Astro 507

Lecture 29

April 8, 2020

Announcements:

- **Problem Set 5 due Friday-ish**
  Revised (reduced) questions posted yesterday
  can post questions in Homework Discussion
  Question 4 may require Friday material
- Office Hours: by email, by appointment, or
  Instructor–after class Wednesday
  TA: noon-1pm Thursday (email)

Last time: particle dark matter–another example of freezout?

Today: shift gears–revisit the big picture

Cosmological Inflation

The Standard Cosmology: Successes and Discontents

"Standard Cosmology" – FLRW

▷ General Relativity with

▷ cosmological principle, and

▷ perfect fluid, endowed with

▷ laboratory physics: atomic, nuclear, particle

How's it going?

Q: what are qualitative, quantitative successes?

Cosmology Scorecard: Triumphs

Standard Cosmology successfully accounts for observed

$\star$ Hubble expansion
  also cosmic time dilation

$\star$ dark night sky (Olber's paradox)
  Q: why is this is a problem? how does FLRW resolve it?

$\star$ existence of a highly isotropic CMB
  with a thermal spectrum
  also its temperature redshifting

$\star$ primordial light element abundances
  ^{4}He to $\sim$ 10%
  D to $\sim$ 5%
  ^{7}Li to $\sim$ factor 3–4

A good list! Enough to inspire some confidence
...but pressing questions, loose ends, assumptions remain
Q: examples of outstanding questions?

Cosmic Loose Ends

Unexplained observations & unanswered puzzles

? what is the dark matter? why is $\rho_{\rm m}/\rho_{\rm B} \sim 7$ today?

? what is the dark energy? why is $\rho_\Lambda/\rho_{\rm m} \sim 2$ today?

? why is $\Omega_0 \approx 1$? **"flatness problem"**

? why is the CMB so isotropic
especially for angular scales $> \theta_{\rm horizon,recomb} \sim 1^\circ$
"horizon problem"

? why is the U so homogeneous on large scales?
*in*homogeneities on small scales?
"lumpiness problem"

Note:

- important questions but not *inconsistencies* per se
- suggests Standard Cosmology incomplete but not wrong
  points to new physics

Standard Cosmology: Quantitative Questions

Flatness Problem

Now: $\Omega_0 \sim 1$, i.e., $|\Omega_0 - 1| = 0.0005^{+0.00033}_{-0.00033} \ll 1$
(Planck 2013 + LSS!)
but Friedmann says

$$|\Omega - 1| \equiv |\Omega_\kappa| = \frac{c^2}{R^2}\left(\frac{1}{aH}\right)^2 = \frac{c^2}{R^2}\left(\frac{1}{\dot{a}}\right)^2$$

$|\Omega - 1|$ smaller in rad-dom, matter-dom past
at $z_{\rm rec} \sim 1000$, $\Omega_{\rm rec} = 1 \pm 10^{-6}$
at $z_{\rm BBN} \sim 10^{10}$, $\Omega_{\rm bbn} = 1 \pm 10^{-19}$
$\Rightarrow$ *what made the Universe this flat?*

Horizon Problem

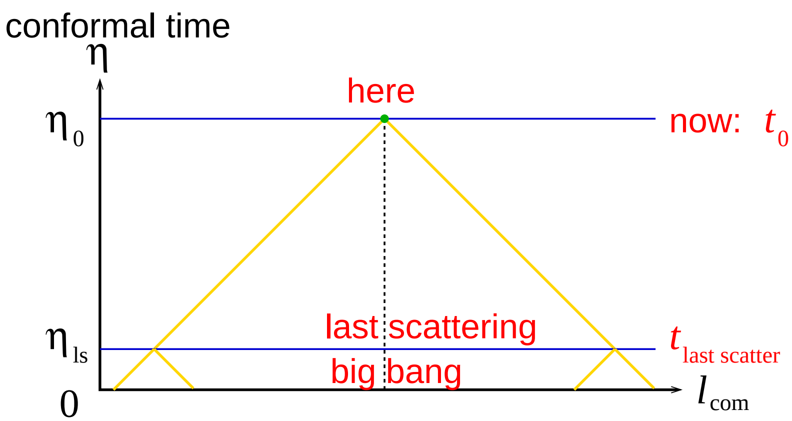
angular size of particle horizon at recombination (PS4):

$$\theta_{\rm hor,rec} \gtrsim 1^\circ \tag{1}$$

Q: implications for CMB regions $> 1^\circ$ *apart?*

CMB regions separated by angles $\theta_{\text{hor,rec}} \gtrsim 1^\circ$
lie outside each other's particle horizon
$\rightarrow$ *causally disconnected*

universe without inflation



so CMB sky surveys contains a number of regions

$$\frac{\Omega_{\text{sky}}}{\Omega_{\text{hor,rec}}} \sim \frac{4\pi}{\pi\theta^2_{\text{hor,rec}}} \sim 10^5 \qquad (2)$$

which are causally disconnected regions
$\Rightarrow$ *how did they become coordinated to $\Delta T/T \sim 10^{-5}$ level?*

Unwanted Relics

Particle theories beyond the standard model
bring trouble as well as benefits
$\rightarrow$ often predict relic particles we *don't* want

canonical example: grand unification (GUTs)
good news: naturally violate baryon number
  source of matter/antimatter asymmetry?
bad news: naturally predict magnetic monopoles
  unobserved, strongly constrained (lead to topological defects)
  $\Rightarrow$ no more than $\lesssim 1$ per horizon today

If GUTs correct, monopole production seems unavoidable
∞ $\Rightarrow$ *how did the U. get rid of monopoles?*

Beyond Standard Cosmology: Inflation

Part I: Abstract Inflation

The basic idea:

Imagine the early U. experienced a phase of

accelerated expansion, huge ($\sim e^{60}$) increase in scale factor a

if so:

several cosmological birds killed with one stone

Q: which problems, how fixed?

Inflation: the Magic of Acceleration

Flatness Problem

qualitatively: inflate away the curvature

⋆ curvature scale $R(t) = a(t)\, R_0$ hugely enlarged

Friedmann curvature term $\kappa/R(t)^2 \rightarrow 0$

⋆ departure from flatness $|\Omega - 1| \equiv |\Omega_\kappa| \sim 1/R^2\dot{a}^2$

changes as $d/dt\ |\Omega_\kappa|\ \propto \ddot{a}$

$\Rightarrow$ **acceleration** drives $\Omega \rightarrow 1$!

but note: then lumpiness problem worse! (for now)

Q: what about horizon problem?

Solving the Horizon Problem: Physical Picture

horizon problem:
seemingly causally disconnected regions on CMB sky
observec to have same T

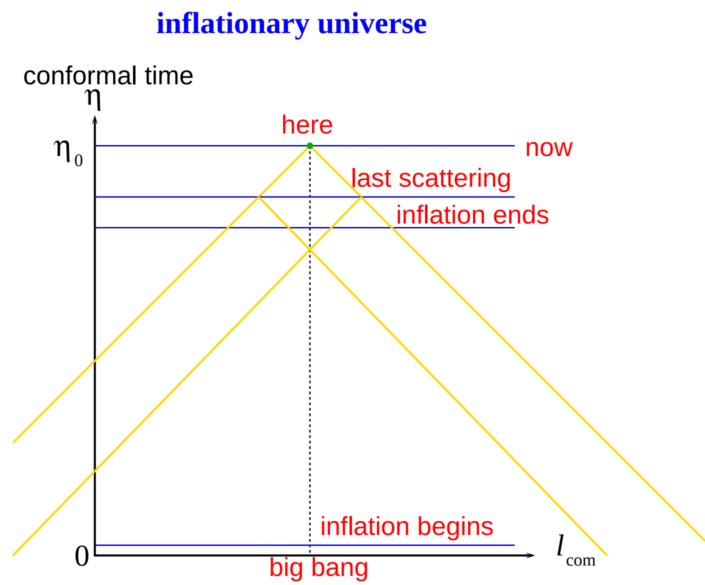
inflation solution:
all these regions are really causally connected!

basic idea:
entire *observable Universe post-inflation*
was *microscopically small pre-inflation*
when it was causally connected

then inflation expands this microscopic region
to cosmologically large scales

Solving the Horizon Problem: Spacetime Picture

spacetime plot is *conformal time* $\eta = \int_0^t dt/a(t)$
versus comoving distance $r_{\rm com}$



inflation: over tiny timeframe Δt,
scale factor $a(t)$ grows by $a_f/a_i \sim e^N$
with $N \approx 60$ "e-foldings"
growth during infation: $\sim$exponential

$$\delta\eta \approx \frac{1}{a_i} \int_0^{\Delta t} \frac{dt}{e^{Ht}} \sim e^N t_f$$

$\Rightarrow$ huge growth in conformal time during inflation
due to acceleration (exponentiation)

Q: but how to make early U accelerate?

Intermission: Hall of Famers

Interlude: The Physics of Fundamental Fields

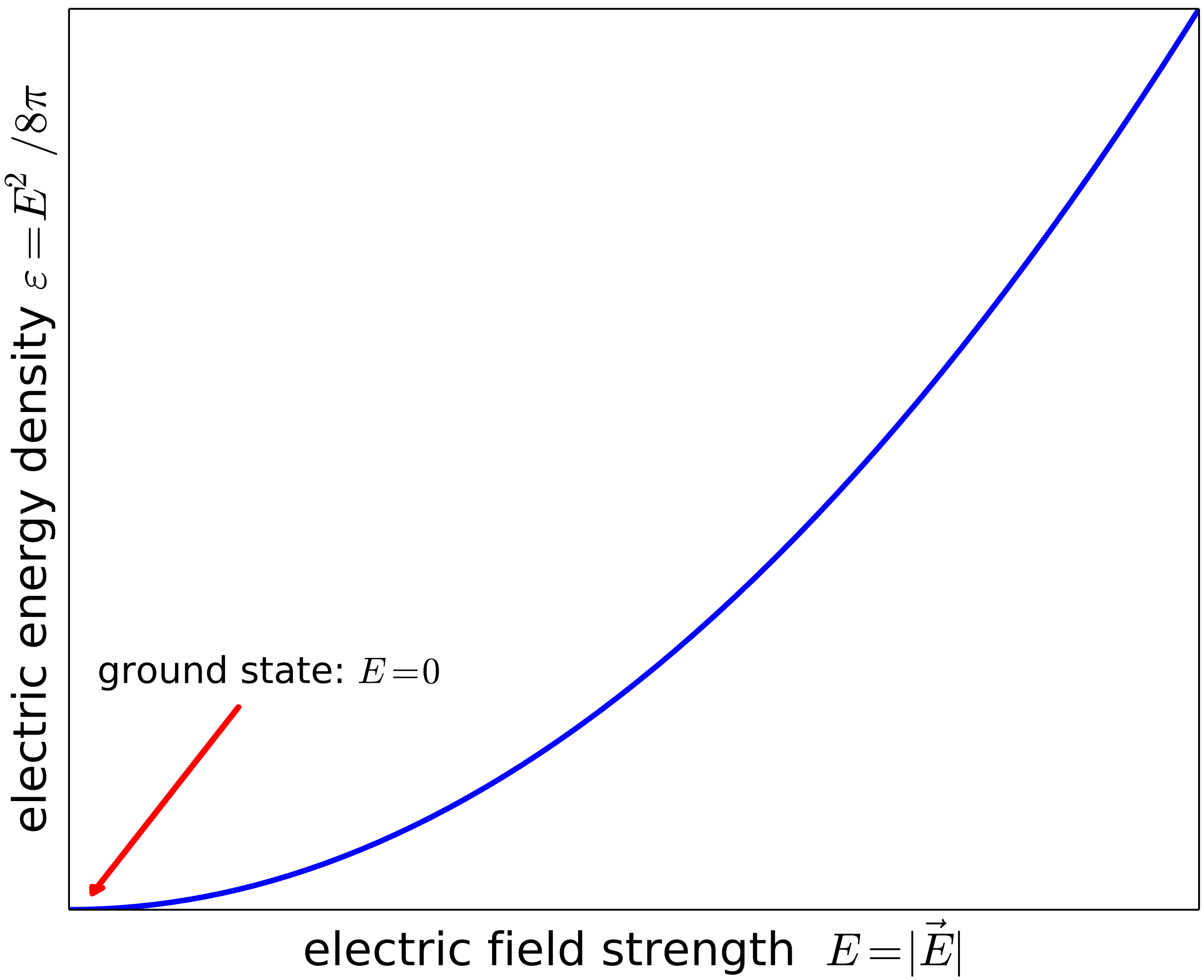
recall: there are four known fundamental forces
each have associated fields and particles
Note: existence of graviton particles not yet directly tested

electromagnetic interaction – a familiar case study

Classically: electric and magnetic fields fill space

- at every time t and every time point $\vec{r}$ in space (=all spacetime) has **field vectors** $\vec{E}(\vec{r}, t)$ and $\vec{B}(\vec{r}, t)$
- field dynamics: Maxwell, e.g., $\partial_t \vec{E} = -c\nabla \times \vec{B}$
- field energy density: $\varepsilon_{\rm EM} = (E^2 + B^2)/8\pi$
  (true) vacuum = ground state = minimum energy *Q: namely?*
- field pressure: $P_{\rm EM} = \varepsilon_{\rm EM}/3$

Q: classical EM-like (vector) fields problematic for cosmo–why?


electric energy density $\varepsilon = E^2\ /8\pi$
ground state: $E = 0$
electric field strength $E = |\vec{E}|$

Quantum mechanically: excitations above vacuum *quantized*

- i.e., excitations are in discrete *field quanta*
- these are particles: photons–EM force carrier!

Generalize:

- each fundamental interaction has a classical field
- ground state of classical field is vacuum
- excitations are quantized into force carrier particles
  note: in EM and Strong interactions, quanta are massless
  but Weak quanta are massive: $W^{\pm}$ and Z^0 bosons

Scalar Fields

Now introduce a new fundamental interaction ("fifth force")

classical field: a *scalar* $\phi(\vec{r}, t)$
a single-valued function at each point of spacetime

simplest case: ϕ only interacts with itself

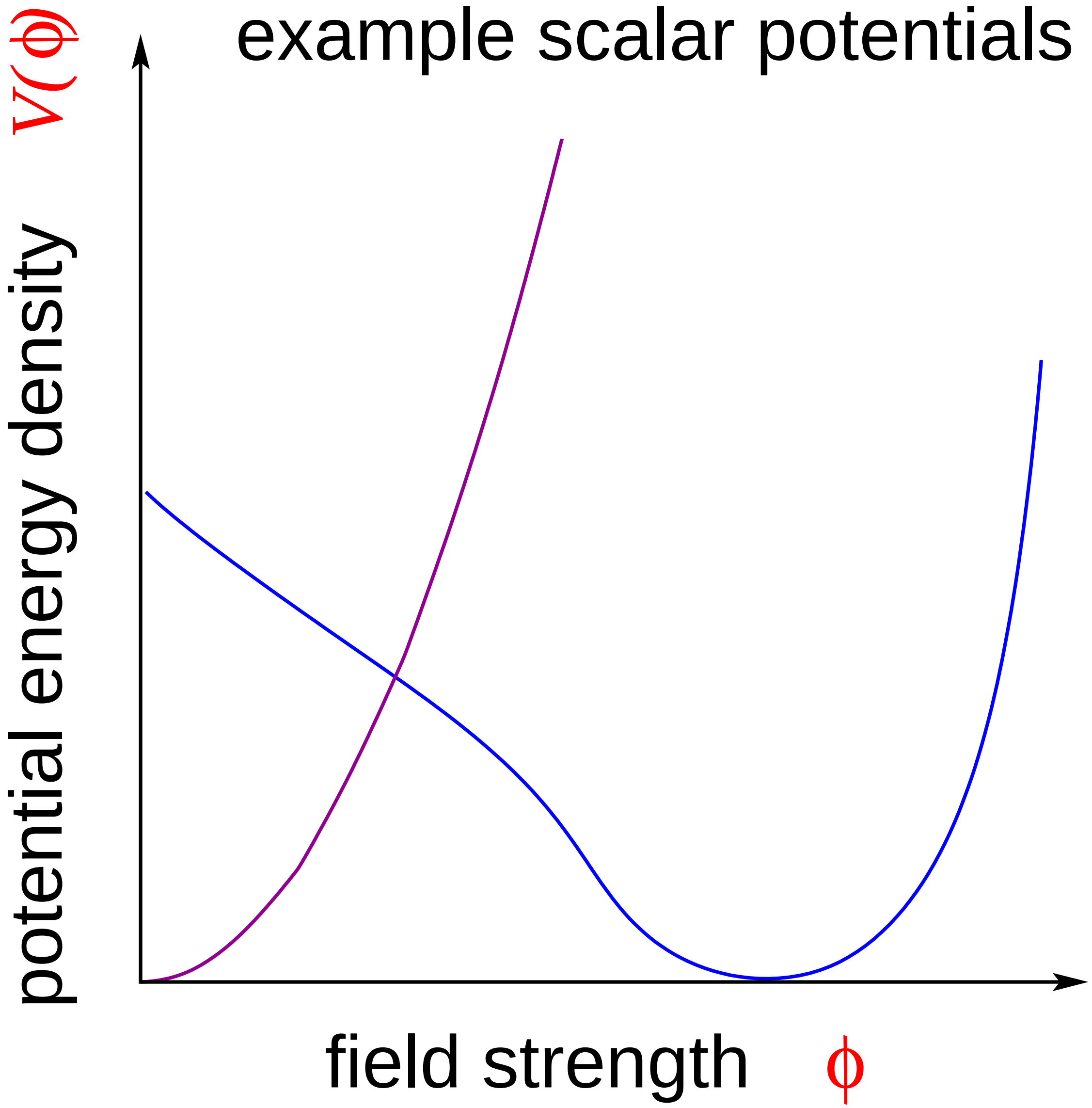
- scalar energy density

$$\varepsilon = \frac{1}{2}\dot{\phi}^2 + V(\phi) \tag{3}$$

kinetic term depends on time change
potential describing self-interaction:
examples: $V(\phi) = m^2\phi^2/2$, or $V = \lambda\phi^4$

- scalar pressure – note crucial sign flip

$$P = \frac{1}{2}\dot{\phi}^2 - V(\phi) \tag{4}$$



example scalar potentials
potential energy density
V(ϕ)
field strength
ϕ

Inflationary Cosmology

recall from Dark Energy discussion: acceleration demands $P < 0$
can't do this with matter or radiation

But:
★ *scalar field* ϕ can have $P_\phi < 0$
★ scalar fields *required* for electroweak unification
and appear in all other unification schemes

Alan Guth (1981)
if early Universe
▷ contains a *scalar field*,
▷ whose *potential energy dominates*: $\rho_\phi \approx V_\phi \approx \rho_{\text{tot}}$

then (in 21st century language) $w_\phi \to -1$
$\rightarrow$ *cosmic acceleration and exponential expansion!*

Director's Cut Extras

From Outer Space to Inner Space:
Other Triumphs and Questions

Elementary particle physics also has Standard Model

⋆ Incorporates (via quantum electrodynamics) non-rel QM
inherits successes of atomic physics ($\sim$ eV scales)

⋆ Incorporates (via quantum chromodynamics) nuke physics
inherits successes at $\sim$ MeV scales

⋆ all lab experiments understandable in terms of
3 families of quarks & leptons
4 fundamental interactions (strong, weak, E&M, gravity)

⋆ E&M and weak forces can be *unified*: "electroweak"
understood as low-energy asymmetric manifestation
of one high-energy symmetric interaction
i.e., at $E \gtrsim 100$ GeV, EM & weak have same coupling, strength
cost: invent new *scalar field/spin-0 particle*: Higgs
without Higgs: massive photon, massless electron!
with Higgs: unification, precision: agree w/ expts to $< 1\%$!

Beyond the Standard Model of Particle Physics

July 5, 2012: Higgs discovery announced!
Nobels distributed 2013!
last particle of Standard Model accounted for
$\rightarrow$ *if other particle every found: new physics*

Spectacular successes raise questions:

- is Higgs a fundamental particle or composite?
- why 3 families?
- why particles masses, interactions?
- why is matter fermionic, force carriers bosonic?
- are other unifications possible?

$\Rightarrow$ Standard Model not wrong but incomplete!

Note similarity to Standard Cosmology: more than coincidence?
solutions might indeed be related
e.g., new interactions, particles $\rightarrow$ dark matter candidates

Particle Standard Model points beyond itself
motivates theories to explain observed patterns

- Supersymmetry (SUSY): boson-fermion symmetry
- unite strong + electroweak: "grand unification theory" (GUT)
  - ⋆ interaction strengths change with energy
  - ⋆ same at $E_{\mathrm{GUT}} \sim 10^{15}$ GeV
- unite gravity too: quantum gravity/string theory
  scale: Compton wavelength (QM) $\sim$ Schwarzchild radius (GR)
  when $E \sim M_{\mathrm{Planck}} = \sqrt{\hbar c/G} \sim 10^{19}$ GeV
  $r \sim 10^{-33}$ cm, $t \sim 10^{-43}$ s: Planck scale

All have major cosmological consequences

▷ e.g., SUSY: essentially *demands* WIMPs!
  a problem if not discovered soon!

▷ but also, present cosmo puzzles more severe
  in Early Universe: worth quantifying more precisely
  since maybe Early U also offers solution