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: $\sum \rho_i = \ldots$?
cosmic history, fate depends qualitatively and quantitatively on values of $\Omega_i$

Key question: What is $\Omega_0$?
• $\rho_{\text{crit},0} = 3H_0^2/8\pi G = 1.4 \times 10^{11} \ M_\odot \ \text{Mpc}^{-3}$
• if we can measure $\rho_0$, we know cosmic curvature, fate!
The Evolution of \( \Omega \)

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

\[
\frac{1}{|\Omega - 1|} \frac{d}{dt} |\Omega - 1| = \dot{a}^2 \frac{d}{dt} \frac{1}{\dot{a}^2} = -2 \frac{\ddot{a}/a}{H^2} H = 2 \ q \ H \tag{2}
\]

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 $\Omega_0$?

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: $\Omega \rightarrow 0$ or $\infty$

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 $\Omega \sim 1$

ω "Dicke coincidence"
What is $\Omega_0$?

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 $M/L \equiv \gamma$
3. solve for mass density $\rho = \gamma \mathcal{L}$

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

Need “fair sample” of mass-to-light ratio $\gamma$

Q: how to measure this?
cosmic mass/light sample: galaxies including dark halos
flat rotation curves \( v(r) \sim \text{const} \)

www: rotation curve

Newtonian gravity, dynamics apply:
circular motion: \( \frac{v^2}{r} \sim g \sim \frac{GM_{\text{enclosed}}(r)}{r^2} \)

Q: expected behavior for \( r > \text{visible matter} \)?

Instead: find \( v \approx \text{const} \) well beyond visible matter
“flat rotation curves”
\( \Rightarrow M(r) \sim \frac{v^2 r}{G} \sim r \) for \( r \gg r_{\text{vis}} \)
dark halo! typically \( M_{\text{halo}} \sim 5 - 10 M_{\text{vis}} \)
summing observed light, total dynamical mass:
\[ \Upsilon_{\text{halo}} \lesssim 25h M_{\odot}/L_{\odot} \rightarrow \Omega_{\text{halo}} \lesssim 0.02 \ll 1 \]

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 $M_{\text{tot}}$ from several methods
e.g., www: cluster gravitational lens
$\Upsilon_{\text{cluster}} \sim 300h \rightarrow \Omega_{\text{cluster}} \sim 0.25h^{-1} \sim 0.3$

Note: since $\Upsilon_{\text{cluster}} > \Upsilon_{\text{halos}}$
→ immediately conclude that halos are not fair sample
→ i.e., halos miss extra dark matter on larger scales
→ hints for galaxy formation...

...but clusters have $\delta \rho/\rho_0 \sim 1$
→ largest bound objects
→ should be fair sample:
⇒ $\Omega_{\text{matter}} \sim 0.3$ (including DM!)
Cosmic Density Measurement Procedure II:

**Microwave background anisotropies** sensitive to cosmic geometry

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

\[
\Omega_{\kappa} \equiv 1 - \Omega_0 = -0.0023 \pm 0.0055
\]

\[
\Omega_0 = 1.0023 \pm 0.0055! \Rightarrow \Omega_0 = 1 \text{ to } \sim 0.2\% \text{ level!!}
\]

⇒ flat universe! theory prejudice correct!

**but:** \( \Omega_{\text{matter}} \approx 0.27 \) (including DM!)

→ \( \Omega_{\text{other}} = 0.73?? \)

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!)
⇒ 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?