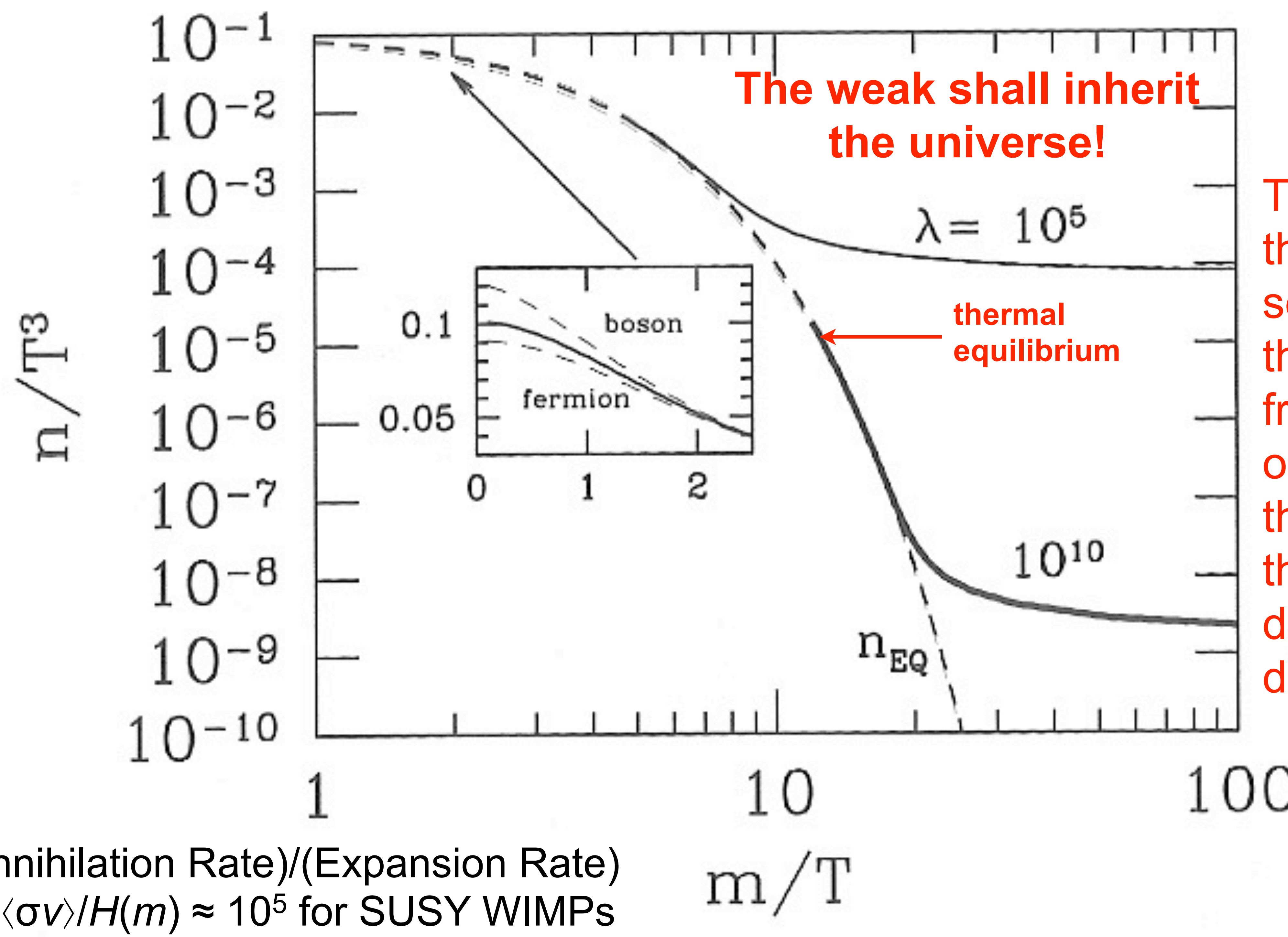
Physics 129 LECTURE 13 February 20, 2014

Dark Matter

- WIMP Abundance from Annihilation: The Weak Shall Dominate the Universe
- History of Dark Matter Observations
- History of Dark Matter Theories
- The Key to Cold Dark Matter
- The Dark Matter Rap
- How Galaxies Form in a ΛCDM Universe
- Searching for WIMPs: Direct Detection
- Searching for WIMPs: Indirect Detection
- WIMP Production at the LHC
- Warm Dark Matter - Sterile Neutrinos: Needed for Neutron Star Kicks? Seen?

WIMP Dark Matter Annihilation



The weaker the cross section, the earlier freezeout occurs, and the larger the resulting dark matter density.

$\lambda \equiv$ (Annihilation Rate)/(Expansion Rate)
$= m^3\langle\sigma v\rangle/H(m) \approx 10^5$ for SUSY WIMPs

Figure 3.5. Abundance of heavy stable particle as the temperature drops beneath its mass. Dashed line is equilibrium abundance. Two different solid curves show heavy particle abundance for two different values of λ, the ratio of the annihilation rate to the Hubble rate. Inset shows that the difference between quantum statistics and Boltzmann statistics is important only at temperatures larger than the mass.

Dodelson, *Modern Cosmology*, p. 76

WIMP Dark Matter Annihilation

The abundance today of dark matter particles X of the WIMP variety is determined by their survival of annihilation in the early universe. Supersymmetric neutralinos can annihilate with each other (and sometimes with other particles: "co-annihilation"). Dark matter annihilation follows the same pattern as the previous discussions: initially the abundance of dark matter particles X is given by the equilibrium Boltzmann exponential exp($-m_X/T$), but as they start to disappear they have trouble finding each other and eventually their number density freezes out. The freezeout process can be followed using the Boltzmann equation, as discussed in Kolb and Turner, Dodelson, Mukhanov, and other textbooks. For a detailed discussion of Susy WIMPs, see the review article by Jungman, Kamionkowski, and Griest (1996). The result is that the abundance today of WIMPs X is given in most cases by (Dodelson's Eqs. 3.59-60; see also Perkins Eq. 7.18)

$$\Omega_X = \left[\frac{4\pi^3 G g_*(m)}{45}\right]^{1/2} \frac{x_f T_0^3}{30\langle\sigma v\rangle\rho_{cr}} = 0.3h^{-2}\left(\frac{x_f}{10}\right)\left(\frac{g_*(m)}{100}\right)^{1/2} \frac{10^{-39}\text{cm}^2}{\langle\sigma v\rangle}.$$

Here $x_f \approx 10$ is the ratio of m_X to the freezeout temperature T_f, and $g_*(m_X) \approx 100$ is the density of states factor in the expression for the energy density of the universe when the temperature equals m_X

$$\rho = \frac{\pi^2}{30}T^4\left[\sum_{i=\text{bosons}} g_i + \frac{7}{8}\sum_{i=\text{fermions}} g_i\right] \equiv g_*\frac{\pi^2}{30}T^4.$$

The sum is over relativistic species i (see the graph of $g_*(T)$ on the next slide). Note that more X's survive, the weaker the cross section σ. For Susy WIMPs the natural values are $\sigma \sim 10^{-39}$ cm^2, so $\Omega_X \sim 1$ naturally. This is known as the WIMP miracle!

A Brief History of Dark Matter

1930s - Discovery that cluster $\sigma_V \sim 1000$ km/s

1970s - Discovery of flat galaxy rotation curves

1980s - Most astronomers are convinced that dark matter exists around galaxies and clusters

1980-84 - short life of Hot Dark Matter theory

1983-84 - Cold Dark Matter (CDM) theory proposed

1992 - COBE discovers CMB fluctuations as predicted by CDM; CHDM and ΛCDM are favored CDM variants

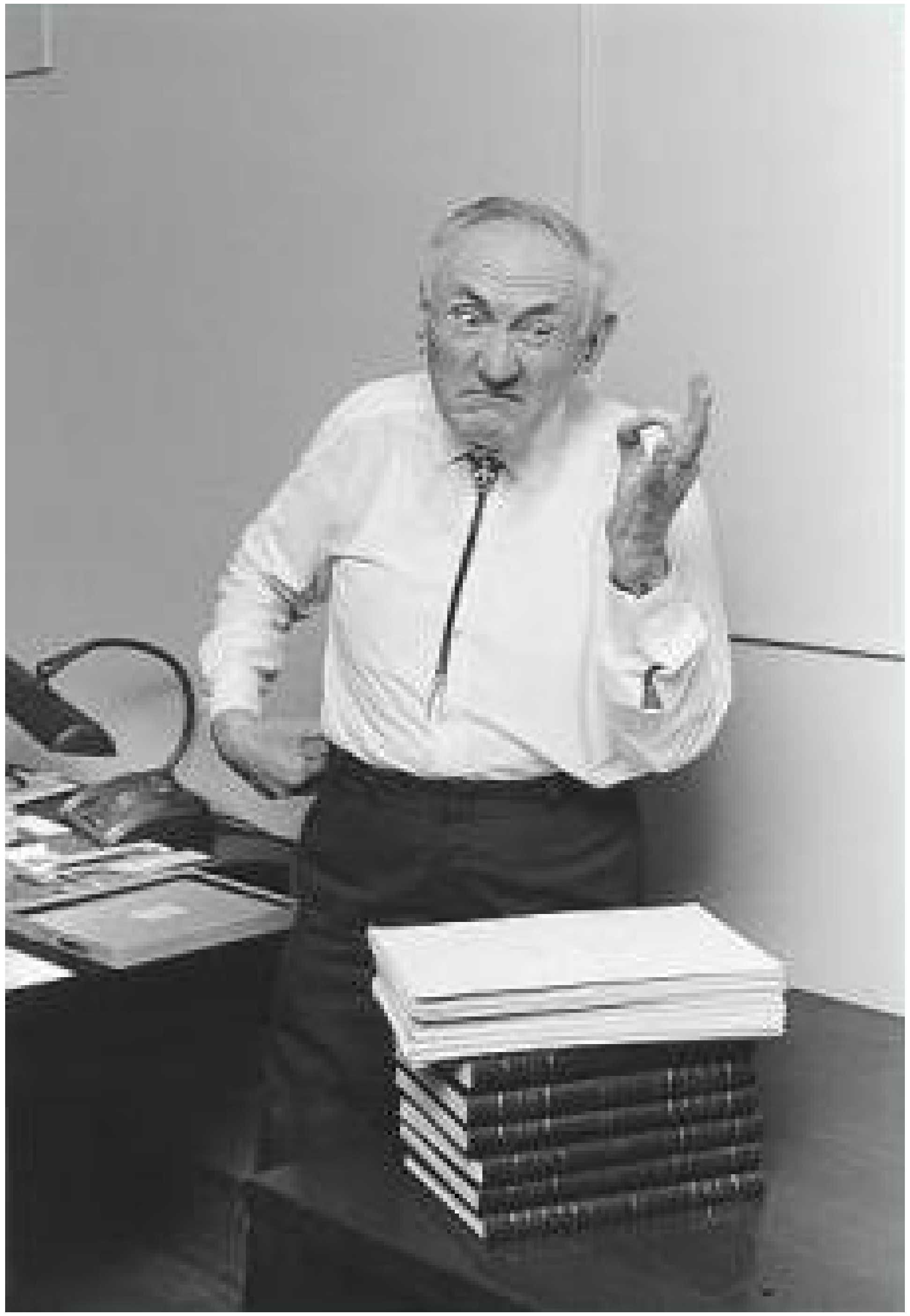
1998 - SN Ia and other evidence of Dark Energy

2000 - ΛCDM is the Standard Cosmological Model

2003-12 - WMAP, Planck, and LSS confirm ΛCDM predictions

~2014 - Discovery of dark matter particles??

1937 ApJ 86, 217



Fritz Zwicky

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

$$\overline{M} > 9 \times 10^{43} \text{ gr} = 4.5 \times 10^{10} M_{\odot} . \tag{36}$$

Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathcal{M}$, the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^7 suns. According to (36), the conversion factor γ from luminosity to mass for nebulae in the Coma cluster would be of the order

$$\text{Mass/Light} = \quad \gamma = 500 \, , \tag{37}$$

as compared with about $\gamma' = 3$ for the local Kapteyn stellar system.

This article also proposed measuring the masses of galaxies by gravitational lensing.

INTERGALACTIC MATTER AND THE GALAXY

F. D. KAHN* AND L. WOLTJER†

1959 ApJ 130, 705

Princeton University Observatory and the Institute for Advanced Study, Princeton, New Jersey

The fact that the motion is one of approach is significant. For if the Local Group is a physical unit, the Galaxy and M31 are not likely to have been formed very far from each other, certainly not at a much greater distance than their present separation. This indicates that they must have performed the larger part of at least one orbit around their center of gravity during a time of about 10^{10} years. Consequently, their orbital period must be less than 15 billion years. From this we obtain the total mass of the system as follows. According to Kepler's third law, we have

$$P^2 = \frac{4\pi^2}{GM^*} a^3 \leq 2 \times 10^{35} \sec^2 , \tag{1}$$

where M^* represents the effective mass at the center of gravity. To obtain a minimum estimate for M^*, we assume that the system has no angular momentum. Then conservation of energy gives, for our Galaxy,

$$\frac{GM^*}{2a} = \frac{GM^*}{D} - E_k , \tag{2}$$

where D denotes the present distance of the Galaxy to the center of gravity (480 kpc) and E_t is its present kinetic energy per unit mass. From these equations we obtain

$$\underline{M^* \geq 1.8 \times 10^{12} m_\odot} , \tag{3}$$

which is six times larger than the reduced mass of M31 and the Galaxy.

The discrepancy seems to be well outside the observational errors.

See Rubin's "Reference Frame" in Dec 2006 Physics Today and her article, "A Brief History of Dark Matter," in T*he dark universe: matter, energy and gravity*, Proc. STScI Symposium 2001, ed. Mario Livio.

1970 ApJ 159, 379

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

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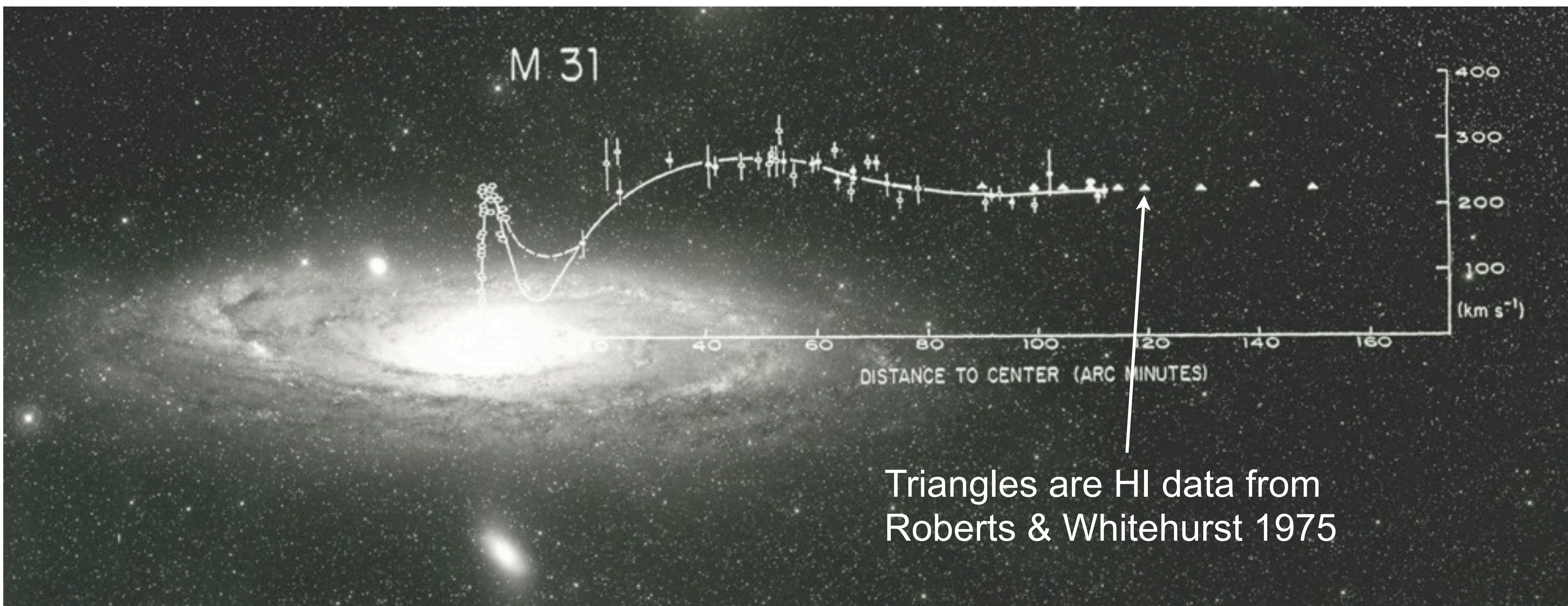
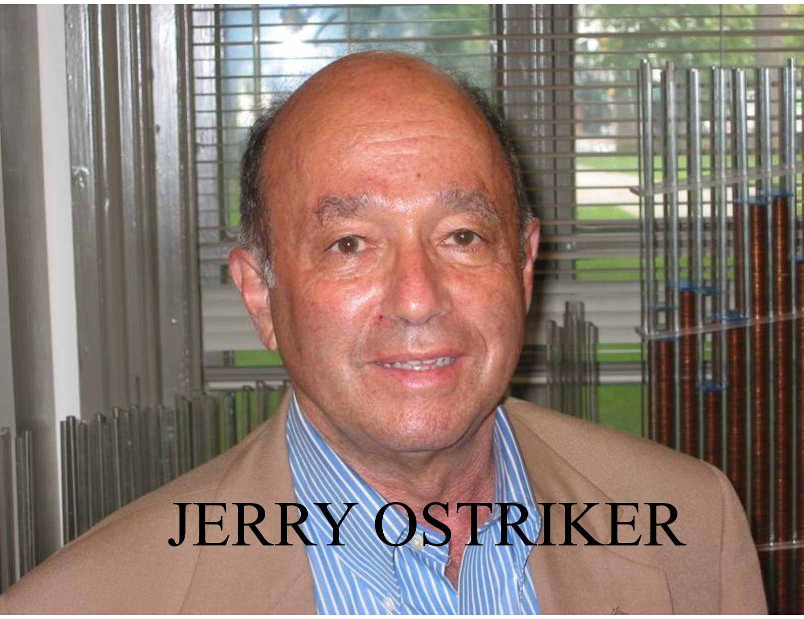


A NUMERICAL STUDY OF THE STABILITY OF FLATTENED GALAXIES: OR, CAN COLD GALAXIES SURVIVE?*



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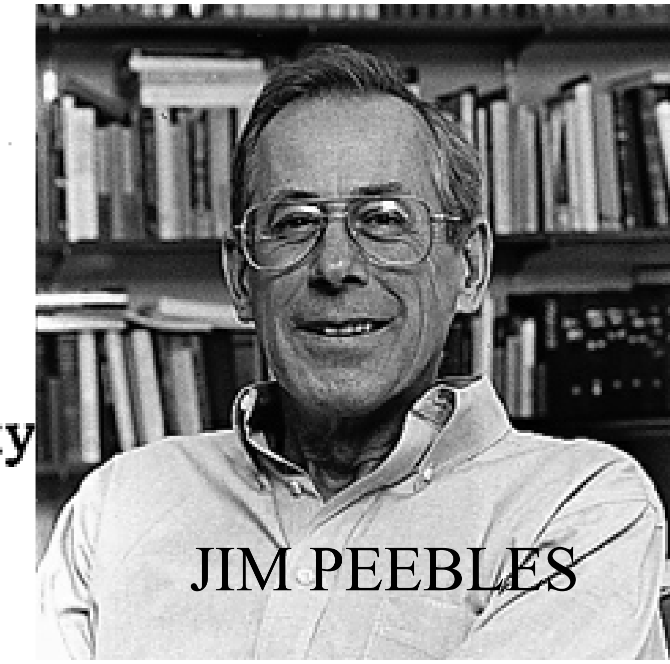
Received 1973 May 29



ABSTRACT

To study the stability of flattened galaxies, we have followed the evolution of simulated galaxies containing 150 to 500 mass points. Models which begin with characteristics similar to the disk of our Galaxy (except for increased velocity dispersion and thickness to assure local stability) were found to be rapidly and grossly unstable to barlike modes. These modes cause an increase in random kinetic energy, with approximate stability being reached when the ratio of kinetic energy of rotation to total gravitational energy, designated t, is reduced to the value of 0.14 ± 0.02. Parameter studies indicate that the result probably is not due to inadequacies of the numerical N-body simulation method. A survey of the literature shows that a critical value for limiting stability $t \simeq 0.14$ has been found by a variety of methods.

Models with added spherical (halo) component are more stable. It appears that halo-to-disk mass ratios of 1 to $2\frac{1}{2}$, and an initial value of $t \simeq 0.14 \pm 0.03$, are required for stability. If our Galaxy (and other spirals) do not have a substantial unobserved mass in a hot disk component, then apparently the halo (spherical) mass *interior* to the disk must be comparable to the disk mass. Thus normalized, the halo masses of our Galaxy and of other spiral galaxies *exterior* to the observed disks may be extremely large.

THE ENORMOUS MASS OF THE ELLIPTICAL GALAXY M87: A MODEL FOR THE EXTENDED X-RAY SOURCE*

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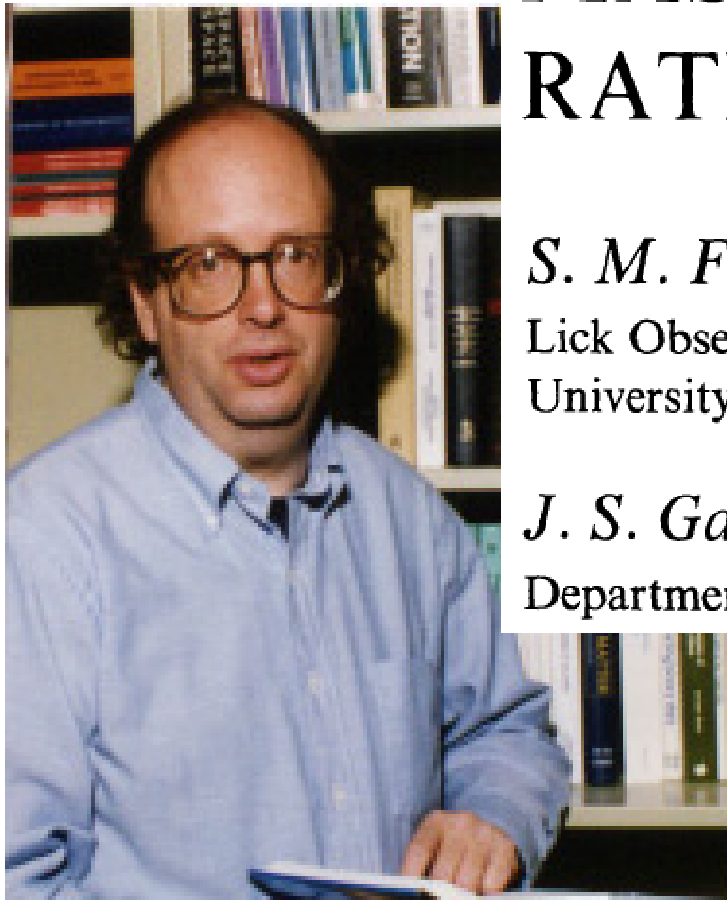
Received 1977 March 28; accepted 1977 July 20

ABSTRACT

An analysis of the X-ray data from the Virgo cluster indicates that the mass of the giant elliptical galaxy M87 exceeds $10^{13}\,\mathfrak{M}_\odot$ and may be $\sim 10^{14}\,\mathfrak{M}_\odot$ or greater. This large mass is required in order to confine the extended thermal X-ray source to its observed projected size—provided the gas which radiates X-rays is essentially isothermal ($T = 3 \times 10^7$ K) and in hydrostatic equilibrium. Isothermality follows from the efficiency of heat conduction and the suggested origin of the gas. If these reasonable assumptions are correct, the bulk of the mass in M87 must be distributed in a low-density, low-luminosity component quite unlike the distribution of luminous matter. The mass of this component, which is uncertain by a factor of about 2, could account for the "missing mass" in the Virgo cluster.

1978 ApJ 219, 413



MASSES AND MASS-TO-LIGHT RATIOS OF GALAXIES

ARAA 1979

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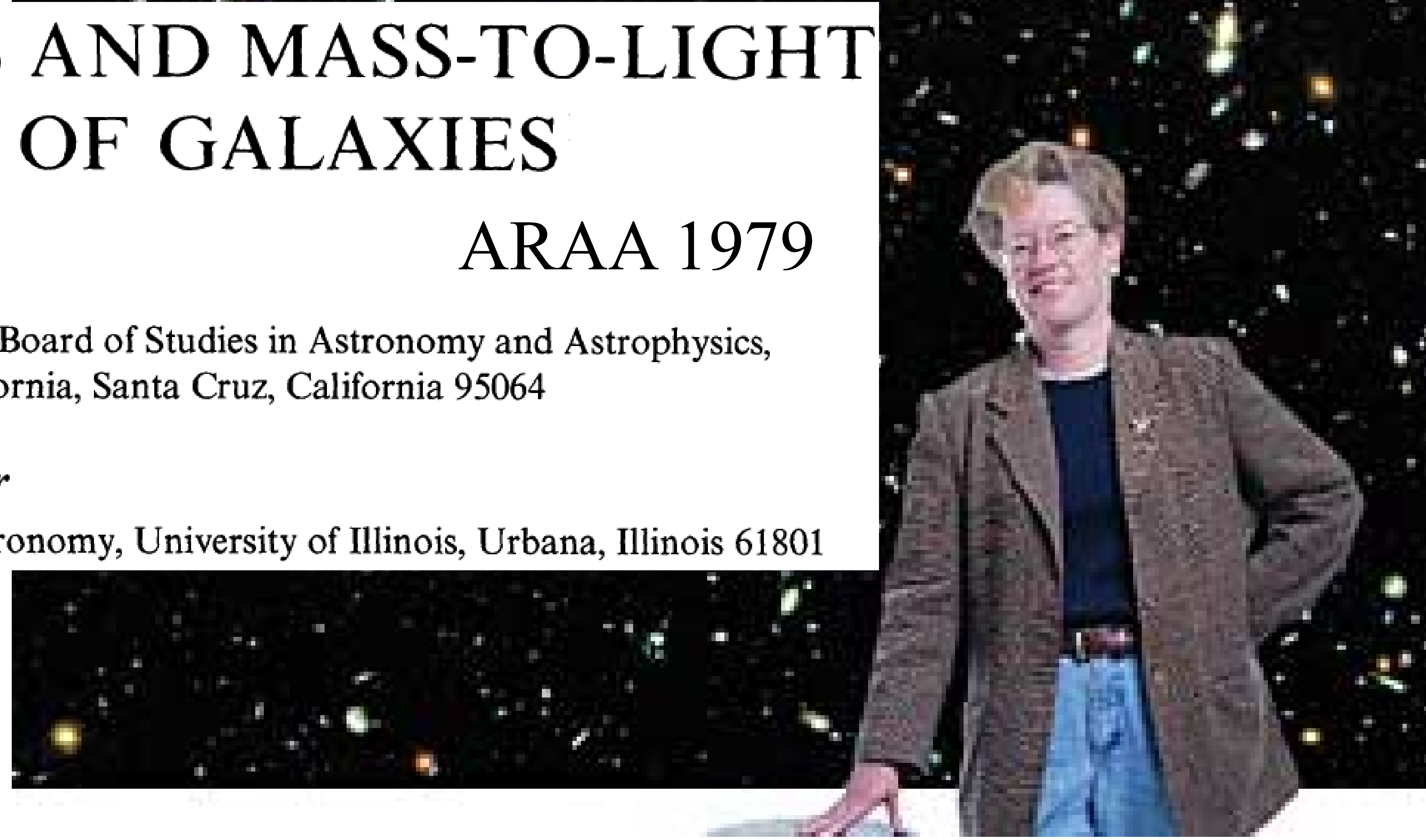


After reviewing all the evidence, it is our opinion that the case for invisible mass in the Universe is very strong and getting stronger. Particularly encouraging is the fact that the mass-to-light ratio for binaries agrees so well with that for small groups. Furthermore, our detailed knowledge of the mass distribution of the Milky Way and Local Group is reassuringly consistent with the mean properties of galaxies and groups elsewhere. In sum, although such questions as observational errors and membership probabilities are not yet completely resolved, we think it likely that the discovery of invisible matter will endure as one of the major conclusions of modern astronomy.

Some steps toward cosmic structure formation

Many people thought the early universe was complex (e.g. mixmaster universe Misner, explosions Ostriker, …).

But Zel'dovich assumed that it is fundamentally simple, with just a scale-free spectrum of adiabatic fluctuations of

(a) baryons

and when that failed [$(\Delta T/T)_{CMB} < 10^{-4}$] and Moscow physicists thought they had discovered neutrino mass

(b) hot dark matter.

Blumenthal and I thought simplicity a good approach, but we tried other simple candidates for the dark matter, first

(c) warm dark matter, and then, with Faber and Rees,

(d) cold dark matter, which moved sluggishly in the early universe.

Giant voids in the Universe

1982 Nature
300, 407

Ya. B. Zeldovich*, J. Einasto†‡ & S. F. Shandarin*

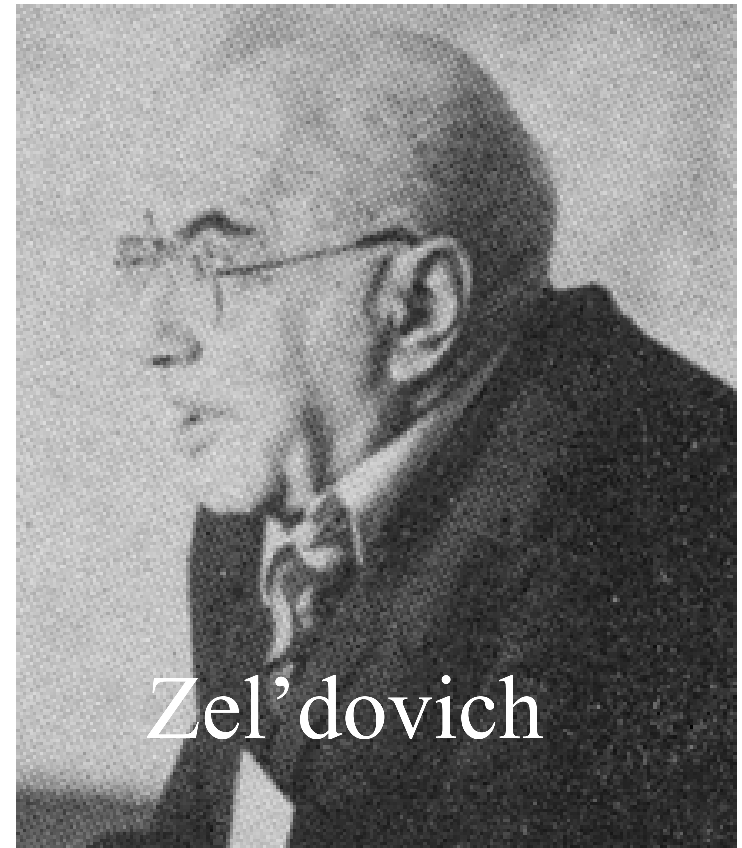
Neutrino dominated Universe

Perhaps the weakest point in the adiabatic scenario is its need for too large an amplitude of density perturbations at the decoupling era: $\delta\rho/\rho \approx 10^{-3}$ if $\Omega = 1$ and $\delta\rho/\rho \approx 10^{-1}$ if $\Omega = 0.02$ (ref. 40). As noted already by Silk[23], density fluctuations at the epoch of decoupling correspond to similar angular fluctuations of the temperature of the microwave background. $\delta T/T \sim 1/3\delta\rho/\rho$. On the other hand, observations give an upper limit of temperature fluctuations of the order 10^{-4} (refs 22, 23).

This controversy would be solved if the Universe were neutrino dominated with the neutrino mass $m \approx 10$ eV. Neutrino gas does not interact with radiation, thus perturbations in the neutrino gas could develop much earlier than in the baryon dominated Universe and could have the necessary amplitude. Baryon gas is bound to radiation and has smaller density fluctuations, after decoupling it simply flows to gravitational wells formed in the neutrino gas.

Thus in the neutrino dominated Universe one has low baryon density $\Omega_b \approx 0.01$–0.1 while the total density is close to the closure once $\Omega_t \approx \Omega_\nu \approx 1$.

The formation of the structure in a neutrino dominated Universe is, essentially, an adiabatic scenario[44–51]. The initial ratio of baryons to neutrinos is the same everywhere (the entropy is constant), small-scale fluctuations are damped, the characteristic mass of objects to form first is $10^{15} M_\odot$ as in the conventional adiabatic scenario.



CLUSTERING IN A NEUTRINO-DOMINATED UNIVERSE

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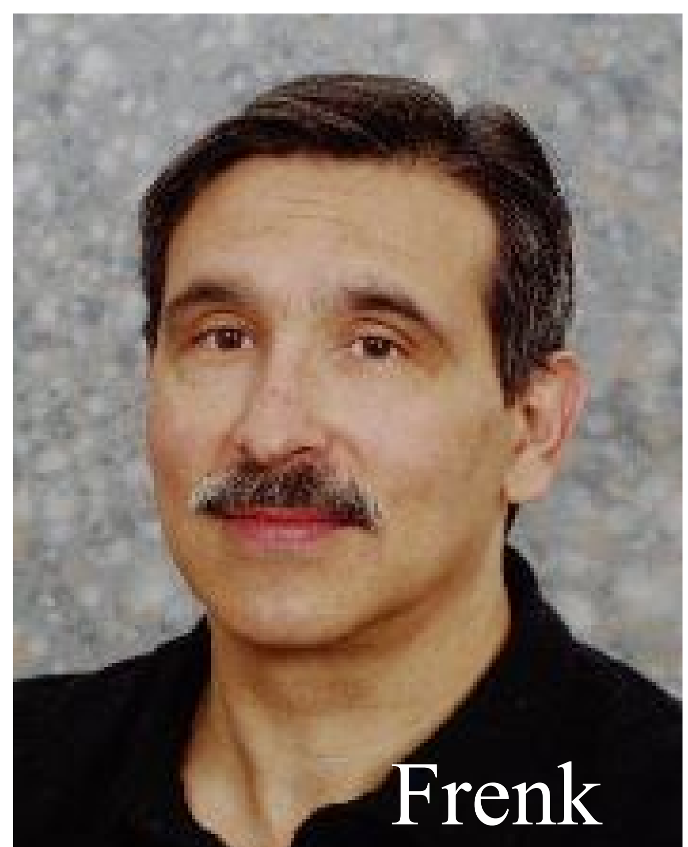
Received 1983 June 17; accepted 1983 July 1

1983 ApJ 274, L1

ABSTRACT

We have simulated the nonlinear growth of structure in a universe dominated by massive neutrinos using initial conditions derived from detailed linear calculations of earlier evolution. Codes based on a direct *N*-body integrator and on a fast Fourier transform Poisson solver produce very similar results. The coherence length of the neutrino distribution at early times is directly related to the mass of the neutrino and thence to the present density of the universe. We find this length to be too large to be consistent with the observed clustering scale of galaxies if other cosmological parameters are to remain within their accepted ranges. The conventional neutrino-dominated picture appears to be ruled out.



Heinz
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1982 PRL 48, 224

Supersymmetry, Cosmology, and New Physics at Teraelectronvolt Energies

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(Received 17 August 1981)

If one assumes a spontaneously broken local supersymmetry, big-bang cosmology implies that the universe is filled with a gravitino ($g_{3/2}$) gas—possibly its dominant constituent. From the observational bound on the cosmological mass density it follows that $m_{g_{3/2}} \lesssim 1$ keV. Correspondingly, the supersymmetry breaking parameter F satisfies $\sqrt{F} \lesssim 2\times 10^3$ TeV, requiring new supersymmetric physics in the teraelectronvolt energy region. An exact sum rule is derived and used to estimate the threshold and cross section for the production of the new states.

Galaxy formation by dissipationless particles heavier than neutrinos

1982 Nature 299, 37

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In a baryon dominated universe, there is no scale length corresponding to the masses of galaxies. If neutrinos with mass <50 eV dominate the present mass density of the universe, then their Jeans mass $M_{J\nu} \sim 10^{16} M_{\odot}$, which resembles supercluster rather than galactic masses. Neutral particles that interact much more weakly than neutrinos would decouple much earlier, have a smaller number density today, and consequently could have a mass >50 eV without exceeding the observational mass density limit. A candidate particle is the gravitino, the spin 3/2 supersymmetric partner of the graviton, which has been shown[1] to have a mass ≤ 1 keV if stable[2]. The Jeans mass for a 1-keV noninteracting particle is $\sim 10^{12} M_{\odot}$, about the mass of a typical spiral galaxy including the nonluminous halo. We suggest here that the gravitino dominated universe can produce galaxies by gravitational instability while avoiding several observational difficulties associated with the neutrino dominated universe.

LARGE-SCALE BACKGROUND TEMPERATURE AND MASS FLUCTUATIONS DUE TO SCALE-INVARIANT PRIMEVAL PERTURBATIONS

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Received 1982 July 2; accepted 1982 August 13

ABSTRACT

The large-scale anisotropy of the microwave background and the large-scale fluctuations in the mass distribution are discussed under the assumptions that the universe is dominated by very massive, weakly interacting particles and that the primeval density fluctuations were adiabatic with the scale-invariant spectrum $P \propto$ wavenumber. This model yields a characteristic mass comparable to that of a large galaxy independent of the particle mass, m_x, if $m_x \gtrsim 1$ keV. The expected background temperature fluctuations are well below present observational limits.

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NATURE VOL. 311 11 OCTOBER 1984

Formation of galaxies and large-scale structure with cold dark matter

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The dark matter that appears to be gravitationally dominant on all scales larger than galactic cores may consist of axions, stable photinos, or other collisionless particles whose velocity dispersion in the early Universe is so small that fluctuations of galactic size or larger are not damped by free streaming. An attractive feature of this cold dark matter hypothesis is its considerable predictive power: the post-recombination fluctuation spectrum is calculable, and it in turn governs the formation of galaxies and clusters. Good agreement with the data is obtained for a Zeldovich ($|\delta_k|^2 \propto k$) spectrum of primordial fluctuations.




Formation of galaxies and large-scale structure with cold dark matter

… We conclude that a straightforward interpretation of the evidence summarized above favours $\Omega \approx 0.2$ in the cold DM picture, but that $\Omega = 1$ is not implausible. …

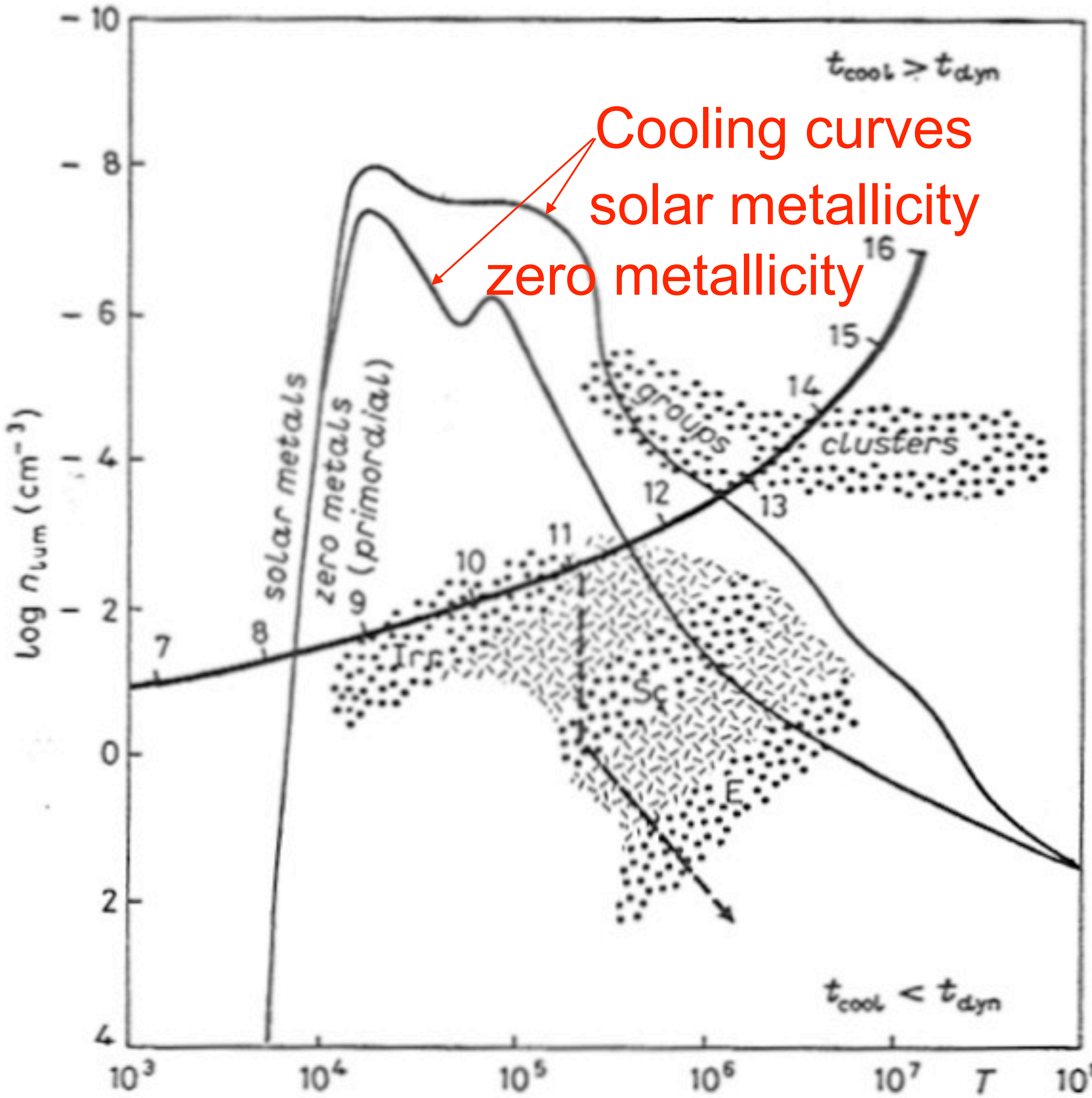
Conclusions

We have shown that a Universe with ~10 times as much cold dark matter as baryonic matter provides a remarkably good fit to the observed Universe. This model predicts roughly the observed mass range of galaxies, the dissipational nature of galaxy collapse, and the observed Faber–Jackson and Tully–Fisher relations. It also gives dissipationless galactic haloes and clusters. In addition, it may also provide natural explanations for galaxy-environment correlations and for the differences in angular momenta between ellipticals and spiral galaxies. Finally, the cold DM picture seems reasonably consistent with the observed large-scale clustering, including superclusters and voids. In short, it seems to be the best model available and merits close scrutiny and testing.

Blumenthal, Faber, Primack, & Rees 1984

CDM Spherical Collapse Model

Primack & Blumenthal 1983 based on CDM, cooling theory of Rees & Ostriker 1977, Silk 1977, Binney 1977 and baryonic dissipation within dark halos White & Rees 1978

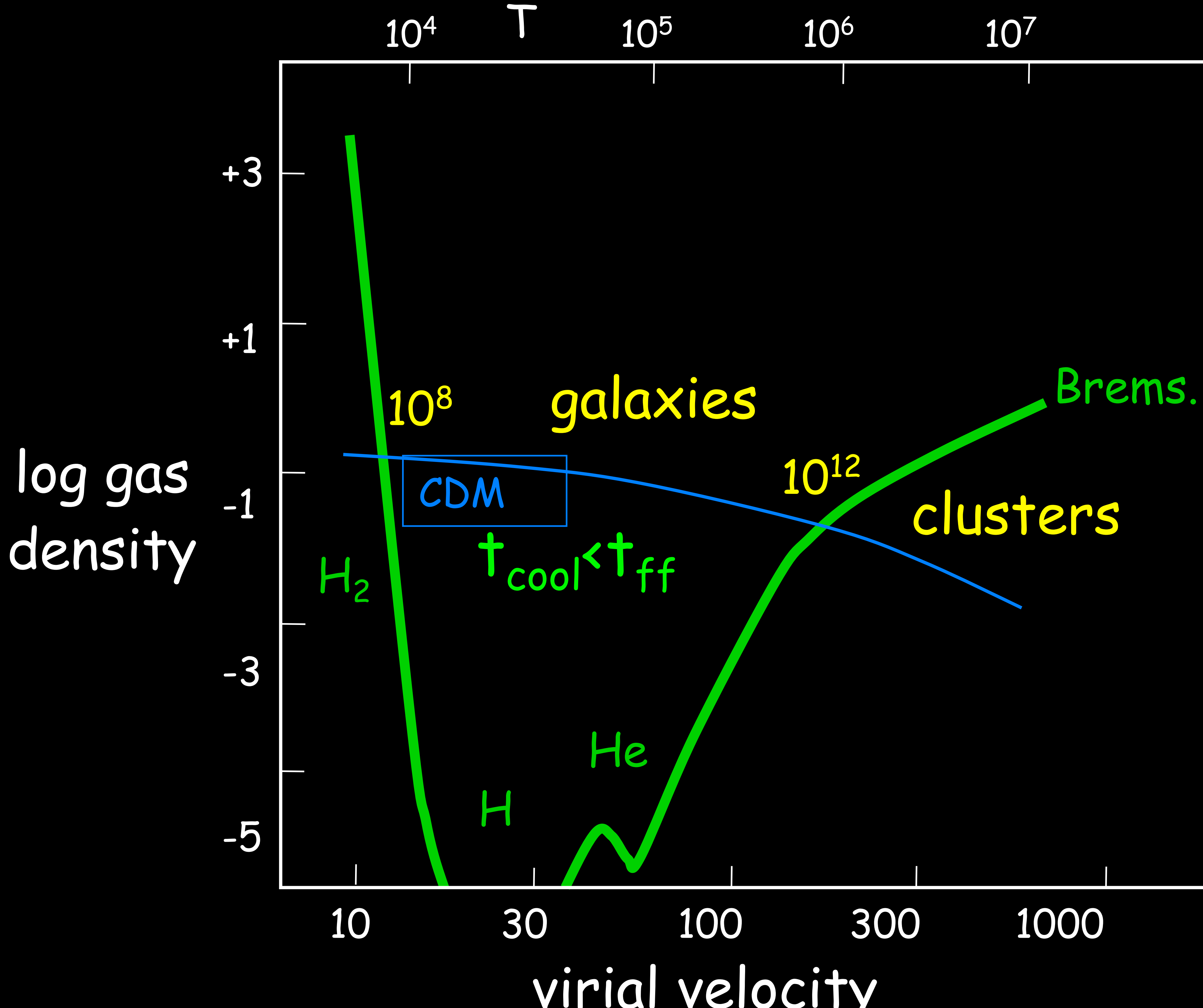


The baryonic density *vs.* temperature as root-mean-square perturbations having total mass M become nonlinear and virialize. The numbers on the tick marks are the logarithm of M in units of $M_\odot$. This curve assumes $n = 1$, $\Omega = h = 1$ and a baryonic to total mass ratio of 0.07. The region where baryons can cool within a dynamical time lies below the cooling curves. Also shown are the positions of observed galaxies, groups and clusters of galaxies. The dashed line represents a possible evolutionary path for dissipating baryons.

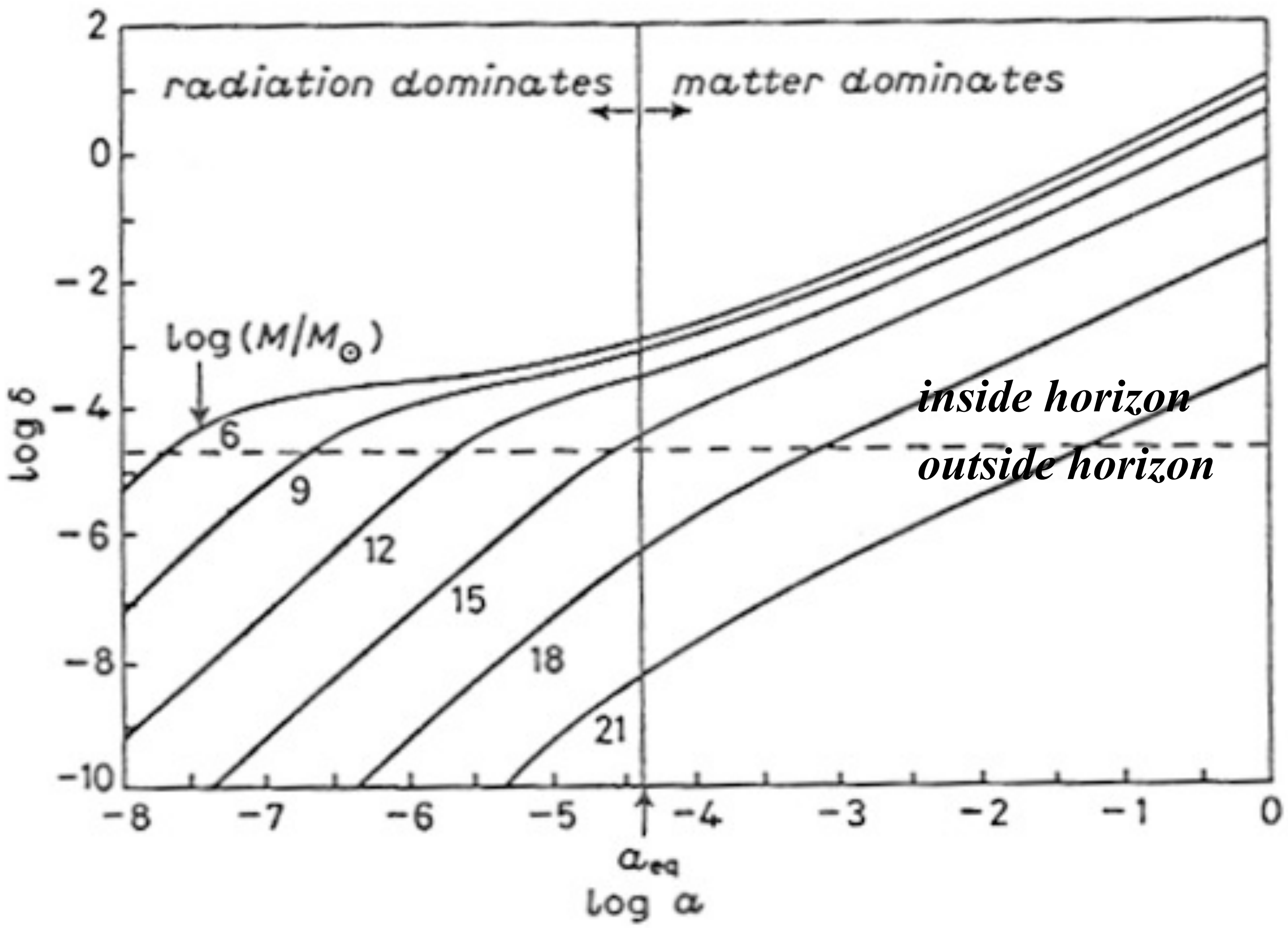
CDM Correctly Predicted the Masses of Galaxies

Rees & Ostriker 77, Silk 77, Binney 77, White & Rees 1978

CDM: Blumenthal, Faber, Primack, & Rees 1984

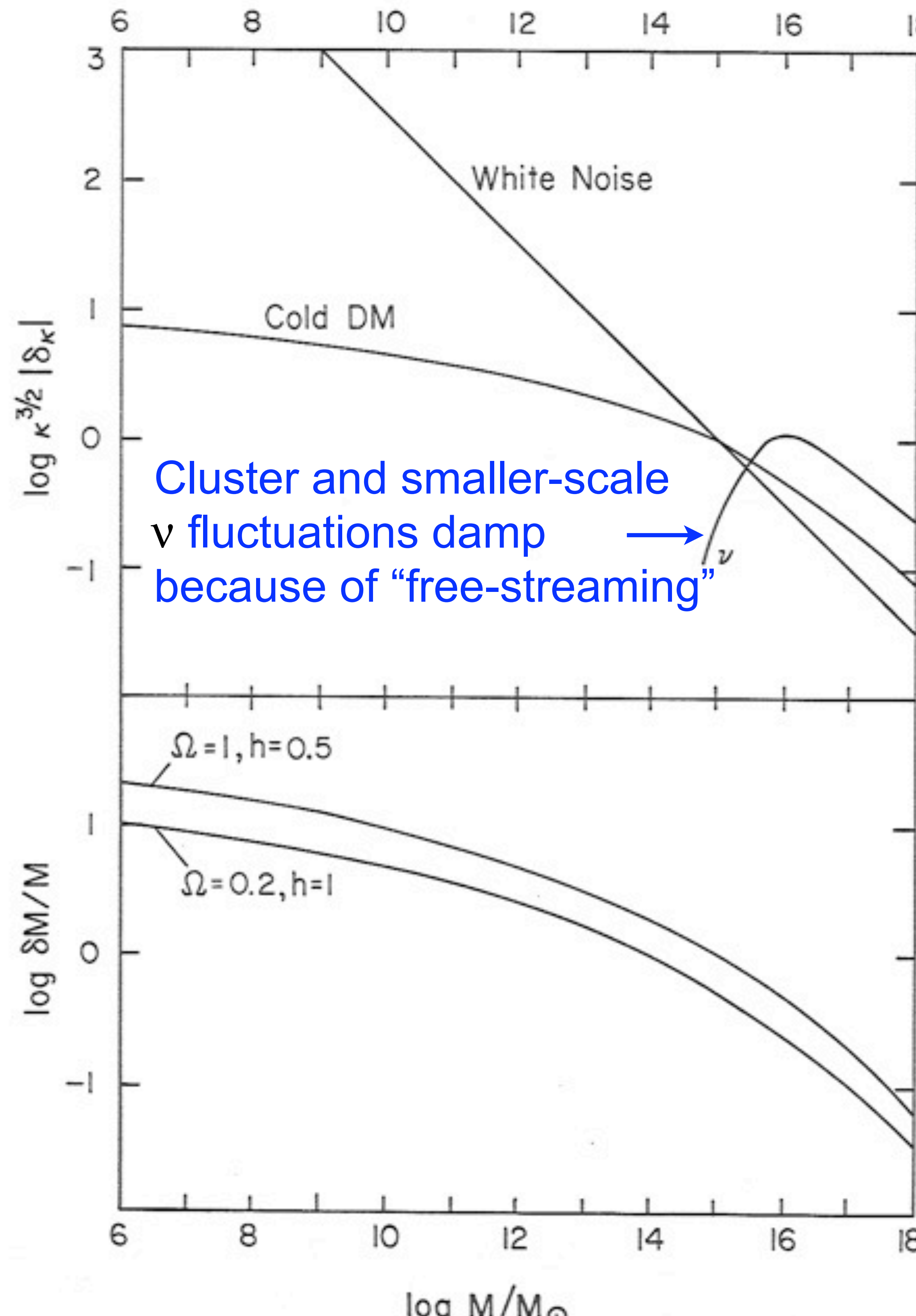


CDM Structure Formation: Linear Theory



CDM fluctuations that enter the horizon during the radiation dominated era, with masses less than about $10^{15} M_{\odot}$ grow only $\propto$ log $\boldsymbol{a}$, because they are not in the gravitationally dominant component. But matter fluctuations that enter the horizon in the matter-dominated era grow $\propto$ $\boldsymbol{a}$. This explains the characteristic shape of the CDM fluctuation spectrum, with $\delta(k) \propto k^{-n/2-2} \log k$

Primack & Blumenthal 1983,
Primack Varenna Lectures 1984



Blumenthal, Faber, Primack, & Rees 1984

The Dark Matter Rap: Cosmological History for the MTV Generation by David Weinberg*

My name is Fritz Zwicky,
I can be kind of prickly,
This song had better start
by giving me priority.
Whatever anybody says,
I said in 1933.
Observe the Coma cluster,
the redshifts of the galaxies
imply some big velocities.
They're moving so fast,
there must be missing mass!
Dark matter.

Dark matter: Do we need it? What is it? Where is it? How much?
Do we need it? Do we need it? Do we need it? Do we need it?

* www.astronomy.ohio-state/~dhw/Silliness/silliness.html (1992)

The Dark Matter Rap: Cosmological History for the MTV Generation by David Weinberg

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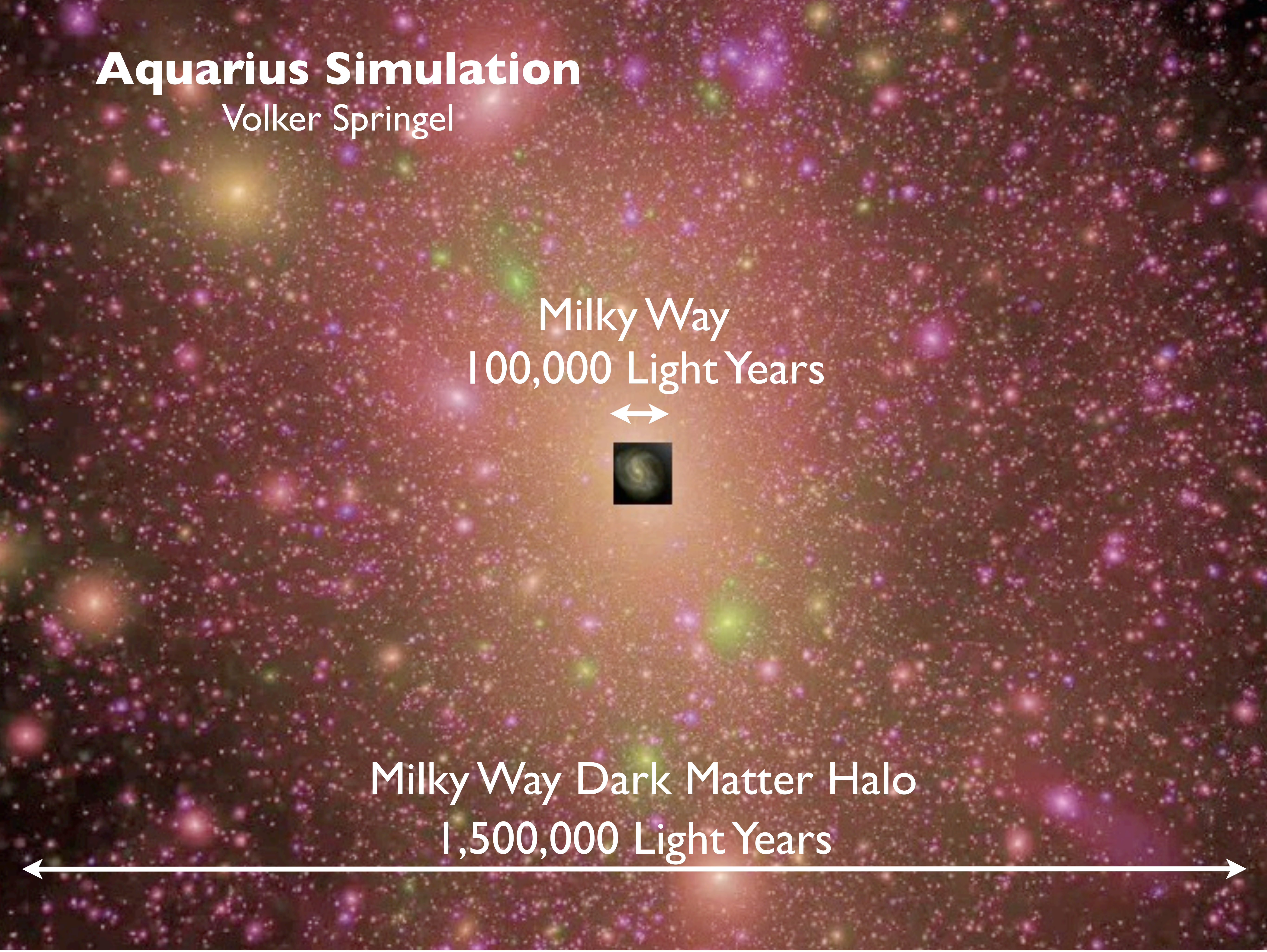
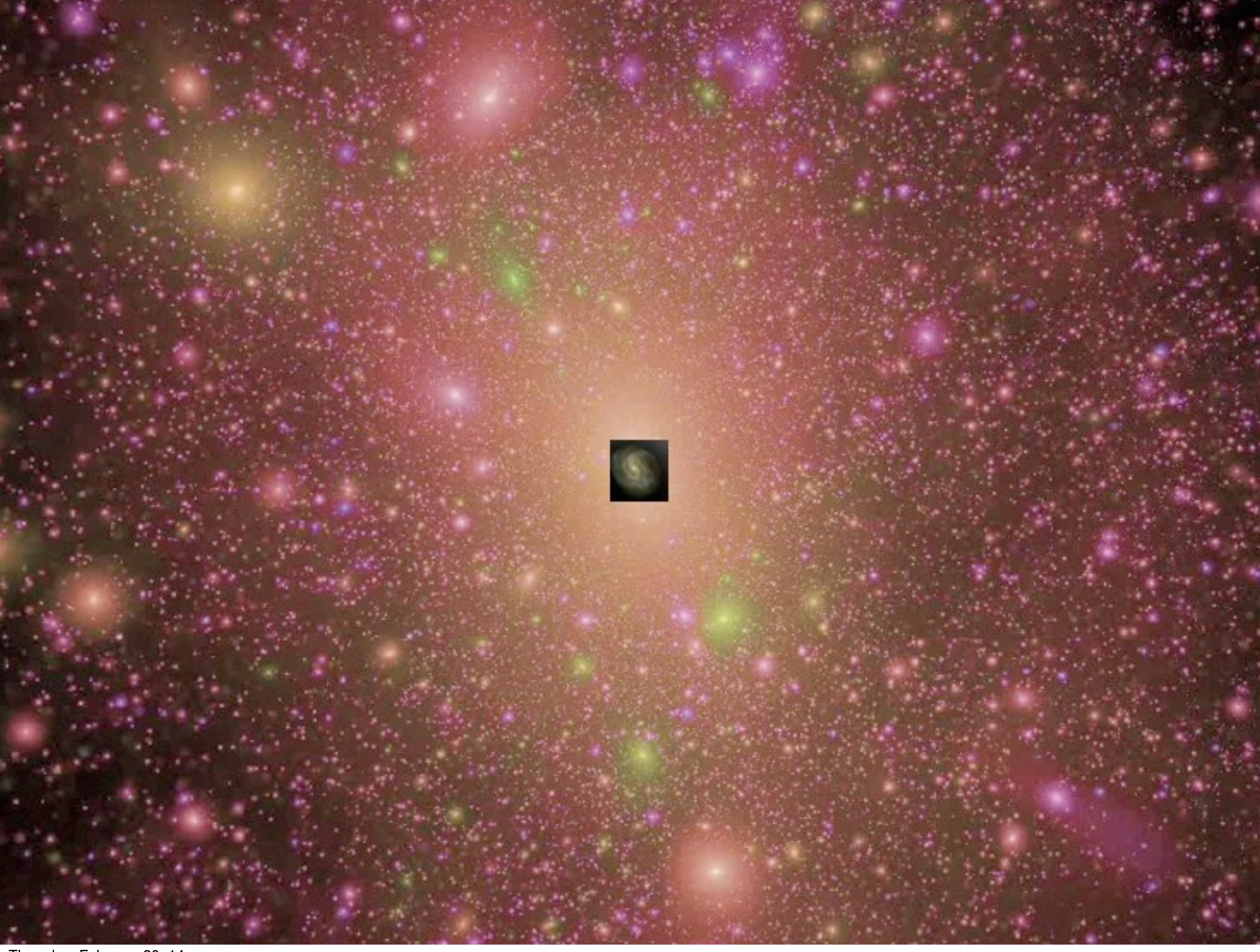
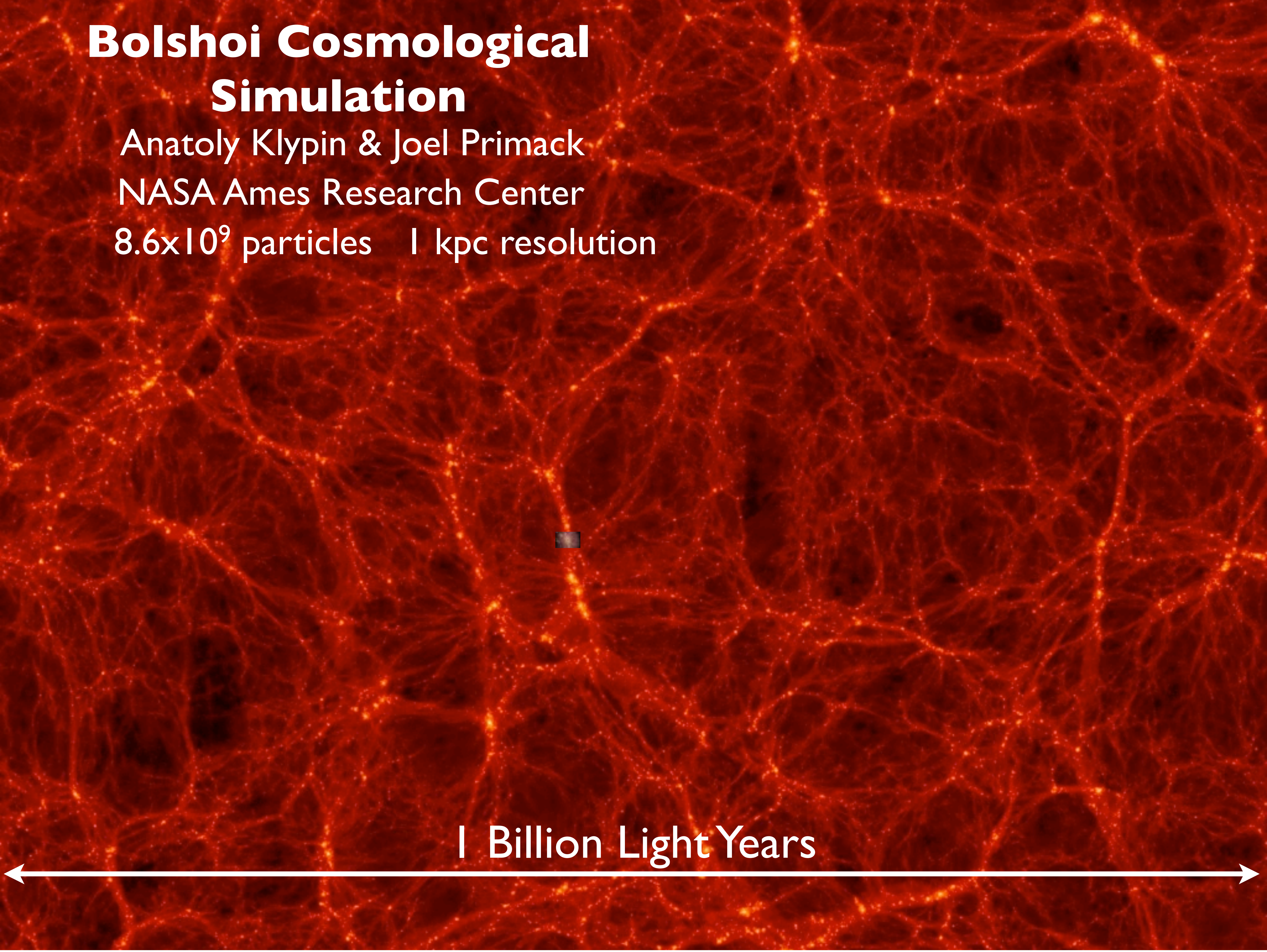
A virtual journey from the centre to the outskirts of the Milky Way


Aquarius Simulation
Volker Springel
Milky Way
100,000 Light Years
Milky Way Dark Matter Halo
1,500,000 Light Years




Bolshoi Cosmological Simulation
Anatoly Klypin & Joel Primack
NASA Ames Research Center
8.6x10^{9} particles 1 kpc resolution
1 Billion Light Years

Galaxy Formation - Introduction

ΛCDM vs. Downsizing

ΛCDM:

hierarchical formation
(small things form first)

"Downsizing":

massive galaxies are old, star formation moves to smaller galaxies

small structures	early	large galaxies
↓		↓
large structures	late	small galaxies

Galaxy Formation - Introduction

ΛCDM vs. Downsizing

ΛCDM:

hierarchical formation
(small things form first)

"Downsizing":

massive galaxies are old, star
formation moves to smaller galaxies

mass assembly

DM simulations

present-day structure

How are these
processes related?

star formation history

semi-analytic models

current stellar population

Galaxy Formation - Introduction

An old criticism of ΛCDM has been that the order of cosmogony is wrong: halos grow from small to large by accretion in a hierarchical formation theory like ΛCDM, but the oldest stellar populations are found in the most massive galaxies -- suggesting that these massive galaxies form earliest, a phenomenon known as "downsizing." The key to explaining the downsizing phenomenon is the realization that **star formation is most efficient in dark matter halos with masses in the band between about 10^{10} and 10^{12} $M_\odot$**. This goes back at least as far as the original Cold Dark Matter paper (BFPR84), from which the following figure is reproduced.

Formation of galaxies and large-scale structure with cold dark matter

Blumenthal, Faber, Primack, & Rees -- Nature 311, 517 (1984)

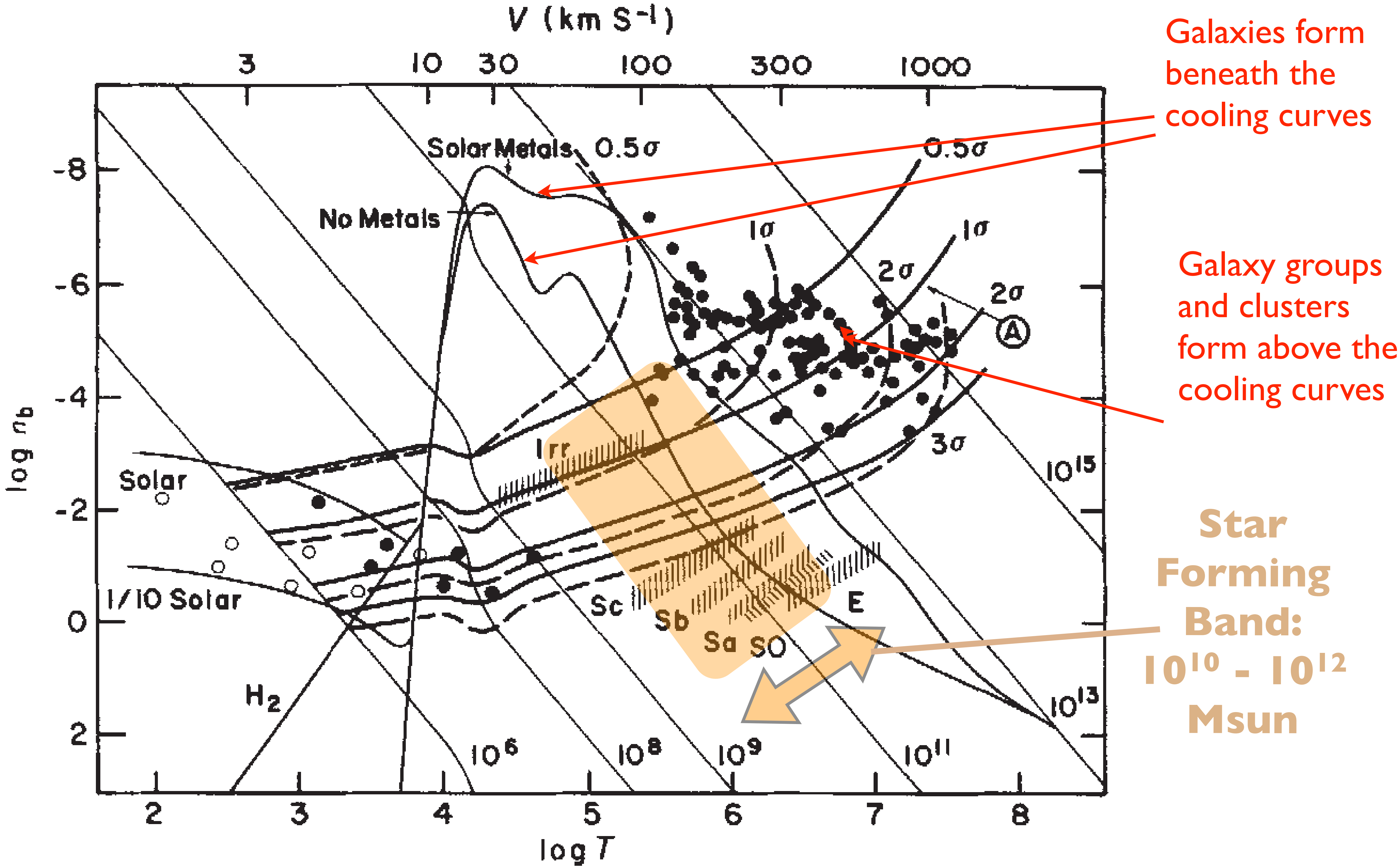
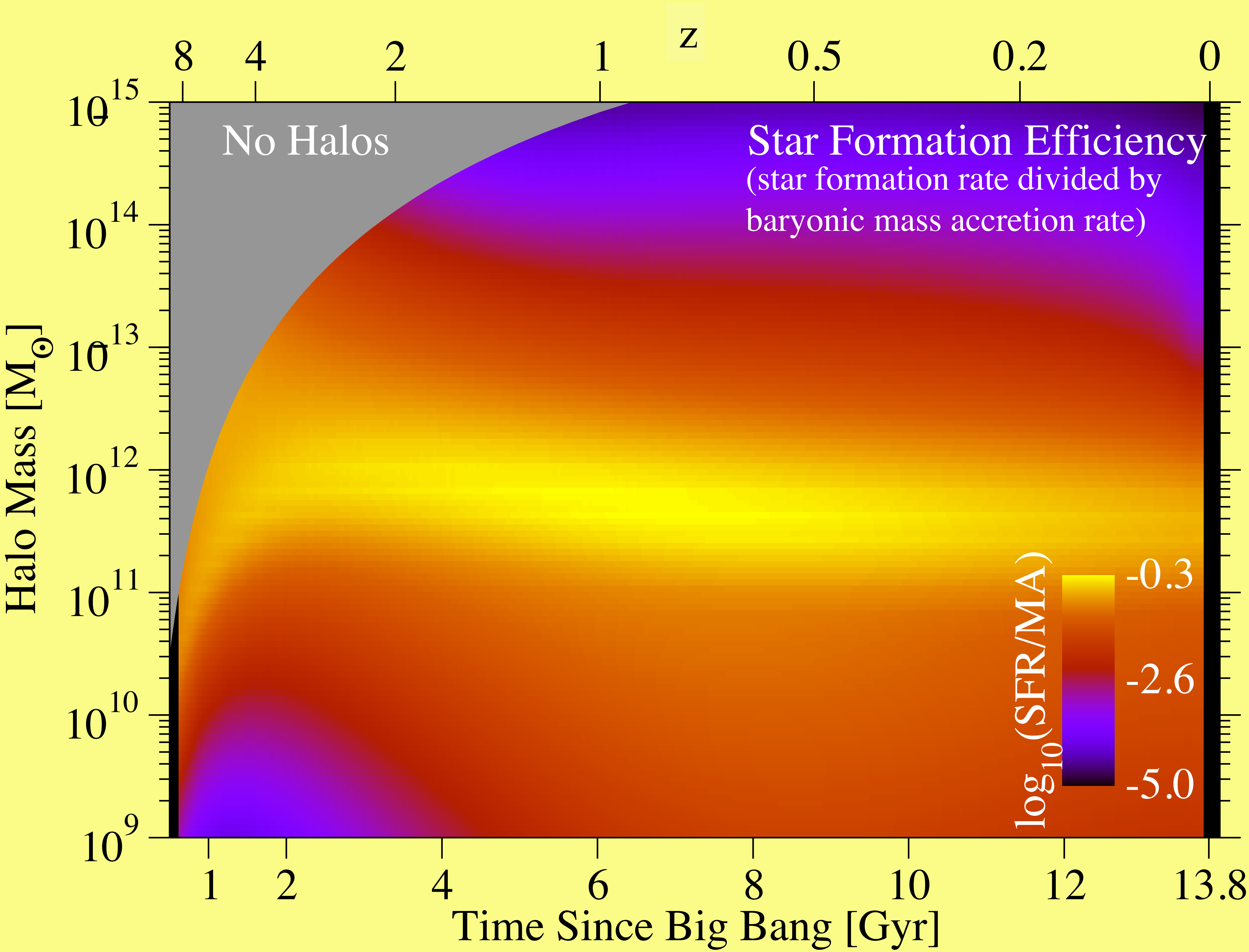
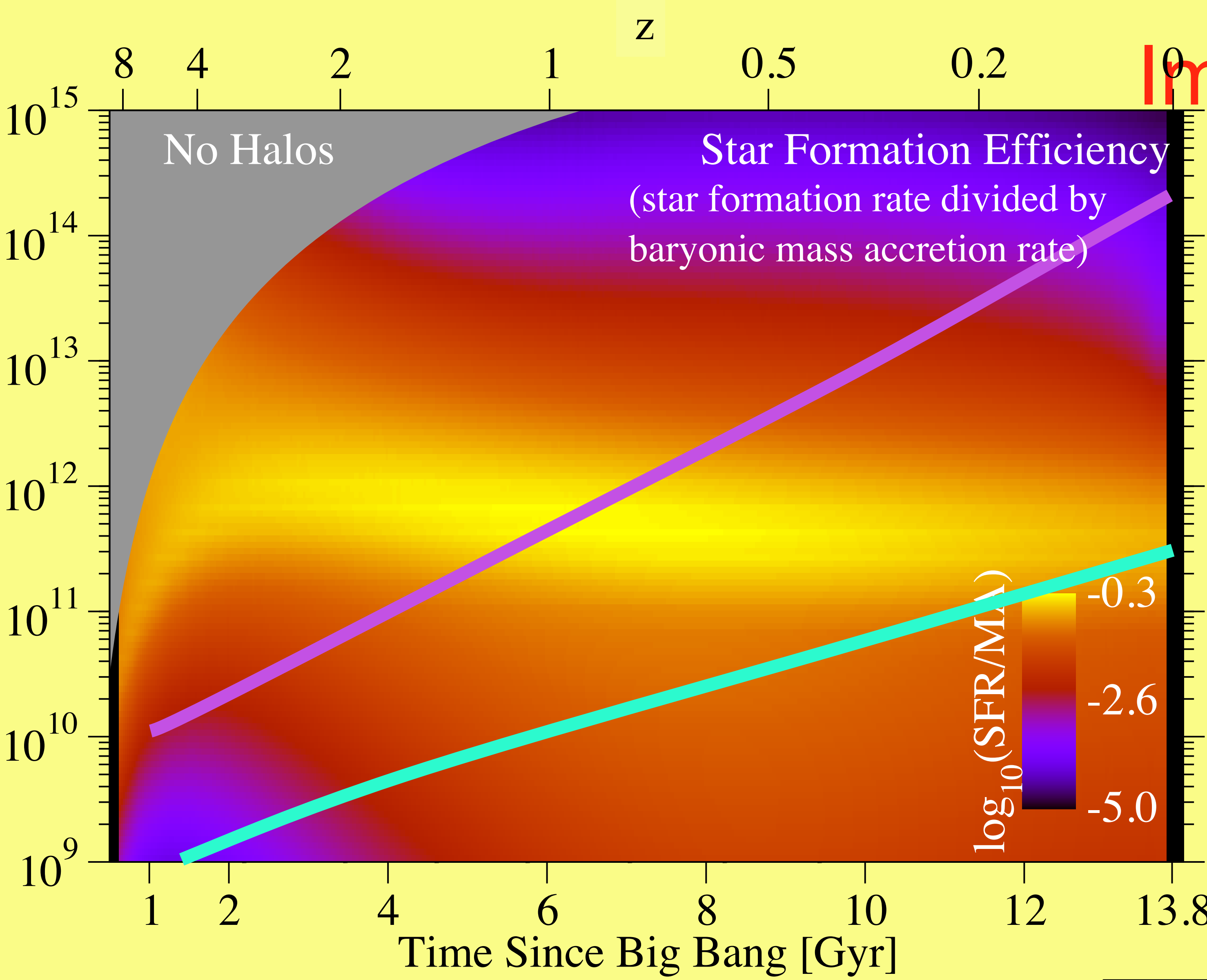


Fig. 3 Baryon density n_b versus three-dimensional, r.m.s. velocity dispersion V and virial temperature T for structures of various size in the Universe. The quantity T is $\mu V^2/3k$, where μ is mean molecular weight ($\approx$0.6 for ionized, primordial H+He) and k is Boltzmann's constant.



From Figure 1 of Behroozi, Wechsler, Conroy ApJL, 762, L31 (2013)

Implications of the Star-Forming Band Model



Massive galaxies:

- Started forming stars early.
- Shut down early.
- Are red today.
- Populate dark halos that are much more massive than their stellar mass.

Small galaxies:

- Started forming stars late.
- Are still making stars today.
- Are blue today.
- Populate dark halos that match their stellar mass.

"Downsizing"

Star formation is a wave that started in the largest galaxies and swept down to smaller masses later (Cowie et al. 1996).

From Figure 1 of Behroozi, Wechsler, Conroy ApJL, 762, L31 (2013)

WHAT IS THE DARK MATTER?

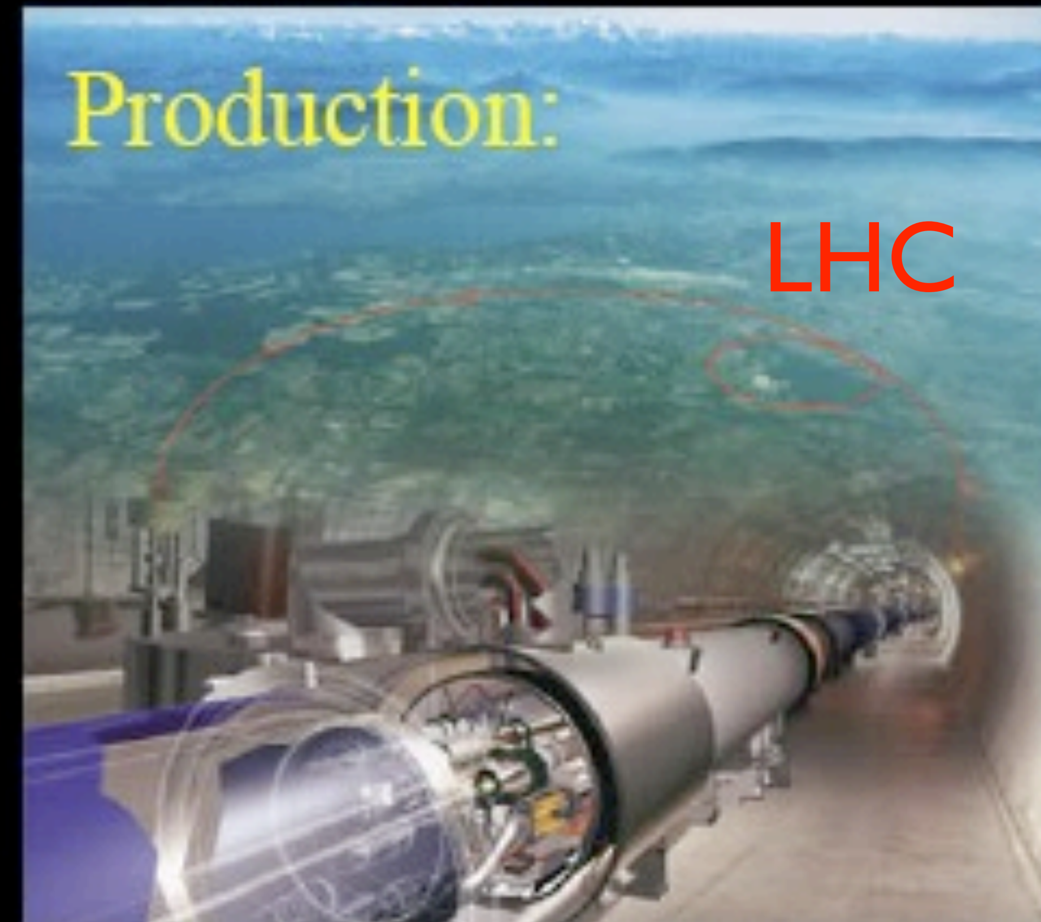
Prospects for DIRECT and INDIRECT detection of WIMPs are improving.

With many ongoing and upcoming experiments

- Production at Large Hadron Collider
- Better CMB data from PLANCK
- Direct Detection
  - Spin Independent - CDMS-II, XENON100, LUX
  - Spin Dependent - COUPP, PICASSO
- Indirect detection via
  - Fermi and larger ACTs
  - PAMELA and AMS

-- there could well be a big discovery in the next few years!

Four roads to dark matter: *catch it, infer it, make it, weigh it*



With all these upcoming experiments, the next few years will be very exciting!