The Contents of the Universe:

Baryons

The Component Densities

at z ~ 0, in critical density units, assuming $h \approx 0.7$

Total matter/energy density: $\Omega_{0,tot} \approx 1.00$ From CMB, and consistent with SNe, LSS

Matter density: $\Omega_{0,m} \approx 0.27$ From local dynamics and LSS, and consistent with SNe, CMB

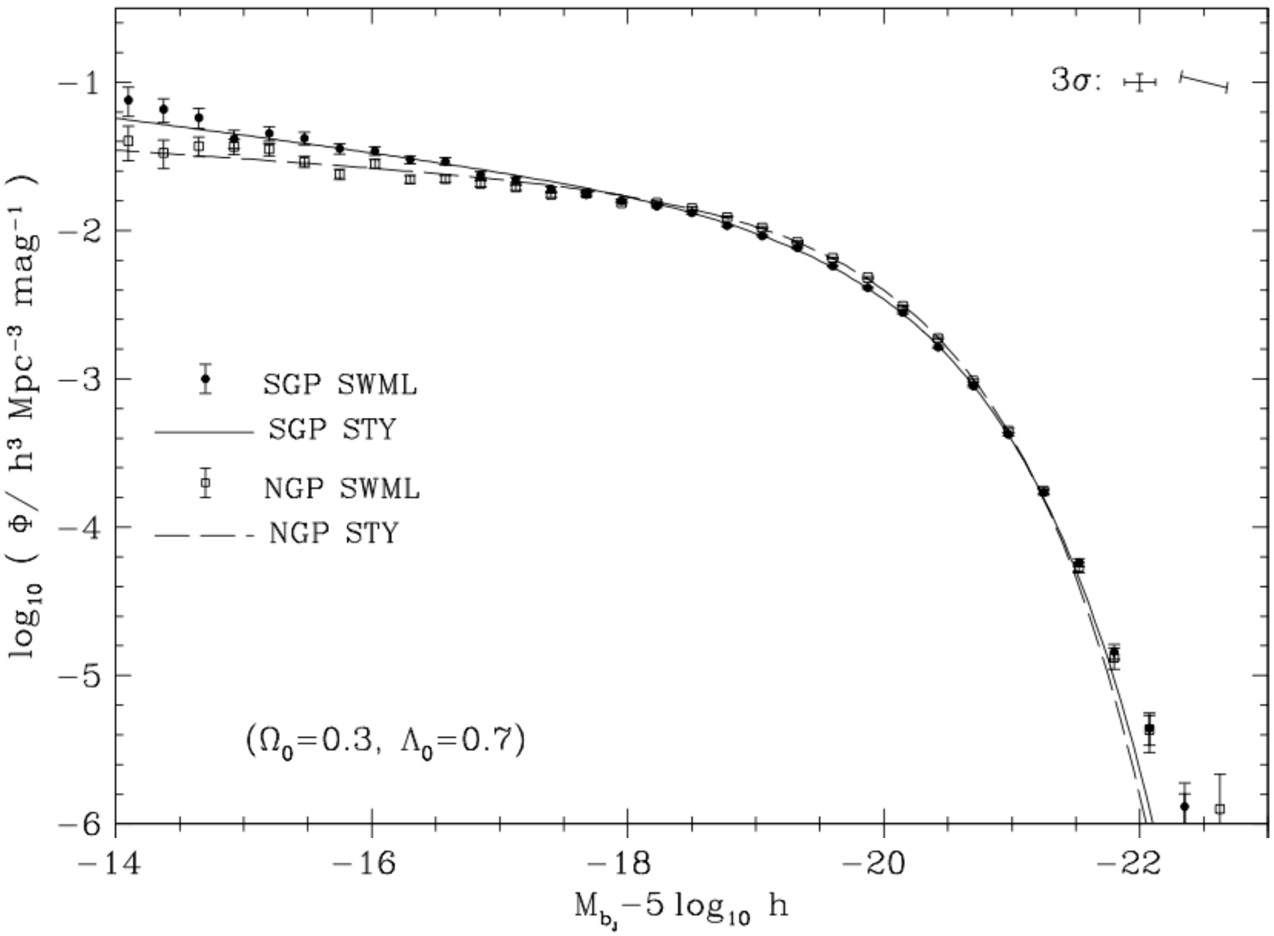
Baryon density: $\Omega_{0,b} \approx 0.05$ From cosmic nucleosynthesis, and independently from CMB

Luminous baryon density: $\Omega_{0,lum} \approx 0.005$ From the census of luminous matter (stars, gas)

Since: $\Omega_{0,tot} > \Omega_{0,m} > \Omega_{0,b} > \Omega_{0,lum}$

- $\Omega_{0,b} > \Omega_{0,lum}$ → There is baryonic dark matter
- $\Omega_{0,m} > \Omega_{0,b}$ → There is non-baryonic dark matter
- $\Omega_{0,tot} > \Omega_{0,m}$ → There is dark energy

The Luminosity Density



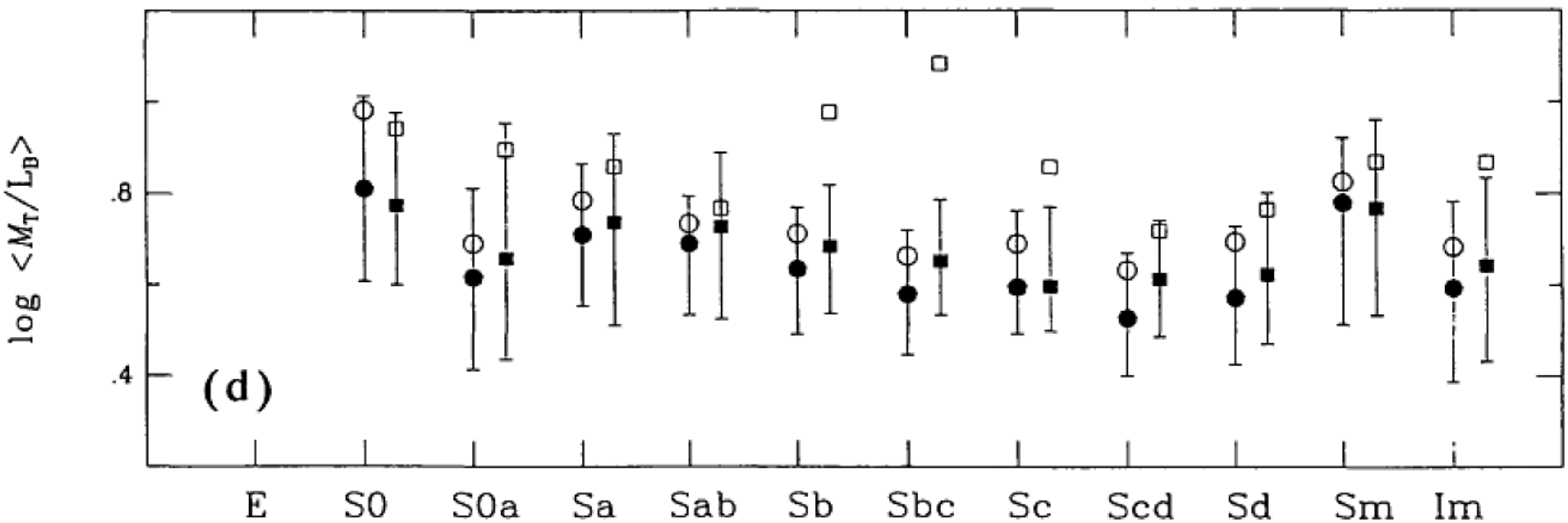
Integrate galaxy luminosity function (obtained from large redshift surveys) to obtain the mean luminosity density at $z \sim 0$

SDSS, *r* band: $\rho_L = (1.8 \pm 0.2) \times 10^8\, h_{70}\, L_\odot/\mathrm{Mpc}^3$

2dFGRS, *b* band: $\rho_L = (1.4 \pm 0.2) \times 10^8\, h_{70}\, L_\odot/\mathrm{Mpc}^3$

Luminosity To Mass

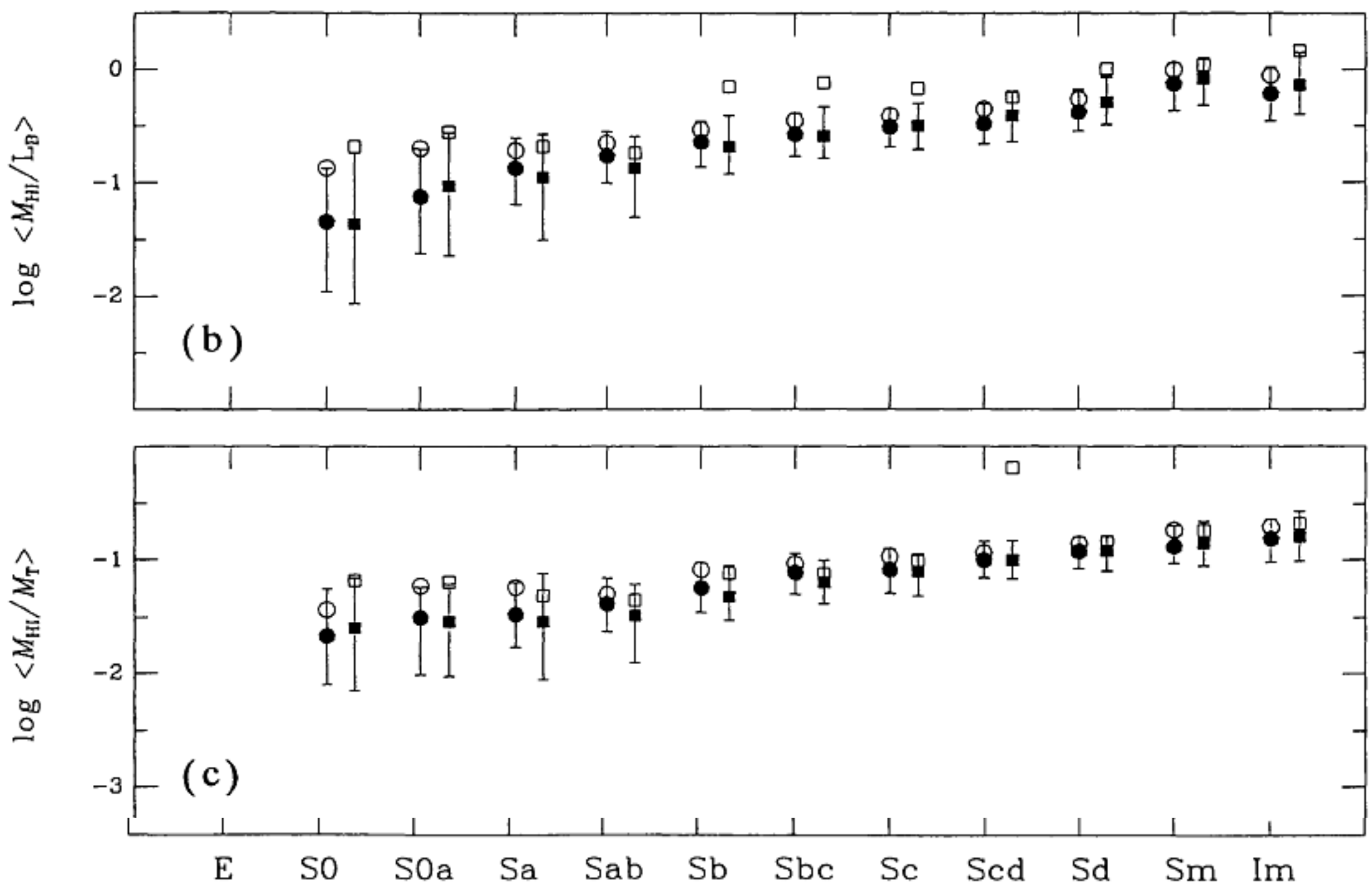
Typical (M/L) ratios in the B band along the Hubble sequence, within the luminous portions of galaxies, are $\sim$ 4 - 5 $M_\odot/L_\odot$



This includes some dark matter - for pure stellar populations, (M/L) ratios should be slightly lower.
Note that in the B band, they are very sensitive to any recent star formation, and to dust extinction.

Luminosity To Mass

To the stellar mass, we need to add the contribution of ISM; this is mainly the H I in spirals, and the x-ray gas in ellipticals. Overall, it is a ~ 10% correction to the luminous mass.



The Local Mass Density of the Luminous Matter in Galaxies

$$\rho_{\rm lum} = \rho_L \times \langle M/L \rangle \times \langle 1 + f_{\rm gas} \rangle \approx (7 \pm 2) \times 10^8\, h_{70}\, M_\odot/{\rm Mpc}^3$$

$$\rho_{\rm lum} \approx (4.7 \pm 1.3) \times 10^{-32}\, h_{70}\ {\rm g\ cm}^{-3}$$

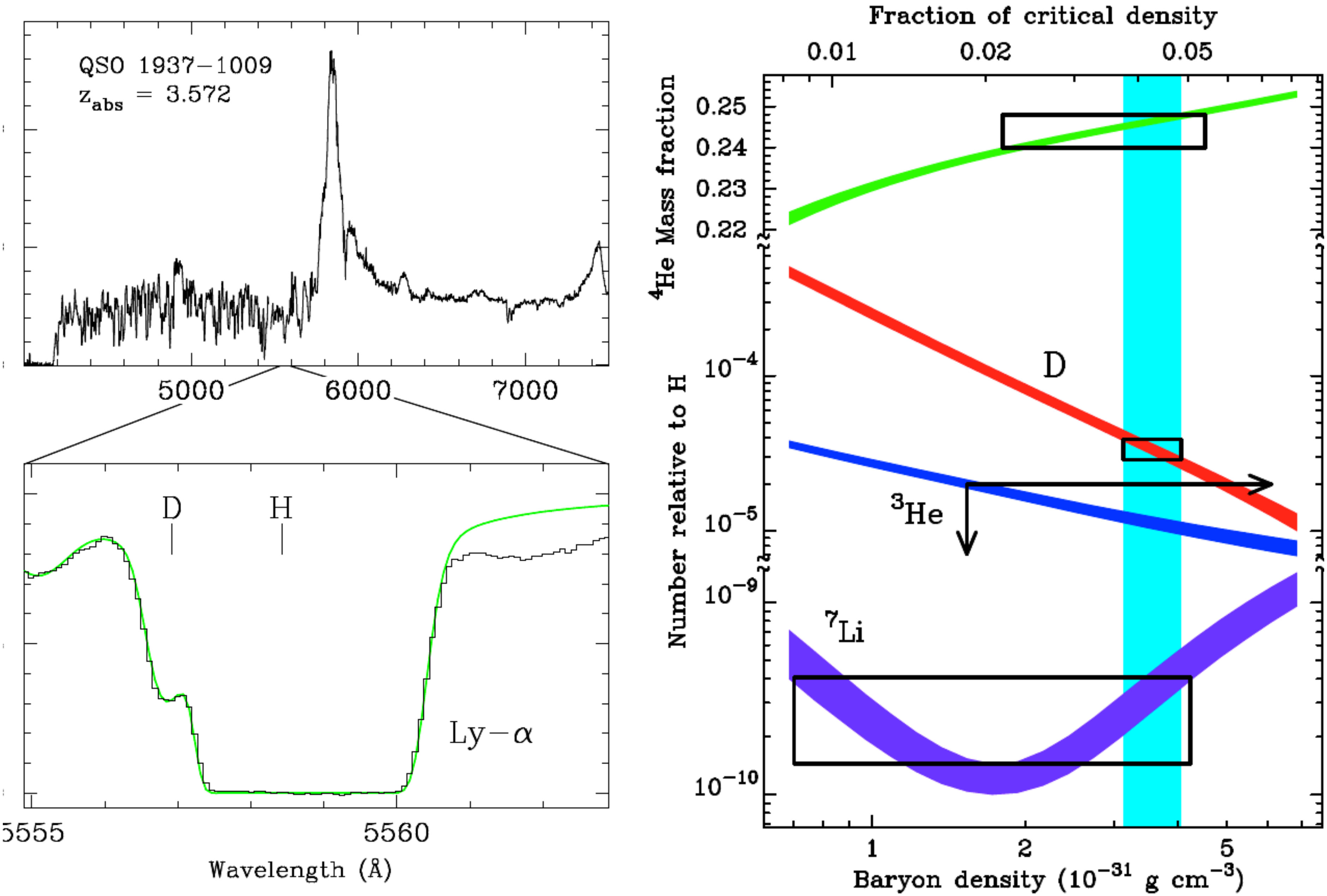
Recall that $\rho_{0,\rm crit} = 3H_0^2/(8\pi G) = 0.921 \times 10^{-29}\, h_{70}^2\ \ {\rm g\ cm}^{-3}$

Thus, $\Omega_{0,lum} \approx (0.0051 \pm 0.0015)\, h_{70}^{-1}$

All of the visible matter amounts to only half a percent of the total mass/energy content of the universe!

(Interestingly, this may be about the same as the contribution from the massive cosmological neutrinos…)

Baryon Density From Cosmic Nucleosynthesis



The Total Baryon Density

It is measured in two completely independent ways:

1. The cosmic nucleosynthesis:

- It occurs in the first few minutes after the Big Bang
- Reaction rates are ~ ρ_{baryon}^2, so the residual abundances of D, He, and Li are very sensitive to ρ_{baryon} (especially for D)
- Measured in spectra of distant QSOs (actually Lyα forest clouds), low metallicity starforming dwarfs, halo stars, etc.

Results give: $\Omega_{baryons} h^2 = 0.021 \rightarrow 0.025$

2. Analysis of CMB fluctuations:

Results give: $\Omega_{baryons} h^2 = 0.024 \pm 0.001$

Thus, $\boldsymbol{\Omega_{0,b}} \approx (0.045 \pm 0.002)\ h_{70}^{-2}$

The Baryonic Dark Matter
(or just "missing", not necessarily "dark"?)

So, where are 90% of baryons hiding? Some possibilities:

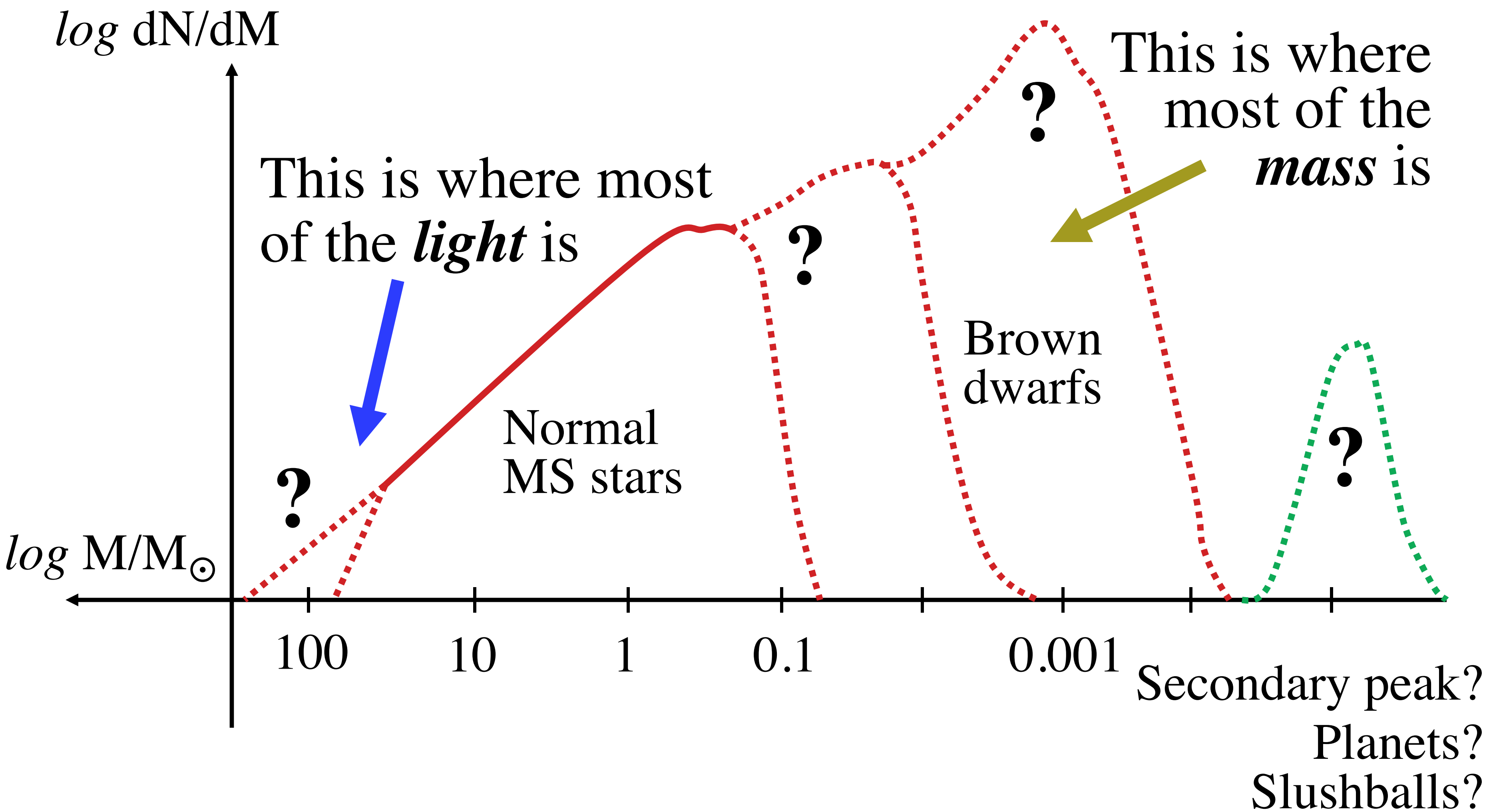
- **MAssive Compact Halo Objects (MACHOs)**
  - Very low mass stars, white dwarfs, neutron stars, black holes (produced post-nucleosynthesis, from baryons), brown dwarfs, interstellar comets, slushballs…
- **Cold molecular (H_2) gas clouds**
  - Would have to be compact, dense, low volume fill factor
  - Very hard to detect!
- **Warm/hot gas**, bound to galaxy groups

The best bet?

  - Leftover gas from IGM, never collapsed to galaxies
  - Virial temperatures ~ 10^5 - 10^6 K, corresponding to the velocity dispersions ~ 300 km/s
  - Very hard to detect! (ISM opaque to FUV/soft-X)

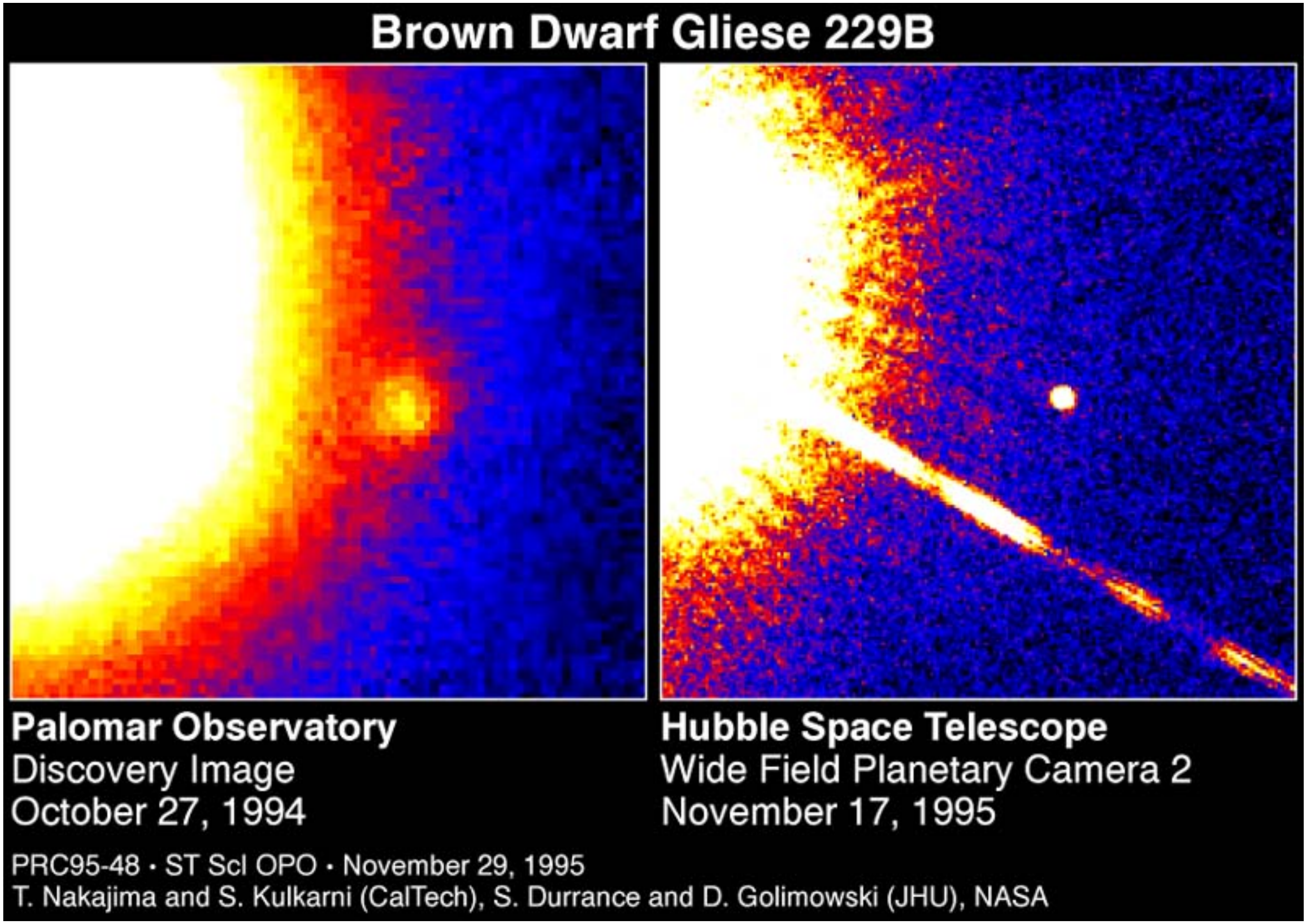
Where are the Baryons?

Depending on the shape of the stellar mass function, one could hide a lot of mass in ***dim, substellar objects, e.g., brown dwarfs***



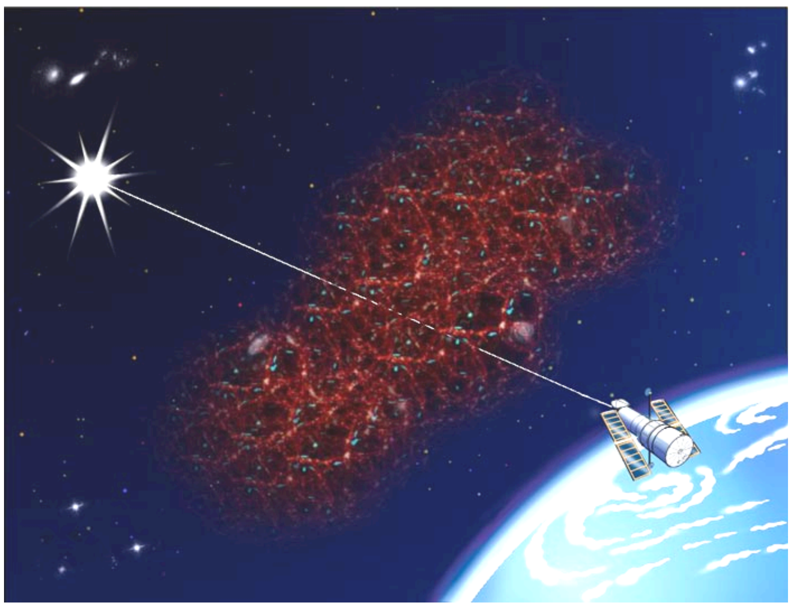
Now we know that brown dwarfs do exist - but the studies so far indicate that there aren't enough of them to account for the BDM

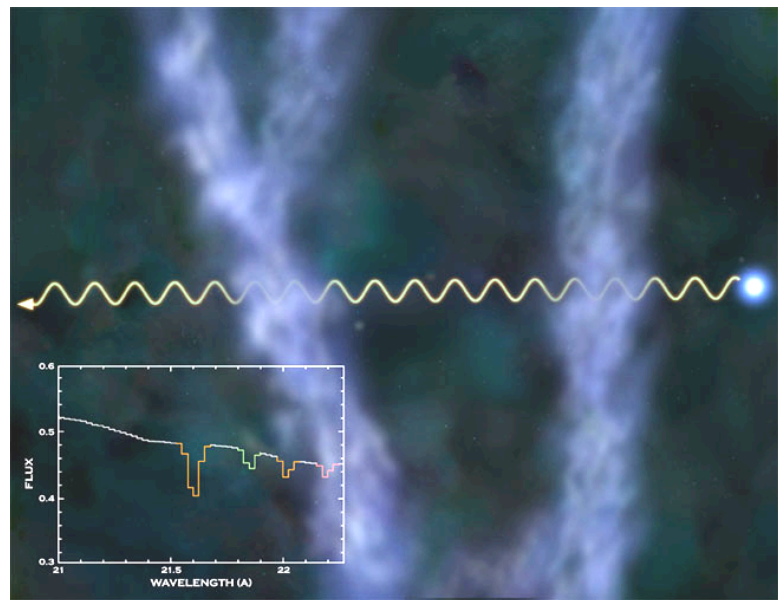
First unambigous detection of a brown dwarf (from Palomar!)



Missing Baryons in Warm/Hot IGM?

This hypothetical Baryon reservoir would have Virial temps. of ~ 10^5 - 10^6 K, where the peak emission is in FUV/soft-X, which is effectively absorbed by the ISM in our Galaxy, and is thus essentially impossible to detect in emission …





However, it might have been ***detected in absorption*** in the UV (HST and FUSE) and X-Rays (Chandra), using O VI, O VII, and O VIII lines


Next:
The Dark Matter