Astro 596/496 PC
Lecture 7
Feb. 3, 2010

Announcements:
- PS1 due Friday
- Physics Colloquium tomorrow: S. James Gates, Jr. (UMD)
  "Is Physical Reality a Matrix?"
- High-Energy Seminar next Monday: Dan Bauer (Fermilab)
  "Recent Results from CDMS" – dark matter hint?!

Last time:
minimal ingredients to a realistic cosmology: $\sum \rho_i = ...?$
cosmic history, fate depends qualitatively and quantitatively
on values of Ω_i
Key question: *What is Ω_0?*
- $\rho_{\rm crit,0} = 3H_0^2/8\pi G = 1.4 \times 10^{11}\ M_\odot\ {\rm Mpc}^{-3}$
- if we can measure ρ_0, we know cosmic curvature, fate!

The Evolution of Ω

Time change of $|\Omega - 1| \propto 1/\dot{a}^2$ is

$$\frac{1}{|\Omega - 1|} \frac{d}{dt} |\Omega - 1| = \dot{a}^2 \frac{d}{dt} \frac{1}{\dot{a}^2} \tag{1}$$

$$= -2 \frac{\ddot{a}/a}{H^2} H = 2\, q\, H \tag{2}$$

where *acceleration parameter* $q = -(\ddot{a}/a)/H^2$

Q: why sign choice in q definition?

- generally, $|q| \sim 0.1 - 10$, so
  $|\Omega - 1|$ changes on timescale $1/2|q|H \sim 1/H = t_H \sim t$

- if $\ddot{a} < 0$: ordinary attractive gravity, *decelerating* U
  then $|\Omega - 1|$ *increasing* with time
  $\rightarrow \Omega$ driven increasingly away from 1
  Q: unless...?

What is Ω_0?

Procedure 0: Pure Theory

$\Omega = \rho/\rho_{\text{crit}} \sim \rho(t)/H^2(t)$ evolves

but if ever $\Omega = 1$, stays 1 always

else: $\Omega \to 0$ or ∞

physically: expand forever or recollapse

occurs on cosmic timescale t: current age

$\Omega = 1$ is only stable value

do the experiment: look around room

$\Omega \neq 0, \infty \rightarrow \Omega = 1$!

else conspiracy: we live just when $\Omega \sim 1$

"Dicke coincidence"

What is Ω_0?

Procedure I: Galaxy Surveys

Goal: measure $\Omega_0 \rightarrow \rho_0$

Q: Why can't we use $\rho_{\text{this room}}$*?*
Q: What is needed?
Q: What do galaxy surveys actually measure?
Q: How can we bridge the gap?

Cosmic Density Measurement Procedure I:
Mass-to-Light Ratios

Seems simple...
1. find fair sample of U., with some volume V
2. if measure total mass M, $\rightarrow \rho = M/V$

...but telescopes don't measure mass, rather: *luminosity* L
1. find cosmic **luminosity density** $\mathcal{L} = L/V$
2. then find cosmic ratio of mass to luminosity:
"mass-to-light" ratio $M/L \equiv \Upsilon$
3. solve for mass density $\rho = \Upsilon \mathcal{L}$

Galaxy surveys: $\mathcal{L}_{\rm obs} \sim 2 \times 10^8 \ h \ L_\odot \ \text{Mpc}^{-3}$
...which you will verify in PS1!

Need "fair sample" of mass-to-light ratio Υ

Q: how to measure this?

cosmic mass/light sample: galaxies including dark halos

flat rotation curves $v(r) \sim const$

`www: rotation curve`

Newtonian gravity, dynamics apply:
circular motion: $v^2/r \sim g \sim GM_{\text{enclosed}}(r)/r^2$
Q: expected behavior for $r >$ visible matter?

Instead: find $v \approx const$ well beyond visible matter
"flat rotation curves"
$\Rightarrow M(r) \sim v^2 r/G \sim r$ for $r \gg r_{\text{vis}}$!
dark halo! typically $M_{\text{halo}} \sim 5 - 10 M_{\text{vis}}$
summing observed light, total dynamical mass:

$$\Upsilon_{\text{halo}} \lesssim 25 h M_\odot/L_\odot \rightarrow \Omega_{\text{halo}} \lesssim 0.02 \ll 1$$

Q: implications? what if this is a fair sample?
Q: why would/wouldn't it be?

cosmic mass/light sample: galaxy clusters

can find cluster $M_{\rm tot}$ from several methods

e.g., `www: cluster gravitational lens`

$\Upsilon_{\rm cluster} \sim 300h \rightarrow \Omega_{\rm cluster} \sim 0.25h^{-1} \sim 0.3$

Note: since $\Upsilon_{\rm cluster} > \Upsilon_{\rm halos}$

$\rightarrow$ immediately conclude that halos are not fair sample

$\rightarrow$ i.e., halos miss extra dark matter on larger scales

$\rightarrow$ hints for galaxy formation...

...but clusters have $\delta\rho/\rho_0 \sim 1$

$\rightarrow$ largest bound objects

$\rightarrow$ should be fair sample:

$\Rightarrow \Omega_{\rm matter} \sim 0.3$ (including DM!)

Cosmic Density Measurement Procedure II:

Microwave background anisotropies

sensitive to cosmic geometry

`www:  WMAP 2010 results, 7-yr data + other observations`

$\Omega_\kappa \equiv 1 - \Omega_0 = -0.0023 \pm 0.0055$

$\Omega_0 = 1.0023 \pm 0.0055!$ $\Rightarrow \Omega_0 = 1$ to $\sim 0.2\%$ level!!

$\Rightarrow$ flat universe! theory prejudice correct!

but: $\Omega_{\rm matter} \approx 0.27$ (including DM!)

$\rightarrow \Omega_{\rm other} = 0.73$?!?

Λ? "dark energy" ?!?

Beyond Newton

Thus far: Newtonian cosmology

- develops intuition
- correct over small ($\ll d_H$) scales

Shortcomings:

- some features "pulled of out a hat"
  e.g., curvature scale R
  presence, coefficient of pressure
- Newtonian physics is incomplete (=wrong!)

$\Rightarrow$ the universe is relativistic!

General Relativity

Relativity for the Impatient Cosmologist

For General Relativity newcomers, we will:

- sketch how GR generalizes special relativity
- sketch basic concepts of GR
- qualitatively discuss similarities, differences with special relativity, Newtonian Gravity
- No substitute for a real, rigorous, in-depth course: *take General Relativity!*

For everyone, we will:

- show how cosmo principle strongly constrains possible cosmic spacetimes
- semi-derive the cosmic (FLRW) metric
- use this to probe lifestyles in an expanding universe

For General Relativity veterans, we will:

- sketch how Einstein equations $\rightarrow$ Friedmann eqs

Spacetime

see S. Carroll, *Spacetime and Geometry*; R. Geroch, *General Relativity from A to B*

evolving view of space, time, and motion:
Aristotle → Galileo → Einstein

Key basic concept: **event**
occurrence localized in space and time
e.g., firecracker, finger snap
idealized → no spatial extent, no duration in time

a goal (*the* goal?) of physics:
describe relationships among events

Q: consider collection of all possible events–what's included?