Matter and Energy in the Universe: What We Know and How We Know It

(A Tour of Modern Cosmology)

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The Universe is Expanding

- Hubble: galaxies have a “redshift” proportional to their distance from us
  - doppler shift in radiation emitted by the galaxy
  \[
  \frac{\lambda'}{\lambda} = \sqrt{\frac{1+v/c}{1-v/c}} \approx 1 + \frac{v}{c}
  \]
- Key fact: as the universe expands, it also cools
  - Wavelengths expand along with everything else: longer wavelength (redder) = lower energy
  - “co-moving” coordinates expand along with universe
  - radiation: \( T \sim 1/\text{size} \)
Evolution of Matter and Radiation Densities with Expansion

- The cosmological scale factor $a(t)$ gives the size as a function of time
- Energy densities:
  - Matter $\rho \propto a^{-3}$
  - Radiation $\rho \propto a^{-4}$
- Vacuum energy is constant!
- Familiar Hubble “constant”
  $$H(t) = \frac{\dot{a}}{a}$$
- Einstein's General Relativity gives $a(t)$ given rho:
  $$H^2 = \frac{8\pi G}{3} \rho$$
  - radiation: $a(t) \propto t^{1/2}$
  - matter: $a(t) \propto t^{2/3}$
  - vacuum: $a(t) \propto e^{Ht}$
Density of “Normal” Matter in the Universe

- Most of the mass in atoms is in the nucleus
  - protons and neutrons (baryons)
  - electrons are very light
- What is the baryon density in the universe?
  - “Big-bang nucleosynthesis”
- Nuclear reactions common at temperatures of 10 billion deg.
  - Early universe, seconds old
- We have two clocks!
  - Hubble expansion
  - Neutron lifetime
- Use these to constrain density
Big Bang Nucleosynthesis

- Hubble expansion clock
  - Radiation dominated universe: $H \sim T^2$
  - Photon number density $\sim T^3$
- Neutron lifetime clock
  - Mean life: 15 minutes
- One input parameter: how many baryons per photon?
  - Early on this is all protons and neutrons
- Calculate relative abundances of light isotopes:
  - H, He4, D, He3, Li7
- Now go measure!
Cosmic Deuterium Abundance

- Deuterium depends on baryon density
- It is not made in stars
- Deuterium atom is slightly different: energy levels slightly shifted
  - deuteron is twice as heavy as proton
  - energy shift one part in 3600
- Observe both H and D and calculate ratio
  - high redshift objects should give a good estimate of the primordial ratio

Fig. 6a
Cosmic Densities

- **Measure densities relative to the “critical” density**
  - $h (=0.7)$ is Hubble constant in units of 100 km / s / Mpc
  - Proton mass is 0.938 GeV
    \[
    \rho_c = \frac{3 H^2}{8 \pi G} = 1.05 \times 10^{-5} h^2 \text{ GeV cm}^{-3}
    \]

- **Density parameters $\Omega$**
  - Often we use $\Omega h^2$
  - $\Omega = 1$ is a “flat” universe
  - Baryons have $\Omega=0.044$
  - This is far less than the total: stay tuned!

- **Background radiation left from the hot early universe**
  - Photons: Cosmic Microwave Background $\Omega=0.0001$
    - 400 photons / cc
    - “easy” to measure: temperature of the microwave radiation
  - Neutrinos
    - Similar number density to photons
    - Mass (heaviest) somewhere in the range milli-eV to $\sim 2$ eV
What Are Galaxies Made Of?

- We now know the baryon density: could galaxies be made of baryons?
- Overwhelming evidence indicates “no”
- Oldest evidence from Zwicky (1930s!)
  - M / L in galaxy clusters is 100x or more than solar
  - Light: “easy”
  - Mass from size, velocity and virial theorem

\[ \frac{GM}{R} \sim v^2 \]
Baryon *Fraction* in Clusters of Galaxies

- **Galaxy clusters are rare**
  - $1e15$ solar masses
  - $1000$s of galaxies
  - most baryons are in hot gas
- **Gas shines in X-rays**
  - how bright? proportional to the total mass in gas
  - how hot? virial theorem again (replace “v” with “T”) and get the total mass
- These disagree: baryons are about $1/5$ of the total mass in clusters
- Next: more evidence for “$1/5$”
Spiral Galaxy Rotation Curves

- Baryons in spiral galaxies mostly in stars; not much gas available
- Stellar density falls exponentially
- Rotation velocities are constant!
  - $\rho \sim 1/r^2$ implied
- Doppler shifts used to get velocities
  - Atomic H (21 cm, Hα)
  - Molecules (CO)
- Milky Way rotates at 220 km / s
- Andromeda is a bit faster at 240 km / s
Large Scale Structure

- How do galaxies cluster on the largest scales?
  - measure 100,000+ redshifts
  - there is a characteristic scale for the clustering
    \[ R \sim \Omega_{CDM} h \]
  - \( \Omega = 0.3 \) fits well
  - galaxies are made of “cold” matter: neutrinos are too light and must be subdominant
    - limit is \( \sim 1/3 \) as much as baryons
    - this limits the neutrino mass better than is possible in the lab: \( m < 0.2 \text{ eV} \)
Cosmic Microwave Background

- CMB ties together all these lines of evidence
- Pattern of fluctuations of microKelvin size encodes:
  - baryon density
  - matter density
  - total density
- Acoustic oscillations
  - slightly overdense region wants to collapse under its gravity
  - gas pressure opposes collapse
  - this is an oscillator
Cosmic Microwave Background II

- The CMB is “emitted” when the universe becomes transparent
  - Hydrogen must recombine: this happens as T falls
  - At emission, CMB has a wavelength of 5 microns (mid-infrared)
- We can calculate the wavelength of oscillations related to age of universe at the time of CMB emission
- From wavelength, we can get the geometry of the universe
Cosmic Microwave Background III

- **Space can be curved**
  - positive: objects appear larger than they are
    - parallel lines converge
  - negative: objects appear smaller than they are
    - parallel lines diverge
- **We know the redshift of the CMB accurately, and we know how to calculate distance**
- **CMB tells us that space is flat, and \( \Omega = 1 \)**
- **We're still missing most of the stuff!!!**
What Are We Missing???

- **Baryons:** 4%
  - Known to exist
- **Neutrinos:** < 1.5%
  - Known to exist
- **Photons:** 0.01%
  - Known to exist
- **Dark Matter:** 23%
  - Known to be unknown
- **“Dark Energy”:** 73%
  - This doesn't cluster much
What If We Have Gravity Screwed Up? Could We Not Need Dark Matter?

- MOND (MOdified Newtonian Dynamics)
- Gravitational acceleration has a minimum $\sim cH$
  - spiral galaxies fit perfectly, clusters have problems
- If baryons and dark matter can be observed to be segregated, there is no hope for MOND
What Could the Dark Matter Be? Good Candidates from Particle Physics

- Supersymmetry?
  - Fixes a serious problem in the Standard Model
  - Why is the weak force so strong?
- Naturally get particles in the 10 GeV – TeV range
  - lightest new one is stable!
- Repeat the BBN exercise (with new interactions) to get the dark matter density
- Compelling conclusion for massive relic particles:
  \[
  \Omega_x \sim \frac{1}{\sigma} \sim \left( \frac{M}{\text{TeV}} \right)^2
  \]

- Axions?
  - Fixes a serious problem in the Standard Model
  - Why no electric dipole moments?
- Very light particles
  - micro-milli eV
  - Made very cold, never in thermal equilibrium
- As dark matter, can be detected by converting axion to microwave photon in a strong magnetic field
  - and having the best radio ever built!
What Could the Dark Matter Be?
“Candidates” Not Ruled Out

- Dark Matter is “cold” and nearly non-interacting
  - not difficult to arrange for particles of any mass
- Fluid on galaxy scales
  - discreteness effects appear with DM “particles” of 10,000 solar masses (or so)
  - this is 1e70 eV
- Classical (not quantum) on galaxy scales
  - fermions > 25 eV or so
  - Pauli exclusion principle!

- bosons > 1e-22 eV
- no that's not a typo
- QM wavelength < kpc or so to confine particle to galaxy
- 90+ orders of magnitude uncertainty
- Most of this isn't terribly likely, but until we have data...
Weakly Interacting Massive Particles: (WIMPs)

- **100 GeV range: many search strategies:**
  - accelerators: make dark matter in the lab @ LHC!
  - underground: look for dark matter particles making the Milky Way
    - VERY weakly interacting, moving 200 km / s (go underground to filter out cosmic rays)
  - in the sky: look for high energy particles coming from (rare) dark matter annihilations
    - gamma rays, antiprotons, positrons...
Dark Energy: Even More Mysterious Than Dark Matter

- Dark Matter, while exotic, could be particles
  - we know about particles
- Dark Energy doesn't behave like any known form of matter
  - it's pressure is negative!
- We know from the CMB that the universe is actually dominated by dark energy at the present day
- How can we learn more?
Back To The Hubble Expansion

- Redshift as a function of distance is not linear
- Small deviations from linearity encode the expansion history
- In a matter or radiation dominated universe, expansion decelerates
- Expansion is now accelerating
  - Negative pressure required
  - Same conditions as cosmic inflation in the exceedingly early universe
The Universe Is Accelerating

- Dark Energy became dominant at $z = 0.4$
  - deceleration stopped, acceleration began
- The material causing this has $p = -\rho$ (or pretty close)
- Quantum mechanics predicts just such a material: the energy of the vacuum
  - the prediction is 120!!! orders of magnitude too large
- We can hope that future measurements clear this up