Dark Universe II

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Dark Universe – Part II

- Is the universe "open" or "closed“ ?
- How does dark energy change our view of the history and future of the universe?

Old View: *Density of the Universe determines its destiny*

$\Omega_{total} = \Omega_M$

where

Ω_M = matter density (including regular and dark matter)

Ω_{tot} = density/critical density

If Ω_{tot} = 1,Universe is flat, expansion coasts to a halt as Universe is critically balanced.

If $\Omega_{tot} > 1$, Universe is closed, collapses on itself.

If $\Omega_{tot} < 1$, Universe is open, expands forever.

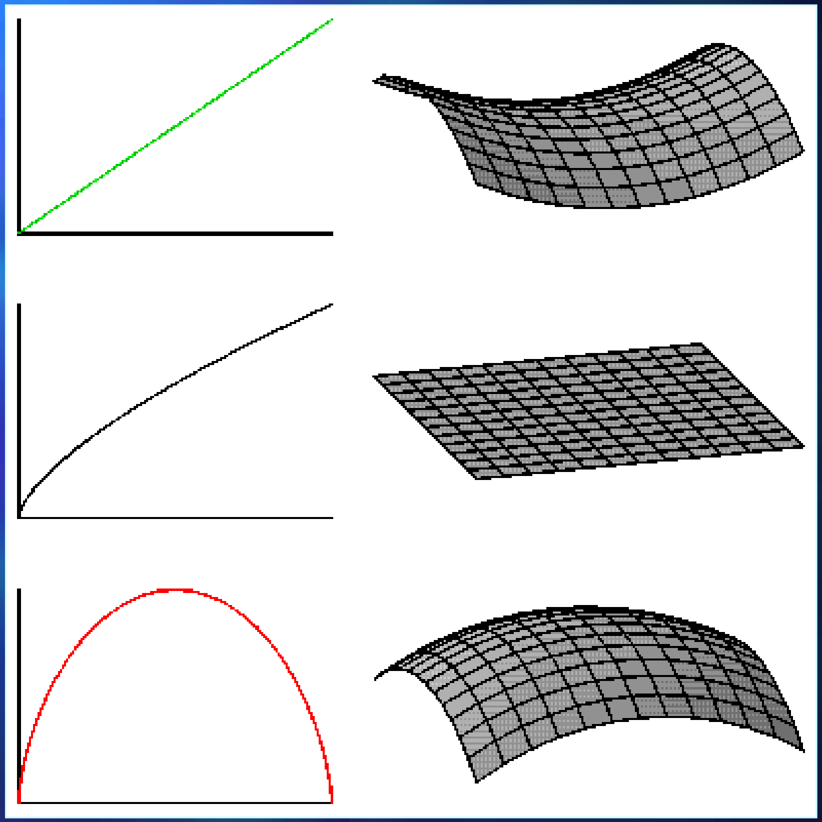
Cosmological curvature

Ω = density of the universe / critical densi

$\Omega < 1$ hyperbolic geometry

$\Omega = 1$ flat or Euclidean

$\Omega > 1$ spherical geometry



New View: Density of the Universe

After inflation ends,

$\Omega_{total} = \Omega_M + \Omega_\Lambda$ **= 1.0**

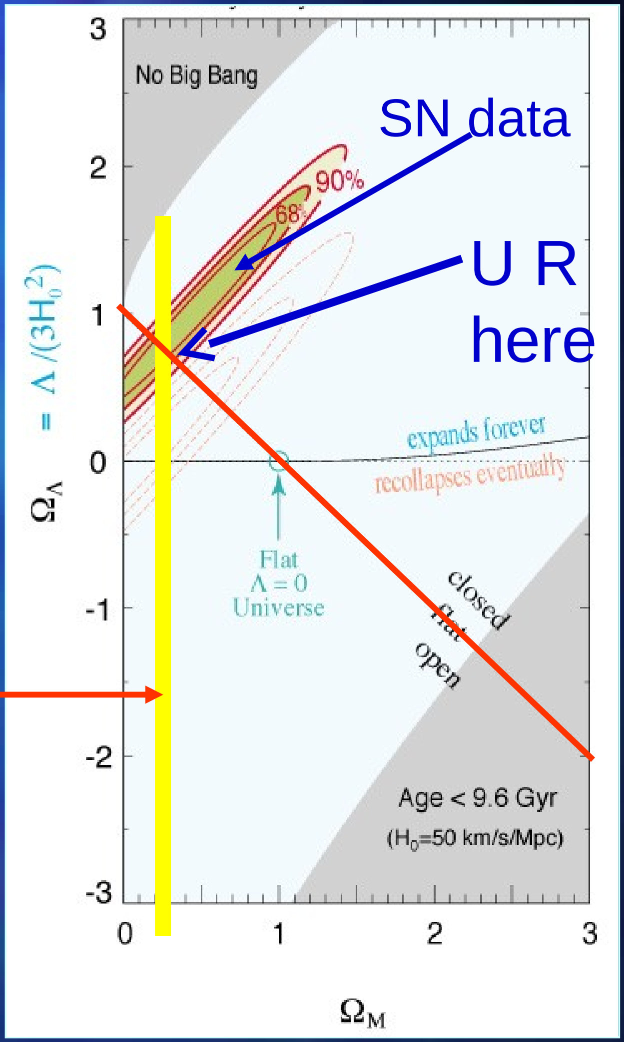
where

Ω_{total} = density/critical density

Ω_M = matter density (including regular and dark matter) = 0.27

So therefore…..

Ω_Λ = cosmological constant or dark energy density = 0.73



Perlmutter et al.

40 supernovae

Today’s Cosmology

- $\Omega_{TOT} = 1.0$ from CMB measurements (WMAP). We live in a flat Universe.
- $\Omega_M < 0.3$ from extensive observations at various wavelengths. Includes dark matter as well as normal matter and light.
- $\Omega_\Lambda \sim 0.7$ derived from Type Ia SN data combined with WMAP and other measurements.
- Hubble constant = 70 km/sec/Mpc from HST observations. Age of Universe = 13.7 billion years.
- Universe ***accelerates and is open, even though it is geometrically flat.***

"Geometry is not Destiny" *– R. Kolb*

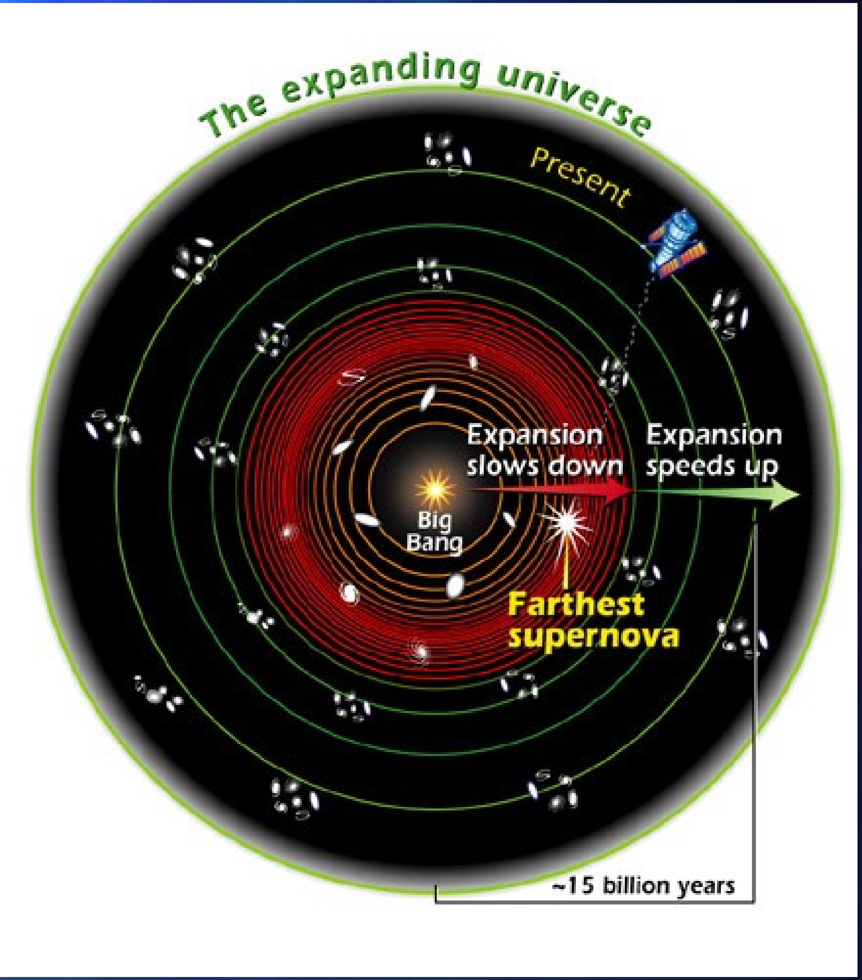
- In the (old) standard picture, a flat Universe would expand more slowly with time, eventually coasting to a stop
- However, the SN data (and other data e.g., from clusters of galaxies) show that the expansion of the universe is actually accelerating
- This supports the existence of mass-energy with a strong negative pressure, such as the cosmological constant (Λ) originated by Einstein

Dark Energy History

- Dark Energy must have been insignificant at early times, otherwise its gravitational influence would have made it almost impossible for ordinary matter to form stars, galaxies and large-scale structure
- In the early Universe, gravity dominated and various structures formed.
- However as the Universe expanded, and self-gravitating structures (such as clusters of galaxies, etc.) grew further apart, the space between them expanded, and dark energy began to dominate gravity

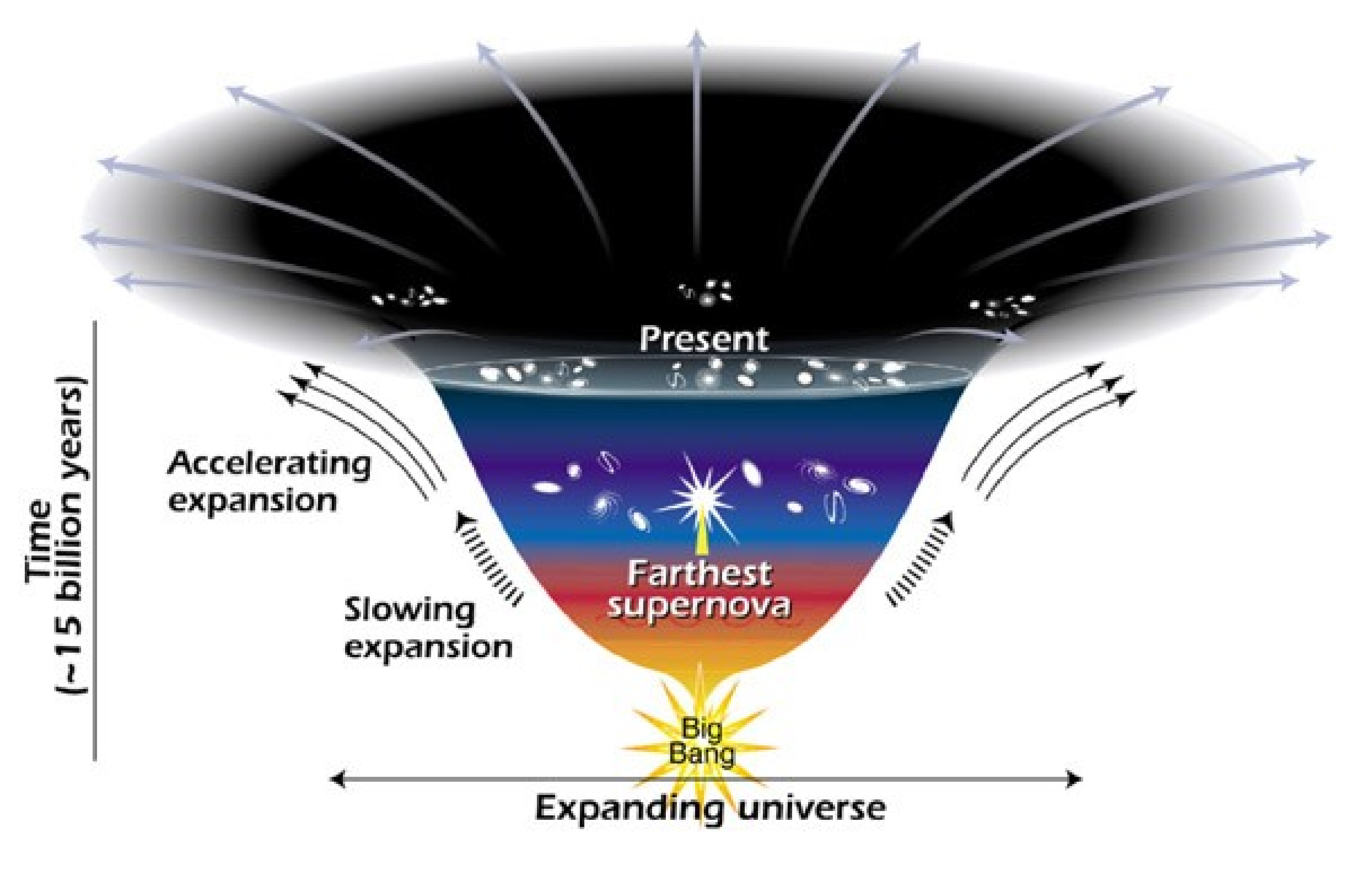
Expansion History of the Universe

- HST (Riess et al.) found most distant Type 1a
- It was so far away that it occurred during the period when the expansion was still slowing down due to gravity from the galaxies in a smaller Universe



Ann Feild (STScI)

Expansion history of the Universe



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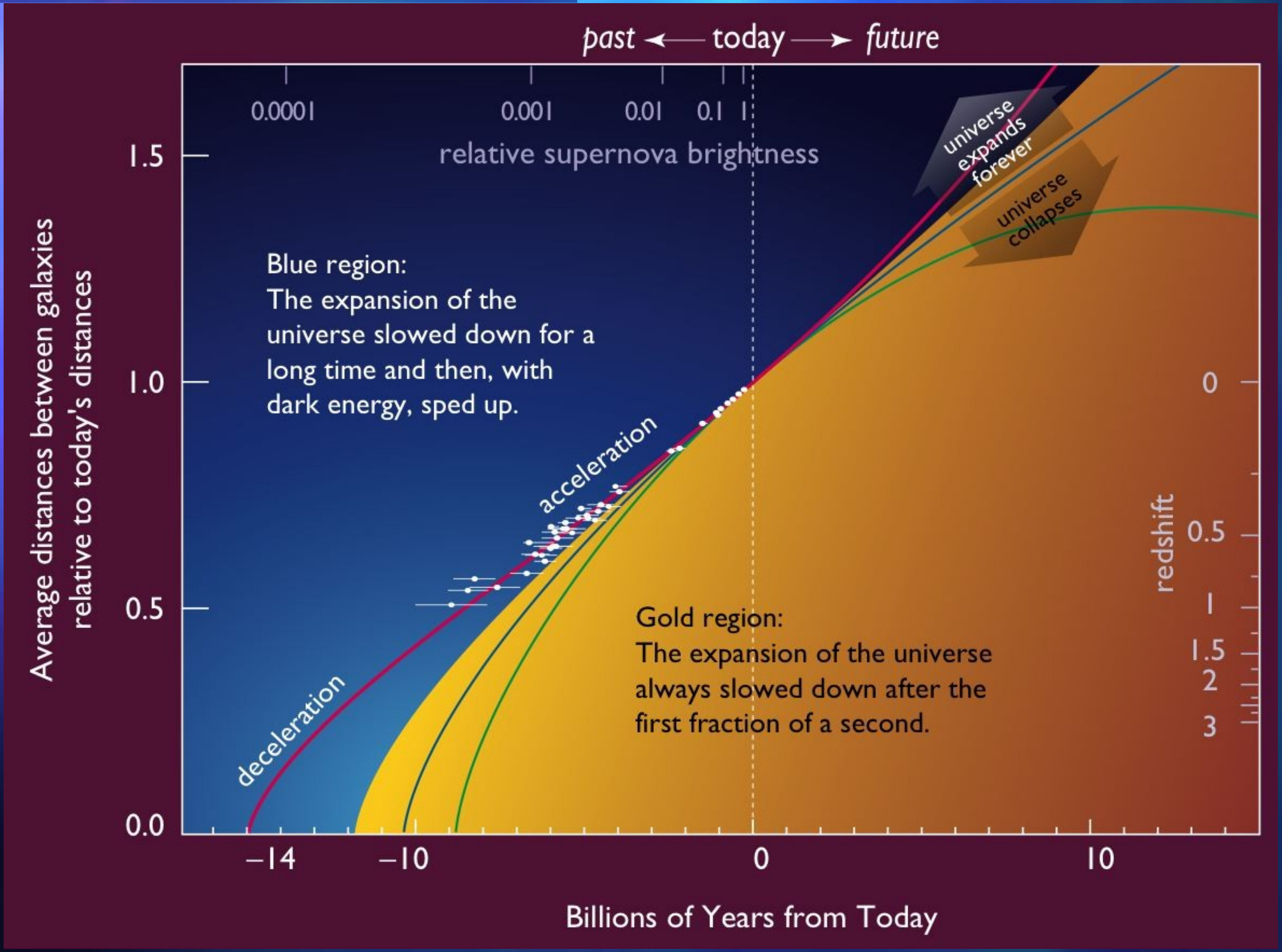
History and fate of the Universe



Data from Supernova Cosmology Project (LBL)

Graphic by Barnett, Linder, Perlmutter & Smoot

Resources

- Inflationary Universe by Alan Guth (Perseus)
- A Short History of the Universe by Joseph Silk (Scientific American Library)
- Before the Beginning by Martin Rees (Perseus)
- Inflation for Beginners (John Gribbin) http://www.biols.susx.ac.uk/Home/John_Gribbin/cosmo.htm
- Ned Wright's Cosmology Tutorial http://www.astro.ucla.edu/~wright/cosmolog.htm

Resources

- Physics Web quintessence http://physicsweb.org/article/world/13/11/8
- Big Bang Cosmology Primer http://cosmology.berkeley.edu/Education/IUP/Big_Bang_Primer.html
- Martin White's Cosmology Pages http://astron.berkeley.edu/~mwhite/darkmatter/bbn.html
- Lindsay Clark's Curvature of Space http://www.astro.princeton.edu/~clark/teachersguide.html
- Before the Beginning by Martin Rees (Perseus)

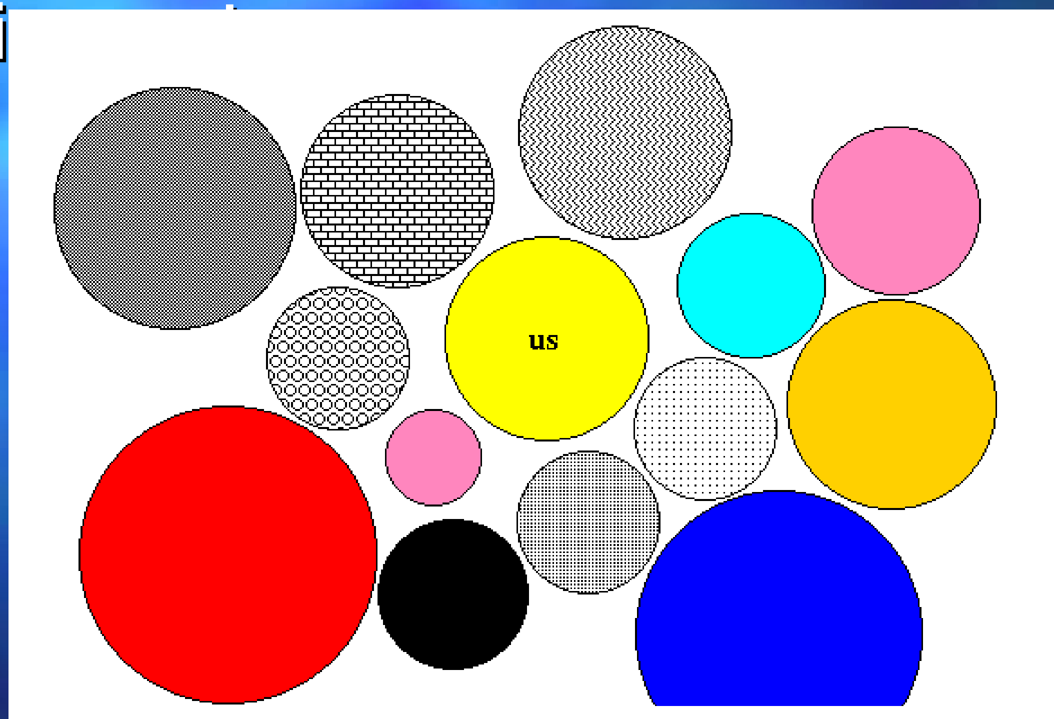
Backups follow

Multiverses

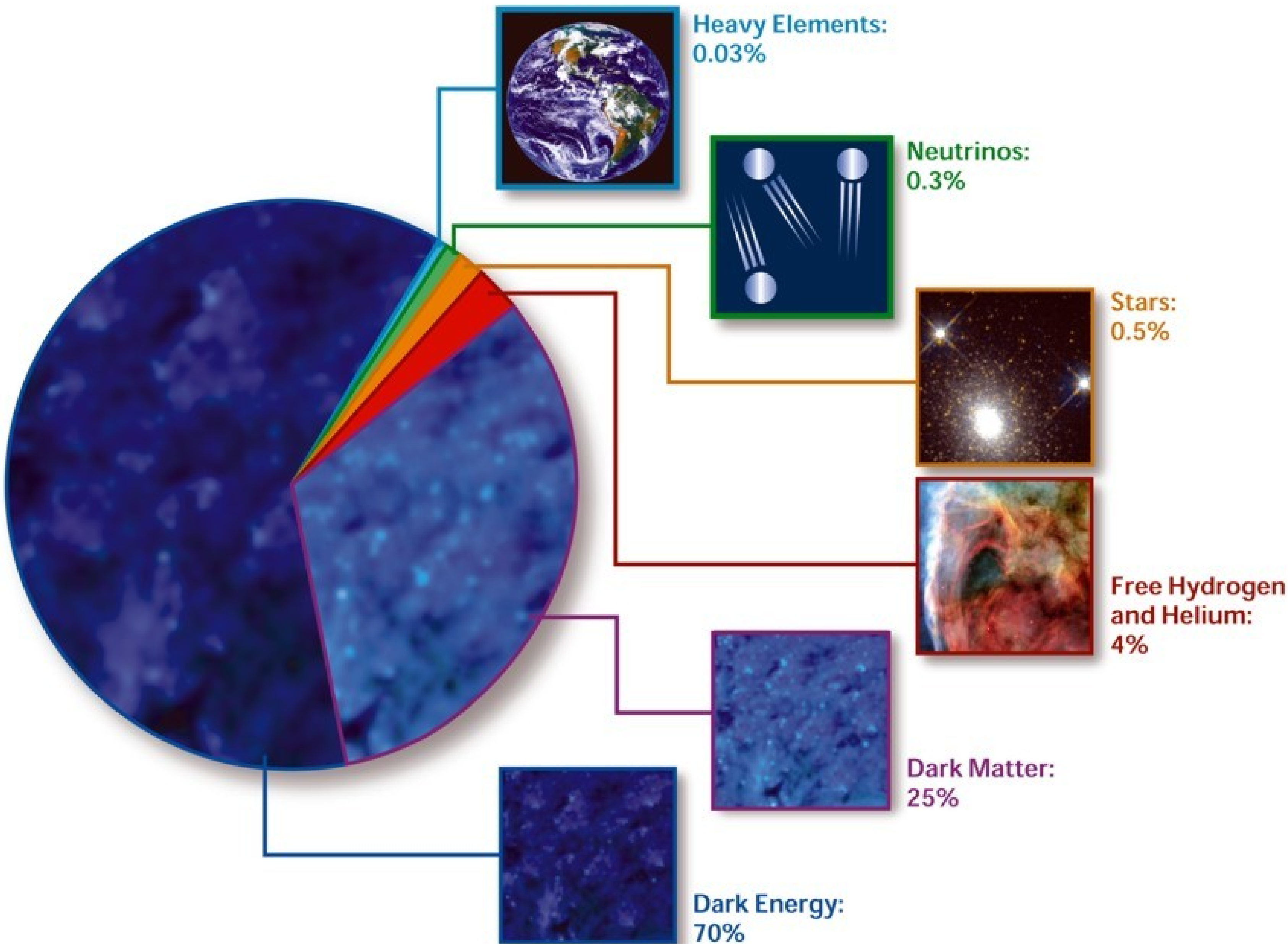
- Universe was originally defined to include everything
- However, the possibility exists that our "bubble universe" is only one of many such regions that could have formed, with the parameters arranged as in the concordance model so that we can be here having this discussion
- Other universes could have very different physical conditions and we will never see them – they may be on different "branes" or in other dimensions that we cannot measure

A Humbling Thought

- Not only do we not occupy a preferred place in our Universe, we may not occupy any preferred universe in the Multi



COMPOSITION OF THE COSMOS



Recall the Uncertainty Principle

- The uncertainty principle states that you cannot know both the position x and the momentum p of a particle more precisely than Planck's constant $h/2\pi$ → "h-bar"
- When dimensions are small, particles must therefore move in order to satisfy the uncertainty principle
- This motion creates a "zero point energy" > 0

Uncertainty Principle $\Delta x \, \Delta p \geq \hbar/2$

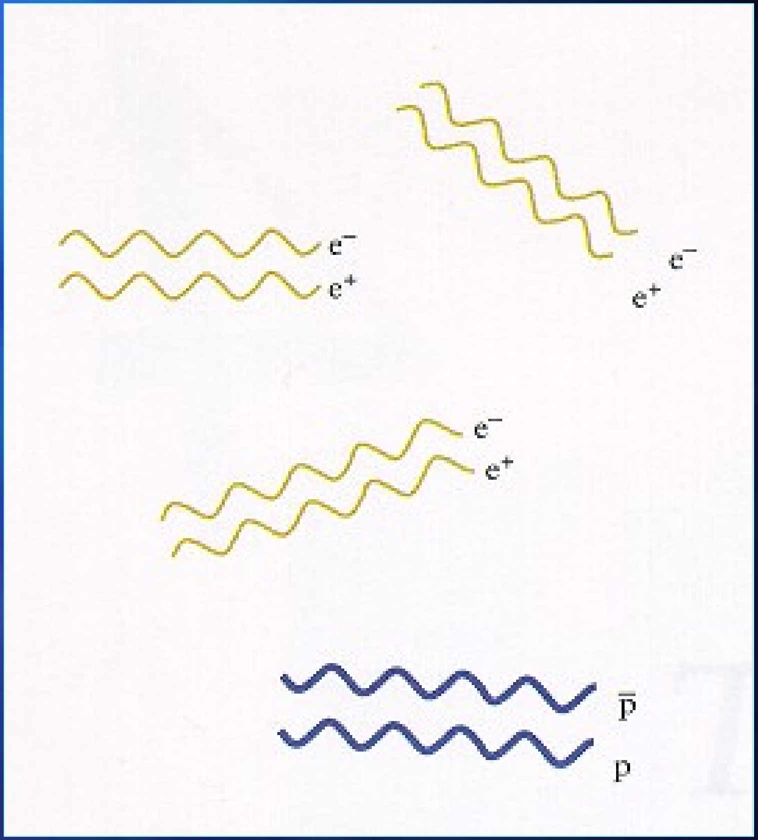
Uncertainty Principle

- Another version of the uncertainty principle relates the energy of a particle pair to lifetime
- This version explains the “virtual particles” that appear as quantum fluctuations
- They do not violate the uncertainty principle as long as their lifetimes are very short, and they are created in pairs which conserve charge, spin and other quantum properties

Uncertainty Principle $\Delta E \, \Delta t \geq \hbar/2$

Quantum fluctuations?

- Virtual particle pairs continually emerge and disappear into the quantum vacuum
- If you observe the particles (hit them with a photon), you give them enough energy to become real
- The particles can also get energy from any nearby force field (like a BH)



The shape of the Universe

- The shape of the Universe is determined by a struggle between the momentum of expansion and the pull of gravity.
- The rate of expansion is determined by the Hubble Constant, H_0
- The strength of gravity depends on the density and pressure of the matter in the Universe.
  - G is proportional to $\rho + 3P$
  - ρ is the density and P is the pressure
- For normal matter, P is negligible, so the fate of a universe filled with normal matter is governed by the density ρ

The fate of the Universe

- As the universe expands, the matter spreads out, with its density decreasing in inverse proportion to the volume. ($V = 4\pi r^3/3$ for a sphere)
- The strength of the curvature effect decreases less rapidly, as the inverse of the surface area. ($A = 4\pi r^2$ for a sphere)
- So, in the (pre-1998) standard picture of cosmology, geometry (curvature) ultimately gains control of the expansion of the universe.

Properties of Dark Energy

- Einstein's cosmological constant Λ has the property that $P = -\rho = -1$. Significant quantities of matter-energy with "negative pressure" will cause the expansion of the universe to accelerate.
- The quantity $P/\rho = w$ is known as the "equation of state" parameter. Best measurements right now (WMAP and others) find that $w = -1$, consistent with the value expected for the "concordance model" aka Λ–CDM (cosmological constant + cold dark matter)

Concordance Model

From Spergel et al. 2006

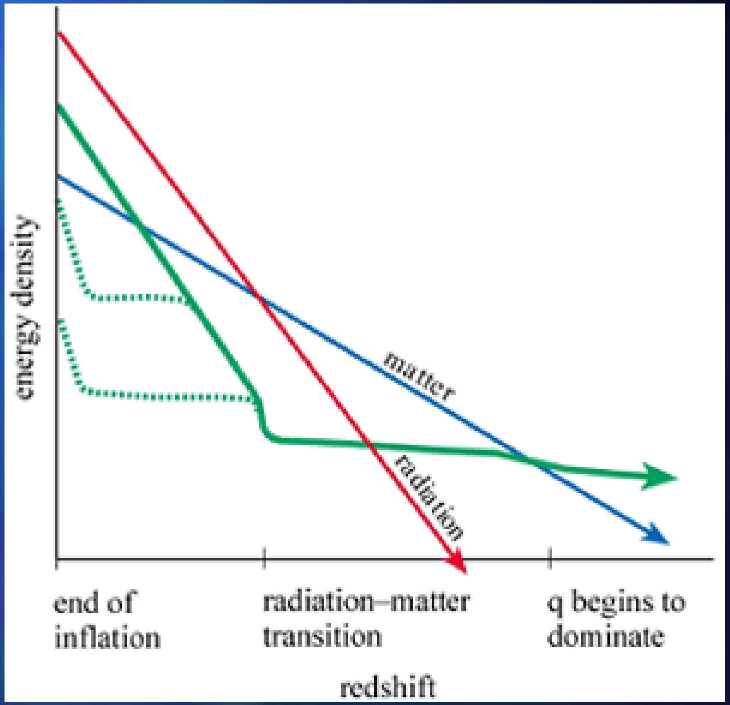
Parameter	Value		Description
	Basic parameters		
H_0	$70.9^{+2.4}_{-3.2}$ km s^{-1} Mpc^{-1}		Hubble parameter
Ω_b	$0.0444^{+0.0042}_{-0.0035}$		Baryon density
Ω_m	$0.266^{+0.025}_{-0.040}$		Total matter density
	Derived parameters		
ρ_0	$10.5^{+2.6}_{-2.9}$	kg/m^3	Critical density
Ω_Λ	$0.772^{+0.036}_{-0.048}$		Dark energy density
t_0	$13.73^{+0.13}_{-0.17} \times 10^9$	years	Age of the universe

Vacuum Energy = Dark Energy?

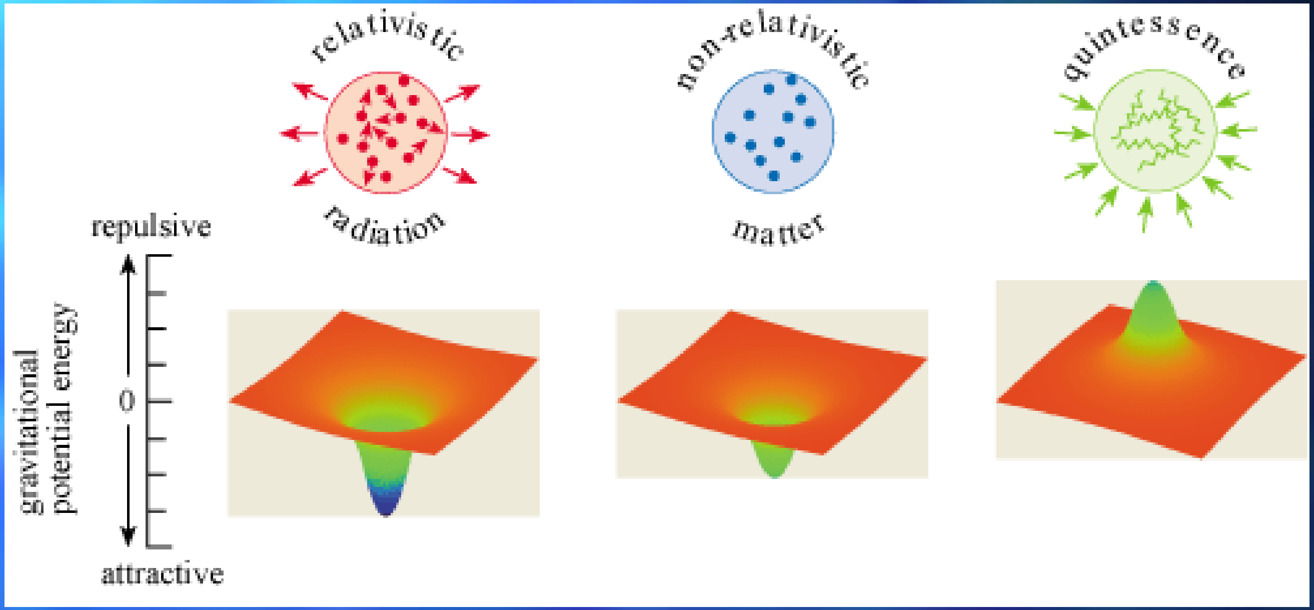
- The cosmological constant Λ may be related to the “zero-point energy” of the Universe which comes from the quantum fluctuations of the vacuum.
- However, the vacuum energy density is 10^{120} too high to allow structure formation to occur
- Something must be canceling almost all of the vacuum energy in order for us to be here
- And that something must have arranged for the ~73% of critical density to be left over at our current time, 13.7 billion years later

Quintessence

- Quintessence is another theory for dark energy that involves a dynamic, time-evolving and spatially dependent form of energy.
- It makes slightly different predictions for the acceleration
- It's name refers to a "fifth essence" or force



Gravity and pressure



Relativistic

$G = \rho + 3P$

$P = \rho/3$

$G = 4\rho > 0$

Non-relativistic

$G = \rho + 3P$

$P = 0$

$G = \rho > 0$

Λ

$G = \rho + 3P$

$P = -\rho < 0$

$G = -2\rho < 0$

Quintessence

$G = \rho + 3P$

$P = -2\rho/3 < 0$

$G = -\rho < 0$