Topics in Extragalactic Astronomy

6. Distant Galaxies & Galaxy Formation

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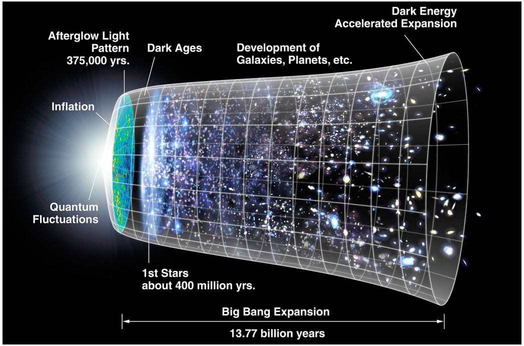
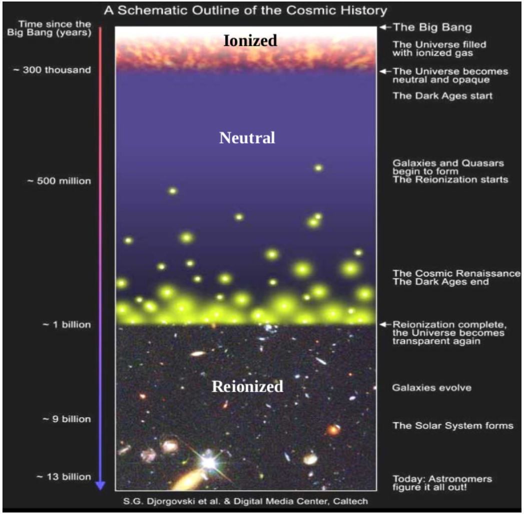
some big questions

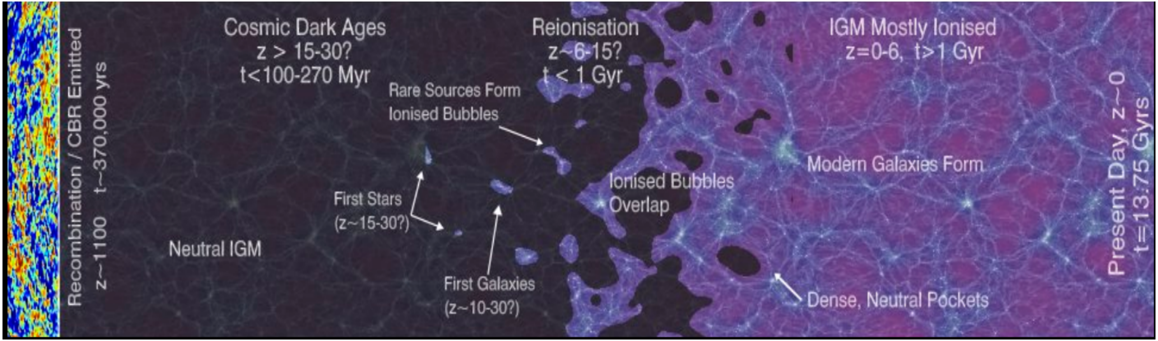
- when the first stars and galaxies were formed?
- how to find distant objects?
- what does a primeval galaxy look like?
- what are the physical processes driving star-formation at high-z?
- what is the nature of the co-evolution of black holes and stellar populations?

the big picture: the reionization





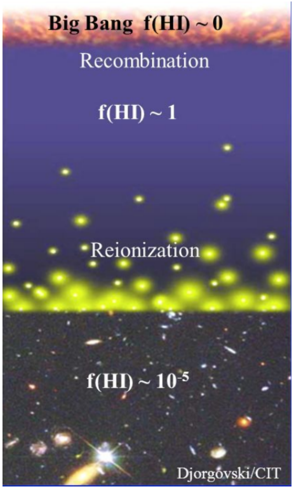
the big picture: the reionization



the reionization and the intergalactic medium

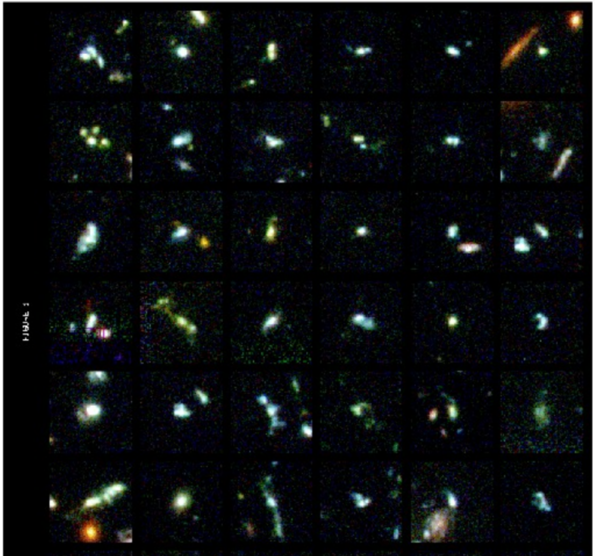
basic scenario:

- $z \sim 1100$: recombination- the universe gets transparent for radiation
- $z \sim 30 - 20$: first clouds collapse in dark matter halos forming the first stars: population III - they are very massive and evolve quickly
- $z \sim 15 - 10$: larger DM halos form in which new stars form from already metal enriched gas: population II stars
- the UV radiation from massive stars, starbursts, and accreting massive black holes creates “Stromgren spheres” of ionized gas
- the Stromgren spheres grow, percolate, the IGM becomes more and more ionized



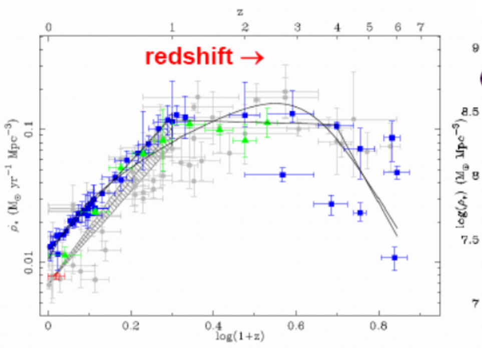
the big picture: galaxies at high-z

Hubble images of these spectroscopically-confirmed galaxies with redshifts z ~ 3 reveal small physical scale-lengths and irregular morphologies: many appear to be merging or assembling from smaller units - immature systems

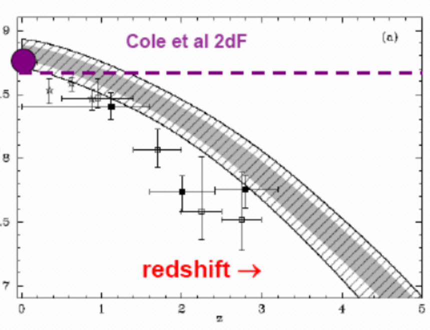


the big picture: the star-formation history

Star formation history

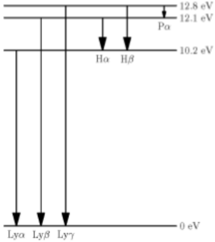


Mass assembly history

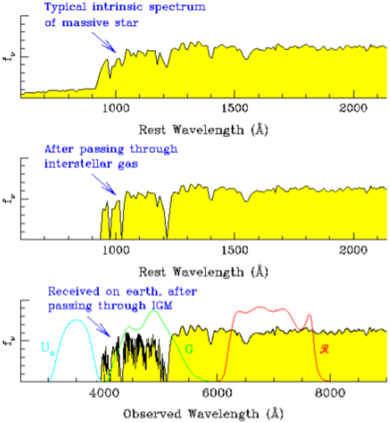


Ly-α photons and the IGM

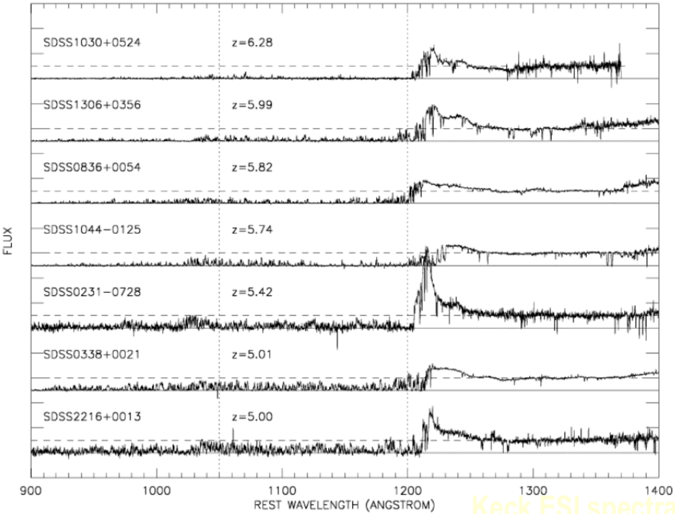
- Ly-α photons are produced by hot stars (and AGN)
- Ly-α photons ($\lambda_{em} = 1216$Å) are absorbed by neutral hydrogen in IGM clouds at $\lambda_{obs} \leq 1216 \times (1 + z_{em})$
- for $\lambda < 912$ Å (the Lyman limit) in the cloud rest-frame, HI absorbs almost totally the radiation



Effect of neutral hydrogen



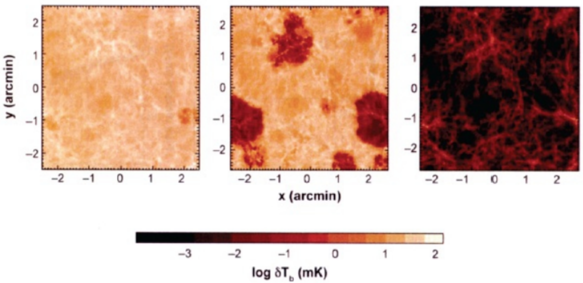
Ly-α photons and the IGM



Keck ESI spectra

the new window to study the IGM: the 21 cm line

Future Possibility to Study the HI Universe at the Reionization Epoch in the 21cm line (e.g. with SKA)

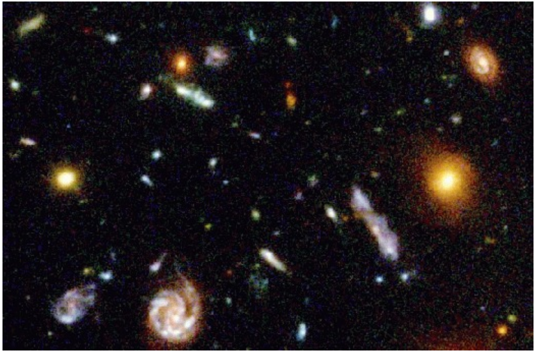


Simulation of the 21cm brightness temperature distribution in the sky during the epoch of reionization at redshifts: 12, 9, 7 [by Furlanetto et al. 2004]. The planned Square Kilometer Area radio interferometer (SKA) can possibly see this radiation. Much effort may be needed to clearly detect this radiation in the presence of various foregrounds.

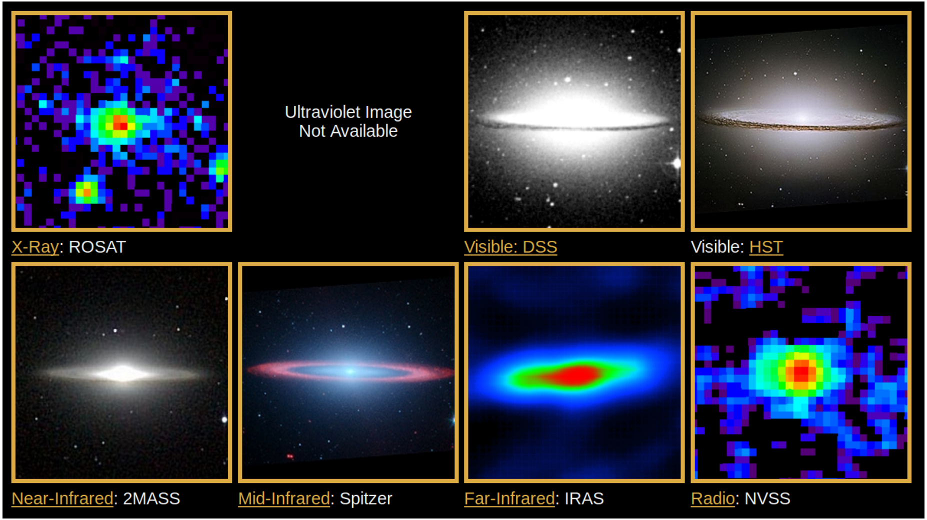
how galaxies look like at high-z

the Hubble Deep Field (HDF):

- 4-band imaging during 200 HST orbits: ~50 h/filter
- main results:
  - most galaxies are at $z > 2$
    notice that for high-z objects we are observing in the rest-frame UV
  - the fraction of blue and morphologically perturbed galaxies is larger than in the local universe
  - many normal galaxies



to keep in mind: the observed wavelength

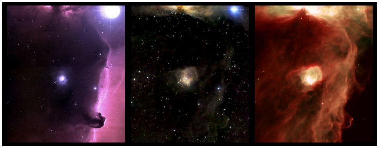


sombrero galaxy: http://coolcosmos.ipac.caltech.edu/cosmic_classroom/multiwavelength_astronomy/multiwavelength_museum/m104.html

to keep in mind: the observed wavelength

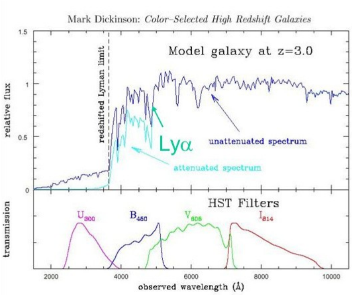
The infrared sky

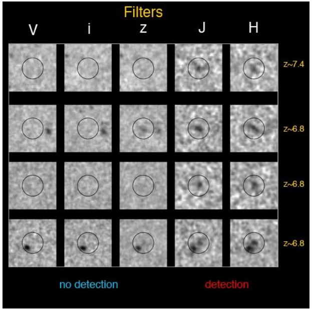
SPECTRAL REGION	WAVELENGTH RANGE (microns)	TEMPERATURE RANGE (degrees Kelvin)	WHAT WE SEE
Near-Infrared	0.7 - 5	740 - 5,200	Cooler red stars Red giants Dust is transparent
Mid-Infrared	5 - 40	93 - 740	Dust warmed by starlight
Far-Infrared	40 - 350	11 - 93	Emission from cold dust Central regions of galaxies Very cold molecular clouds

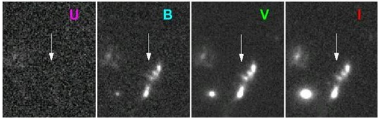


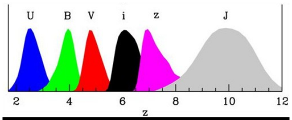
Visible Near Infrared Mid-Infrared

identification of high-z galaxies: dropouts









Dropout Redshift Selection Functions

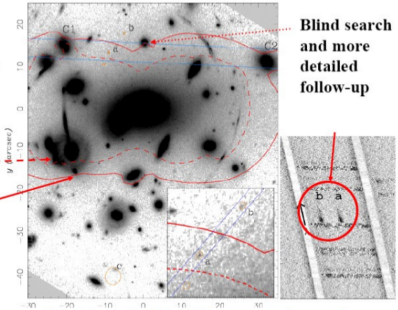
identification of high-z galaxies: dropouts in gravitational telescopes

Critical lines (points of high magnification) for background sources at

z=1

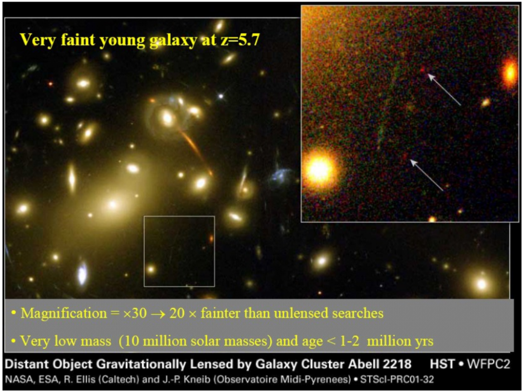
and for

z=5



Blind search and more detailed follow-up

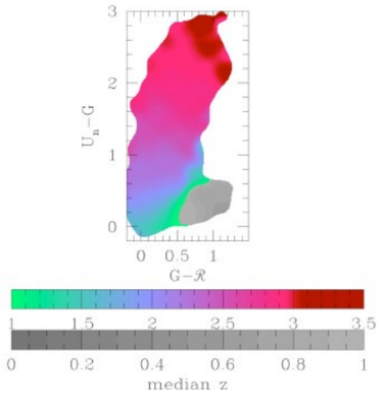
Utilizing strong magnification (×10-30) of clusters, probe much fainter than other methods but in small areas

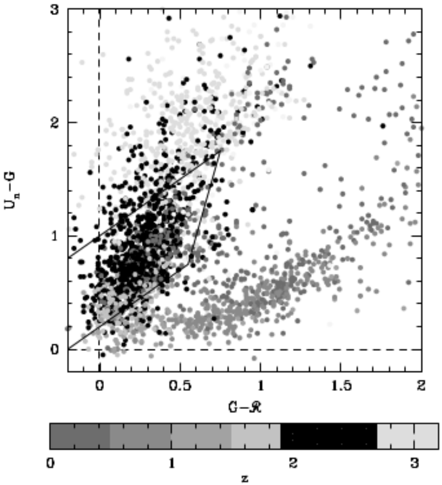


identification of high-z galaxies: color selection

- rest UV selection
  - UGR criteria: identify LBGs at several redshifts

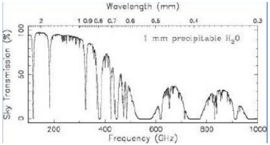
    (Steidel + 2003, Aldenberger + 2004)

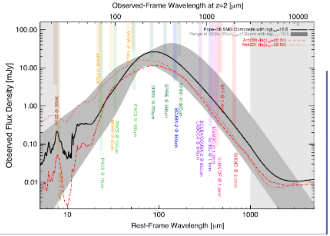




identification of high-z galaxies: sub-mm galaxies

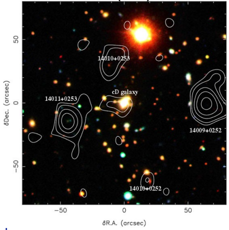
- mid-IR observations are done in selected windows: 0.35, 0.45, 0.85 mm
- objects detected by their dust continuum emission
- dusty star-forming galaxies and AGNs
- found originally by SCUBA at JCMT (1998)
- also observed with SCUBA-2, Herschel, Spitzer, WISE, ALMA
- an open issue: the origin of the large luminosity ($> 10^{12}\, L_\odot$) of some sources

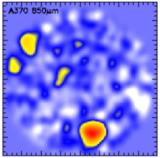




Casey+ 2014

A1835 (Blain+)

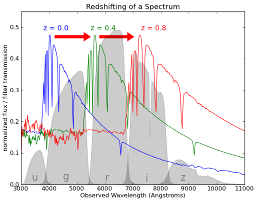


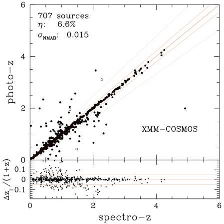


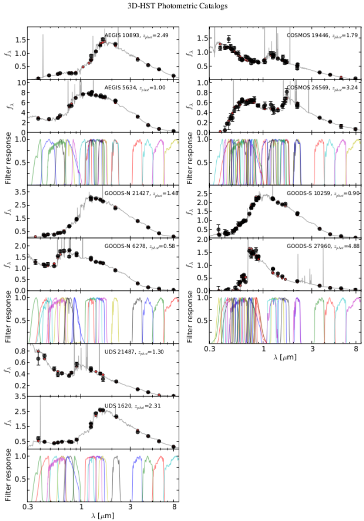
Smail

identification of high-z galaxies: photometric redshifts

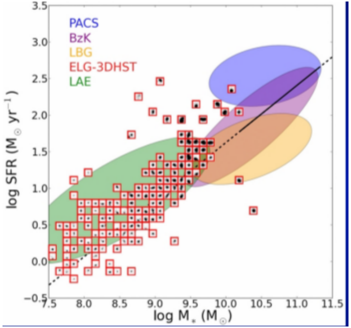
- photometric redshifts: estimated from photometry







the high-z zoo



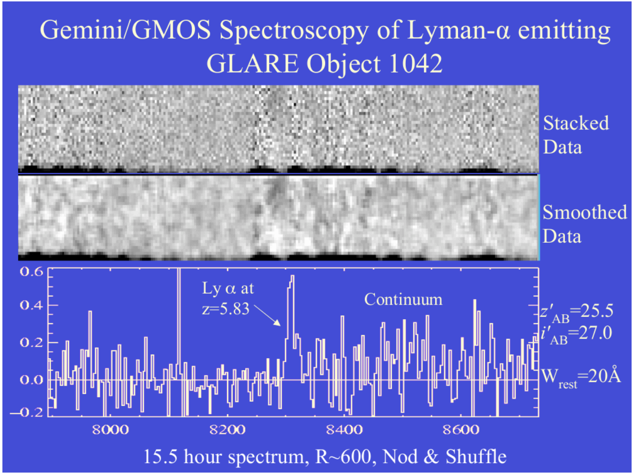
(Zeimann+ 2014)

- different techniques select different galaxies and probe different regions in the space of M_* , SFR, extinction, age, clustering, ...
- strong selection effects!

the zoo

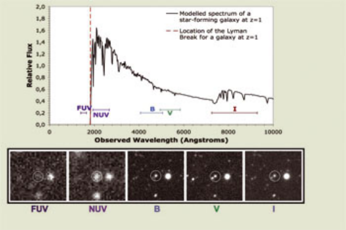
- Lyman-break galaxies
- Starburst galaxies
- Extremely Red Objects (EROs)
- Dusty star-forming galaxies
- Damped Lyman-alpha systems
- Lyman-alpha blobs
- ...

the high-z zoo: spectroscopic challenges



the high-z zoo: Lyman-break galaxies

- LBGs: star-forming galaxies detect by the dropout technique
- Ly-α photons:
  - hot stars ionize the H (photons with $\lambda < 912$ Å); the H recombines and emitts a Ly-α photon
  - efficient process: up to 10% of the bolometric luminosity of a galaxy can be emitted by the line
  - dust is very efficient in destroying Ly-α: as a consequence it is heated and emitts in the FIR

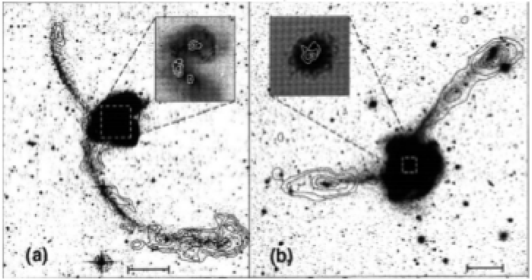


the high-z zoo: dusty star-formation

ULIRG

Ultraluminous Infrared Galaxy

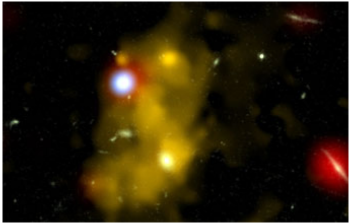
- Local counterparts to high-redshift SMGs
- $L_{IR} > 10^{12} L_{\odot}$ **Extremely bright!**
- Concentrated luminous region at site of merger

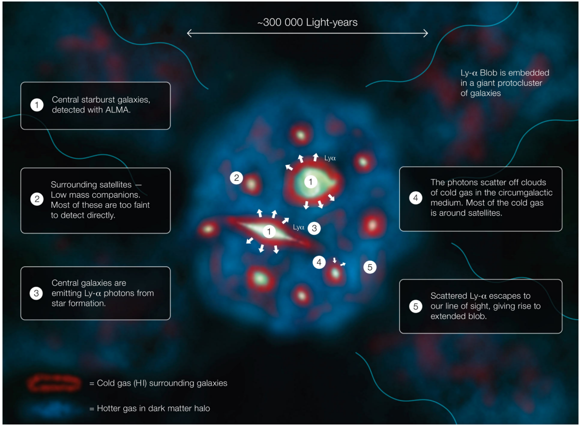


Sanders & Mirabel, 1996.

the high-z zoo: Ly-α blobs

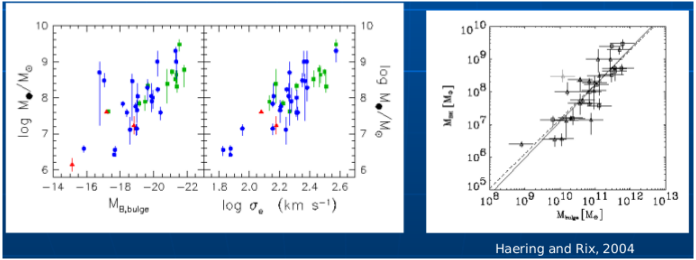
- detected through narrow band imaging
- most objects are associated to luminous galaxies
- the spatial extent of the blueshift absorption shows the presence of strong outflows: superwinds driven by SF and SNe explosions
- in at least one case the Ly-α emission seems to be driven by an AGN
- SSA22-Lyman-alpha blob 1 (LAB-1): active galaxies illuminating the intragroup gas- scattered Ly-α escapes to our line of sight, producing the blob





galaxy populations: the galaxy-massive black hole connection

- Gebhardt+ (1999); Ferrarese and Merritt (1999): Black hole mass correlates with the stellar velocity dispersion of the host galaxy's bulge
- the galaxy and the central massive black hole seem to grow together

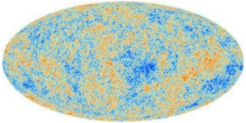


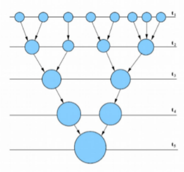
galaxy formation: the need of a theory

- we observe galaxies only for $z < 7$:
  what happened before?
  $t \sim 750$ Myr, $t/t_0 \sim 0.1$

- high-z objects are detected through different techniques in different redshift intervals: how one population relates to the other?

- we need models to understand how galaxies form and evolve!





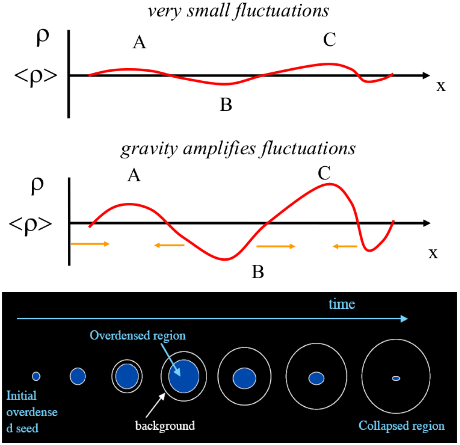
basic scenario

primordial fluctuations

- quantum fluctuations at the beginning of the universe are the seeds of the structures and grow by gravity
- these density fluctuations grow by accreting matter from their neighborhoods until they collapse and virialize

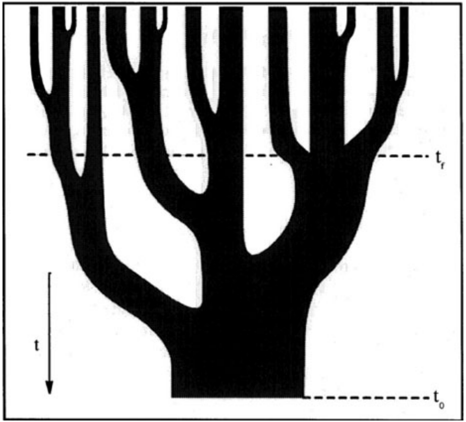
$$\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}}$$

ρ: density



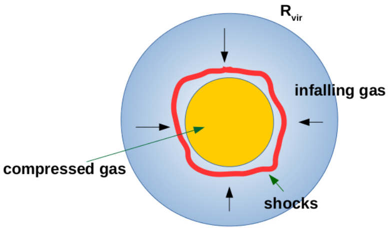
merger trees

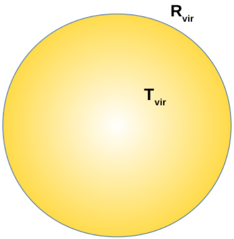
- structures grow hierarchically by merger of their dark halos: merger trees



gas infall in dark matter halos

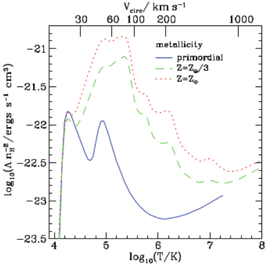
- if $\delta << 1$, the baryonic component is distributed as the DM
- when the overdensity enters a non-linear regime, starting to collapse, the behavior of baryons and DM is very different:
  - DM is collisionless, feels only gravity
  - baryons are collisional: they are heated by friction/collision; this may delay or halt the collapse by the increased gas pressure
  - shocks transform the kinectic energy of the gas in heat
  - after infall, the gas reaches the “virial temperature”
  - example: hot gas in galaxy clusters: $kT \sim 10$ keV $\sim 10^8$ K





cooling of the gas

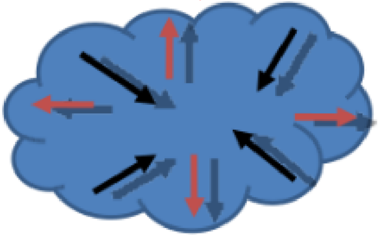
- to form stars the gas must cool
- the pressure of the hot gas prevents the infalling gas to condense further, unless the gas can cool and increase its density
- two major cooling processes:
  - free-free emission in ionized gas due to scattering between electrons and nuclei
  - collisional excitation: collisions excite electrons in atoms or molecules; when an electron decays, it emits a photon



- effect of metals
  - elements heavier than He have small number densities but dominate the cooling
  - for solar abundance, the cooling is more than one order of magnitude than for primordial abundance
- molecules:
  - rich spectrum of energy levels at very low energies, allowing the gas to cool to very low temperatures
  - that is why SF occurs in molecular clouds: gas can efficiently cool and compress to high densities

cooling time vs free-fall time

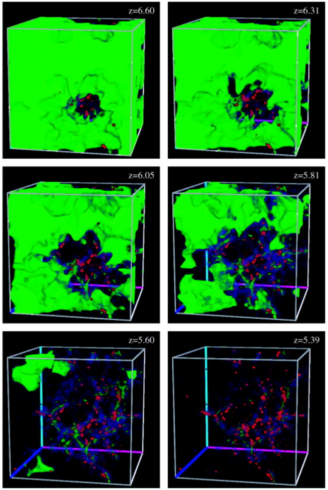
- cooling vs collapse times: t_{cool} vs t_{ff}:
  - if $t_{cool} < t_{ff}$: the gas fall free to the halo center, unaffected by the gas pressure
  - if $t_{cool} > t_{ff}$: the gas sinks to the center at a rate given by the cooling rate $\longrightarrow$ cooling is inefficient
  - $t_{cool} = t_{ff}$: separates situations in which the gas can easily fall inside the halo and form concentrations from those where gas compression is prevented
- hypothesis: the reionization starts with the first generation of stars
- first stars: the gas should be able to fall in to the dark halos and to cool, condensing in clouds and forming stars
- Jeans mass M_J:
  - critical mass: mass for which $t_{cool} > t_{ff}$
  - to form stars, $M > M_J$



population III and population II stars

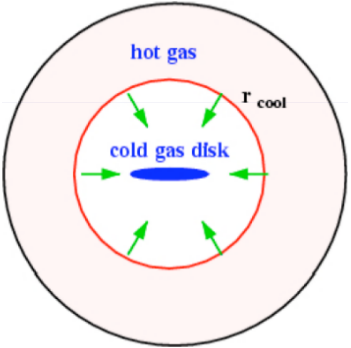
- the first stars should have been very different from today's stars: they contain no metals: population III stars
- they are very massive ($\sim 100 M_\odot$) and evolve quickly (~ 3 Myr)
- as soon as they are formed, they ionize their vicinities preventing further cooling and star formation
- at this point the universe contains a low density of ionized bubbles
- population III stars explode as SNe injecting metals in the IGM, ionizing their neighborhood and preventing further star formation
- population II stars appear at $z \sim 15 - 10$ for $M \sim 10^7 M_\odot$, forming the first protogalaxies
- they form HII regions around, which expands and percolate, reionizing the IGM
- reionization the has two stages:
  - it starts with population III stars by the cooling of H_2, which is soon destroyed ("early reionization")
  - later, the cooling of atomic H and the formation of population II

    stars completes the reionization



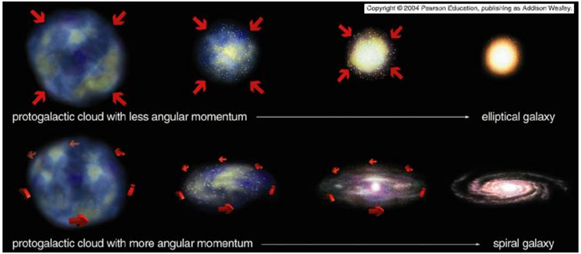
formation of disk galaxies

- a non-spherical overdensity can achieve angular momentum due to torques in the tidal field: DM halos are born with some angular momentum
- when the gas cools, it collapses toward the center conserving angular momentum
- friction/collision between clouds drives the gas to approximately circular orbits in a plane perpendicular to the direction of $\vec{J}$, forming a disk
- the disk forms, SF starts: we are left with a thin stellar disk with some gas



formation of elliptical galaxies

- disks & ellipticals:
  - disks: cold systems- low velocity dispersion (σ)
  - ellipticals: hot systems- high σ
- the monolitic collapse scenario:
  - the gas collapse ($z > 2$) and is “instantaneously” transformed in stars
  - no gas is left, no further SF, the result is an old stellar population at $z = 0$



formation of elliptical galaxies

- the merger scenario:
  - E are found in regions of high galaxy density
  - E often have complicated kinematics, with small disks, shells and ripples

⟶ E are formed in major mergers plus many minor mergers

- "normal" E: formed by wet major mergers at high z, preferentially in overdense regions (groups)
- massive E: grow by dry mergers in high density environments
- classical bulges of disk galaxies: a major merger can occur, forming a small E which later accretes more gas in a disk

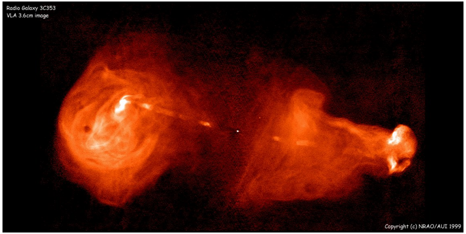
supernovae feedback

- motivations: the *overcooling problem* in the first numerical models
- feedback by supernovae
  - shortly after SF starts, massive stars evolve to SNe
  - part of the mechanical energy of the explosion heats the gas, making it to expand, reduce the density, and, consequently, reducing the cooling efficiency
  - feedback process: if the SF increases, more energy is injected

    in the ISM, preventing or delaying further SF
- if the feedback is too efficient, the local gas in the disk can be ejected to the halo, forming a hot corona
- in low mass halos the gas can even be removed from the halos: outflows in the spectra of Ly-break galaxies at rates similar to their SF and with velocities of several km/s

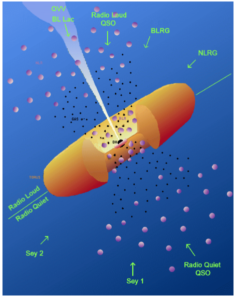
AGN feedback

- in massive halos, SNe feedback is not efficient, and other processes are necessary to avoid the overcooling
- SF and AGN activity are associated, but the details of this association are uncertain
- galaxy clusters: AGN produces hot bubbles in the IGM through jets



- AGN modes
  - *radio mode*: low accretion rate; feedback by jets
  - *quasar mode*: high accretion rate; feedback by photoionization

    via photons produced in the accretion disk around a SMBH



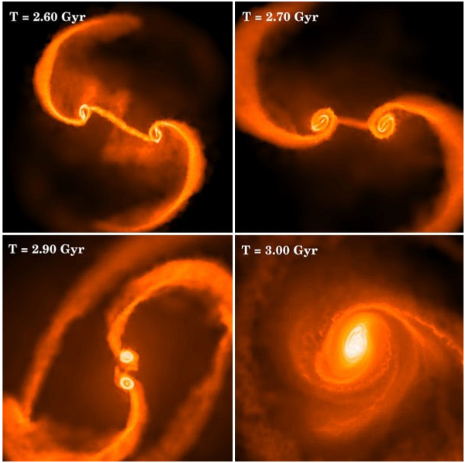
formation and evolution of supermassive black holes

- SMBH should form at high z: quasars are already observed at $z > 6$
- how did they form?
  - remnants of population III stars
  - gas-dynamical processes with H_2 cooling
  - stellar-dynamical processes in protogalaxies
- remnants of population III stars
  - pop III stars are very massive, $M > 100 M_{\odot}$
  - if $M > 250 M_{\odot}$, they form a BH of $> 100 M_{\odot}$
  - this route produces a seed population of SMBH at $z \sim 20$
- gas-dynamical processes
  - assume that the gas is able to loose angular momentum (e.g. by a bar) and accumulates in the galaxy center
  - H_2 cooling may produce a rotating, supermassive star, $M \sim 10^6 M_{\odot}$
  - the evolution of this object may produce a BH of $> 10^5 M_{\odot}$
- stellar-dynamical processes
  - star-star collisions in the central regions of proto-galaxies can produce super massive stars, $M > 10^3 M_{\odot}$, whose remnants could be SMBH seeds
  - condition: the collisions should be fast enough, before the explosions of the first SNe which enriche the gas, reducing the cooling

formation and evolution of supermassive black holes

- BH mass growth: by accreting mass
- mergers also affect the evolution of SMBHs:
  - mergers can provide gas for feeding BHs
  - SMBH masses scale with the velocity dispersion of the stars- what happens with the SMBH of two merging galaxies?
  - due to the dynamical friction, the two BHs will loose orbital energy, approach each other, and eventually merge, emitting a burst of gravitational waves
  - one of the BHs may scatter and escape from the galaxy,

    becoming an intergalactic black hole



the future (... one of them)

Giant Magellan Telescope (GMT)