Astro 596/496 NPA
Lecture 13
Sept. 23, 2009

Announcements:

- Problem Set 2 due next time
- Note on nuke reaction rate databases (all on course `links`): NACRE link now fixed; you are also welcome to use instead the more up-to-date Reaclib database at JINA
- Note on NACRE: tabulated rates given for recommended "adopted" (`ado`) and for `high` and `low` limits
- Medium Energy Seminar today: 4pm Loomis 464
  Mark Chen "Neutrino Physics Beyond SNO"

Q: what is meant by Ω? Ω_0? $\Omega_{\rm matter}$?
Q: who cares?

Density Determines Destiny

can determine $\Omega_0 = \rho_0/\rho_{\rm crit,0} = 8\pi G\rho_0/3H_0^2 \propto \rho_0/H_0^2$
from *locally measurable quantities* ρ_0 and H_0:
$\rightarrow$ cosmic fate & geometry knowable!
...and become *experimental* questions!

In particular: Fate (and geometry) of U. depend on
$\Omega_0 = \rho_{\rm tot,0}/\rho_{\rm crit,0}$, where **critical density** is

$$\begin{aligned} \rho_{\rm crit,0} &= 3H_0^2/8\pi G \\ &= 1.9 \times 10^{-29}\ h^2\ {\rm g/cm^{-3}} \approx 10^{-29}\ {\rm g/cm^{-3}} \\ &= 2.78 \times 10^{11}\ h^2\ M_\odot\ {\rm Mpc^{-3}} \approx 1.4 \times 10^{11}\ M_\odot\ {\rm Mpc^{-3}} \\ &\approx 6\ {\rm H\,atoms\ m^{-3}} \end{aligned}$$

Empirical question: is $\rho_{\rm tot,0}$ bigger or smaller than this number?

★ *Density is destiny! Weight is fate!*
Q: how can we determine Ω_0? What will be challenging?

What is Ω_0?

Procedure 0: Pure Theory

In general:
$\Omega = \rho/\rho_{\text{crit}} \sim \rho(t)/H^2(t)$ evolves with time

But: if *ever* $\Omega = 1$, then $\Omega = 1$ *always*
Otherwise: $\Omega \rightarrow 0$ or ∞
Q: what physically occurs at these limits?

Thus: $\Omega = 1$ is only stable value!

Experiment: *look around the room!*
obviously $\Omega \neq 0, \infty$
$\Rightarrow$ we must have $\boxed{\Omega = 1}$!
or else conspiracy: we live just when $\Omega \sim 1$
"Dicke coincidence"

Procedure I: Mass-to-Light

1. find *fair sample* of the Universe *Q: meaning?*
2. want: M, $V \to \rho$

but telescopes directly measure energy *flux* F

which gives light *power* output: *luminosity* $L = 4\pi d^2 F$

- find cosmic luminosity density $\mathcal{L} = L/V$
- find a "mass-to-light ratio" $M/L \equiv \Upsilon$

$\Rightarrow$ combine to solve for $\rho = \Upsilon \ \mathcal{L}$

Galaxy surveys: $\mathcal{L} \sim 2 \times 10^8 \ h \ L_\odot \ \mathrm{Mpc}^{-3}$

Need "fair sample" of mass-to-light Υ

- galaxy dark halos: flat rotation curves $\to \Upsilon_{\rm halo} \lesssim 25 h M_\odot / L_\odot$

$\to \Omega_{\rm halo} \lesssim 0.02 \ll 1$

- Clusters: $\Upsilon_{\rm cluster} \sim 300 h M_\odot / L_\odot$

`www: cluster lens`

$\to \Omega_{\rm cluster} \sim 0.25 h^{-1} \sim 0.3$

Q: implications?

Procedure II: Microwave background anisotropies

Cosmic Microwave Background (CMB)
literally is a *image* of the Universe
when photons last scattered with matter
tiny T fluctuations seen: $\delta T \rightarrow$ small matter inhomogeneities $\delta\rho$

angular pattern of δT sensitive to cosmic geometry
`www: WMAP results`
$\Omega_0 = 1.02 \pm 0.02!$ consistent with $\Omega_0 = 1!!$

to within our ability to measure: $\kappa = 0$:
the universe is spatially Euclidean: "flat"

but: WMAP also confirms
$\Omega_{\text{matter}} \approx 0.30$ (including DM!)
Q: and so?

Dark Energy and Cosmic Acceleration

CMB (WMAP):

⋆ flatness $\rightarrow$ $\Omega_{\text{tot}} = 1$ to within $\sim 1\%$

⋆ $\Omega_{\text{matter}} \approx 0.30$ (including DM!)

Most of the universe today is something else:

$\rightarrow$ $\Omega_{\text{other}} = 0.70$?!?

Stranger still: measures of recent expansion history $H(t)$

e.g., distant Type Ia supernova explosions

reveal that U. is **accelerating!**

...requiring $\Lambda \neq 0$ (or dark energy)

such that $\Omega_\Lambda \approx 0.7 \rightarrow$ independent evidence!

Q: so what's really going on?

Dark Matter and Dark Energy: What's the Deal?

Multiple lines of evidence suggest

⋆ *most* mass-energy today is in dark energy!?!

⋆ *most* matter is in dark matter!?!

the visible universe is a small fraction of the total

> Hey hey, my my [...]
> There's more to the picture
> Than meets the eye
> Hey hey, my my
> – Cosmologist Niel Young

Surely this has implications for particle physics

Q: what properties must dark matter have?

what would this mean for particle dark matter?

Q: how about dark energy?

The Invisible Universe and Fundamental Physics

Dark Matter–what we know

- it exists
- is dark: can't have been detected yet
- is matter: $w_{\mathrm{dm}} \approx 0$

If DM is relic from early universe, DM particles must be

▷ stable (or long-lived)

▷ weakly interacting

▷ non-relativistic today

Good news:

particle theory offers many well-motivated DM candidates
fitting this description

Dark Energy–what we know

- it exists
- is dark
- is energy, i.e.,$w < 0$

implications for fundamental physics

need substance with $P \sim -\varepsilon$: pressure huge, negative!

but non-relativistic matter: $0 < w \ll 1$

relativistic matter: $w = 1/3$

$\rightarrow$ suggests any particle gas has $0 \leq w \leq 1/3$

Q: which means?

Bad news: particle theory taken by surprise!

no well-motivated dark energy candidates "off the shelf"

Good news: job security for cosmologists!

Cosmic Archaelogy: The Early Universe

is particle physics the key to the dark side?

When are high-energy processes/particles abundant?

- Universe has temperature now: CMB $T_0 = 2.725$ K
  $\Rightarrow$ cosmic matter was once in thermal equilibrium
- in thermal bath, typical particle energy is $E \sim kT$
- cosmic temperature $T \propto 1/a = 1 + z$

Therefore:

- when primordial soup at high-E $\rightarrow$ high T $\rightarrow$ early times

⋆ the early universe is the realm of particle physics
⋆ cosmic *particle* history $\Leftrightarrow$ cosmic *thermal* history

Interlude

Cosmologist W. Allen

Annie Hall (1977)