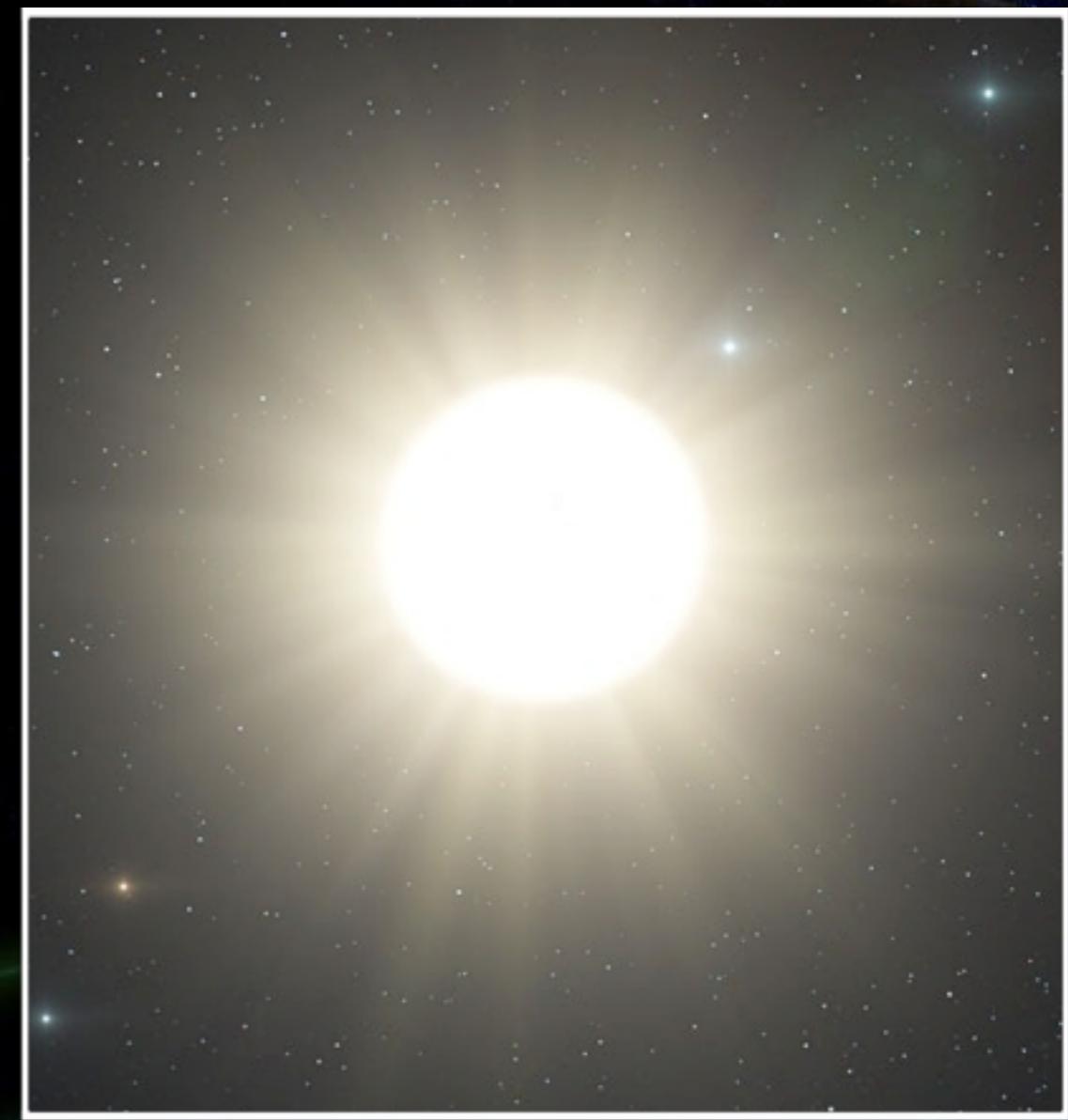
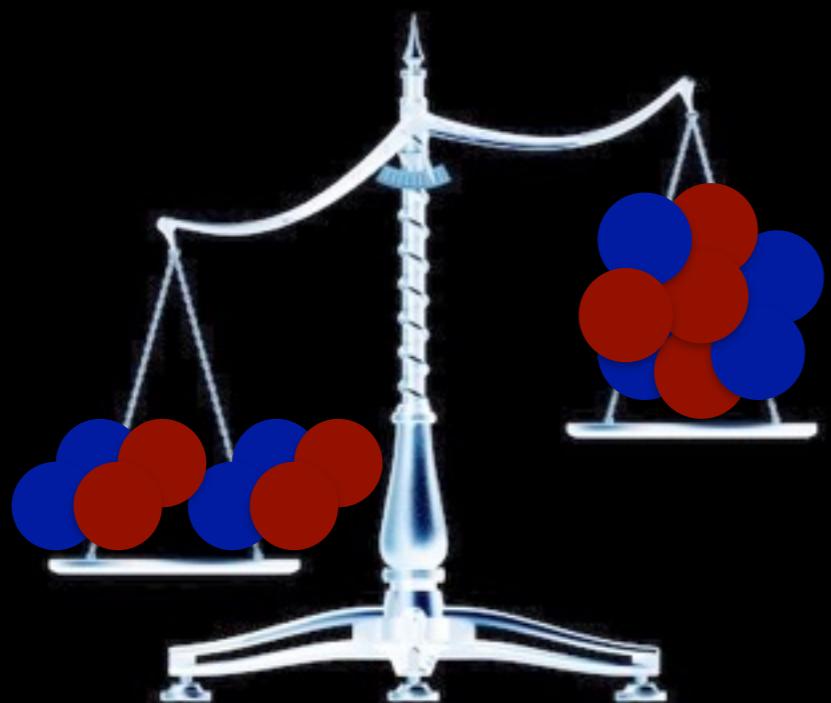
**The nuclear force is stronger than the electric force**



# The Process of Nuclear Fusion

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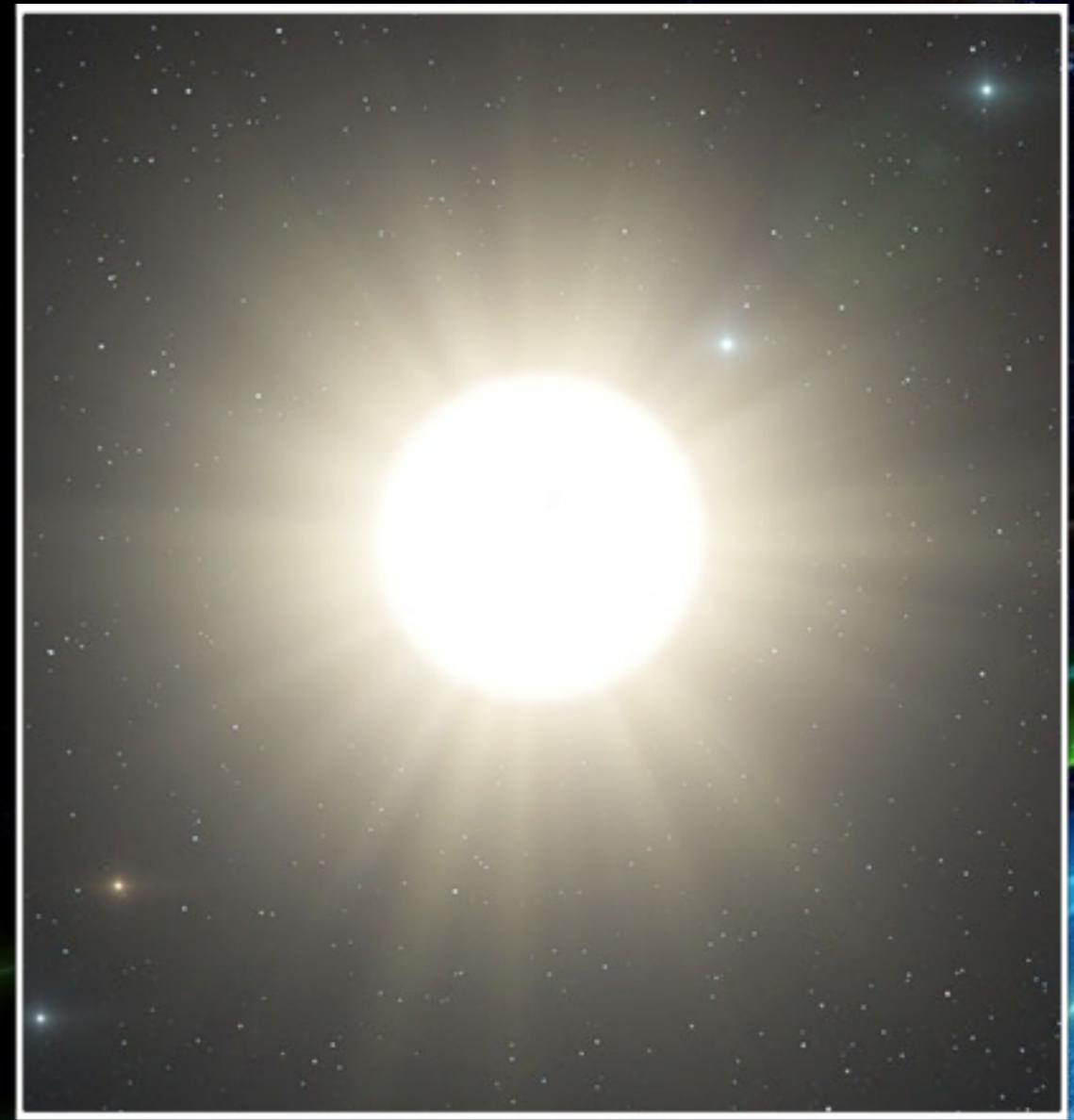
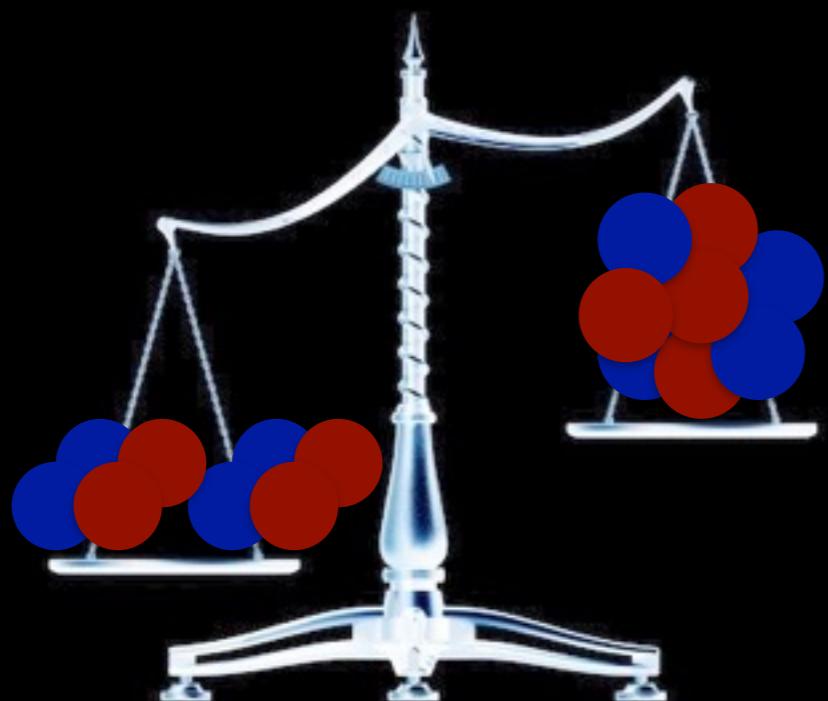
$$E = mc^2$$



# The Process of Nuclear Fusion

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

$$E = mc^2$$



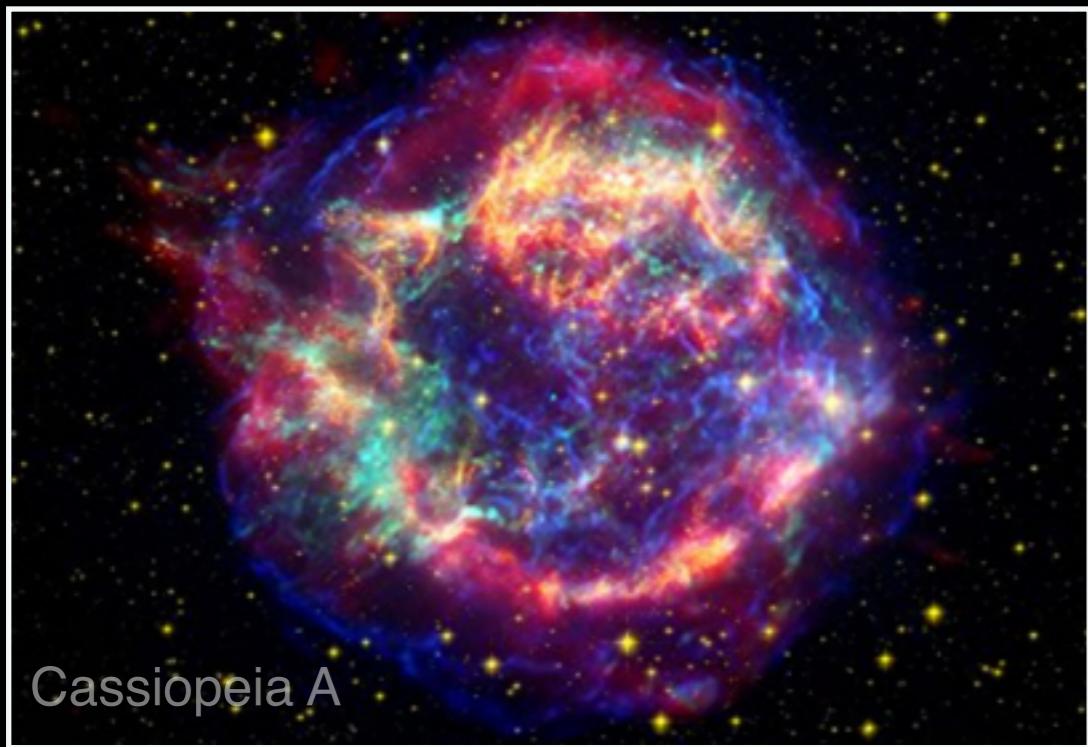
# New Elements Ejected in Space

Core-collapse supernovae



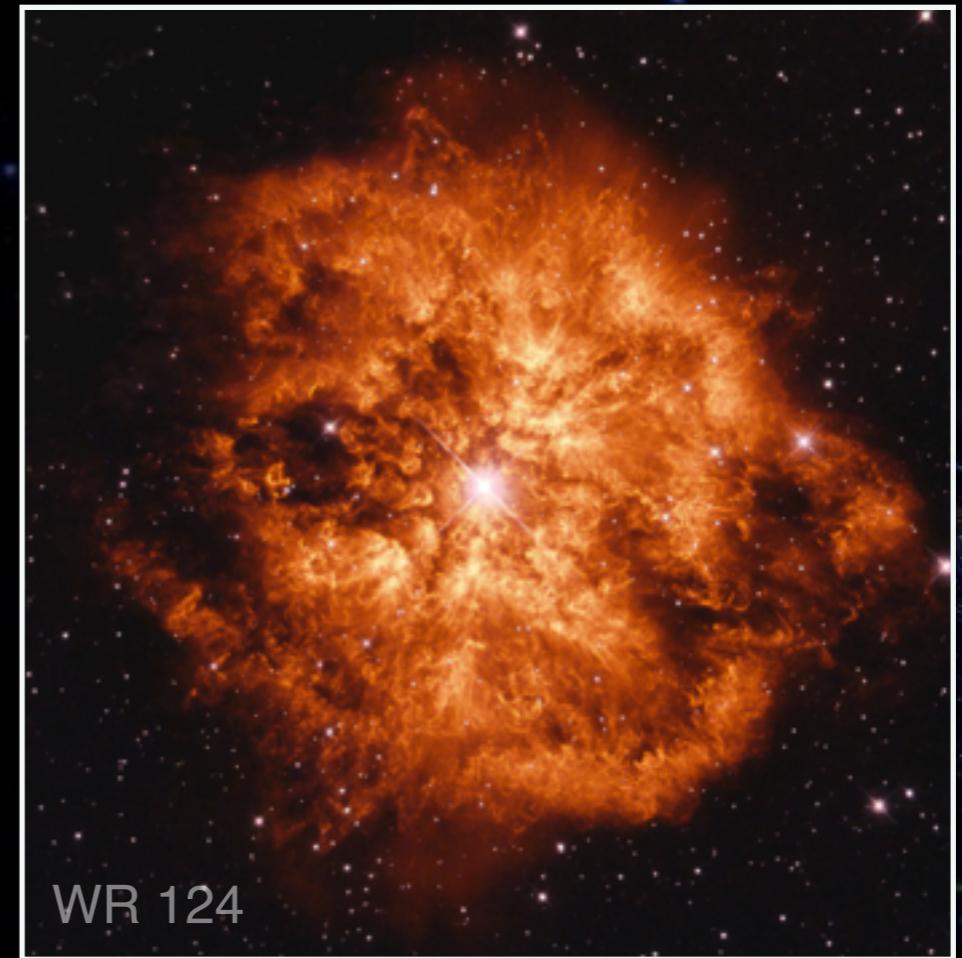
Crab nebula

Type Ia supernovae



Cassiopeia A

Stellar winds from massive stars



WR 124

Stellar winds from low-mass stars



Cat eye nebula

Stellar winds from massive stars

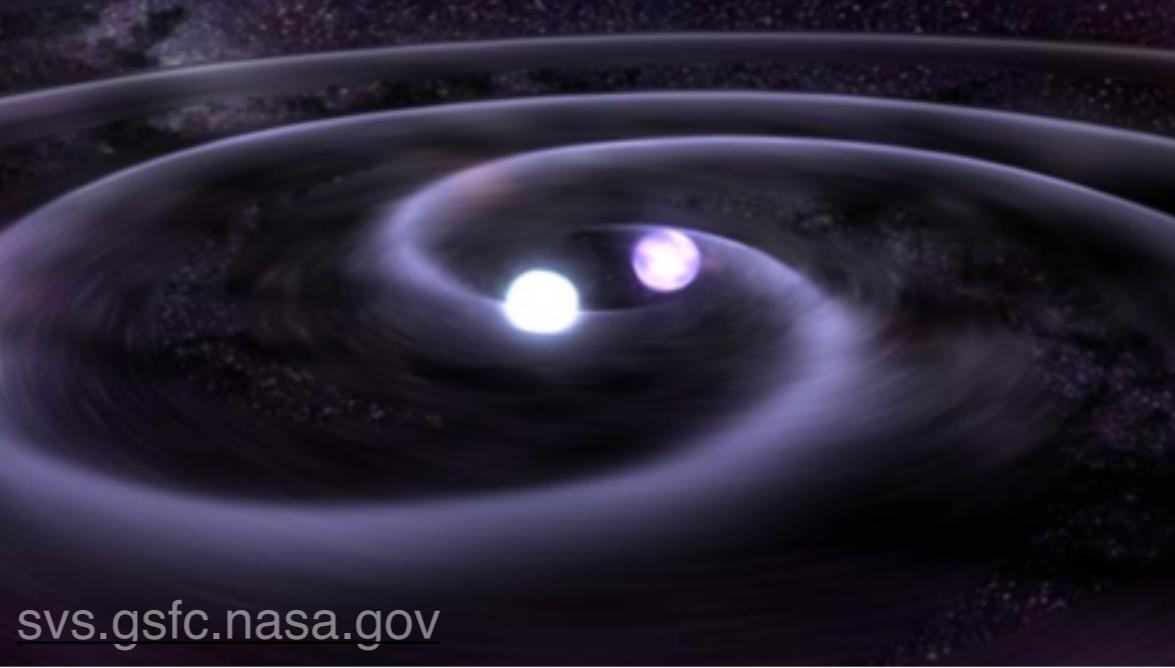
# New Elements Ejected in Space

Core-collapse supernovae



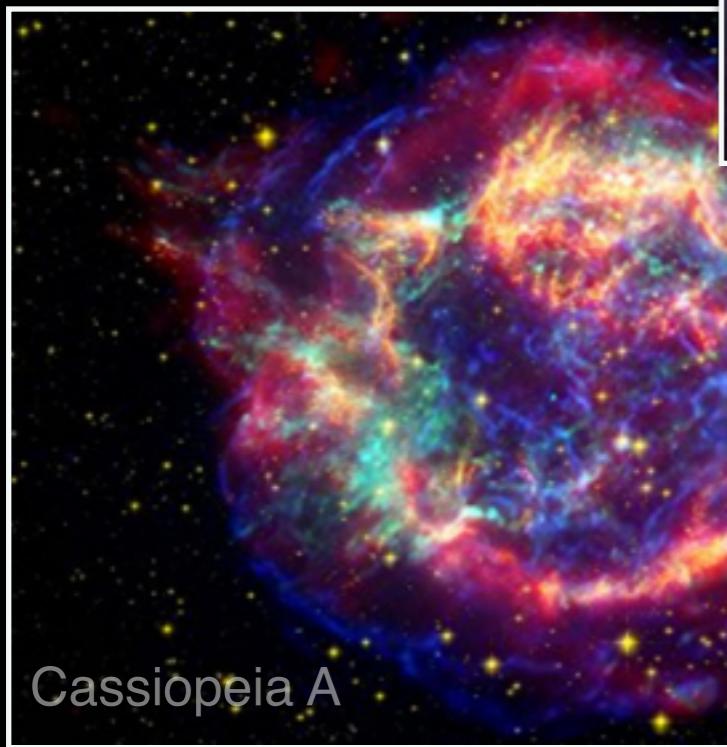
Crab nebula

Neutron star mergers

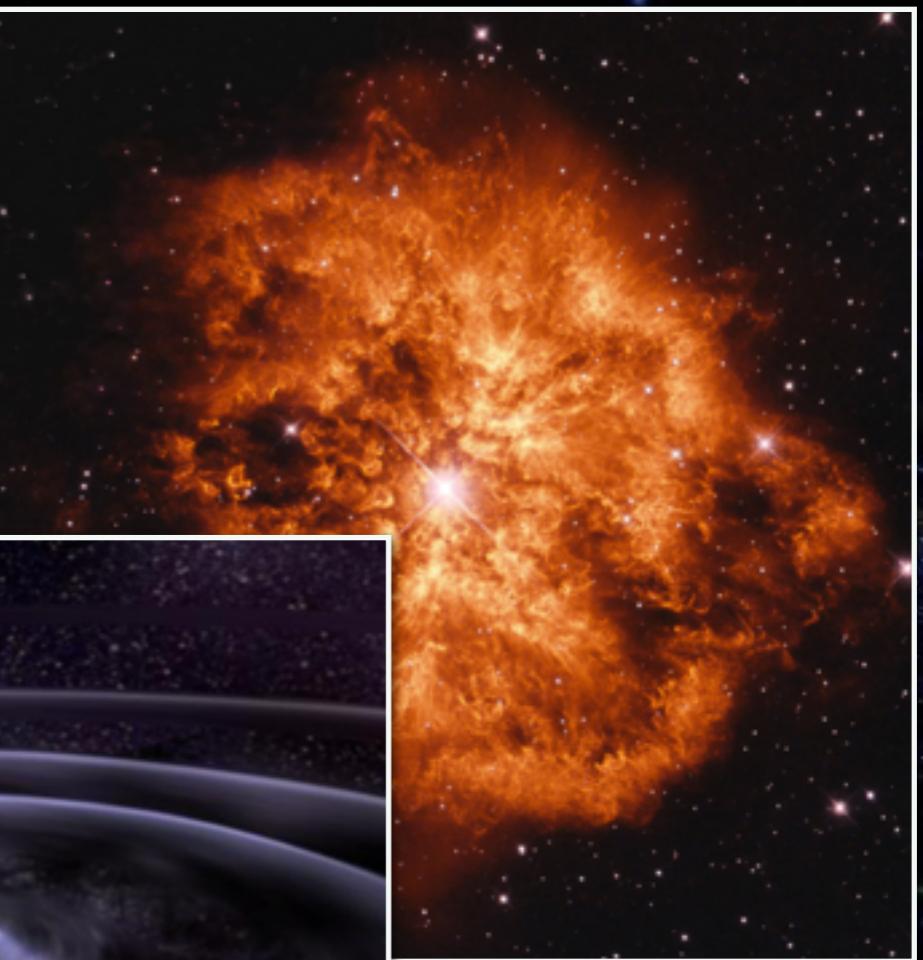


[svs.gsfc.nasa.gov](http://svs.gsfc.nasa.gov)

Type Ia supernovae



Cassiopeia A

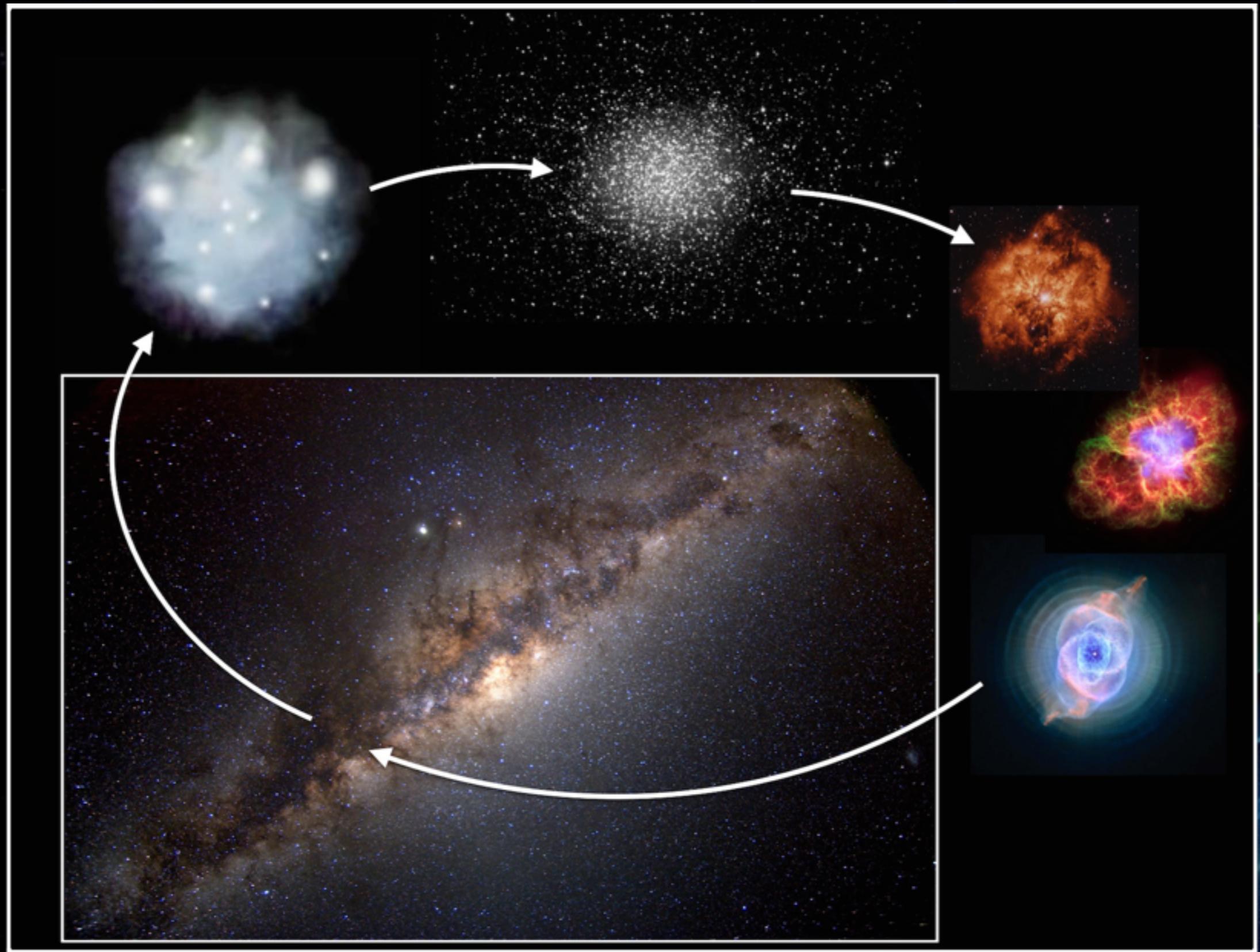


mass stars

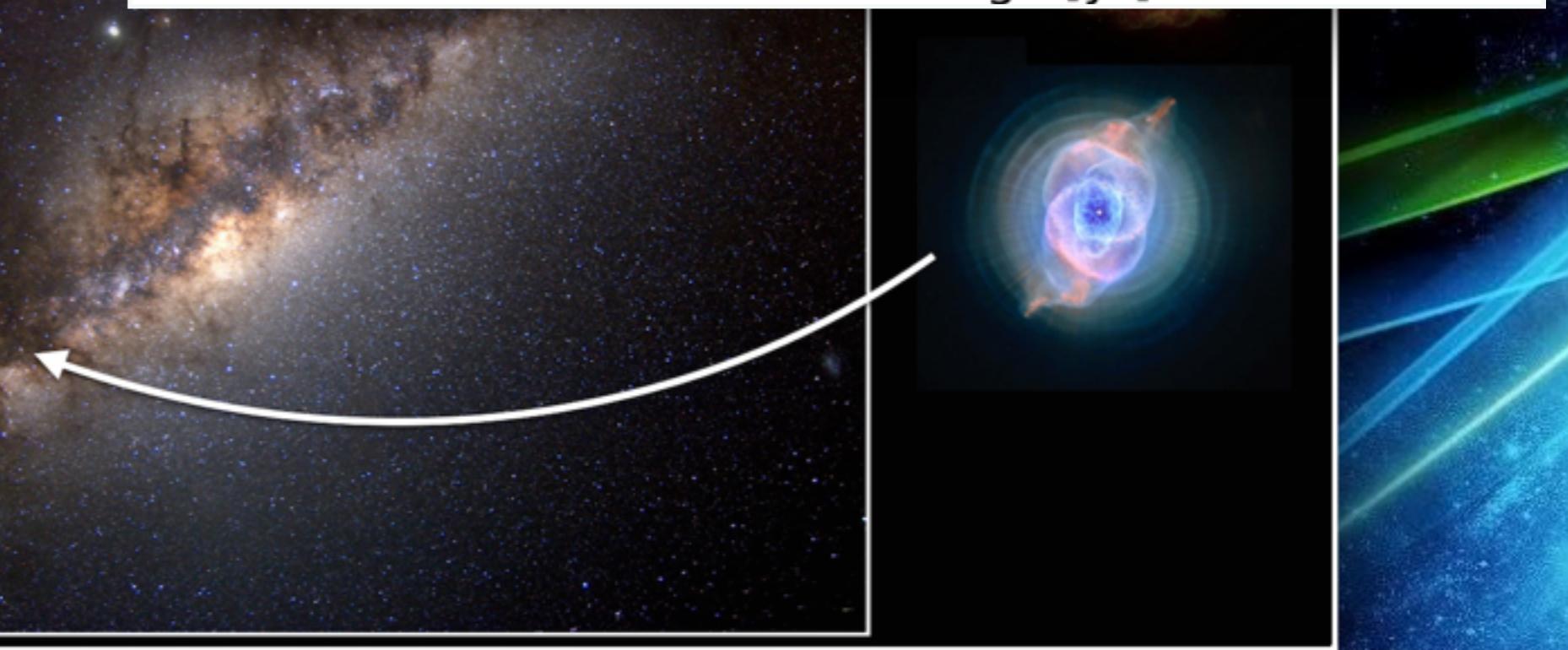
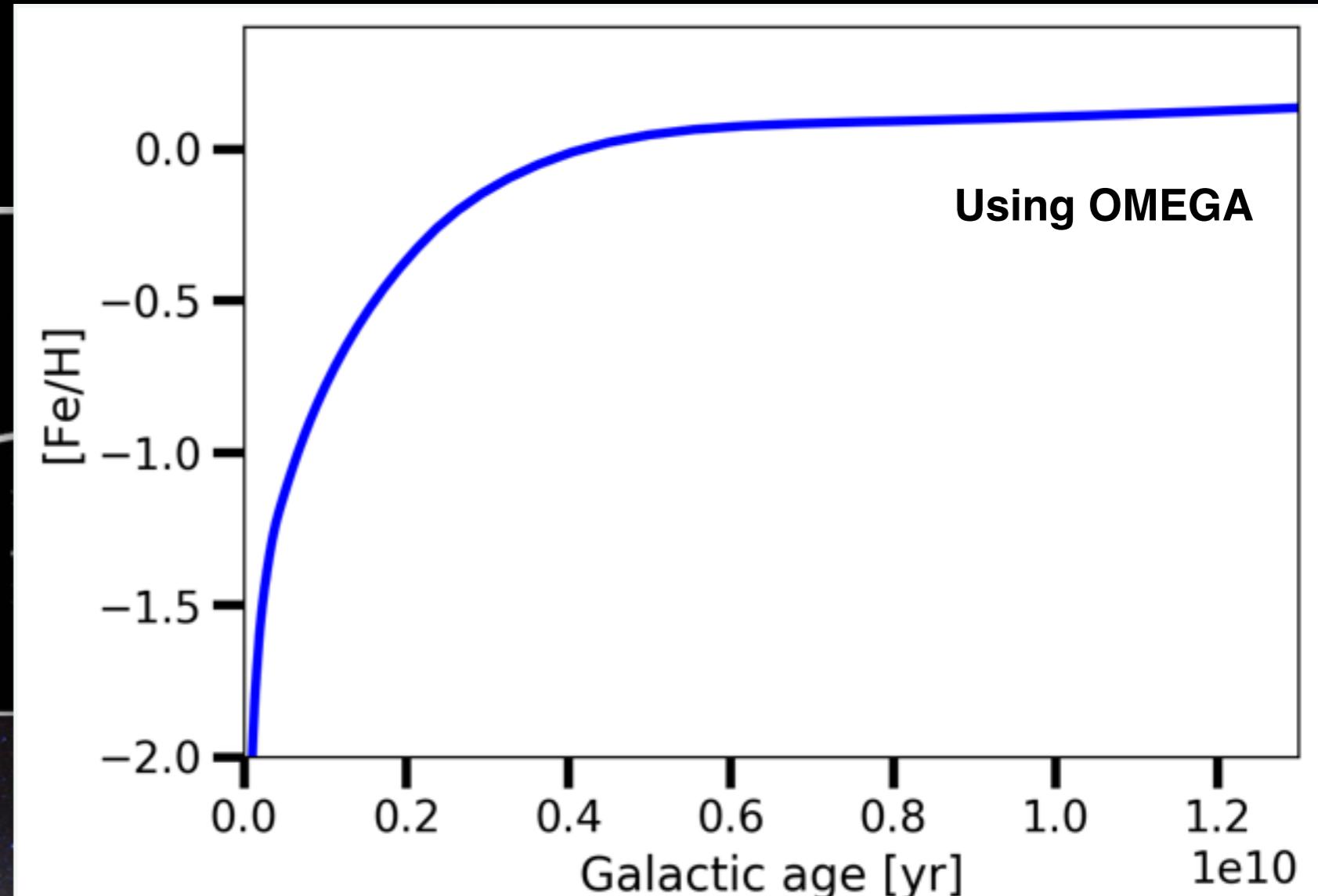
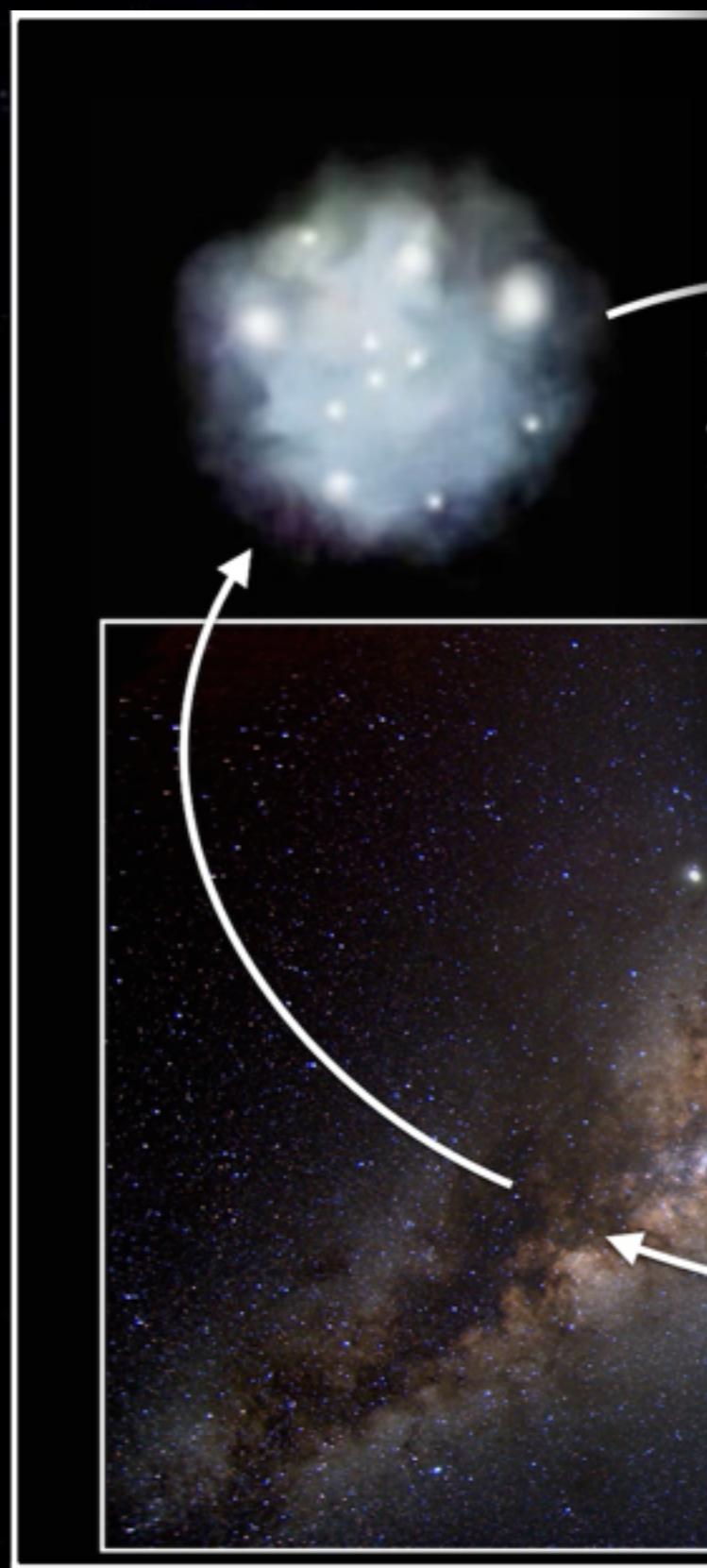


Cat eye nebula

# The Life Cycle of Stars



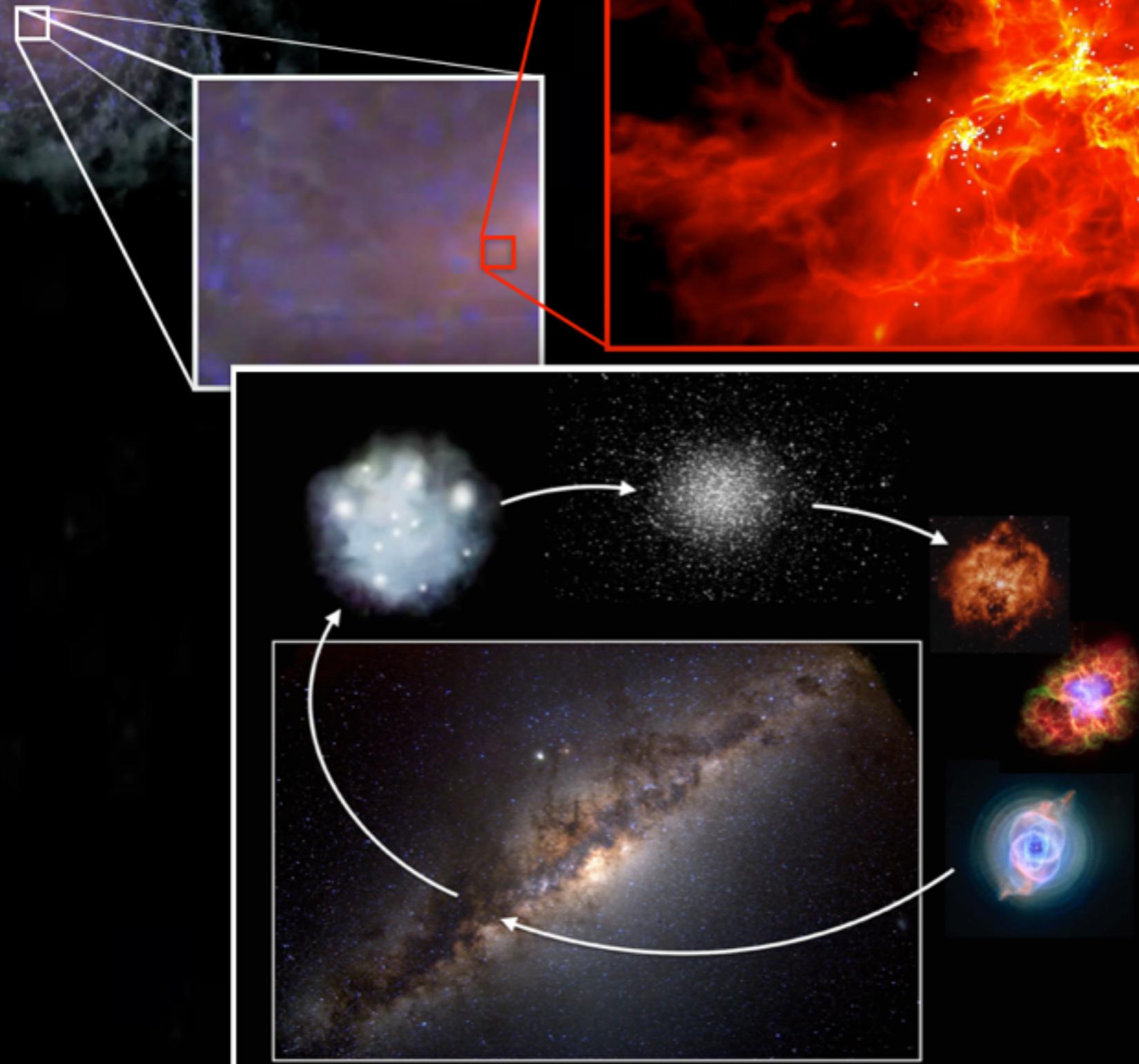
# The Life Cycle of Stars



# Chemical Evolution

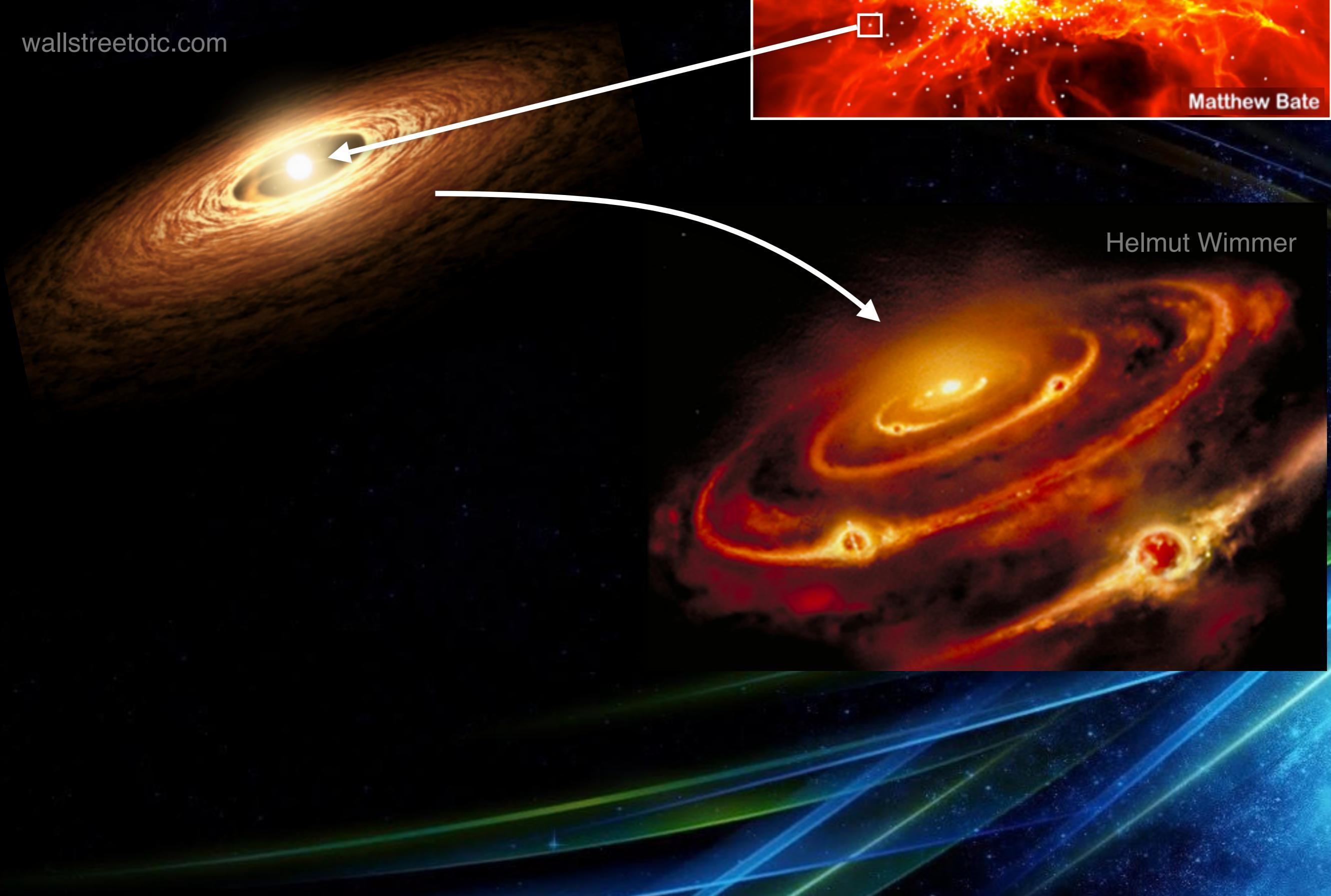
UK Astrophysical  
Fluids Facility

Matthew Bate 



# The Formation of our Solar System

wallstreetotc.com

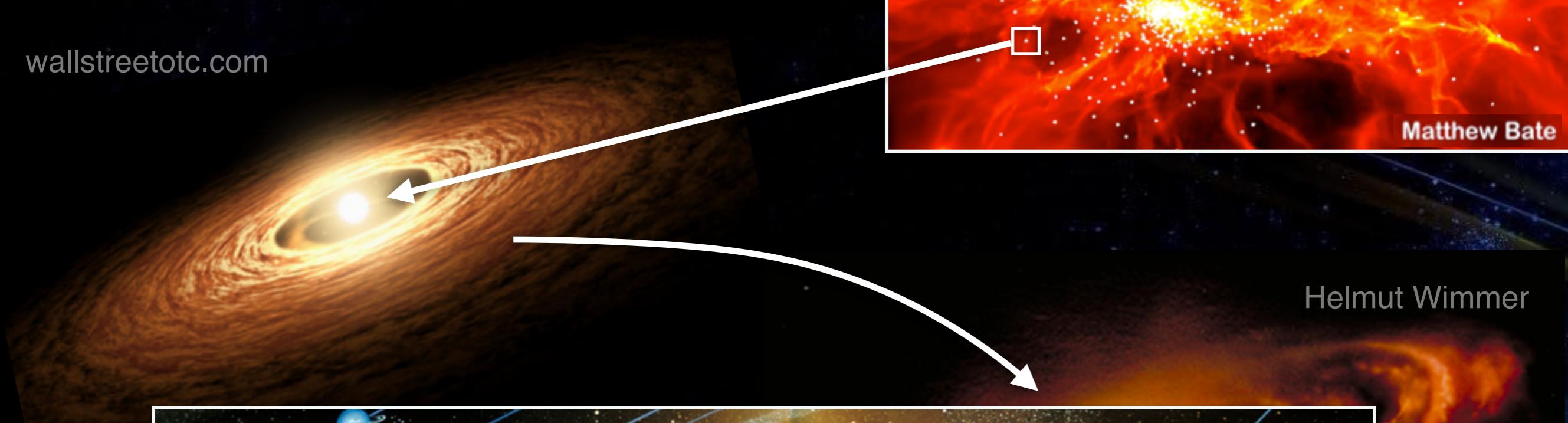


Matthew Bate

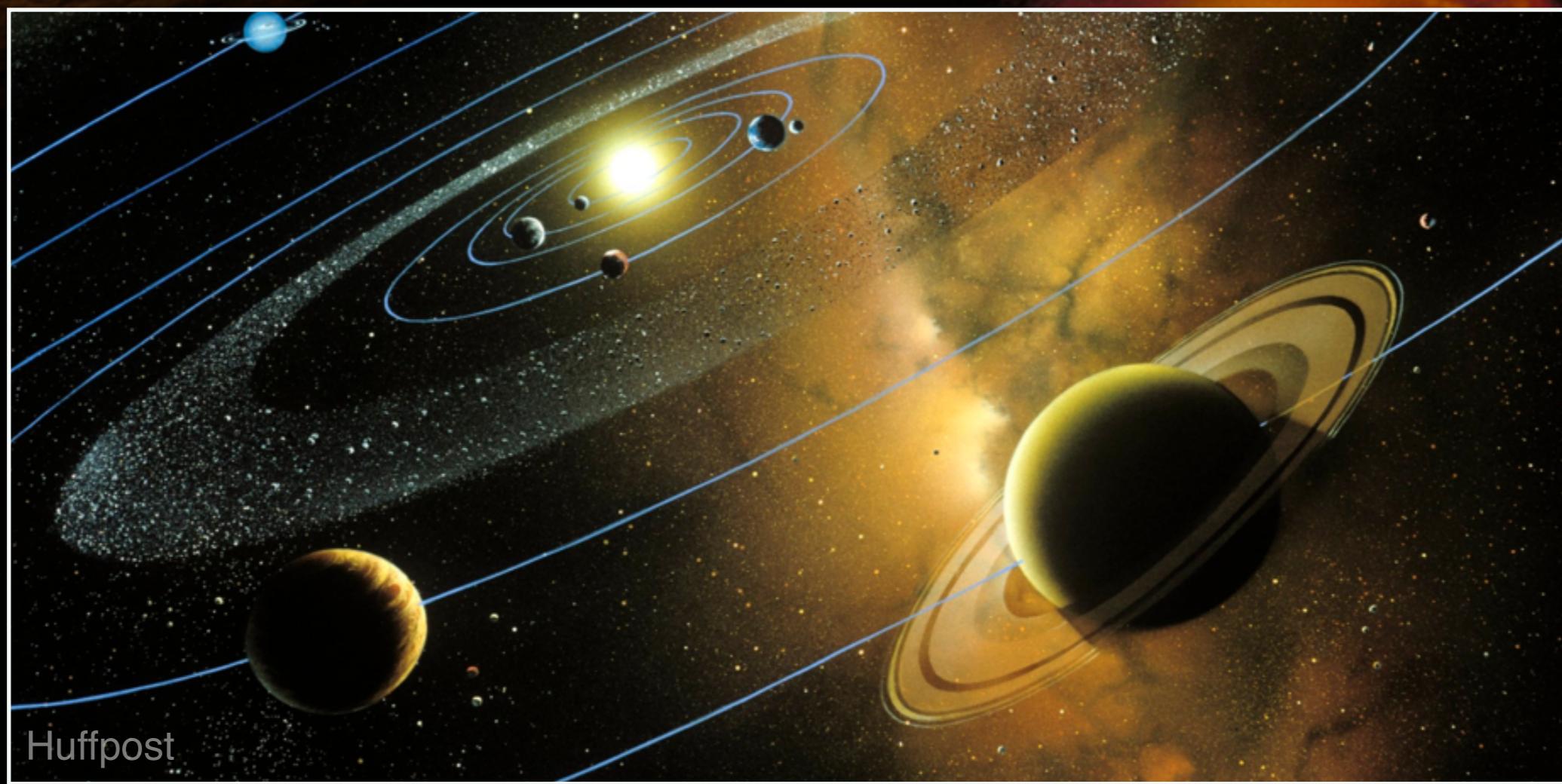
Helmut Wimmer

# The Formation of our Solar System

wallstreetotc.com

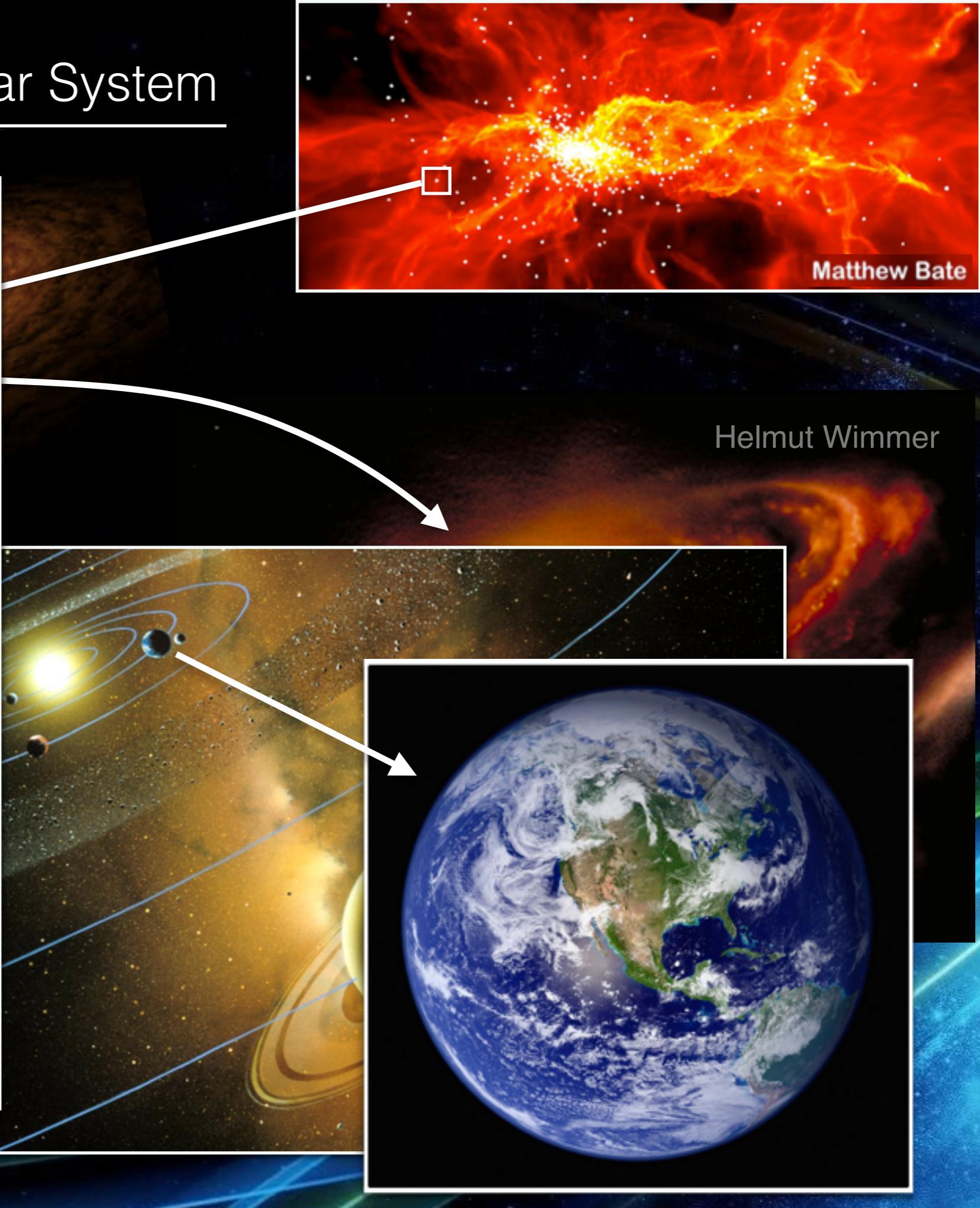
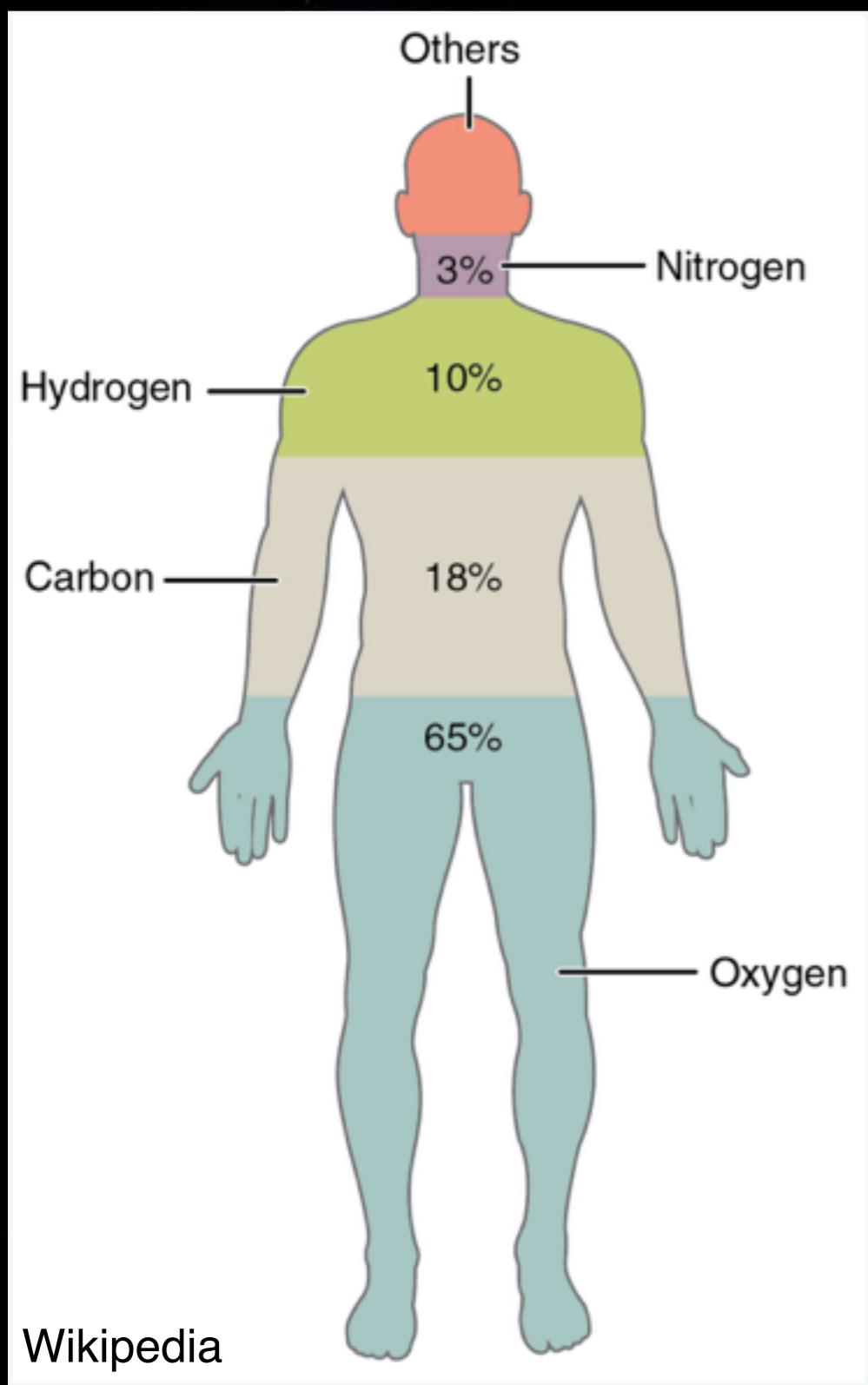


Matthew Bate



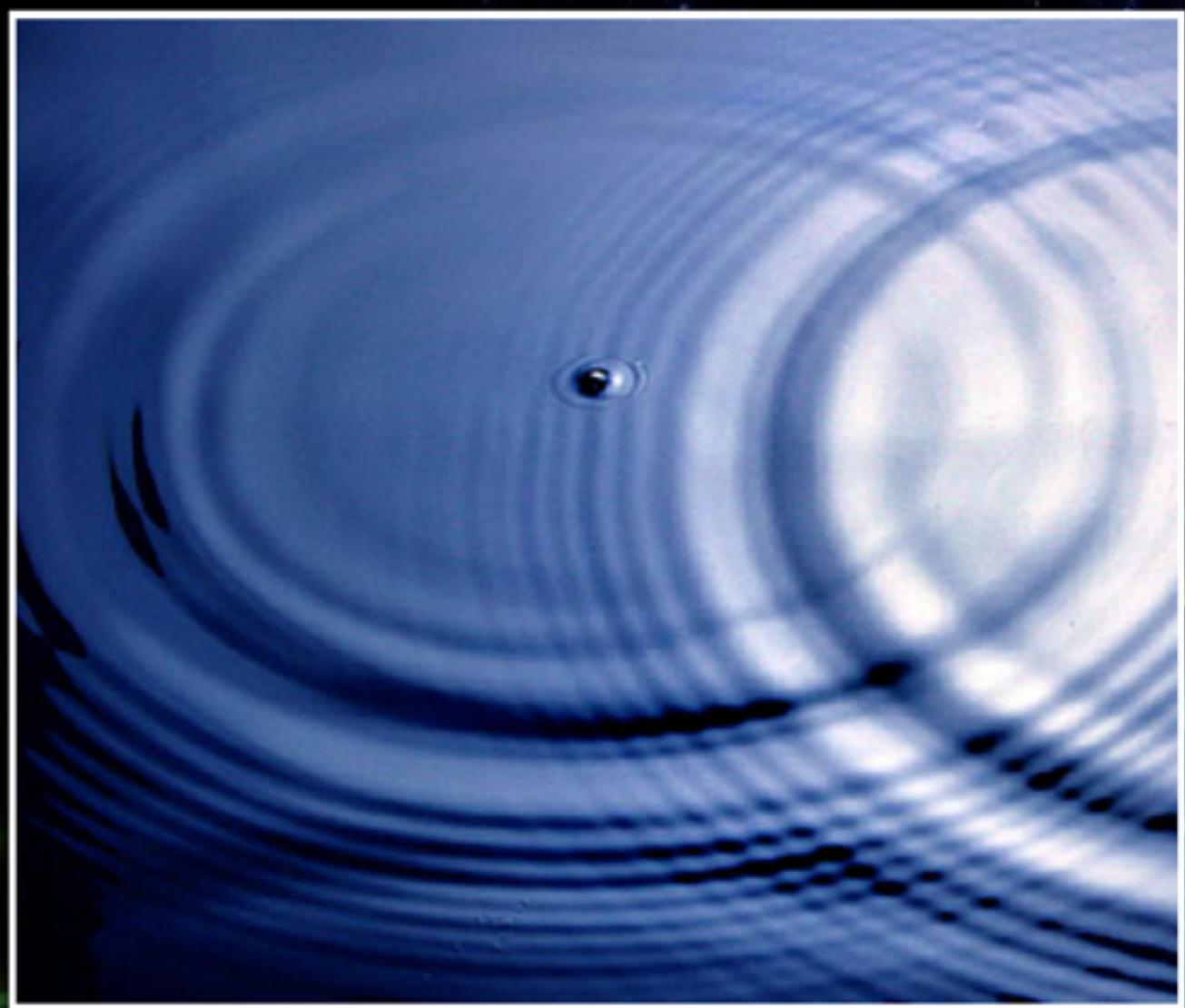
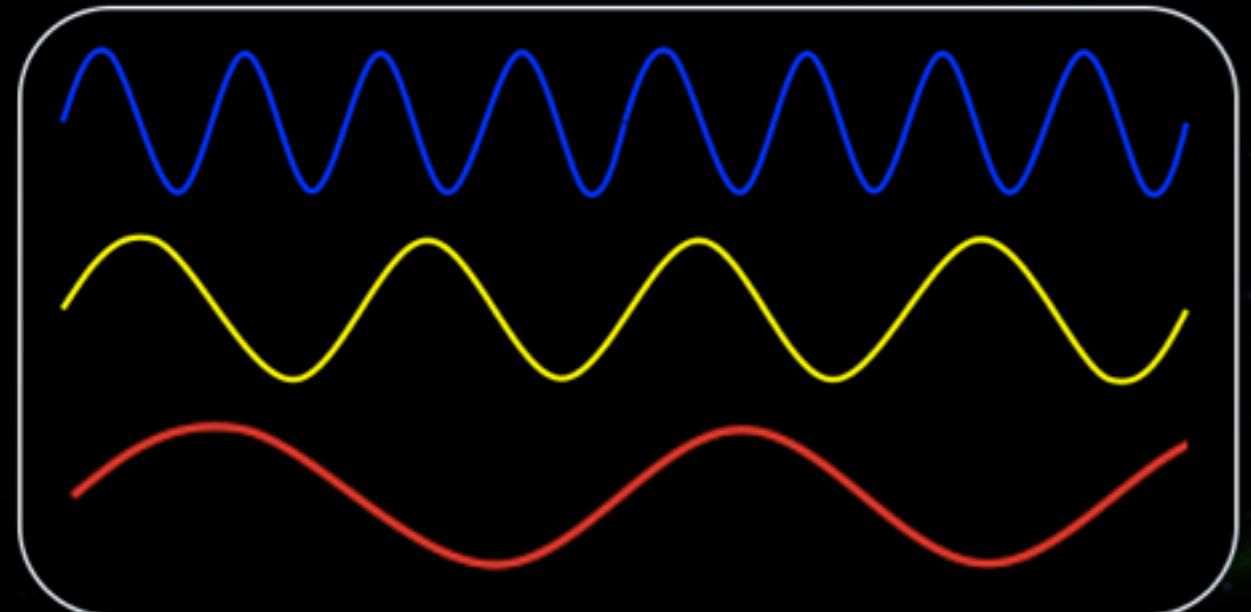
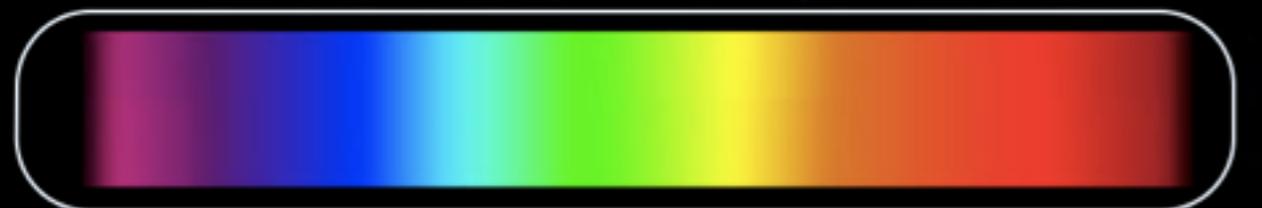
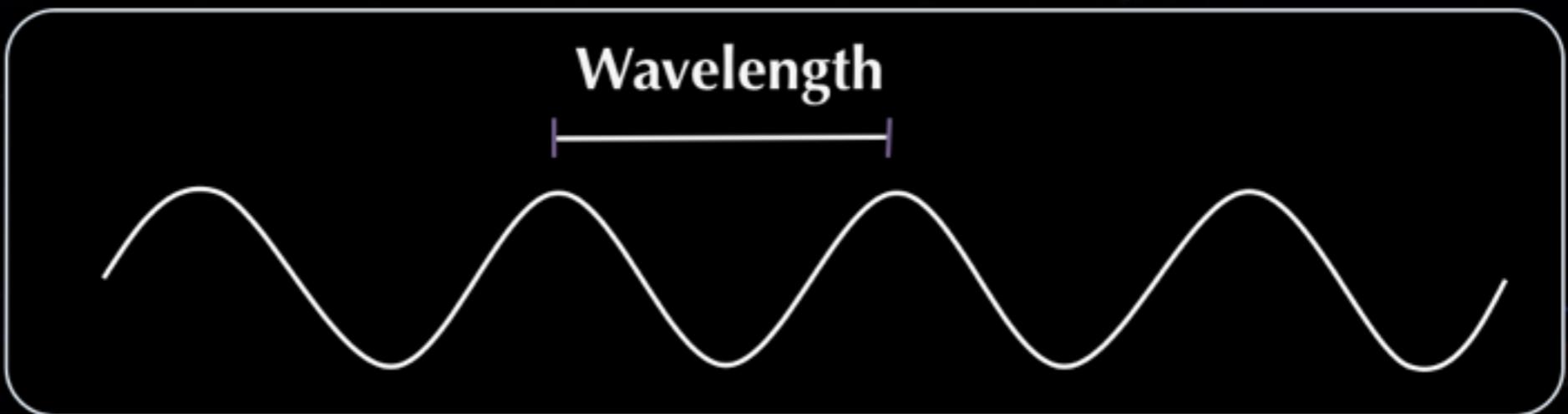
Helmut Wimmer

# The Formation of our Solar System

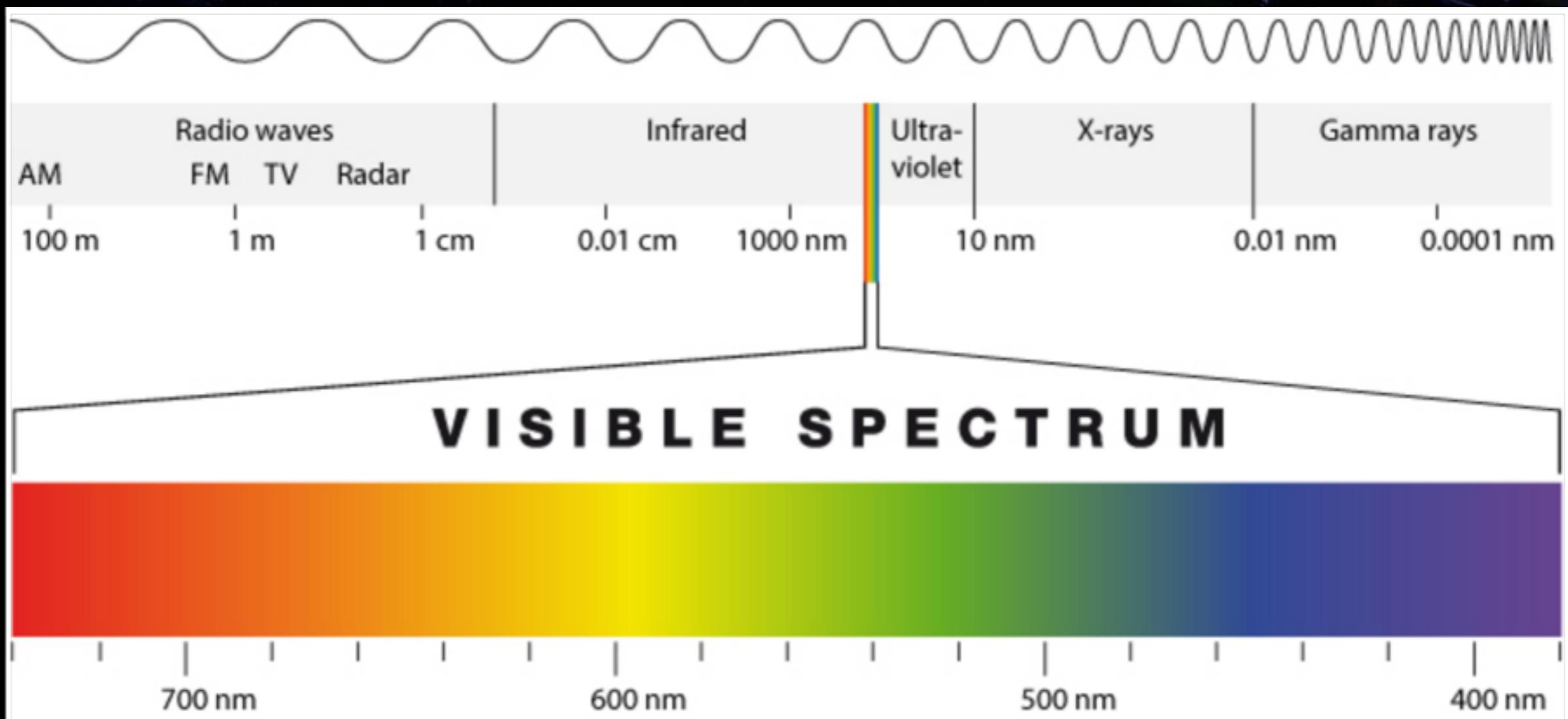


# Observing the Evolution of Chemical Elements

# Light



# Light



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

# Decomposing Light Into Colors

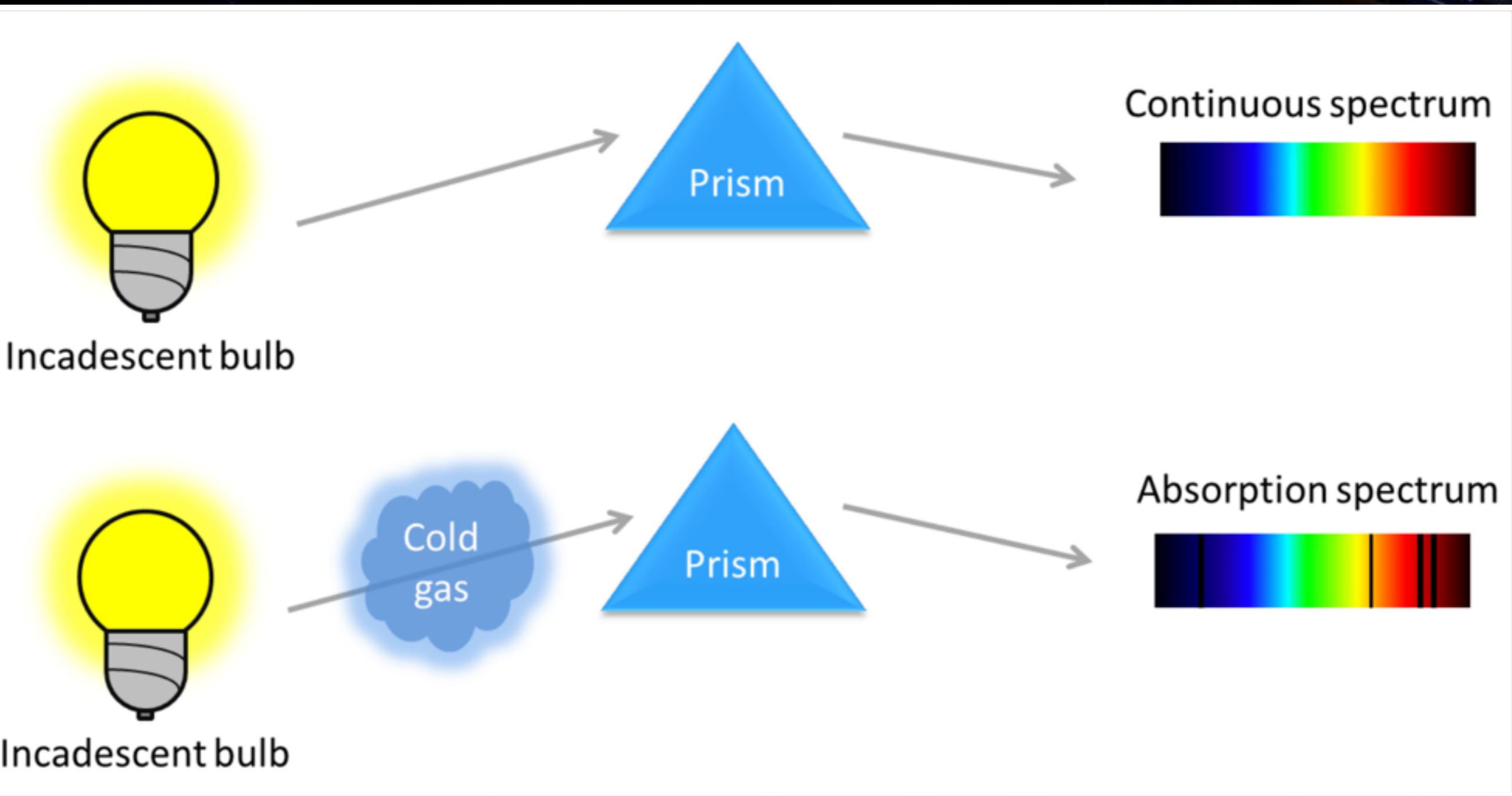


<https://www.quora.com/Which-color-deviates-the-least-when-a-light-passes-through-a-prism-Why>

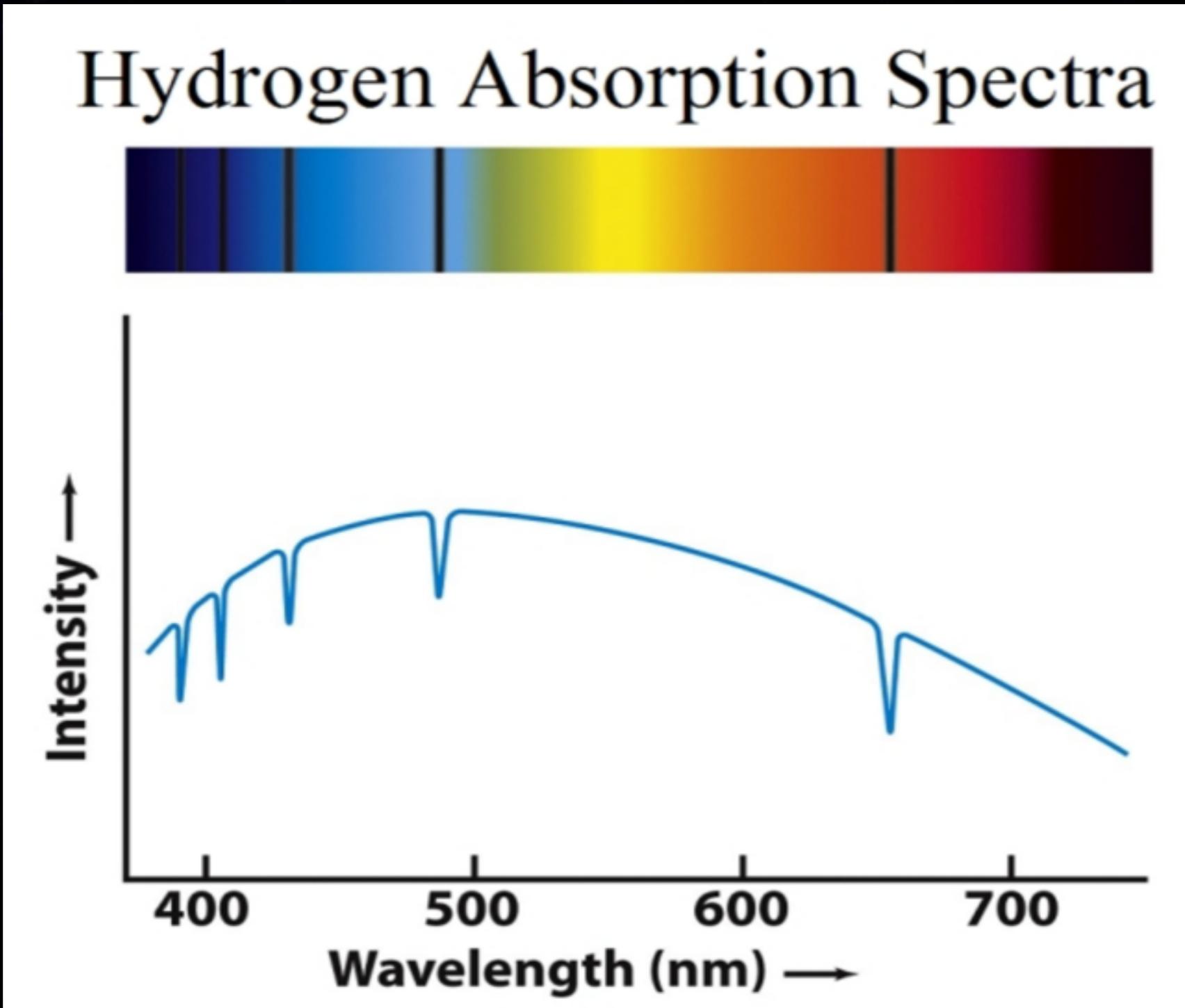
# Spectroscopy

Each element will absorb specific colors.

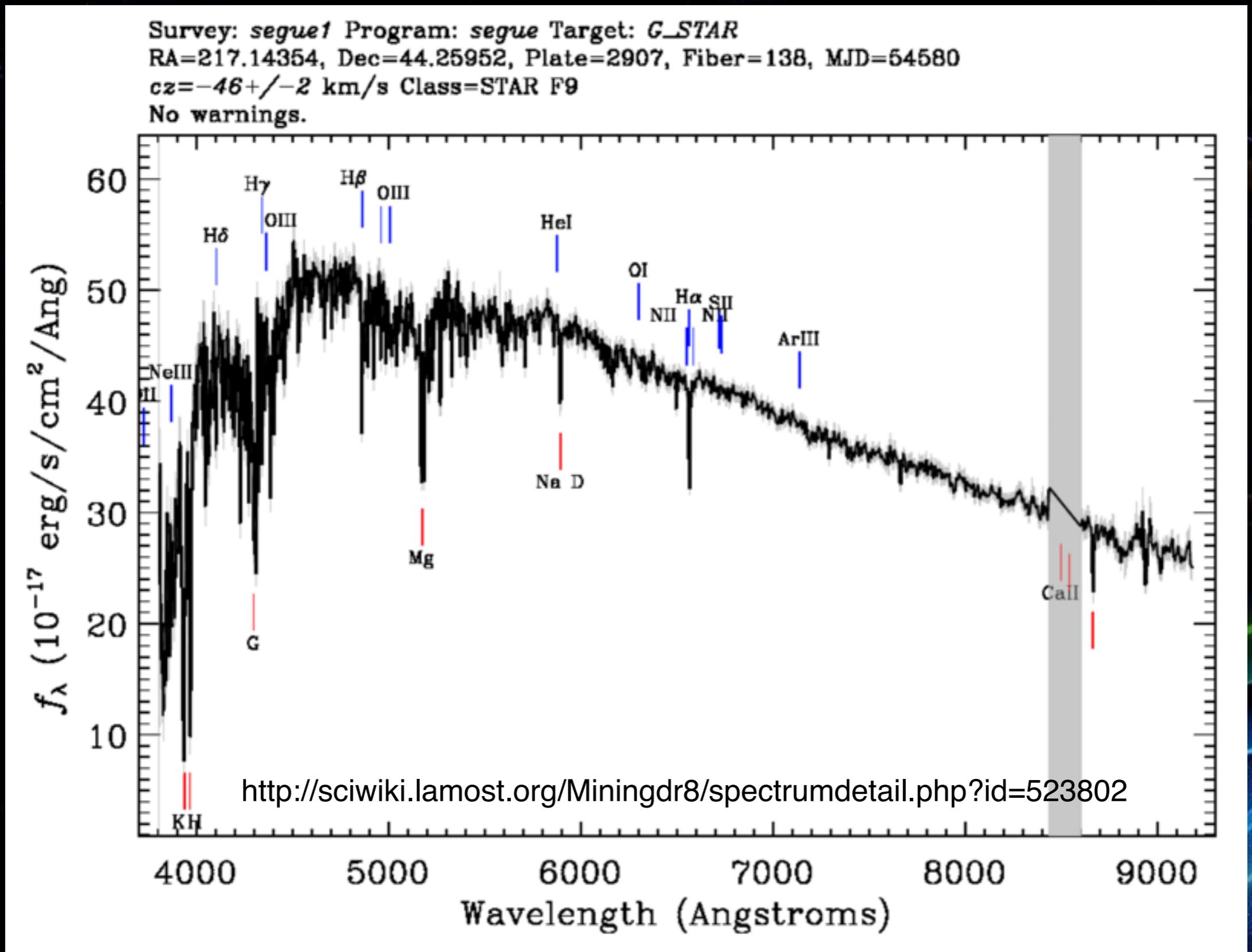
Different elements do not absorb the same colors.



# Spectroscopy



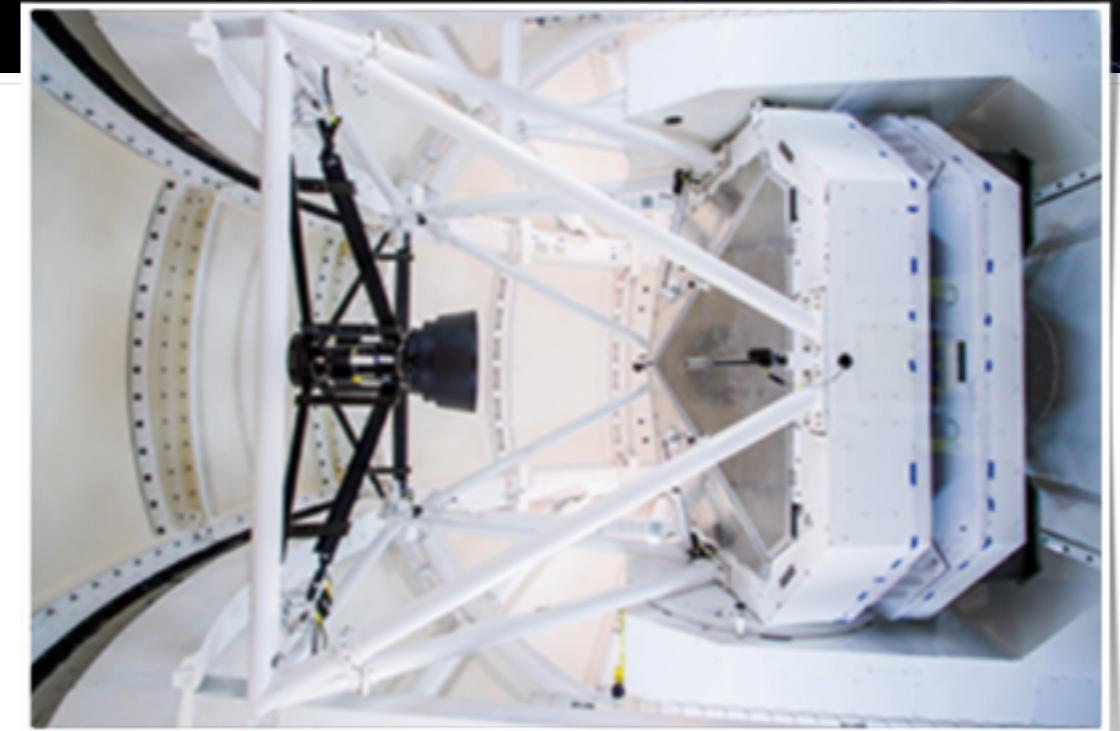
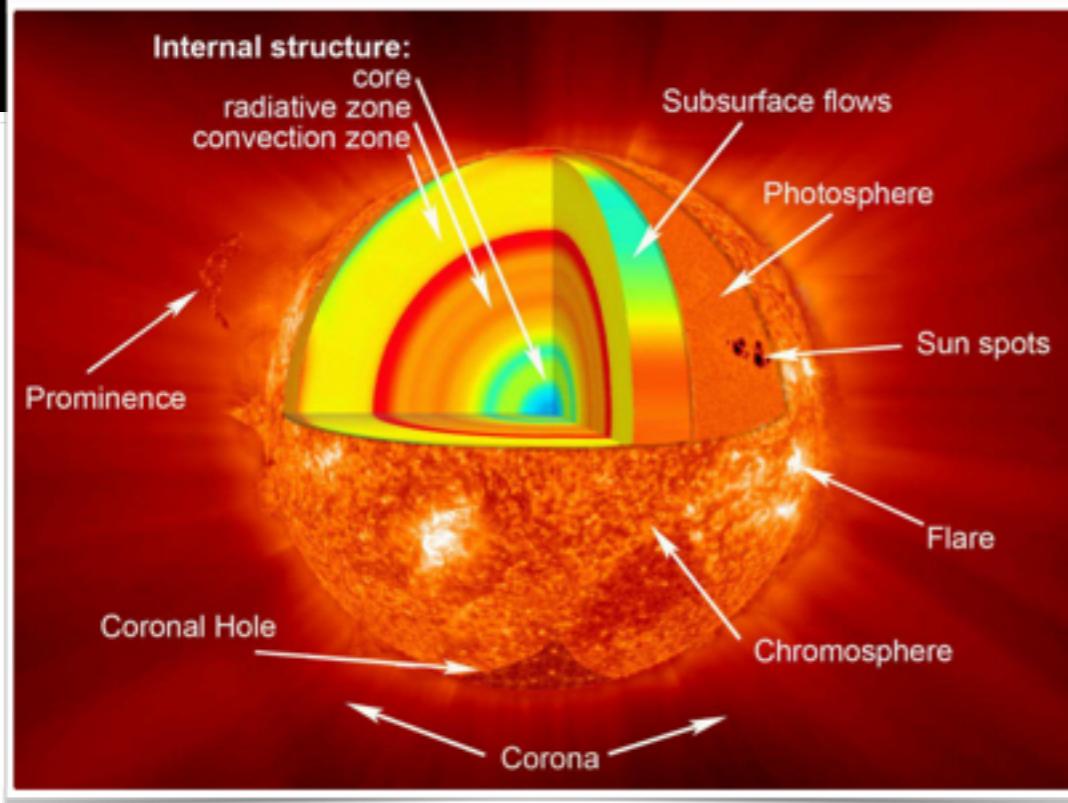
# Spectroscopy



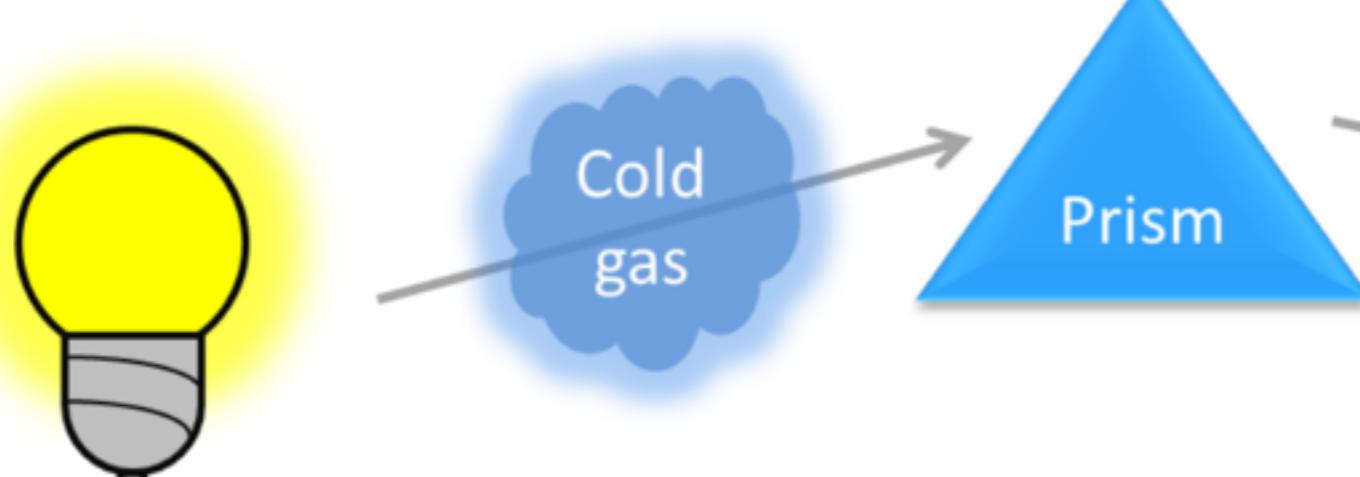
# Spectroscopy

Each element will absorb specific colors.

Different elements do not absorb the same colors.



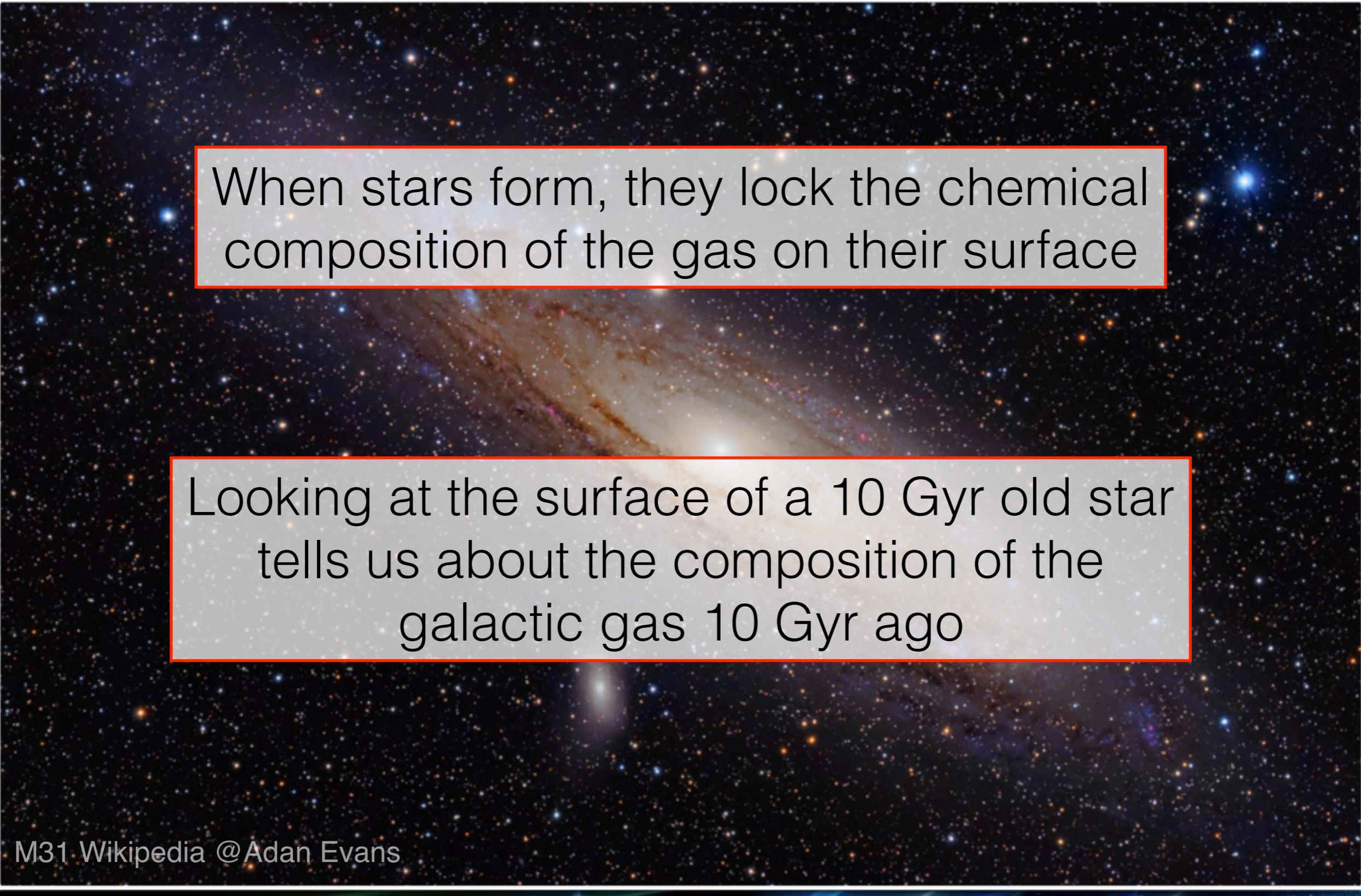
NARIT Thai National Telescope



Incandescent bulb



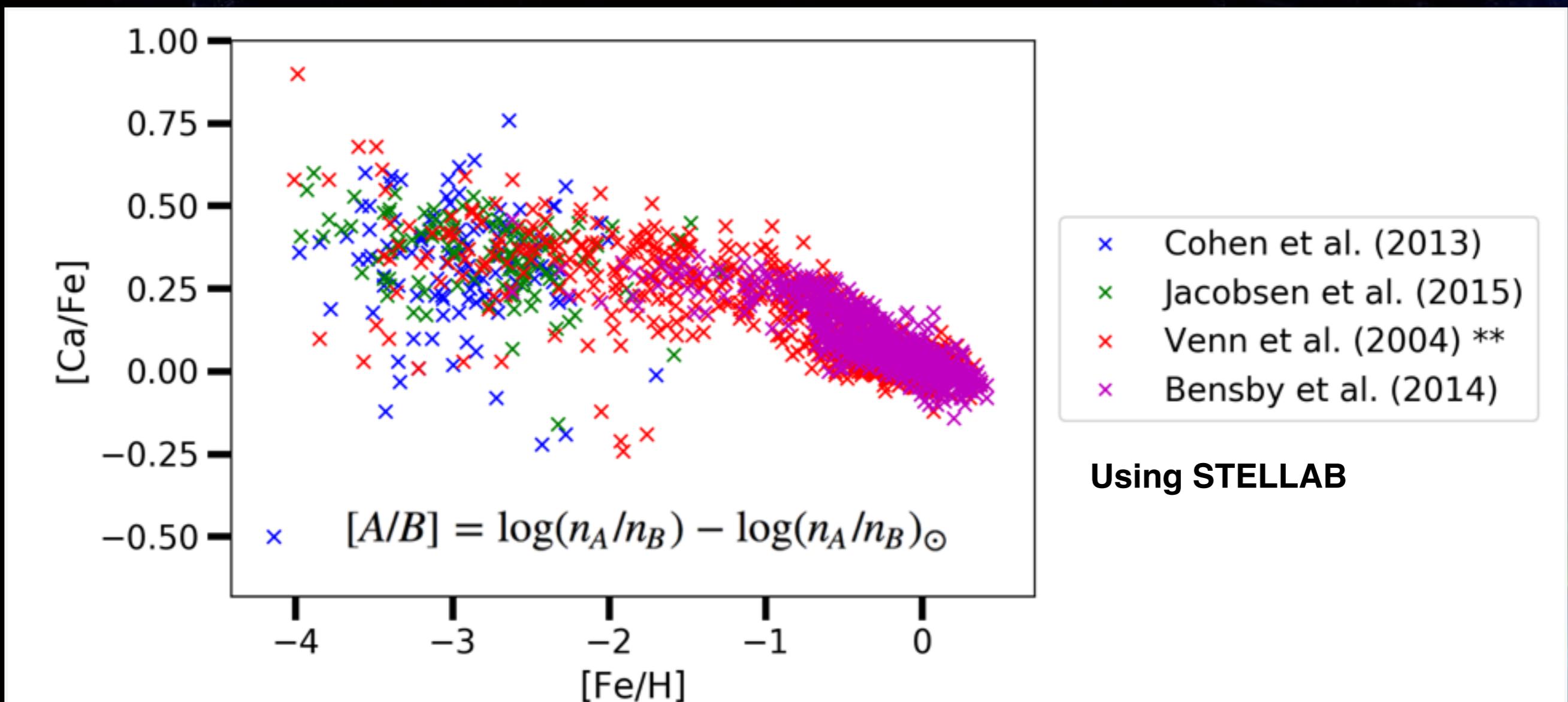
# Observing Chemical Evolution using Spectroscopy



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

# Observing Chemical Evolution using Spectroscopy

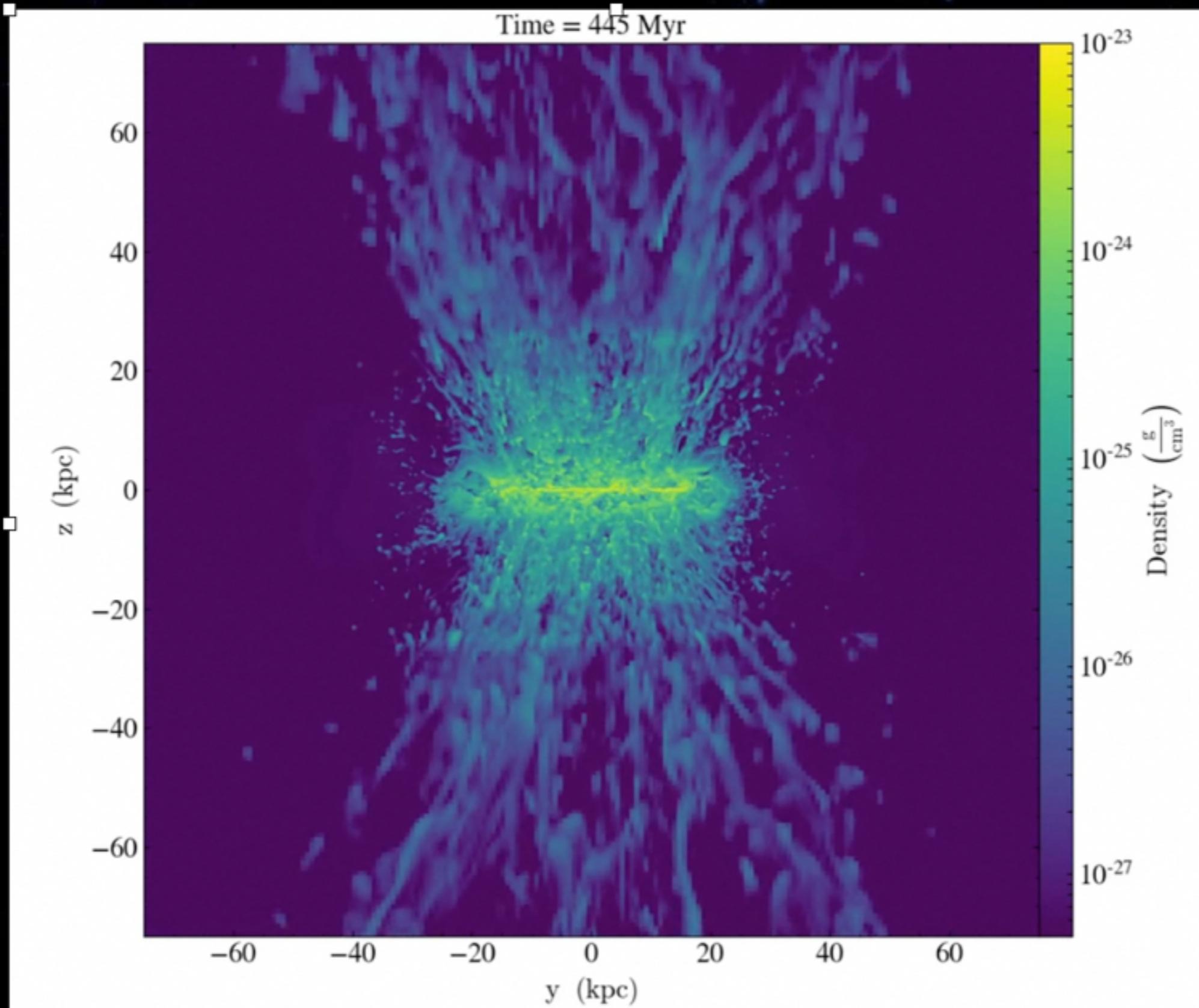


Past

Present

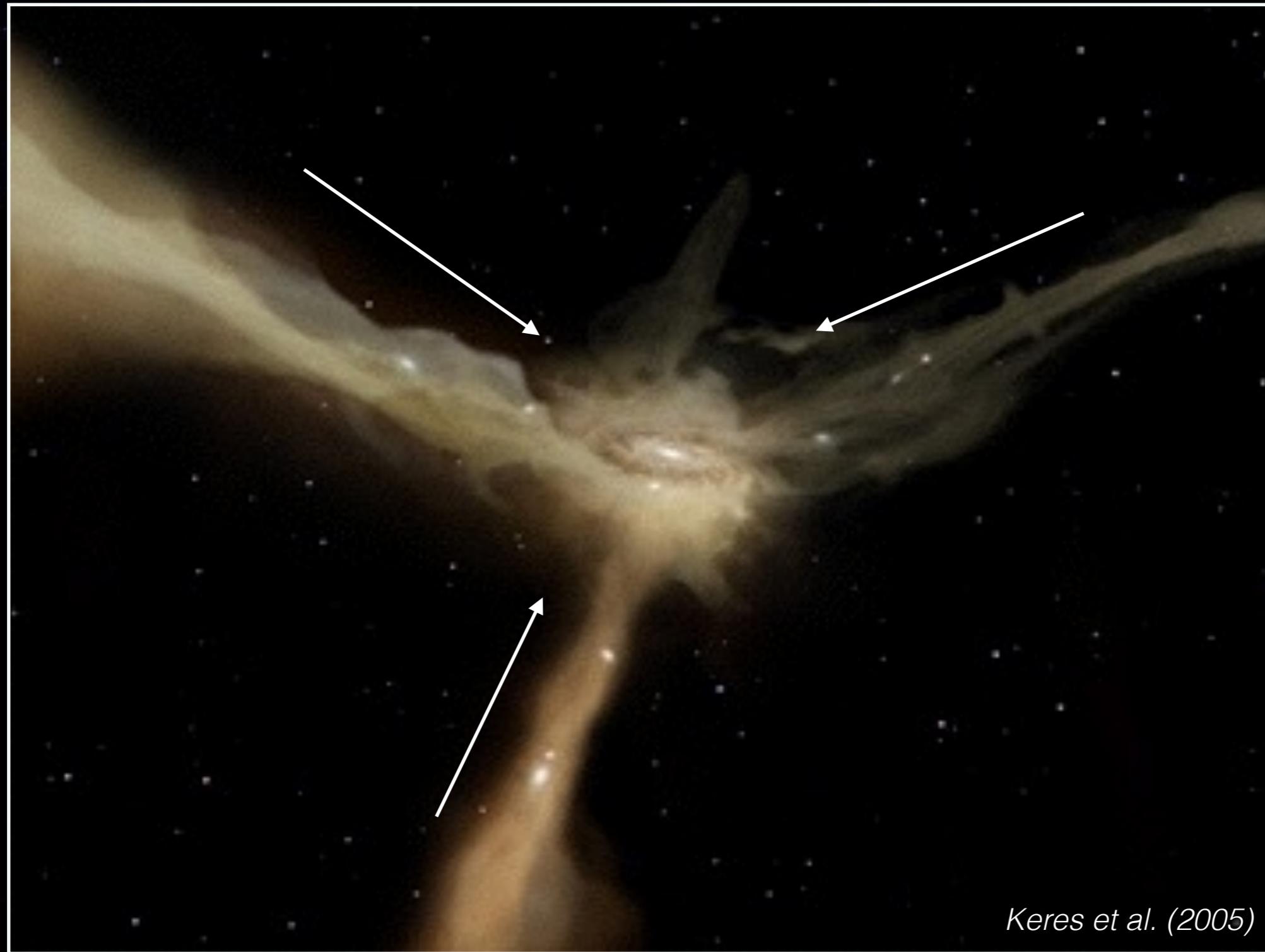
# Galactic Outflows

@Dr. Devin Silvia



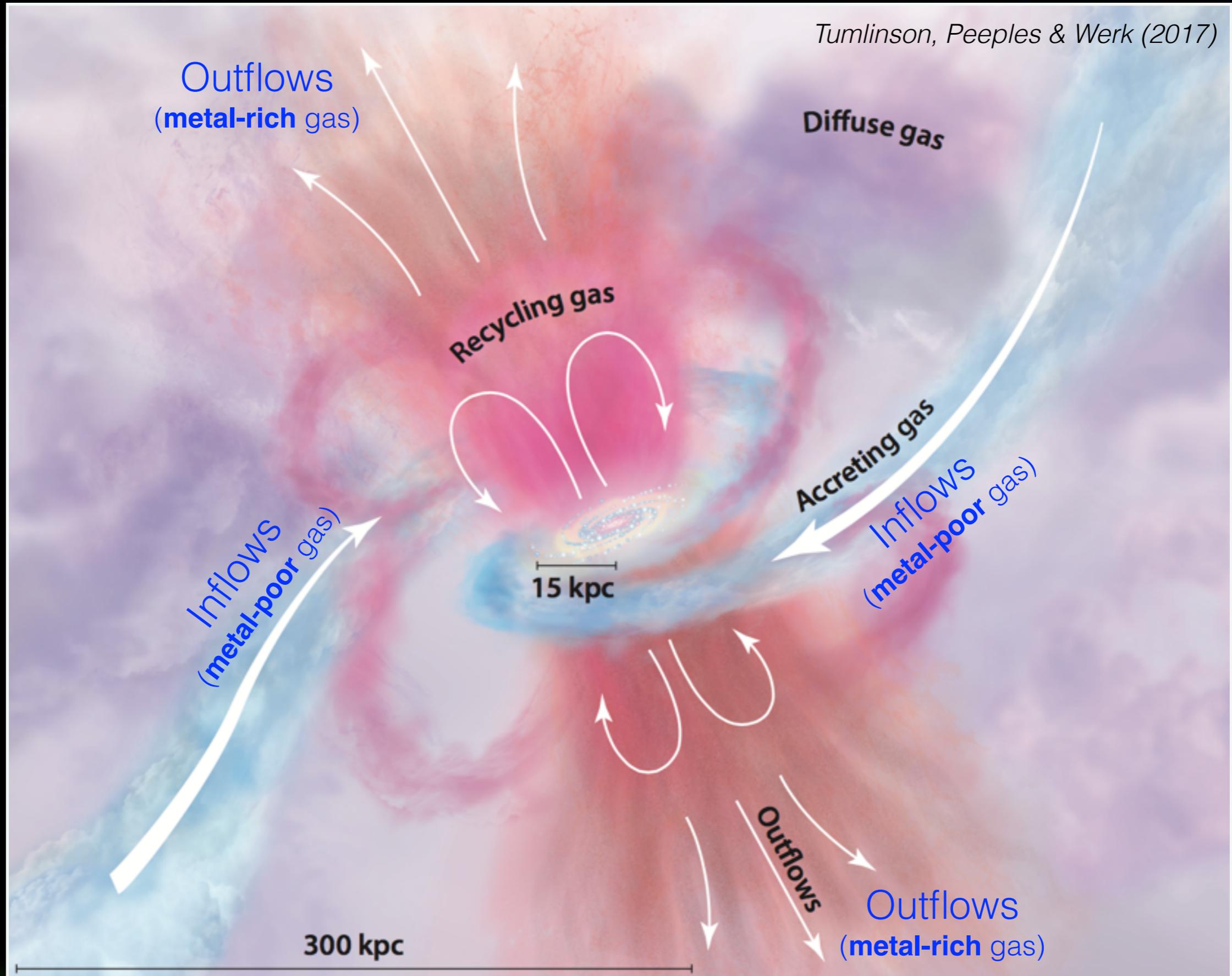
# Galactic Inflows

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Keres et al. (2005)

# Galactic Inflows and Outflows



# Modeling Chemical Evolution

Inflows

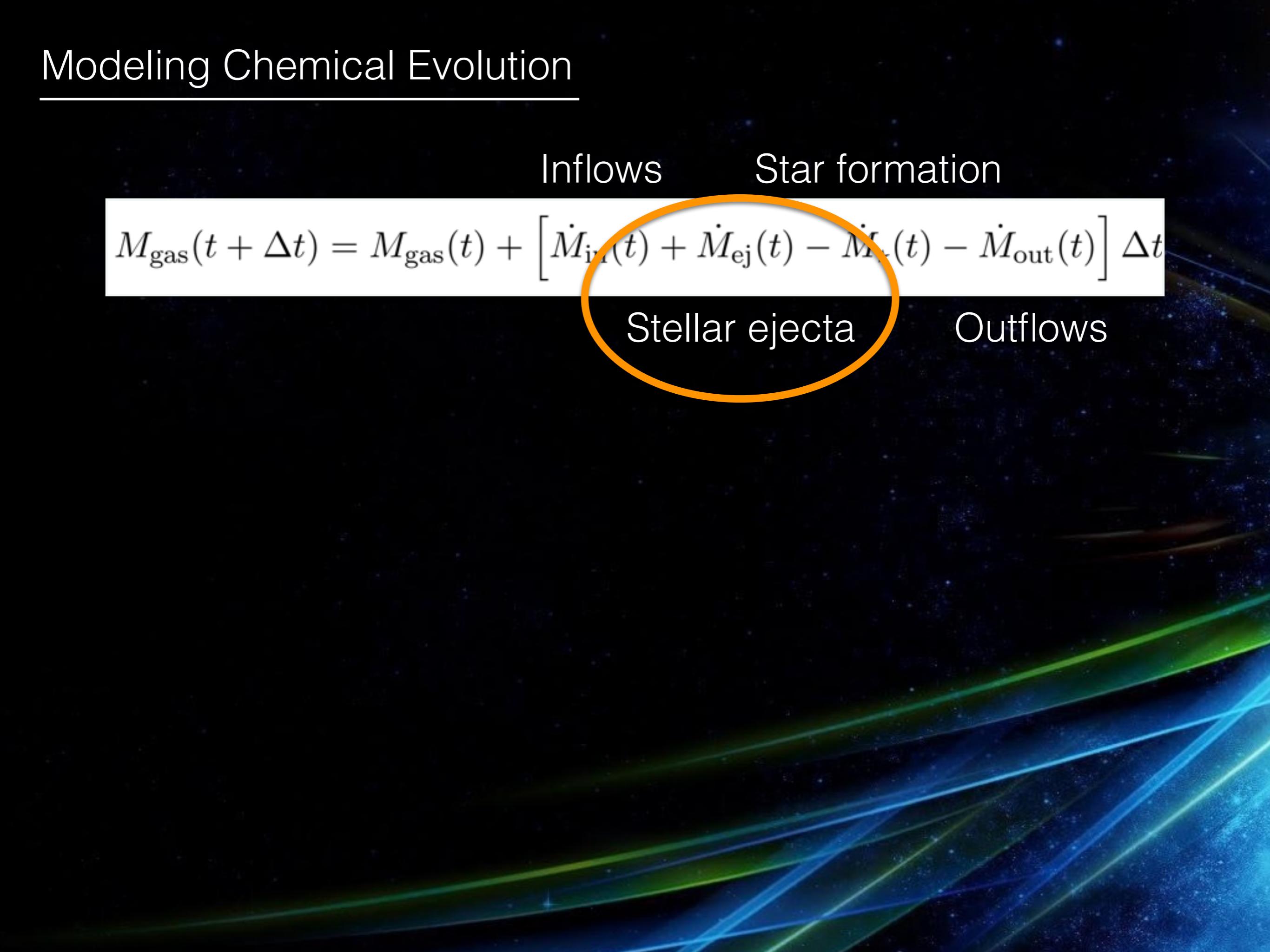
Star formation

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

Stellar ejecta

Outflows

# Modeling Chemical Evolution



Inflows                      Star formation

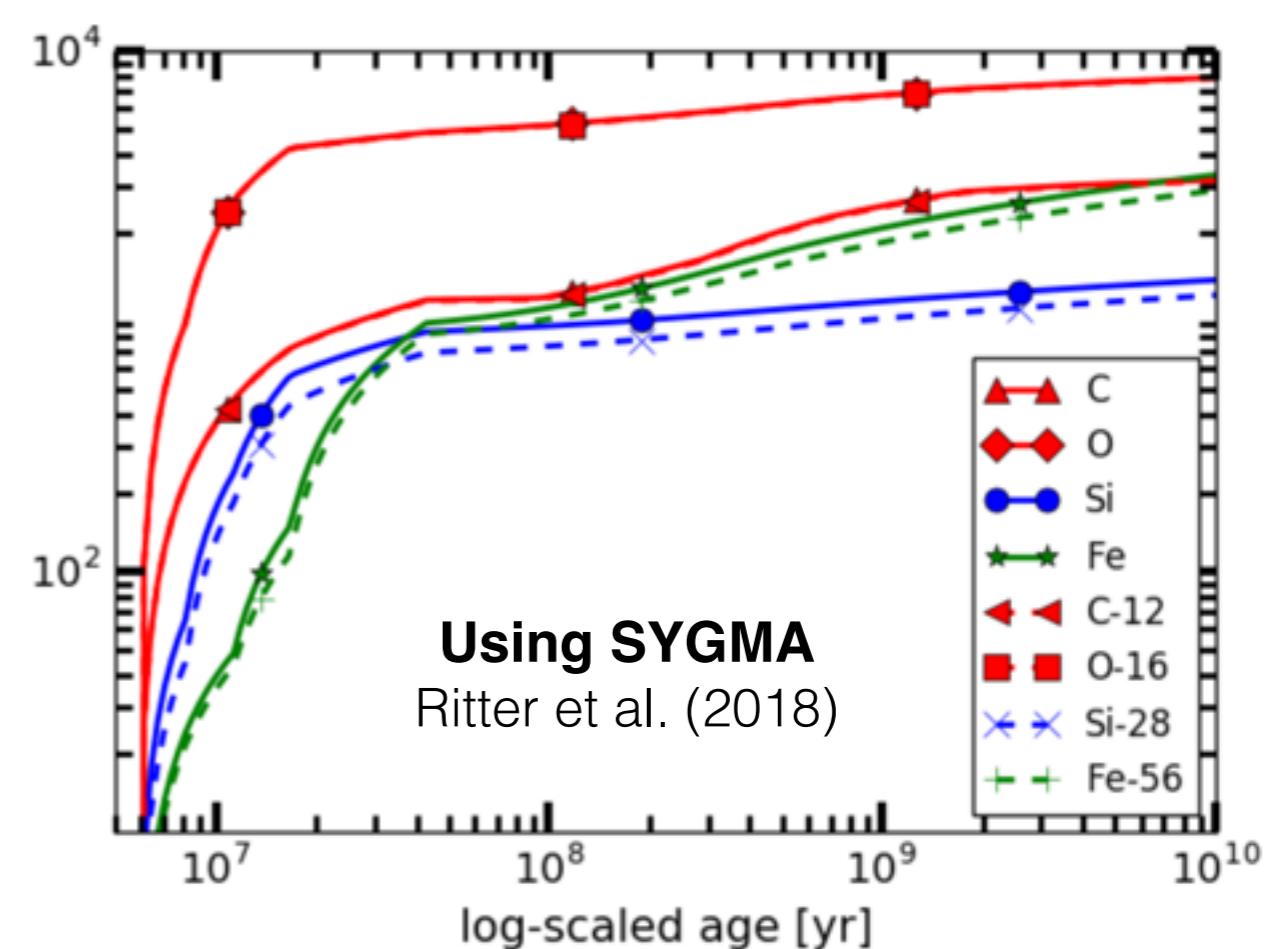
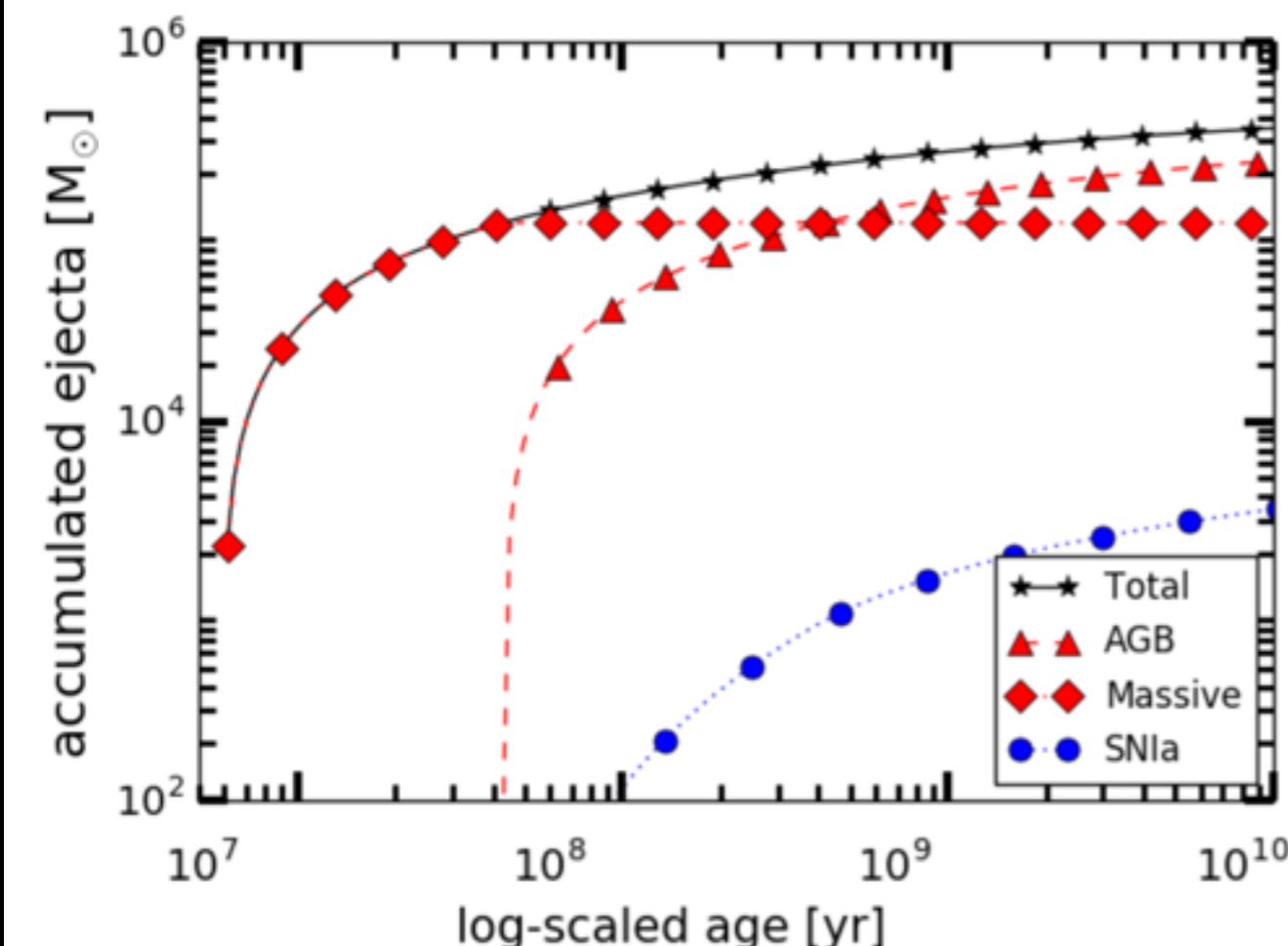
$$M_{\text{gas}}(t + \Delta t) = M_{\text{gas}}(t) + [\dot{M}_{\text{in}}(t) + \dot{M}_{\text{ej}}(t) - \dot{M}_{\text{sf}}(t) - \dot{M}_{\text{out}}(t)] \Delta t$$

Stellar ejecta                      Outflows

A mathematical equation for modeling chemical evolution is shown. The equation is  $M_{\text{gas}}(t + \Delta t) = M_{\text{gas}}(t) + [\dot{M}_{\text{in}}(t) + \dot{M}_{\text{ej}}(t) - \dot{M}_{\text{sf}}(t) - \dot{M}_{\text{out}}(t)] \Delta t$ . The terms  $\dot{M}_{\text{in}}(t)$ ,  $\dot{M}_{\text{ej}}(t)$ , and  $\dot{M}_{\text{out}}(t)$  are circled in orange. The term  $\dot{M}_{\text{ej}}(t)$  is labeled "Stellar ejecta" and the term  $\dot{M}_{\text{out}}(t)$  is labeled "Outflows". The terms  $M_{\text{gas}}(t + \Delta t)$ ,  $M_{\text{gas}}(t)$ ,  $\Delta t$ , and  $\dot{M}_{\text{sf}}(t)$  are not circled.

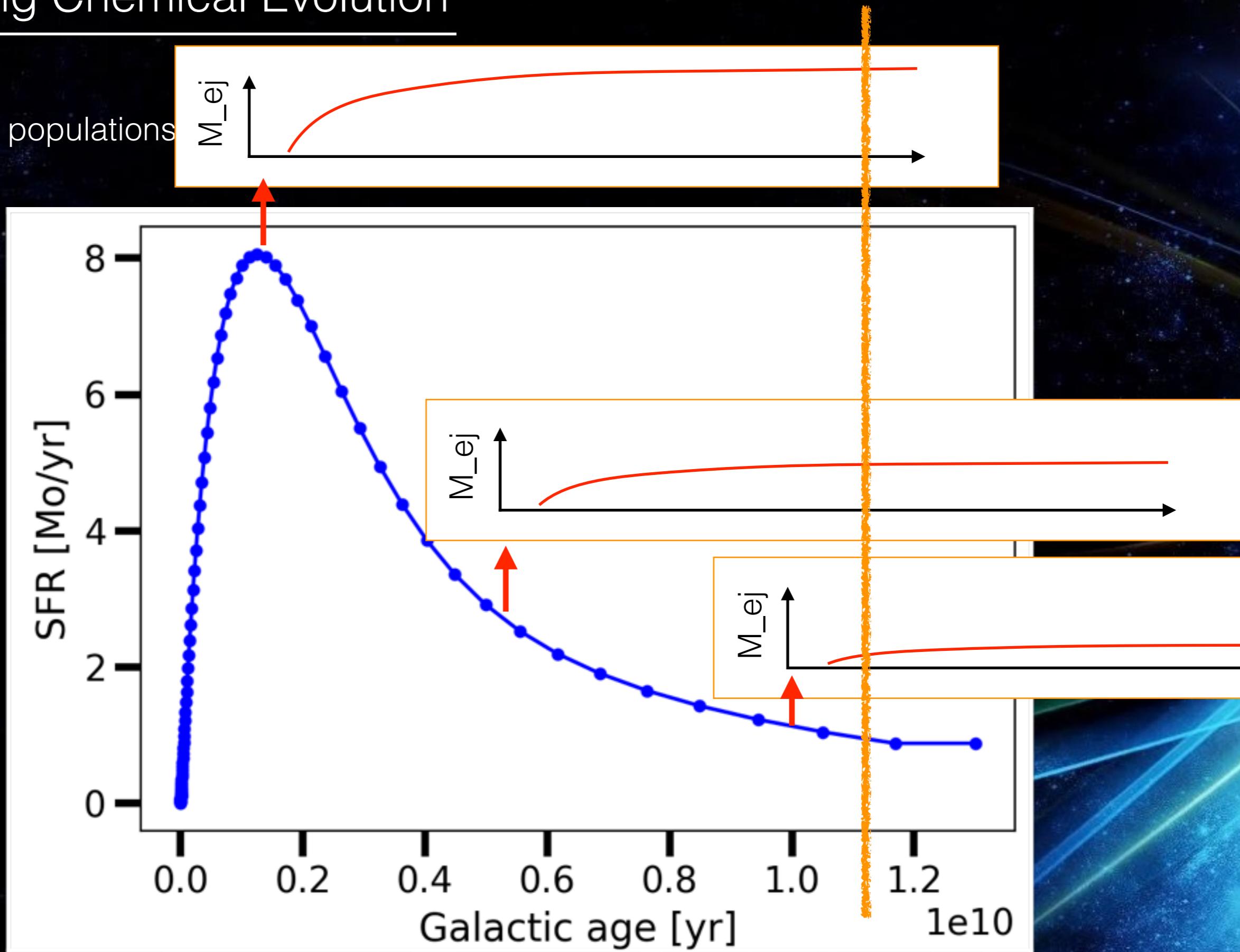
# Modeling Chemical Evolution

One stellar population



# Modeling Chemical Evolution

Many stellar populations



# Modeling Chemical Evolution

The diagram illustrates the mass balance equation for gas evolution and a detailed equation for stellar ejecta.

At the top, two boxes define terms:

- "Inflows" and "Star formation" are shown above the first equation.
- "Outflows" is shown above the second equation.

The first equation is:

$$M_{\text{gas}}(t + \Delta t) = M_{\text{gas}}(t) + [\dot{M}_{\text{in}}(t) + \dot{M}_{\text{ej}}(t) - \dot{M}_*(t) - \dot{M}_{\text{out}}(t)] \Delta t$$

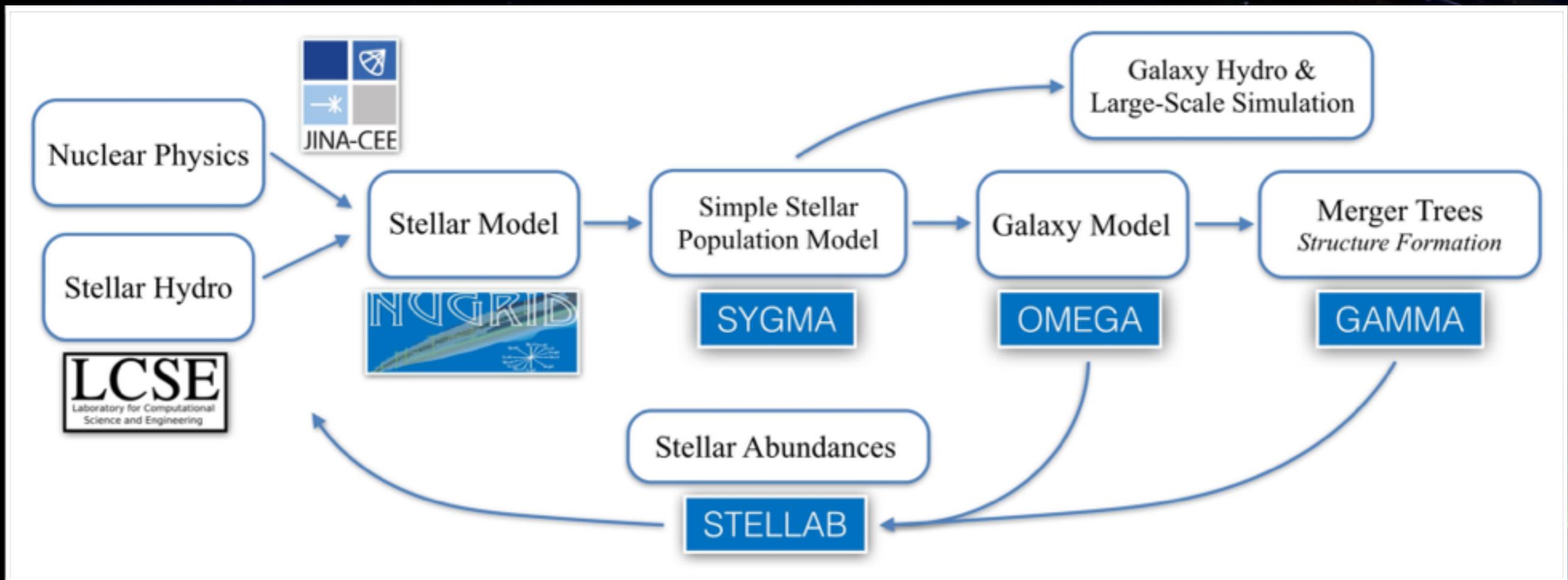
The term  $\dot{M}_{\text{ej}}(t)$  is circled in orange.

An orange arrow points from the word "Stellar ejecta" to the term  $\dot{M}_{\text{ej}}(t)$  in the second equation.

The second equation is:

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

# Modeling Chemical Evolution



# Modeling Chemical Evolution

