C1

- expansion → ↓T → ↓ photoionization → ↑ HI
- Wien's tail of CMB blackbody spectrum
- ↑HI → ↓free e^- → ↓Thomson scattering → ↓opacity → photon-matter decouple → CMB

Recombination

Recombination was the period ($t \sim 380$ kyr, $z \sim 1100$) during which the universe transitioned from a sea of e^-'s and atomic nuclei (and γs) to neutral atoms as the temperature ($T \sim 3700$ K, ~0.3 eV) decreased due to expansion such that photoionization no longer occurred often enough to maintain the ionization fraction of H. The Saha eqn relates ionization fraction to T:

$$\frac{n_{i+1}}{n_i} \propto T^{3/2} \exp(-1/T)$$

The temperature had to fall far below the ionization T of H (~10^5 K, 13.6 eV) because the Wien's tail of the CMB blackbody distribution still contained a non-negligible # of γs able to ionize H, made even worse by the fact that γs outnumbered baryons ~$10^9:1$ (due to baryogenesis and resultant particle/antiparticle annihilation).

The process was not instantaneous. As recombination progressed, the # of free e^-s available for Thomson scattering, which kept γs and baryons in thermal equilibrium, decreased. This caused a drop in the opacity for the γs until the optical depth was low enough ($\tau \approx 1$) that photons could stream freely through the universe: The CMB. This corresponds to the surface of last scattering, when radiation and matter decoupled.

If the γ:baryon ratio was higher, there would be more ionization and thus recombination would happen later

If the ionization energy of H was lower, it would take longer to cool off significantly past this temperature (due to Wien's tail), so recombination would happen later.

- density of universe determines its geometry
- for flat universe, $\Omega_0 = 1$ and angles $\approx 1°$
- Measure density components of universe (SNe, tSZ, BAOs, grav. lensing) and angular size of CMB fluctuations.

C2

Flat Universe

- Properties
  - parallel lines don't converge or diverge
  - sum of angles in triangle = 180°
  - density of the universe = critical density $\left(\rho_c = \frac{3H^2}{8\pi G}\ ;\ \Omega_0 = \frac{\rho_0}{\rho_c} = 1\right)$

- By the Friedmann eqn, the density of the universe determines its geometry and tells us how the scale factor evolves over time.

$$H^2/H_0^2 = \Omega_r a^{-4} + \Omega_m a^{-3}\ \Omega_k a^{-2} + \Omega_\Lambda$$

$$\Omega_0 = \Omega_r + \Omega_m + \Omega_\Lambda,\quad 1 - \Omega_0 = \Omega_K \rightarrow \text{if } \Omega_0 = 1,\ \Omega_K = 0 \rightarrow \text{Flat!}$$

- By measuring the density of the universe we can determine the curvature. We can probe the different components many ways (C_ℓ spectrum of CMB, galaxy cluster distribution, etc). We can also look at the angular scale of CMB fluctuations, which depend on the universe's geometry.
  - if the universe was ⊕'ly curved, the peak of the CMB C_ℓ power spectrum would occur at larger angular scales (lower multipoles) and if it was ⊖'ly curved, the peaks would be at smaller angular scales (higher multipoles)
  - since the expansion rate evolves differently for different densities, we can also use Type Ia SNe to map distance to z and infer Ω_0.

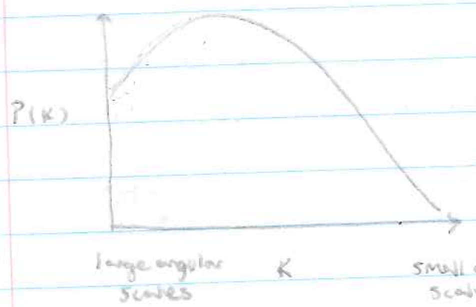
- The universe must have been even flatter in the early universe, as even slight deviations in the density would've changed our expansion significantly by now. Inflation solves this flatness problem by flattening everything out through exponential expansion, so it didn't matter how curved the universe was pre-inflation.

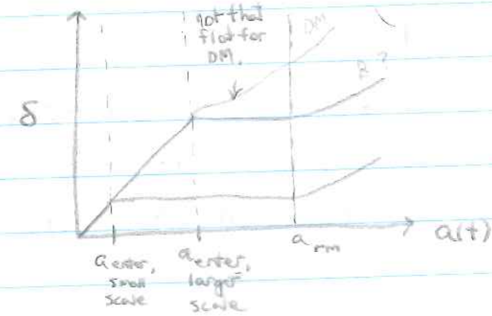
$$\Omega = 1 + \left(\frac{Kct_0}{a(t)}\right)^2 \qquad \text{if } a \sim e^t,\ \Omega \approx 1, \text{ so } K \text{ isn't important.}$$

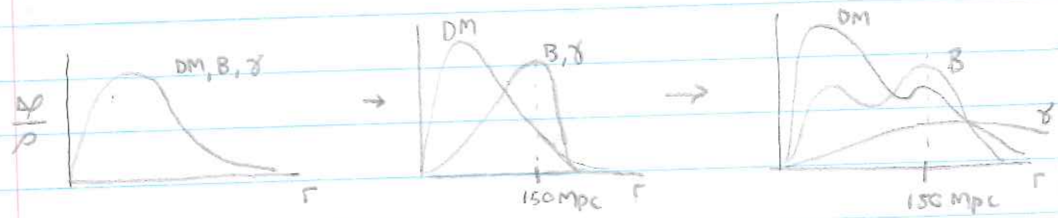
• density perturbations start to grow on all scales
• as the horizon expands to encompass them, grav. coupling to γ-B fluid damps out DM fluctuation
• peak corresponds to max growth in rad. era before being encompassed & slowed in matter era.

C3

• CDM spectrum of density fluctuations





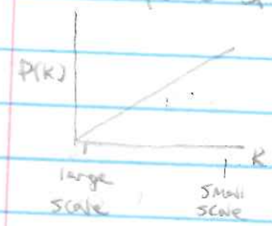


• The 1st part of the power spectrum follows basically a linear power law (Harrison-Zeldovich spectrum), where density fluctuations on large scales have just increased in power over time, starting from P(k) = 0 and rising. The peak corresponds to the angular scale at which the density perturbation was encompassed by the horizon at the same time as the matter-radiation energy density equality (50 kyr), so these modes (?) had the longest possible time to grow. At smaller angular scales, the power is lower, because these have been damped out by the diffusion of γs and stuff.

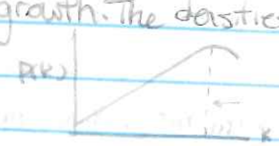
• I think that the smaller scales are lower power because these modes entered the horizon sooner, and were grav. coupled to the baryons and photons, slowing their density growth as the baryons & photons pushed outward and tried to pull the DM into their potential well. The angular scale at which the most power is output corresponds to a size that would only just have reached the horizon when the energy density (and thus expansion) of the universe switched from radiation to matter dominated, and would have had maximal growth in the radiation era. Perturbation theory tells us that the density perturbations grew as a^2 during this time. In

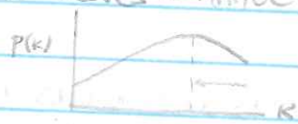
the matter dominated era, perturbations grew linearly with $a(t)$. So any fluctuations that entered the horizon at later times (post a_{rm}) would not grow as quickly. The initial part of the power spectrum will just look like the initial power spectrum (linear power law) with higher amplitude as the density perturbations grow over time.
IDFK I HATE THIS LEMME TRY AGAIN.

• initial power spectrum = linear, Harrison-Zeldovich:



• As the horizon grows to encompass progressively larger scales, the DM is gravitationally coupled to the baryon-photon plasma, which damps out the DM density growth. The densities on all scales continue to grow.





• When the energy density of the universe flips over from radiation dominated to matter dominated, there's a specific angular scale associated with the size of the horizon.

YES THAT'S A TEAR STAIN

As time continues, eventually the baryons have fallen as far into the DM over densities as they ever will, so as the horizon expands there isn't a lot of damping happening on the angular scales being encompassed by the horizon, probably, but IDFK.

Screw this question

- recessional velocities of galaxies
- CMB homogeneity and isotropy
- primordial abundances of elements predicted by BB theory.

C4

Big Bang evidence

Hubble's Law

- at large scales, all galaxies are receeding from us ($v = H_0 d$), implying the universe is expanding. If we extrapolate backward, there must have been a time when everything was much closer together. Hence, the Big Bang.

CMB

- thermal blackbody radiation from when baryons and photons were in thermal equilibrium. It's homogeneous and isotropic, implying that at some point the entirety must have been in causal contact and therefore the universe must have been much smaller and hotter in the past

$T = (1+z)T_0 = (1+z) \cdot 2.73\,K \therefore z \to \infty \Rightarrow T$ really hot

BBN

- subatomic particles combined to form the lightest elements first, as the universe expanded and cooled enough for the photon energy to decrease past the atomic binding energies
- by knowing / assuming the universe's initial conditions, and knowing the relevant interaction cross sections, you can calculate the expected primordial abundances of elements and compare to current measurements.

C5

- Universe isn't expanding → photons travel some distance → lose energy → change in p → blurring of distant sources → we don't see this
- Universe is expanding, but infinite in size and age → requires constant matter creation → violates conservation laws
- can't explain quasar distr. in z, CMB, Metal abundance

· Tired Light and Steady State Universes

· Tired Light
- rather than cosmological redshift (due to expanding space), photons lose energy as they travel, with an exponential dependence on distance
  $E = E_0 \exp(-d/R_0)$
- photons can't lose energy w/out a change in their momenta, which would lead to blurring of distance galaxies. This is observationally disproven.

· Steady State
- the universe is infinite in both size and age, and is homogeneous and isotropic on large scales. To keep the universe in a steady state requires constant creation of matter to account for the expanding universe (const. ρ)
- this violates conservation laws and can't explain the presence of quasars (more prevalent at $z \sim 3$), the CMB (light from ancient stars scattered by galactic dust... that was their solution), or the abundance of elements and lower metallicity stars at higher z.

Yup, TEARS

Hilroy

C6

- Deuterium Bottleneck – low binding energy and limited neutrons
- A = 5 road block – no stable nuclei and little D, ^3H, ^3He available
- A = 8 road block – no stable nuclei; expansion rate exceeds reaction rates

- Synthesis of Light Elements during BBN

- Deuterium acted as a bottleneck for further synthesis. Basically all of the neutrons were bound up in D, but D has a relatively low binding energy so its easy to photo dissociate. The temperature had to cool past $\sim 10^9$ K ($\sim$2 min?) before a significant fraction of D could be built up, and this was a race against neutron decay (w/ a half life of $\sim$10 min).

- After this ^4He forms rapidly, w/ a high binding energy making it very stable. Almost all D is converted to ^4He. Building heavier elements than this is difficult, since their is a road block at A=5. No stable nuclei exist w/ 5 nucleons. You can only make small amounts of Li via:

$^4He + D \rightarrow {}^6Li + \gamma$

$^4He + {}^3H \rightarrow {}^7Li + \gamma$

$^4He + {}^3He \rightarrow {}^7Be + \gamma \quad (\tau \sim 53\,d \rightarrow {}^7Li)$

- There is limited D, ^3H, and ^3He available, so you only get trace amounts of Li. Another roadblock occurs for A=8, since no stable nuclei exist here. Fusing higher elements is nearly impossible, since getting over this bump is tough and the reaction rates are quickly being exceeded by the rate of expansion until further synthesis is not possible.

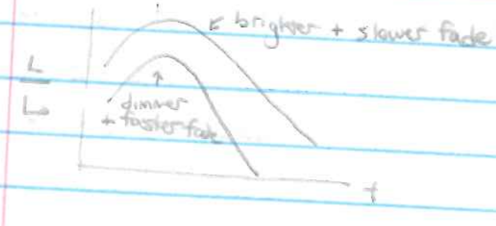
- 75% H, 25% He, Trace Li

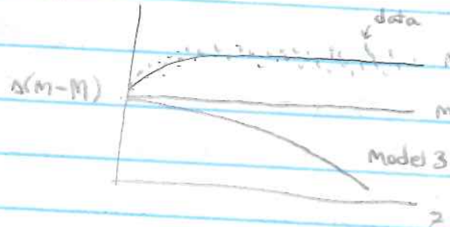
C7

- M related to light curve shape
- get $M, m \rightarrow d_L \rightarrow z$
- shape of $\Delta(m-M)$ v. z varies w/ choice of cosmological parameter values

Type Ia Supernovae

- The absolute magnitude of a Type Ia SN is directly related to the shape of its light curve. By measuring the light curve shape we can determine the absolute magnitude and use this (plus the apparent mag) with the distance modulus to measure their distance. This allows us to trace the expansion of the universe, because we can plot their $\Delta(m-M)$ as a function of z and compare to models w/ different cosmological parameters, like Ω_m and Ω_Λ.





- The luminosity of Type Ia SNe is almost uniform, but does have some variance as SN explosions aren't all the exact same. To get them to be useful as standard candles, we have to account for their <u>'stretch factor'</u>, which standardizes the peak luminosity based on the stretched-out-ness of the light curve relative to some template. The <u>Multicolor light curve shape</u> (MLCS, how the light curve changes for ~15d post peak brightness) allows us to compare the observed light curve to a parametrized one to get the peak L. It allows the reddening and dimming / extinction effect of ISM dust to be detected and removed.

- I believe the difference in decay times for different light curves is due to the abundance of ^{56}Ni. This decays into ^{56}Co & ^{56}Fe, which leads to a slower decline as $\uparrow$ opacity $\rightarrow \uparrow T \rightarrow \uparrow$ peak L ...? ^{56}Ni: $\tau \sim 9$ days, releases energy during decay

- Apparent SNe at $\uparrow z$ look brighter... $D_L \sim \frac{c}{H_0} z \sim \sqrt{\frac{L}{4\pi F}}$

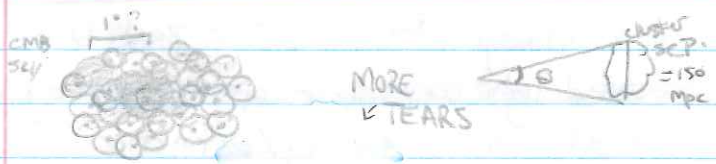
C8

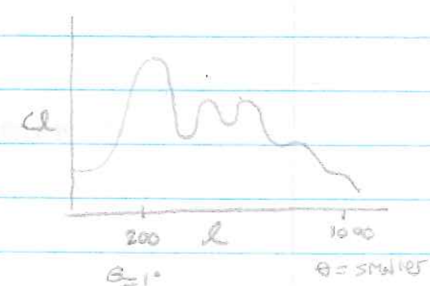
- BAOs result from density fluctuations and produce structure on 150 Mpc scale → can be used as standard rulers
- Use BAOs to probe density of baryons, DM, γs, and use angular size to get flatness → Ω_0
- C_ℓ spectrum describes amplitude of T fluctuations on different scales, can be used to determine density of baryons, DM

Determining Cosmological Parameters Observationally

BAOs

- Initial quantum fluctuations in the early universe resulted in slight over- and under-densities growing as the gravitationally coupled DM & photon-baryon fluid fell inward. The resulting compression produced a bit of heating until radiation pressure pushed the baryon-photon fluid outward. This produced sound waves that oscillated due to the interaction b/w pressure and gravity. The characteristic distance these sound waves could travel before recombination, when the photons de-coupled and the baryons were left in a shell around the DM over densities, was 150 Mpc. We thus expect an increase in the amount of structure we see in the universe at this separation.
- This makes BAOs useful as a standard ruler. We can measure the average separation b/w galaxy clusters, which would've formed at the over-density locations, and use that to probe things like the baryon to photon to DM ratio. By looking at the angular size of the large scale structure we probe the flatness of the universe, which tells us about Ω_0.





Angular Power Spectrum of CMB

- The CMB map is a superposition of BAO shells, w/ the temperature anisotropies resulting from the level of compression/expansion that the baryon-photon fluid underwent before decoupling. Since the oscillations arise from spherical harmonics, we can express the temperature fluctuations in terms of them, and determine their average amplitude at different scales (ie the power spectrum, C_ℓ v. ℓ). The temperature variation will be highest at maximum compression at the time of decoupling, which explains the 1st peak. There will also be a large temperature anisotropy if the BAO reaches

Maximum expansion at decoupling, producing the 2nd peak. Because the DM pulls the baryon-Photon fluid in more during compression, the 2nd peak is lower than the 1st. By comparing their relative heights we can learn about Ω_m, and by comparing 2 and 3 we can learn about DM. The location of the 1st peak (ie its angular scale) tells us about curvature. It would shift left/right if the universe was positively/negatively curved, respectively.

↑
larger angular scales

- Also weak gravitational lensing but fck that.
- Also CMB foregrounds like SZ and ISW effects

C9

- Density perturbations → development of quadrupole moment → higher intensity on one axis → linear polarization
- Can be due to infalling matter or grav. waves
- Need instrument w/ polarized antennae to measure E field direction of photons.

CMB Polarization

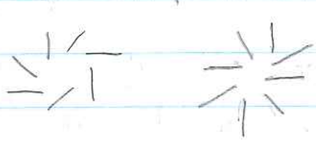
- The density (and thus T) fluctuations produce a local quadrupole moment that results in more radiation coming toward an electron along one axis than another (higher intensity). Thomson scattering produces linearly polarized light when the electron interacts with this radiation. The quadrupole can come about 2 ways:

- as an electron falls into a grav. potential well (a hot spot), the neighboring fluid looks like this:

So a quadrupole moment develops. You can also think in terms of a T quadrupole: cold Hot • Hot cold

This results in scalar E modes, which produces a polarization pattern directed radially away from cold regions and tangent to hot regions.

- as primordial gravitational waves stretch and squeeze space, they affect the density of the photon-baryon fluid as well. These tensor B-modes produce a polarization pattern with a 'handedness' that spirals out from the temperature fluctuations



- Measuring polarization requires a detector with polarized sensors to measure the electric-field components of the CMB. BICEP2 had 2 antennae (?) polarized in different directions, then thought they were seeing CMB B-modes but were actually seeing polarization due to galactic dust.

- TSZ effect increases CMB T on large scales due to hot ICM, w/ typical separation of 150 Mpc. Will increase amplitude of 1st peak and inform you about Ω_m
- ISW effect increases CMB T on large scales due to gravitational red shift, expanding universe. Tells you about expansion and Ω_m

C10

CMB Foregrounds

- A lot of stuff messes w/ the CMB photons on their journey to us. A lot of those things are just various forms of galactic stuff, like synchrotron radiation and dust, but some can tell us about cosmological parameters.

- Thermal Sunyaev-Zeldovich effect
  - As CMB photons travel through the hot ICM of a galaxy cluster, they undergo inverse Compton scattering and gain energy from the relativistic electrons they encounter. This shifts the Planck spectrum of the CMB so there are fewer photons at low frequencies and more at higher ν. This will lead to regions of slightly higher temperature wherever the cluster is located in the CMB sky. Since clusters are generally 150 Mpc apart, the SZ effect will increase the amplitude of the 1st peak of the C_ℓ spectrum, informing us about Ω_m.

- Integrated Sachs-Wolfe effect
  - As CMB photons travel toward us they can encounter regions over over-(and under)-densities in the universe, and will fall into their grav. potential wells. When they fall in they gain a little bit of energy, but as they climb out, the universe's expansion reduces the strength of gravitational well, so it requires less energy to escape. The photons will thus gain energy on their passage through overdense regions, appearing as hotter spots in the CMB (similar to SZ). Underdense regions will result in the opposite effect. The ISW effect thus tells you about large scale structure (ie what causes the density region [OR VICE VERSA B/C FML]) as well as the expansion of the universe.

- Also polarization due to epoch of reionization, which I guess informs you about the optical depth at EoR which is a cosm. parameter.

C11

- Expansion of true vacuum bubbles in the false vacuum universe was driven by false vacuum's ⊖ ε, so expanded exponentially with time
- Solves magnetic monopole, horizon, and flatness problem

- Inflation

- At ~10^{-36} s the universe underwent a period of exponential expansion. The idea is that prior to inflation, the universe was in a weird false vacum state where it had supercooled while remaining in a high energy density state (ie not the preferred energy state w/ lowest energy). Due to tiny quantum fluctuations, small regions of space would actually be in the true vacum state. These regions would've started expanding rapidly, since the false vacum had a negative pressure and the true vacum had zero pressure (zero > negative ⇒ expansion). So the negative pressure (and thus const. energy density) of the false vacuum dominated exponential expansion. by like 10^{30}.
  ↑ like dark energy in today's universe, $a \sim e^t$

- Magnetic Monopoles
- Monopoles are expected to be very prevalent in the universe, since they would occur any time there was a defect in the quantum field following the break up of GUT force. With inflation, these monopoles can be described as remnants of the false vacum, still w/ high energy density and thus a lot of mass. Such defects would exist on the boundaries of the true vacum bubbles, so when inflation caused exponential expansion these monopoles became far removed from what we can observe today.

- Flatness Problem
- our universe is incredibly flat, so much so that it must have been even flatter in the past otherwise the universe would have deviated significantly away from flatness by this time. Inflation solves this by exponental expansion. The curvature of the universe was flattened out by the expansion so that the initial curvature is irrelevant.
  $\Omega = 1 + \left(\frac{kct}{a}\right)^2 \rightarrow a \sim e^t$ so k doesn't matter, second term → 0, $\Omega = 1$.

- Horizon Problem
- the CMB appears to be homogeneous & isotropic on large scales, implying every part of it was in thermodynamic equilibrium at some

earlier time. However, with the original Big Bang model, there would be no way the entire universe could have been in causal contact at the time of

BB? → recombination. Inflation suggests every part of our universe was in causal contact prior to the expansion, and thus in thermal equilibrium, which is why the CMB looks smooth on large scales - inflation spread everything out so that any inhomogeneities lie far outside our observable universe.

- The universe has to have very specific values for us to observe it / exist
- We exist because the universe was tuned specifically for us
- The universe is too flat

C12

- Fine Tuning and the Anthropic Principle

- The fine tuning problem is that the universe appears to require very specific values for its fundamental constants in order to allow us to exist and observe it to have such values. For instance, the flatness of the universe. Right now it's $\Omega_K = 0 \pm 0.02$, and scaling that back to Planck time implies flatness to 1 part in 10^{60}. That's WEIRD.

$1 - \Omega_0 = \Omega_K$

- The anthropic principle attempts to resolve this by saying that we can only exist in a universe with such specific parameters, otherwise we wouldn't be able to observe it, so it shouldn't be that surprising that the parameters are finely tuned. Perhaps we're but one possibility of many. Or, stated even more strongly, perhaps the universe is made for us, so it's inevitable that intelligent life should arise to observe the universe with such parameter values.

I think this is stupid and implies that humans are special in some way when really we all suck and it's just chance that we developed in the first place.

C13

- 2PCF describes prob of finding galaxies w/ some separation
- Related to Power Spectrum via Fourier transform
- C_ℓ's relate to low z galaxy clustering via 2ndary anisotropies, like ISW, + SZ, grav. lensing.

Two-Point Correlation Function

- The 2PCF describes the likelihood of finding a galaxy at point X given that another galaxy exists with some characteristic separation. Worded differently, given some distance, what is the probability of finding 2 galaxies separated by that distance?

$$\xi(r) = (r/r_0)^{-\gamma}, \quad \gamma \approx 1.7$$

- If galaxies are more concentrated, $\xi(r) > 0$, and v.v.

- The 2PCF is related to the power spectrum via Fourier transform:

$$P(k) = 2\pi \int_0^\infty dx\, x^2 \frac{\sin(kx)}{kx} \xi(x)$$

- We can measure the correlation/separation b/w galaxies and determine the functional form of the 2PCF, which we can then use to describe the level of structure we see on different scales in the form of the power spectrum. So we can use one to determine the other.

- The relevance of low z galaxy clustering to the C_ℓ spectrum of the CMB is through secondary anisotropies. Low z galaxies can produce changes to the spectrum via the ISW effect, the SZ effect, and grav. lensing (that one effects higher multipoles, small angular scales).

C14

- Friedmann eqn describes $\dot{a}$ w/ Ω
- eventually Ω_Λ dominates as $a \uparrow$
- Draw current model

- Expansion with a positive cosmological constant Λ

- Starting from the Friedmann equation:

$$\left(\frac{\dot{a}}{a}\right)^2 = \left(\frac{H}{H_0}\right)^2 = \Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_K a^{-2} + \Omega_\Lambda$$

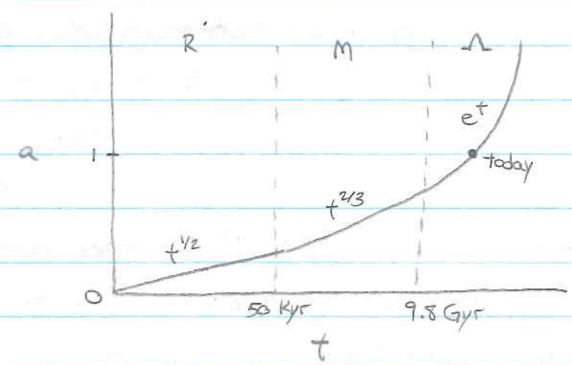
- Eventually, the scale factor will grow large enough that the 1st three parameters will approach zero and only Ω_Λ will matter. In this case:

$$\frac{\dot{a}}{a} = \sqrt{\Omega_\Lambda}$$

$$a(t) = \exp^{\sqrt{\Omega_\Lambda}\, t}$$

$$\therefore \boxed{a(t) \sim e^t}$$

- Current model of the universe:



$\Omega_m \approx 0.3$

$\Omega_\Lambda \approx 0.7$

$\Omega_r \approx 10^{-5}$

- Scale factor when radiation = matter:

$$\frac{\Omega_r}{a^4} = \left(\frac{\dot{a}}{a}\right)^2 = \frac{\Omega_m}{a^3}$$

$$a = \Omega_r / \Omega_m$$

$$= 10^{-5} / 0.3$$

$\therefore$ very small!

C15

- First stars and galaxies/AGN reionize universe by photo ionization
- See evidence in metal lines of quasar spectra, GP trough, 21 cm line strength, increased CMB polarization

Epoch of Reionization

- The reionization of the universe was due (almost exclusively) to photo-ionization processes. Collisional ionization can be ruled out, since the IGM wasn't hot enough for efficient collisional ionization. Reionization took place from $z \sim \overset{?}{12} - 6$.

- As baryons fell into the DM wells, the gas needed to cool to form the 1st stars. This was accomplished mostly by H_2 cooling. The 1st stars (Pop'n III) would have been a lot hotter and brighter due to their lack of metals, as metals increase opacity. The higher L meant they were efficient sources of ionizing photons, but also had shorter lifetimes. These massive stars ionized the H in bubbles around them, ironically destroying the H_2 capable of further cooling and thus continued star formation. The explosions of these stars as SNe enriched the IGM with metals, which we can observe in high z quasar spectra, since the Ly-α forest of the IGM shows metal absorption lines.

- Further ionization occurred on larger scales, due to the 1st proto-galaxies and AGN. Cooling by atomic H works best for more massive halos, allowing the 1st galaxies to form and continue reionization. The regions of ionized material gradually expands and grows until they overlap, and eventually the entire universe is ionized by $z \sim 6$.

- We see evidence of this EoR in the Ly-α forest & Gunn-Peterson Trough of quasars, which are very sensitive to even small amounts of HI capable of producing absorption lines at $\lambda_{rest} = 1216$ Å. The GP Trough allows us to place constraints on the end of reionization.

- We also see evidence of the EoR in secondary anisotropies of the CMB + its polarization. The increase in free e^-'s from this time resulted in additional Thomson scattering, producing further polarization. The increase in scattering events also increased the optical depth, affecting the amplitude of T fluctuations (Maybe? IDK). At low multipoles in the polarization spectrum we observe a reionization bump, since this took place on the horizon scale.

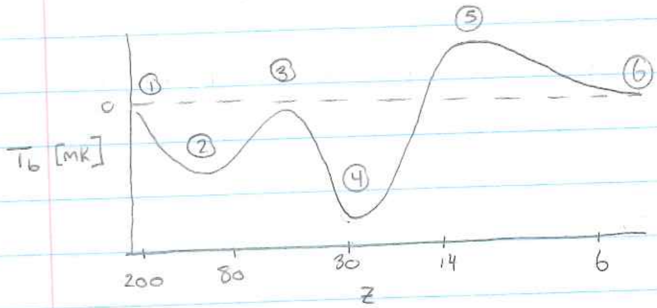
- The Kinetic SZ-effect can also be seen in the temperature fluctuations of the CMB. The peculiar velocities of the ionized bubbles produces a Doppler shift of CMB photons, and the strength of this effect scaled w/ the # of ionized bubbles present. This anisotropy tells us the duration of reionization.

- Also consider 21 cm spin flip of H I during EoR.

- collisional coupling, then can't be maintained as universe expands, so get absorption
- galaxies form, Ly-α coupling, but then more absorption induced by Ly-α interactions
- IGM is heated by x rays, produces emission
- Reionization decreases HI, so less emission

C16

21 cm absorption and emission against CMB



Spin-flip of e^- in is ground state of neutral H.

↑ Emission of 21 cm

↓ Absorption of 21 cm

$p^+ + e^-$ mag. mom
Aligned ↑↑ ↓↓
1S 21 cm 0.068K
Antialigned ↑↓

$T_b \approx$ Measure of radio intensity

$I_\nu = 2 k_B T_b \nu^2 / c^2$

Collisional coupling — ① Post recombination, the IGM is still dense enough to couple baryons and photons a bit via collisions, so we don't see any significant absorption or deviation from the CMB temperature. No 21 cm signal.

② As the universe expands, the gas cools adiabatically, and the excitation T of the 21 cm H transition decouples from T_{gas}. The Dark ages take over. The diffusion of the IGM by expansion means collisions can't keep baryons + photons coupled, so HI absorbs γs at 21 cm. I think...

Ly-α coupling — ③ The first galaxies form, and they produce Ly-α photons that couple the excitation T of 21 cm spin states to T_{gas} by scattering. This results in strong absorption, with spatial variance since galaxies aren't evenly distributed.

X-ray heating — ④ Heating of the IGM begins as galaxies emit x-ray emission which heats gas, producing a 21 cm emission signal that counteracts the Ly-α absorption trough.

UV photoionization — ⑤ Reionization begins as first stars produce ionizing UV photons. The 21 cm signal develops spatial holes where no 21 cm emission is seen in regions of ionized bubbles surrounding groups of galaxies, until the entire universe is ionized by $z \sim 6$.

C17

- Scalar modes have only a magnitude, no direction, and will produce E mode polarization
- Tensor modes have magnitude and multiple dimensions as they're distortions of the metric, and will produce B mode polarization
- We can detect them in the CMB polarization map

Scalar and Tensor Modes of Perturbation

- Scalar perturbations are just single order perturbations, with some magnitude but no direction. They come in the form of density perturbations which result in temperature fluctuations and polarized variations - but only E-mode polarization. The temperature fluctuations produce quadrupole moments which linearly polarize light $\frac{\text{Hot}}{\text{cold}\ +\ \text{cold}}_{\text{Hot}}$. We can detect their presence in the CMB by looking at the polarization power spectrum and C_ℓ power spectrum for temperature fluctuations.

- Tensor perturbations are a distortion of (the metric) space time (in the form of grav. waves). They're an extension along one axis and a compression on another, propagating forward at the speed of light, and which don't damp out because there's nothing to do so. They're thought to be very faint but we haven't detected them yet! at least not primordial ones. Tensor perturbations should seed not only temperature and E-mode variations, but B-modes as well since tensors can have a handed-ness, while scalars cannot as they're just a magnitude.

- To detect such modes we can observe the CMB and determine its linear polarization. That polarization map can then be decomposed into E- and B-modes. BICEP2, for instance had linearly polarized antennae and just stared at the sky.

- E-modes can be sheared into B-modes if the CMB photons are gravitationally squished by ~~the~~ massive galaxy clusters. Grav. lensing mixes E-modes and B-modes, but only on small scales since it's hard to shear large scale modes. B-modes can be transformed into E-modes too.

- Vector modes have a magnitude and a single direction, so they're basically traveling through space. These are easily damped out by the expansion of the universe since sub-luminal velocities are difficult to maintain. We don't observe these and don't expect to.

C18

- Neutrinos decoupled b/c universe's T decreased below interaction cross section; γs decoupled b/c no more free e^-'s for Thomson scattering
- Both have Planck distribution(?), were in T.E. before
- Different T, t, particle type

Cosmic Neutrino Background

- The CNB was produced when neutrinos decoupled from the photon-baryon fluid at $t \approx 1s$. This happened because the expansion rate of the universe exceeded the reaction rate of neutrino interactions, or in other words, the temperature-dependent interaction cross section became too small as the universe cooled. Neutrinos were then able to stream freely through the universe, and by now they would have a peak temperature of $\sim 1.9K$. It's incredibly difficult to detect energetic neutrinos from our own sun, so detecting the CNB seems impossible. Instead, we can look for indirect evidence of it, such as its effect on the small scale part of the C_ℓ spectrum (neutrinos diffusing outward damps the structure at small angular scales, like Silk damping), or the impact the neutrinos had on element abundance due to their part in neutron production/decay, I think...

	CNB	CMB
Particle	Neutrinos	Photons
Decoupling of	Neutrinos + photon-baryon fluid	photons + baryons
Time	1s	380,000 yr
Temp. then	10^{10} K	3000 K
Temp. now	1.9 K	2.73 K

- If the universe cools uniformly for all its constituents, why is $T_{CNB} < T_{CMB}$? Electron-positron annihilation. This event produced an influx of photons w/ more energy, giving the overall CMB progenitor photon distribution a slightly higher temperature than the neutrinos. This annihilation period occurred around $t \approx 6s$, when it became more energetically favorable to produce γs rather than $e^{\pm}$'s.

C19

- adiabatic = proportional density fluctuations resulting in net change + curvature
- isocurvature = balanced fluctuations, not net change or curvature
- Compare C_ℓ spectrum to models; isocurvature smears things out.

- Isocurvature and Adiabatic Modes.

- Adiabatic Modes are when the density fluctuations of all the universe's components are proportional to each other - if the density of baryons goes up in a certain region, the densities of photons, neutrinos, and DM will go up as well, so the total density goes up in that region. This results in a change in the local curvature of spacetime.

- Isocurvature Modes are when the density fluctuations are all balanced such that there's no net over/under density. If the density of one component goes up, the densities of others go down to compensate. Thuse there's no effect on the local curvature, and hence 'isocurvature'.

- We know the initial conditions of the universe must have mostly been in the form of adiabatic modes based on the shape of the C_ℓ power spectrum of the CMB. If we had more isocurvature modes, the power spectrum would be more smeared out, as over-densities in baryons and photons, etc. wouldn't necessarily follow each other, and the resulting temperature fluctuations would have different amplitudes, probably being smoothed out among angular scales. Comparing observations of the C_ℓ spectrum with models containing adiabatic v. isocurvature perturbations tells us that the former must dominate.

C20

- MACHOs should result in more lensing and be more spread out (less pt like) to explain rotation curve
- Neutrinos would diffuse out from + damp small scale structure, require top down formation model
- WIMPs are theoretical new elementary particles; massive and non relativistic so no damping.

· Dark Matter Candidates

· Dark matter is expected to account for ~80% of all matter in the universe and is invoked to explain things like the M/L ratio of galaxy clusters and the rotational velocity curves of our own galaxy. It's thought to be non-baryonic (mostly) and to only really interact gravitationally, not electromagnetically, ie cold DM.

· MACHOs - Massive Compact Halo Objects

- To explain the flat rotation curve of the MW at large radii, there must be a lot of mass in the halo which we can't see. Perhaps this non-luminous objects (or just weakly luminous) are black holes, neutron stars, brown dwarfs, and rogue planets. If this were the case, we'd expect to detect them via gravitational lensing events. In fact we do see such events, but only enough to account for ~20% of the mass we expect. Plus, these MACHOs are large point sources, which wouldn't quite produce the smooth rotation curve - we need a more diffuse source.

· Neutrinos as HDM

- because neutrinos only interact via gravity and the weak force, they don't really interact w/ normal baryonic matter very much. This makes them very difficult to detect and thus potential DM candidates, but because they're so light there must be a huge number of them to account for the mass we know exists in the universe. We can rule out HDM models for a couple reasons. An increase in neutrinos (to account for the DM) in the early universe would have resulted in less structure on small scales, as neutrinos leaking out of density perturbations would've suppressed this structure growth. This means structure would only really be able to form on large scales, and the rest of the structure we see today would've formed via fragmentation. We know this top-down method is incorrect because we see small structures in the early universe.
- also neutrinos are relativistic and the best guess for their mass is < 2 eV.

• WIMPS – Weakly Interacting Massive Particles
– these are hypothetical, new kinds of elementary particles that could have been produced thermally in the early universe alongside all the other particles we see today. Like neutrinos, they would interact gravitationally, but they would be a lot heavier and not relativistic (otherwise they'd diffuse out from over densities on small scales like neutrinos do). We don't have any evidence for these particles yet, but supersymmetric extensions of the standard model of particle physics does predict particles with such properties.