

# THE SKELETON OF OUR UNIVERSE

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# THE UNIVERSE IS A TIME MACHINE

**Light takes time to travel**

so we see things as they were  
in the past...

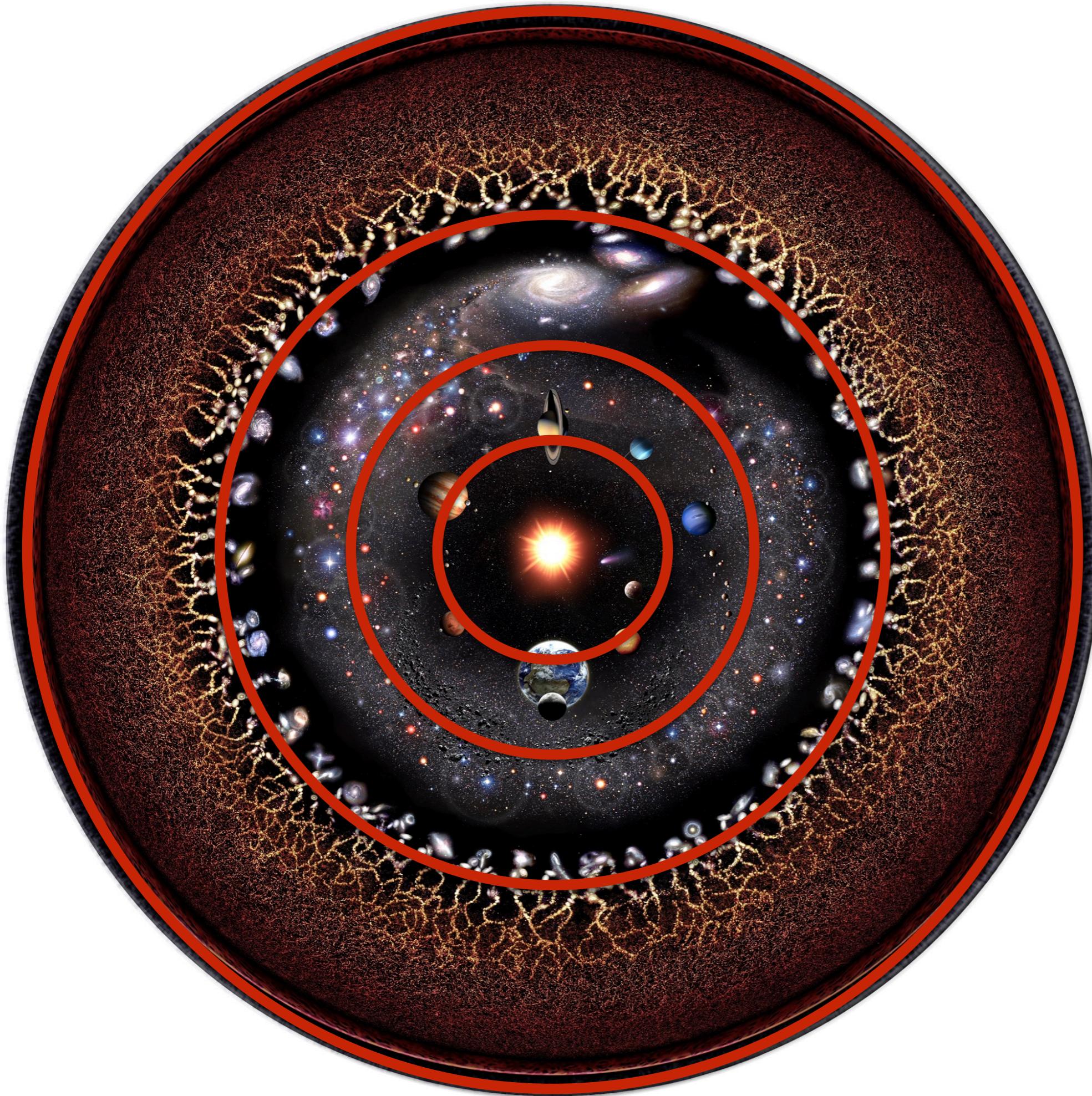
1 (light)-second = 300,000 km  
1 (light)-year = 10 trillion km

# GAIN PERSPECTIVE

Planet Earth

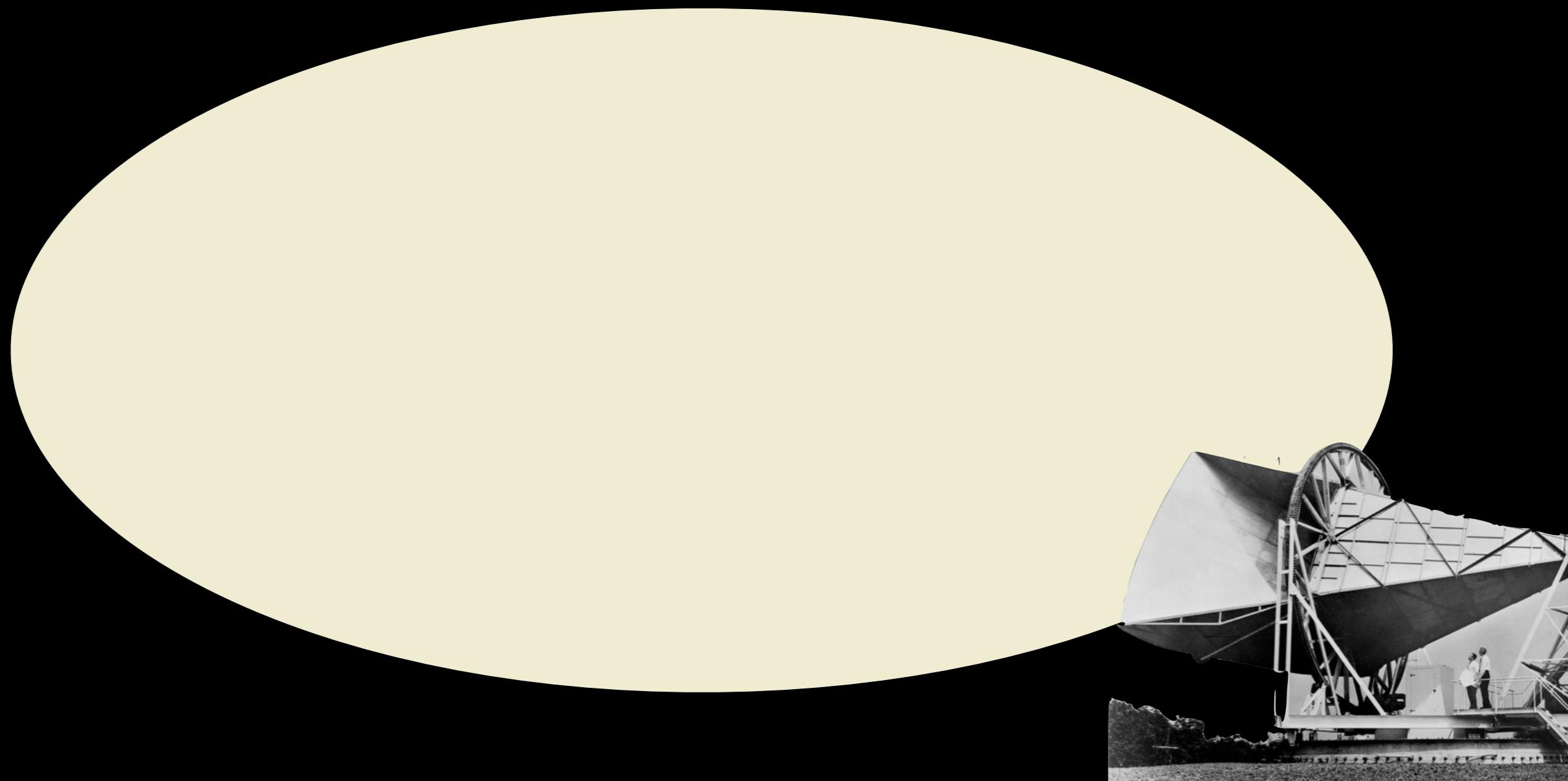


← →  
10 Thousand Kilometers



Created by:  
Pablo Carlos Budassi

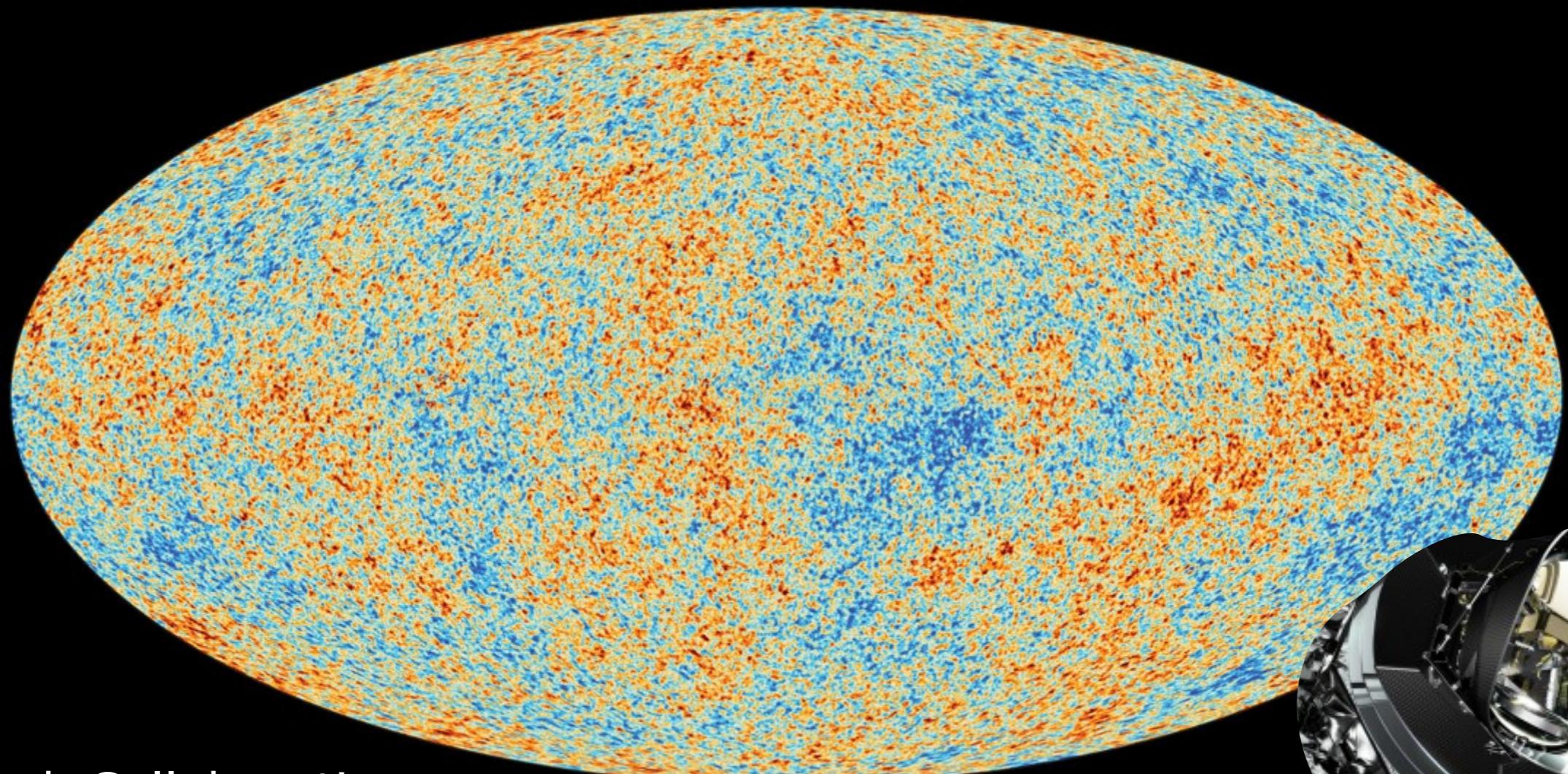
# BABY PICTURE



# **GHOST OF THE EARLY UNIVERSE**

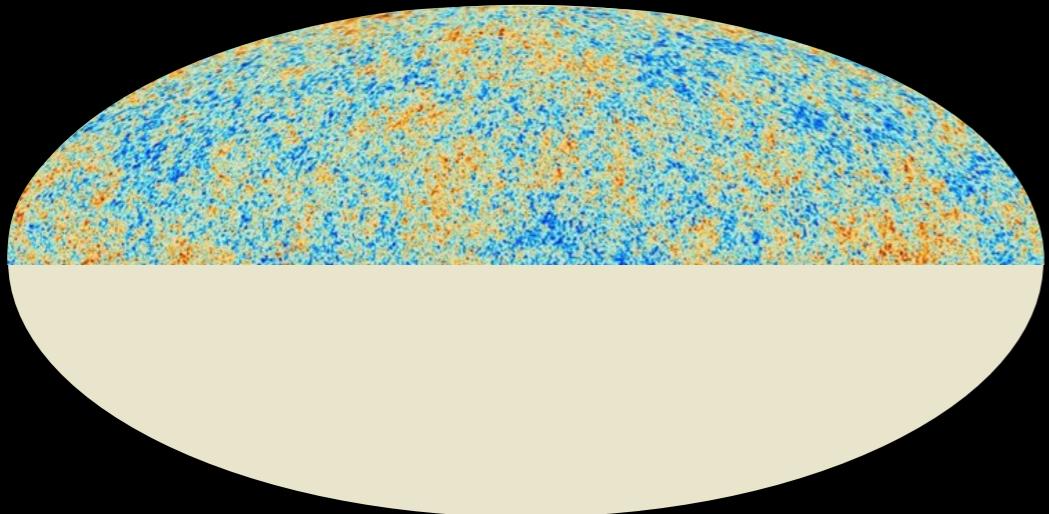
**light stretched by expansion**

**universe cooled by expansion**



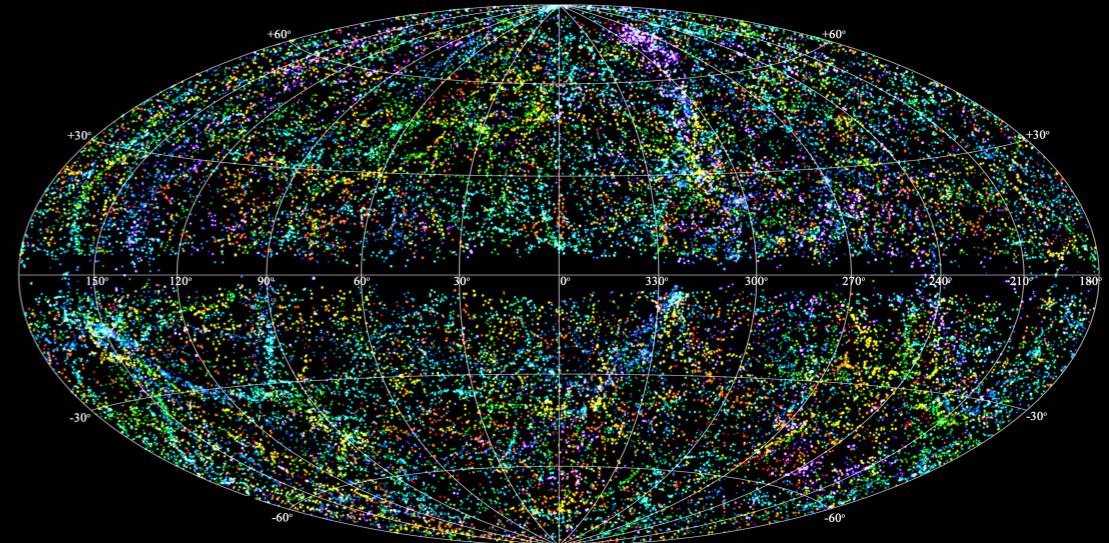
Planck Collaboration

# COMPARING THEN & NOW



tiny density differences

~0.00001x mean density

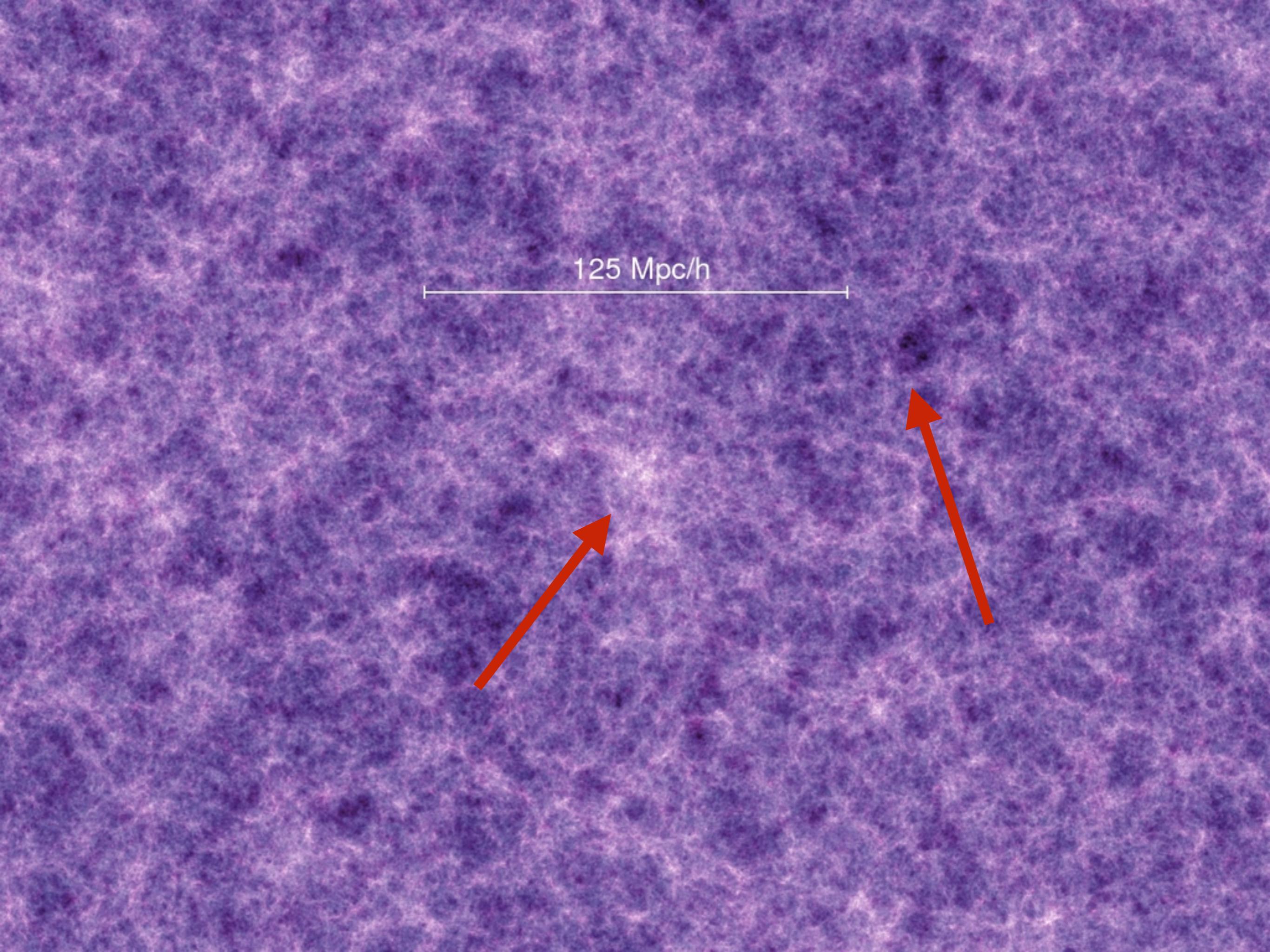


large density differences

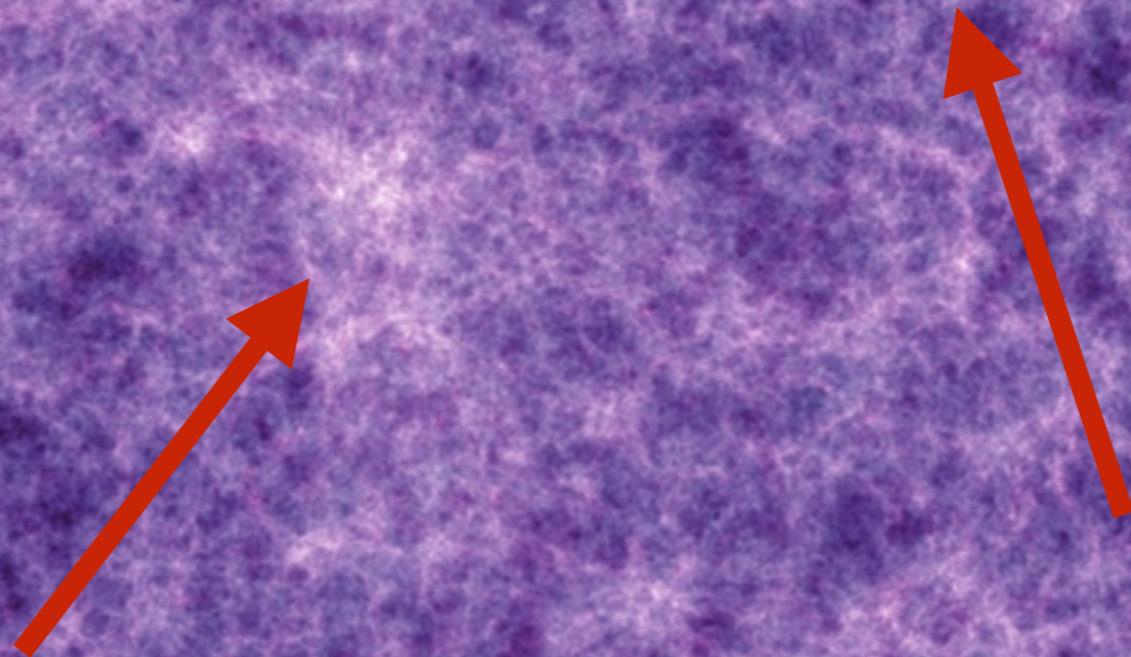
~100x mean density

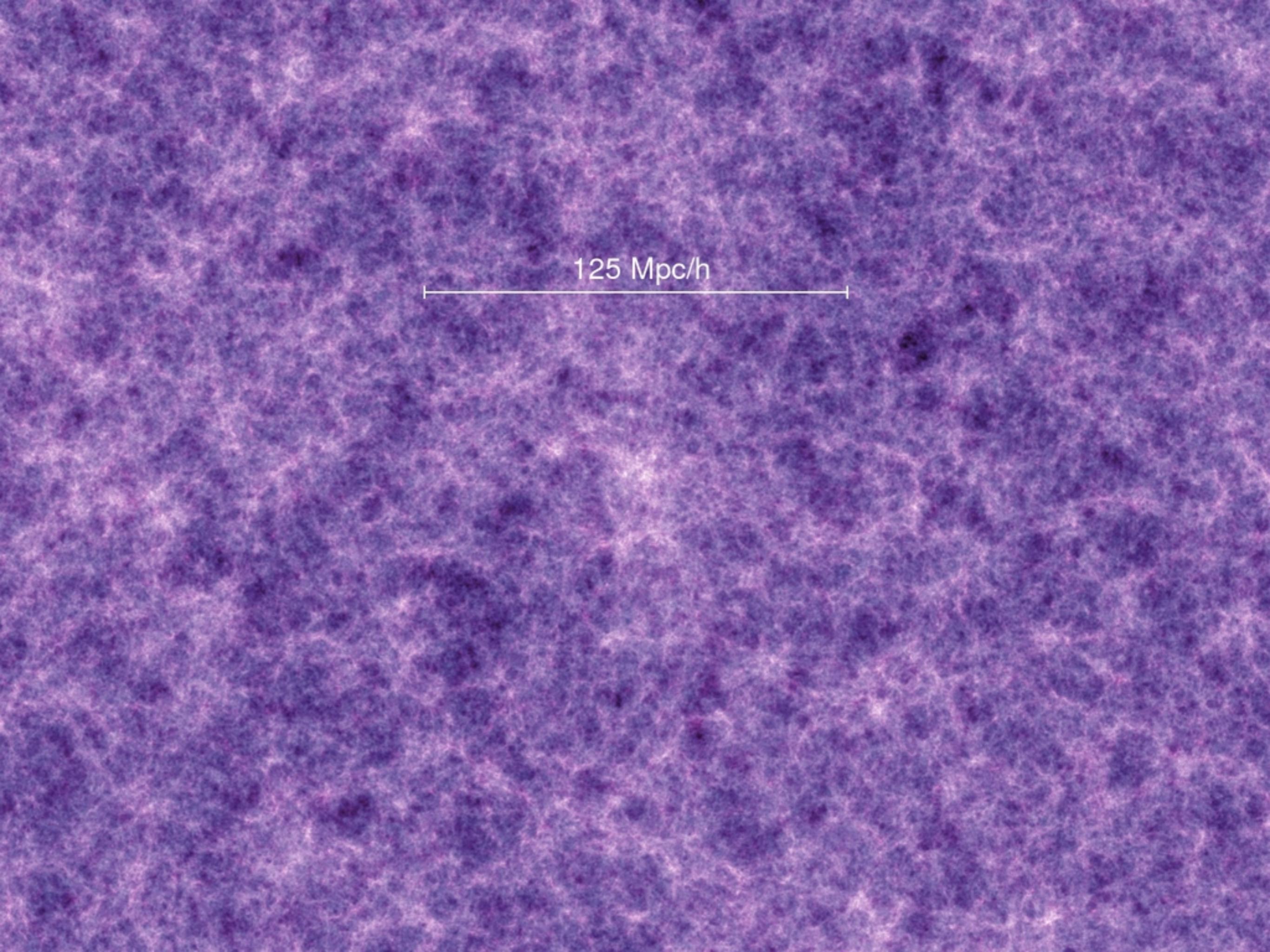


density differences grow by factor of 10 billion!

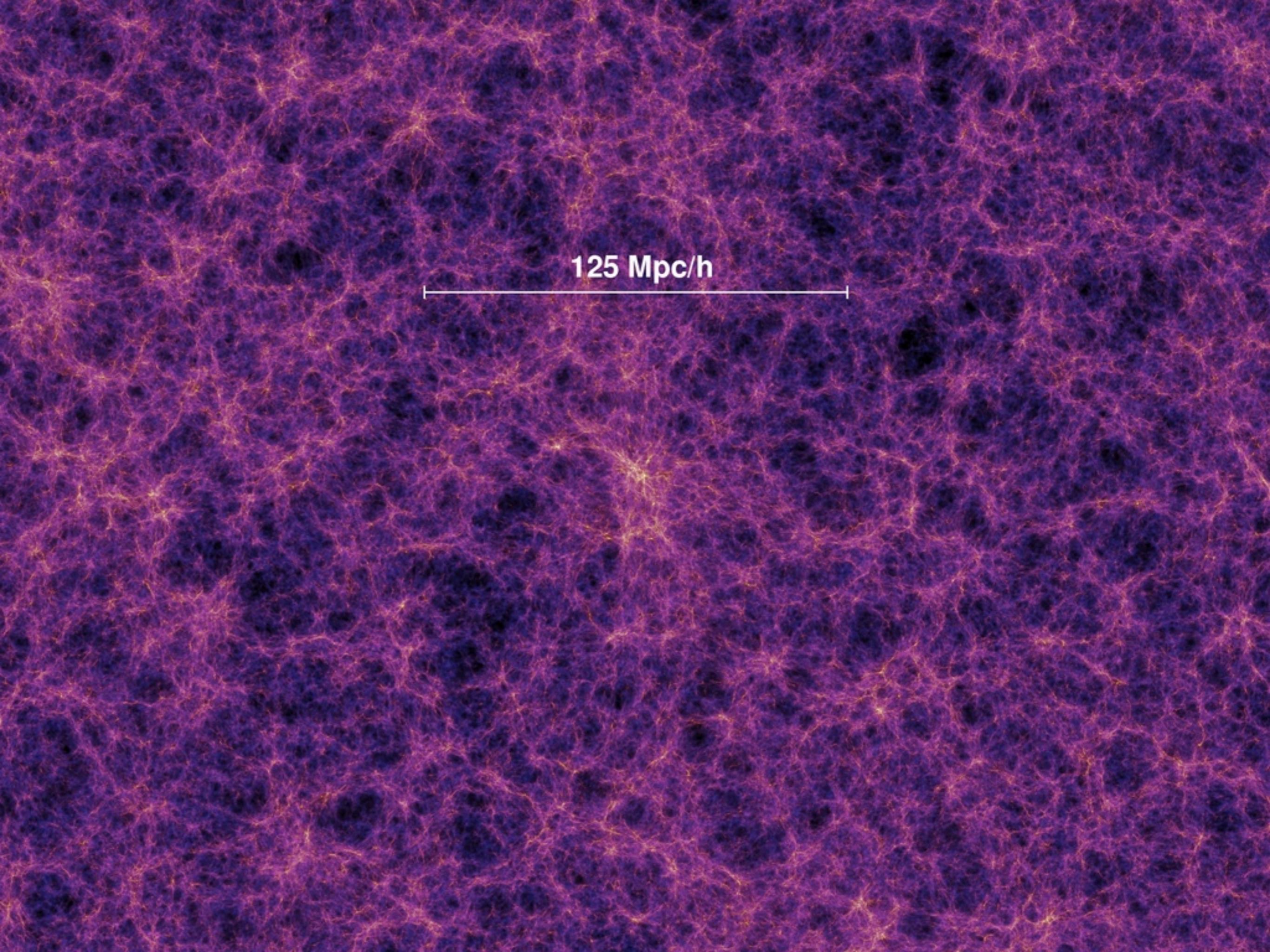


125 Mpc/h

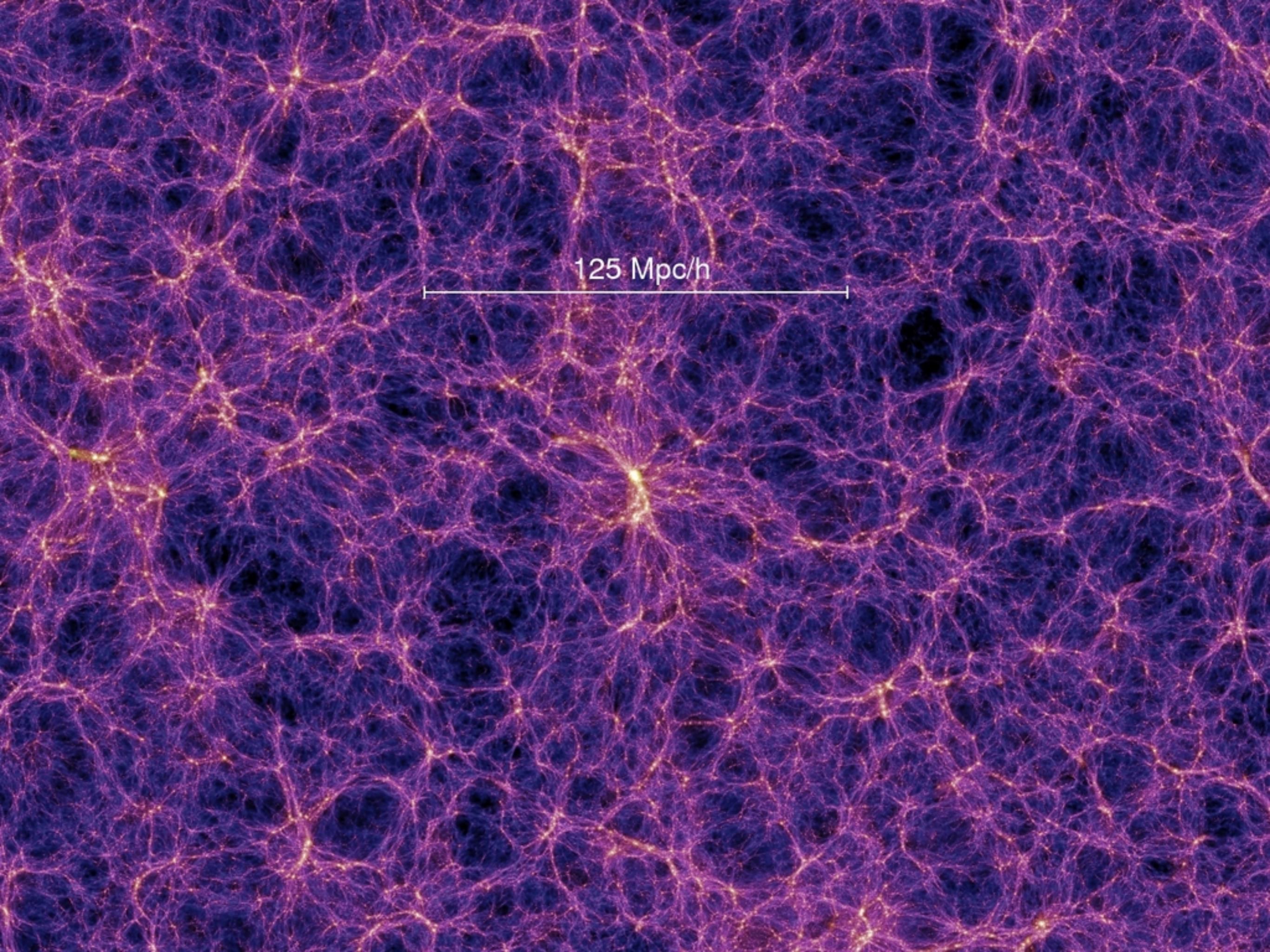




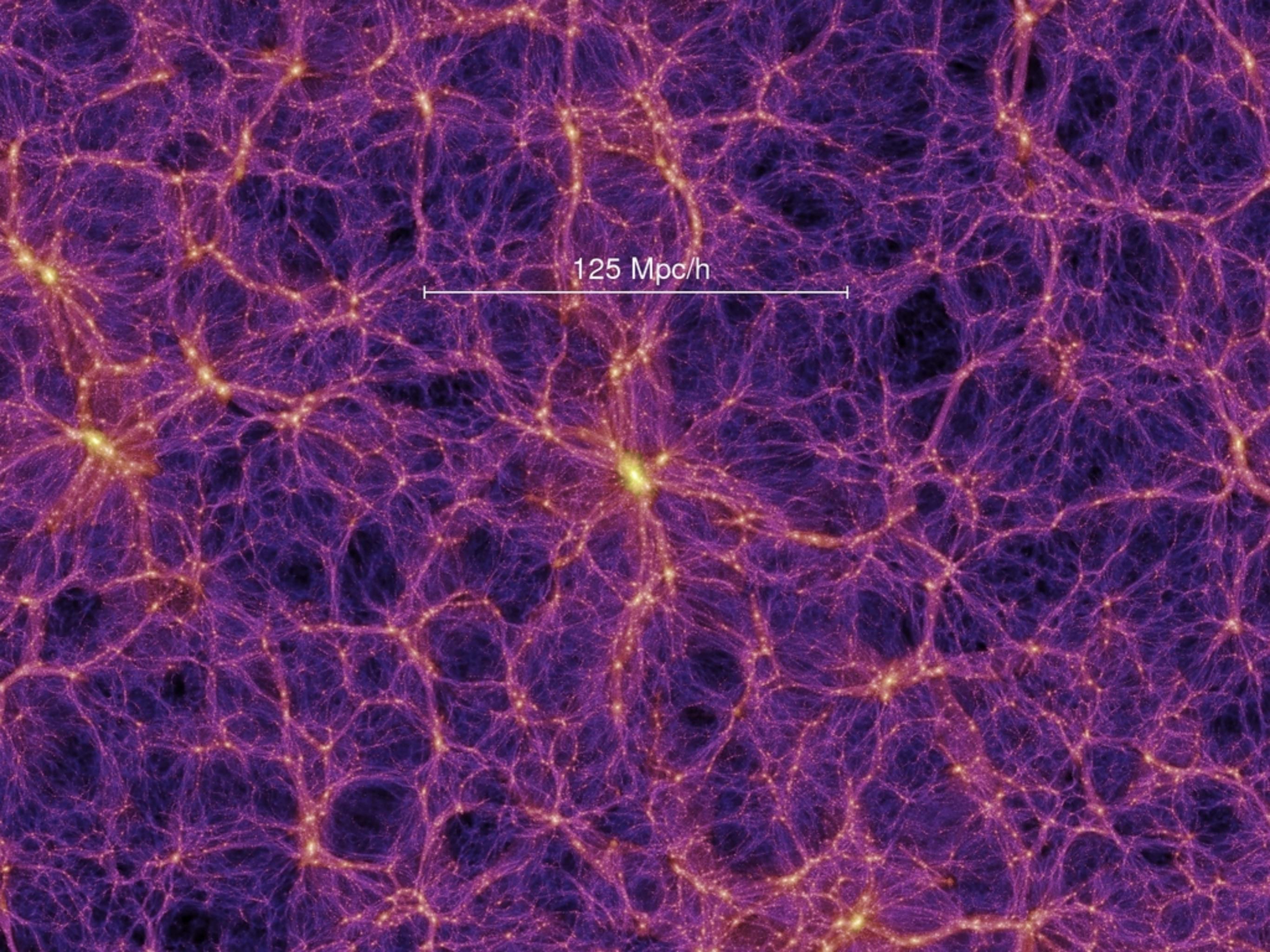
125 Mpc/h



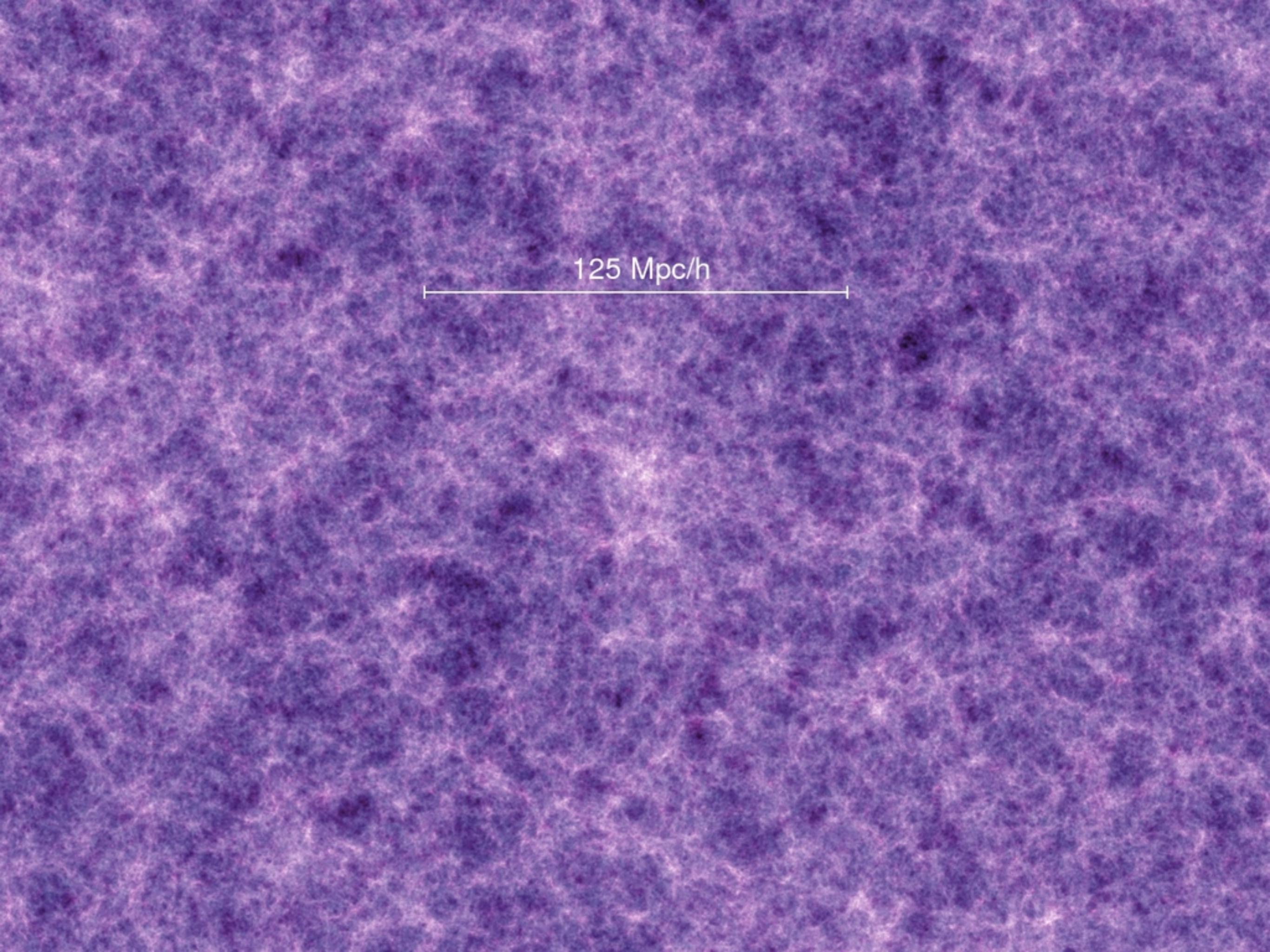
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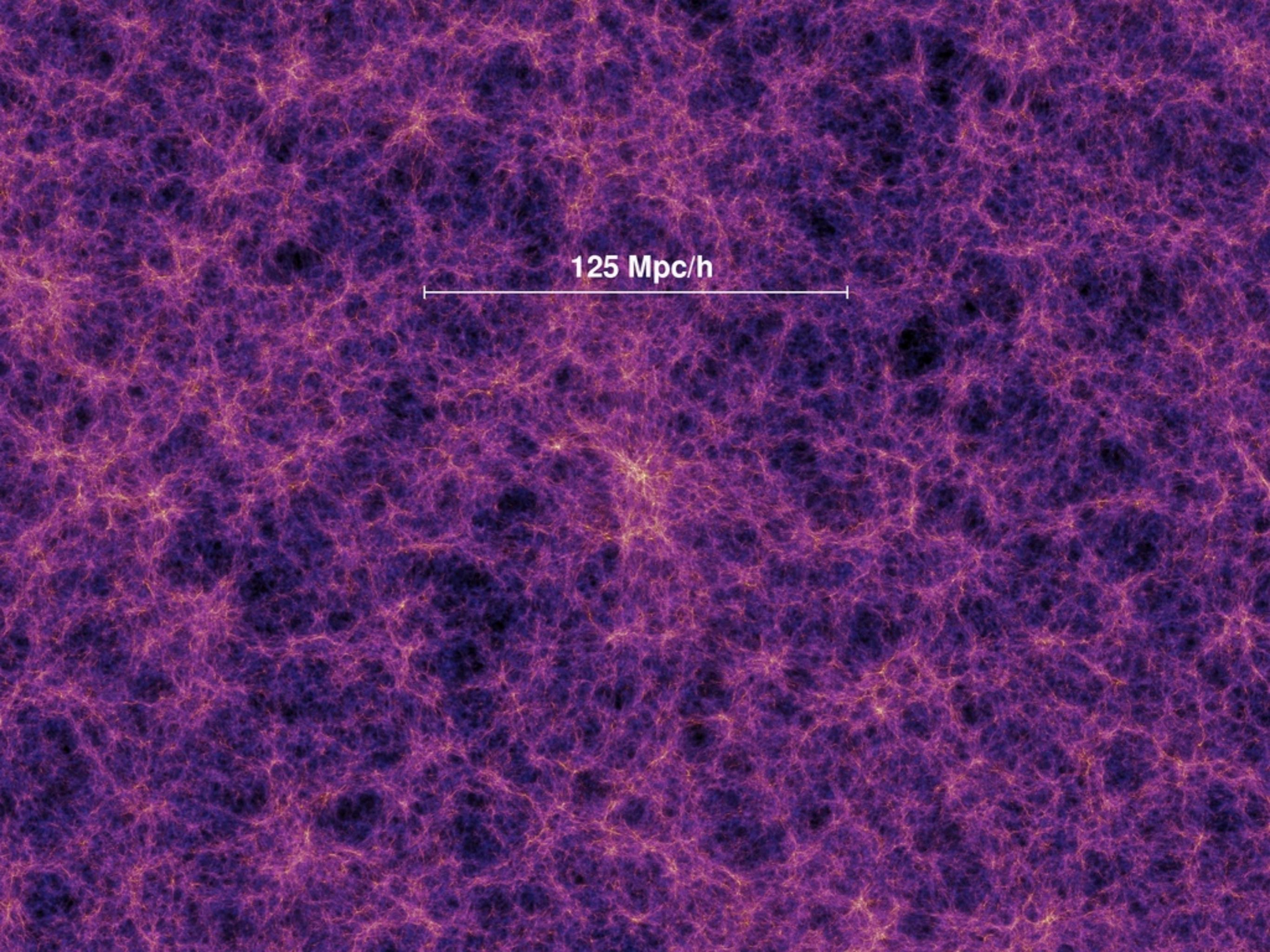
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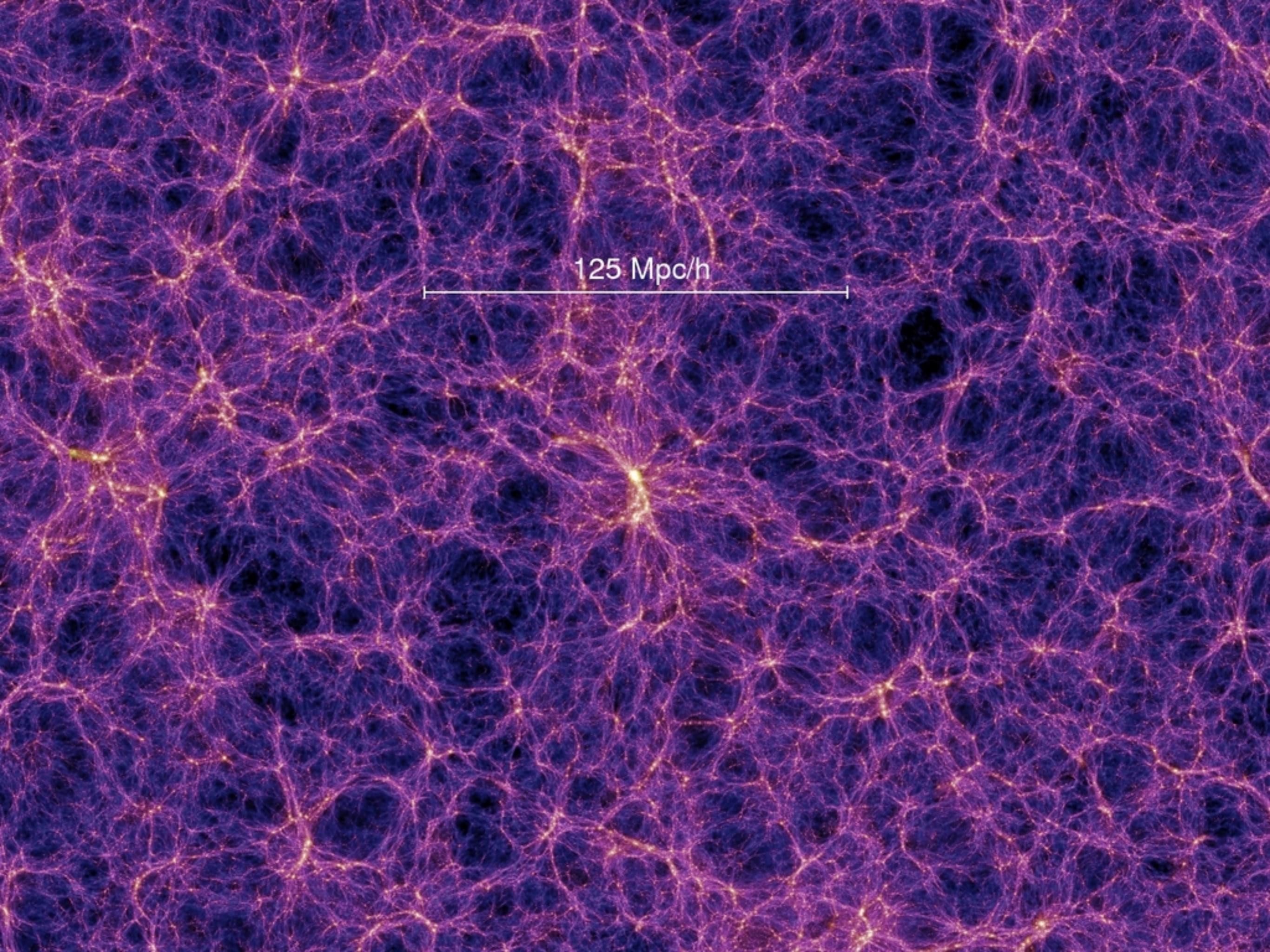
125 Mpc/h



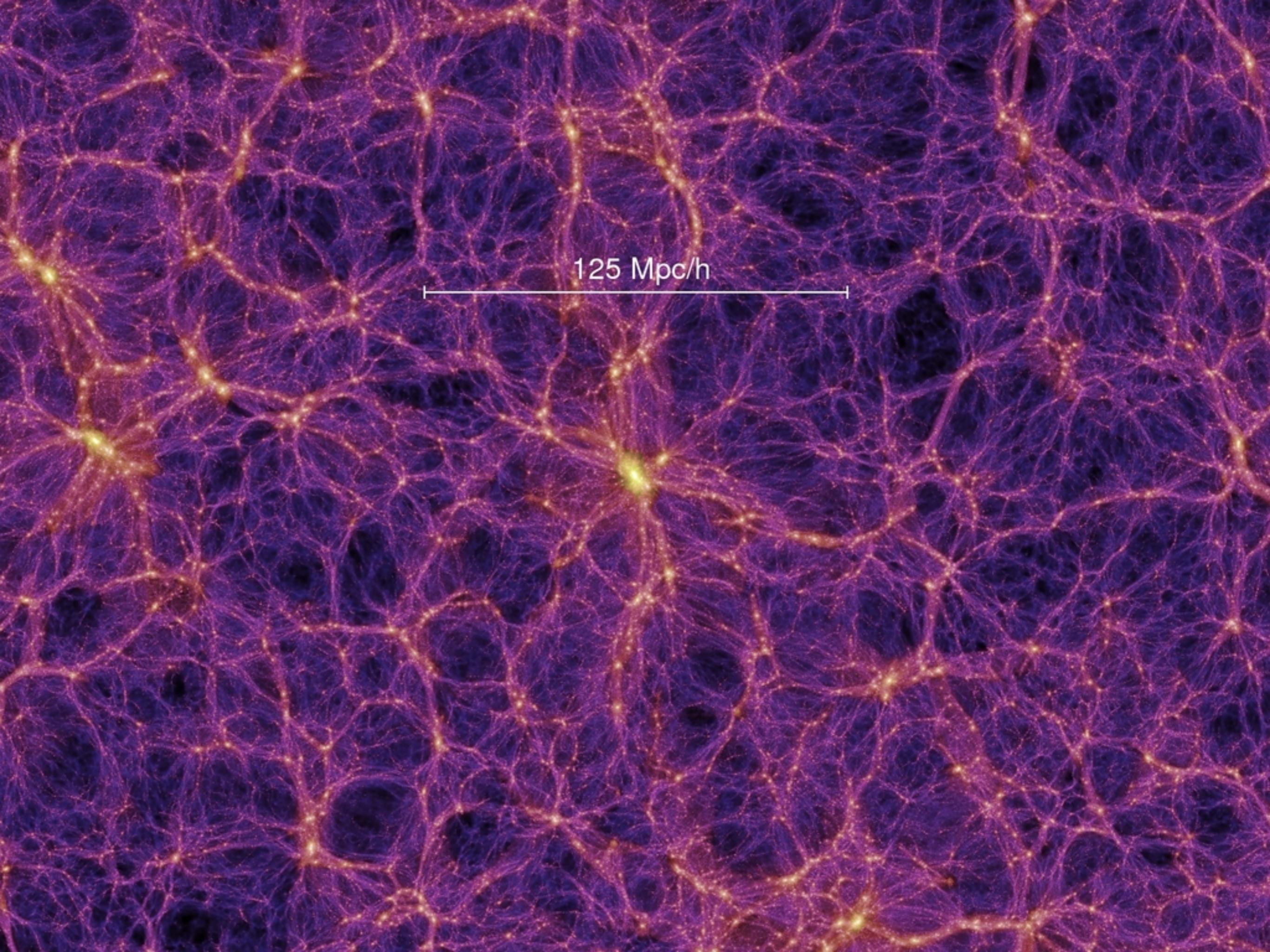
125 Mpc/h



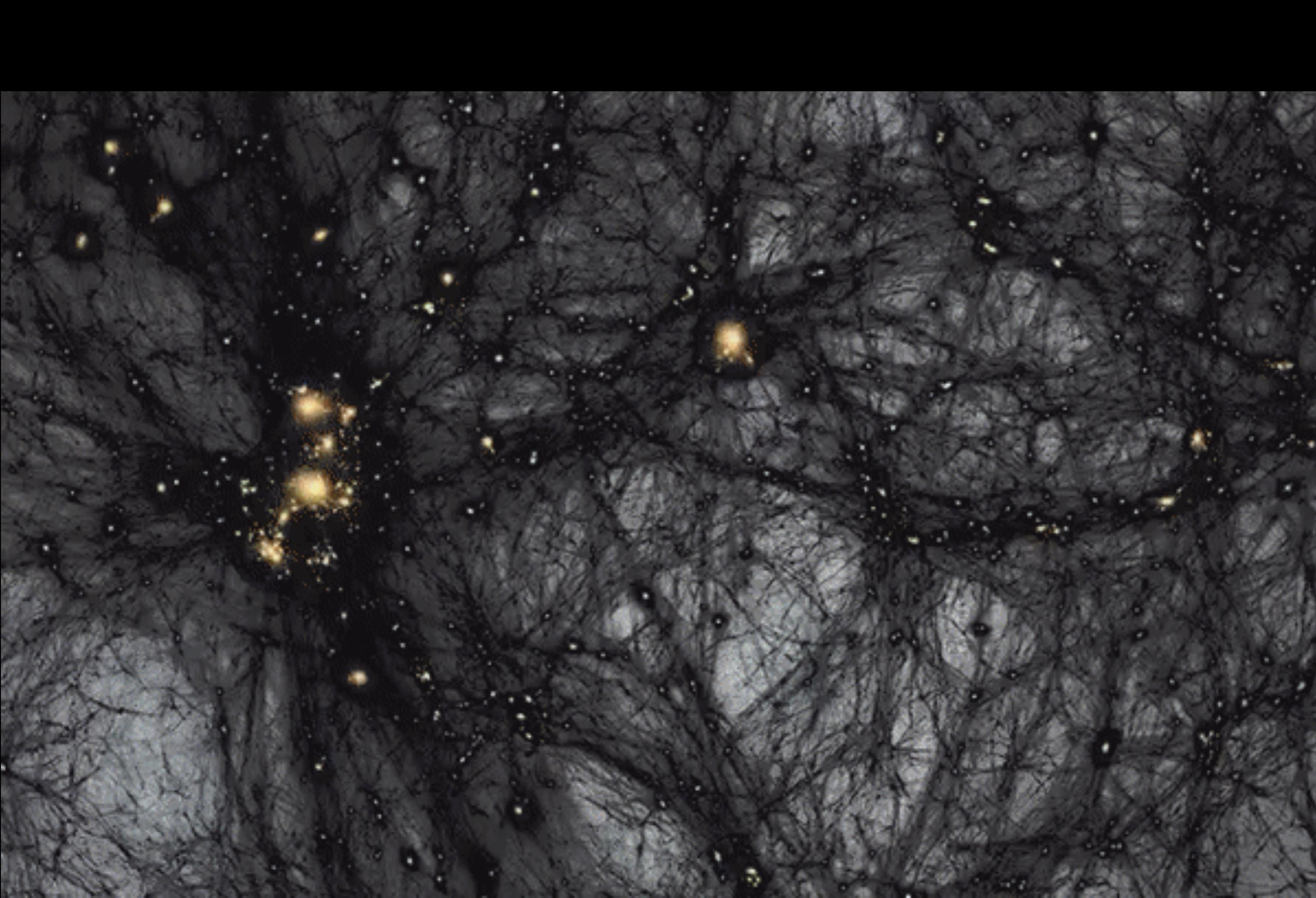
125 Mpc/h



125 Mpc/h

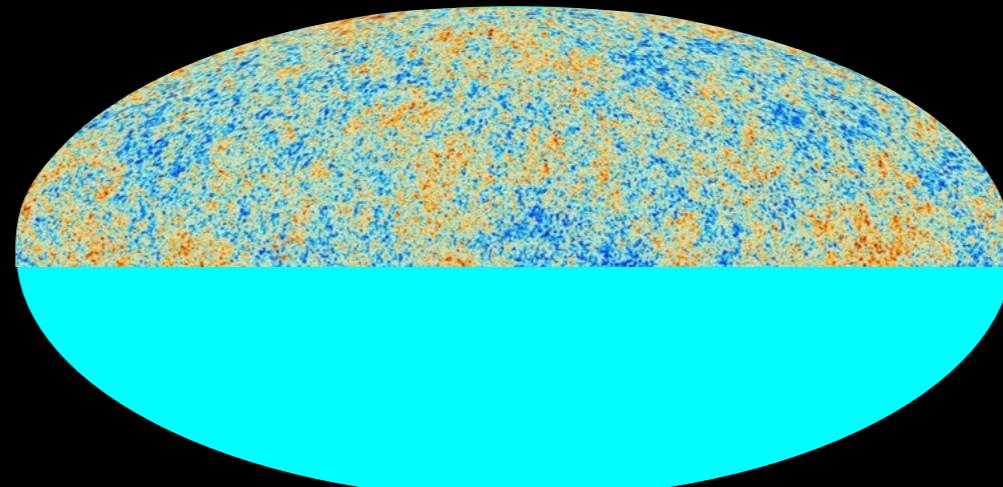


125 Mpc/h



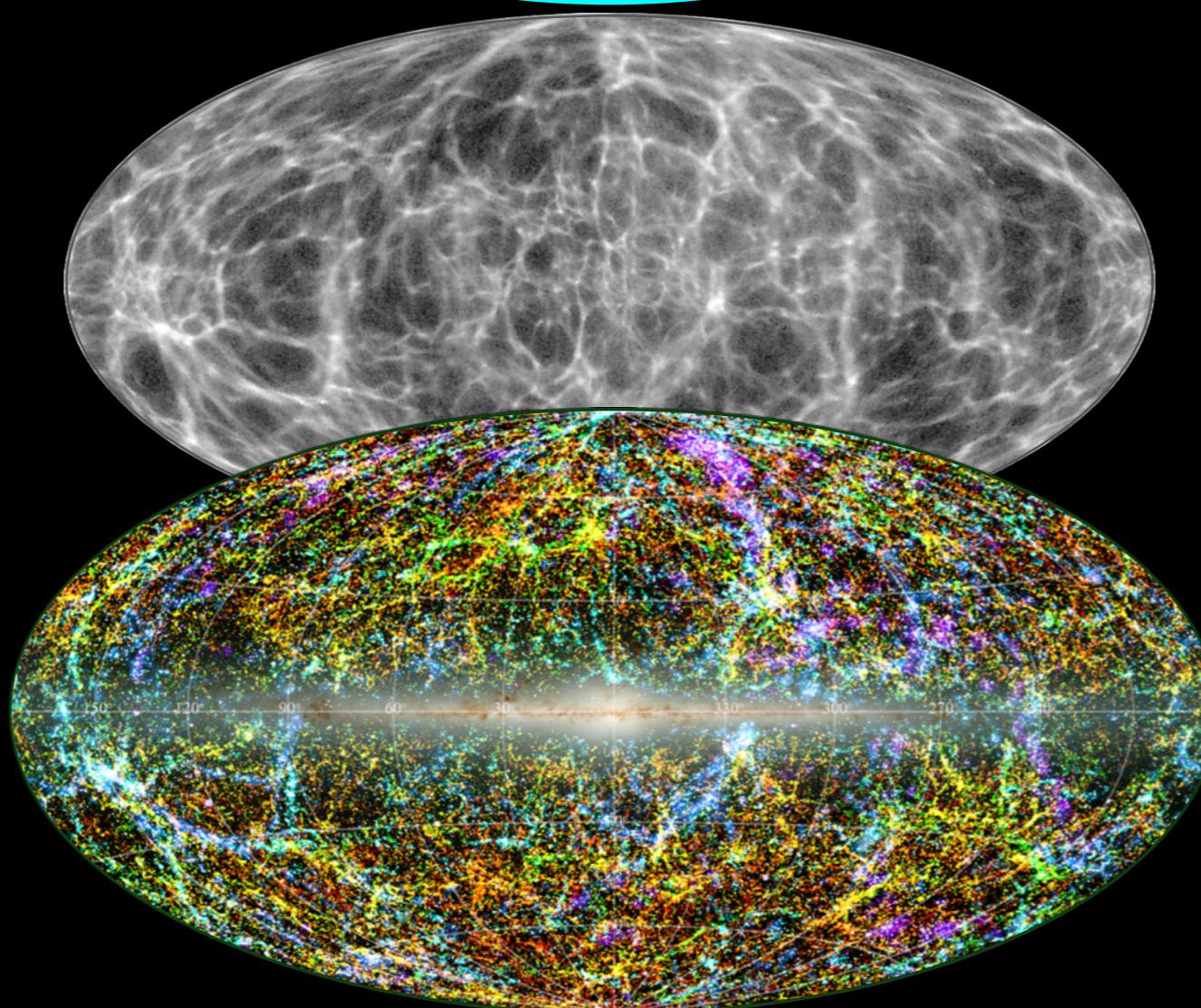
# COSMIC MYSTERIES

beginning  
nearly  
uniform



**GHOST**  
of early universe

today  
rich  
structure



SKELETON  
of universe

**SPIDERWEB**  
of galaxies

# **HOW DO WE MEASURE DISTANCES?**

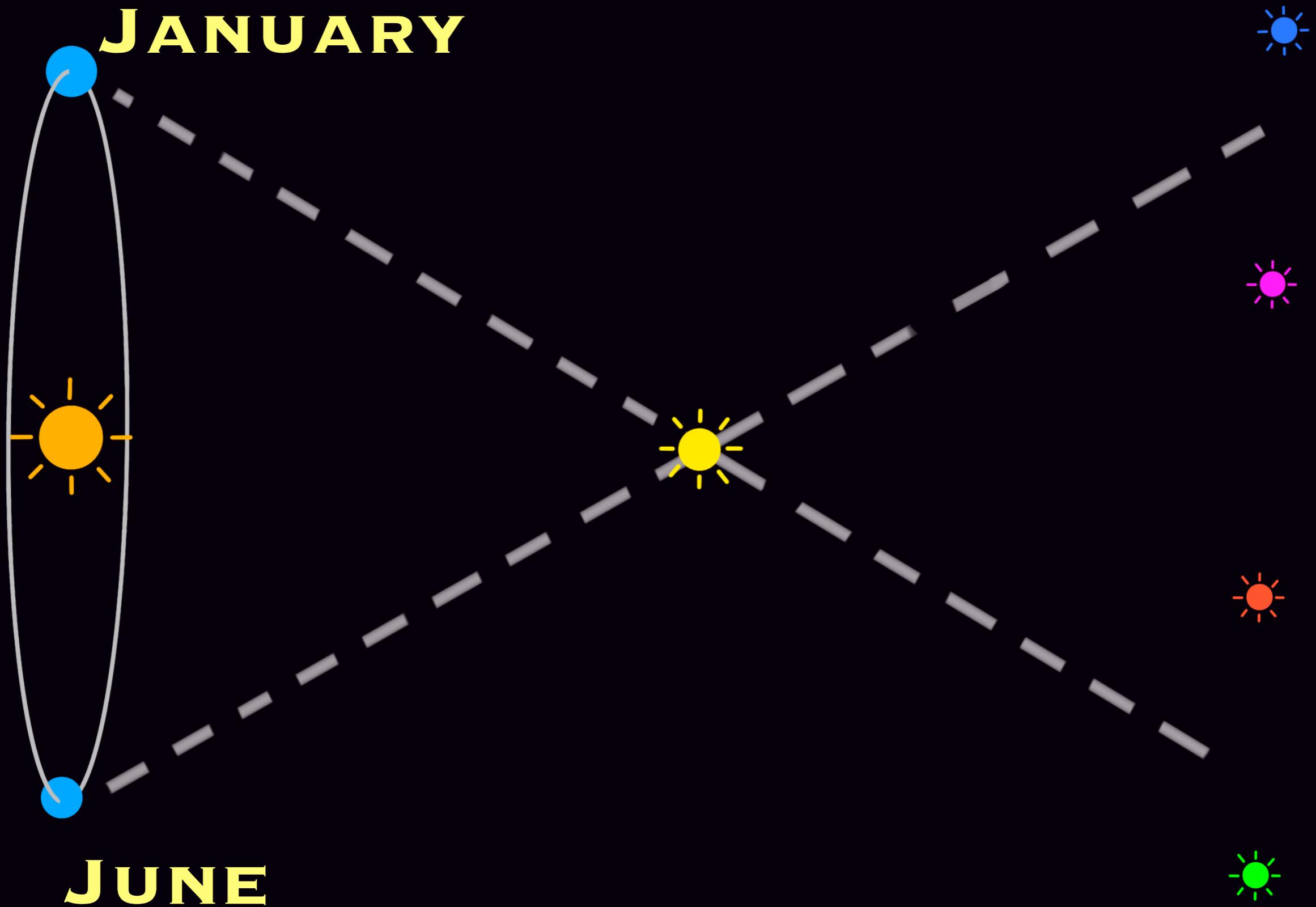
Distances are  
important

**how far in the past  
things happened**

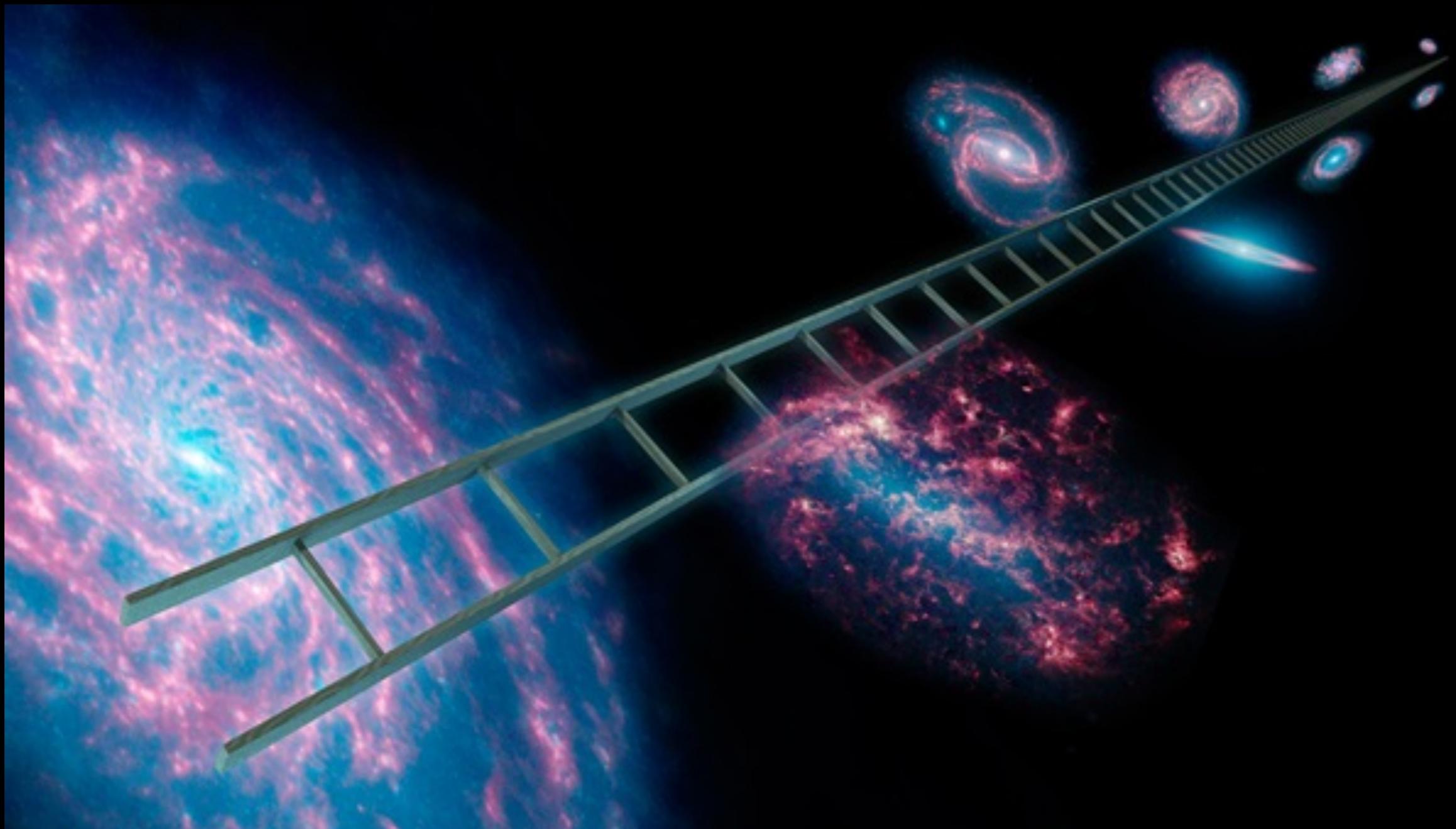
Distances are  
difficult

**we have to measure  
3D distance on a 2D  
sky**

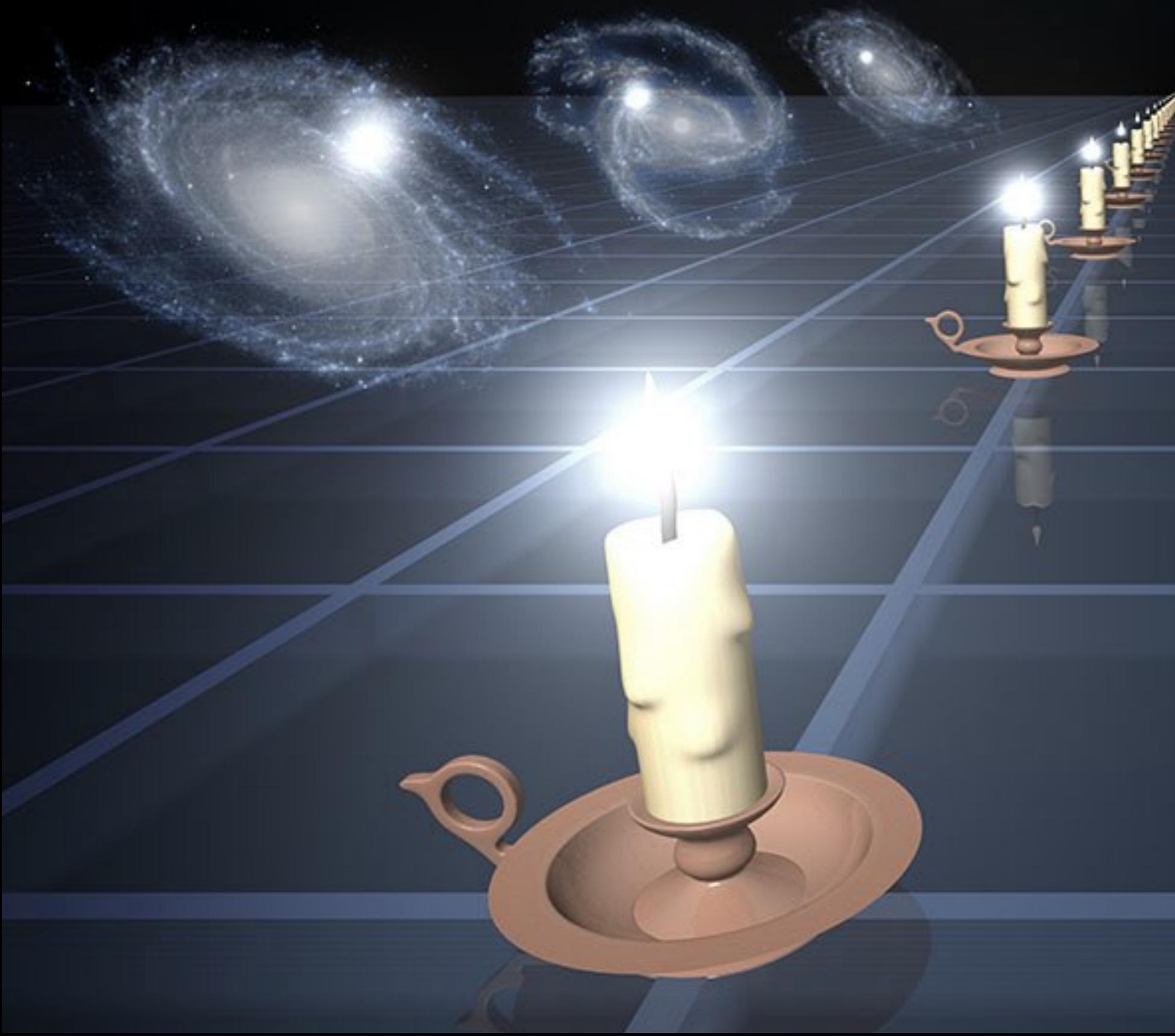
# CLOSE BY: PARALLAX



# THE DISTANCE LADDER



# STANDARD CANDLES: SUPERNOVAE



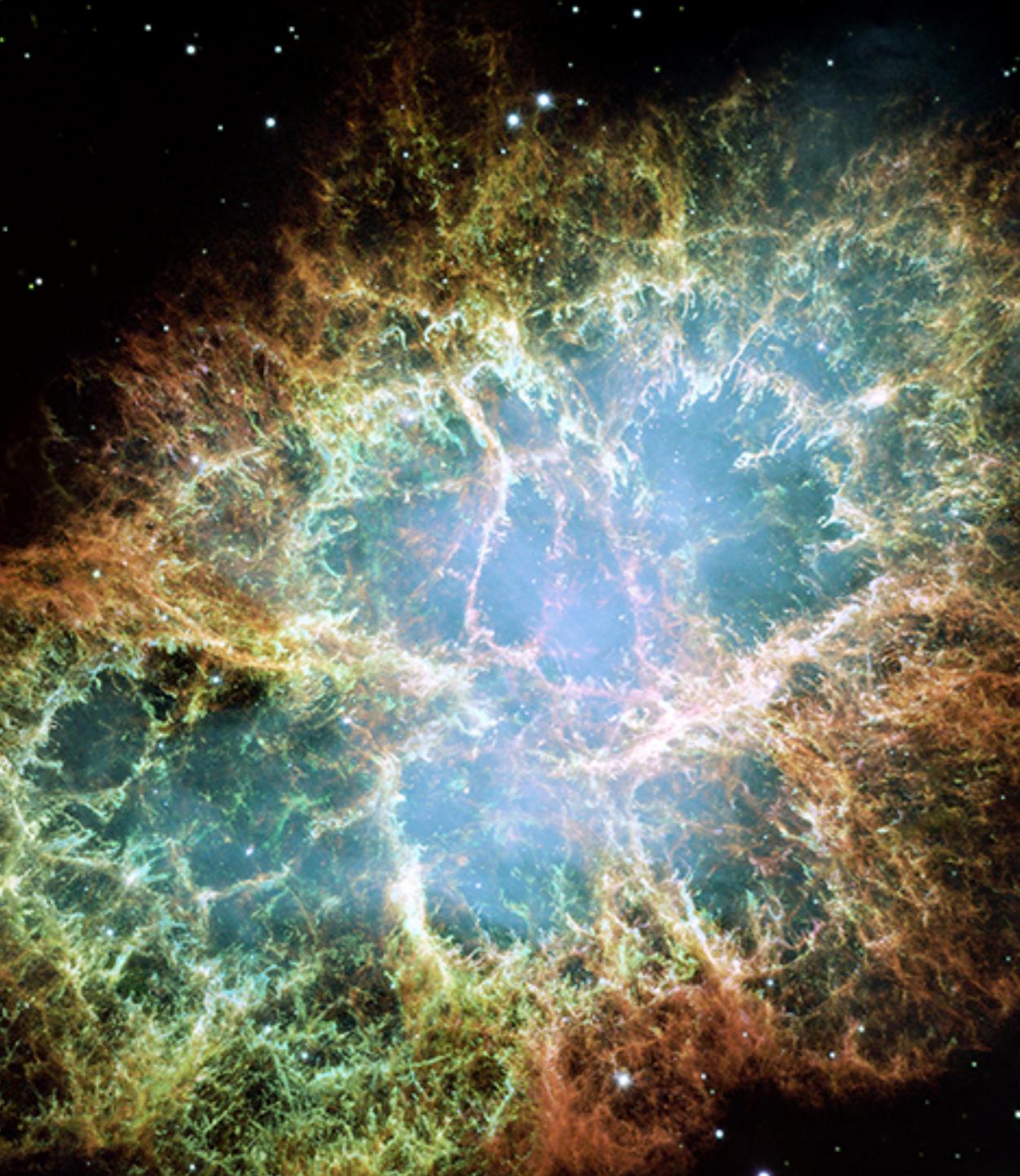
**dim =**

**far away**

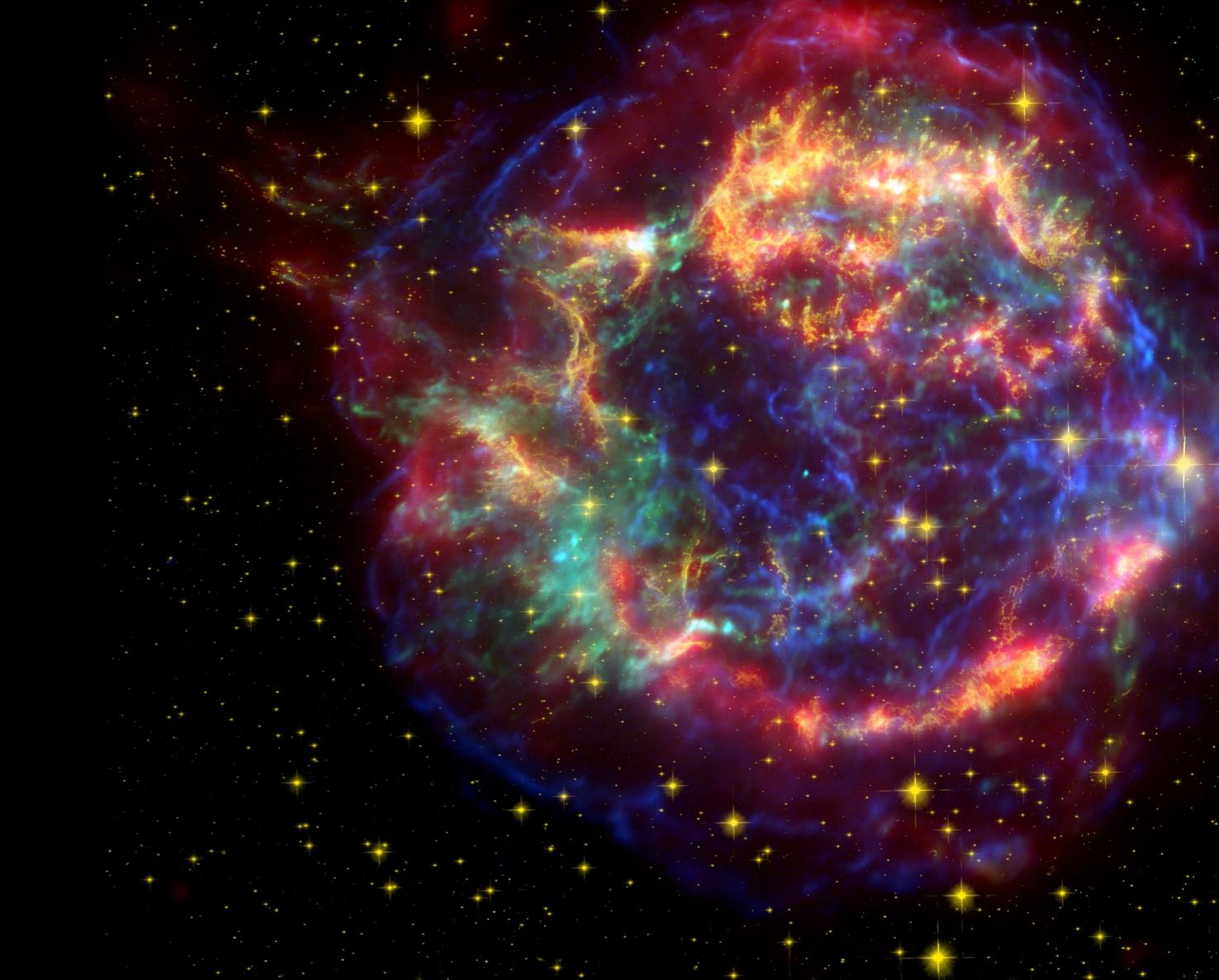
**bright =**

**close by**

**Crab nebula**  
**Imaged by Hubble**

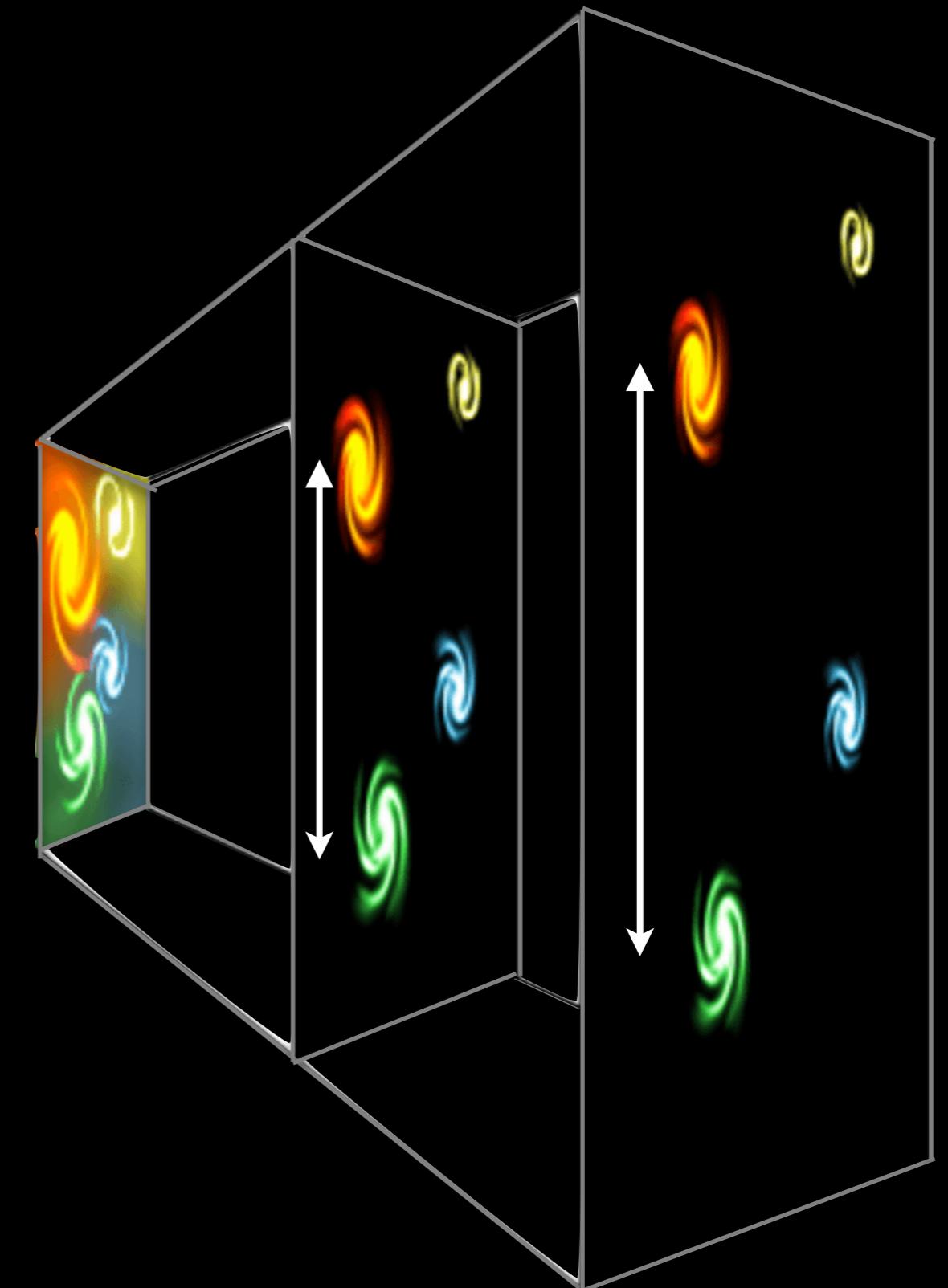


**Cassiopeia A**  
**Imaged by**  
**Spitzer (IR)**  
**Hubble (visible)**  
**Chandra (x-ray)**



# EXPANDING UNIVERSE

**distances between  
extragalactic objects  
increase**

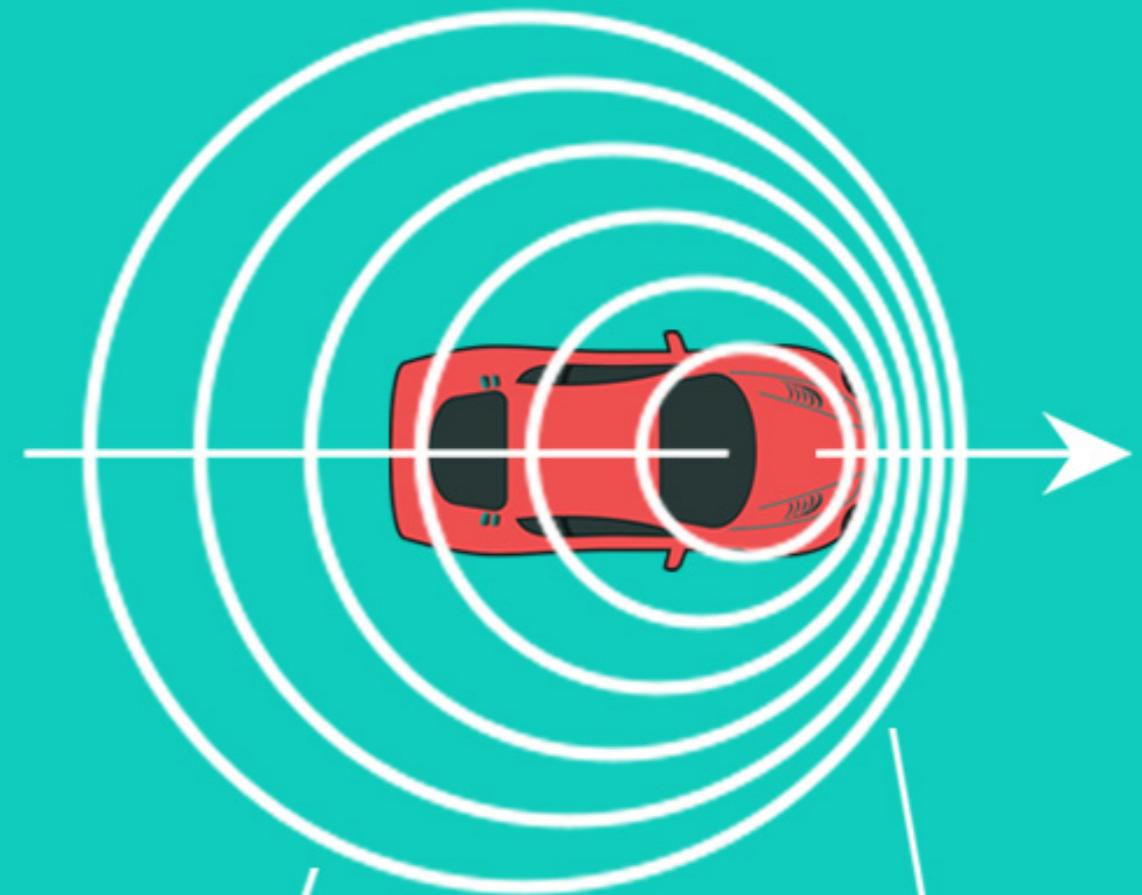


# DOPPLER SHIFT

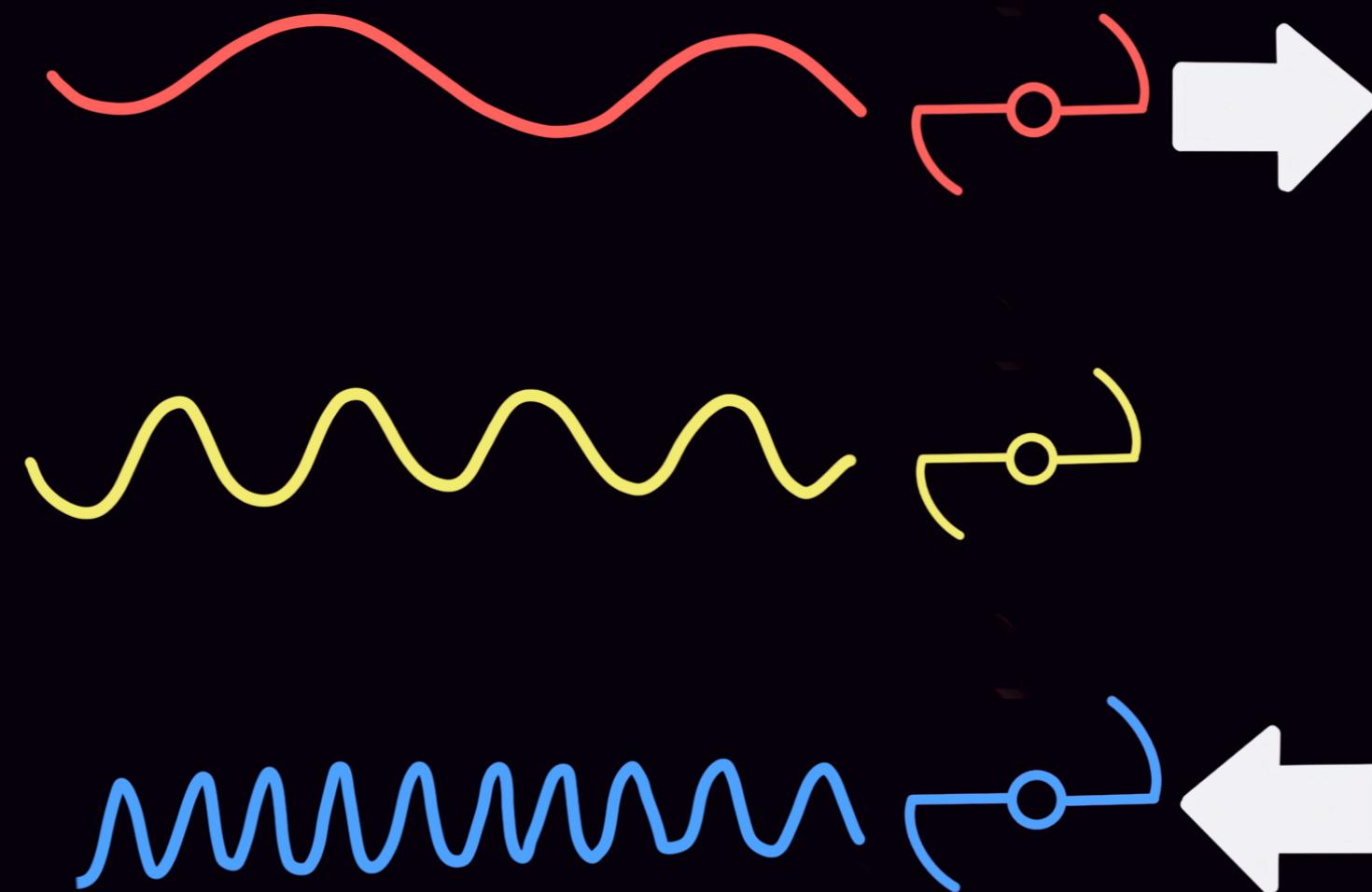
**static sound source**

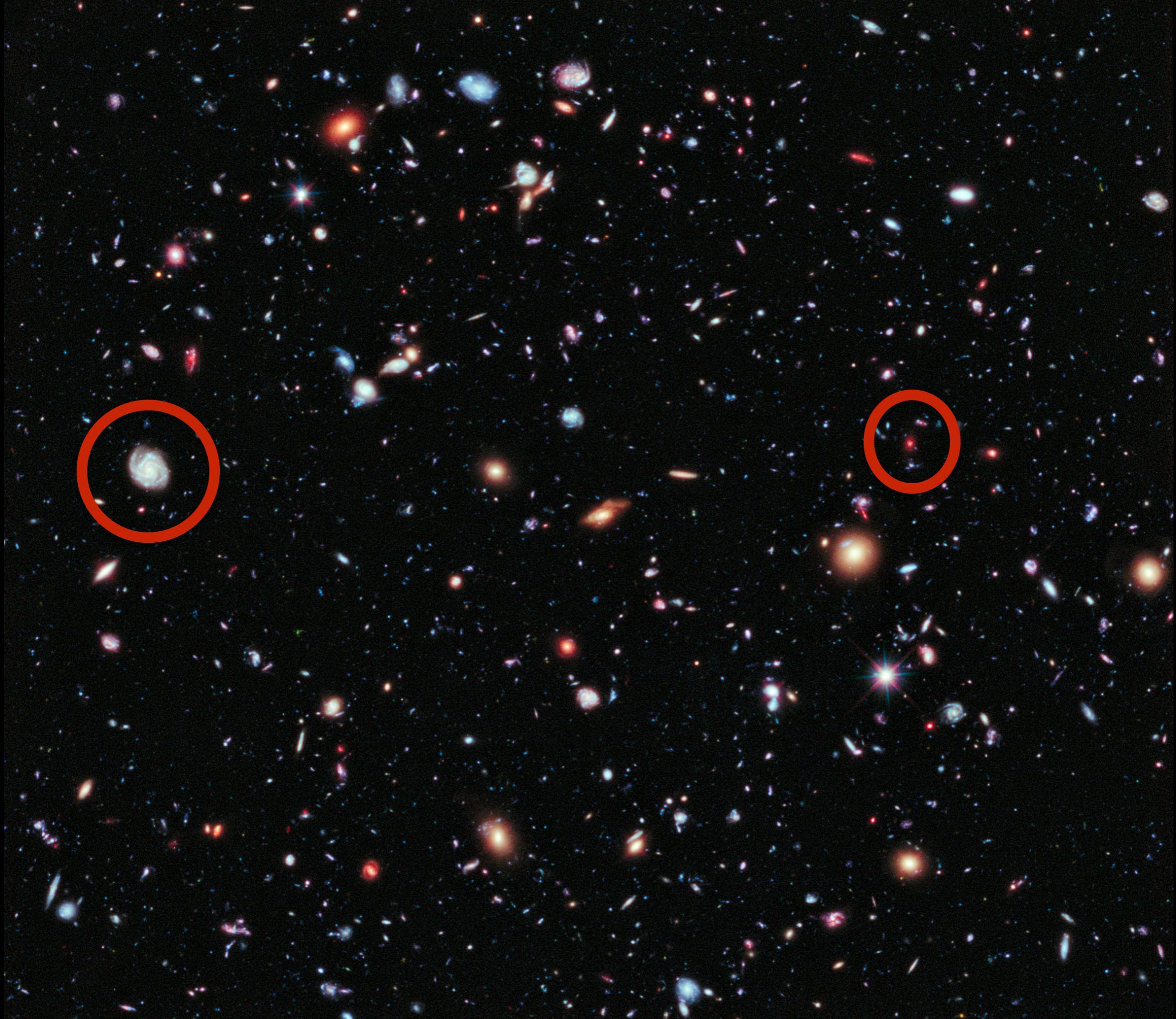


**moving sound source**



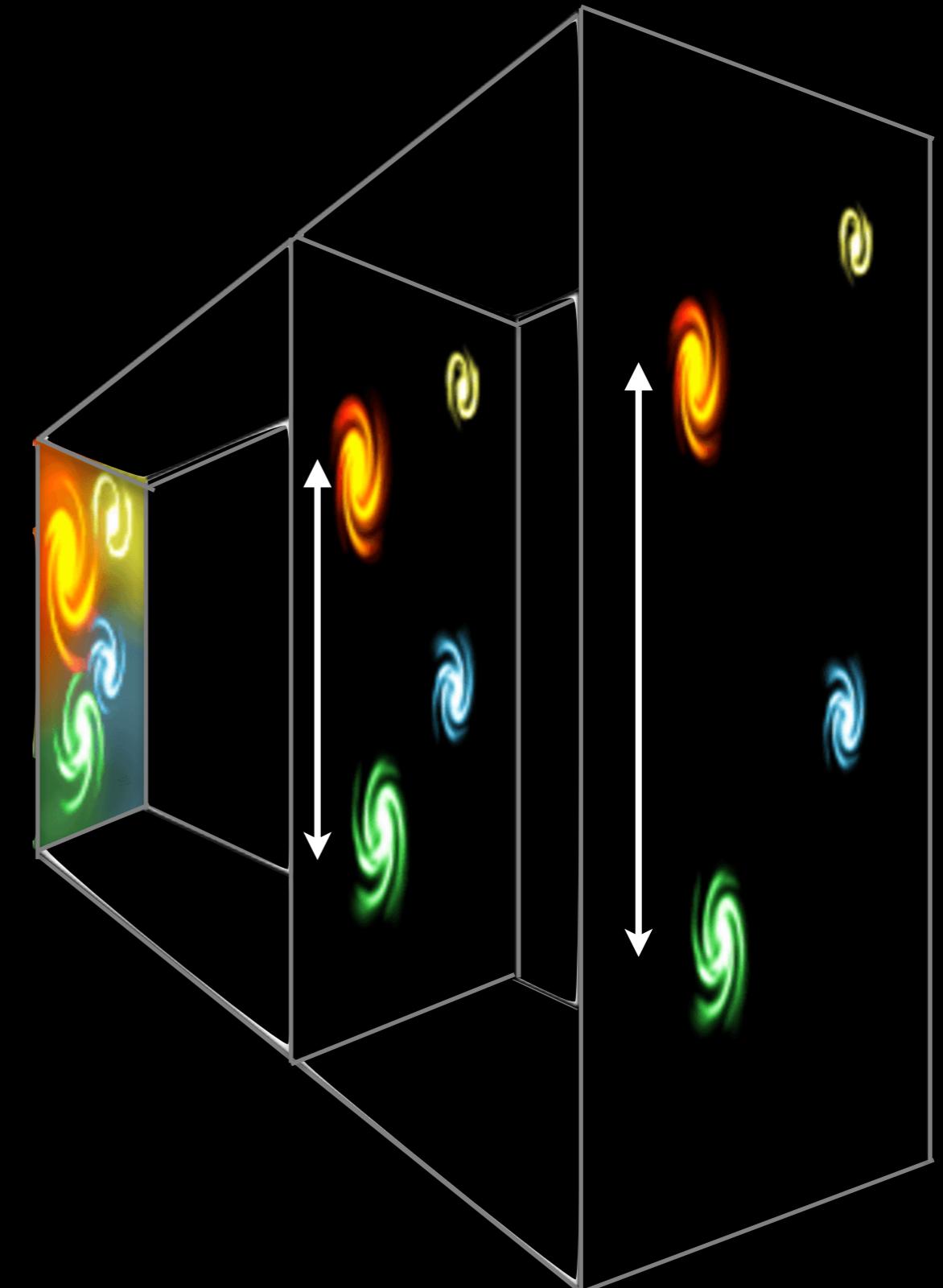
# REDSHIFT



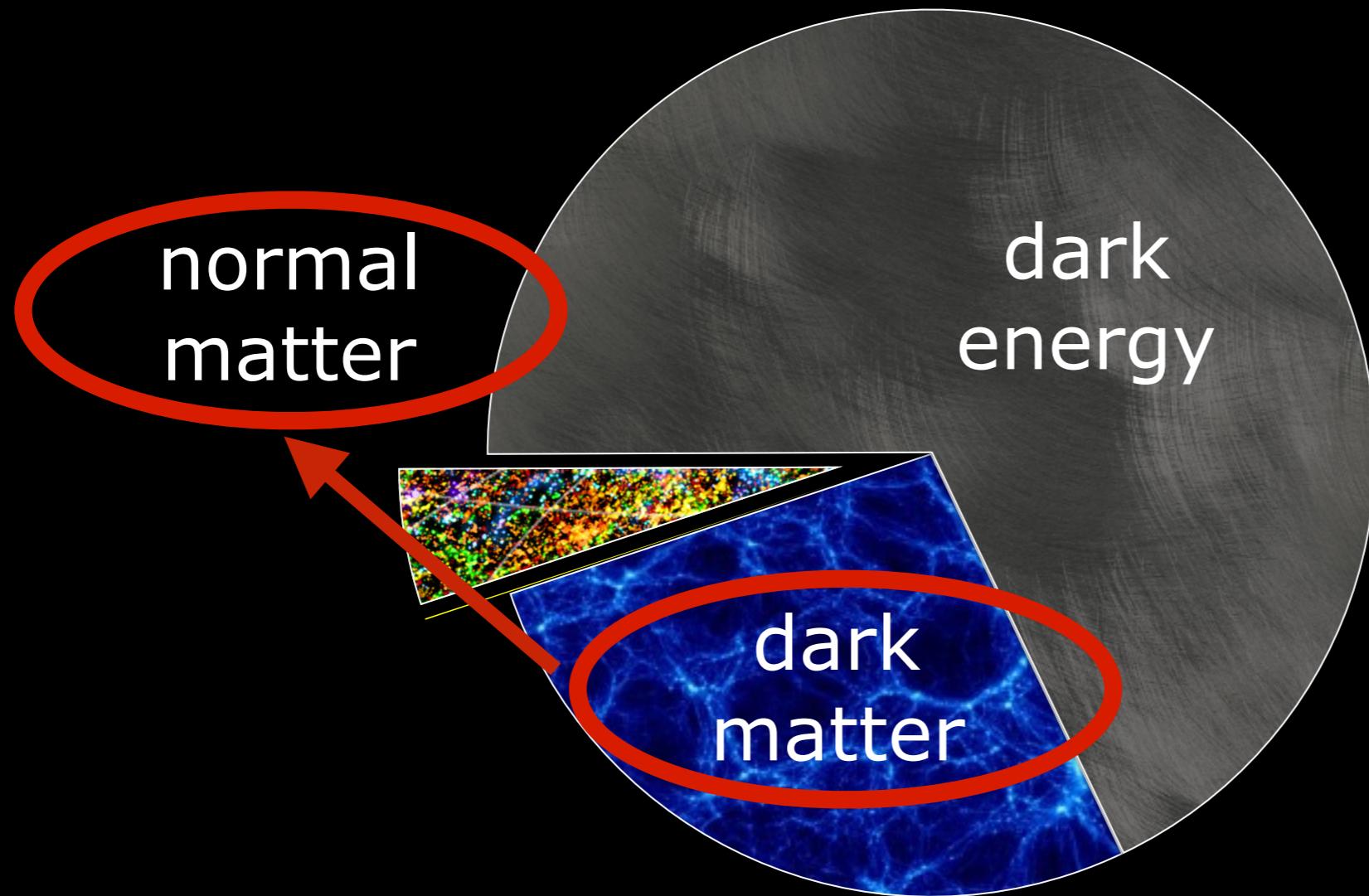


# **EXPANDING UNIVERSE**

**distances between  
extragalactic objects  
increase  
  
the speed they are  
moving apart is  
accelerating**



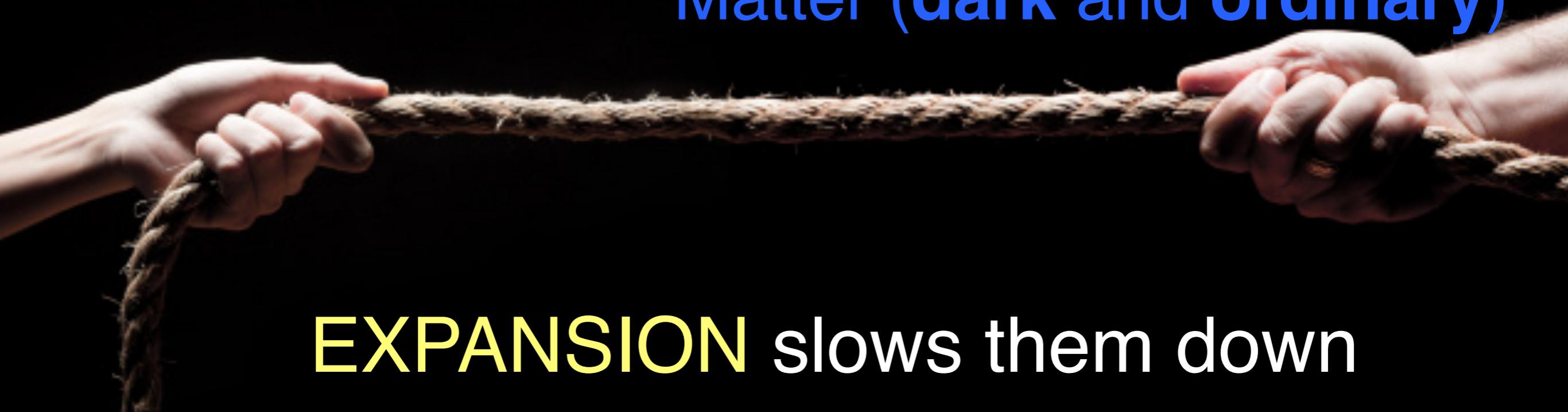
# PIE RECIPE



# COSMIC TUG OF WAR

density differences start small

GRAVITY makes them grow  
Matter (**dark and ordinary**)



EXPANSION slows them down  
Driven by **dark energy**

# **WHAT DO WE NEED TO BUILD THE UNIVERSE?**

**How many numbers do we need to measure?**

Surprisingly few!

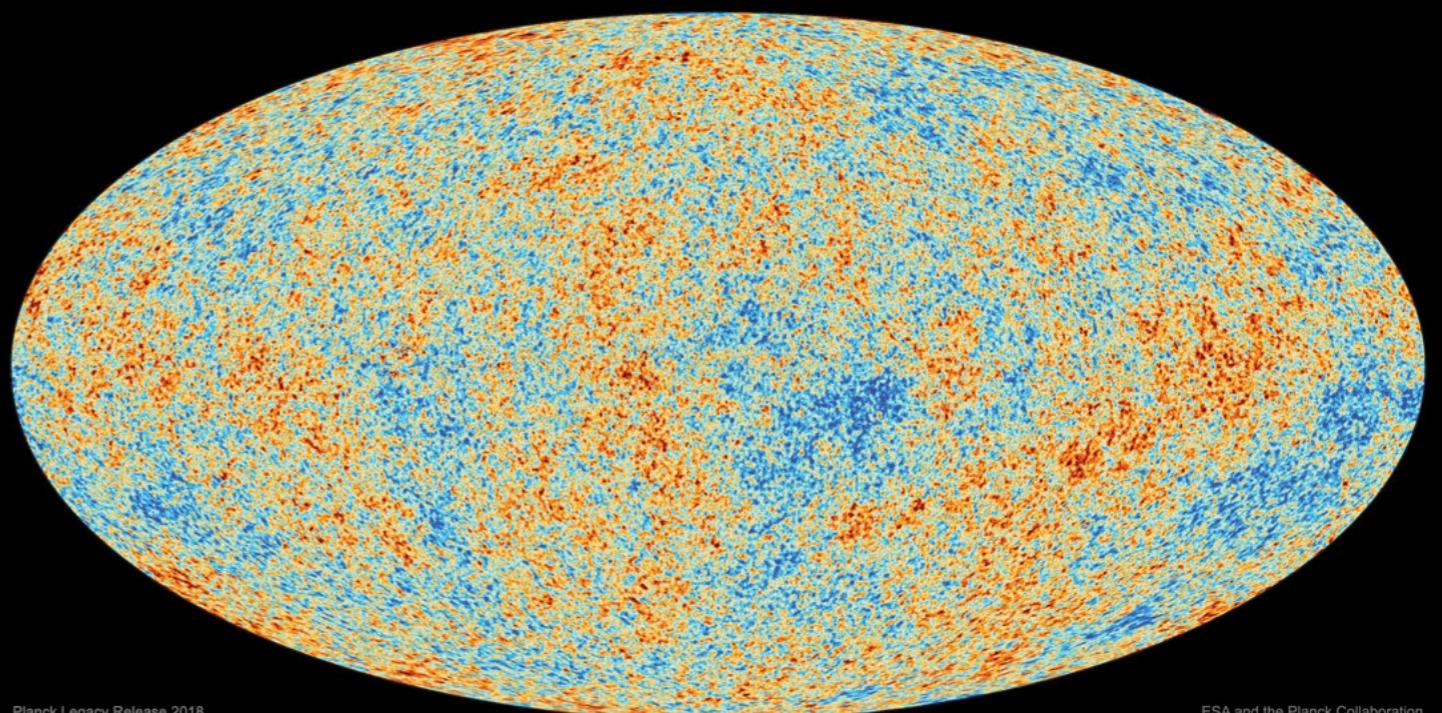
Only 6

# 6 NUMBERS FOR THE UNIVERSE

**seeds of structure**

amplitude

scale dependence



Planck Legacy Release 2018

ESA and the Planck Collaboration

# 6 NUMBERS FOR THE UNIVERSE

**seeds of structure**

amplitude

scale dependence

**pie recipe**

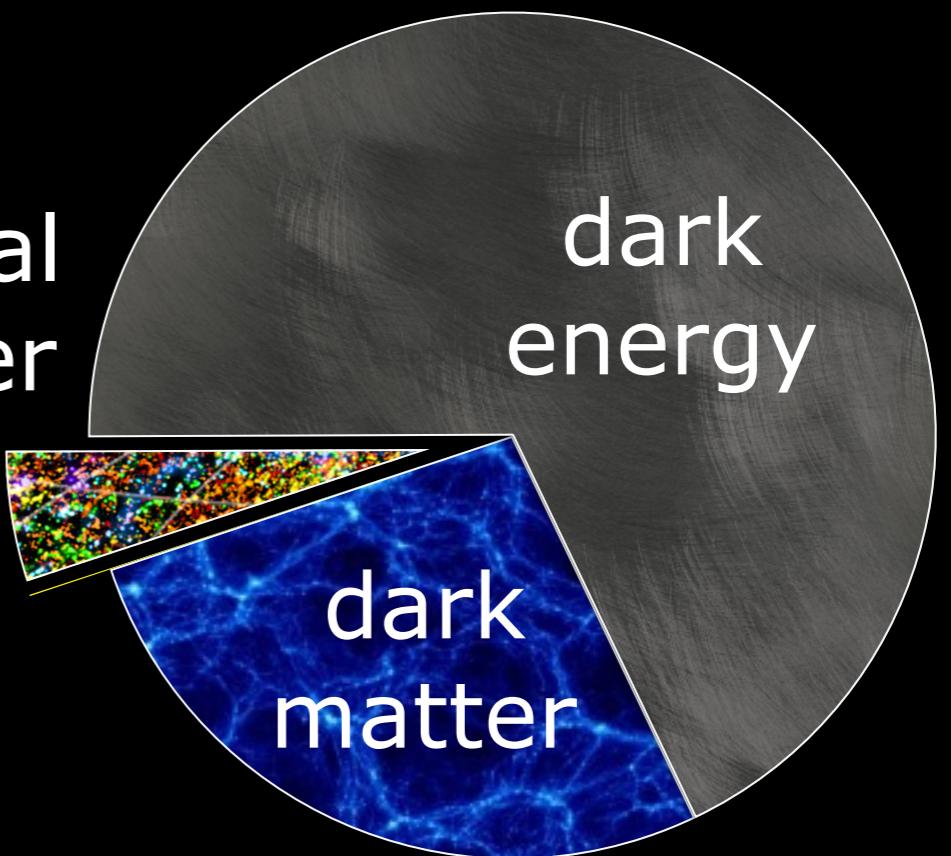
dark matter

dark energy

normal  
matter

dark  
energy

dark  
matter



# 6 NUMBERS FOR THE UNIVERSE

**seeds of structure**

amplitude

scale dependence

**pie recipe**

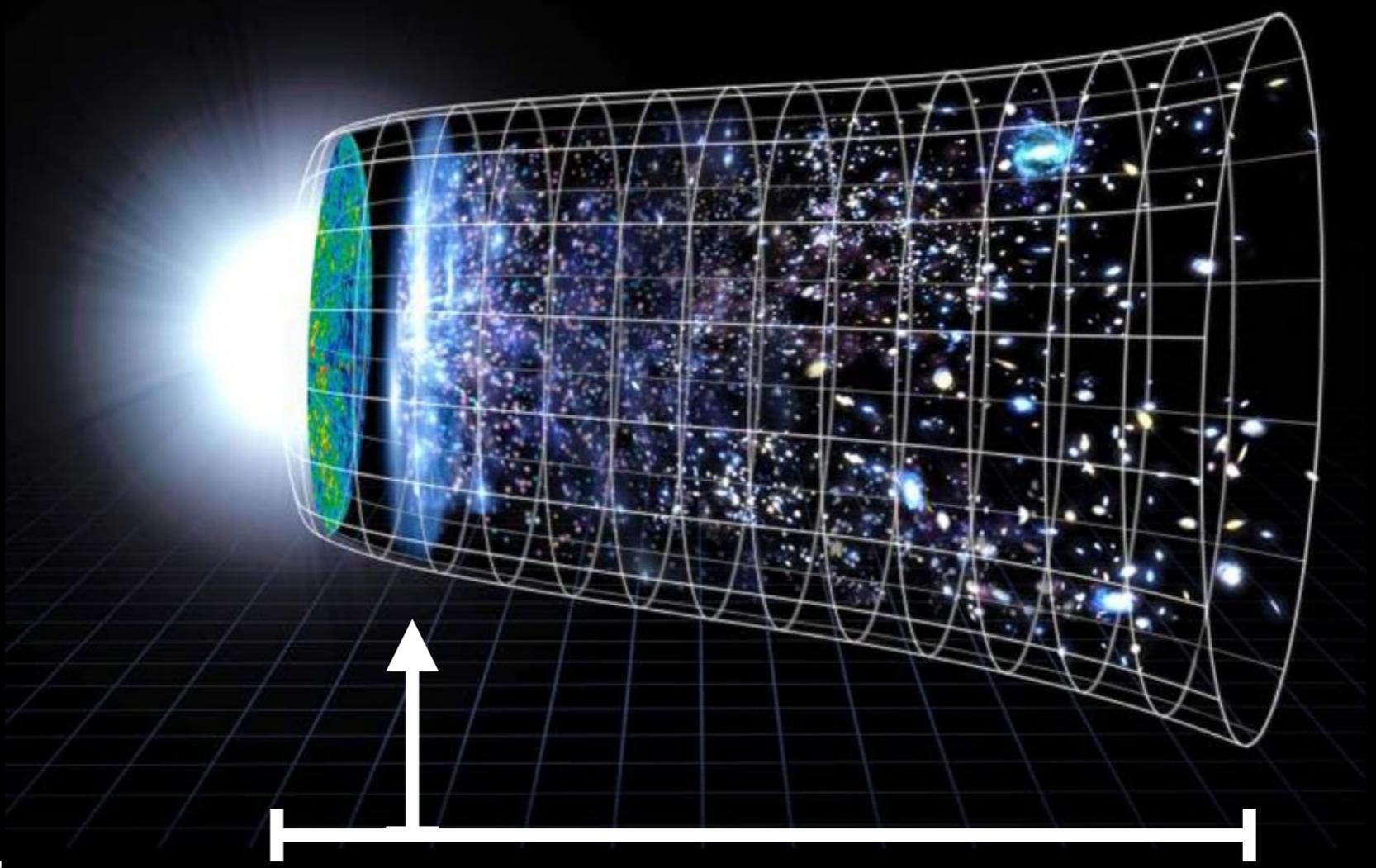
normal matter

dark matter

**timings**

age of universe

first stars & galaxies

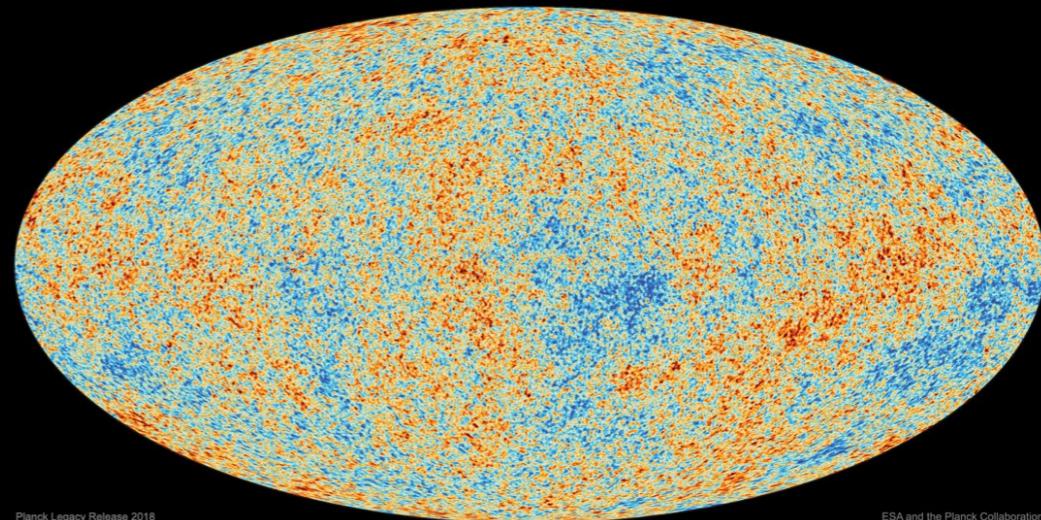


# 6 NUMBERS FOR THE UNIVERSE

**seeds of structure**

amplitude

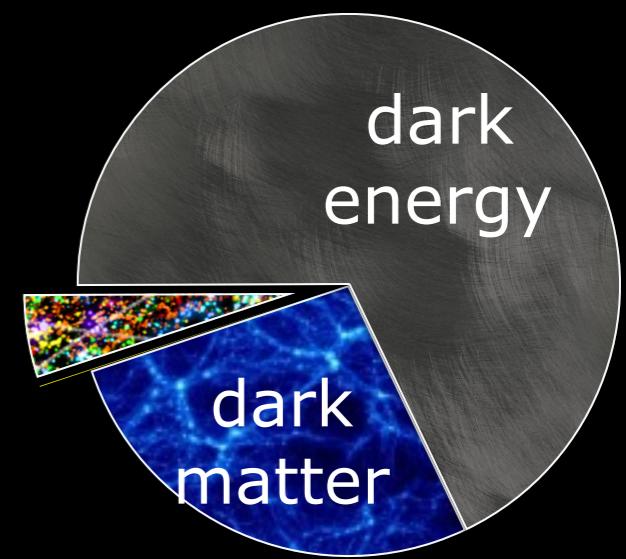
scale dependence



**pie recipe**

dark energy

dark matter



**timings**

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