2

- Expanding Universe
- Cosmic Microwave Background
- Computing the Universe

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Hubble's Discovery of the Expanding Universe (1929)

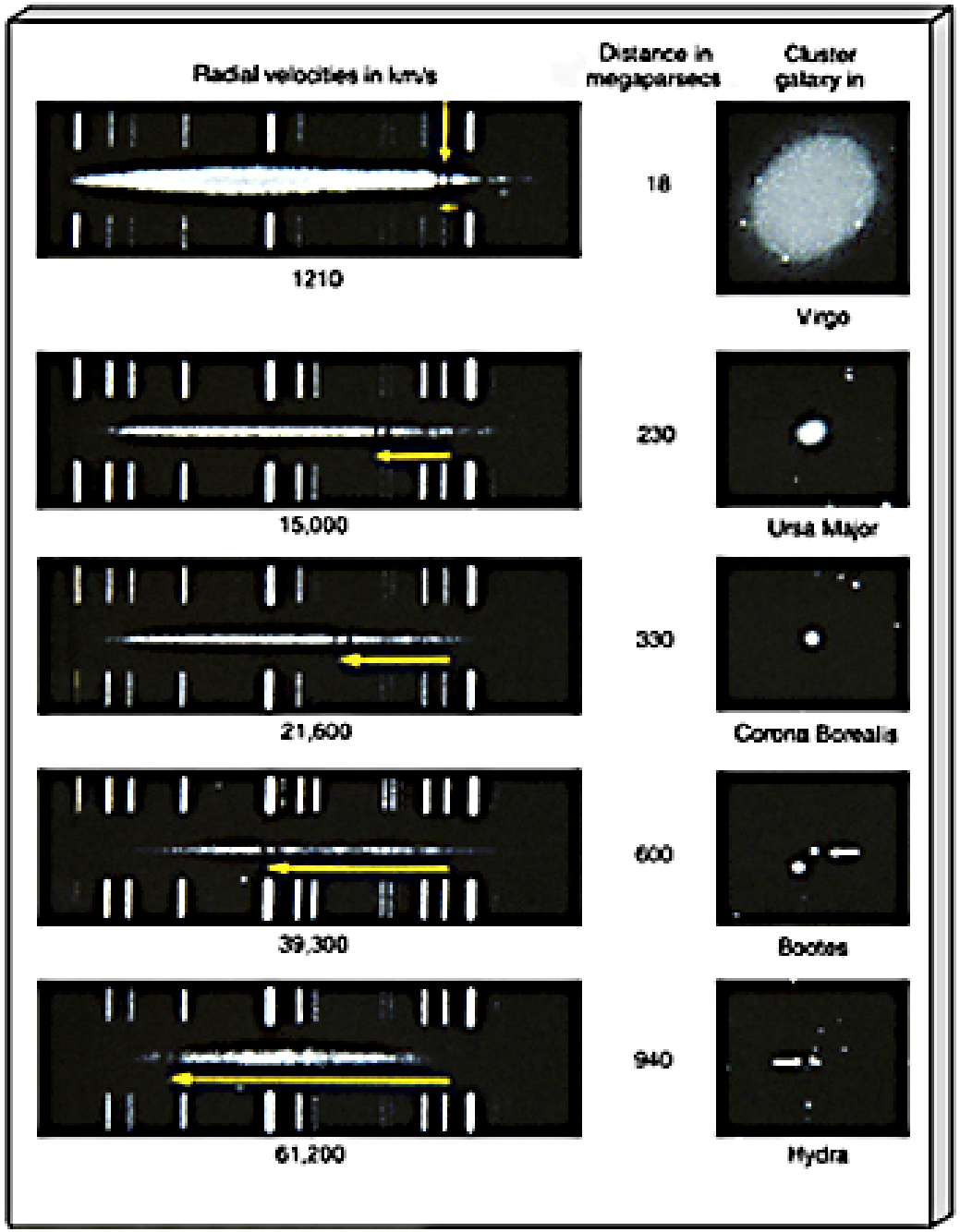
- Spiral nebulae known to have redshifted spectra
- Hubble and Humason carry out quantitative study
- Hubble shows velocity of recession is proportional to distance

Hubble's Law

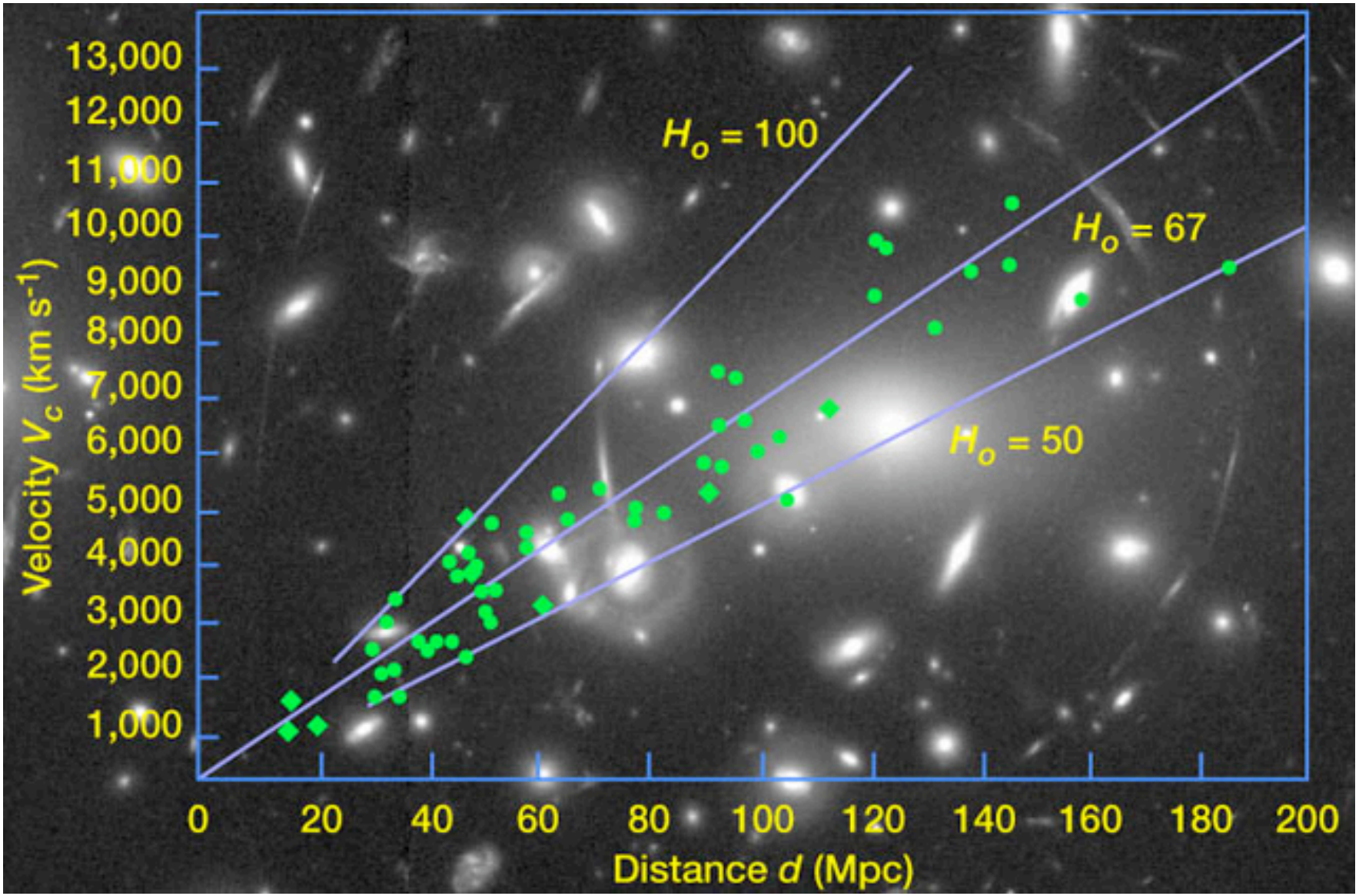
- All galaxies are moving away from us *with a speed which is proportional to their distance*

- $v = H_0 d$

Hubble constant

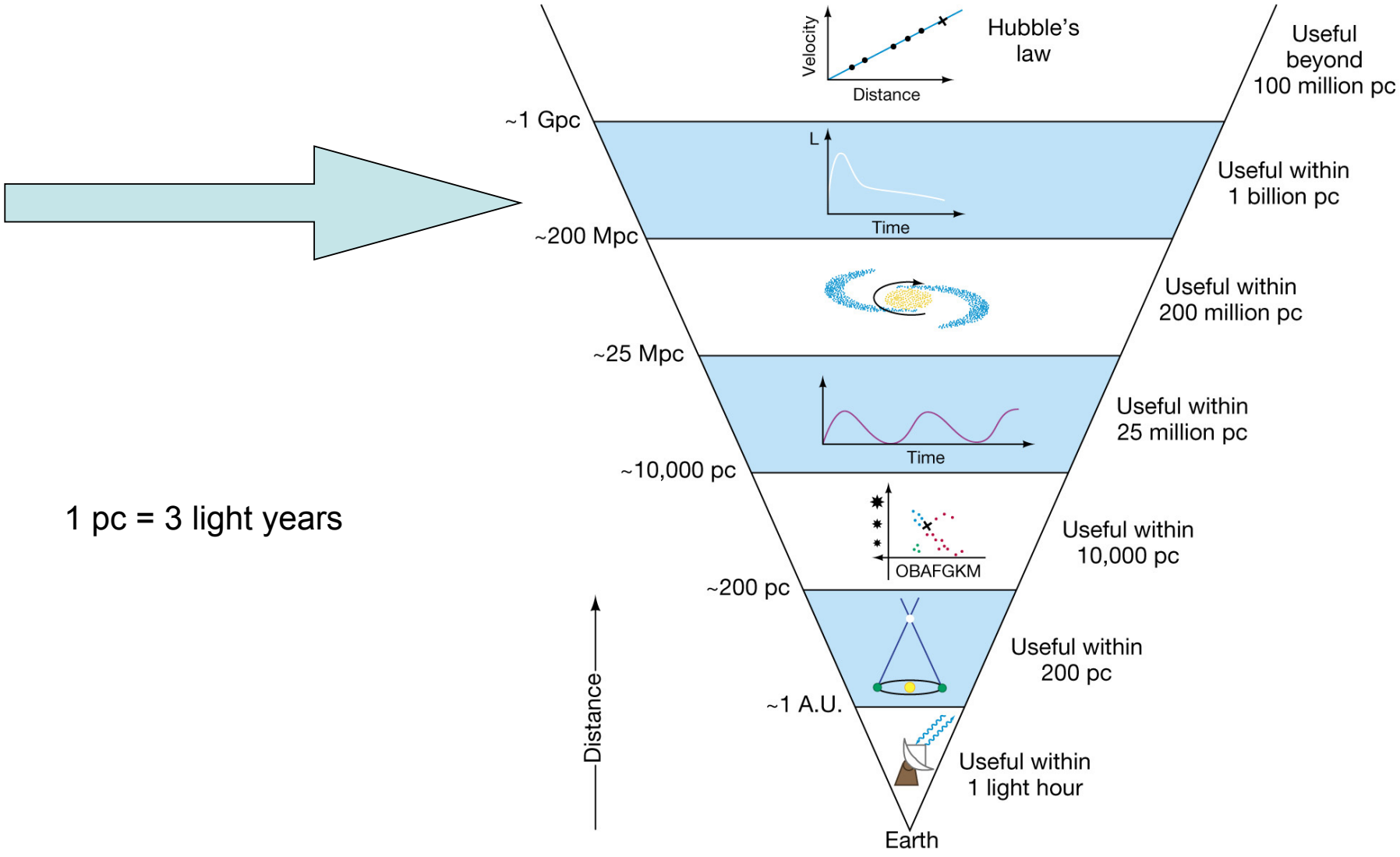


Modern Hubble Diagram



http://www.hubbleconstant.com

Using Hubble's Law to Extend Cosmic Distance Ladder



1 pc = 3 light years

Simple estimate of the age of the universe from the Hubble Law

velocity = H_o x distance

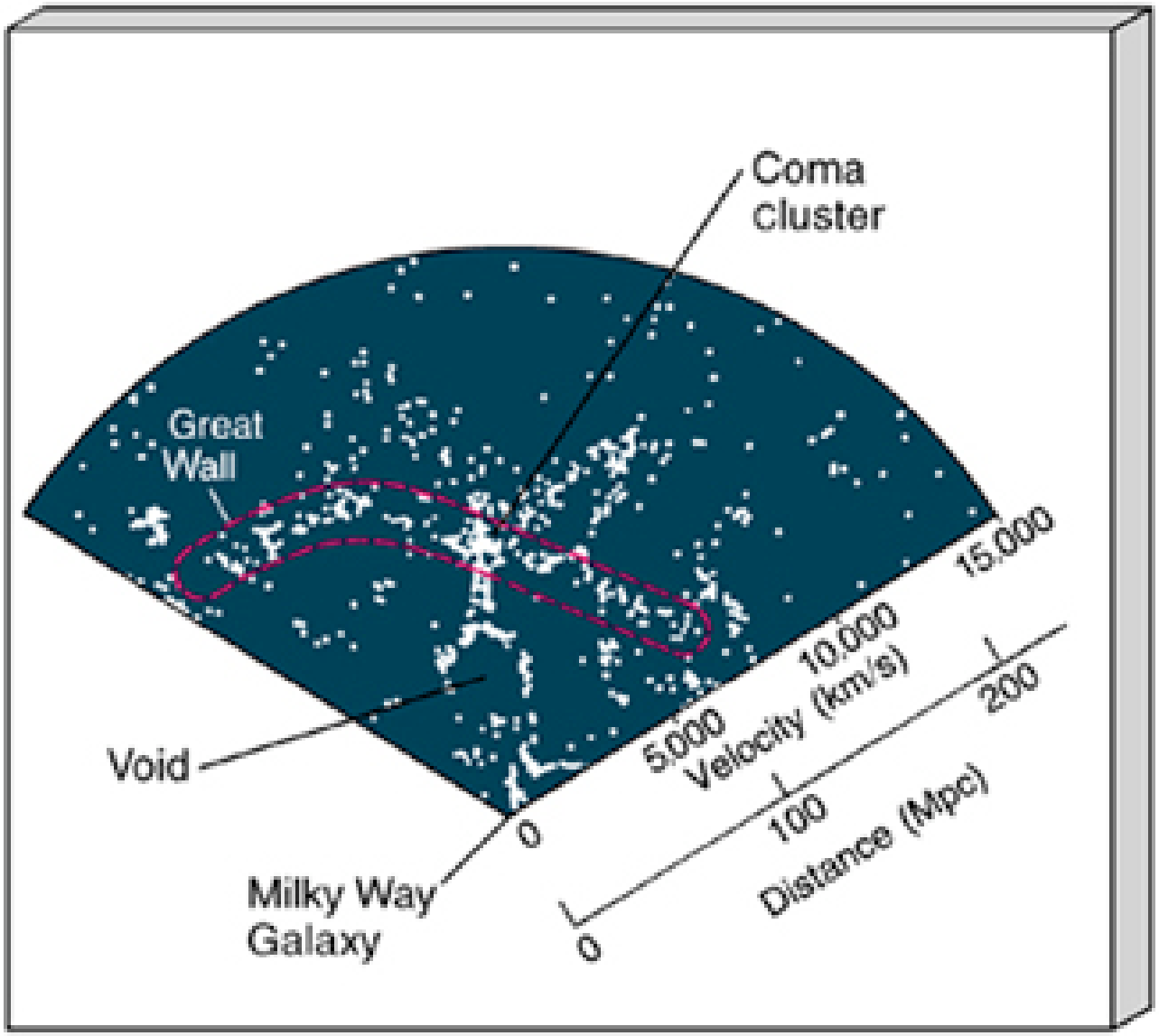
distance = velocity / H_o

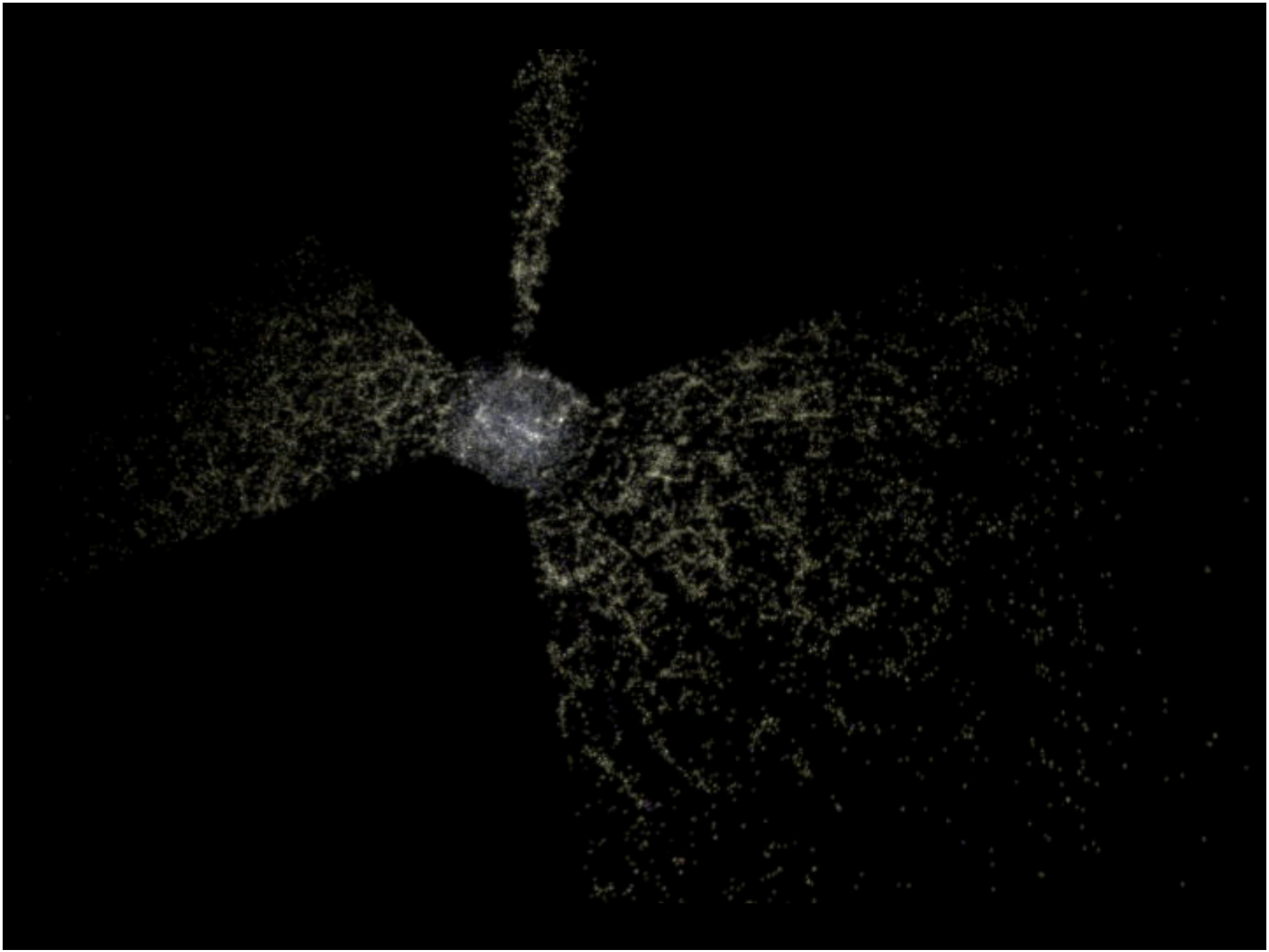
velocity = distance/time
time = distance/velocity = $1/H_o$

age ~ time = $1/H_o$ = 1/(65 km/s/Mpc) =

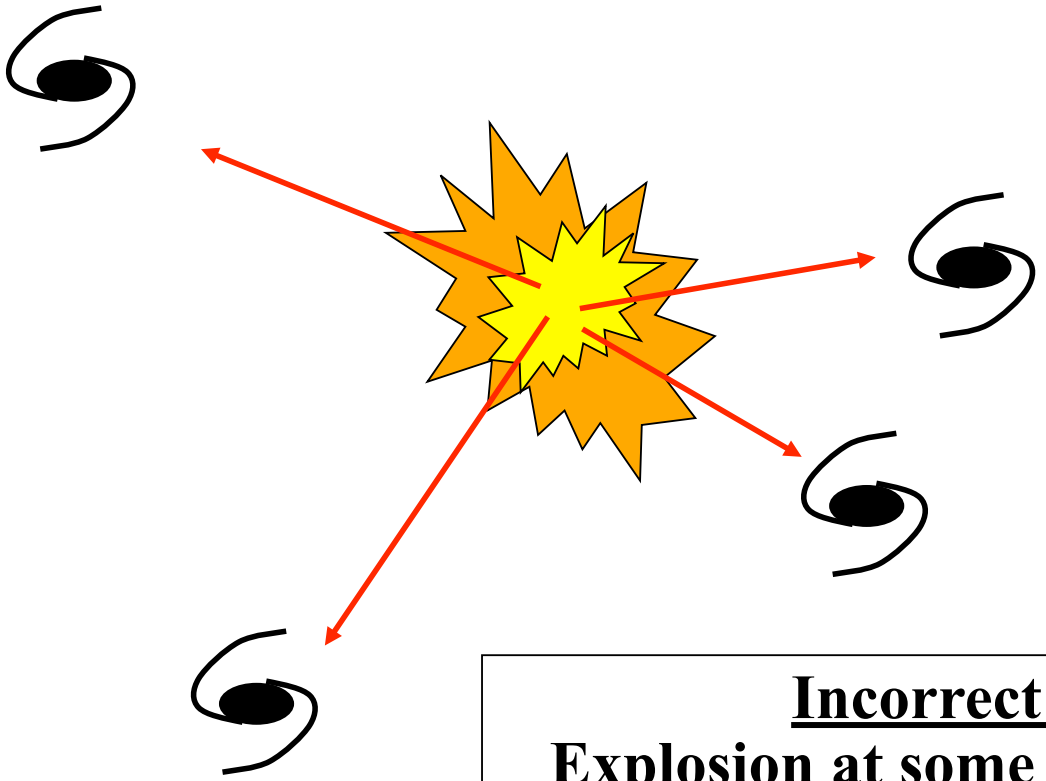
=1/(65 1000/(3 10^{22})) =4.7 10^{17} s =
= 15 billion years

Galaxy Redshift Surveys

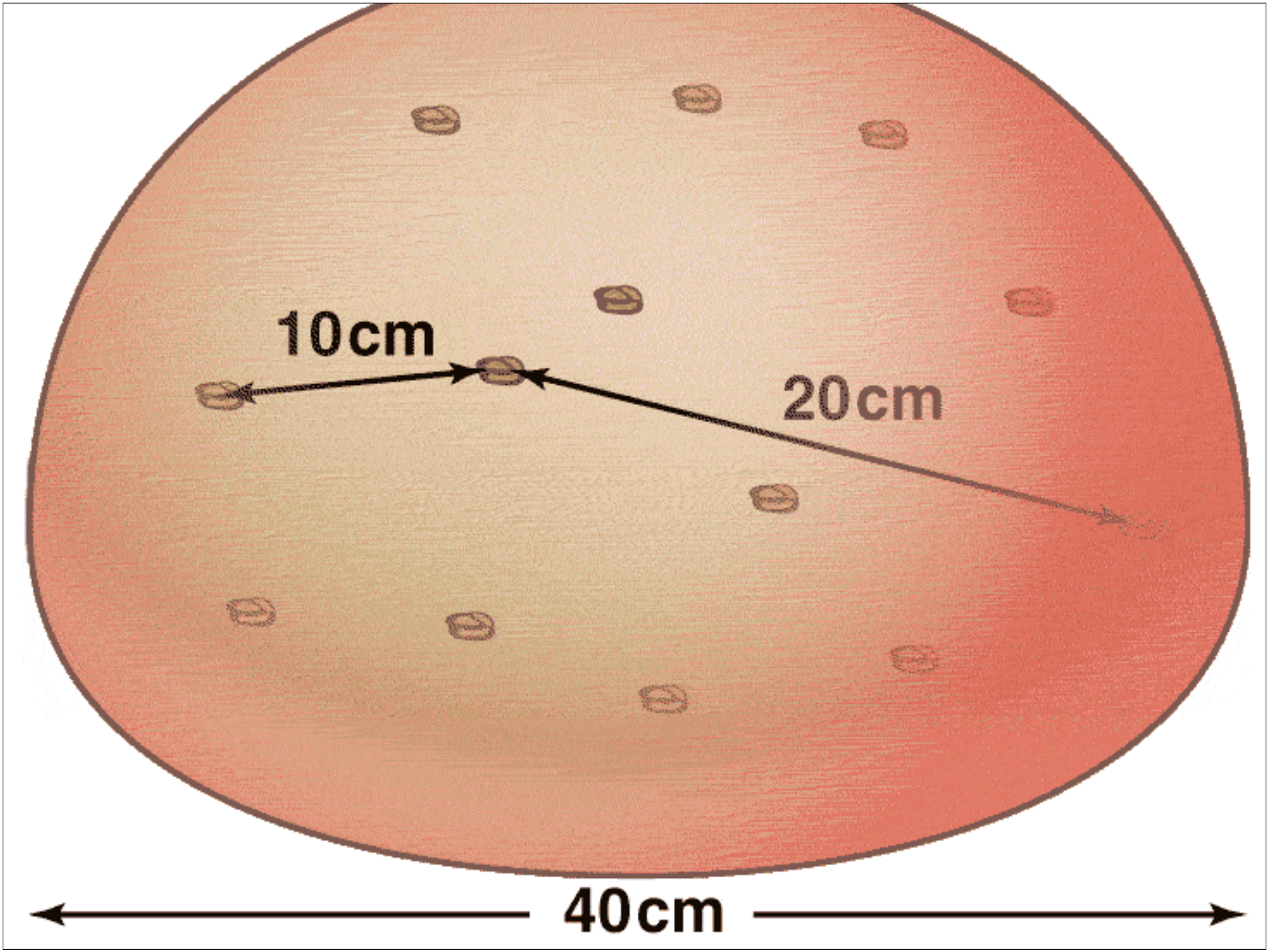


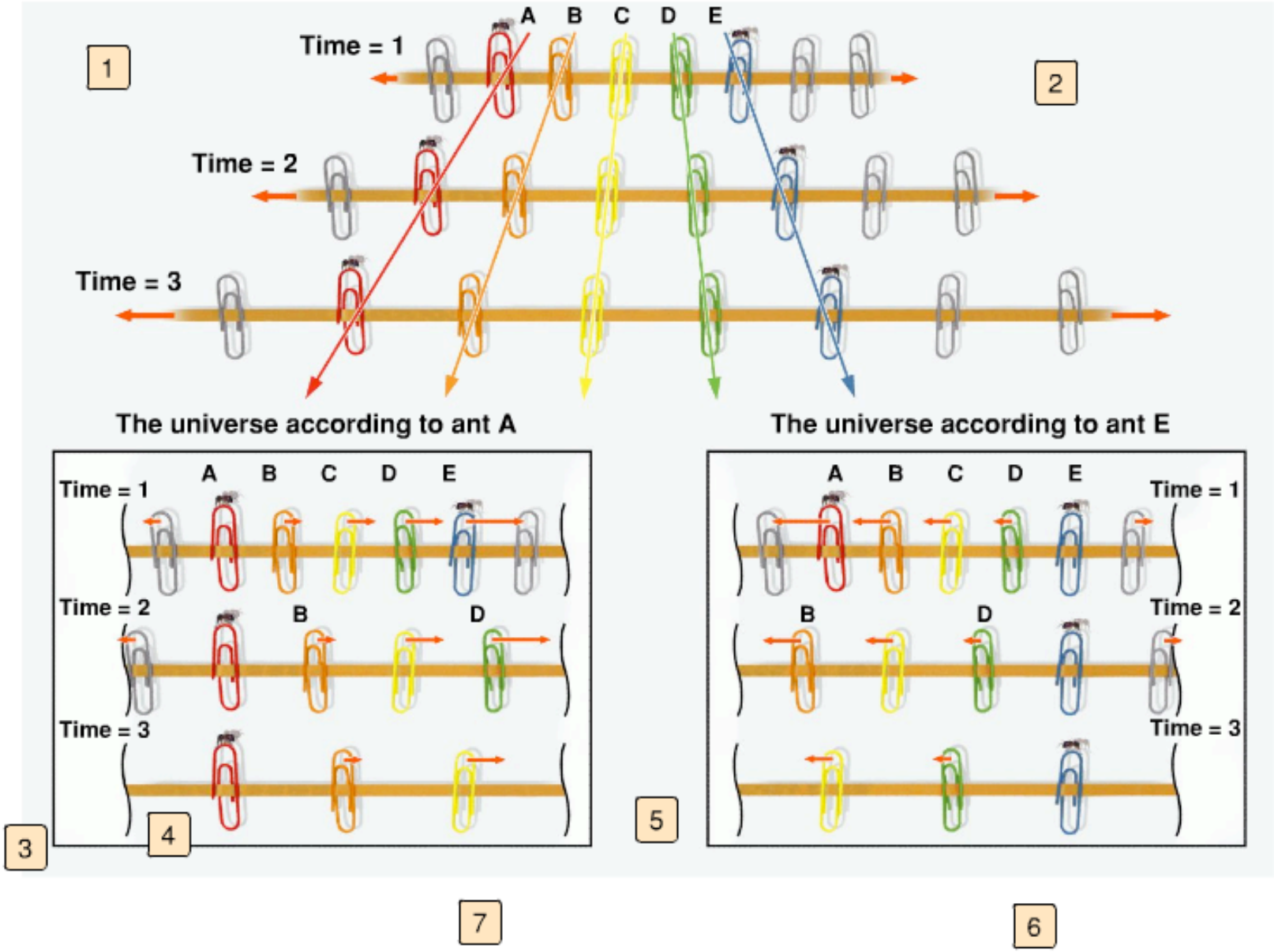


Interpretations of Hubble Law



<u>Incorrect view:</u>
Explosion at some point in space; galaxies fly out like shrapnel


10cm
20cm
40cm



Space expanding everywhere with no center
Galaxies carried along like "markers"

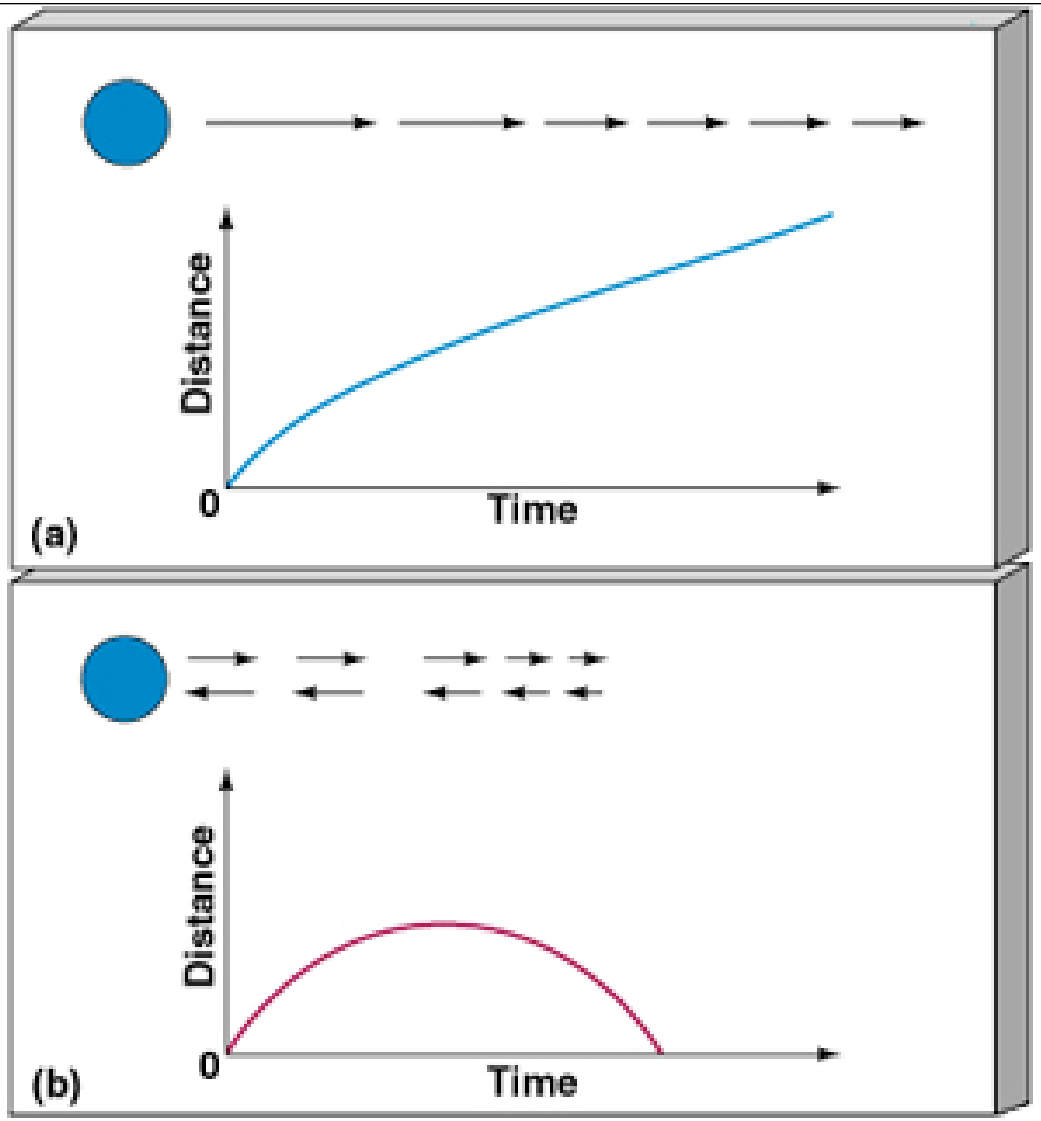
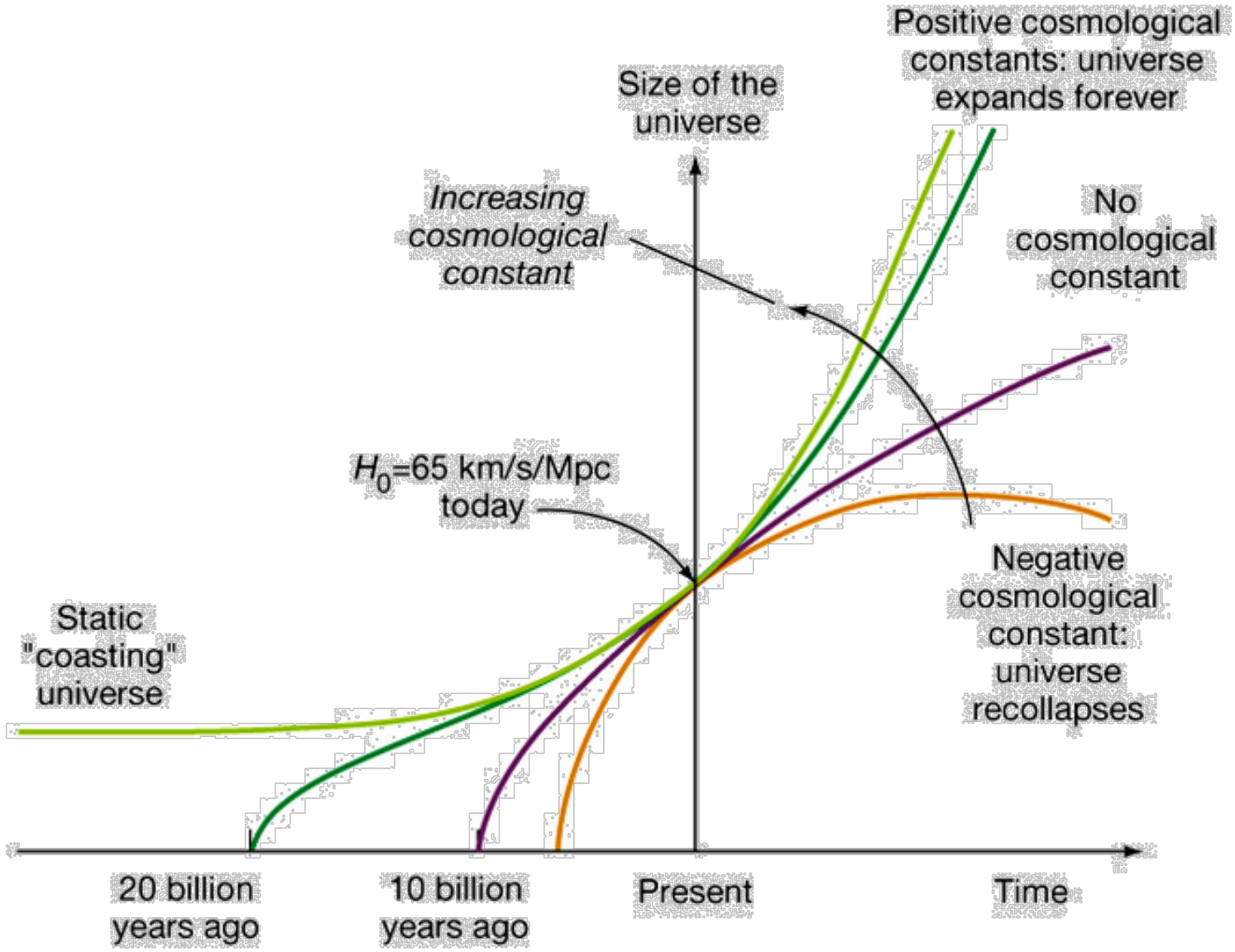


Figure 17.5 ***Escape Velocity*** *(a) A rocket ship (arrow) leaving a planet (blue ball) with a speed greater than the escape speed follows an unbound trajectory. The graph shows the distance between the ship and the planet as a function of time. (b) If the launch speed is less than the escape speed, the ship eventually drops back to the planet. Its distance from the planet first rises, then falls.*

Critical density

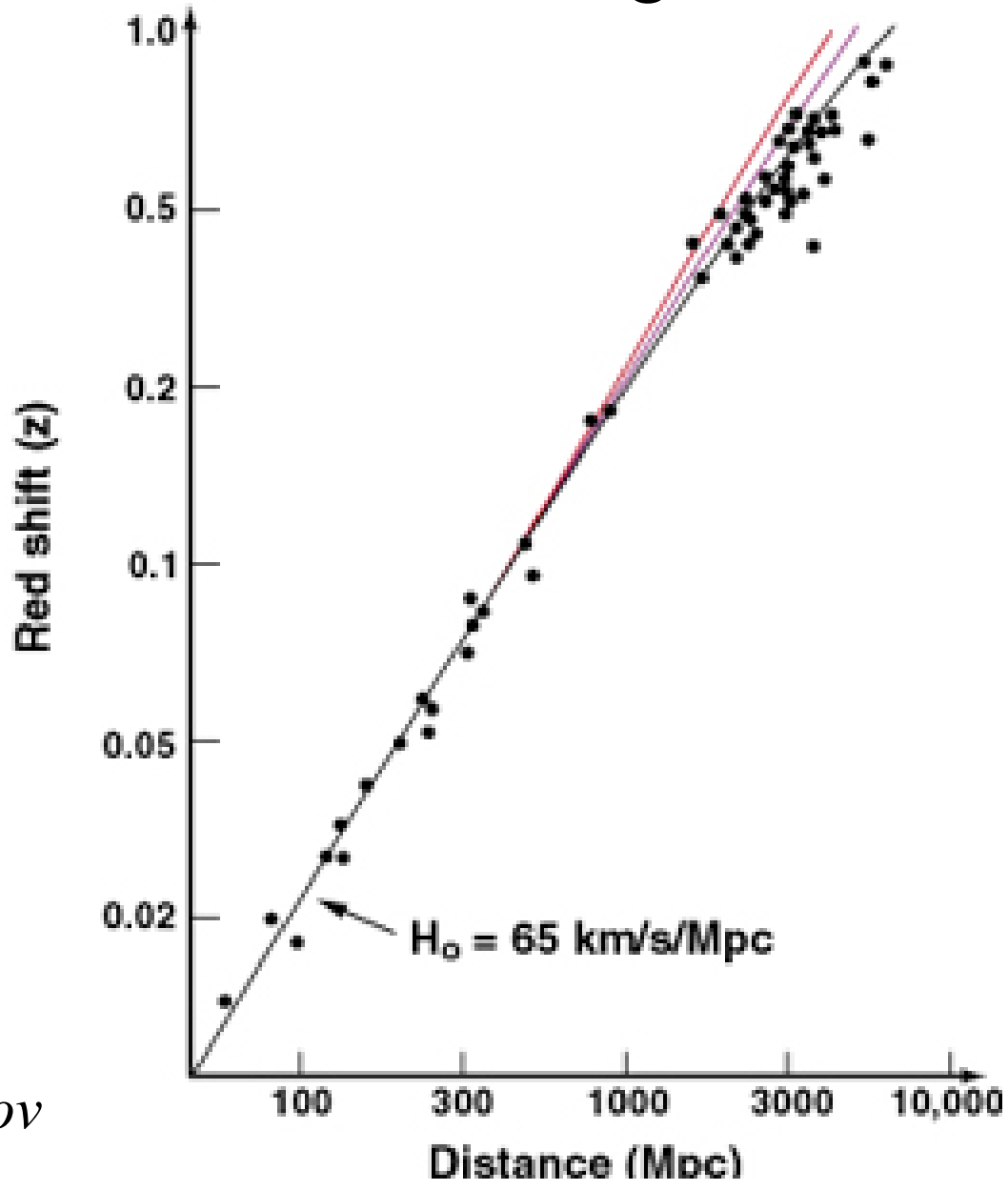
- A universe with more than critical density will recollapse. One with equal or less this density will expand forever.
- For H_0=65 km/s/Mpc it is 8 x 10^{-27}kg/m^3.
- That is 5 hydrogen atoms per cubic meter … (not much in the closet)
- However, only 4 percent of the universe is in baryons. Hence, only one hydrogen atom for 2 cubic meters (one in the closet)

Evolution of the Universe



Evidence for an Accelerating Universe

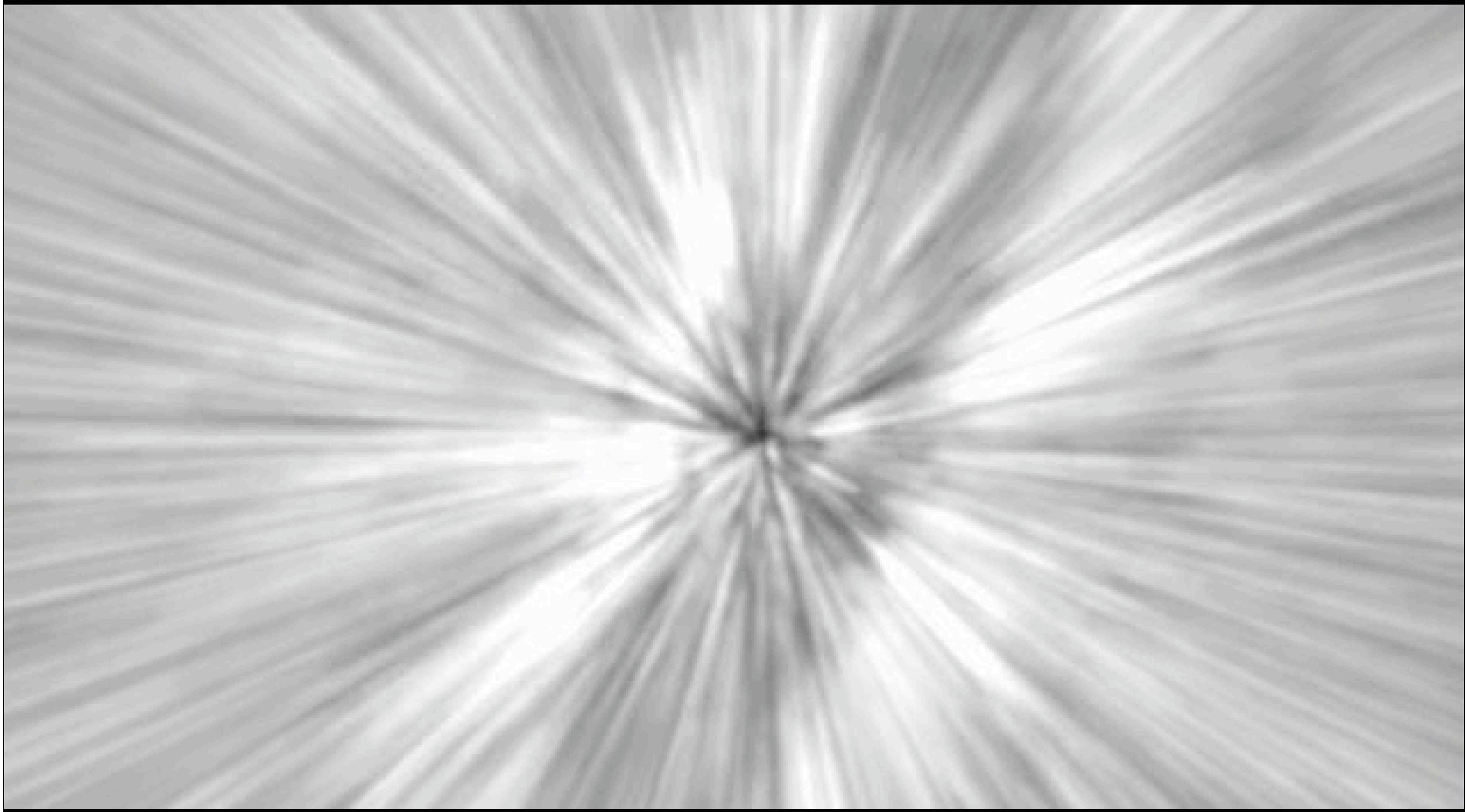
In 1998, two independent teams of astronomers concluded universal expansion is *accelerating* based observed departures from Hubble law at very large distances



www.supernova.lbl.gov

What could make universal expansion accelerate?

- Since gravity causes deceleration, something that *acts like antigravity*
- antigravity would require a negative mass density
- but by $E=mc^2$, mass and energy are equivalent
- therefore, need a *negative energy density*
- such a thing is known in QM as *vacuum energy*
- cosmologists call this *dark energy*
- origin and nature is completely unknown



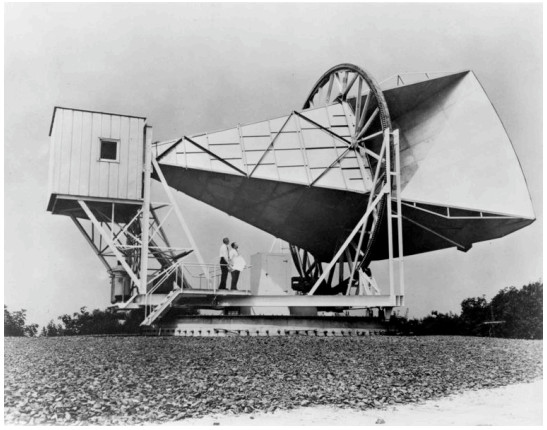
Best Time machine uses radio waves gives Baby Pictures of Universe

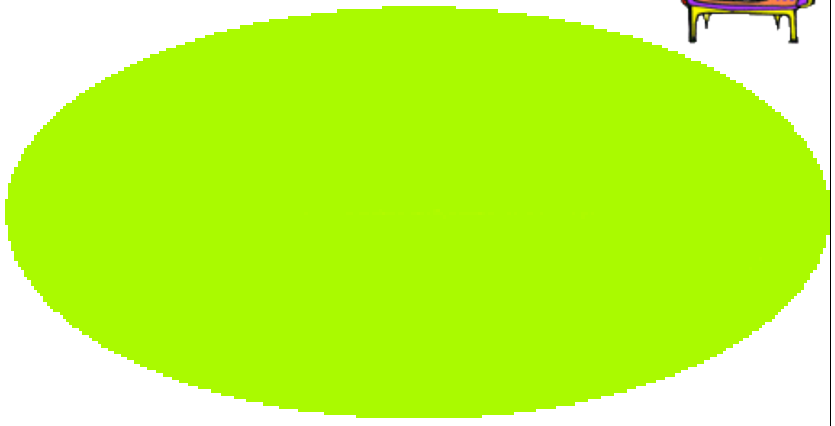
Universe at 400,000 years of Age

13.7 billion years

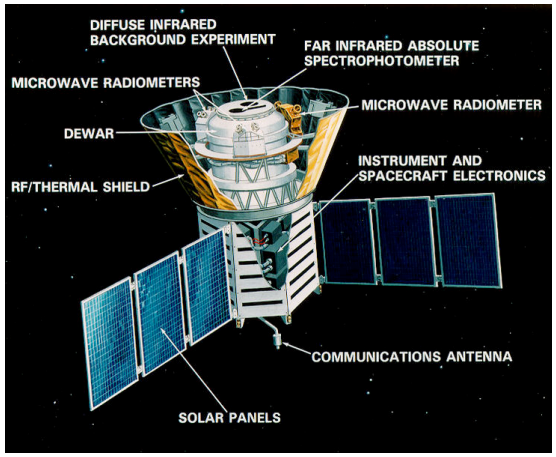
ionized -> neutral

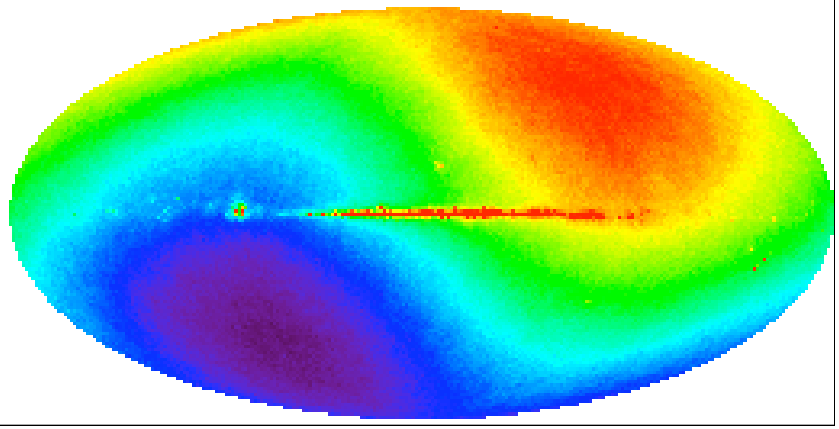
Nobel 1978:
Penzias & Wilson

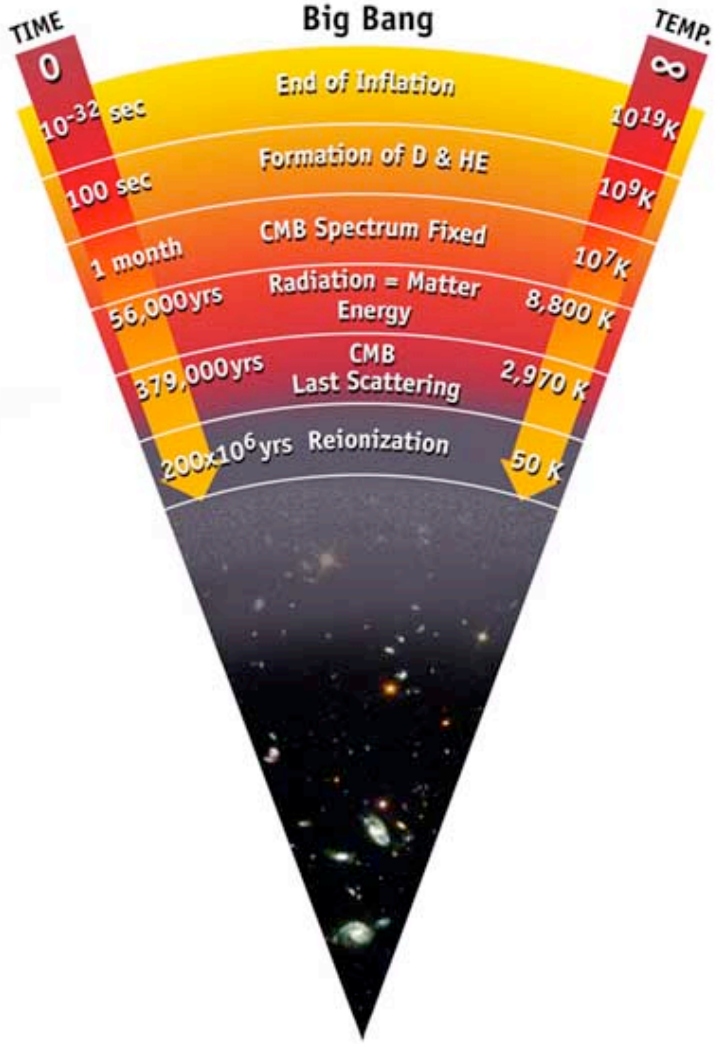




Nobel 2006:
Mather & Smoot

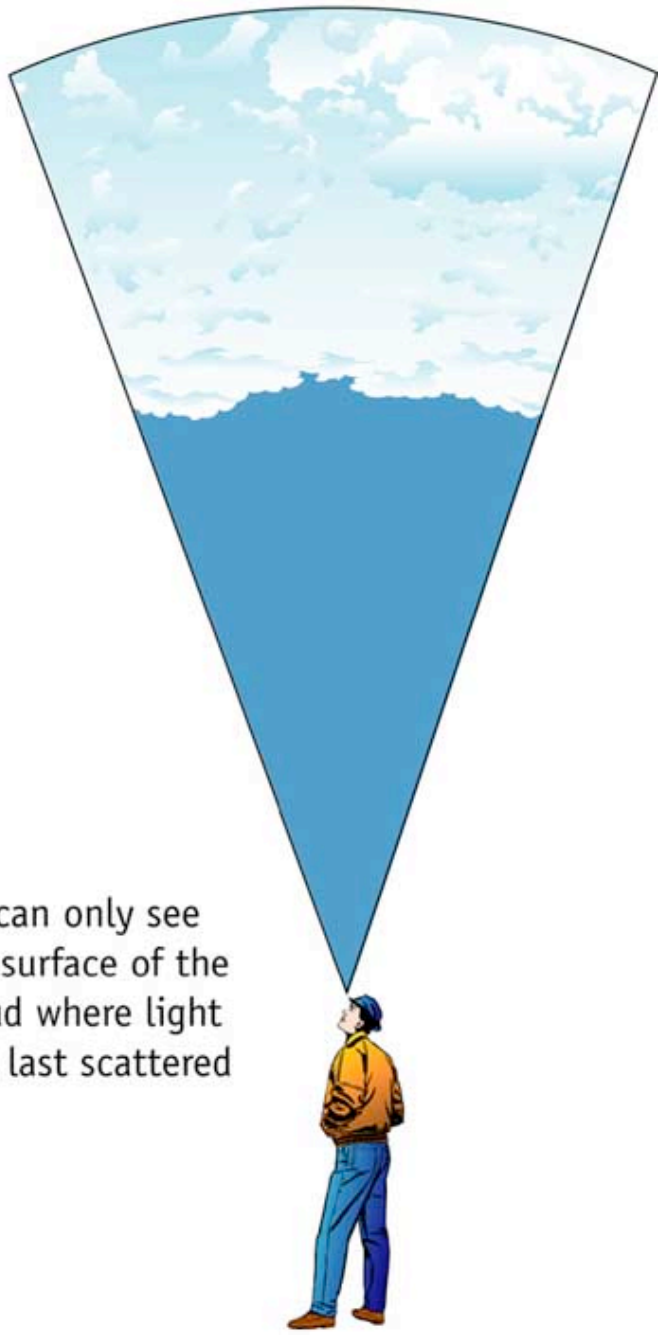






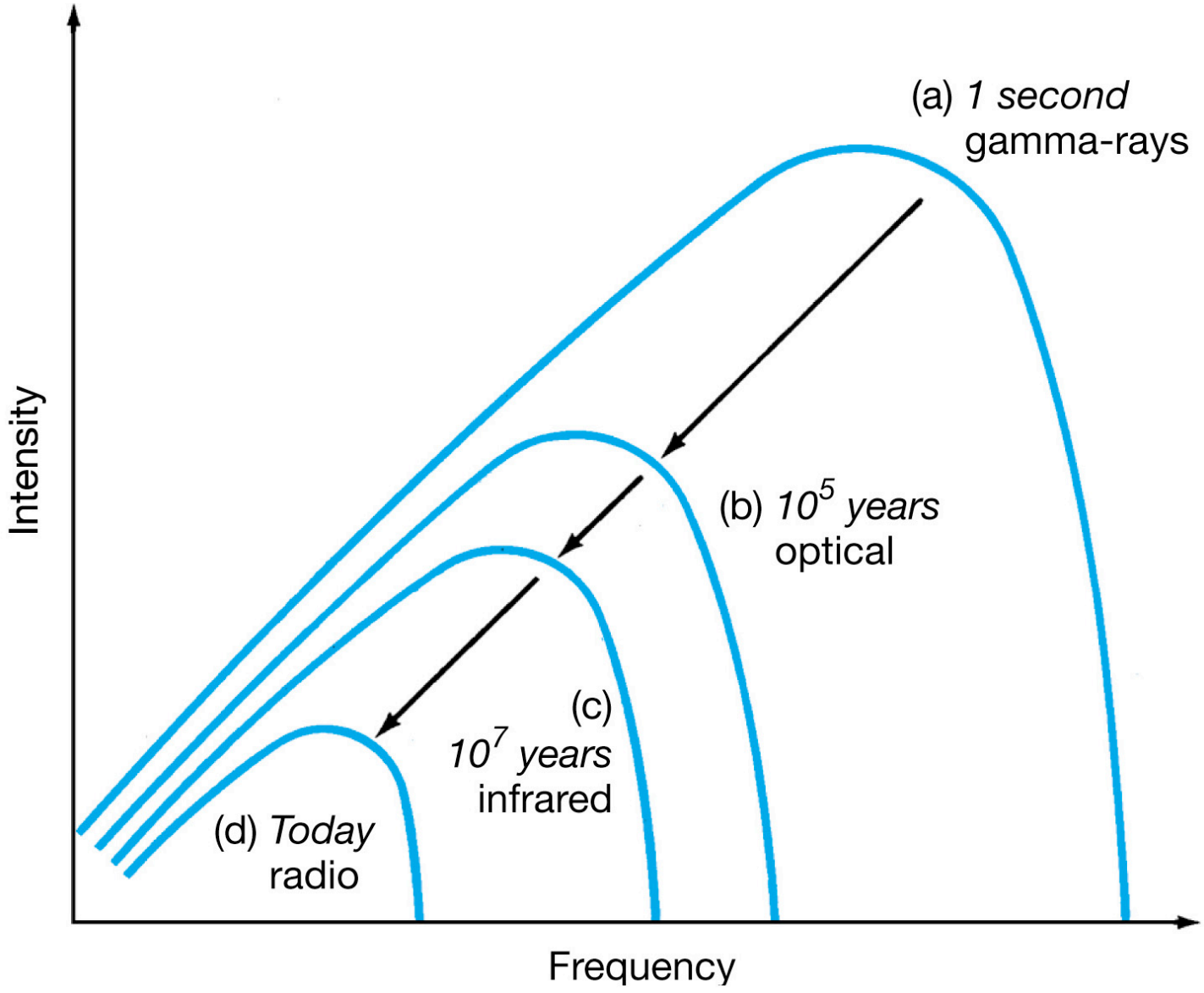
PRESENT
13.7 Billion Years after the Big Bang

The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

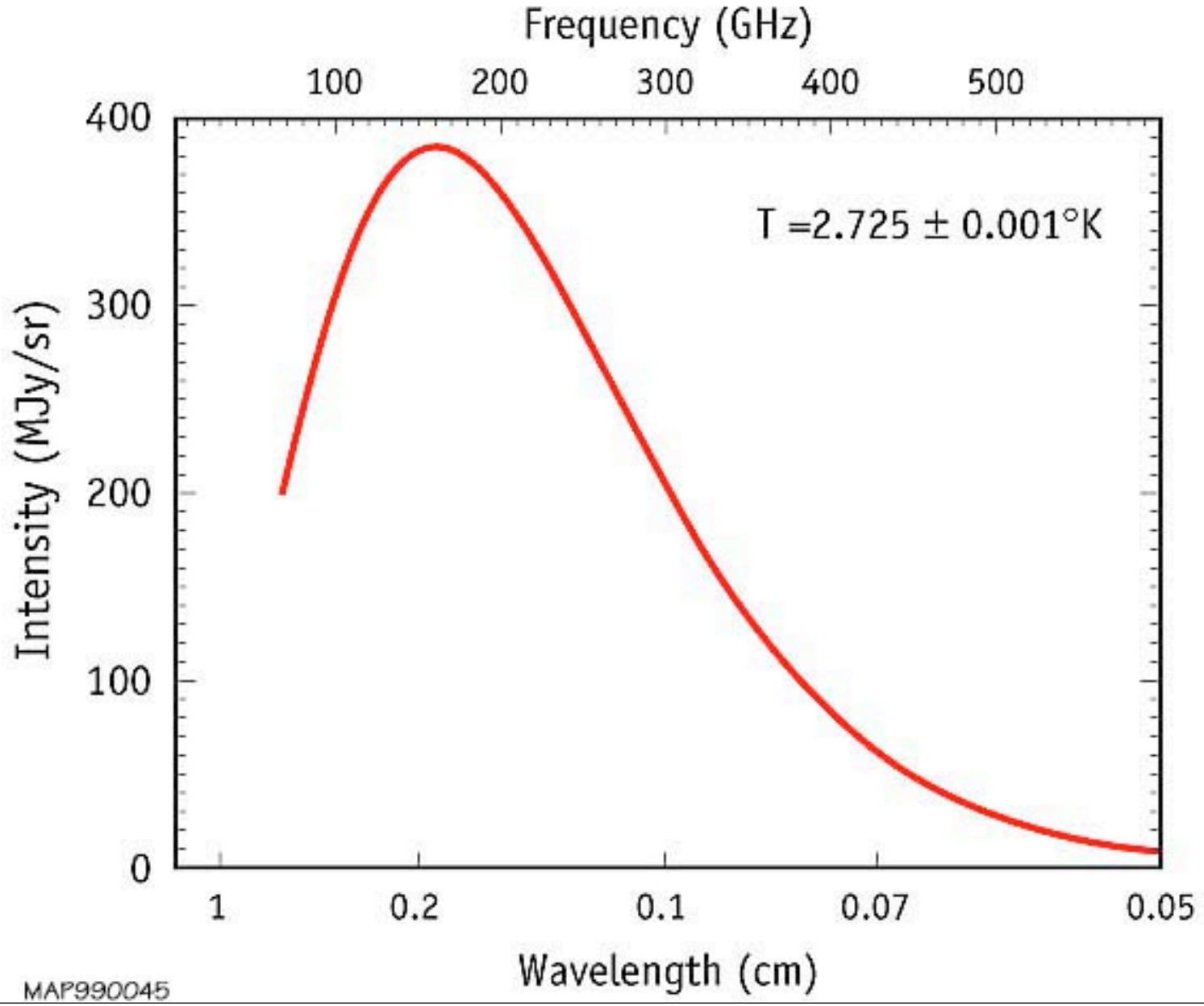


We can only see the surface of the cloud where light was last scattered

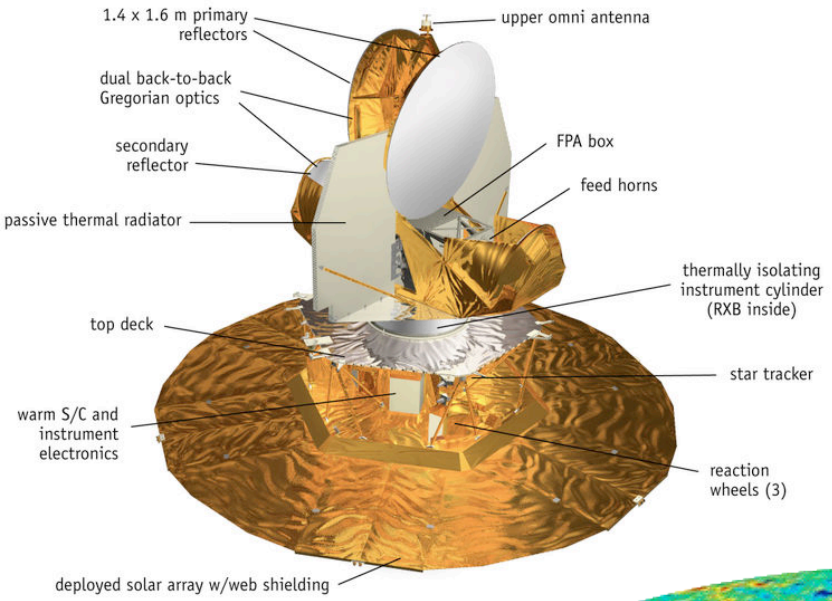
Cosmic Blackbody Curves

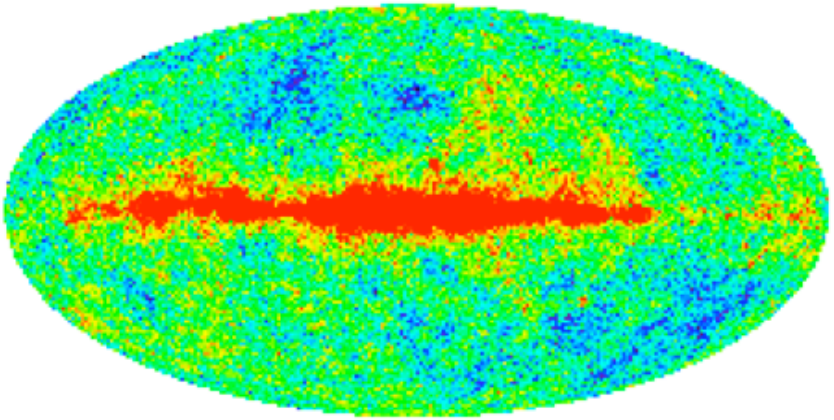


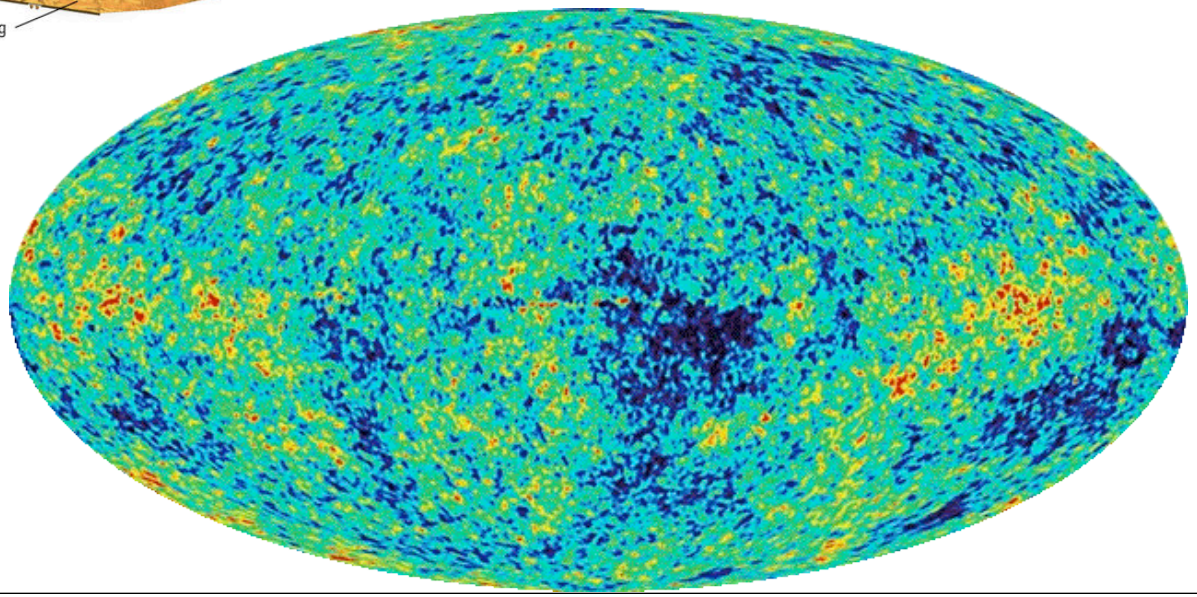
Spectrum of the Cosmic Microwave Background



One of the best time machines today: the Universe at 400,000 years of age







Cosmological Reionization

Simulation: Alvarez & Abel (2007)

Visualization: Alvarez, Kähler & Abel

Simple!

- Initial Conditions from observations of the cosmic microwave background radiation
- Physics: Gravity, fluids, chemistry, radiation, etc.
- Transition from Linear to Non-Linear; fancy for easy to difficult
- Using patched based structured adaptive (space & time) mesh refinement
- Differs from current day star formation:
  - Complete initial conditions known
  - all physical processes are understood

Ralf Kähler & Tom Abel for PBS Origins. Aired Dec 04

$$\frac{R_\odot}{R_{MilkyWay}} \approx 10^{-12}$$

$$\frac{P_{\odot,Kepler}}{t_{Hubble}(z=30)} \approx 10^{-12}$$

Primordial Gas Chemistry

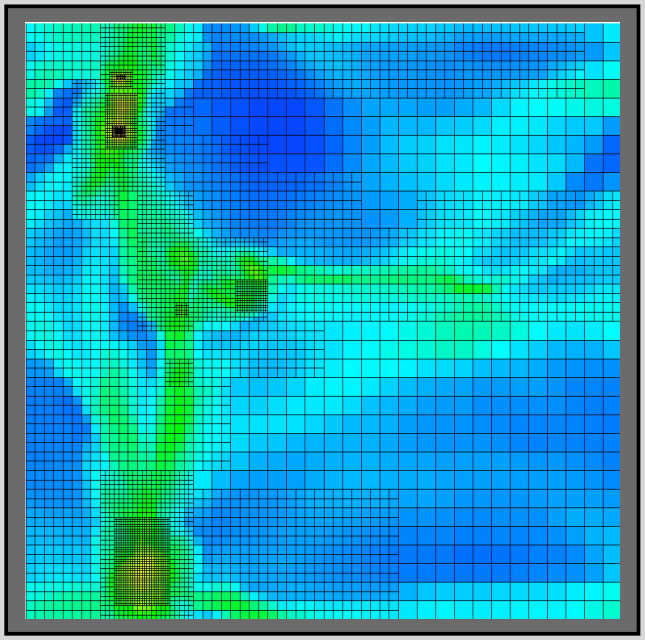
(1)	H	+	e^-	$\rightarrow H^+$	+	$2e^-$	(10)	H_2^+	+	H	$\rightarrow H_2$	+	H^+	
(2)	H^+	+	e^-	$\rightarrow H$	+	$h\nu$	(11)	H_2	+	H^+	$\rightarrow H_2^+$	+	H	
(3)	He	+	e^-	$\rightarrow He^+$	+	$2e^-$	(12)	H_2	+	e^-	$\rightarrow 2\ H$	+	e^-	
(4)	He^+	+	e^-	$\rightarrow He$	+	$h\nu$	(13)	H_2	+	H	$\rightarrow 3\ H$			
(5)	He^+	+	e^-	$\rightarrow He^{++}$	+	$2e^-$	(14)	H^-	+	e^-	$\rightarrow H$	+	$2e^-$	
(6)	He^{++}	+	e^-	$\rightarrow He^+$	+	$h\nu$	(15)	H^-	+	H	$\rightarrow 2\ H$	+	e^-	
(7)	H	+	e^-	$\rightarrow H^-$	+	$h\nu$	(16)	H^-	+	H^+	$\rightarrow 2\ H$			
(8)	H	+	H^-	$\rightarrow H_2$	+	e^-	(17)	H^-	+	H^+	$\rightarrow H_2^+$	+	e^-	
(9)	H	+	H^+	$\rightarrow H_2^+$	+	$h\nu$	(18)	H_2^+	+	e^-	$\rightarrow 2\ H$			
(10)	H_2^+	+	H	$\rightarrow H_2$	+	H^+	(19)	H_2^+	+	H^-	$\rightarrow H_2$	+	H	

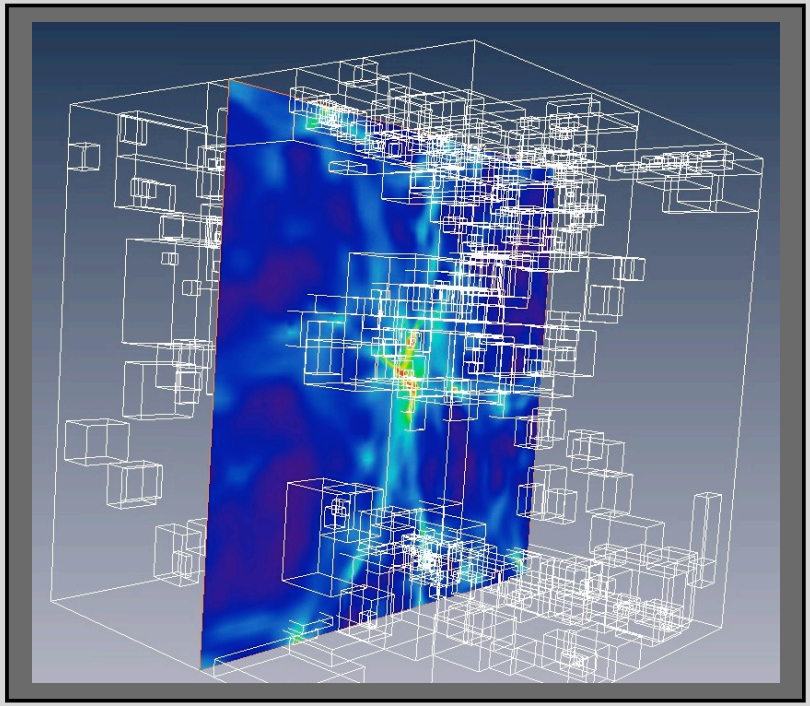
- Reaction 8 is much faster than reaction 7.
- I.e. (7) will continue as long as free electrons are available -> H2 formation timescale = recombination timescale
- However, $k_7 \propto T^{0.88}$ hence adiabatic contraction important. Requires sufficiently high virial temperatures and so introduces a temperature (mass) scale based on chemistry

$$T_{vir}^{Chem} \approx 10^3\,\mathrm{K}$$

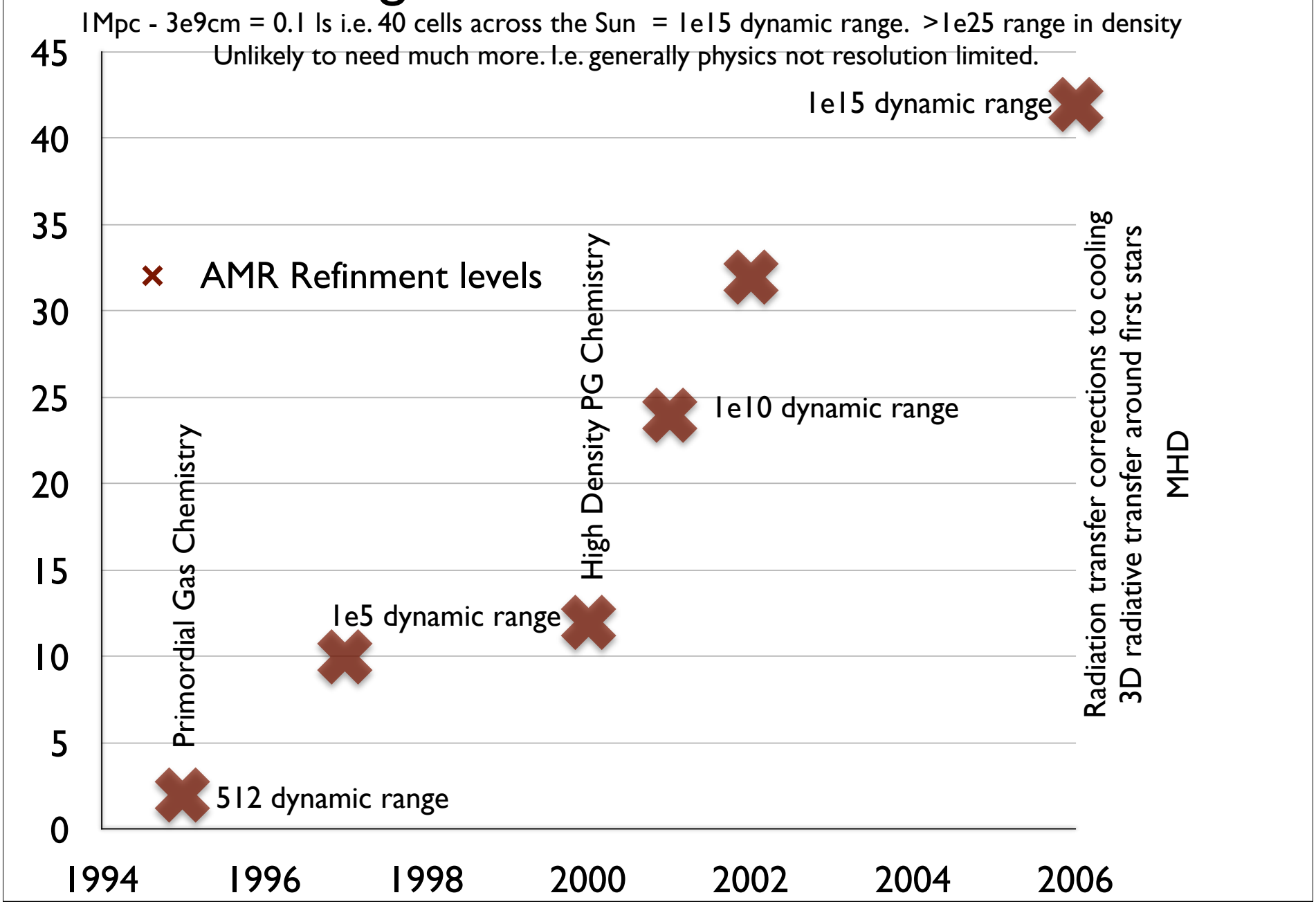
Cosmological Adaptive Mesh Refinement

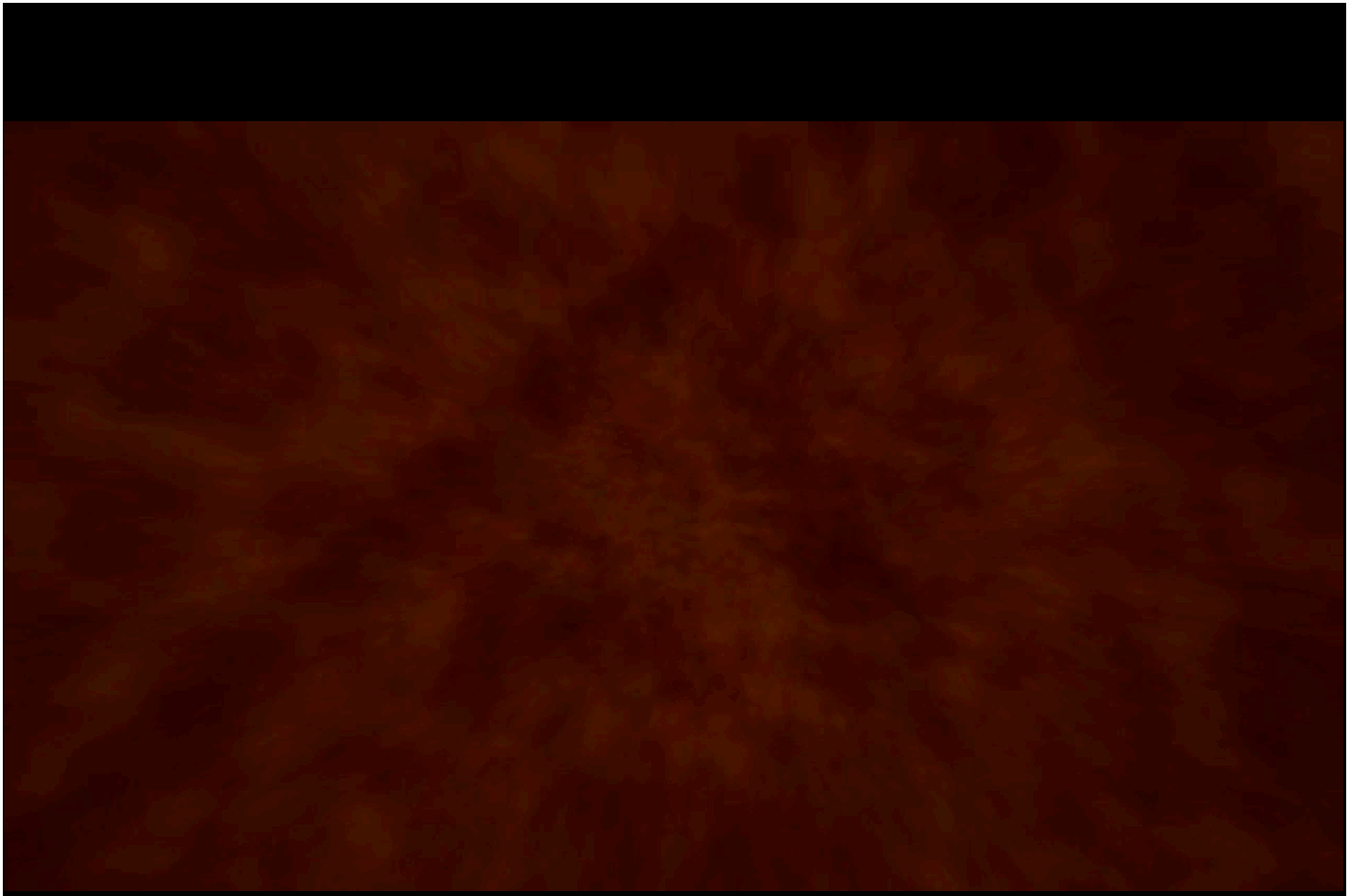
- **Enzo:** Bryan and Norman 1997-; Abel et al 97; Anninos et al 97; Bryan, Abel & Norman 2002; O'Shea et al; Abel, Wise & Bryan 2006
  - 87,000 lines of code in C++ and F77
  - Cosmological Radiation Hydrodynamics adapting in space and time
  - Dynamic range up to 1e15 using quadruple precision coordinates in space and time
  - Dynamically load balanced parallel with MPI
  - Gravity, DM, Gas, Chemistry, Radiation, star formation & feedback
  - Current new Developments at KIPAC: exact 3D radiation transport, very high density chemistry, HD & fine structure line cooling, relativistic hydro, passive MHD, ideal MHD, new visualization toolkit, new parallel data format





Technical Progress with *Enzo*





13.5 billion years ago ...

Simulation: Brian O'Shea, Greg Bryan, Mike Norman (UCSD)
Viz: Ralf Kähler (AEI, ZIB), Bob Patterson, Stuart Levy, Donna Cox (NCSA)

Summary

- The Universe is expanding and lately accelerating ...
- Observations of the Cosmic Microwave Background show the Initial Conditions of the Universe
- It is becoming feasible to realistically compute how structure originates in the Universe