Astro 596/496 PC

Lecture 15

Feb. 22, 2010

Announcements:

- PF3 out, due next Friday noon
  short, sweet, and Nobel-packed!

Last time: the physics of cosmic acceleration

- *Q: novel property required of any cosmic accelerant?*
- *Q: simplest cosmic accelerant?*
- *Q: fate of Universe with simplest accelerant?*
- *Q: antigravity? vacuum energy?*
- *Q: quantum expectations for vacuum energy?*

Vacuum Energy: Λ and Quantum Mechanics

Can view Λ as "substance" with energy density, pressure:

$$\rho_\Lambda = \frac{\Lambda c^2}{8\pi G} \quad \text{and} \quad P_\Lambda = -\rho_\Lambda$$

- $w_\Lambda = -1$
- ρ_Λ "energy density of the vacuum"

From quantum perspective, zeropoints of field quanta give

$$\varepsilon_{\text{zeropoint}} \sim \int_0^{\omega_{\text{max}}} \omega^3 \, d\omega \sim \omega_{\text{max}}^4$$

Q: i.e., at what scale might energies "max out"?

if quanta have $E_{\text{max}} = M_{\text{Pl}}$, then
$\rho_{\text{vac,Pl}} \sim M_{\text{Pl}}^4 \sim 10^{110}$ erg/cm^3 $\sim 10^{89}$ g/cm^3 *Q: implications?*

Compare to the vacuum density in Λ:

$$\rho_{\rm vac,Pl} \sim 10^{89}\ {\rm g/cm}^3 \sim 10^{120} \rho_{\rm Lambda}$$

mismatch is ~ 120 orders of magnitude!!

So the real question is not: *"Why have Λ at all?"*
but rather: *"Why isn't Λ gi-normous?"*

quantum gravity?
maybe some underlying symmetry set $\Lambda = 0$
  to avoid "fine-tuning" Λ
if so, then dark energy is not vacuum energy
  but some other energy density with negative pressure

high-energy phase transitions/symmetry breaking?
maybe symmetry breaking processes set vacuum energy
e.g., GUT, SUSY, electroweak, QCD
if so, how does each contribute to total vacuum?
run the numbers: best case is QCD

$$\varepsilon_{\rm qcd} \sim \Lambda_{qcd}^4 \sim (100\ {\rm MeV})^4 \sim 10^{30} \varepsilon_{\rm dark\,energy} \qquad (1)$$

many orders of magnitude improvement, but not quite a fix!

Bottom line:
known quantum fields do not provide viable candidate
for source of vacuum energy $\rho_{\rm vac} = \rho_\Lambda$

Dark Energy: Parameterized Ignorance

Theoretical Ignorance

No good (i.e., pre-existing) candidates for cosmic acceleration
unlike dark matter: high-E theory predicts stable exotic particles

Lacking guidance, look for general way to describe
cosmic substance responsible for acceleration: **dark energy**
recall: matter, radiation, Λ described by $P = w\rho c^2$
with w a constant

Write dark energy density and pressure with

$$P_{\rm DE} = w\rho_{\rm DE}c^2$$

"parameterize our ignorance" in w (possibly not constant)
cosmo constant is limiting case *Q: Namely?*
Q: what can we say about w values?

Dark Energy: the Little We Know

What is w today?

In DE-only case

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) = -\frac{4\pi G}{3}\rho(1 + 3w) \tag{2}$$

$\rightarrow$ acceleration requires $w < -1/3$ today

Recall: cosmic first law is

$$d(\rho a^3) = -p\ d(a^3) = -w\rho\ d(a^3) \tag{3}$$

For constant w:

$$\rho_{\rm DE} \propto a^{-3(1+w)} \tag{4}$$

Q: sanity check–results for w = matter, radiation, Λ?
Q: connection between "w" dark energy and Λ?

Data: generalize Ω_Λ limits
to Ω_w and w (now two parameters)

`www: current limits`

$$\Omega_w \sim 0.7 \quad , \quad w < -0.76 \text{ (95\%CL)}$$

- w close to -1: cosmo constant value!
- tests for w change weak but null
  $\rightarrow$ also like cosmo const!

The Preposterous Universe

We already knew (Copernicus et al):

- ▷ we're not the center of the solar system
- ▷ we're not at the center of the Galaxy
- ▷ we're not at the center of the Universe

  ...in fact, no center at all

Now observations tell us:

- $\Omega_{\text{baryon}} \simeq 0.04$
- $\Omega_{\text{matter}} \simeq 0.3$
- $\Omega_{\text{dark energy}} \simeq 0.7$

★ we're not made of the dominant matter

★ we have never directly detected the dominant matter

★ matter isn't the dominant mass-energy form

★ we have never directly detected the dominant mass-energy form

Q: rebirth of Mercury precession or of luminiferous æther?

Dark Energy Coincidence?

at present, just barely DE-dominated

matter-Λ equality was at

$a_{\rm eq} = (\Omega_{\rm m}/\Omega_\Lambda)^{1/3} = 0.75$

$z_{\rm eq} = 0.33$: "yesterday" – after Earth born

`www: cosmic epochs`

Nancy Kerrigan problem

$\longrightarrow$ "Why me?" "Why now?"

$\longrightarrow$ we seem to live in a special time?

Q: possible solutions?

Conspiracies and Coincidences

- **Anthropic Principle**

a nonzero Λ value couldn't be very different
or no intelligent life would have arisen to think about it
$\rightarrow$ bigger $\Lambda > 0$, and U exponentiates before stars, planets form
$\rightarrow$ if too much $\Lambda < 0$, U recollapses before stars, planets form
...okay, but prediction? tests? falsification?

- **Dark Energy as a Field**

if dark energy is due to a field throughout space
the field can evolve, and be coupled with matter, radiation
then perhaps dark energy can "track" other components

New field $\rightarrow$ new interactions
in addition to 4 known interactions (strong, weak, EM, gravity)
$\Rightarrow$ "fifth essence" – **quintessence**

Dark Energy as a Field

acceleration demands $P < 0$

particles can't to this:

$P = w\rho$, with $w = \langle v^2 E\rangle / 3\langle E\rangle \in (0, +1/3)$

what about fields?

Recall:

- fields $\leftrightarrow$ forces
  e.g., electric, magnetic forces $\rightarrow \vec{E}, \vec{B}$ (for experts: $F_{\mu\nu}$)
  forces $\rightarrow$ fields carry momentum $\rightarrow$ pressure
  e.g., $P_{\rm EM} \sim (E^2 + B^2)/3$
- fields also store and transmit energy across space
  e.g., $\varepsilon_{\rm EM} \sim E^2 + B^2 = 3P$

$\Rightarrow$ then $w_{\rm EM} = P_{\rm EM}/\varepsilon_{\rm EM} = 1/3$

Goal: treat dark energy as new field
with negative pressure ($w < 0$)
need to guess at properties
(ideally, guided by particle physics)

What kind of field?

- objects like $\vec{E}$ are *vector* fields
  assign vector $\vec{E}$ at each spacetime point
  not a good idea *Q: why?*

Q: what kind of field automatically cures this problem?

The Physics of Scalar Fields

scalar field: $\phi(\vec{x}, t)$

scalar $\rightarrow$ single-valued object = *function*

no directionality $\rightarrow$ kosher with cosmo principle

field $\rightarrow$ function takes values at all points in space(time)

Scalar fields abound in all areas of physics

Q: examples of known, physical scalar fields?

in particle physics, scalar fields arise in

force unification, origin of mass

in cosmology: DE, inflation $\rightarrow$ can't avoid!

"Scalar fields are the cosmologist's blunt instrument."

– J. Frieman