Astro 507

Lecture 42

May 7, 2014

Announcements:

- Final Preflight posted, due next Wednesday 9am
  fun, optional, easy bonus points
- **ICES** available online – please do it!

Final Problem Set (PS7):

- takes place of final exam
- open book, notes, web
- but: do not collaborate!
- assigned Mon May 12, due Thurs May 15 4:30pm
- Office Hours: Wed May 14, noon

ASTR 496 APA: The Art and Practice of Astronomy

Fall Semester 2014, Thursday 4-5pm
Instructors: Charles Gammie & BDF

how to live long and prosper in astrophysics research

art: unwritten/informal research tools
order of magntidue estimates

practice: “sociology” of astrophysics
career worldline: grad school and beyond
unwritten expectations, opportunities, challenges

Goal: give you an unfair advantage!

Last time: baryon acoustic oscillations

best understood as real-space evolution of
an adiabatic point perturbation

Q: dark matter evolution? baryon/photon fluid?

Q: observable consequences

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

$$\xi(r) = \langle \delta(\vec{x})\ \delta(\vec{x}+\vec{r}) \rangle \tag{1}$$

Q: what should we see?

`www: SDSS data`

in k space: power spectrum

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

Q: why is this incredibly powerful?

BAO: A Standard Ruler

the baryon acoustic oscillation scale fixed by recombination physics
$\rightarrow$ $r_{\text{shell,com}} = c_s \eta_{\text{dec}}$ 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

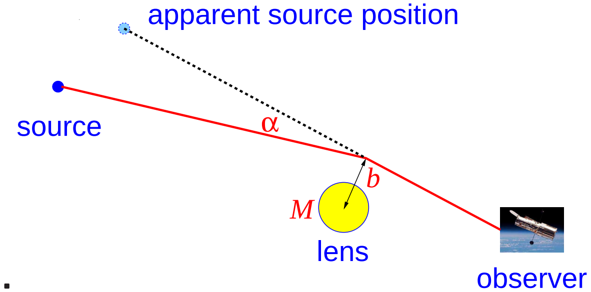
Shedding Light on the Dark Universe

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 $\Phi(\vec{r})$
gravitational lensing acts like *index of refraction*

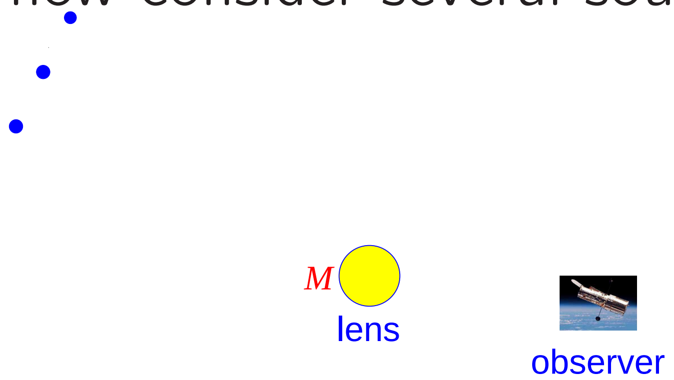
$$n(\vec{r}) = 1 - \frac{2\Phi(\vec{r})}{c^2} \geq 1 \text{ for bound objects} \tag{2}$$

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



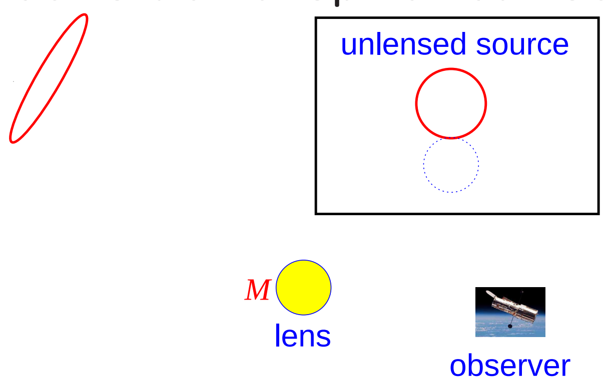
$$\alpha = \frac{4GM}{c^2 b} = 2 \text{ arc sec} \left(\frac{M}{M_\odot}\right) \left(\frac{R_\odot}{b}\right) = 0.2 \text{ arc sec} \left(\frac{M}{10^{12} M_\odot}\right) \left(\frac{100 \text{ kpc}}{b}\right)$$

now consider several sources



Q: unlensed source image? lensed image? lessons?

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

Observable Effects

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

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 $z \to$ 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 $\to$ elliptical
  but elliptical $\to$ elliptical too!
  $\Rightarrow$ need statsitical 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 $\rightarrow$ use a backlighting
intervening neutral hydrogen absorbs all photons
wth $E_\gamma > 13.6$ eV $\Rightarrow$ in absorber rest frame

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

Gunn & Peterson (1965): look for absorption trough
below "Lyman limit" $\lambda < (1 + z_{\rm qso})\lambda_{\rm Ly}$
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:

$$\Omega_{\rm HI} \simeq 10^{-7} \ll \Omega_{\rm baryon} \tag{3}$$

▷ 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 $\rightarrow$ free e^- $\rightarrow$ 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 $\tau_{\rm reion} = \sigma_{\rm T} \int_{d_H} n_e ds \sim 0.17$ constrains ion history

Hydrogen reionization: Energetics

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

Helium reionization

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

$\Rightarrow$ even more energetic photons needed

⋆ recent observations: He reionization at $z_{\rm He} \sim 3$

Q: Whodunit–candidates for reionization?

Reionization Candidates

The First Quasars

- very luminous
- flat spectra $\rightarrow$ 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

The Cosmic History of Star Formation

history of cosmic star formation encodes a wealth of information:

- baryonic matter cycling: gas $\leftrightarrow$ 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!
$\rightarrow$ 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 $\tau_m \sim 10$ 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

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

15 `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.,

$$\dot{\rho}_\star(z) = \frac{dM_\star}{dt_{\rm em}\, dV_{\rm comov}} \tag{4}$$

key observed features:

- rise from present $z = 0$ value to peak at $z \sim 1 - 2$
- peak rate ~ 10 times higher than today
  $\rightarrow$ 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

Predictions for the Coming Decade: Yours

Hot Topics in 2024 Cosmology

In 10 years, I expect that we'll still be talking a LOT about dark energy. Even though surveys like DES are going to be able to more precisely quantify how dark energy works, I don't think we will be all that much closer to understanding what it is.

Another topic that I'm sure will be very prevalent in a decade is the B-mode polarization in the CMB. Between mapping the rest of the sky and interpreting the results, this will be a fruitful field for awhile.

I think there will likely be a resurgence in inflation research in the next 10 years due to the recent gravity wave detection.

I expect the main topics in cosmology would be to reveal the nature of dark matter (DM) and the mechanism of inflation in the 2020s, or even 2030s.

Quantum mechanics will work closely with cosmologists to see if their picture of what is going on at microscopic levels could be dark energy.

Settled/Advanced Questions

Assuming Cold War 2 doesn't turn hot ... Dark matter particles will be created in the laboratory for the first time, expanding our understanding of the universe to 25

More candidates for WIMPs. Huge improvements in studying Higgs Bosons.

Within the next ten years, I dont think anything will be completely settled. But asides from my beef with the definition of settled, I think well have most of dark matter figured out. ... (I guess a good analogy is Higgs boson:today::dark matter:10 years from now).

I believe that the LHC or some other experiment will discover dark matter particles.

The questions will probably be settled by then: detection of dark matter candidates; determine neutrino mass; lithium problem; more independents experiments other than BICEP2 confirm B-mode signal; gravitational wave detection from LIGO or other experiments.

Remaining Open/Unsettled Questions

There is just so little that we actually know about DE at the moment that it's hard to even think about being able to confirm its existence in 10 years without some unprecedented breakthrough.

I believe that the exact mechanism behind inflation will not be known in ten years. There also may not be a definitive model of dark energy. The topic I am most confident about is the continued unresolved status of string and multiverse theories, which seem to lack directly observable signatures.

I dont think we will have established a unified forces theory by then. There seems to be too much work left to do before we can establish any solid theory in that respect.

Surprises, both hopeful and cynical

If string theory/quantum loop guys have put forward something that can be tested it would also not be a small surprise. Although I believe any of those can be more likely to happen than all of us have found faculty jobs.

I'm also hoping that dark energy ends up being the vacuum energy of space like Einstein put into his equations. So, I may be close minded...but I feel like the changes that happen in the next 10 years will be small. I think we have a lot of observing to do!

Surprises might be that we might find relation between dark energy and inflation (which I do believe they are related).

I also think some condensed matter theorist will figure out one of the big cosmological questions, like Dark Energy, and complain when particle physicsts/cosmologists independently discover the same mechanism a few years later.

I hope we find that dark energy can be extracted from the universe and used for power.

I don't expect or even want this, but sometimes I cynically imagine the General Relativity is wrong. Also, I think theories of dark energy will significantly expand beyond the scope of scalar fields.

Supersymmetry is correct. (a pleasant surprise, perhaps)

DE weakens and the universe decelerates again.

Predictions for the Coming Decade: Mine

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

Observations/Experiments

- dark energy evolution probed by DES, EUCLID, Pan-STARRS, LSST, ...
- CMB 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
- Fermi (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
- Webb (NGST): supernovae from first stars (Pop III) imaged
- gravity waves detected from NS/NS merger, associated with γ burst
- completely unexpected result(s) makes some of the above look naive

My Fondest Cosmological Wish for the Decade
The Dark Matter Trifecta

⋆ WIMP underground detectors find and confirm signal

⋆ LHC at CERN finds supersymmetric partners
consistent with WIMP evidence

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

Nobel prizes all around!

Theory

- supersymmetry detection leads to detailed inflation, baryogenesis theories
- dark energy motivates/constrains quantum gravity progress
- supernova models achieve successful 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

Into the Sunset

We are living in the golden age of cosmology

There is much more to learn
$\rightarrow$ stay tuned to future colloquia, seminars, prelims, defenses!

Last Thoughts

This is the last class for many graduating undergraduates and for some grads

CONGRATULATIONS!

I will be teaching less for the next few years
$\Rightarrow$ I'm very grateful for the great sendoff!
I appreciate your hard work, great questions, lively online discussion

THANK YOU!

FIN

Director's Cut Extras

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

$$d\tau = \Gamma_{\rm sc} dt = n_e \sigma_{\rm T} ds = \frac{ds}{\lambda_{\rm mfp}} \tag{5}$$

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

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

Q: which means?

CMB Scattering by Intracluster Gas

mean free path is that for Thompson scattering:
$\ell_\nu^{-1} = \alpha_\nu = n_e \sigma_\mathsf{T}$ independent of frequency
and thus optical depth is integral over cloud sightline

$$\tau_\nu = \int \alpha_\nu \; ds = \sigma_\mathsf{T} \int n_e \; ds \tag{6}$$

thus transmission probability is $e^{-\tau_\nu}$, and so
absorption probability is $1 - e^{-\tau_\nu}$

but for galaxy clusters: $\tau < 10^{-3} \ll 1$,
and so *absorption probability* is just τ
Q: implications?
Q: effect of scattering if electrons cold, scattering is elastic?
Q: what if electrons are hot?

if electrons are hot, they transfer energy to CMB photons
change temperature pattern, in frequency-dependent way

What is net change in energy?
initial photon energy density is $u_0 = u_{\rm cmb} = 4\pi B(T_{\rm cmb})/c$
power transfer per electron is $P_{\rm Compt} = 4(kT_e/m_e c^2)\sigma_{\rm T} c\ u_0$, so

$$\frac{\partial u}{\partial t} = P_{\rm Compt}\ n_e = 4\frac{kT_e}{m_e c^2}\sigma_{\rm T} c\ u_0\ n_e \tag{7}$$

and thus net energy density change

$$\Delta u = 4\sigma_{\rm T}\ u_0 \int \frac{n_e\ kT_e}{m_e c^2} ds = 4\frac{kT_e}{m_e c^2}\tau\ u_0 \tag{8}$$

Q: implications?

CMB energy density change through cluster

$$\Delta u = 4\sigma_{\rm T}\ u_0 \int \frac{n_e\ kT_e}{m_e c^2} ds = 4 \frac{kT_e}{m_e c^2} \tau\ u_0 \equiv 4y\ u_0 \tag{9}$$

- dimensionless **Compton-y parameter**

$$y \equiv \sigma_{\rm T} \int \frac{n_e\ kT_e}{m_e c^2} ds \simeq \tau \frac{kT_e}{m_e c^2} \simeq 3\tau\beta^2 \tag{10}$$

- note $n_e kT_e = P_e$ electron pressure
  $\rightarrow y$ set by line-of-sight pressure

fractional change in (integrated) energy density $\Delta u / u_0 = 4y$
- positive change $\rightarrow$ (small) net heating of CMB photons
- since $u \propto I$, this also means

$$\frac{\Delta I_{\rm cmb}}{I_{\rm cmb}} = 4y \tag{11}$$

cluster generated net CMB "hotspot"

Q: expected frequency dependence?

SZ Effect: Frequency Dependence

on average, we expect photons to gain energy
adding intensity at high ν, at the expense of low ν

but note that in isotropic electron population
- some scatterings will reduce energy
- while others will increase it

detailed derivation is involved:
- allow for ordinary and stimulated emission
- include effects of electron energy distribution
- allow for Compton shift in energy
- use Thomson (Klein-Nishina) angular distribution

full equation (Kompaneets and generalization)
describes *"diffusion" in energy (frequency) space*
but key aspect comes from basic Compton property *Q: namely?*

Thermal SZ Effect as a Probe of Galaxy Cluster

in each line of sight
SZ measures Comptonization parameter in a cluster:

$$y = \sigma_{\mathsf{T}} \int \frac{n_e \; kT_e}{m_e c^2} ds = \frac{\sigma_{\mathsf{T}}}{m_e c^2} \int P_e \; ds \approx \frac{\sigma_{\mathsf{T}} \; kT_e}{m_e c^2} \int n_e \; ds \tag{12}$$

direct measurement of *projected pressure* in column
and if T_e known, a measure of electron column density

SZ flux measures

$$\int \cos\theta \; y \; d\Omega \approx \int y \; d\Omega = \frac{\int y \; dA}{D_{\mathsf{A}}^2} \tag{13}$$

where $D_{\mathsf{A}}(z)$ is the (angular diameter) distance

$$\int y \; dA \approx \frac{\sigma_{\mathsf{T}} \; kT_e}{m_e c^2} \int n_e \; ds \; dA \propto M_{\mathrm{gas}} \tag{14}$$

$\rightarrow$ SZ flux gives *intracluster cluster gas mass!* *Q: cosmo apps?*

SZ Effect: Cosmological Applications

- *SZ identifies all clusters without redshift bias!*
  $\rightarrow$ SZ can be used to discover high-z clusters

- SZ + X-ray gives cluster size, gas mass, T_e
  if cluster physics well-understood (Ricker, Vijayaraghavan)
  $\rightarrow$ *cluster mass*

- cluster number density ("abundance") and mass vs z
  i.e., cluster *mass function* a sensitive probe of cosmology

today: clusters are the *largest bound objects*; in early U: rare
number and mass vs time sensitive to *cosmic acceleration*
that competes with *structure growth via gravitational instability*
$\Rightarrow$ clusters probe this competition

Q: so how to find clusters, measure redshifts?

note that SZ redshift independence also means
SZ does not give cluster redshift

Dark Energy Survey key project:
optical images, redshifts of clusters
compare with SZ survey by South Pole Telescope

`www: SPT survey image`

SZ Effect: More Cosmological Applications

even for clusters not clearly imaged in SZ
SZ effect from all clusters still imprinted on CMB
affects $\Delta T_{\rm cmb}$ perturbation pattern on sky

typical angular size of cluster SZ:
for large cluster $\theta_{cluster} \sim R_{\rm cluster}/d_{\rm H} \sim 3 \text{ Mpc}/4 \text{ Gpc} \sim 3 \text{ arcmin}$
i.e., SZ affects small angular scales
in C_ℓ multipole space this corresponds to $\ell \sim 200/\theta_{\rm deg} \sim 4000$

SZ statistical imprint on CMB anisotropies:
exquisitely sensitive measure of *cosmic structure*
for experts: angular power spectrum $C_\ell^{\rm SZ} \propto \sigma_8^7$!

To date: SZ contribution to power spectrum not seen! *Planck*?

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 $\rightarrow$ 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 $\rightarrow$ hard to depressurize, collapse
only available molecules are H_2, traces of HD, LiH
$\rightarrow$ 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 $\rightarrow$ slow evolution $\rightarrow$ accretion unimpeded
$\rightarrow$ 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 $pp \rightarrow de\nu$ until self-enrich with CNO
- no metals in atmosphere $\rightarrow$ much lower opacity
  radiation-driven winds inefficient $\rightarrow$ less/no mass loss?
  difficulty stopping accretion

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

- low opacity $\rightarrow$ more compact $\rightarrow$ 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?