Astro 596/496 PC
Lecture 40
May 3, 2010

Announcements:

- Final Preflight posted, due next Wednesday noon
  fun, optional, easy bonus points
- **ICES**! please don't skip written comments

Last time: Press-Schechter analysis

- input: initial/primordial density fluctuation spectrum: $P(k)$
- output: mass function $dn/dM(M,z)$
  mass distribution of structures over cosmic time
- strategy: evolve linearized density field
  with variance $\sigma(M,z) = (1+z)\sigma_{\text{init}}(M)$
  spherical collapse model links $\delta_{\text{lin}} \leftrightarrow \delta_{\text{nonlin}}$
  objects with $\delta_{\text{lin}}(t_0) > \delta_c = 1.69$ have collapsed
- tests: a very idealized scheme, but works unreasonably well!

Applications of Press-Schechter

Mergers

PS very powerful because gives mass function vs time:

$$\mathcal{N}(M,t) = M\frac{dn}{dM}(t) \sim \nu(t)\ e^{-\nu^2(t)/2} \tag{1}$$

with

$$\nu(t) = \frac{\delta_c}{\sigma(M,t)} = \frac{\delta_c}{D(t)\sigma_{\rm init}(M)} = \frac{a(t_{\rm init})}{a(t)}\nu_{\rm init} \tag{2}$$

recall: $\sigma_{\rm init}(M)$ *decreases* with M *Q: why?*

So to find time change: just take derivative

$$\dot{\mathcal{N}} \sim |\dot{\nu}|(\nu^2-1)e^{-\nu^2/2} \sim \text{creation} - \text{destruction} \tag{3}$$

Q: merging for large, small ν? large, small M?

at fixed time t

$$\dot{\mathcal{N}} \sim |\dot{\nu}|(\nu^2 - 1)e^{-\nu^2/2} \tag{4}$$

small M → largest σ: $\nu = \delta_c/\sigma(m) < 1$

$\dot{\mathcal{N}} > 0$: net destruction

and so large M → net creation – at expense of small objects

PS Application II: Quasar Abundance

- Quasars must be massive (Eddington limit) black holes at galaxy centers → demands $M_{\text{gal}} > M_{\text{bh}} \gtrsim 10^{12} M_{\odot}$
- Quasars found out to high redshift $z > 3$ (in fact $\gtrsim 7$)

PS: can find number density of objects with $M > 10^{12} M_{\odot}$ at epoch $z = 3$

$$n_{\text{com}}(> 10^{12} M_{\odot}; z = 3) = \int_{10^{12} M_{\odot}} \frac{dn}{dM} dM \sim 10^{-8}\ \text{Mpc}^{-3} \tag{5}$$

about right!

Cosmology with Clusters: S-Z Effect

clusters contain $T \sim 1/4$ keV gas seen in X-rays
$\rightarrow$ intracluster medium (ICM) fully ionized $\rightarrow$ free e^-
these are targets which scatter photons–including CMB!

Sunyaev & Zel'dovich 1972
consider CMB photon passes thru a cluster
scattering rate per photon $\Gamma_{\rm sc} = n_e \sigma_{\rm T} c$
in time to move increment $ds = c\,dt$, # scatterings is

$$d\tau = \Gamma_{\rm sc} dt = n_e \sigma_{\rm T} ds = \frac{ds}{\lambda_{\rm mfp}} \tag{6}$$

i.e., number of mean free paths $\lambda_{\rm mfp} = (n\sigma)^{-1}$ traversed
total # scatterings: optical depth in line-of-sight thru cluster

$$\tau = \sigma_{\rm T} \int_{\rm los} n_e ds \simeq \sigma_{\rm T} \frac{f_{\rm baryon} M_{\rm cluster}/m_p}{R^2_{\rm cluster}} \sim 0.004 \left(\frac{M_{\rm cluster}}{10^{15} M_\odot}\right) \left(\frac{2 \text{ Mpc}}{R_{\rm cluster}}\right)^2$$

Q: which means?

S-Z Effect

Optical depth small $\tau \lesssim 0.004$ but nonzero
→ small fraction of CMB photons scattered
but this by itself would not generate anisotropy *Q: why?*

Consider energy transfer in scattering:
$T_{\rm ICM} \gg T_{\rm CMB} = (1+z)T_0$ for any epoch after recombination
→ electrons much more energetic than photons
→ CMB photons "upscattered" (inverse Compton):
gain energy on average

How much?
detailed treatment requires Compton (Thompson) scattering
by gas with distribution of electron speeds v_e
of a photon bath with distribution of frequencies ν
→ Kompaneets equation
but order of magnitude can be gotten quickly, dirtily

Go to center of mass (momentum) frame
since e^- has most momentum, boost by $v \sim v_e \rightarrow \gamma \sim 1/\sqrt{1 - v_e^2}$
in CM: photon with initial freq $\nu_{\gamma,\mathrm{cm}}$
scattered isotropically, with $\nu'_{\gamma,\mathrm{cm}} = \nu_{\gamma,\mathrm{cm}}$

but now boost back: in lab frame, energy gain of order

$$\frac{\delta\nu}{\nu} \sim \gamma - 1 \approx \frac{1}{2}\left(\frac{v_e}{c}\right)^2 = \left(\frac{m_e v_e^2/2}{m_e c^2}\right) \sim \frac{kT}{m_e c^2} \tag{7}$$

in fact, careful treatment shows scattering ν-dependent

Observable is CMB *energy* flux: energy change × scattering prob:
"Comptonization parameter" $dy = (kT_e/m_e c^2) d\tau$
see temperature increase (with correct factor by hand)

$$\left(\frac{\Delta T}{T}\right)_{\mathrm{SZ}} = 2\Delta y = 2\sigma_{\mathrm{T}} \int_{\mathrm{los}} \frac{n_e\, kT}{m_e c^2} ds = 2\sigma_{\mathrm{T}} \int_{\mathrm{los}} \frac{P_e}{m_e c^2} ds \tag{8}$$

S-Z Observed

S-Z Observables

- temperature increment
- frequency dependence: upscatterings give
  nonthermal spectral distortion
  deplete low-ν photons, move them to higher ν
  "crossover" at $\nu_{\text{null}} \simeq 220$ GHz

S-Z Data

- Effect first observed in 1970's
- Note: T, ν effects independent of distance to cluster!
  $\Rightarrow$ can observe S-Z from high-z clusters!
  `www: S-Z clusters over redshift range`
  S-Z is cluster discovery tool
- given cluster z, angular size, and $d_A(z) \rightarrow$ radius R_{cluster}
  $\rightarrow$ S-Z line of sight! from this, get M!
  S-Z weighs clusters

Cluster surveys (e.g., DES) exploit both effects

Gravitational Lensing

Shedding Light on the Dark Universe

General relativity says matter warps space
deflects photon paths, distorts images of distant objects

Key idea: lensing is really lensing
in (peculiar) gravitational potential $\Phi(\vec{r})$
gravitational lensing acts like index of refraction

$$n(\vec{r}) = 1 - \frac{2\Phi(\vec{r})}{c^2} \geq 1 \text{ for bound objects} \tag{9}$$

Einstein: light passing by point mass M
with impact parameter (min $\perp$ distance) b deflected thru angle

$$\alpha = \frac{4GM}{c^2 b} = 2\,\mathrm{arc\,sec}\left(\frac{M}{M_\odot}\right)\left(\frac{R_\odot}{b}\right) = 0.2\,\mathrm{arc\,sec}\left(\frac{M}{10^{12} M_\odot}\right)\left(\frac{100\ \mathrm{kpc}}{b}\right)$$

Q: generalization to an extended mass?
Q: implications for galaxies? clusters? cosmology?

Sketch of Lensing Physics

General setup: background source, foreground lens
lens distortion maps source plane into image plane
mapping depends on both source, lens

Spherical mass distribution: $\alpha(b) = 4GM(<b)/c^2 b$
aligned source–lens–obs: Einstein ring in image plane
otherwise: multiple arcs, symmetric about S-L axis on sky

General mass distribution: no symmetry
α set by lens projected surface mass density
$\Sigma(\vec{r}_\perp) = \int_{\mathrm{los}} \rho(\vec{r}_\perp, z)dz$; $\alpha(r_\perp) \sim \int dr \Sigma(r)$

Observable Effects

- amplification ("convergence") from symmetric piece of Φ
- shear from asymmetric piece of Φ

Strong Lensing and Dark Halos

If background QSO/galaxy light passes thru
  foreground galaxy/cluster
can resolve lensed arcs of background object `www: arcs`
use to reconstruct total mass distribution of foreground gal
⇒ direct probe of dark matter distribution!

Status: already done for tens of objects
`www: map of DM in cluster`

Pro: prominent signal
Con: rare lucky superposition
  labor-intensive modelling for each object

Weak Lensing and Large-Scale Structure

In fact, U. has density inhomogeneities on all scales
▷ $\delta(x)$ field lenses all objects!
▷ if measure effects over z → tomographic "slices"
⇒ recover 3-D map of cosmic matter distribution!
and more! power spectrum, correlation function, ...

But: the effects are small and subtle–*weak* lensing

- amplification non-trivial to measure
- shear more promising: circular gal → elliptical
  but elliptical → elliptical too!
  ⇒ need statstical sample

Status: preliminary attempts done
future large surveys planned specifically for lensing `www: LSST`

Pro: no luck needed
Con: need large datasets, great care over systematics

In Search of the Intergalactic Medium

Quasars and the Gunn-Peterson Effect

Quasars excellent cosmic beacons → use a backlighting
intervening neutral hydrogen absorbs all photons
wth $E_\gamma > 13.6$ eV ⇒ in absorber rest frame

- "Lyman edge" $\lambda_{\rm Ly} < 912$ Å

Gunn & Peterson (1965): look for absorption trough
below "Lyman limit" $\lambda < (1 + z_{\rm qso})\lambda_{\rm Ly}$
not seen out to $z \sim 5-6$! detect QSO photons in this regime!

Q: implications for IGM?
Q: what is actually seen? implications?

The Reionized Intergalactic Medium

Rather than uniform Gunn-Peterson trough, see Lyman-α forest implied mass in neutral H small:

$$\Omega_{\mathrm{HI}} \simeq 10^{-7} \ll \Omega_{\mathrm{baryon}} \tag{10}$$

▷ most baryons must be highly ionized at $z \gtrsim 6$: $1 - X_e \sim 10^{-5}$!
▷ the universe was somehow reionized by then
▷ IGM contains islands of neutral gas in ocean of ionized H

Pollution Began Early

quasar absorption systems also show metal lines

- IGM contained heavy elements
- metallicities vary but never fall below "floor" at $\sim 10^{-2}$ solar!

What made these metals and distributed them so widely?

When was reionization?

recent evidence for reionization commencement!

$\star$ SDSS discovery of $z \sim 6$ quasars with G-P trough

$\star$ reionization → free e^- → CMB scattering, pol'n (à la SZ)

non-primordial fluctuations horizon at reionization

= observe at → large scales

WMAP 2003: reionization at $z = 10.9^{+2.7}_{-2.3}$ if instant

optical depth $\tau_{\mathrm{reion}} = \sigma_{\mathrm{T}} \int_{d_H} n_e ds \sim 0.17$ constrains ion history

(model dependent!)

Whodunit?

enormous energy injection required: $\gtrsim 13.6$ eV/baryon

Q: Whodunit–candidates for reionization?

These hints about the IGM demand an understanding
of baryonic evolution of the universe
from the largest scales down to the formation of stars