DARK MATTER

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SPRING 2024
TR 11:30AM-12:45PM
SEARS 552

http://astroweb.case.edu/ssm/ASTR333/

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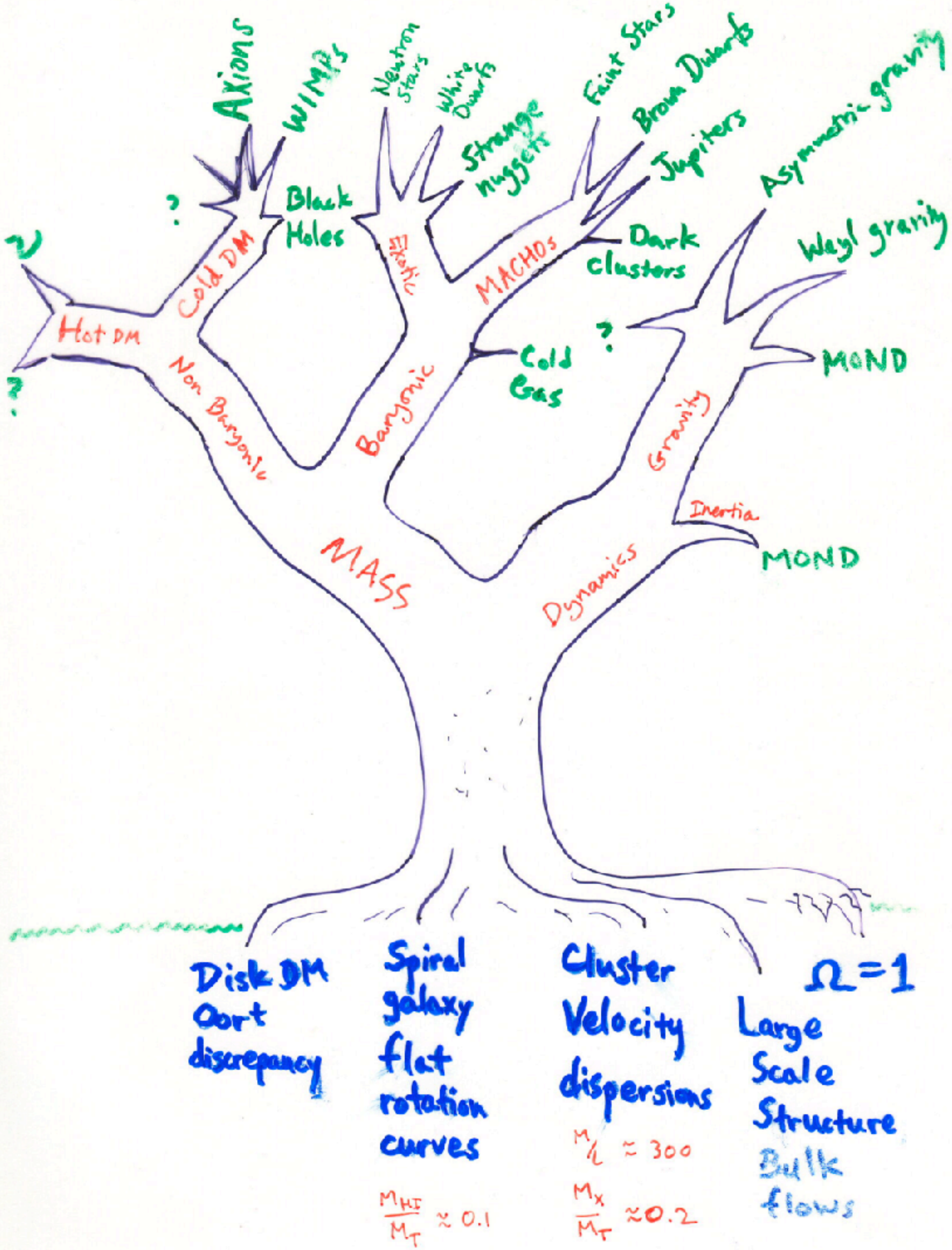
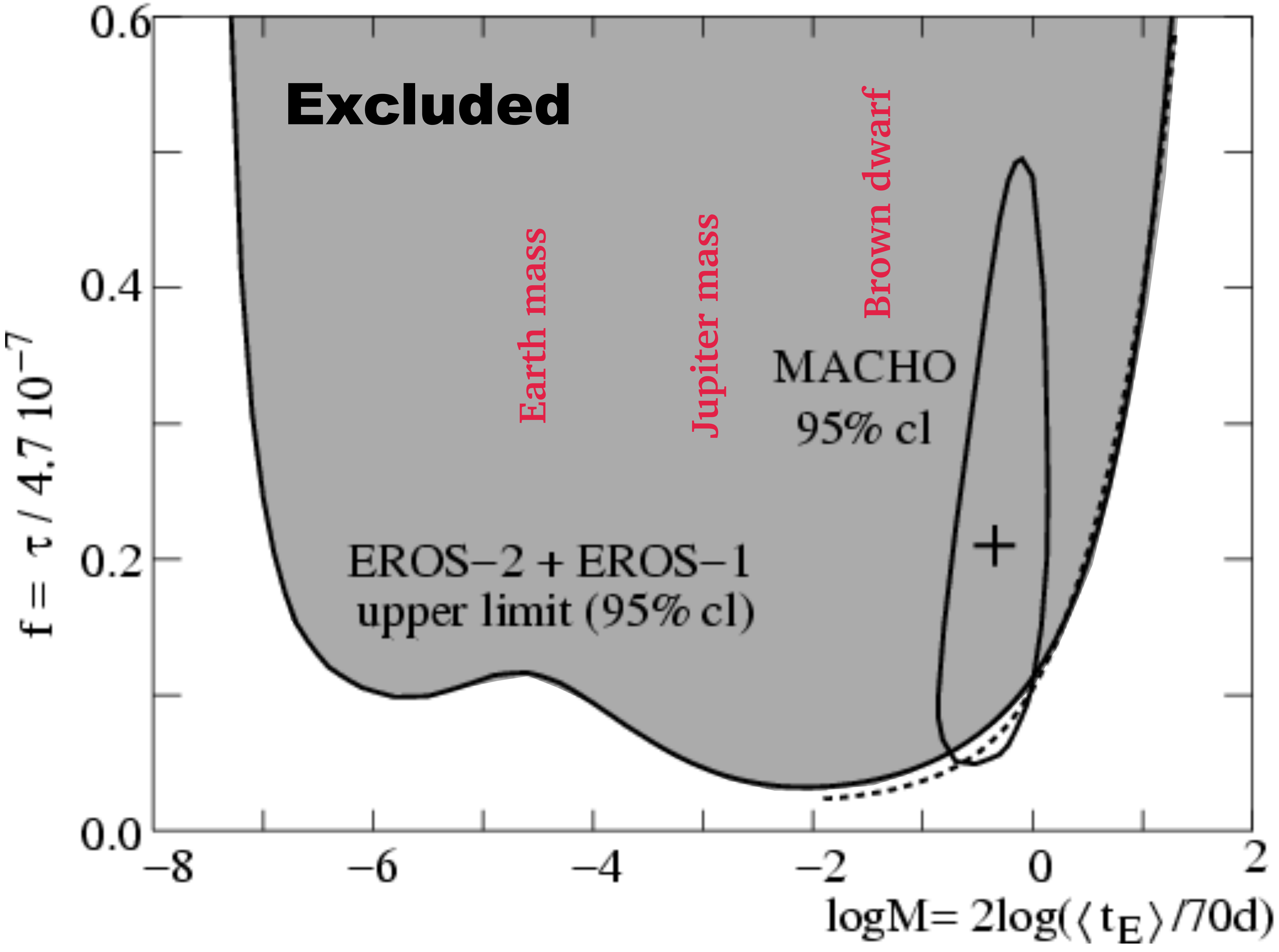
Homework due next time

CASE WESTERN RESERVE UNIVERSITY EST. 1826



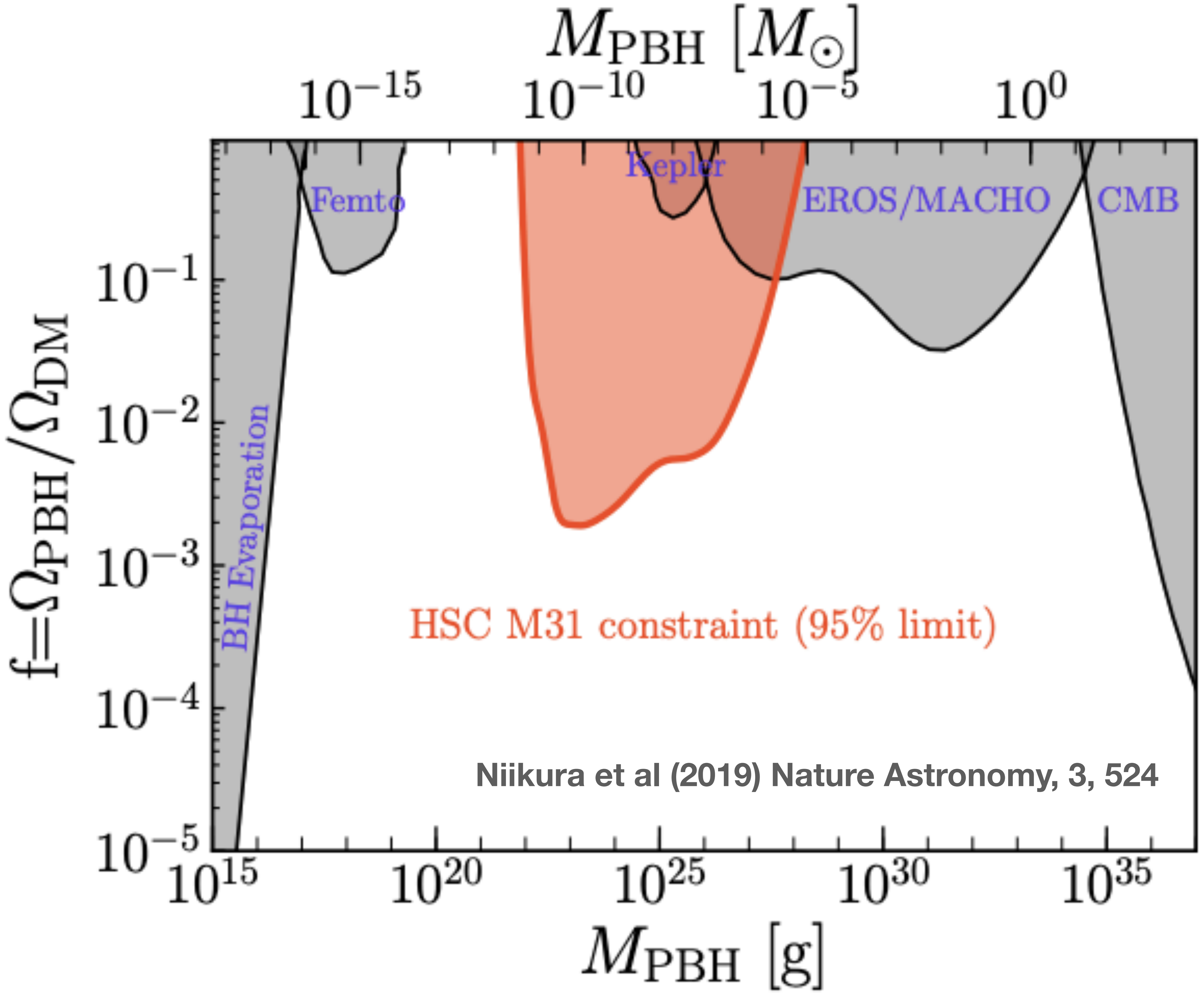
Microlensing exclusion diagram

logM= 2log(⟨t_E⟩/70d)



The observed rate of microlensing events leaves no room for the dark matter halo of the Milky Way to be composed of massive compact objects like brown dwarfs or black holes in the mass range $10^{-7} < M < 10$ solar masses.

Subaru study of microlensing towards M31



Niikura et al (2019) Nature Astronomy, 3, 524

M31

The red shaded region corresponds to the 95% C.L. upper bound on the PBH mass fraction to DM in the halo regions of MW and M31, derived from our search for microlensing of M31 stars based on the “single-night” HSC/Subaru data and fills a large gap in the existing constraints by closing the PBH DM window around lunar mass scale. To derive this constraint, we took into account the effect of finite source size, assuming that all source stars in M31 have a solar radius, as well as the effect of wave optics in the HSC r-band filter on the microlensing event (see text for details). The effects weaken the upper bounds at M <~ 10−7M , and give no constraint on PBH at M <~ 10−11M . Our constraint can be compared with other observational constraints as shown by the gray shaded regions: extragalactic γ-rays from PBH evaporation [32], femtolensing of γ-ray burst (“Femto”) [33], microlensing search of stars from the satellite 2-years Kepler data (“Kepler”) [18], MACHO/EROS/OGLE microlensing of stars (“EROS/MACHO”) [15], and the accretion effects on the CMB observables (“CMB”) [34], updated from the earlier estimate [35].

PBH = primordial black holes

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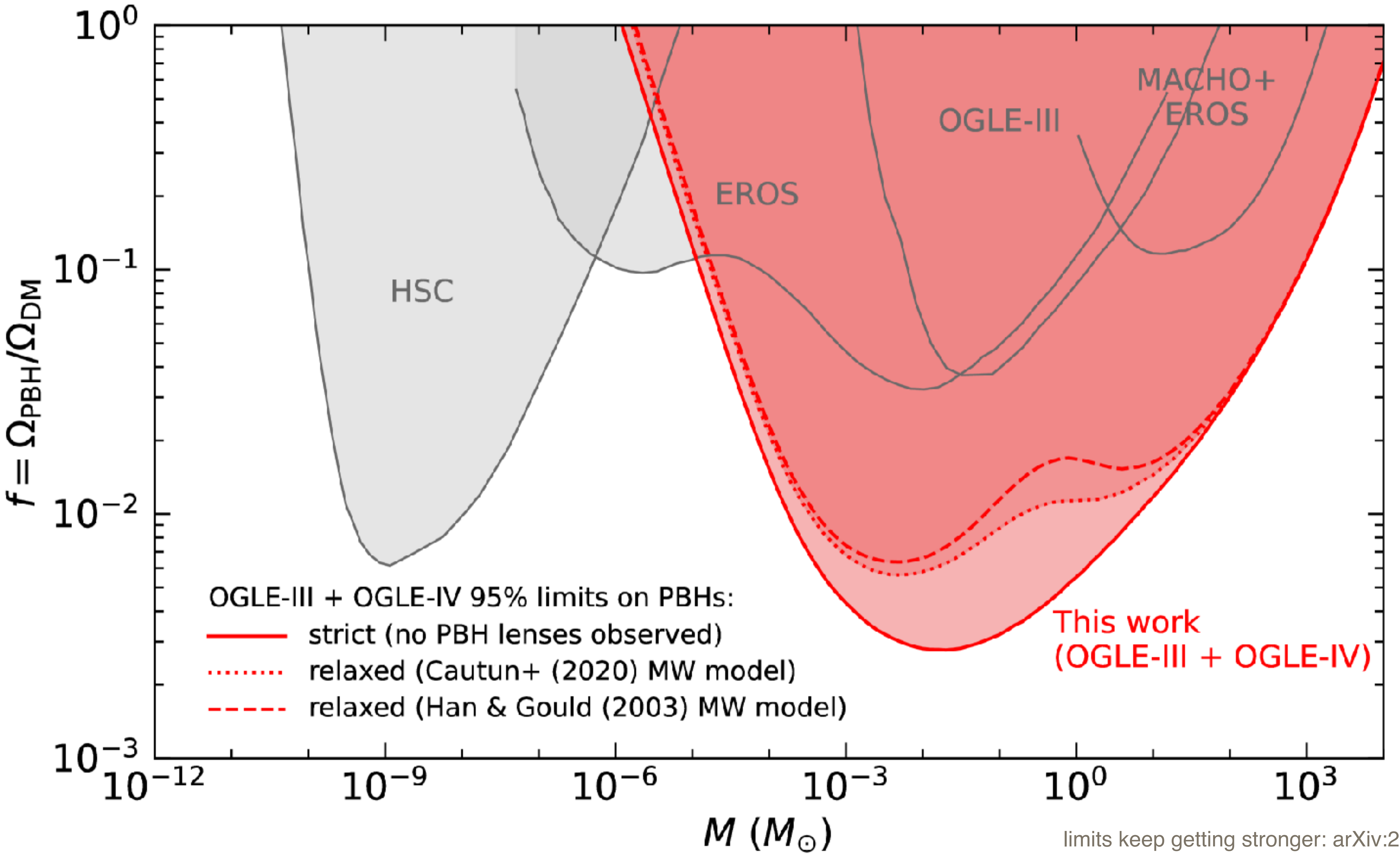
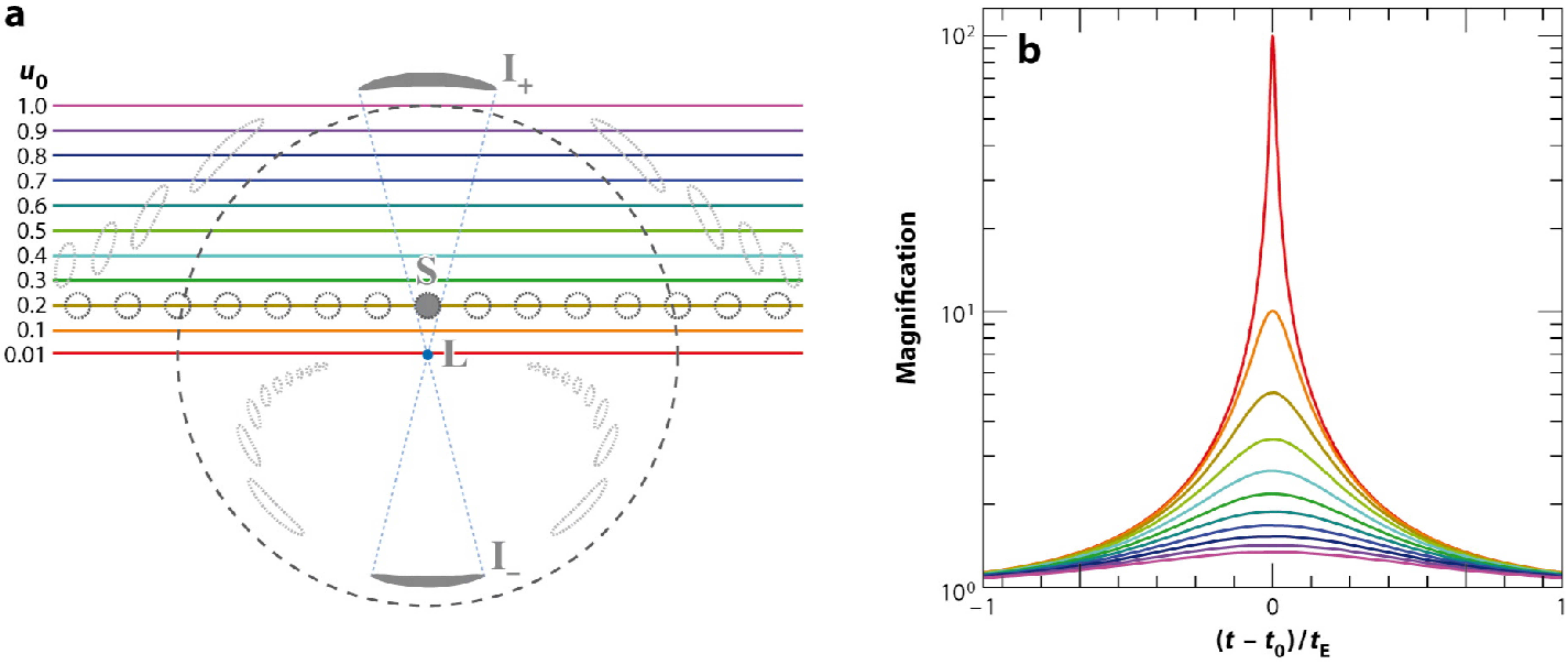


limits keep getting stronger: arXiv:2403.02386

Figure 1: 95% upper limits on PBHs (and other compact objects) as constituents of dark matter. The solid red line marks the limits derived in this paper under the assumption that all gravitational microlensing events detected by OGLE in the direction of the LMC are due to objects in the LMC itself or the Milky Way disk. If this assumption is relaxed, the limits (dotted and dashed lines) depend on the choice of the Milky Way disk model ([23] or [24], respectively). The gray lines mark the limits determined by the following surveys: EROS [16], OGLE-III [17], Hyper Suprime-Cam (HSC) [25], and MACHO+EROS [18]. The new limits are publicly available online at `https://www.astrouw.edu.pl/ogle/ogle4/LMC_OPTICAL_DEPTH/`.



Microlensing towards Galactic Center

Expect ordinary stars to dominate microlensing signal

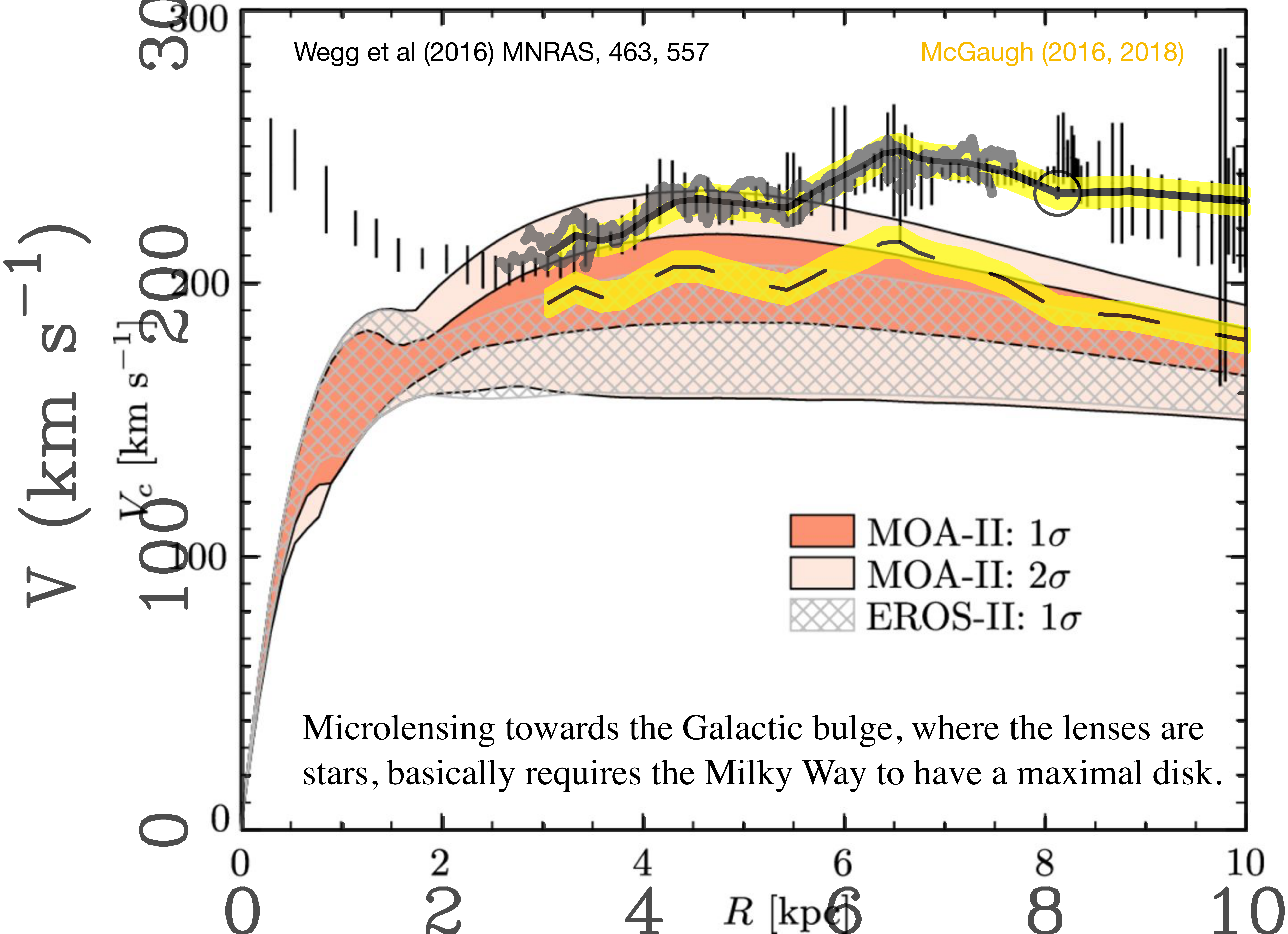
$$t_E = \frac{\theta_E}{\mu_{rel}}$$

Einstein crossing time: time to cross Einstein ring.

lens mass *parallax* *proper motion*

$$t_E \approx (24.8\ \mathrm{days}) \left(\frac{M}{0.5\ \mathrm{M}_\odot}\right)^{1/2} \left(\frac{\pi_{rel}}{125\ \mu\mathrm{as}}\right)^{1/2} \left(\frac{\mu_{rel}}{10.5\ \mathrm{mas\,yr}^{-1}}\right)^{-1}$$

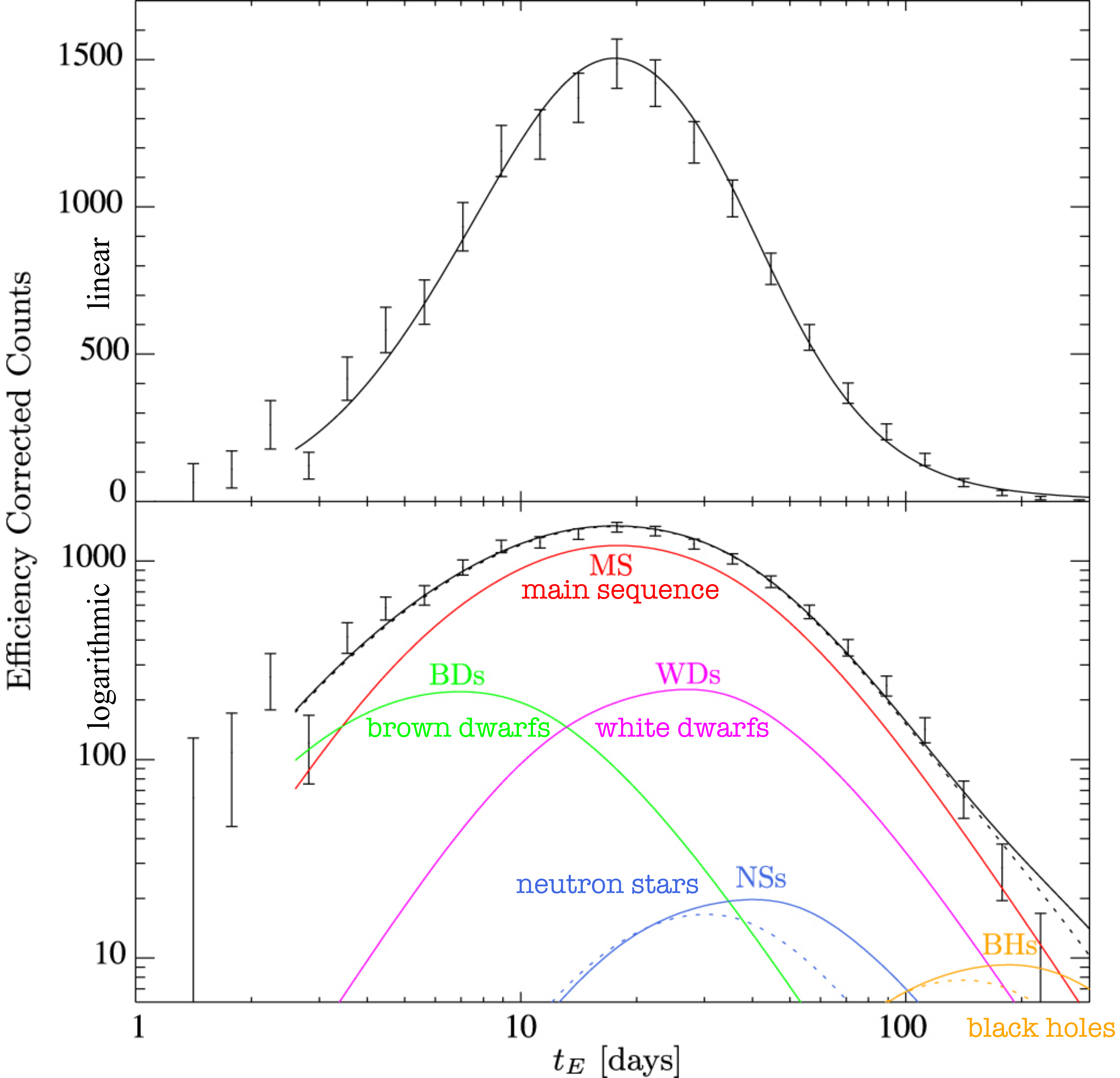
for lensing events towards the Galactic bulge.



Microlensing towards the Galactic bulge, where the lenses are stars, basically requires the Milky Way to have a maximal disk.

Microlensing towards the Galactic Center consistent with known stellar populations

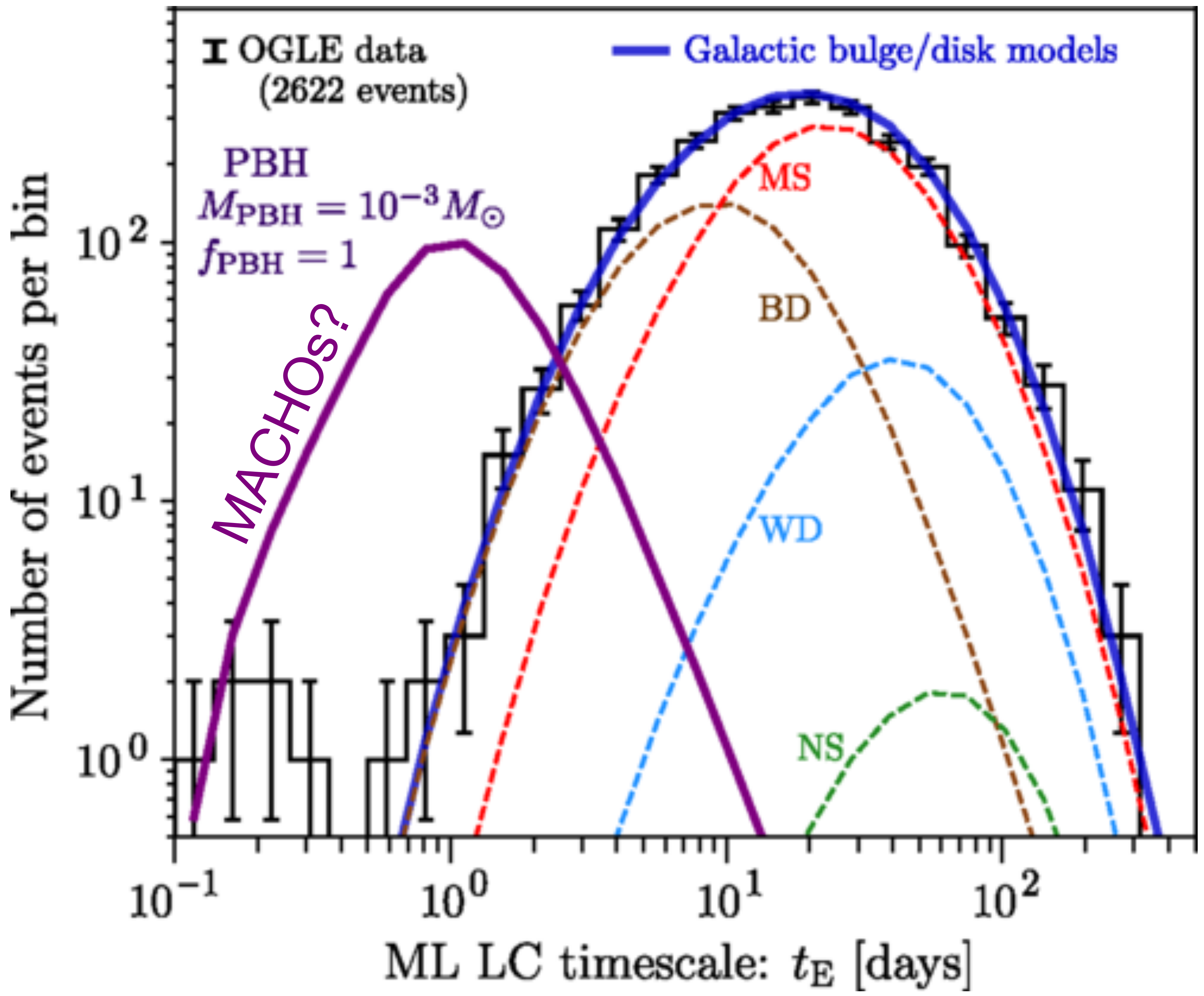
Constrains the IMF to be basically the same as seen everywhere else.



Wegg et al (2017) ApJ, 843, L1

Just stars -
There is no room for extra MACHOs

Microlensing events towards the Galactic Center



well explained by known stars and stellar remnants
without room for extra MACHOs

microlensing summary

- microlensing is rare but routinely detected
- optical depth consistent with known stars & stellar remnants
- no positive evidence for MACHO type dark matter
- broad range of MACHO masses excluded:

$$10^{-7} < M_{\mathrm{MACHO}} < 10\ \mathrm{M}_{\odot}$$

basically ruled out

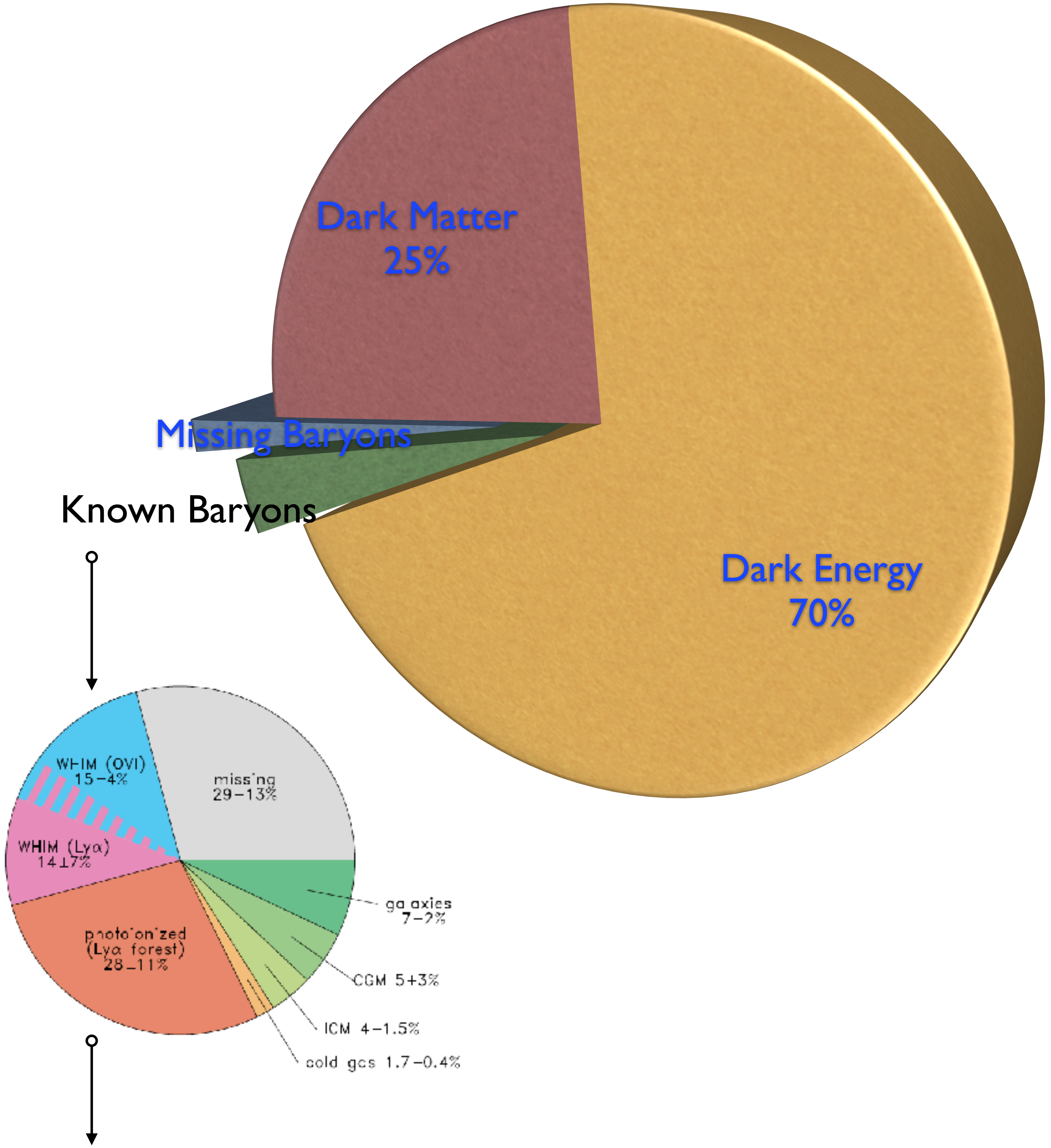
Cosmological Dark Matter

ΛCDM Cosmology

- non-baryonic cold dark matter
  - whatever it is (e.g., WIMPs)

- dark energy
  - whatever that even means

- dark baryons
  - 29% not accounted for



We have direct knowledge of < 5% of the total mass-energy density of the universe

Current mass-energy content of the universe

mass density	Ω_m	0.30	give or take a bit
normal matter	Ω_b	0.05	baryons - from BBN
mass that is *not* normal matter	$\Omega_{\rm CDM}$	0.25	cold dark matter
cosmic background radiation	Ω_r	5×10^{-5}	photons
neutrinos	$0.001 < \Omega_\nu < 0.002$		for 3 neutrino flavors with $0.06 < \sum_{i=1}^{3} m_{\nu_i} < 0.12$ eV
dark energy	Ω_Λ	0.70	energy density of vacuum

e.g, $\Omega_\nu = \dfrac{\sum m_\nu}{93 \text{ eV}}$

since $n_\nu = \dfrac{9}{11} n_\gamma$

definitions:

$$\Omega_x = \frac{\rho_x}{\rho_{crit}} \qquad \rho_{crit} = \frac{3H_0^2}{8\pi G}$$

$$\Omega_b \approx 0.05$$

BBN baryon density

$$\Omega_m \approx 0.30$$

gravitating mass density

$$f_b = \frac{\Omega_b}{\Omega_m}$$

baryon fraction

There is a hierarchy of missing mass problems

$$\Omega_b < \Omega_m$$

cosmic missing mass problem
(not enough BBN baryons to explain all the gravitating mass in the Universe)

$$\sum \Omega_b \text{ (observed)} < \Omega_b \text{ (BBN)}$$

cosmic missing baryon problem
(not enough baryons for BBN)

$$M_b < f_b M_{200}$$

halo missing baryon problem
(not enough baryons in each DM halo)

$\Omega_b \approx 0.05$	BBN baryon density
$\Omega_m \approx 0.30$	gravitating mass density
$f_b = \dfrac{\Omega_b}{\Omega_m}$	baryon fraction

There is a hierarchy of missing mass problems

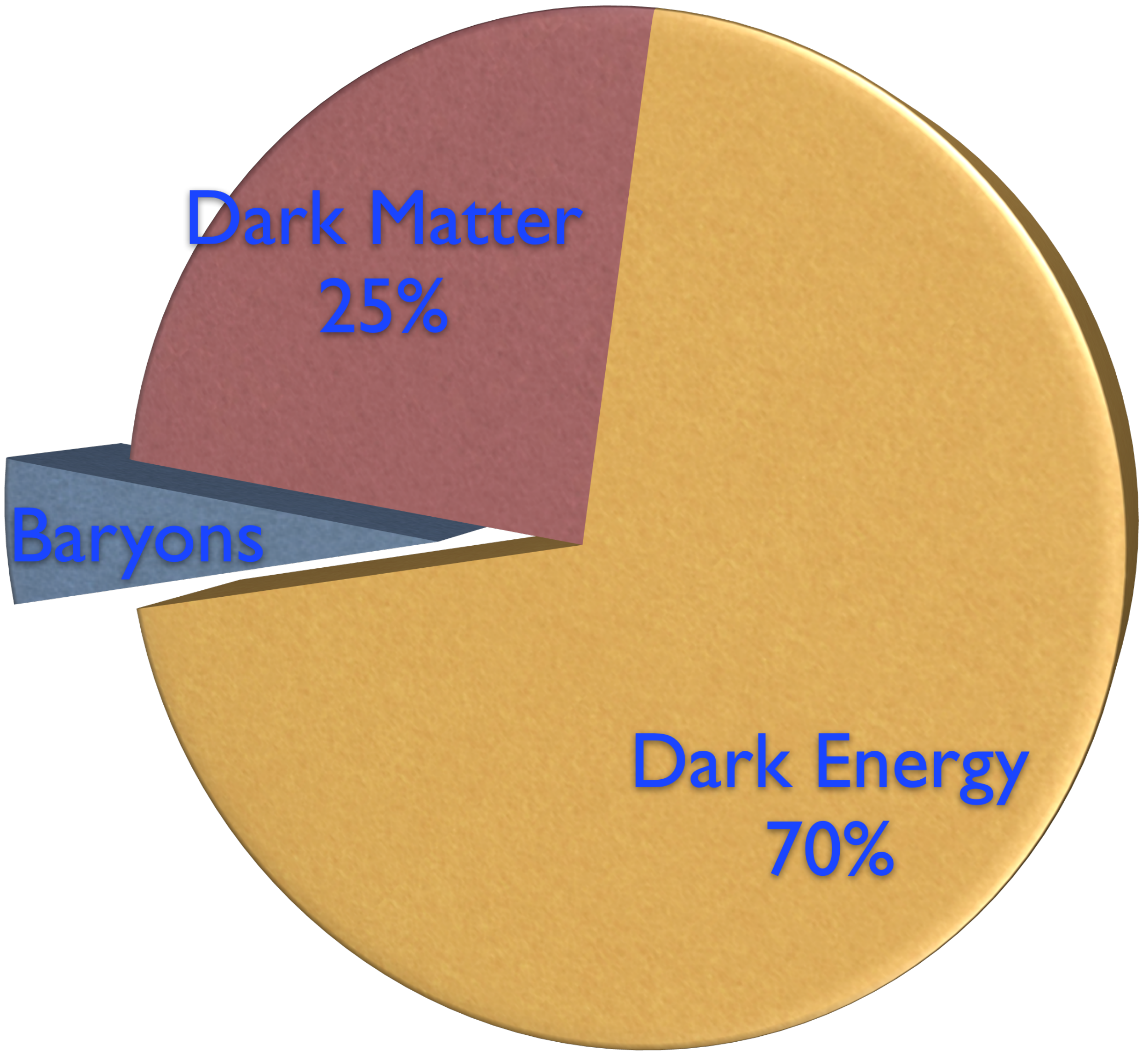
$\Omega_b < \Omega_m$	cosmic missing mass problem (not enough BBN baryons to explain all the gravitating mass in the Universe)
$\sum \Omega_b\,(\text{observed}) < \Omega_b\,(\text{BBN})$	cosmic missing baryon problem (not enough baryons for BBN)
$M_b < f_b M_{200}$	halo missing baryon problem (not enough baryons in each DM halo)

The cosmic missing baryon problem

This is usually what people mean when the say “dark matter” or “missing mass”

Measurements of the gravitating mass density

- Cluster M/L
  - measure M/L of a cluster, combine with measured luminosity density of universe.
- Weak lensing
  - measure shear over large scales
- Peculiar Velocity Field
  - measure deviations from Hubble flow
- Power spectrum of galaxies
- Acoustic power spectrum of the CMB



All yield $\Omega_m \approx 0.3$

$\Omega_b \approx 0.05$ BBN baryon density

$\Omega_m \approx 0.30$ gravitating mass density

$f_b = \dfrac{\Omega_b}{\Omega_m}$ baryon fraction

There is a hierarchy of missing mass problems

$\Omega_b < \Omega_m$ cosmic missing mass problem
(not enough BBN baryons to explain all the gravitating mass in the Universe)

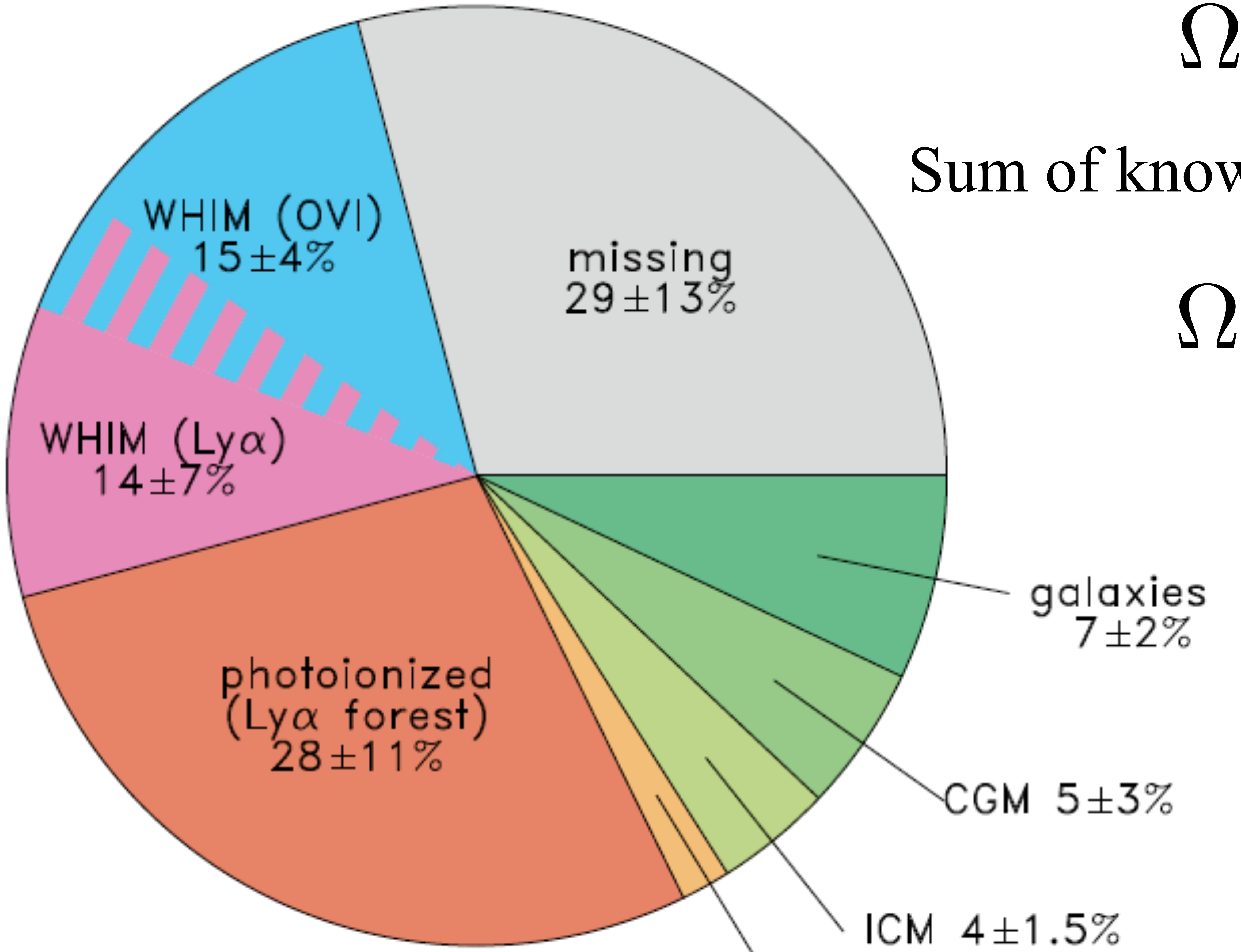
$\sum \Omega_b \text{ (observed)} < \Omega_b \text{ (BBN)}$ cosmic missing baryon problem
(not enough baryons for BBN)

$M_b < f_b M_{200}$ halo missing baryon problem
(not enough baryons in each DM halo)

The cosmic missing baryon problem

Cosmic baryon budget
(Shull et al arXiv:1112.2706)

$@\ z = 0$



$$\sum \Omega_b \text{ (observed)} < \Omega_b \text{ (BBN)}$$

Big Bang Nucleosynthesis
CMB fits give

$$\Omega_b h^2 = 0.022$$

Sum of known baryons only

$$\Omega_b h^2 \approx 0.017$$

Total mass density

$$\Omega_m h^2 \approx 0.13$$

Baryon reservoirs

- Galaxies
  - Stars 7% → integrate luminosity function; estimate M*/L
  - cold gas 2% → integrate HI mass function; estimate molecular gas fraction
  - circumgalactic medium (CGM) 5% → absorption of highly ionized gas along sight lines; estimate ionization fraction and covering factor
- Clusters
  - intracluster gas (ICM) 4% → integrate X-ray cluster luminosity function
- Intergalactic Medium (IGM)
  - Warm-Hot IGM 29% → absorption of highly ionized gas along sight lines; estimate ionization fraction
  - Lyman α forest 28% → Lyα absorption lines in QSO spectra

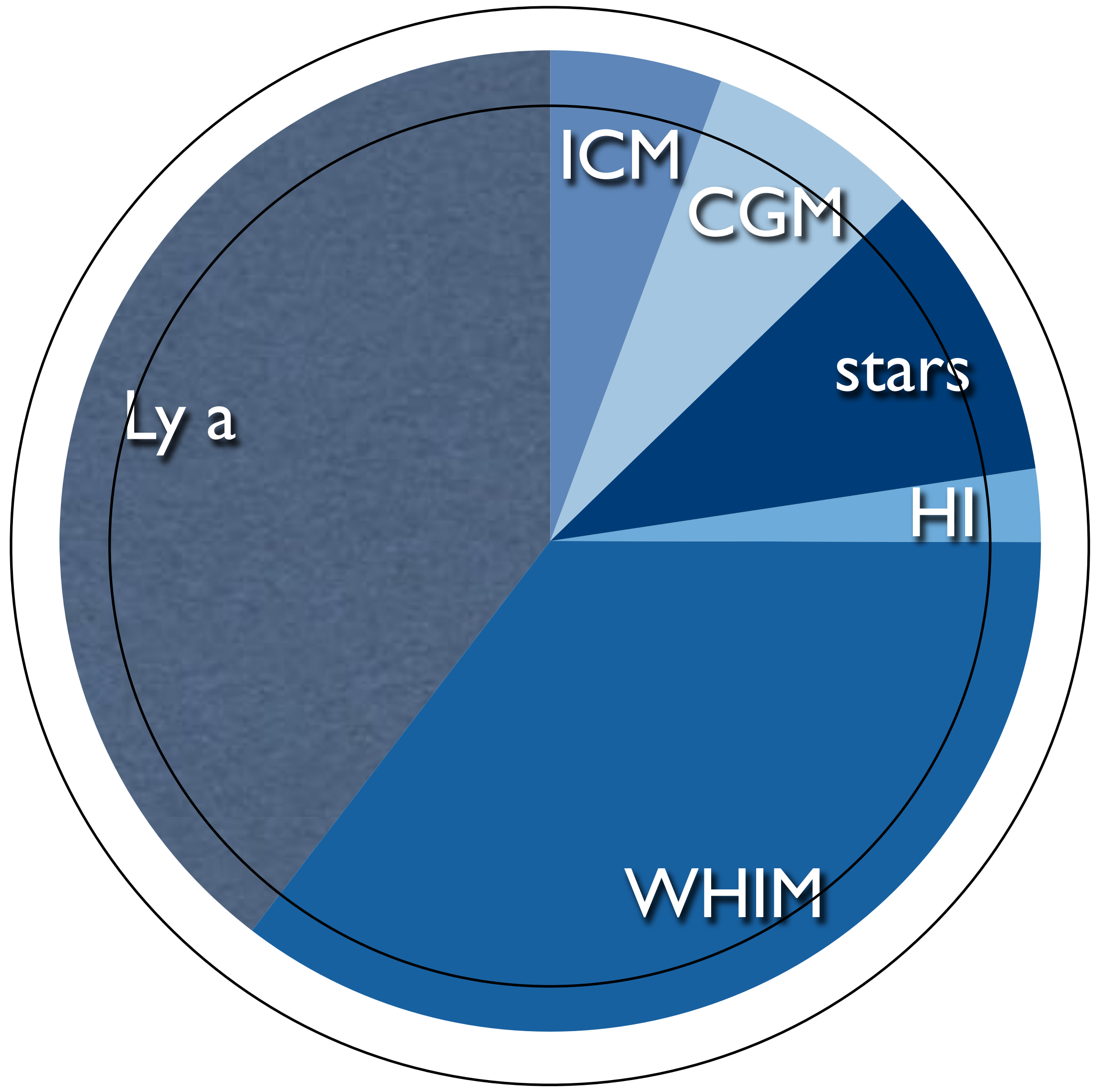
Maybe some extra in large scale filaments?

$$\sum \Omega_b \text{ (observed)} < \Omega_b \text{ (BBN)}$$

Percentages are relative to the BBN baryon density.
The uncertainties are large

How many baryons are missing depends on how many BBN predicts

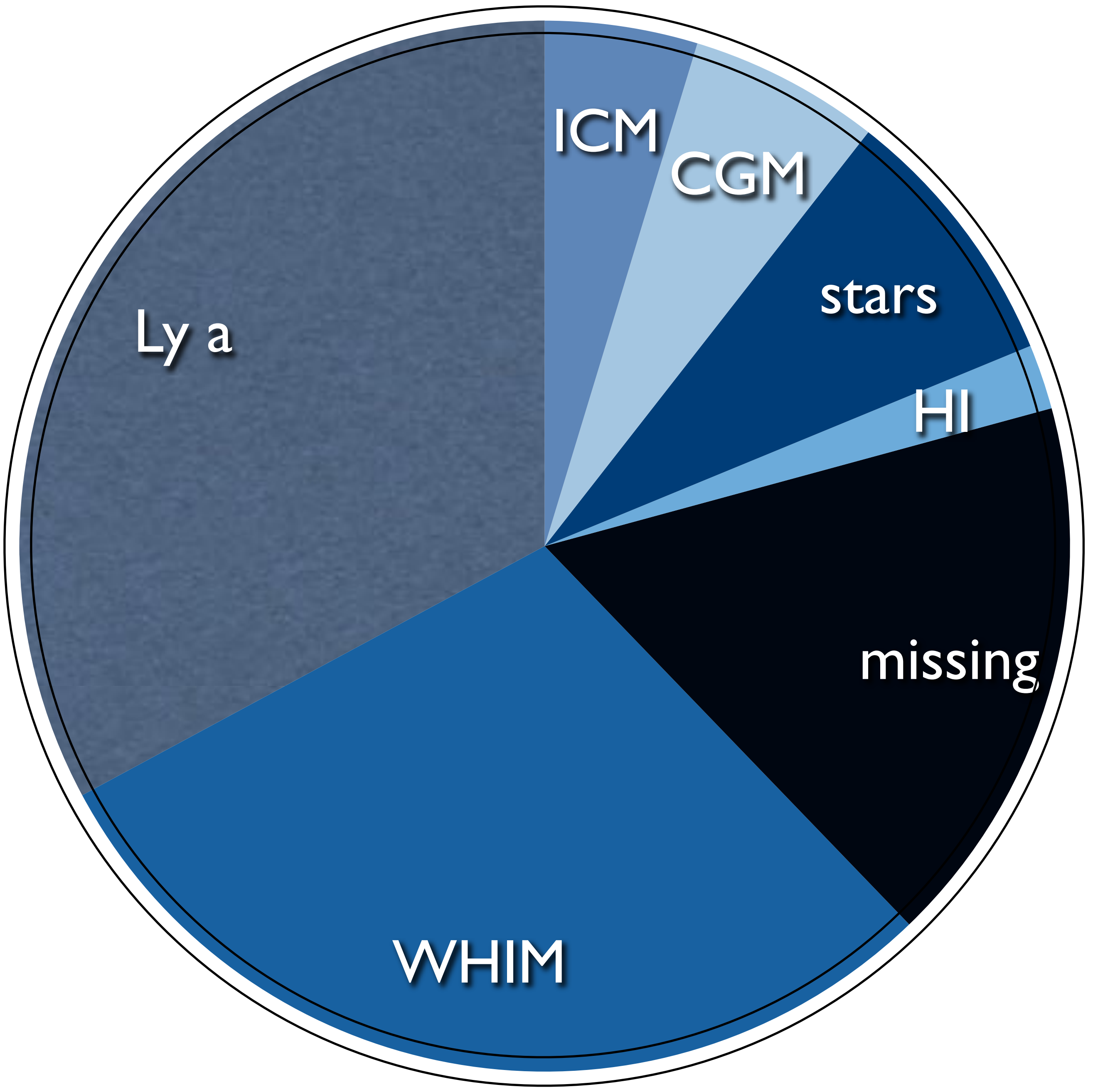
BBN 1991 (Walker et al.)



$$\Omega_b h^2 = 0.0125 \pm 0.0025$$

$$\Omega_b = 0.0255$$

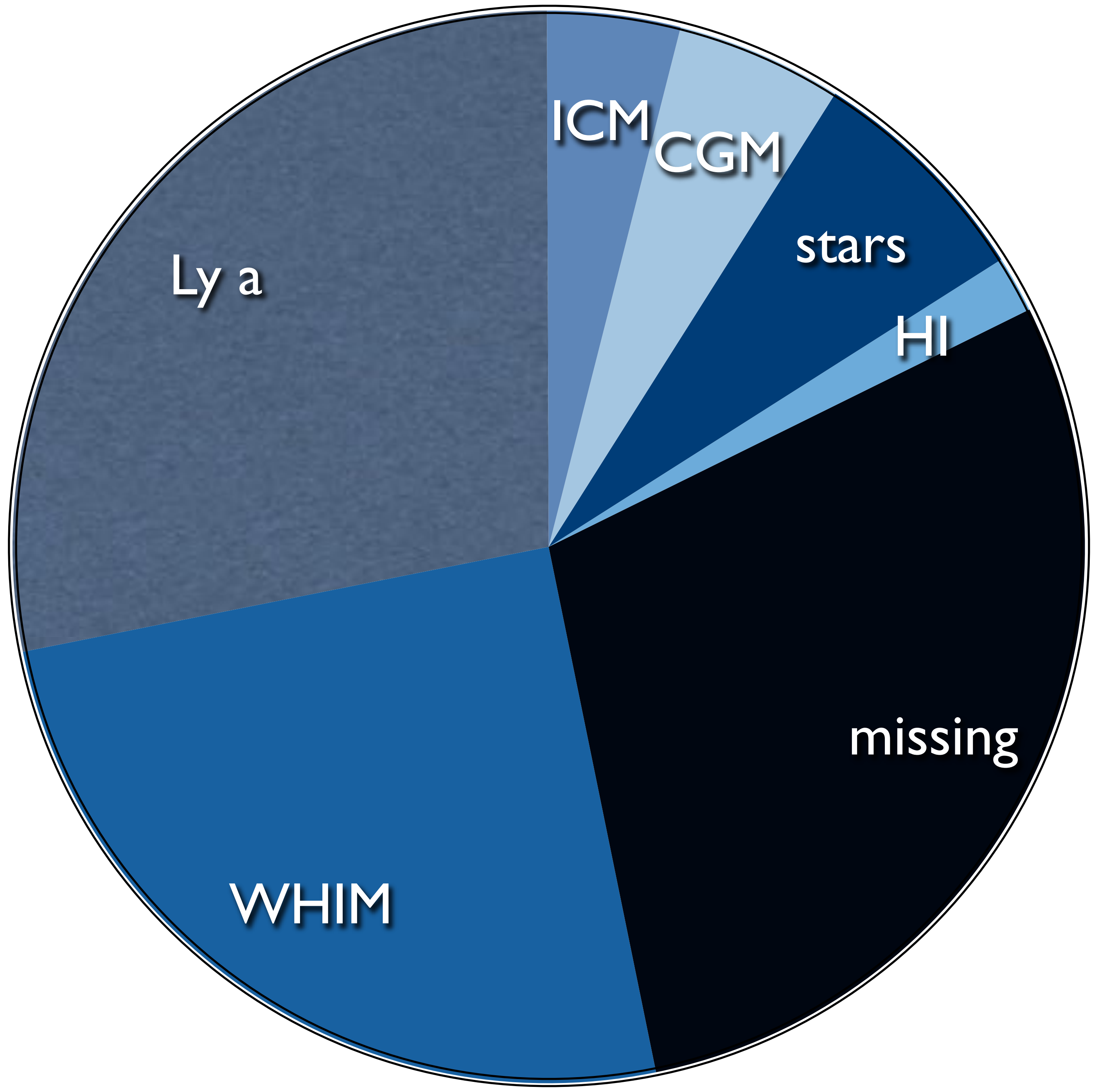
BBN 1999 (pre-CMB D/H)



$$\Omega_b h^2 = 0.019 \pm 0.001$$

$$\Omega_b = 0.0388$$

CMB 2015 (Planck)



$$\Omega_b h^2 = 0.02230 \pm 0.00023$$

$\Omega_b = 0.0455$ for $H_0 = 70$
$\Omega_b = 0.05$ for $H_0 = 66.8$
$\Omega_b = 0.04$ for $H_0 = 74.7$

Our estimate of the baryon density Ω_b has grown over time.
The first step was in response to improved deuterium data;
the second was due to observation of the CMB acoustic power spectrum.