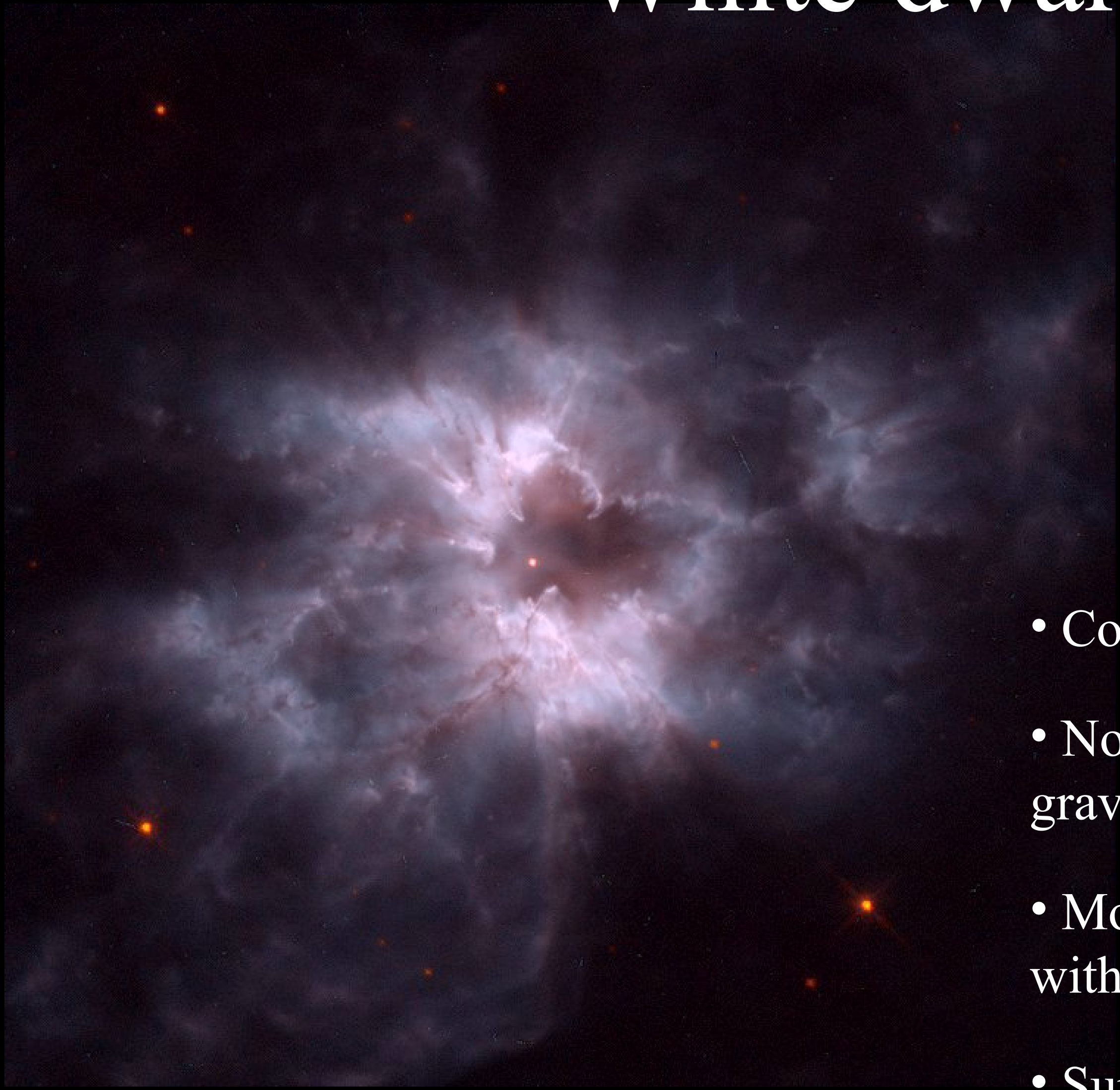
Really, what universe do we live in?

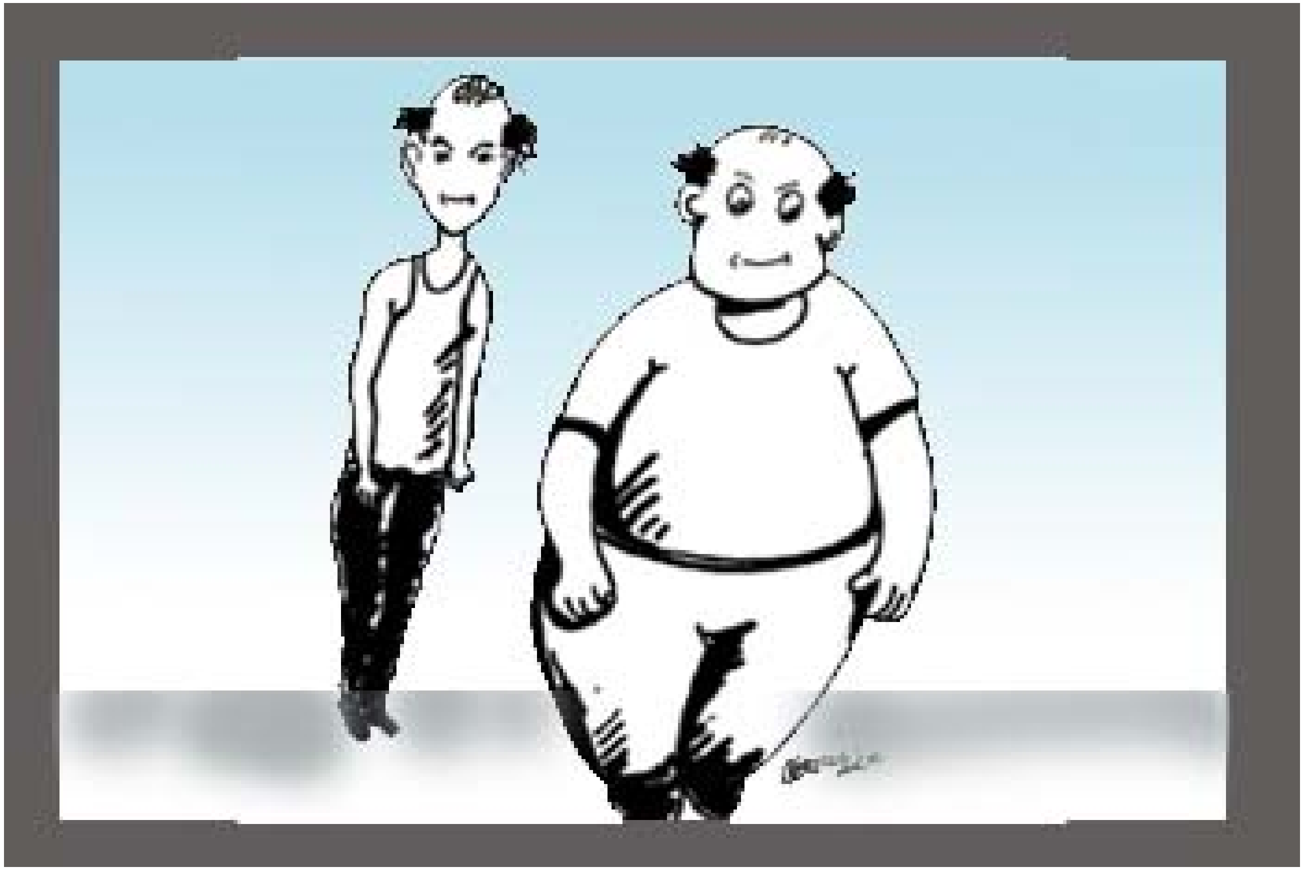
- White dwarfs
- Supernova type Ia
- Accelerating universe
- Cosmic shear
- Lyman α forest

White dwarf



- Core of solar mass star
- No energy from fusion or gravitational contraction
- Most oxygen and carbon nulcei 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: $\Delta x \Delta p \geqslant \hbar$
- Electron density $n = \frac{3\mathrm{N}}{4\pi \mathrm{R}^3} \approx \frac{M}{m_p R^3}$

$$\Delta x \approx n^{-1/3} \qquad \Delta p \approx \frac{\hbar}{\Delta x} \approx \hbar n^{1/3}$$

- Kinetic energy $\varepsilon = \frac{p^2}{2\mathrm{m}_e}$ $\qquad K = N\varepsilon = \frac{M}{m_p}\varepsilon \approx \frac{\hbar^2 M^{5/3}}{m_e m_p^{5/3} R^2}$

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*

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

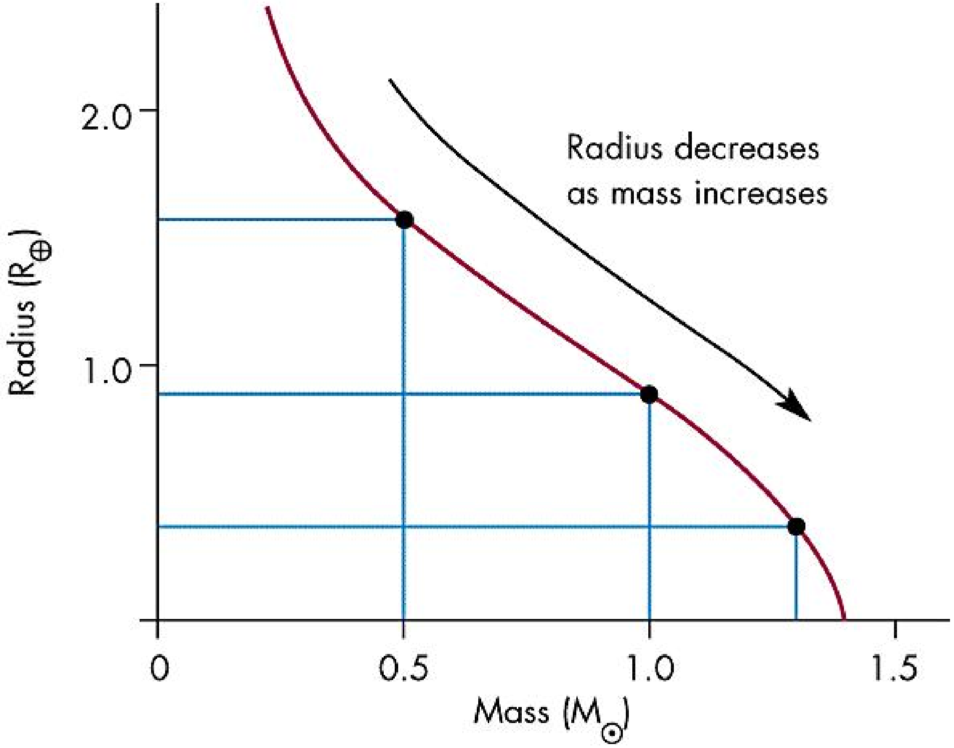
$$R \approx \frac{\hbar^2 M^{-1/3}}{G m_e m_p^{5/3}}$$

- Radius decreases as mass increases

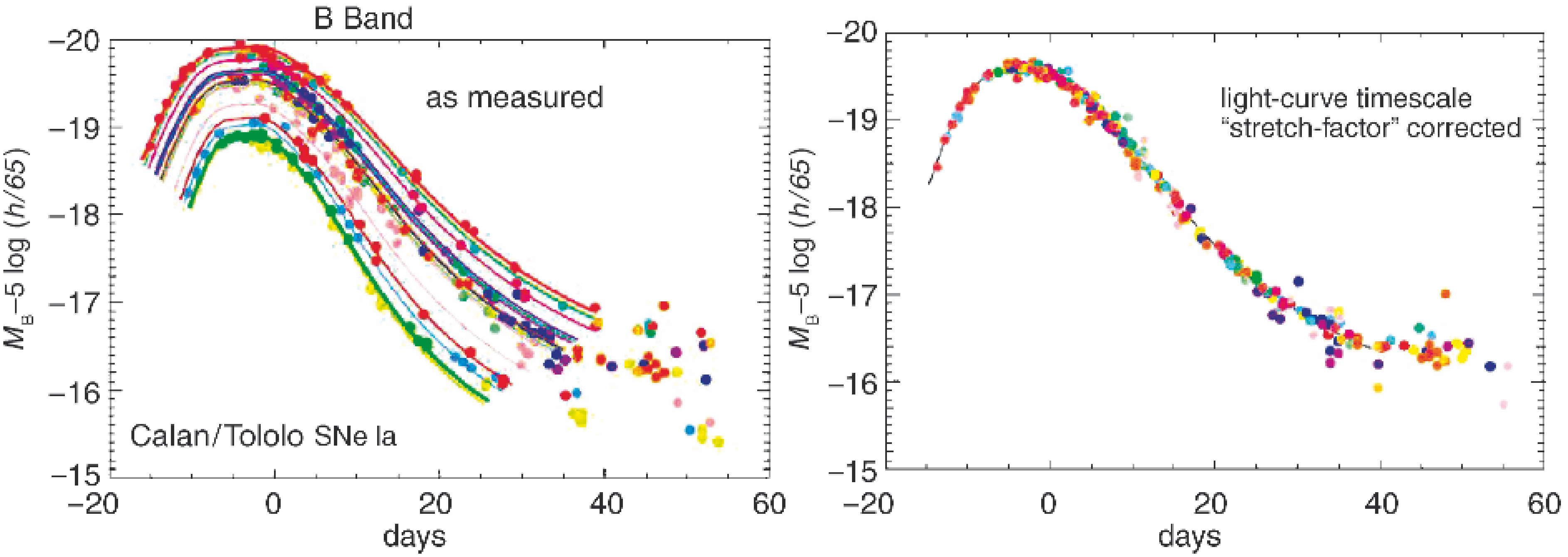
Maximum white dwarf mass

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

$$M = K\left(\frac{\hbar^3 c^3}{G^3 m_p^4}\right)^{1/2}$$



Supernovae type Ia

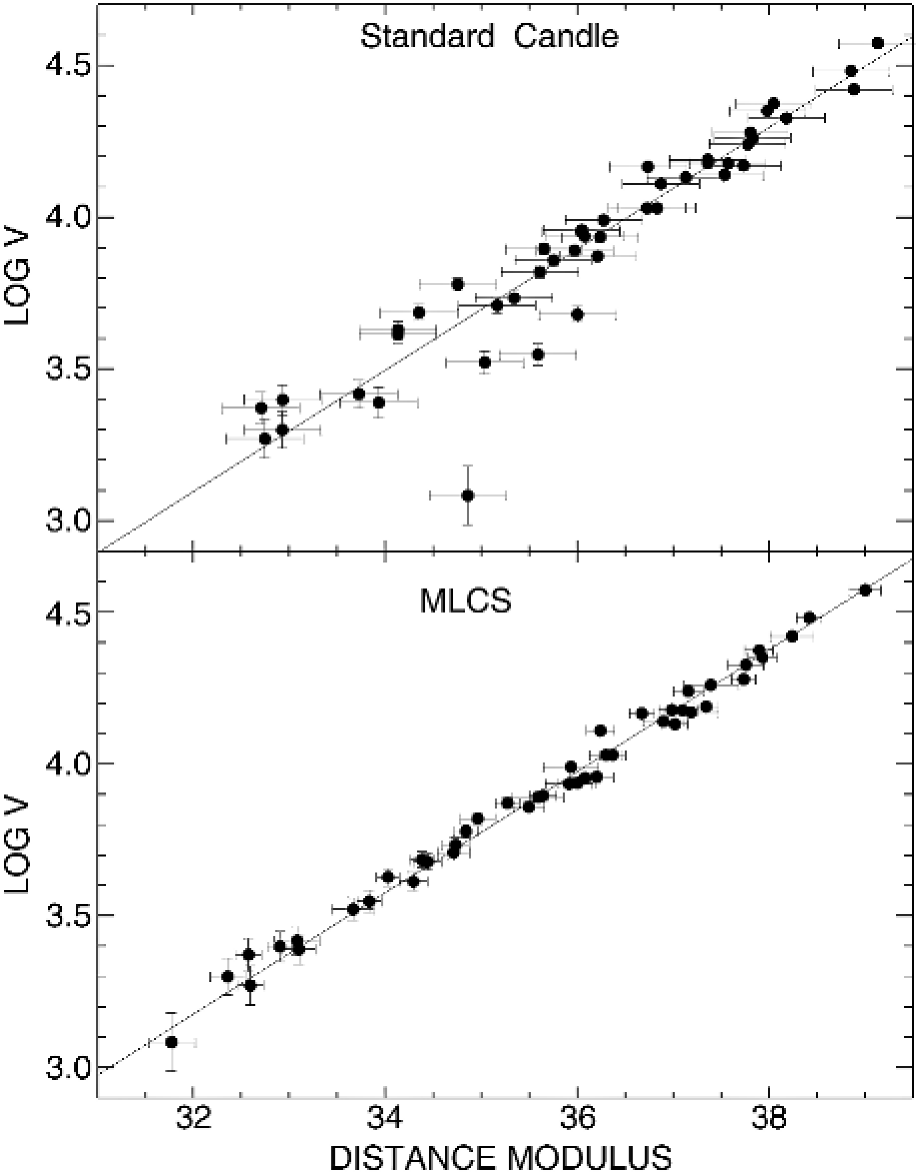


- Type Ia supernovae occur when the mass of a white dwarf exceeds the Chandrasakar limit (1.4 Msun). May occur via accretion from a companion or collision with another star.
- Because starting condition is the same, reasonable that all Ia have same luminosity.
- Maximum luminosity does vary, but is well 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 $\mu = 5 \log(d/\mathrm{pc}) - 5$



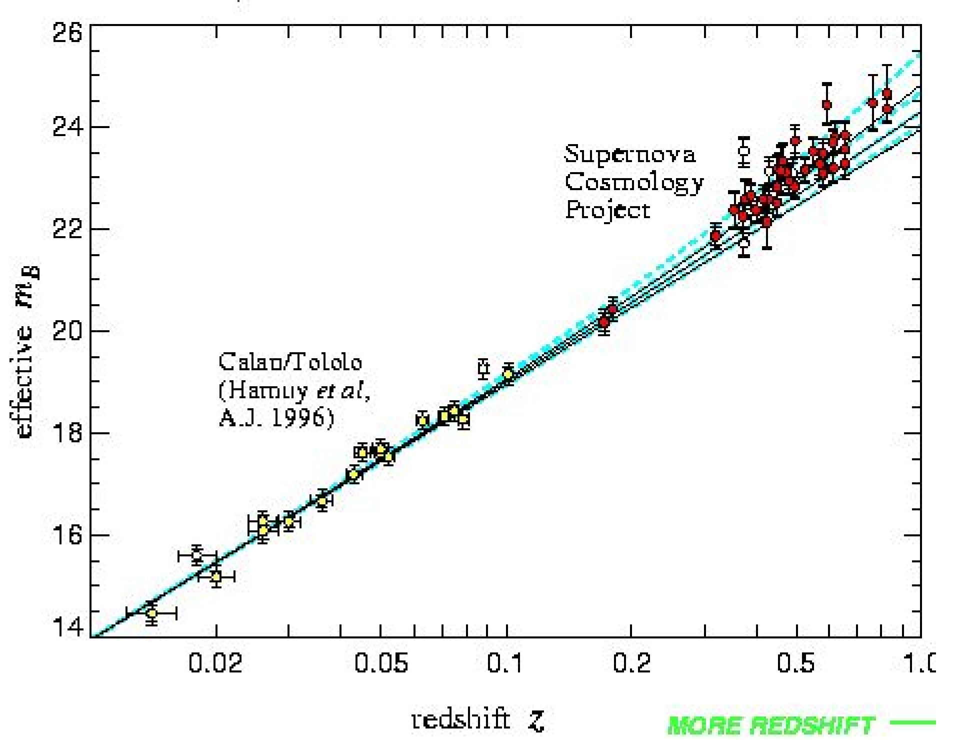
Searching for supernovae

- 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

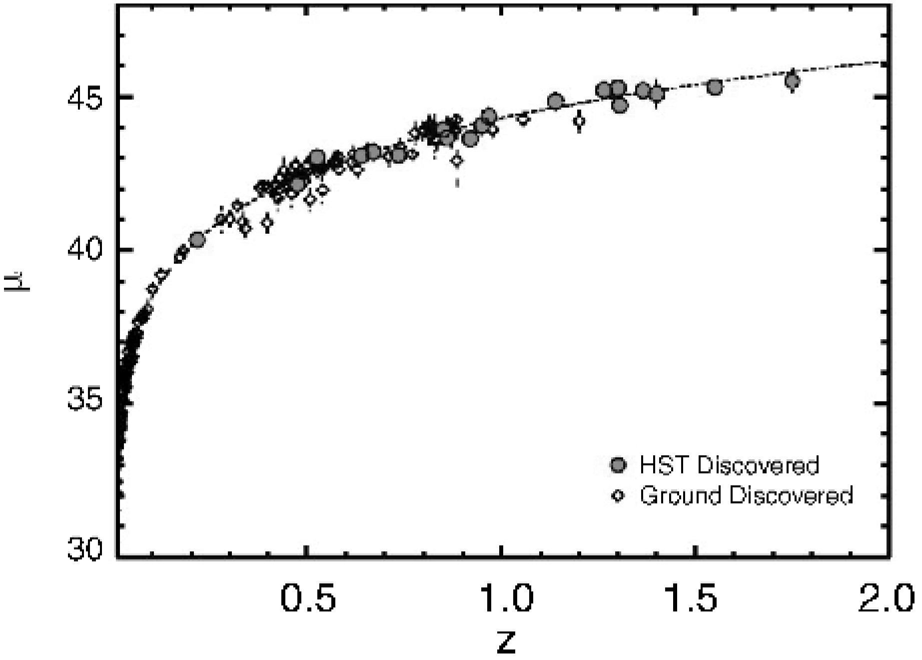
- Originally, SN searches done by the Berkeley group had a very hard time in arranging telescope time for follow-up because they would need to bump observers off big telescopes (target of opportunity observations = TOOs).
- Important threshold was when search observations could discover a new SN every 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

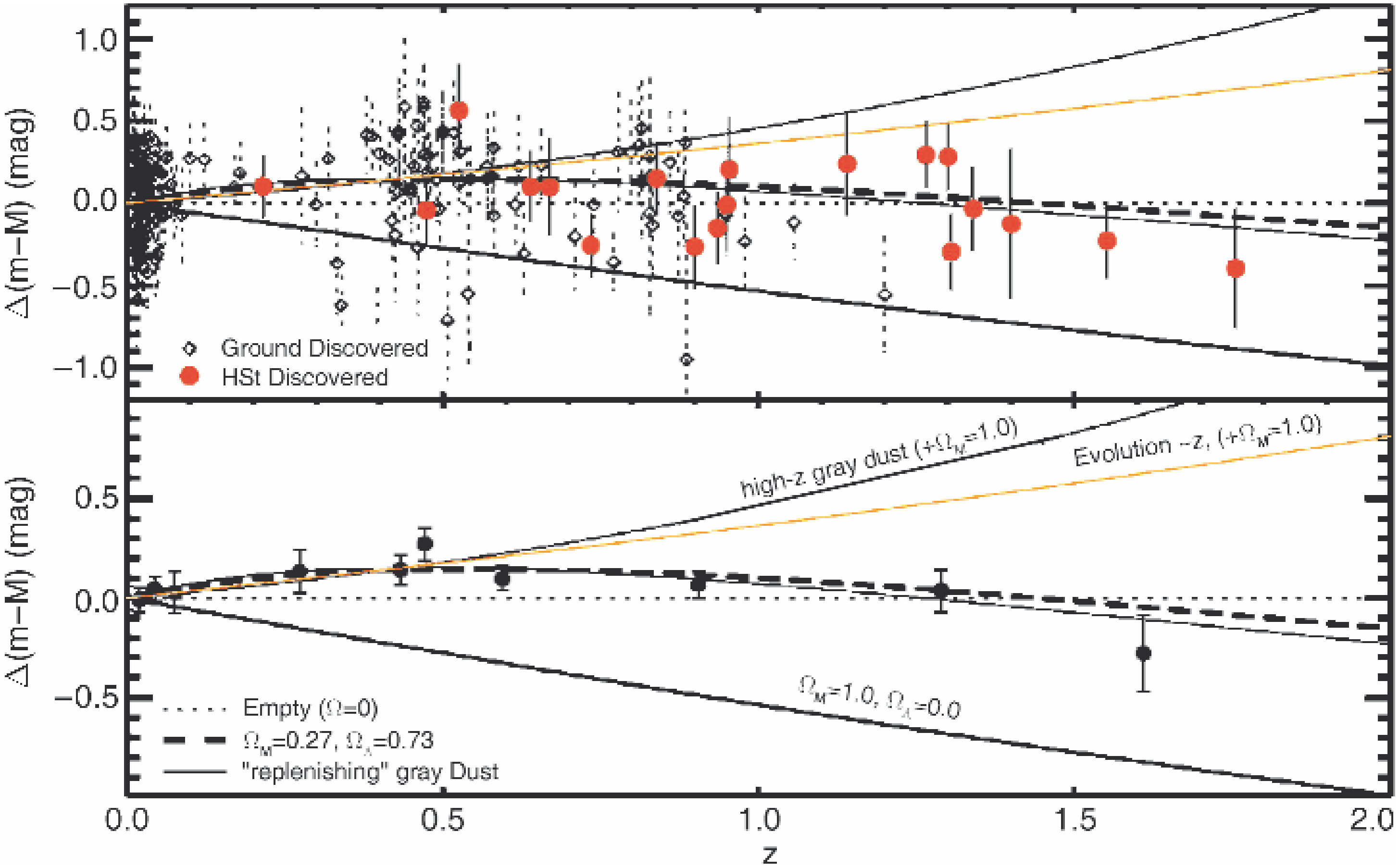
- Plot of distance vs redshift for SNIa is a Hubble diagram, extending to high *z*.
- Diagrams probe expansion history of the universe.



MORE REDSHIFT



Supernova cosmology

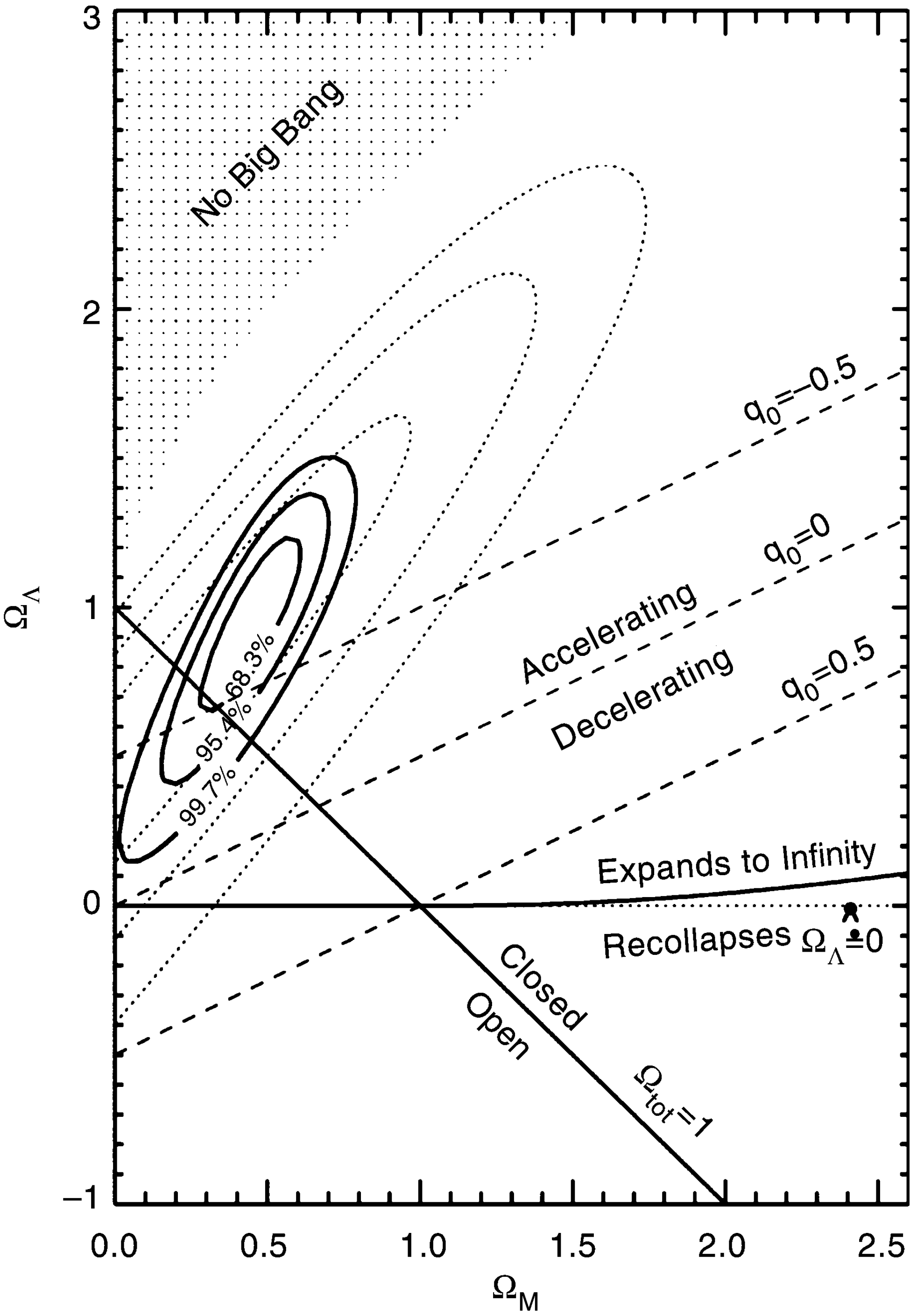


- Plot of mag – mag in empty universe. Empty universe means constant expansion (dotted).
- Points above dotted line mean that expansion has accelerated, e.g. $\Omega_\Lambda > 0$.
- Thick dashed curve $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$. Lower solid curve $\Omega_m = 1$, $\Omega_\Lambda = 0$.
- Two upper curves, evolution of SN or grey dust with *z*.
- High *z* points show turn over, important for confirming cosmological nature.

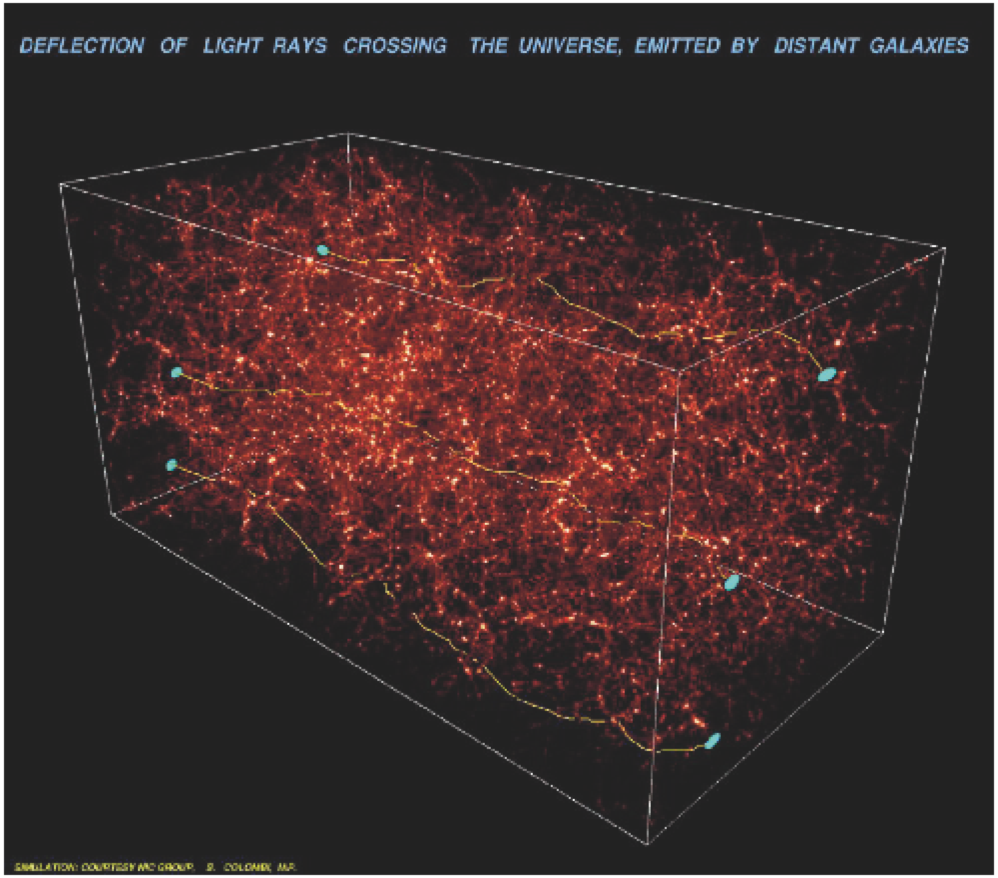
Supernova cosmology

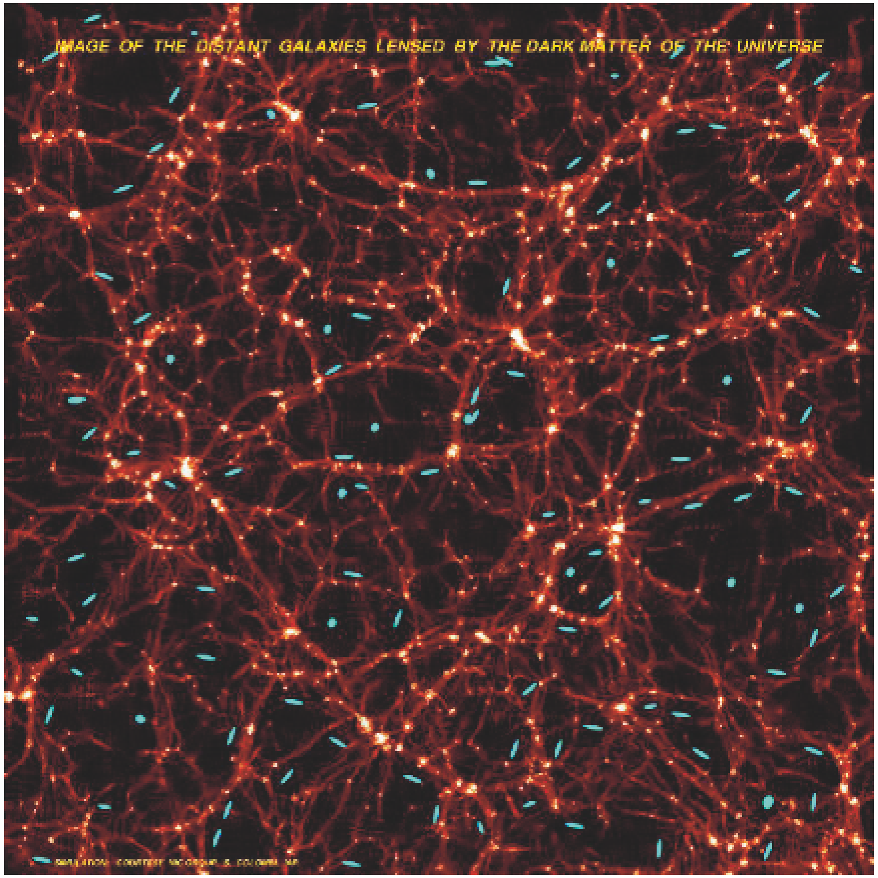
- Solid contours from data on previous slide. Dotted contours from 1998 data. expansion has accelerated, e.g. $\Omega_\Lambda > 0$.
- If we require $\Omega_{tot} = 1$ (from CMB), then best fit is $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$.

- Ω_Λ may be true cosmological constant or could be a quantum field with equation of state $P = w\rho c^2$, $w = -1$ is same as CC.
- Primary goal of future dark energy surveys is to measure *w*.



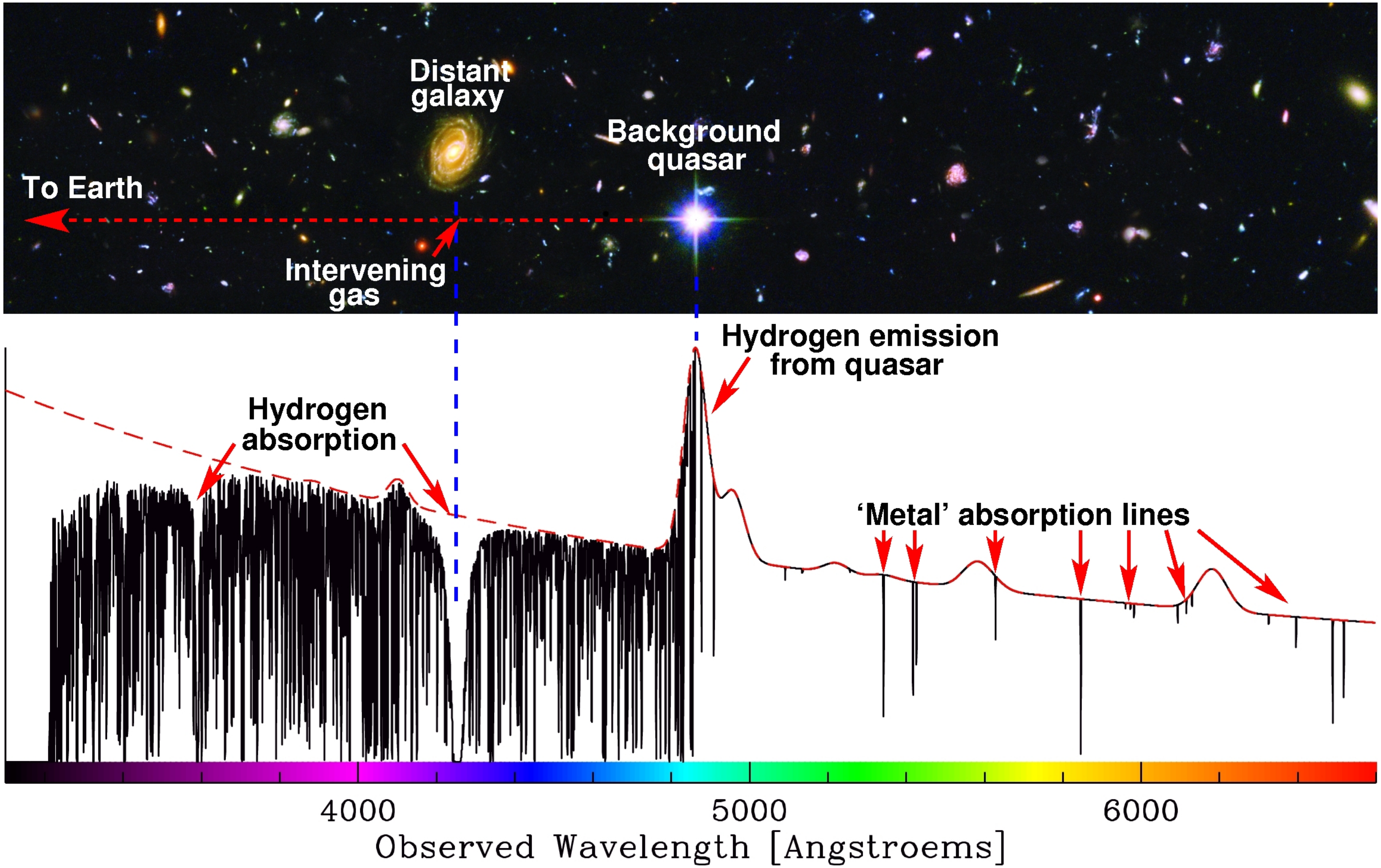
Cosmic shear





- 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.

QSO absorption lines



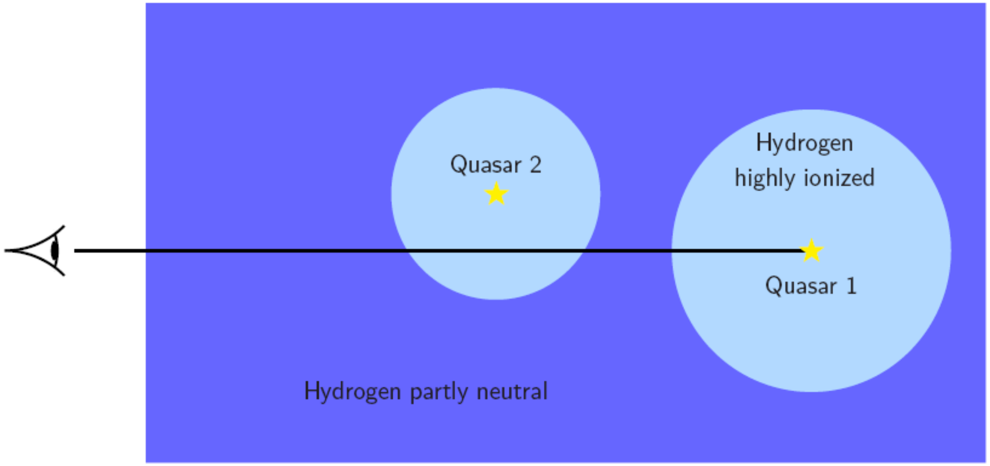
- Gas within quasars or in gas clouds or galaxies between us the and quasar can produce absorption lines.

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(blue)/S(red) = $e^{-\tau}$ where $\tau \sim 6\times10^{10}$ (n_{HI}/cm^{-3}) at $z = 0$.
- If $\Omega_{HI} \geq 10^{-6}$ 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_{HI}(comoving) $< 3\times10^{-13}$ cm^{-3} or $\Omega_{HI} < 3\times10^{-8}$.
- 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.

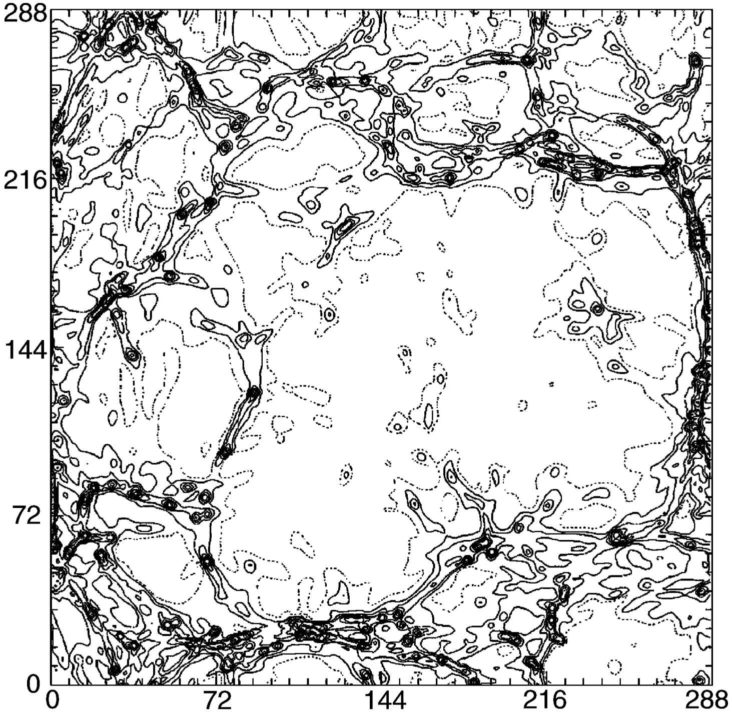
Lyman α forest



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

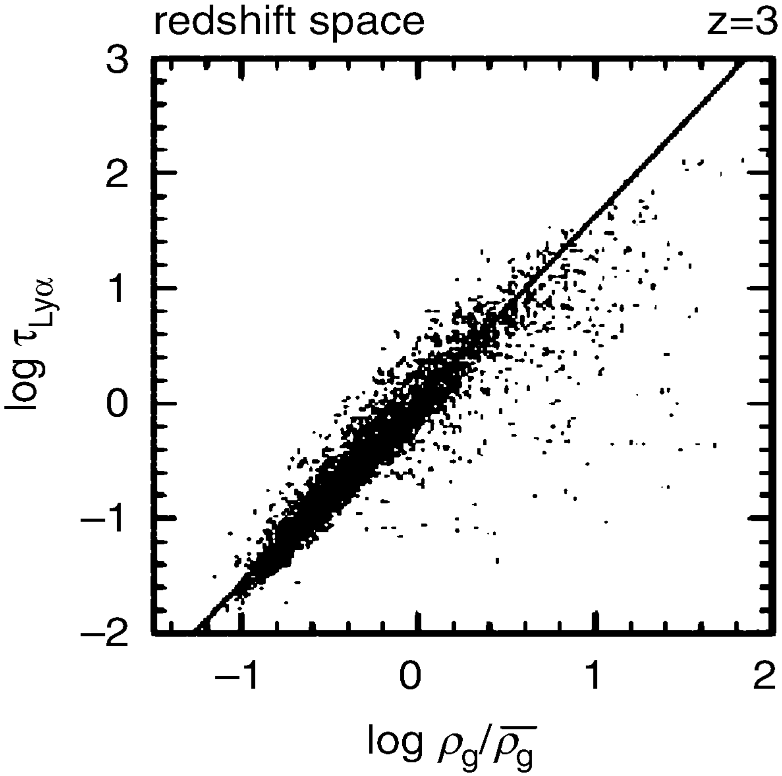
Lyman α forest

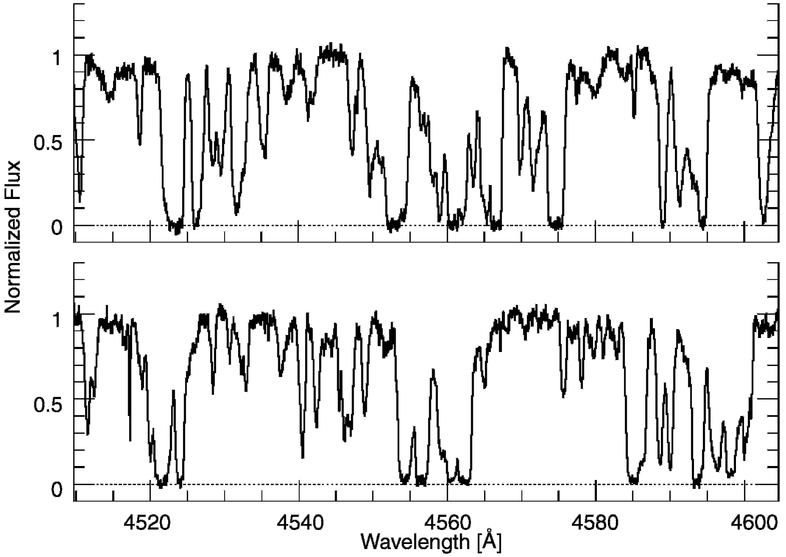
- How did Lyα forest arise?
- Galaxies and clusters formed when baryons fell into dark matter gravitational potential wells after recombination.
- Gas clouds in the Lyα forest formed the same way. However, smaller density perturbations produced smaller baryon concentrations.
- These smaller perturbations 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 $n_{HI} = \alpha n_p^2/\Gamma$, temperature dependence of α.
- Find $\tau = A(n_p/\bar{n}_p)^\beta$ 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.