Astro 596/496 PC
Lecture 17
Feb. 26, 2010

Announcements:

- PF3 was due noon
- PS3 out, due in class next Friday

Last time: a quintessential solution to dark energy?

Q: what makes scalar fields appealing dark energy candidates?

Q: what's the DE coincidence problem? how do "tracker" models solve it?

Today:

- dark energy finale
- begin CMB

Cosmic Acceleration/Dark Energy

The Future

Challenges for theory:

Q: open questions?

Q: what tools needed to address them?

Q: possible implications of answers?

Challenges for observations:

Q: open questions?

Q: what tools needed to address them?

Q: possible implications of answers?

Cosmic Acceleration/Dark Energy

The Future: Job Security!

Challenges for theory: Formidable!

- a failure of Friedmann → General Relativity?
  hints at quantum gravity?
- ...*or*... Friedmann/GR okay, dark energy exists
  what is it?
  is it connected to dark matter?
  how does it fit into the rest of physics?
- is it truly a cosmo constant Λ?
  if so, why this value? why nonzero?
- if DE $\neq \Lambda$, what is it?
  how does it evolve?
  how does it couple to matter, rad?
  participation in structure formation?
  what is the fate of the universe?
  is there an early U. connection–inflation?

Challenges for observation: Formidable!

- is the universe accelerating?
  SNIa are (for now) most direct evidence
  systematic errors?
- what is precise value of w_0?
- is $w \neq -1$, i.e., can we rule out cosmo constant
  and rule *in* an evolving cosmic energy component?
- does w itself evolve? was $w < -1$ ever (or will it be)?

Future Dark Energy Experiments

Dark Energy Survey Illinois, FNAL, Chicago, ...

Strategy Multi-pronged attack:

- optically monitor 4000 deg^2 $\sim$ 1sr of sky
  discover $\sim$ 1900 SNIa in $0.3 < z < 0.8$
- overlaps with CMB (S-Z) survey
  discover, map 20,000 clusters

Scientific Payoff

▷ luminosity distances

▷ galaxy distribution vs z
  angular correlations
  angular distortions: “weak lensing”

▷ cluster counting and spatial distribution

▷ w_0 to $\sim 5\%$, dw/dz to $\sim 30\%$

▷ multiple methods: checks on systematics

Joint Dark Energy Mission NASA, NSF
- space mission, 1.8 m telescope: SNIa

Large Synoptic Survey Telescope (LSST) Illinois et al
repeated scan of $\Omega_{\rm lsst} \sim 20,000\ {\rm deg}^2 \simeq$ half of sky, yields:

The Sky: The Movie
transient universe on minute–year timescales
down to $24 - 27^{\rm mag}$ in 5 bands
SN count approaching 10^6, bazillion Type Ia's to $z \sim 1.3$
also gamma-ray burst afterglows, exoplanet transits,
Galactic & extragalactic microlensing, stellar parallax,
variable stars, Kuiper belt objects, killer asteroids, ...

The Sky: The Wallpaper
SDSS-type digital photometric map
down to $m_{AB} \sim 29^{\rm mag}/{\rm arcsec}^2$ in 5 bands
galaxy clusters, strong and weak lensing, galaxy clustering,
Galactic structure ...

Dark Energy: Epilogue

Jim Peebles, *The Large Scale Structure of the Universe* (1980) end of the final paragraph (on a different topic, but still apt):

> ... we must still bear in mind Bondi's caution that "there are probably few features of theoretical cosmology that could not be completely upset and rendered useless by new observational discoveries." For the present subject we might add, "or by a good new idea."

The Cosmic Microwave Background

Cosmic Whiplash

From the Ridiculous to the Sublime

Dark energy: confusing situation
progress difficult

- no guidance from laboratory physics
- observational data very sparse
- job security, but existential doubt

$\Rightarrow$ still the wild west: "cowboy cosmology"

Now turn to the CMB: huge contrast
progress exponential

- underlying physics rock-solid
- observation data aplenty!
- excellent theory-observational concordance
  $\rightarrow$ confidence in big bang framework

$\Rightarrow$ highly developed: "precision cosmology"

The CMB: Warmup

Plan & Schedule:

1. CMB in *homogeneous* universe $\rightarrow$ *isotropic* component
   today–next week
2. CMB in real *inhomogeneous* universe $\rightarrow$ *anisotropies*
   next month–after inflation has made inhomogeneities

Observational Tools, Issues:

Q: what are CMB observables?

Q: how are they quantified?

Theoretical Tools, Issues:

Q: What is relevant physics?

Q: What are relevant cosmic ingredients?

Q: What are irrelevant (presumably?) cosmic ingredients?

Q: What are relevant equations/analyses?

CMB Observables

- brightness pattern across sky
- polarization pattern across sky
- frequency spectrum of the above

More specifically:

▷ (total= bolometric=calorimetric) surface brightness
or **intensity** $I = dE_{\rm tot}/dA\,dt\,d\Omega$
measure $I(\theta,\phi)$ on sky; can write as

$$I(\theta,\phi) = I_0 + \Delta I(\theta,\phi) \quad (1)$$

with sky-averaged intensity $I_0 = \int I(\theta,\phi)\, d\Omega/4\pi \;\; \Rightarrow \langle \Delta I \rangle = 0$

▷ spectrum: specific intensity
$I_\nu = dI/d\nu$, i.e., $I = \int I_\nu d\nu$

If radiation is thermal (blackbody), with $T(\theta,\phi)$ across sky
Q: then what is I? I_ν?

If blackbody, then *spectrum* (in each direction)

- follows Planck distribution
- characterized by a *single parameter*

$$T(\theta, \phi) \equiv T_0 + \Delta T(\theta, \phi) \tag{2}$$

Planck spectrum:

$$I_{\nu,\text{Planck}} \equiv B_\nu(T) = \frac{2h}{c^2} \frac{\nu^3}{e^{h\nu/kT} - 1} \tag{3}$$

$$I_{\text{Planck}} = \int d\nu \; I_{\text{Planck}} = \frac{\sigma_{\text{SB}}}{\pi} T^4 \tag{4}$$

where $h = 2\pi\hbar$

Note: for $h\nu \ll kT$ (Rayleigh-Jeans limit)

$$I_{\nu,\text{Planck}} = \frac{2h}{c^2} \frac{\nu^3}{e^{h\nu/kT} - 1} \longrightarrow \frac{c^3}{4\pi^2} \nu^2 kT \tag{5}$$

so define “antenna temperature”

$$T_{\text{antenna}} \equiv \frac{c^2}{2k} \frac{I_\nu}{\nu^2} \tag{6}$$

- a measure of surface brightness *at a single ν or λ*
- practical experimentally: compare astro (i.e., antenna) signal to intensity of source at known “load” $T_{\text{reference}}$

Q: for blackbody, what is magnitude, shape of $T_{\text{antenna},\nu}$ vs ν?
Q: significance of $T_{\text{antenna},\nu}$ if not blackbody pattern?

CMB: Discovery

Penzias & Wilson (1965)
"A Measurement of Excess Antenna Temperature at 4080 Mc/s"

- Bell Labs (Holmdel, NJ) radio telescope
- careful checks of systematics! this is most of their paper!
  ...obligatory pigeon story
- $T_{\text{ant},\nu} = 3.5 \pm 1.0$ K at $\nu = 4.080$ GHz
- other properties:

> This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964 - April, 1965).

Q: what does this imply about thermal/nonthermal components?
Q: why seasonal variations important?
Q: how did P&W know the spectrum is thermal?

Note: the strict empiricism in 2-page P&W writeup:

- *none* of the words "cosmology," "universe," or "background" appear in any form
- not even any direct claim that the signal is extraterrestrial!

Entire P&W interpretive discussion follows:

> A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter...

...which is entitled
"Cosmic Black-body Radiation"