Dark Matter

ASTR/PHYS 4080: Intro to Cosmology

Week 7

How much visible matter is there?

Can only see matter that emits light.

Surveys tell us that in the local universe $(\mathrm{out\ to\ } d \sim 0.1c/H_0)$ the luminosity density in the V band is

$$\Psi_V = 1.1 \times 10^8\ L_{\odot,V}\ \mathrm{Mpc}^{-3}$$

where $L_{\odot,V} \approx 0.12 L_{\odot} \approx 4.6 \times 10^{25}\ \mathrm{W}$

But we want their mass, which we can infer if we know the typical *mass-to-light ratio*

Because astronomers do things in relative terms, we compare to the Sun:

$$\langle M/L_V \rangle = 1\ M_{\odot}/L_{\odot,V}$$

But of course, different stars have different M/L values:

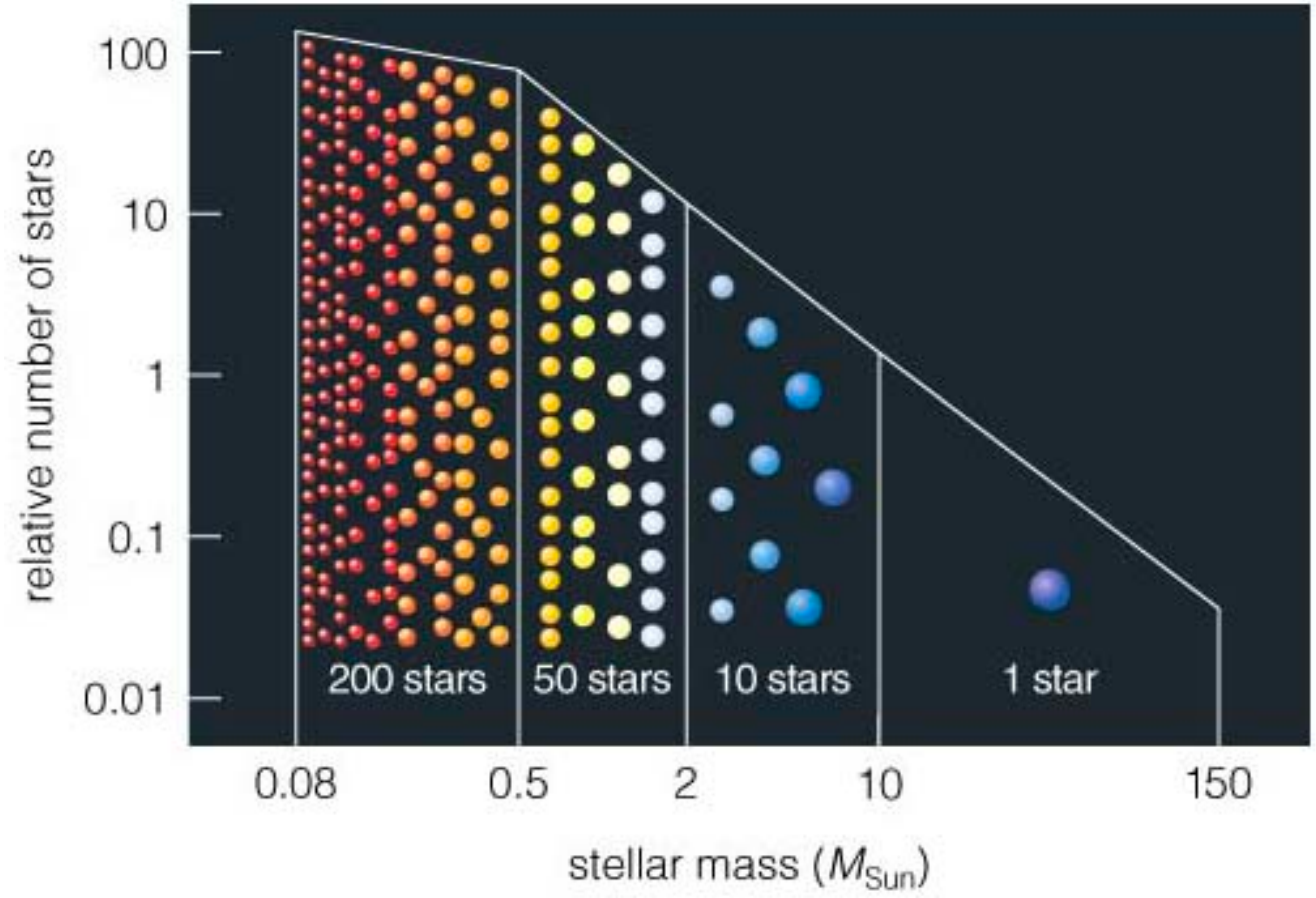
O star: $M = 60\ M_{\odot},\ L \approx 2 \times 10^4\ L_{\odot,V}$

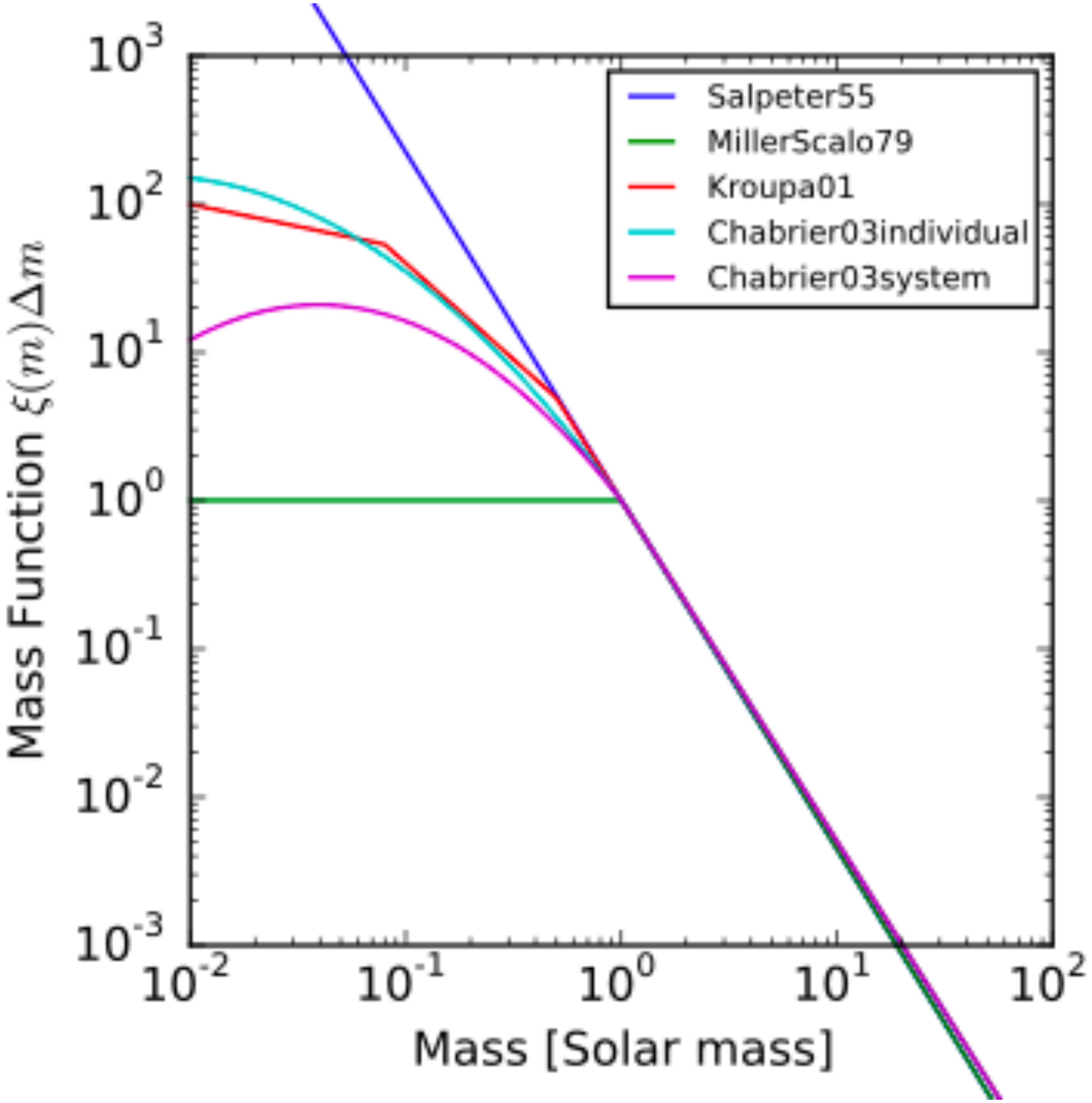
$$\langle M/L_V \rangle = 0.003\ M_{\odot}/L_{\odot,V}$$

M star: $M = 0.1\ M_{\odot},\ L \approx 5 \times 10^{-5}\ L_{\odot,V}$

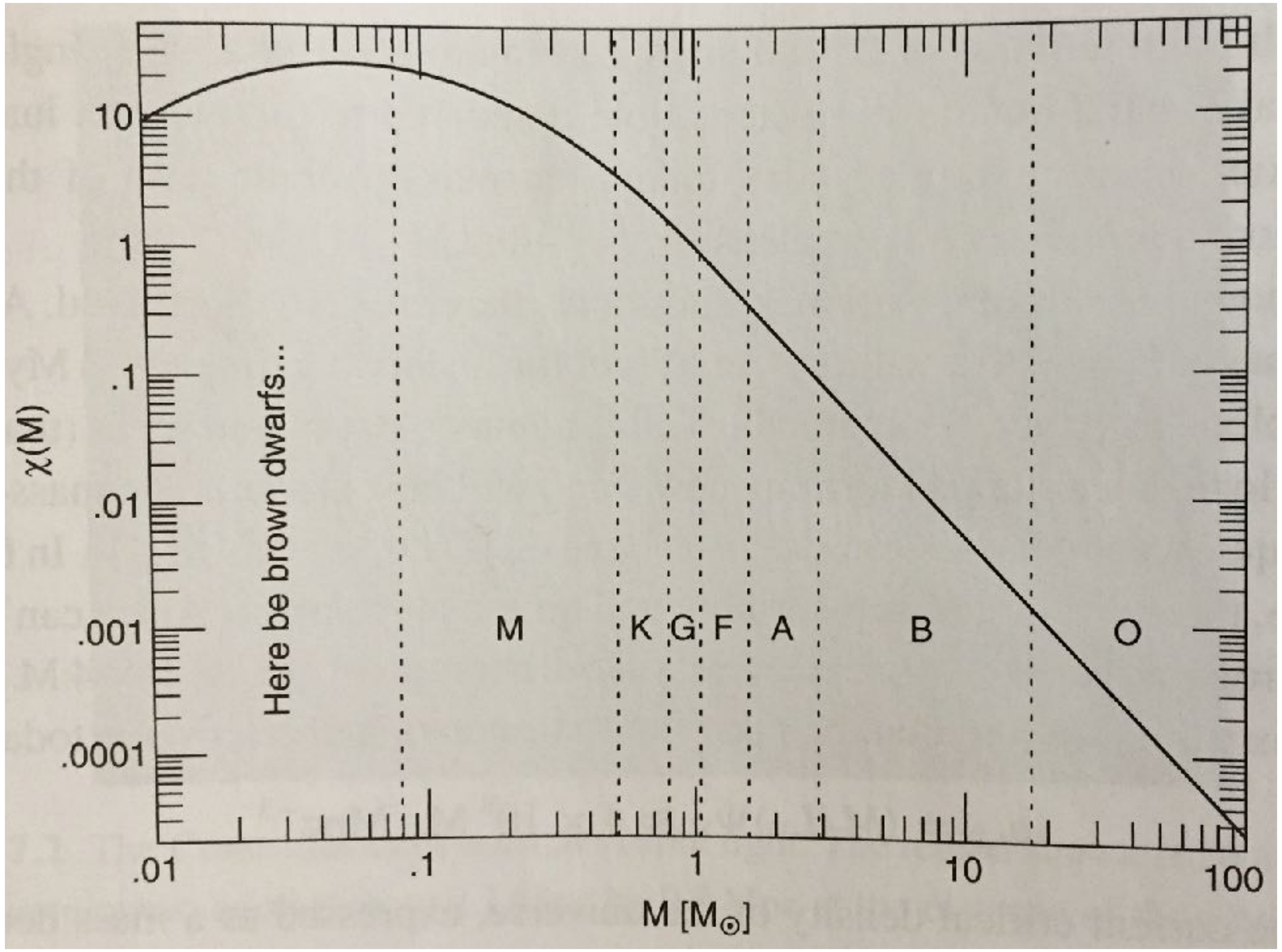
$$\langle M/L_V \rangle = 2000\ M_{\odot}/L_{\odot,V}$$

Mass function of stars





Mass function of stars



$M < 1\ M_\odot$

$$\chi(M) \propto \frac{1}{M} \exp\left(-\frac{(\log M - \log M_c)^2}{2\sigma^2}\right)$$

$M > 1\ M_\odot$

$$\chi(M) \propto M^{-\beta}$$

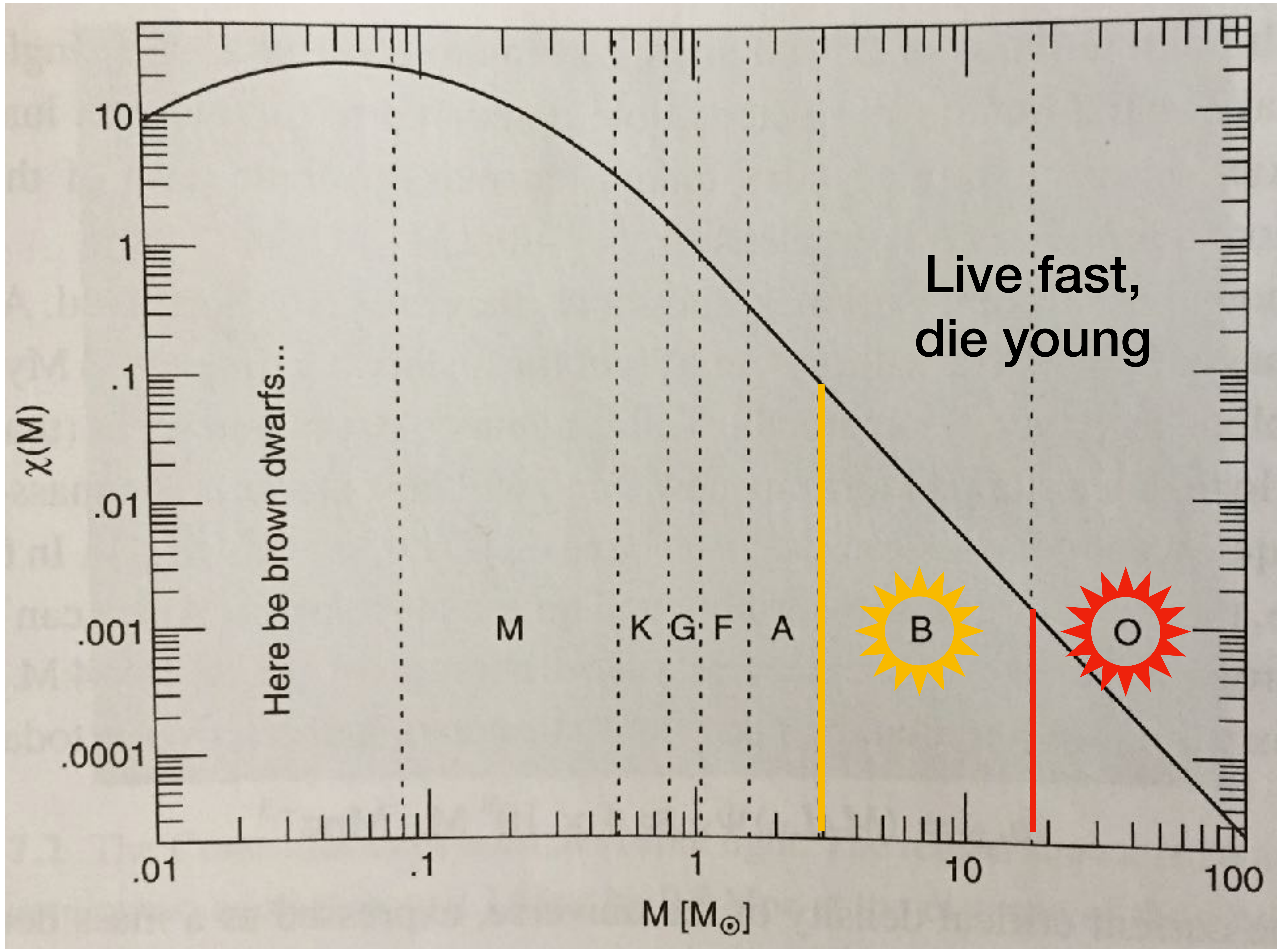
1 60 $M_\odot$ O star for every

10^5 0.2 $M_\odot$ M stars

but most light from O star

$\langle M/L_{\odot,V} \rangle \approx 0.3\ M_\odot/L_{\odot,V}$

Mass function of stars



quiescent (red and dead) galaxies

$$\langle M/L_{\odot,V}\rangle \approx 8\ M_{\odot}/L_{\odot,V}$$

mix of quiescent & SF galaxies

$$\rho_{*,0} = \langle M/L_{\odot,V}\rangle \Psi_V$$

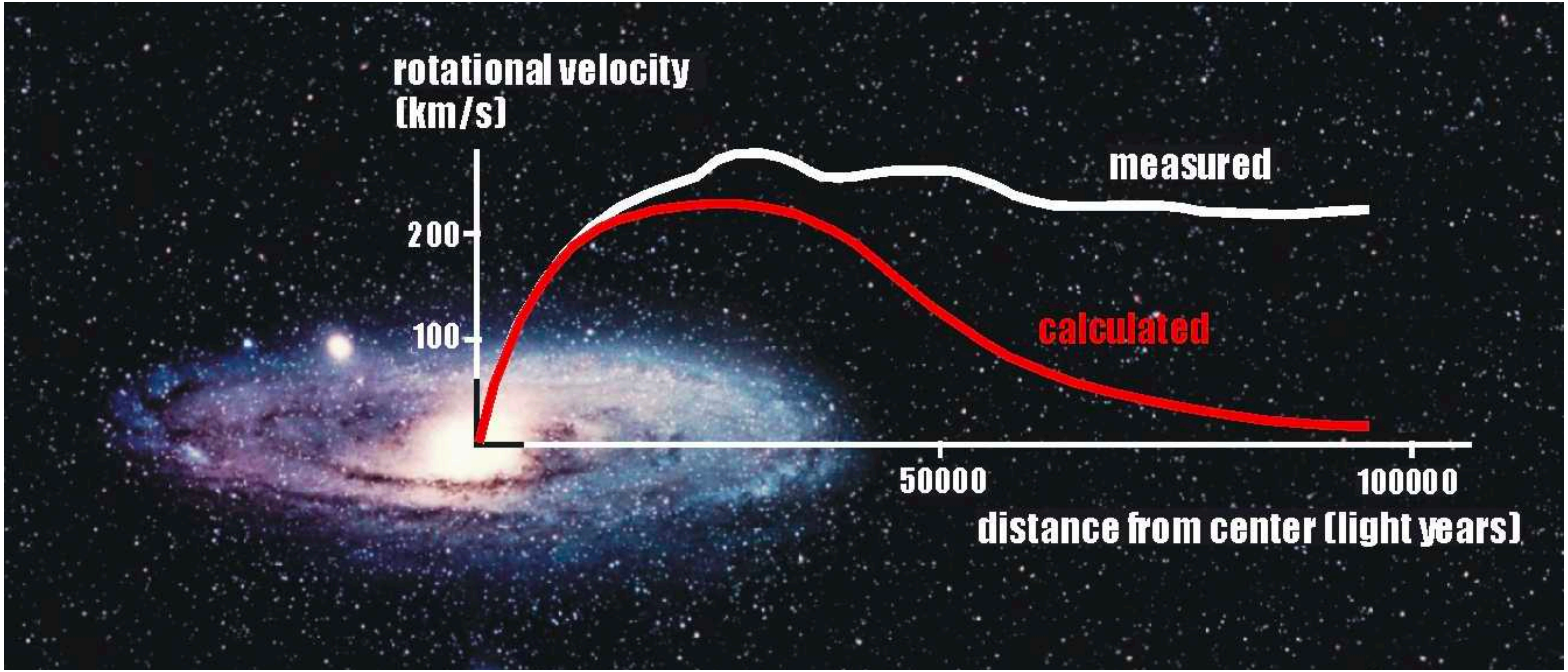
$$\approx 4\times 10^{8}\ \mathrm{M_{\odot}\ Mpc^{-3}}$$

$$\Omega_{*,0} = \frac{\rho_{*,0}}{\rho_{*,c}}$$

$$\approx \frac{4\times 10^{8}\ \mathrm{M_{\odot}\ Mpc^{-3}}}{1.28\times 10^{11}\ \mathrm{M_{\odot}\ Mpc^{-3}}}$$

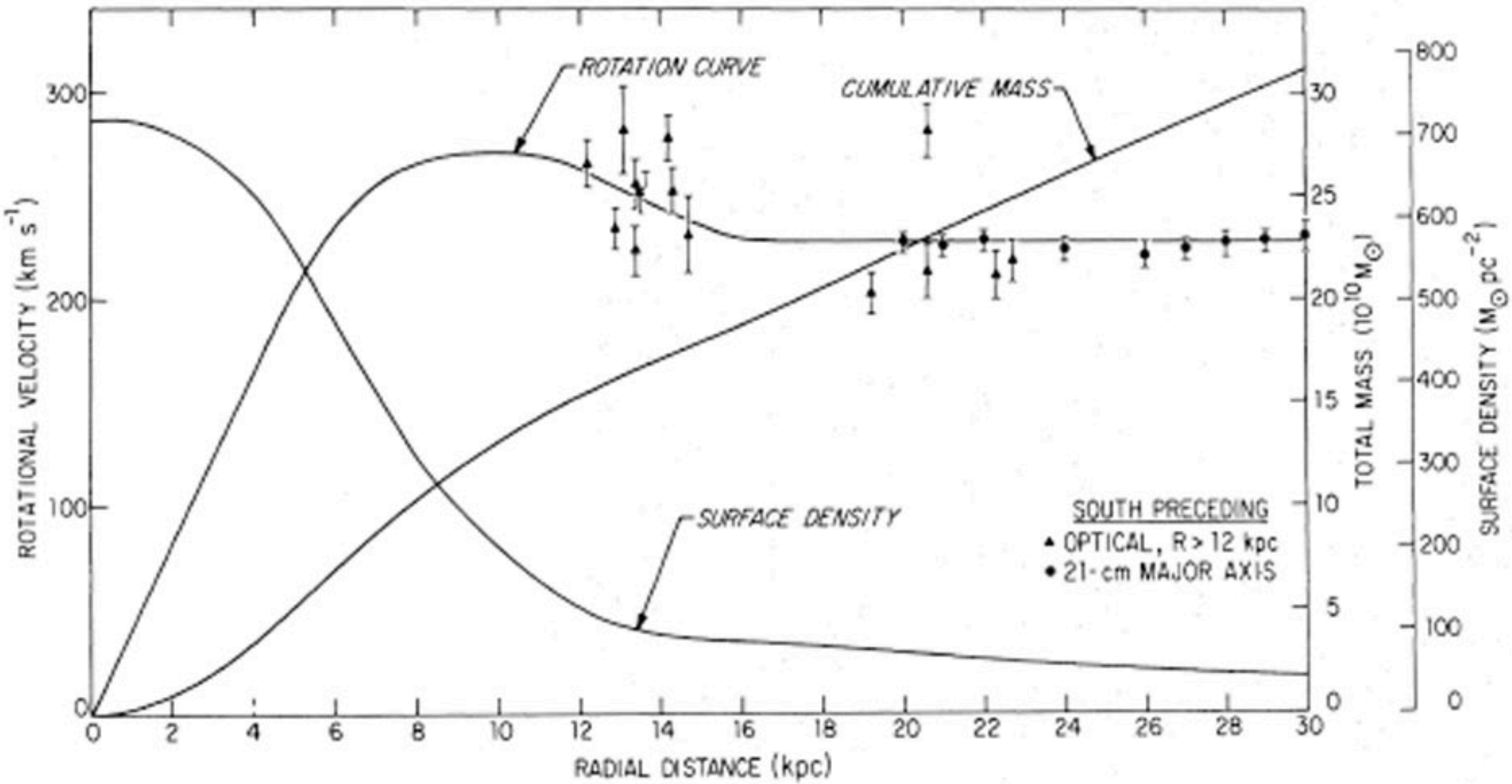
$$\approx 0.003$$

Dark Matter in Galaxies

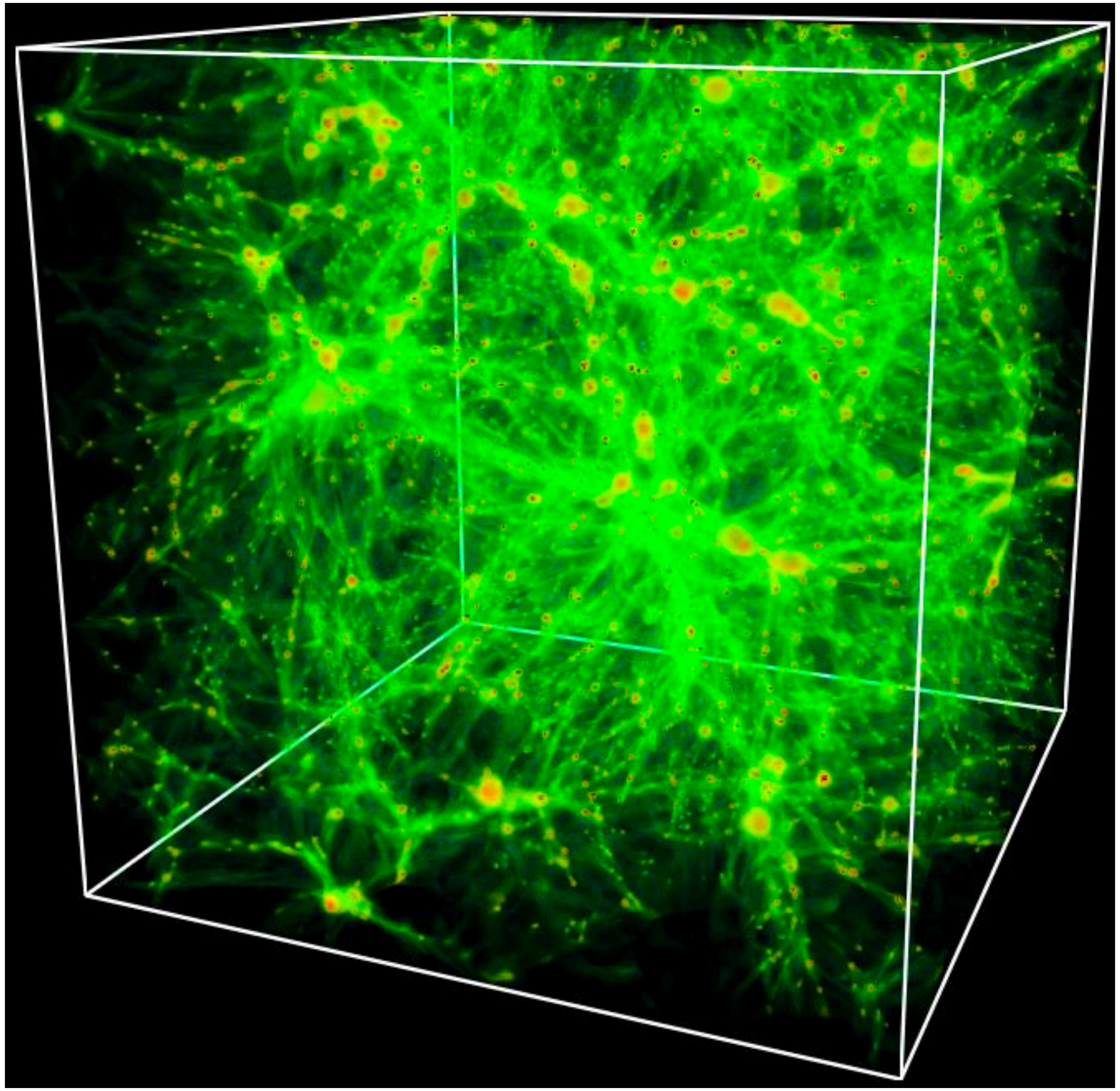


$$M(R) = \frac{v^2 R}{G} = 1.05 \times 10^{11}\ \mathrm{M}_\odot \left(\frac{v}{235\ \mathrm{km\ s^{-1}}}\right)^2 \left(\frac{R}{8.2\ \mathrm{kpc}}\right)$$

Dark Matter in Galaxies



Not all baryons are in stars, however

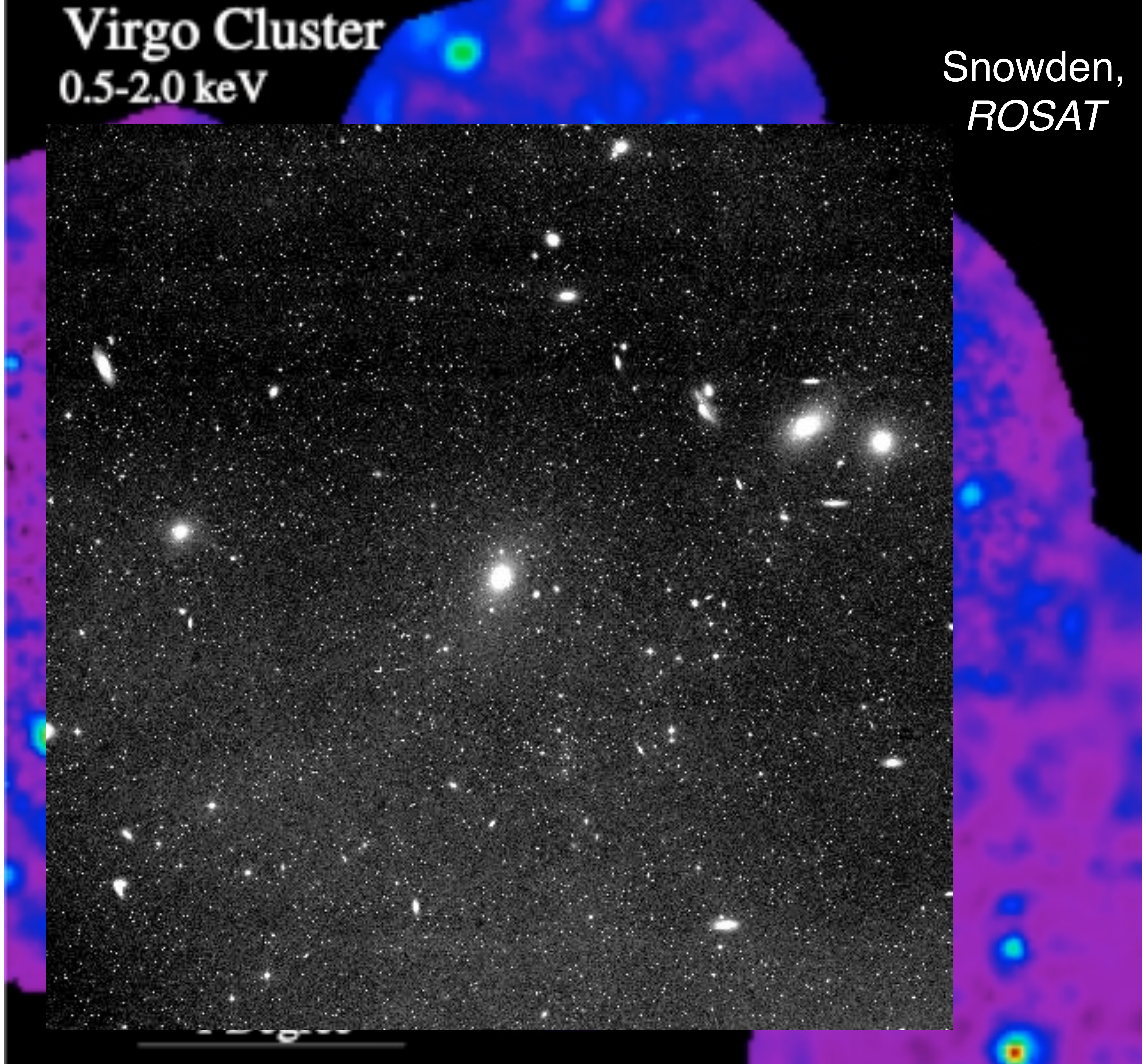


cosmological simulation showing the “warm-hot” gas in between galaxies in intergalactic space

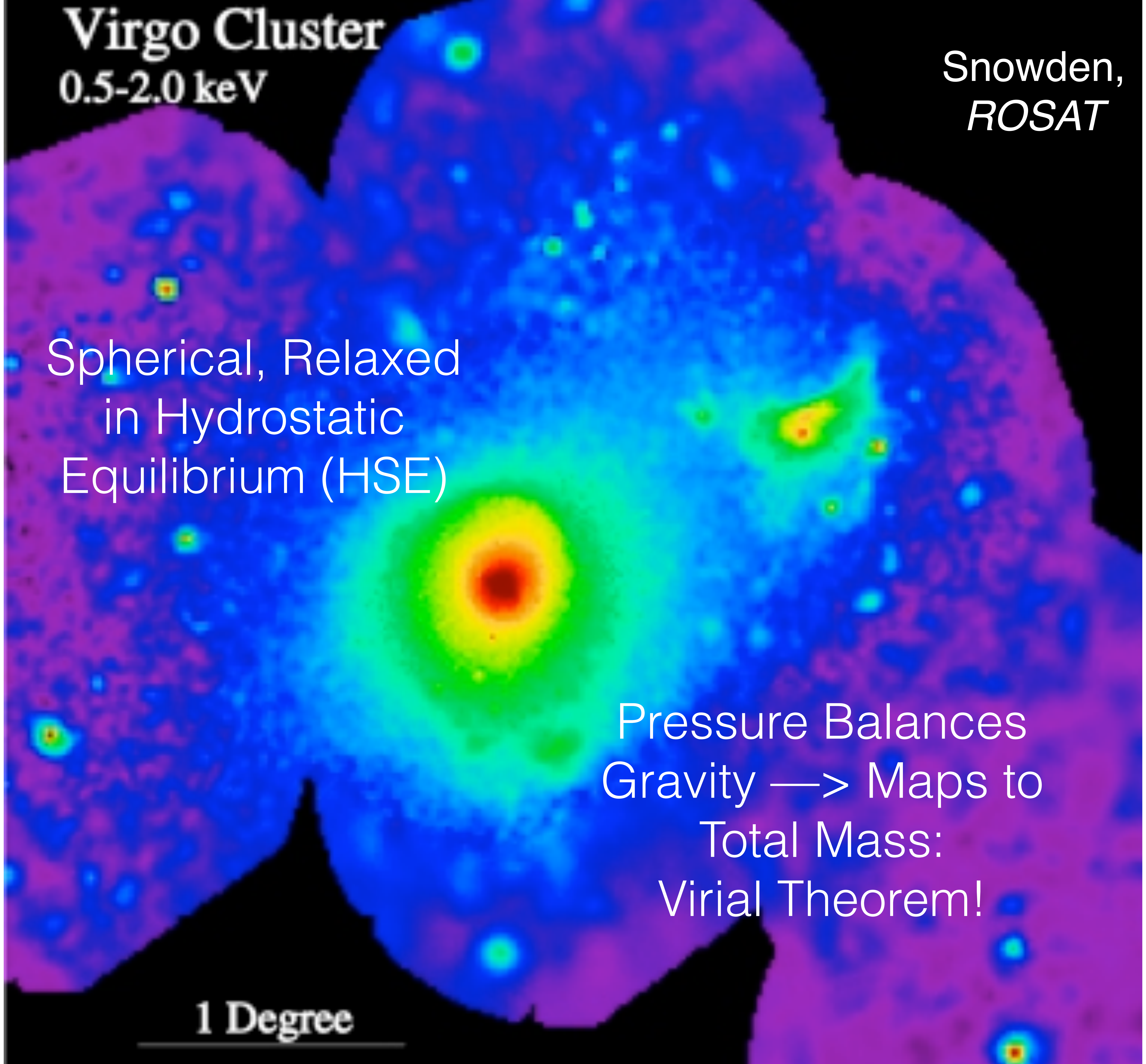
Group of Galaxies

Galaxy

Group of Galaxies



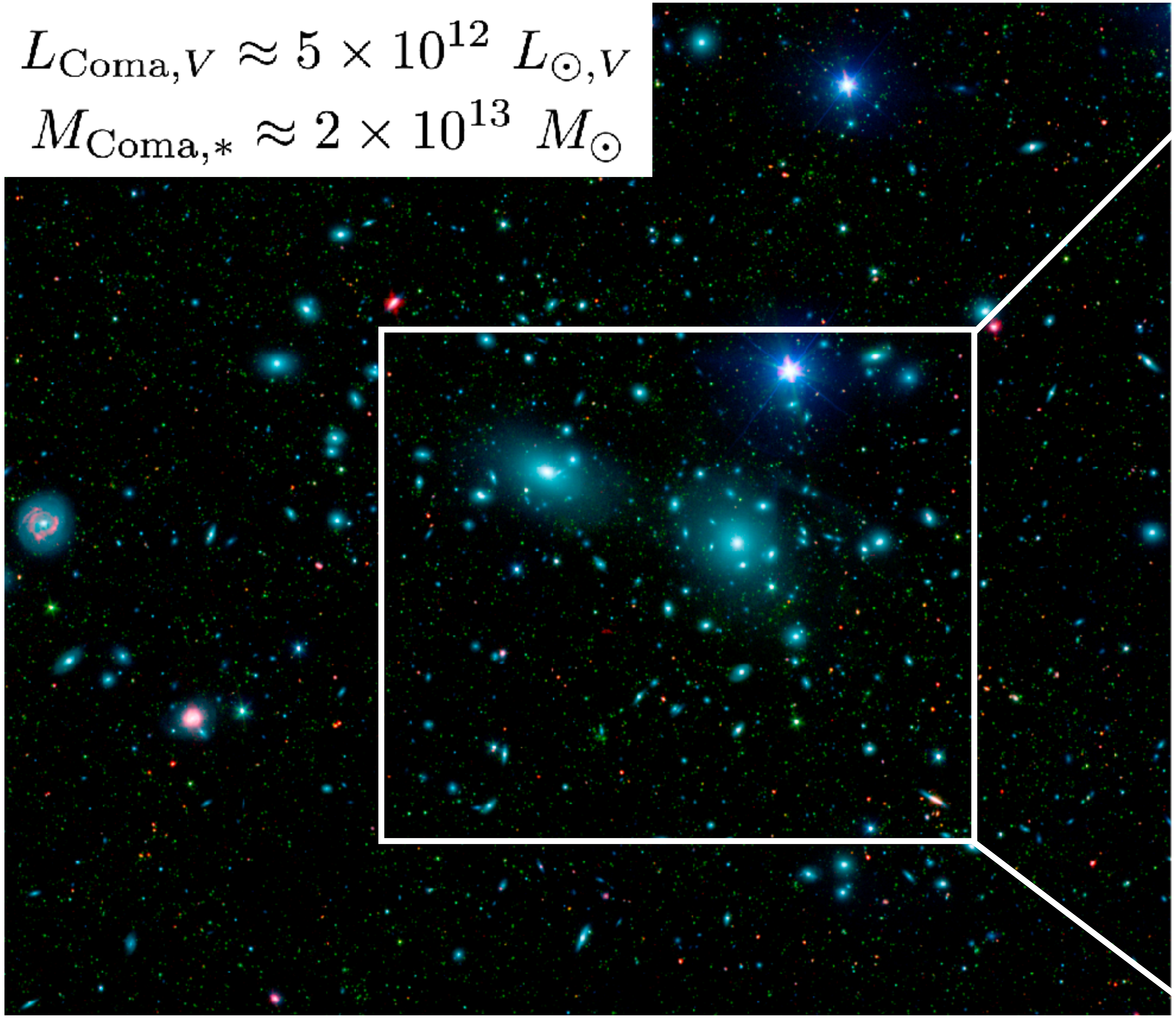
Snowden, *ROSAT*


Virgo Cluster
0.5-2.0 keV
Snowden,
ROSAT
Spherical, Relaxed
in Hydrostatic
Equilibrium (HSE)
Pressure Balances
Gravity —> Maps to
Total Mass:
Virial Theorem!
1 Degree

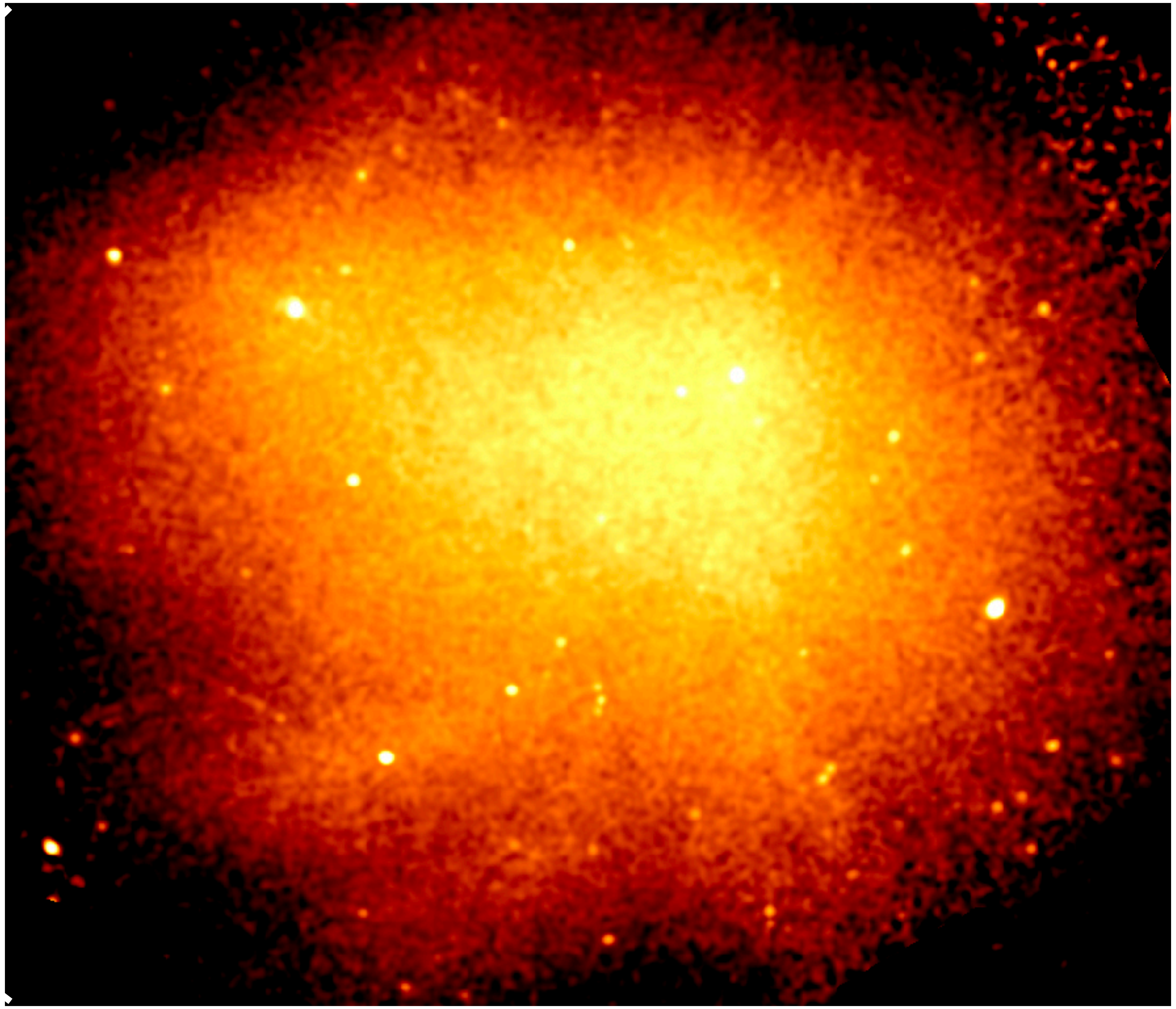
The Coma Cluster

$$L_{\mathrm{Coma},V} \approx 5 \times 10^{12}\ L_{\odot,V}$$

$$M_{\mathrm{Coma},*} \approx 2 \times 10^{13}\ M_{\odot}$$



$$M_{\mathrm{Coma,gas}} \approx 2 \times 10^{14}\ M_{\odot}$$



Baryonic Matter

$$\Omega_{*,0} \lesssim 0.005$$

$$M_{\text{gas},0} \approx 10 \times M_{*,0}$$

early universe measurements

$$\Omega_{\text{bary},0} = 0.048 \pm 0.003$$

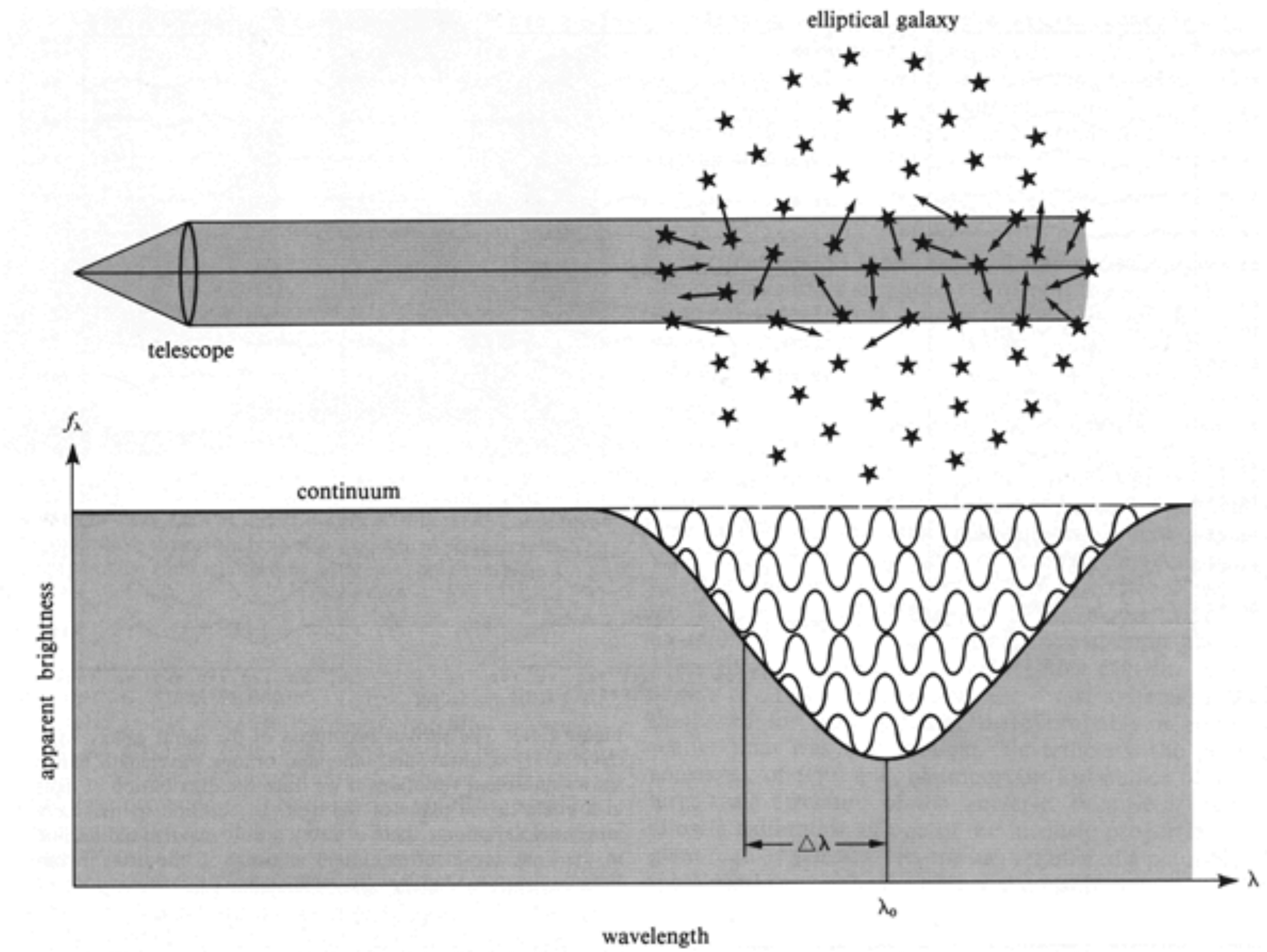
$$\Omega_{m,0} = 0.31$$

baryonic matter only 15%

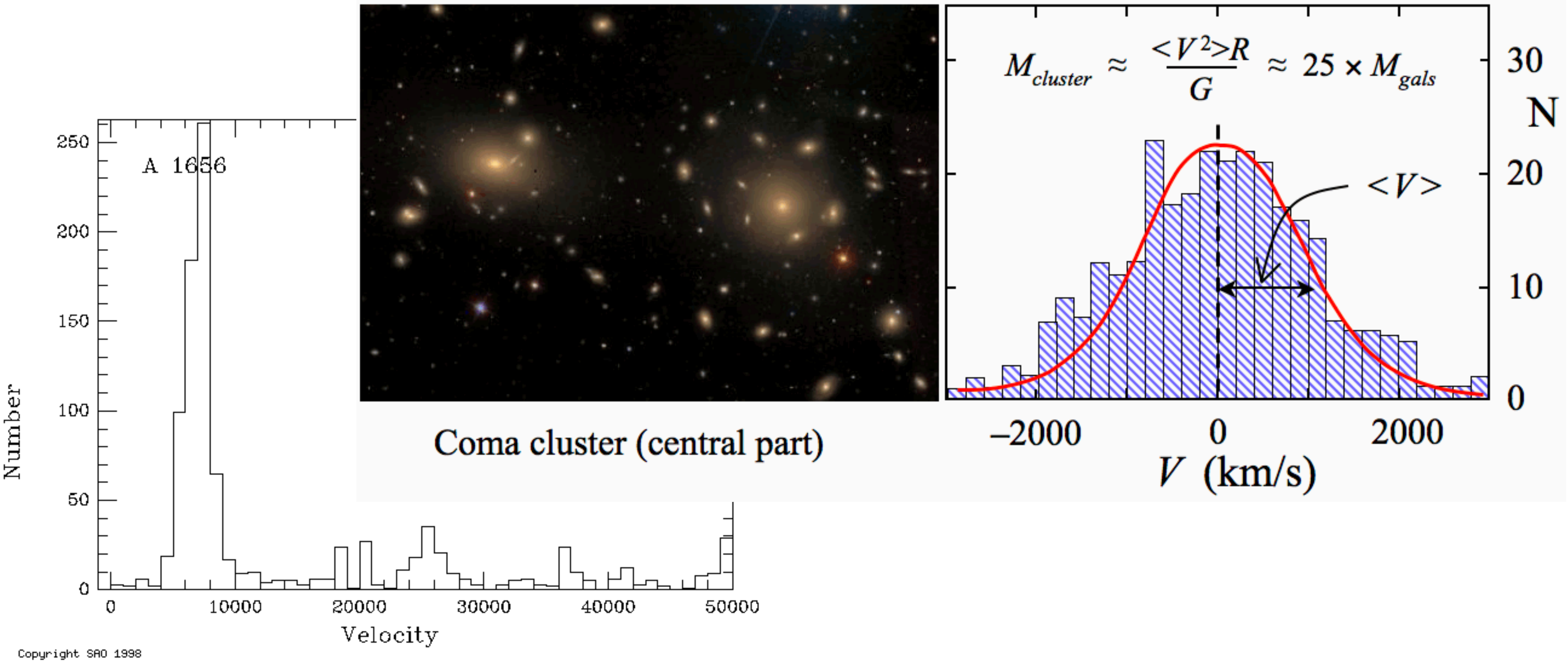
By the time of the Big Bang and thereafter, normal matter is the subdominant form of matter in the universe, with some other form of matter (non-baryonic dark matter) making up the majority of non-relativistic matter in the universe

Could be primordial black holes that were made before this time (i.e., not from stars).

Dark Matter in Clusters



Dark Matter in Clusters



Total mass from the hot gas

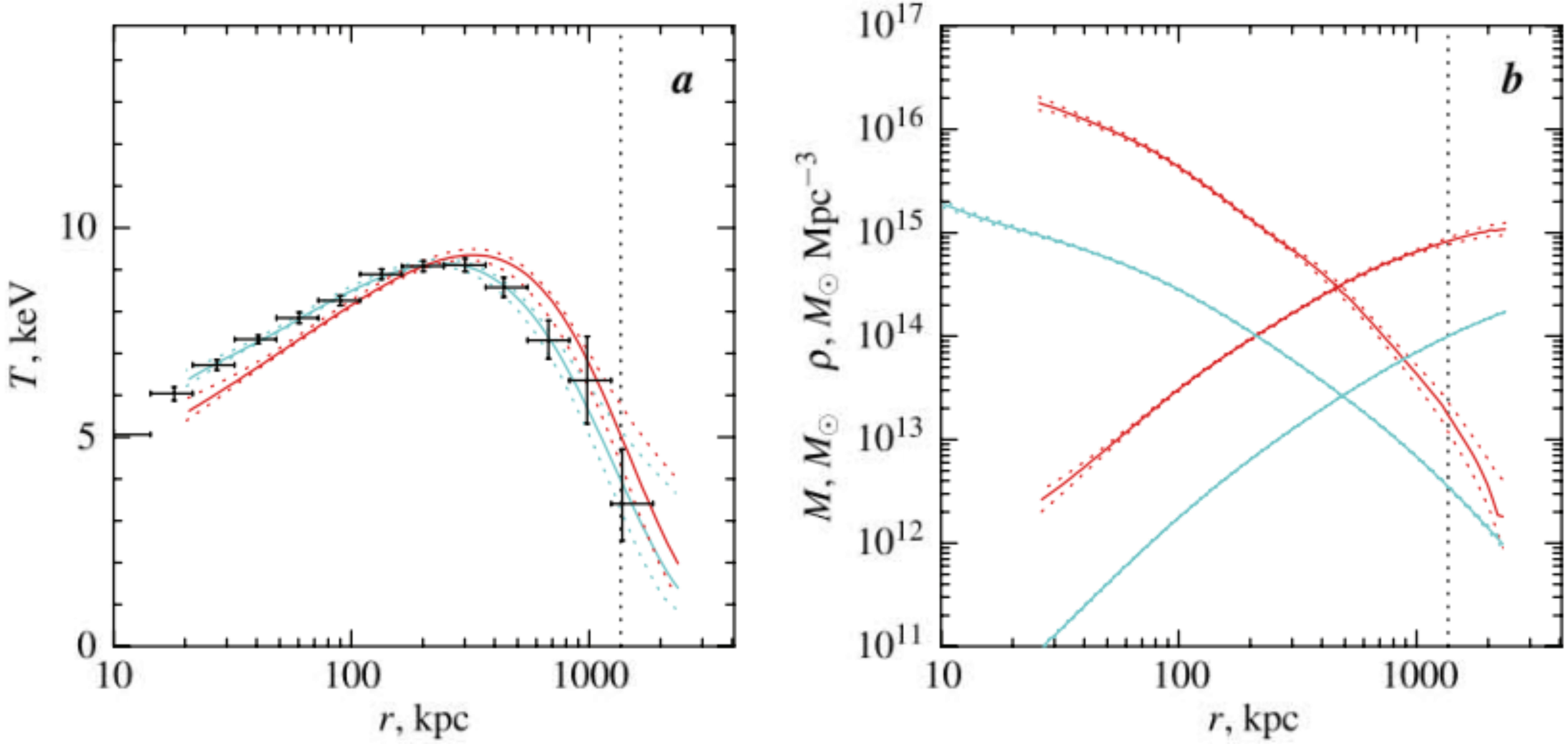
$$\frac{dP_{\rm gas}}{dr} = -\frac{GM(r)\rho_{\rm gas}(r)}{r^2}$$

$$P_{\rm gas} = \frac{\rho_{\rm gas} k T_{\rm gas}}{\mu}$$

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

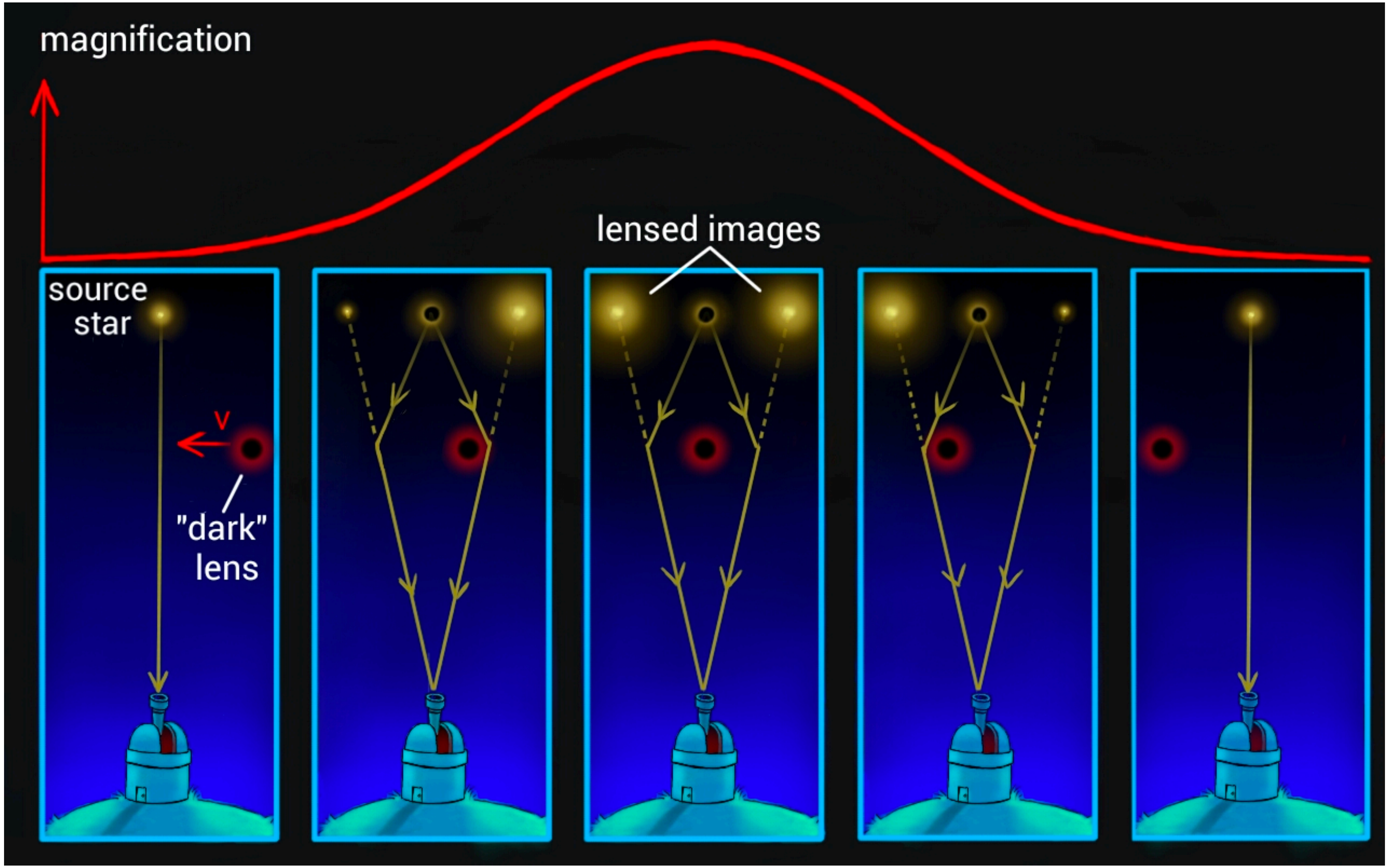
Total mass of clusters alone yield —> $\Omega_{\rm clus,0} \approx 0.2$ (lower limit on $\Omega_{m,0}$)

Total mass from the hot gas

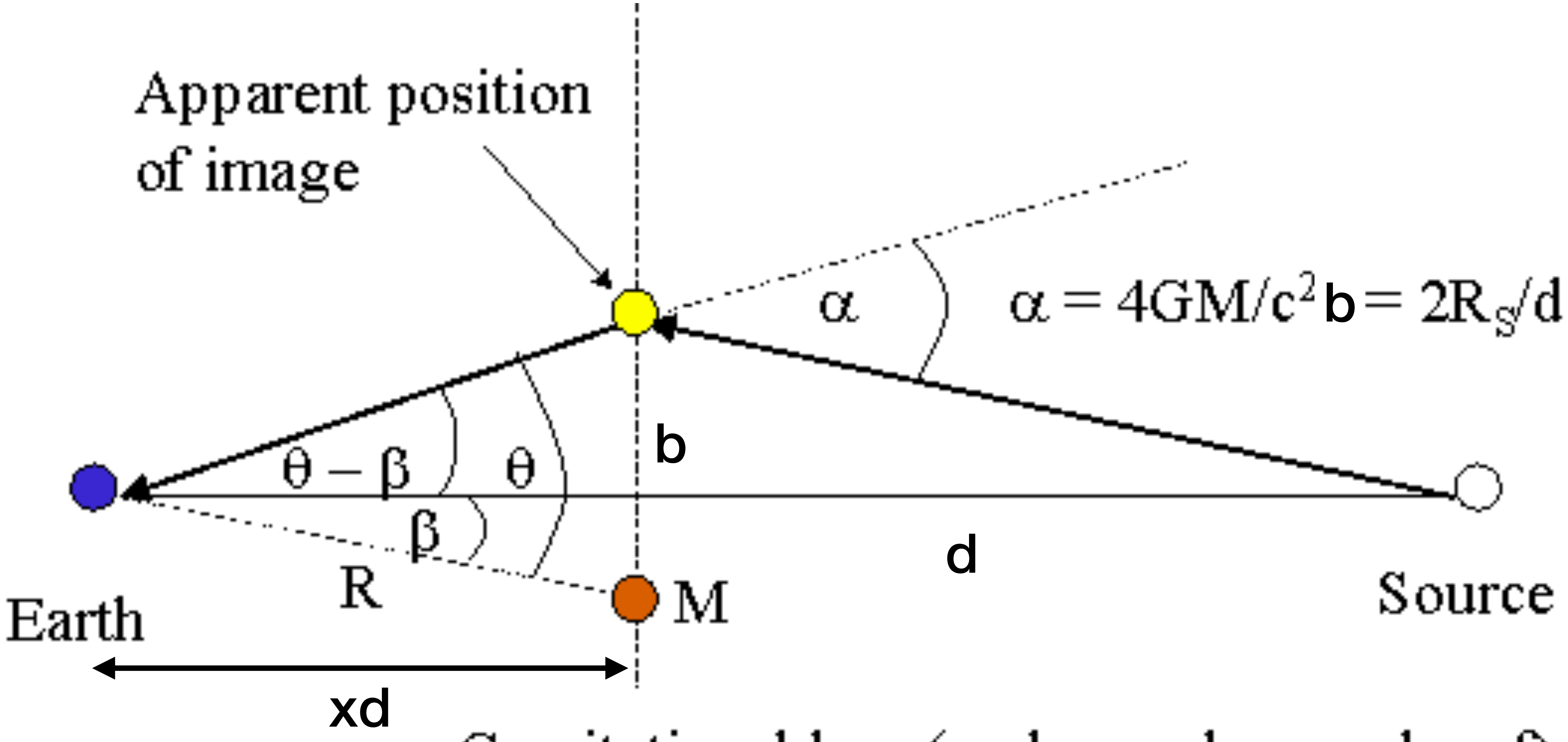


Detecting MACHOs via gravitational lensing

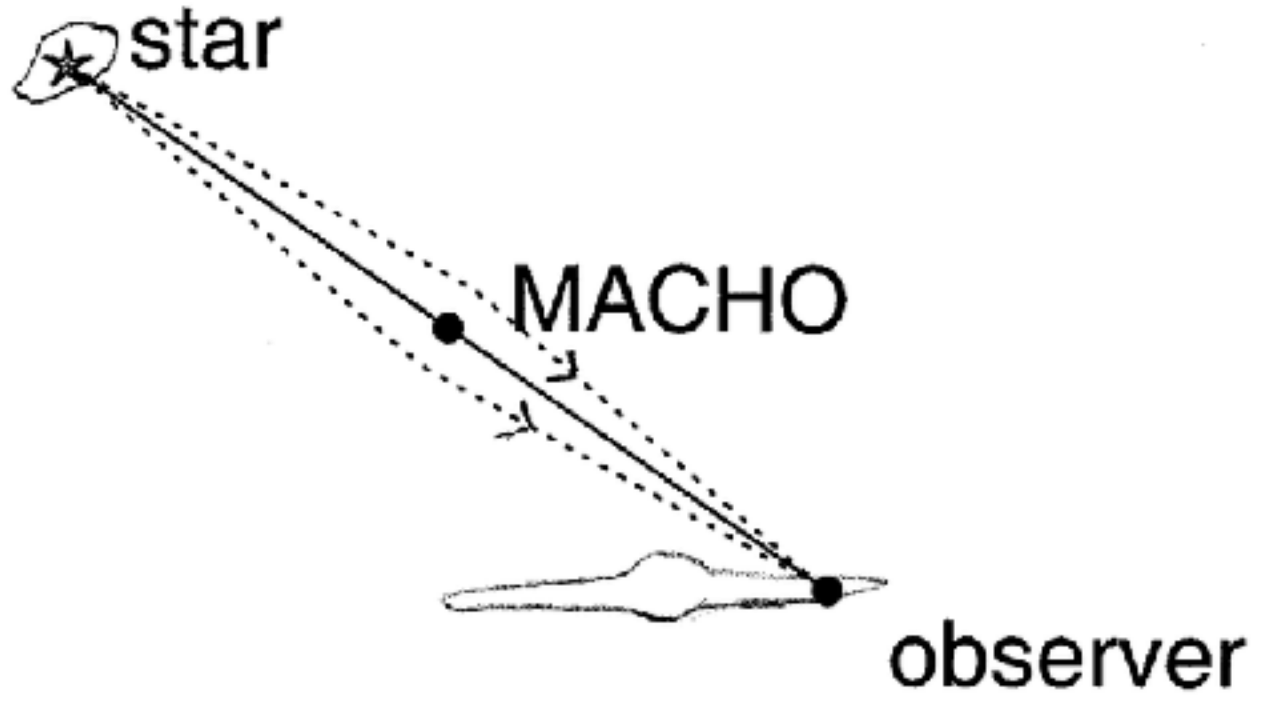
MAssive
Compact
Halo
Object



Detecting MACHOs via gravitational lensing



Gravitational lens (perhaps a brown dwarf)

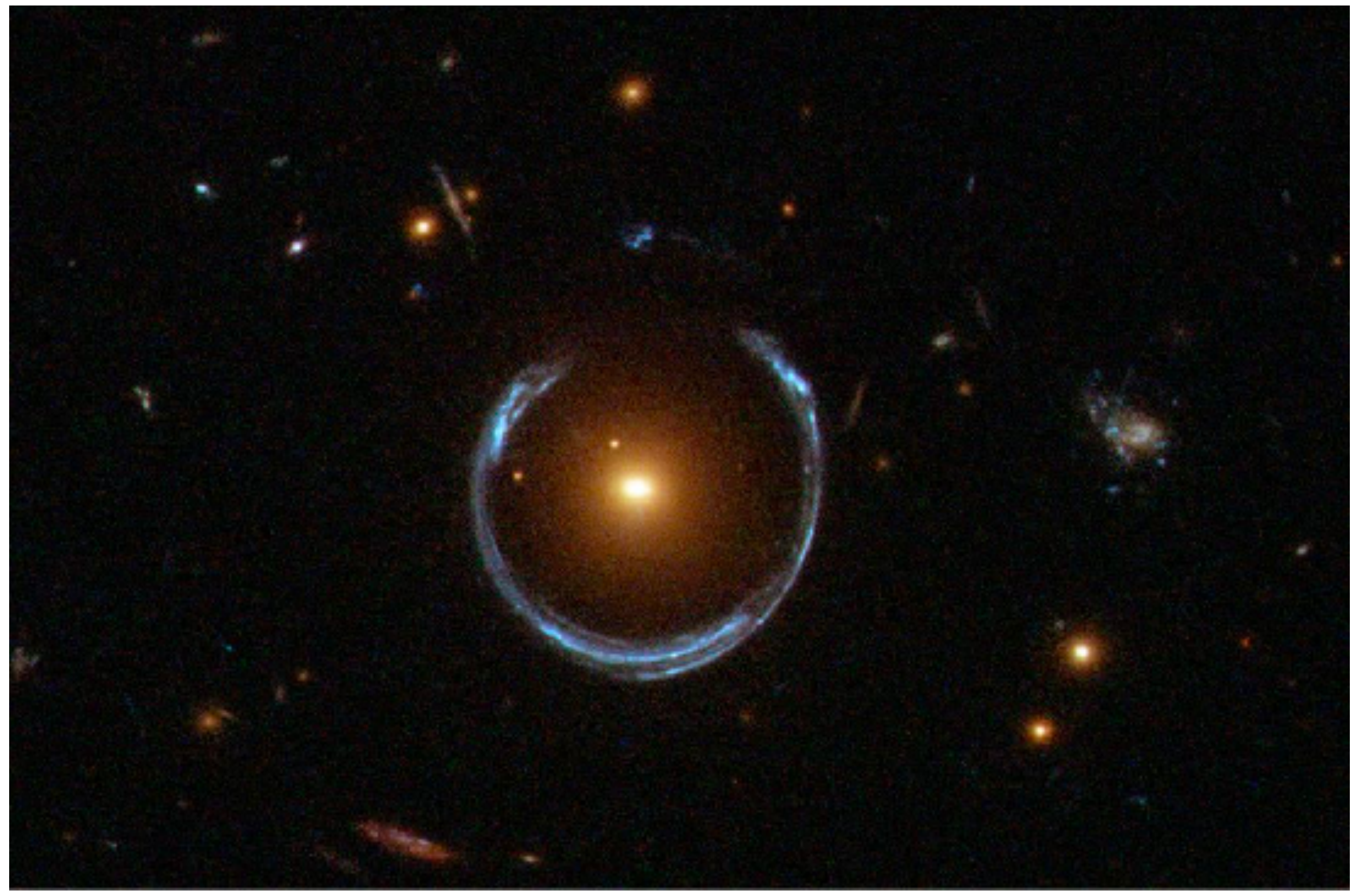


R = distance to lens (of mass M)

d = distance to source

b = distance between lens and image

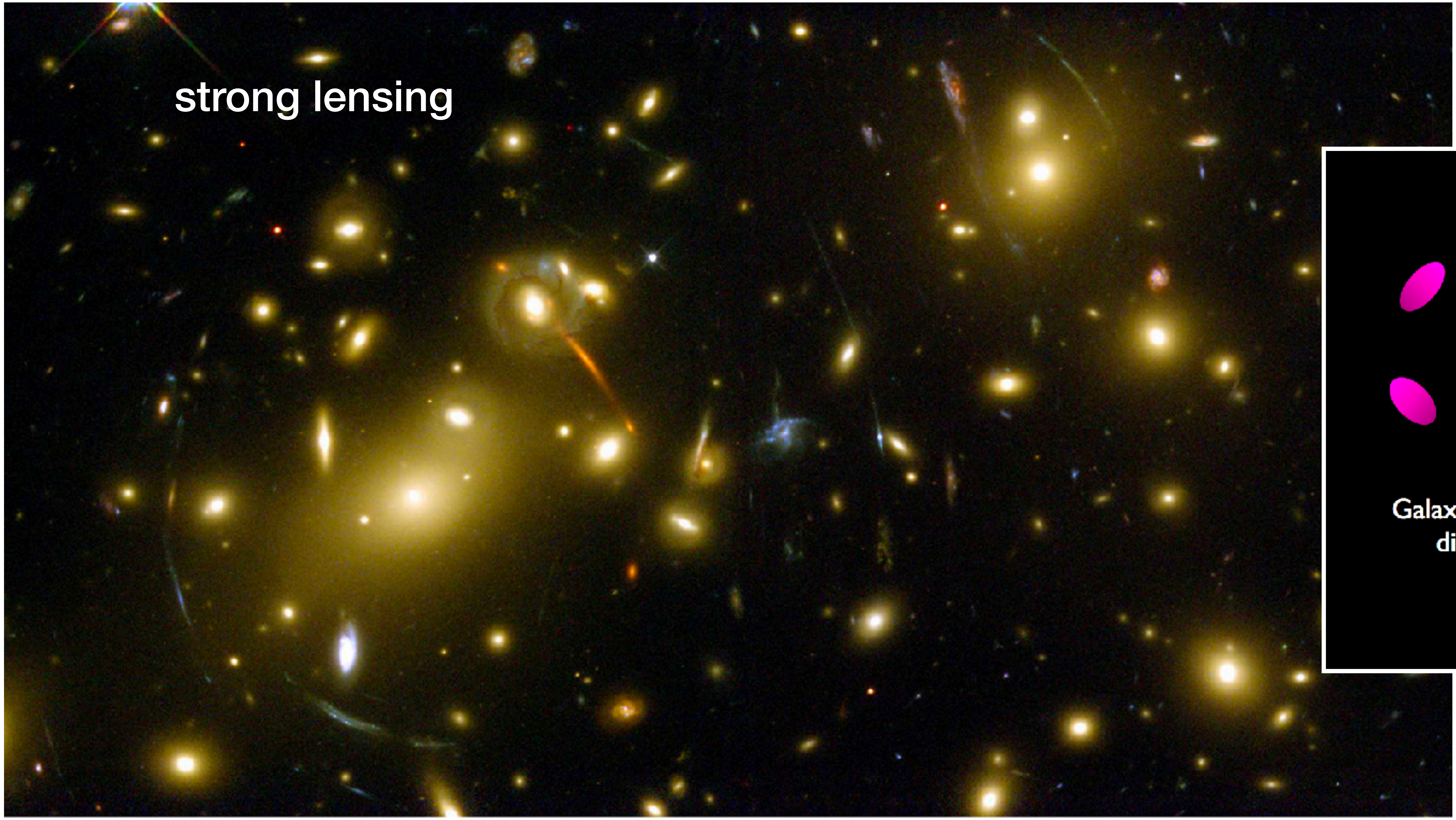
R_S = Schwarzchild radius of lens

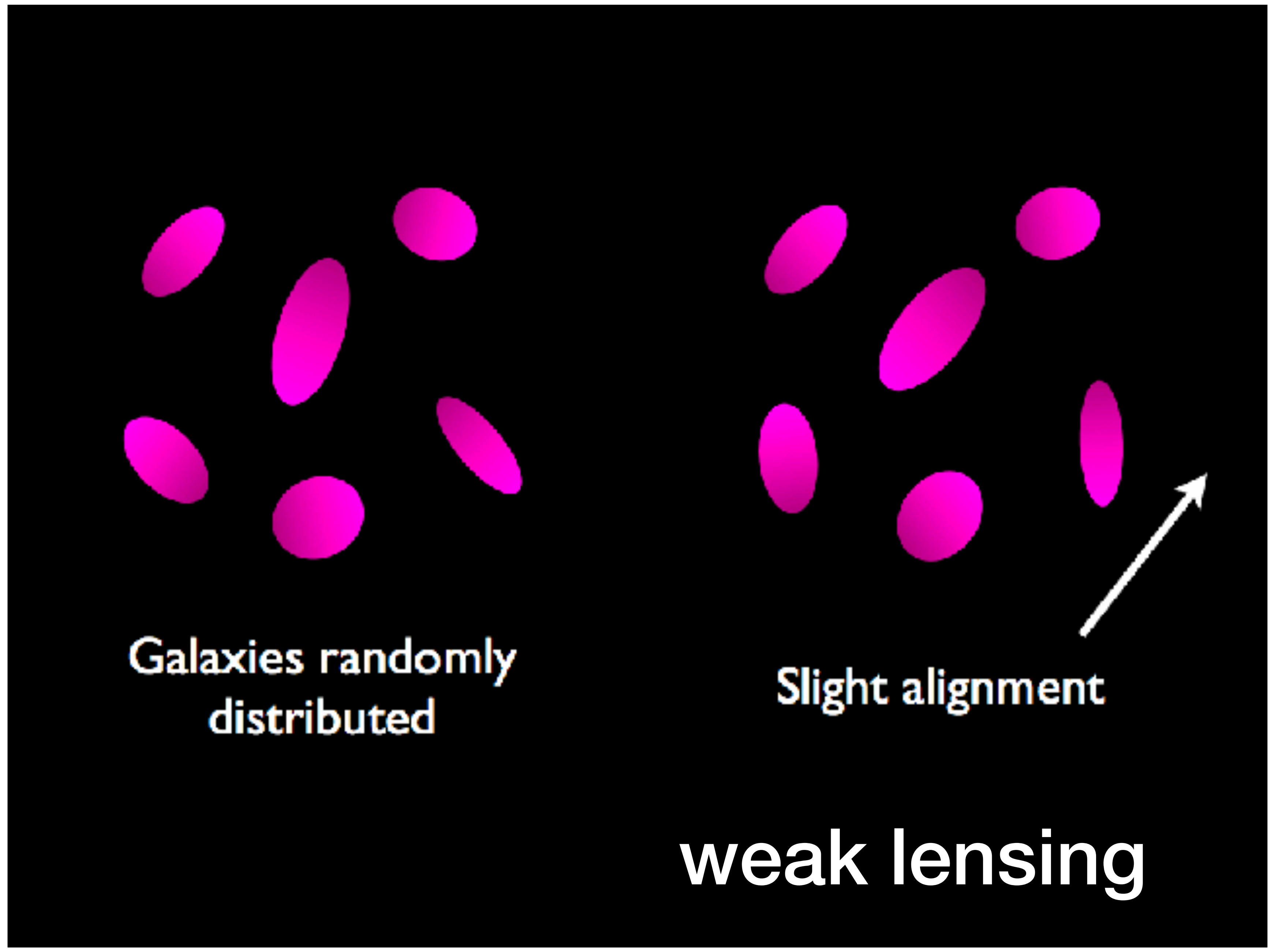


$$\theta_E = \left(\frac{4GM}{c^2 d} \frac{1-x}{x} \right)^{1/2}$$

$$\theta_E \approx 4 \times 10^{-4} \text{ arcsec } \times \left(\frac{M}{1 \text{ M}_\odot} \right)^{1/2} \left(\frac{d}{50 \text{ kpc}} \right)^{-1/2}$$

Gravitational lensing by galaxy clusters





What could (non-baryonic) dark matter be?

cosmic neutrinos?

in the Standard Model, neutrinos are massless (but we now know that’s not the case)

their number density is set by early universe calculations,
so knowing their mass yields their density parameter

constraints on their mass:

$$0.019 \text{ eV} < m_\nu c^2 < 0.1 \text{ eV}$$

lead to constraints on the density parameter:

$$0.0013 < \Omega_{\nu,0} < 0.007$$

Non-baryonic dark matter candidates

WIMPs

Weakly Interacting Massive Particles

(supersymmetric extension of the Standard Model)

Axions

(hypothetical particle that explains why quantum chromodynamics does not “break CP symmetry”)

Sterile Neutrinos

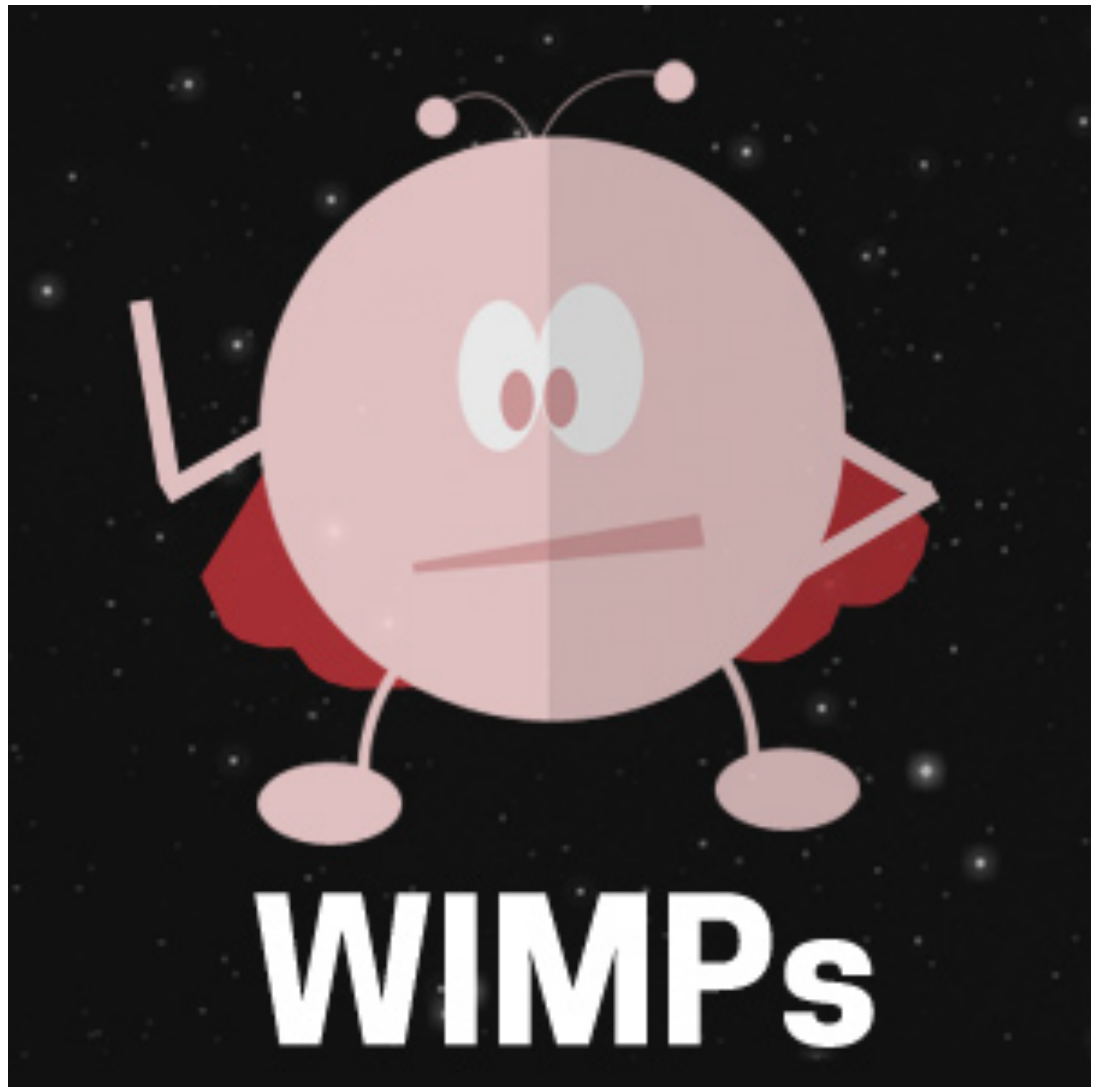
(right handed partner to known neutrinos, but doesn’t experience weak force interactions)

WIMPs

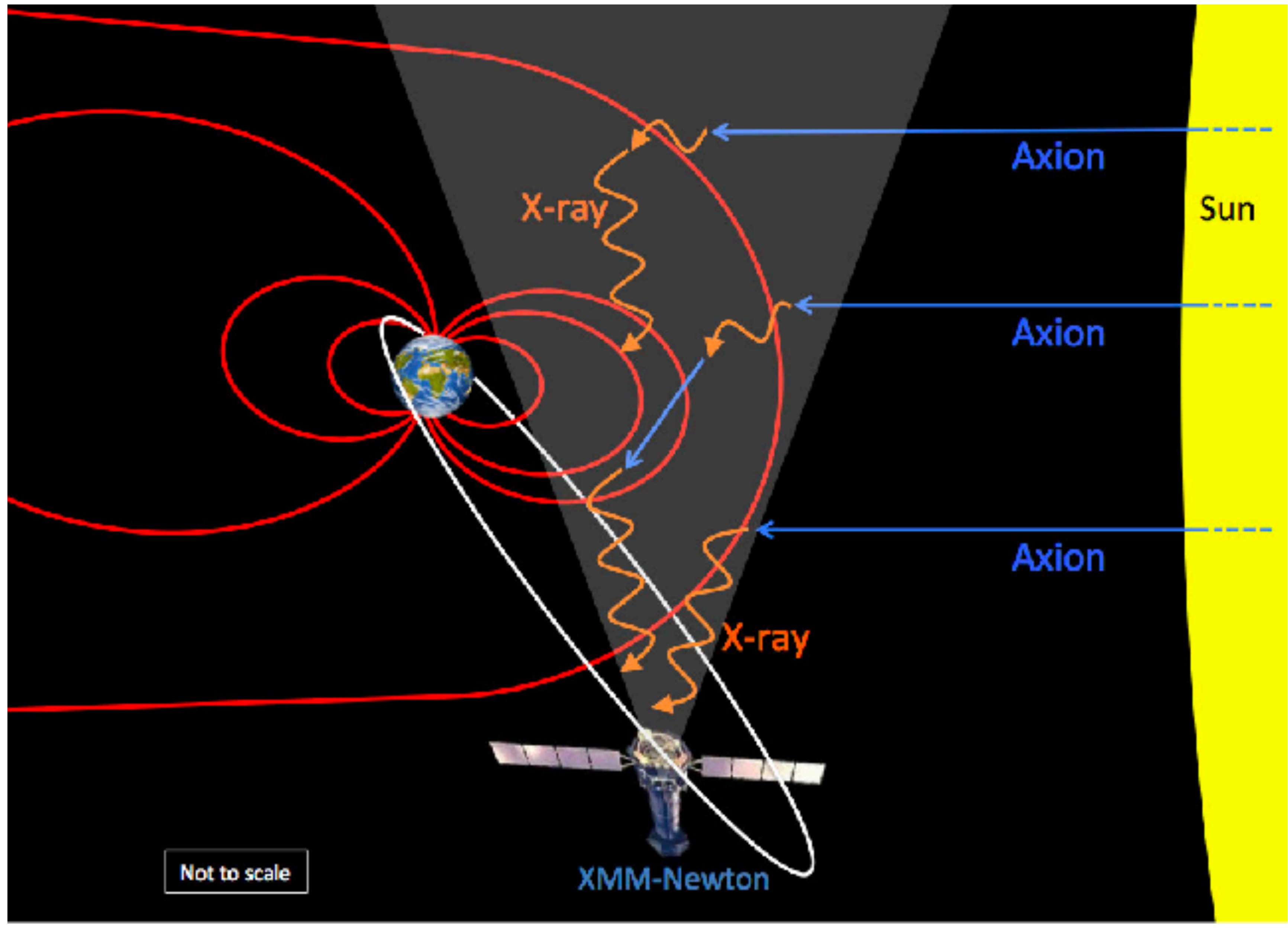
very loosely defined (any new particle that's relatively massive and interacts via gravity [and potentially other sources])

supersymmetric extensions of the SM (positing more massive versions of all known particles) naturally lead to WIMP production in the Big Bang —> called the "WIMP miracle" (direct detection searches and the LHC have failed to find WIMPs at these "miraculous" masses)

their self-annihilation (into gamma ray photons) could be detected in dark matter concentrations, such as the centers of galaxies and clusters of galaxies
(no definitive observations — without other reasonable explanations — have been made)



Axions

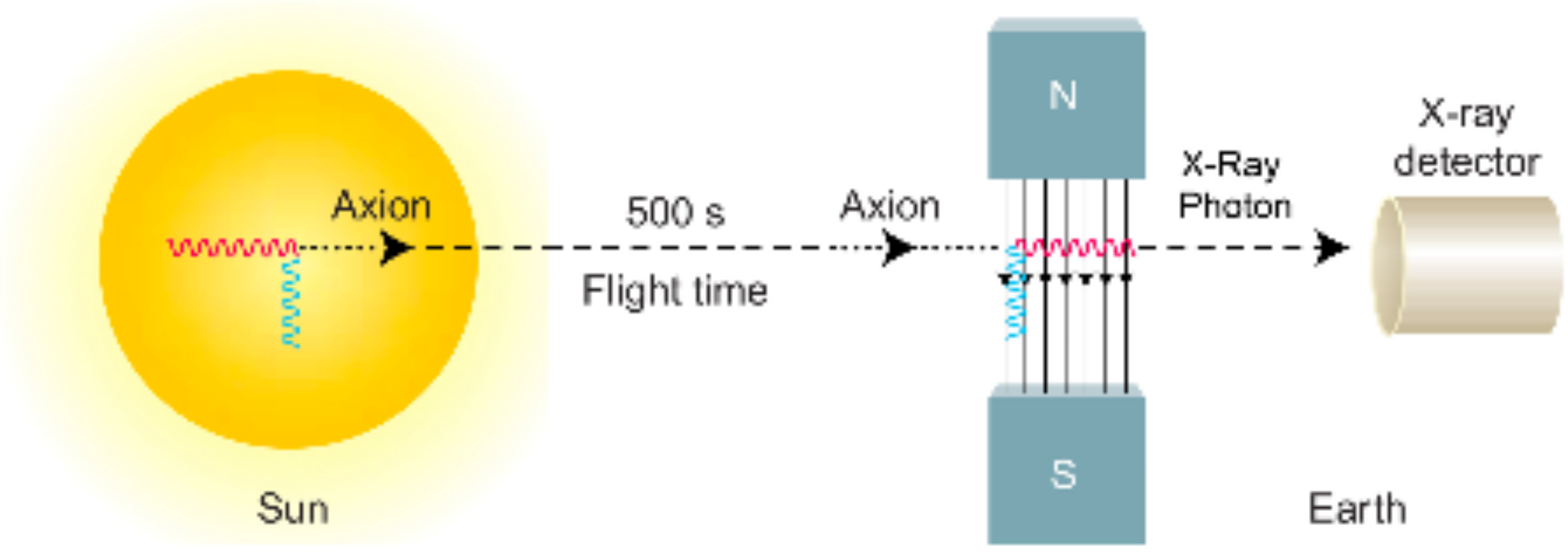


in QCD, strong interactions permit violations of charge conjugation (that if you swap the charge signs of particles and anti-particles, the laws of physics remain unchanged) and parity (no “handedness” in interactions)

—> would lead to an electric dipole moment for the neutron, which has been measured to be consistent with zero (with an upper limit making it very small)

—>—> this requires a term, which in SM theory could be any number b/t 0 and 2pi, to be very close to 0, and by “naturalness” arguments this is a “problem”

—>—>—> can be solved if there’s a new particle (the axion) that could also serve as a dark matter particle



original version of the axion has been ruled out by experiment

current dark matter axion candidates are variations on this idea, but not as well motivated by theory

can be converted into photons in a strong magnetic field and detected that way

Sterile Neutrinos

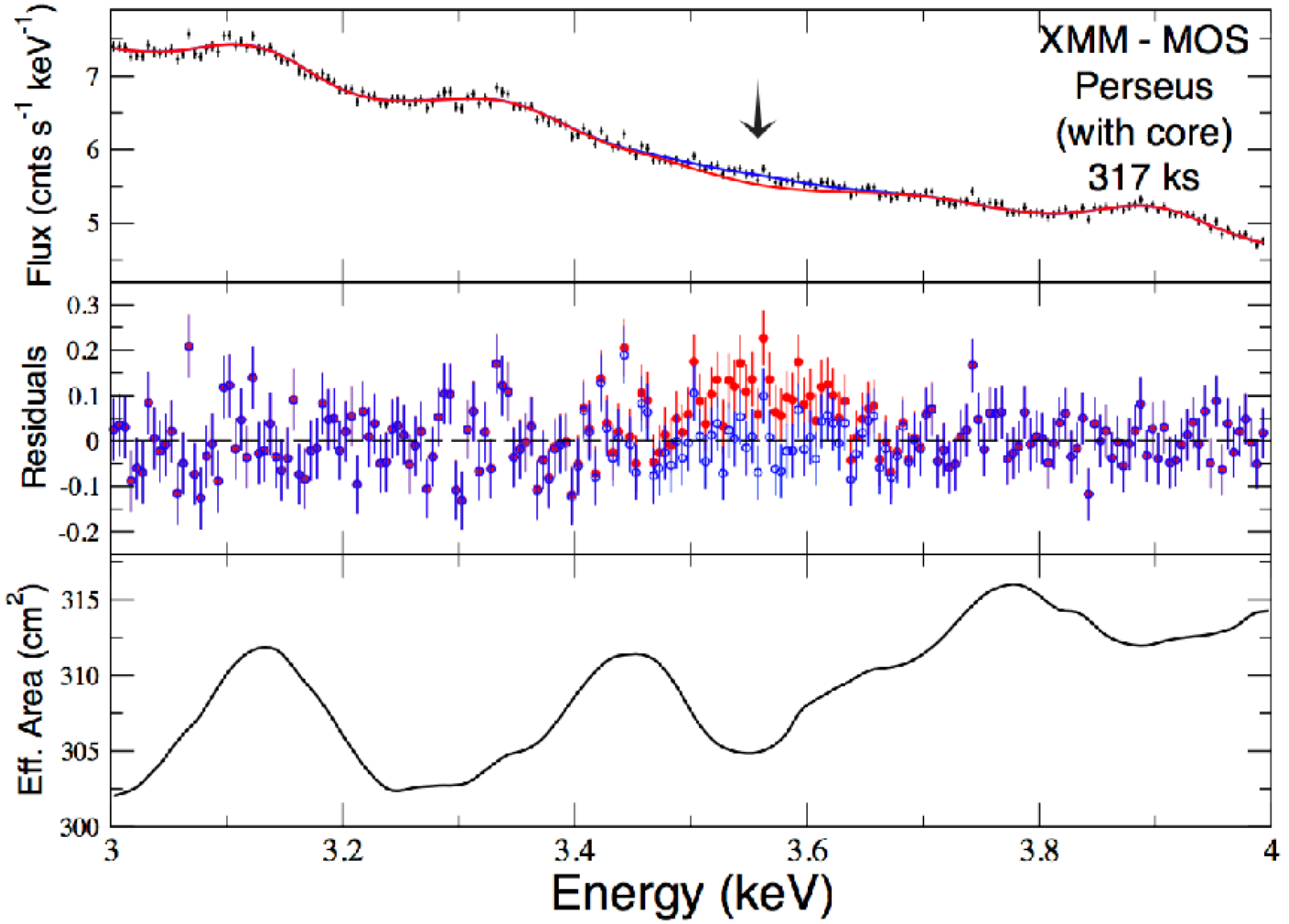
"sterile" because they don't interact via the weak force like SM neutrinos

right-handed chirality (spin vector relative to momentum)
SM particles have left and right varieties, SM neutrinos are left-handed only

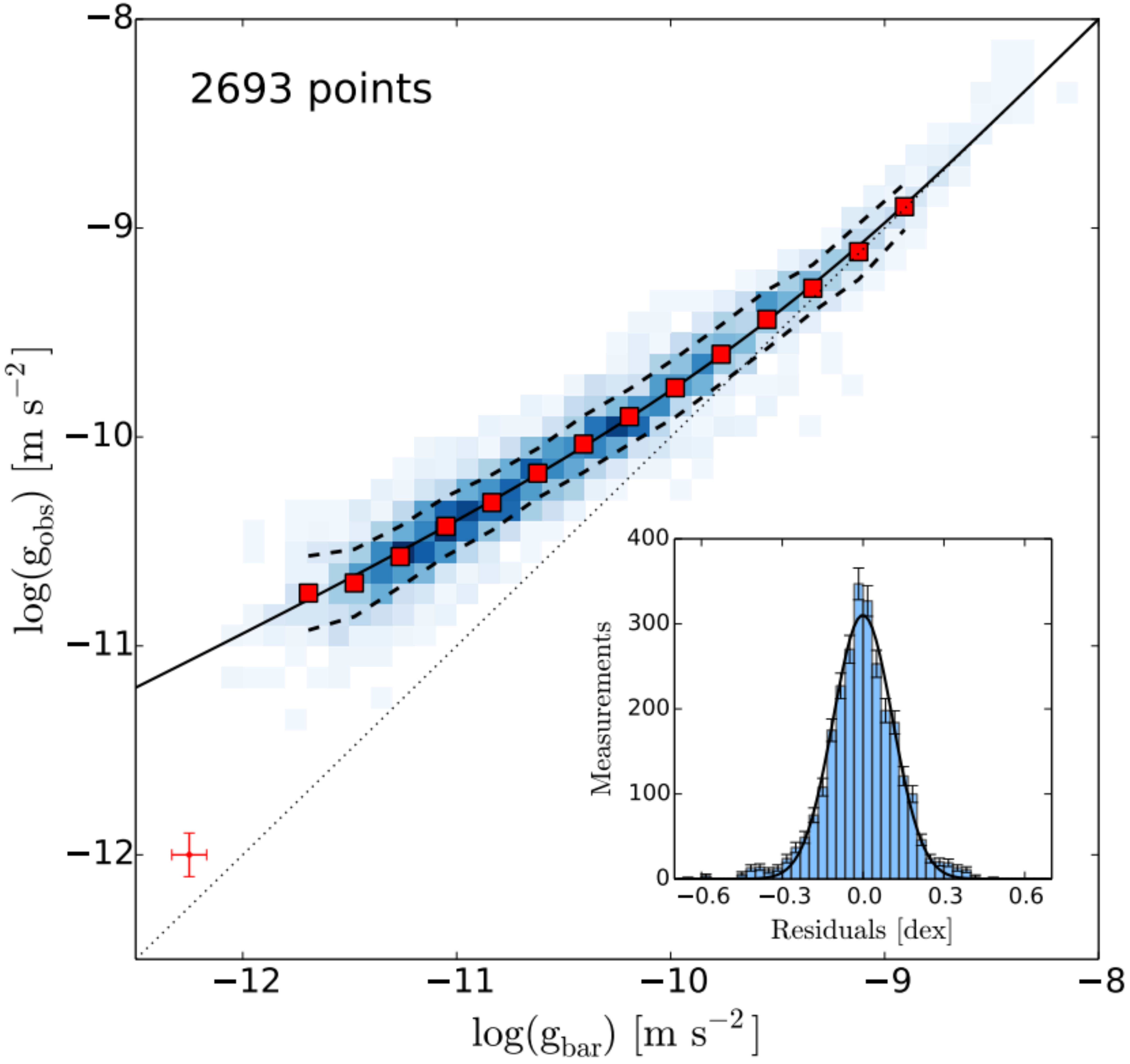
can have any mass (1 eV to 10^{15} GeV)

their decay would produce 2 photons (each with half the energy of the neutrino, which for dark matter would have to be non-relativistic so $E=mc^2$)

detection (and non-detections) at X-ray (keV) energies



Modified Gravity



Radial Acceleration Relation (RAR) - natural consequence of MOND, not DM

Newtonian Gravity

$$\Phi = -\frac{MG}{R}$$

$$F = \frac{MG}{R^2}$$

Modified Newtonian Gravity

$$\Phi = \sqrt{MGa_0}\ln\left(\frac{R}{MG}\right)$$

$$F = \frac{\sqrt{MGa_0}}{R}$$

$$a_0 \approx \sqrt{\Lambda/3}$$

Emergent Gravity

Also consistent with Superfluid Dark Matter, which has similar behavior