Dark Matter and the invisible Universe

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DESY, Oct 2017

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Durham Uni [UK]
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Questions AP physicists focus on

- What are our origins?
- What is the Universe made of?
- What is our future?

Cosmology	Astronomy Astrophysics	Particle Physics

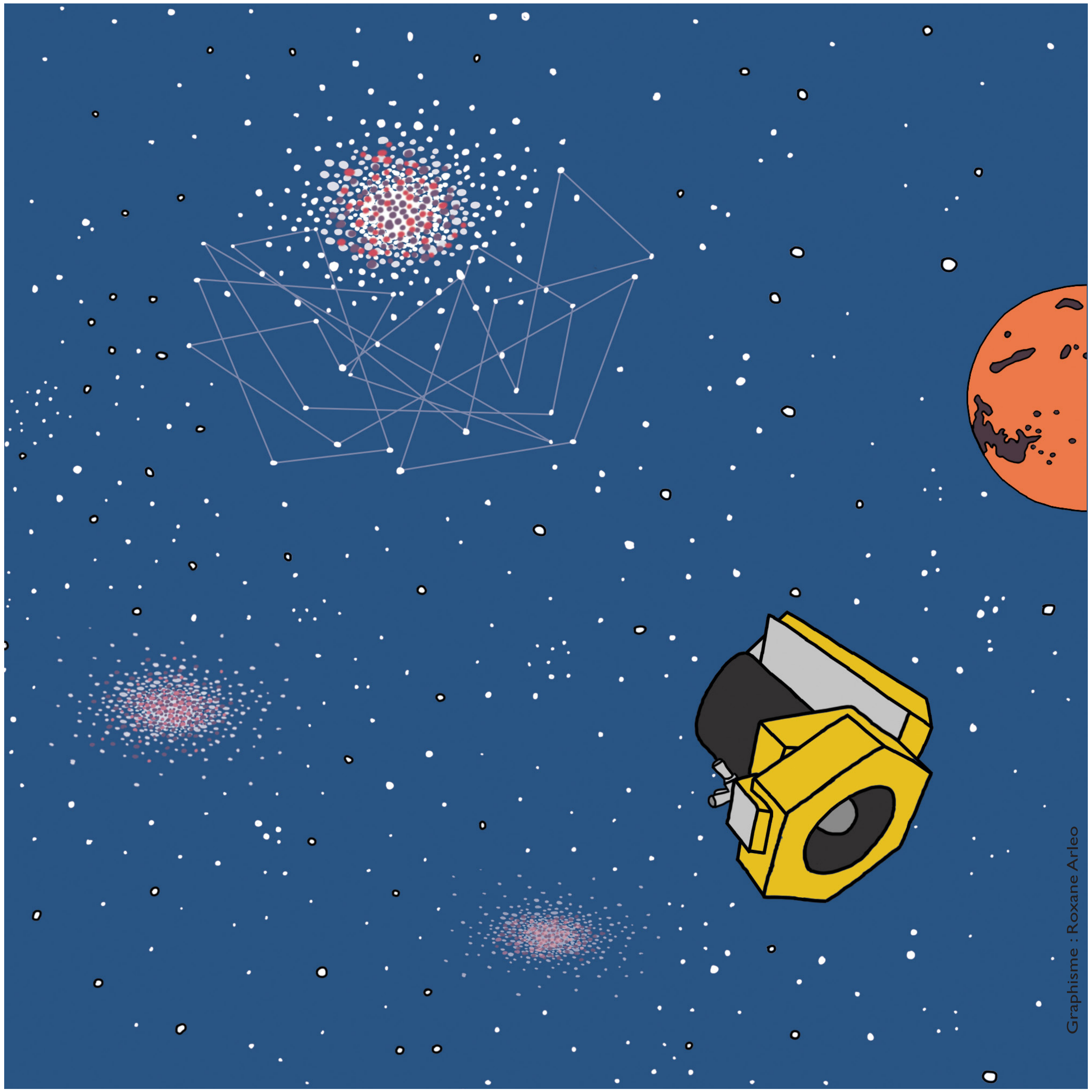
Astro Particle Physics

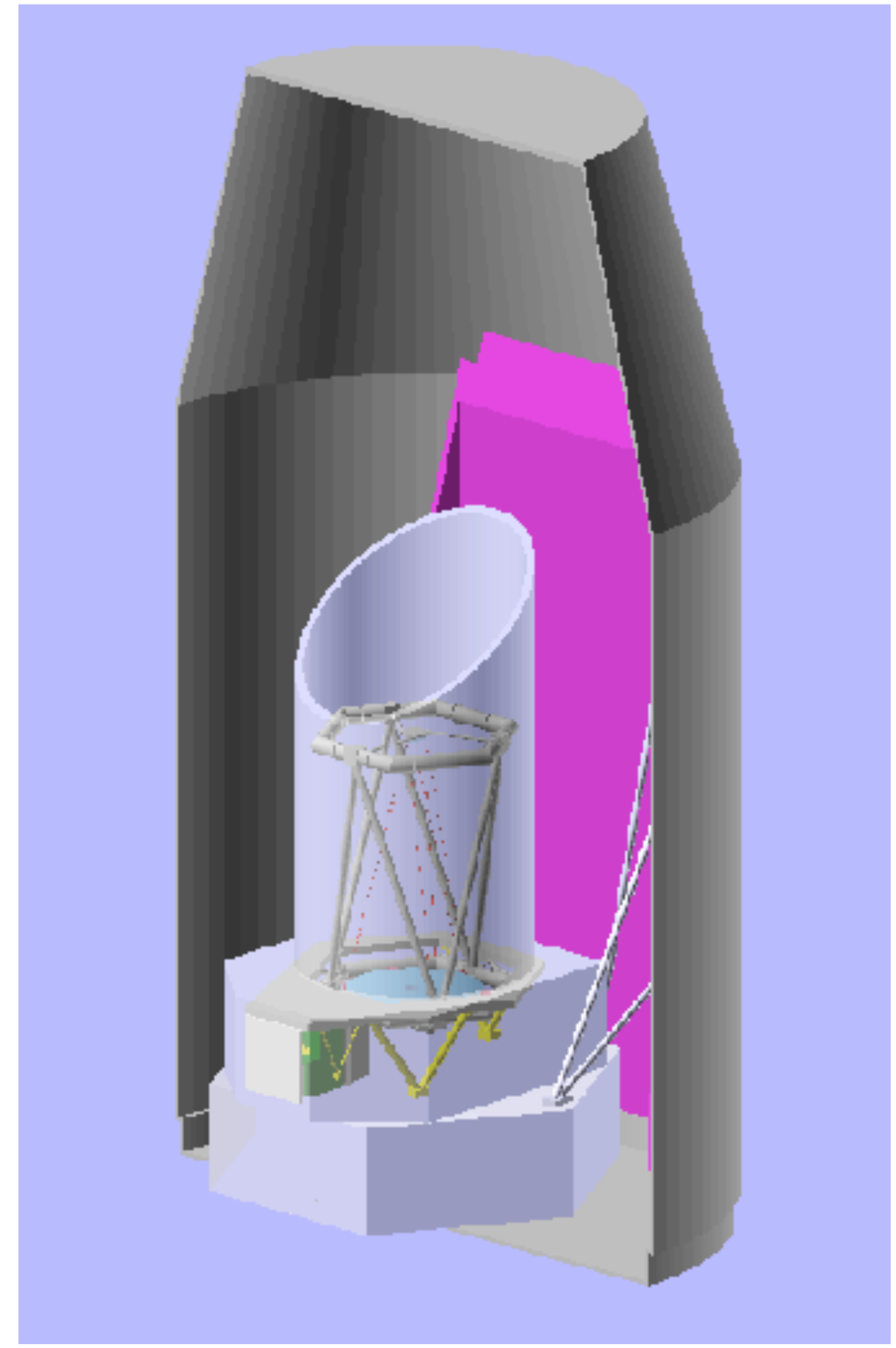
Trying to determine the constituents of the Universe (95% unknown!)

THEIA

Microarcsecond Astrometric Observatory

Proposed to ESA in 2017
22 countries, +200 participants





Faint objects in motion : the new astrometry frontier

Proposal for a medium size mission opportunity in ESA's science programme (M5) mission

Lectures organisation

I. Introduction
II. Candidates
III. Signatures

V. Cosmology
VI. New research avenues

Please don't hesitate to interrupt me

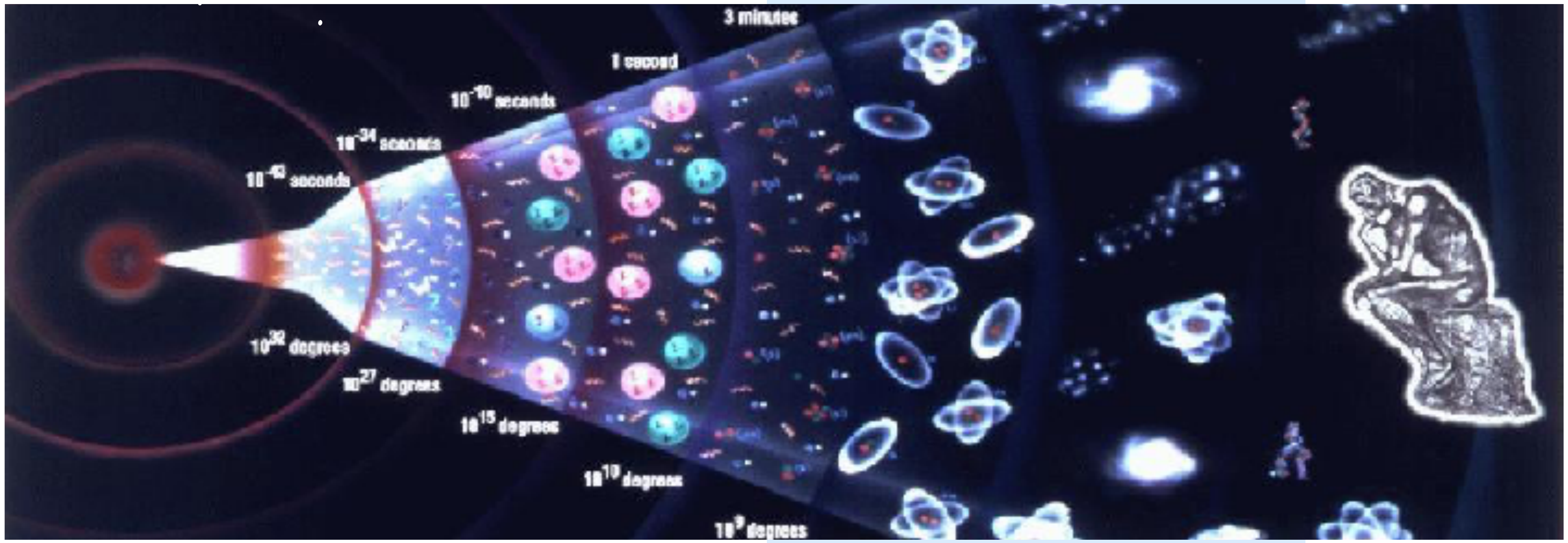
I. Introduction

Evidence for Dark Matter

* Current picture
* Rotation curves
* Gravitational lensing
* Early Universe and Large-Scale-Structures

Current picture

Radiation | Matter | Energy



Particle Standard Model

Cosmology Astrophysics

dark matter essential for galaxy formation

dark energy essential for accelerated expansion

Brief history

1920s—30s — Evidence of missing mass in clusters of galaxies

1966—67 — Progress on primordial fluctuations

1970s — Discovery of flat galaxy rotation curves

1977— 1982 — Neutrinos are (not) the dark matter; Birth of the WIMP concept

1982—1984 — Birth of the cosmology of the Cold Dark Matter (CDM) scenario

1985—1988 — DM particles can be detected in a lab and in the sky

1992—2003 — DM only makes up 25% of the energy content of the Universe

A lot of progress since then but no major discovery

Brief history

(more people contributed!)

J. Oort, 1932 — **Doppler redshift values of stars moving near the galactic plane; The Galaxy needs to be twice as massive to prevent stars to escaping**

F. Zwicky 1933

1937 ApJ 86, 217

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

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

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

$$\text{Mass/Light} = \gamma = 500 , \qquad (37)$$

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

more mass in the Coma Cluster than is visible

based on 21 radial velocities of galaxies in the Coma cluster

I. Introduction

Rotation curves *(many people contributed!)*

The rotation of galaxies was discovered in 1914 — Slipher (1914)

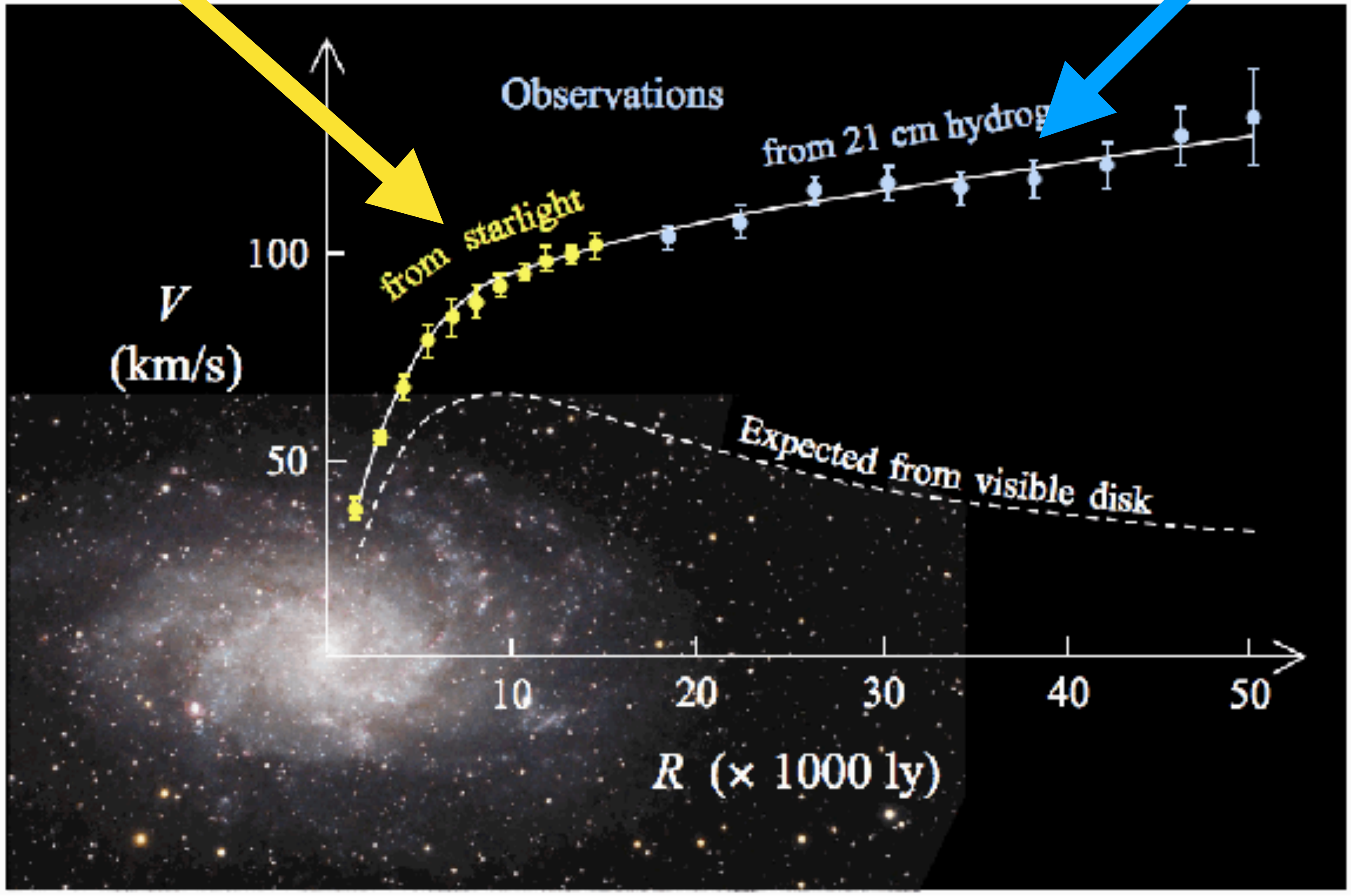
Freeman (1970) for M33 and NGC 300:

rotation curve peaks at the edge of the optical disk

so ~ 1/3 of the mass outside the optical radius.

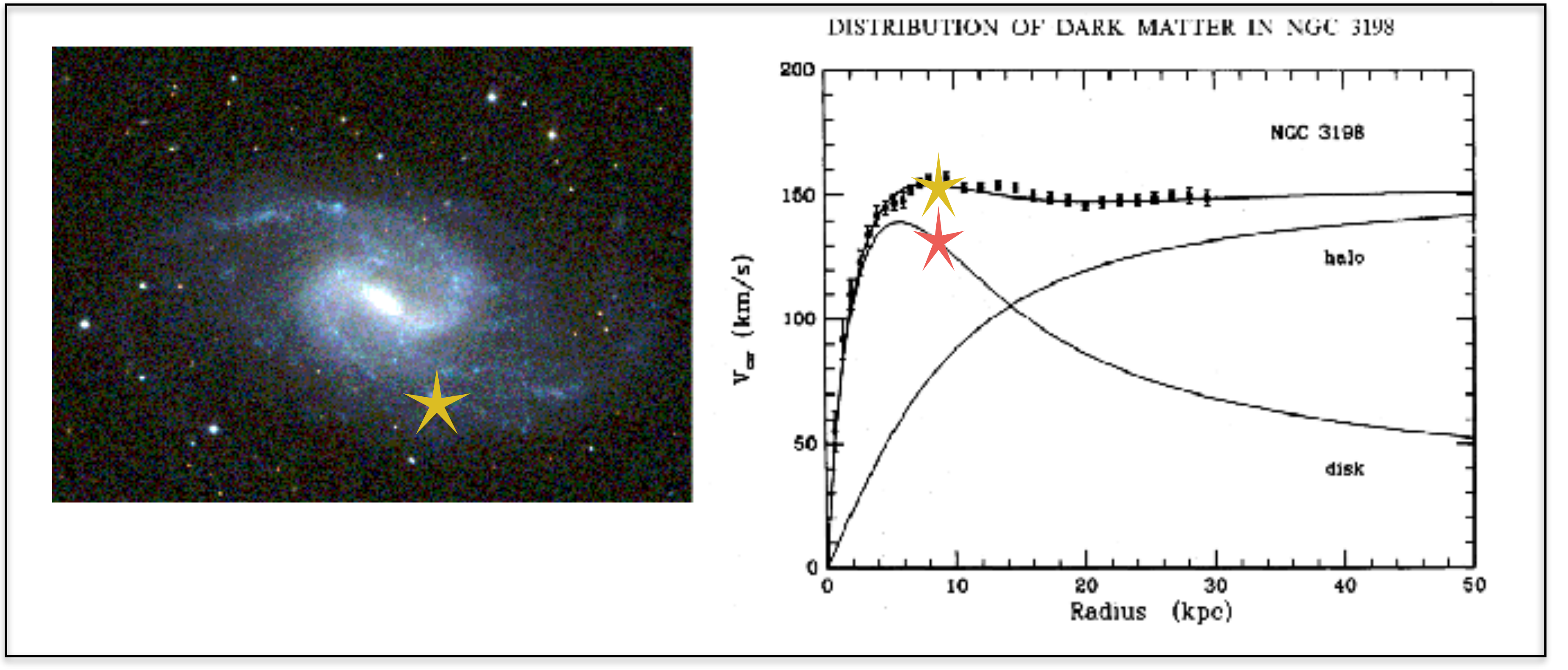
Shostak & Rogstad (1973), Seielstad & Wright (1973). M31: (Roberts 1975a, Roberts & Whitehurst 1975); Final straw: Bosma (1978)

1970ApJ...159..379R



Key discovery

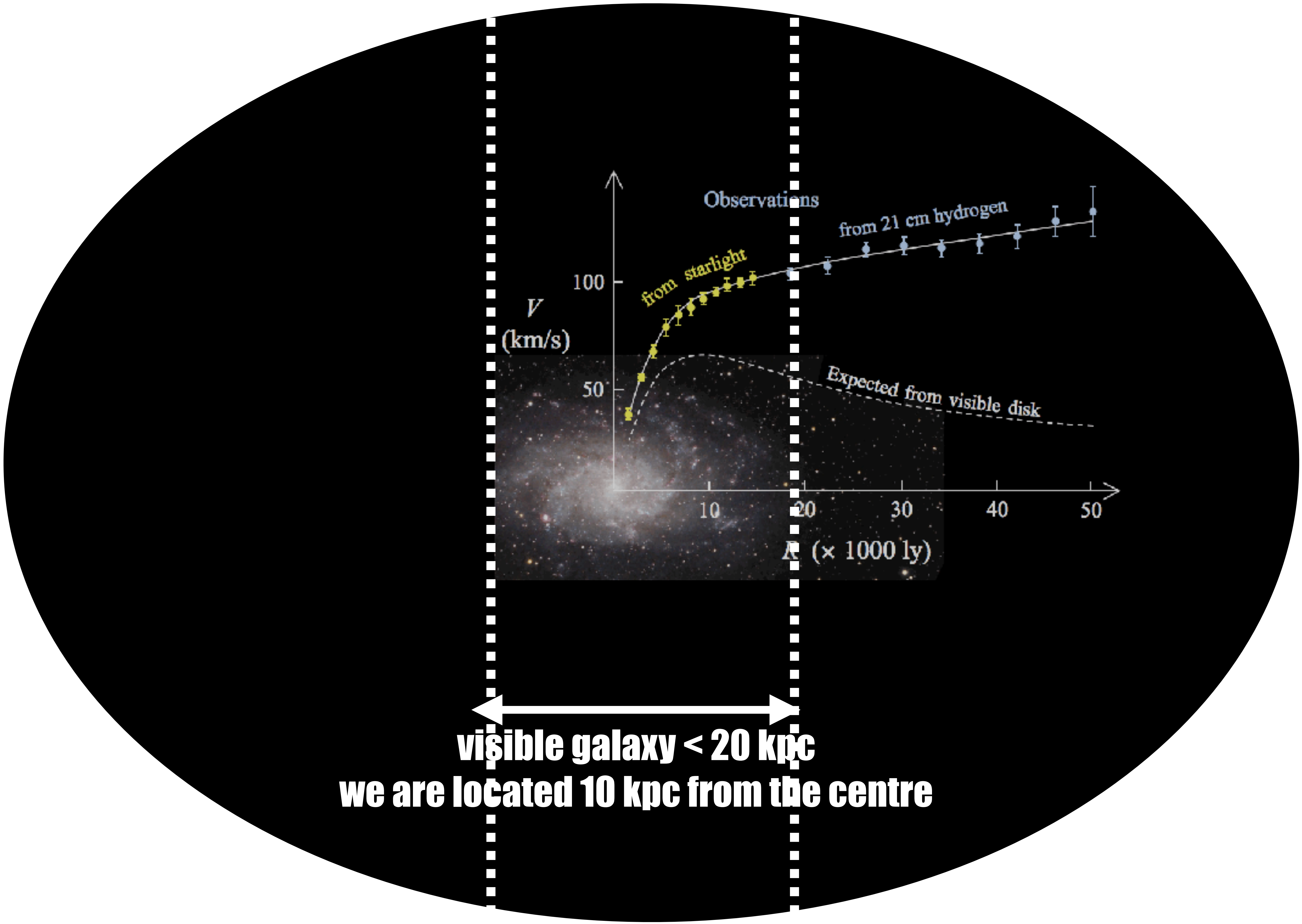
Rotation curves of galaxies



We need DM to explain the flat rotation curves **far from the GC**

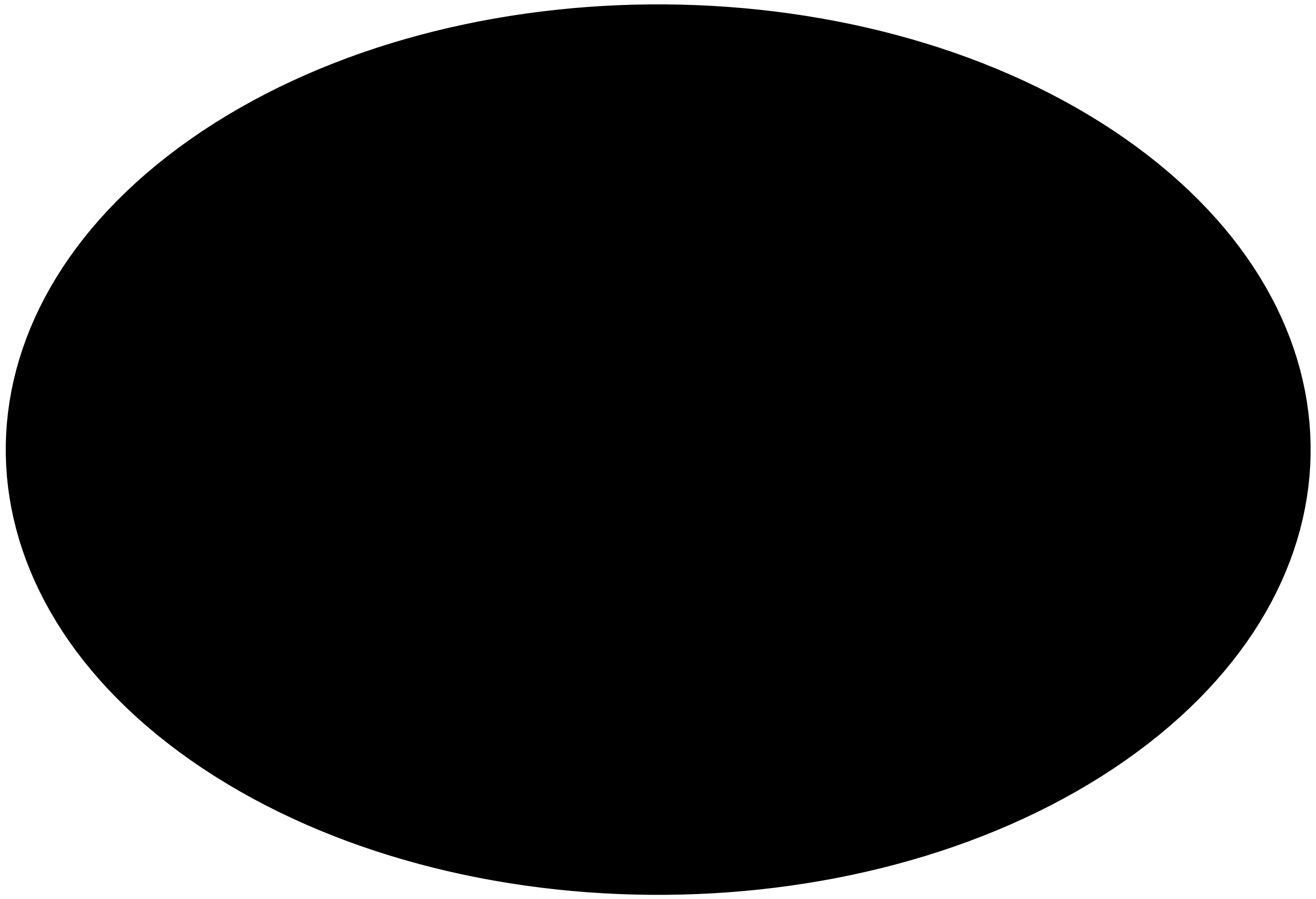
$$v_c^2 = \frac{G\,M(r)}{r} \qquad M(r) = \int 4\pi^2 \rho(r)\, d^3r$$

But the highest mass density would be in the inner part of the galaxy...



Complexed structure ; much more extended

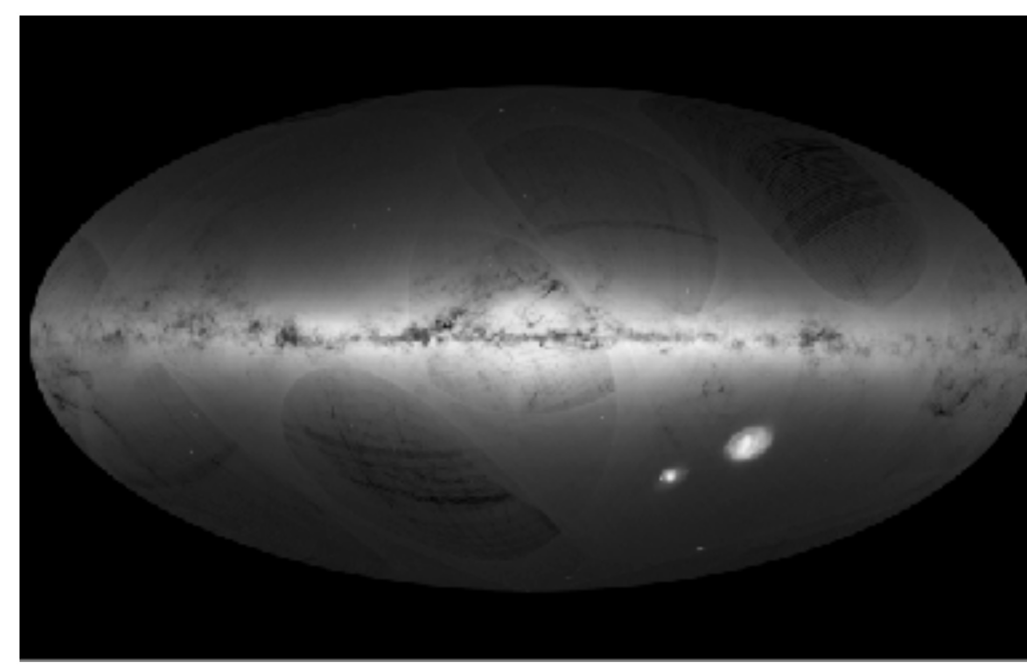
The Milky Way



A “dark matter” halo

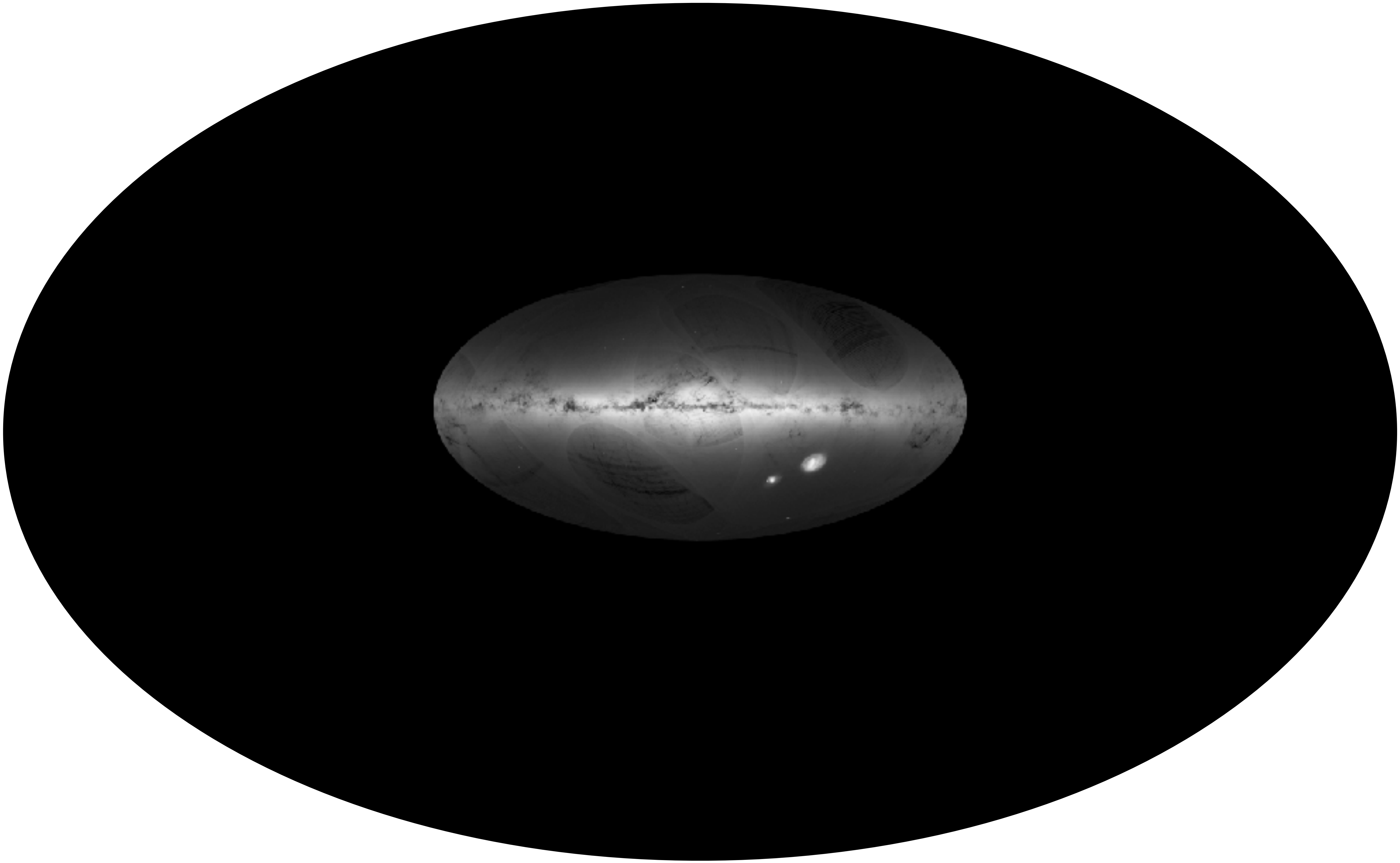
+

A visible disc made of stars



MW seen by ESA/Gaia

The Milky Way

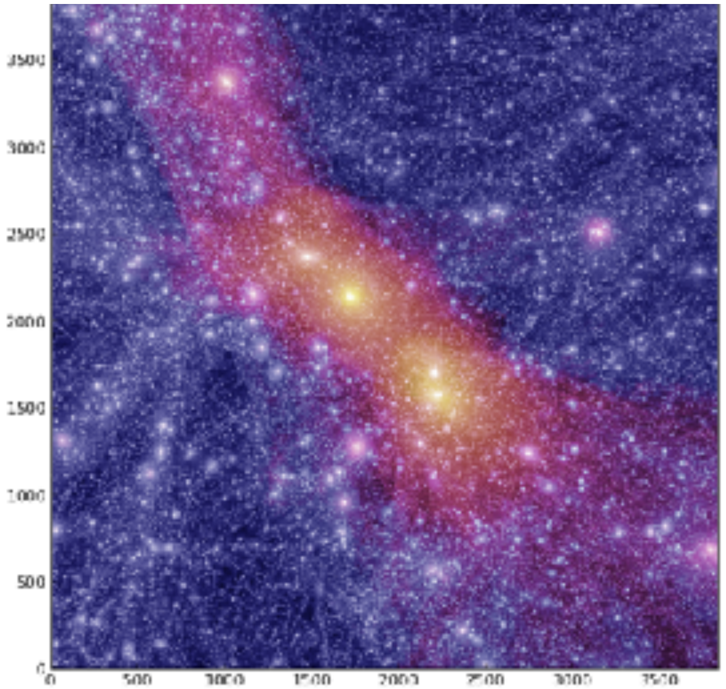


Dark Matter is every where

Cluster of galaxies

NGC 6814 Credit: NASA

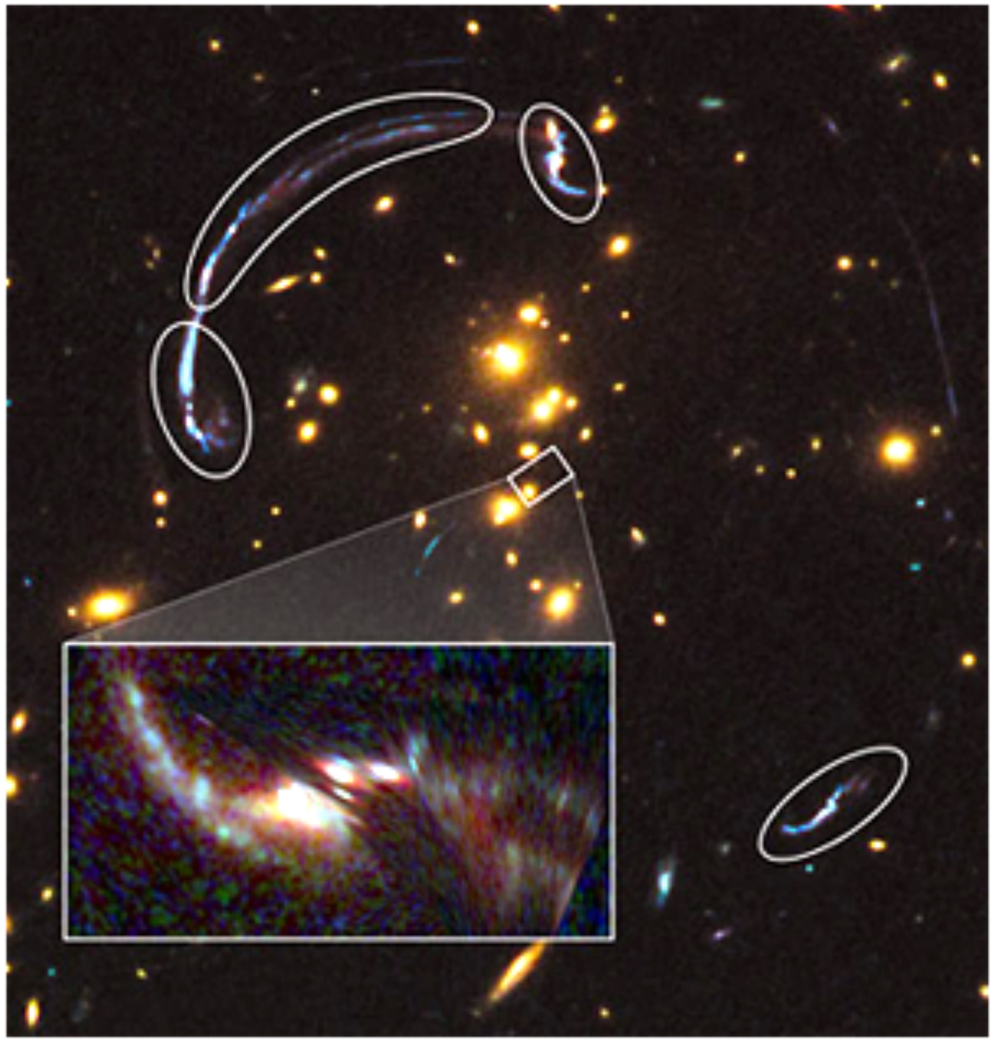
NGC 4621 Credit: WikiSky/SDSS



But what is the DM?

Gravitational lensing evidence…

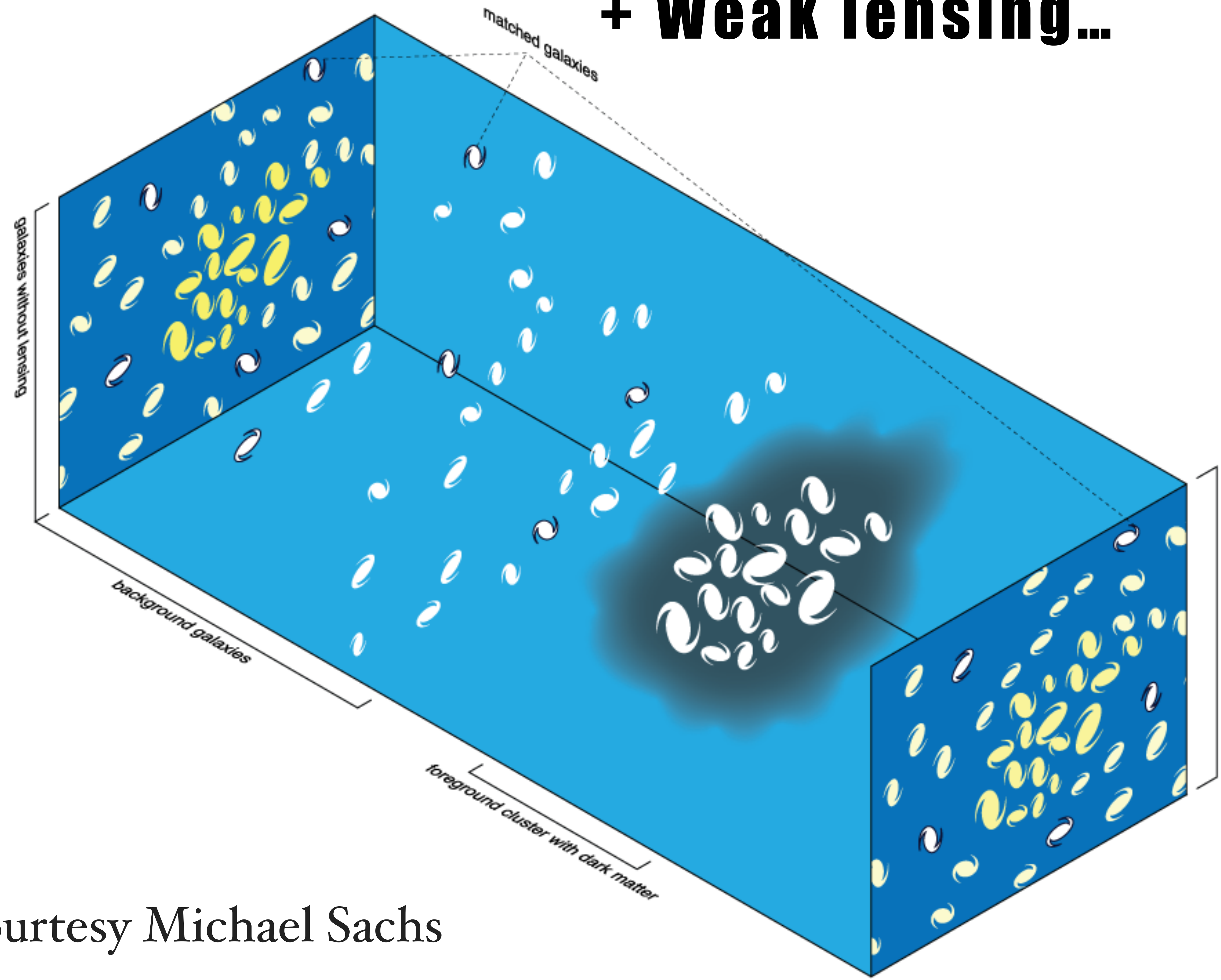
Illustration Credit: NASA, ESA, and Z. Levay (STScI)
Science Credit: NASA, ESA, J. Rigby
(NASA Goddard Space Flight Center),
K. Sharon (Kavli Institute for Cosmological Physics,
University of Chicago), and M. Gladders & E. Wuyts
(University of Chicago)



Reconstruction (lower left) of the brightest galaxy whose image has been distorted by the gravity of a distant galaxy cluster.

The small rectangle in the center shows the location of the background galaxy on the sky if the intervening galaxy cluster were not there. The rounded outlines show distinct, distorted images of the background galaxy resulting from lensing by the mass in the cluster.
The image at lower left is a reconstruction of what the lensed galaxy would look like in the absence of the cluster, based on a model of the cluster's mass distribution derived from studying the distorted galaxy images.

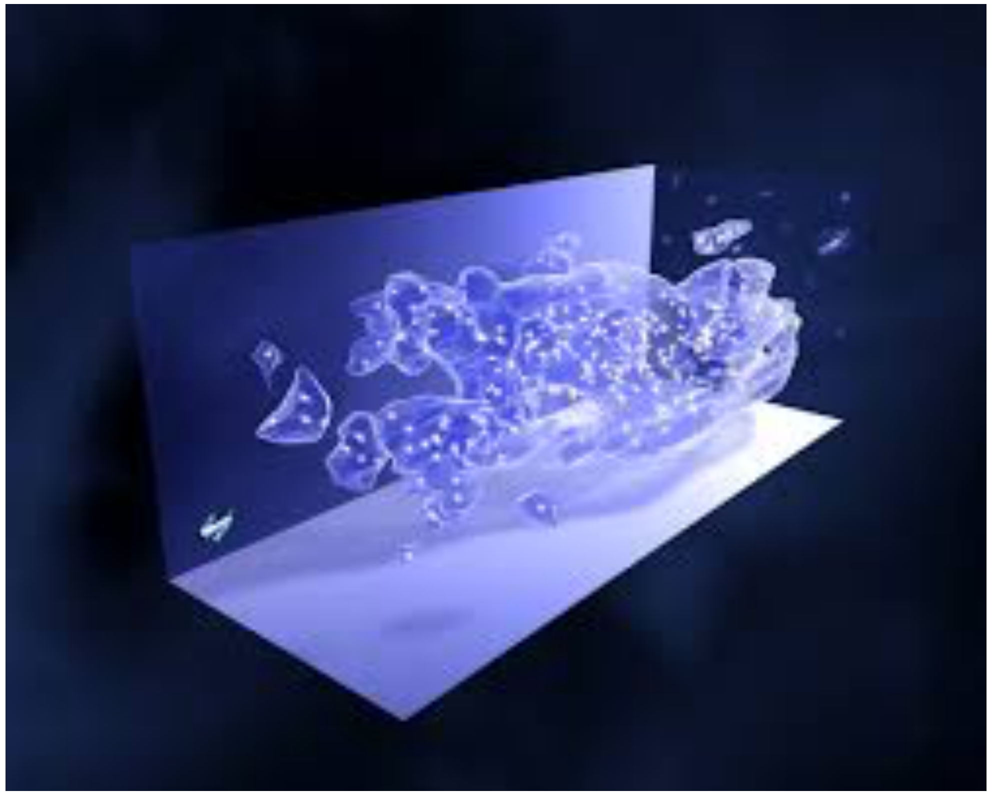
+ Weak lensing...

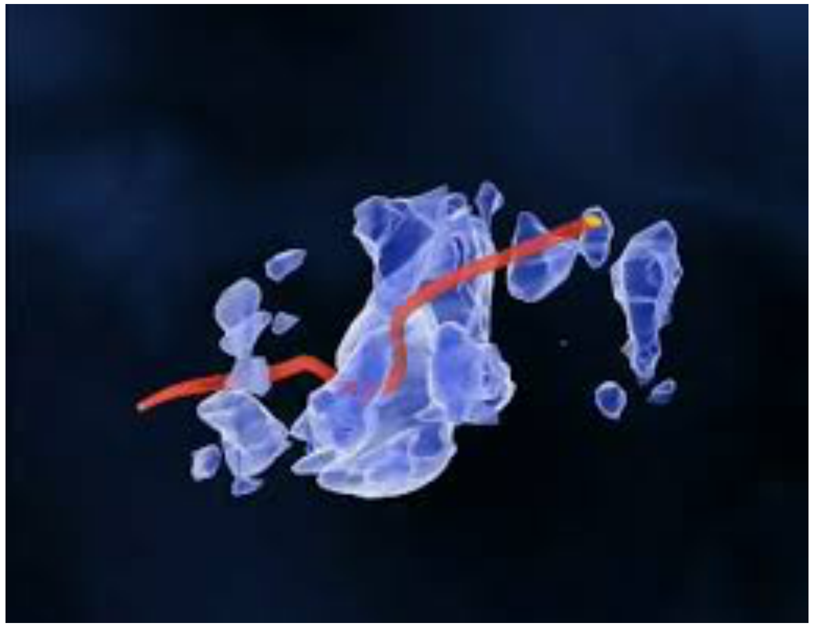


Courtesy Michael Sachs

More lensing evidence...

X-ray emitted by gas
(Thomson interactions, Bremsstrahlung,...)
But the gravitational potential is dominant
in the blue region where no light is emitted





The cosmological evidence

J. Peebles

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- Citations to the Article (85) (Citation History)
- Refereed Citations to the Article
- Also-Read Articles (Reads History)
- Translate This Page

Title:	The Gravitational Instability of the Universe
Authors:	Peebles, P. J. E.
Publication:	Astrophysical Journal, vol. 147, p.859 (ApJ Homepage)
Publication Date:	03/1967
Origin:	ADS
DOI:	10.1086/149077
Bibliographic Code:	1967ApJ...147..859P

Abstract

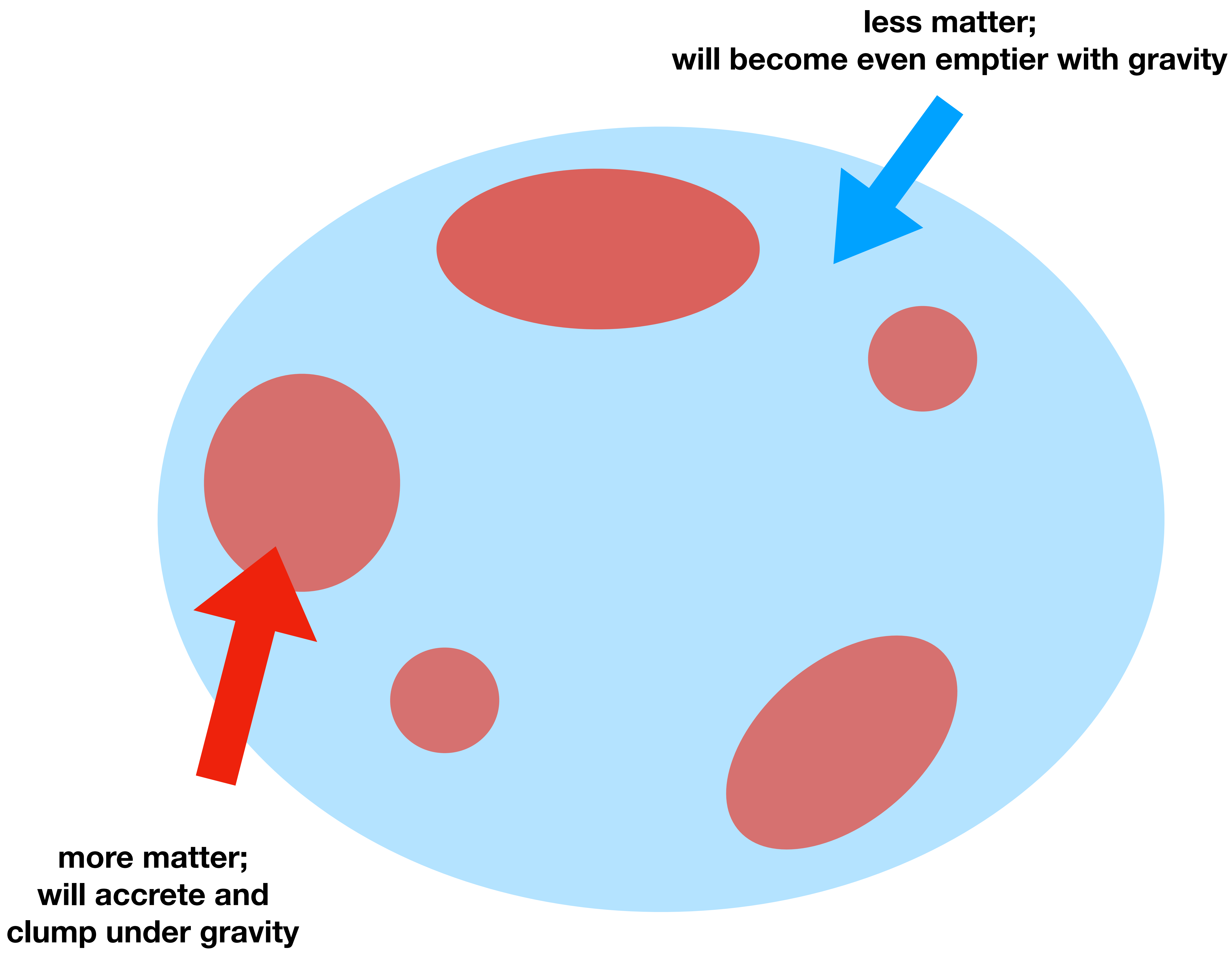
It is argued that the expanding universe is unstable against the growth of gravitational perturbations. The argument is directed toward two problems, the physical conditions in the early, highly contracted phase of the expanding universe, and the formation of the galaxies.

Followed Peebles, P. J. E., *Astrophys. J.*, **142**, 1317 (1965)

http://adsabs.harvard.edu/abs/1970ApJ...162..815P

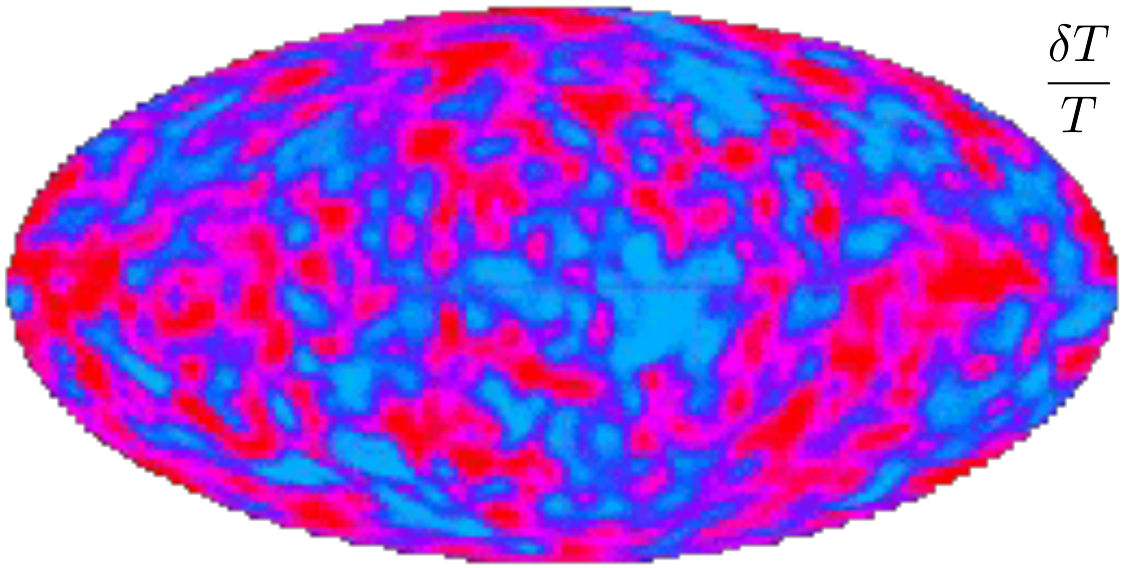
Primordial fluctuations in the Early Universe grow under gravity (Peebles, 66)

$$I(x) \propto \frac{x^3}{e^x - 1} \qquad x = \frac{h\nu}{\kappa T} \qquad \Longrightarrow \qquad \frac{\Delta T}{T} \simeq 10^{-5}$$

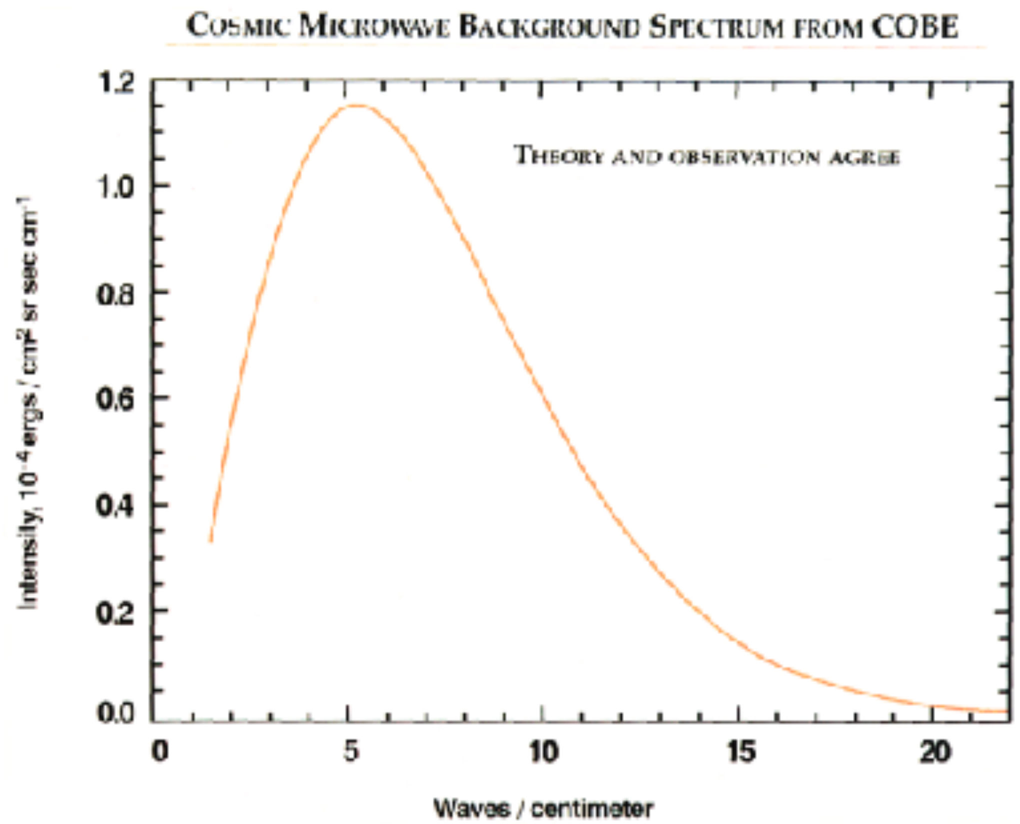

less matter;
will become even emptier with gravity
more matter;
will accrete and
clump under gravity

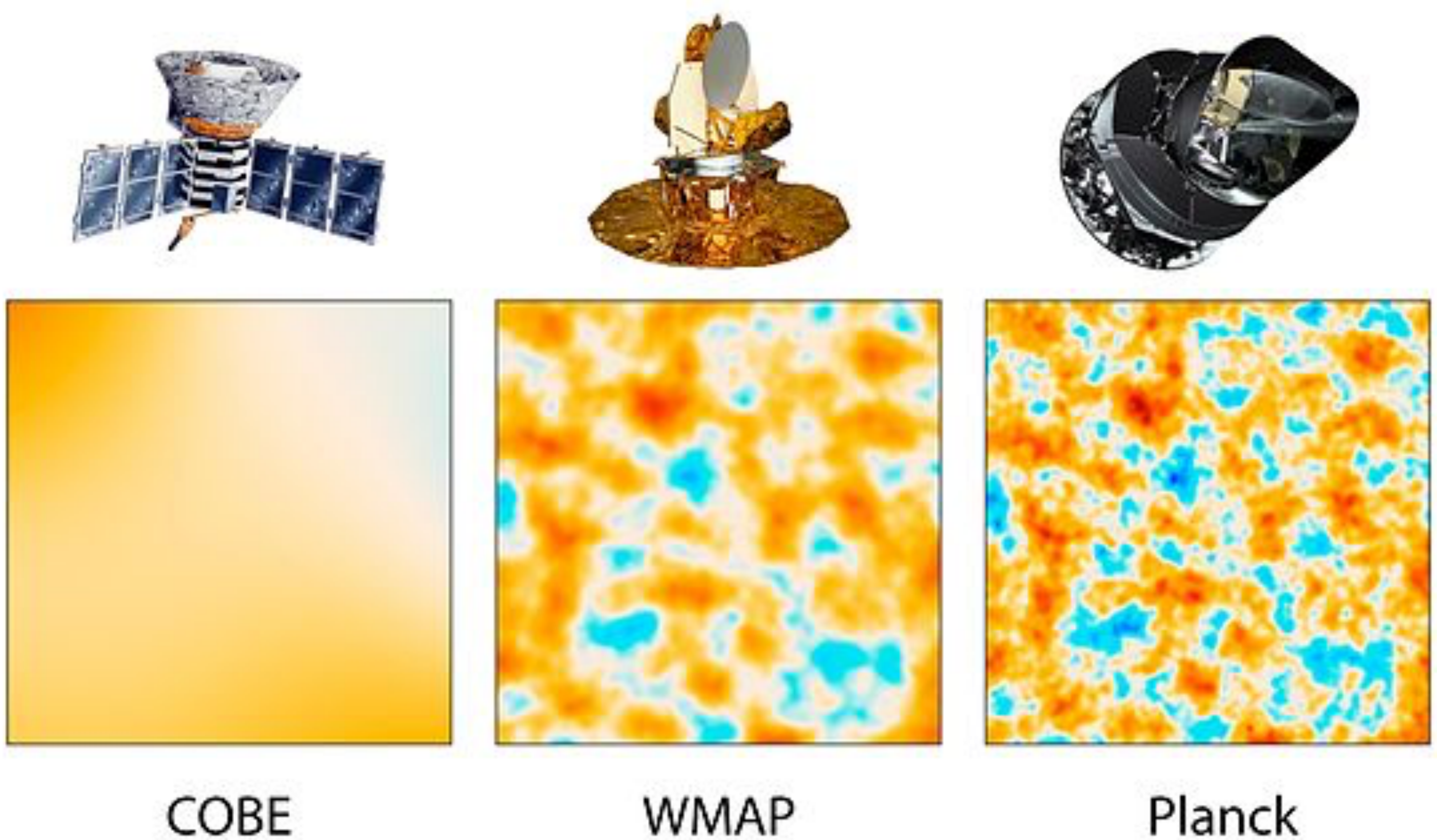
The cosmological evidence

Was Peebles right?



$$\frac{\delta T}{T} \simeq 10^{-5}$$





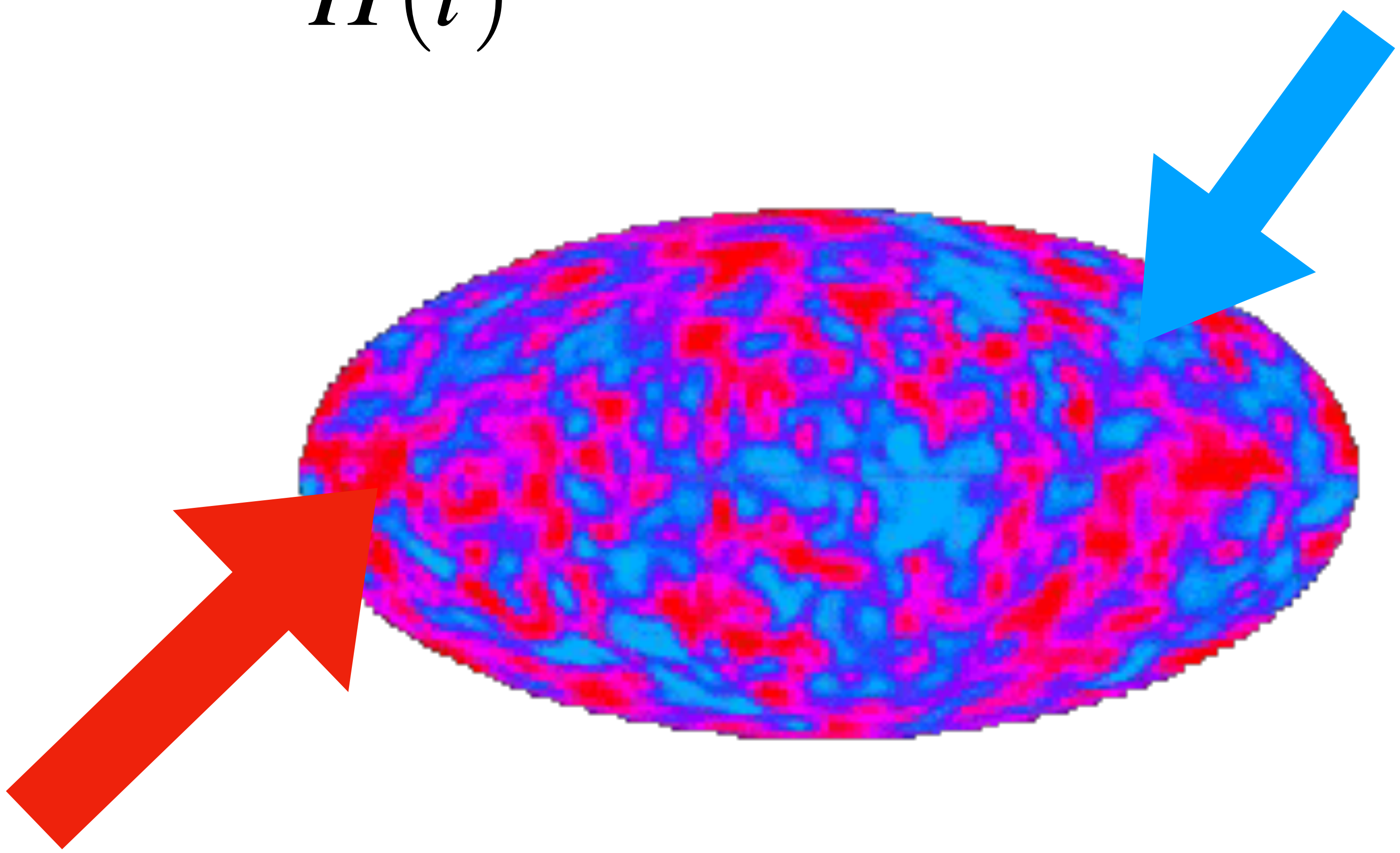
courtesy wikipedia!

YES!

so either Silk wrong or more matter than baryons

The cosmological evidence

$$d(t) = \frac{c}{H(t)}$$

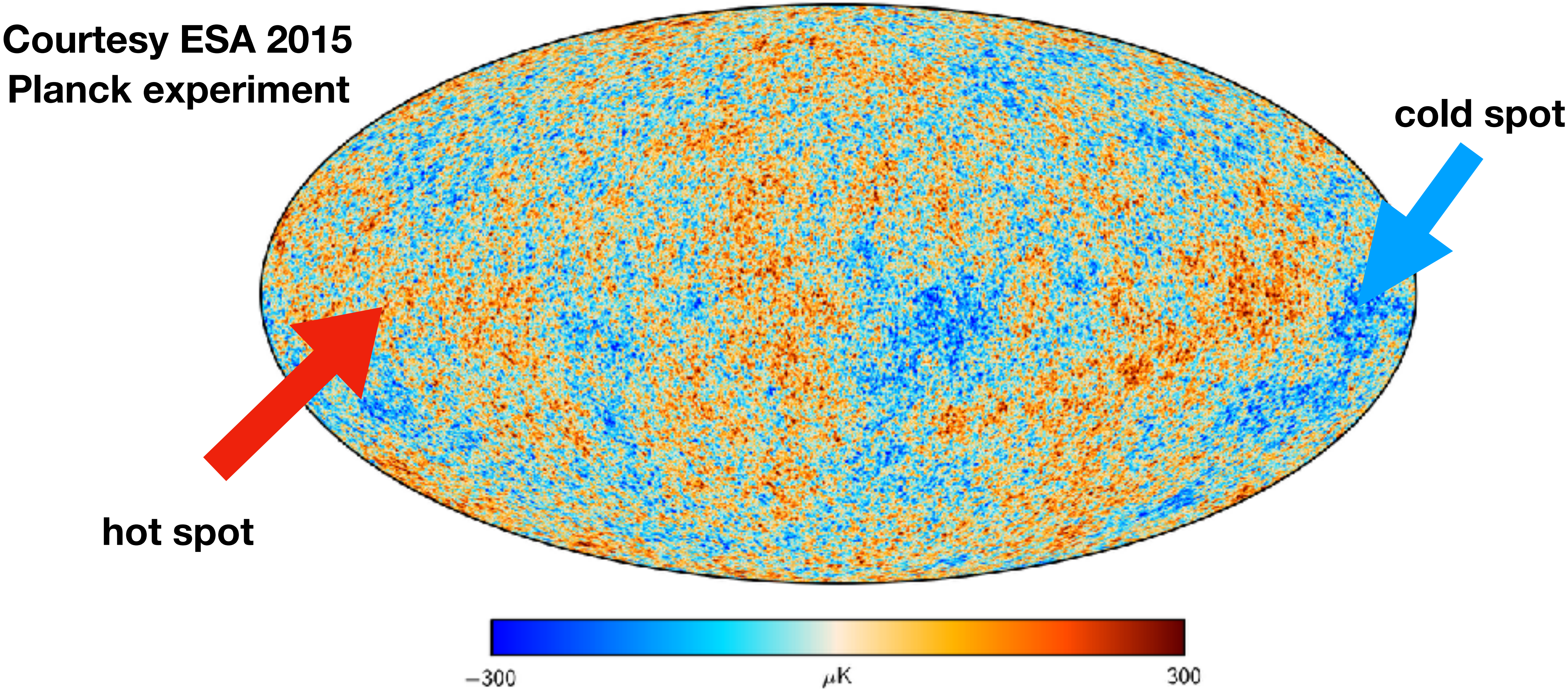


>> galaxy scale (1 Mpc ~ 10^27 cm)

All regions of the sky have a temperature around 2.7k! $\frac{\delta T}{T} \simeq 10^{-5}$

How come?

The cosmological evidence

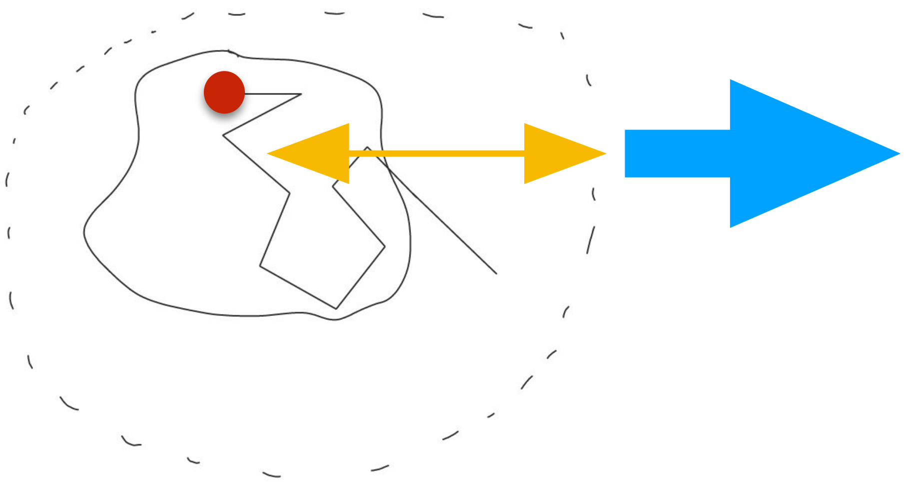


>> galaxy scale (1 Mpc ~ 10^27 cm)

All regions of the sky have a temperature around 2.7k + $\frac{\delta T}{T} \simeq 10^{-5}$

How come such a tiny difference on such gigantic scales?

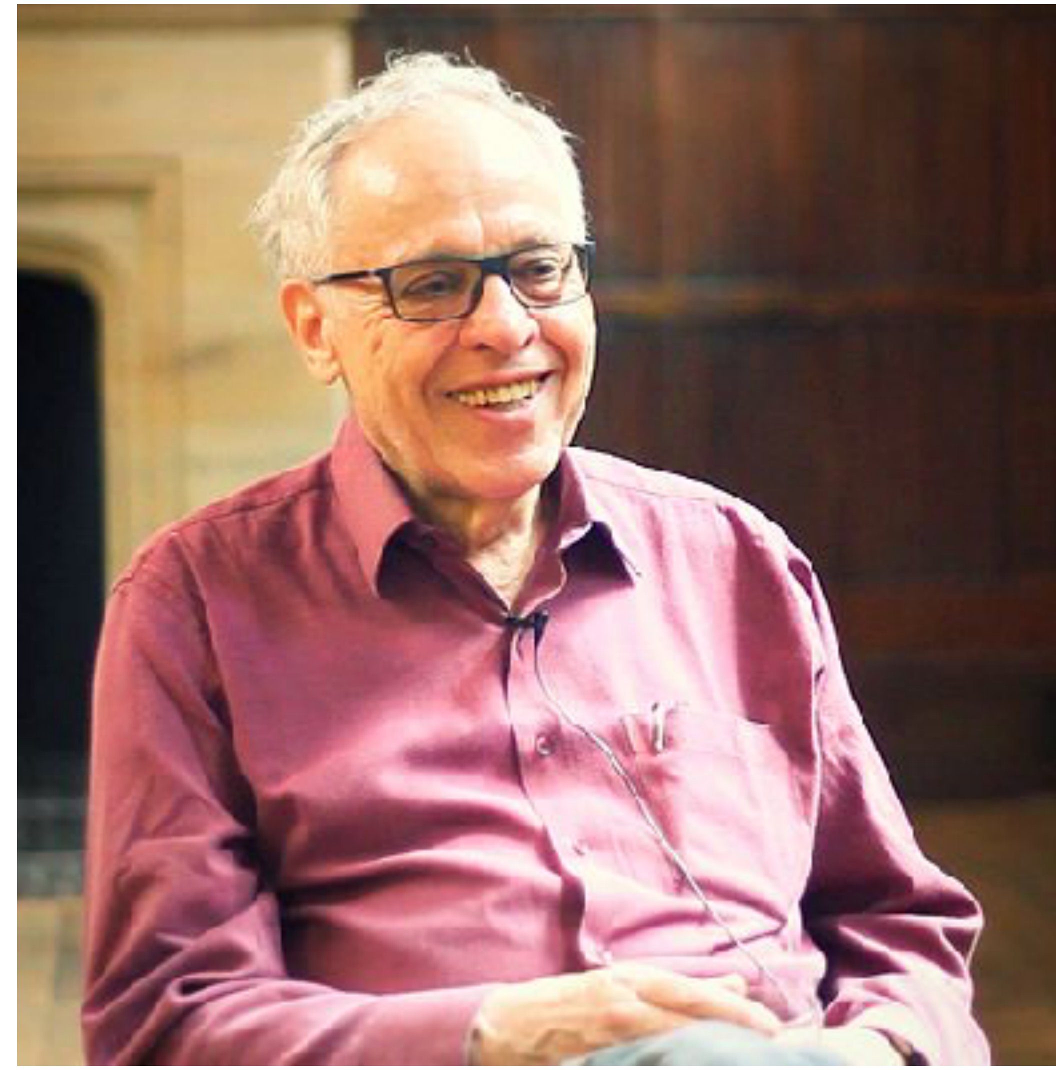
The cosmological evidence



Deficit of galaxies

baryonic fluctuations do not survive the baryon scattering off the photon background.

(Question first asked by Misner for neutrinos)



J. Silk

letters to nature

Nature **215**, 1155 - 1156 (09 September 1967); doi:10.1038/2151155a0

Fluctuations in the Primordial Fireball

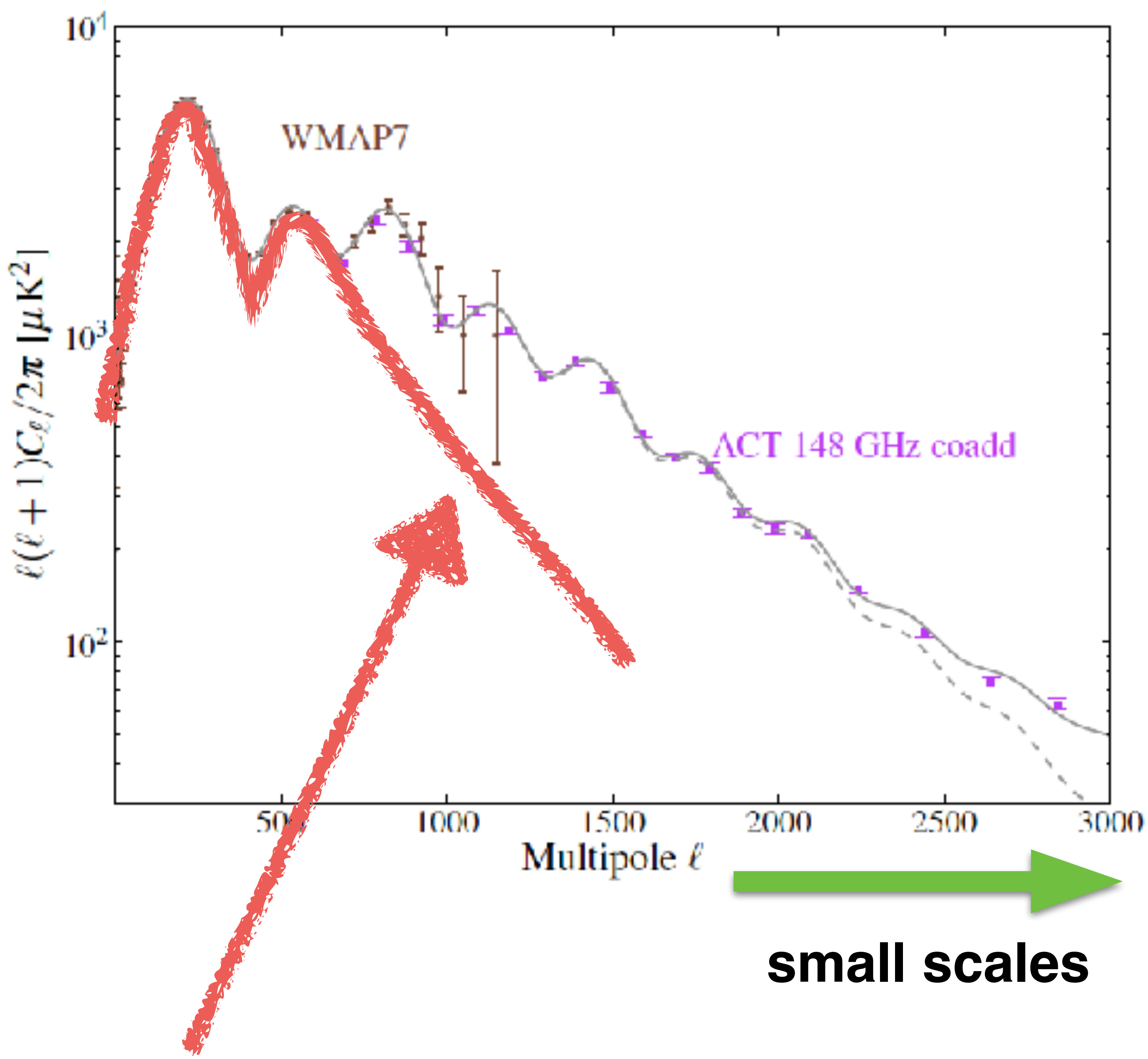
JOSEPH SILK

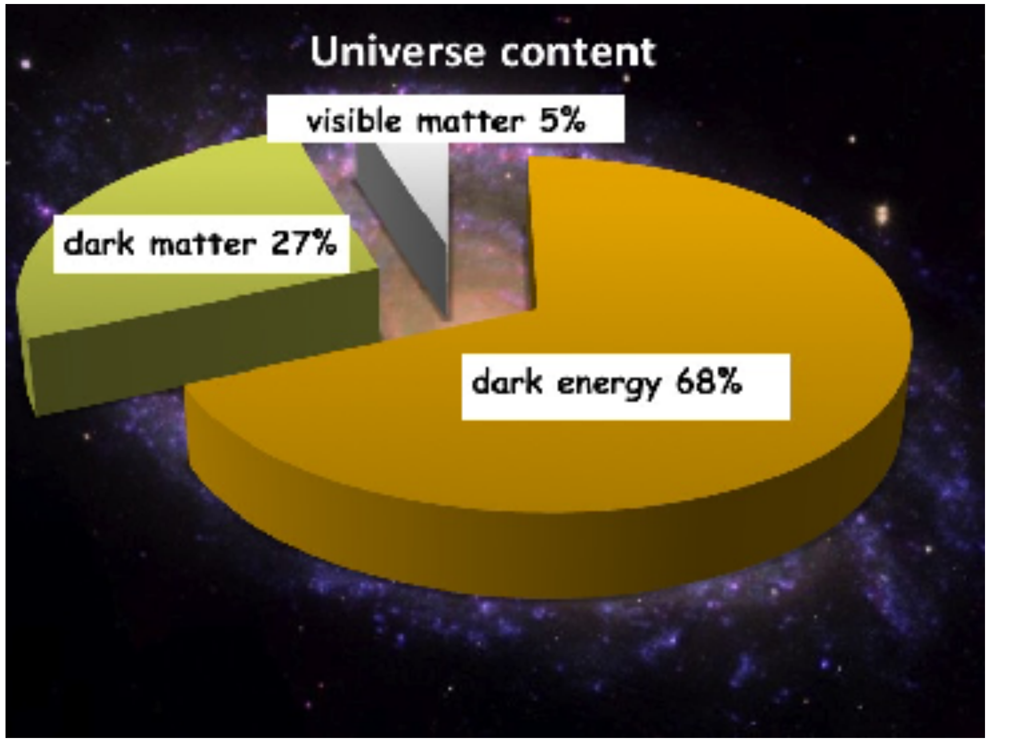
Harvard College Observatory, Cambridge, Massachusetts.

ONE of the overwhelming difficulties of realistic cosmological models is the inadequacy of Einstein's gravitational theory to explain the process of galaxy formation[1–6]. A means of evading this problem has been to postulate an initial spectrum of primordial fluctuations[7]. The interpretation of the recently discovered 3° K microwave background as being of cosmological origin[8,9] implies that fluctuations may not condense out of the expanding universe until an epoch when matter and radiation have decoupled[4], at a temperature T_D of the order of 4,000° K. The question may then be posed: would fluctuations in the primordial fireball survive to an epoch when galaxy formation is possible ?

Was Silk right?

The CMB evidence





the red curve = baryons only
grey curve = baryons + DM

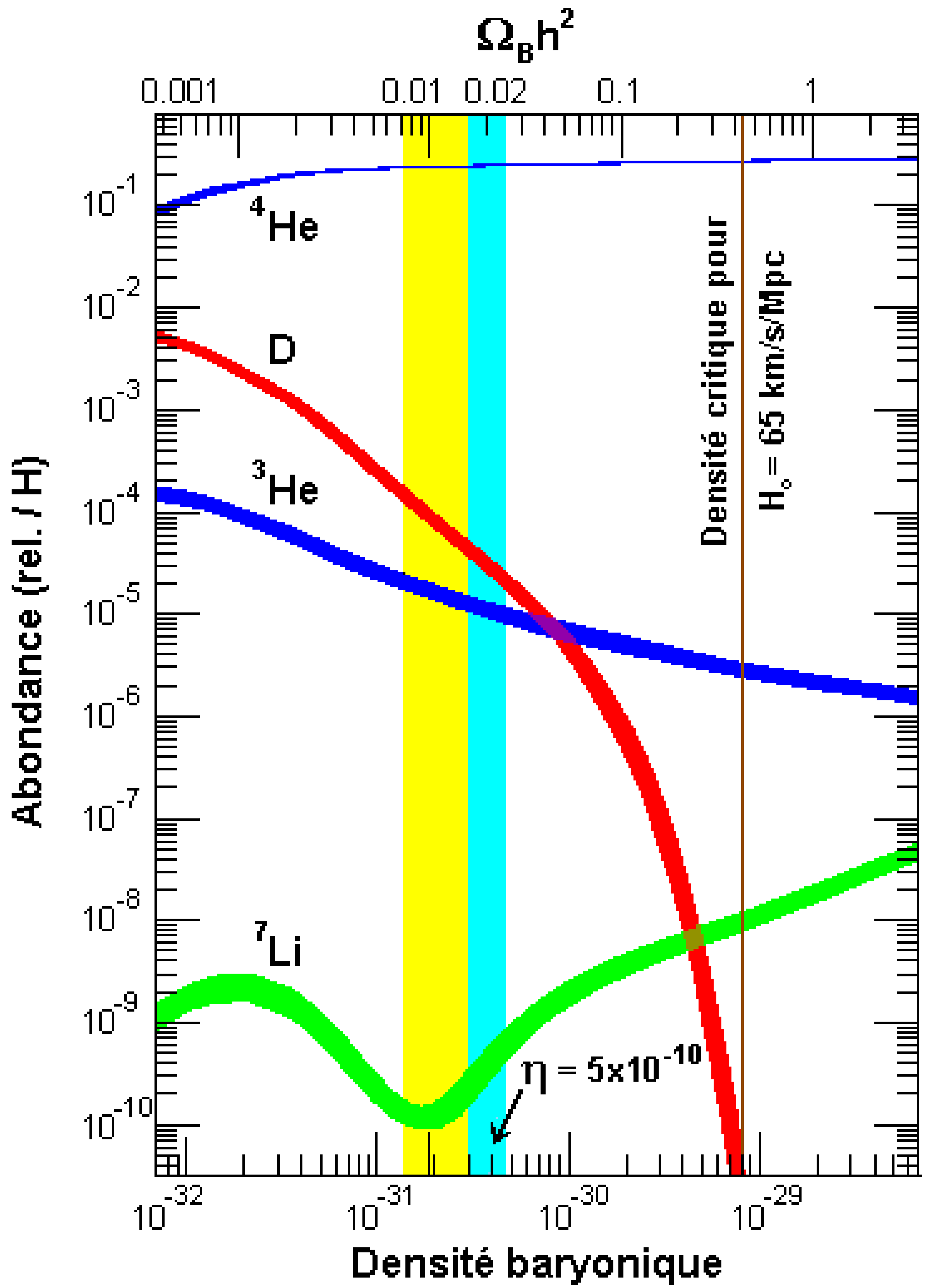
but also … the suppression of small-scales is indicative of the presence of baryons

Baryons scatters off photons (which are relativistic and the most abundant particles in the early Universe). They diffuse on large scales, leading to a **deficit of small-scale fluctuations.**

Based on the Silk damping
we can conclude that ordinary matter
cannot dominate the Universe's energy content.

yes, so only need 5% of baryons (!?)

Baryons in the Universe



Baryons can be dark but cannot be (all) the dark matter.

Only **~5% max** of baryons

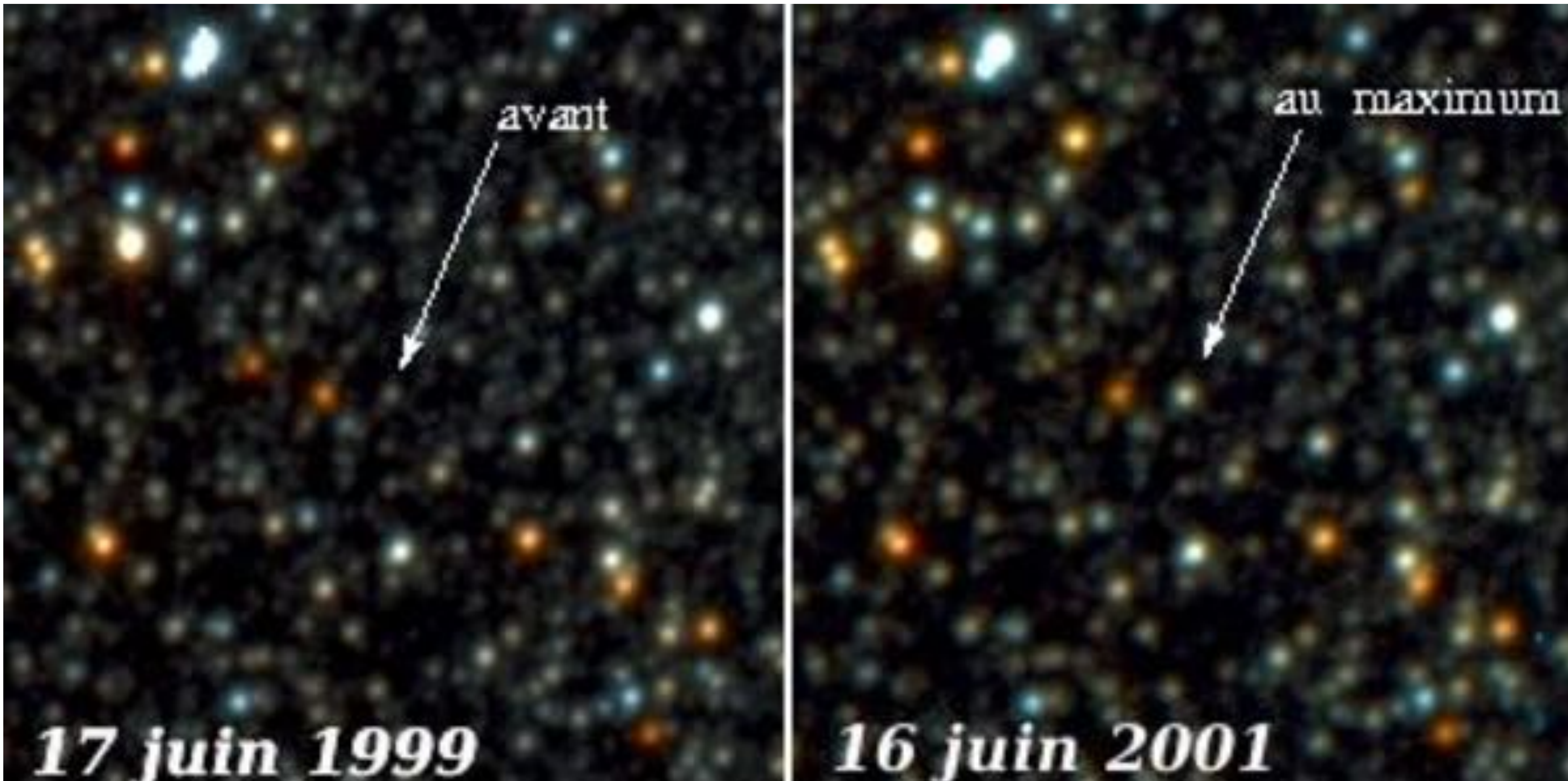
Consistent with CMB!

Where are the baryons?

Baryons in the Universe

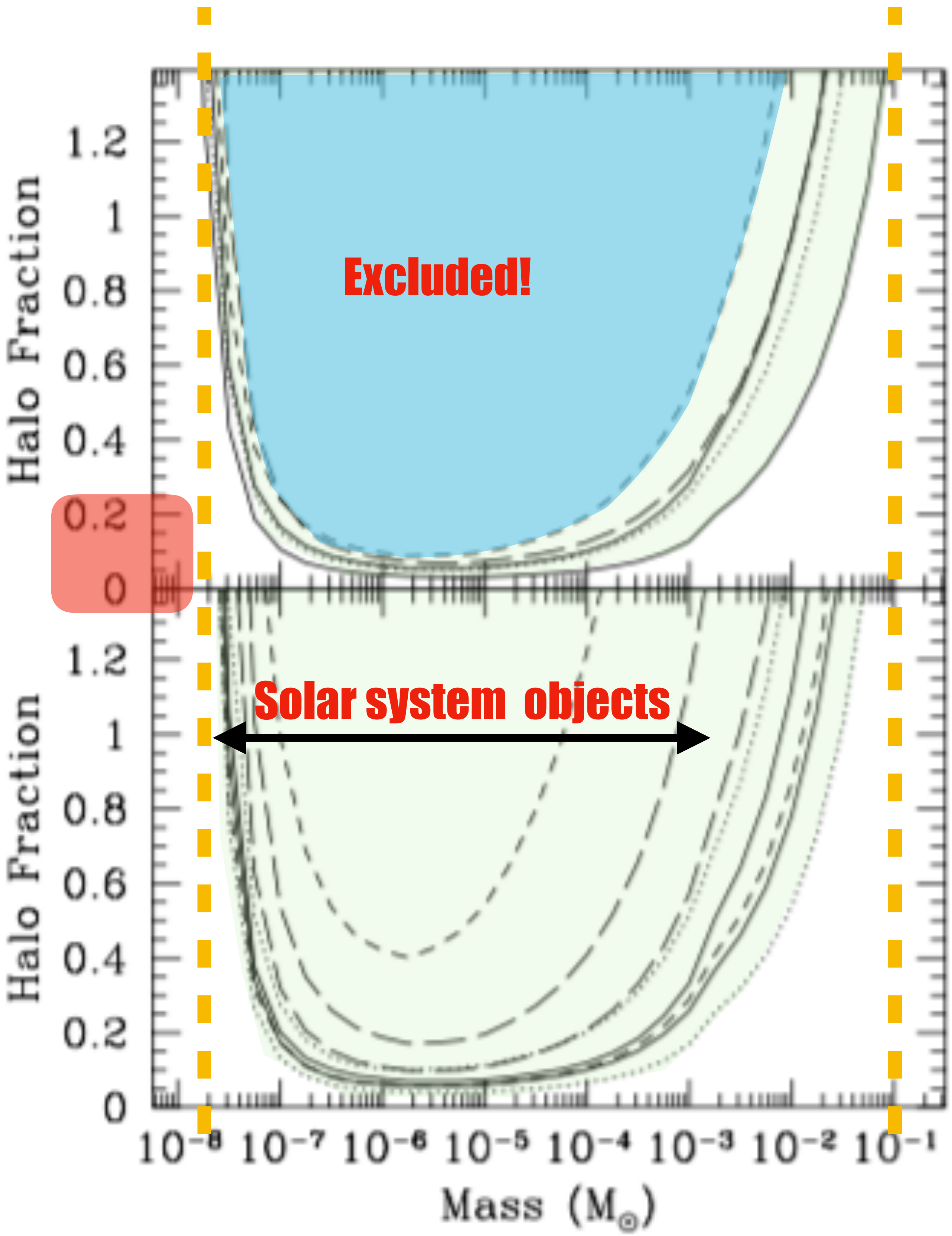
<u>*Microlensing effect...*</u>

Before and two years after (during the maximum of amplification)



Courtesy: EROS experiment. They were looking for "brown dwarfs" or "MACHOs" which belong gravitationally to our Galaxy. This was made possible by their gravitational microlensing effects on stars in the Magellanic Clouds (two dwarf galaxies, Milky Way satellites).

Is the dark matter made of planets?



EROS and MACHO

(La Silla vs Mount Stromlo Observatory, Australia)

Earth $3\ 10^{-6}\ M_\odot$

Jupiter $\simeq\ 10^{-3}\ M_\odot$

Pluto $\simeq 6\ 10^{-8}\ M_\odot$

MACHO fraction < 10%

Fig. 3.— Halo fraction upper limit (95% c.l.) versus lens mass for the five EROS models (top) and the eight MACHO models (bottom). The line coding is the same as in Figure 2.

I.

Free (charged) baryons = 5% of the energy content of the Universe.

II.

We need a collisionless species to help forming structures

IS DM a neutrino?

1973

GRAVITY OF NEUTRINOS OF NONZERO MASS IN ASTROPHYSICS

R. COWSIK* AND J. MCCLELLAND
Department of Physics, University of California, Berkeley
Received 1972 July 24

ABSTRACT

If neutrinos have a rest mass of a few eV/c^2, then they would dominate the gravitational dynamics of the large clusters of galaxies and of the Universe. A simple model to understand the virial mass discrepancy in the Coma cluster on this basis is outlined.

Subject headings: cosmology — galaxies, clusters of — neutrinos

1977 - Hut, Lee&Weinberg : massive neutrinos would work well

1980 - Zel'dovich et al develop Hot Dark Matter (HDM) theory (modified) slide from J. Primack

MASSES AND MASS-TO-LIGHT RATIOS OF GALAXIES[1]

S. M. Faber[2]
Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, California 95064

J. S. Gallagher
Department of Astronomy, University of Illinois, Urbana, Illinois 61801

ARAA 1979

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.

DM is dead, let us have DM again

1983 - White, Frenk, Davis: numerical simulations rule out HDM

Galaxy formation by dissipationless particles heavier than neutrinos

GEORGE R. BLUMENTHAL*, HEINZ PAGELS† & JOEL R. PRIMACK‡

*Lick Observatory, Board of Studies in Astronomy and Astrophysics, ‡Board of Studies in Physics, University of California, Santa Cruz, California 95064, USA
†The Rockefeller University, New York, New York 10021, USA

In a baryon dominated universe, there is no scale length corresponding to the masses of galaxies. If neutrinos with mass <50eV 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.

End of Brief history

1920s-30s — Evidence of missing mass in clusters of galaxies
1966s — Peebles&Yu: fluctuations seed structure formation;
1966 — Misner: neutrino dissipate on small scales
1967 — Silk: baryons also dissipate but on large scales.
1970s — Discovery of flat galaxy rotation curves
1970s — Supersymmetry is proposed (1972/1974)
1977 — Hut, Lee&Weinberg: Relic density for thermal DM particles
1978 — Gunn, Lee, Lerche, Schramm, Steinman: Heavy stable neutral leptons (WIMPs)
1981 — Davis, Lecar, Prior&Witten: light neutrinos can't make Milky Way-like galaxies
1982 — Blumenthal, Pagels&Primack/Peebles: Structure formation for WIMPs
1984 — Cosmological simulations of Cold Dark Matter (CDM)
1985 — Goodman&Witten: birth of Direct detection
1986 — Frukier, Freese&Spergel: Annual modulation
1988 — Indirect detection signatures of DM particles
1992 — COBE discovers CMB fluctuations, Peebles was right and so Silk damping…
1998 — Accelerated expansion of the Universe: DM only 25% of total
2001 — Official end of LEP; LHC is coming — no Higgs found; no SUSY
2001 — Boomerang measures the 1 peak of CMB. Universe is flat.
2003-08 — WMAP and LSS data confirm ΛCDM predictions

Loads of progress since but no major discovery

From J. Primack's "History of dark matter" but slightly modified

Dark Matter and the invisible Universe

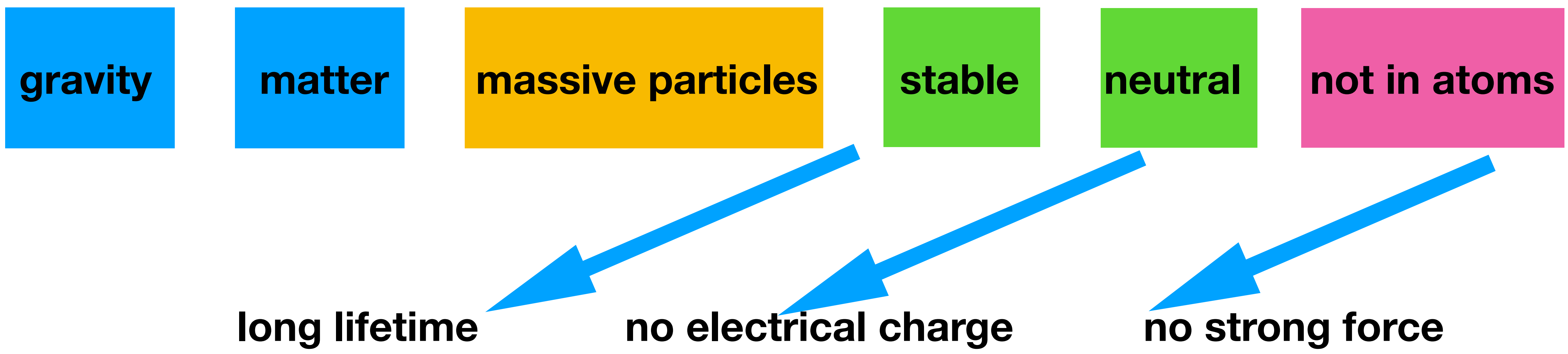
Céline Boehm

IPPP, Durham — Durham University

LAPTH, Annecy — CNRS

DESY, Oct 2017

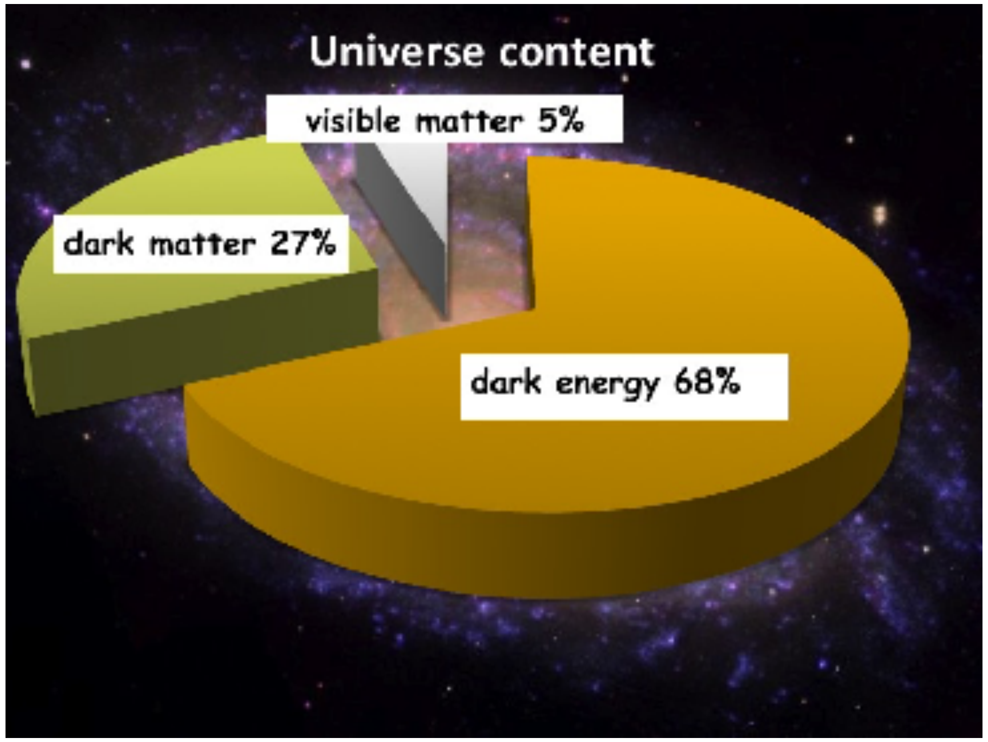
II. A. Particles



Weakly interacting

Relic density

Why 27%?



How many DM particles were produced in the Early Universe?

How much should there be today if DM was made of particles?

Does it match observations?

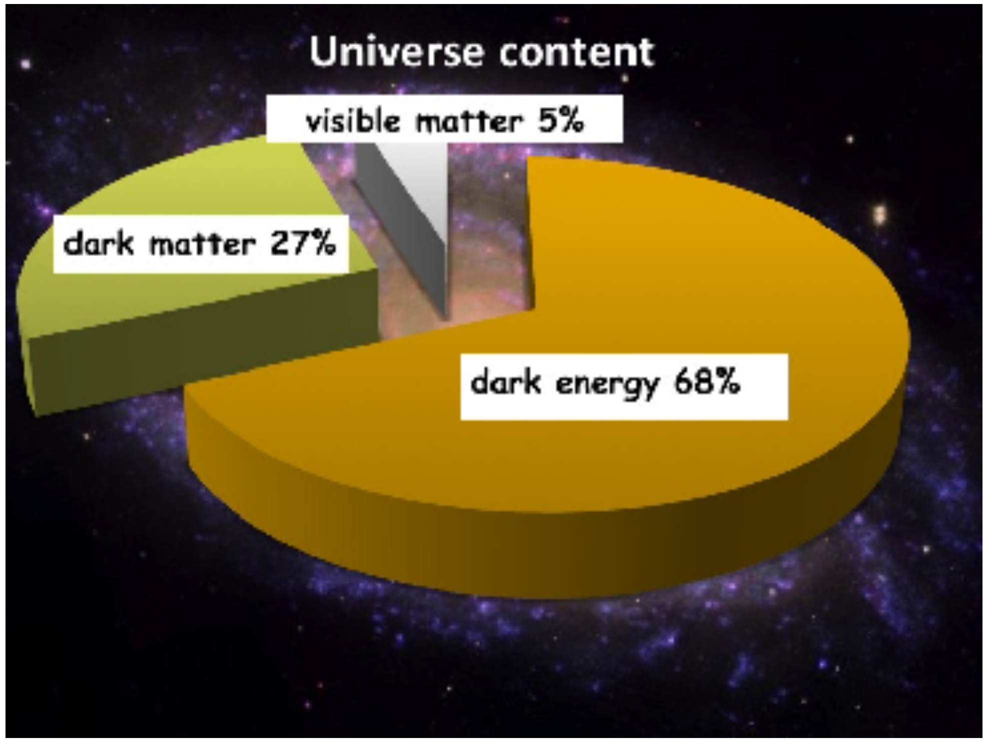
Relic density

For the "baryons"

Thermal production

$$e^+e^- \to \gamma\gamma$$

$$\sigma_T \sim 6\ 10^{-25}\ \text{cm}^2$$



The annihilation process is so efficient that there would be no electrons left at all

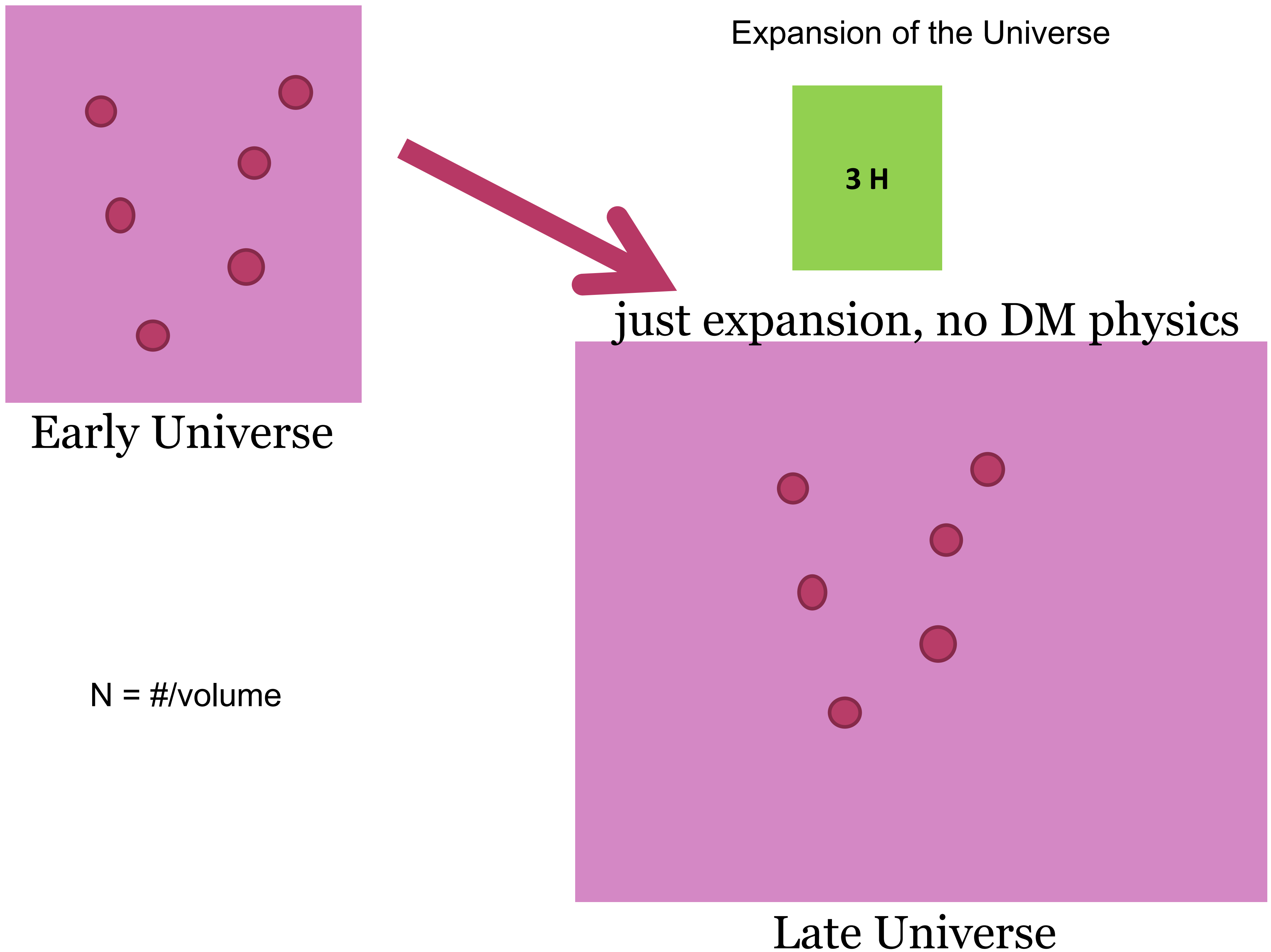
Asymmetry

For the Dark Matter

Thermal production but … non-thermal,freeze-in

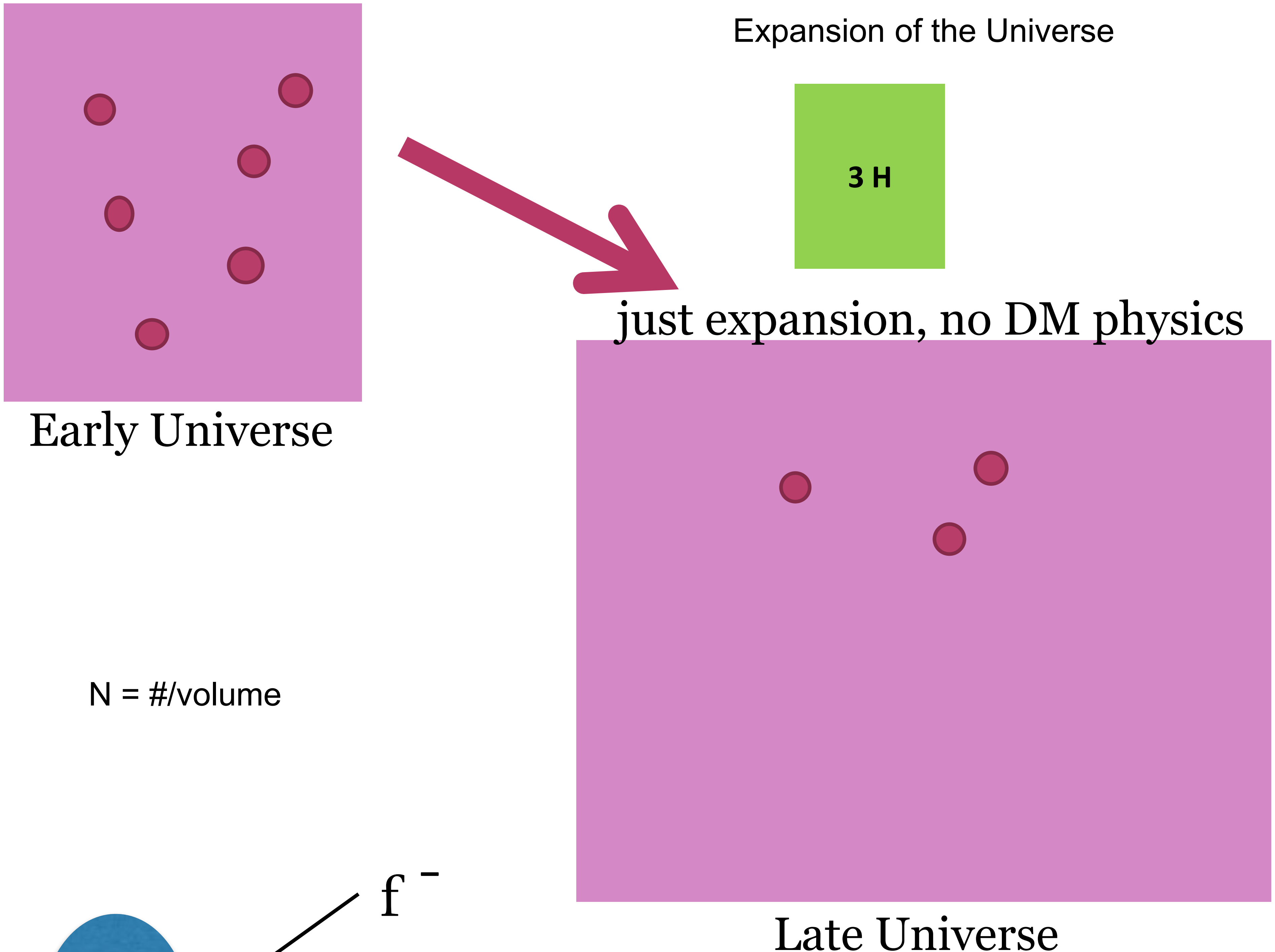
No asymmetry! but …

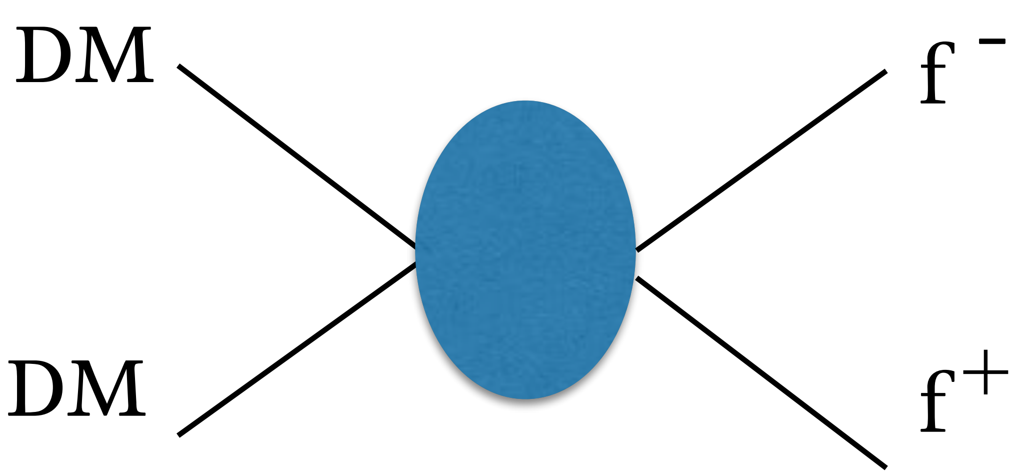
Relic density



Massive DM particles can overclose the Universe!

Relic density





Number is reduced due to annihilations

The Boltzmann equation

Expansion of the Universe

number density of DM

(#/V)

$$\frac{dn}{dt} = -3Hn - \sigma v (n^2 - n_0^2)$$

Time evolution of the number density

Annihilations change the number density

Deriving the Boltzmann equation

$$\frac{df}{d\lambda} = C(f)$$

$$\frac{df}{d\lambda} = \frac{\partial f}{\partial x^\mu}\frac{dx^\mu}{d\lambda} + \frac{\partial f}{\partial p^\nu}\frac{dp^\nu}{d\lambda} = p^\mu \frac{\partial f}{\partial x^\mu} - \Gamma^\nu{}_{\alpha\beta}\, p^\alpha p^\beta \frac{\partial f}{\partial p^\nu}$$

using $\frac{dp^\nu}{d\lambda} + \Gamma^\nu{}_{\alpha\beta}\, p^\alpha p^\beta = 0$

Isotropic Universe

$$p^i \frac{\partial f}{\partial x^i} = 0$$

$$\frac{df}{d\lambda} = E\frac{\partial f}{\partial t} - \Gamma^0{}_{\alpha\beta}\, p^\alpha p^\beta \frac{\partial f}{\partial E}$$

$$E\frac{\partial f}{\partial t} - \Gamma^0{}_{\alpha\beta}\, p^\alpha p^\beta \frac{\partial f}{\partial E} = C(f)$$

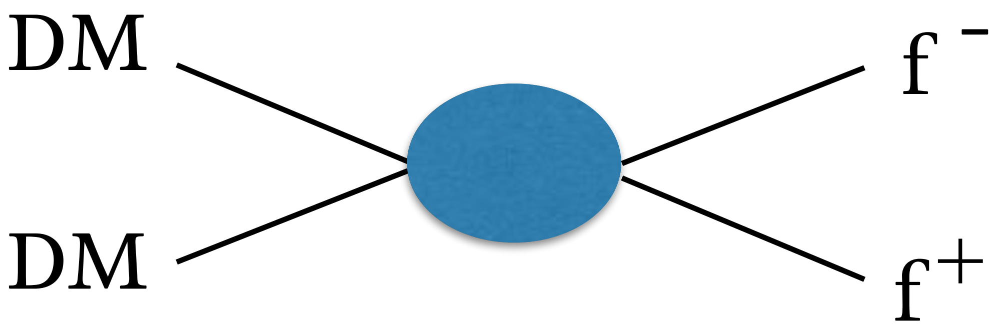
$$\frac{\partial f}{\partial t} - H\frac{E^2-m^2}{E}\frac{\partial f}{\partial E} = \frac{1}{E}C(f)$$

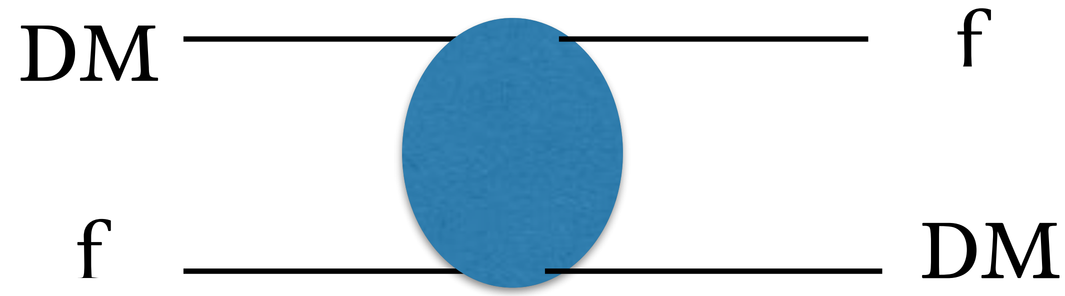
$$\frac{g}{(2\pi)^3}\int\left(\frac{\partial f}{\partial t} - H\frac{E^2-m^2}{E}\frac{\partial f}{\partial E}\right)d^3p = \frac{g}{(2\pi)^3}\int\frac{1}{E}C(f)d^3p.$$

$$\frac{\partial n}{\partial t} + 3Hn = \frac{g}{(2\pi)^3}\int\frac{1}{E}C(f)d^3p.$$

Deriving the Boltzmann equation

$$\frac{\partial n}{\partial t} + 3Hn = \frac{g}{(2\pi)^3} \int \frac{1}{E} C(f) d^3 p.$$





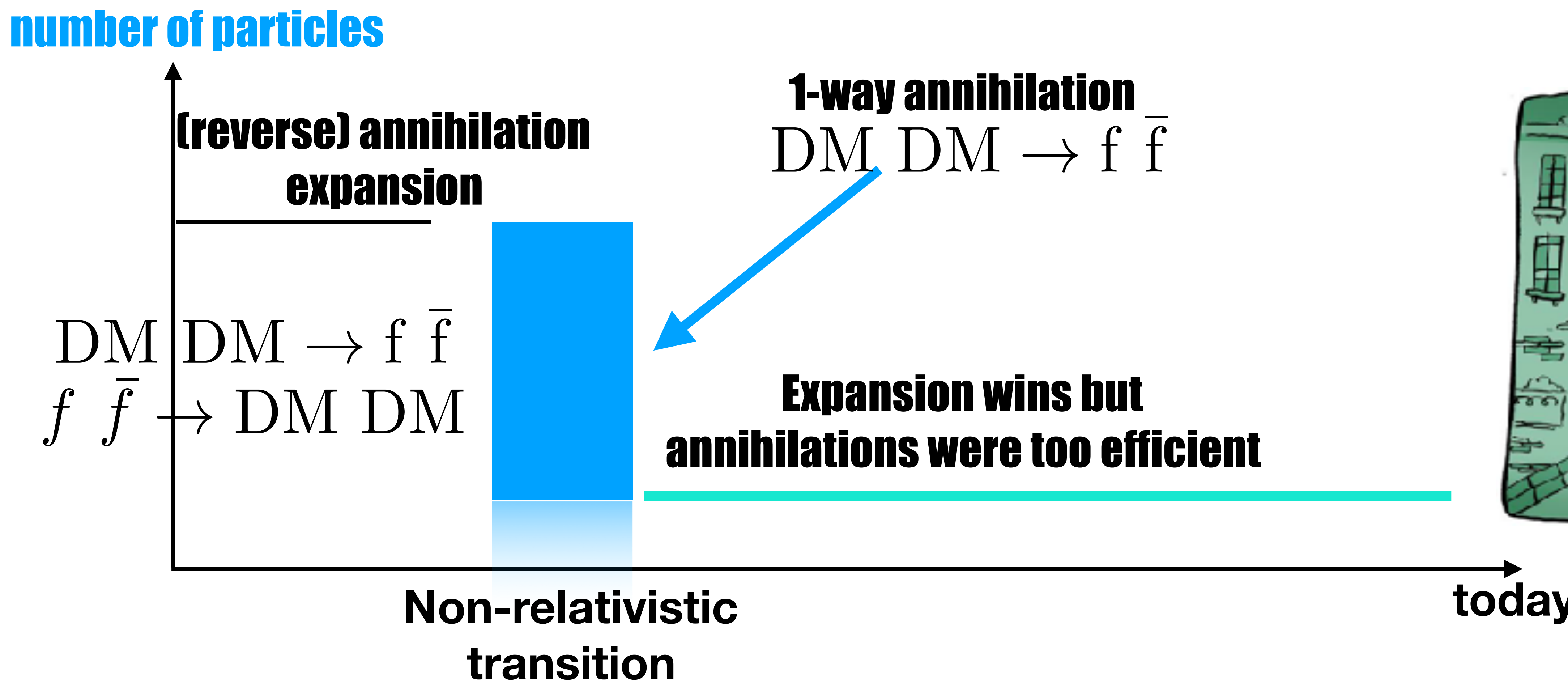
annihilations; change the number density **elastic scattering; do not change density**

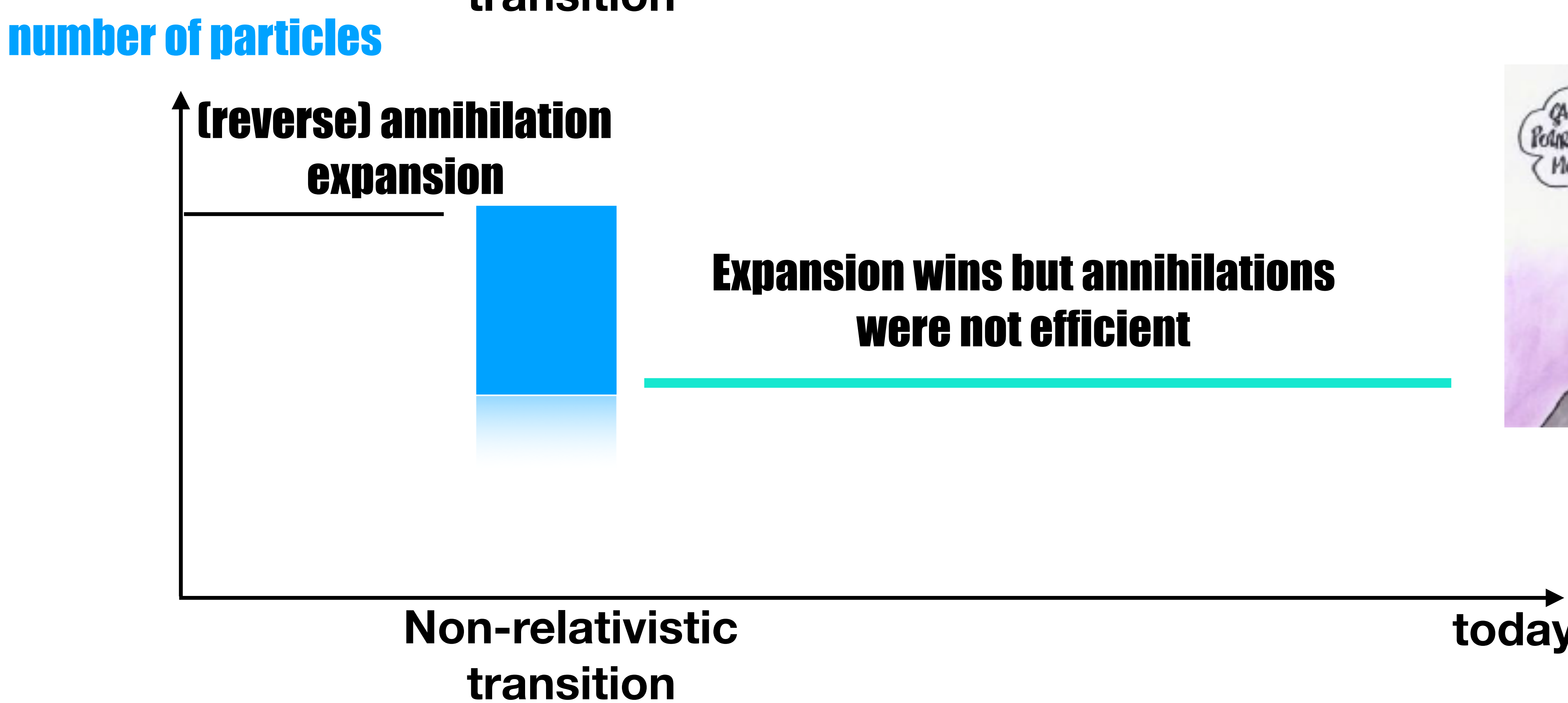
$$C(f) = -\frac{1}{2} \sum_{spins} \int \left[f f_2 (1 \pm f_3)(1 \pm f_4) \left| \mathcal{M}_{12\to34} \right|^2 - f_3 f_4 (1 \pm f)(1 \pm f_2) \left| \mathcal{M}_{34\to12} \right|^2 \right]$$

$$(2\pi)^4 \delta^4 (p + p_2 - p_3 - p_4) \frac{d^3 p_2}{(2\pi)^3 2E_2} \frac{d^3 p_3}{(2\pi)^3 2E_3} \frac{d^3 p_4}{(2\pi)^3 2E_4}$$

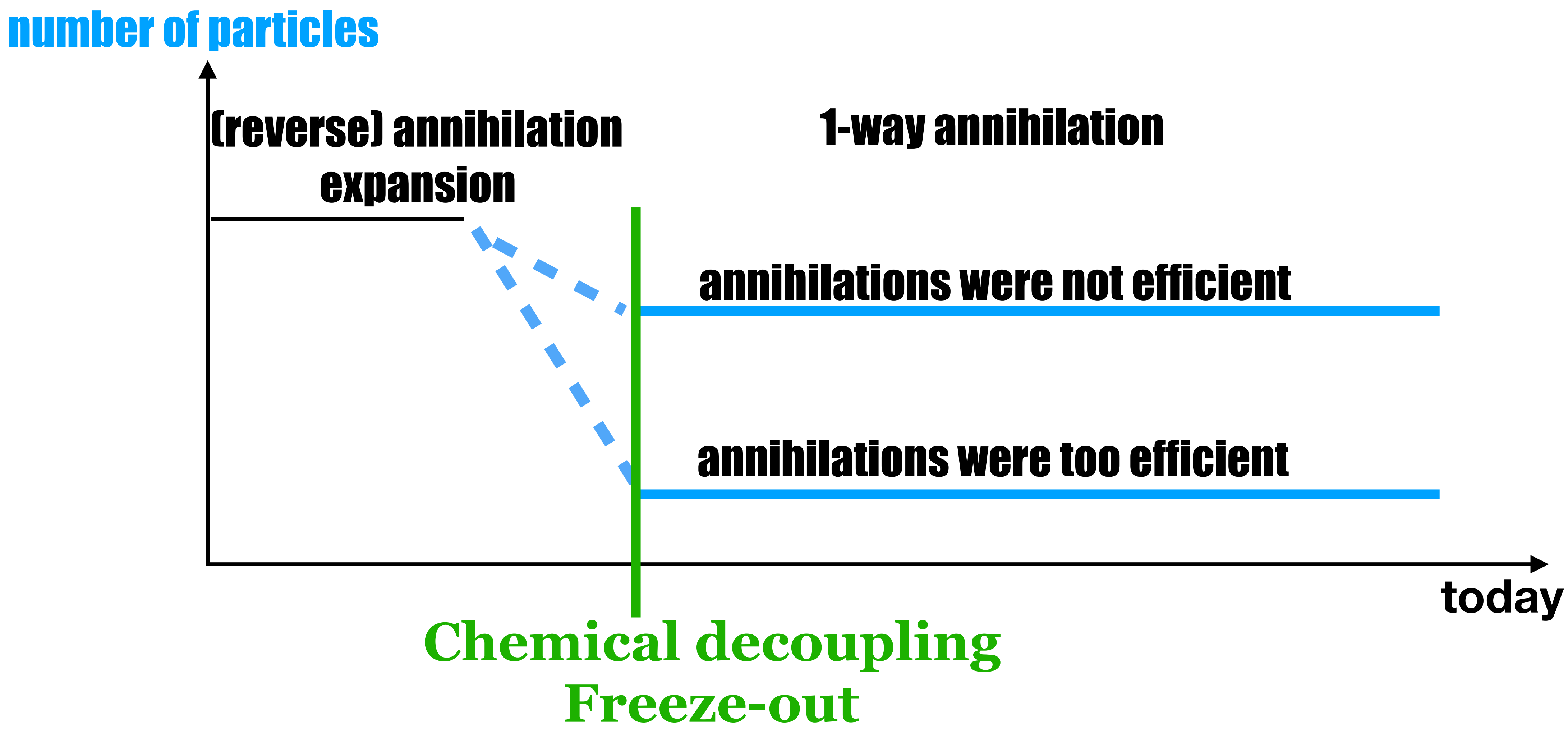
$$\dot{n} = -3Hn - \langle \sigma v \rangle \left(n^2 - n_{eq}^2 \right)$$

Boltzmann equation caught in the act





Boltzmann equation caught in the act



Only one cross section gives the observed number of DM particles!

Interactions maintaining the thermal equilibrium can continue

$$\frac{dn}{dt} = -3Hn - \sigma v(n^2 - n_0^2)$$

$$\sigma v \; n_{DM}^2 \simeq H \; n_{DM} \;\rightarrow\; \sigma v \; n_{DM} \simeq H$$

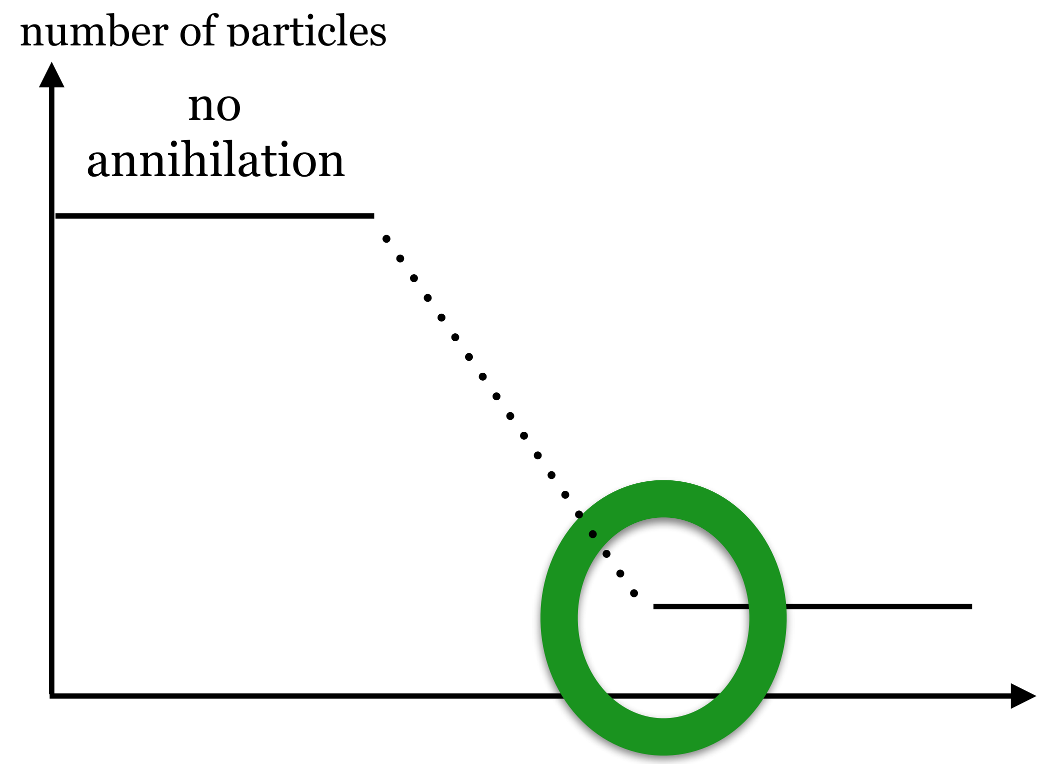
Analytical solution

$$\langle\sigma v\rangle n_{\mathrm{DM}} = H$$

$$n_{\mathrm{DM}} a^3 = n_{\mathrm{DM},0}\ a_0^3$$

$$a(T) = \frac{T_0}{T} \quad \text{and} \quad H = H_r T^2$$

$$n_{\mathrm{DM},0} = \frac{H_r}{\langle\sigma v\rangle}\frac{T_0}{T_{fo}}$$



$$\Omega_0 = \frac{\rho_{\mathrm{DM},0}}{\rho_{c,0}} \rightarrow \Omega_0 = \frac{n_{\mathrm{DM},0}}{\rho_{c,0}} m_{\mathrm{DM}} \rightarrow \boxed{\Omega_0 = \frac{H_r}{\rho_{c,0}}\frac{T_0}{\langle\sigma v\rangle}\frac{m_{\mathrm{DM}}}{T_{fo}}}$$

x_{fo}

At freeze-out, the density obeys Boltzmann statistics

$$n(T) \propto (m_{\mathrm{DM}} T)^{3/2}\ e^{-\frac{m_{\mathrm{DM}}}{T}} \qquad n_{\mathrm{DM},0} = \frac{H_r}{\langle\sigma v\rangle}\frac{T_0}{T_{fo}} \qquad x_{fo}^{-1} \simeq \ln \frac{\langle\sigma\ v\rangle\ T_0^2\ m}{H_\alpha\ (2\pi)^{3/2}\ \sqrt{x_{fo}}}.$$

$$x_{fo} \approx 12 + (\approx 2)\log\left(\frac{m_{dm}}{MeV} \times \frac{\sigma v}{3.10^{-26} cm^3/s}\right)$$

Numerical solution

Numerically:

- re-write Boltzmann to remove T^3 factors in number density by using $n = y\, T^3$

$$\frac{dy}{dt} = -\sigma v \times (y^2 - y_0^2) \times T^3$$

- solve dy/dT instead of dy/dt

$$\frac{dy}{dT} = \frac{\sigma v}{2 t_r T_0^2} \times (y^2 - y_0{}^2)$$

Tempted to use:

$$\frac{y_{i+1} - y_i}{\Delta T} = \Lambda \times (y^2 - y_0{}^2)$$

???

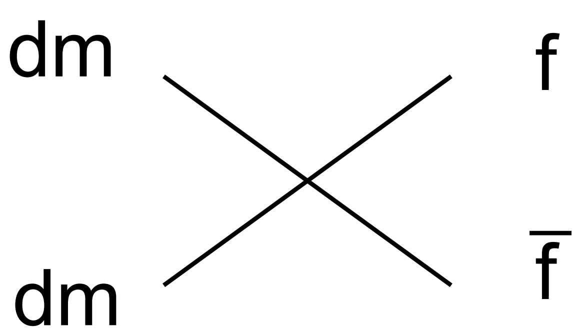
$$\frac{y_{i+1} - y_i}{\Delta T} = \frac{\Lambda}{2} \times \left[(y_i{}^2 - y_{0_i}{}^2) + (y_{i+1}{}^2 - y_{0_{i+1}}{}^2) \right]$$

The Hut, Lee&Weinberg argument

$$\frac{dn}{dt} = -3Hn - \sigma v(n^2 - n_0^2)$$

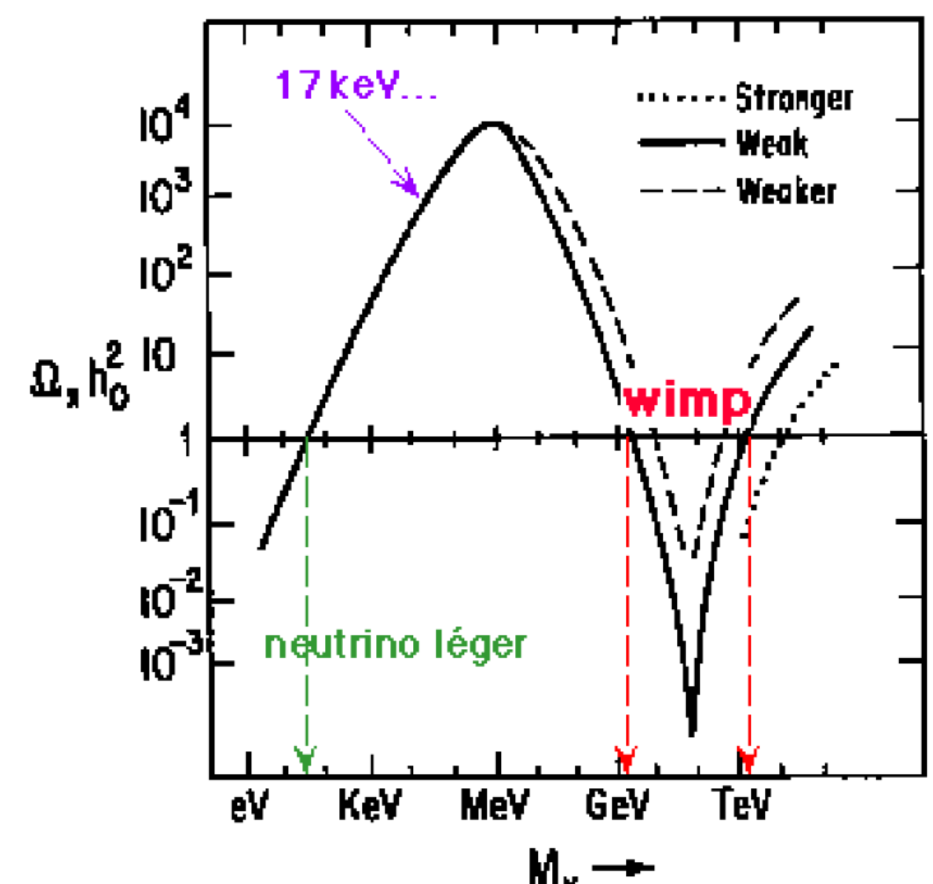
$$\Omega h^2 \simeq \frac{3 \times 10^{-27} \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle}$$

$$\sigma v \sim 3\ 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$



$$\sigma\ \mathrm{v} \propto \frac{\mathrm{m_{dm}}^2}{\mathrm{m_w}^4}$$

$$\Omega_{\mathrm{DM}} h^2 \propto m_{\mathrm{DM}}^{-2}$$



Dark Matter needs to be heavier than a proton to not over close the Universe