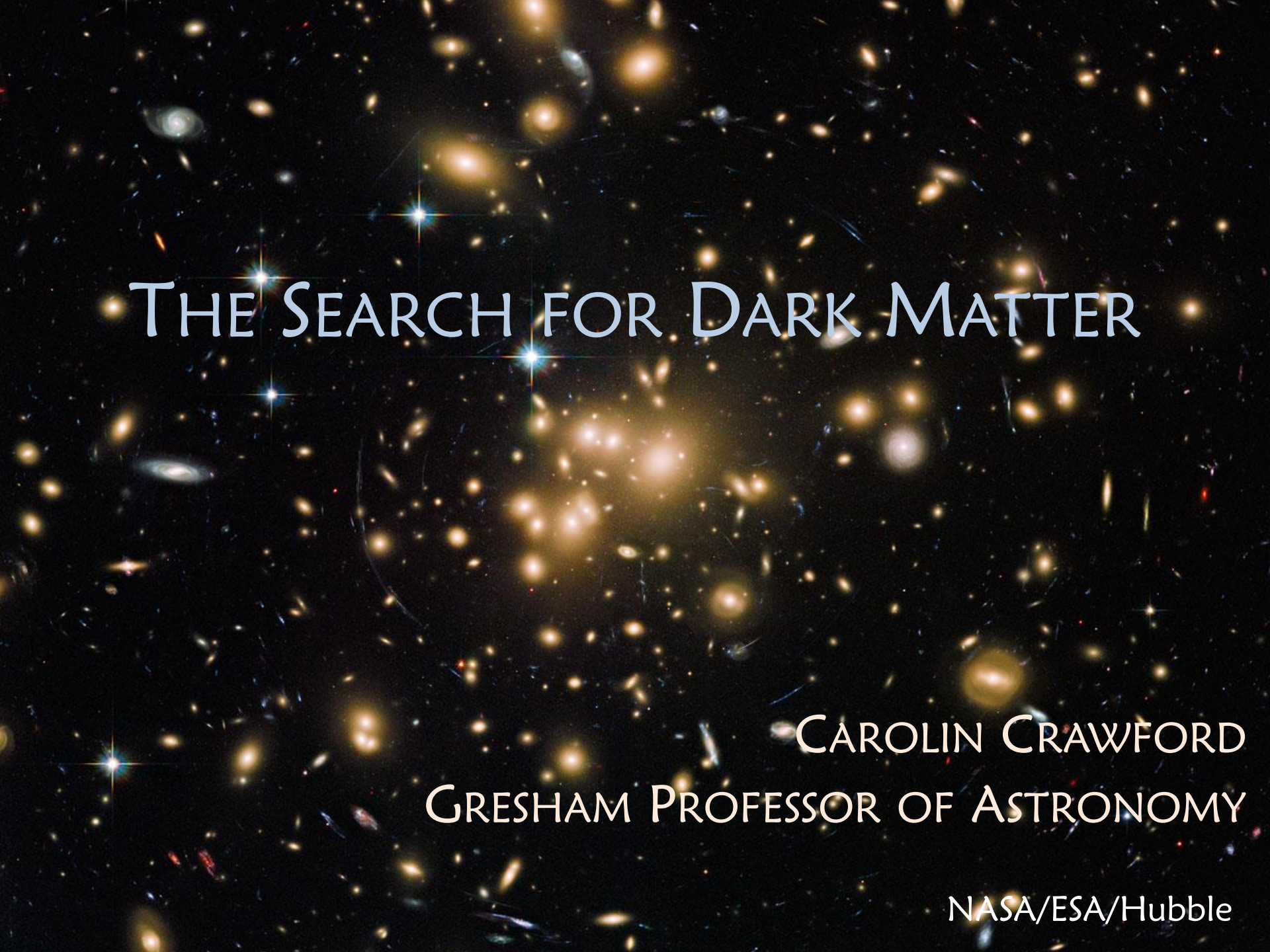


The background of the slide is a deep-field astronomical image, likely from the Hubble Space Telescope. It shows a vast field of galaxies and distant stars against a black background. The galaxies are of various shapes and sizes, some appearing as bright, diffuse clouds, while others are more compact and distant. The stars are small, bright points of light, some with visible diffraction patterns. The overall scene is a dense, colorful representation of the universe's structure.

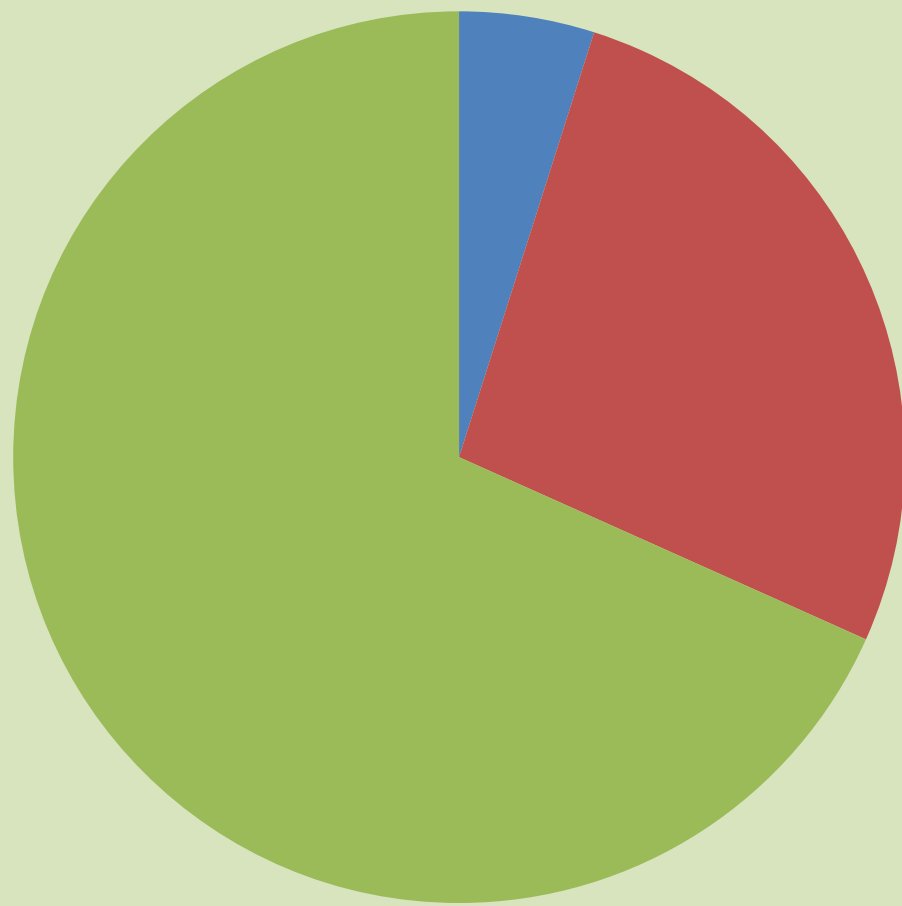
THE SEARCH FOR DARK MATTER

CAROLIN CRAWFORD
GRESHAM PROFESSOR OF ASTRONOMY

NASA/ESA/Hubble



HST/NASA



■ 4.9 % ordinary matter

■ 26.8 % dark matter

■ 69 % dark energy

4 FORCES

GRAVITY

GENERAL
RELATIVITY

- WEAK
- DROPS OFF WITH INVERSE SQUARE LAW
- DEPENDS ON **MASS** PRESENT
- ALWAYS **ATTRACTIVE**
- ACTS ON ALL MATTER
- ALWAYS **ADDITIVE**

4 FORCES

GRAVITY

GENERAL
RELATIVITY

ELECTROMAGNETISM

- DROPS OFF WITH INVERSE SQUARE LAW
- DEPENDS ON CHARGE PRESENT
- CAN BE ATTRACTIVE OR REPULSIVE
- DOES *NOT* INFLUENCE ALL MATTER

4 FORCES

GRAVITY

ELECTROMAGNETISM

WEAK

STRONG

GENERAL
RELATIVITY

QUANTUM
PHYSICS

SUSY?

4 FORCES

GRAVITY

GRAVITY

ELECTROMAGNETISM

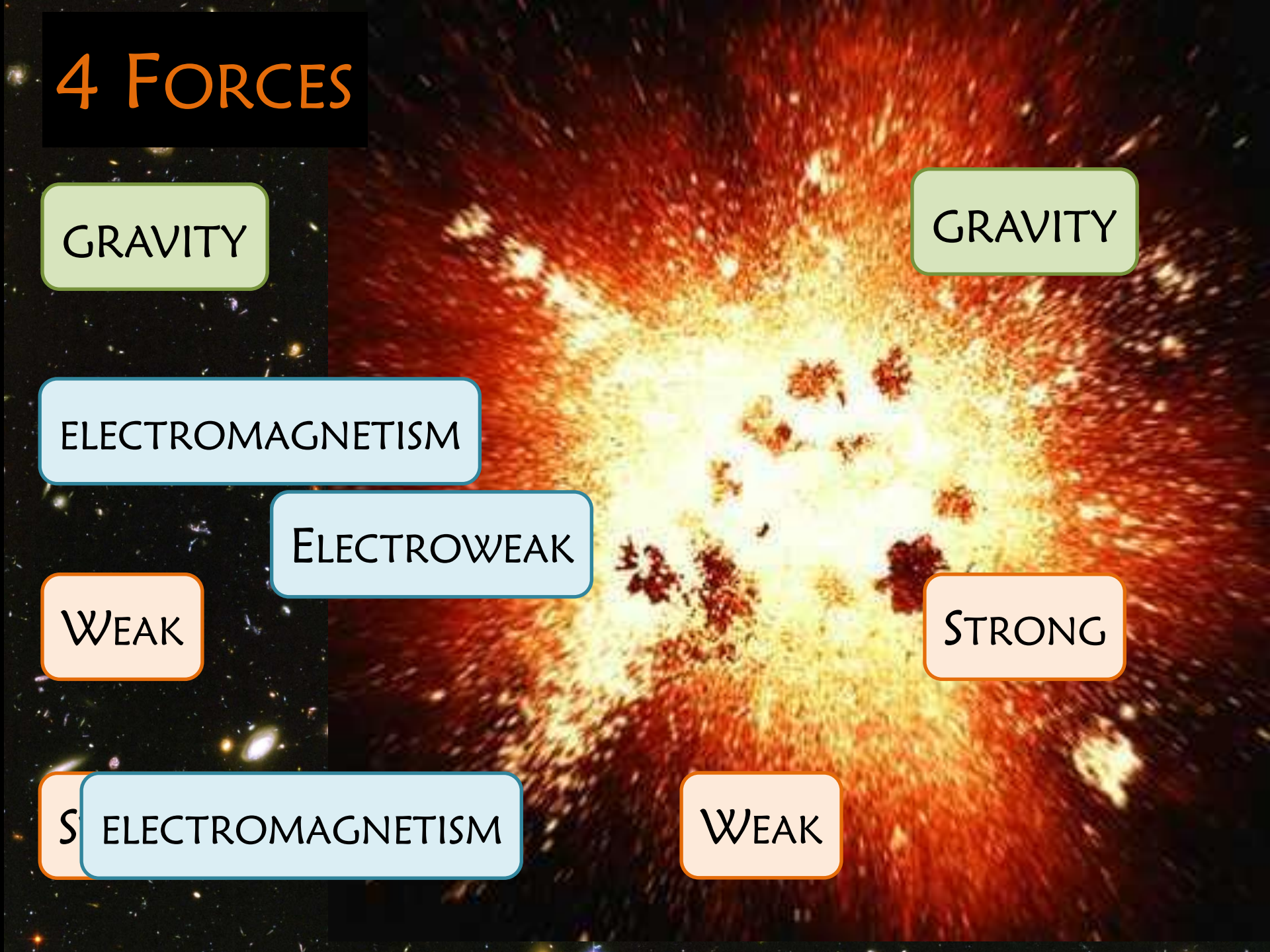
ELECTROWEAK

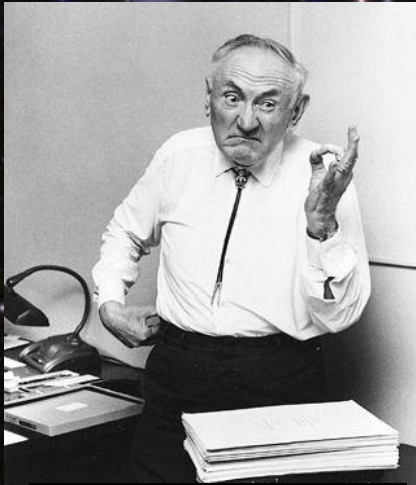
WEAK

STRONG

S ELECTROMAGNETISM

WEAK





Fritz Zwicky

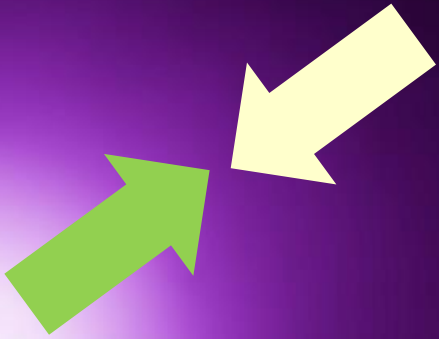
Dean Rowe



optical
X-rays

NASA/STScI
NASA/CXC/MIT/Peng et al

X-RAY CLUSTER MASSES



Balance the

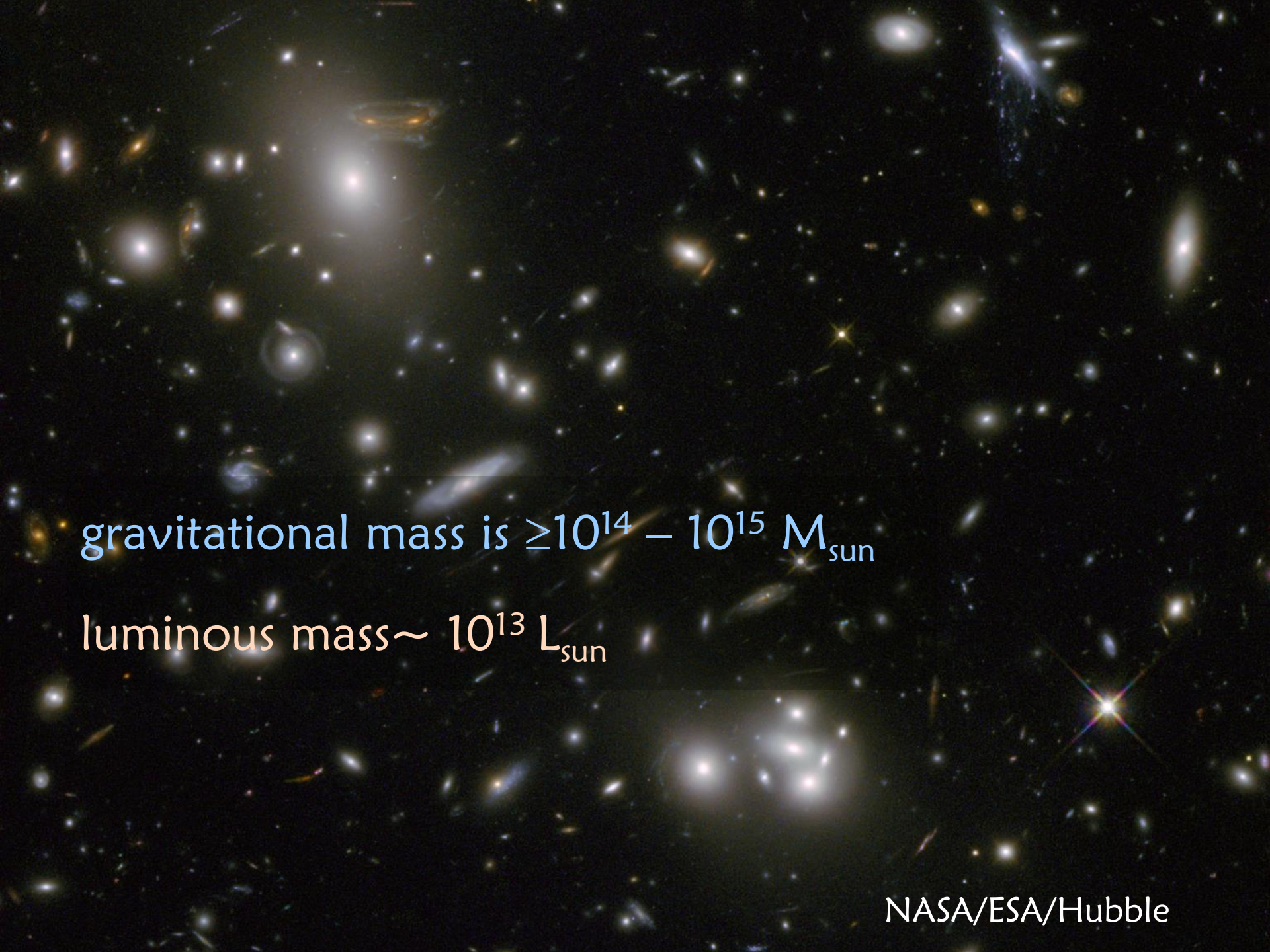
inward force of gravity

(depends on the *total mass* of the cluster)

by the

outward pressure of the hot gas

(depends on its *temperature & density*)



gravitational mass is $\geq 10^{14} - 10^{15} M_{\text{sun}}$

luminous mass $\sim 10^{13} L_{\text{sun}}$



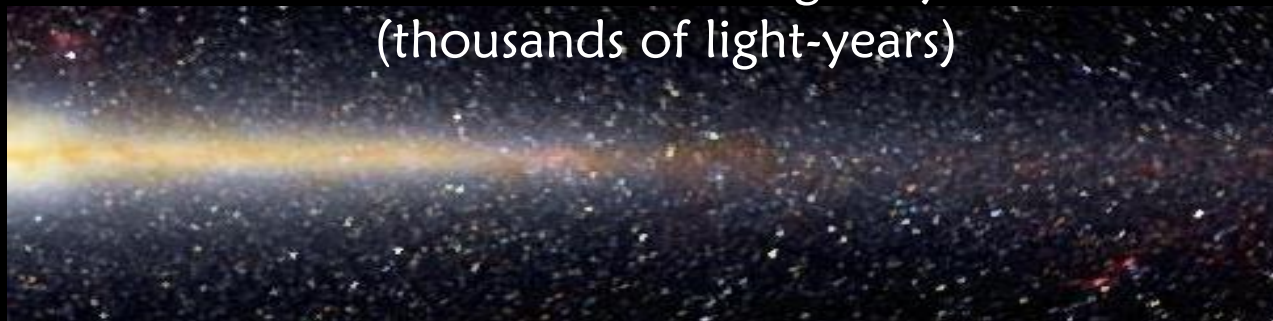
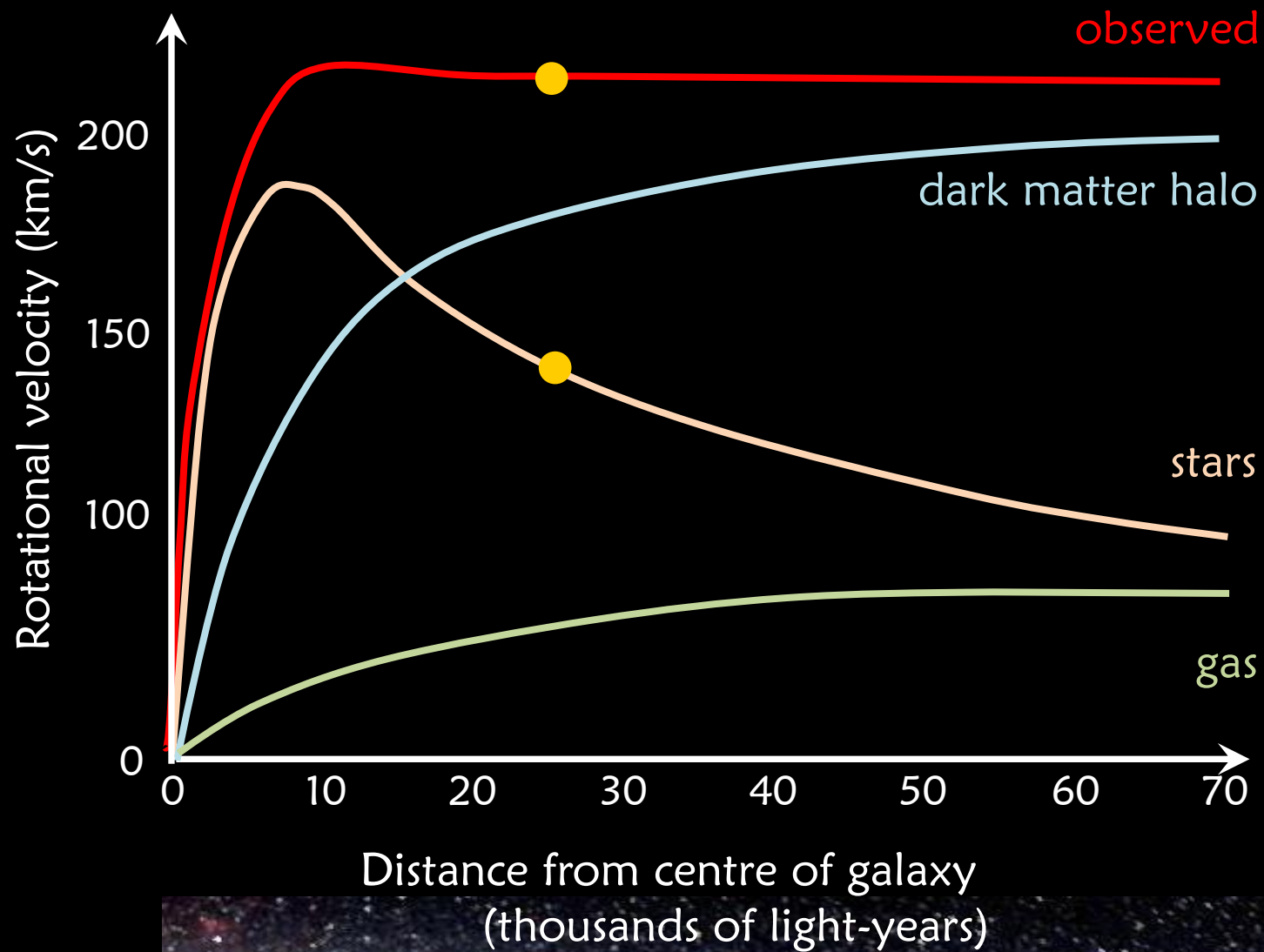
NASA/ESA/Hubble Collaboration



NASA/ESA/Hubble

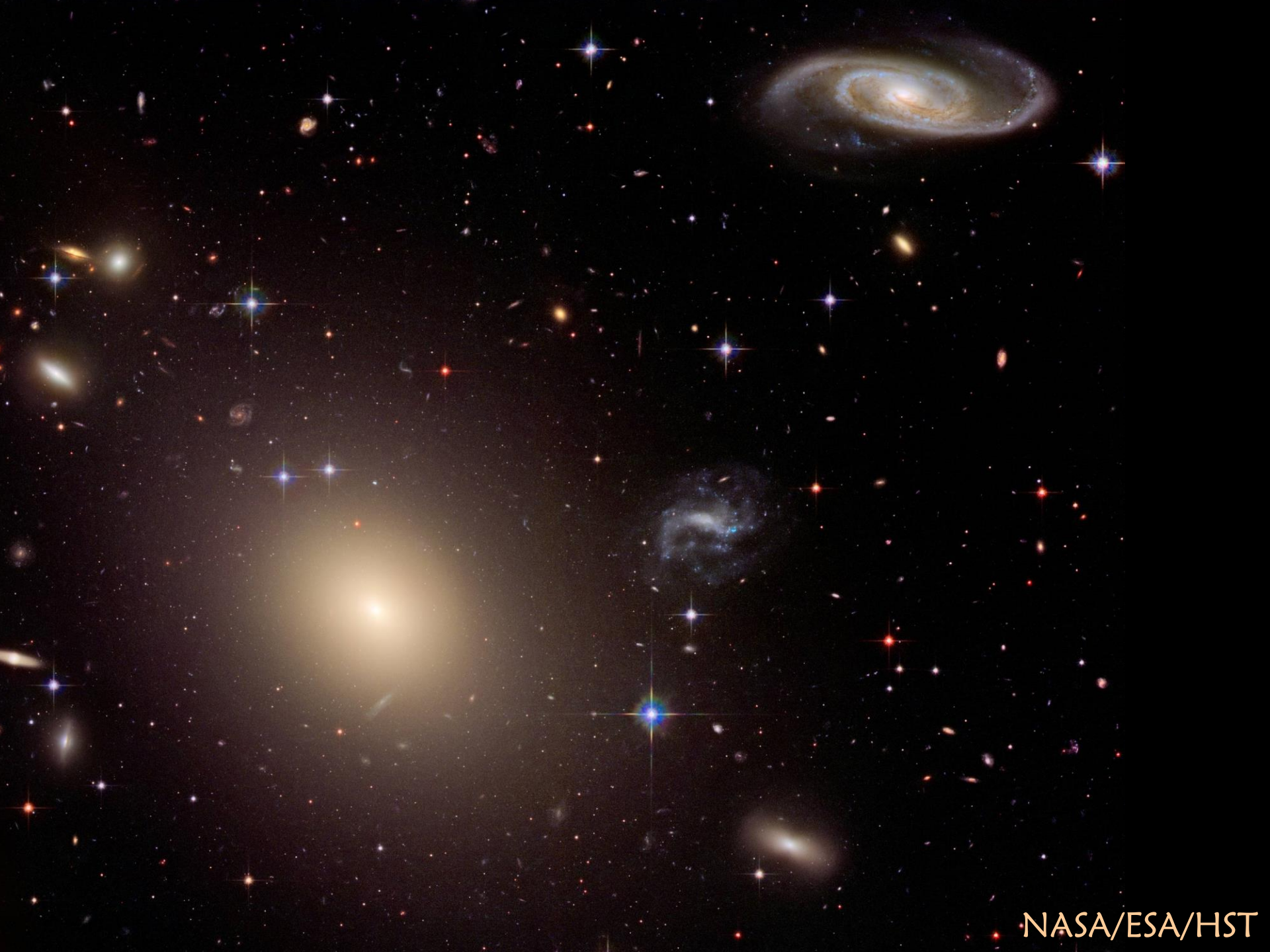


NASA/ESA/Hubble Heritage Team



DARK MATTER

total mass: $\sim 1,200$ billion M_{sun}
luminous mass: ~ 120 billion M_{sun}



NASA/ESA/HST



NASA/ESA/HST

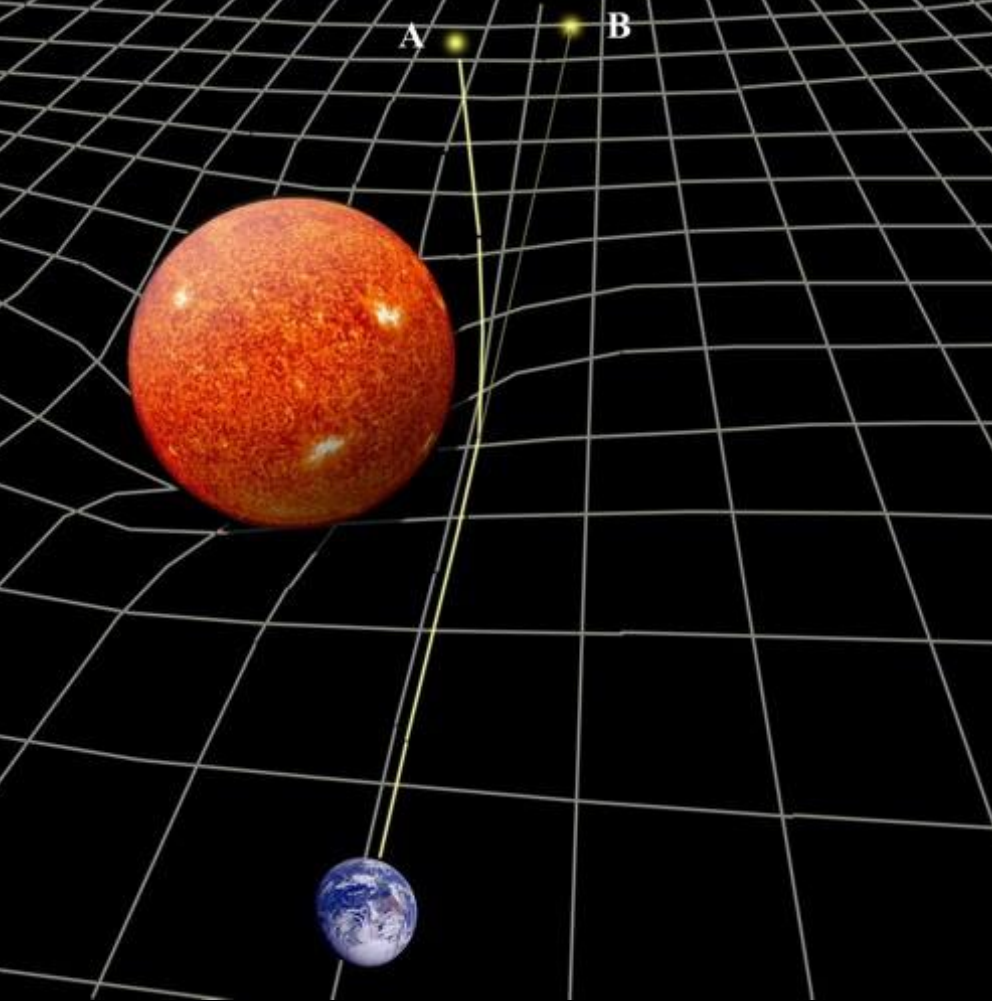


optical
X-rays

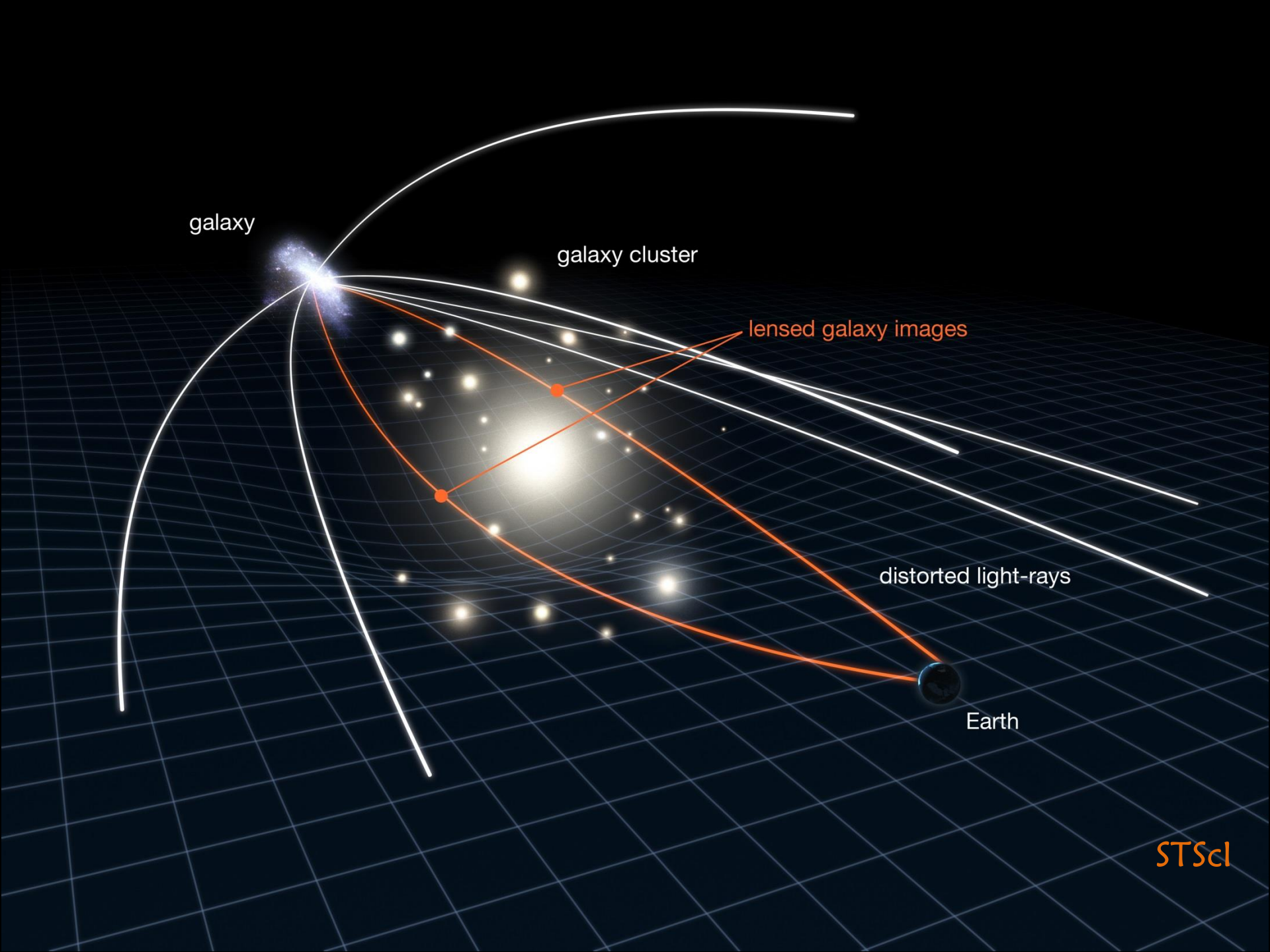
LENSING CLUSTER MASSES

This is a deep-field astronomical image, likely from the Hubble Space Telescope, showing a massive galaxy cluster. The image is filled with hundreds of galaxies, many of which are distorted into arcs and multiple images, a phenomenon known as gravitational lensing. The galaxies are primarily yellow and white, with some blue and red ones scattered throughout. The background is a deep black, and the overall scene is a testament to the power of gravitational lensing in revealing distant and faint objects in the universe.

Fruchter/HST/NASA



matter in the Universe
influences
the *shape* of space



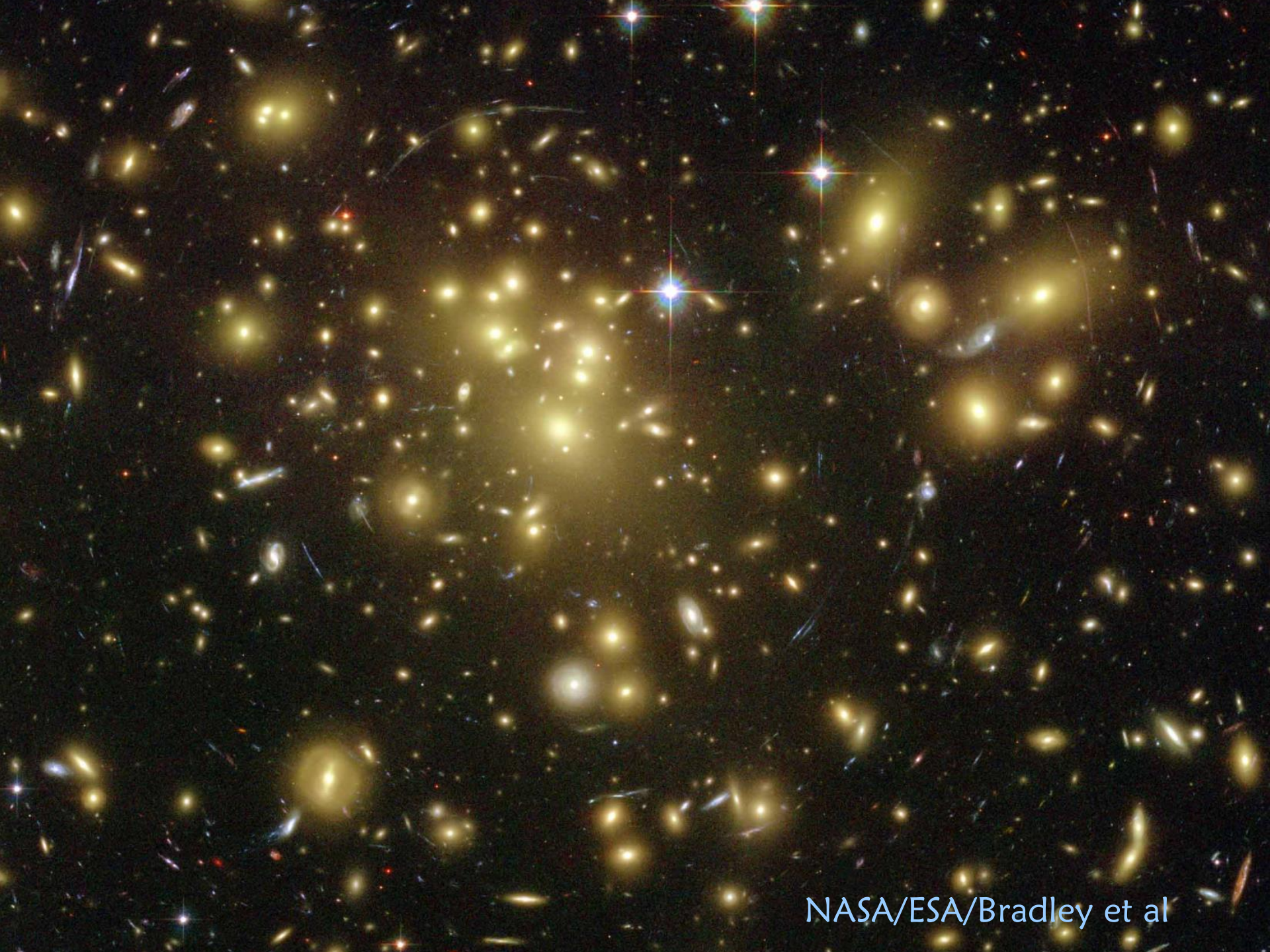
galaxy

galaxy cluster

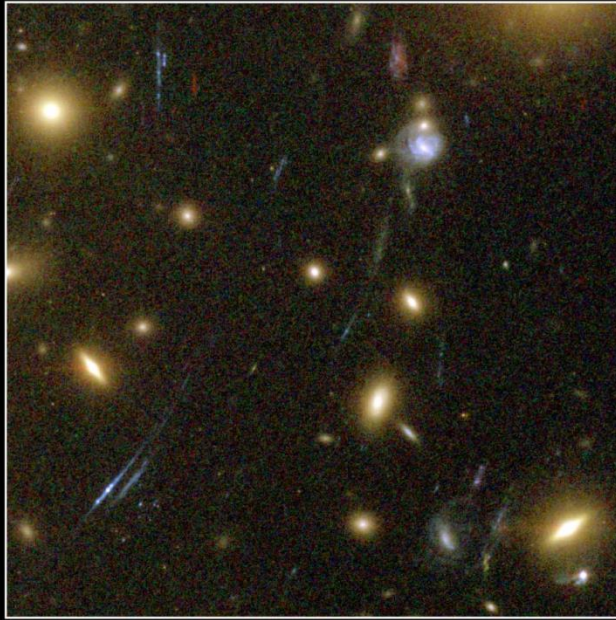
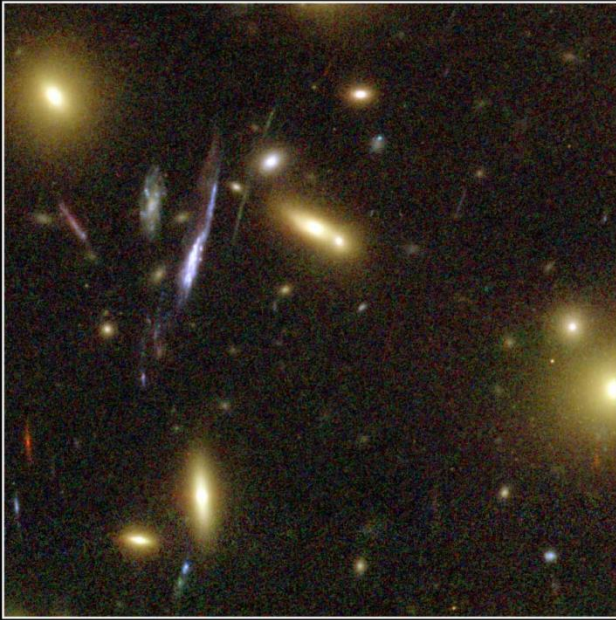
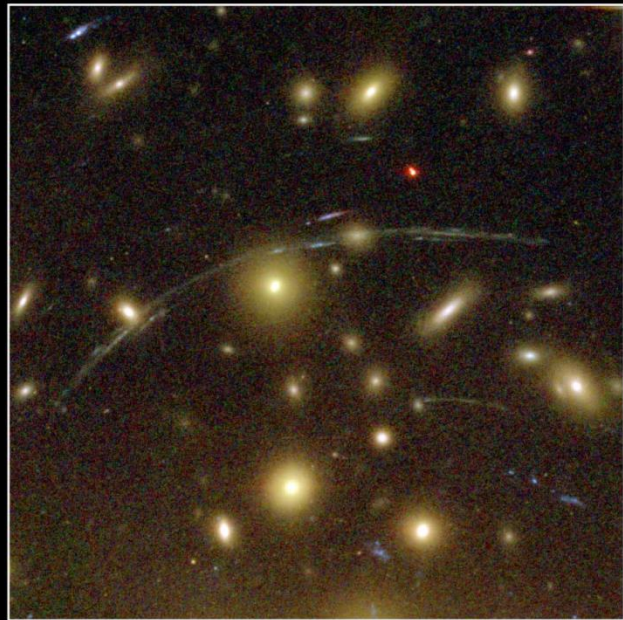
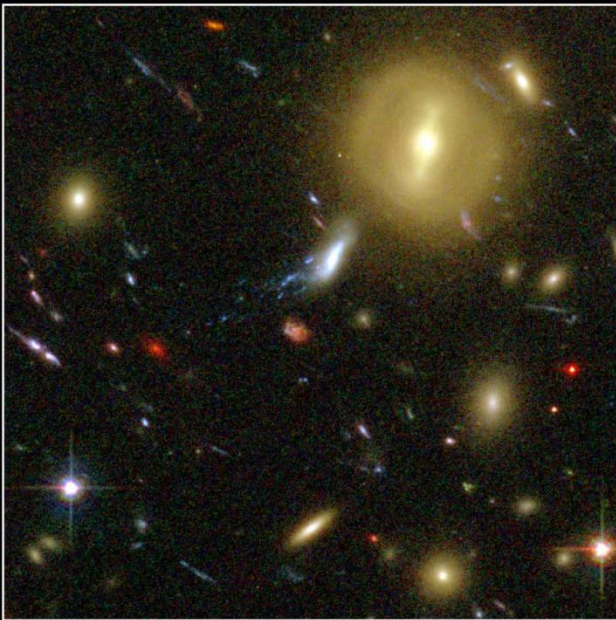
lensed galaxy images

distorted light-rays

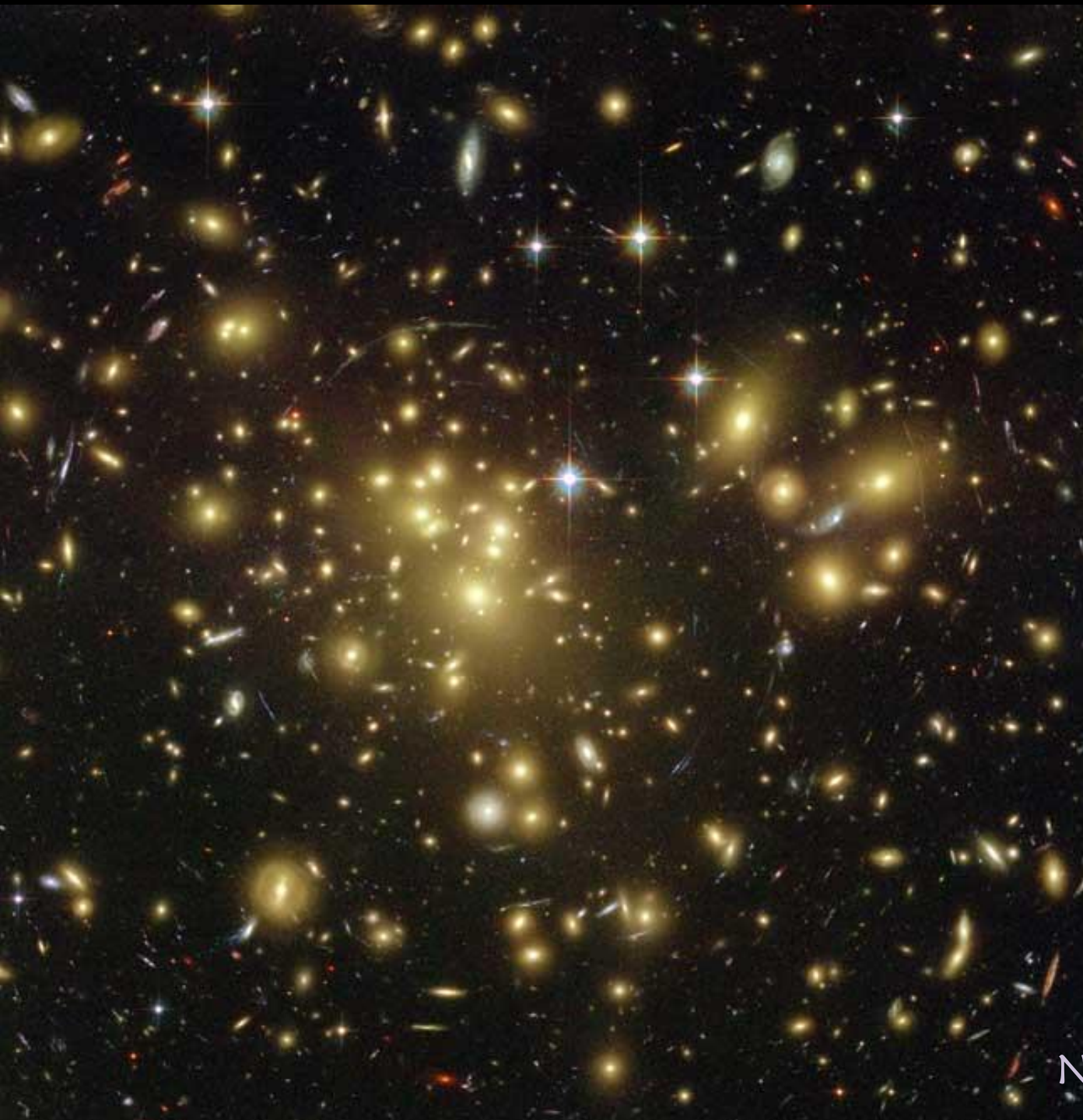
Earth



NASA/ESA/Bradley et al



NASA/ESA/Bradley et al



optical

NASA/STSci/D Coe/ESA



optical
lensing

NASA/STSci/D Coe/ESA



optical

X-ray

lensing

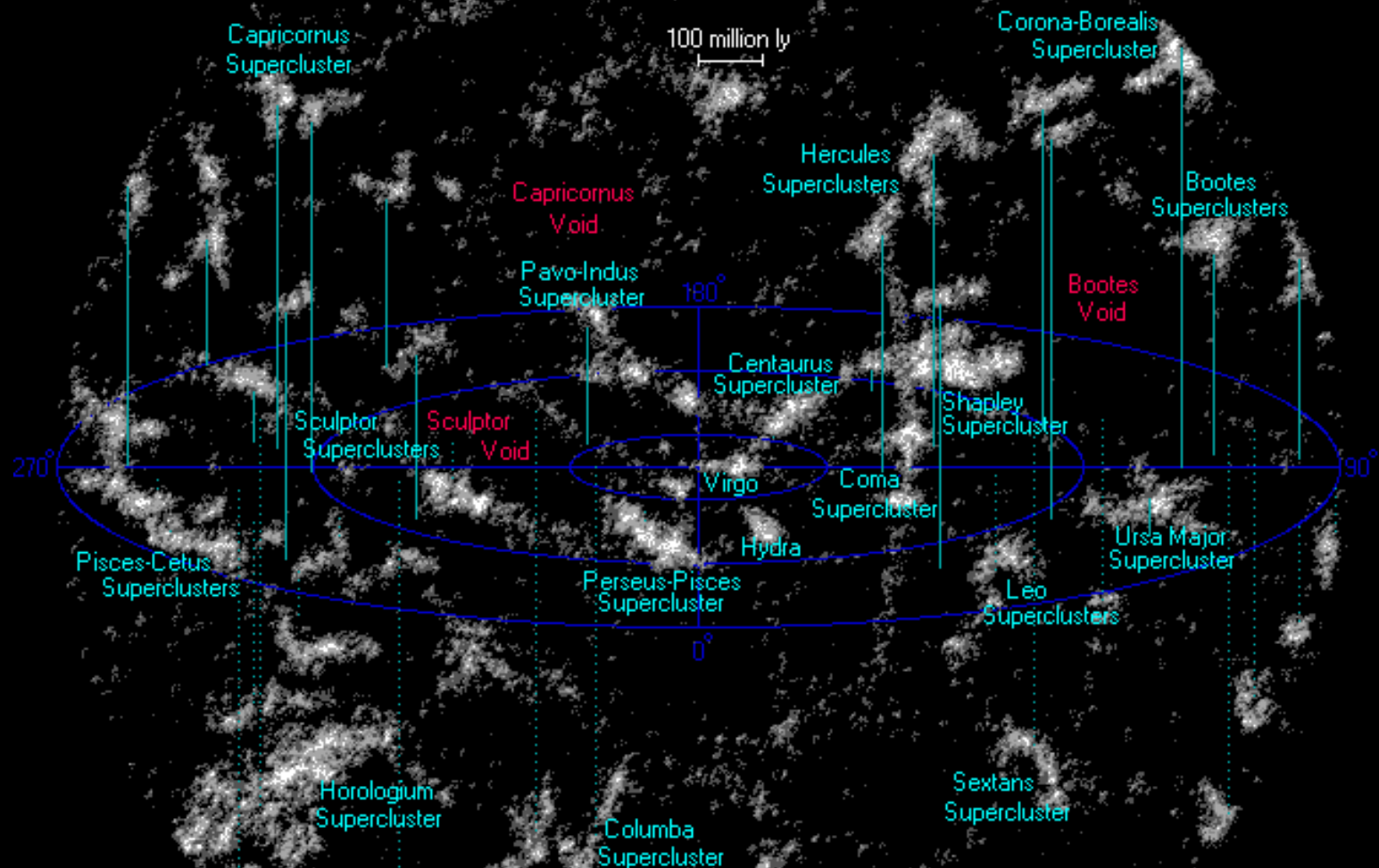
NASA/ESA/HST/Chandra

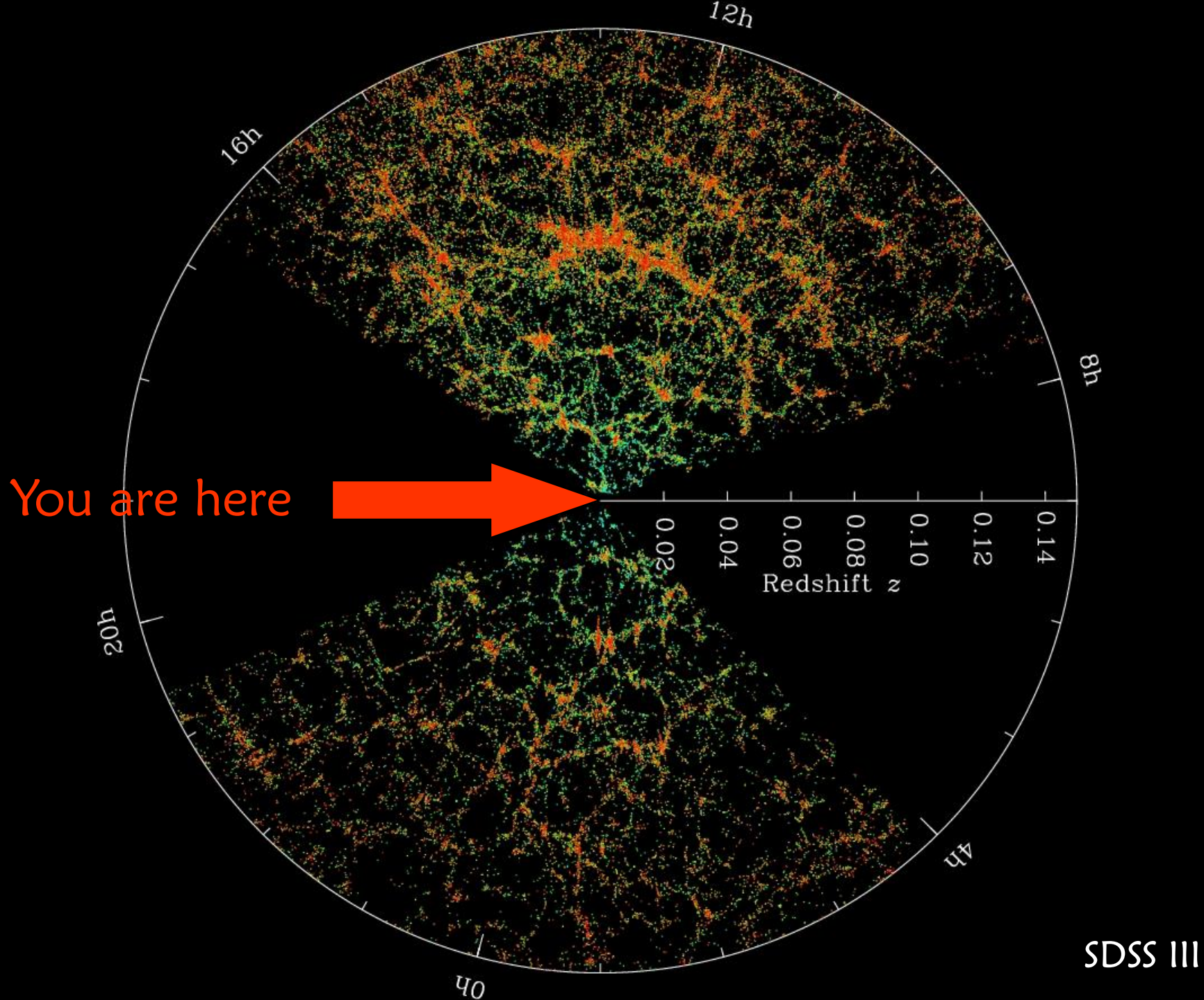
BIG BANG NUCLEOSYNTHESIS



HST/NASA

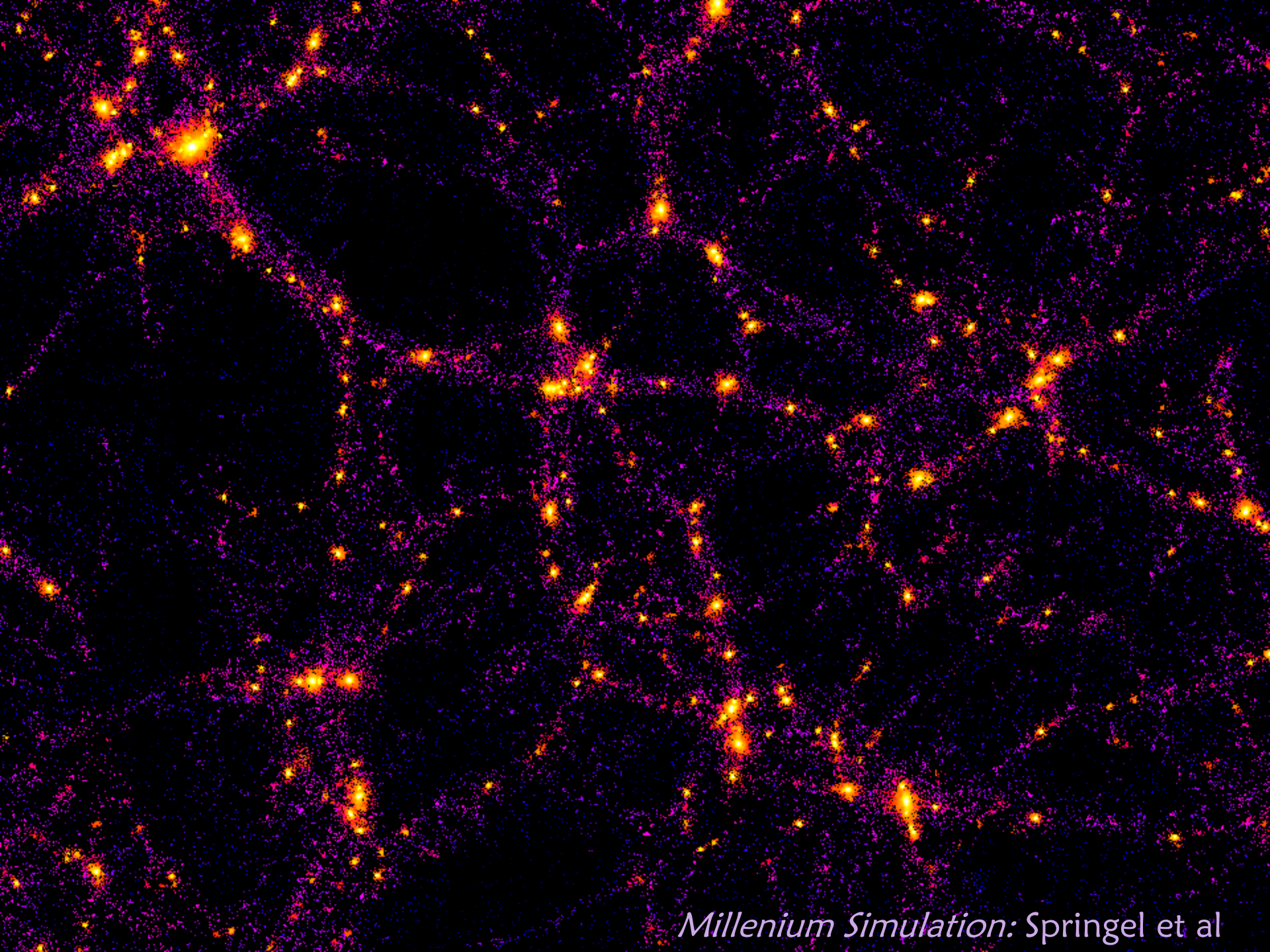
within 1 billion light-years



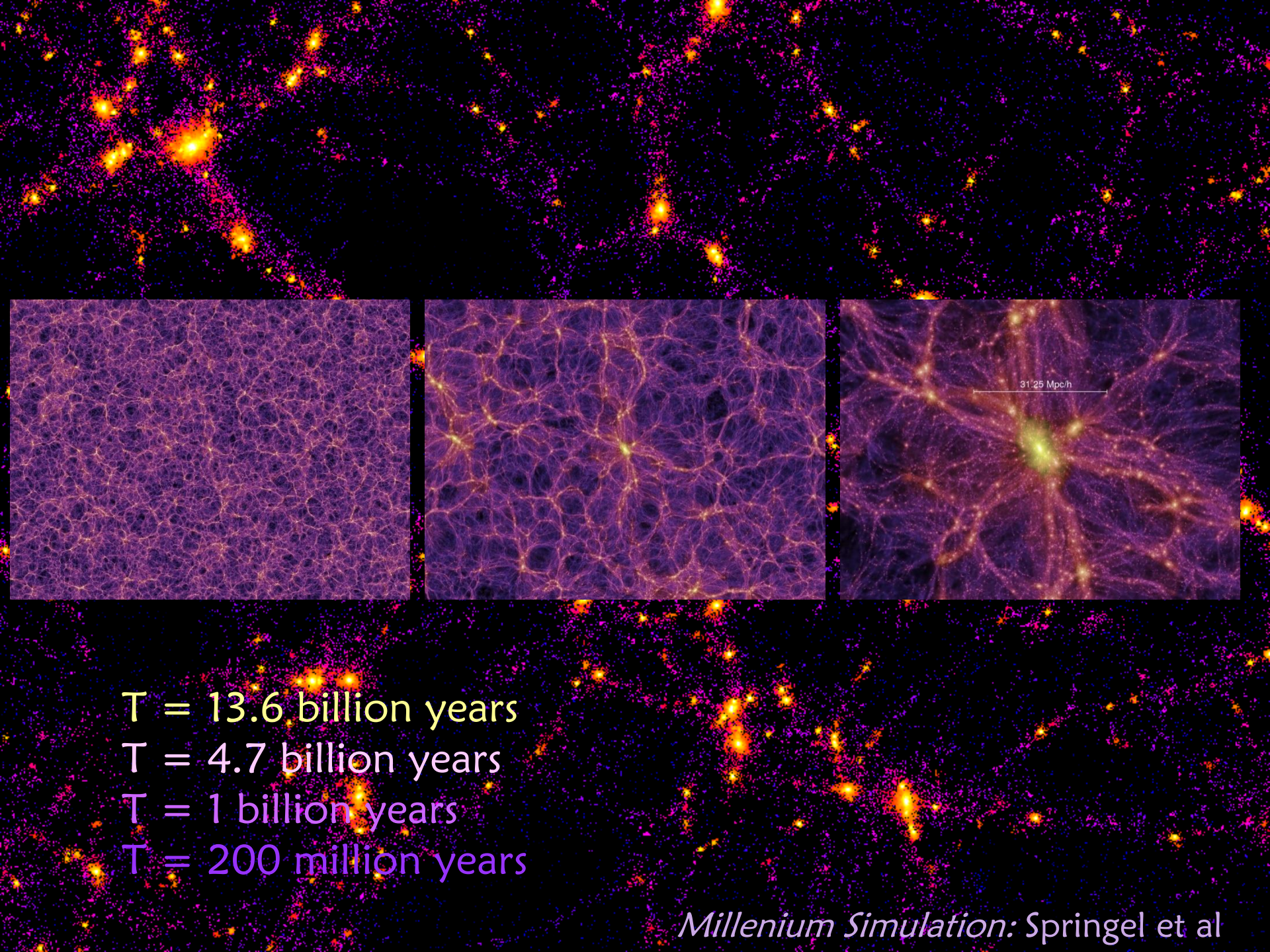




SDSS III/Aragon, SubbaRao & Szalay



Millenium Simulation: Springel et al



$T = 13.6$ billion years

$T = 4.7$ billion years

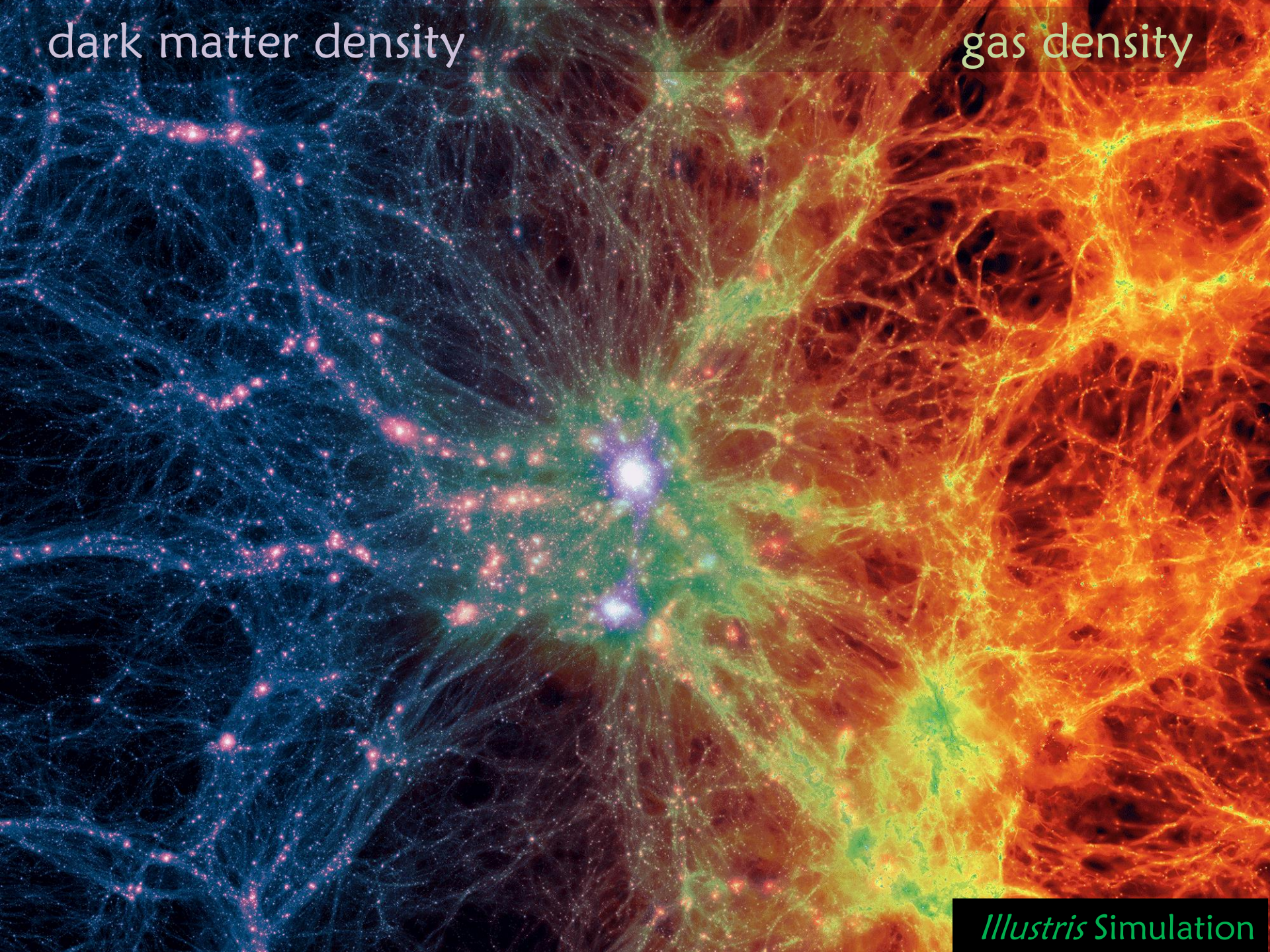
$T = 1$ billion years

$T = 200$ million years

Millennium Simulation: Springel et al

dark matter density

gas density



Illustris Simulation

A detailed visualization of the cosmic web from an Illustris simulation. The image shows a dense network of dark matter filaments in blue and purple, with bright orange and yellow clusters of baryonic matter (galaxies and gas) at the intersections and along the filaments. The overall structure is a complex, interconnected web of matter.

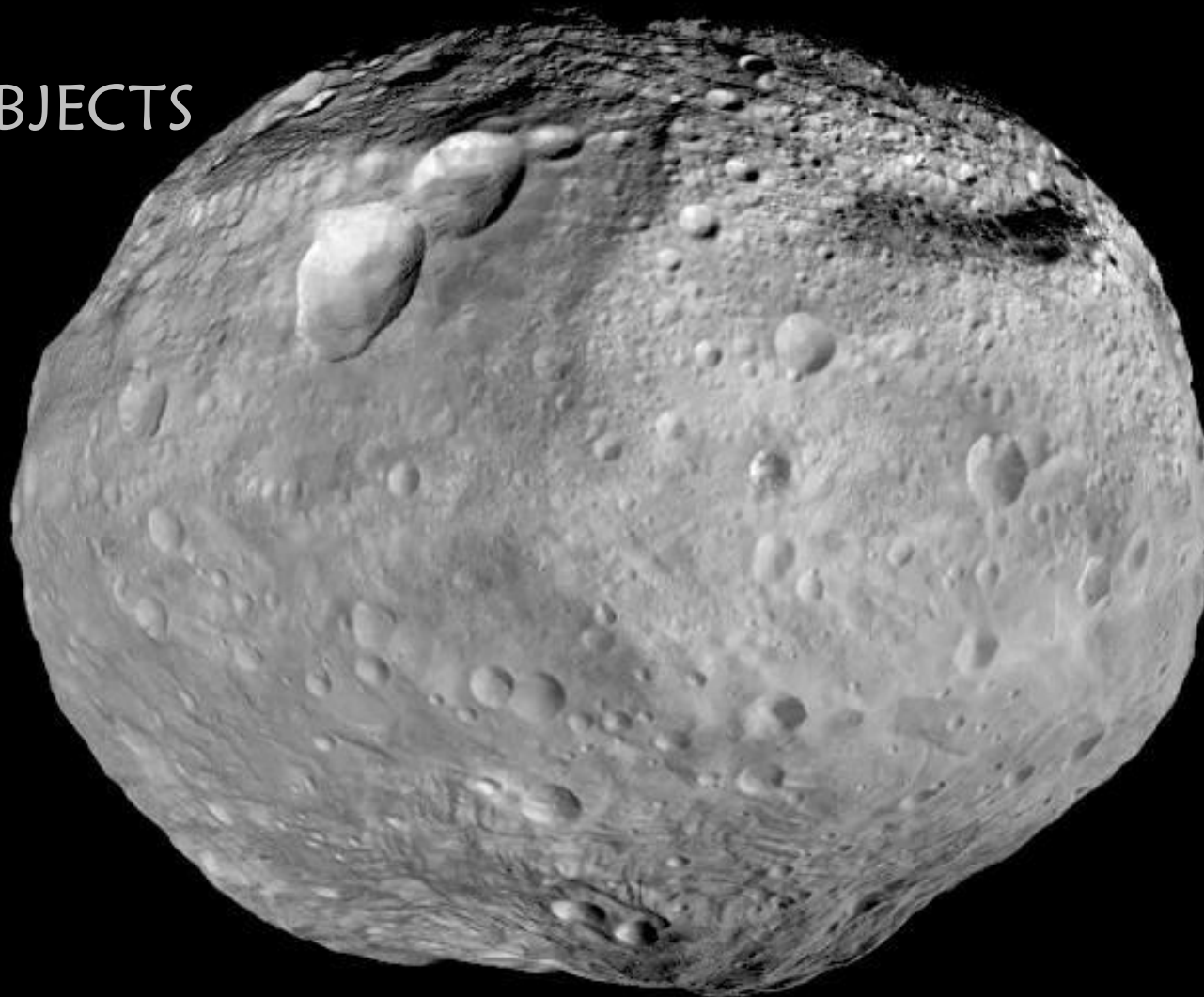
DARK MATTER CAN BE...

BARYONIC

NOT BARYONIC

BARYONIC DARK MATTER

ROCKY OBJECTS

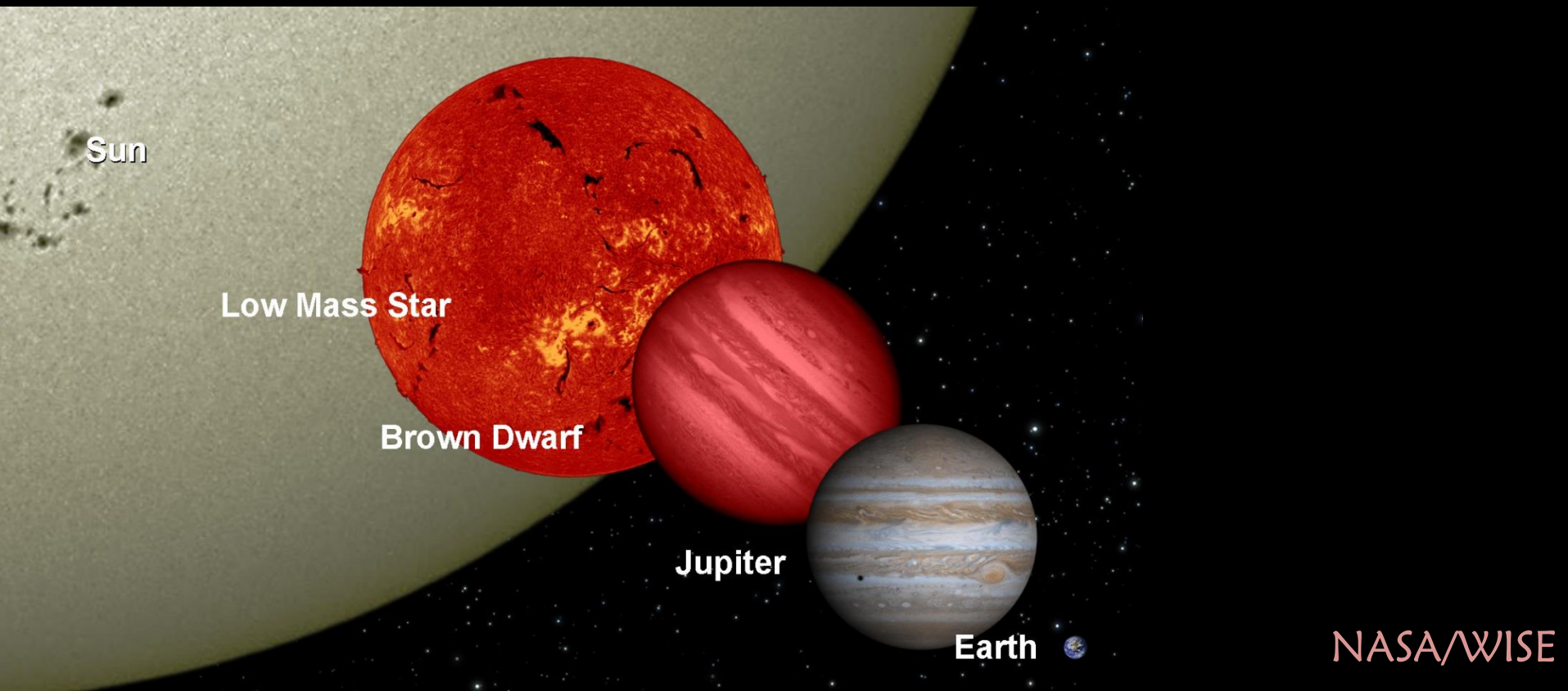


NASA/JPL-Caltech/UCLA

BARYONIC DARK MATTER

ROCKY OBJECTS

BROWN DWARFS



BARYONIC DARK MATTER

ROCKY OBJECTS

BROWN DWARFS

STELLAR REMNANTS

BARYONIC DARK MATTER

ROCKY OBJECTS

BROWN DWARFS

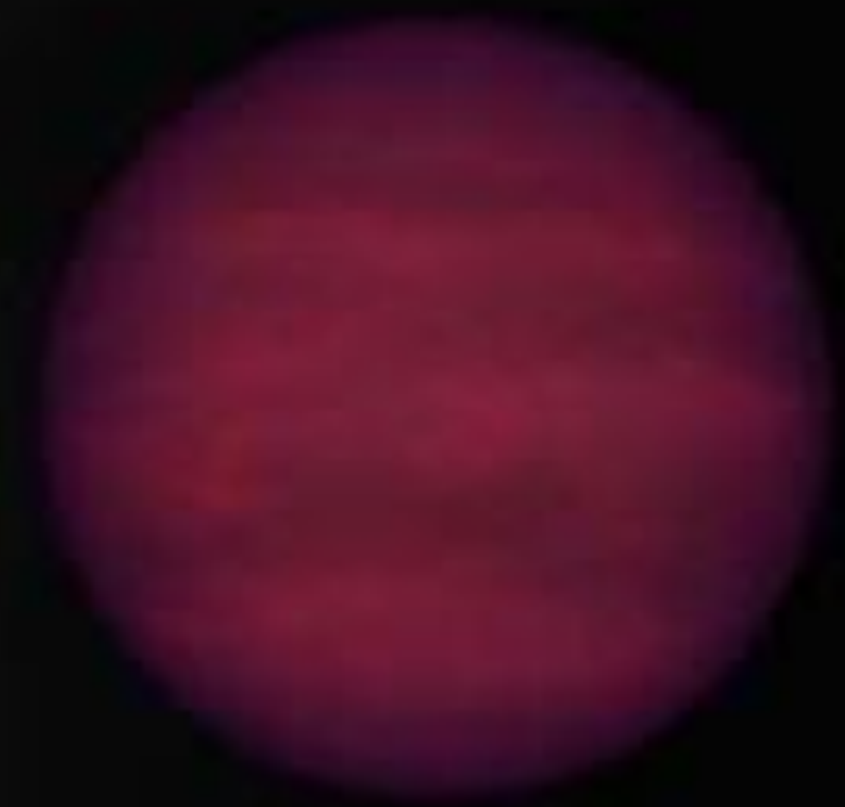
STELLAR REMNANTS

BARYONIC DARK MATTER

~~ROCKY OBJECTS~~

BROWN DWARFS

~~STELLAR REMNANTS~~



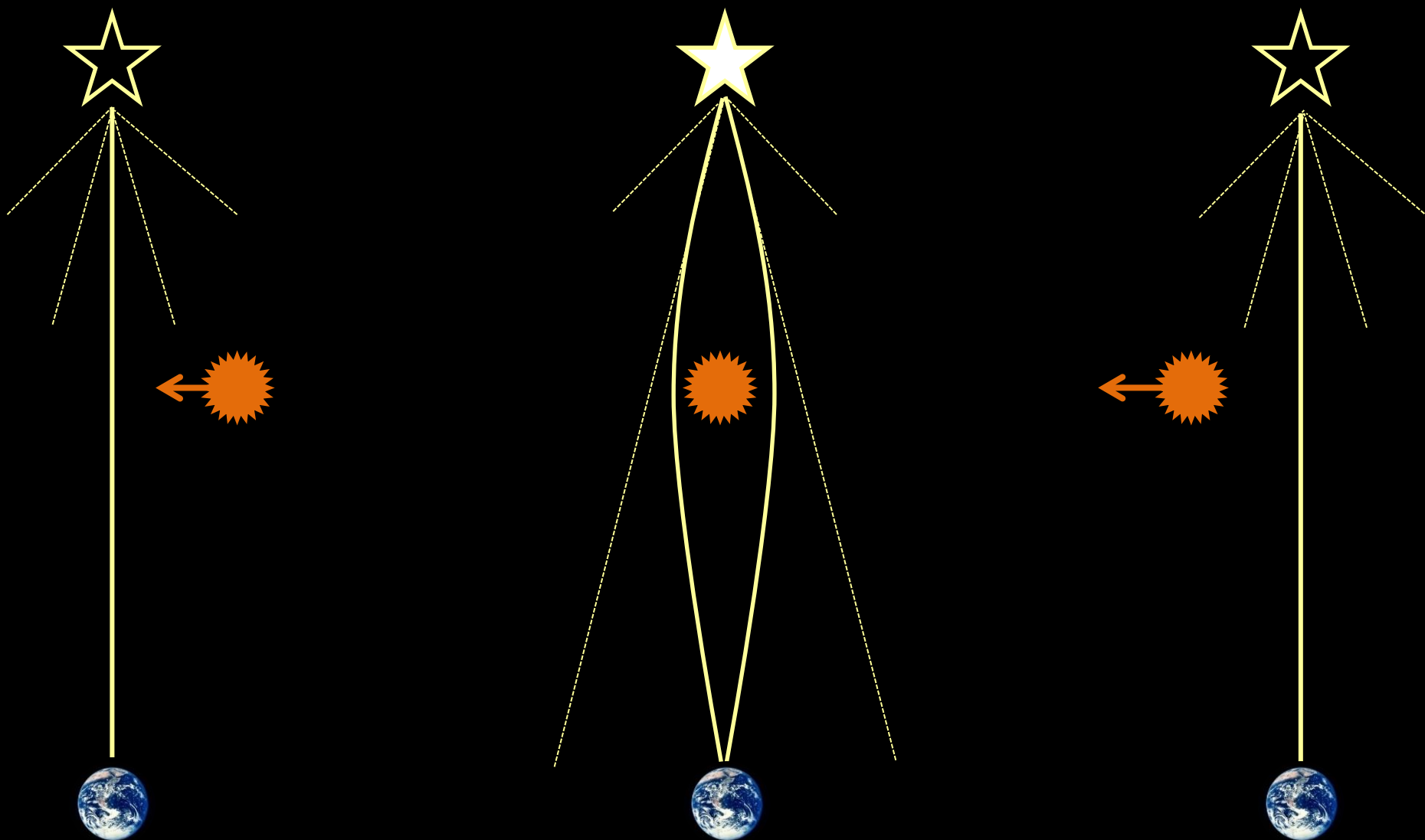
BARYONIC DARK MATTER

~~ROCKY OBJECTS~~

~~BROWN DWARFS~~

~~STELLAR REMNANTS~~

magnification



BARYONIC DARK MATTER

~~BARYONIC DARK MATTER~~

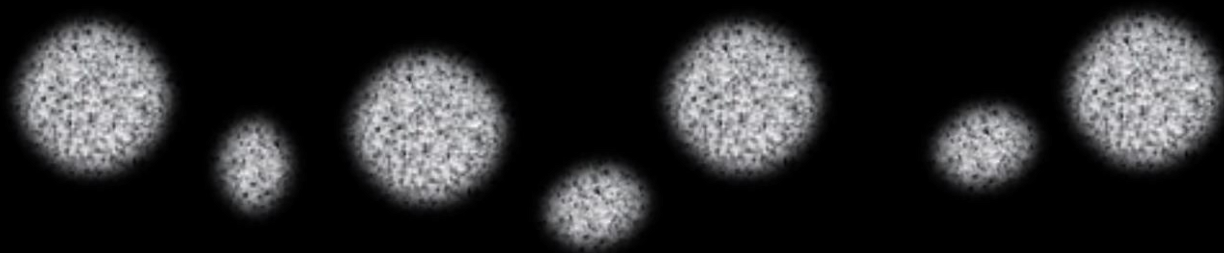
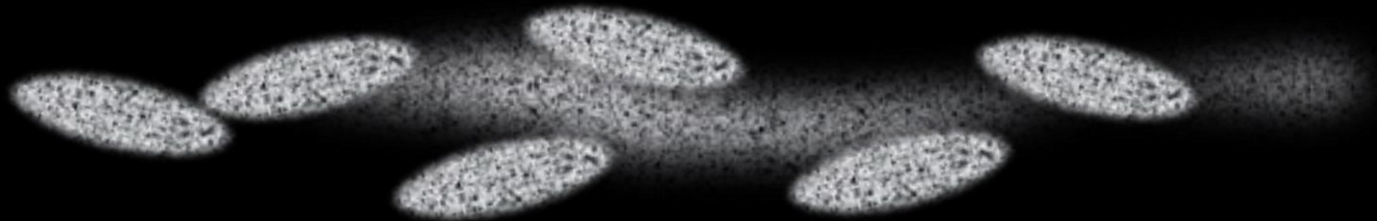
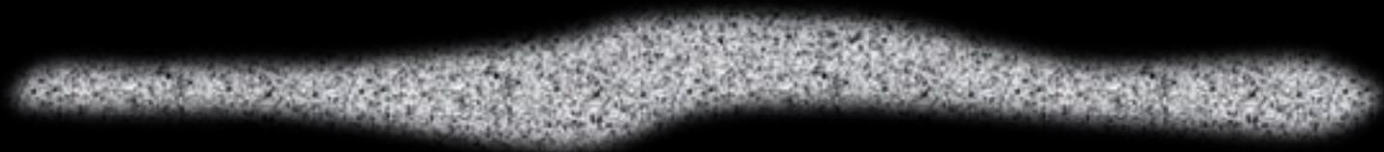
NON-BARYONIC DARK MATTER

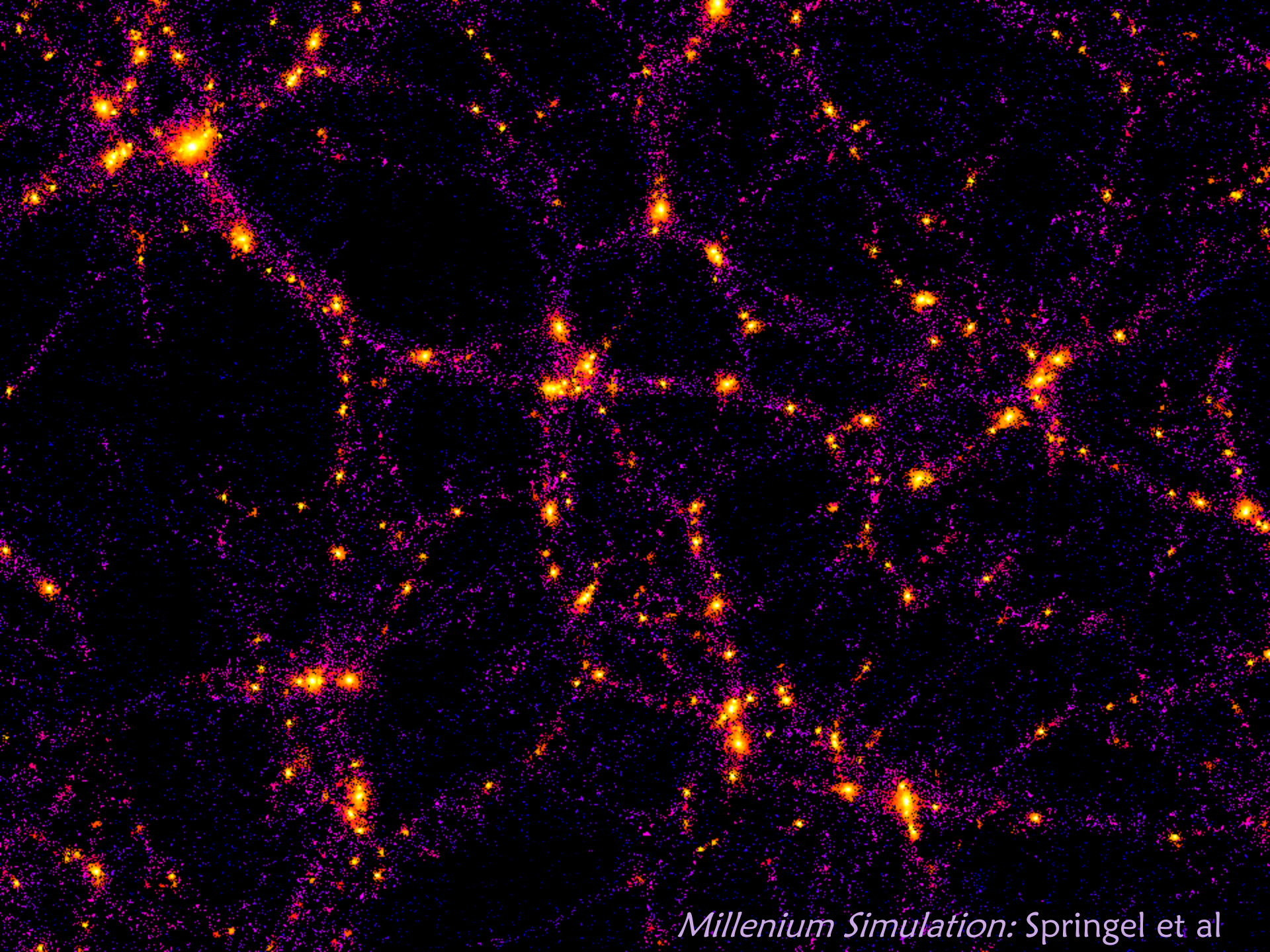
- ✓ EXPERIENCES GRAVITY
- ✓ WILL REACT TO WEAK FORCE
- ✓ DOES NOT REACT TO E-M FORCE
- ✓ DOES NOT RESPOND TO STRONG FORCE

- ENOUGH MASS?
- TRAVELS TOO FAST!



neutrino





Millenium Simulation: Springel et al



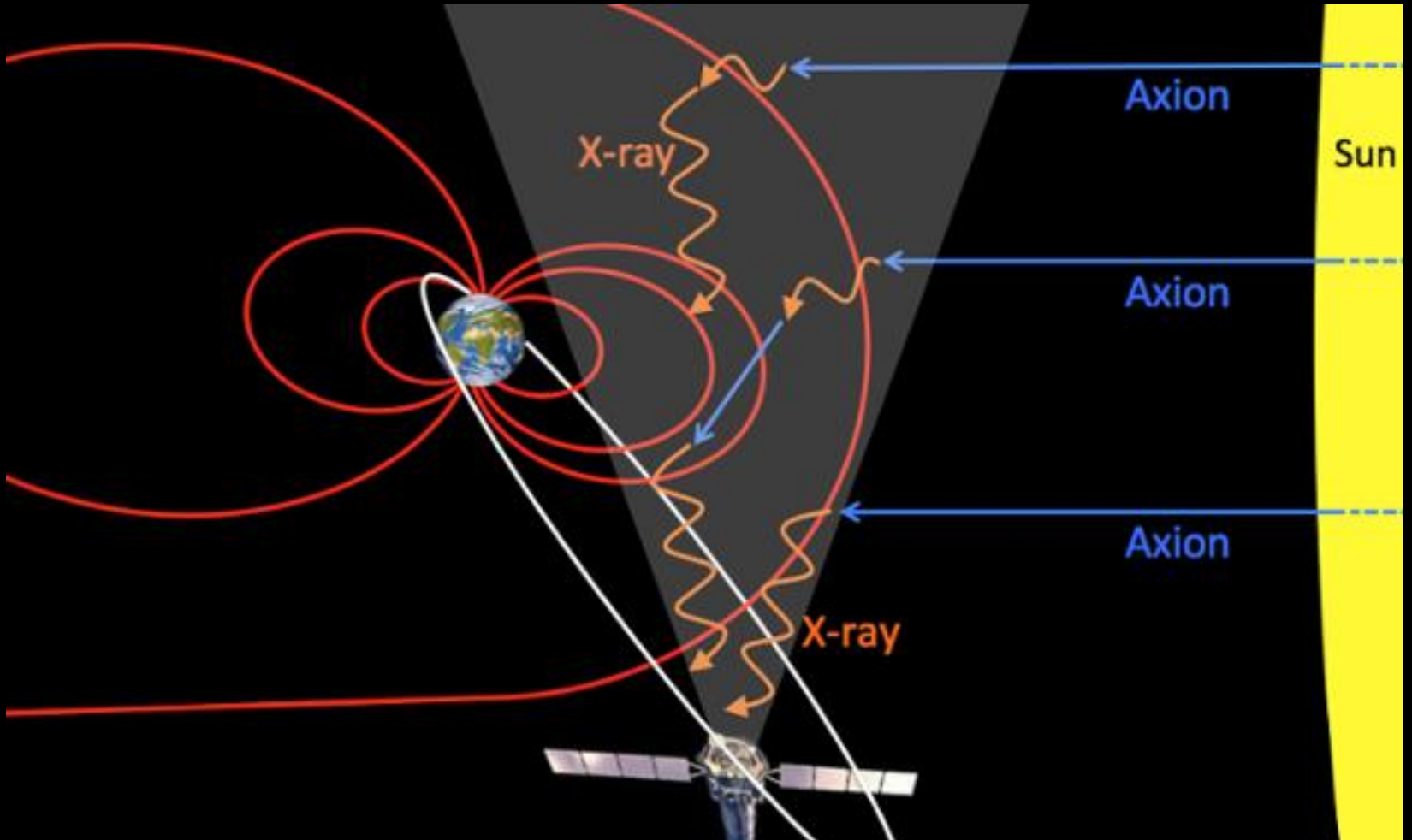
NON-BARYONIC DARK MATTER

- ✓ EXPERIENCES GRAVITY
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- ✓ DOES NOT REACT TO E-M FORCE
- ✓ DOES NOT RESPOND TO STRONG FORCE

- ENOUGH MASS?
- TRAVELS TOO FAST!



AXIONS



WIMPS...

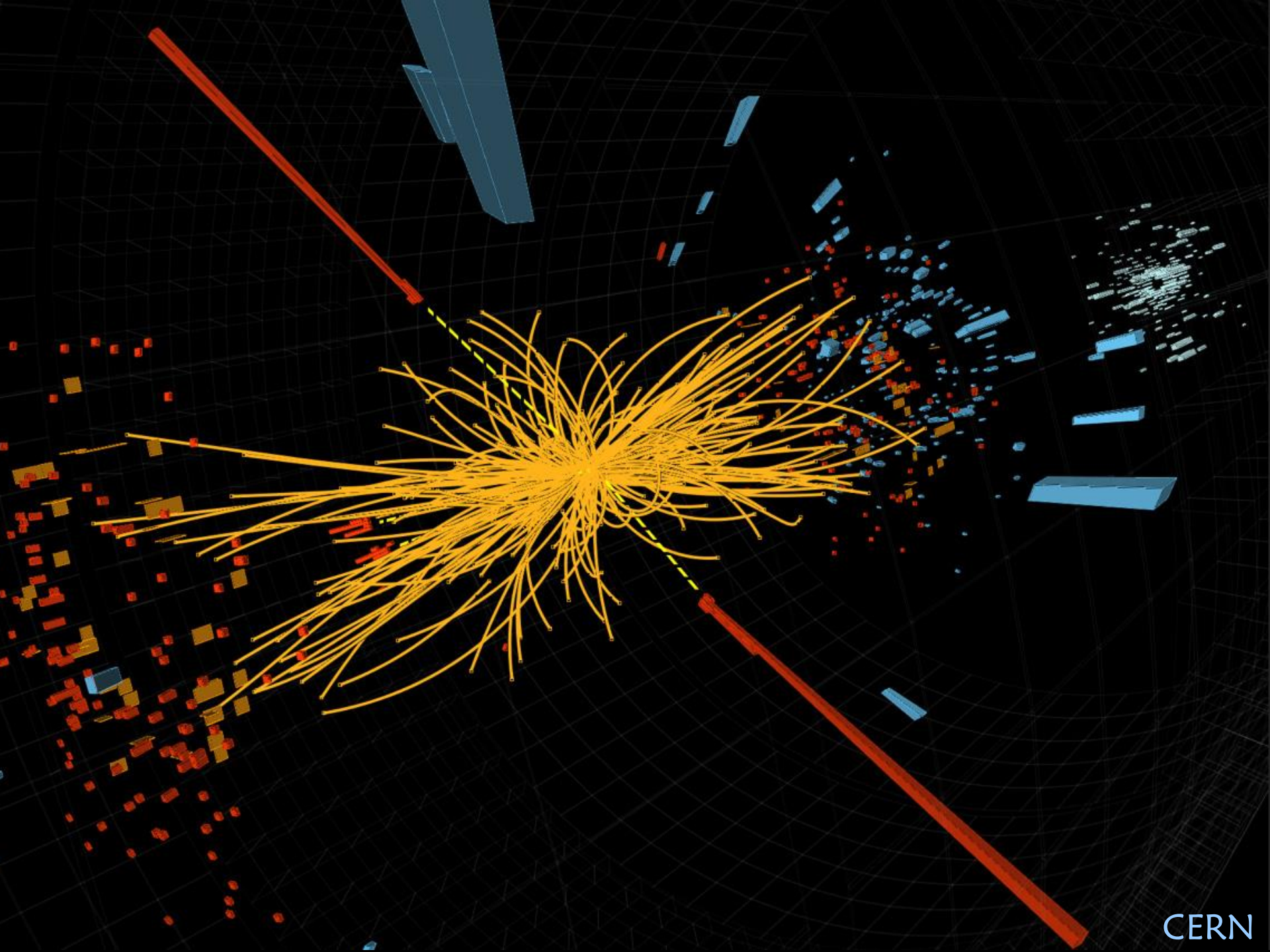
WEAKLY INTERACTING MASSIVE PARTICLES

WIMPS...

FROM PARTICLE COLLISIONS

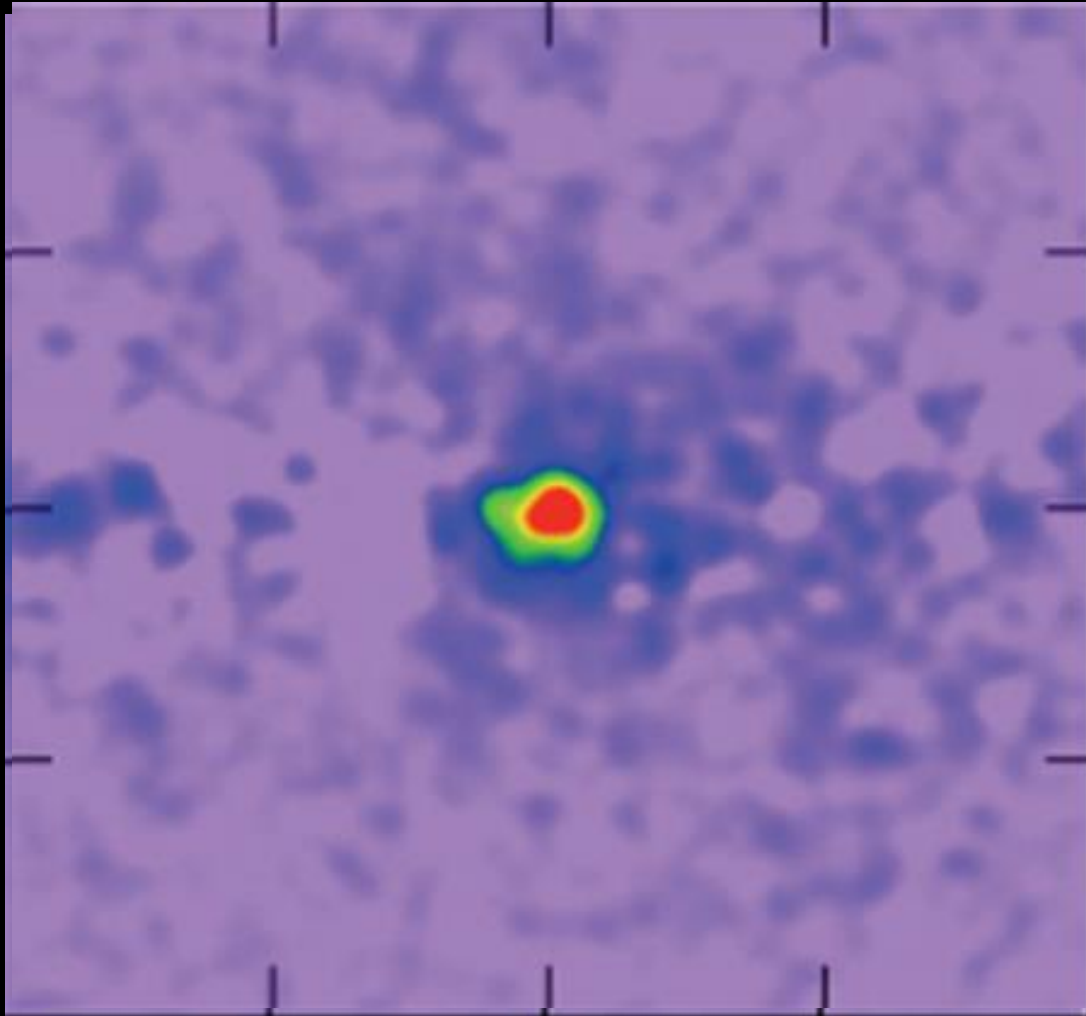


LHC/CERN



WIMPS...

FROM SEARCHES FOR BY-PRODUCTS

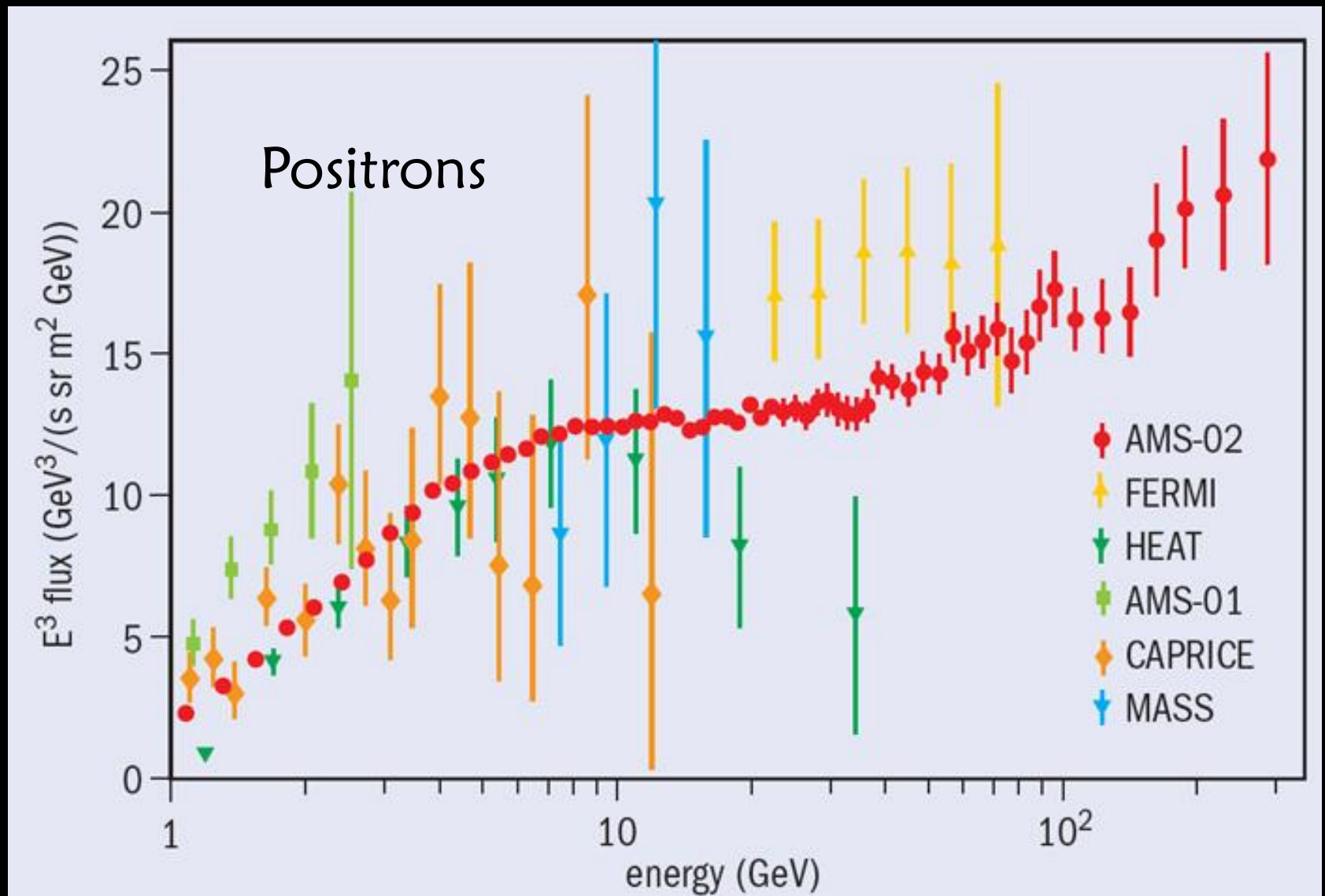


γ -rays from the
centre of the
Galaxy...

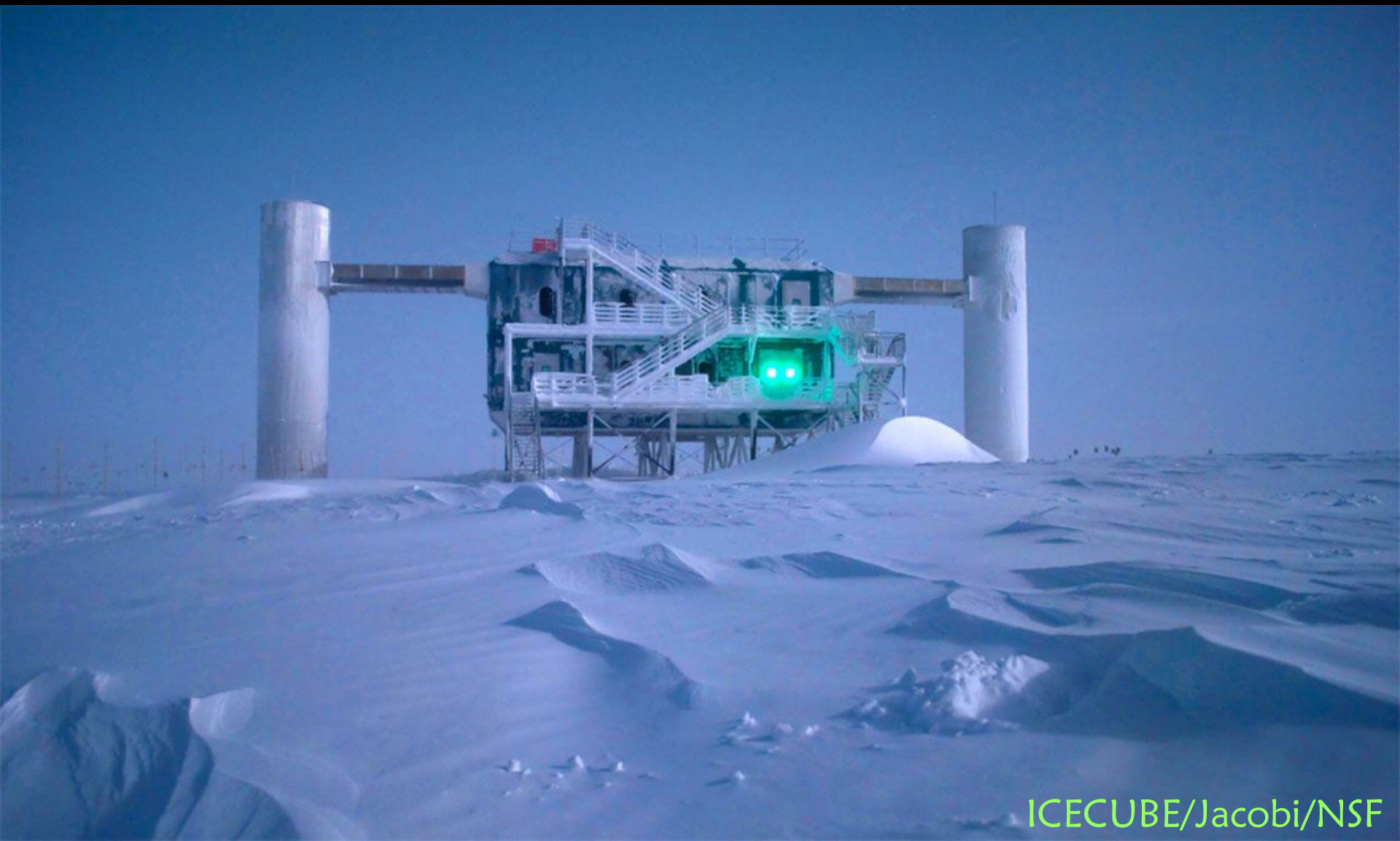
Garan & Expedition 28 crew, NASA

excess of cosmic rays





neutrinos



ICECUBE/Jacobi/NSF

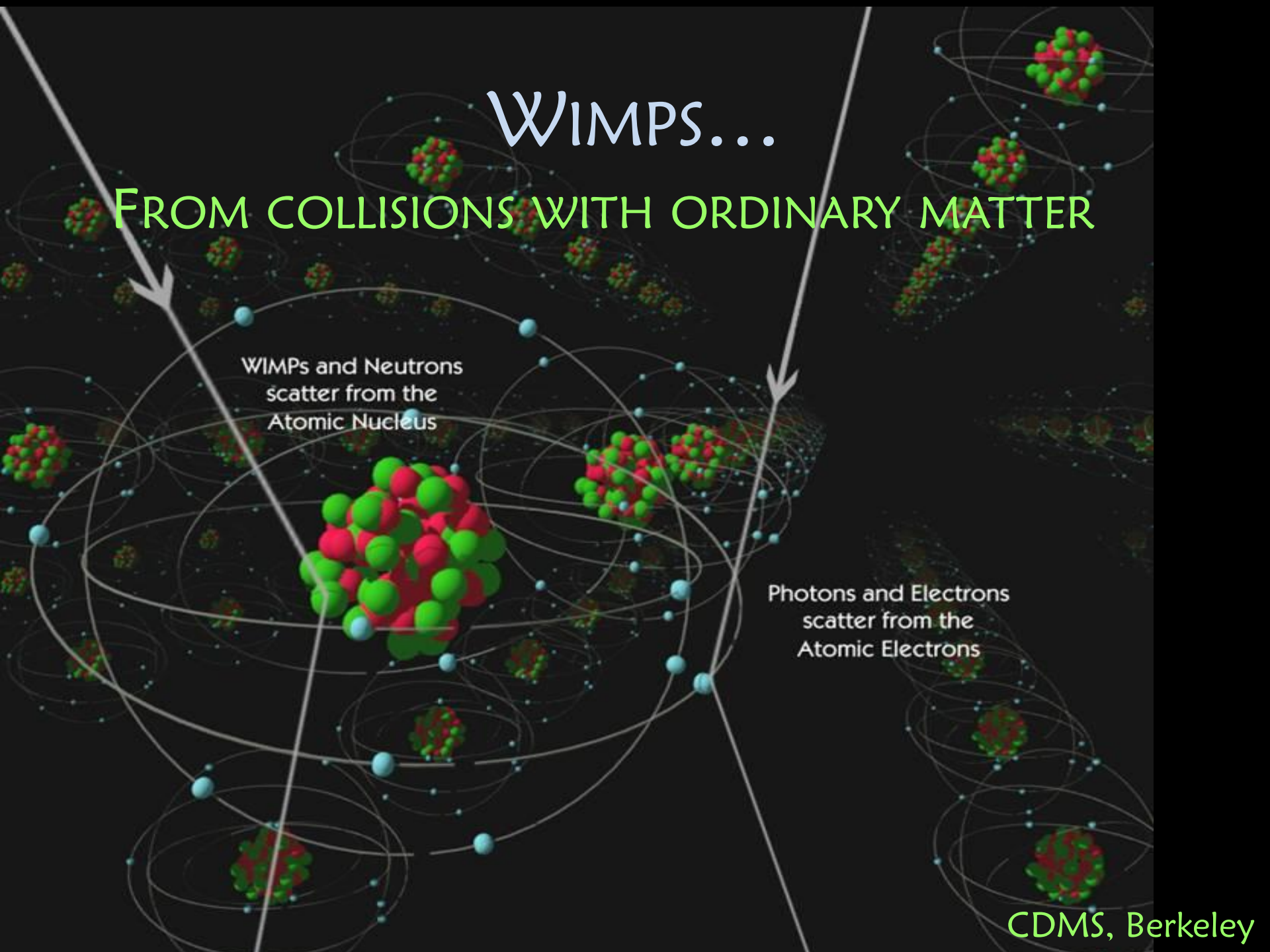
WIMPS...

FROM COLLISIONS WITH ORDINARY MATTER

WIMPs and Neutrons
scatter from the
Atomic Nucleus

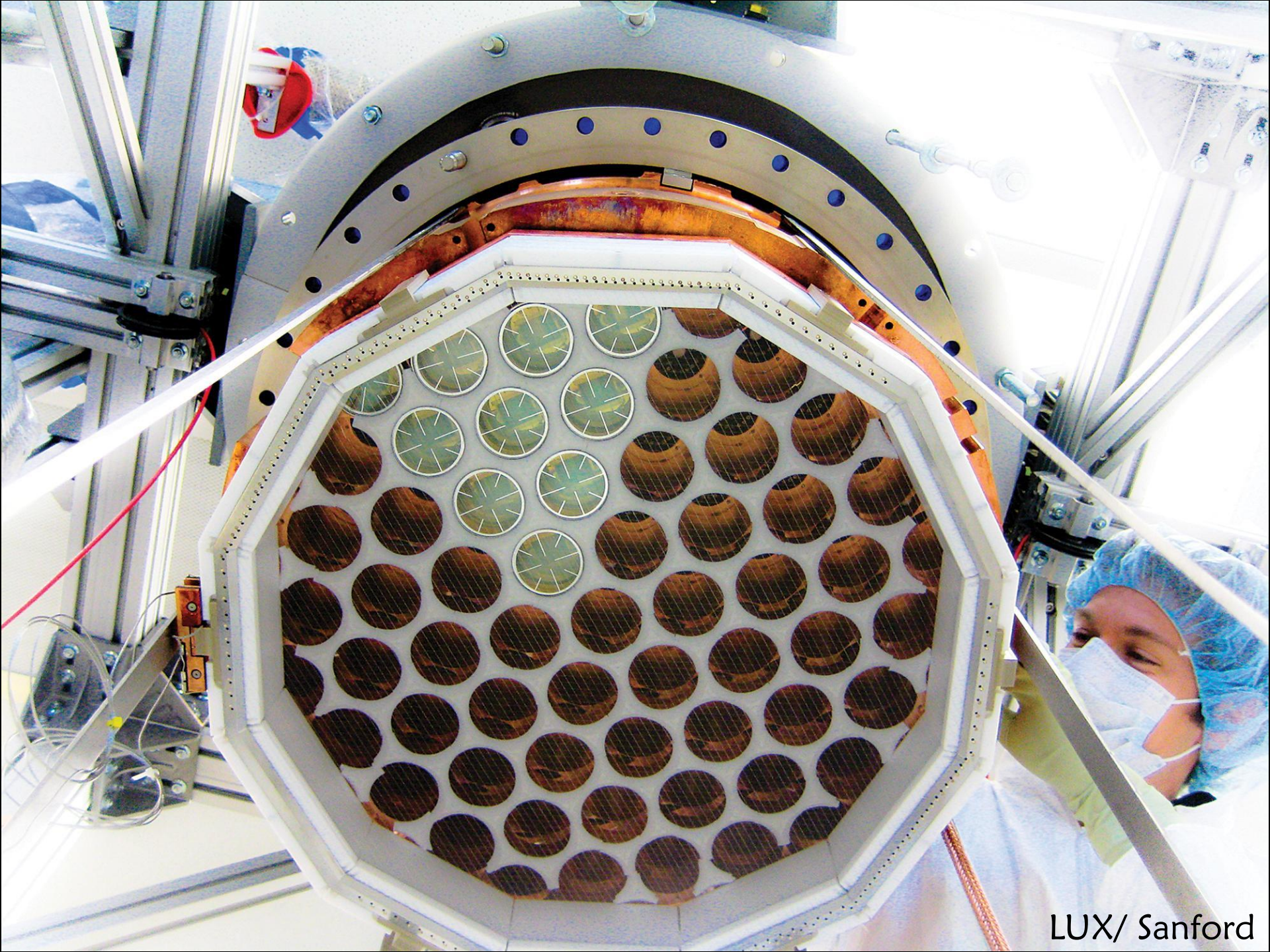
Photons and Electrons
scatter from the
Atomic Electrons

CDMS, Berkeley



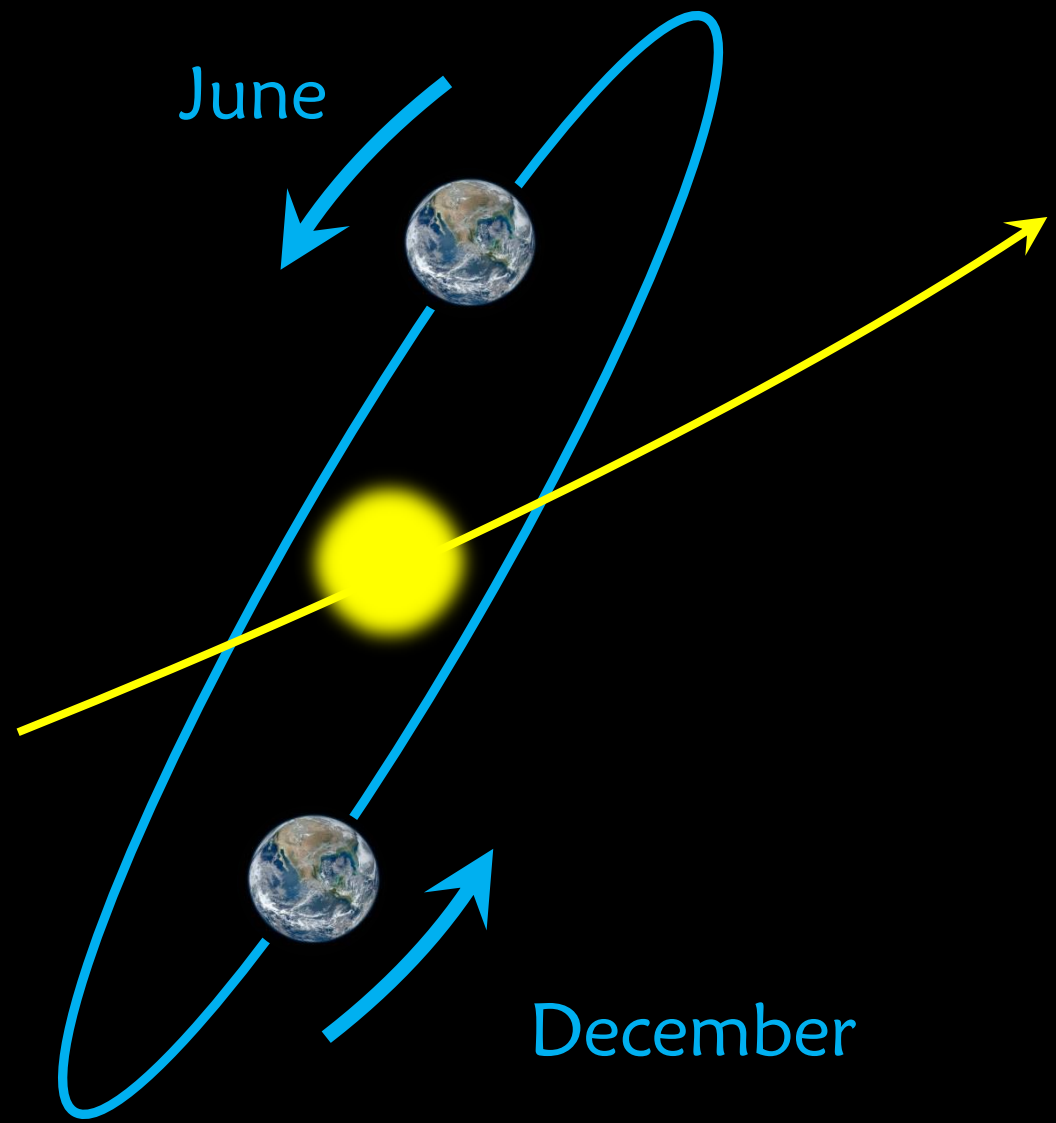
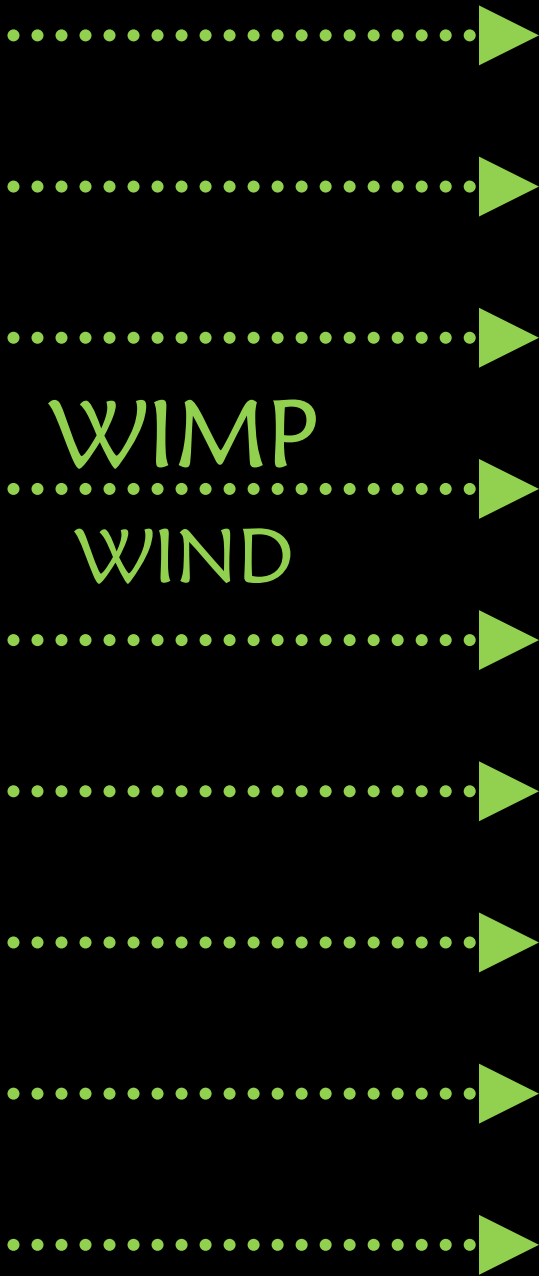


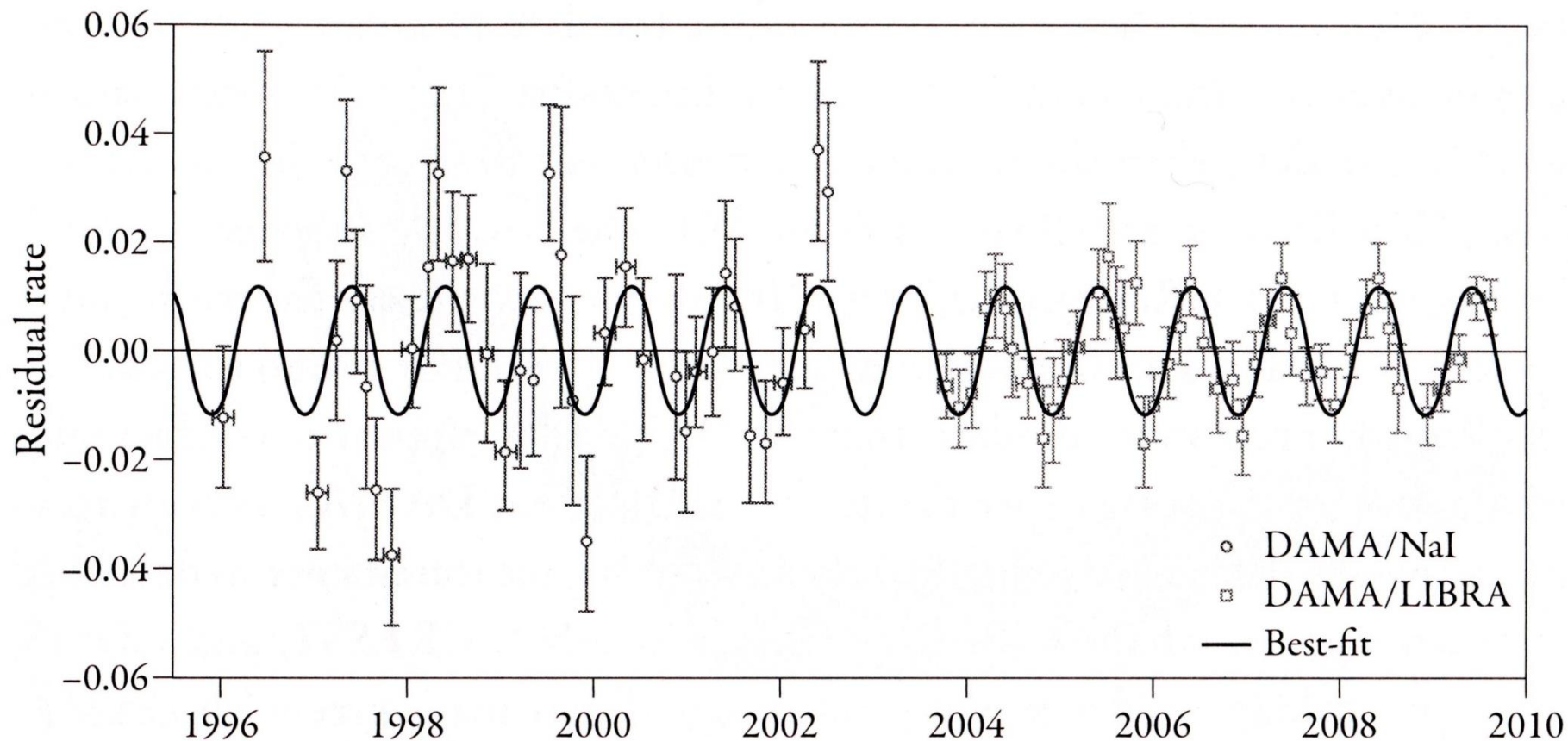
LUX/ Matt Kapust

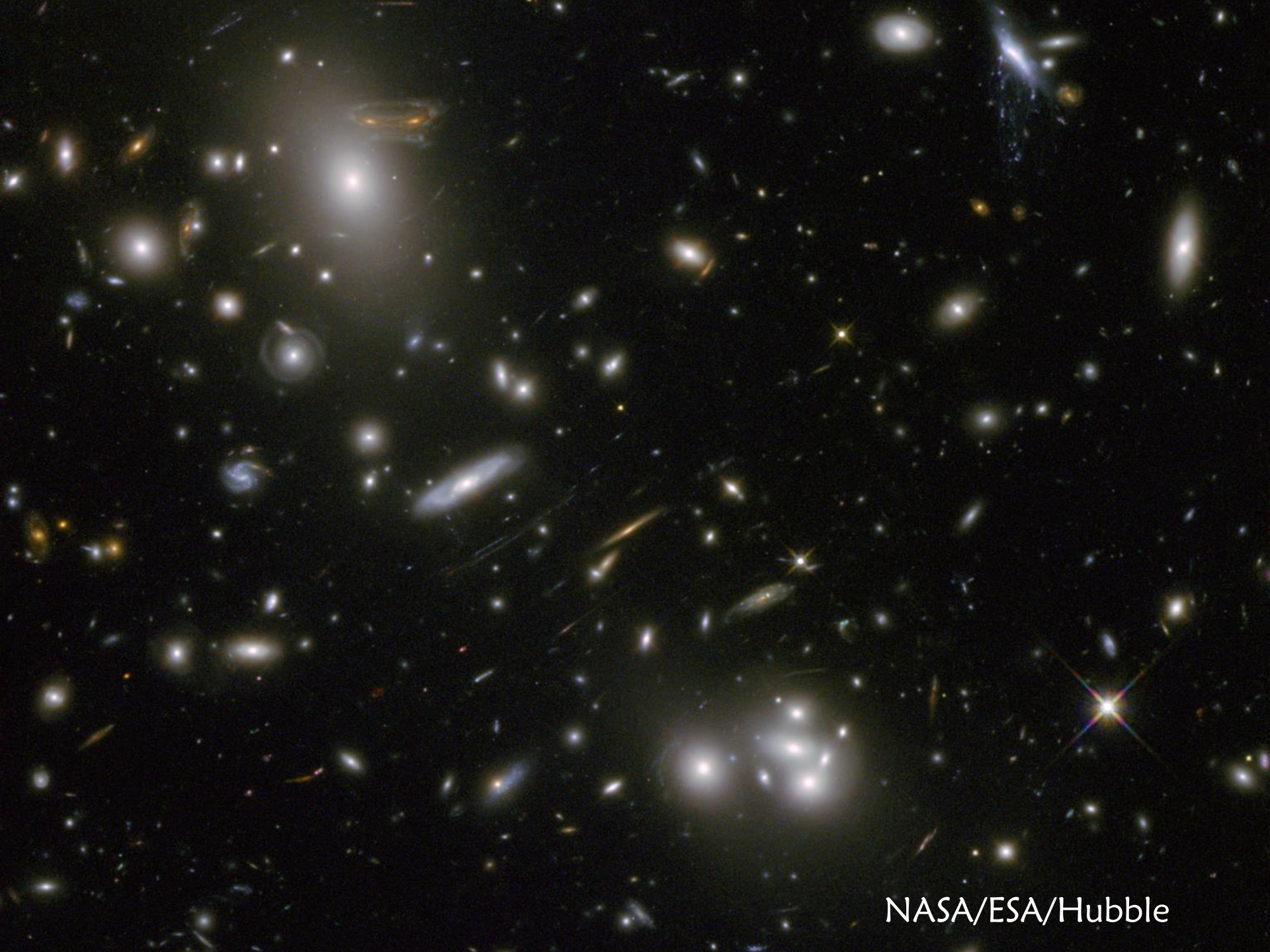


LUX/ Sanford









NASA/ESA/Hubble

THE TRANSIENT UNIVERSE

WEDNESDAY 26TH NOV 2014 1PM



NASA/ESA/France et al