Astro 507
Lecture 41
May 6, 2014

Announcements:

- **Preflight 6c due tonight**
  post give feedback to your classmates
- **Preflight 6d due Friday**
  update and post to Wikipedia
- **Final Problem Set due Wed May 15**
  treat as ordinary problem set
- **ICES** available online – please do it!

Last Time: the ΛCDM Standard Cosmology
Q: what's that? what does "cold" mean?

Today: Grand Finale

ΛCDM

"Standard" Cosmology today: ΛCDM ...namely:

- FLRW universe
- today dominated by cosmological constant $\Lambda \neq 0$
- with cold dark matter
  $\Rightarrow$ hierarchical, bottom-up structure formation
- ...and usually also inflation: scale invariant, Gaussian, adiabatic

This is the "standard" model but not the only one
Q: arguments in favor?
Q: arguments for other possibilities?
Q: which pieces most solid? which shakiest?

At minimum: ΛCDM is *fiducial* / *benchmark* model
standard of comparison for alternatives

...and so we will adopt ΛCDM the rest of the way

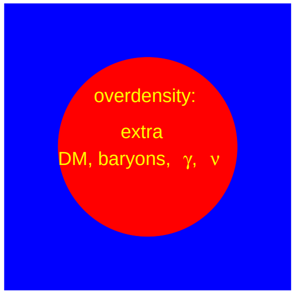
Recombination Re-Revisited

so far: theory of small-scale CMB anisotropies worked in k space

- before recombination: modes are standing waves
- CMB records phase at recombination

but can also work in *real space*

- consider a single localized *overdensity*
- initially *adiabatic*



$$\delta_{\rm m}(t_{\rm init}) = \delta_{\rm b}(t_{\rm init}) = \delta_\gamma(t_{\rm init}) = \delta_\nu(t_{\rm init}) \tag{1}$$

Q: pre-recombination initial behavior of the dark matter?
baryons & photons? neutrinos?

Before Recombination/Decoupling `www: simulations`

dark matter: cold, pressureless
overdensity grows with time, drawing in surrounding matter

baryon/photon fluid: high-pressure
fluid sees large *pressure gradient*: drives forces that try to smooth

- overdense, pressurized region propagates out at speed c_s
- generates a shell of comoving radius $r_{\rm com} \sim c_s \eta$
- shell continues until recombination, when radius is

$$r_{\rm shell,com} = \int c_s d\eta \approx c_s \eta_{\rm dec} \sim 150 \text{ Mpc} \qquad (2)$$

neutrinos: hot, pressureless
fly out at speed c from overdensity
continue until nonrelativistic

Q: post-recombination/decoupling behaviors?
Q: effect of DM on baryon/photon fluid? on neutrinos?

At decoupling: baryonic "rings" at $r_{\rm shell,com} \approx c_s \eta_{\rm dec} \sim 150$ Mpc

After Recombination/Decoupling `www: simulations`

baryon/photon fluid: attracted by central DM potential

- nearby baryons falls in
- distant ring feature remains

dark matter: attracted by baryonic feature at $r_{\rm shell,com}$

- DM also forms rings at $r_{\rm shell,com}$
- overdensity lower than center by $\sim \Omega_{\rm b}/\Omega_{\rm m} \sim 1/7$

neutrinos: attracted to overdensities

but while relativistic, smooth perturbations

Q: what if many local perturbations? observable signature?

Baryon Acoustic Oscillations

around recombination, perturbations still linear

- density field well-described by superposition
- overdensities all surrounded by rings at $r_{\text{shell,com}}$
- randomness of initial field obscures ring patterns
- but still excesses of mater 150 Mpc away from other excesses
  $\Rightarrow$ *correlations are observable!*

in real space: correlation function

$$\xi(r) = \langle \delta(\vec{x}) \; \delta(\vec{x} + \vec{r}) \rangle \tag{3}$$

Q: what should we see?

`www: SDSS data`

in k space: power spectrum

sharp feature in real-space → oscillations in $P(k)$

Q: why is this incredibly powerful?

Weak Lensing: Twitter Version

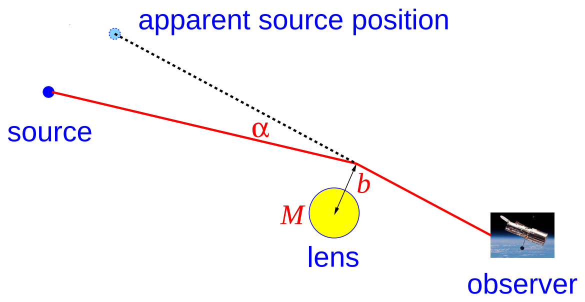
Shedding Light on the Dark Universe

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

Key idea: lensing truly is lensing = light bending
in (peculiar) gravitational potential $\Phi(\vec{r})$
gravitational lensing acts like *index of refraction*

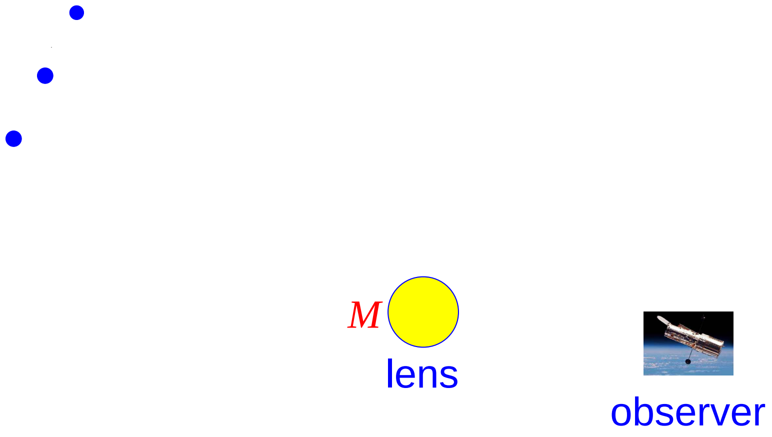
$$n(\vec{r}) = 1 - \frac{2\Phi(\vec{r})}{c^2} \geq 1 \text{ for bound objects} \tag{4}$$

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

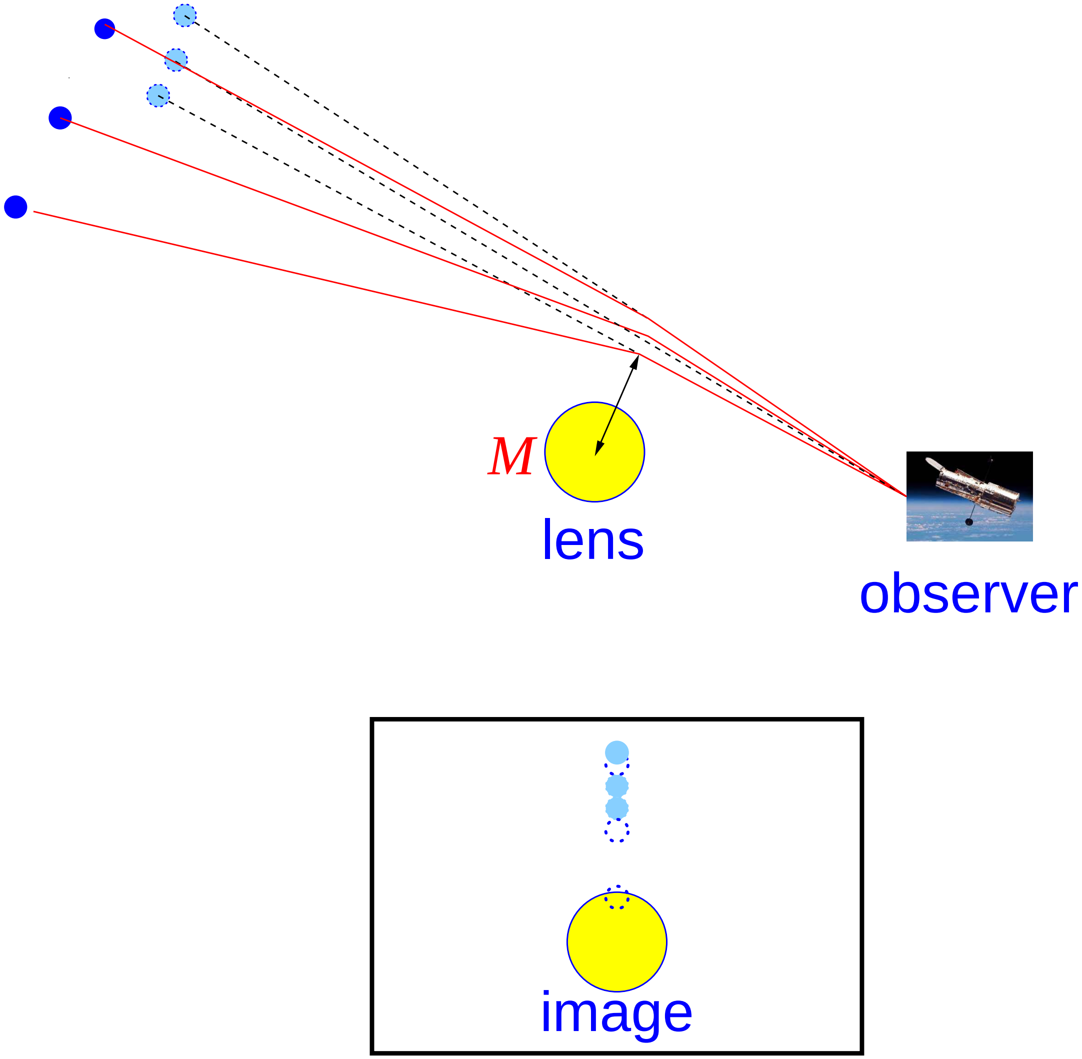


$$\alpha = \frac{4GM}{c^2 b} = 2 \text{ arcsec} \left(\frac{M}{M_\odot}\right)\left(\frac{R_\odot}{b}\right) = 0.2 \text{ arcsec} \left(\frac{M}{10^{12} M_\odot}\right)\left(\frac{100 \text{ kpc}}{b}\right)$$

now consider several sources

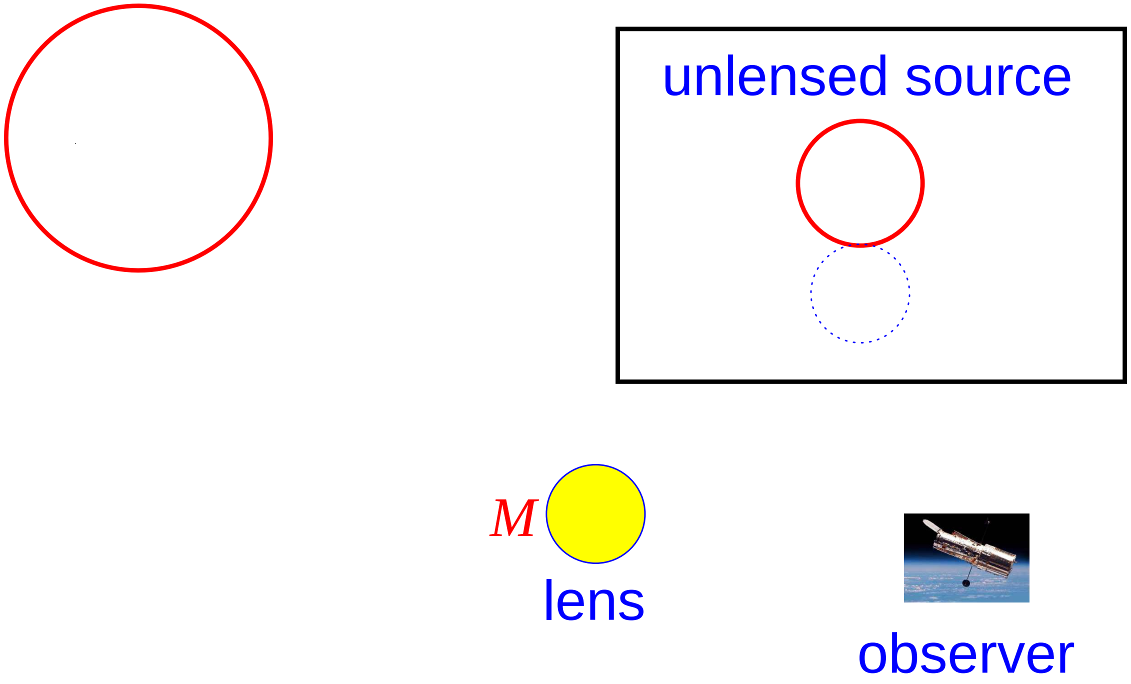


Q: unlensed source image? lensed image? lessons?

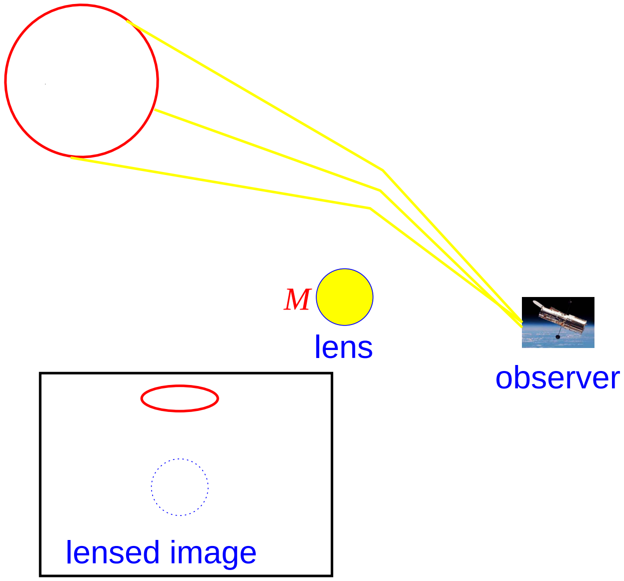


multiple point sources:

point lens “repels” images in radial direction now consider a spherical source



Q: lensed image? lessons? challenges?



circular source:

point lens distorts image to **ellipse**

Lessons:

- lensing introduces ellipticity
- also rotation and magnification

Q: implications for galaxies? clusters? cosmology?

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 $z \rightarrow$ tomographic "slices"
$\Rightarrow$ 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!
  $\Rightarrow$ need statistical 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

The Cosmic History of Star Formation

history of cosmic star formation encodes a wealth of information:

- baryonic matter cycling: gas ↔ stars, remnants
- energy exchange/feedback: starlight, supernova blasts
- element production ("chemical evolution")
- high-energy stellar events: supernovae, gamma-ray bursts

nice property of stars: they light up!
→ can hope to measure cosmic star formation *directly*
by imaging the stars

Q: which stars trace current/*recent star formation?*
what (rest-frame) wavelengths/bands would trace these?
Q: so how can we mesure the cosmic star formation history?

Decoding The Cosmic Star-Formation Rate

recall: stellar lifetimes strongly decrease with mass
roughly $\tau_m \sim 10 \text{ Gyr } (1\, M_\odot/m)^3$

high-mass stars are short-lived: die “instantly”
trace “instantaneous” star formation rate
bonus: massive stars also the most luminous

- dominate broadband *blue*, *UV* light from galaxies
- also power H ii regions, traced by Hα

⇒ in individual galaxies: luminosity in each of these tracers
gives galactic star formation rate
⇒ cosmic luminosity *density* of each tracer
gives cosmic star formation rate at each z

`www: Observed Cosmic Star Formation Rate`
Q: impressions? questions raised by this behavior?

The Cosmic Star-Formation Rate Observed

quantity plotted: cosmoving rate density of mass going into stars in rest frame, i.e.,

$$\dot{\rho}_\star(z) = \frac{dM_\star}{dt_{\mathrm{em}}\, dV_{\mathrm{comov}}} \tag{5}$$

key observed features:

- rise from present $z = 0$ value to peak at $z \sim 1 - 2$
- peak rate ~ 10 times higher than today
  → star formation is on the decline!
- behavior at $z \gtrsim 2$ uncertain

Open Questions:

- why is there a peak? why at $z \sim 1 - 2$?
- what is behavior at high z?
- how does the observed rate encode the interplay of star formation physics and structure/galaxy formation?

Finale: The Universe and Beyond the Infinite

Physical Cosmology: Present Status

A Sampler of Presently Open Questions in Cosmology

- What is the nature of dark matter? Can we detect it? Is dark matter relic particles left over from the early U.?

- What is the nature of the dark energy? Is it related to inflation?

- Did the universe undergo inflation? If so, what was the microphysics at work–i.e., what was the inflaton ϕ? If not, what is the origin of density fluctuations, and what solves the horizon and flatness problems?

- Did the universe undergo a singularity at $t = 0$? What is the nature of quantum gravity and what does this mean for the origin of the U.?

- What is the long-term fate of the universe?

- What is the geometry of the universe? the topology?

- What is the nature of the first stars? What role do they play in reionization? nucleosynthesis? the origin of supermassive black holes?

- What is the distribution of matter–all matter–in the universe? How do the cosmic components–baryons, DM, neutrinos, DE–contribute to the growth of structures? How is this written into galaxy evolution?

- Do astrophysical magnetic fields have a cosmological origin? Did the early universe play a role?

- How many of these questions are answerable?

- Are we fooling ourselves? Does modern cosmology contain epicycles which our grandchildren will find quaint? Is there some basic physics we have totally missed and awaits discovery?

COSMIC PREDICTIONS

My Predictions for the Coming Decade

For sure: a huge flood of precision data
"telescopes" from 30m mirrors to LIGO/VIRGO+ to LHC
What will we learn?

Observations/Experiments

- dark energy evolution probed by EUCLID, LSST, WFIRST, ...
- CMB-S4: T, polarization anisotropy (B modes!) to high precision inflationary gravity waves seen, plus non-gaussianity, ...
- deuterium in QSO absorbers to $< 1\%$: probe early U.
- cosmic 21-cm radiation detected over wide redshift range, probes structure, star formation
- CTA (high-E γs) finds dark matter annihilation γs
- IceCUBE (high-E νs): PeV extragalactic sources classified
- X-ray observations probe structure, state of intergalactic baryons
- β-decay experiments detect ν mass
- JWST: supernovae from first stars (Pop III) imaged
- more NS/NS mergers seen in gravity+light, precise H_0 measure
- completely unexpected result(s) makes some of the above look naive

Theory

- dark sector detection informs inflation, baryogenesis theories
- dark energy motivates/constrains quantum gravity progress
- supernova models achieve robust explosions
  more confidence in Type Ia a cosmo probe
- chemical evolution models married with structure formation
  Galactic stellar abundances probe Galactic merger tree
- job security as unexpected new results challenge theorists

A Cosmological Wish for the Decade
The Dark Matter Trifecta

⋆ WIMP underground detectors find and confirm signal

⋆ LHC at CERN produces dark sector particles
consistent with WIMP evidence

⋆ γ-rays & radio see WIMP annihilation in Galactic center

Nobel prizes all around!

Into the Sunset

We are living in the golden age of cosmology

There is much more to learn
and the great work continues:
→ future colloquia, seminars, prelims, defenses!

Stay Tuned!

Last Thoughts

This is the last class for many graduating undergraduates

CONGRATULATIONS!

Thanks for doing Quarantine Cosmology
With great spirits in the fact of difficult circumstances

I appreciate your hard work, great questions
lively online discussion

THANK YOU and STAY SAFE!

FIN

Director's Cut Extras

The First Stars

Some sobering facts:

our understanding of local, resolved, high-metal star formation is at best incomplete

- birthplaces are molecular clouds
- most stars form in clusters, not isolated
- dust an essential ingredient `www: IRAS cores`
- magnetic fields present, surely important, possibly crucial
- mass distribution (IMF) strongly biased to low mass

theoretically: basic mechanism still debated

high-mass star formation especially poorly understood (rare objects, heavily enshrouded, rapid evolution)

but one must try, and besides ...

First Star Formation certainly different
exceedingly challenging observationally, but
maybe theoretically simpler?

⋆ no dust!
⋆ no/small magnetic fields?
⋆ no radiation, outflows, ejecta from previous stars
⋆ “first principles” initial conditions (environment, composition)

First Star Formation

Birthplaces: first collapsed halos containing baryons
hierarchical cosmic structure → lowest mass halos most common
smallest scale: baryonic Jeans mass a recomb: $\sim 10^6 M_\odot$

Composition: primordial–H, He, and Li only, no dust
lack of efficient coolants → hard to depressurize, collapse
only available molecules are H_2, traces of HD, LiH
→ molecule formation (i.e., chemistry) critical in setting masses!

Abel Bryan & Norman (2001): cosmochemical simulations
one protostar per $10^6 M_\odot$ halo
inefficient cooling → slow evolution → accretion unimpeded
→ massive star $\gtrsim 30 M_\odot$... but fragmentation?

conventional wisdom: first stars massive ($\gtrsim 10 M_\odot$)
bad news: none left today
good news: they don't go quietly! they do leave traces!

Population III Stars: Lifestyles

As usual, astro naming backwards (theorists dropped the ball)

- Population I: high-metallicity stars, disk distribution
- Population II: low-metallicity, halo distribution, kinematics
- Population III: zero metallicity, unobserved (to date!)

Stellar evolution sans metals

Massive star lives most strongly effects

- main sequence H burning normally via CNO cycle
  now must begin with $pp \to de\nu$ until self-enrich with CNO
- no metals in atmosphere → much lower opacity
  radiation-driven winds inefficient → less/no mass loss?
  difficulty stopping accretion

⇒ supermassive ($> 100 M_\odot$) stars possible?

- low opacity → more compact → faster rotation
  easier to make gamma-ray bursts?

Population III Stars: Death

As usual:
$\lesssim 10 M_\odot$: AGB, PN, white dwarf
$\sim 10 - 30 M_\odot$: supernova, neutron star
$\sim 30 - 50 M_\odot$: supernova, fallback, black hole

But new twists:
$\sim 50 - 100 M_\odot$: direct collapse to BH
$\sim 100 - 200 M_\odot$: "pair instability," complete disruption!
$\gtrsim 300 M_\odot$: direct black hole formation
nucleosynthesis patterns unlike "normal" supernovae

Open questions:
which masses actually created?
will very massive supernovae lead to superluminous explosions?
was a population of $\sim 10 - 100 M_\odot$ black holes created?

Baryon Acoustic Oscillations

around recombination, perturbations still linear

- density field well-described by superposition
- overdensities all surrounded by rings at $r_{\text{shell,com}}$
- randomness of initial field obscures ring patterns
- but still excesses of mater 150 Mpc away from other excesses

  $\Rightarrow$ *correlations are observable!*

in real space: correlation function

$$\xi(r) = \langle \delta(\vec{x}) \; \delta(\vec{x} + \vec{r}) \rangle \tag{6}$$

Q: what should we see?

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in k space: power spectrum

sharp feature in real-space → oscillations in $P(k)$

Q: why is this incredibly powerful?

BAO: A Standard Ruler

the baryon acoustic oscillation scale fixed by recombination physics
→ $r_{\text{shell,com}} = c_s \eta_{\text{dec}}$ is a *standard ruler*

- measure angular size θ_{BAO}
- infer *angular diameter distance* $d_A(z) = c_s \eta_{\text{dec}} / \theta_{\text{BAO}}$

incredibly powerful opportunity:
we can measure BAO scale *at many different* z

- trace evolution $d_A(z)$
- *probe dark energy! also neutrinos!*

observables

- CMB: anisotropy angular scale gives BAO at $z = z_{\text{dec}}$
- Large Scale Structure: BAO observable at any z
  as long as feature can be resolved in power spectrum

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 truly is lensing = light bending
in (peculiar) gravitational potential $\Phi(\vec{r})$
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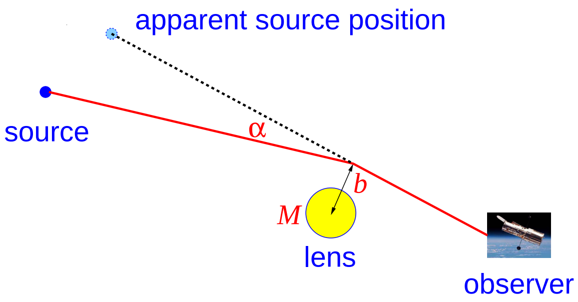

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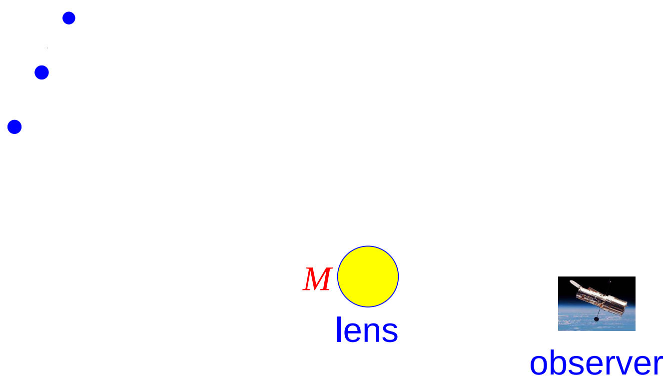
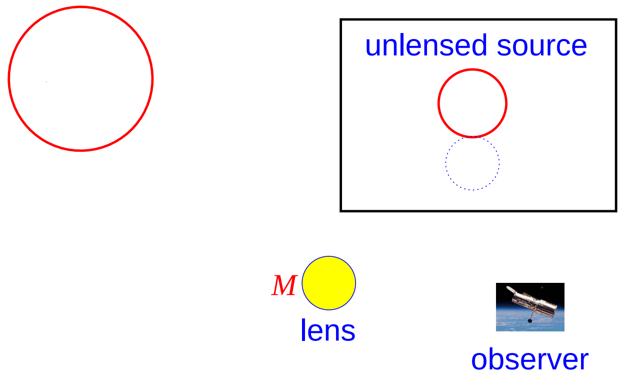


Q: unlensed source image? lensed image? lessons?

consider a spherical source



Q: lensed image? lessons? challenges?

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
$\Sigma(\vec{r}_\perp) = \int_{\text{los}} \rho(\vec{r}_\perp, z) dz$

Observable Effects

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

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" $\lambda_{\mathrm{Ly}} < 912$ Å

Gunn & Peterson (1965): look for absorption trough
below "Lyman limit" $\lambda < (1 + z_{\mathrm{qso}})\lambda_{\mathrm{Ly}}$
i.e., integalactic H atoms should make U *opaque*
to these UV photons

but can detect QSO photons in this regime!
UV trough *no seen* out to $z \sim 5 - 6$!

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:

$$\Omega_{\mathrm{HI}} \simeq 10^{-7} \ll \Omega_{\mathrm{baryon}} \tag{8}$$

- ▷ 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

When was reionization?

recent evidence for reionization commencement!

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

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

non-primordial fluctuation source 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

Hydrogen reionization: Energetics

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

Helium reionization

He II= He^{+1} reionization requires $Z_{\mathrm{He}}^2 E_{1,\mathrm{H}} = 54.4$ eV photons

⇒ even more energetic photons needed

★ recent observations: He reionization at $z_{\mathrm{He}} \sim 3$

Q: Whodunit–candidates for reionization?

Reionization Candidates

The First Quasars

- very luminous
- flat spectra → bright in UV photons
  promising candidates for helium reionization
- but relatively rare, and emission highly beamed

The First Stars

- more numerous than quasars
- if massive, also very luminous and UV-bright
  less promising for helium 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