

Quarks to the Cosmos:

the deep connections between the largest and
smallest scales in the Universe

Scales of the Universe Lecture Series



16 November 2007

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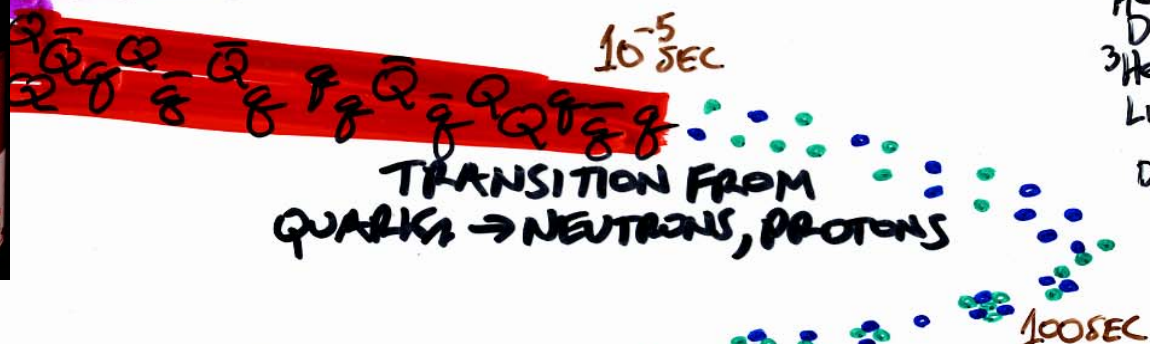
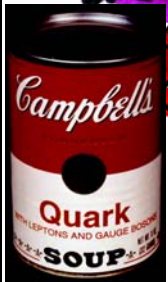
Full Scale Model of Universe a Fraction of a Second After the Beginning



ORDINARY MATTER: FROM QUARKS TO US

INFLATION
BARYOGENESIS

BBN

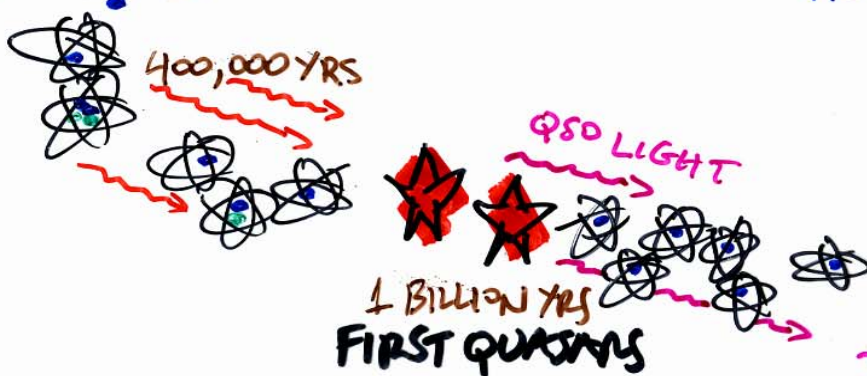
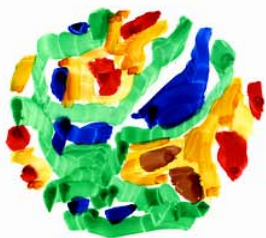


$D/H = (3 \pm 0.2) \times 10^{-5}$

$\Omega_B = 0.04 \pm 0.002$

BIG-BANG NUCLEOSYNTHESIS
Formation of H, D, He, He-3, Li

FORMATION OF ATOMS
COSMIC MICROWAVE BACKGROUND



(Ω_B / Ω_M) TODAY

$\Omega_B / \Omega_M = 0.15 \pm 0.01$

$\Omega_{bh} = 0.20 \pm 0.01$

$\Omega_B = 0.04 \pm 0.002$

CMB

CMB

RATIO OF FIRST-TO-SECOND PEAKS: 2/1



$\Omega_B = 0.045 \pm 0.006$

INTERGALACTIC GAS

ABSORPTION OF QUASAR LIGHT BY HYDROGEN

$\Omega_B \geq 0.04$

HERE & NOW

14 Billion YRS

stars, gas, dust, ...

BHs, NSs, people ...



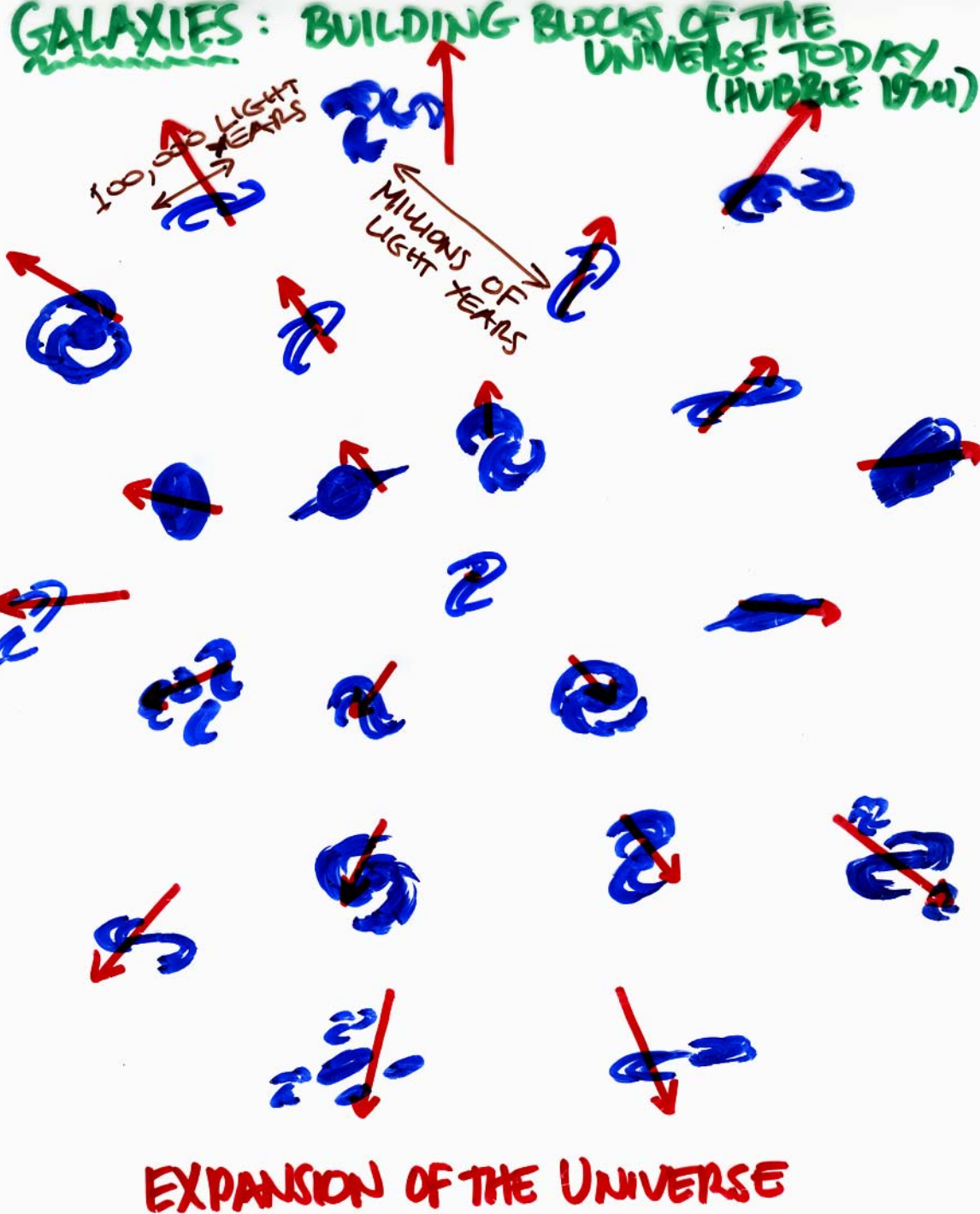
Amazing as it is, the
connections go far
beyond the fact that
it began as Quark
Soup

NB: No deep connections between quarks and chemistry even though are made of quarks!



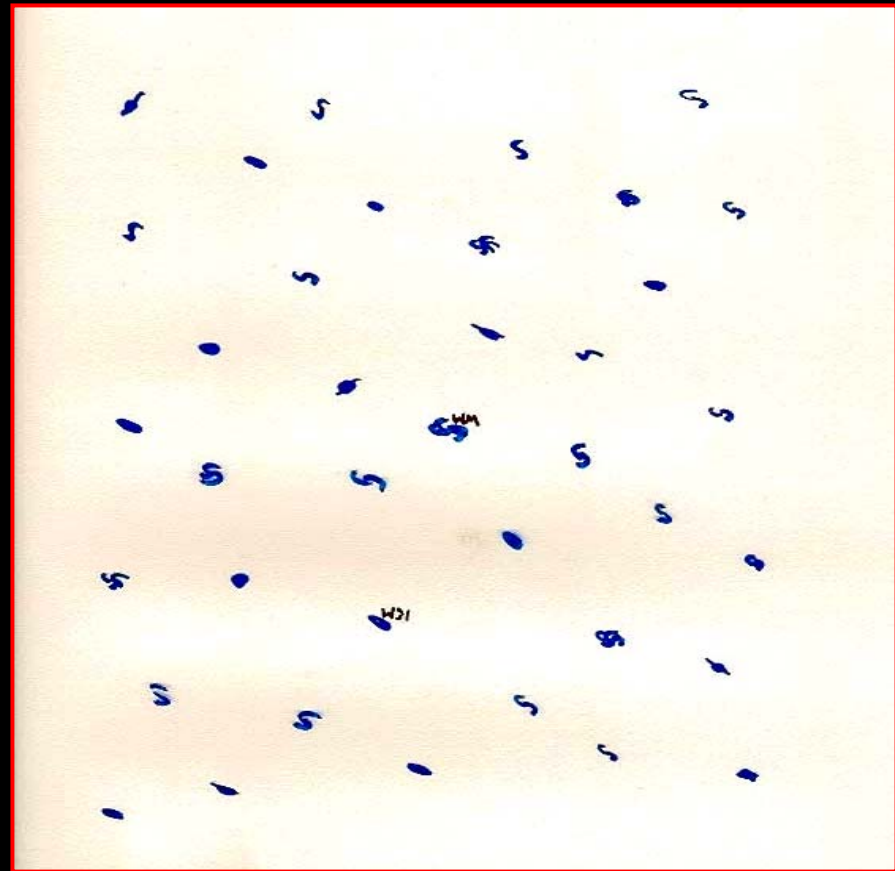
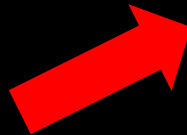
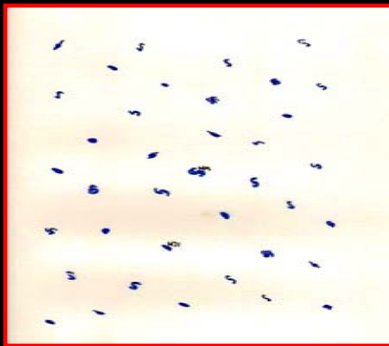
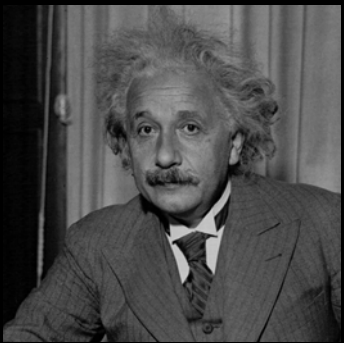
- The Atoms we and the stars of made of
- The Dark Matter that holds the Universe together
- The Dark Energy that is causing the expansion of the Universe to speed up
- The Seeds of all structures (clusters, galaxies, stars, ...)

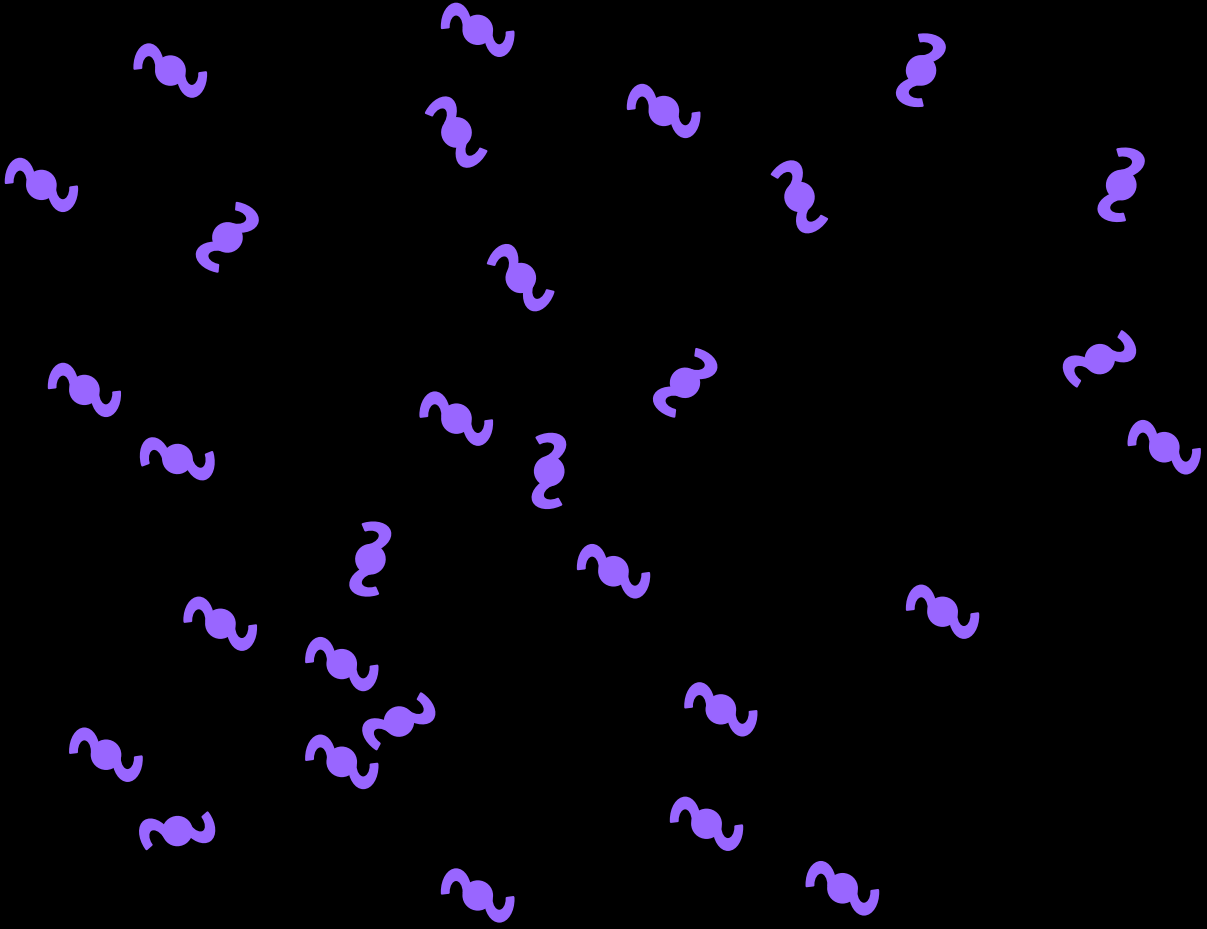
The Universe is getting bigger – expanding

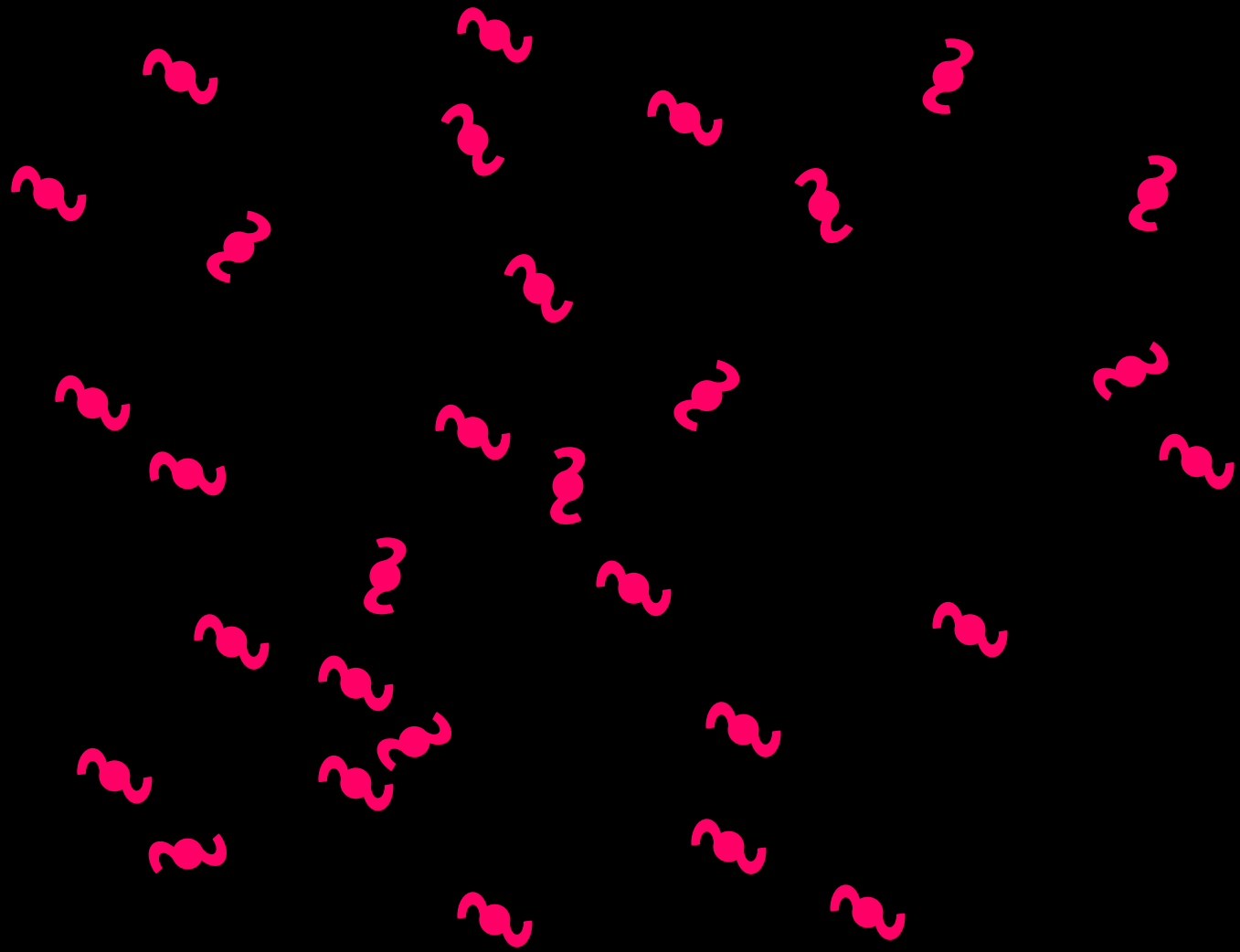


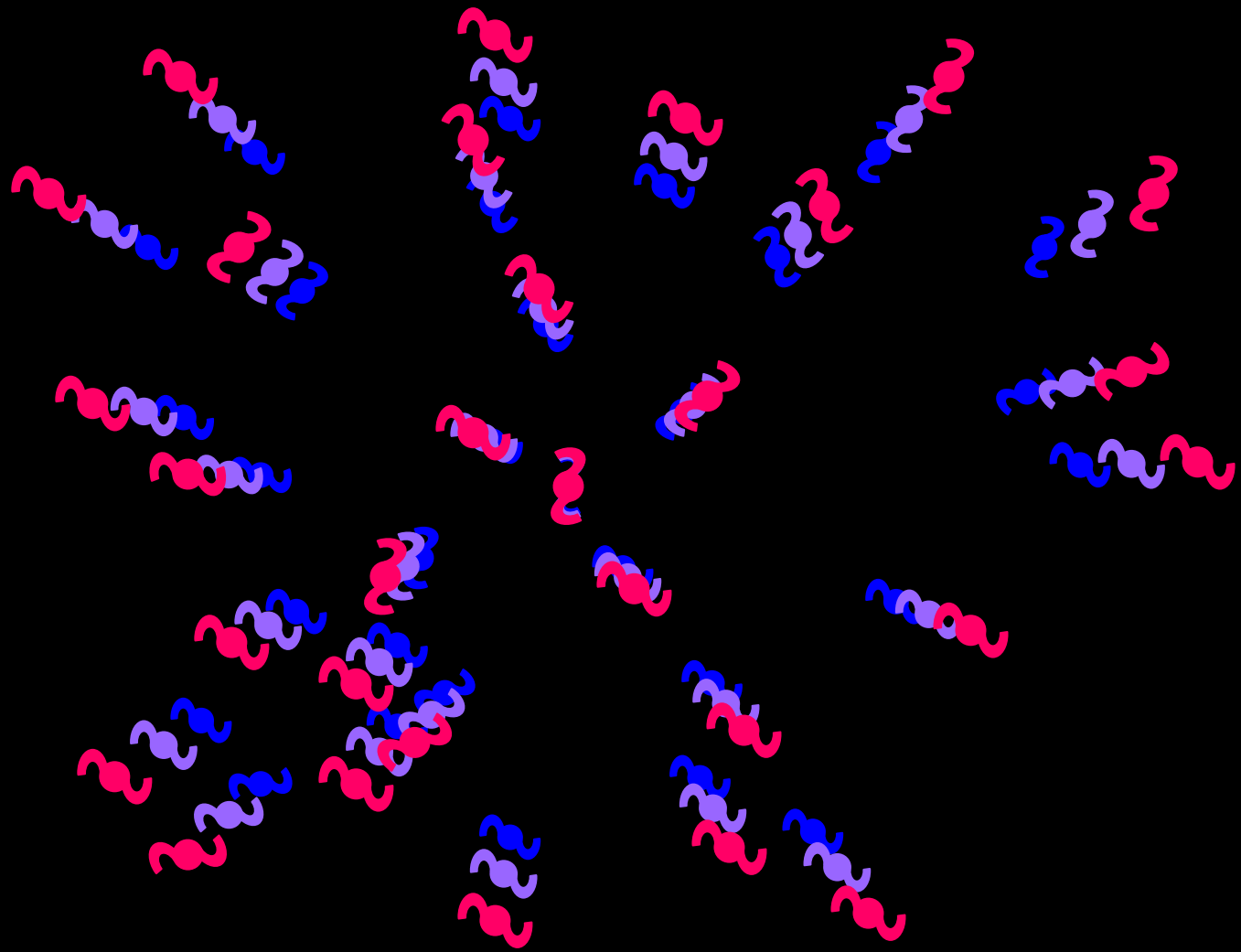
Expanding Universe is expanding space

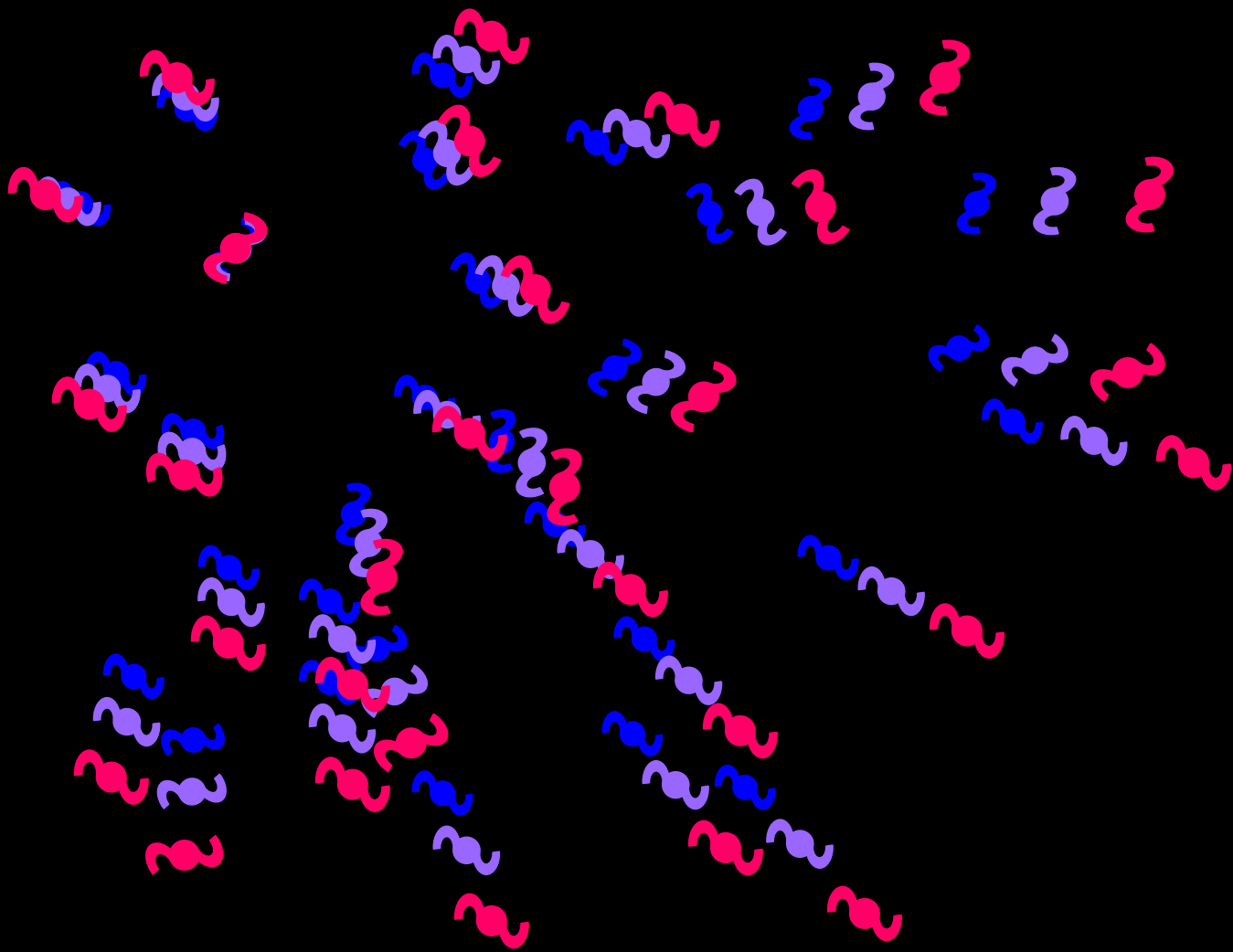
- Hubble's law (correlation between velocity and distance)
- Redshift of light
- General relativity

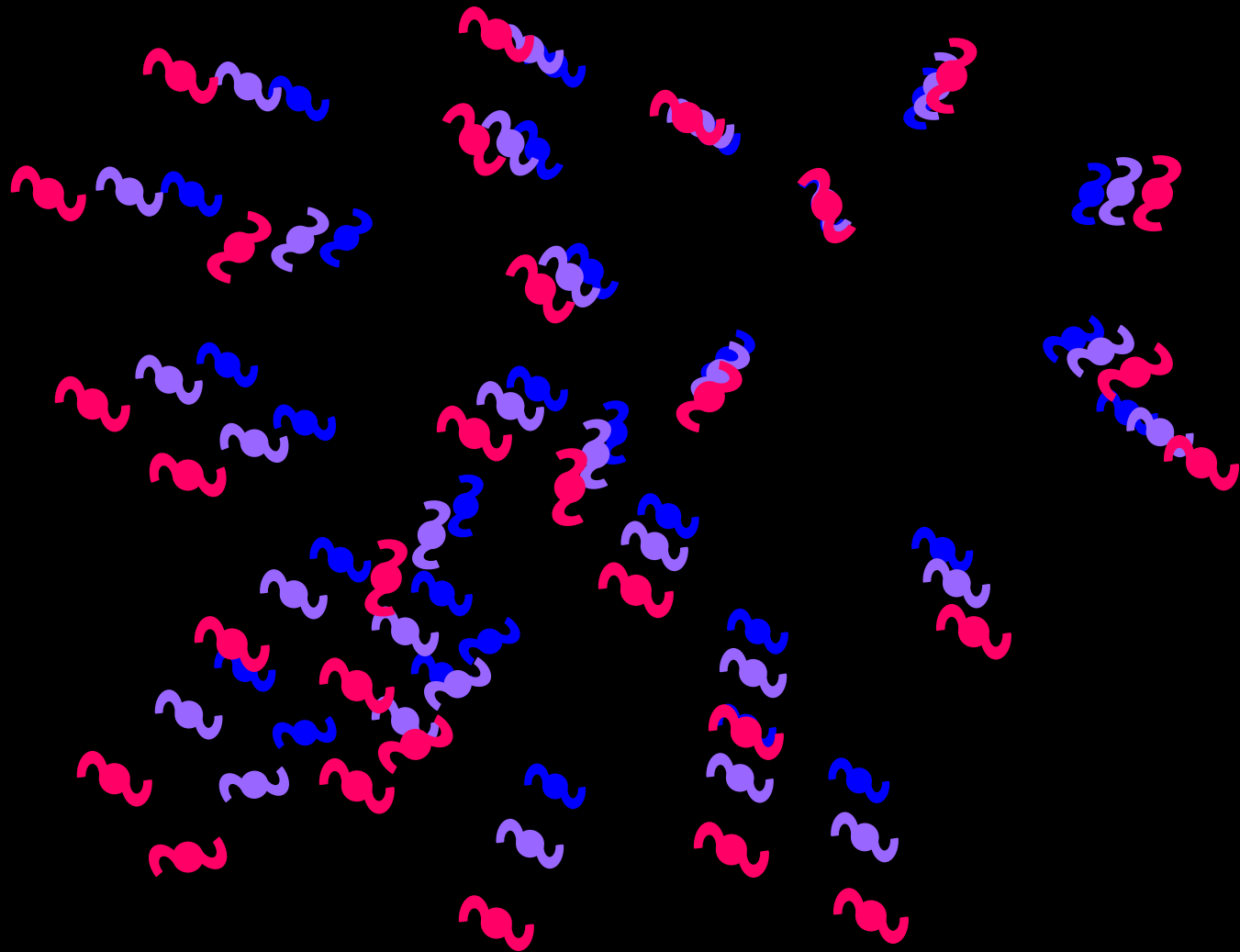






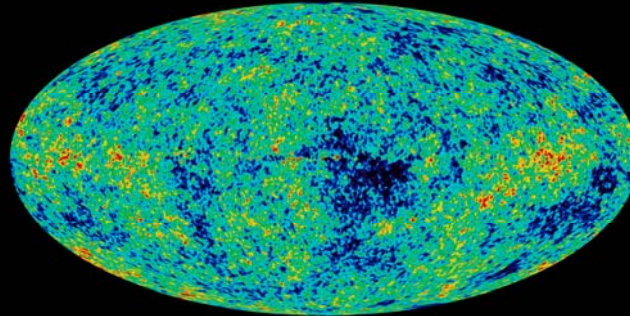




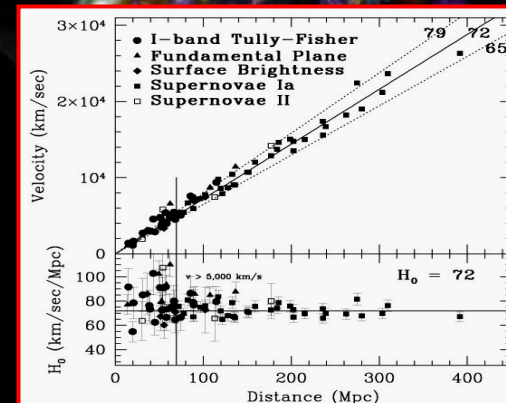
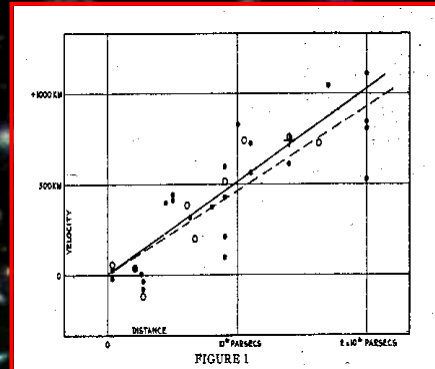


**No Center
Just Different
Perspectives**

Evidence for Hot Big Bang



- Expansion of Universe
- Cosmic microwave background: microwave echo of big bang
- Abundance of the elements H, D, He, Li
- Consistent age: expansion age, oldest stars, age of radioactive elements, cooling of white dwarf stars, age of oldest astronomers
- Formation of structure by gravity



SEEING THE BEGINNING WITH MICROWAVES

QUARK SOUP

REGION OF MORE MATTER

DARK AGES

REGION OF LESS MATTER

50,000 yrs
Last scattering
Formation of Atoms

0.16yr
First stars

0.56yr
Proto galaxies

16yr
First Quasars

56yr
Peak of Galaxy Formation

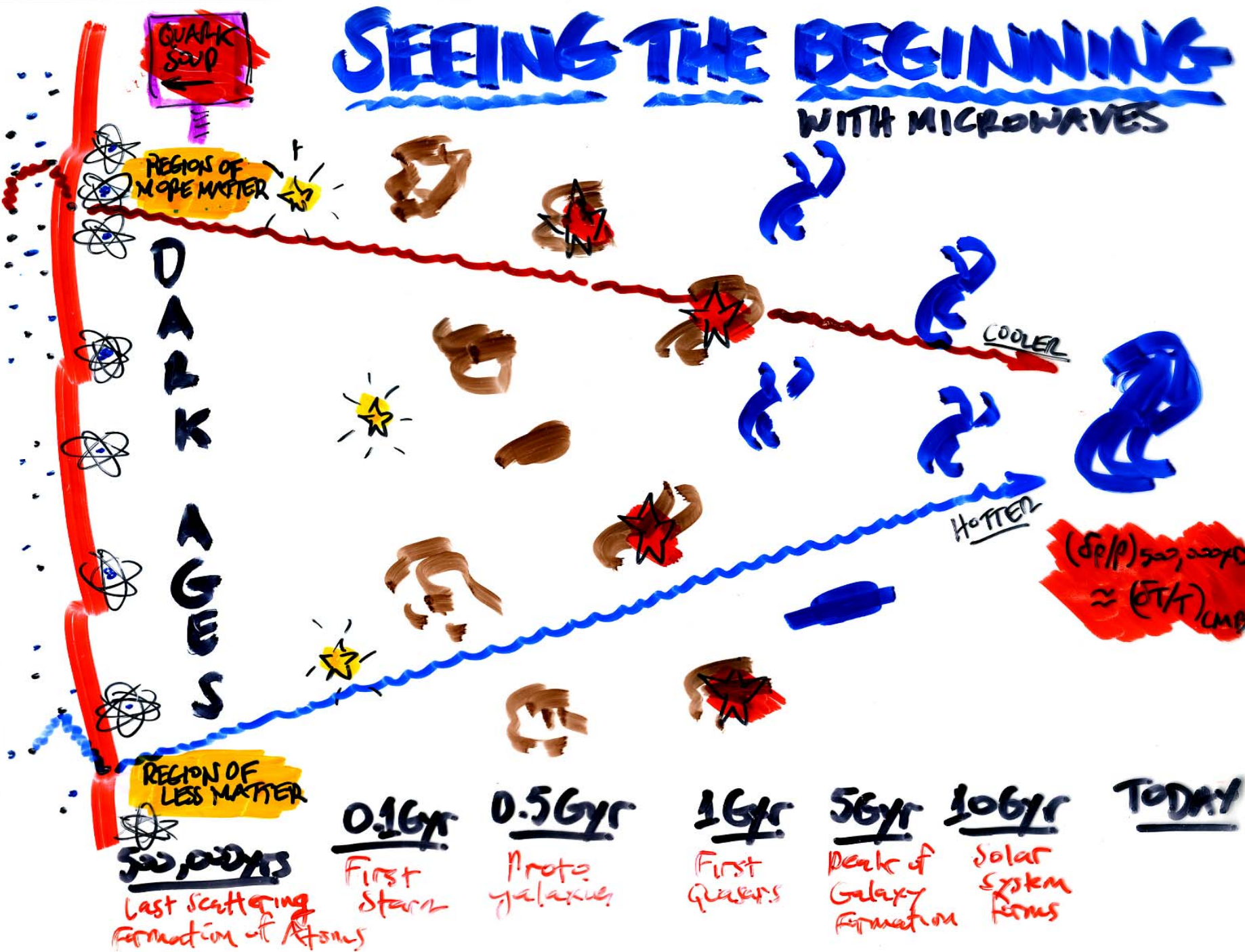
106yr
Solar System forms

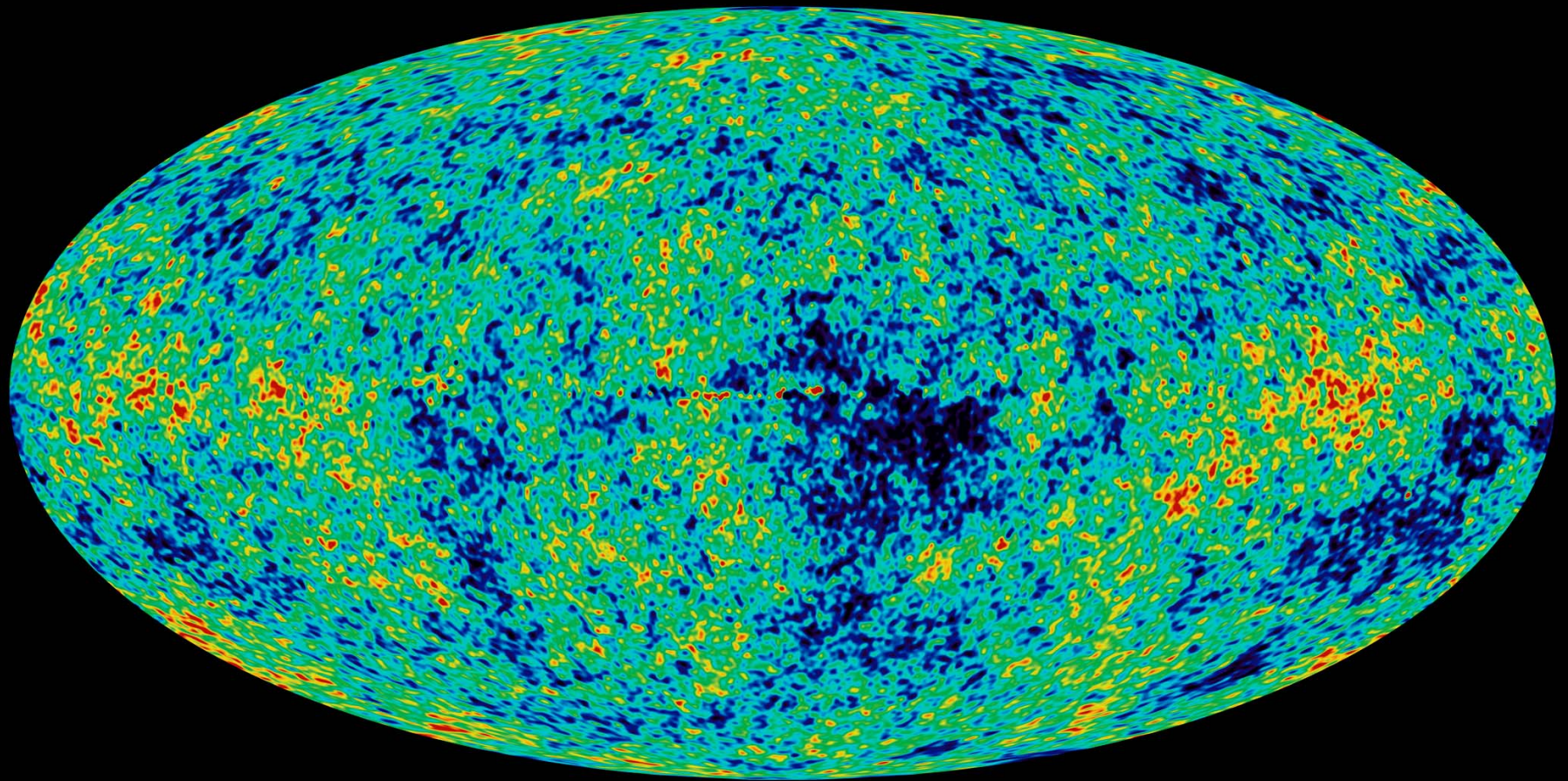
TODAY

COOLER

HOTTER

$$\left(\frac{\delta p}{p}\right)_{500,000} \approx \left(\frac{\delta T}{T}\right)_{CMB}$$





The Universe at 400,000 years
No galaxies or stars, just a tiny
amount of lumpiness (0.001%)
– the seeds of all structure

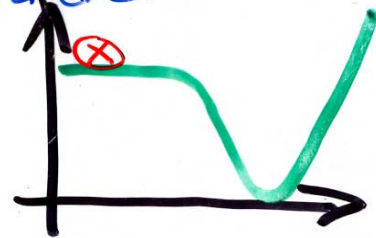
Where did the
lumpy quark
soup come
from?



COSMIC INFLATION

Guth; Linde;
Albrecht-Steinhardt

VACUUM ENERGY



SHORT PERIOD OF RAPID EXPANSION DRIVEN BY "FALSE-VACUUM" ENERGY

★ MORE EXPANSION IN 10^{-32} SEC THAN NEXT 15 BYR

★ OBSERVED UNIVERSE BEGAN FROM INCREDIBLY SMALL PATCH → FLAT & SMOOTH

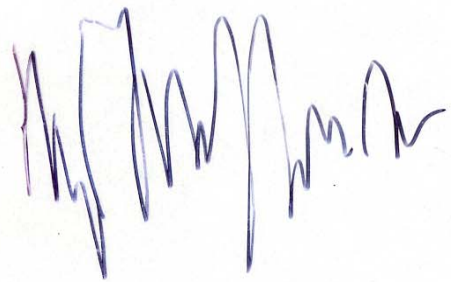


★ MICROSCOPIC PHENOMENA (QUANTUM FLUCTUATIONS) CAN INFLUENCE MACROSCOPIC SCALES → QUANTUM ORIGIN OF "LUMPINESS"

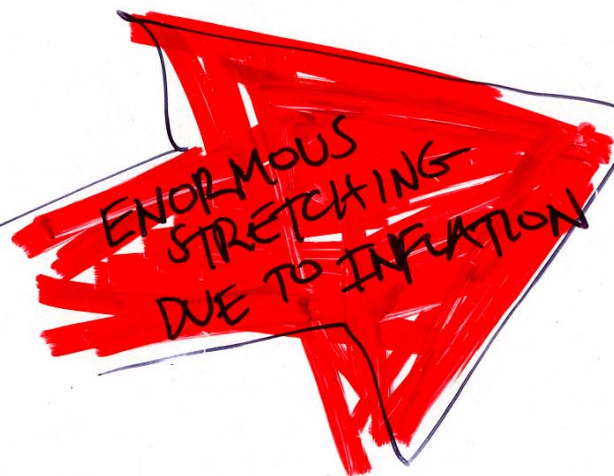
FLUCTUATIONS:

MICRO TO MACRO

Bardeen-Steinhardt-MST; Guth-Pi;
Hawking; Starobinski 1982



←→
≪ 10^{-8} cm



ENORMOUS
STRETCHING
DUE TO INFLATION

MORE
MATTER

LESS
MATTER

←→
≫ LIGHT YRS

QUANTUM FLUCTUATIONS
ON SUBATOMIC SCALE

"LUMPY" DIS-
TRIBUTION OF
MATTER ON
MACRO SCALE



INFLATION IN THE UNIVERSE

EARLY EPOCH OF TREMENDOUS EXPANSION DRIVEN BY VACUUM ENERGY

10^{-32} sec $\gg 10^{40}$

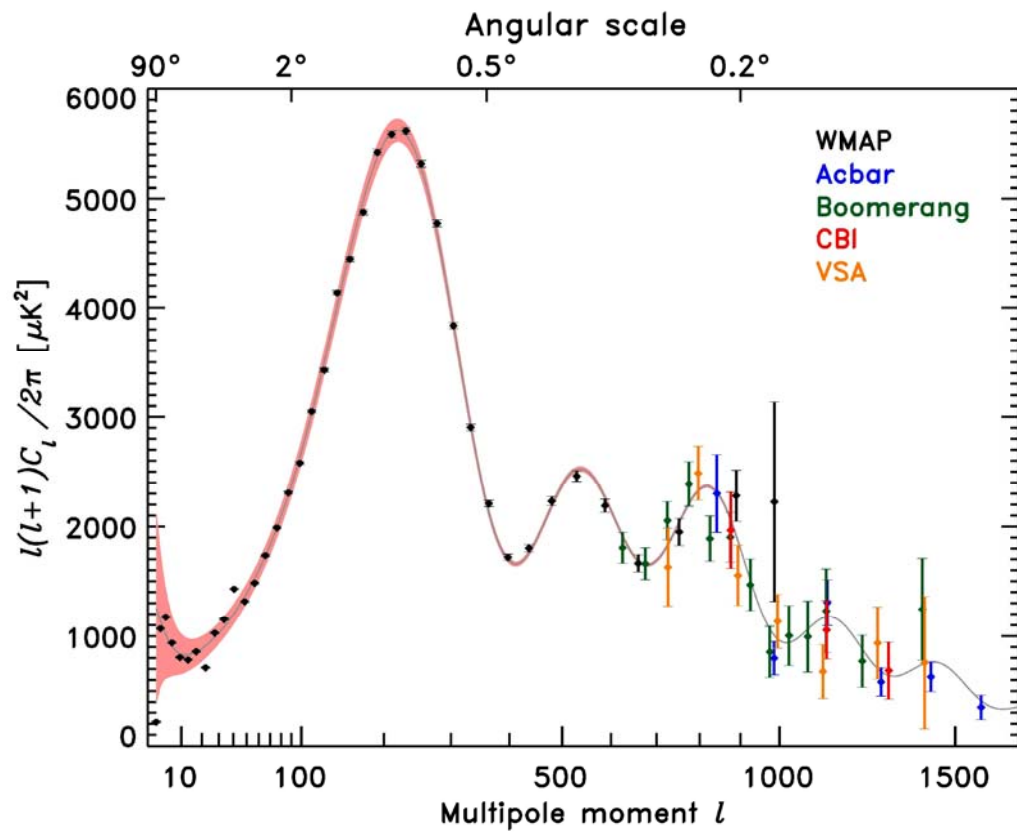
SCALAR FIELD ENERGY

ACCOUNTS FOR:
SMOOTHNESS, HEAT OF BIG-BANG & ABSENCE OF MONOPOLES

& PREDICTS:

- "FLAT UNIVERSE" ($\Omega_0 = \frac{\rho_{TOT}}{\rho_{CRIT}} \approx 1.0$)
- NEARLY SCALE-INVARIANT DENSITY PERTURBATIONS
- NEARLY SCALE-INVARIANT GRAVITY WAVES

Robust Predictions



What we've learned from WMAP

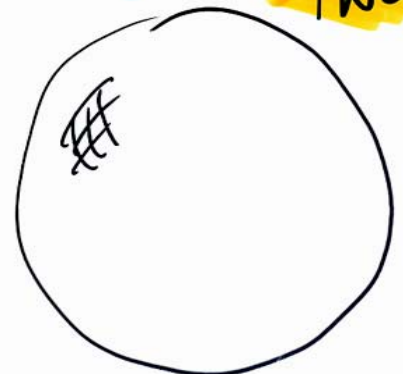
- ★ UNIVERSE IS SPATIALLY "FLAT" $\pm 2\%$
- ★ ATOMIC MATTER IS $4\% \pm 1\%$
- ★ AGE OF UNIVERSE IS $13.7 \text{ Gyr} \pm 0.2 \text{ Gyr}$
- ★ COLD DARK MATTER IS $25\% \pm 4\%$
- ★ DARK ENERGY IS $70\% \pm 4\%$
- ★ FIRST STARS AT $z \approx 15 \pm 5$
- ★ EVIDENCE FOR INFLATION

SHAPE OF UNIVERSE DEPENDS UPON AMOUNT OF MATTER & ENERGY

TWO-DIMENSIONAL ANALOGUES

HIGH DENSITY

CURVES BACK ON ITSELF

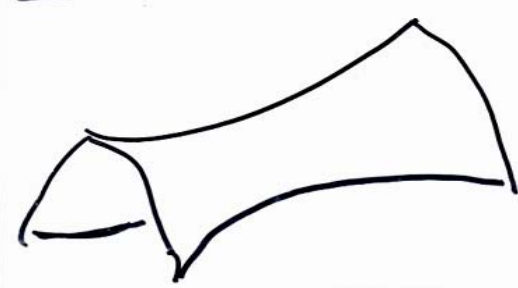


CRITICAL DENSITY
UNCURVED ("flat")



LOW DENSITY

CURVED LIKE SADDLE



Our
Universe



INFLATION SCORECARD

PREDICTIONS

WMAP

FLAT UNIVERSE

★ $\Omega_0 = 1.000$

NOW

1.02 ± 0.02

$\Omega_0 = 1.03 \pm 0.03$ ++*

GRADE

GOAL

± 0.001

* FOR DOING IT THE HARD WAY

DENSITY PERTURB FROM QM FLUC

★ ADIABATIC

≥ 3 ACOUSTIC PEAKS ++

≥ 7

★ NEARLY SCALE-INVARIANT $(n-1) \sim 0 (\pm 0.1)$

0.93 ± 0.03

$n = 1.05 \pm 0.09$ +

± 0.001

★ NEARLY POWER-LAW $dn/dlnk \sim \pm 10^{-3}$

-0.03 ± 0.02

$dn/dlnk = -0.02 \pm 0.04$ ✓

$\pm 10^{-3}$

★ GAUSSIAN

NO EVIDENCE AGAINST ✓



CDM

"HAS MUCH OF THE TRUTH" ++

GRAV WAVES FROM QM METRIC FLUC ?

★ $T/S \geq 10^{-3}$ (??)

$T/S \leq 0(1)$

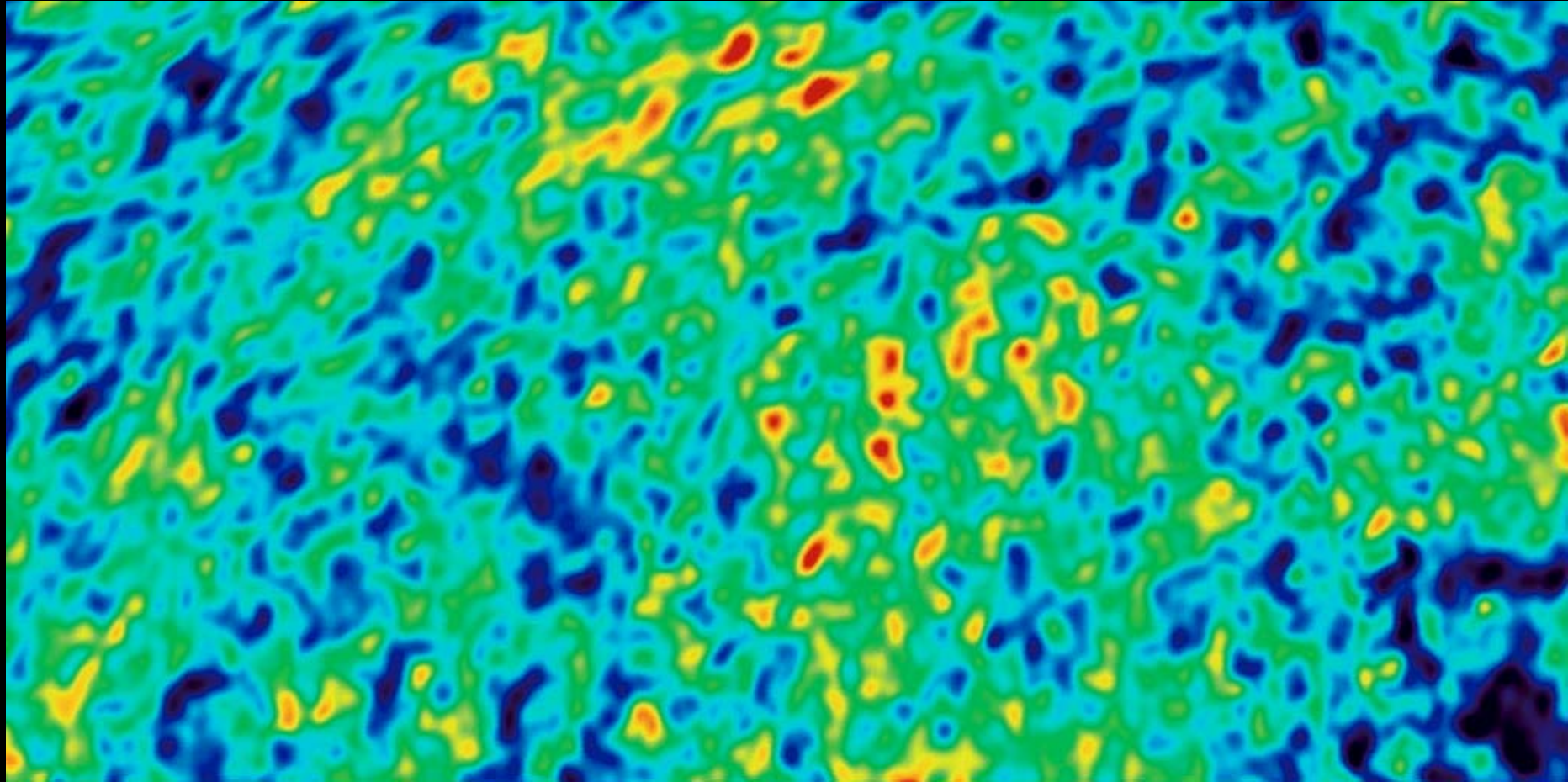
$10^{-3}/10^{-4}$

★ NEARLY SCALE INVARIANT $n_T = -1/2 T/S$

0.71 (95% cl)

± 0.03

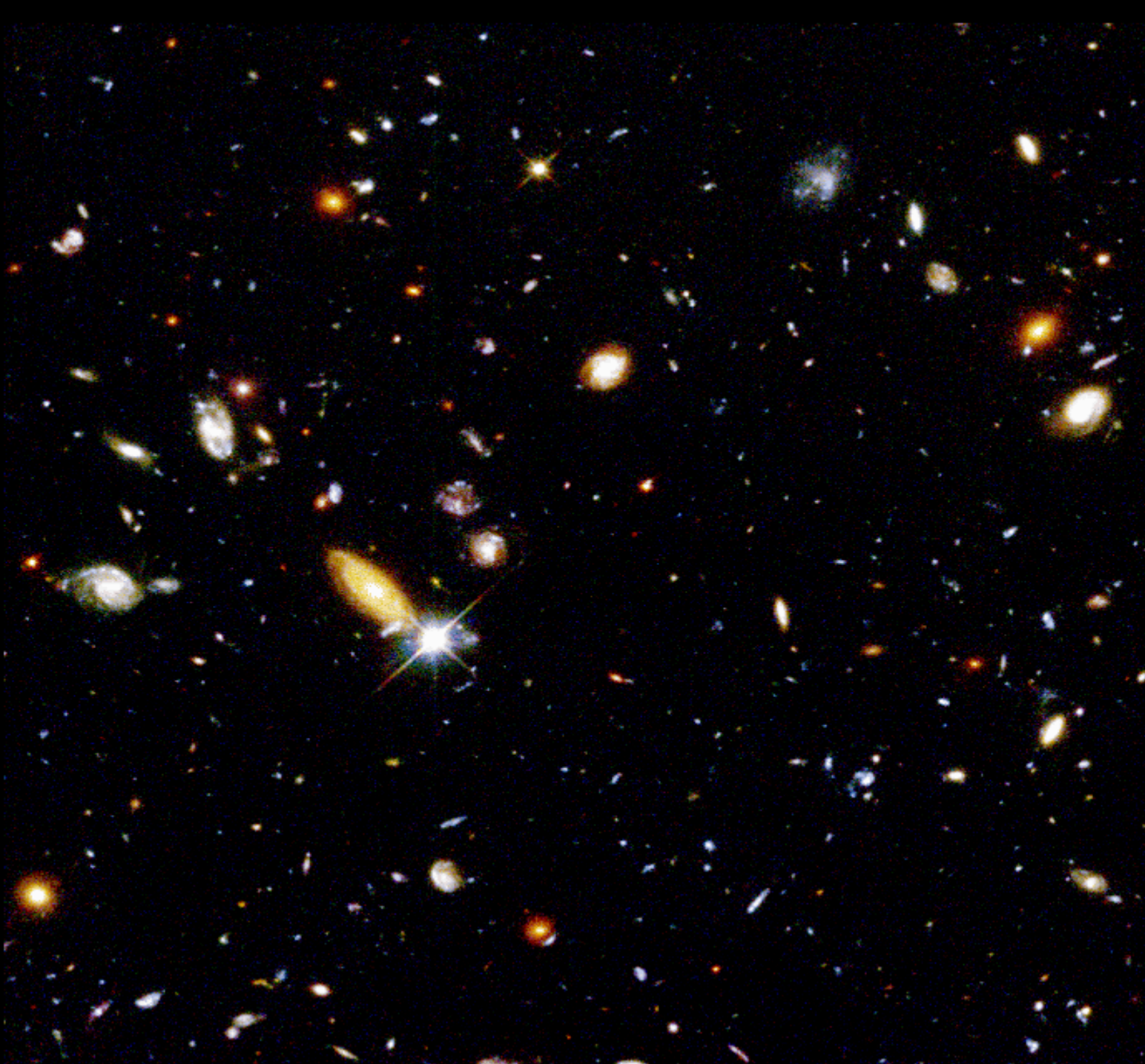
Quantum World Projected Across the Sky by the Expansion of the Universe



< one billionth the size
of a proton



**Hubble
Deep
Field:
As Far
as You
Can
See on
a Clear
Day**





DON'T LET THE BRIGHT
LIGHTS FOOL YOU

THE DARK SIDE

CONTROLS THE UNIVERSE

OUR UNIVERSE

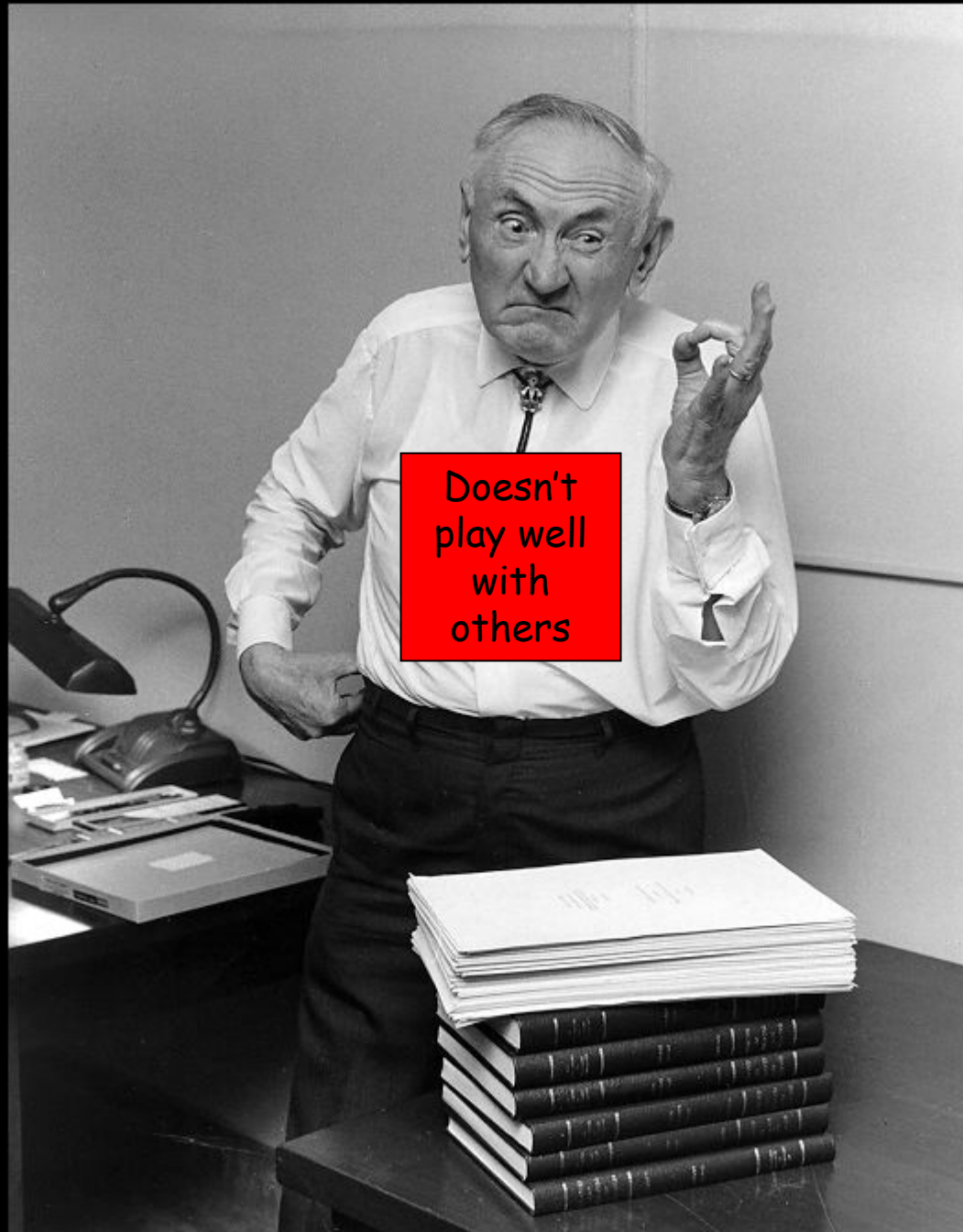
STARS: 0.5%

DARK MATTER: 33%

DARK ENERGY: 66%

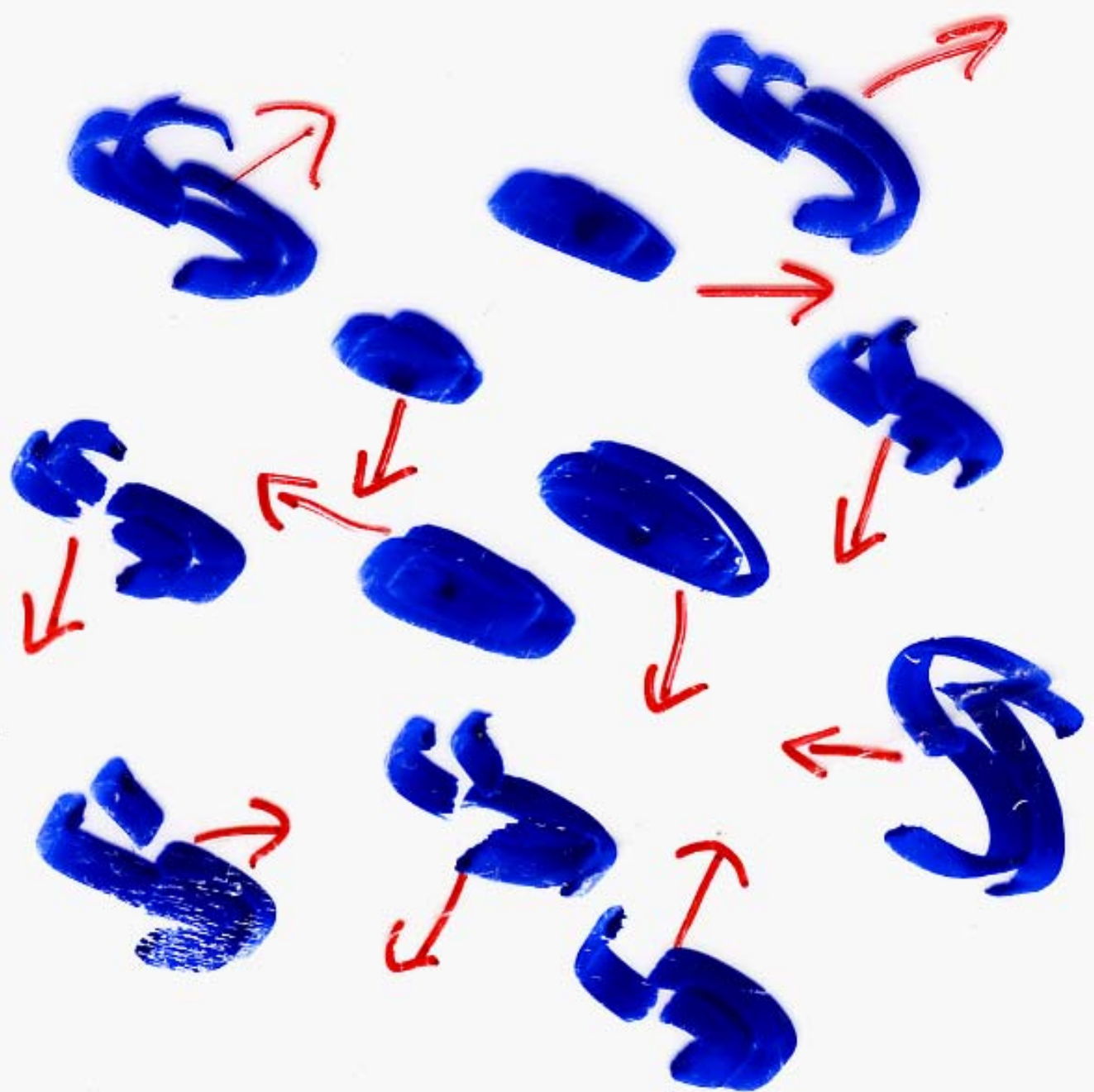
DARK MATTER HOLDS IT TOGETHER

DARK ENERGY DETERMINES HIS DESTINY



Doesn't
play well
with
others





The Gravity of the Stars is not Enough to Hold Clusters Together

**Zwicky: Clusters Must be
Held Together by the Gravity
of Unseen “Dark Matter”**

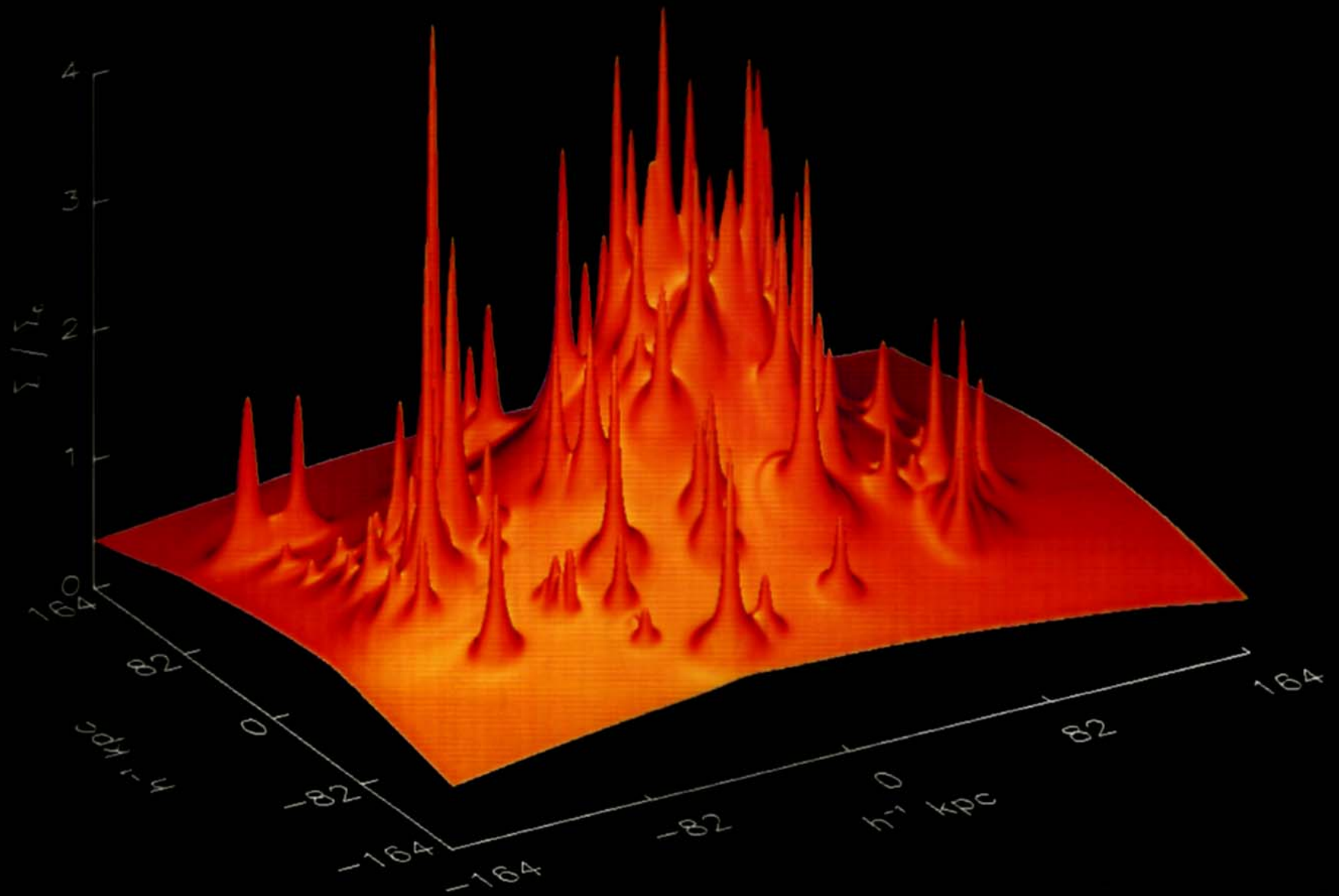


**Gravitational Lens
Galaxy Cluster 0024+1654**

HST · WFPC2

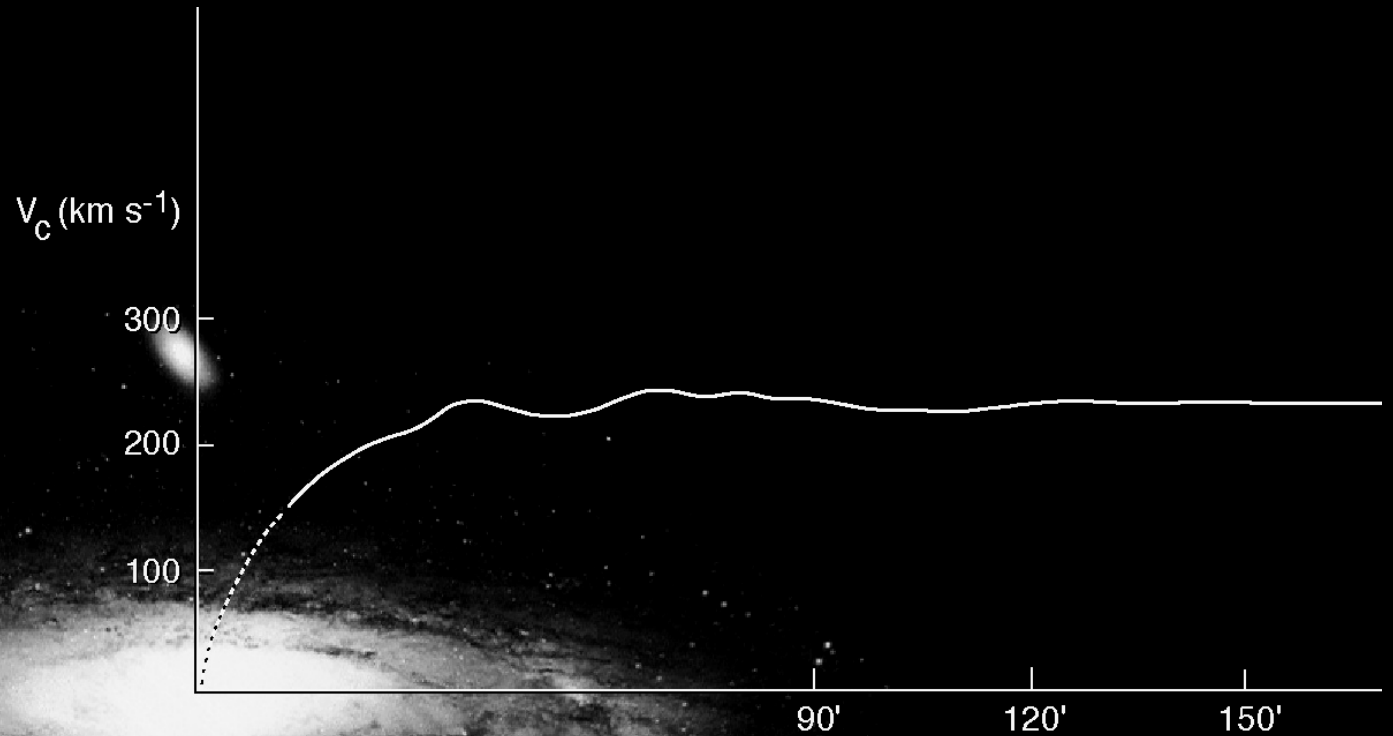


PROJECTED MASS DENSITY: CLOO24

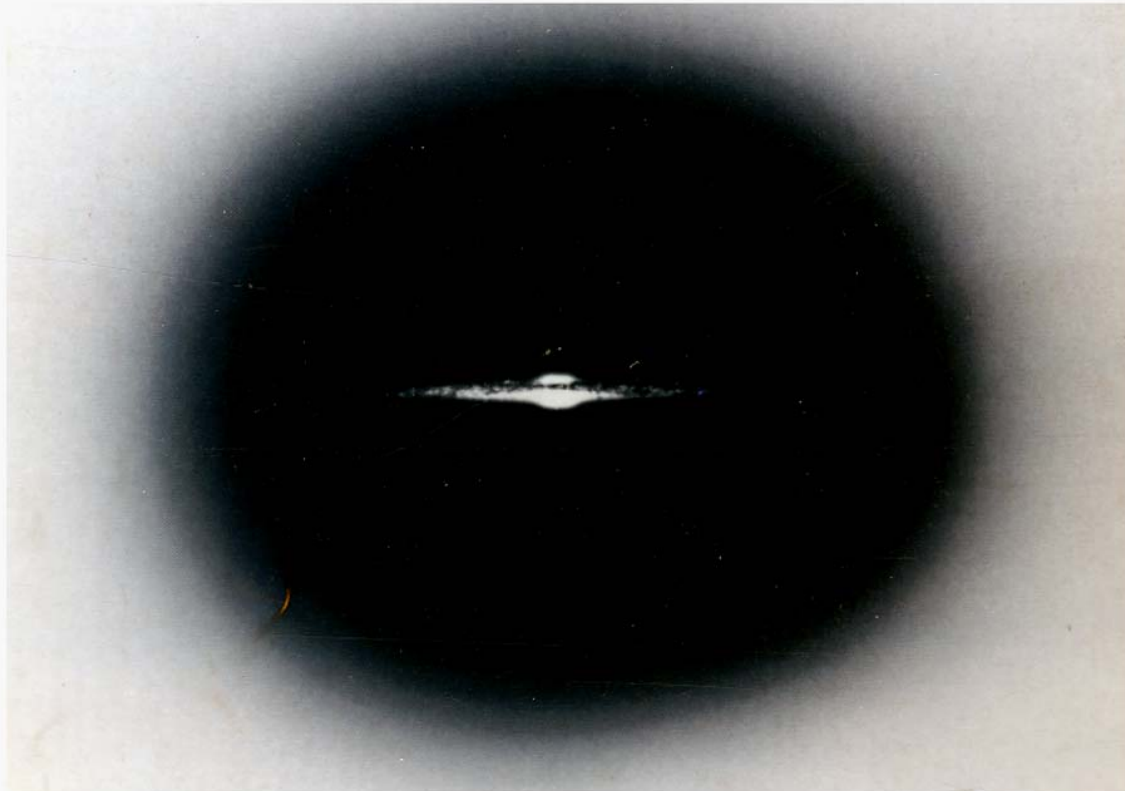


Vera Rubin and Flat Rotation Curves

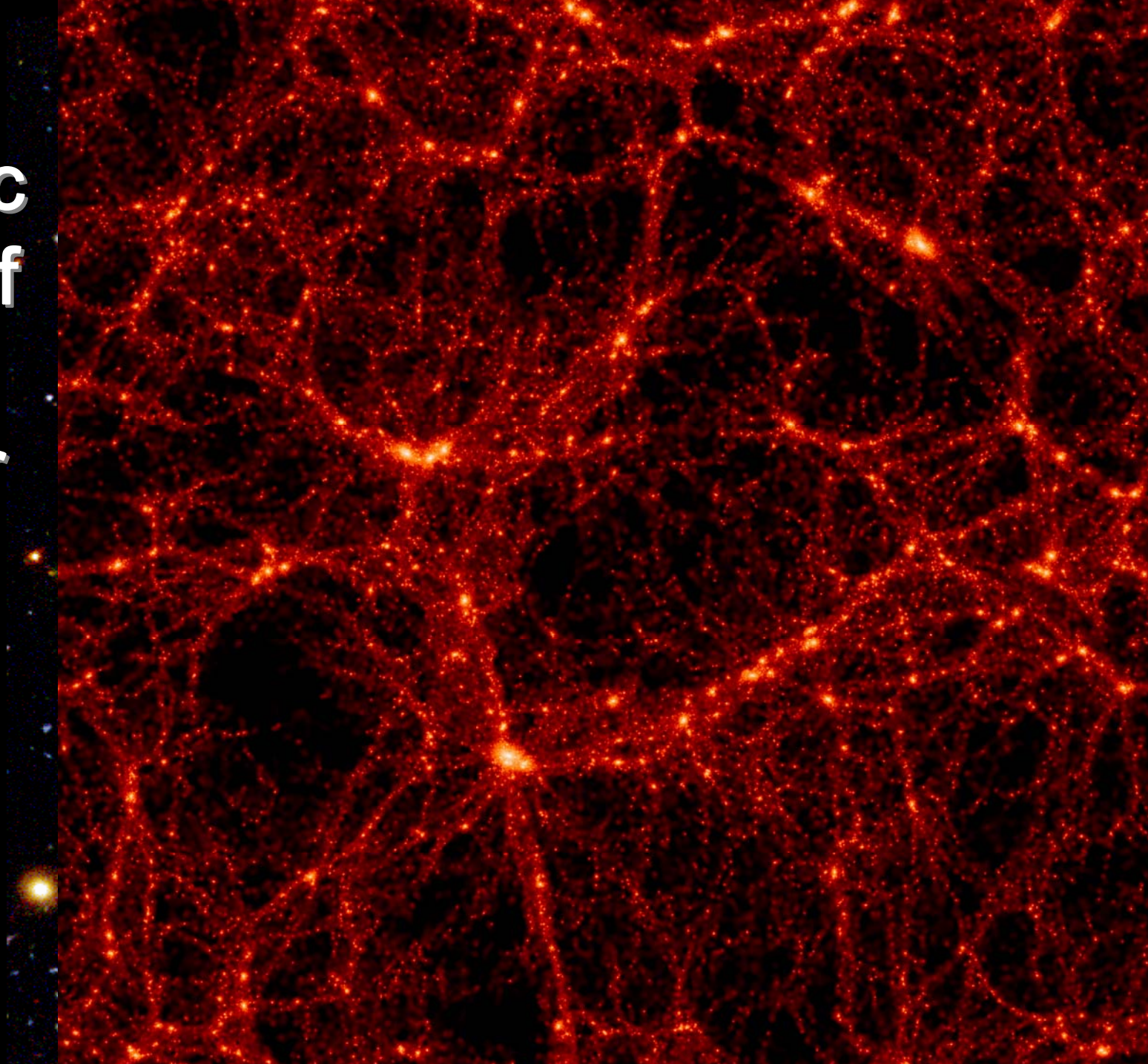
Dark Matter Close to Home



LOTS OF DARK
MATTER-RIGHT
HERE!



Cosmic Web of Dark Matter



NOT ENOUGH
ORDINARY MATTER

4%
OF CRITICAL

TO ACCOUNT FOR

THE AMOUNT OF
DARK MATTER

33%
OF CRITICAL



DARK MATTER
IS A NEW FORM OF
MATTER! "COLD DARK MATTER"

OF MOOSE DIAGRAM DARK MATTER CANDIDATES

MT90



**Dark Matter
Particles
Came from
the Quark
Soup!**



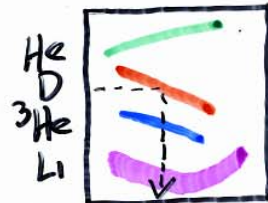
ORDINARY MATTER: FROM QUARKS TO US

INFLATION
BARYOGENESIS



10^{-5} SEC

TRANSITION FROM
QUARKS \rightarrow NEUTRONS, PROTONS



DENSITY OF MATTER

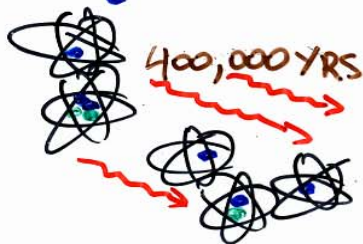
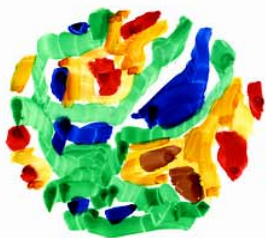
BBN
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 $\Omega_B = 0.04 \pm 0.002$

BIG-BANG
NUCLEOSYNTHESIS

Formation of H, D,
He, He-3, Li

FORMATION OF ATOMS

COSMIC MICROWAVE
BACKGROUND



400,000 YRS

QSO LIGHT

1 BILLION YRS
FIRST QUASARS

(Ω_B / Ω_M) TODAY
 $\Omega_B / \Omega_M = 0.15 \pm 0.01$
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CMB

CMB

RATIO OF FIRST-TO-
SECOND PEAKS: 2/1



$\Omega_B = 0.045 \pm 0.006$

INTERGALACTIC GAS

ABSORPTION OF
QUASAR LIGHT
BY HYDROGEN

$\Omega_B \geq 0.04$

HERE & NOW
14 Billion YRS
stars, gas,
dust, ...
BAM, NISZ,
people ...

By the way,
where did the
atoms come
from?



There were slightly more quarks than antiquarks (1 per billion) leaving a small of quarks after most of the quarks & antiquarks annihilate.

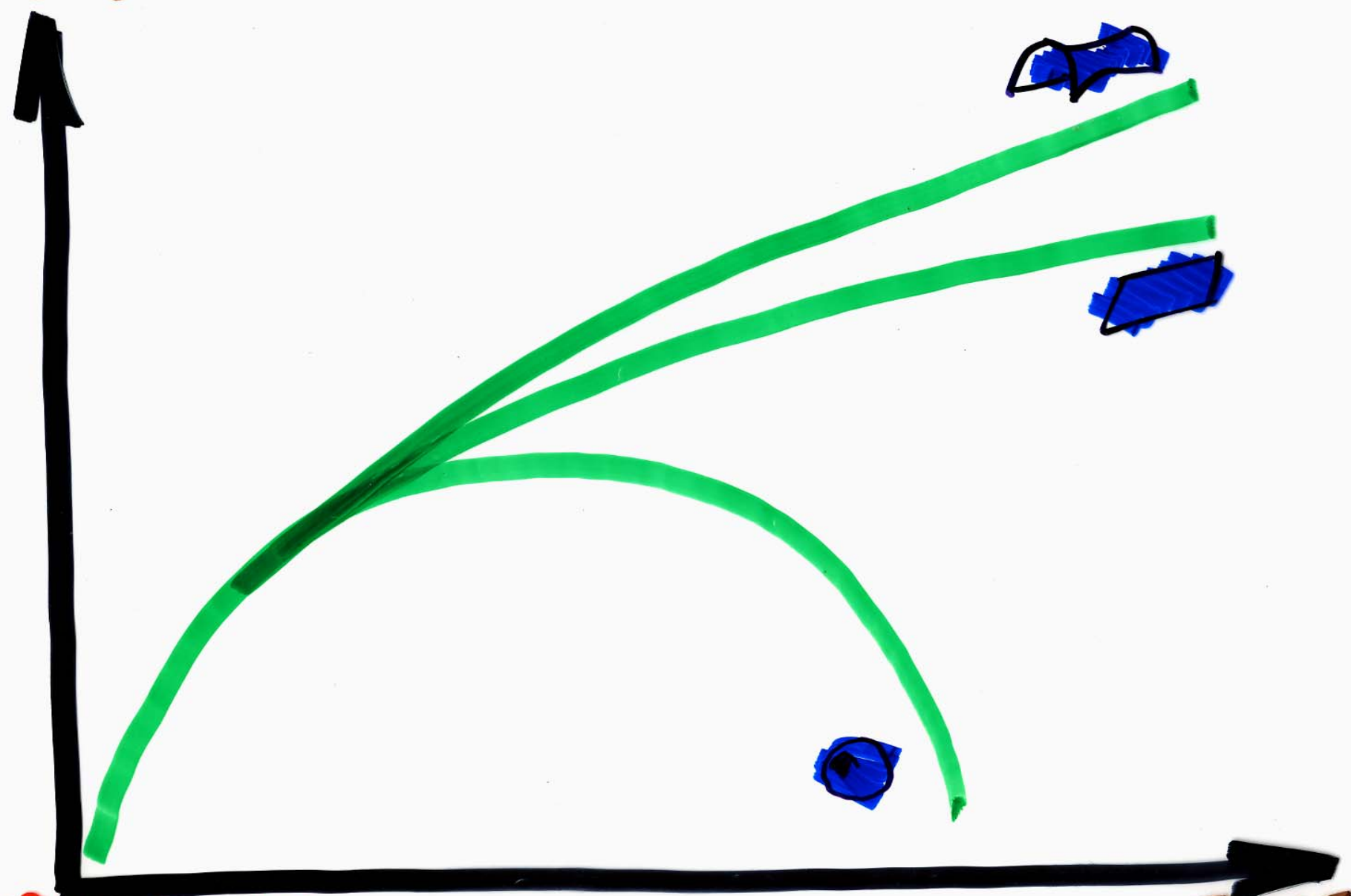


Where did the
slight excess of
quarks over
antiquarks come
from?

Quark
interactions in the
early Universe.



SIZE



BIG BANG

TIME

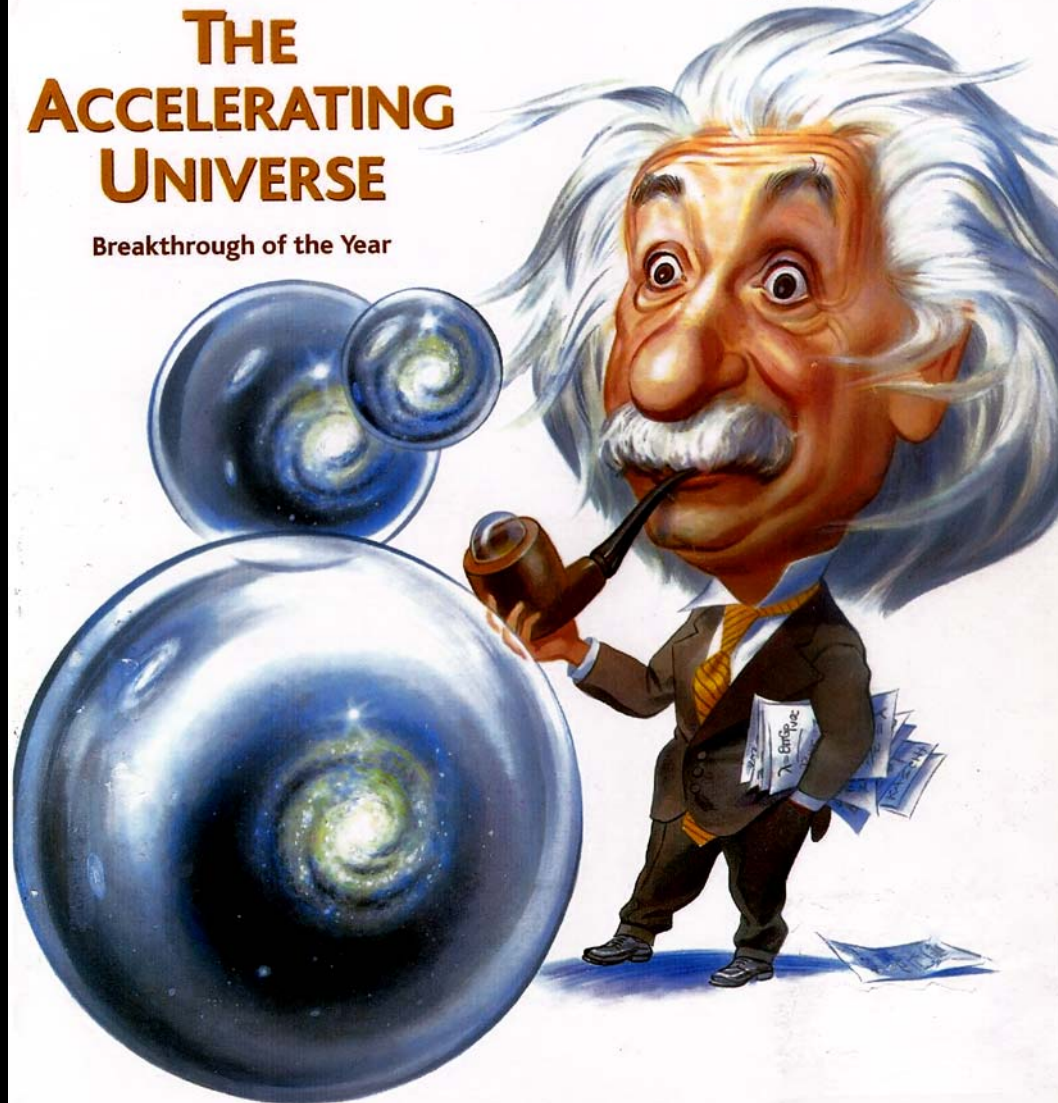
18 December 1998

Science

Vol. 282 No. 5397
Pages 2141-2336 \$7

THE ACCELERATING UNIVERSE

Breakthrough of the Year



AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

REPULSIVE GRAVITY

IS A FEATURE

NOT A
BUG!

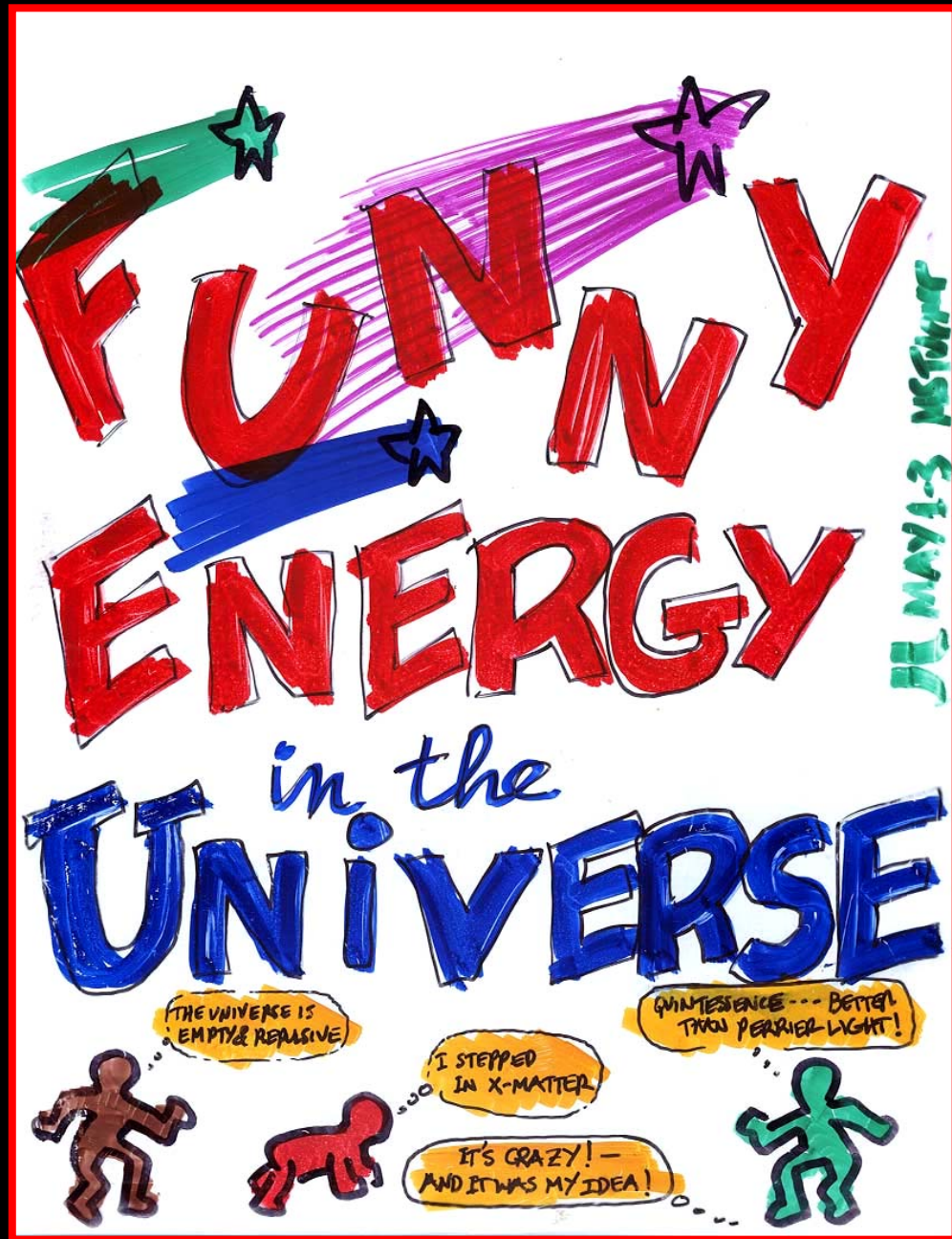
OF EINSTEIN'S
THEORY

... but only really weird
stuff has repulsive gravity

"DARK ENERGY"

**So, Accelerated
Expansion is Caused by
the Repulsive Gravity of
Dark Energy**

Any Questions?



May 1998
 Birth of Funny Energy
 But, Focus Groups
 Didn't Like Name
August 1998
 Birth of Dark
Energy
 Third Stromlo Symposium
 astro-ph/9811454

QUANTUM NOTHINGNESS HAS REPULSIVE GRAVITY!



How REPULSIVE?

JUST ABOUT RIGHT --- GIVE OR TAKE 10^{55}

SOLVING THE
COSMIC ACCELERATION
RIDDLE WILL REQUIRE
A CRAZY, NEW IDEA!

NB: NOT EVERY CRAZY IDEA IS A
SOLUTION TO A PROFOUND
PROBLEM!



@ Joe Turner, Age 6

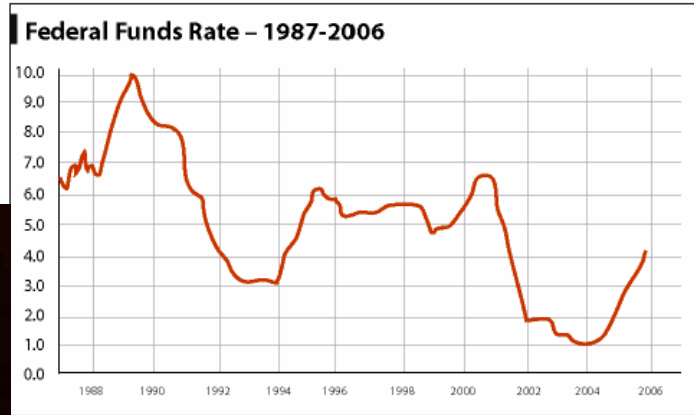
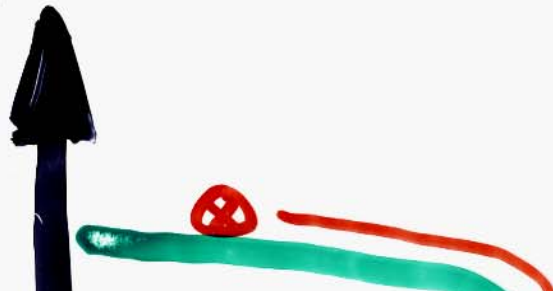
A BRIEF EPISODE OF INFLATION

" (aka decaying cosmological constant, quintessence, rolling scalar field)

... mild episodes of inflation are unavoidable "

A. GREENSPAN

$V(\phi)$



time,
really
negative



NO DARK ENERGY

NEW ASPECT OF GRAVITY

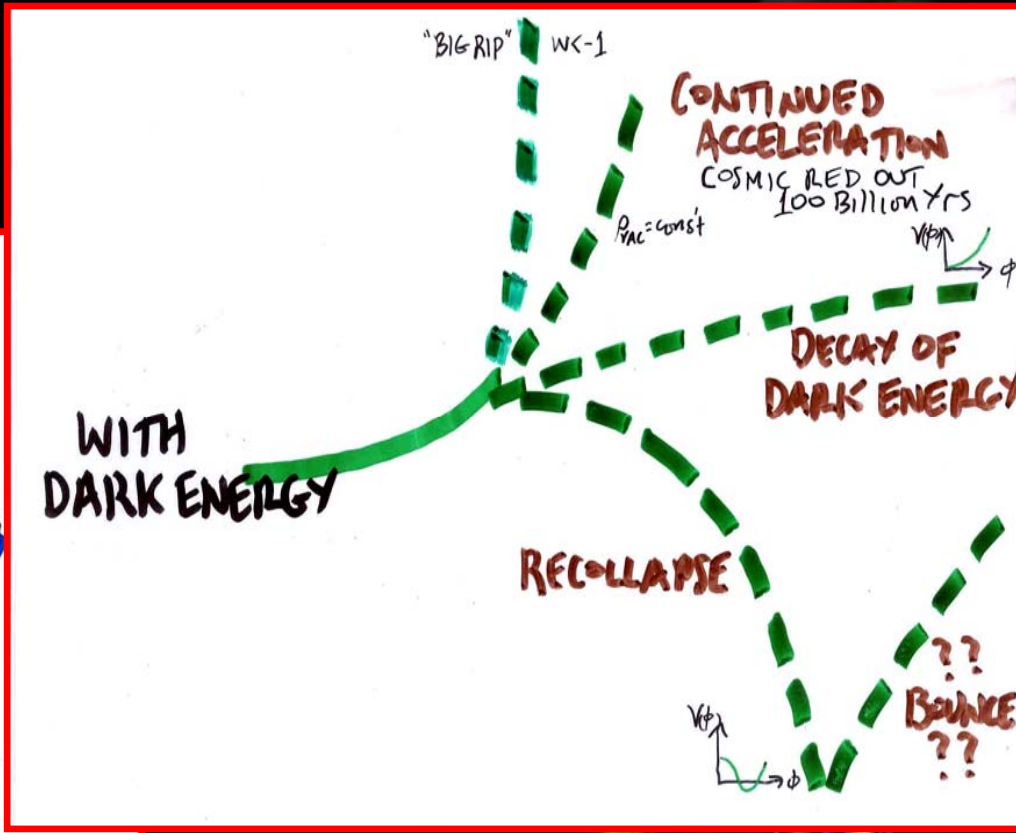
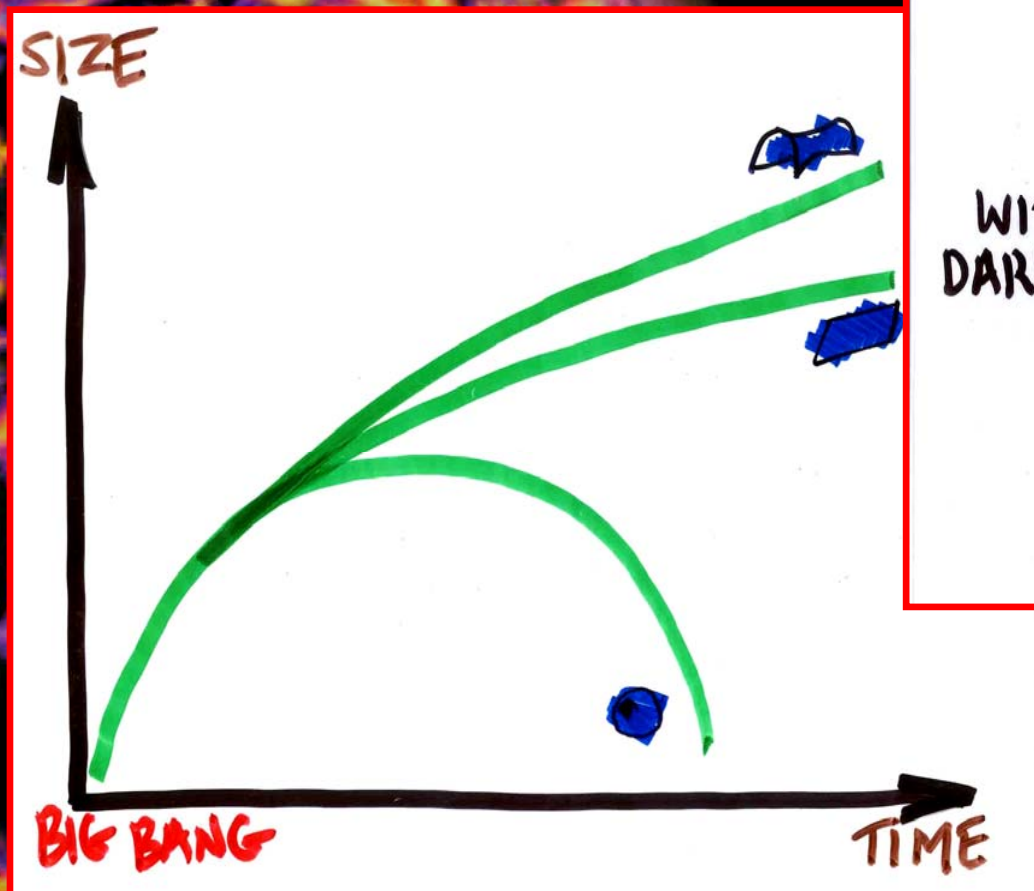
→ "EMPTY" UNIVERSE
UNDERGOES ACCELERATED
EXPANSION!

AVERAGE MATTER DENSITY TODAY $\approx 10^{-29}$ g/cm³
 $\approx 10^{-100} \times$ DENSITY AFTER INFLATION

From Here to Eternity



In the Presence of Dark Energy, a Flat Universe Can Expand Forever, Re-collapse, or Even Experience a Big Rip!



Cannot Understand Our Cosmic Destiny Until We Understand What Dark Energy Is!

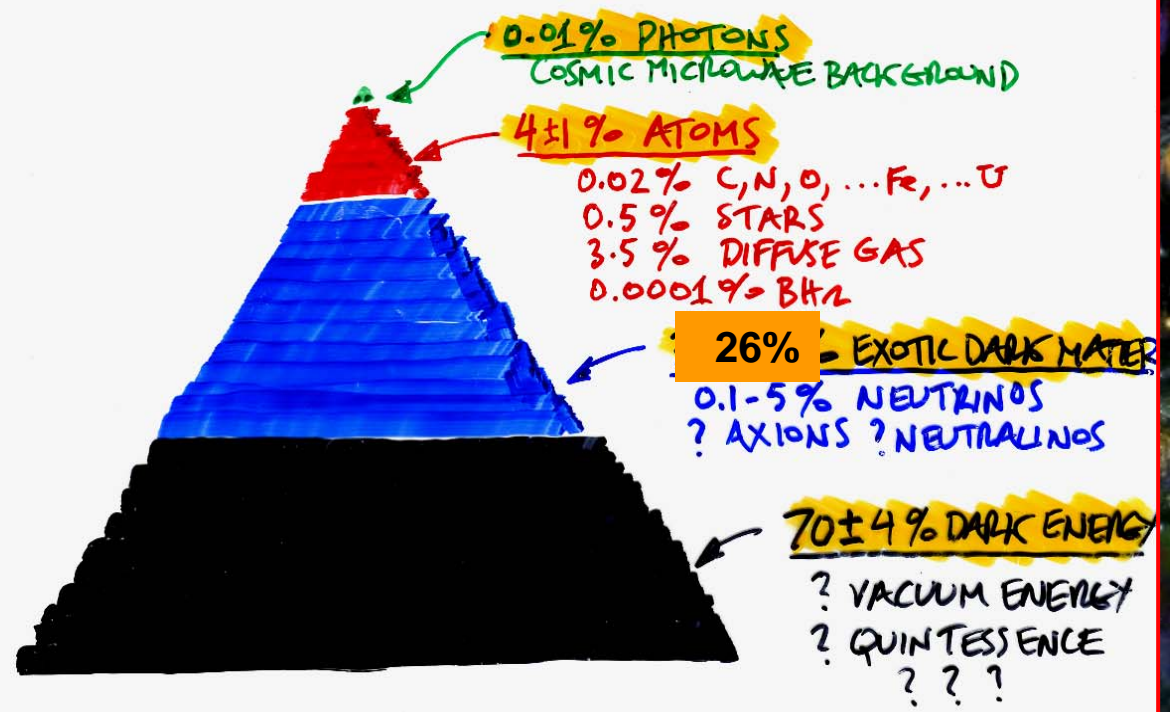
The background of the slide features a cosmic scene. On the left, there is a dense cluster of galaxies, appearing as a complex web of orange, yellow, and purple filaments. On the right, several individual galaxies are visible, including a prominent spiral galaxy with a bright yellow core and blue star-forming regions. The overall color palette is dark with vibrant highlights from the celestial objects.

Connections Between Quarks and Cosmos Profoundly Shaped Our Universe

**Atoms, Dark Matter, Dark Energy and Galaxies
owe their very existence to the deep connections
between the very big and the very small!**

COSMIC STUFF

0.5% STARS + 30% DARK MATTER + 70% DARK ENERGY



➡ 96% IN NEW FORMS OF MATTER & ENERGY

WE KNOW MUCH



INFLATION



STRING COSMOLOGY



HOT BIG BANG MODEL



DARK ENERGY
COSMIC
ACCELERATION



MASSIVE
NEUTRINOS



BARIONS



COLD
DARK
MATTER

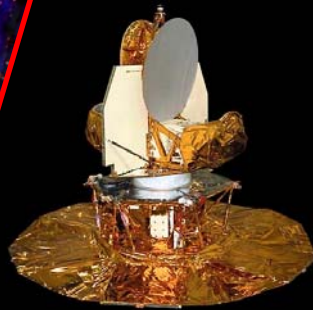
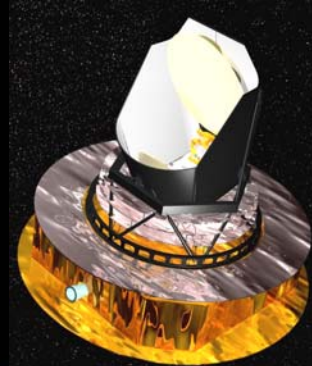
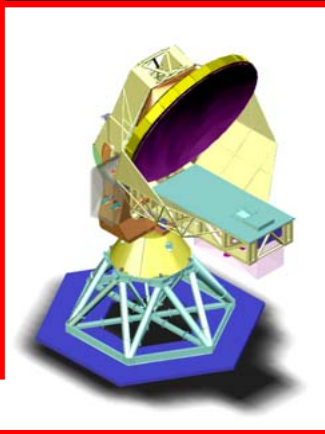
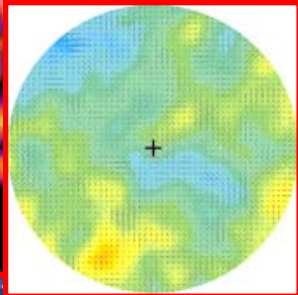
CAN WE PUT
IT ALL TOGETHER?

THE BIG PICTURE



OUR UNIVERSE

Poised to Answer the Big Questions

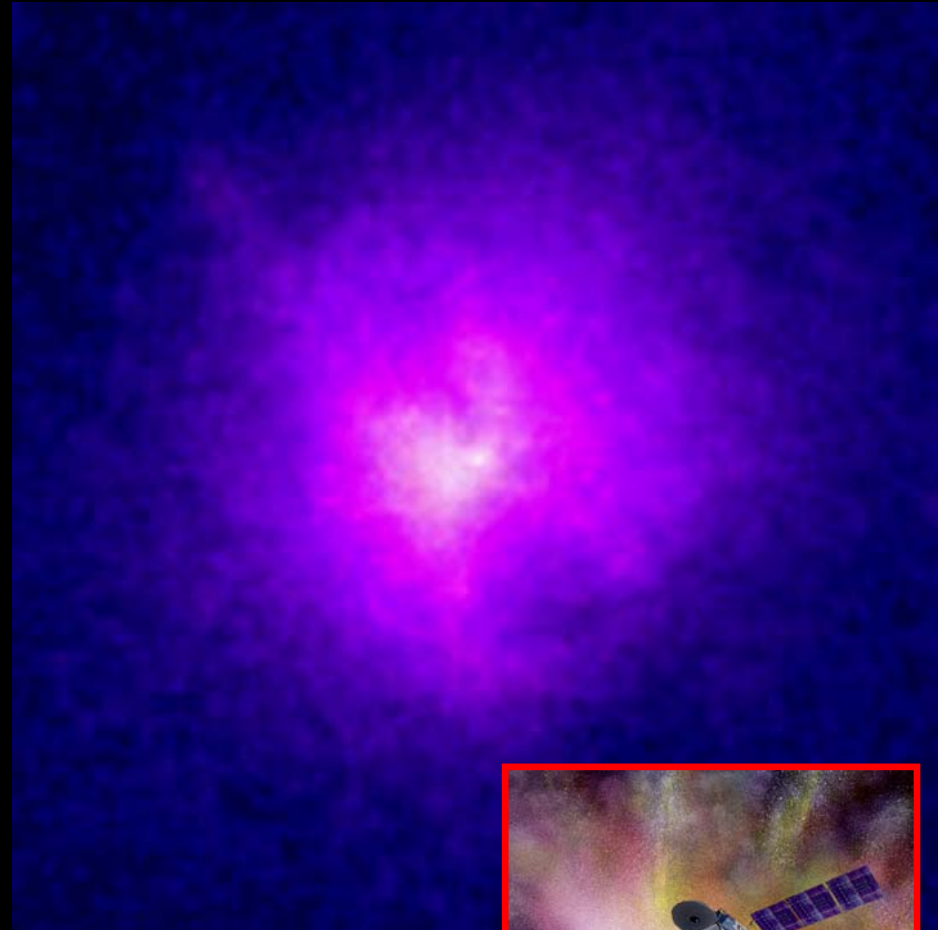


Lots of Hot, X-ray Gas

**Accounts for Most of the
Atoms in Clusters**

**... But a Factor of 6 Short of
Accounting for the Dark Matter**

More than Meets the Eye



... but not enough to account for the dark matter