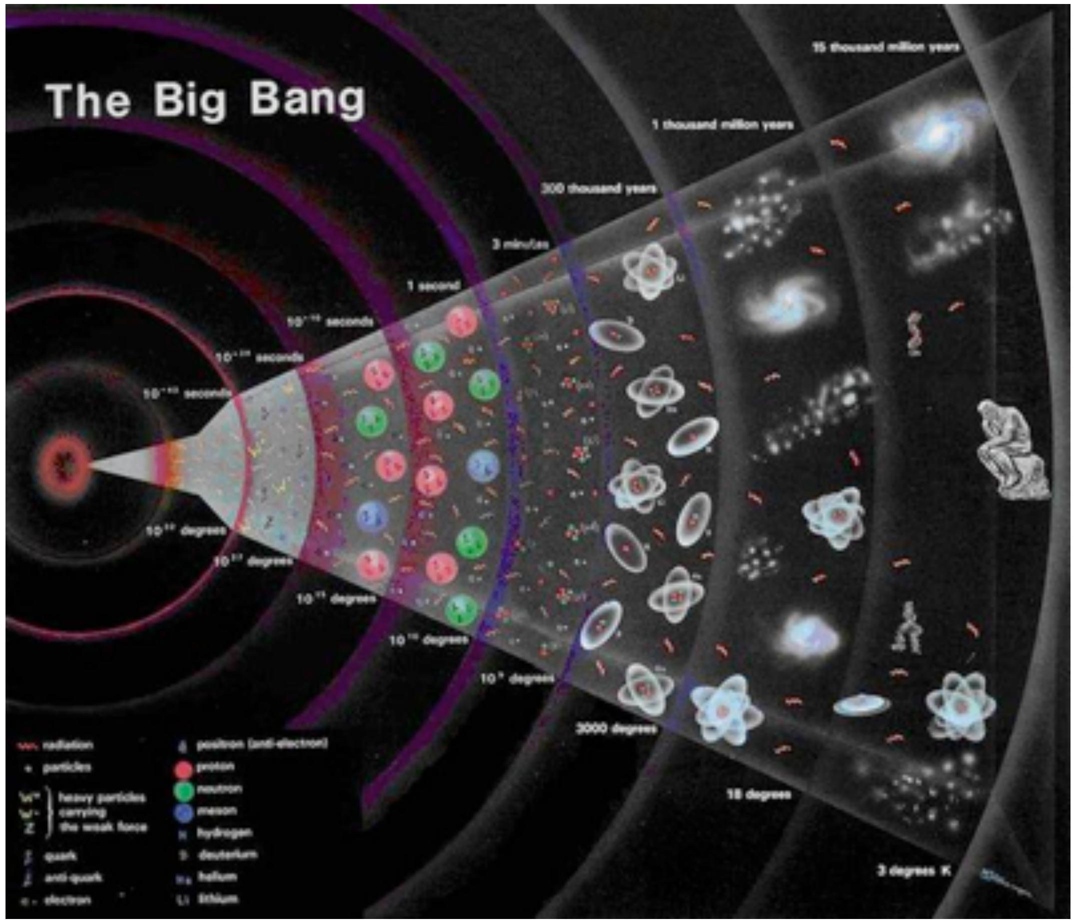
Astronomy 150: Killer Skies
Lecture 35, April 23

Assignments:

- ICES available online
- HW11 due next Friday: last homework!
  - note: lowest HW score dropped
  - but: HW11 material will be on Exam 3, so be sure to look at it
- Hour Exam 3: next Wednesday, June 2, in class
  - details on course website

Last time: The Big Bang

Today: The Past: Early Universe; The Future: Dark Energy



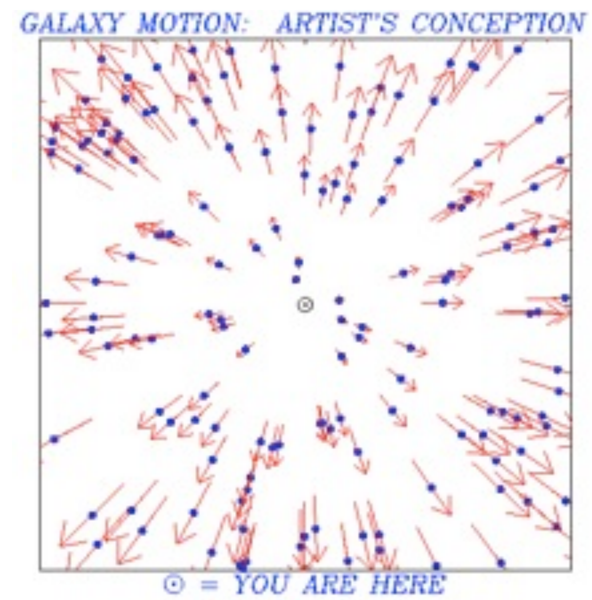
ICES

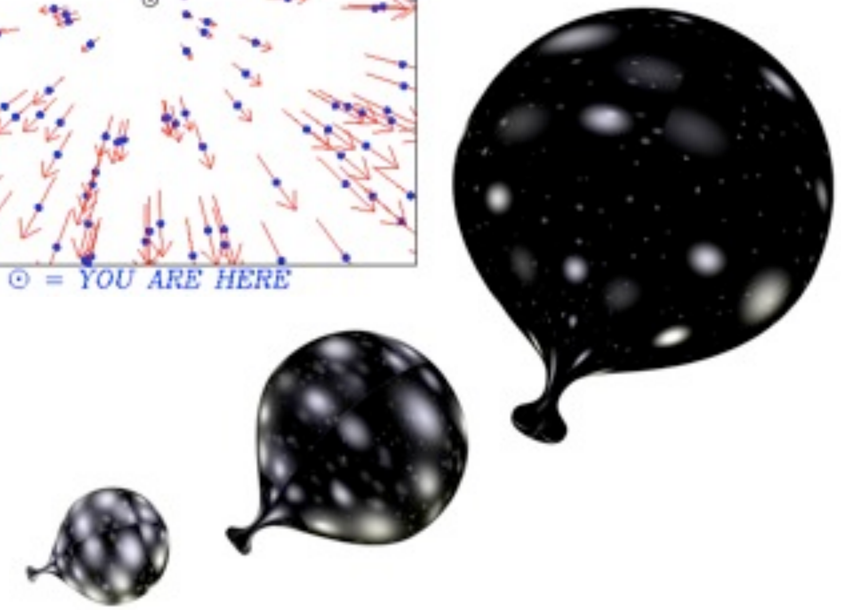
ICES course evaluation is now available, done online.

Please do it!

- Written comments are the most useful and important
- I do read the comments, and I do modify the course as a result.
- Note that this course is relatively new, so your comments will have a particularly large impact.

Recap: Cosmology



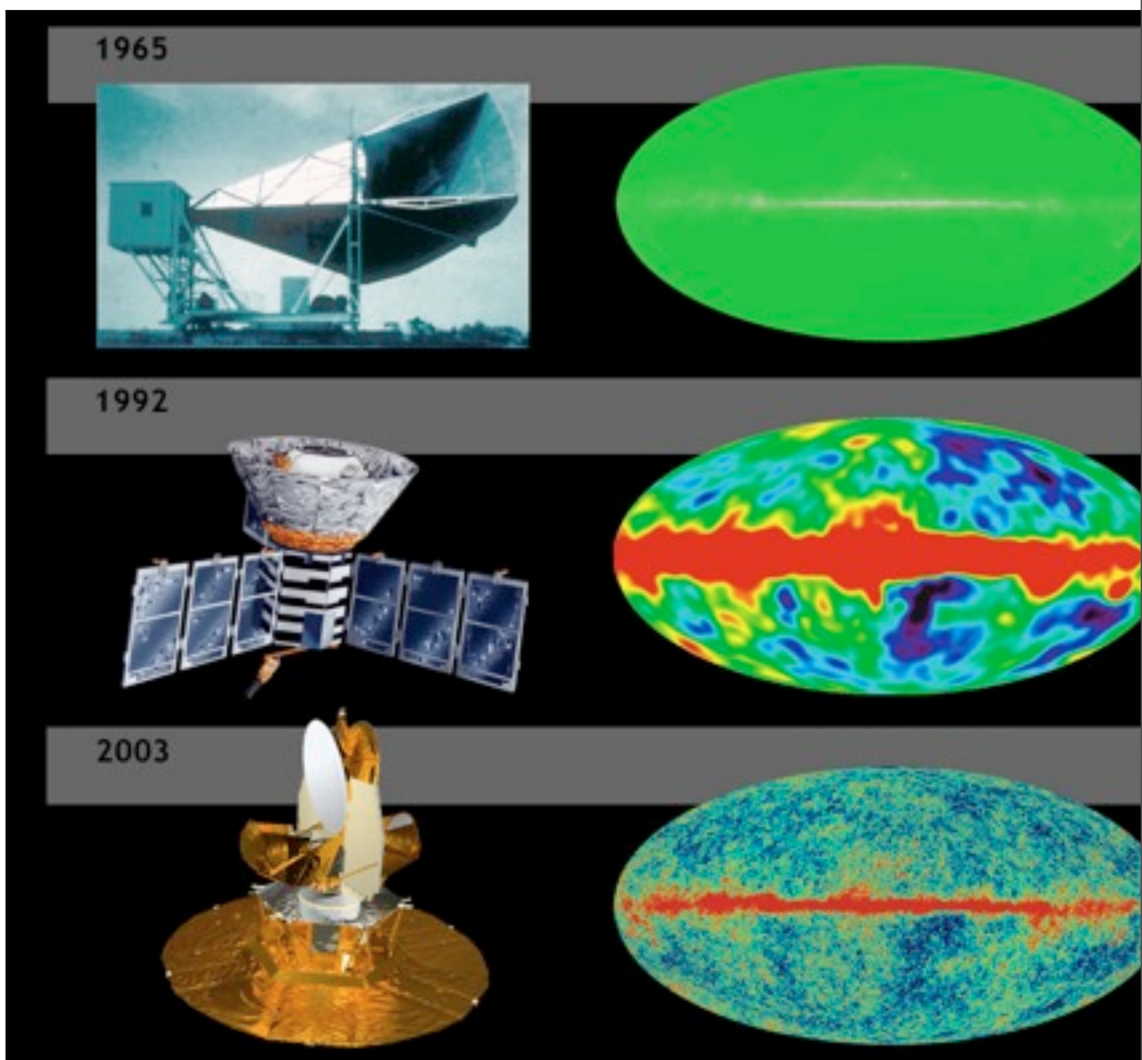


The Universe today

- cosmic layout in space (large-scale structure)
  - homogeneous: contents uniformly, smoothly, evenly distributed
  - isotropic: looks same in all directions
- cosmic motions:
  - everything moving away from everything else
  - farther away = moving faster
  - Hubble's law: $v = H_0 D$

How to be both homogeneous yet also obey Hubble's law?

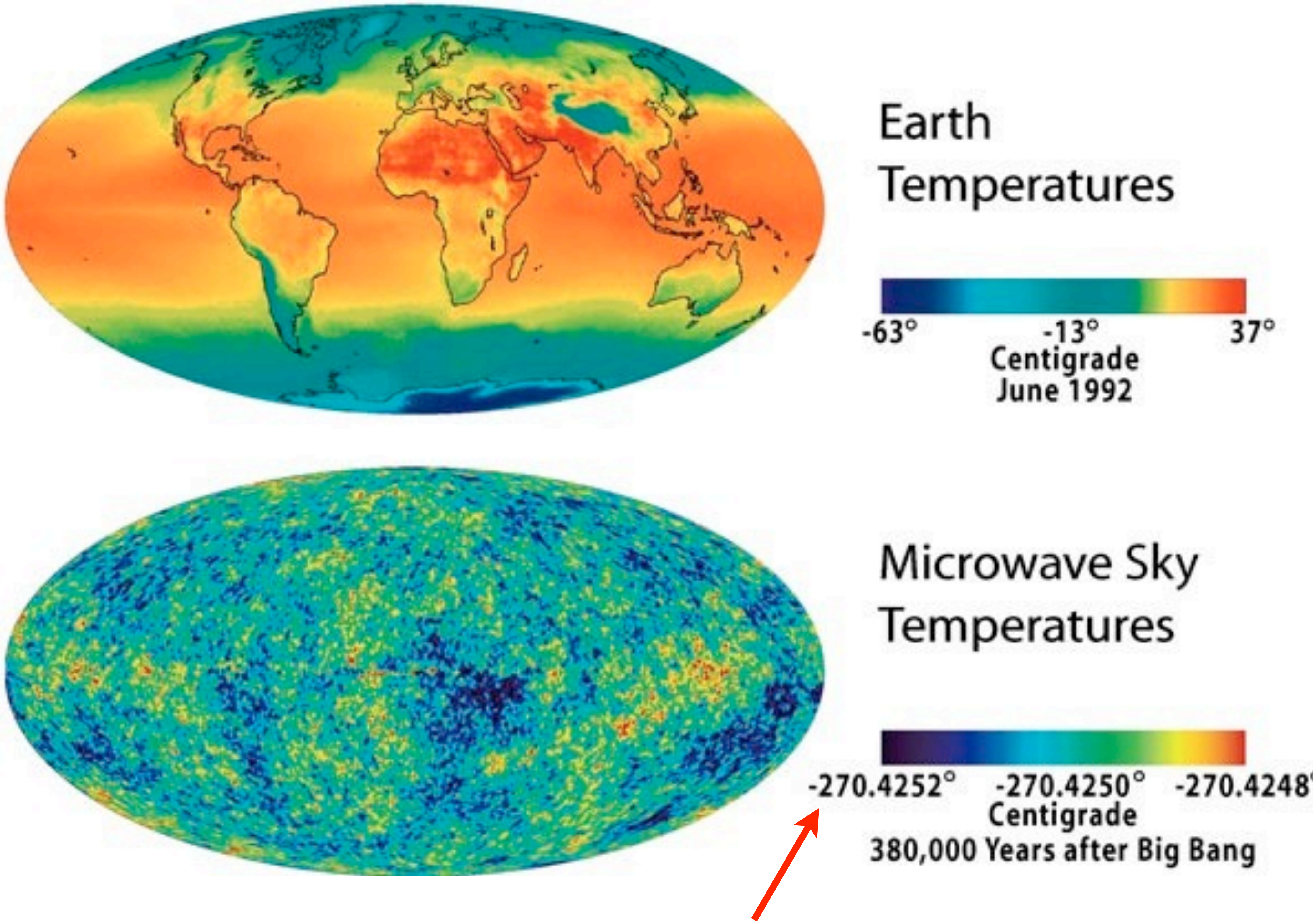
- the Universe is expanding!
- space "stretching" like rubber sheet
- galaxies carried along for the ride



Life in an expanding universe

- expansion: matter spreading out
- in the future: matter more dilute--less dense
- in the past: matter more concentrated: denser
- But if dense in past, should also be hot
  - should see blackbody radiation ... and we do!
  - shows that the universe has very uniform temperature
  - but not perfectly so: high-contrast shows tiny T fluctuations

WMAP took a “baby picture” of the Universe– only 400000 yrs old.



note tiny temperature range

lesson: temperature very nearly

The Age of the Universe

Imagine: "switch off" gravity (!?)

- then galaxies are free bodies
- each coasts with its own constant speed v

if Universe today has age t_0

- then a galaxy with constant speed v has gone
- distance: $d = v\, t_0$

Combine with Hubble's law

- which says $v = H_0\, d$
- with H_0 a measured constant (Hubble's constant)

Math:

- $d = v\, t_0 = H_0\, d\, t_0$
- distance cancels! $H_0\, t_0 = 1$

solve: age of Universe $\boxed{t_0 = 1/H_0 = 13.6 \text{ billion years}}$

In reality: gravity not switched off!

- our analysis too simple
- but more careful job gives same answer!

Context:

- age of Sun & Earth: 4.55 billion years -- good!
- age of oldest stars 13 billion years -- good!

The Universe Past, Present, and Future

Today: the Universe we observe is

- expanding
- homogeneous and isotropic on large scales
- inhomogeneous (lumpy) on small scales
- filled with
  - ordinary matter (atoms)
  - dark matter (whatever that is!)
  - light = blackbody radiation

Given all this, what was past and future like?

Cosmologist's game:

- imagine homogeneous box filled with matter and radiation
- ask how it behaves as it expands and cools

The Past:

- Universe was hotter and denser

The Future:

- Universe will be cooler and matter less dense


The Past
OLLI 2011

The Cosmic Past

As we peer back into the past,

good to recall some oldies but goodies

matter

- ordinary matter (not dark matter!) made of atoms
- which are made of nuclei and electrons
- nuclei are made of protons and neutrons
- protons and neutrons are made of quarks

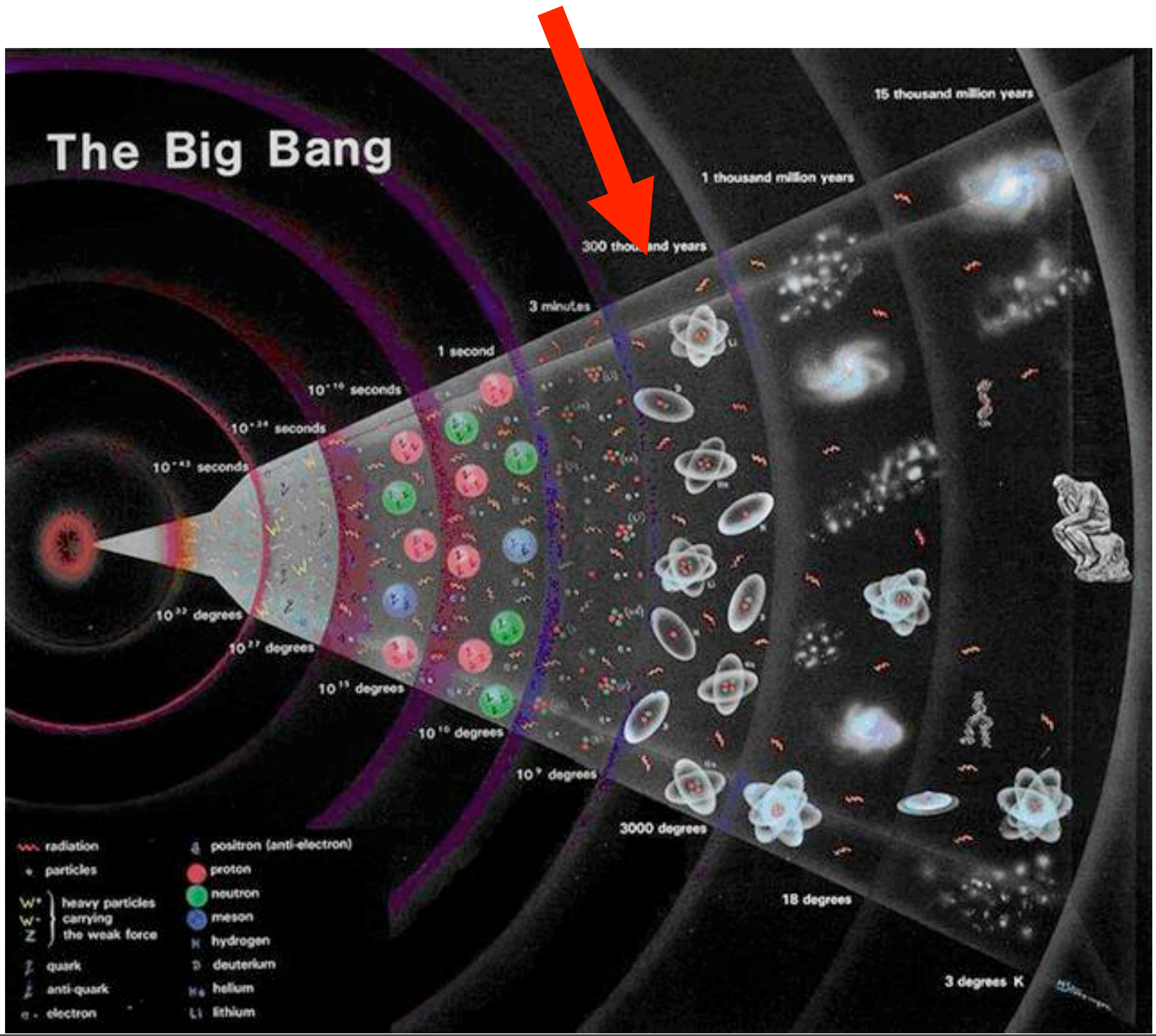
matter and temperature

- at the microscopic level: temperature = particle motion and energy
- hotter = particles faster, have more kinetic energy
  collide with more and more energy

the Universe starts hot and dense but expands and cools

- begin with collisions too violent for any particles to stick together
  no protons, nuclei, atoms, molecules; only quarks and electrons
- but then cool: particles can begin to "condense" into larger and more complex forms
  protons, then nuclei, then atoms

A Brief History of the Universe: Atoms Formed

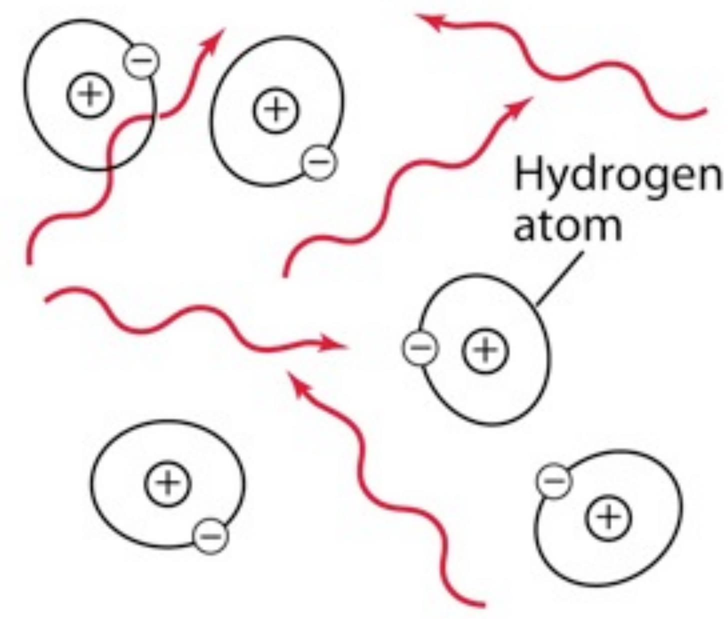


The Atomic Age

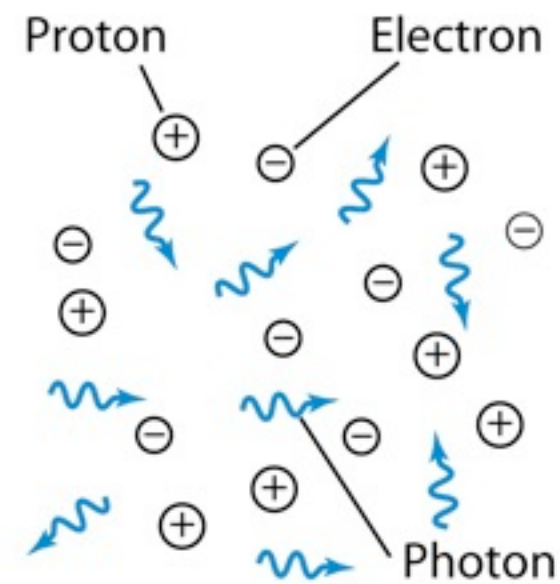
- Today: at t = 13.6 billion years
  - Universe very cold: T = 2.725 K
  - barely above absolute zero
  - matter condensed into atoms

- At t = 380,000 years
  - much hotter: T = 3000 K
  - same as surface T of red giant star, but this was entire Universe!
  - cosmic blackbody radiation would have been visible -- red glow!
  - atom collisions with each other and with radiation very violent
  - atoms ripped apart to nuclei and electrons

- So if "run movie forwards"
  - early Universe ionized!   no atoms!
  - until 380,000 years, when electrons and nuclei "recombine"
  - the first atoms appear!

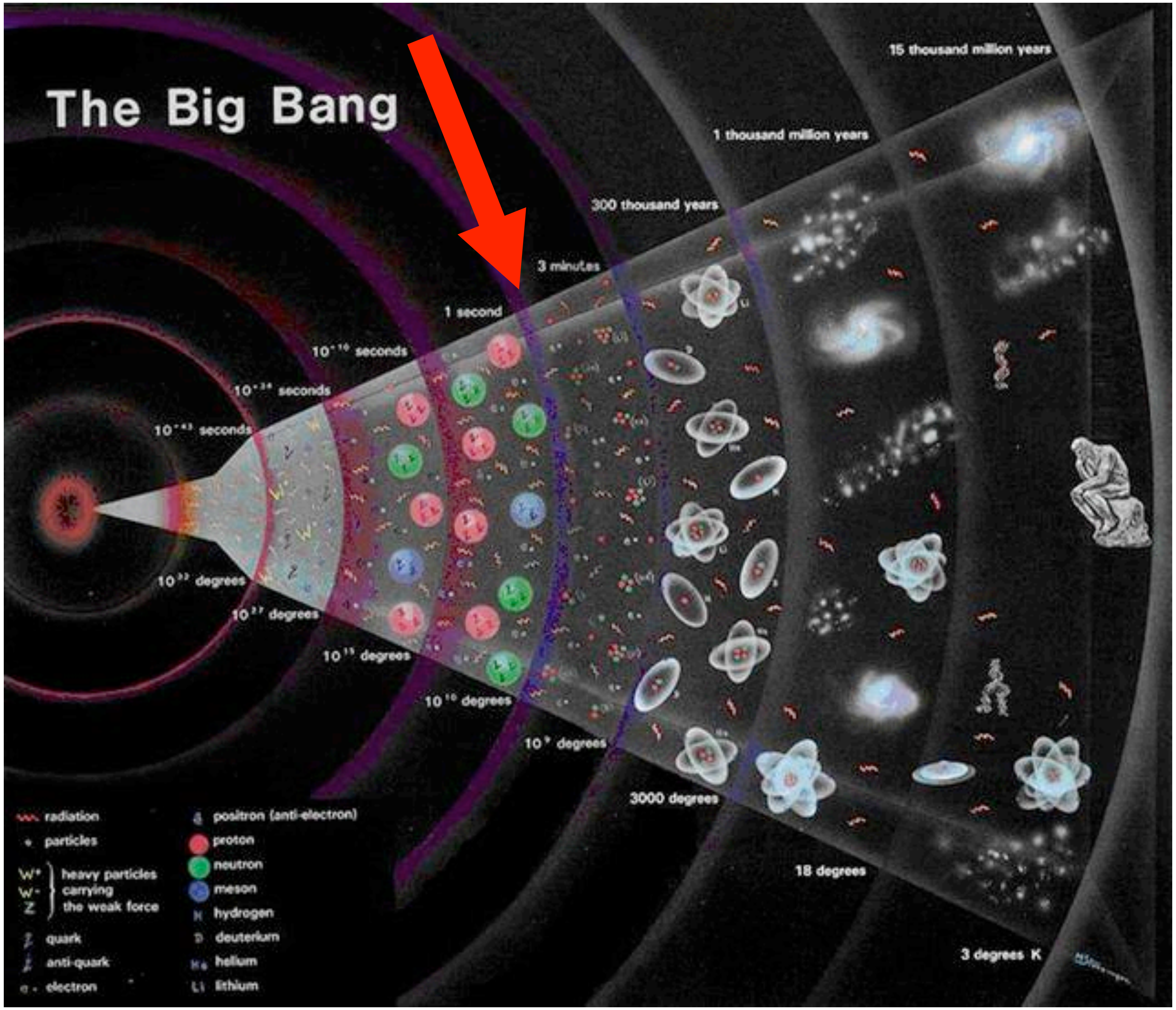


b After recombination



a Before recombination

Origin of the Light Elements



The Nuclear Age

At t = 380,000 years

- cool enough for atoms to survive
- before this: nuclei and electrons

At t = 1 second (!)

- really hot: $T = 10^{10}$ K = 10 billion K
  - much hotter than Sun's center today, 16 million K
- collisions so violent nuclei ripped apart
  - before 1 sec: only protons, neutrons, electrons

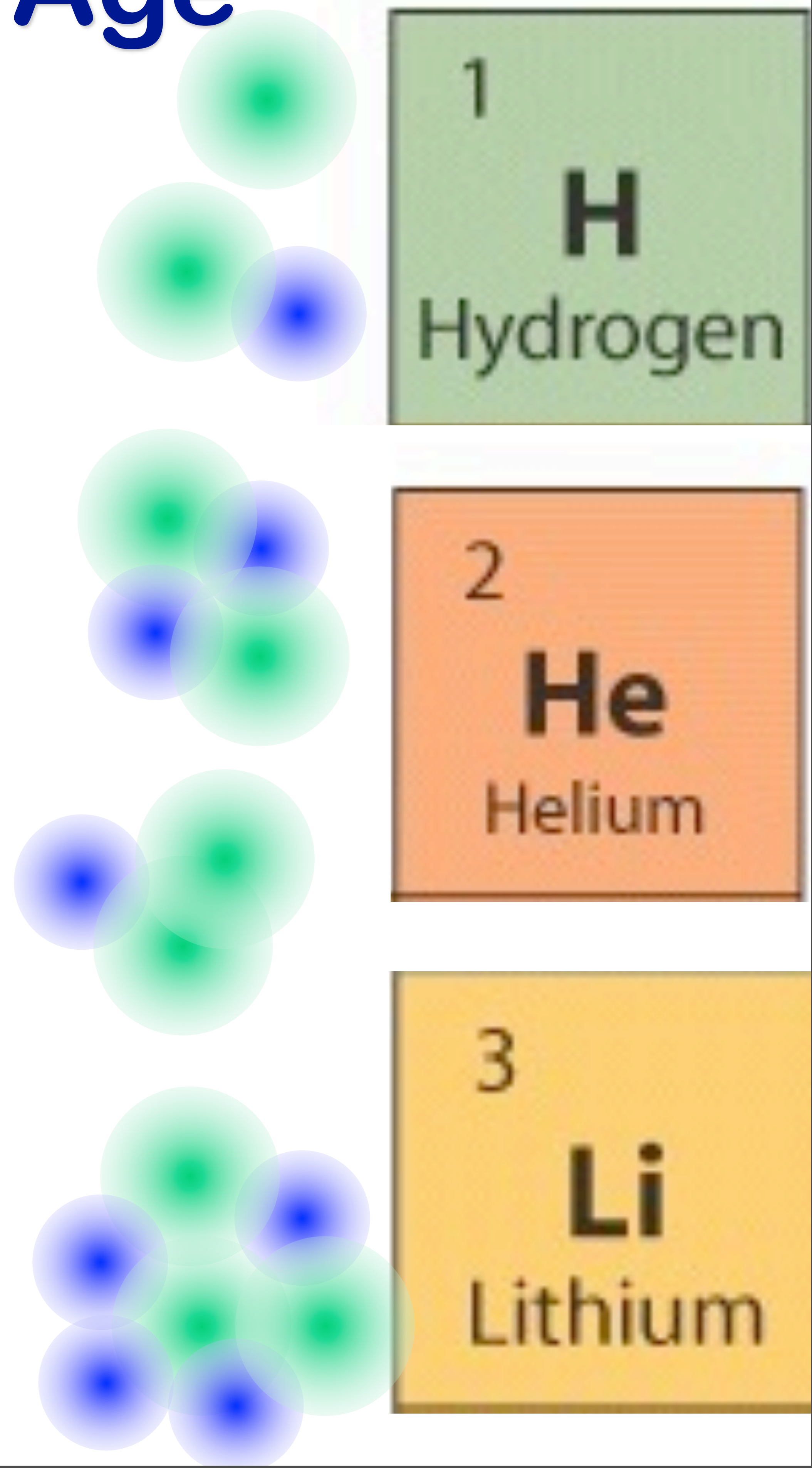
"Running the movie forwards"

- at t<1 sec: "ionized" neutrons + protons
- then at t = 1 sec: n + p "condense" to nuclei
- which ones?
  - hydrogen (75%)
  - helium-4 (25%)
  - small amounts of deuterium, lithium
- the lightest elements formed!
  - hydrogen & helium & some lithium come from the big bang!

Note: we can predict how much of these elements the big bang would create

- and then measure the amount that the Universe contains
- and they agree!

big bang working well back to t = 1 sec!



End Result:
Big Bang Correctly Predicts Abundances

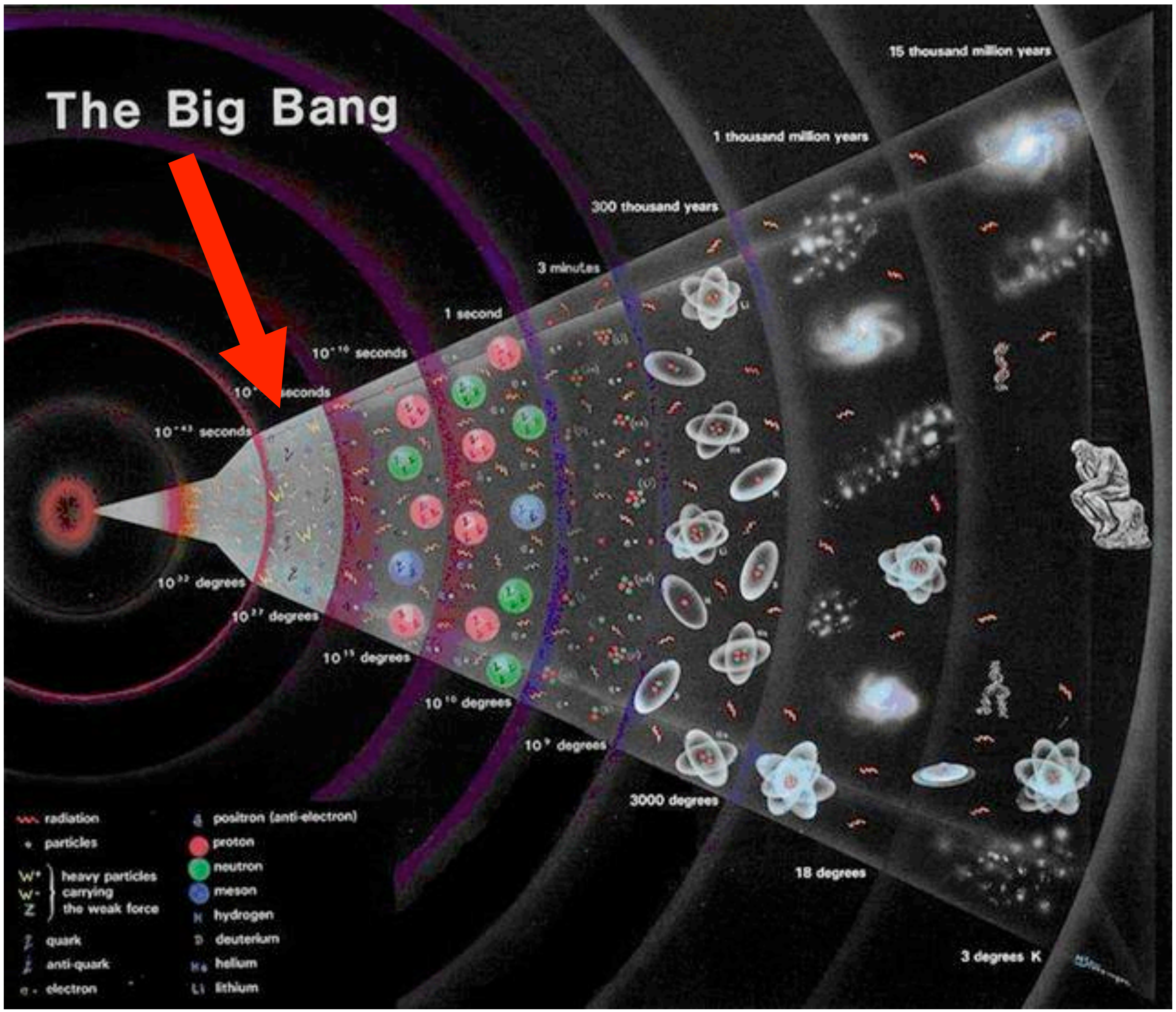
Nutrition Facts

Serving Size 1 g
Servings Per Universe many many

Amount Per Serving

Hydrogen	**0.75 g**
Helium	**0.25 g**
Deuterium	**10^{-4} g**
Lithium, etc.	**10^{-10} g**

Origin of Dark Matter



ORIGIN OF DARK MATTER:
THE VERY EARLY UNIVERSE?

The early Universe was enormously hot and dense

- hot: particles had high speeds = high energies
- dense: particles packed closely
- hot+dense: many high-energy collisions

suggests intriguing idea...

Maybe Dark Matter = exotic particles created at times << 1 sec !?

- arose in extreme environment when temperatures, energies ultra-high
- in collisions when $E_{collision} > m_{dark\ matter}\, c^2$
- remain until today: shadow fossils of the big bang

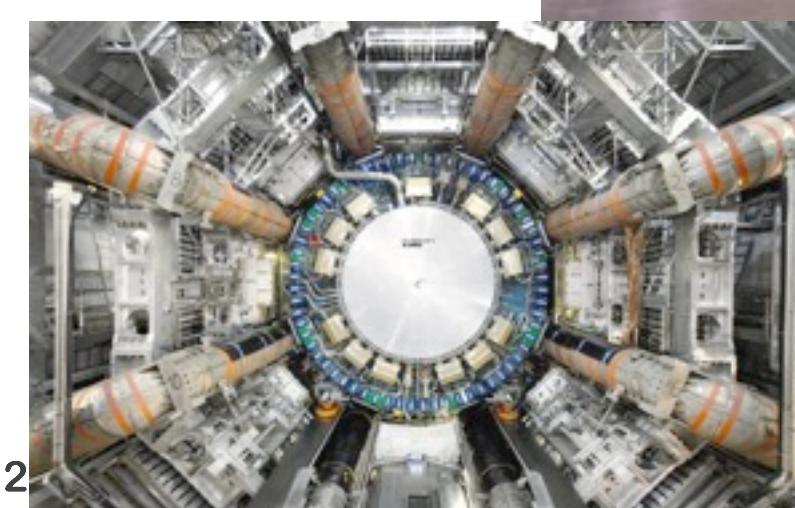
Q: how probe such high energies?

Hint: players are in Illinois and in Europe

Fermilab

The competition, now only game in town:

- Large Hadronic Collider (LHC)
- CERN laboratory, Geneva Switzerland



INNER SPACE / OUTER SPACE

Fermilab is a telescope!

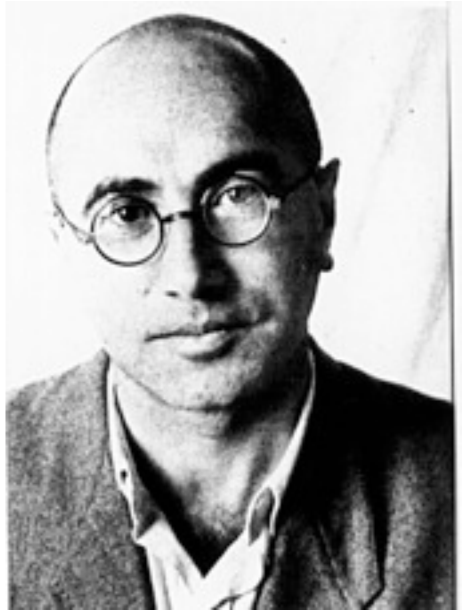
Probes conditions in Universe at 10^{-12} seconds

and maybe can recreate dark matter!

...but also...

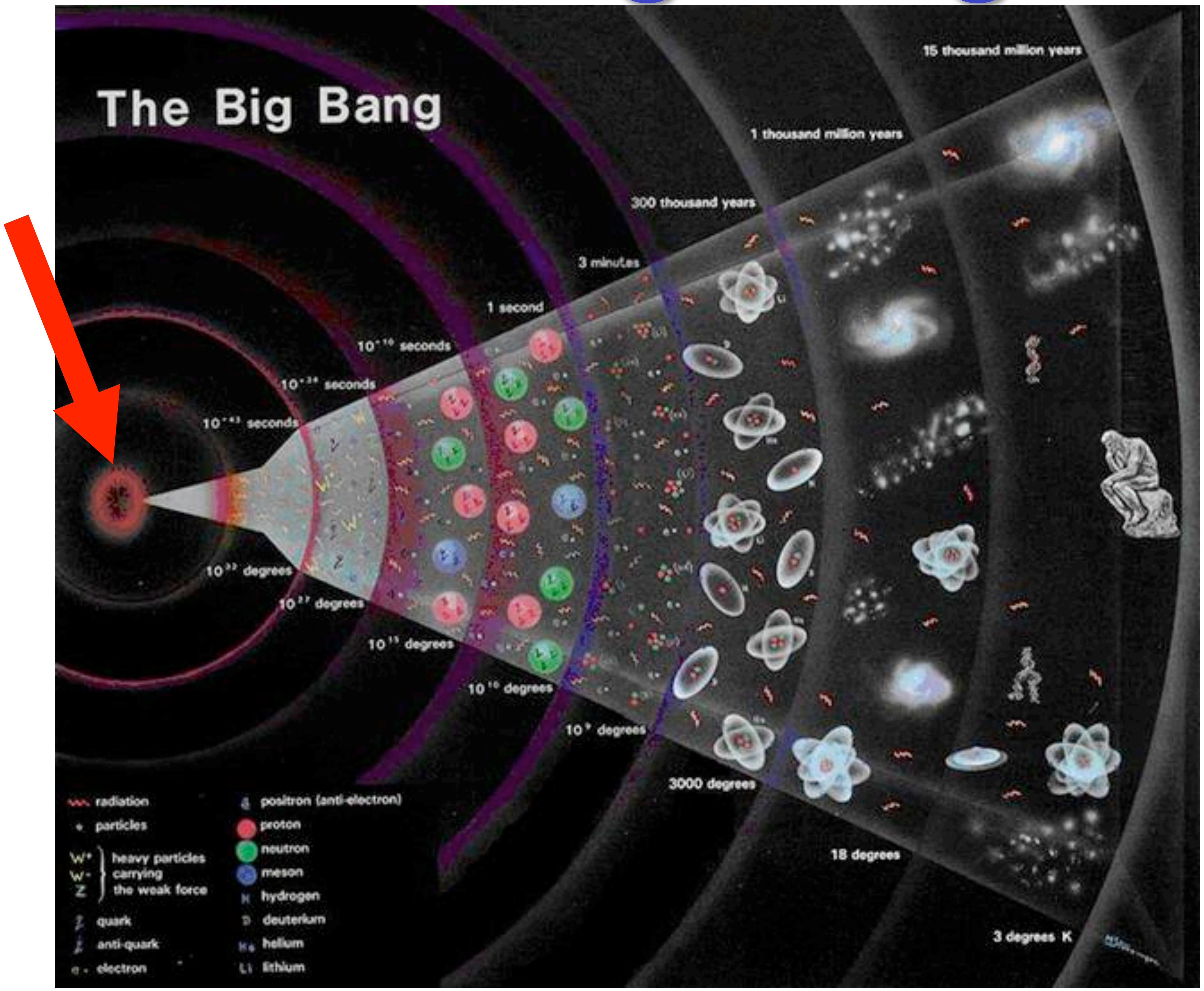
"The Universe is the poor person's accelerator"

Probes conditions inaccessible at laboratories



Russian cosmologist Yakov Zel'dovich

The Beginning



The First Moments
$t=0$ to $t=10^{-43}$ seconds

Universe expanding today

so in the past:

- everything closer together
- densities higher, particles packed together

but at time $t=0$, the big bang itself:

- distances between all particles is zero
- volume of space = 0!
- so densities become infinite!

Laws of physics break down at $t=0$!

- in a very similar way to breakdown at center of black hole

to understand $t=0$: need theory of quantum gravity

- which we don't have yet
- but ideas exist: string theory, braneworlds

What we do know:

- quantum gravity mandatory to even talk about $t<10^{-43}$ sec
- so earlier times--including big bang--are beyond our current ability to understand


The Future
OLLI 2011

What is the Universe's Fate?

Today: Universe is expanding. What do you expect to happen next?

Competition: gravity vs inertia

Compare: Pop fly and rocket!

- Quantitative question
- Launch speed vs speed to escape Earth

or

?

What is the Universe's Fate?

For Universe it is still gravity vs speed.

- Gravity acts on mass of galaxies (pulling back)
- The speed is the speed of expansion

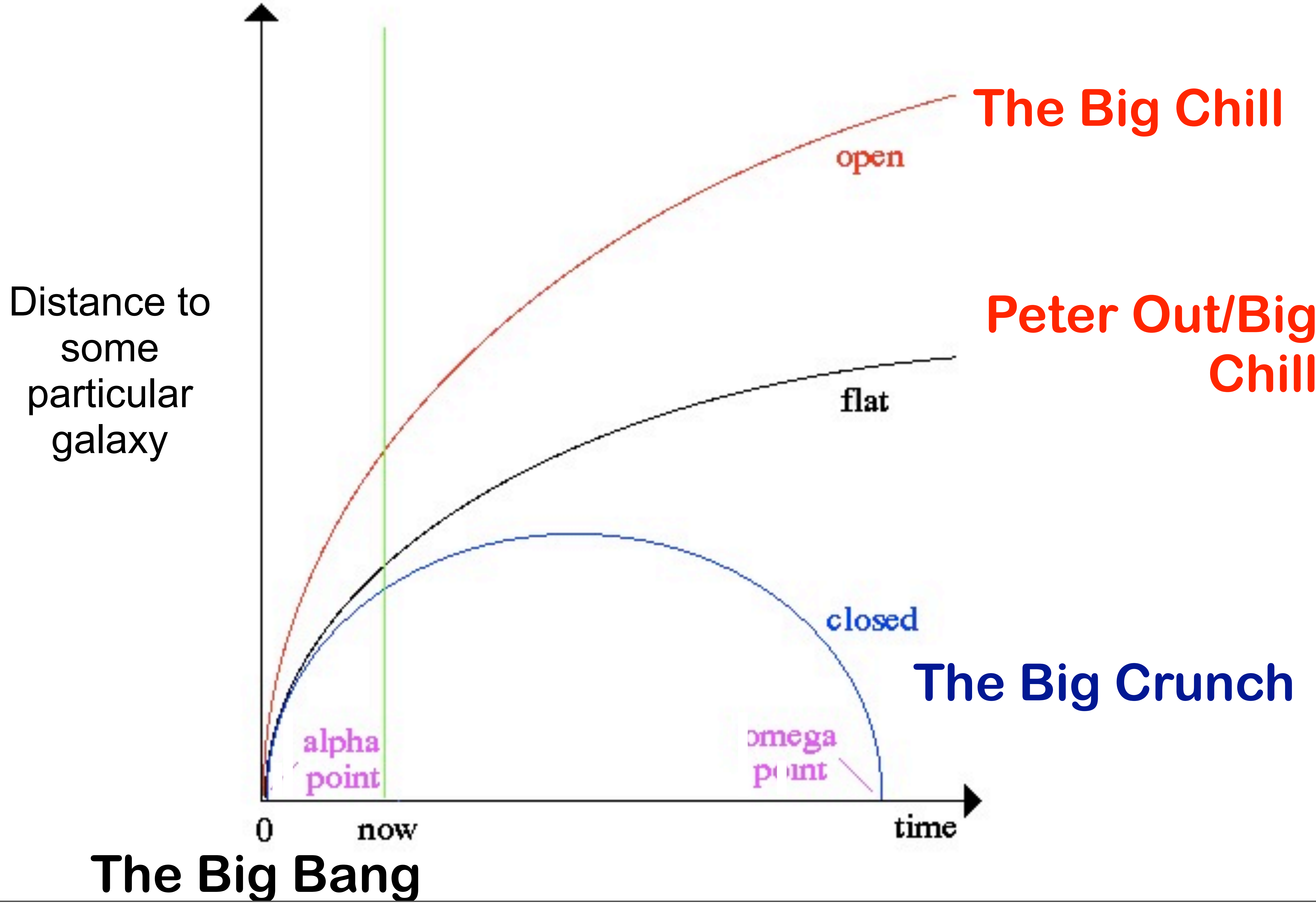
or

Both are observable!

Our fate is a quantitative question :

- If our mass (really, mass density) is small enough we expand forever.
- If our density is large enough expansion halts, and we collapse back.

What kind of Universe do we live in?



Big Chill or Big Crunch?

Low density:

Universe will end in a Big Chill:

- gravity < inertia, expand forever
- Galaxies exhaust their gas supply
- No more new stars
- Old stars eventually die, leaving only dust and stellar corpses

High density:

Universe will end in a Big Crunch:

- gravity > inertia, expansion keeps slowing until
- Expansion will stop, and the Universe will re-collapse
- Ends as it began, incredibly hot and dense

The Fate of the Universe

Fate of the Universe related to motion of Universe

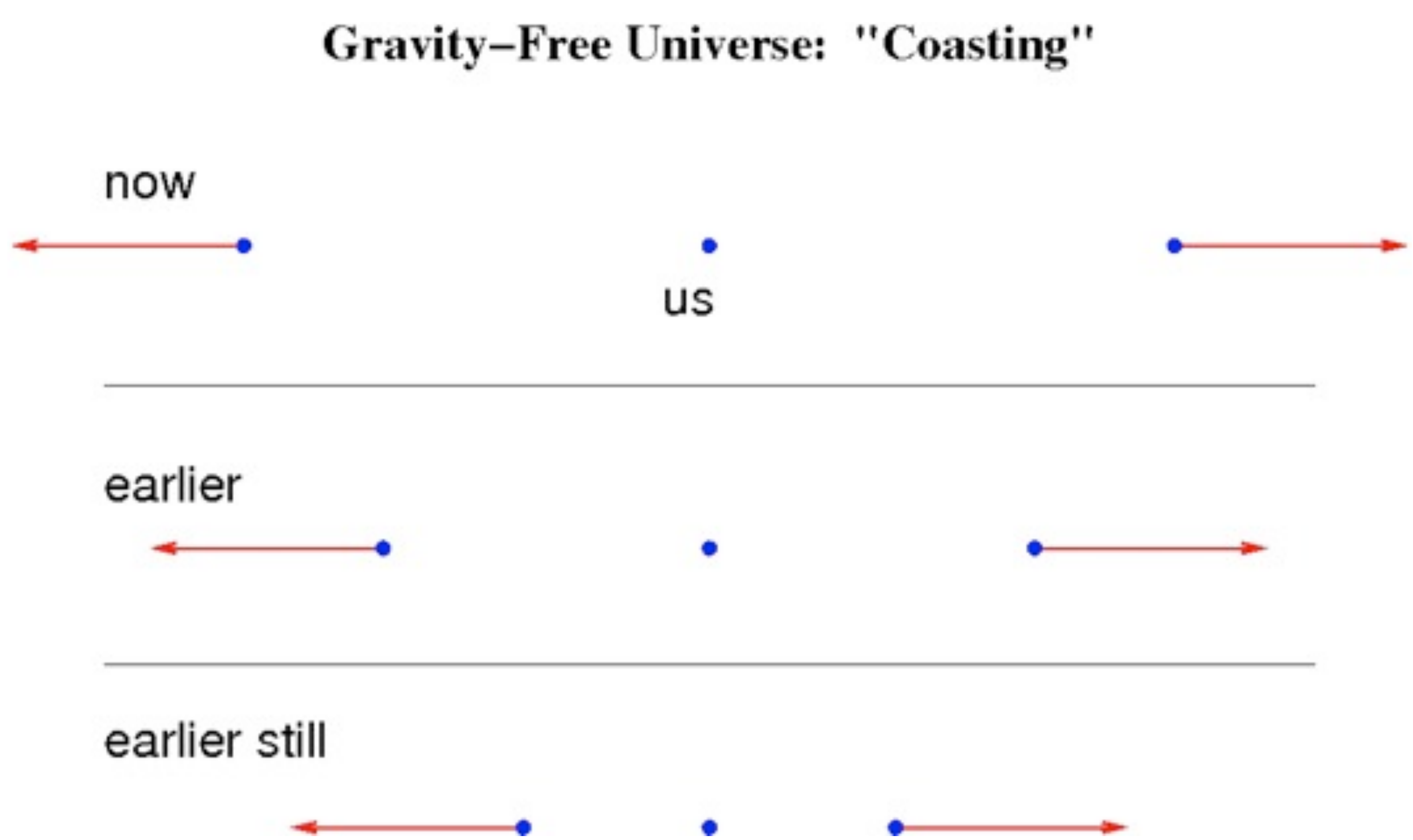
Today:

- The Universe is expanding
- galaxies spreading out
- matter density dropping

What does this mean for the future?

If “switch off” gravity

- galaxies would continue to coast at same speed



iClicker Poll: Gravity and Expansion

Galaxies are moving apart today

Without gravity:

- galaxies would coast, keep same speed

With gravity, what should happen?

A. galaxies should slow down

B. galaxies should speed up

C. galaxies should keep same speed

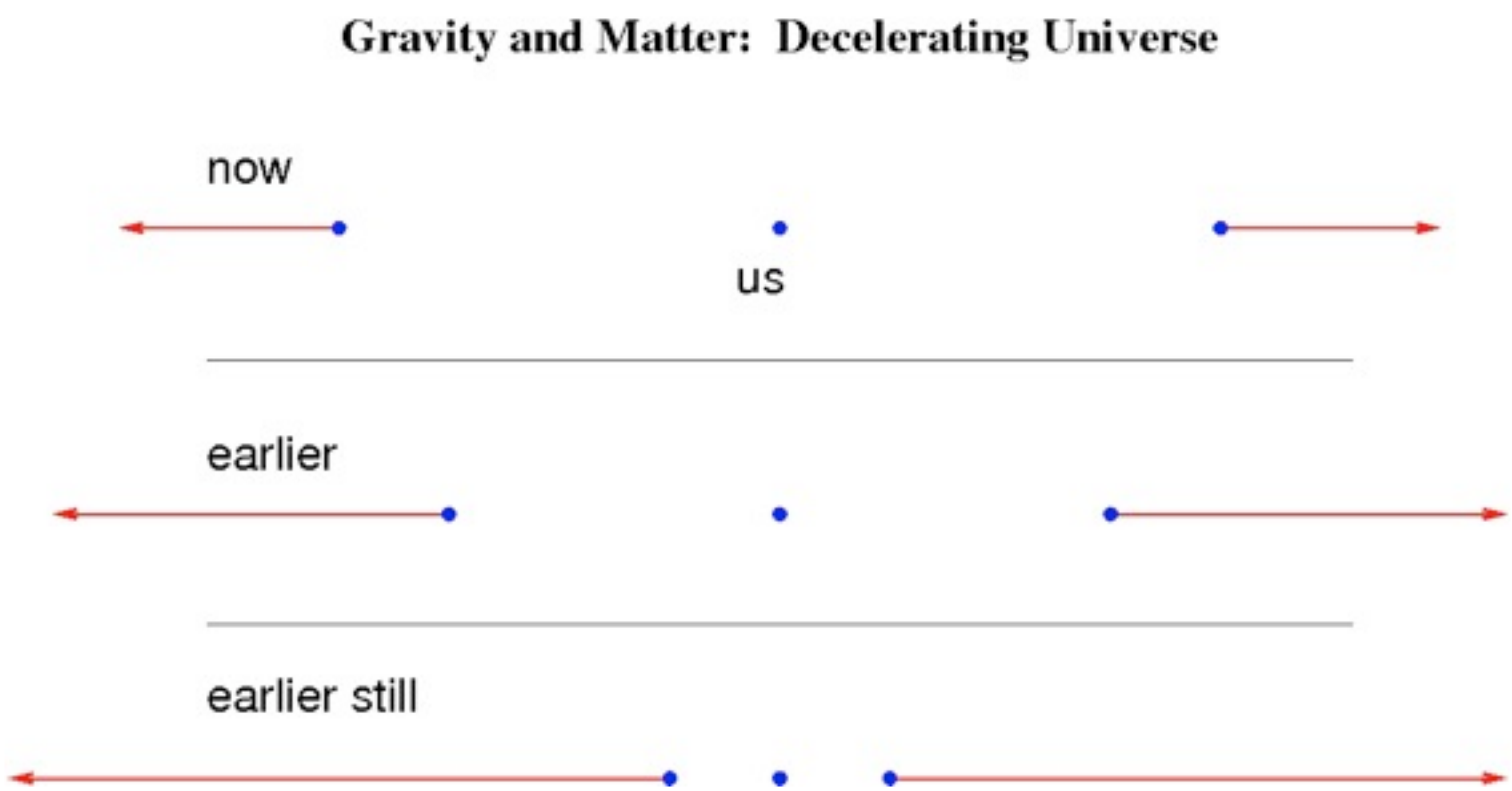
Gravity and Expansion

In the real Universe, galaxies made of matter

both ordinary and dark!

Gravity: all matter attracts all other matter

- so galaxies attract each other
- inward force opposes outward expansion
- so expect galaxies to constantly slow down
- that is, expansion should decelerate
- to achieve observed speed today, had to travel faster in past



The Observed Expansion History

In 1998:

- supernova explosions in distant galaxies used to map out recent history of cosmic expansion
- these observations test for expansion deceleration

Result:

- galaxies moved slower in recent past
- expansion accelerating!

like pop fly leaping out of your hand and away from Earth!?