Astro 507
Lecture 17
March 4, 2020

Announcements:

- **Problem Set 3 posted, due this Friday March 6**
- Instructor F2F office hours 15 min after class today but online discussion available
- TA Office hours noon-1pm Thursday

No Class Meeting Friday

Instead: **Lecture Video Online**
along with usual notes, webpage

Next Monday March 9: back in class
will assume you have watched Friday's lecture!

also: jokes!

Dark Energy: The Story Thus Far

Embarrassing anecdote: BDF ASTR 100 circa 1999–2000

Last time: implications of cosmic acceleration

Q: three basic explanations?

Q: what is needed if we keep Friedmann?
Q: simplest way to do this?

ignorance parameterized–*dark energy*
Q: why dark energy?
Q: connection between Λ and dark energy?
Q: definition, units, significance of w?

cosmic acceleration demands $\boxed{P < -\rho c^2/3}$

Cosmic pressure must be

★ non-negligible

★ **negative!** *Q: meaning?*

★ (for GR experts) violation of strong energy condition

$\rho + 3P \geq 0$ fails!

With $\Lambda \neq 0$, new term in both Friedmann eqs

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{\kappa c^2}{R^2 a^2} + \frac{c^2}{3}\Lambda \qquad (1)$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3P}{c^2}\right) + \frac{c^2}{3}\Lambda \qquad (2)$$

Λ Looms Large

acceleration demands $\Omega_\Lambda \sim 0.7$
roughly independent of CMB

- Einstein-de Sitter expectations of $\Omega_m = \Omega_0 = 1$
  totally ruled out!

- $\Omega_\Lambda \neq 0$: cosmo constant (or worse!) seems to exist!

- $\Omega_\Lambda \gtrsim 2\Omega_m$: U *dominated* by Λ *now*!

- *two mysteries seem related quantitatively:*
  CMB + galaxy clusters: $\Omega_0 - \Omega_m = \Omega_{other} \approx 0.7$
  SNe Ia: $\Omega_\Lambda \approx 0.7$
  a consistent picture of a bizarre universe!

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

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

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

Recall: cosmic first law is

$$d(\rho a^3) = -p\ d(a^3) = -w\rho\ d(a^3) \tag{4}$$

For constant w:

$$\rho_{\rm DE} \propto a^{-3(1+w)} \tag{5}$$

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)
for a flat universe with *constant* w:

`www: current limits`

$$w = -1.026 \pm 0.041 \quad \text{Scolnic, ..., Narayan et al 2018}$$

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

What if w not constant?
Empirical approach: Taylor expand

$$w(a) = w_0 + w_a\,(1 - a) \tag{6}$$

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

Dark Energy Equation of State: Evolution?

Changing w: 2-parameter fit

$$w(a) = = w_0 + w_a\,(1-a) \tag{7}$$
$$w(z) = = w_0 + w_a\,\frac{z}{1+z} \tag{8}$$

interpolates between w_0 now and $w_0 + w_a$ at early times

Scolnic, ..., Narayan, et al 2018 `www: plot`

$$w_0 = -1.007 \pm 0.089 \tag{9}$$
$$w_a = -0.222 \pm 0.407 \tag{10}$$

consistent with *non-evolution* in general

∞ and a cosmological constant in particular

$$(w_0, w_a)_\Lambda = (-1, 0) \tag{11}$$

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 $\rho_{\rm de} \sim a^{-3(1+w)}$
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

$$(\dot{a}/a)^2 \approx \Omega_w H_0^2 a^{3\|w+1\|} \quad (12)$$

$$a^{-3\|w+1\|/2}\, da/a = \sqrt{\Omega_w} H_0 dt \quad (13)$$

Q: what's peculiar about this?

integrate to get future cosmic evolution:

$$a(t) = \left(\frac{t_r}{t_r - \Delta t}\right)^{2/3\|w+1\|} \tag{14}$$

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

$$t_r = \frac{2H_0^{-1}}{3\|w+1\|\sqrt{\Omega_w}} \tag{15}$$

is a timescale

Q: plot of a vs t?

Q: implications?

Q: how differs from, say, Λ case?

Cosmic Doomsday

Phantom energy domination

$$a(t) = \left(\frac{t_{\mathsf{r}}}{t_{\mathsf{r}} - \Delta t}\right)^{2/3\|w+1\|} \tag{16}$$

has $a \to \infty$ when $\Delta t = t_{\mathsf{r}} \sim 11\,\|w+1\|^{-1}$ 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 $\varepsilon_{\mathsf{de}}$ grows with time
eventually enclosed Earth-Sun dark energy $E_{\mathsf{de}} = 4\pi\, r_{\oplus}^3\, \varepsilon_{\mathsf{de}}/3$
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:

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

★ 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

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

$z_{\mathrm{m}-\Lambda} \approx 0.33$: "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 $w = \left\langle v^2 E \right\rangle / 3 \langle E \rangle \in [0, +1/3]$

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

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

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

– J. Frieman