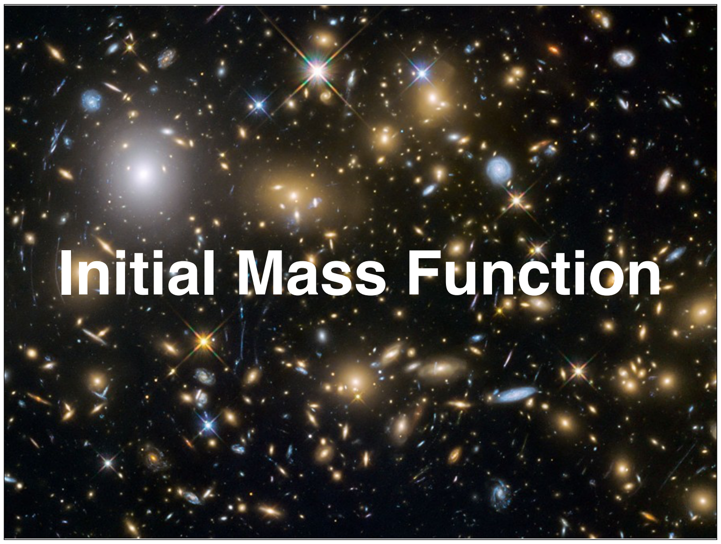
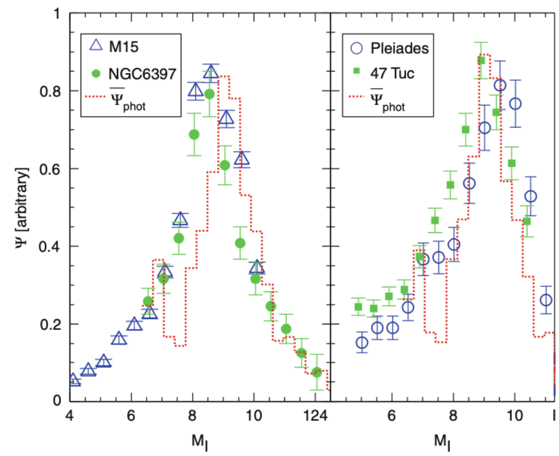
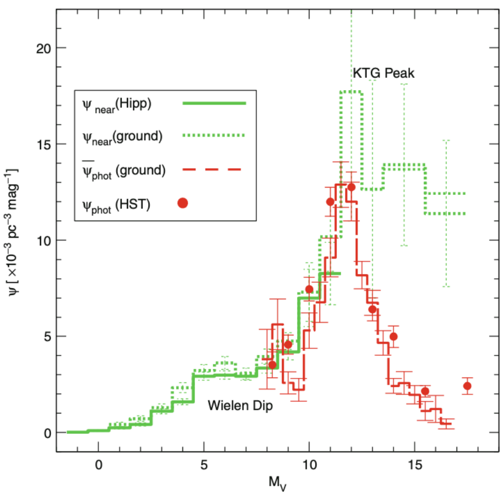


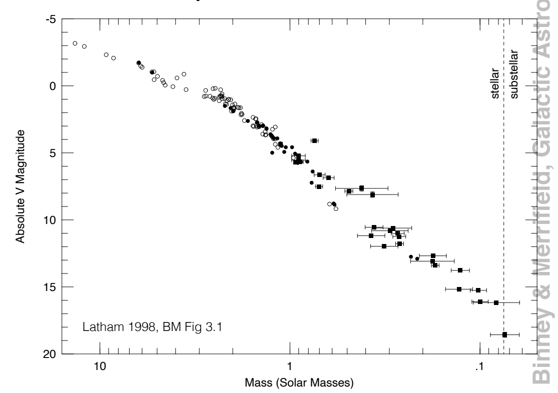
Present-Day Stellar Luminosity Function in Star Clusters



Present-Day Stellar Luminosity Function in MW Disk



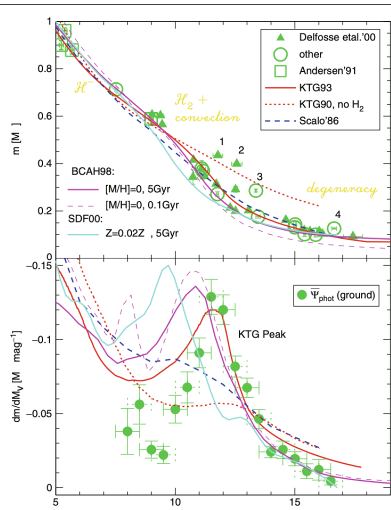
Mass-Luminosity Relation: $L \sim M^{3.5} \Rightarrow M/L \sim M^{-2.5}$



mass-luminosity relation of main sequence stars

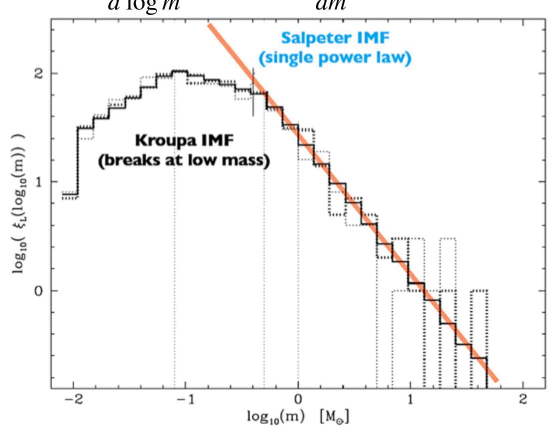
and

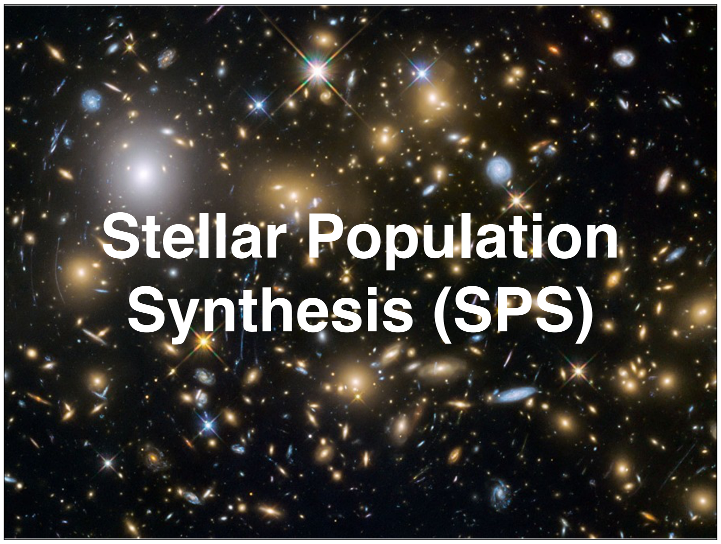
its derivative



Derived Initial Mass Function in MW Disk & Star Clusters

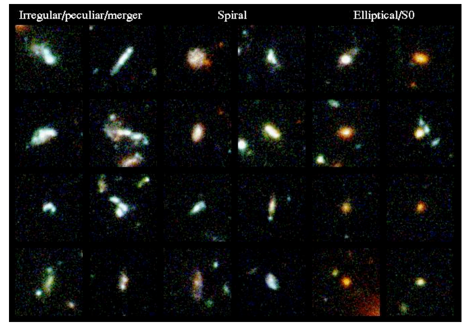
$$\xi_L(m) = \frac{dN}{d\log m} = \ln(10)\ m\ \frac{dN}{dm} = \ln(10)\ m\ \xi(m)$$





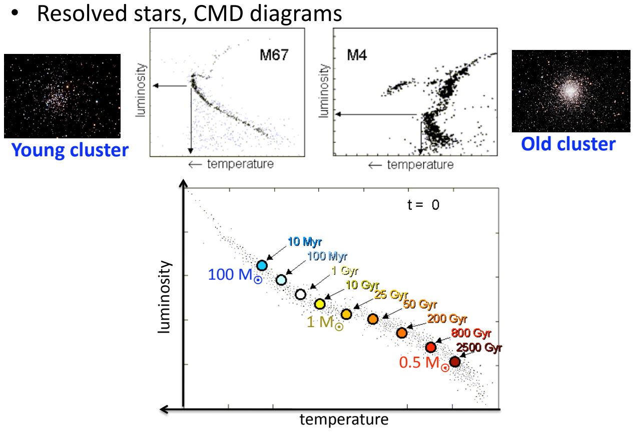
Non-resolved Populations

- Galaxies formed by several SSPs, sometimes we only know their integrated light spectra.
- Integrated light of a galaxy: colours, SED, spectra



Resolved Populations

- Resolved stars, CMD diagrams



Isochrones of stellar populations vs. evolution tracks of individual stars

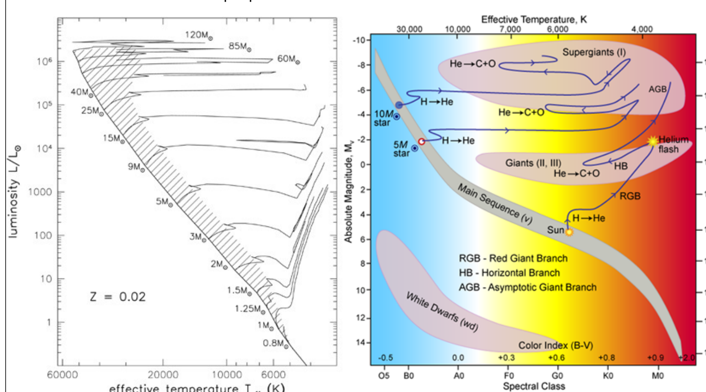
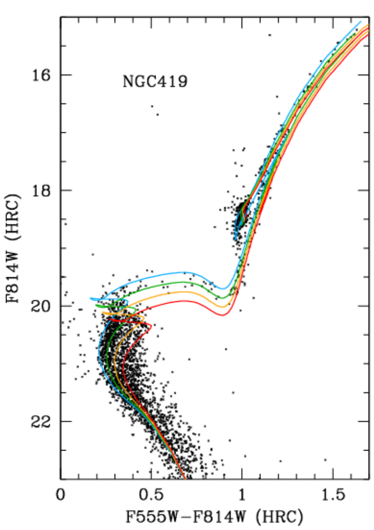
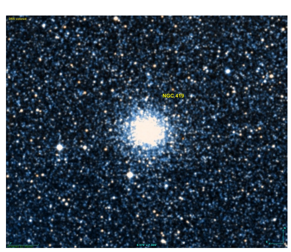
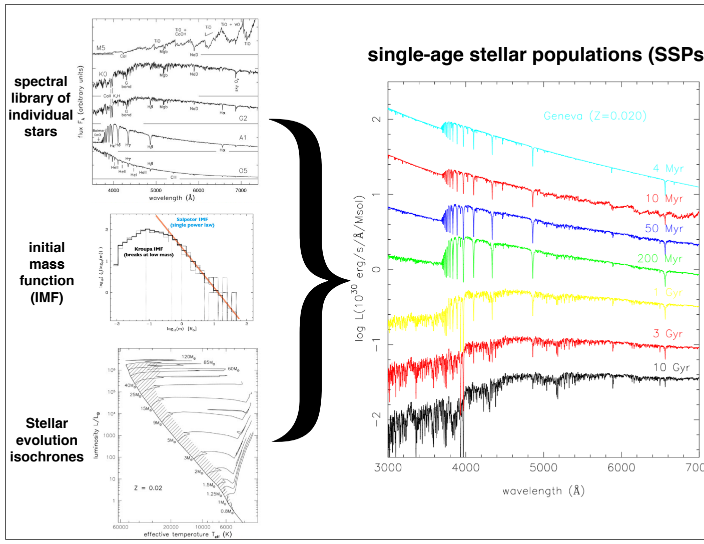


Fig 1.4 'Galaxies in the Universe' Sparke/Gallagher CUP 2007



- Bressan+2012
- Th star cluster NGC 419
- The isochrones are for Z = 0.004, ages log(t/yr) = 9.15, 9.20, 9.25, 9.30

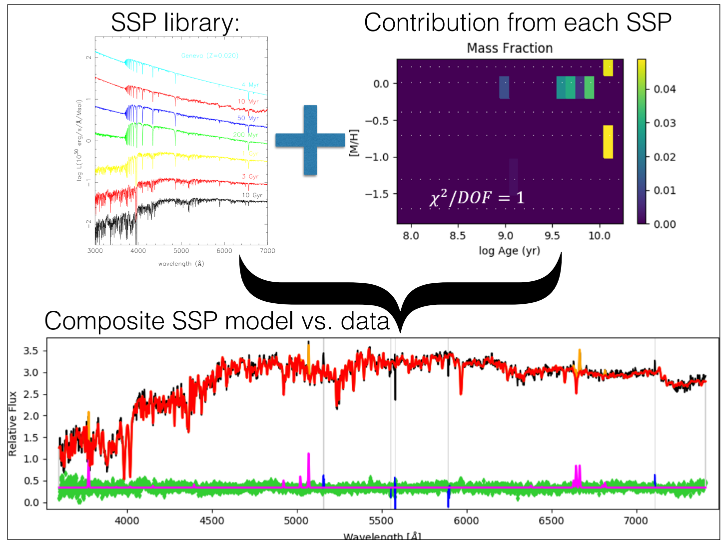


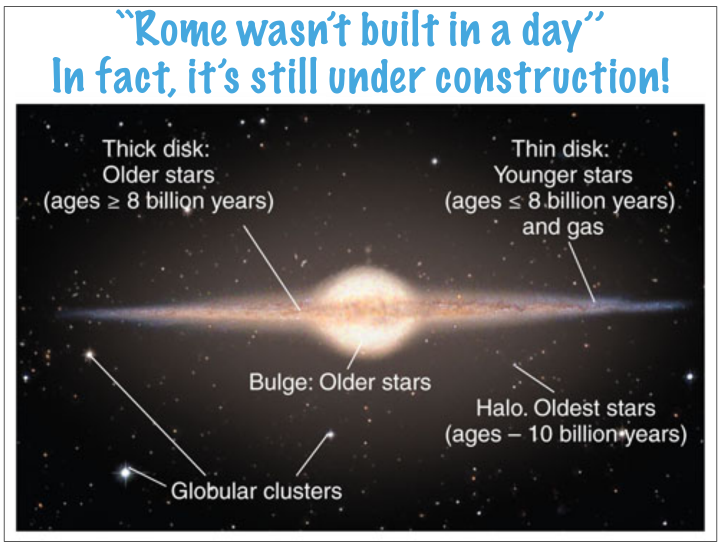


A bounded-variables linear least squares problem: solve for mass weights

$$\sum \mathrm{SSP}(\lambda; t, Z) \times w(t, Z) \approx \mathrm{Galaxy\ SED}(\lambda)$$

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 2 & 1 \end{bmatrix} \times \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \approx \begin{bmatrix} 1 \\ 3 \\ -2 \end{bmatrix}$$





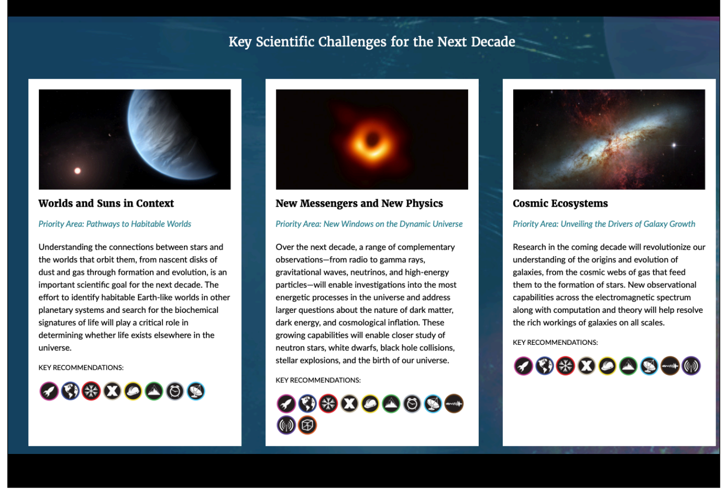
Stellar Population Synthesis

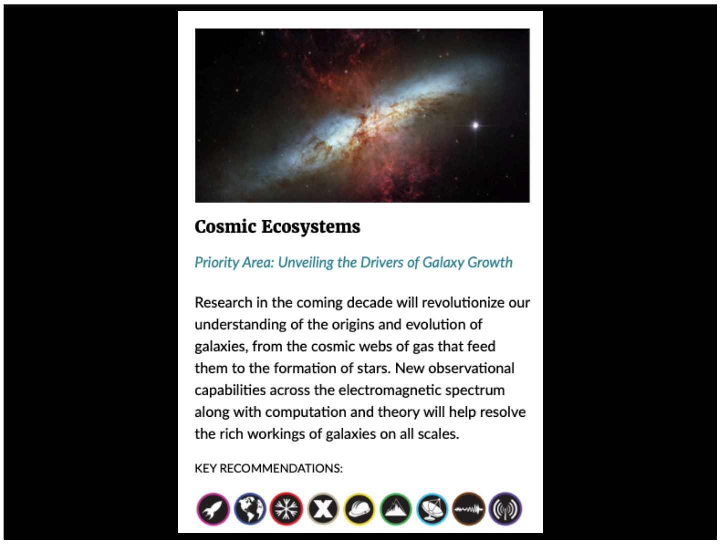
- **Why?** For most external galaxies, individual stars cannot be spatially resolved. So the observer only gets the total integrated spectrum from all of the stars in the galaxy.
- **How?** By observing the stars in the MW, we have a library of stellar spectra from stars in different parts of the HR diagram. Given an IMF and an isochrone from stellar evolution models, one can add all of the stellar spectra together and compare this integrated spectrum with the observed spectrum. Such single-age stellar populations are called a single-age (simple) stellar populations (**SSPs**).
- It is unlikely that a galaxy is made of a single SSP. Instead, it may have a complicated history of star formation. So in practice, one usually has to add a number of different SSP weighted by the star-formation history (dM/dt vs. t)

Challenges of Stellar Population Synthesis

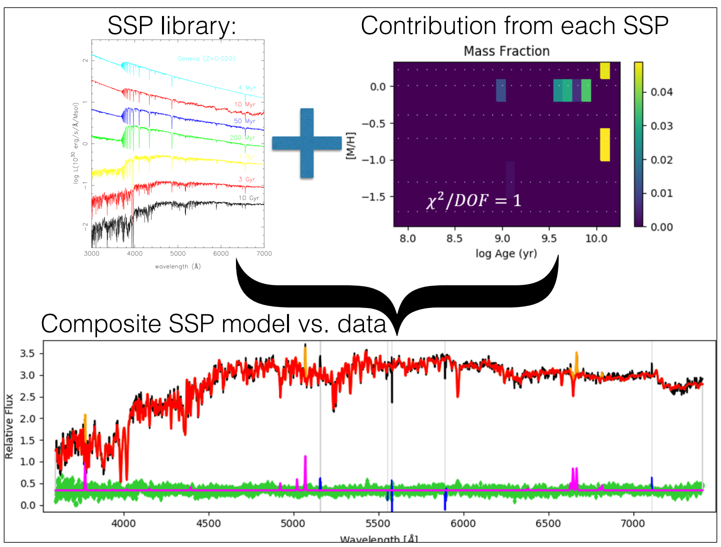
- Stellar evolution models
- Dust extinction
  - extinction law depends on properties and distributions of dust grains
- Initial Mass Function (IMF)
- Stellar spectral libraries
- Metallicity evolution and distribution
- Degeneracy in star formation history

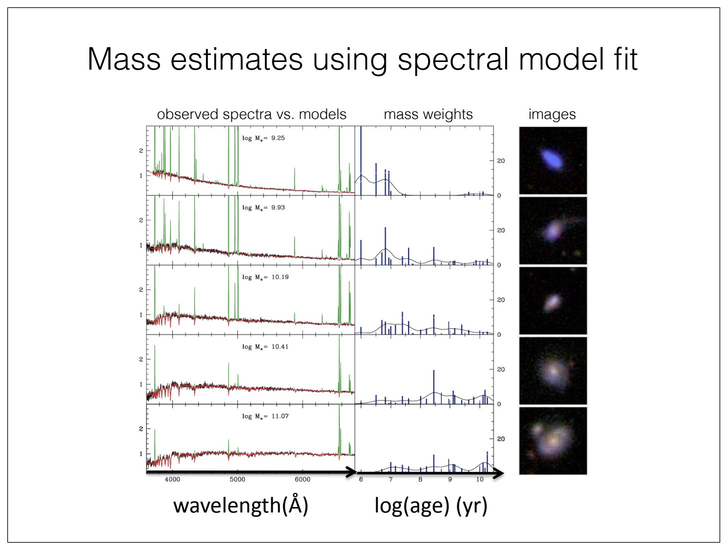
Astro2020 Decadal Survey

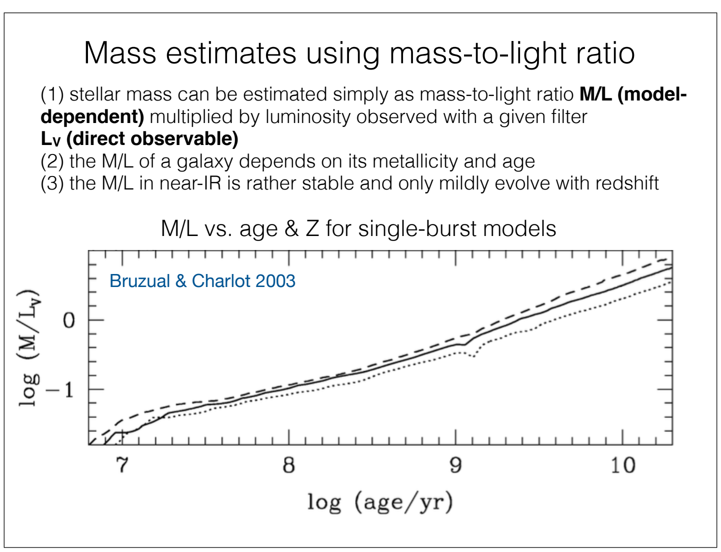


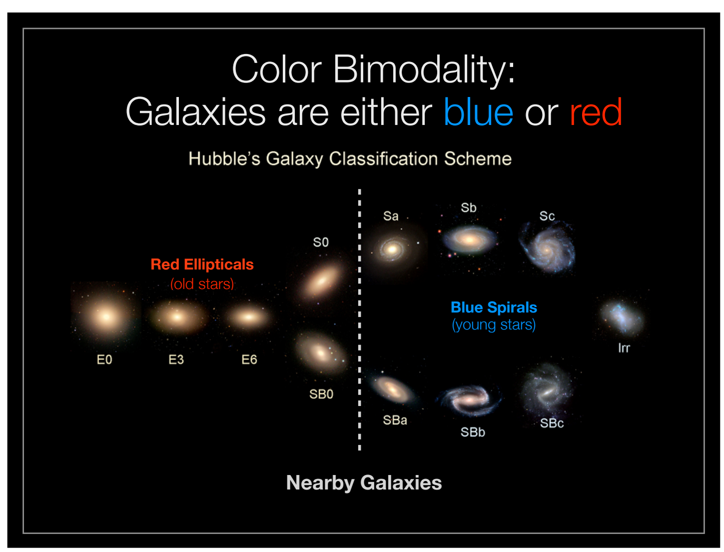

Cosmic Ecosystems
Priority Area: Unveiling the Drivers of Galaxy Growth
Research in the coming decade will revolutionize our understanding of the origins and evolution of galaxies, from the cosmic webs of gas that feed them to the formation of stars. New observational capabilities across the electromagnetic spectrum along with computation and theory will help resolve the rich workings of galaxies on all scales.
KEY RECOMMENDATIONS:


Stellar Mass

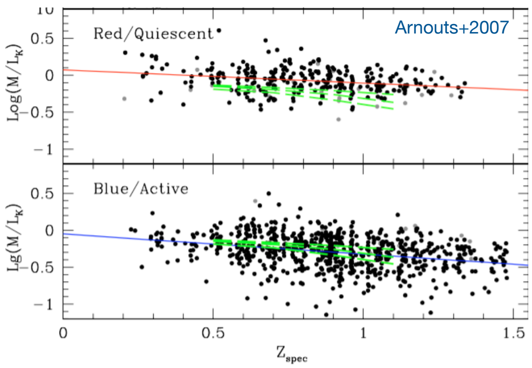

SSP library:
Contribution from each SSP
Mass Fraction
$\chi^2/DOF = 1$
[M/H]
log Age (yr)
Composite SSP model vs. data
Relative Flux
Wavelength [Å]

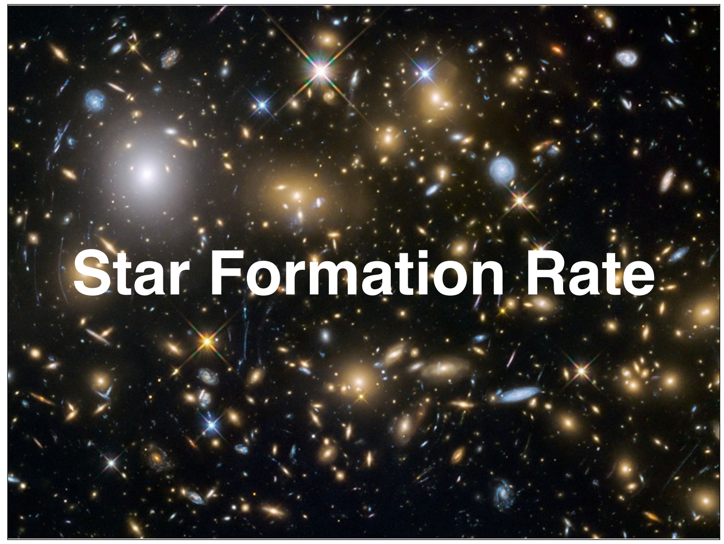

Mass estimates using spectral model fit
observed spectra vs. models
mass weights
images
wavelength(Å)
log(age) (yr)


Mass estimates using mass-to-light ratio
(1) stellar mass can be estimated simply as mass-to-light ratio **M/L (model-dependent)** multiplied by luminosity observed with a given filter **L_V (direct observable)**
(2) the M/L of a galaxy depends on its metallicity and age
(3) the M/L in near-IR is rather stable and only mildly evolve with redshift
M/L vs. age & Z for single-burst models
Bruzual & Charlot 2003
$\log\ (M/L_V)$
$\log\ (age/yr)$

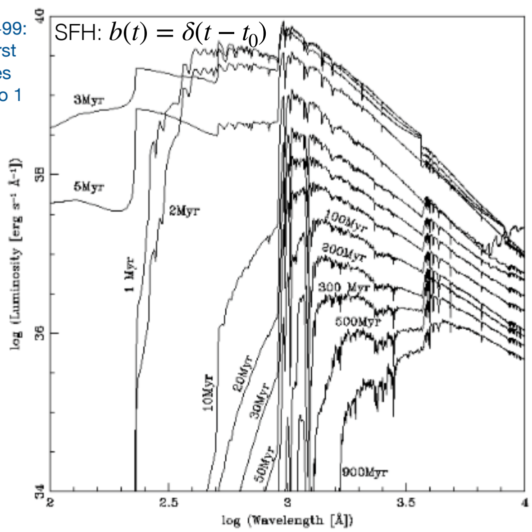

Color Bimodality:
Galaxies are either blue or red
Hubble's Galaxy Classification Scheme
Red Ellipticals
(old stars)
Blue Spirals
(young stars)
E0
E3
E6
S0
SB0
Sa
Sb
Sc
SBa
SBb
SBc
Irr
Nearby Galaxies

Galaxy-integrated M/L$_K$ vs. redshift relation for red and blue galaxies

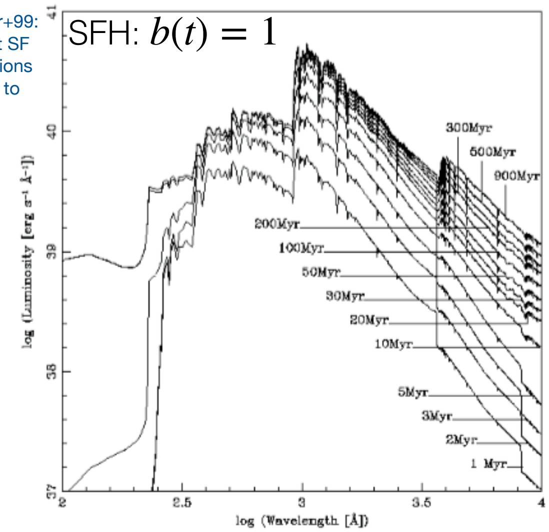




Leitherer+99: single-burst SF w/ ages of 1 Myr to 1 Gyr



Leitherer+99: constant SF w/ durations of 1 Myr to 1 Gyr



SFR estimators

Murphy+11: using the Kroupa IMF and Starburst99 SPS models

the following relation between the SFR and production rate of ionizing photons, $Q(H^0)$, at an age of ~100 Myr:

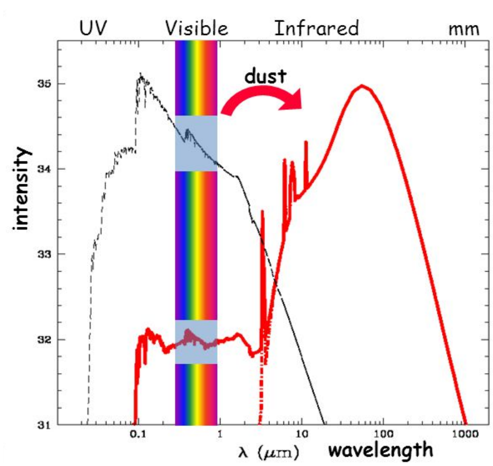
$$\left(\frac{\mathrm{SFR}}{M_\odot\ \mathrm{yr}^{-1}}\right) = 7.29 \times 10^{-54} \left[\frac{Q(H^0)}{\mathrm{s}^{-1}}\right]. \quad (1)$$

$$\left(\frac{\mathrm{SFR_{H\alpha}}}{M_\odot\ \mathrm{yr}^{-1}}\right) = 5.37 \times 10^{-42} \left(\frac{L_{\mathrm{H\alpha}}}{\mathrm{erg\ s^{-1}}}\right). \quad (2)$$

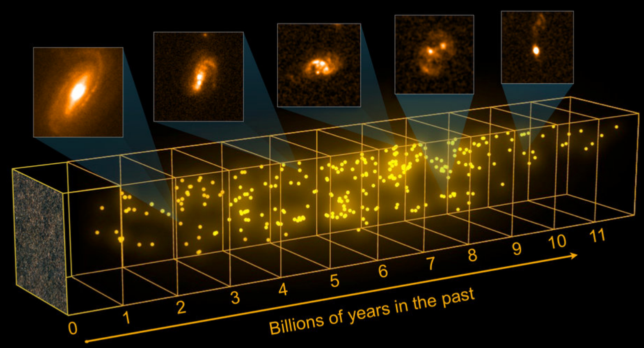
$$\left(\frac{\mathrm{SFR_{FUV}}}{M_\odot\ \mathrm{yr}^{-1}}\right) = 4.42 \times 10^{-44} \left(\frac{L_{\mathrm{FUV}}}{\mathrm{erg\ s^{-1}}}\right). \quad (3)$$

$$\left(\frac{\mathrm{SFR_{IR}}}{M_\odot\ \mathrm{yr}^{-1}}\right) = 3.88 \times 10^{-44} \left(\frac{L_{\mathrm{IR}}}{\mathrm{erg\ s^{-1}}}\right). \quad (4)$$

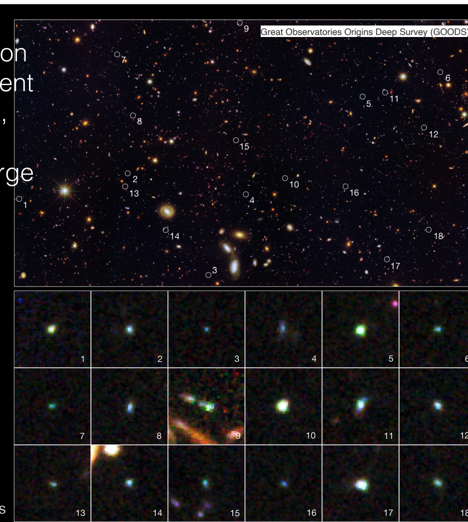
Dust attenuated galaxies: use UV + IR luminosities



Observing the Evolution of Galaxies



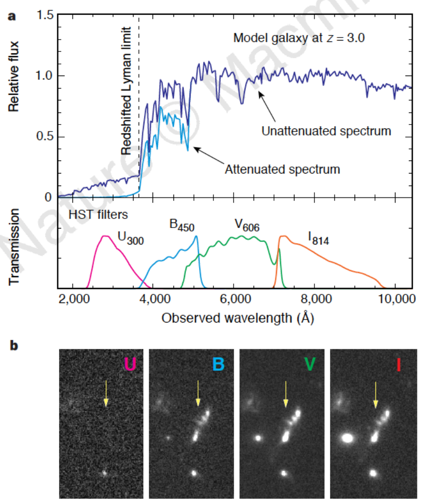
Photometric selection of galaxies at different redshifts is needed, because Spectroscopy of large samples of faint, distant galaxies is prohibitively expensive



example z=1.5 galaxies

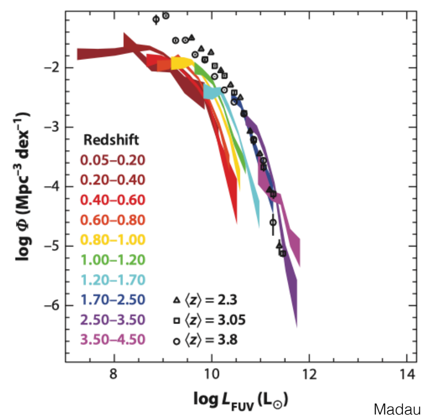
The Lyman Break:

Most Lyman continuum photons ($\lambda_{\rm rest} < 912\text{Å}$) are absorbed by either the ISM or the IGM



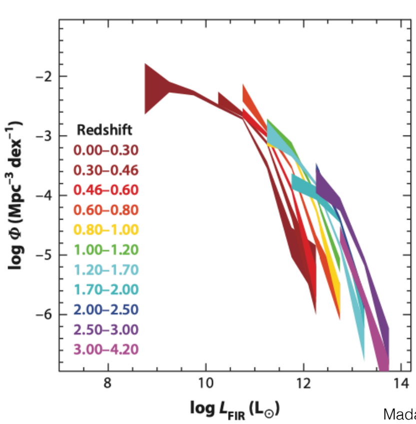
Steidel 98, 03
Ellis 98
Adelberger+04

Evolution of LF and MF at 0 < z < 4



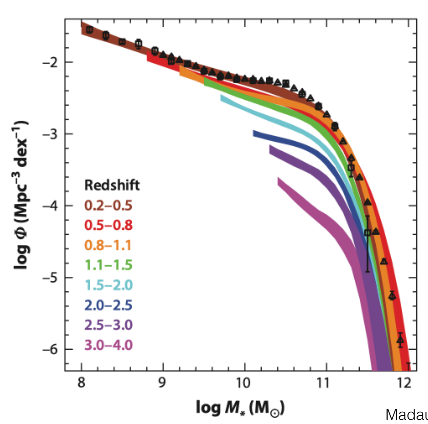
Madau & Dickinson 2014

Evolution of LF and MF at 0 < z < 4



Madau & Dickinson 2014

Evolution of LF and MF at 0 < z < 4

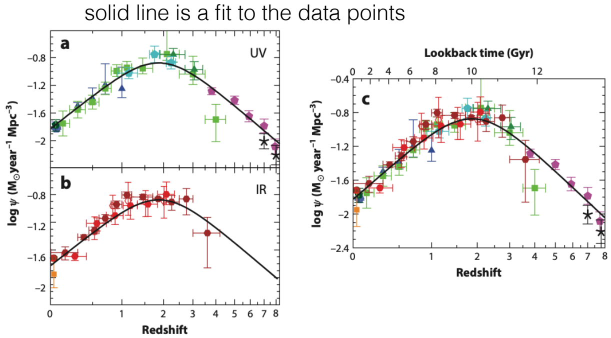


Madau & Dickinson 2014

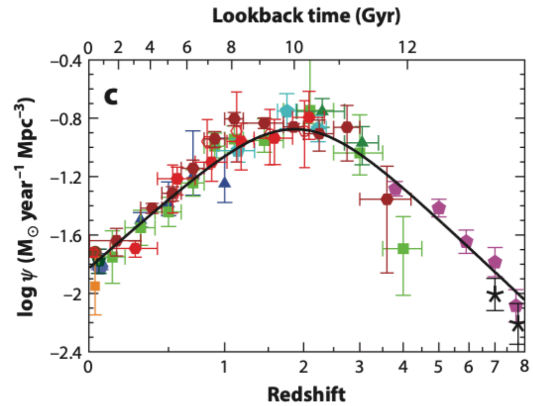
Integrated LFs -> Cosmic SF History

$$\psi(z) = 0.015 \frac{(1+z)^{2.7}}{1+[(1+z)/2.9]^{5.6}} \, M_\odot \, \text{year}^{-1} \, \text{Mpc}^{-3}. \quad (15)$$

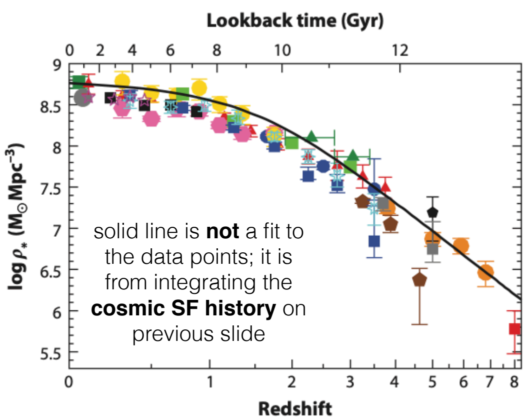
solid line is a fit to the data points



Integrated LFs -> Cosmic SF History



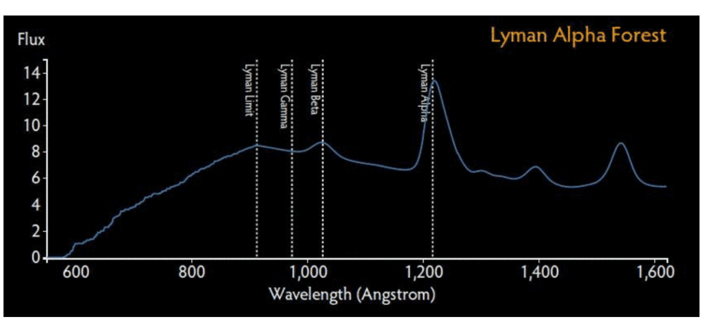
Integrated MF -> Cosmic Mass Buildup



The Reionization of the IGM

Formation of Lyman alpha Forest in Quasar Spectrum

animation showing a quasar spectrum being continuously redshifted due to cosmic expansion, encountering various HI absorbers at different redshifts.



Gunn-Peterson (1965): Optical Depth of Lyman alpha Photons

$$\tau_{GP} = \int_0^{z_e} \sigma[\nu_o(1+z)] n_{HI}(z) \frac{d\ell}{dz} dz,$$ *total integrated optical depth*

$$\tau_{GP}(z) = \left(\frac{\pi e^2 f}{m_e c \nu_\alpha}\right) \frac{n_{HI}}{(1+z)} \frac{d\ell}{dz}.$$ *optical depth per redshift*

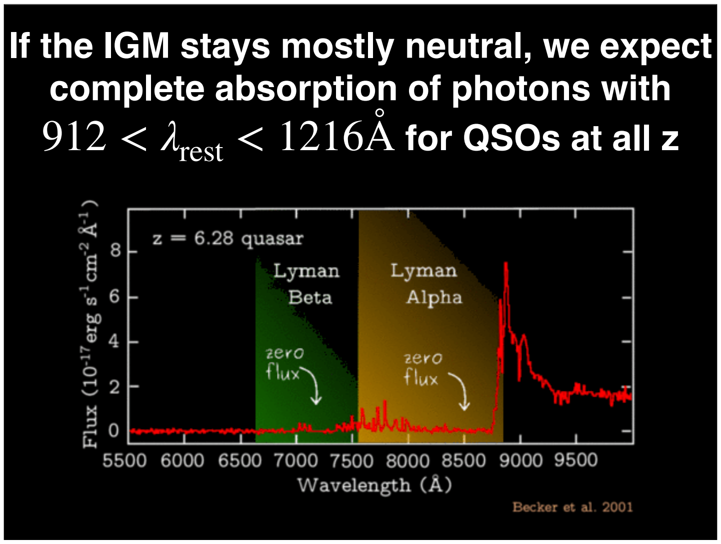
$$d\ell/dz = cH_0^{-1}(1+z)^{-1}[\Omega_M(1+z)^3 + \Omega_\Lambda]^{-1/2}$$ *proper distance per redshift*

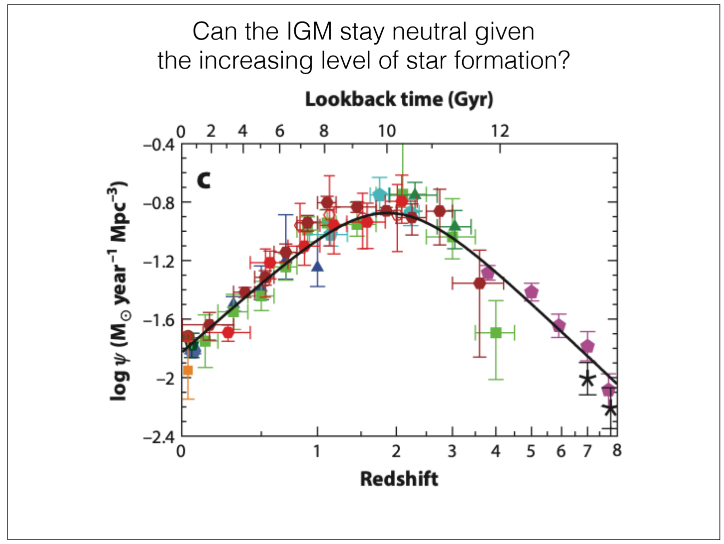
The Gunn-Peterson (1965) optical depth to Lyα photons is

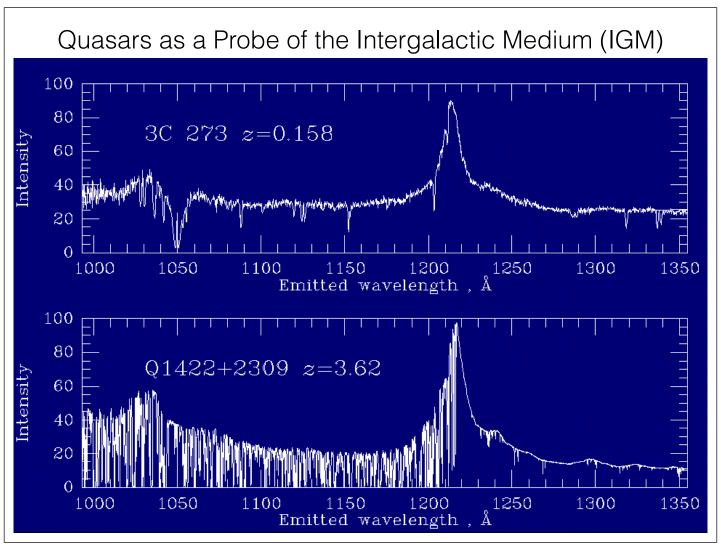
$$\tau_{GP} = \frac{\pi e^2}{m_e c} f_\alpha \lambda_\alpha H^{-1}(z) n_{HI}, \quad (1)$$

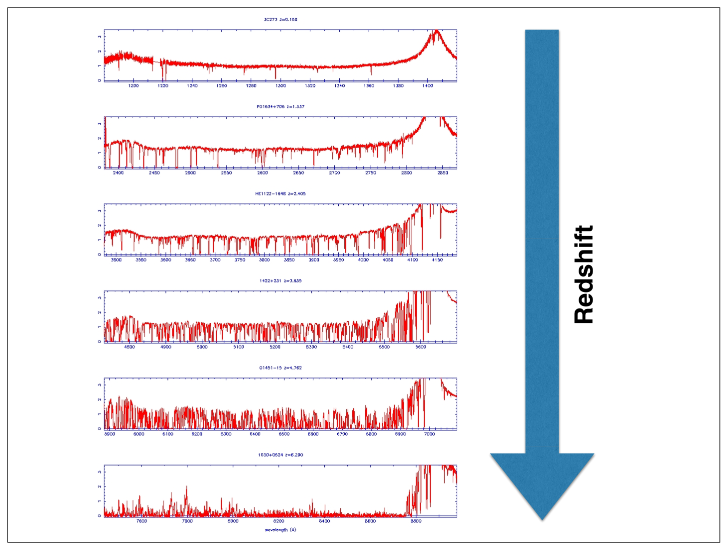
where f_α is the oscillator strength of the Lyα transition, $\lambda_\alpha = 1216$ Å, $H(z)$ is the *Hubble* constant at redshift z, and n_{HI} is the density of neutral hydrogen in the IGM. At high redshifts,

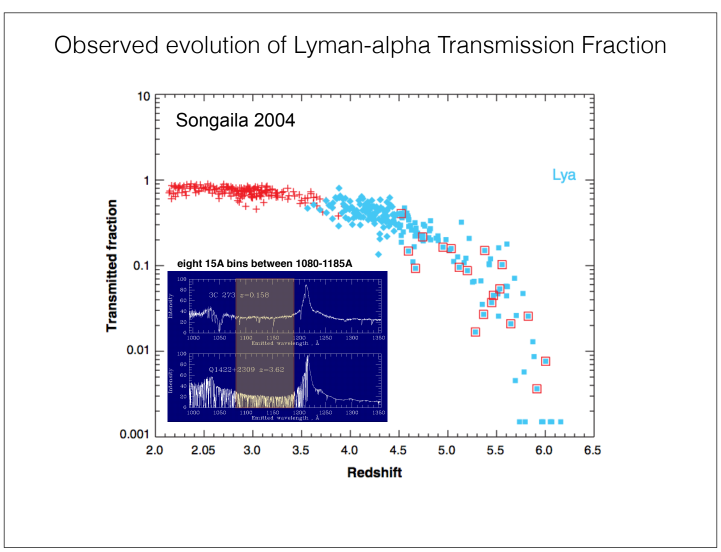
$$\tau_{GP}(z) = 4.9 \times 10^5 \left(\frac{\Omega_m h^2}{0.13}\right)^{-1/2} \left(\frac{\Omega_b h^2}{0.02}\right) \left(\frac{1+z}{7}\right)^{3/2} \left(\frac{n_{HI}}{n_H}\right) \quad (2)$$

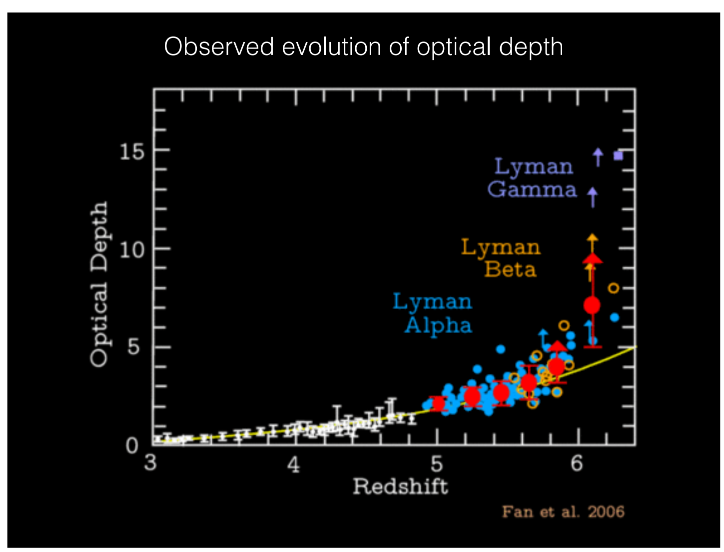

If the IGM stays mostly neutral, we expect complete absorption of photons with
$912 < \lambda_{\rm rest} < 1216\text{Å}$ for QSOs at all z
z = 6.28 quasar
Lyman Beta
Lyman Alpha
zero flux
zero flux
Flux (10^{-17} erg s^{-1}cm^{-2} Å^{-1})
Wavelength (Å)
Becker et al. 2001


Can the IGM stay neutral given
the increasing level of star formation?
Lookback time (Gyr)
c
log ψ ($M_\odot$ year^{-1} Mpc^{-3})
Redshift

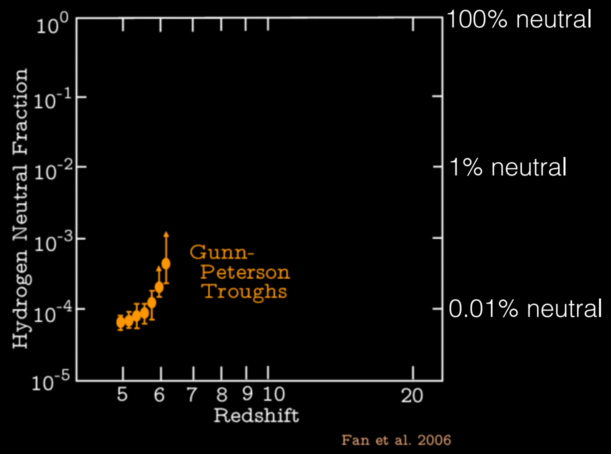

Quasars as a Probe of the Intergalactic Medium (IGM)
3C 273 z=0.158
Q1422+2309 z=3.62
Intensity
Emitted wavelength , Å


Redshift

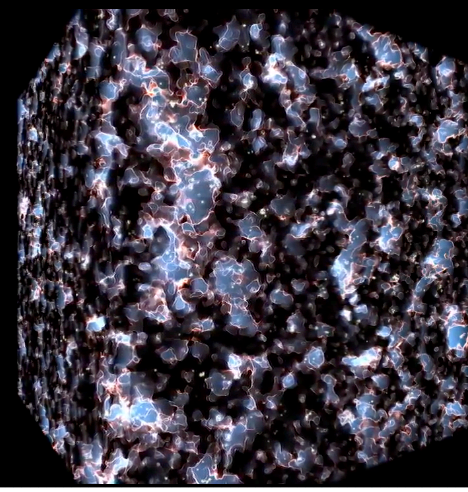

Observed evolution of Lyman-alpha Transmission Fraction
Songaila 2004
Lya
eight 15A bins between 1080-1185A
Transmitted fraction
Redshift


Observed evolution of optical depth
Lyman Gamma
Lyman Beta
Lyman Alpha
Optical Depth
Redshift
Fan et al. 2006

Inferred neutral fraction of the IGM



Simulation of the Reionization of the IGM



One more thing …

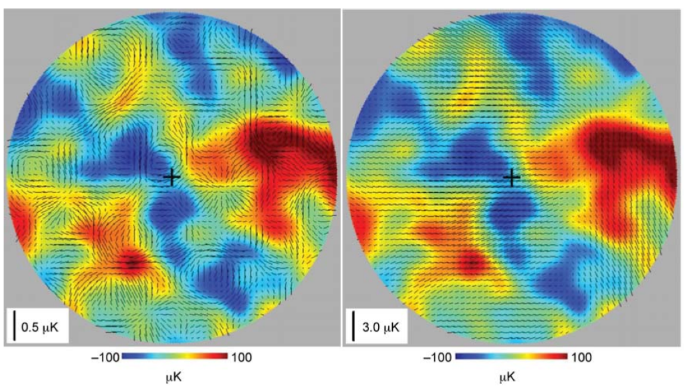


Figure 9
Large angular scale temperature (color scale) and polarization (lines) simulations in real-space.

Fan+2006