Really, what universe do we live in?

- White dwarfs
- Supernova type Ia
- Accelerating universe
- Cosmic shear
- Lyman α forest
White dwarf

- Core of solar mass star
- No energy from fusion or gravitational contraction
- Most oxygen and carbon nuclei with degenerate gas of electrons
- Supported by quantum mechanical motions of electrons
Mass versus radius relation

- For objects made of normal matter, radius tends to increase with mass
Mass/radius relation for degenerate star

- Star mass = $M$, radius = $R$
- Gravitational potential energy = $-\frac{3GM^2}{5R}$
- Heisenberg uncertainty: $\Delta x \Delta p \geq \hbar$
- Electron density $n = \frac{3N}{4\pi R^3} \approx \frac{M}{m_p R^3}$
  
  $\Delta x \approx n^{-1/3}$  $\Delta p \approx \frac{\hbar}{\Delta x} \approx \hbar n^{1/3}$

- Kinetic energy $\varepsilon = \frac{p^2}{2m_e}$  $K = Ne\varepsilon = \frac{M}{m_p} \varepsilon \approx \frac{\hbar^2 M^{5/3}}{m_e m_p^{5/3} R^2}$
Mass/radius relation for degenerate star

- Total energy $E = K + U \approx \frac{\hbar^2 M^{5/3}}{m_e m_p^{5/3} R^2} - \frac{GM^2}{R}$

- Find $R$ by minimizing $E$

$$\frac{dE}{dR} \approx - \frac{\hbar^2 M^{5/3}}{m_e m_p^{5/3} R^3} + \frac{GM^2}{R^2} = 0$$

$$R \approx \frac{\hbar^2 M^{-1/3}}{G m_e m_p^{5/3}}$$

- Radius decreases as mass increases
Maximum white dwarf mass

- As mass increases, electron speed $\rightarrow c$, kinetic energy $\rightarrow K=pc$
- Electron degeneracy cannot support a white dwarf heavier than 1.4 solar masses, the “Chandrasekhar limit”.

$$M = K \left( \frac{\hbar^3 c^3}{G^3 m_p^4} \right)^{1/2}$$
Type Ia supernovae occur when the mass of a white dwarf exceeds the Chandrasakar limit (1.4 Msun). May occur via accretion from a companion or collision with another star.

Because starting condition is the same, reasonable that all Ia have same luminosity.

Maximum luminosity does vary, but is well correlated with time scale of light curve.

Can correct using measured light curves and recover standard luminosity. Note need to first correct for cosmological time dilation = 1+z.

Also need to correct for extinction in host and MW galaxy.
SN Ia as distance indicators

- Uncorrected maximum luminosity of SNIa has scatter of ~ 0.42 mag.
- Correction improves this to 0.15 mag.
- Luminosity estimate is good to 15%.
- Distance estimates good to 8% if extinction is measured accurately.

- Distance modulus $\mu = 5 \log(d/\text{pc}) - 5$
Searching for supernovae

• Need to repeatedly obtain images of target galaxies or fields.
• Search for new sources appearing.
• Cadence of monitoring is set by time scale of SNIa light curves, ~ 10 days.
• Then need to:
  – follow each SN with ~daily photometry, preferably in several bands
  – Obtain spectrum to confirm Ia identification and measure redshift

• Originally, SN searches done by the Berkeley group had a very hard time in arranging telescope time for follow-up because they would need to bump observers off big telescopes (target of opportunity observations = TOOs).
• Important threshold was when search observations could discover a new SN every few nights, so there was always at least one SN to observe on any given night.
• Searches have also been done with the Hubble Space Telescope that found SN at $z \sim 1.7$. 
Supernova cosmology

- Plot of distance vs redshift for SNIa is a Hubble diagram, extending to high $z$.
- Diagrams probe expansion history of the universe.
• Plot of mag – mag in empty universe. Empty universe means constant expansion (dotted).
• Points above dotted line mean that expansion has accelerated, e.g. $\Omega_\Lambda > 0$.
• Thick dashed curve $\Omega_m = 0.27, \Omega_\Lambda = 0.73$. Lower solid curve $\Omega_m = 1, \Omega_\Lambda = 0$.
• Two upper curves, evolution of SN or grey dust with $z$.
• High $z$ points show turn over, important for confirming cosmological nature.
Supernova cosmology

- Solid contours from data on previous slide. Dotted contours from 1998 data. Expansion has accelerated, e.g. $\Omega_\Lambda > 0$.
- If we require $\Omega_{\text{tot}} = 1$ (from CMB), then best fit is $\Omega_m = 0.27, \Omega_\Lambda = 0.73$.
- $\Omega_\Lambda$ may be true cosmological constant or could be a quantum field with equation of state $P = \omega \rho c^2$, $\omega = -1$ is same as CC.
- Primary goal of future dark energy surveys is to measure $\omega$. 
• Shapes of galaxies are distorted as light moves through gravitational potentials to us.
• Similar to weak lensing by clusters, one can use the distortions (averaged over many galaxies) to directly probe the total matter distribution.
• Hard to do, really want redshifts for all galaxies.
Gas within quasars or in gas clouds or galaxies between us the and quasar can produce absorption lines.
Diffuse intergalactic medium

• If diffuse IGM is neutral, it should absorb light shortward of Lyα, $\lambda < 1216$ Å.
• Expect jump in continuum radiation from quasars between the red and blue sides of their Lyα line, $S(\text{blue})/S(\text{red}) = e^{-\tau}$ where $\tau \sim 6 \times 10^{10} (n_{\text{HI}}/\text{cm}^{-3})$ at $z = 0$.
• If $\Omega_{\text{HI}} \geq 10^{-6}$ then $\tau > 1$ and universe is opaque.
• For $z < 3$, find $\tau < 0.05$; for $z \sim 5$, find $\tau < 0.1$.
• From these limits, find $n_{\text{HI}}(\text{comoving}) < 3 \times 10^{-13}$ cm$^{-3}$ or $\Omega_{\text{HI}} < 3 \times 10^{-8}$.
• Compare with baryon density from BBN, $\Omega_b = 0.04$.
• Hydrogen in a diffuse component of the intergalactic medium must be essentially fully ionized.

• Searching for this gas in the nearby universe ($z \sim 0$), figuring out when the ionization occurred ("reionization"), and explaining what caused reionization are major topics of current interest.
Lyman $\alpha$ forest

• We do see Ly$\alpha$ absorption features in spectra of distant quasars.
• Number density of Ly$\alpha$ lines for $z > 2$ follows $dN/dz \sim k(1+z)^\gamma$ with $\gamma \sim 2.5$ and $k \sim 4$.
  – Increases strongly with $z$.
• Can determine HI column density from line strength.
• Widths of lines often $\sim 10,000$ km/s, origin?
  – Massive cluster, outflow, or thermal ($\sim 10^4$ K)
• Proximity effect: quasars ionize nearby gas, suppressing Ly$\alpha$ forest.
  – Ionization rate $= \Gamma \cdot n_{\text{HI}} = \text{recombination rate} = \alpha n_p n_e$, where $\alpha = \alpha(T)$
  – In highly ionized medium $n_{\text{HI}} \ll n_p = n_e$
  – Thus $n_{\text{HI}} = \alpha n_p^2 / \Gamma$
Lyman α forest

• How did Lyα forest arise?
• Galaxies and clusters formed when baryons fell into dark matter gravitational potential wells after recombination.
• Gas clouds in the Lyα forest formed the same way. However, smaller density perturbations produced smaller baryon concentrations.
• These smaller perturbations are better described by linear theory.
• Lyα forest can be probed to higher $z$ than galaxy and cluster distributions, up to $z \sim 4$.
• Can do same sorts of statistics (power spectrum, correlation function) as with galaxies but have disadvantage that probes are along a limit number of lines of sight.
Lyman α forest

- Simulations follow evolution of dark matter. Must convert dark matter perturbations into gas density perturbations and then into the observable which is optical depth of Lyα absorption.
- As gas falls into potential well, it gains energy and heats up. Temperature depends on density.
- Use \( n_{\text{HI}} = \alpha n_p^2 / \Gamma \), temperature dependence of \( \alpha \).
- Find \( \tau = A(n_p / \langle n_p \rangle)^\beta \) with \( \beta \sim 1.6 \) and \( A \) depends on \( z \), intensity of ionizing radiation, average temperature of universe.
- This provides relation to convert simulation results into simulated spectra.
- Figure shows two spectra, one simulated, one observed.
For next class

- Read 8.6-8.7.
- HW #8 due on November 5.
- Project presentations on November 12 and 14. Should be full presentations with all results.