“seeing” the invisible: dark matter & dark energy

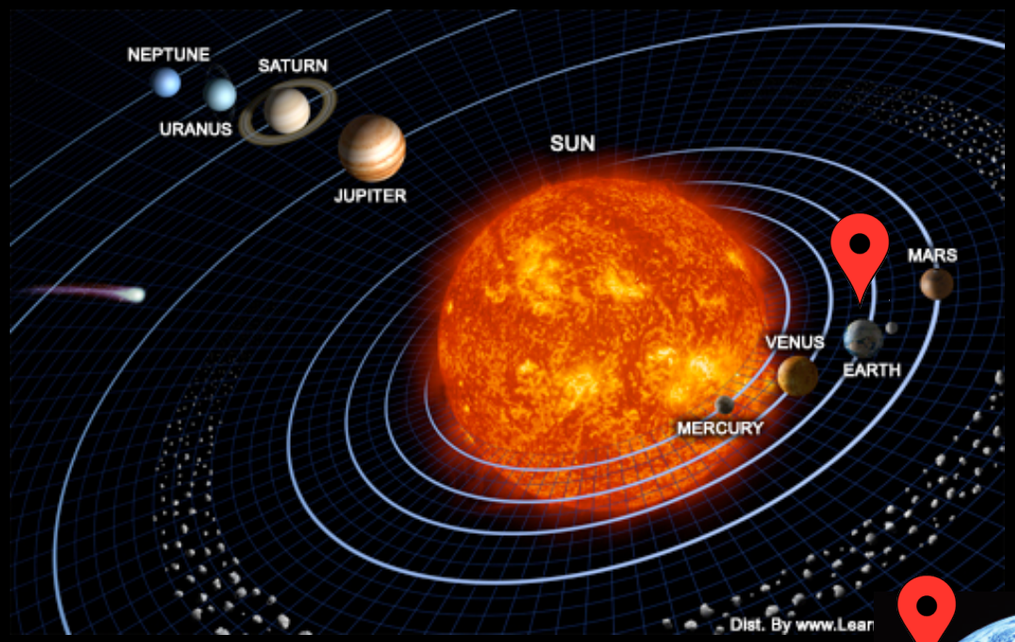
Mustafa A. Amin

RICE

Asst. Professor of Physics and Astronomy

an orientation

we are here


NEPTUNE
SATURN
URANUS
JUPITER
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MARS
VENUS
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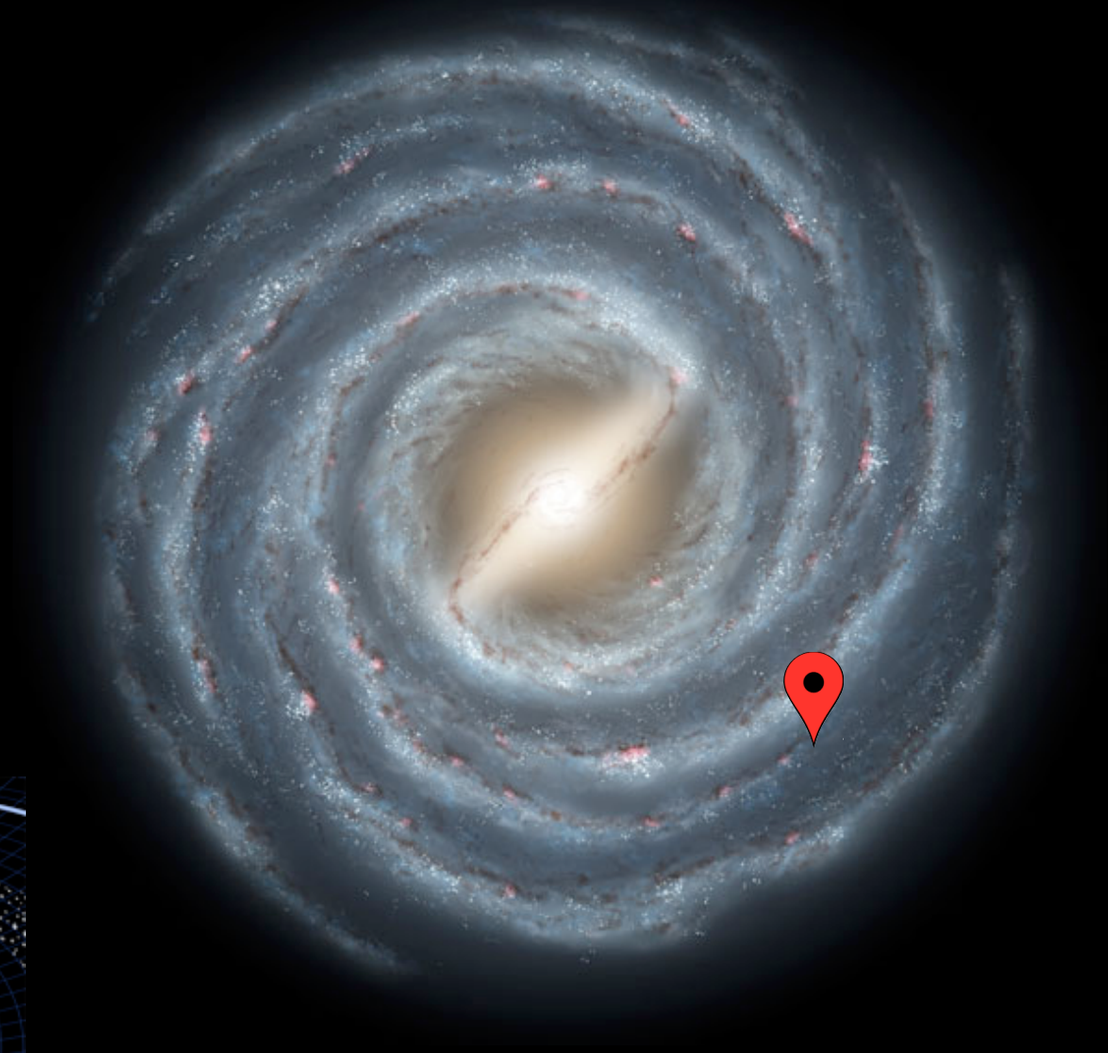
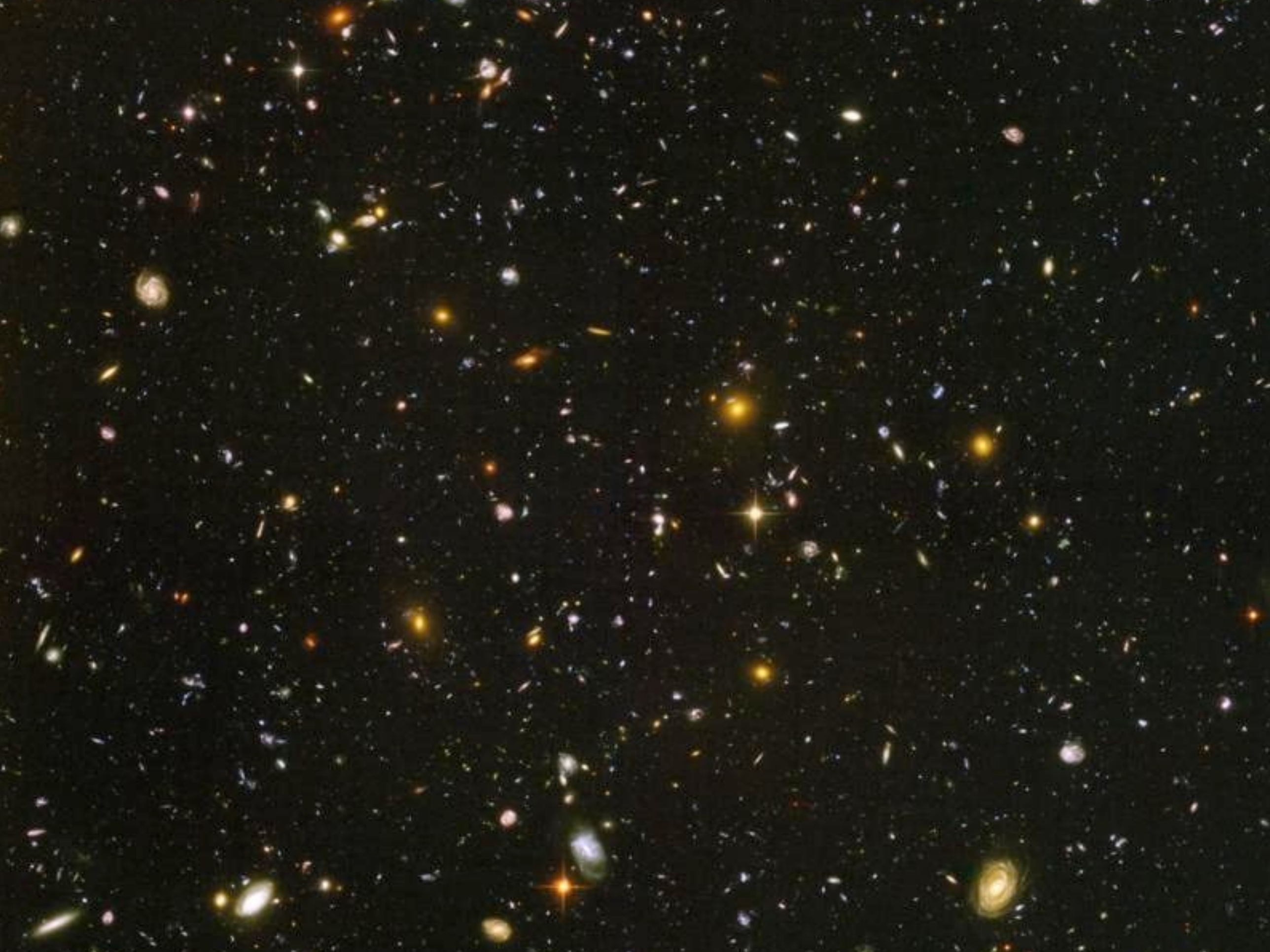
MERCURY
Dist. By www.Lear

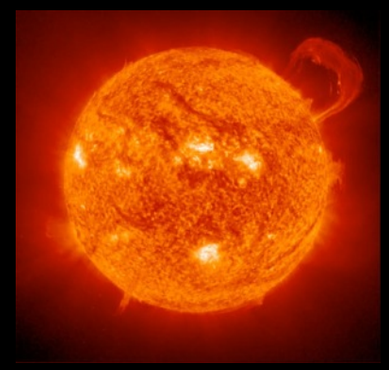


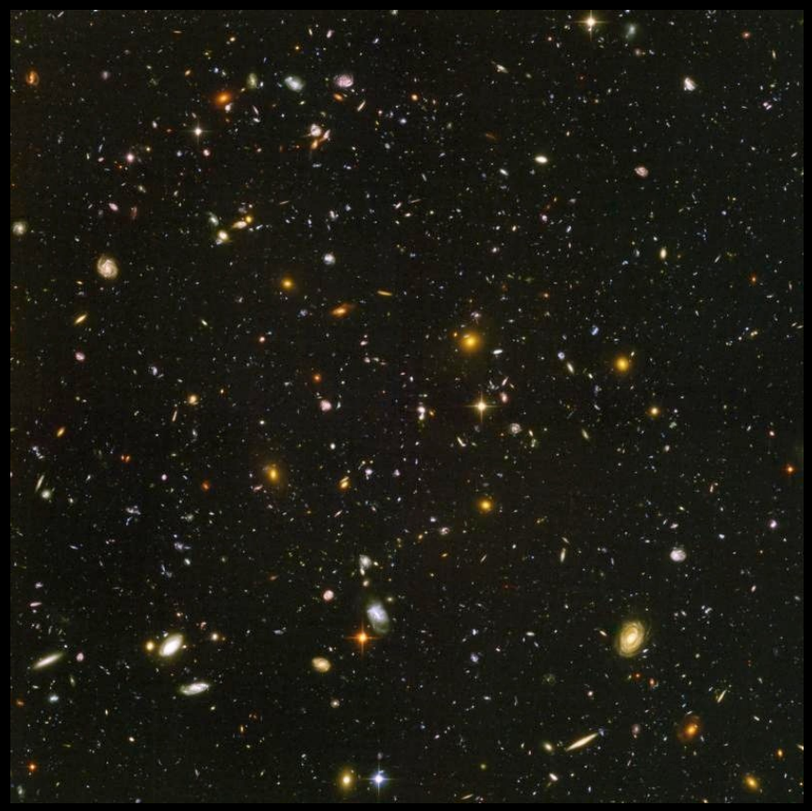
we are here



a lot of stuff !

~ 100 billion

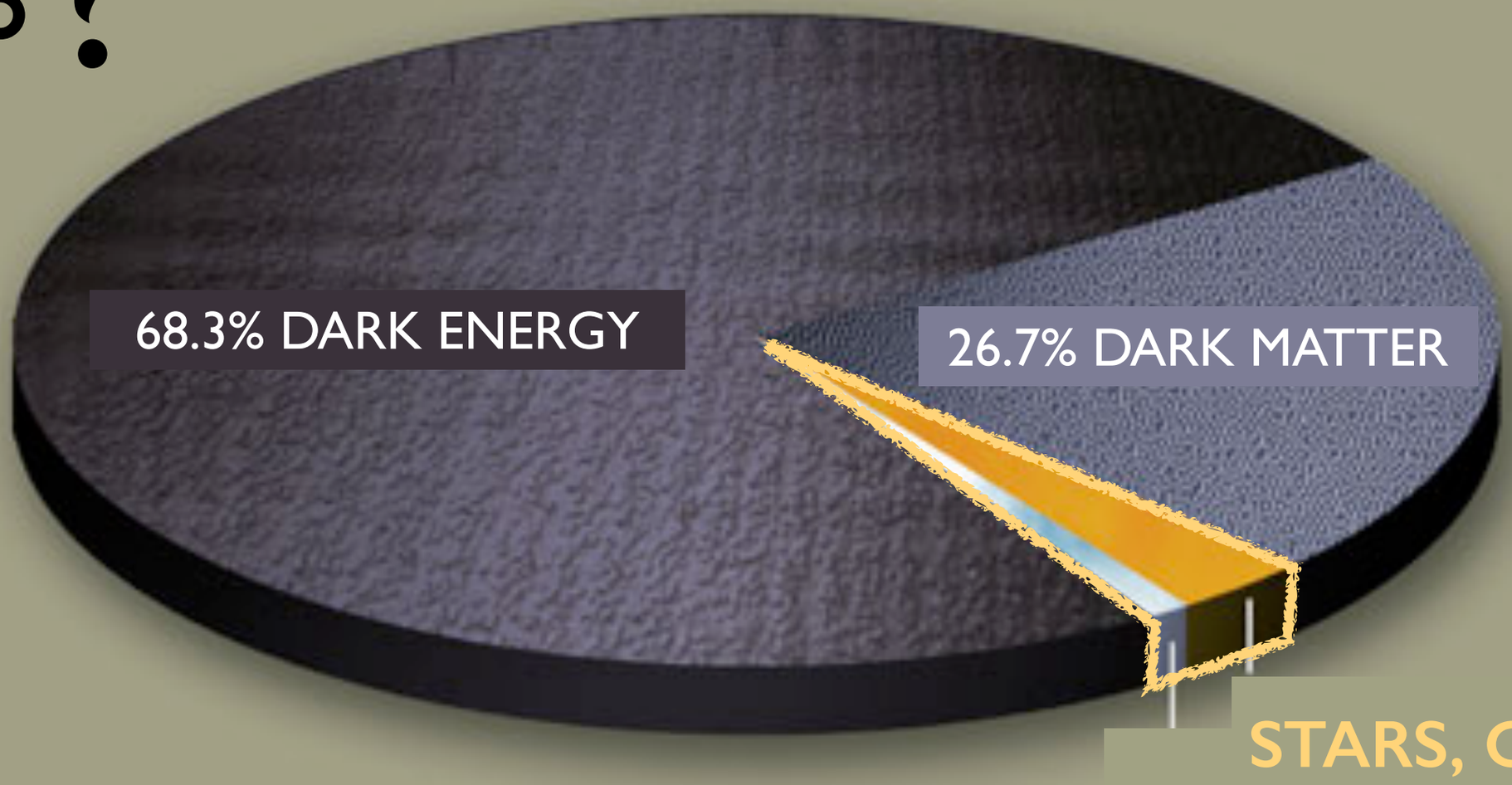




~ 100 billion

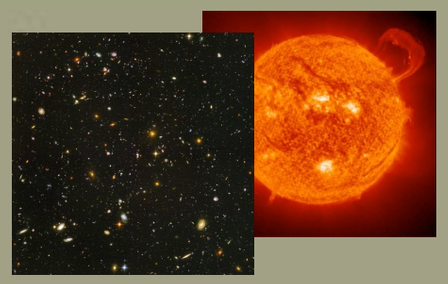
all this "stuff" — 5%

95%?



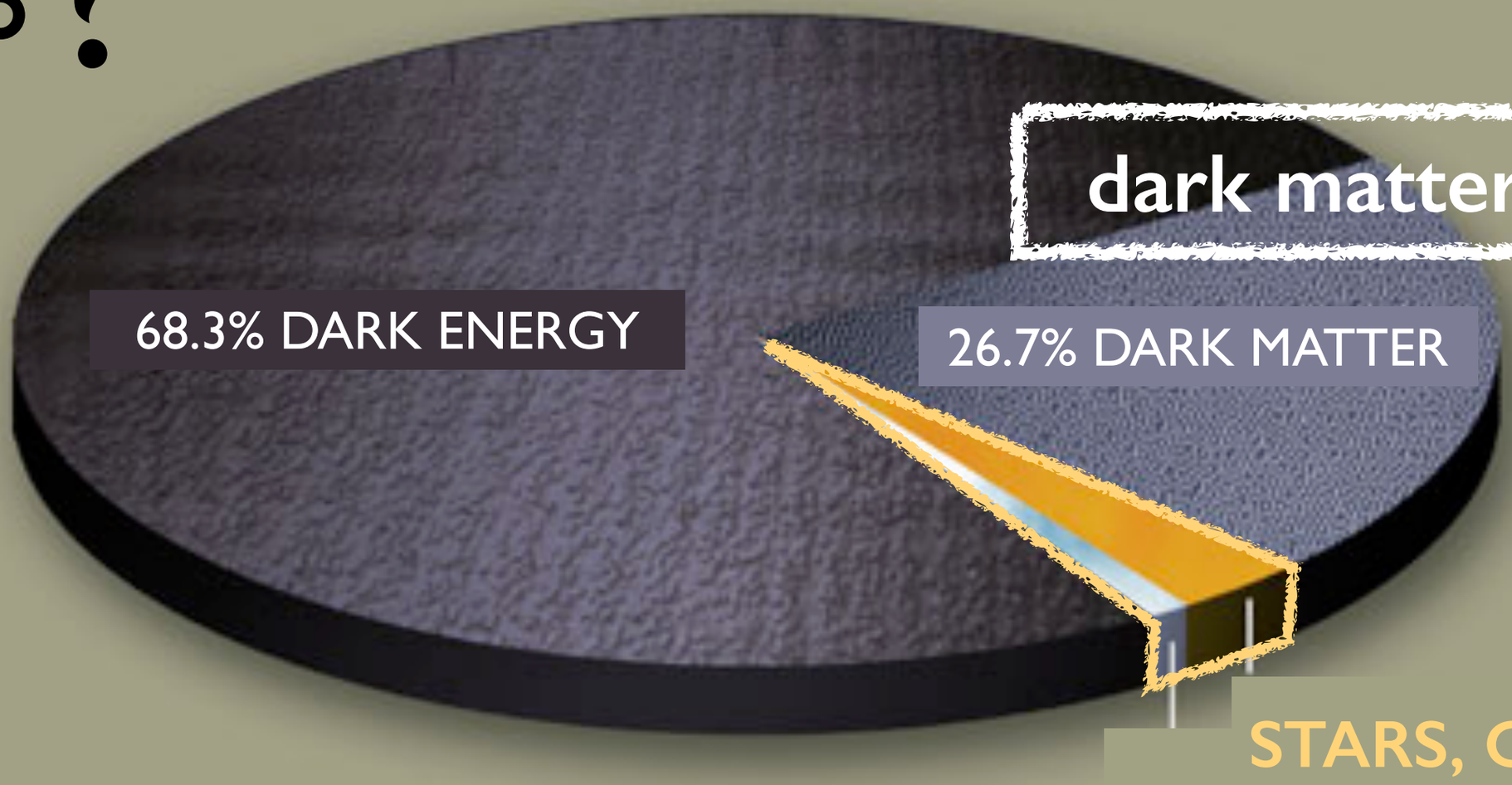
STARS, GAS, ETC

5%



all this "stuff" — 5%

95%?



STARS, GAS, ETC

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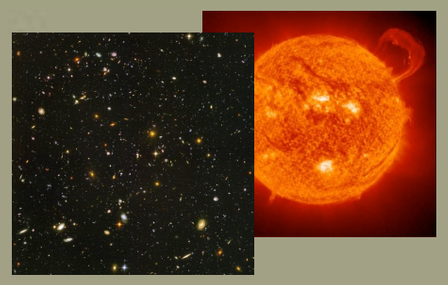
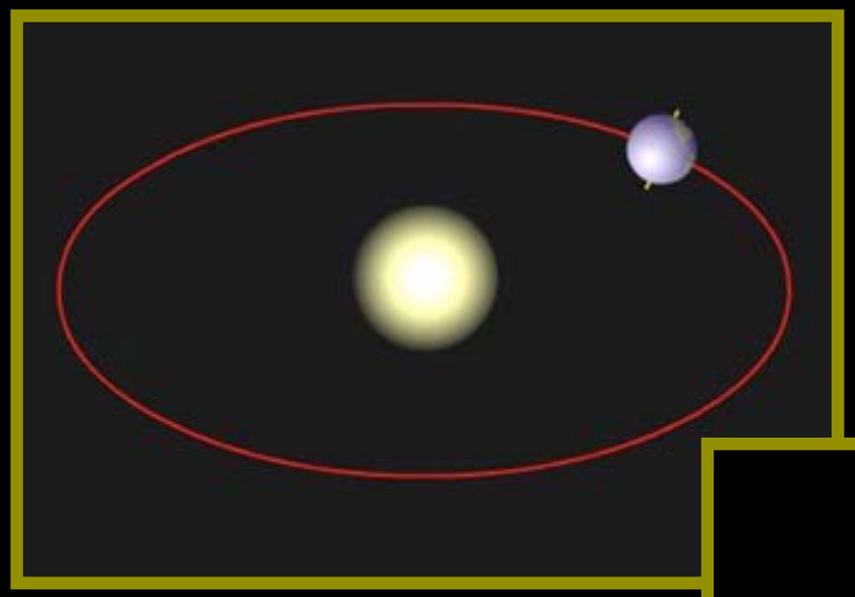


inferring the invisible

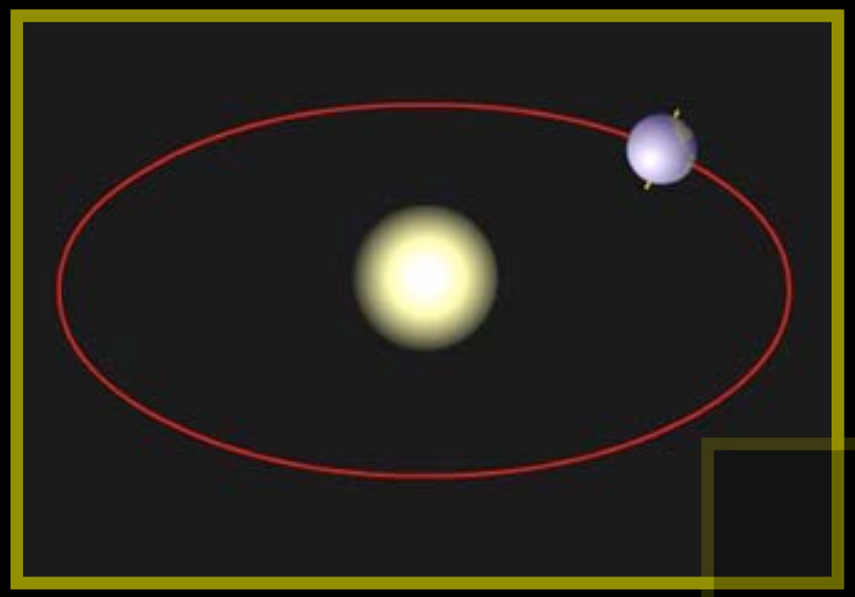


how stuff moves

image distortions

holding things together

inferring the invisible



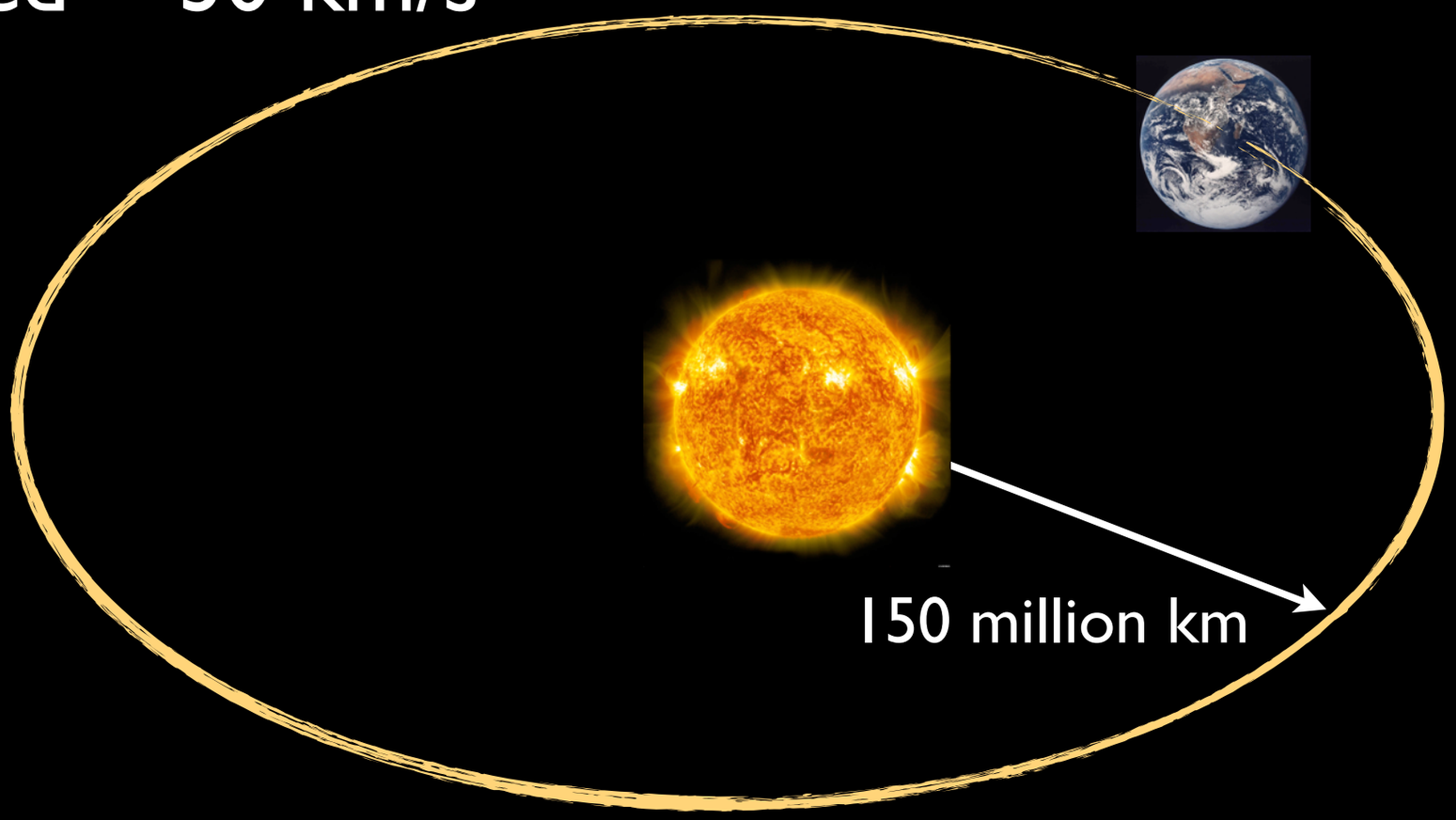
how stuff moves

holding things together

image distortions

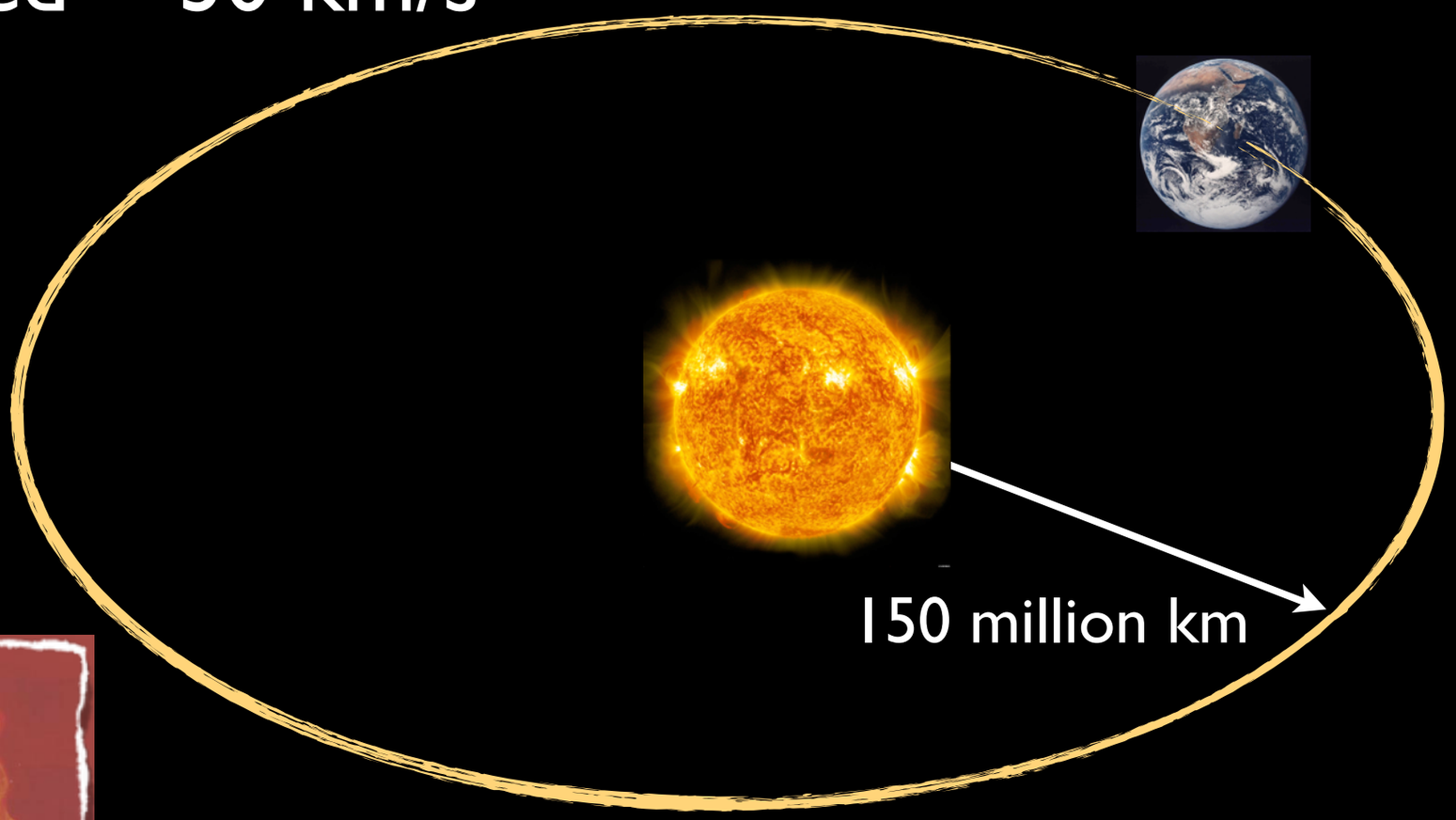
how can we "see" the invisible?

speed = 30 km/s



how can we "see" the invisible?

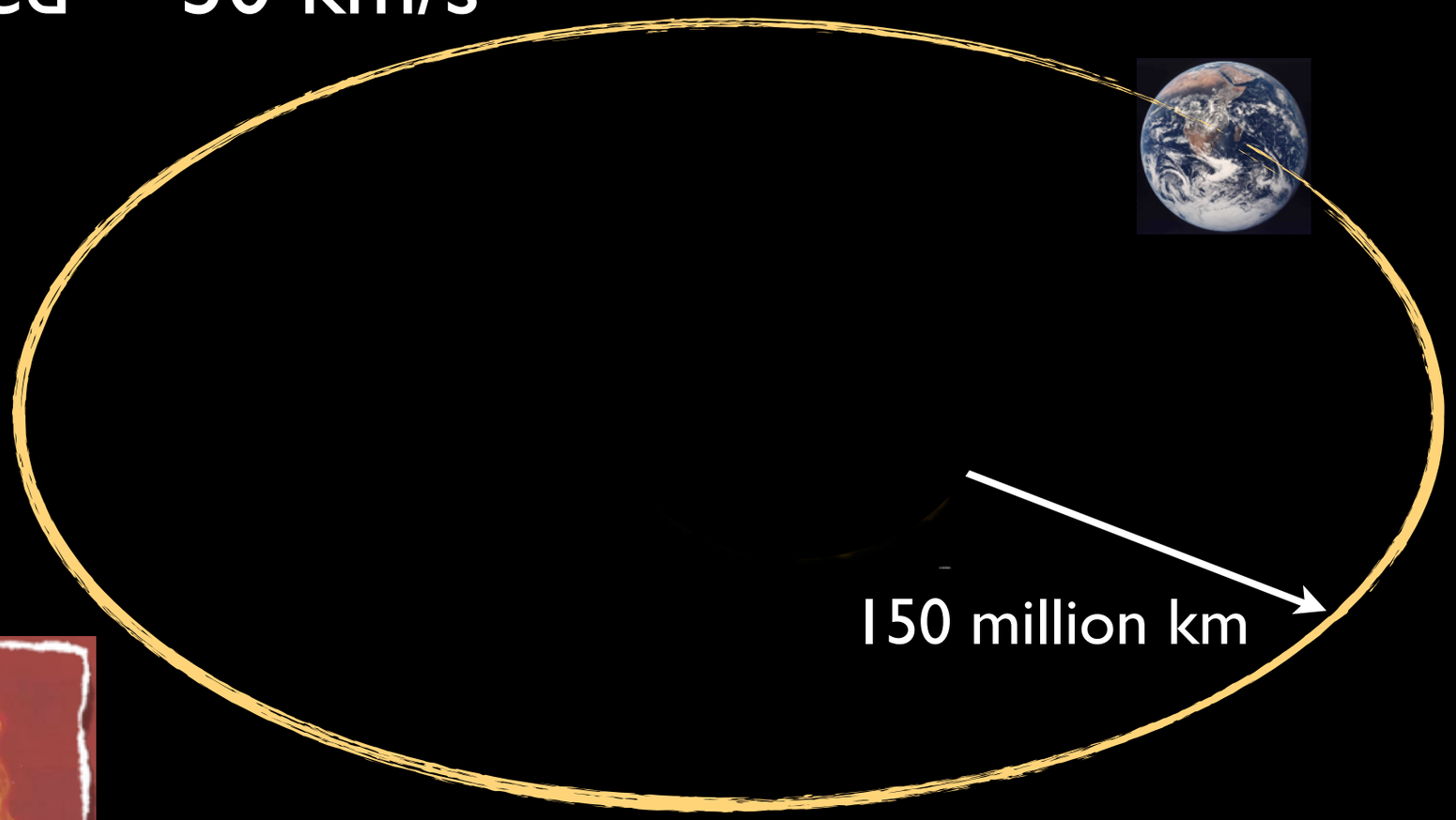
speed = 30 km/s



$M_{\rm sun} = 2 \times 10^{30}\,{\rm kg}$

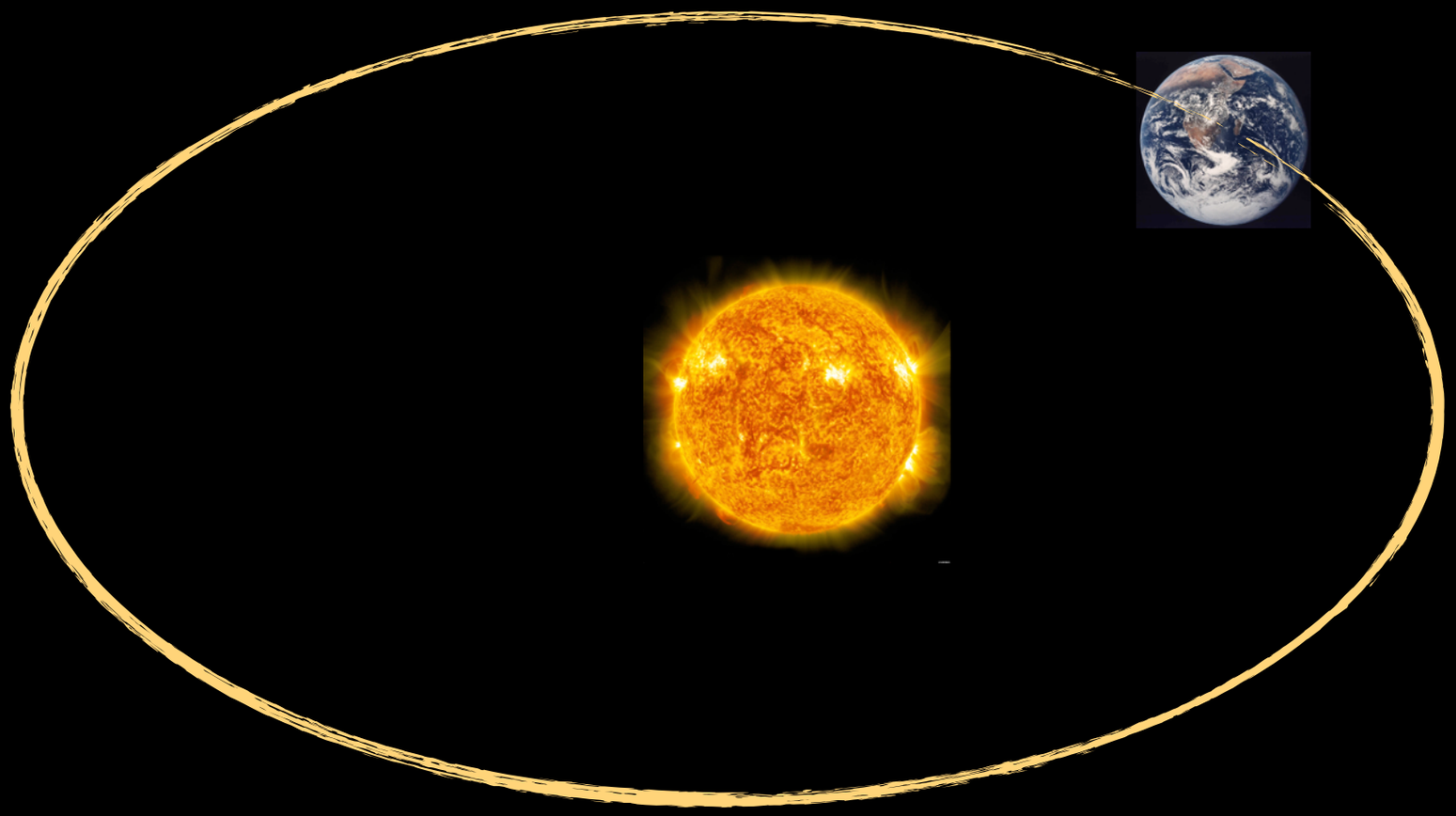
how can we "see" the invisible?

speed = 30 km/s



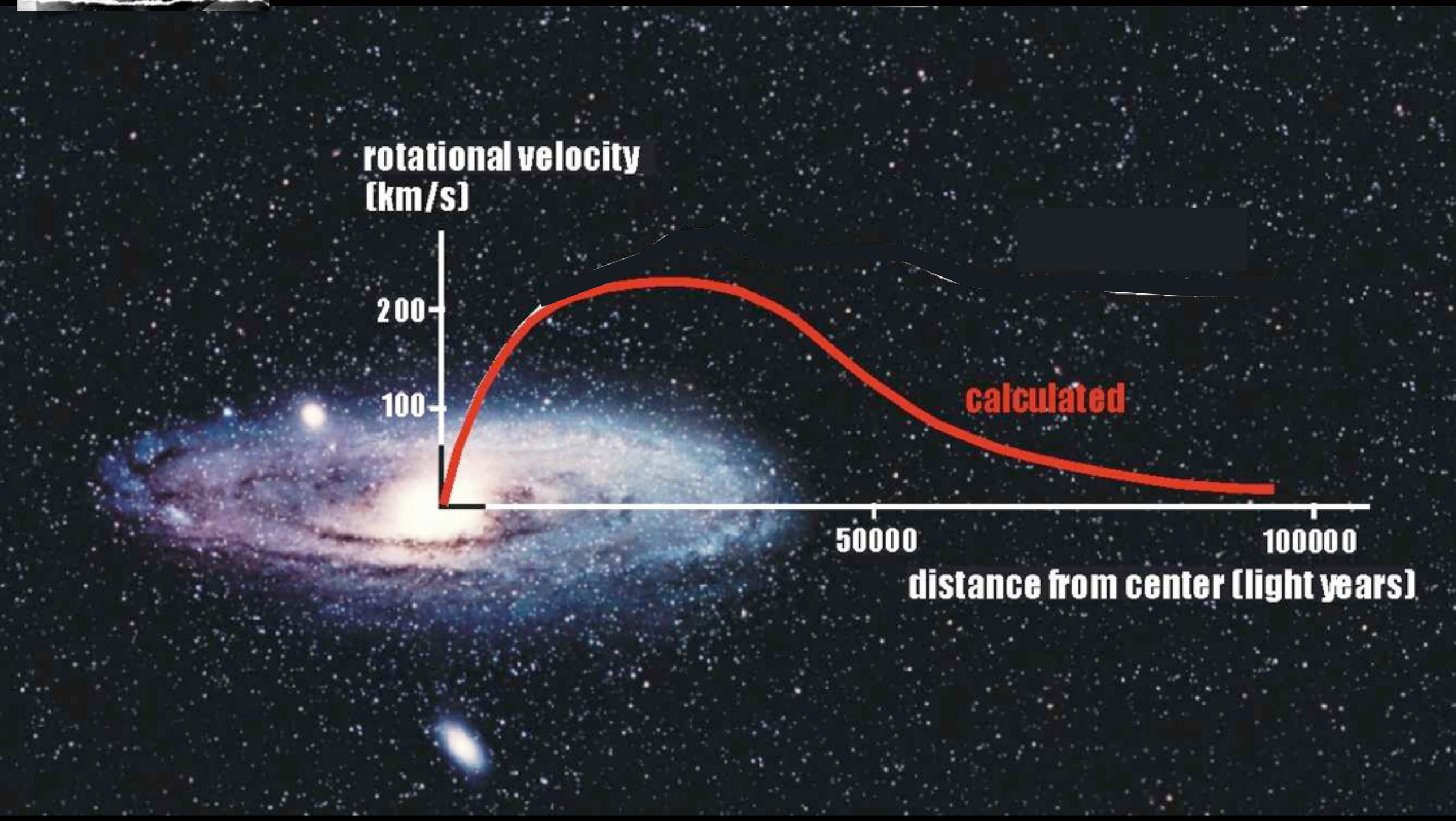
$M_{\text{sun}} = 2 \times 10^{30}\,\text{kg}$

speed increases with mass

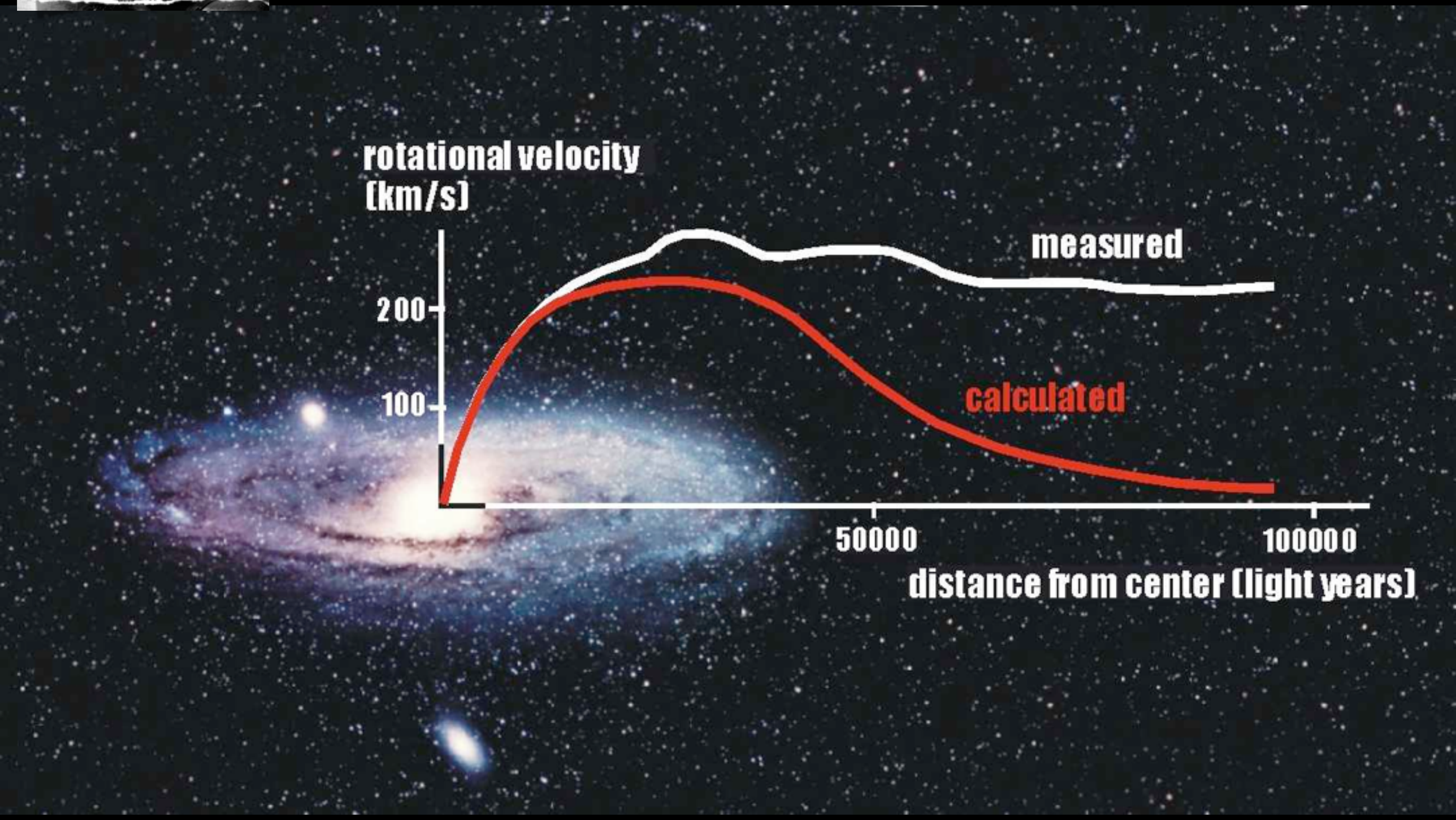


$$v \propto \sqrt{M_{\text{sun}}}$$

galaxy rotation curve

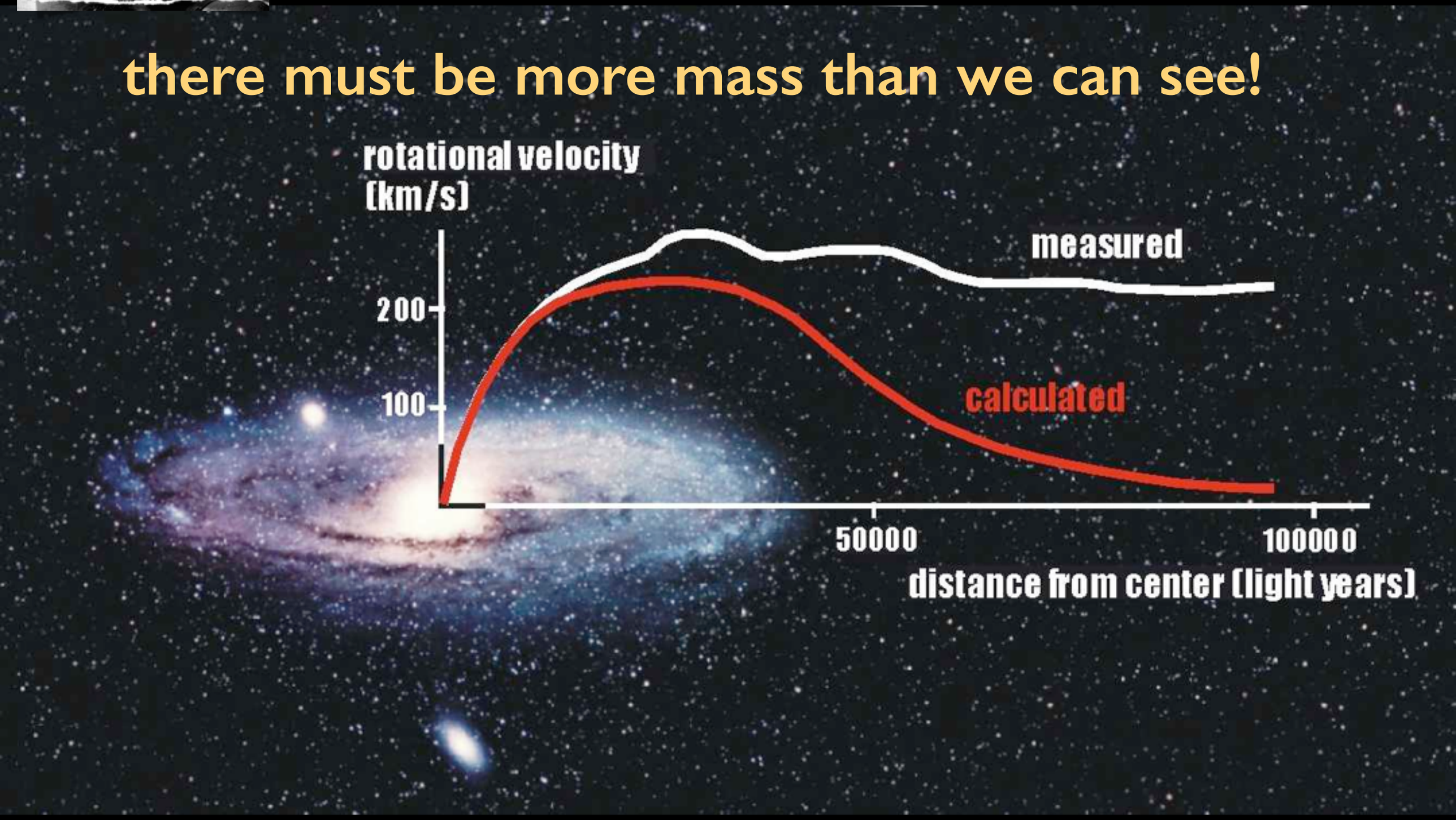


galaxy rotation curve

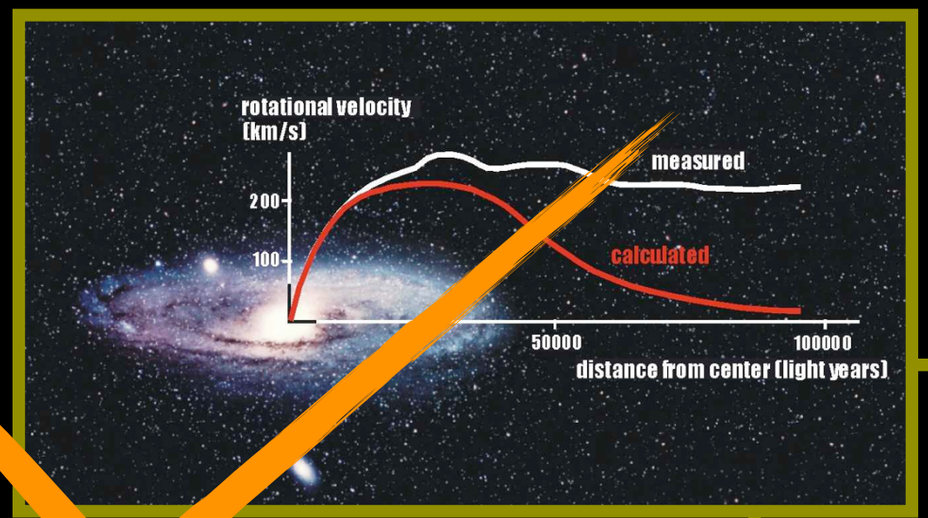


galaxy rotation curve

there must be more mass than we can see!



inferring the invisible



how stuff moves

holding things together

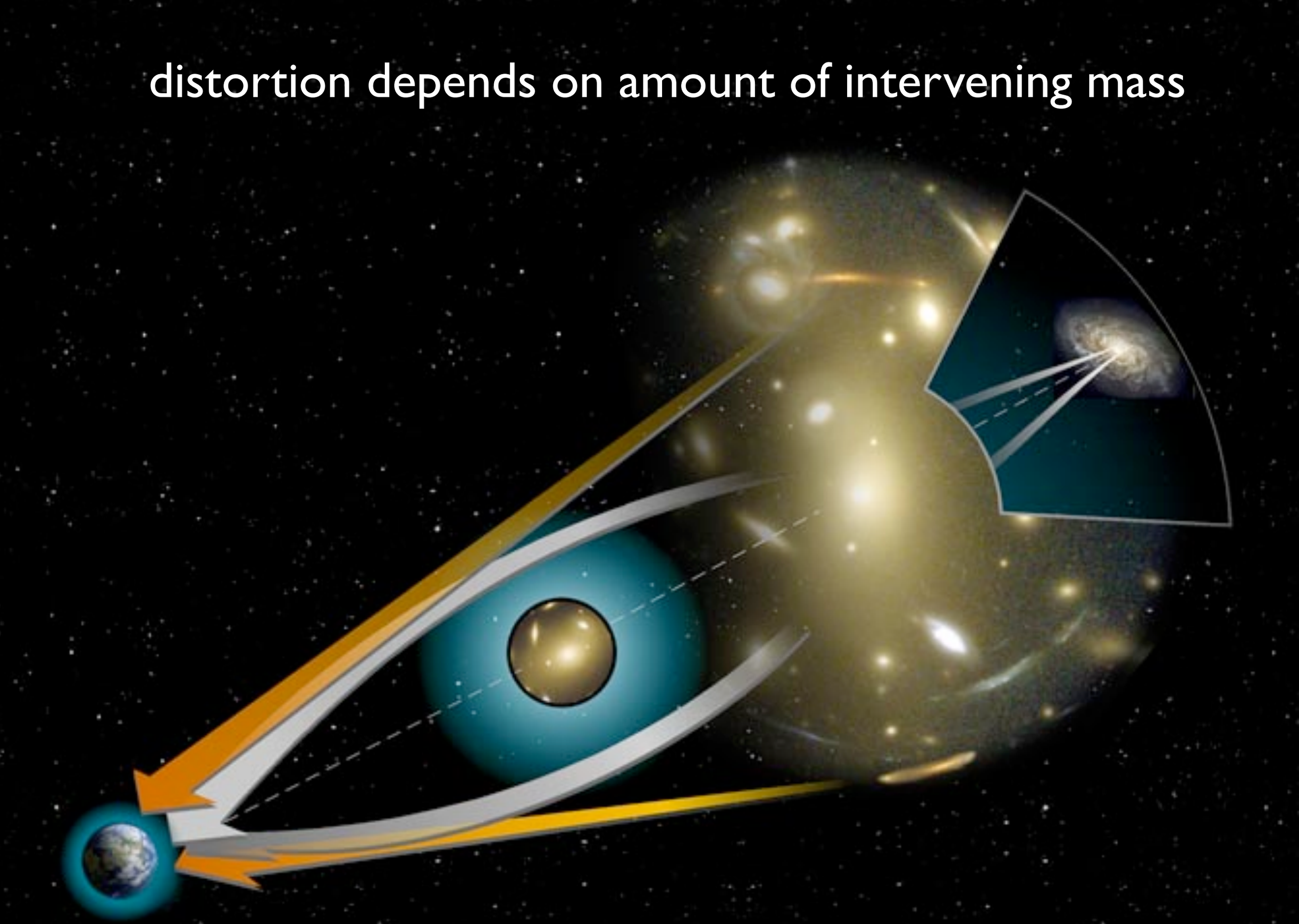
image distortions

inferring the invisible:

from image distortions

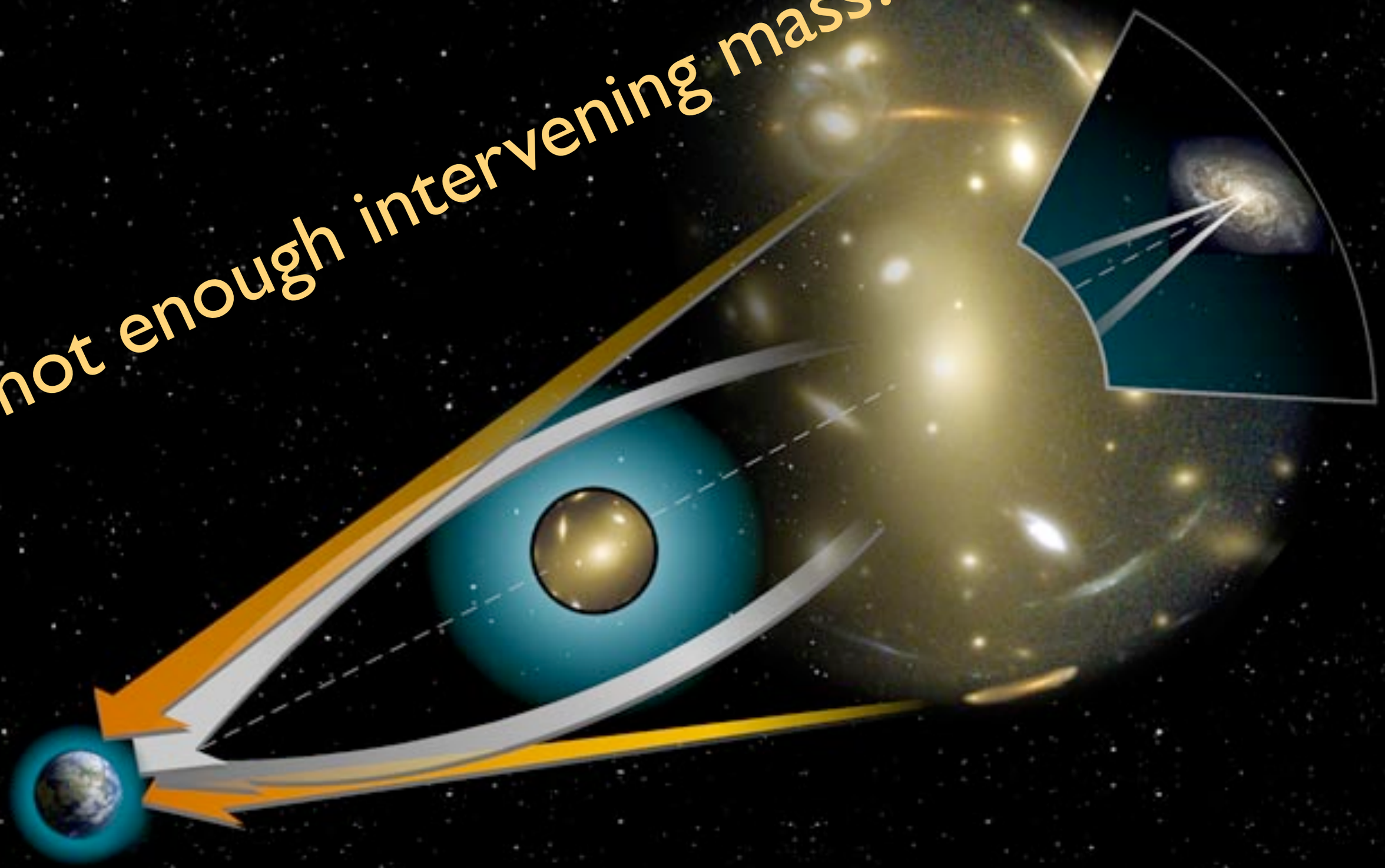
image distortion by gravity

distortion depends on amount of intervening mass

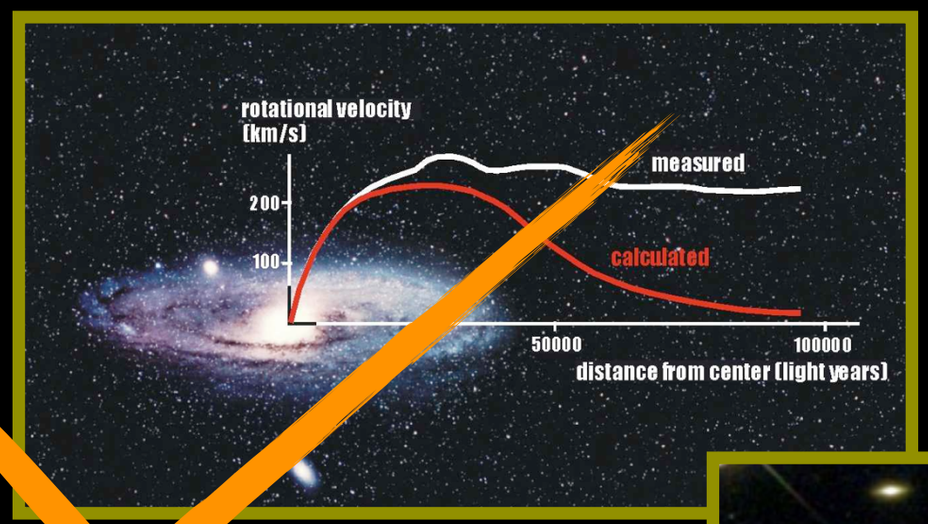


distortion depends on amount of intervening mass

not enough intervening mass!



inferring the invisible



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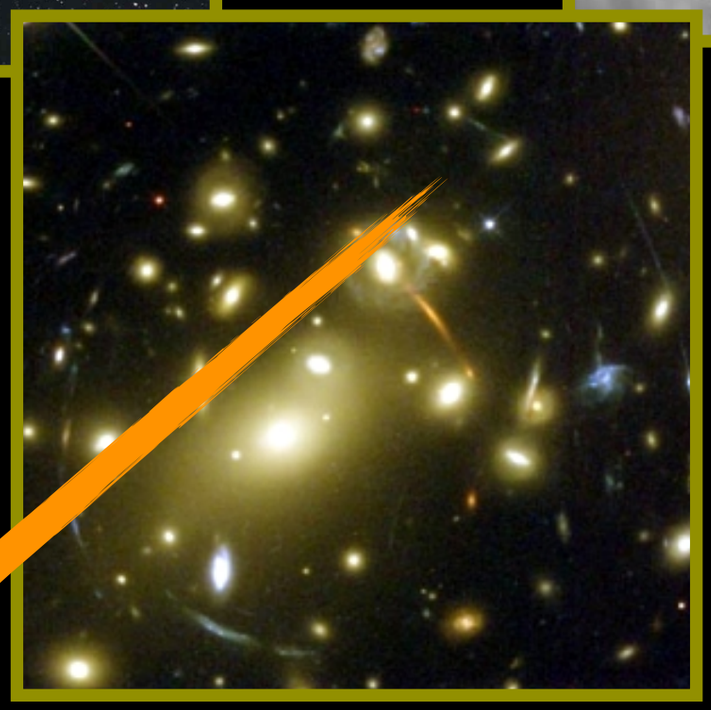
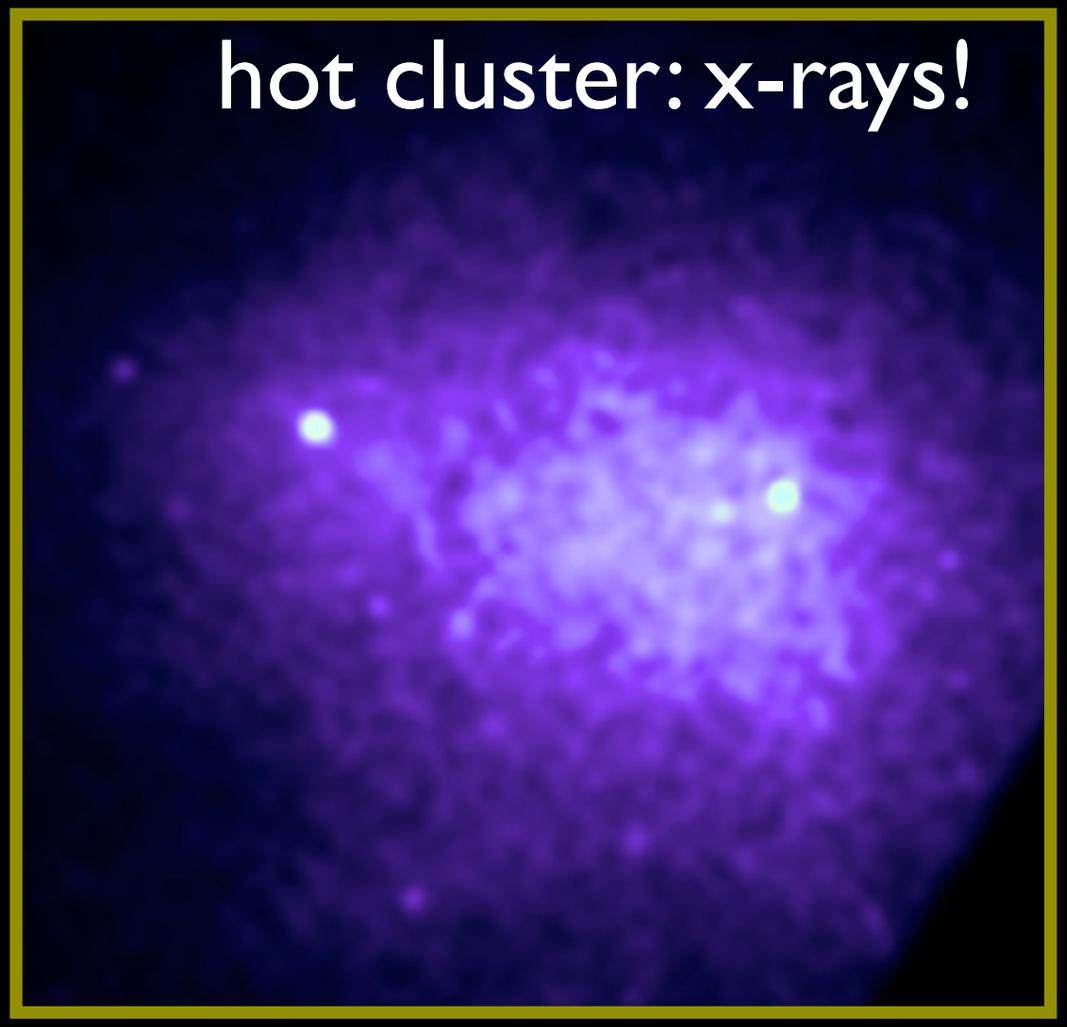


image distortions

hot stuff evaporates

galaxy clusters are too hot!



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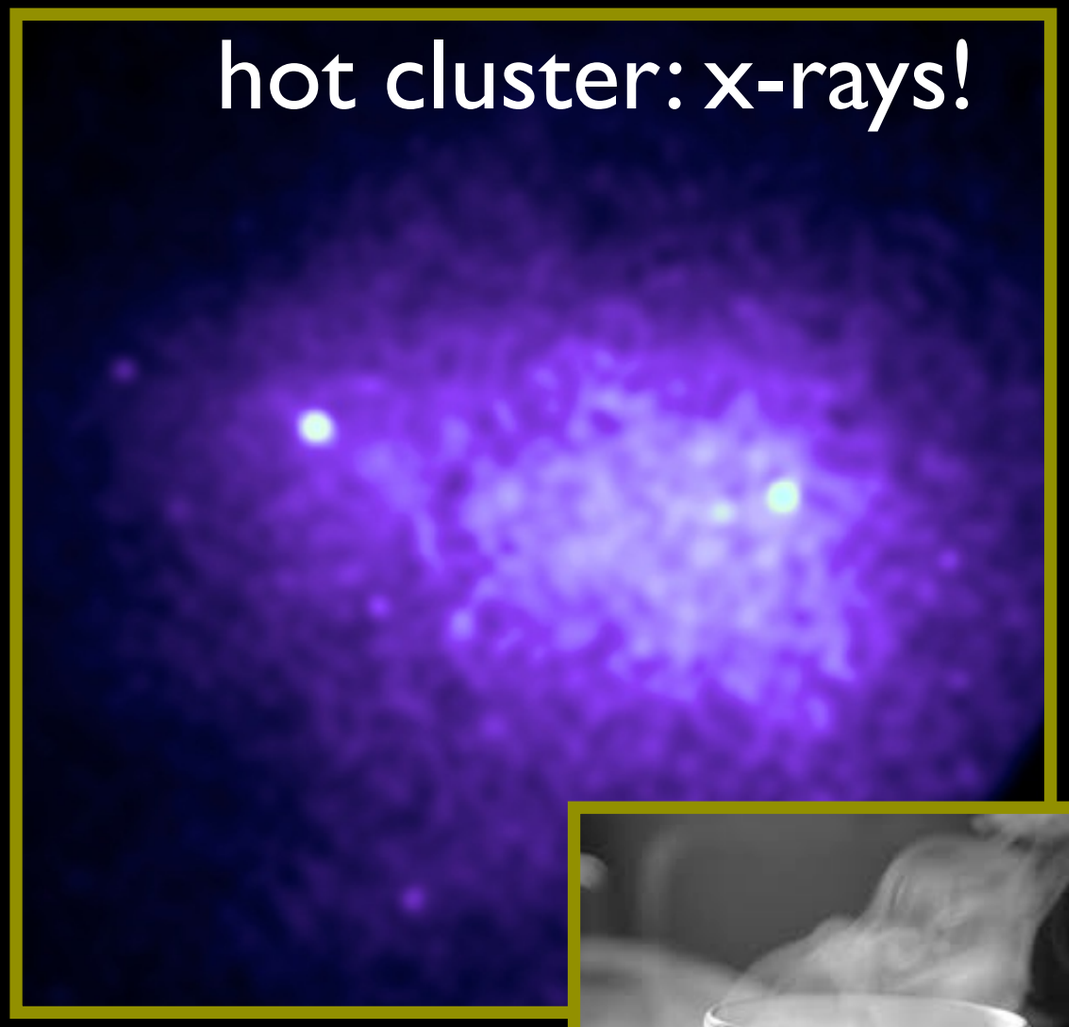
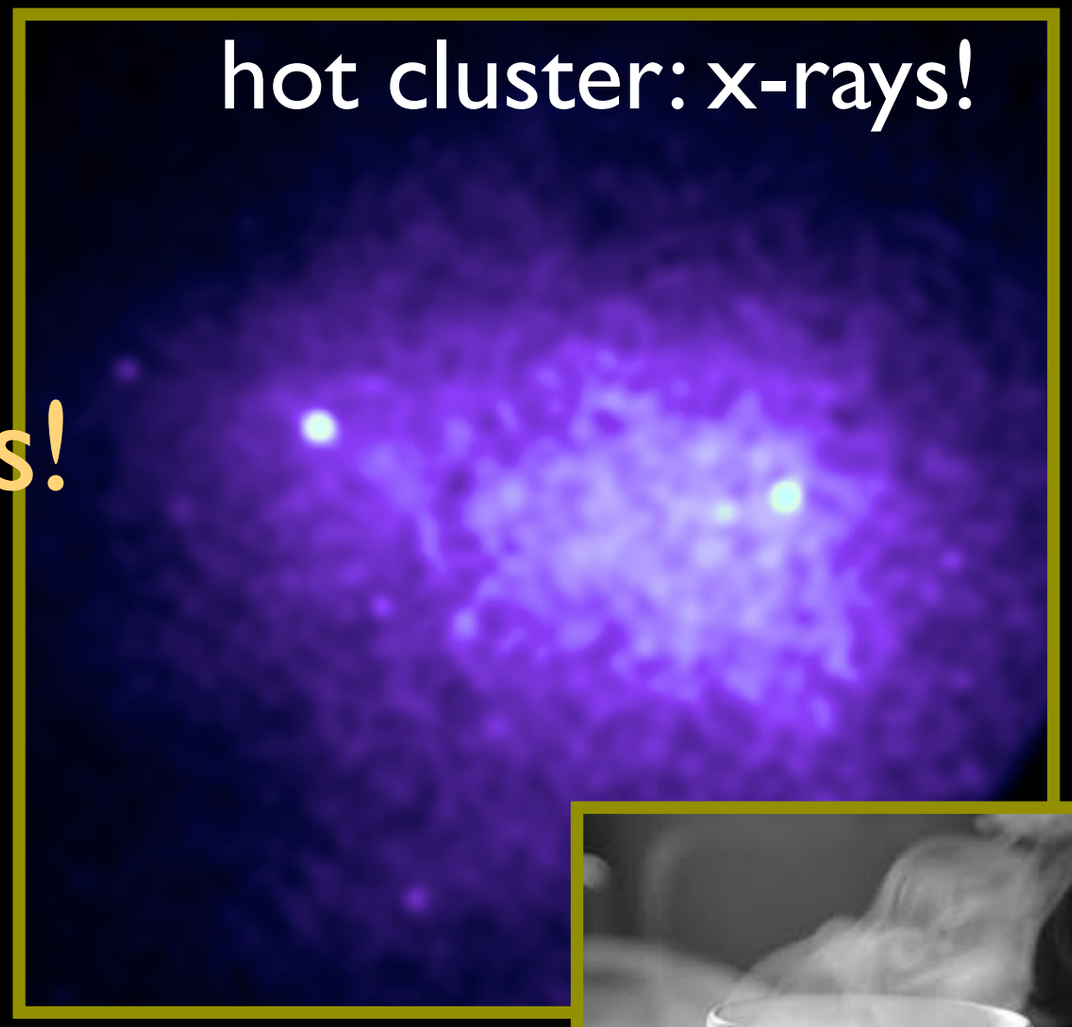
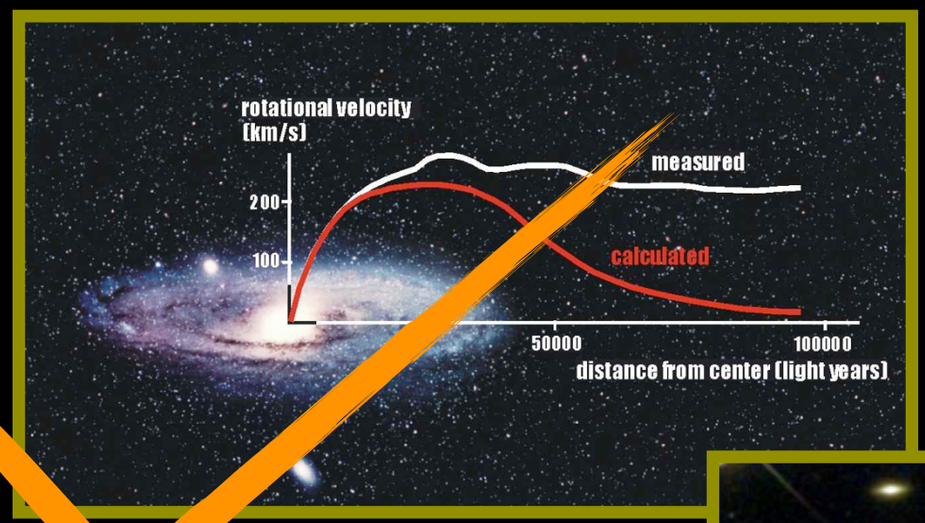


galaxy clusters are too hot!

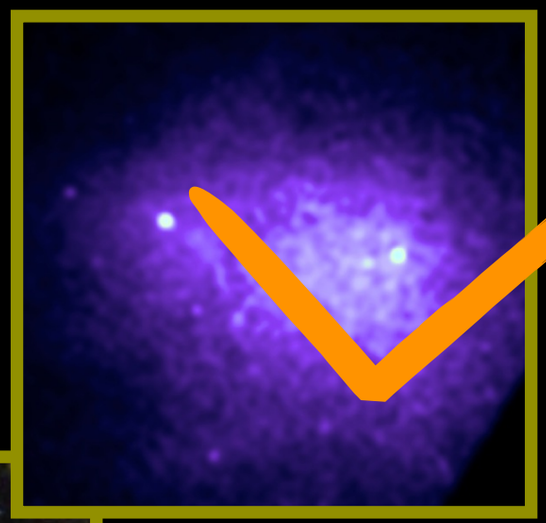
need more invisible mass!



inferring the invisible



how stuff moves



holding things together

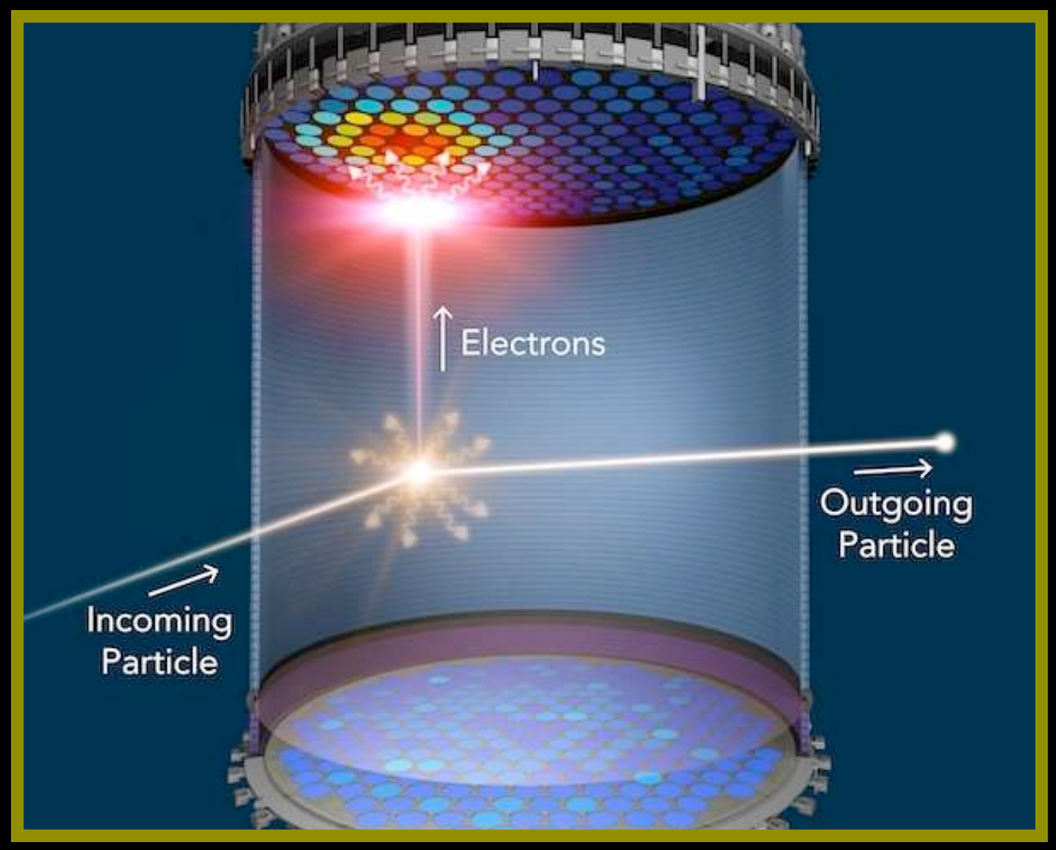
image distortions

dark matter network !
(in which galaxies are embedded)

what is dark matter ?
how will we know?

a new, undiscovered particle ?

large hadron collider (LHC)



liquid xenon detectors (LZ experiment)

however . . .

dark energy

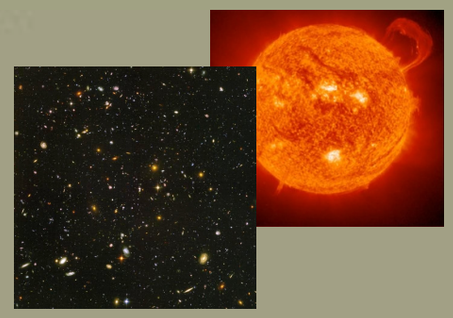
dark matter

68.3% DARK ENERGY

26.7% DARK MATTER

STARS, GAS, ETC

5%



what are the (distant) galaxies doing?

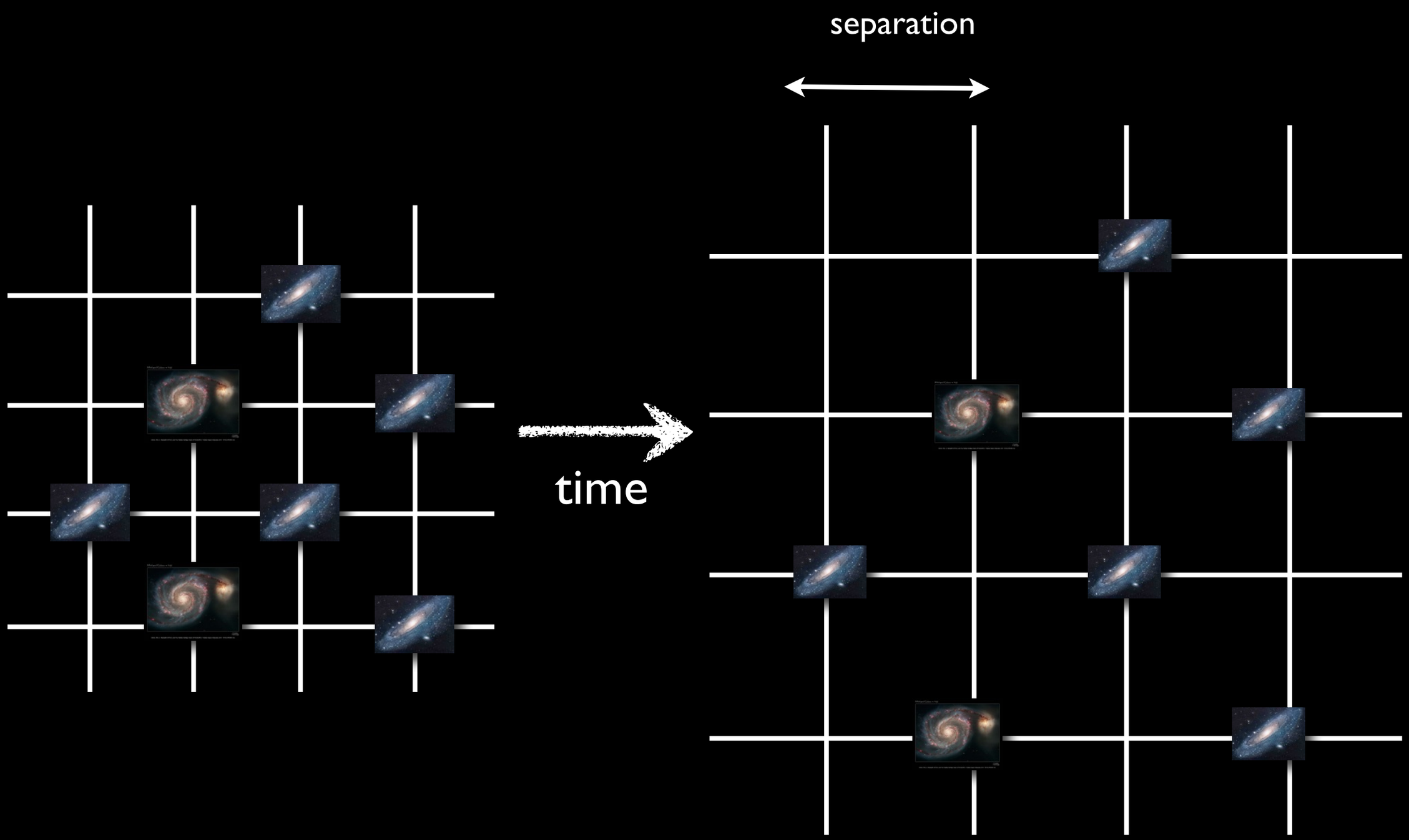
Image Credit: Hubble Ultra-Deep Field, NASA/ESA

1930's

1930's

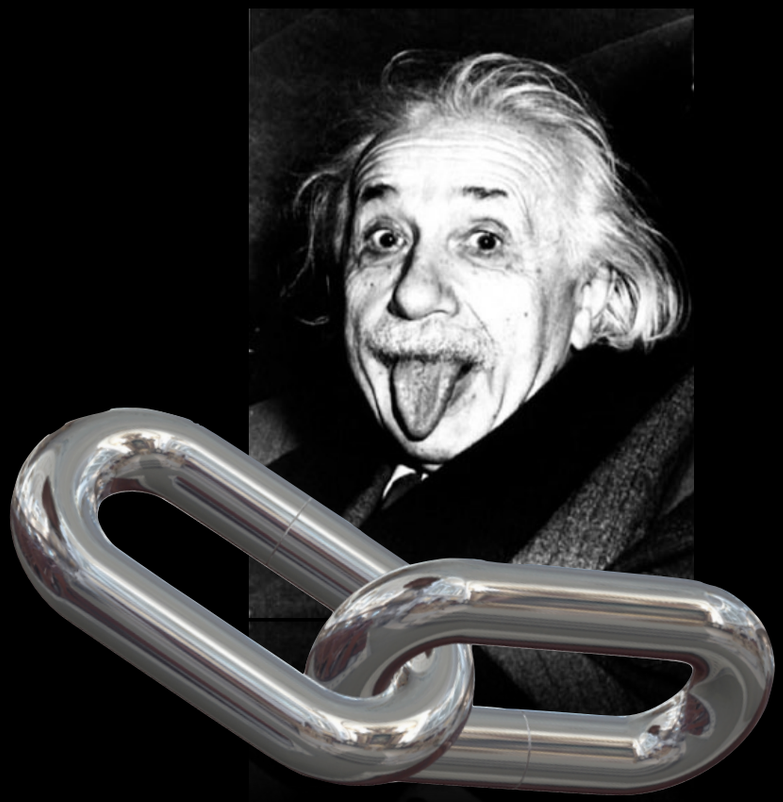
1998 …

speed of expansion is increasing !



why is this exciting ?

expansion



contents

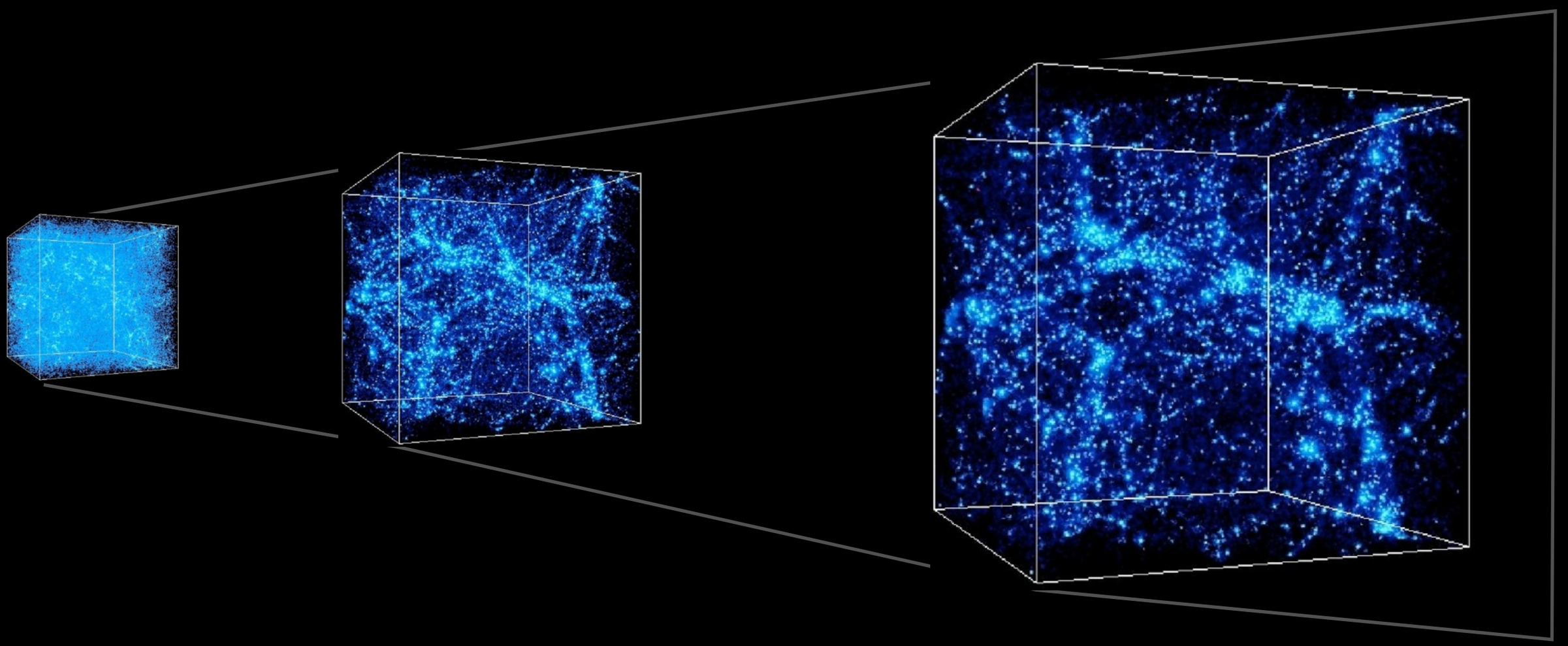
normal matter should

slow down expansion !

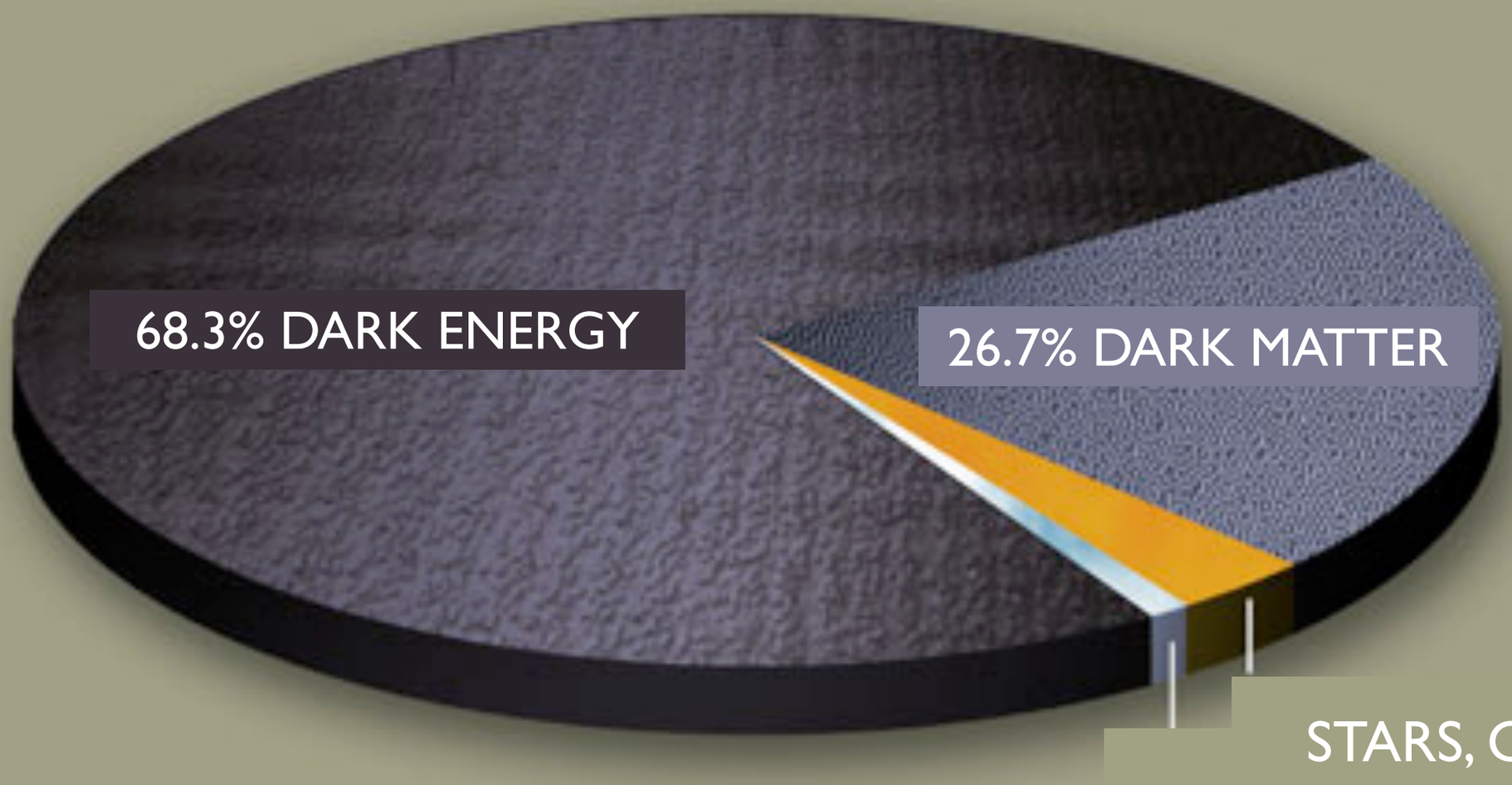
need some stuff with
“repulsive gravity”

— DARK ENERGY —

dark energy: accelerated expansion
dark matter: clumpiness

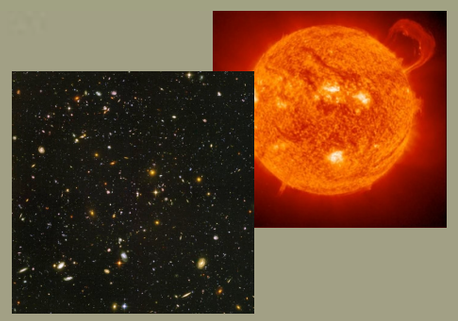


might seem like a lot is unknown …



STARS, GAS, ETC

5%



— a lot is also known —

lumpier

homogeneous

expanding

hot

(filled with radiation + matter)

cold

credit: adapted from NASA

— a lot is also known —

universe gets populated with particles

Reheating after inflation

Inflation

Accelerators

LHC protons

RHIC & LHC heavy ions

Size of visible universe

Cosmic Microwave Background radiation is visible

Structure formation

Dark energy accelerated expansion

TODAY

POSSIBLE DARK MATTER RELICS

NUCLEONS FORM

NUCLEI FORM

$t = 10^{-36}$ s, $E = 10^{16}$ GeV

$t = 10^{-10}$ s, $E = 10^{2}$ GeV

$t = 10^{-4}$ s, $E = 10^{-1}$ GeV

$t = 10^{2}$ s, $E = 10^{-4}$ GeV

$t = 3 \times 10^{5}$ y, $E = 3 \times 10^{-10}$ GeV

$t = 10^{9}$ y, $E = 10^{-12}$ GeV

$t = 13.8 \times 10^{9}$ y, $E = 2.3 \times 10^{-13}$ GeV

t = Time (seconds, years)

E = Energy of photons (units GeV = 1.6×10^{-10} joules)

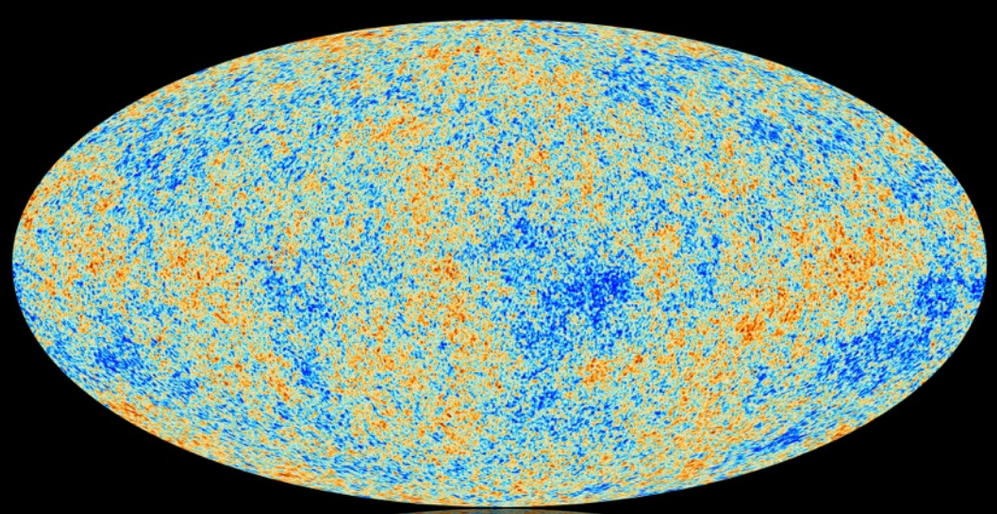
Key

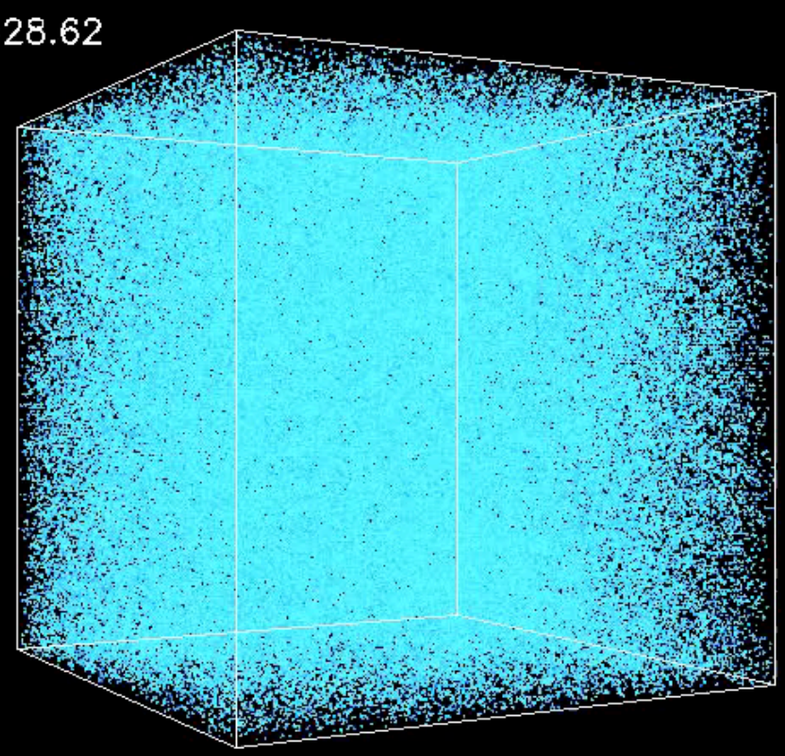
quark, gluon, electron, muon, tau, neutrino, bosons, meson, baryon, ion, atom, photon, star, galaxy, black hole

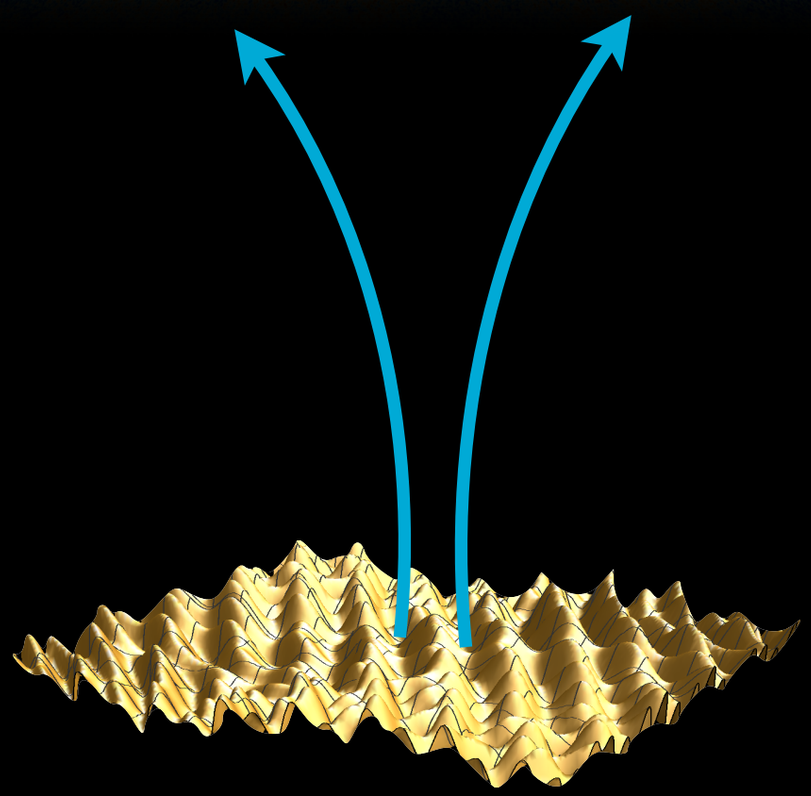
The concept for the above figure originated in a 1986 paper by Michael Turner.

Supported by DOE

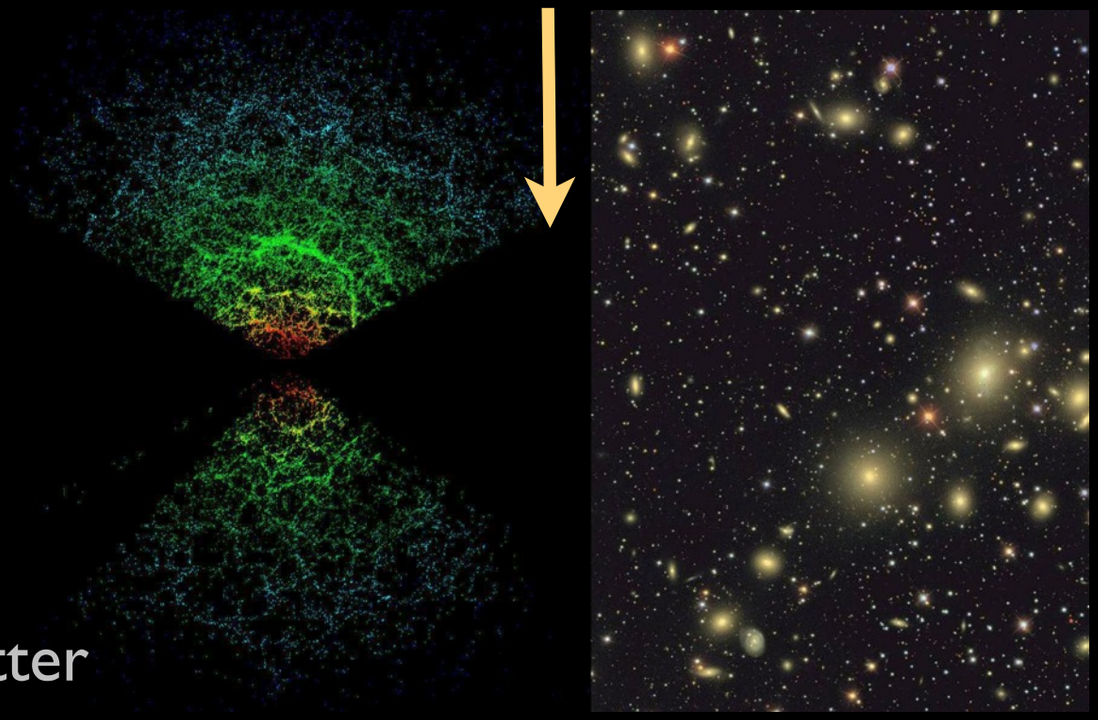
gravity & quantum mechanics at work





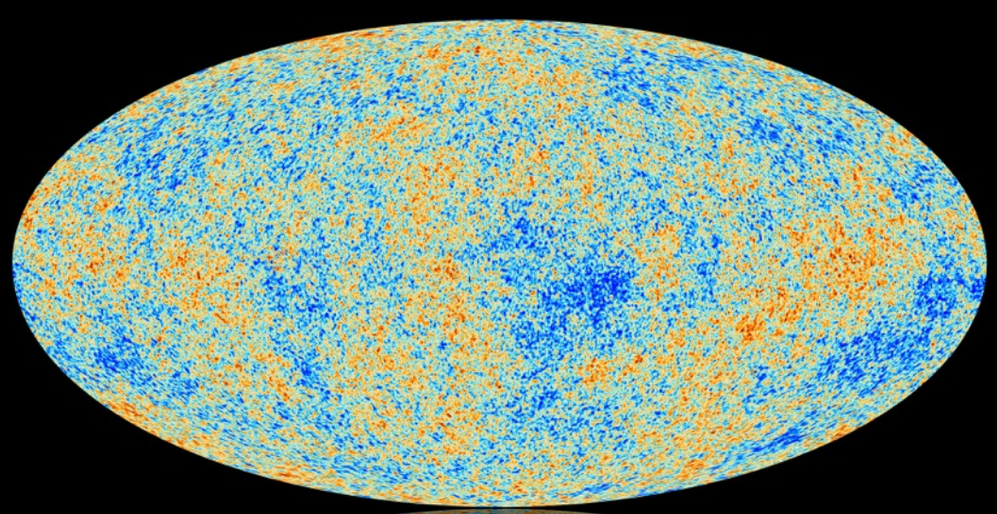


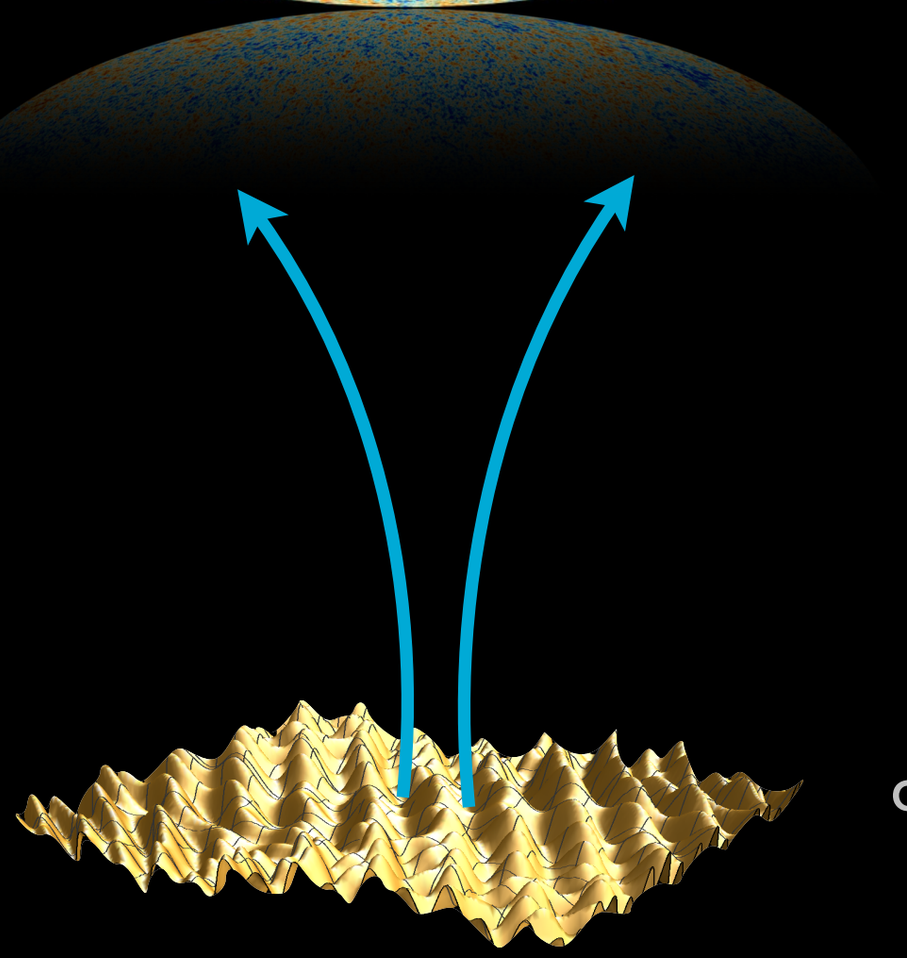
quantum jitter
in space-time



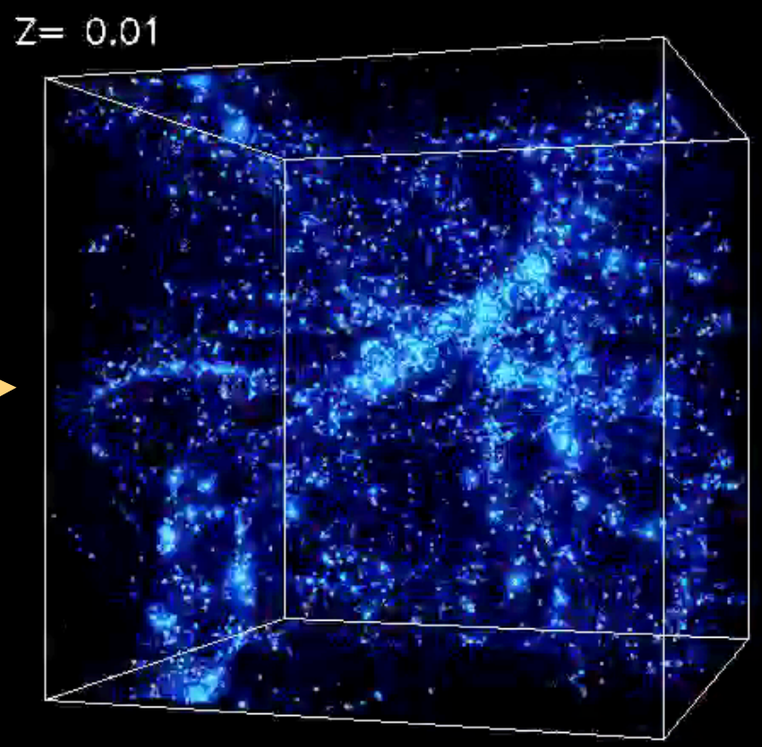
happened in 14 billion years!

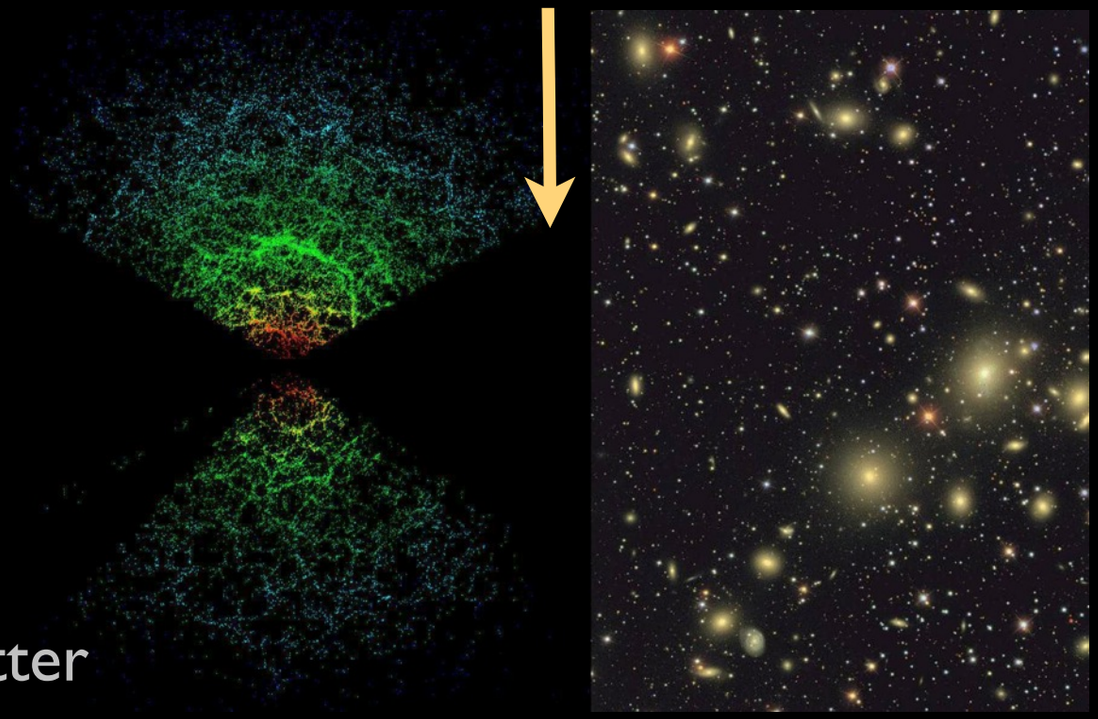
gravity & quantum mechanics at work





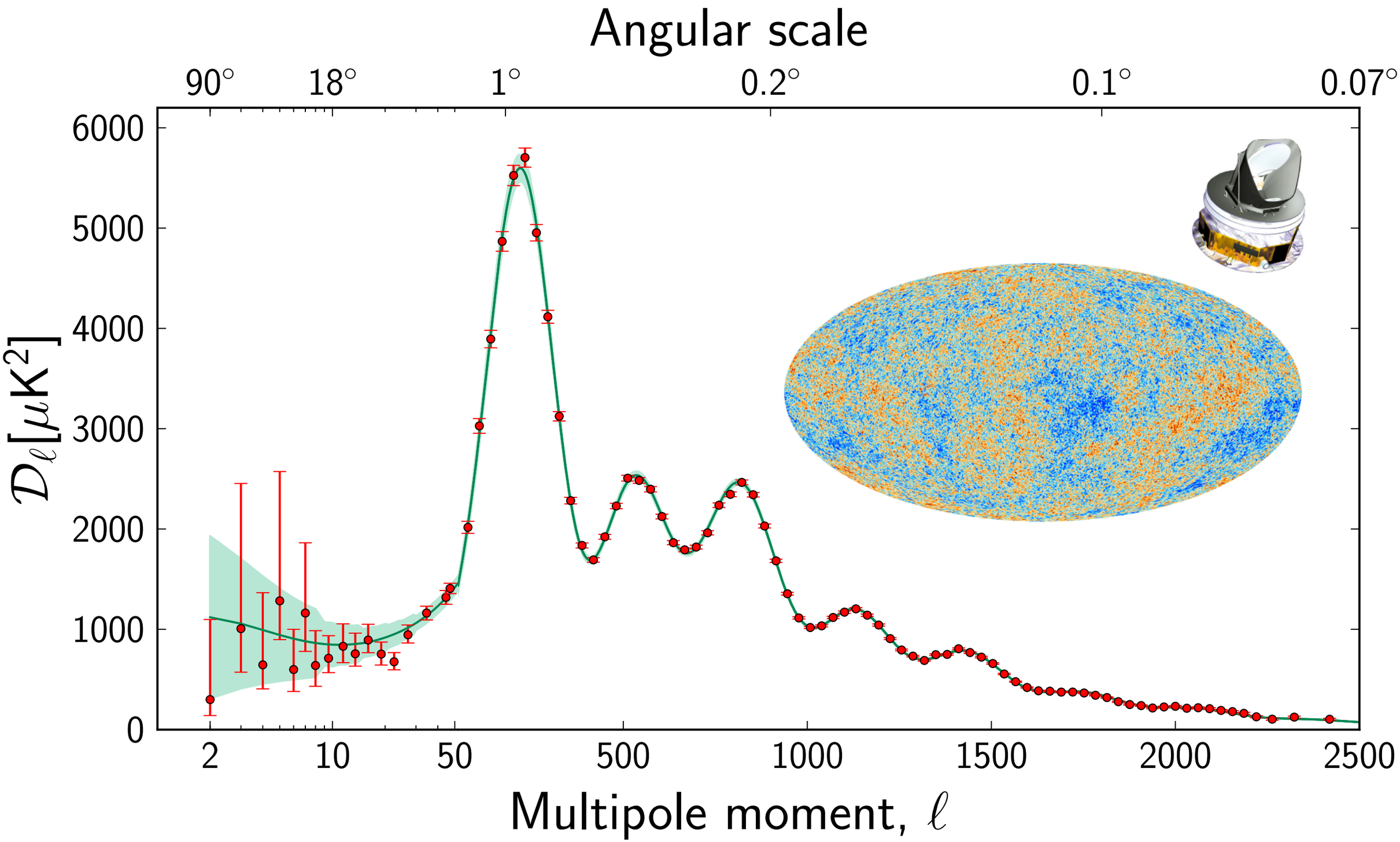
quantum jitter
in space-time



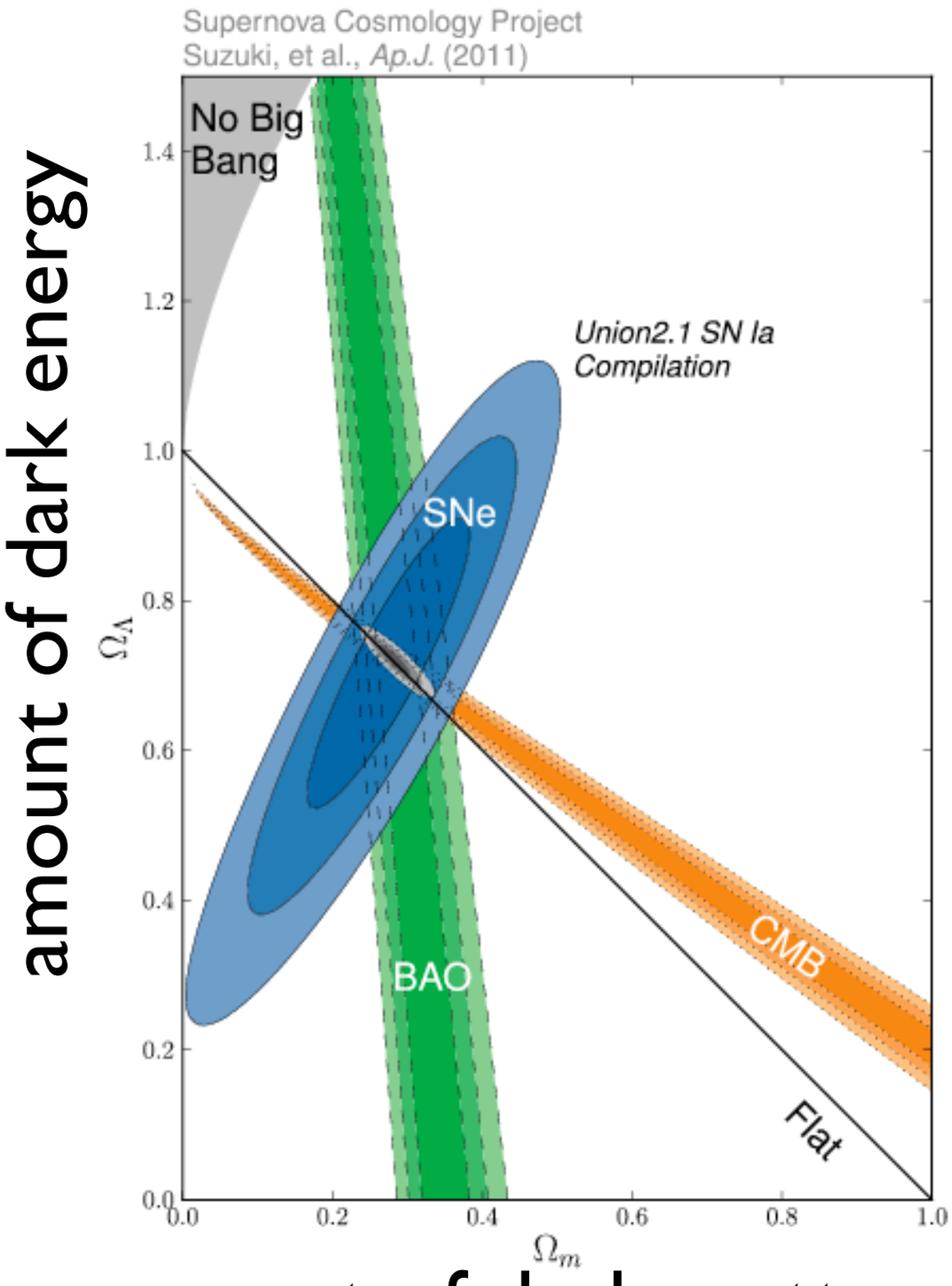


happened in 14 billion years!

including dark matter and dark energy gives excellent agreement with observations



excellent model consistent with independent observations!



amount of dark matter

exciting times!

how will dark matter and dark energy fit in with the rest of ‘known’ physics?

— paradigm shift? —