To Do Today

☆ Hand in assignment
☆ Class discussion: the “pro” side of the anthropic principle
☆ Dark Energy finale: the future
☆ End of class: 10 minute essay on the anthropic principle.

Final Project

☆ Essay 7: prep work, rough draft, and final draft worth 20 points.
☆ 6-8 pages presenting an argument about the anthropic principle.
☆ Rough draft due Tuesday, April 21st
☆ Peer review on Thursday, April 23rd
☆ Final draft due Thursday, April 30th (last day of class)

Conferences

☆ Sign ups next time
☆ Will be Monday afternoon, Tuesday morning, and Wednesday afternoon
☆ Check your schedules!
☆ Weekend assignment will be a proposal due at the conference
☆ See online; we’ll go over it and start putting it together next time!
☆ After conferences are over, I’ll be available in office hours and for scheduled meetings!

Rough Draft

☆ Longer essays
☆ Would you prefer that I respond to them via email so that I can turn it around quicker?
☆ Track changes/send back a PDF
Class Discussion
☆ When you were looking for articles that portrayed the anthropic principle in a positive light, what did you find?
☆ What did your articles and their arguments have in common?
☆ Did you find anything really interesting?

Group Discussion
☆ Groups:
☆ Justin, Yan, Ryan, Rashik
☆ Sam, Meghan, DJ, Nicki
☆ Dipesh, Jonathon, Dan, Faheem
☆ John, Colleen, Eli, Ethan

Group Discussion
☆ Share your summaries
☆ What was good about the articles you found?
☆ What was not so good or was missing?
☆ What more do you think you need to find before you have what you need to write your essay?

Group Discussion
☆ Talk about your essays
☆ Right now, what are you thinking about discussing in your essay? What do your peers think?
☆ How will you come up with your thesis statement?
☆ How will you make an argument?
☆ Does your idea have 6-8 pages worth in it?
☆ Do you have any questions that your peers can help you with?
Pro Anthropic Principle

How to come up with an essay topic?
- Look at the list of possible topics I handed out last time. There are lots of ways to go.
- Do you think the anti-anthropic arguments are going too far or taking it too seriously? Can you pick just one version that you support and make an argument for it? Can you make an argument about why one version makes sense but another doesn’t?
- How do you come up with evidence for an argument that science has no evidence for?
  - Remember, this is a class from a science department, but you’re not scientists!
  - I’m not expecting you to discover the multiverse!
  - Evidence means information, explanation, quotations from experts, or any other convincing bit of argument. It doesn’t have to be “a piece of multiverse,” just a coherent explanation of your point and why someone else should think about your POV.
  - In this case, “evidence” might come from a source that we might not read in this class, so you might need to expand outward from the journals and magazines (Science, Nature) that we’ve been focusing on so far.
  - If you have a topic but are having trouble finding sources, please let me know and I’ll help!

Dark Energy

- Are supernovae the only ways to find dark energy?
- SNe: Rare, hard to catch, dimmer with distance
- Plus, we want to be able to see whether dark energy EVOLVES so we need a lot more data!
- What we need:
  - A distance
  - A redshift
  - ... So that we can make a timeline of the expansion history of the Universe
- Note: this is just for fun!

Expansion of the Universe

- Redshift measurements tell us that all the galaxies are moving apart from each other . . .
- The universe is expanding!

- If the pennies are galaxies, it turns out that they’re NOT randomly distributed at the time that they form
**Expansion of the Universe**

- Instead, they have some typical distance separation.
- We can use THAT as our distance measurement or “yardstick” and see how it changes with redshift.

**Initial Conditions**

- Oscillations between the Big Bang and the epoch of recombination produce the patterns in the CMB, but also affect the distribution of dark and baryonic matter.

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**Expansion of the Universe**

- This is great because galaxies are BIG and BRIGHT and we can see them very far away.
- But they are not standard candles!
Prediction of Baryon Acoustic Oscillations

- Acoustic signatures are formed by sound waves excited by perturbations in the early Universe.
- At recombination, the sound speed decreases dramatically, ending the wave propagation.
- The modes of oscillation are "frozen in".

\[ c_s = \frac{c}{\sqrt{3}} \sim 0.57c \]

Cosmological Relevance

- Dark matter dominates.
- \( \sim 150 \) Mpc scale is seen as only a little "bump".

\[ \frac{\delta}{\delta z} \]

Overdensities in dark matter and in the baryon shell both become sites for future galaxy formation.
Cosmological Relevance

“Smoking gun” evidence for the theory of linear growth of structure

Further evidence for the necessity of dark matter at z=1000

Sample: Why is this hard?

46,748 Luminous Red Galaxies
3816 square degrees
0.72 h⁻³ Gpc³

Sample

☆ This is a spectroscopic sample, but LRGs are in general useful for photometric redshifts.

Strong 4000Å break

Future work can take advantage of photo-z’s to detect very large samples without costly spectroscopic followup.

4000 Angstrom Break in LR Ellipticals

☆ Old (11 Gyr) stellar populations
☆ Among the most luminous galaxies (visible to high z)
☆ Photometric redshifts can be determined with accuracies of σ_z = 0.03 for z > 0.55

Image credit: Padmanabhan et al, Bruzual & Charlot stellar population synthesis spectra
Utility of LRGs

☆ To trace Large Scale structure, you want to select a sample that
☆ Probes a large cosmological volume
☆ Is sufficiently dense to reduce shot noise
☆ Can be uniformly and completely selected over the volume of interest
☆ Is well-suited to spectroscopic redshifts (e.g., HI) or photometric redshifts (e.g., the Luminous Red Galaxies)

~50k Spectroscopic LRGs

☆ These are selected separately from the main SDSS sample
☆ Statistically complete
☆ Nearly constant comoving number density out to z=0.36, dropping thereafter
☆ Survey volume 0.72$h^{-3}$ Gpc$^3$
☆ Roughly 700 cubes of 100$h^{-1}$ Mpc size in the survey

Two-Point Correlation Function

☆ Probability that, once a galaxy is located, another galaxy will be found within a physical radius $r$ or an angular separation $\theta$.

$$dP = \bar{n}^2(1 + \xi(r,\theta))dV_1dV_2$$

☆ Measures the scale of clustering and the degree of clustering.
☆ BAO predicts that galaxies are slightly more likely to be separated by 150 Mpc than other separations.

What is a correlation?

☆ Correlation: a relationship between two or more variables
☆ Correlated galaxies will show up near each other, with specific patterns.
☆ As an example related to dark energy, if a correlation tells you that two galaxies are likely to form 150 Mpc away from one another, then you are likely to see a pattern of galaxies with typical separations of 150 Mpc when you look at the sky.
**What is a correlation?**

Question: which of the two galaxy distributions below has a correlation? Which is completely random?

Your brain is too good at finding patterns!
The left is “anticorrelated”: there’s a bubble where no galaxies are allowed near each point.

**Result**

In all models, $\Omega_b h^2 = 0.024$. The “no bao” model is shown for the case where all matter is CDM.

Peak at $100 h^{-1}$ Mpc at $z=0.35$, this corresponds to $6^\circ$ on the sky.
Tests for Systematic Errors

- Calibration
  - Selection of the sample is based on SDSS $g$, $r$, and $i$ bands.
  - Errors in calibration thus lead to errors in selection.
  - Errors in calibration along SDSS's scan direction could lead to large-scale angular correlations
    - None are found via a test for this, in which the survey volume is broken up into ten "slabs" and cross-correlations between non-adjacent pairs are measured.

Separate Redshift Slices

- Higher z sample is noisier, but the two correlation functions are similar and both show evidence for the acoustic peak. The similarity indicates that calibration errors are minimal.

Dark Energy Constraints

- Knowledge of $\Omega_m h^2$ limits our knowledge of $w$.
  - For $\Omega_m h^2$ known to 1% (i.e. Planck), $w$ could be constrained to 10% (assuming constant $w$).

- Geometrical evidence for the existence of dark energy
  - Completely inconsistent with a model lacking dark energy (would require an age of 8 Gyr)
Summary: Acoustic Peak as a “Smoking Gun”

- 3.4σ detection of the acoustic peak at 100h⁻¹ Mpc
- Scale and amplitude agree well with ΛCDM predictions.
  - Proof that oscillations occur (z=1000) and survive.
  - Dark matter must exist, because fully baryonic models produce very strong peaks.

Future Work

- Because the acoustic peak has been found to be a narrow feature, it can be used to probe the angular diameter distance to greater and greater redshifts.
- New application: LSS surveys can now potentially be used as a powerful probe for dark energy.

Why HI?

HI detections come with a redshift

By looking at different populations, we can try to understand (or ameliorate) selection bias

Always pays to try to detect baryonic matter rather than optical light

A future instrument like the SKA could be used to trace HI in a deep and wide FOV survey, increasing our ability to work with BAO.

10 Minute Essay

- Pretend (even if it’s not true!) that you believe the anthropic principle is scientifically valuable. Tell me:
  - Why you feel that way!
  - What sort of arguments could have convinced you
  - What you find to be the most convincing argument from the “anti” side and how you respond to it
Reading

Three articles that portray the anthropic principle in a *negative sense* (write summaries, just like last time)