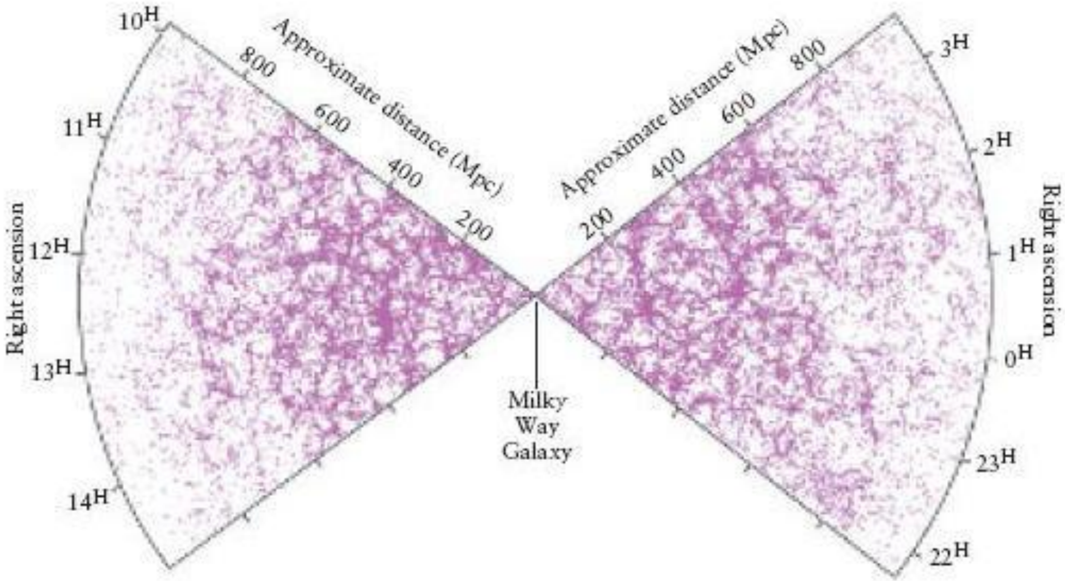
Cosmology

- Origin, early history, and fate of the Universe
- Does the Universe have a beginning? An end? What physics processes "caused" the Universe to be what it is? Are other universes possible? Would they look like ours (have the same physics)?
- Olber's Paradox (sky dark at night → Universe is finite in time and/or space)
- Cosmological Principle - the Universe appears the same from any location - Isotropic

Isotropic Universe

- the Universe appears the same from any location on any large scale
  - no center, no edge → size is unknown infinite vs finite
  - same number of galaxies, same types, in any large "box"
- A civilization on a planet 12 BLY away we see exactly what we do – expanding Universe and same Hubble law



The 2dF Galaxy Survey

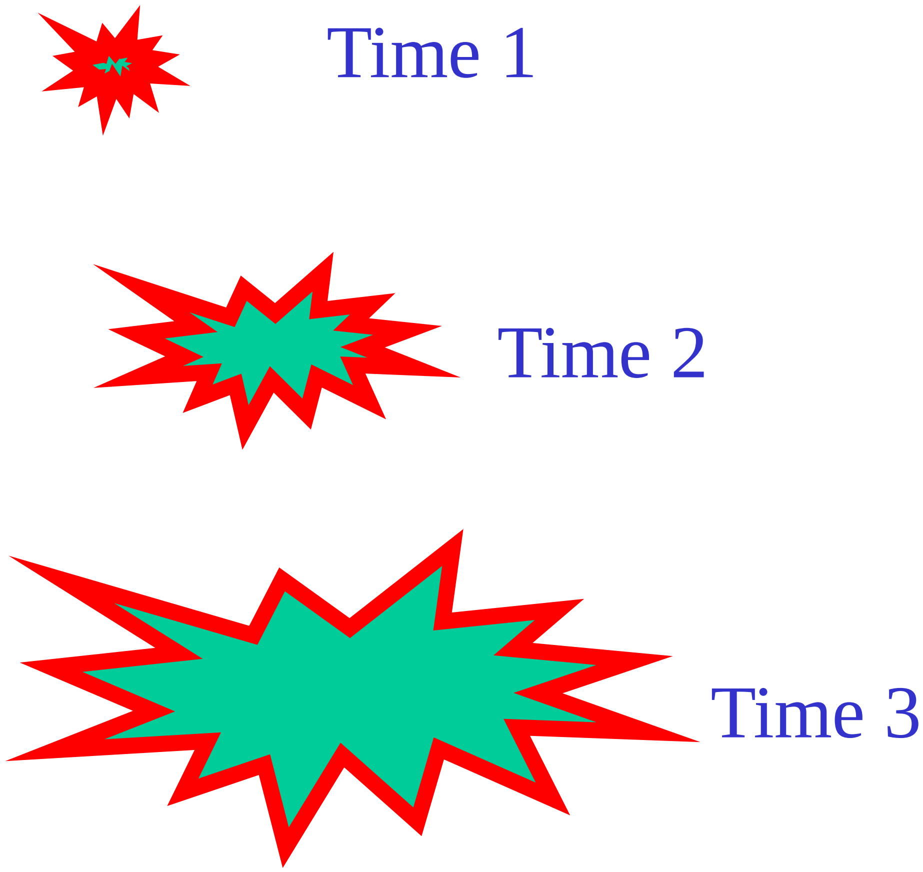
Fluctuations in galaxy distributions due to small differences in matter/energy concentrations at very early times

partially explained by "inflation" at extremely early times. We'll skip in this course

Beginning of Universe

- Called the "Big Bang" but not normal explosion moving outward into existing 3D space
- "explosion" occurred everywhere (either finite or infinite in spatial dimensions) at same time and expanding universe "creates" its own space as it expands "outward"
- Einstein predicted in 1915 General Theory of relativity (though he initially thought it was a mistake)

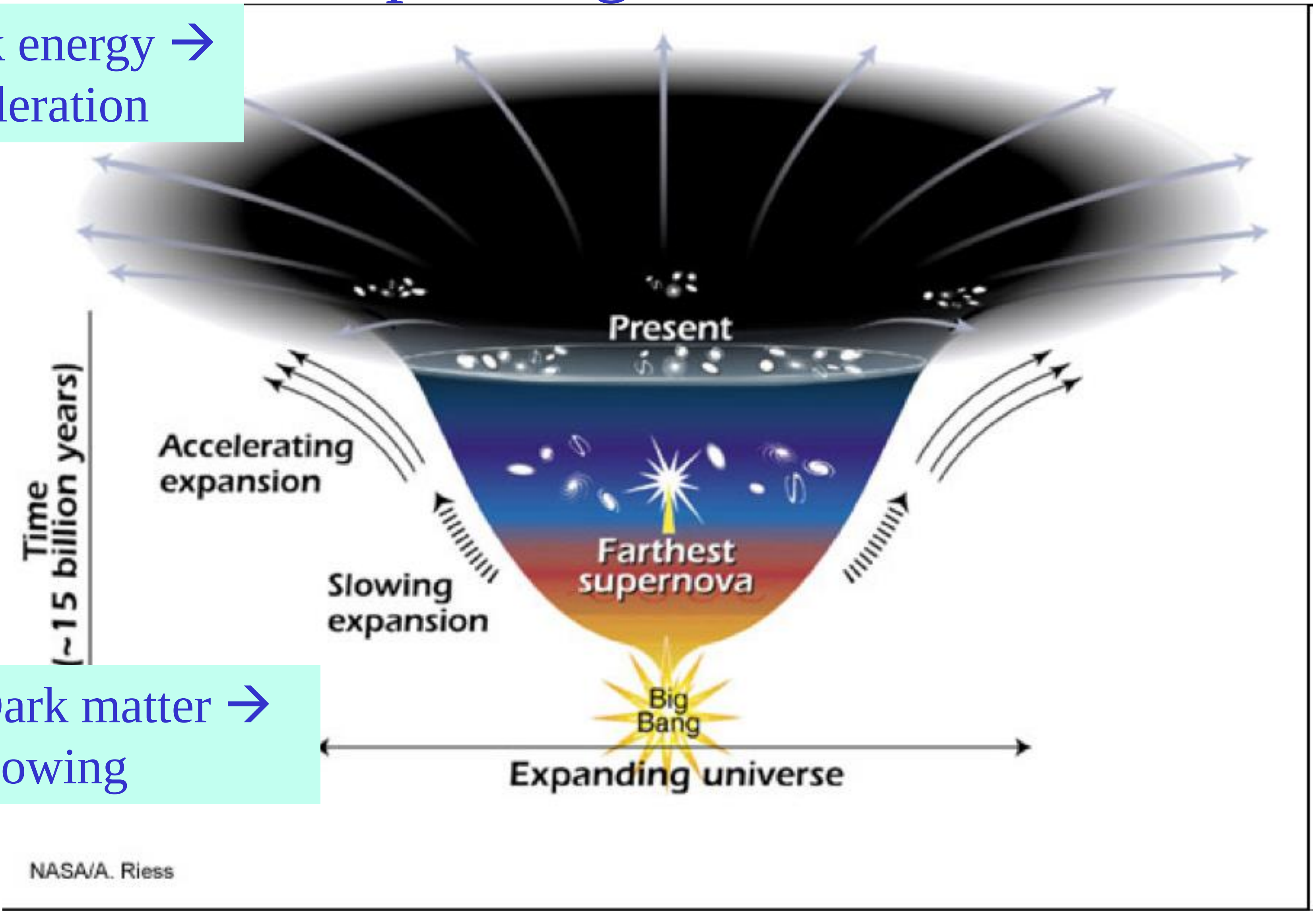
Expanding Universe – if finite in size



Red = void = nothingness (hard to picture). Space just gets bigger with time

Expanding Universe

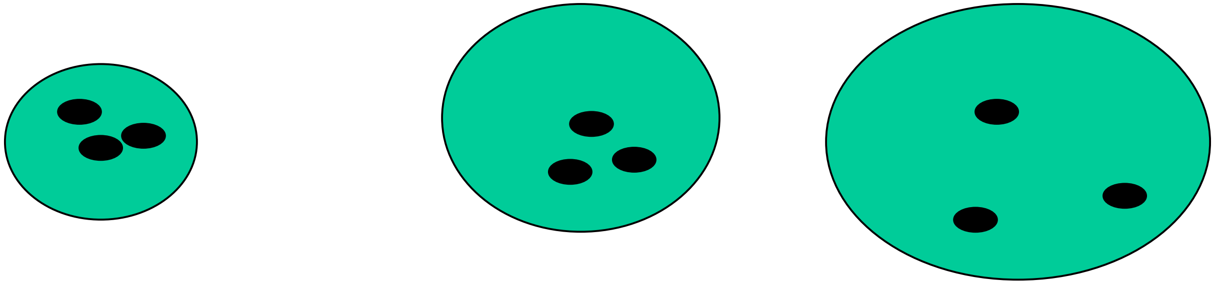
Dark energy → acceleration



Dark matter → slowing

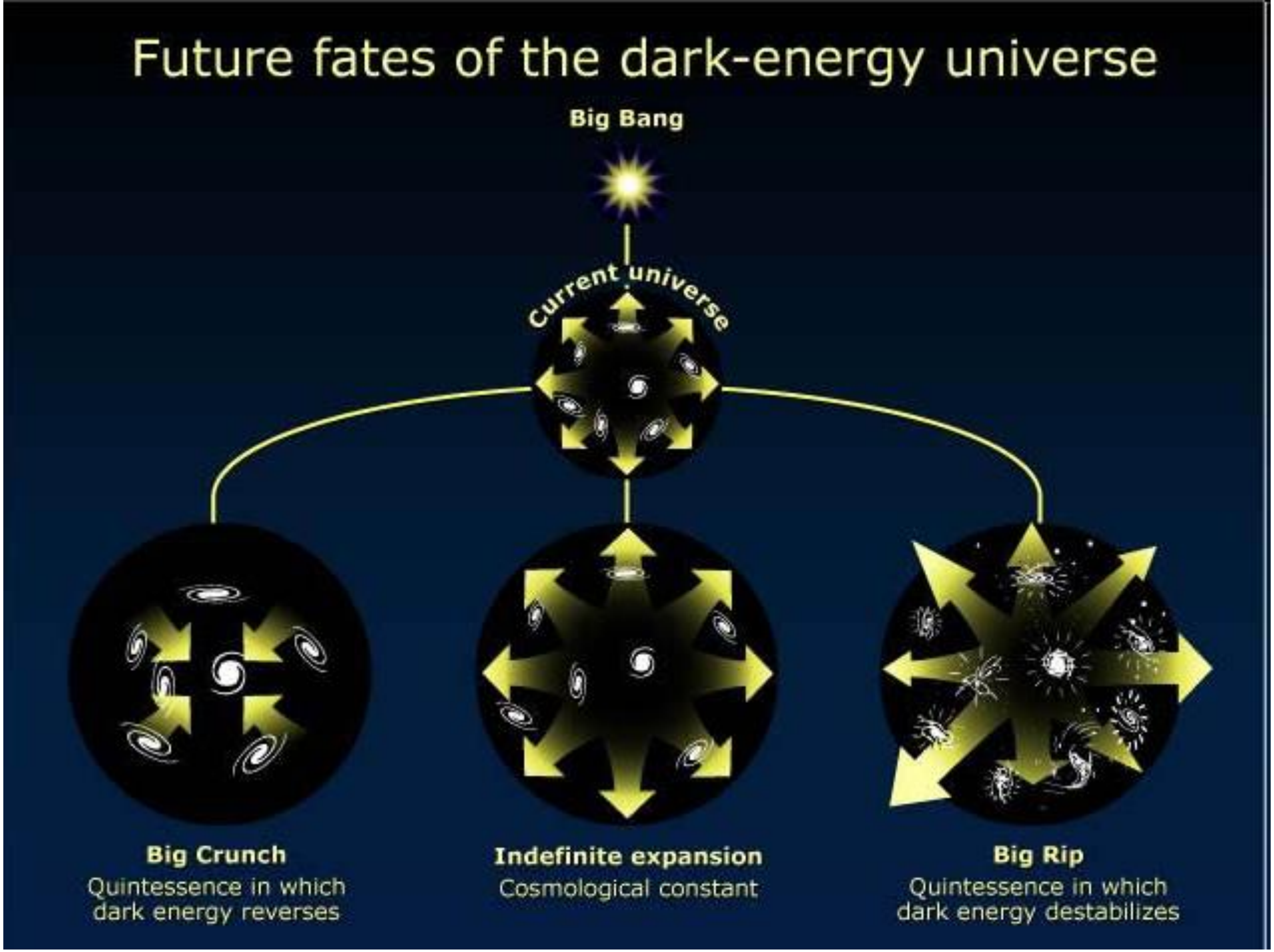
Expanding Universe

- No edge, no center to Universe
- Consider balloon. 2D surface in 3D space. All points moving away from each other with v = Ad. All points are the same: no edge or center
- Universe is 3D surface on a 4D manifold (wormholes “burrow” through this) with v=Hd



Expanding Universe

- Observation of galaxies: v = Hd → Universe is expanding →age about 13-14 billion years - depends on how Hubble "constant" is changing with time → amount of matter and energy
- As the Universe expands it cools down. At its earlier times it was much, much hotter.
- If expansion continues → cold (Open Universe)
- if the expansion stops and a contraction begins → heats up (Closed Universe)


Future fates of the dark-energy universe
Big Bang
Current universe
Big Crunch
Quintessence in which dark energy reverses
Indefinite expansion
Cosmological constant
Big Rip
Quintessence in which dark energy destabilizes

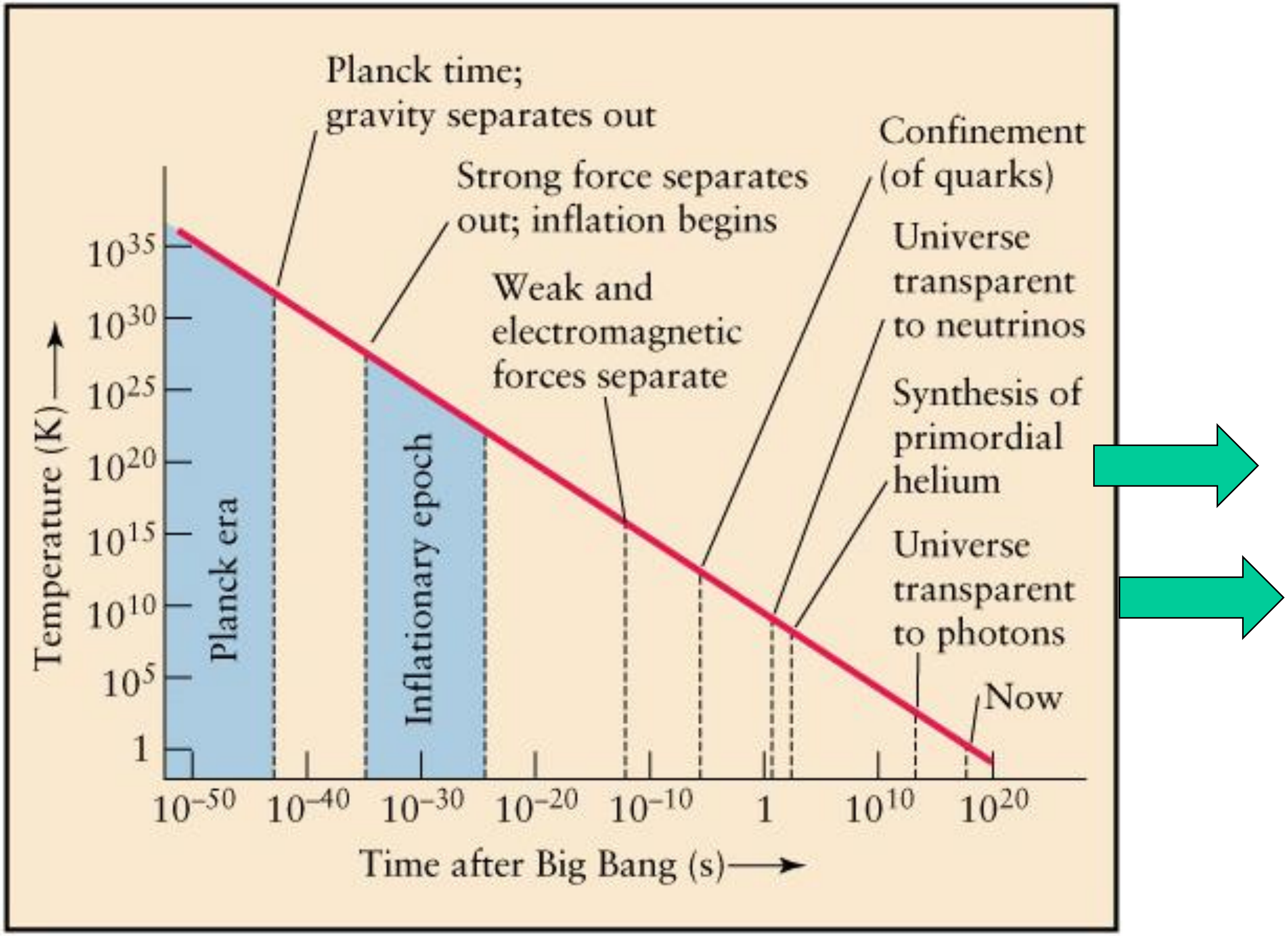
Fire and Ice
Robert Frost - 1923

Some say the world will end in fire,
Some say in ice.
From what I've tasted of desire
I hold with those who favor fire.
But if I had to perish twice,
I think I know enough of hate
To say that for destruction ice
Is also great
And would suffice.

Expanding Universe

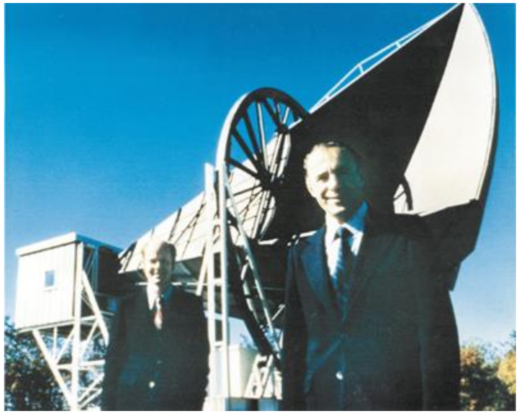
- As Universe expands it cools
- Physical processes at any time depend on:
  - -Temperature
  - -Nature of forces and particles
- Current Temperature is 3 degrees K

Temperature vs Time



Cosmic Microwave Background

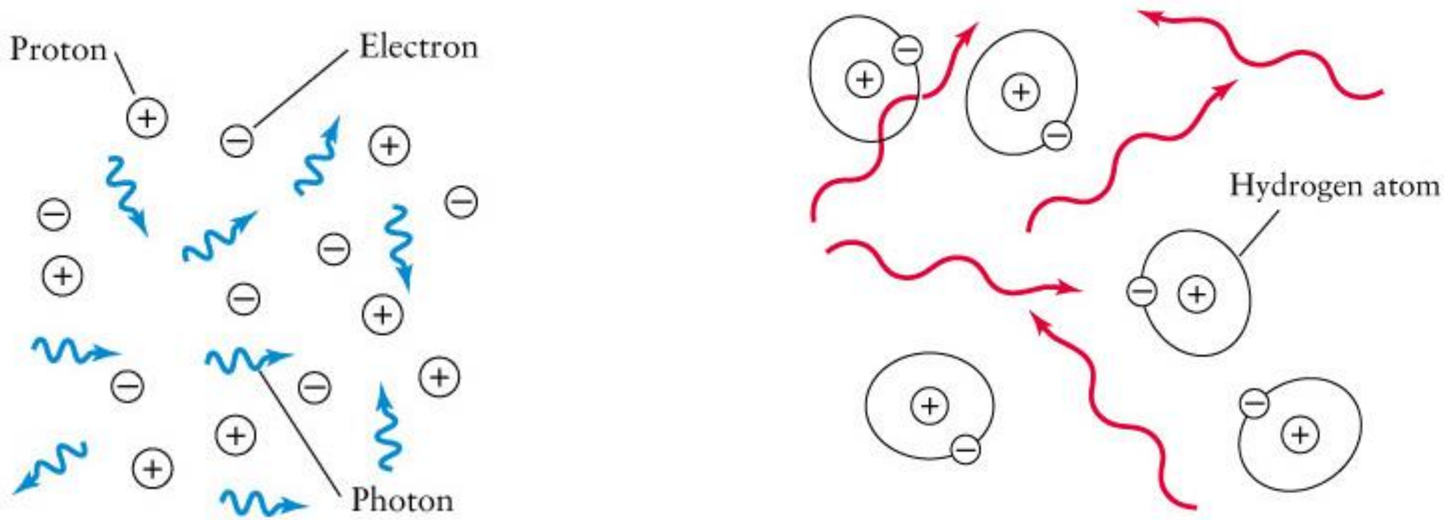
- Temperature > 3000 degrees Universe opaque → atoms ionized - free H, He nuclei plus free electrons
- T<3000 **atoms form** → transparent Universe -- 400,000 to 1,000,000 years after Big Bang
- Burst of light everywhere - now observed as 3 degree microwave background -- (1964: Bell Labs)



Wilson and Penzias

New Jersey 1965

Recombination – Occurs at ~400,000 years



a Before recombination:

- Temperatures were so high that electrons and protons could not combine to form hydrogen atoms.
- The universe was opaque; photons underwent frequent collisions with electrons.
- Matter and radiation were at the same temperature.

b After recombination:

- Temperatures became low enough for hydrogen atoms to form.
- The universe became transparent; collisions between photons and atoms became infrequent.
- Matter and radiation were no longer at the same temperature.

Microwave Background

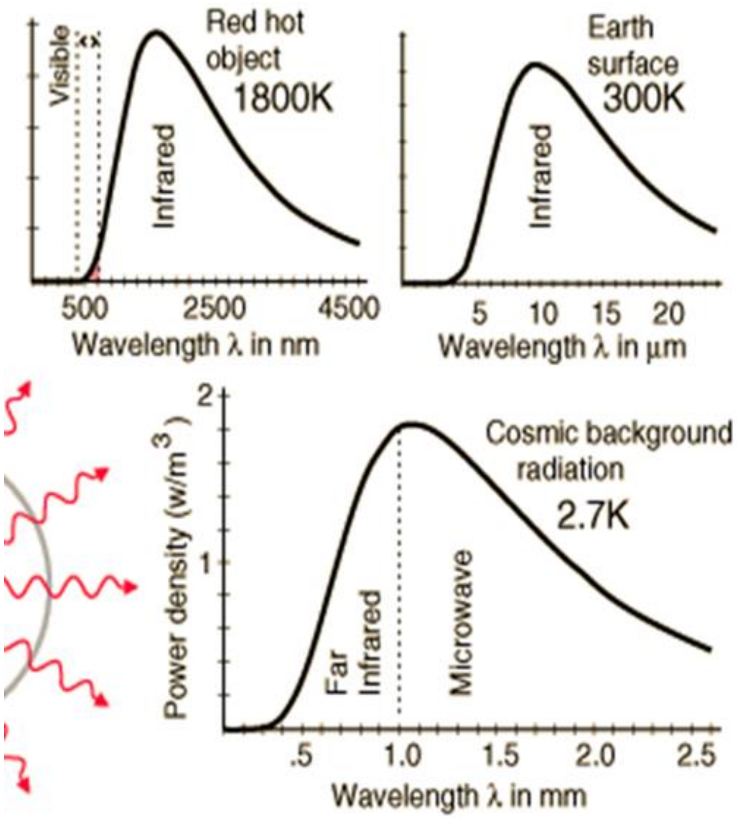
- At original time = 400,000 years

  Temp = 3000 degrees

  wavelength = 1 micron (visible)
- Same photons observed now. Universe has expanded/stretched by about 1000 (all directions)

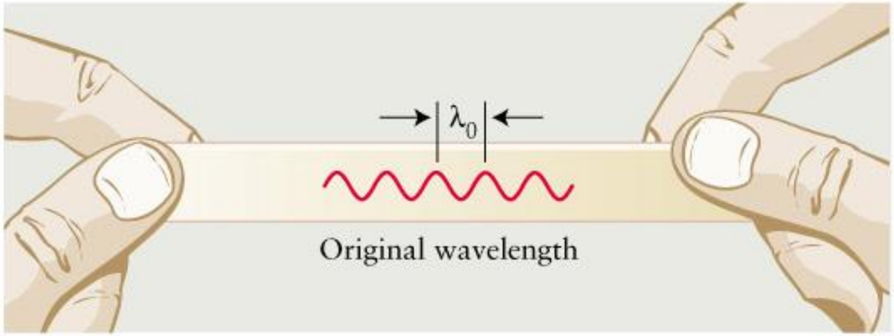
  Temp = 3 degrees

  wavelength = 1 mm (microwave)

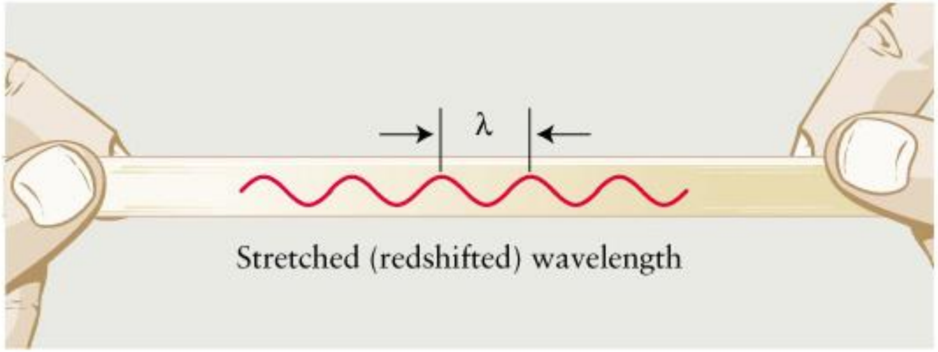


Microwave Background

- Universe has expanded/stretched by 1000 → "Cosmological Redshift" (different then redshift due to Doppler effect)

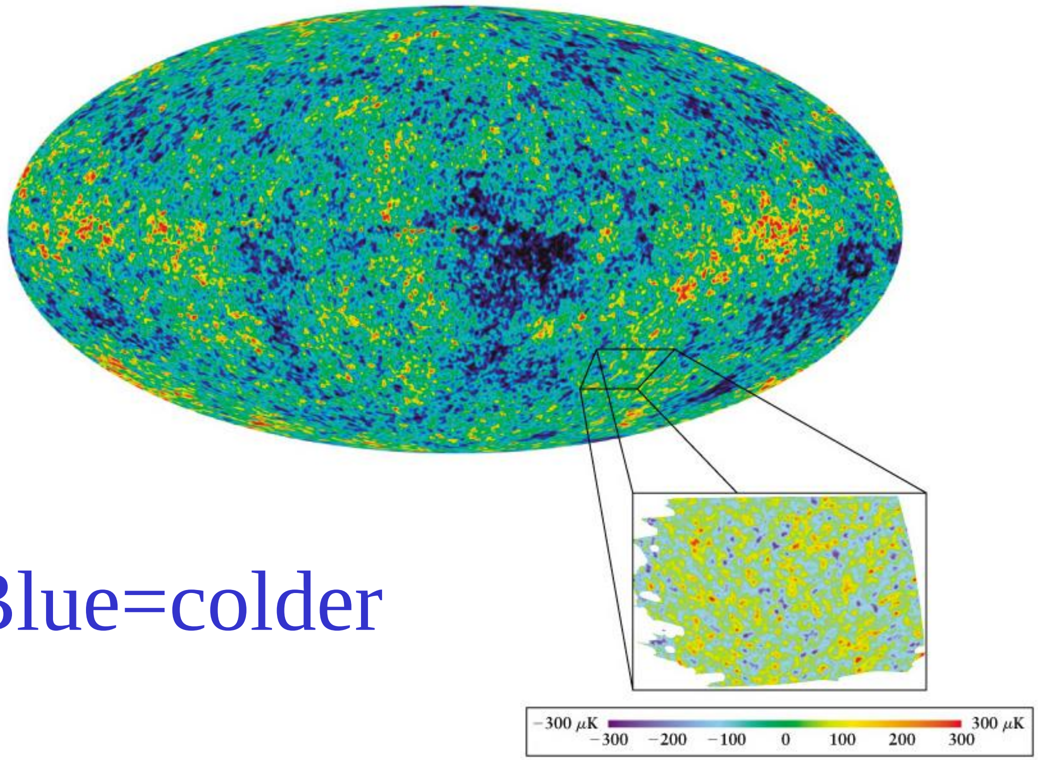


a A wave drawn on a rubber band ...



b ... increases in wavelength as the rubber band is stretched.

Cosmic Microwave Background



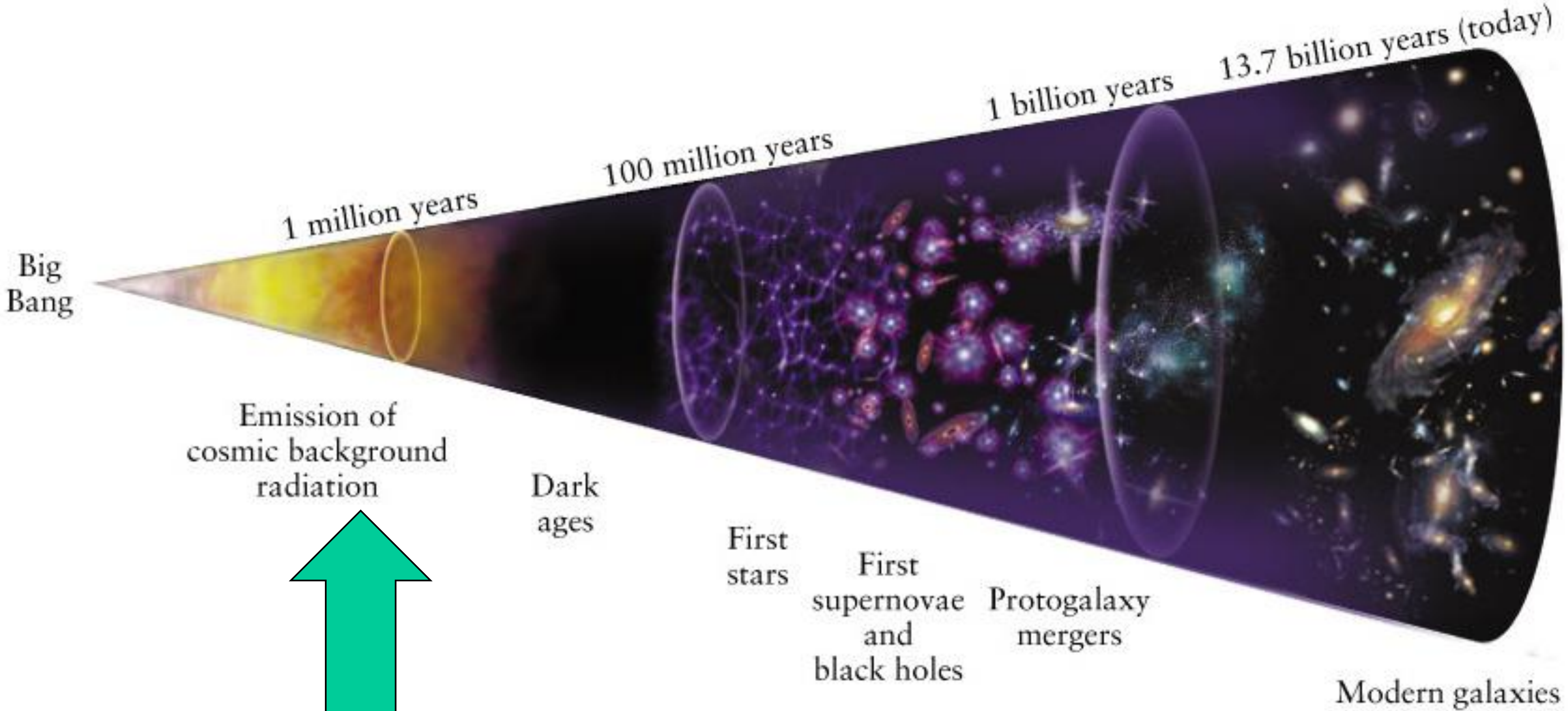
Blue=colder

photons permeate Universe

fluctuations in "temperature" → granularity in early Universe (fossil record)

leads to galaxy formation from primordial clumps of matter

History of Universe



Creation of Matter

early Universe hot enough to make particle-antiparticle pairs out of very high energy photons.

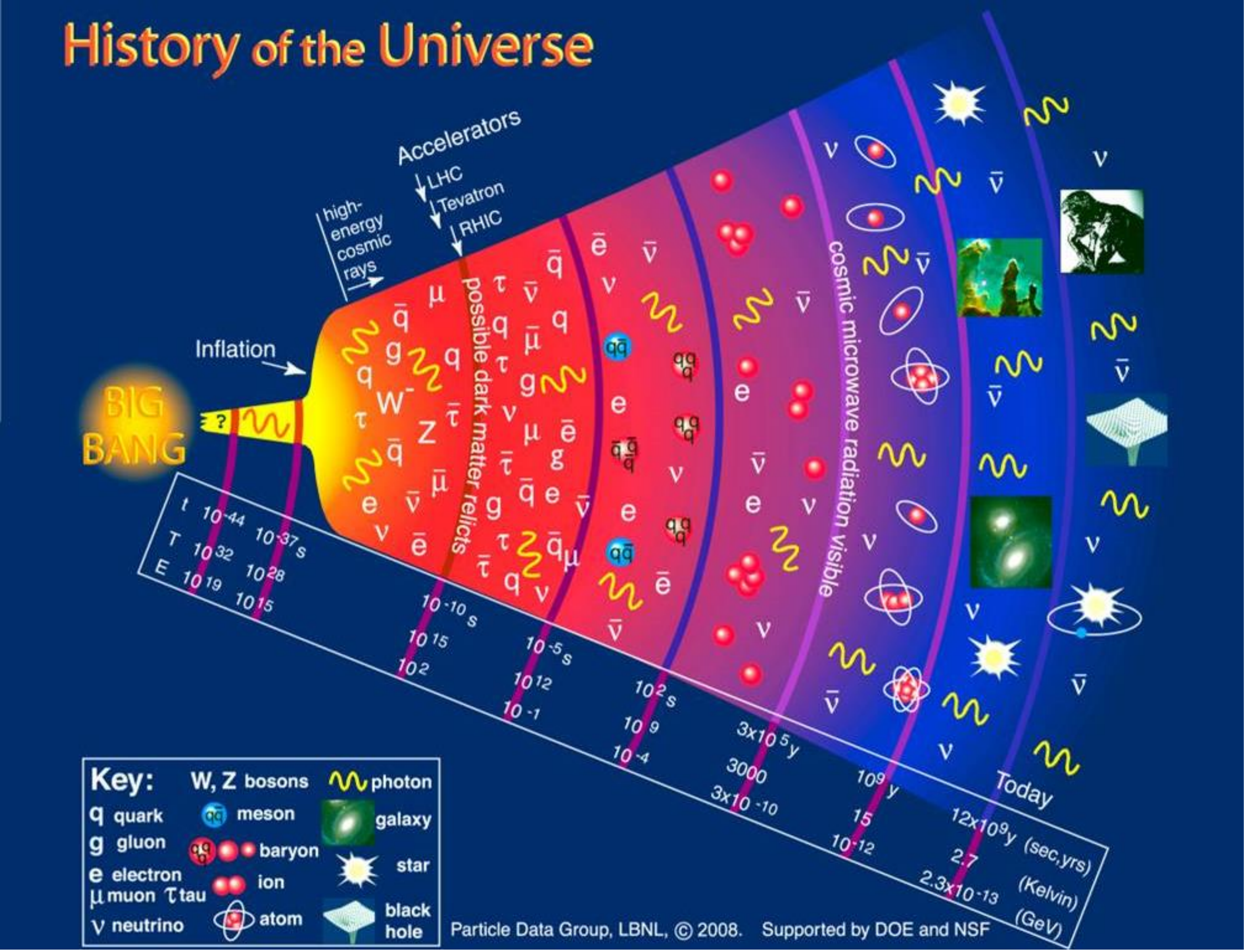
Examples

$$photon \rightarrow electron + positron$$

$$photon \rightarrow quark + antiquark$$

$$photon \rightarrow proton + antiproton$$

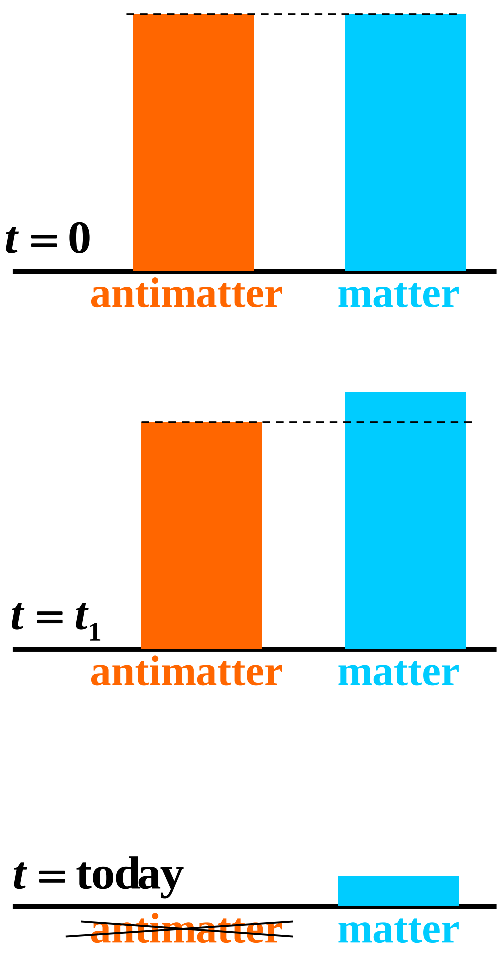
Protons and neutrons made from quarks



after 0.000001 seconds, too cool to make protons and antiprotons neutrons and antineutrons

Matter – Antimatter Asymmetry

- early universe: very hot, makes matter-antimatter
- For some reason matter becomes more abundant in the early stages of Universe
  1,000,000,001 protons
  1,000,000,000 antiprotons
- Antimatter completely annihilated
- Hence we're left only with matter today:
  (0.25 protons, ~10^9 photons, ~10^8 neutrinos+antineutrinos)/m^3
- One of major challenges of particle physics – explain the dominance of matter in our Universe



Symmetries vs Asymmetries

- Ancient scientists (e.g. Archimedes): Universe is made from perfectly symmetric objects like circles and spheres → wrong models of the orbits of the planets

- Now know: “perfect” symmetry gives a lifeless Universe → it is the asymmetries that give it complexity

- Differences in DNA (you vs me, humans vs clams)

- Difference in particle properties: neutron mass is larger then proton mass → n decays while p is stable → we exist
- matter is slightly different than antimatter → we exist

Observations 50 Years ago

1 Universe is mostly matter, need matter-antimatter differences in very early Universe. Andrei Sakharov

2 matter-antimatter differences observed in strange quarks Jim Cronin and Val Fitch

3 matter-antimatter differences observed in electron and muon charge asymmetries in strange quark decays. Mel Schwartz

Sakharov, 1975 Nobel Peace Prize

Cronin and Fitch, 1980 Nobel Prize for Physics

Schwartz, 1988 Nobel Prize for Physics (for discovering the muon type neutrino)

Matter-antimatter difference experiment at Fermilab Proposed in 1979

A Study of Direct CP Violation in the Decay of the Neutral Kaon via a Precision Measurement of $|\eta_{oo}/\eta_{+-}|$

R. Bernstein, J.W. Cronin, and B. Winstein

University of Chicago, Enrico Fermi Institute, Chicago, Illinois

B. Cousins, J. Greenhalgh, and M. Schwartz

Stanford University, Department of Physics, Stanford, California

D. Hedin and G. Thomson

University of Wisconsin, Department of Physics, Madison, Wisconsin

CP violation in strange quark decay
Fermilab proposal 617 January 1979

wrong. very small effect. new physics must come from somewhere else

ABSTRACT

In this proposal, we describe an experiment to measure the ratio R of the CP violating amplitudes $|\eta_{oo}|$ and $|\eta_{+-}|$ to a precision of better than 1% thereby improving the present results by about one order of magnitude. If the CP violation is confined to the mass matrix, R = 1.0 exactly. Recent theoretical considerations which unify the CP violating interaction with the CP conserving weak and electromagnetic interactions among six quarks predict R differing from 1.0 by sizable amounts.

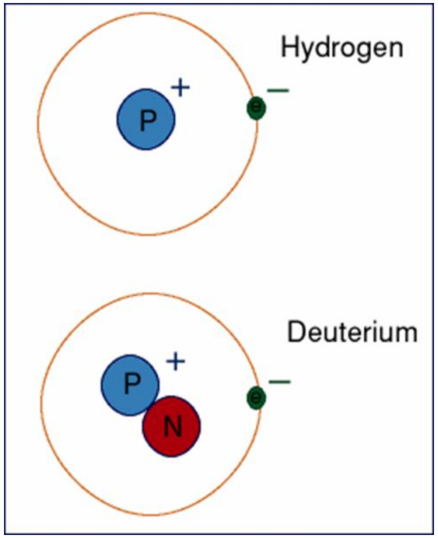
Experimental Observation vs Matter in Universe

All observations of matter-antimatter differences BEFORE 2017 are much, much lower than the amount needed in the first instance of creation to explain the amount of matter in the Universe

→ Need something new. High priority for past 40 years. Still no definitive answer. One of primary reason for future muon (heavy electron, common in cosmic rays) and neutrino program at Fermilab.

Creation of Light Nuclei

- During first few minutes have about the same number of protons and neutrons and can have the following reactions

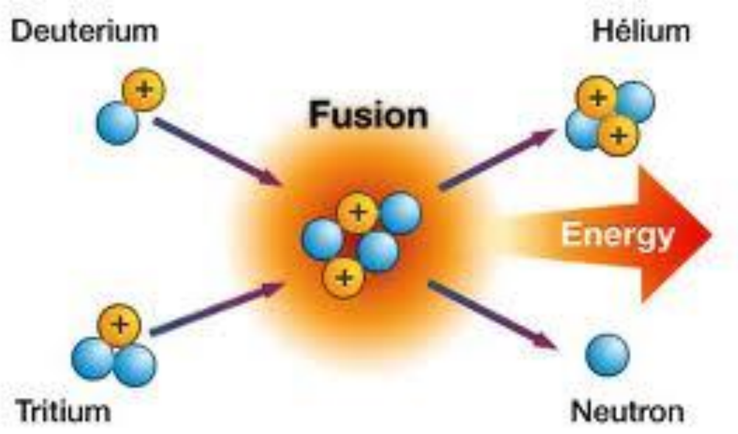


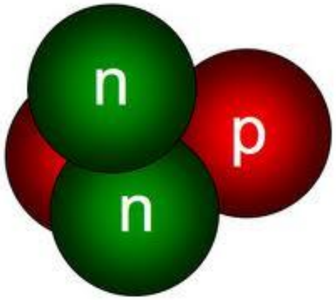
p + n → pn (deuterium) + gamma

pn + n → pnn (tritium) + gamma

pn + pn → Helium-4 + gamma

pnn + pn → He-4 + n

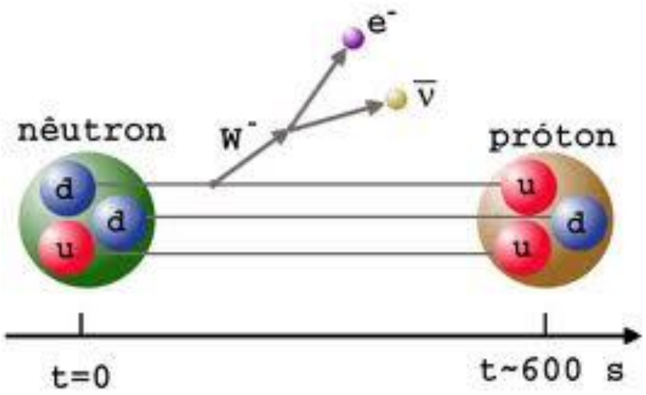




Creation of Light Nuclei

Relative number of protons and neutrons depends on:

- neutron being a little heavier than the proton
- neutron decays with 890 s lifetime
- how quickly Helium is made



- We end up with #n/#p = 14% or 2 neutrons for every 14 protons
- Almost all the neutrons are in He giving about 75% H and 25% He after first 3 minutes (and still mostly today)
- fraction of H, He, H2, He3, Li are "fossil" record from this time. Tell temperature of Universe at t=1 minute

Neutron Lifetime

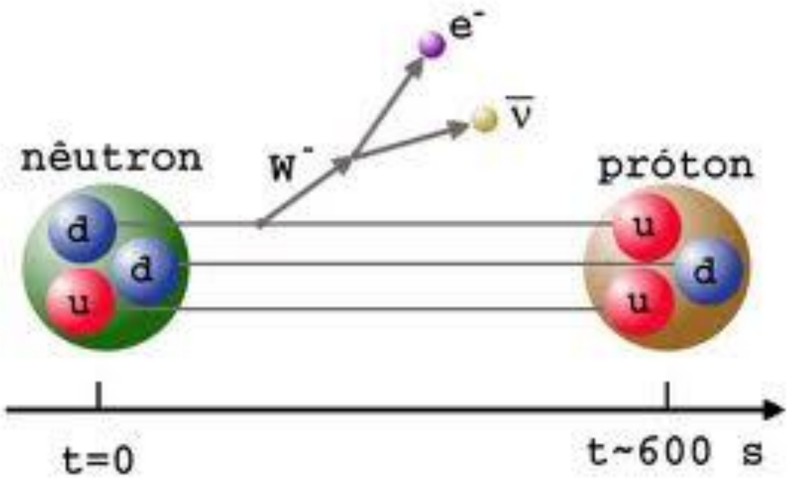
- neutron decays with 15 minute lifetime
- What is lifetime was 15 hours?

→ About same number of protons and neutrons and all go into making Helium

→ Universe is mostly composed of He and Hydrogen relatively rare

→ Stars are very different

→ Life as we know it does not exist



Evidence for Big Bang

- galaxies all moving away from us (Hubble Law)
- cosmic microwave background at 3 degrees K
- relative amount of Hydrogen to Helium (plus other light elements) seen throughout the Universe

→ moment of Creation about 13-14 billion years ago

But somehow 40% of Americans don't "believe" in this as it is "against" their religious views. Which seems to deny the wonder of the Universe that was created!!

I don't get it……..

Test 3 Overview

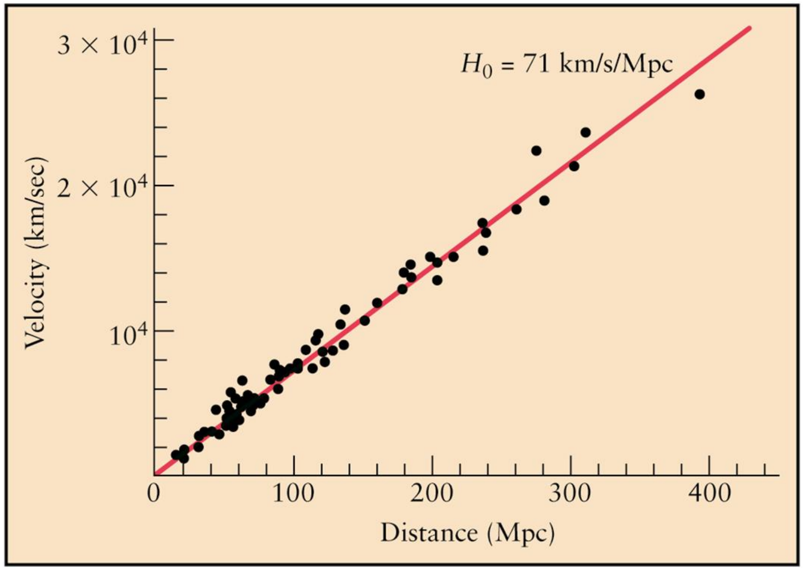
- Formation of planets. temperature of solar nebula, and how it varies with distance → type of planet formed. Heavy elements freeze out first. Extrasolar planets detected in a number of ways (motion of stars, planet eclipsing star, directly). Planetary atmospheres: high temp and/or low surface gravity prevent the planet from holding on to light gases like hydrogen.
- Life in the Universe. Need star to be long-lived and not in binary system. Need planet to be the right distance from its star. Communicate with ET by radio with Drake equation giving estimate of number of possible civilizations in Milky Way.

Galaxies. Measure distance (next slide). Ellipticals:little rotation, little gas/dust or active star formation. Spiral: rotation/gas/dust and active star formation. Irregulars: active star formation but indistinct shape. Galaxies are moving away from us with v=Hd v=velocity, d=distance, and H=Hubble constant. Milky Way has inner nucleus, spiral arms (active star formation, halo of old stars (early shape)

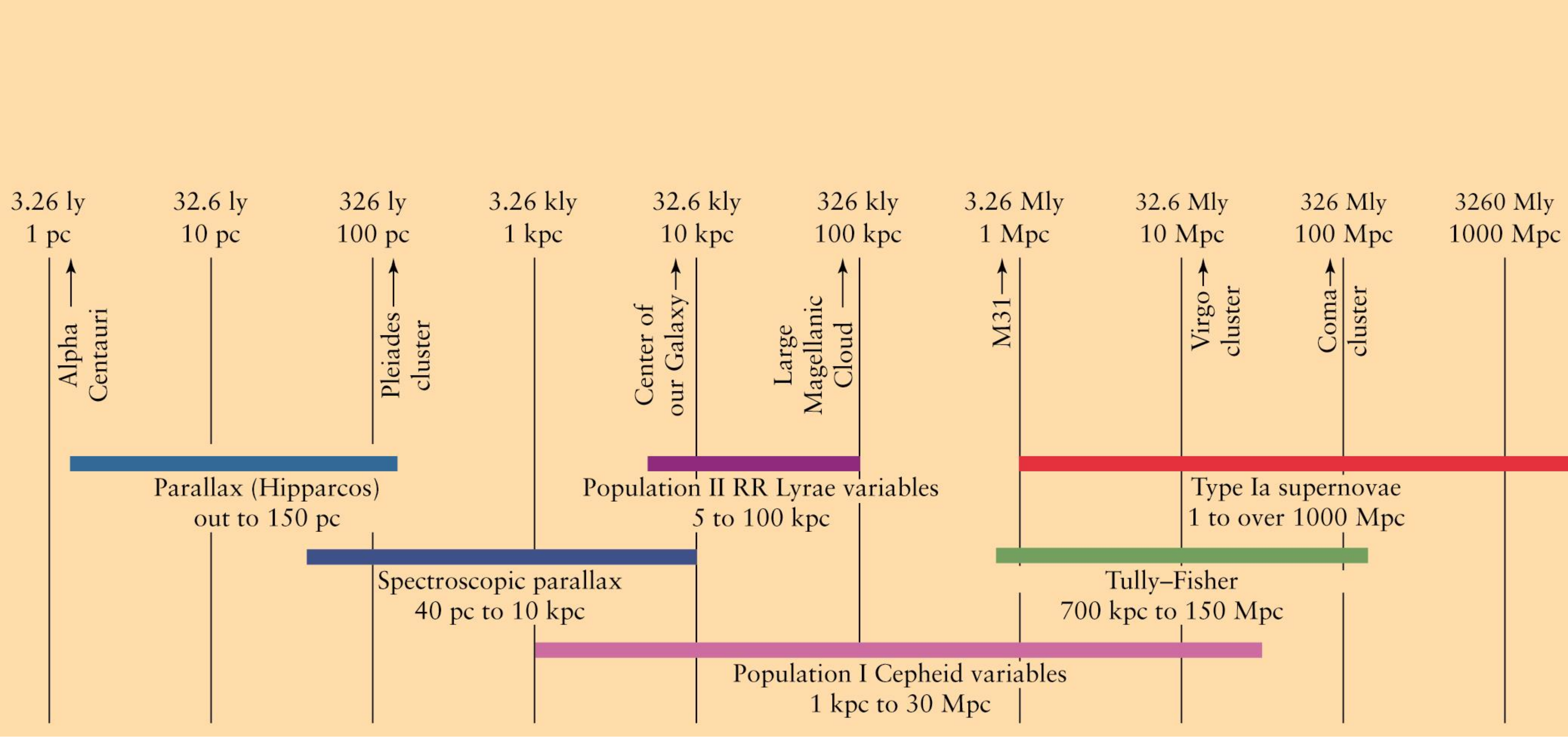
Cosmology. Hubble law → Universe is expanding, gives universe's age, depends on Hubble "constant" changes with time. Closed universe has gravity slowing the expansion so it starts to contract. Open universe expands forever. Early universe was very hot and when matter was created. First electrons, protons and neutrons, then protons and neutrons give hydrogen and helium nuclei minutes after the Big Bang. 400,000 years later atoms form, Universe became transparent, and light appeared, seen as the cosmic microwave blackbody radiation temperature of 3 degrees K.

Measuring Distances to Galaxies

- Type Ia supernovas (white dwarves which hit the Chandrashekar limit) are best for distant galaxies
- Cepheid Variables are best for closer galaxies
- Once understood, use Hubble Law v=Hd to measure distance for any galaxy → measure v by Doppler shift. Know H → get d



Measuring Distances – summary



- Type Ia supernovas (white dwarves which hit the Chandrashekar limit) are best for distant objects. Once understood, use Hubble Law v=Hd to measure distance (measure v get d).