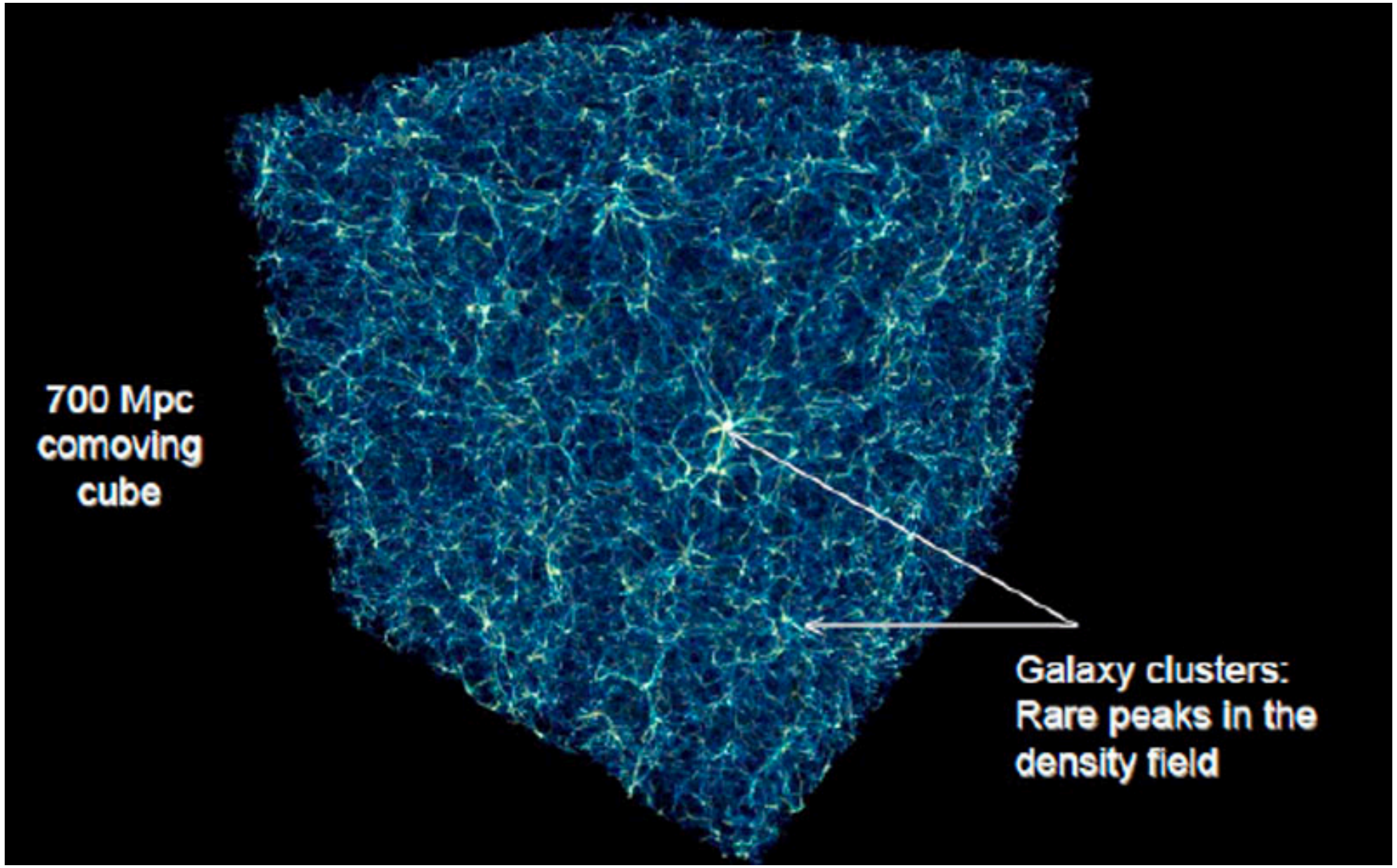
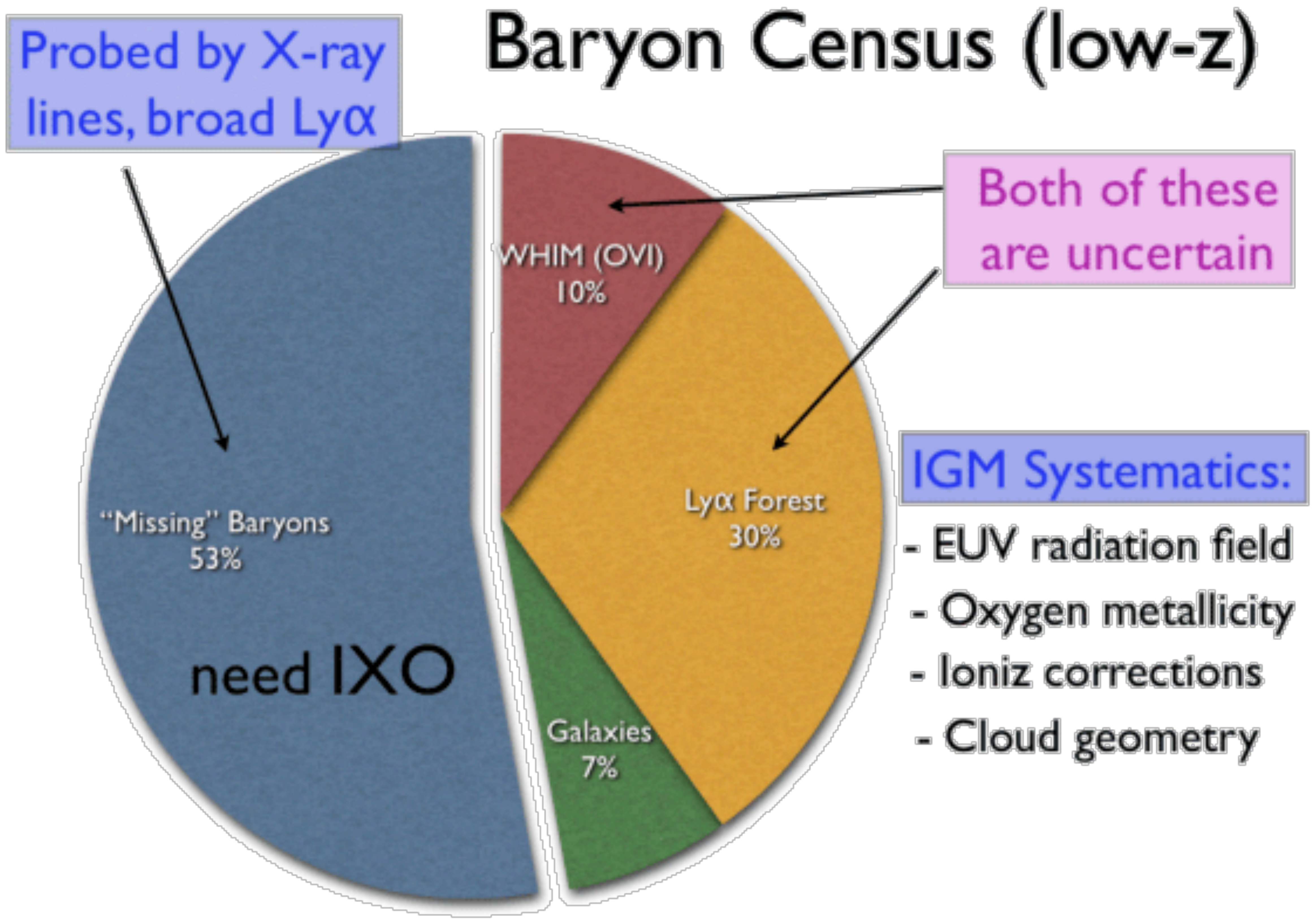
Structure Formation: Baryons and Photons

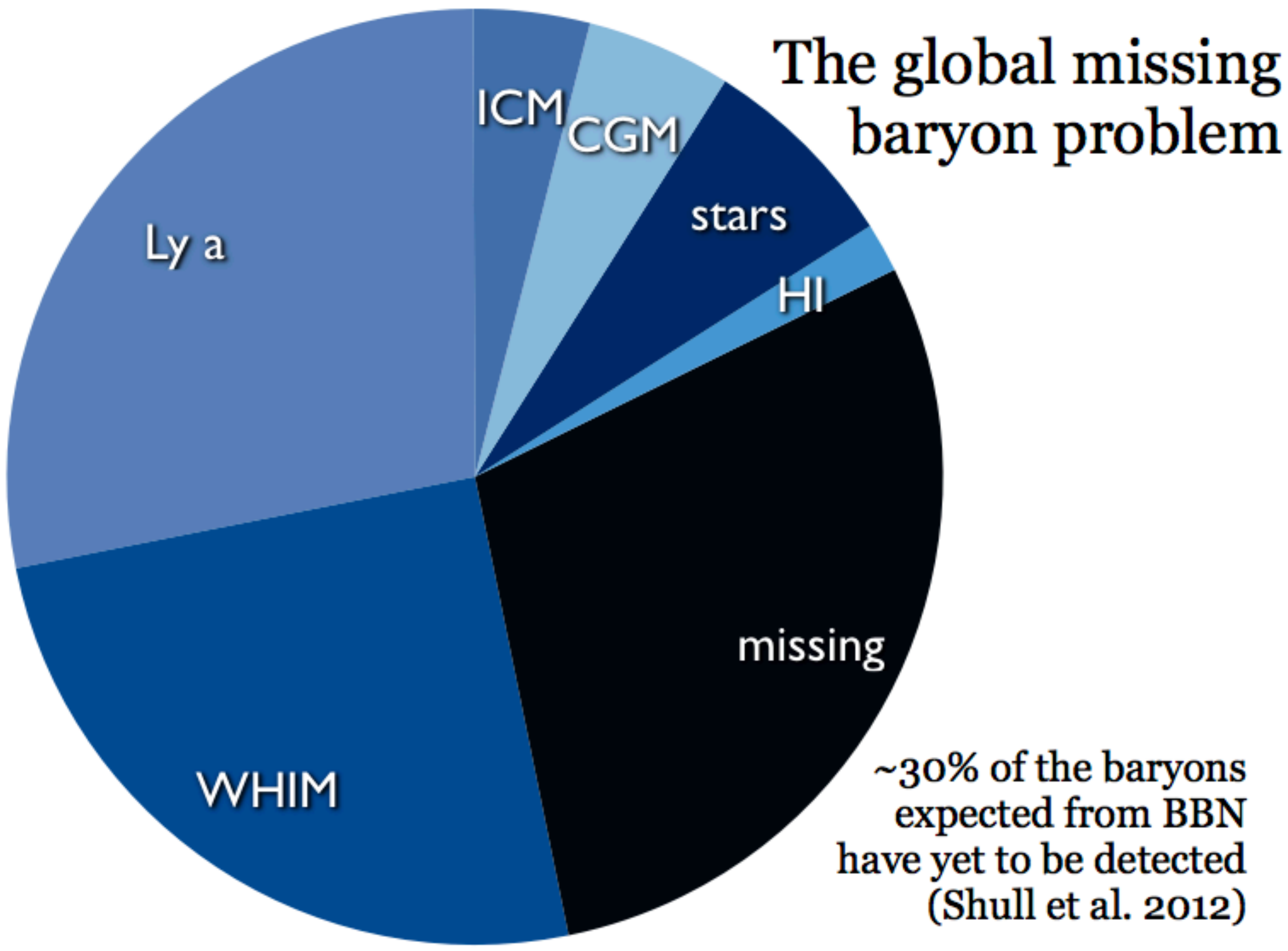
ASTR/PHYS 4080:
Intro to Cosmology
Week 14



What are the baryons up to now?

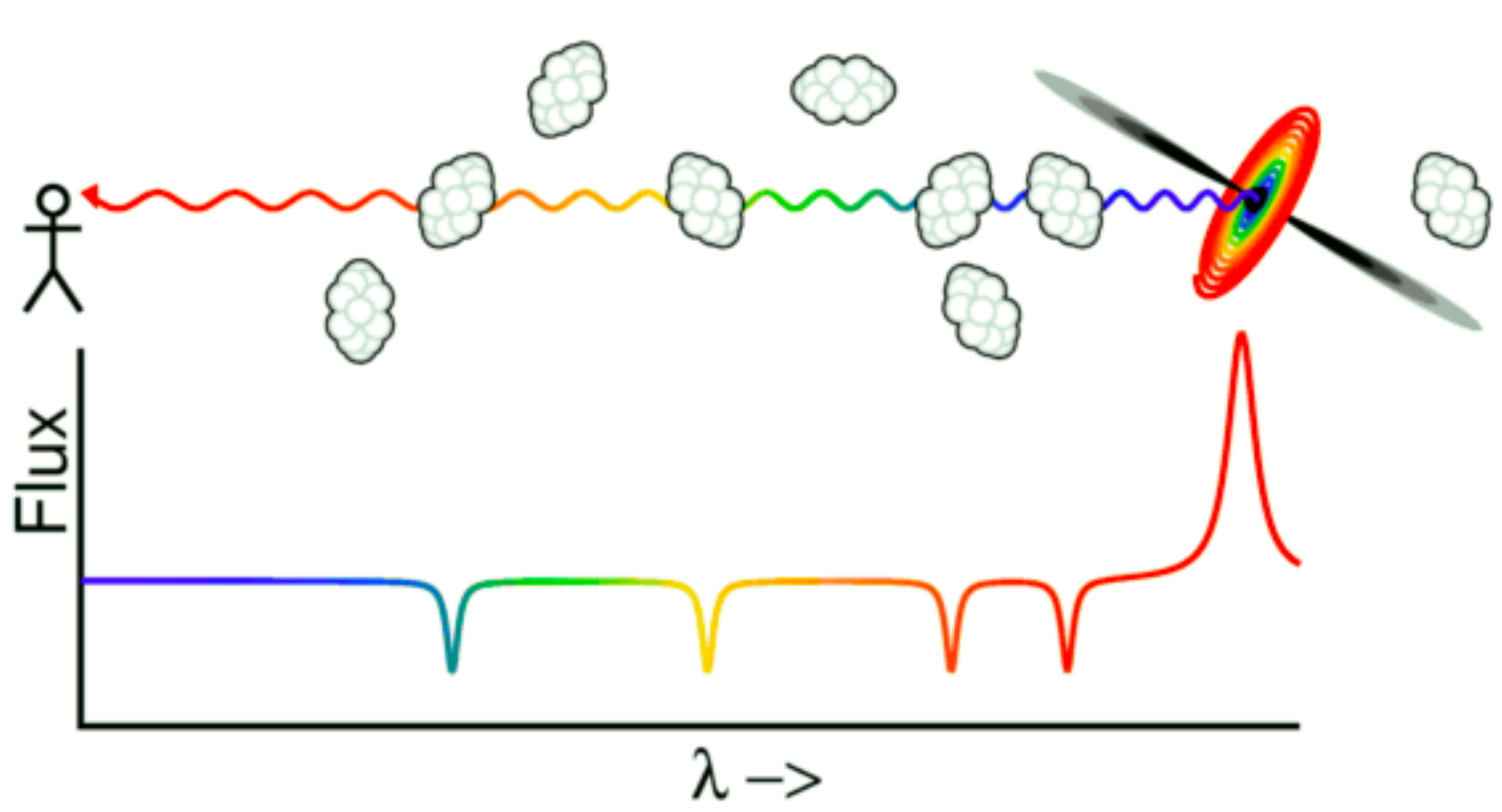
Unlike DM, baryons can interact with light to help them cool, which allows them to fall deeper into DM potential wells, accumulate at high density, and form stars and galaxies.

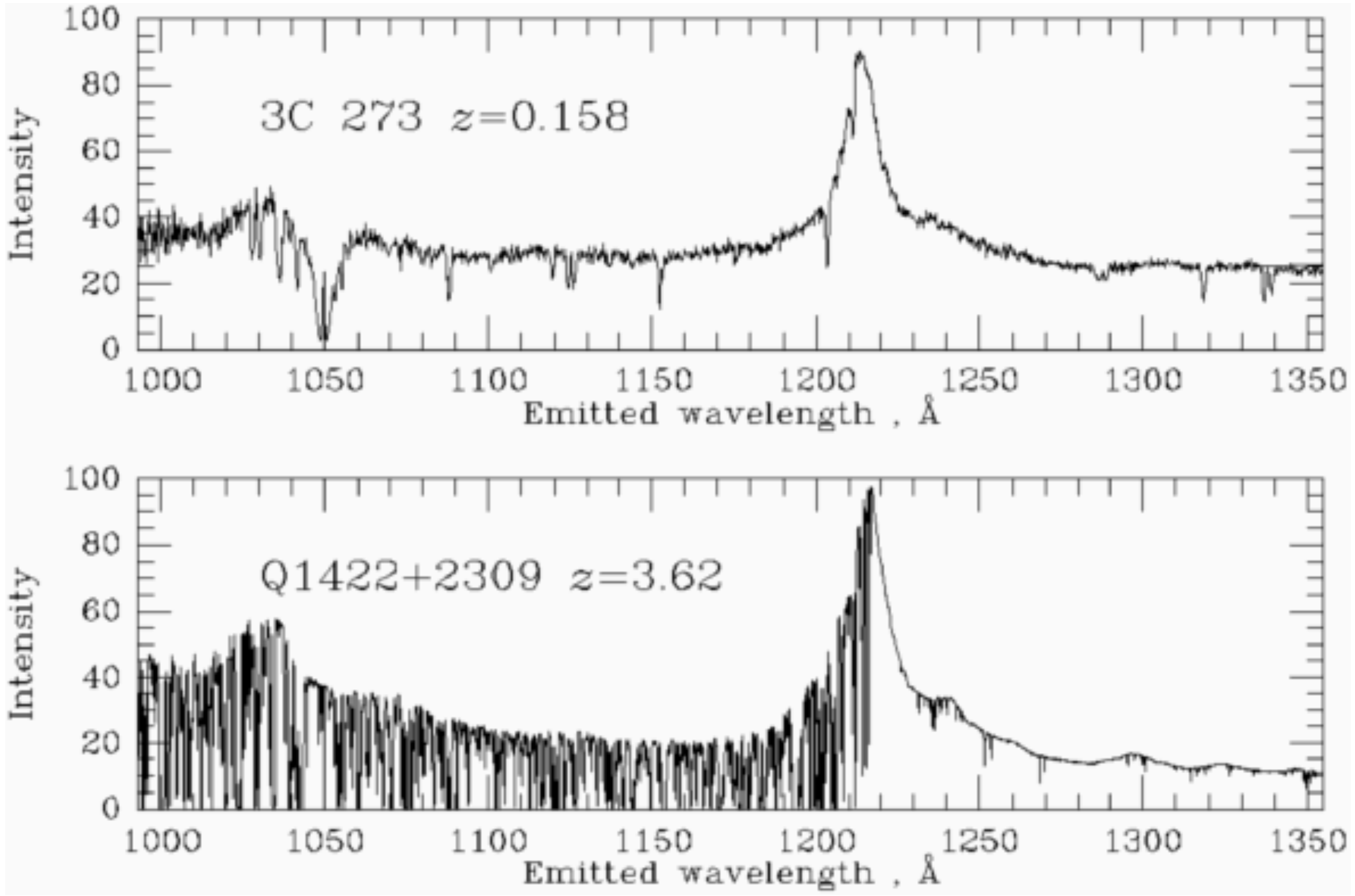




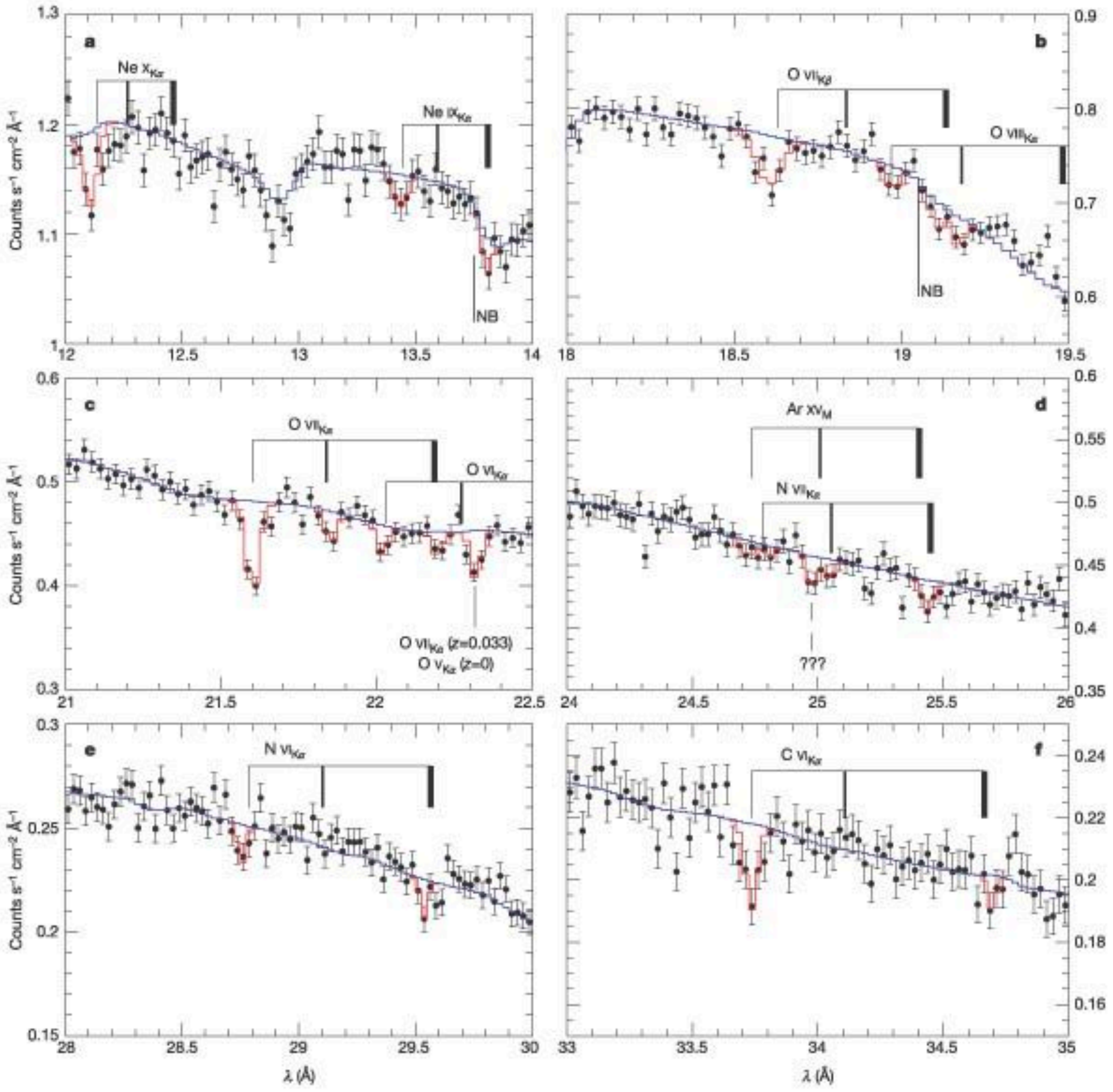
Detecting Baryons

Lyman-alpha Forest



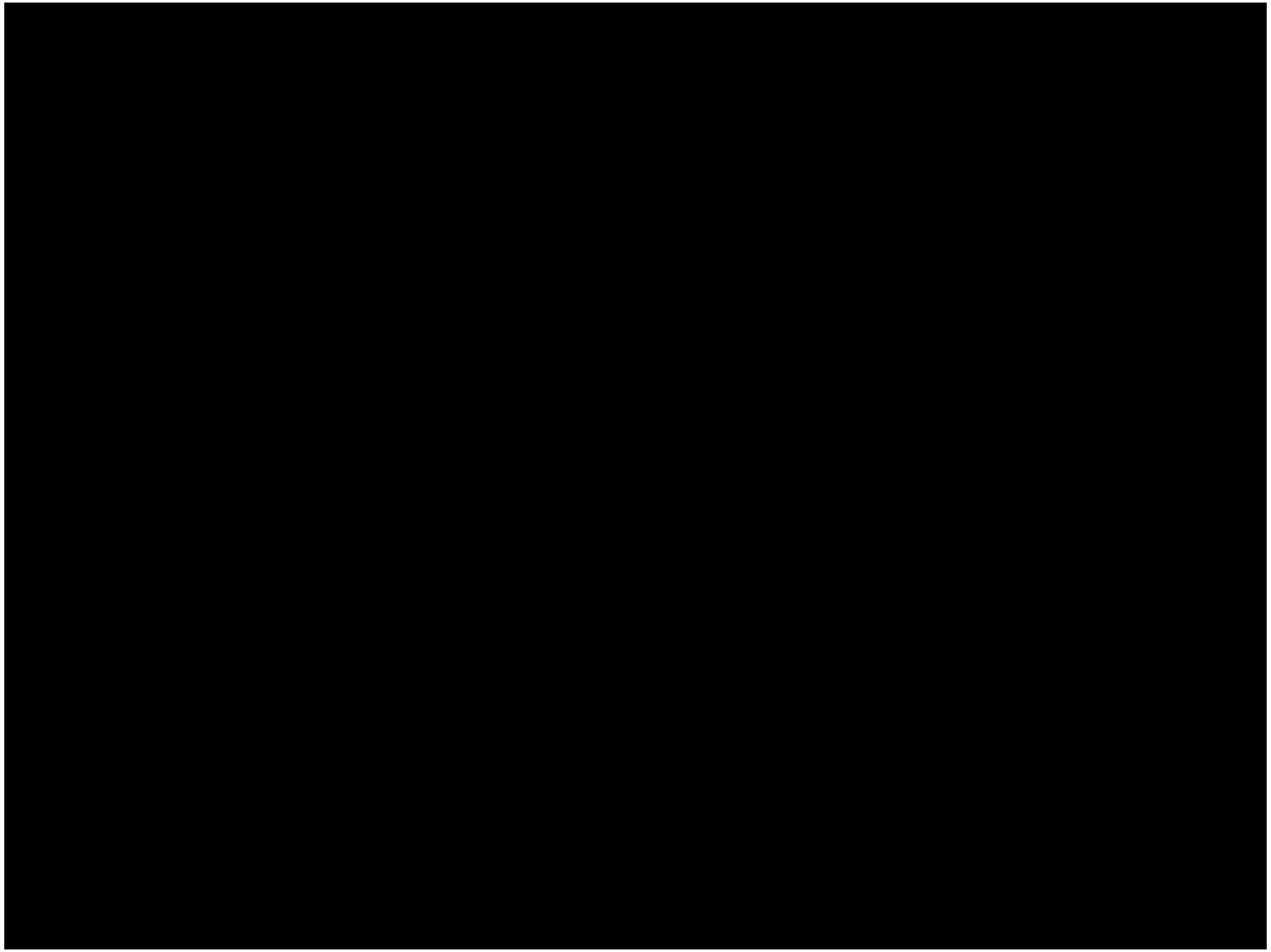


WHIM

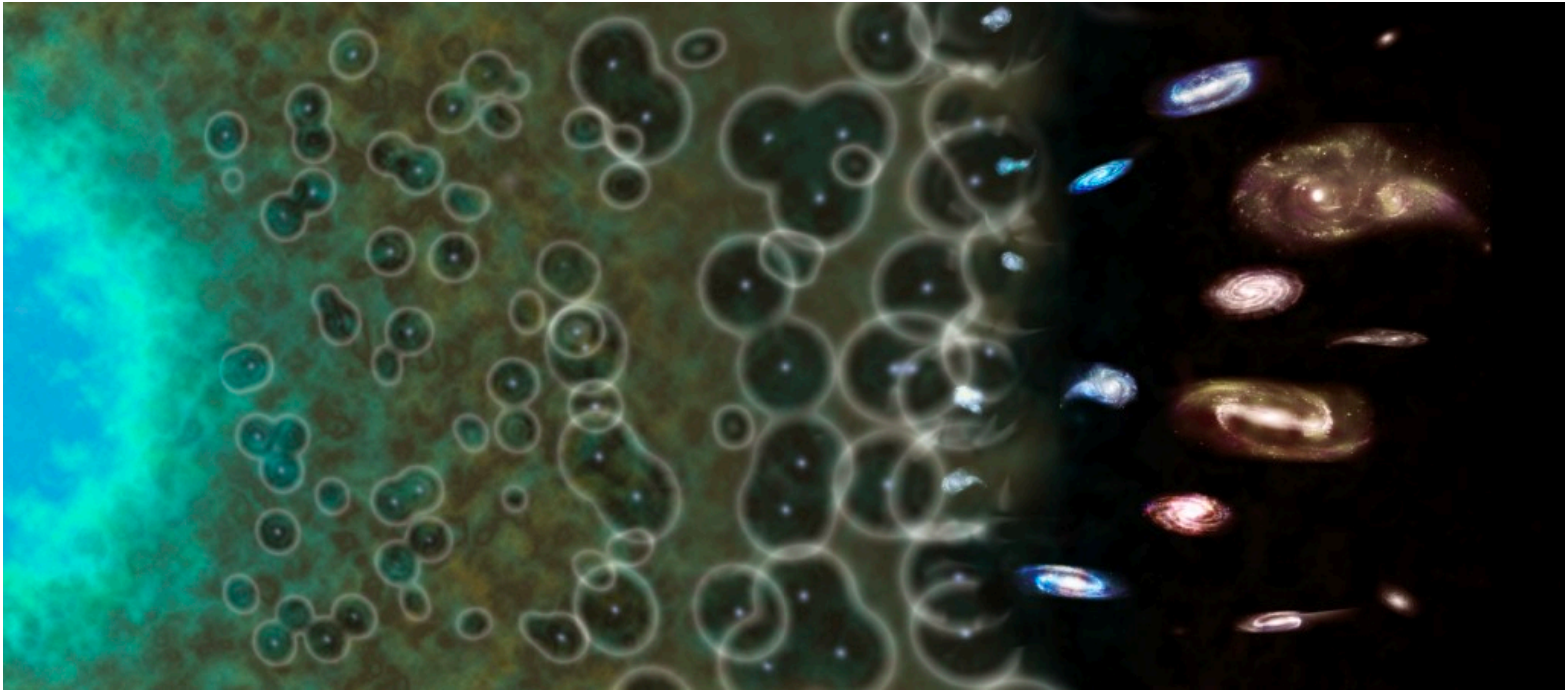


History of the Universe

Reionization



Reionization



Reionization

Need something to produce enough ionizing photons to *ionize them all*

$$h\nu > 13.6 \text{ eV}$$

O Stars

(less massive stars don't emit many UV photons)

$$\dot{N}_{\text{Ostar}} \approx 5 \times 10^{48} \text{ s}^{-1}$$

live for 6 Myr: 10^{63} photons per star

Quasars

(AGN accreting at a high rate)

$$\dot{N}_{\text{AGN}} \approx 3 \times 10^{56} \text{ s}^{-1} \left(\frac{L_{\text{AGN}}}{10^{13} \text{ L}_{\odot}} \right)$$

One bright AGN is more effective

However, most photons can't escape the host galaxy — they're absorbed by surrounding gas, which also enjoy interacting with ionizing photons

Reionization

How many atoms are there in a given volume?

$$n_{\rm bary} = 0.25\ {\rm m}^{-3} = 7.3 \times 10^{66}\ {\rm Mpc}^{-3}$$

$$n_* = \frac{n_{\rm bary}}{f_{\rm esc}} = 3.7 \times 10^{67}\ {\rm Mpc}^{-3} \left(\frac{0.2}{f_{\rm esc}}\right)$$

O Stars

$$\dot{N}_{\rm Ostar} \approx 5 \times 10^{48}\ {\rm s}^{-1}$$

need 40,000 O stars

Quasars

$$\dot{N}_{\rm AGN} \approx 3 \times 10^{56}\ {\rm s}^{-1} \left(\frac{L_{\rm AGN}}{10^{13}\ {\rm L}_\odot}\right)$$

need 10^{13} solar luminosity AGN shining for 4000 years

→ in 1 cubic Mpc ←

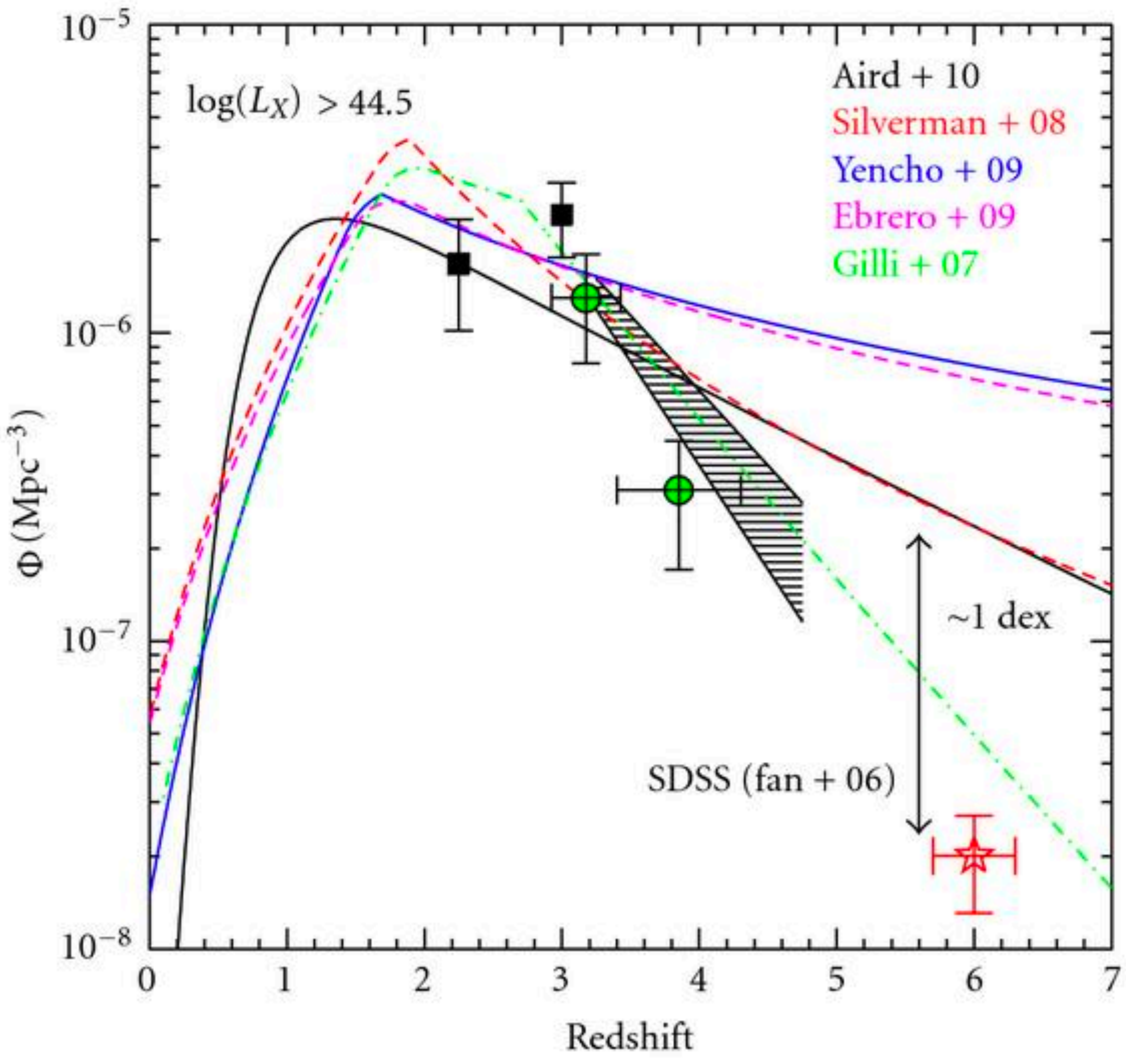
Reionization by AGN?

Around z~8, only 1 AGN per 10^9—>10^{10} Mpc^3

Would need 40,000 Gyr to ionize that whole volume

Age of the universe at reionization was ~650 Myr, so not enough time

Lower luminosity AGN could be more numerous, but they're fainter and harder to detect, so it's uncertain what their contribution was



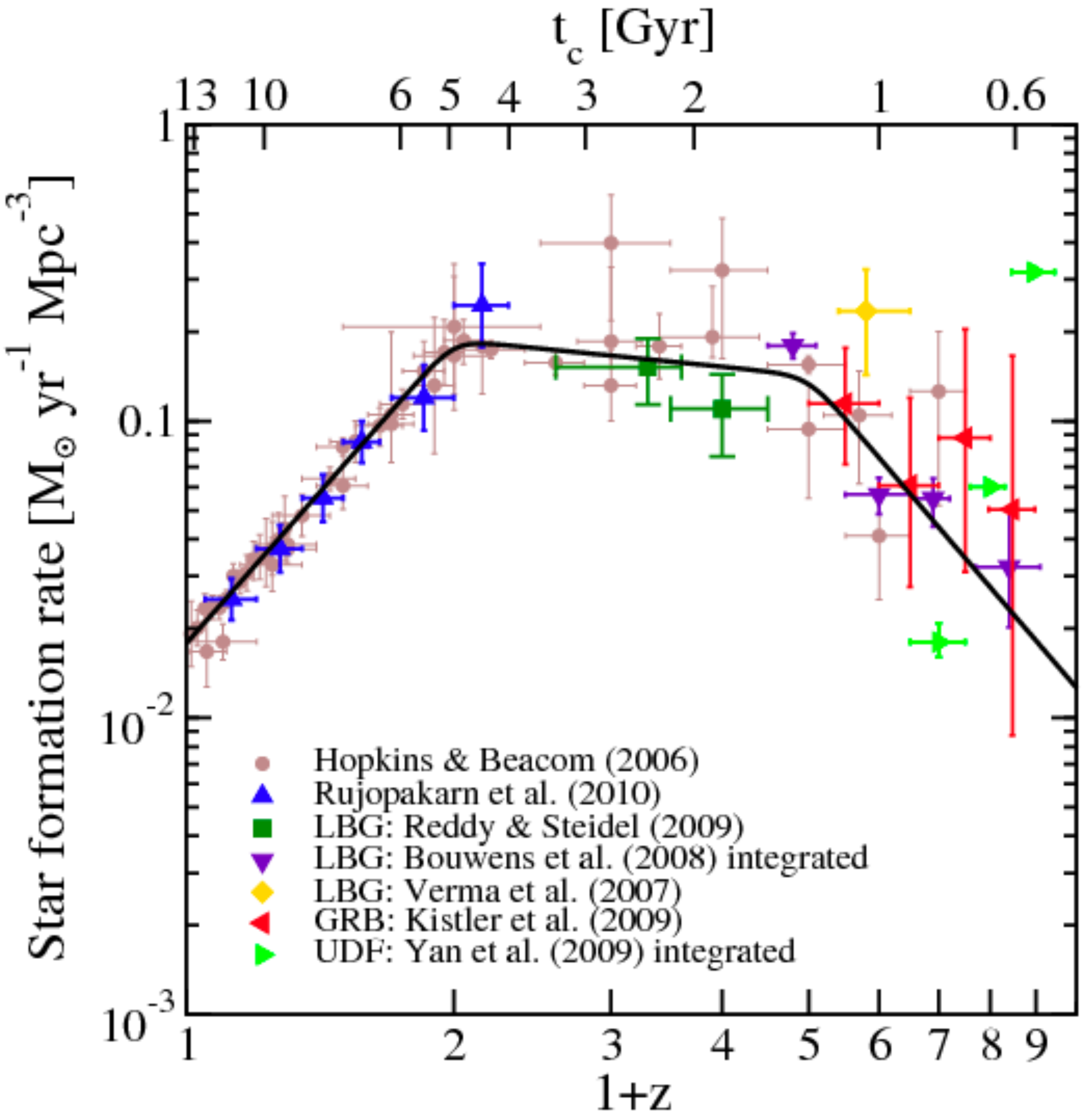
Reionization by Stars?

Around z~8, around 0.02 solar masses of stars are being created in a Mpc^3 per year, but only 10% of that consists of massive ($M>30\ M_{sun}$) O stars

Assuming M~30 Msun with a 6 Myr lifetime for each O star, we expect 0.002 * 6e6 / 30 = 400 O stars per Mpc^3

Before, we needed 40,000 O stars to accomplish reionization, so star formation needs to last ~100 Myr

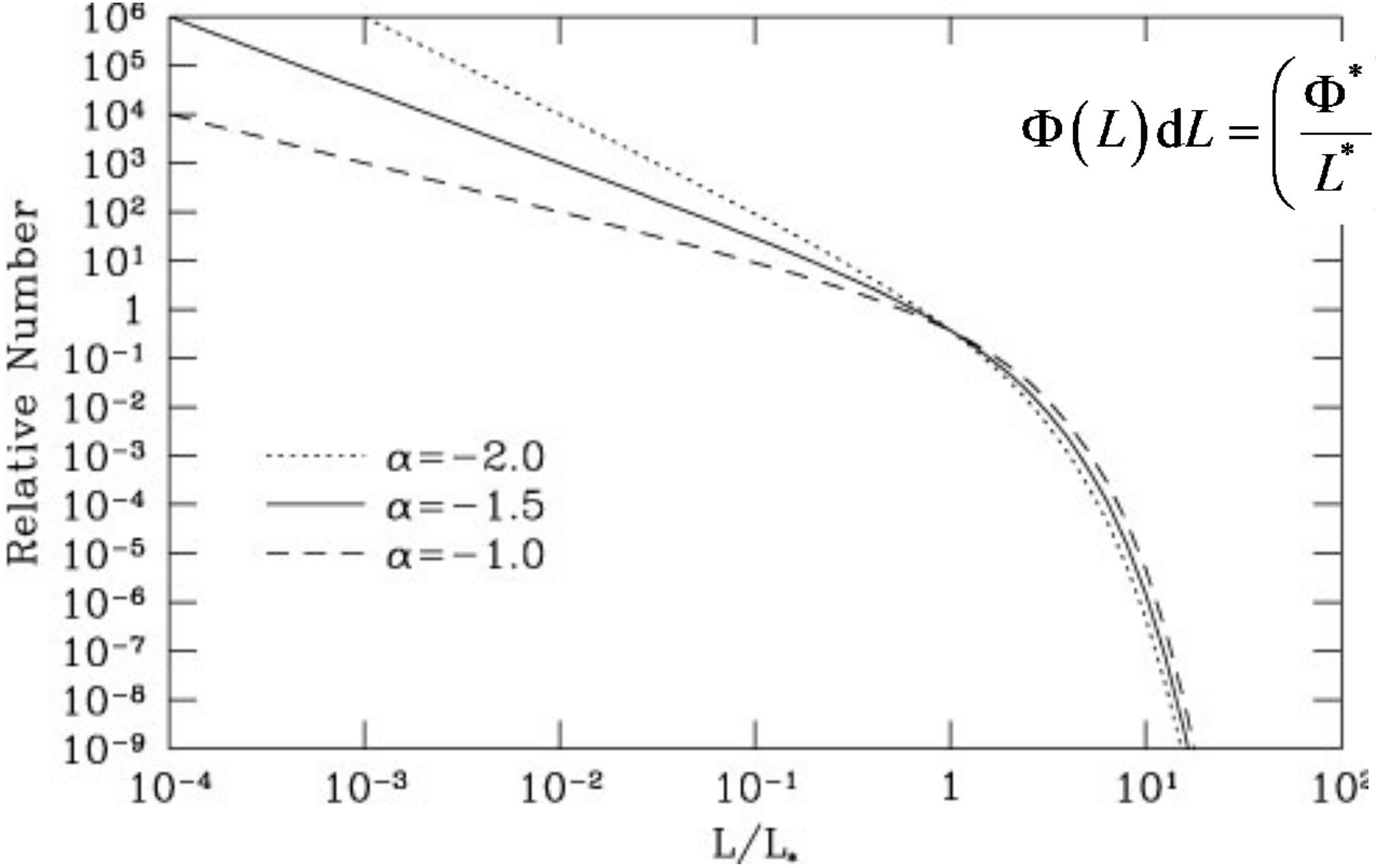
Or, if only 20% of UV photons escape, more like 600 Myr — comparable to t_{age}



Making Galaxies and Stars


z=4.00
$\log_{10}(M_*)=10.4$
SFR=80.0
sSFR=3.07Gyr^{-1}
ILLUSTRIS

Schechter Luminosity Function



$$\Phi(L)\,\mathrm{d}L = \left(\frac{\Phi^*}{L^*}\right)\left(\frac{L}{L^*}\right)^{\alpha}\exp\left(-\frac{L}{L^*}\right)\mathrm{d}L$$

why the exponential drop-off?

DM halos have a similar turnover, but at much higher mass

Spherical Cow Collapse

When does an overdensity collapse and start forming a galaxy?

overdensities decouple when they are comparable in density to the universal average

$$1 + z_{\rm coll} \approx \delta_{rm}(1 + z_{rm})$$

$$\delta(t_{\rm coll}) \approx 1$$

$$\bar{\rho}(t_{\rm coll}) \approx 2\rho_m(t_{\rm coll}) \approx 2\rho_{m,0}(1 + z_{\rm coll})^3$$

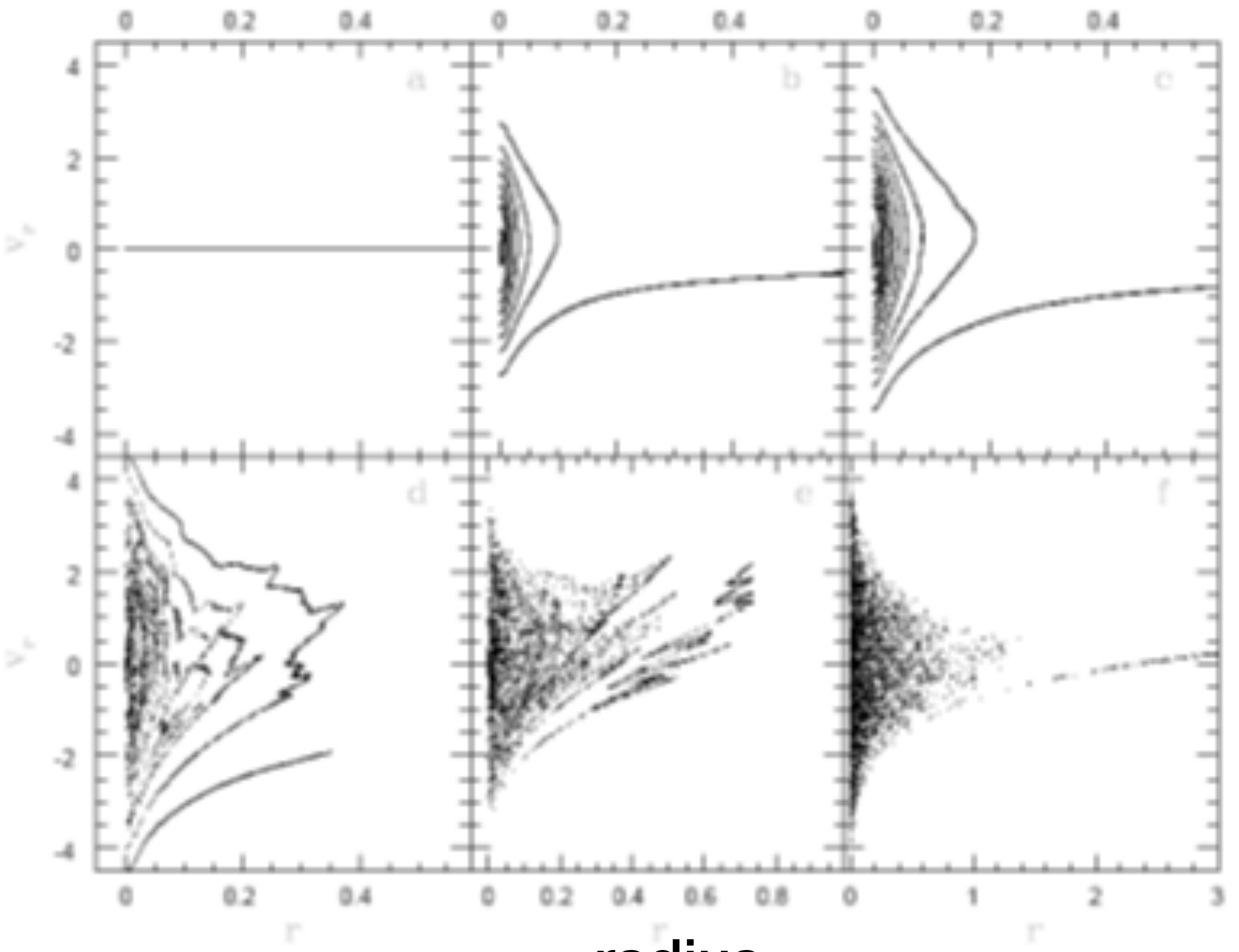
after collapse, the gas will eventually support the gravitational attraction with its pressure (when the radius shrinks by ~2x)

$$R_{\rm halo} \approx R(t_{\rm coll})/2$$

$$\bar{\rho}_{\rm halo} \approx 8\bar{\rho}(t_{\rm coll}) \approx 16\rho_{m,0}(1 + z_{\rm coll})^3$$

Gas equilibrates: virialization

messy process — “violent relaxation”



velocity

radius

(from: Henriksen & Widrow 1997)

Collapse of a spherical system with $\rho_{\rm init} \propto r^{-3/2}$

Gas equilibrates: virialization

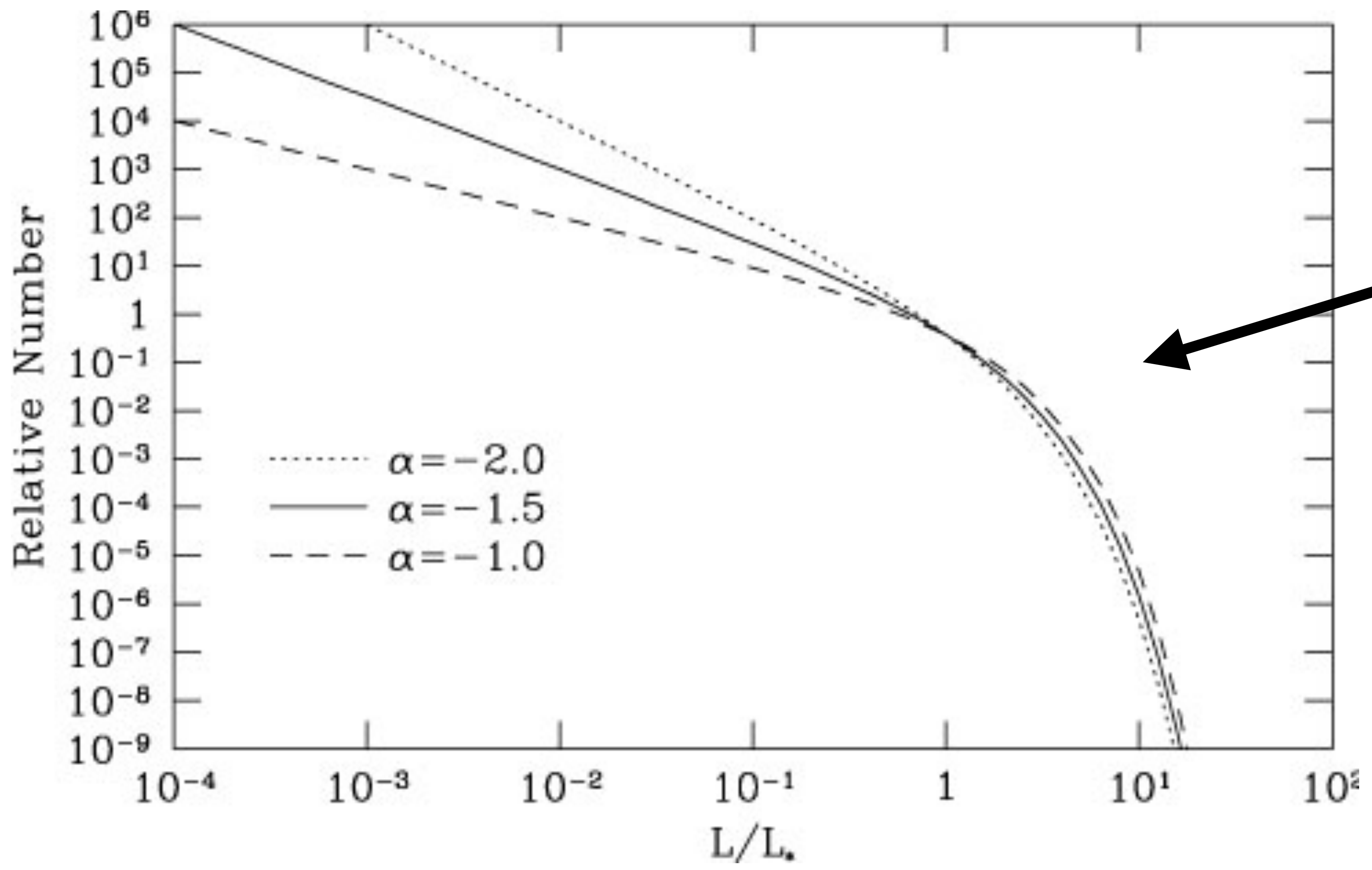
messy process — "violent relaxation"

$$M(<r) = \frac{kT_{\mathrm{gas}}(r)r}{G\mu}\left[-\frac{d\ln\rho_{\mathrm{gas}}}{d\ln r} - \frac{d\ln T_{\mathrm{gas}}}{d\ln r}\right]$$

$$kT_{\mathrm{gas}} = \frac{GM_{\mathrm{tot}}\mu}{\beta R_{\mathrm{halo}}} \qquad Y_p = 0.24 \longrightarrow \mu = 0.59$$

$$T_{\mathrm{gas}} \approx 1.0\times10^6\ \mathrm{K}\left(\frac{M_{\mathrm{tot}}}{10^{12}\ \mathrm{M}_\odot}\right)^{2/3}\left(\frac{1+z_{\mathrm{coll}}}{5}\right)$$

No L > L* galaxies because the gas is too hot



$$t_{\rm cool} = \frac{\varepsilon_{\rm th}}{\Psi_{\rm em}} = 13 \text{ Gyr} \left(\frac{\rho_{\rm gas}}{10^{-24} \text{ kg m}^{-3}}\right)^{-1} \left(\frac{T}{10^6 \text{ K}}\right)^{1/2}$$

$$\bar{\rho}_{\rm bary} \approx 0.8 \times 10^{-24} \text{ kg m}^{-3} \left(\frac{f}{0.15}\right) \left(\frac{1 + z_{\rm coll}}{5}\right)^3$$

$z_{coll} < 4$ halos can't cool

Example: 1st 10^{14} M_{sun} halo to collapse in the observable universe

Making Stars

gas with $t_{cool} < t_0$ loses pressure support and collapses further

we know stars form with typical masses around 0.1 Msun, so somehow the much larger halo must break up into smaller clumps and eventually stop at some minimum mass

stars form in molecular clouds (formation of first stars probably somewhat different) where they cool first through atomic then molecular line emission down to 20 K (equilibrium between cosmic ray heating and FIR emission by dust grains)

The Jeans mass can be calculated from the dynamical time (density$^{-1/2}$) and the sound speed (this temperature):

$$M_J \approx 15\ \mathrm{M}_\odot \left(\frac{\rho_{\rm core}}{10^{-15}\ \mathrm{kg\ m^{-3}}}\right)^{-1/2} \left(\frac{T_{\rm core}}{20\ \mathrm{K}}\right)^{3/2}$$

Making Stars

this minimum mass is much higher than typical stars — what gives?

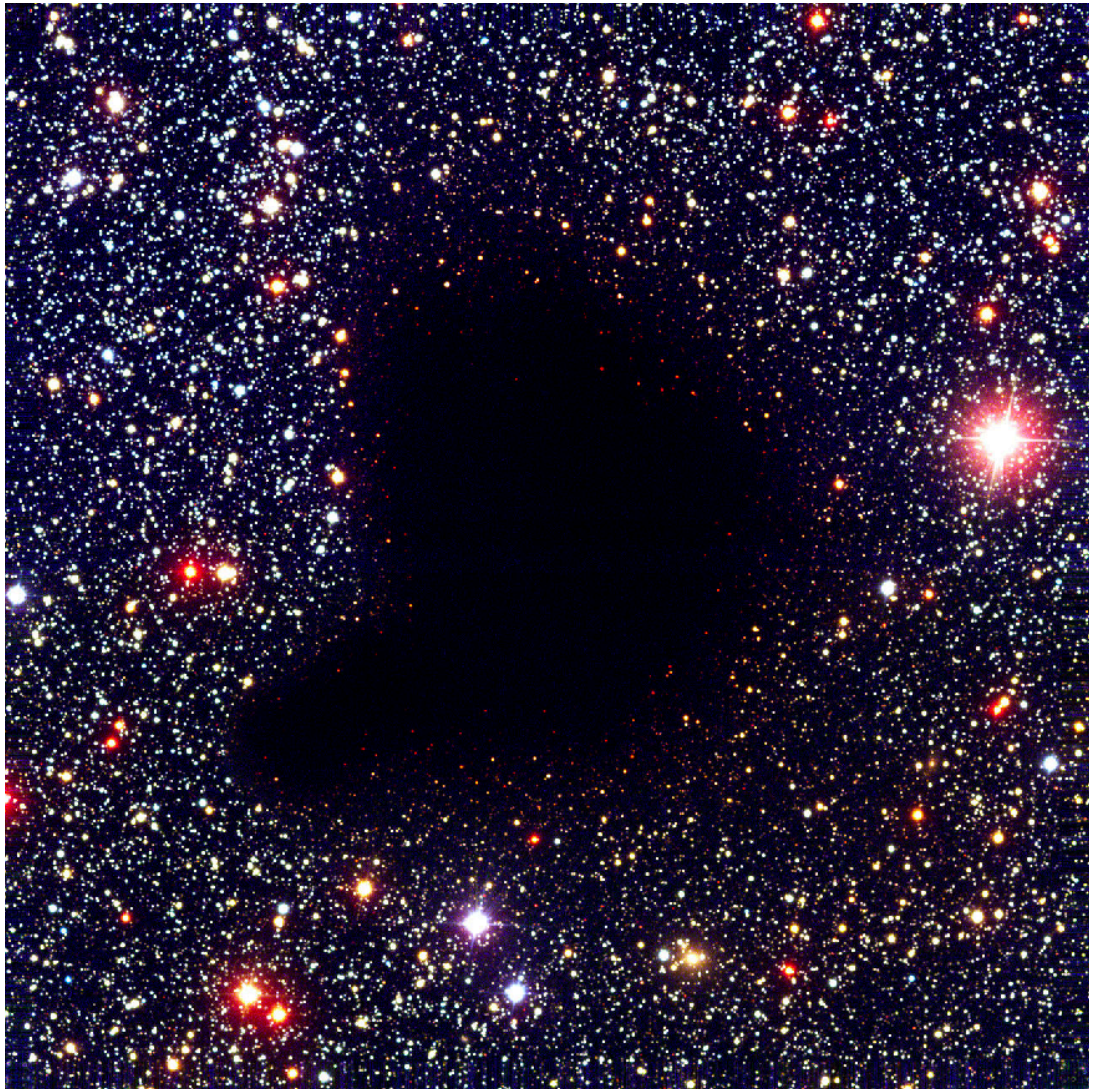
density is not constant — cores are denser and can continue to shrink IF they maintain their temperature

how? thermal energy increases as the volume of a gas decreases, which should raise the temperature, UNLESS it can be radiated away on timescales faster than the dynamical time:

$$t_{dyn} > t_{em}$$

the core must produce enough radiation to continue collapse, presumably through blackbody radiation (which assumes high optical depth)

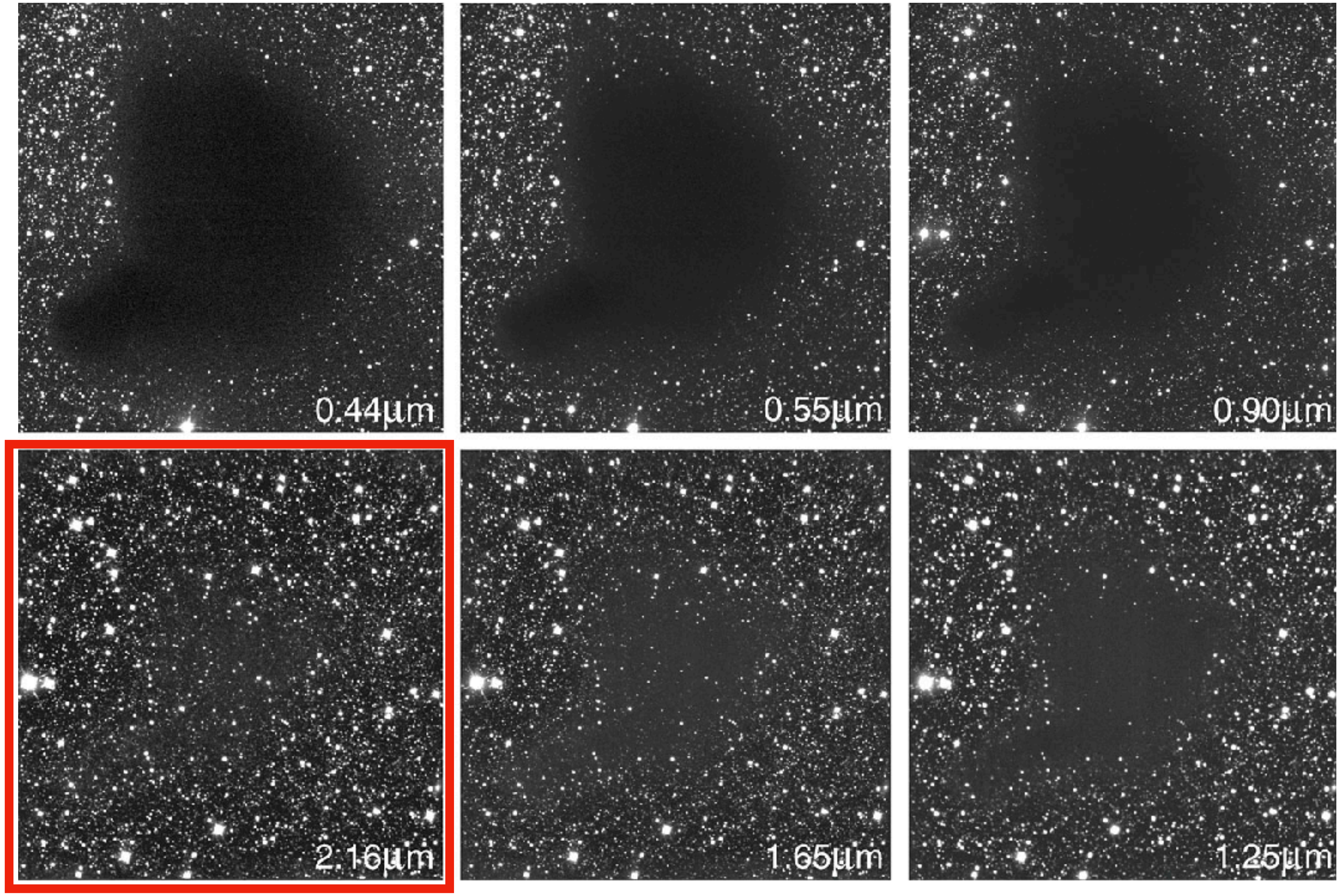
Making Stars



Barnard 68
molecular cloud

Making Stars

emission is in the far infrared, where the cloud is actually pretty transparent



however, as long as the efficiency is larger than 10^{-5} of a blackbody, the core can continue collapse

Making Stars

as the core collapses and its density increases, the Jeans Mass decreases

$$M_J \propto \rho^{-1/2} T^{3/2}$$

once the density of a 15 M_{sun} core increases by 4x, the Jeans Mass has dropped to 7.5 M_{sun}, so the core splits into two cores

those cores increase in density by 4x again and will also split, etc etc

called <u>Hierarchical Fragmentation</u>

if this process were 100% efficient, you'd end up with a bunch of tiny stars, not the broad distribution in mass we actually observe

Making Stars

fragmentation can't continue forever, so what stops it?

a core's luminosity is proportional to its surface area, which is ever-shrinking

once the luminosity drops below that dictated by the dynamical time, the internal temperature must increase, also increasing the Jeans Mass, so the core can no longer collapse

starting from 15 M_{sun} clumps, no more than 9 fragmentations can occur, placing the minimum mass of a star at ~0.03 M_{sun}, consistent with observed mass functions

protostars form as the stable gas clumps slowly radiate away energy, allowing them to collapse further until their density is high enough to fuse hydrogen

INTRODUCTION OVER

that's everything there is to know about the universe…

except the details

and man are there a lot of details…