Astro 507

Lecture 16

Feb. 26, 2014

Announcements:

- **Preflight 3 due Friday at 9am**

Embarrassing story: ASTR 100 circa 1999–2000

Last time: ignorance parameterized–dark energy

Q: why dark energy?

Q: connection between Λ and dark energy?

Q: definition, units, significance of w?

Q: current limits on w, Ω_w?

Q: why would it be a Big Deal if we prove, e.g., $w = -0.9$?

or $w_{z=1} - w_{z=0} = 0.1$?

Data: generalize Ω_Λ limits
to Ω_w and w (now two parameters)
for a flat universe with *constant w*:

`www:   current limits`

$$w = -1.10 \pm 0.08$$

• w close to -1: consistent with cosmo constant value!

What if w not constant?
Empirical approach: Taylor expand

$$w(a) = w_0 + w_a\,(1 - a) \tag{1}$$

observations constrain parameters (w_0, w_a)
Q: does this allow a pure Λ universe? if so how?

`www:   present data`

Phantom Energy

If allow $w < -1$, i.e., $\|w\| > 1$
- consistent with SN+other dat
- in most recent analyses, even gives best fit!

But this violates "dominant energy condition"
i.e., $\rho + P > 0$ fails
acts to, e.g., prevent energy flows moving locally $> c(!)$
"phantom energy"
allowed in some quantum gravity models

Q: what's life like if $w < -1$?

recall—for constant w: $\rho_w \propto a^{-3(1+w)}$

The Phantom Menace

phantom dark energy density $\rho_{\text{de}} \sim a^{-3(1+w)}$
with $w < -1$, *density increases* with expansion!
as does pressure magnitude

scale factor expansion and acceleration both increase with time
new cosmic dynamics emerges

when phantom energy dominates

$$(\dot{a}/a)^2 \approx \Omega_w H_0^2 a^{3\|w+1\|} \tag{2}$$
$$a^{-3\|w+1\|/2}\, da/a = \sqrt{\Omega_w} H_0 dt \tag{3}$$

Q: what's peculiar about this?

integrate to get future cosmic evolution:

$$a(t) = \left(\frac{t_r}{t_r - \Delta t}\right)^{2/3\|w+1\|} \tag{4}$$

where $\Delta t = t - t_0$ is *time from now*; i.e., $\Delta t = 0$ today
and

$$t_r = \frac{2H_0^{-1}}{3\|w + 1\|\sqrt{\Omega_w}} \tag{5}$$

is a timescale

Q: plot of a vs t?
Q: implications?
Q: how differs from, say, Λ case?

Cosmic Doomsday

Phantom energy domination

$$a(t) = \left(\frac{t_r}{t_r - \Delta t}\right)^{2/3\|w+1\|} \qquad (6)$$

has $a \to \infty$ when $\Delta t = t_r \sim 11 \, \|w+1\|^{-1}$ Gyr
i.e., infinite expansion occurs a finite time from now!
$\Rightarrow$ doomsday occurs at a date certain!

and there's more...

because phantom energy density ε_{de} grows with time
eventually enclosed Earth-Sun dark energy $E_{de} = 4\pi \, r_\oplus^3 \, \varepsilon_{de}/3$
will be larger than $\|E_\oplus\| = GM_\odot M_\oplus/2r_\oplus$
Q: implications?

The Big Rip

it gets worse...

as t_r approaches, $\rho_{de} \to \infty$ everywhere

overwhelms binding energies → bound structures torn apart:
  first clusters, then galaxies, planets, people, atoms, nuclei...

→ all particles separated from all others

new and worse(?) cosmic fate: **the Big Rip**

the big rip foretold:

cosmologist W. Allen, *Annie Hall* (1977)

cosmologist H. Ramis, *Ghostbusters* (1984)

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

★ 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

$a_{m-\Lambda} = (\Omega_m/\Omega_\Lambda)^{1/3} \approx 0.75$

$z_{m-\Lambda} \approx 0.33$: "yesterday" $-$ after Earth born

`www:  cosmic epochs`

Nancy Kerrigan problem

$\rightarrow$ "Why me?" "Why now?"

$\rightarrow$ *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 (relativistic or not) can't to this:

$P_{\text{particles}} = w\rho$, with $w = \left\langle v^2 E \right\rangle / 3 \left\langle E \right\rangle \in [0, +1/3]$

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., $P_{\text{EM}} \sim (E^2 + B^2)/3$

- fields also store and transmit energy across space

  e.g., $\varepsilon_{\text{EM}} \sim E^2 + B^2 = 3P_{\text{EM}}$

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

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?

Note: 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 → single-valued object $=$ *function*

   no directionality → kosher with cosmo principle

field → 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 (Higgs!)
in cosmology: DE, inflation → can't avoid!

"Scalar fields are the cosmologist's blunt instrument."
        − J. Frieman