Introduction to dark matter

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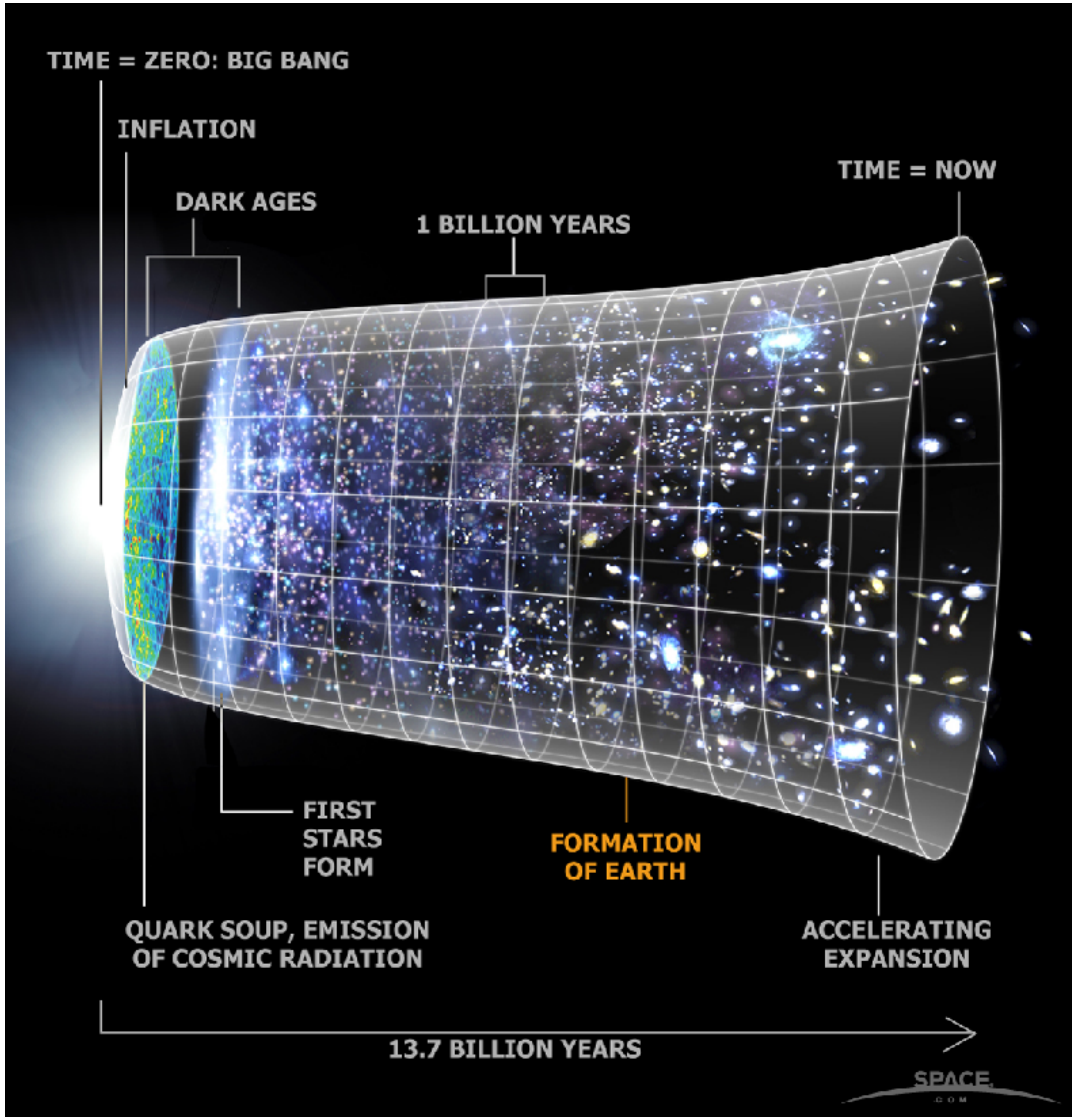
Understanding Dark Matter

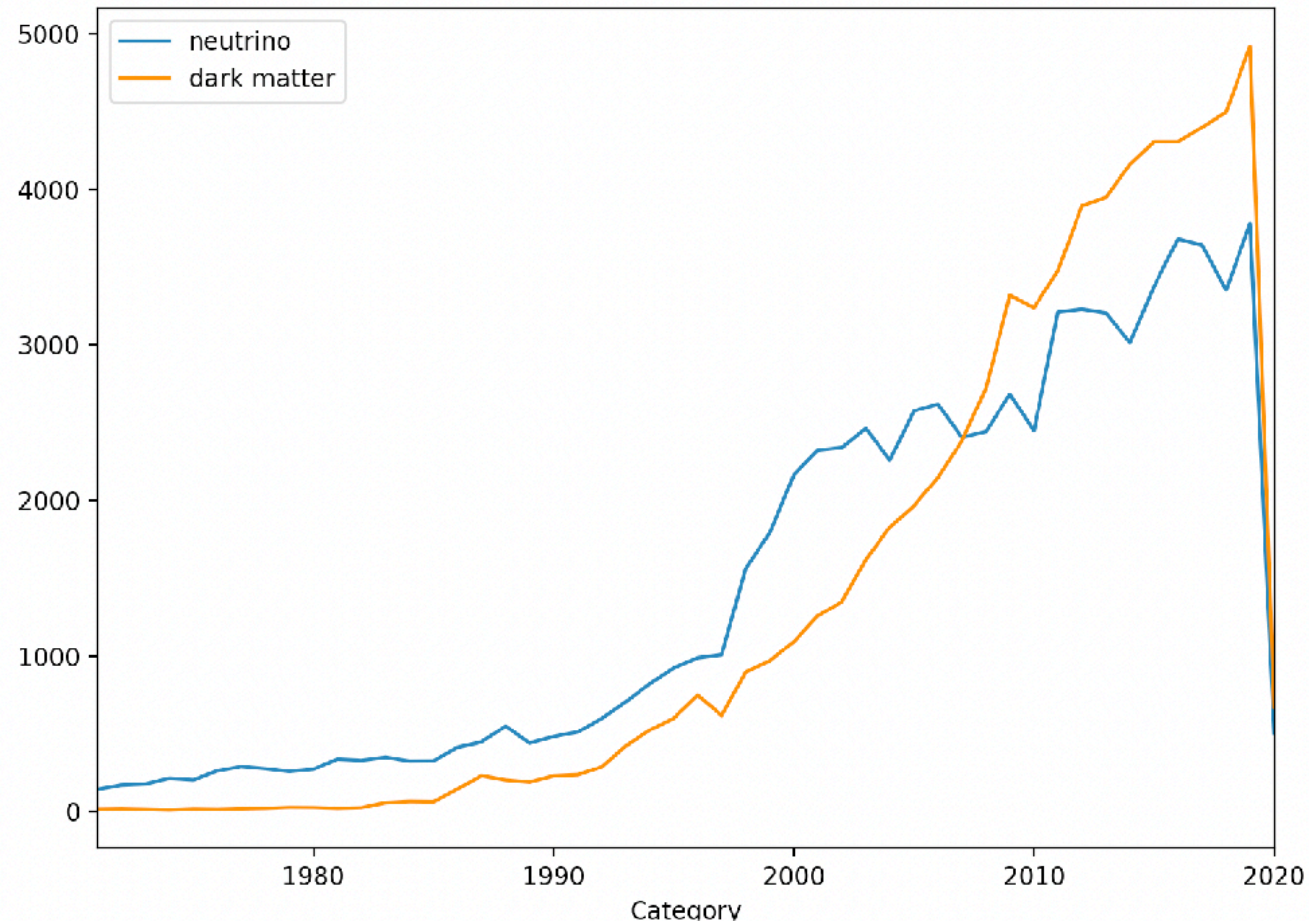
- **Why** introducing dark matter in the Universe?
- What is (or is not) dark matter **made of**?
- Where is it **located** in the Universe?
- How can we **detect** it?

To answer these questions, we need to explore the distant Universe (**cosmology**), extreme phenomena (**astrophysics**), and the nature of dark matter itself (**particle physics**).



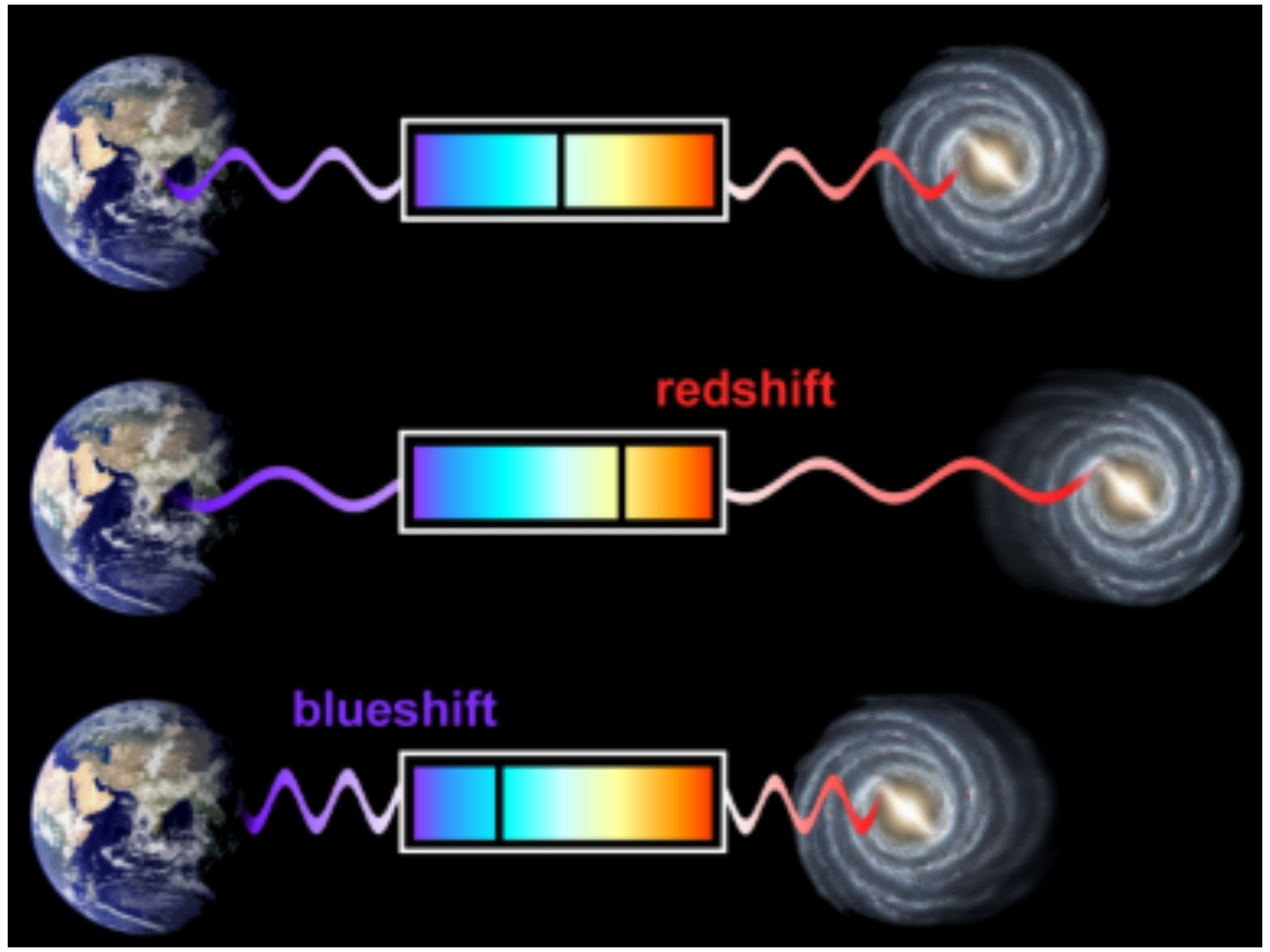
Dark Matter and Neutrinos: A Holistic Parallel

Rate of publications



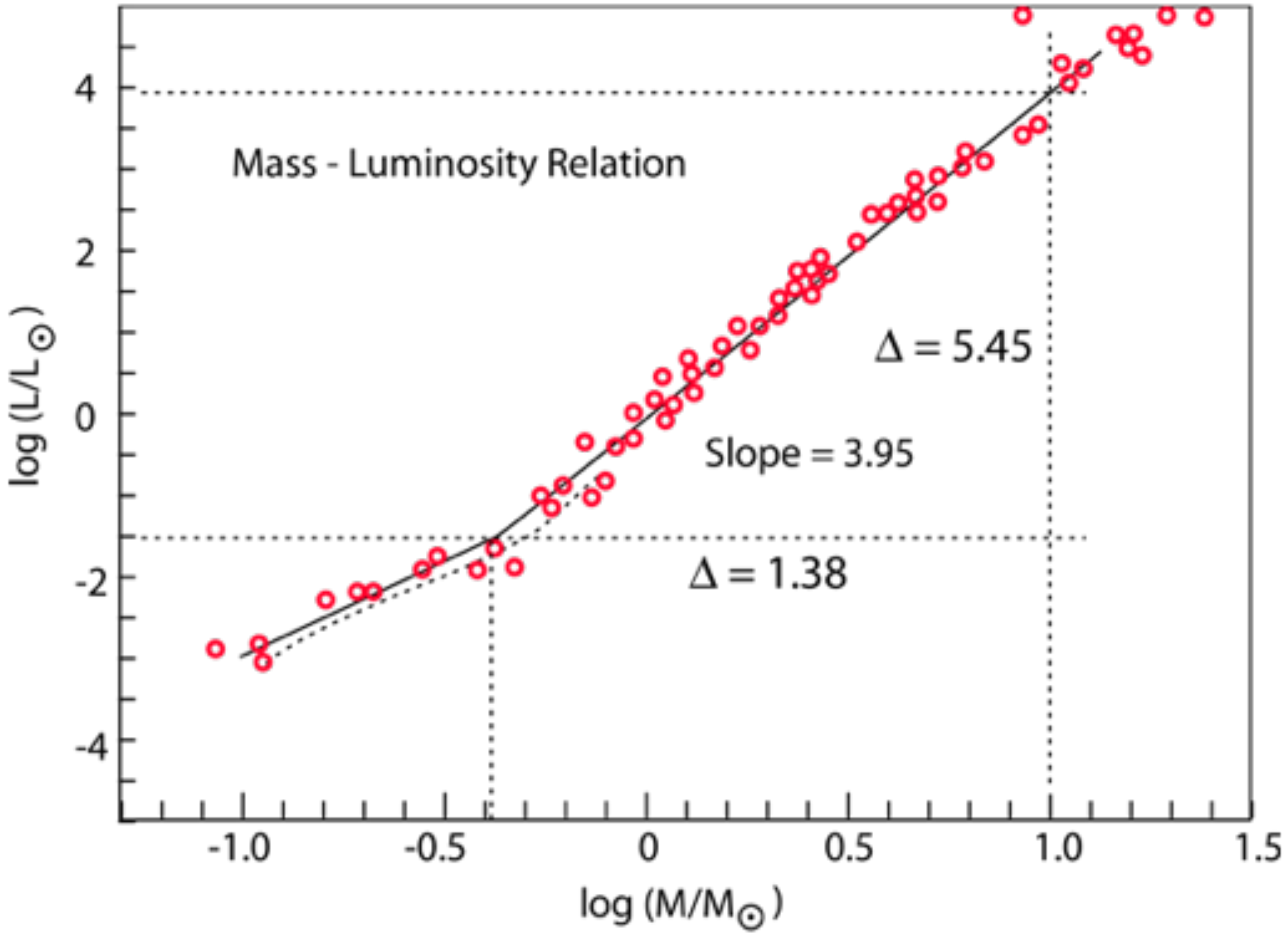
Some Background

Red shift



Thanks to redshift, we can measure the velocity of stars and galaxies.

Correlation between the **luminosity** and **mass** of celestial objects



Thanks to luminosity, we can measure the mass of stars, galaxies, or galaxy clusters.

Quelques préalables

The Virial Theorem

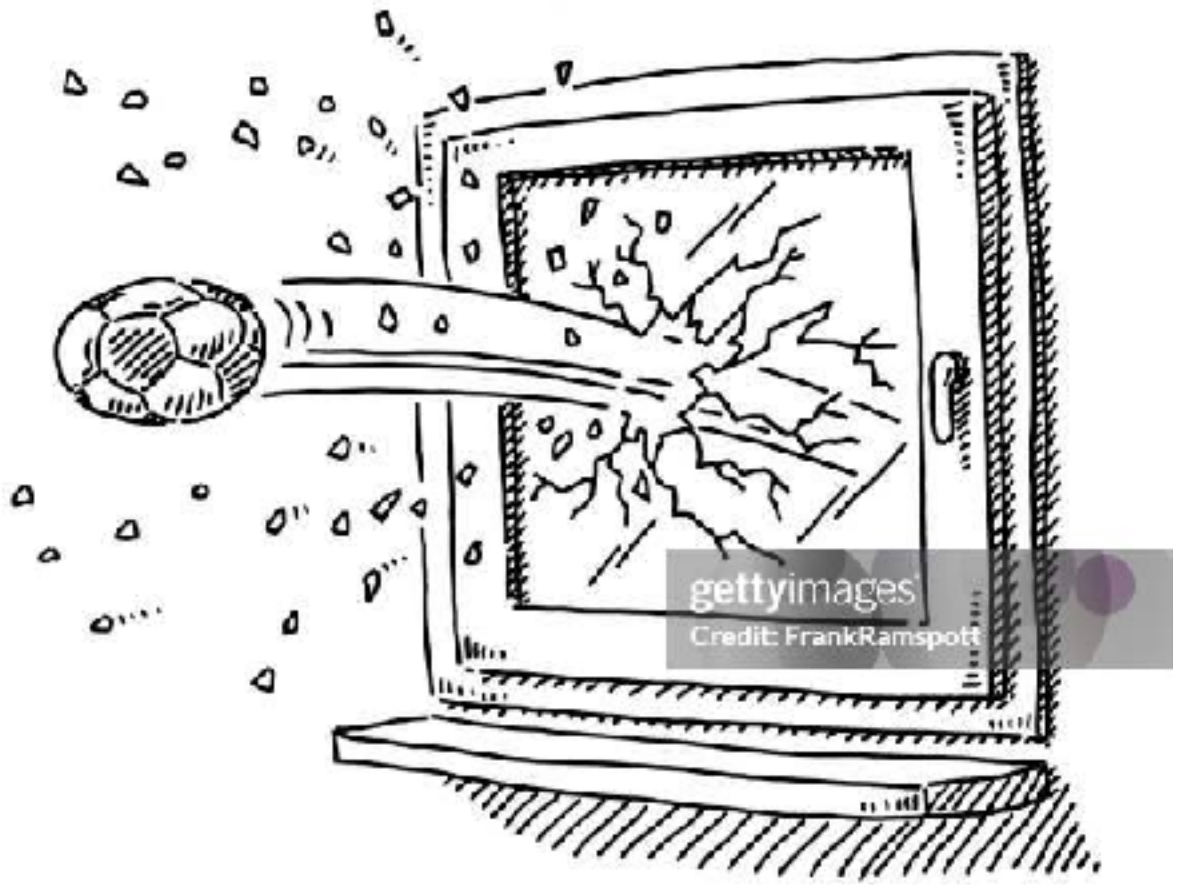
In a system in **dynamic equilibrium**, such as a galaxy cluster, measuring the **velocities** of galaxies allows us to estimate the **total mass** of the cluster.

système en équilibre

$$2T + U = 0$$

Kinetic Energy ← **Velocity**

Gravitational Potential Energy ← **Mass**

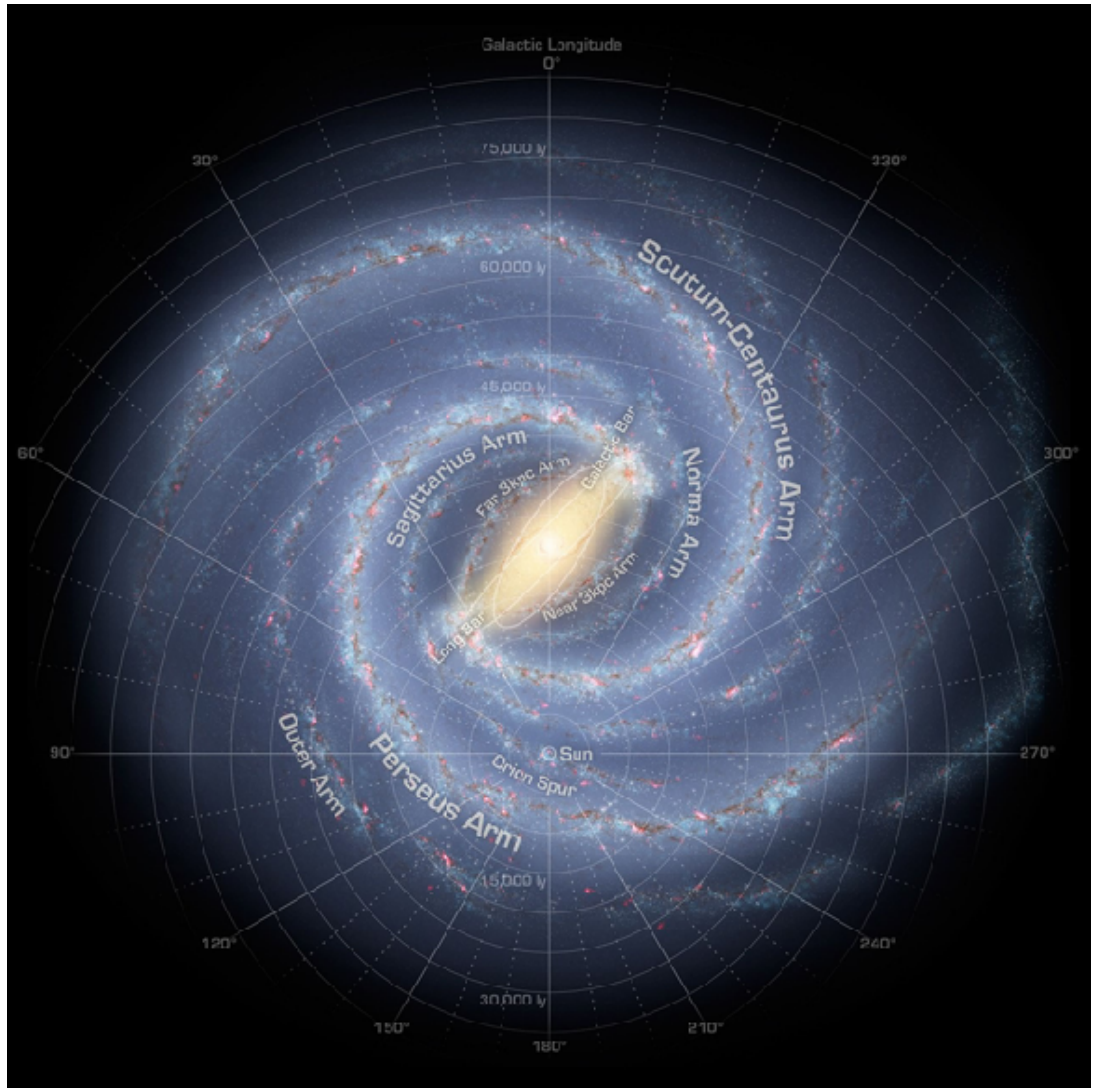


système non en équilibre

Une (pré) histoire: 1932

Jan Oort

Astronomer with significant contributions to the understanding of the Milky Way and a pioneer in the field of **radio astronomy.**



Velocity of stars in the Milky Way, near the galactic plane, by Doppler shifts

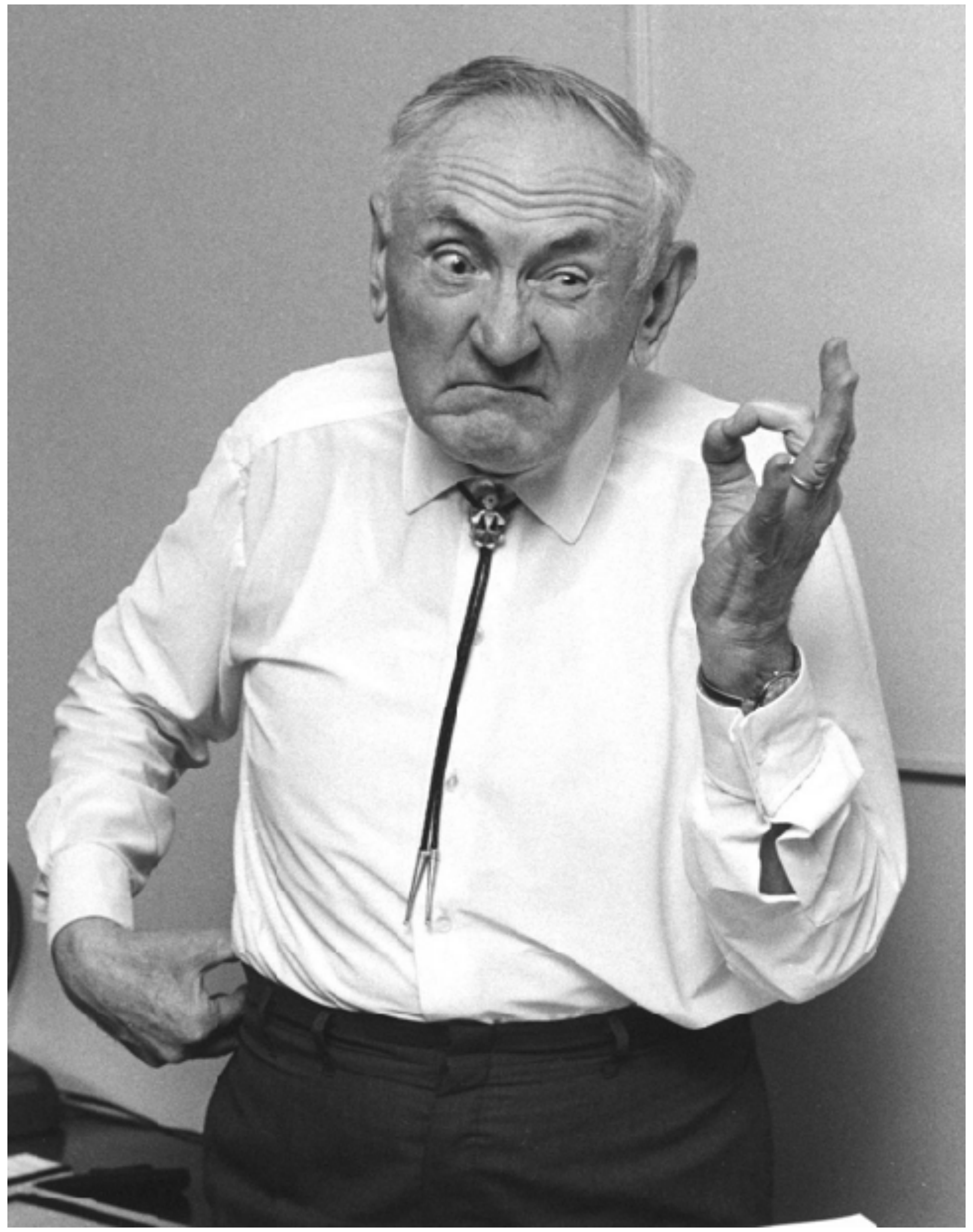
They should be faster than escape velocity from gravitational pull of luminous mass in the galaxy

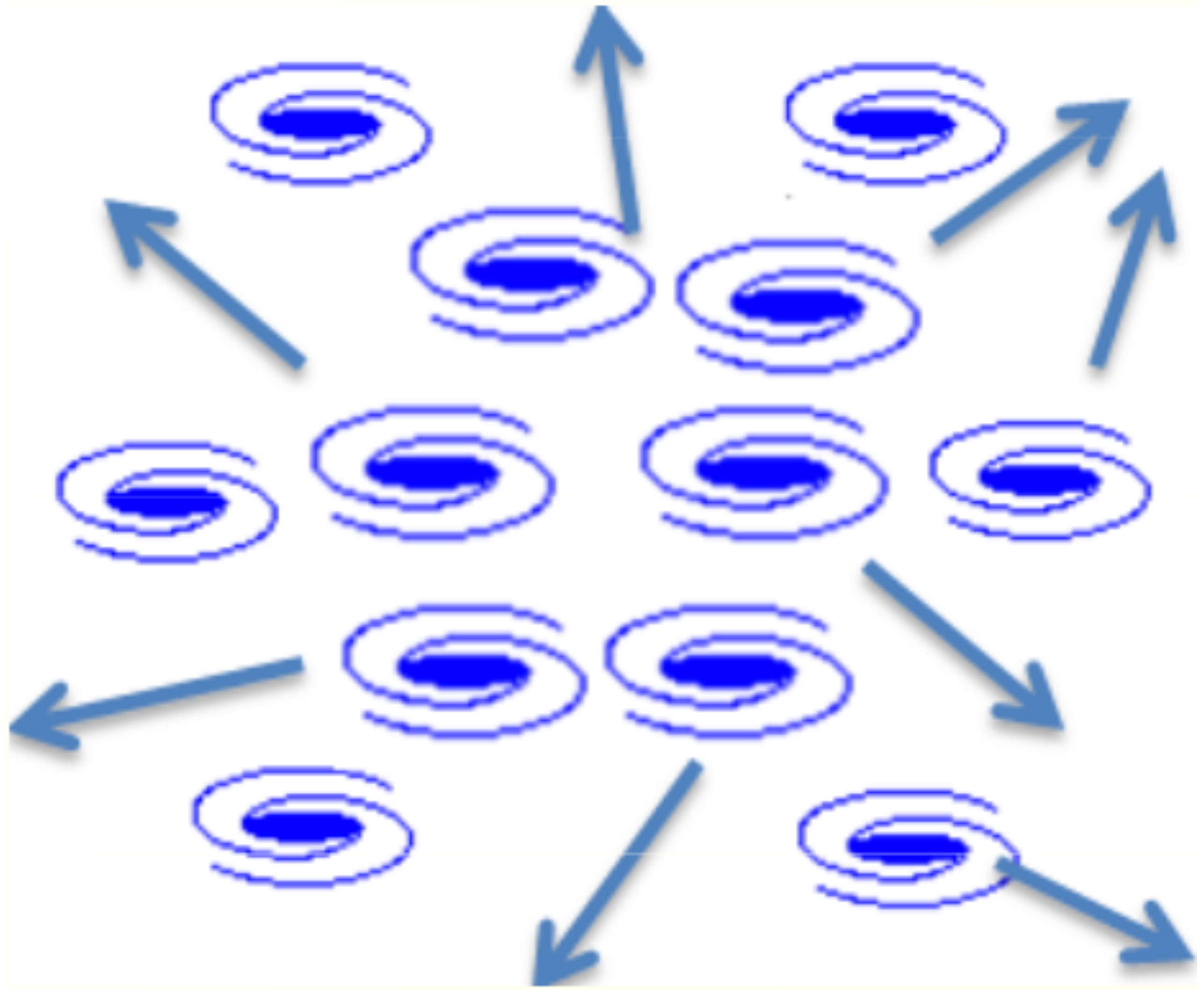
More mass in the Milky Way?

Dust obscures 85% of light from galactic center ?

The official beginning

Fritz Zwicky (1933)
Velocity dispersion (i.e. kinetic energy) of individual galaxies in the Coma cluster, assuming only gravitational interactions and Newtonian gravity



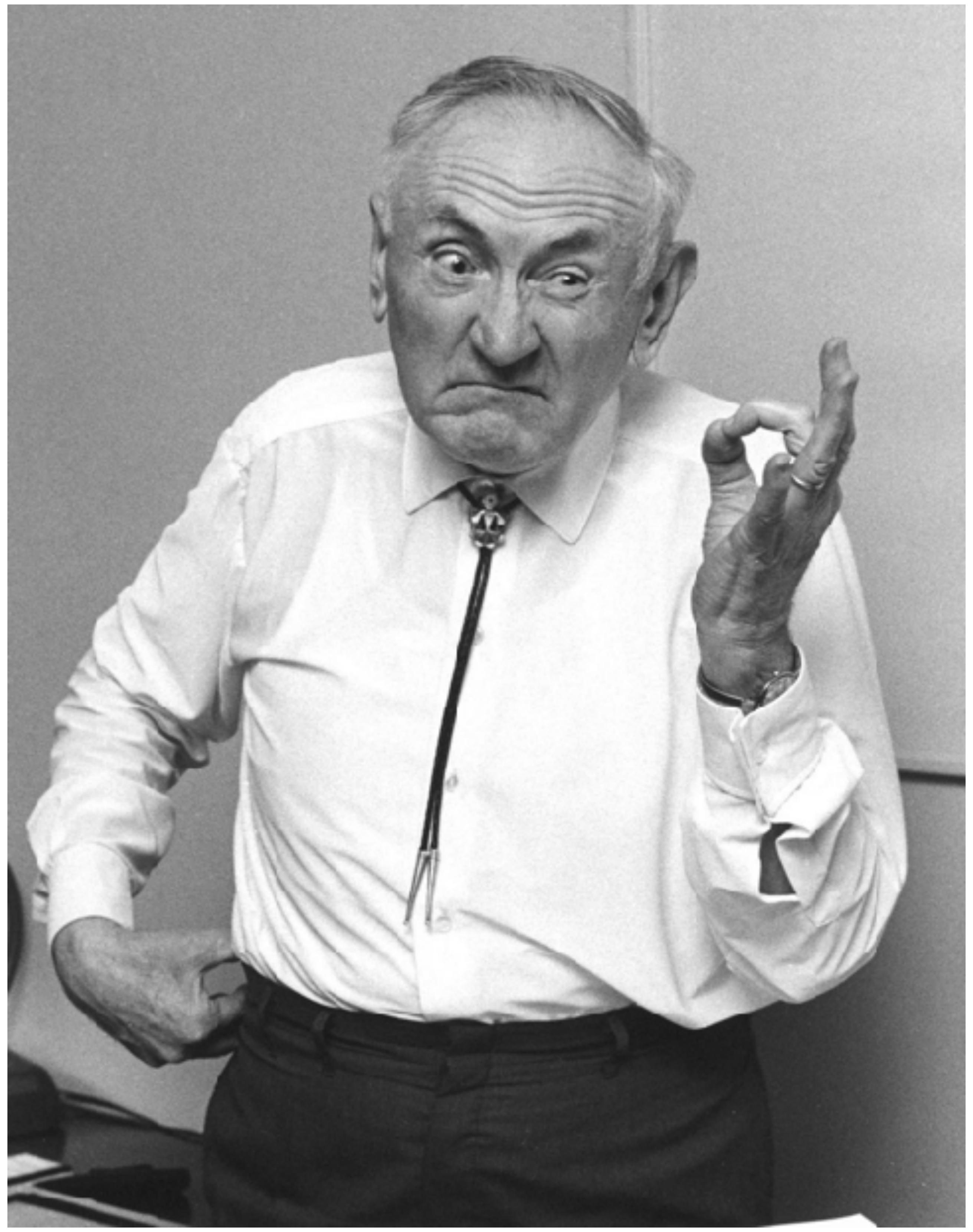


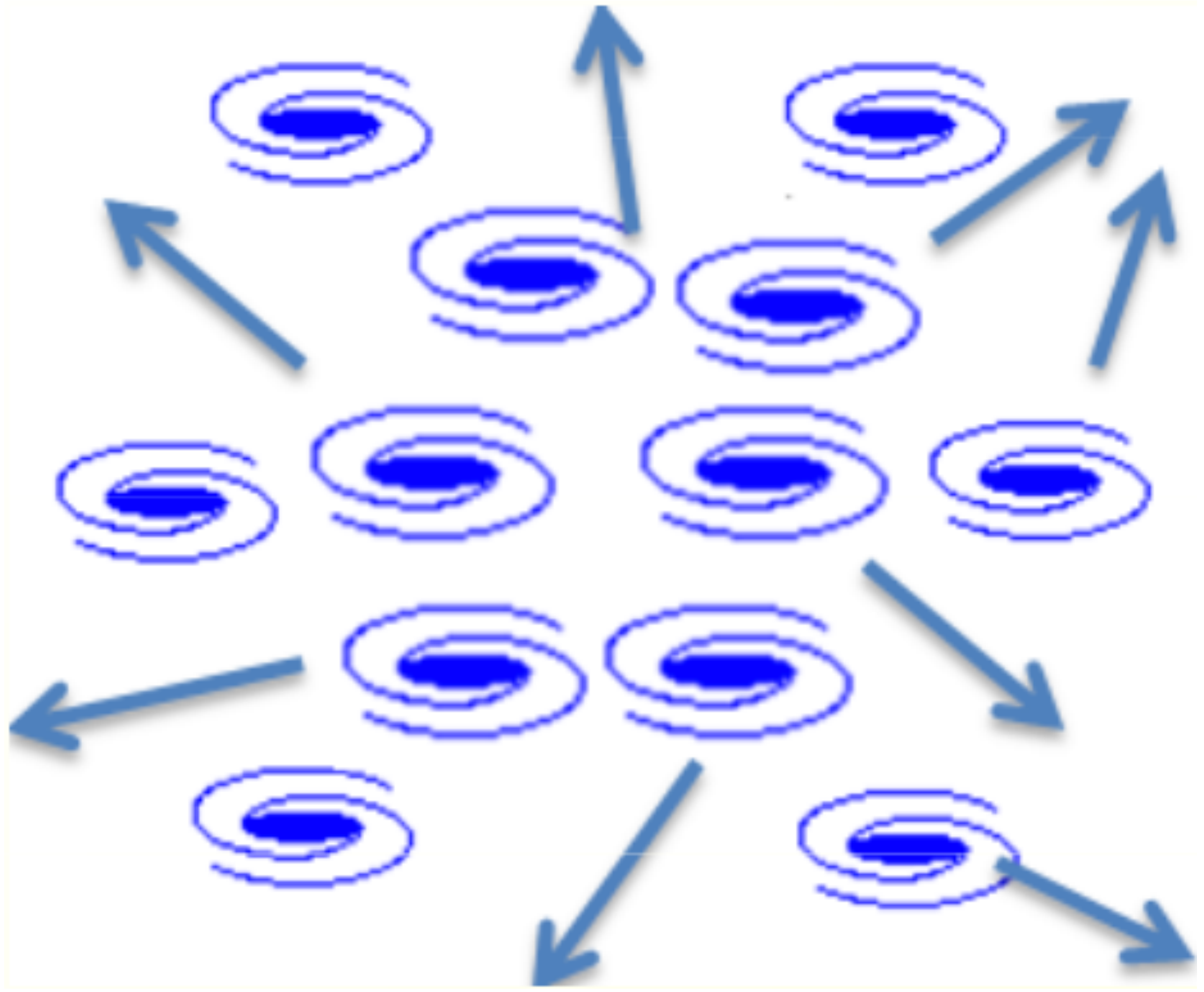
$$\langle T \rangle = -\frac{1}{2}\langle U \rangle$$

COMA cluster: velocity dispersion ~1000km/s

The official beginning

Fritz Zwicky (1933)
Velocity dispersion (i.e. kinetic energy) of individual galaxies in the Coma cluster, assuming only gravitational interactions and Newtonian gravity



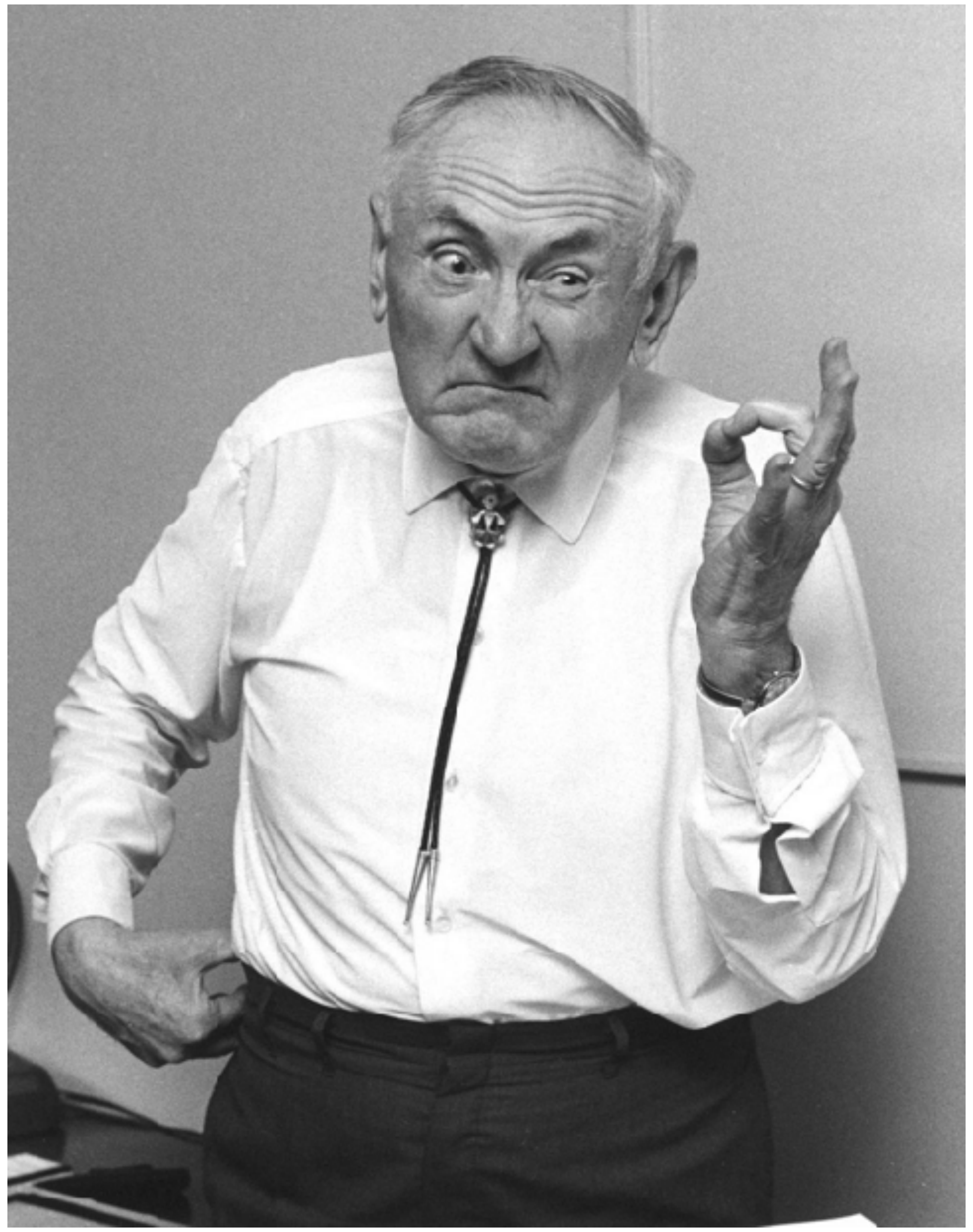


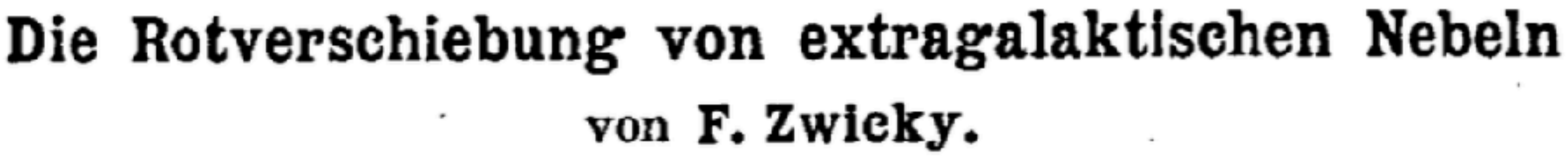
$$\langle T \rangle = -\frac{1}{2}\langle U \rangle$$

- Zwicky observed **~1,000 nebulae** for a a total mass of the cluster M ~ 4.5×10^{13} M⊙ => average nebulae mass ~4.5×10^{10} M⊙
- From M/L, mass of a nebulae ~9×10^{8} M⊙: **~2% of what observed**
- Zwicky didn't know that ~10% of the missing cluster mass is contained in the **intracluster gas**. But this doesn't solve the missing matter problem

The official beginning

$$\frac{M}{L} = 500\,\frac{M_\odot}{L_\odot}$$





Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(Le redshift des nébuleuses extragalactiques)

> "In order to obtain the observed value of (velocity), the average density in the Coma system would have to be at least 400 times larger than that derived on the grounds of observations of luminous matter. If this would be confirmed **we would get the surprising result that *dark matter* is present in much greater amount than luminous matter** "

Multiple hypotheses

- Dark matter
- Dust in the cluster + light absorption
- Newton dynamics at large scales?

After Zwicky…

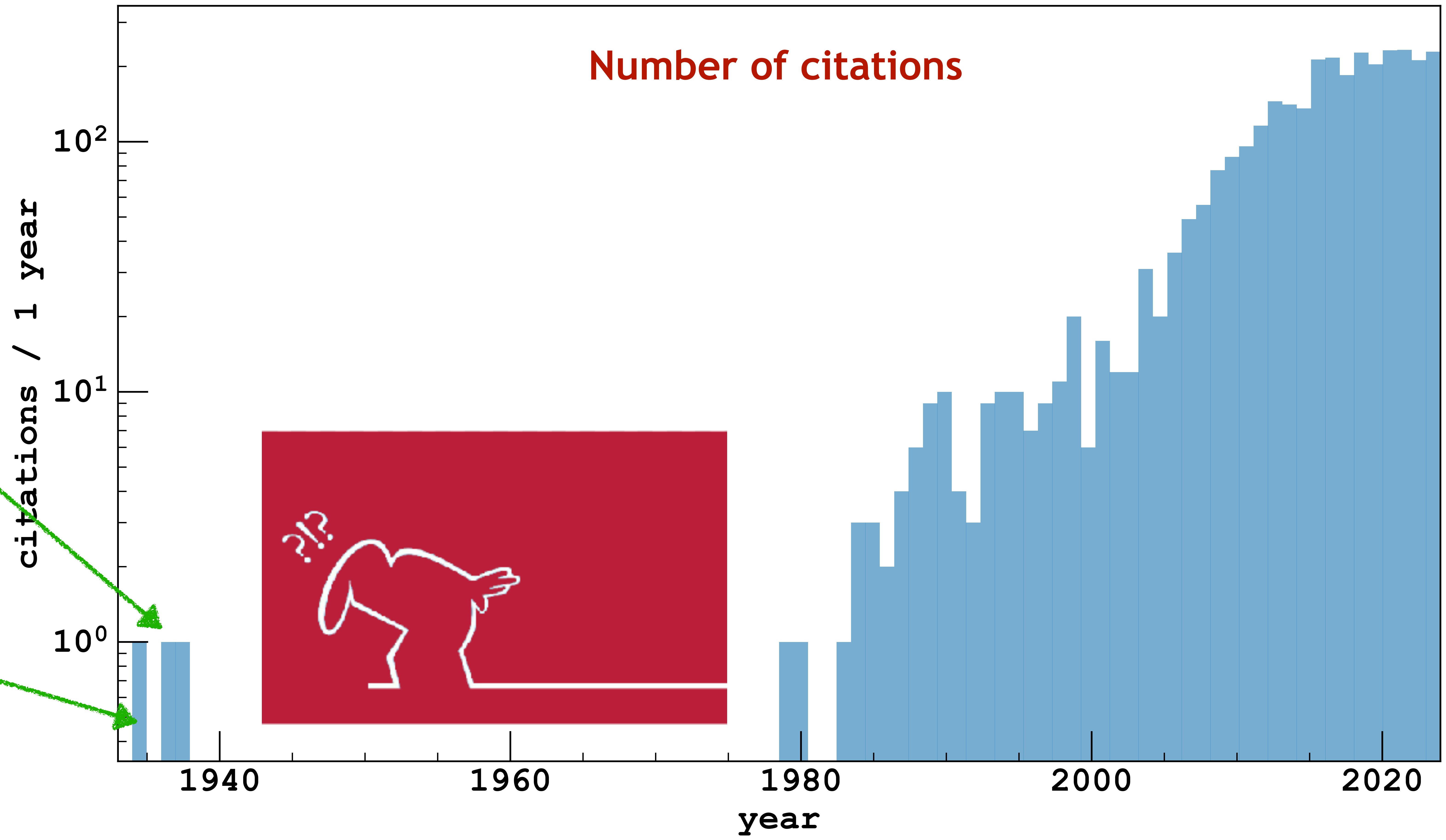
Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

Helv. Phys. Acta 6 (1933) 110-127,

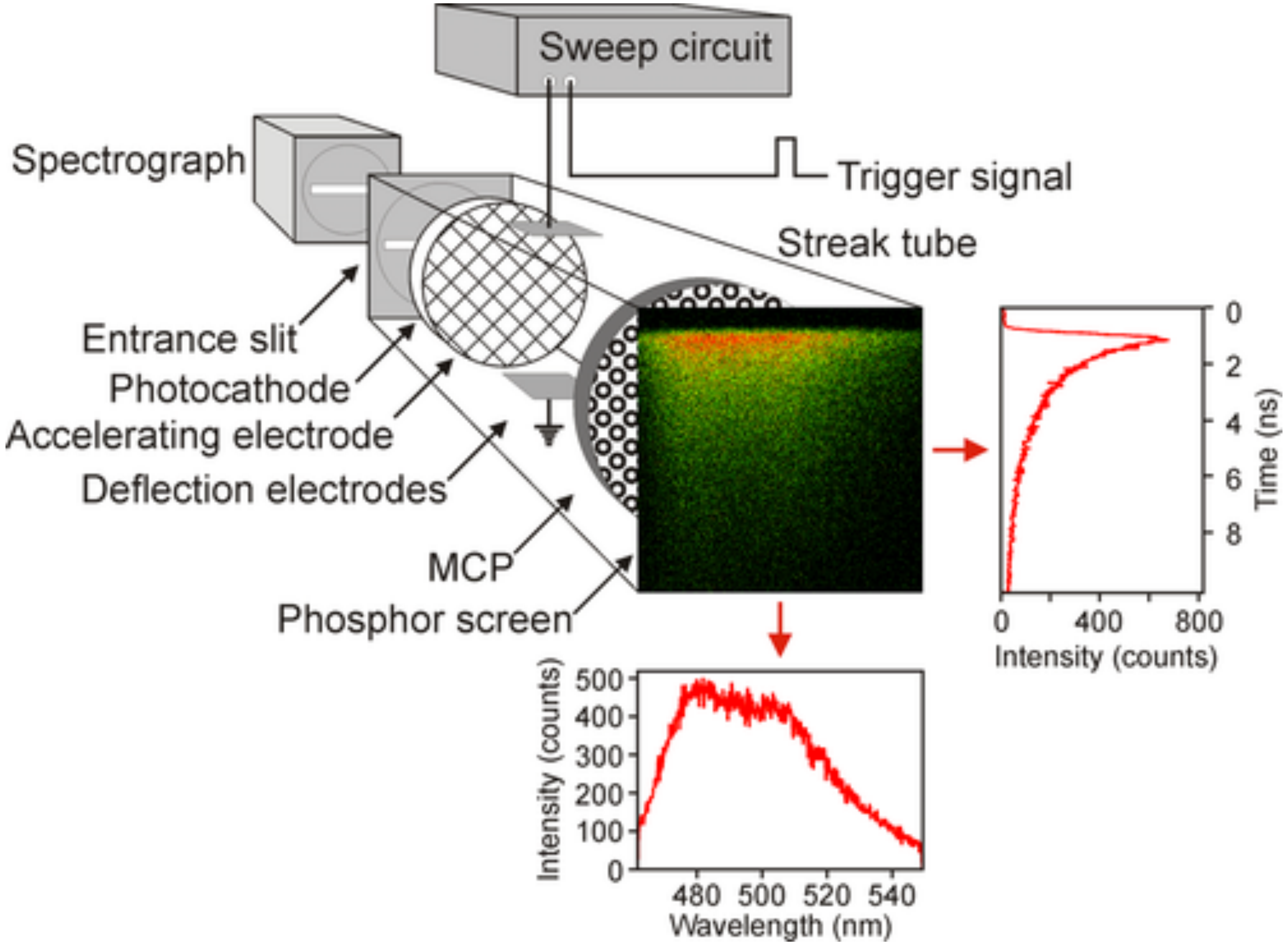
1937
On the Masses of Nebulae and of Clusters of Nebulae
by Fritz Zwicky

1935
The Mass of the Virgo Cluster
by Sinclair Smith



Kent Ford and the revolution of the 1970’

In the 1960s, **Kent Ford** developed an image tube spectrograph that Vera Rubin and he used to perform spectroscopic observations of the Andromeda Galaxy. The observations of the M31 rotation curve Rubin and Ford published in 1970 represented a step forward in terms of quality.



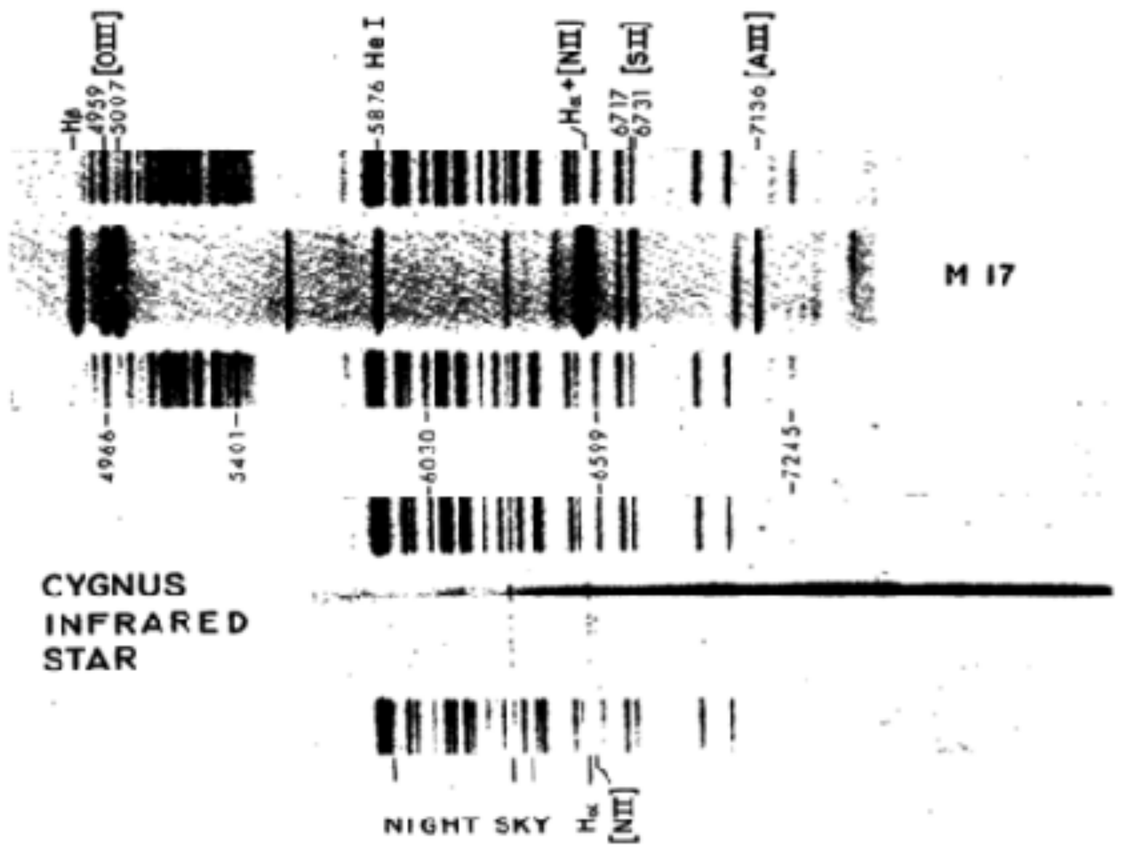


Plate 2. Image tube spectra at 175 Å/mm of M 17, an emission line galactic nebula, and the Cygnus infrared star.

Vera Rubin and the galaxy curves

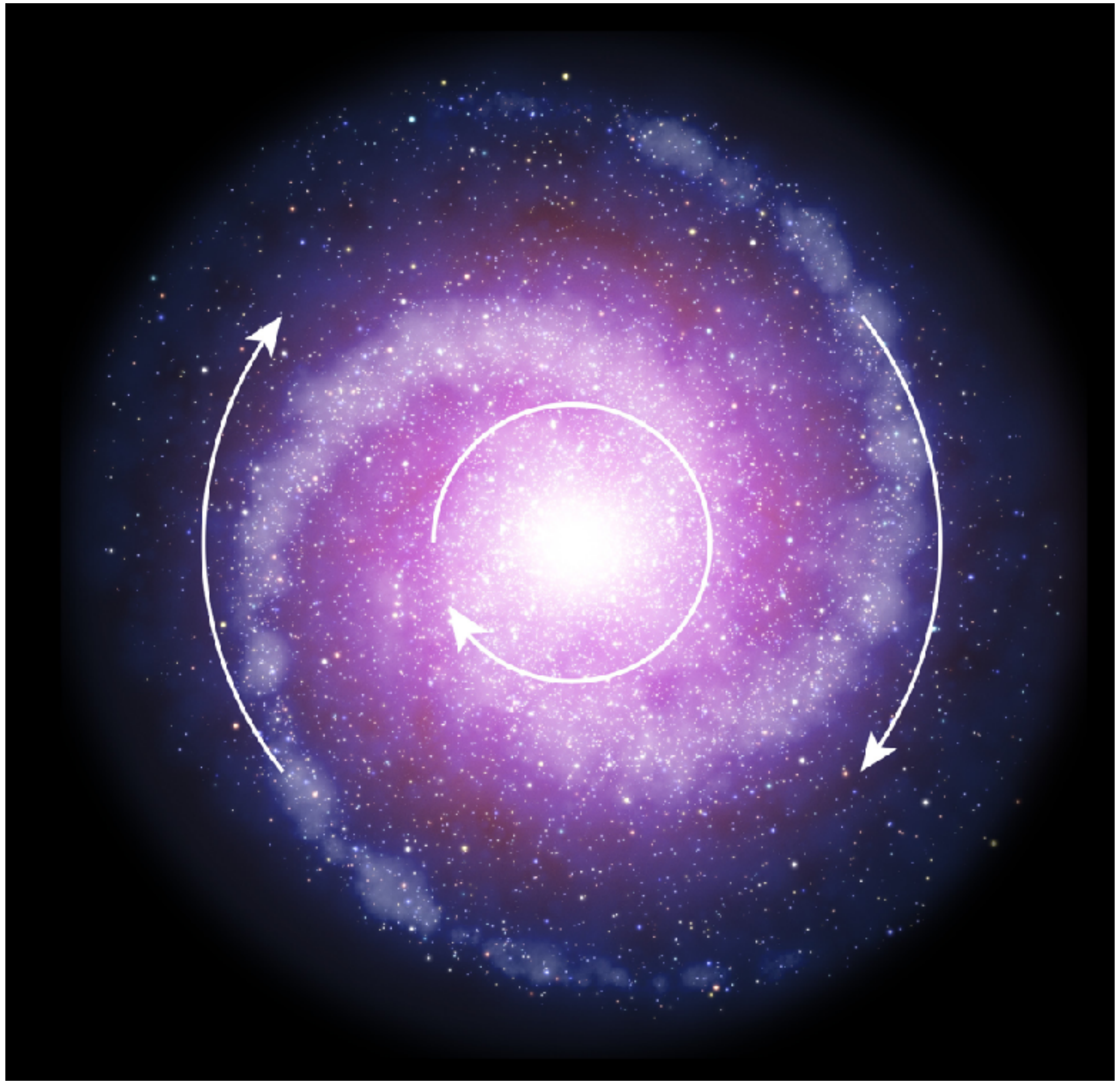
Late 1970s – V. Rubin

Extensive study of **rotation curves** of 60 isolated galaxies.

The galaxies chosen were oriented in such a way so that material on one side of the galactic nucleus was approaching our galaxy while material on the other side was receding; thus the **analysis of spectral lines (Doppler shift) gave the rotational velocity of regions of the target galaxy**.

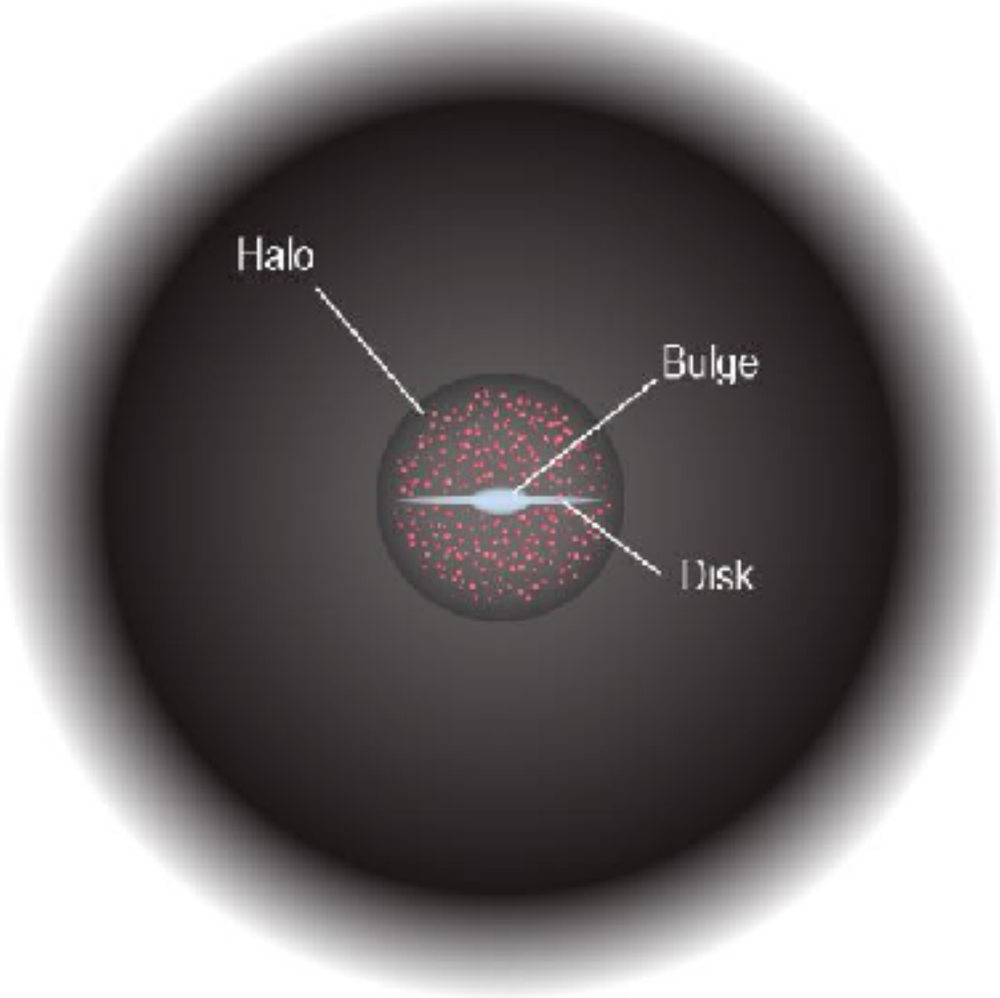
Ideally one would target individual stars to determine their rotational velocities; however, individual stars in distant galaxies are simply too faint, so Rubin used **clouds of gas rich in hydrogen and helium** that surround hot stars as tracers of the rotational profile.

Vera Rubin and the galaxy curves

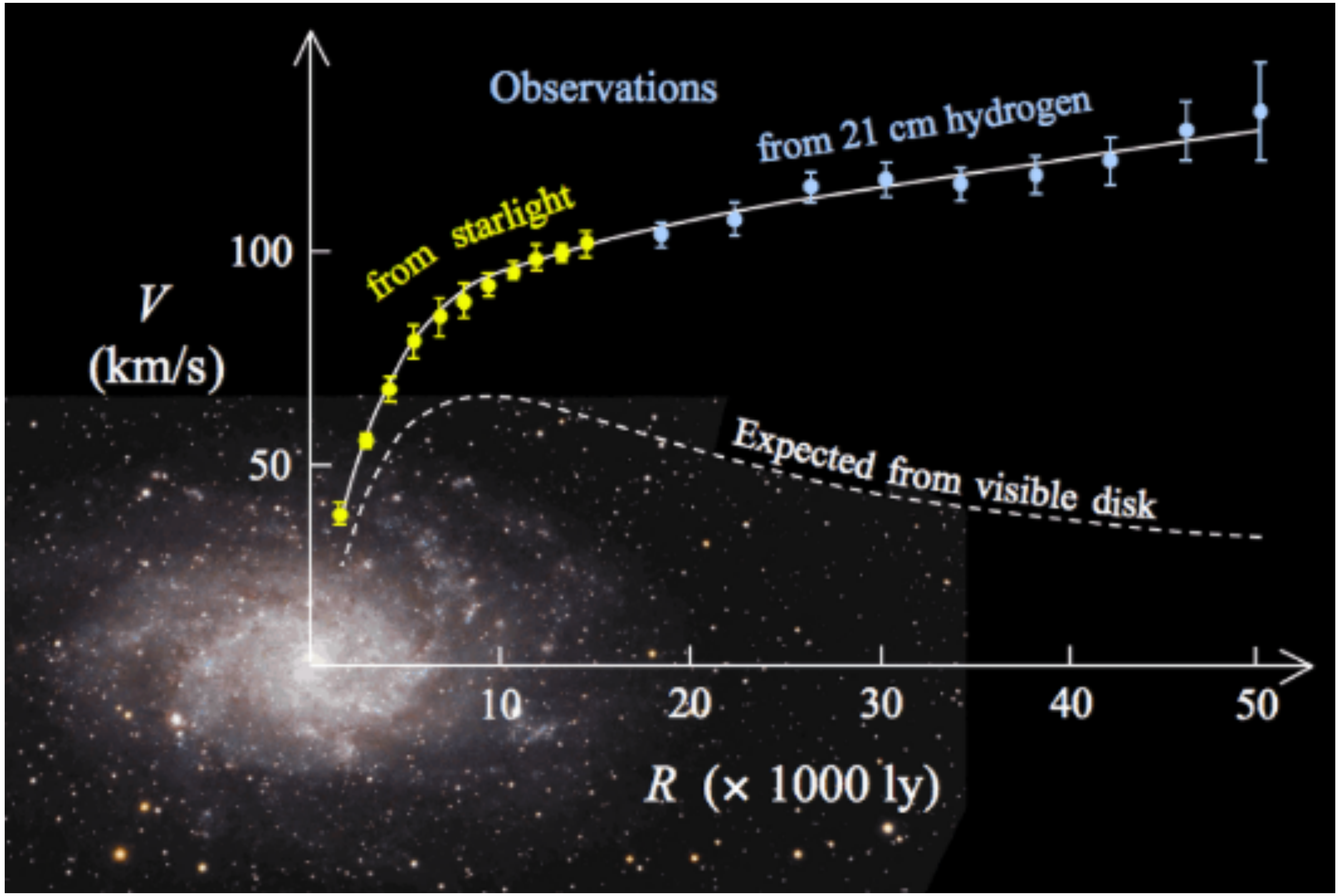


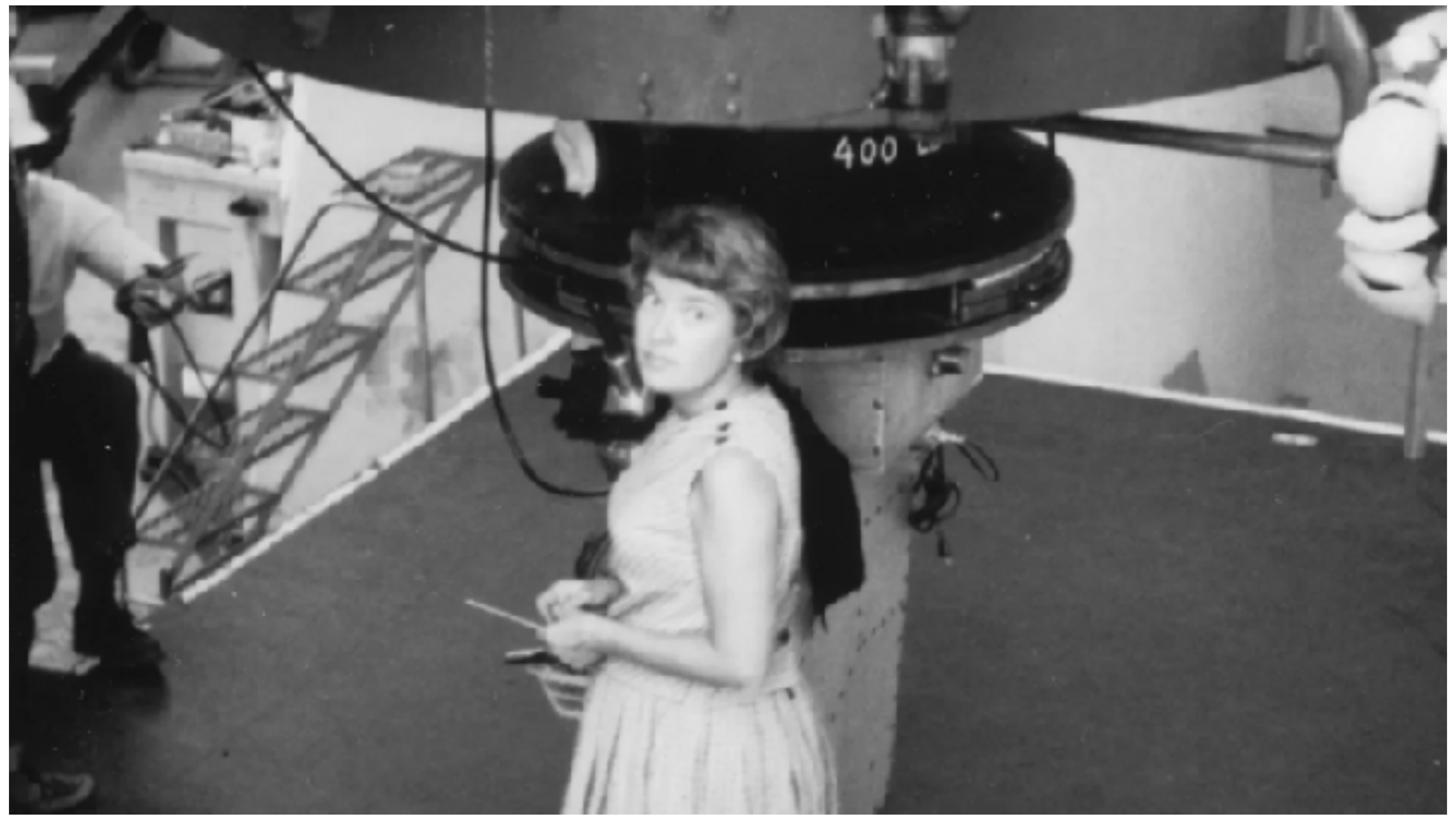
For an isolated self-gravitating system,

$$\begin{tikzcd}
 & 2K + U = 0 \arrow[dl] \arrow[dr] & \\
K = \frac{1}{2} M \langle v^2 \rangle & & U = -\frac{\alpha G M^2}{\mathcal{R}}
\end{tikzcd}$$



Rotation curves and dark matter



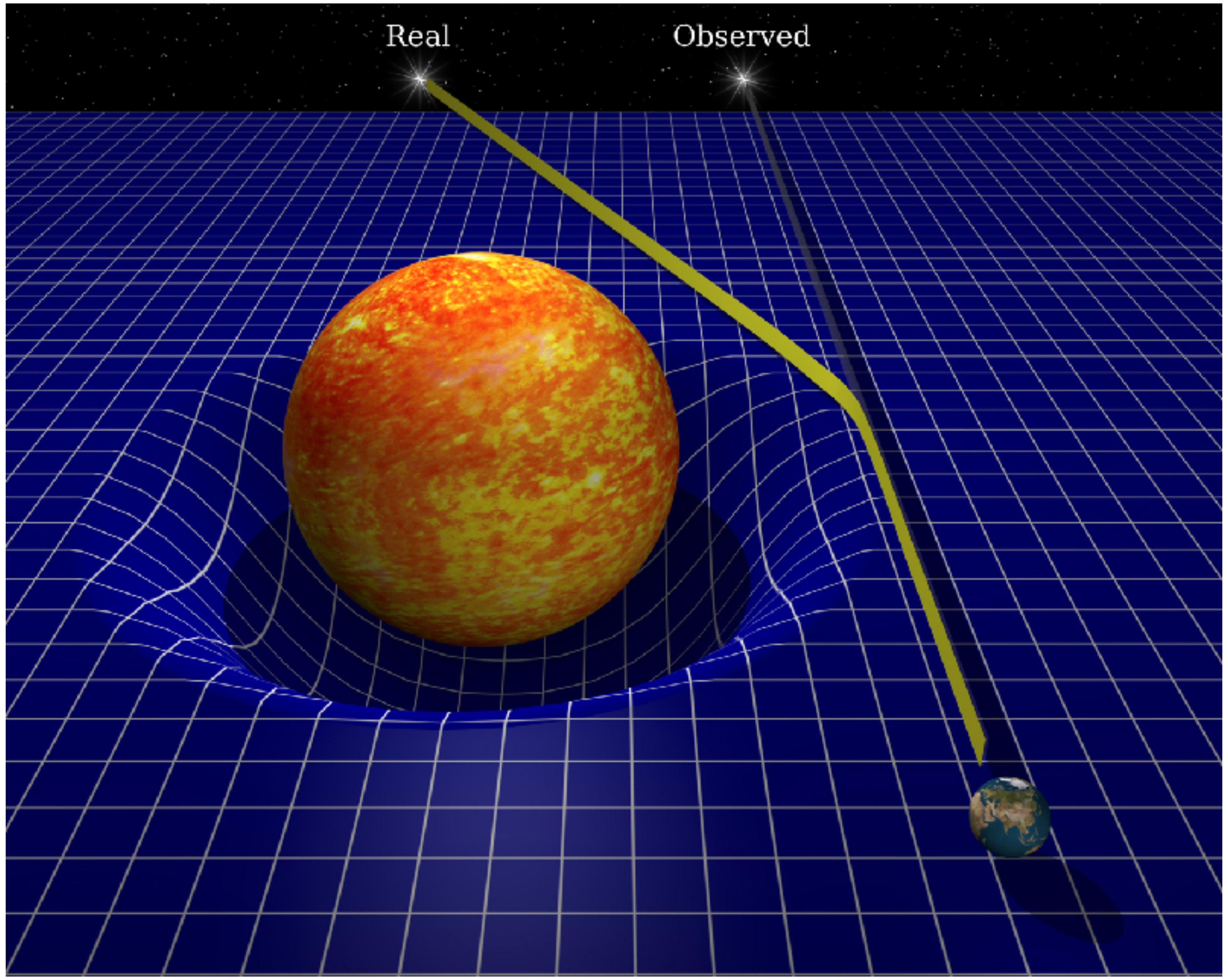


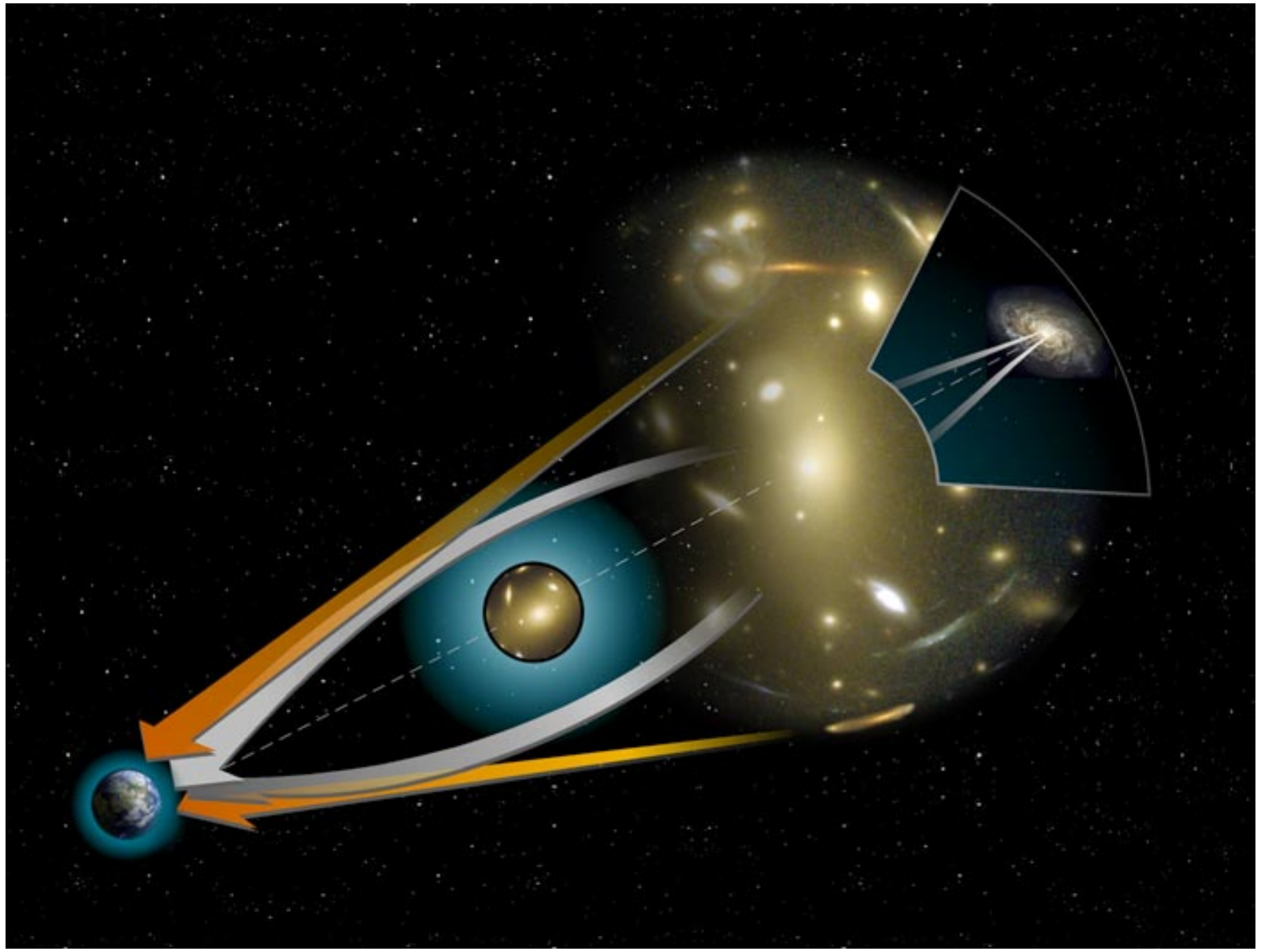
"*The conclusion is inescapable: mass, unlike luminosity, is not concentrated near the center of spiral galaxies. Thus the light distribution in a galaxy is not at all a guide to mass distribution.*" (**Vera Rubin**)

The gravitation lensing effect

Gravitational lensing results from Einstein's theory of relativity, which describes the Universe as a **flexible fabric of space-time**

In 1937, **Fritz Zwicky** suggested that dark matter can be "detected" thanks to the gravitational lensing effect

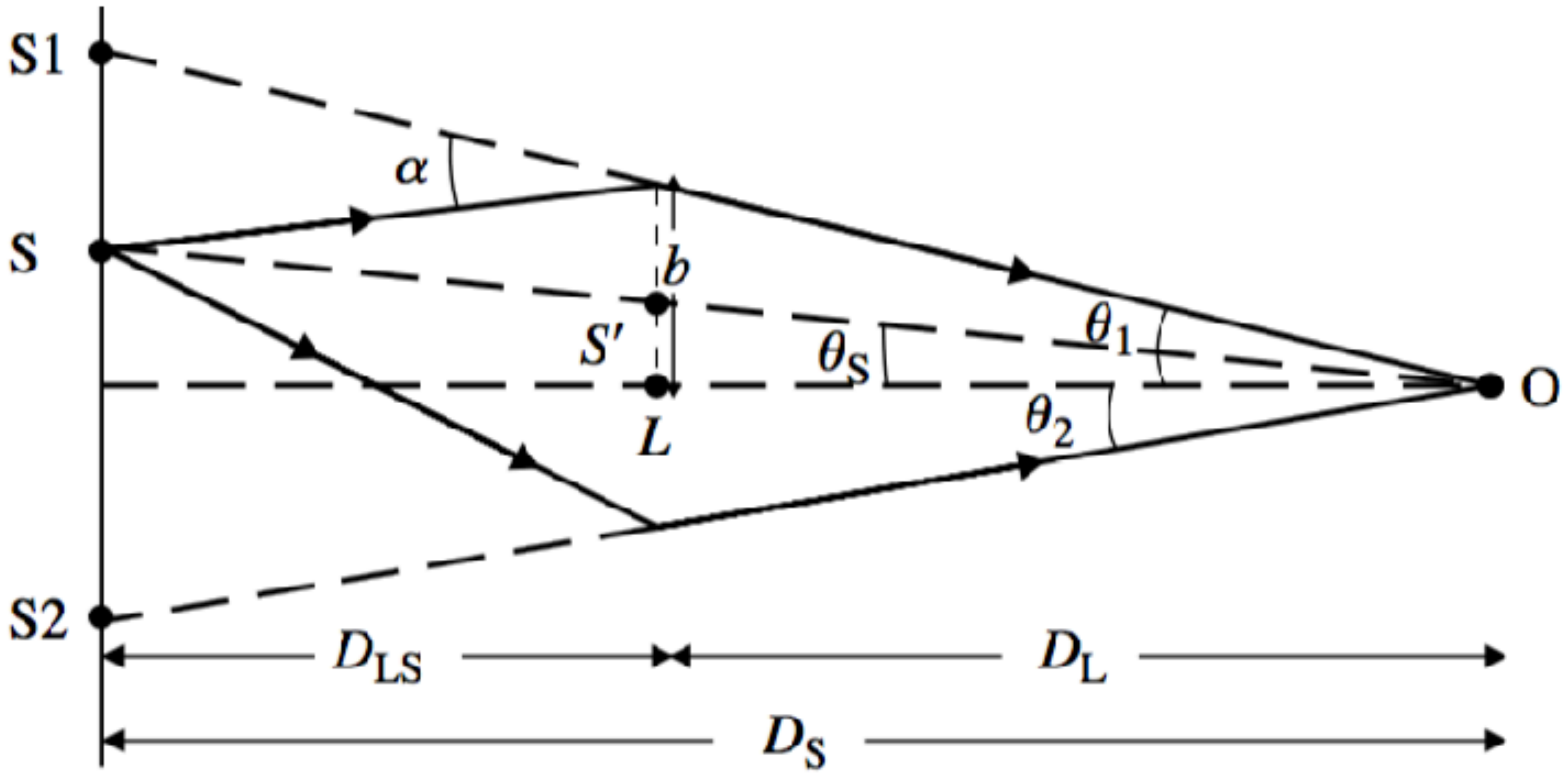




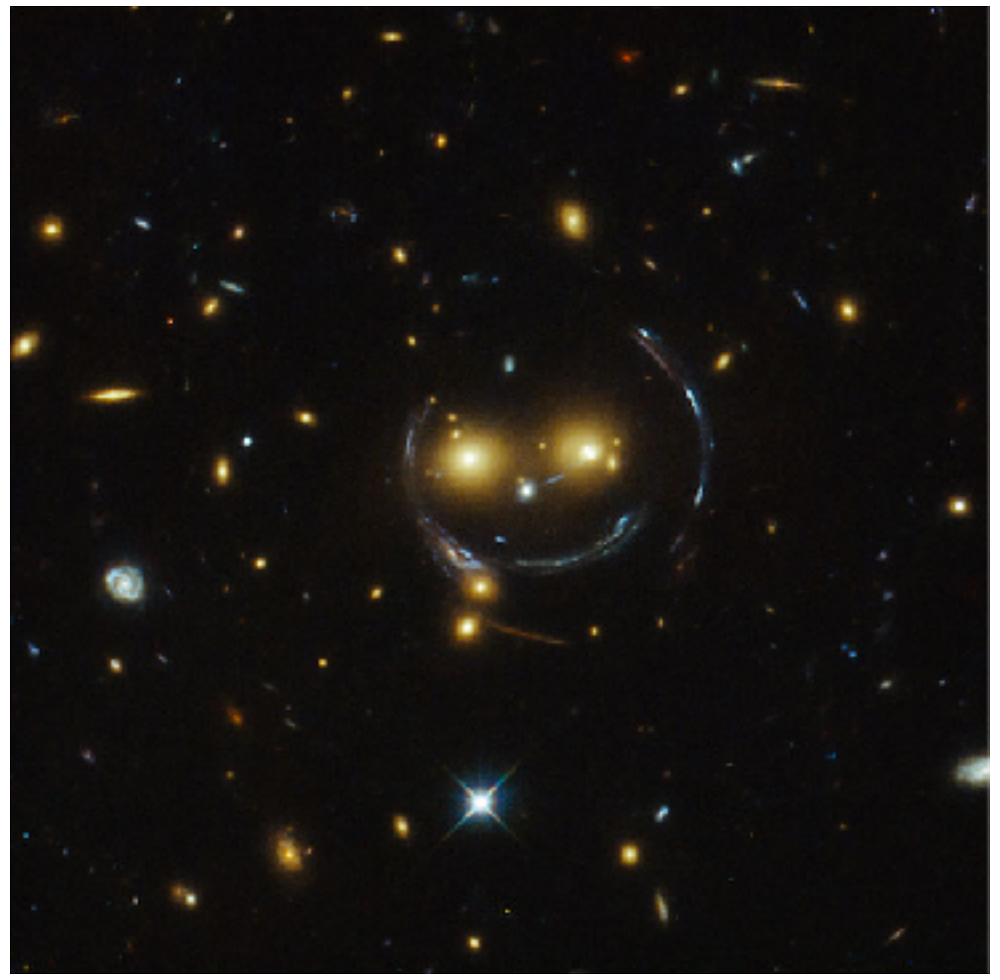
The gravitation lensing effect

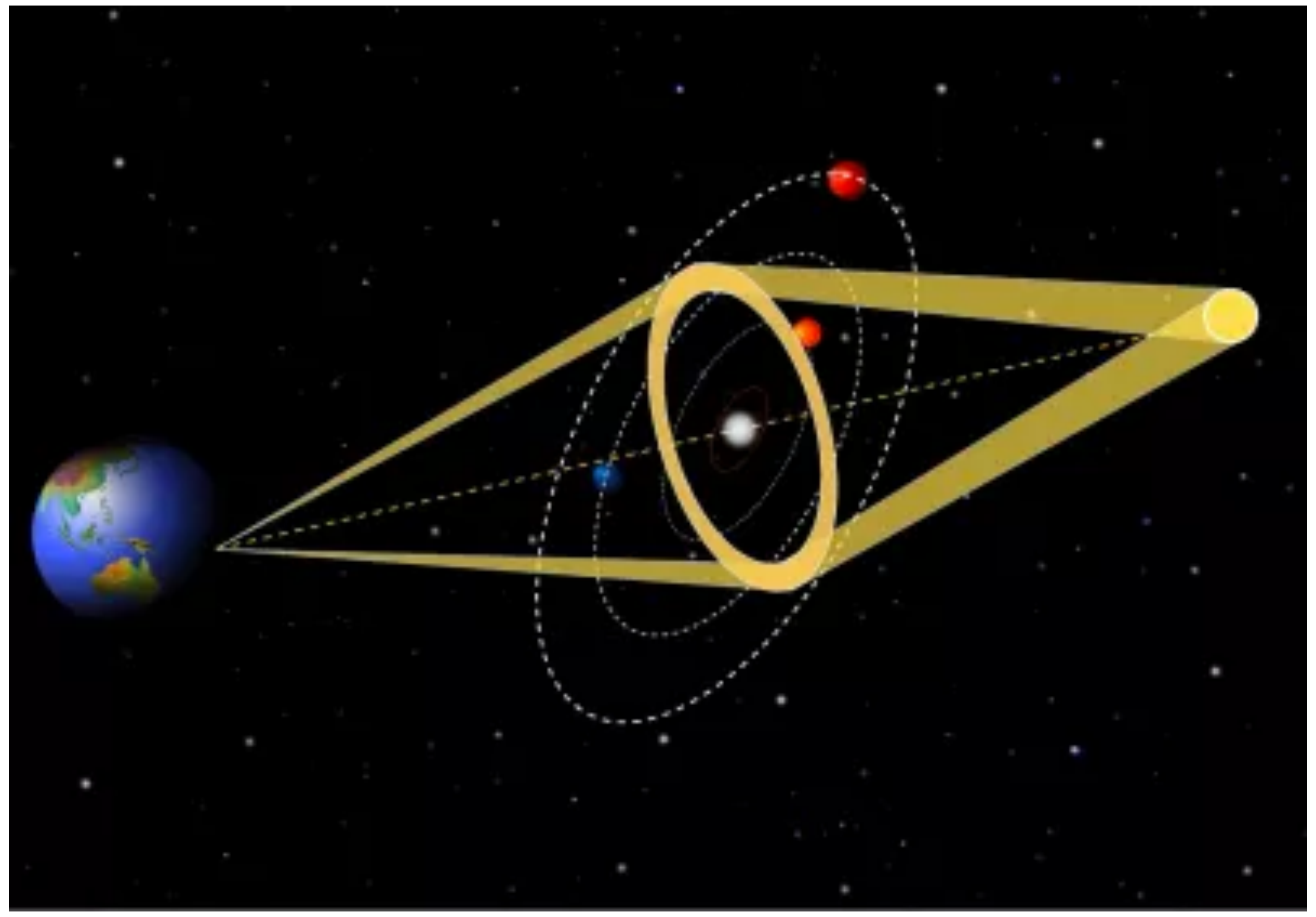
The source (S)

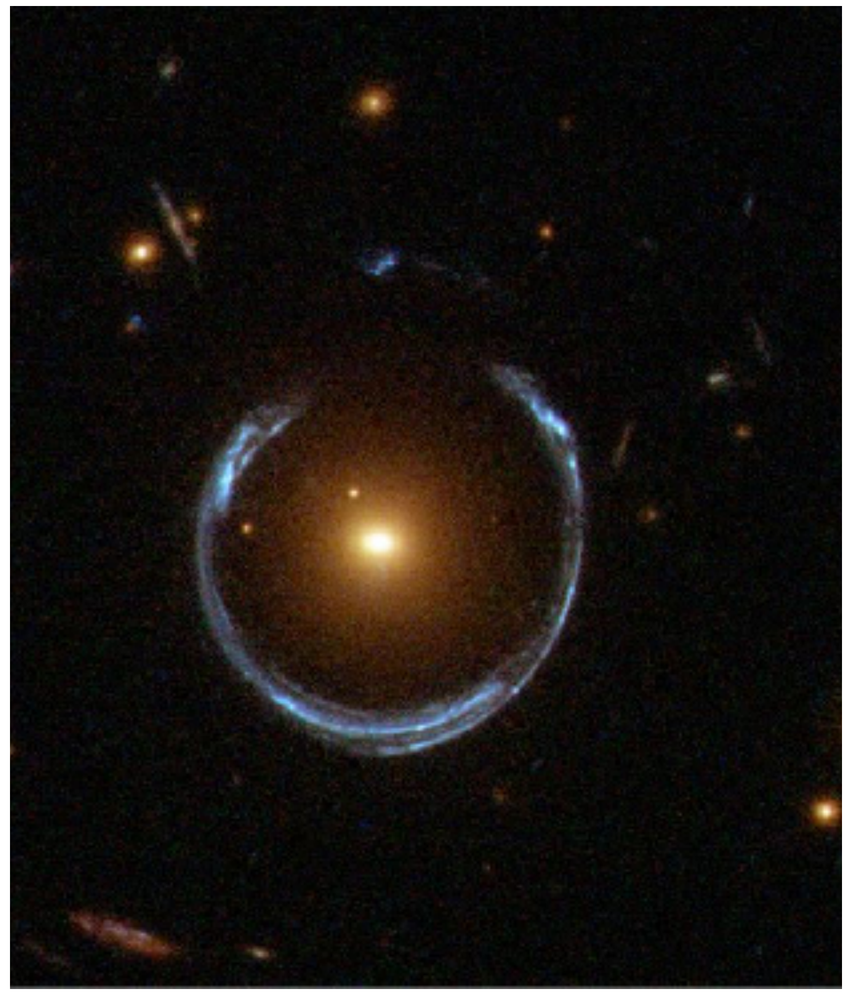
$$\alpha = \frac{4GM}{c^2 b}$$



The observer (O)

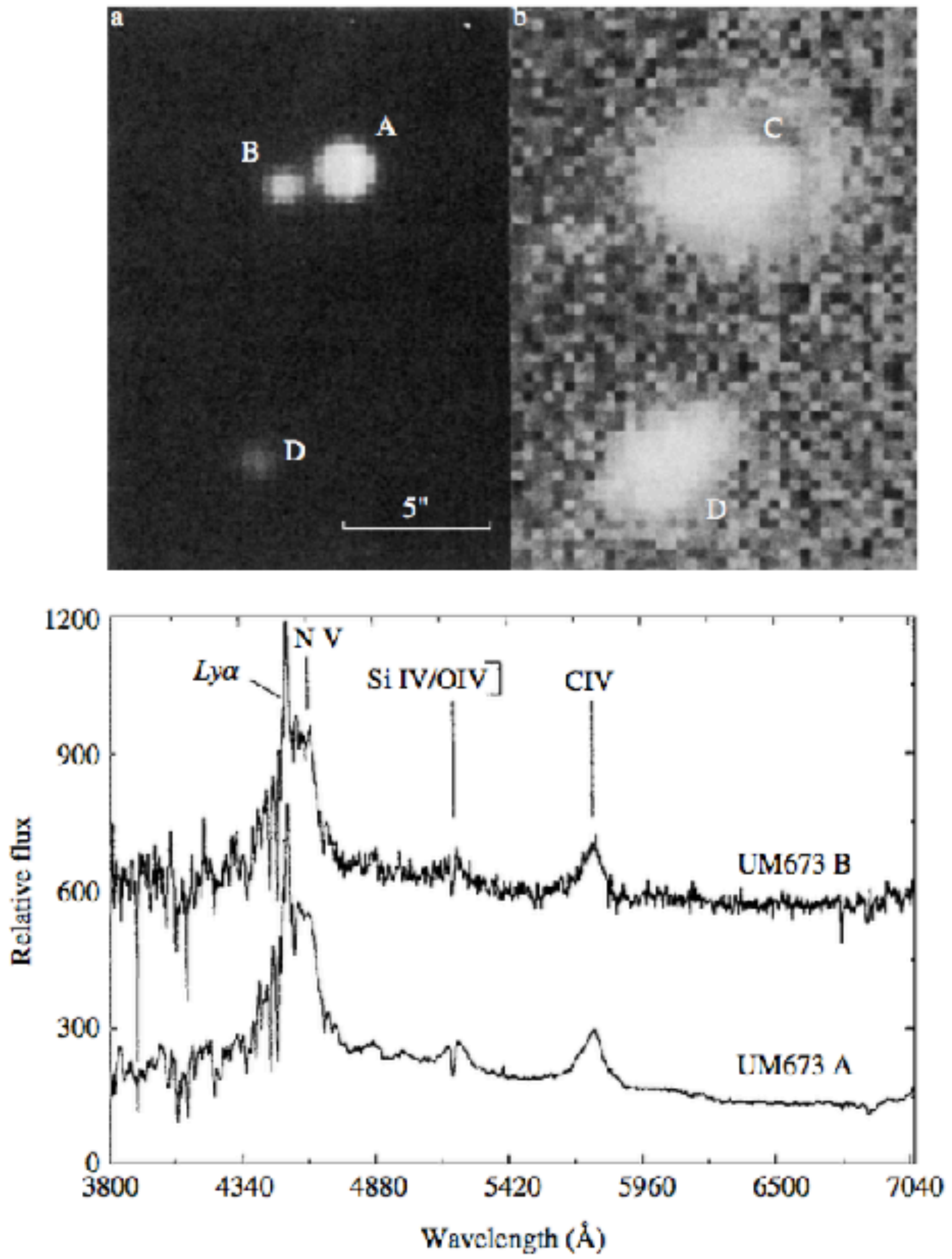






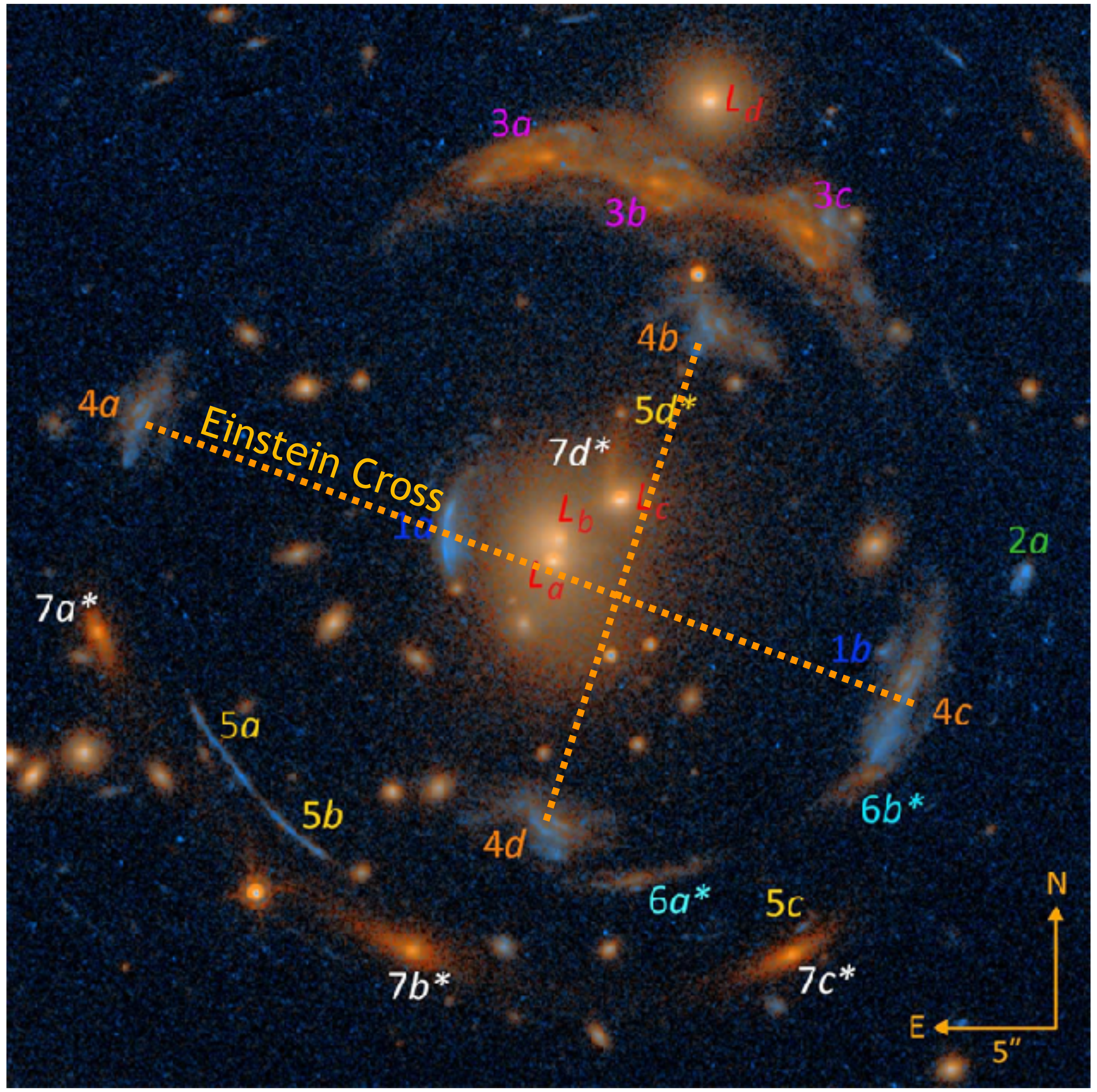
The gravitation lensing effect

Comment associer les images multiples ?



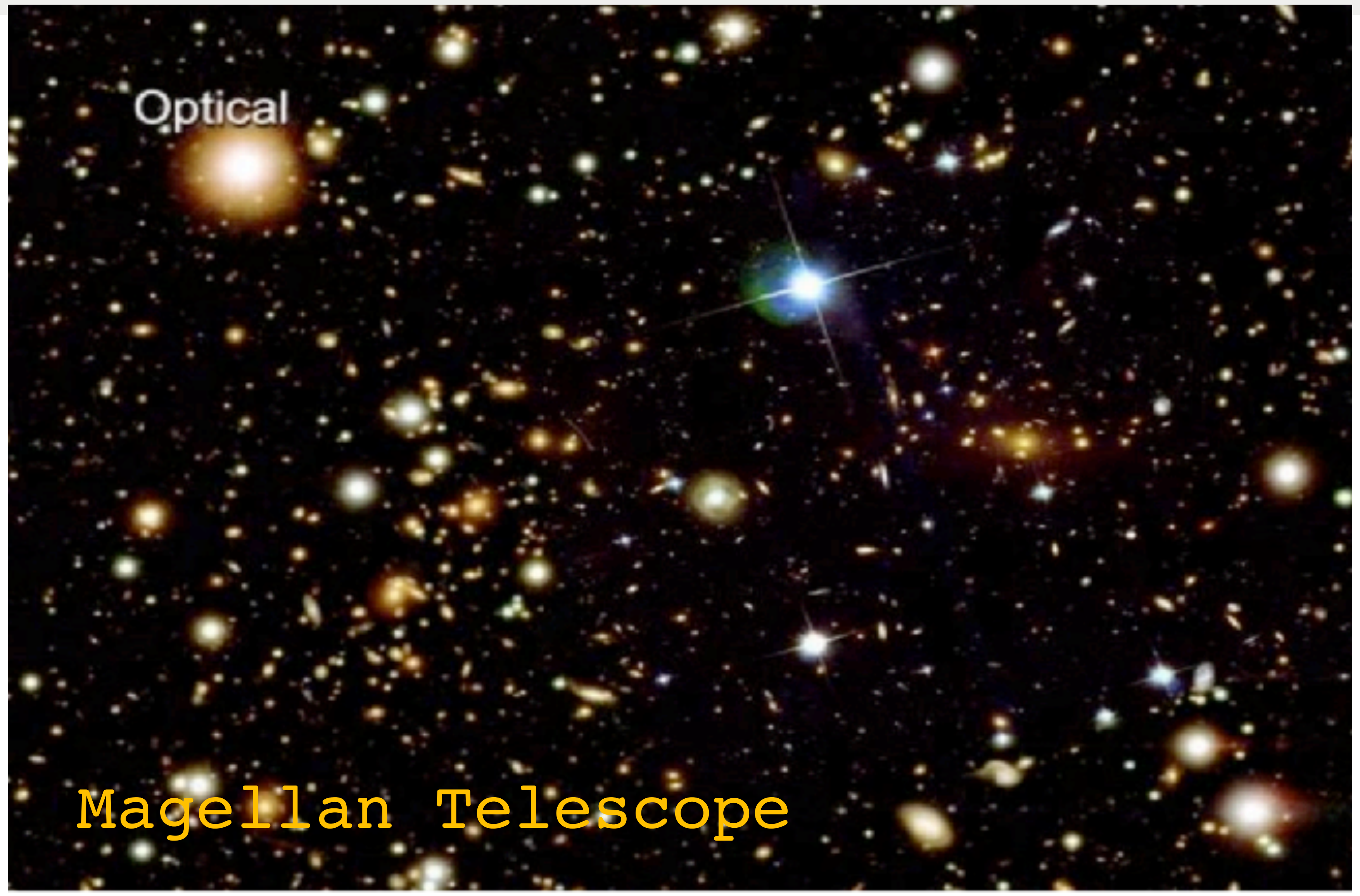
Grâce à leur “empreinte digitale”

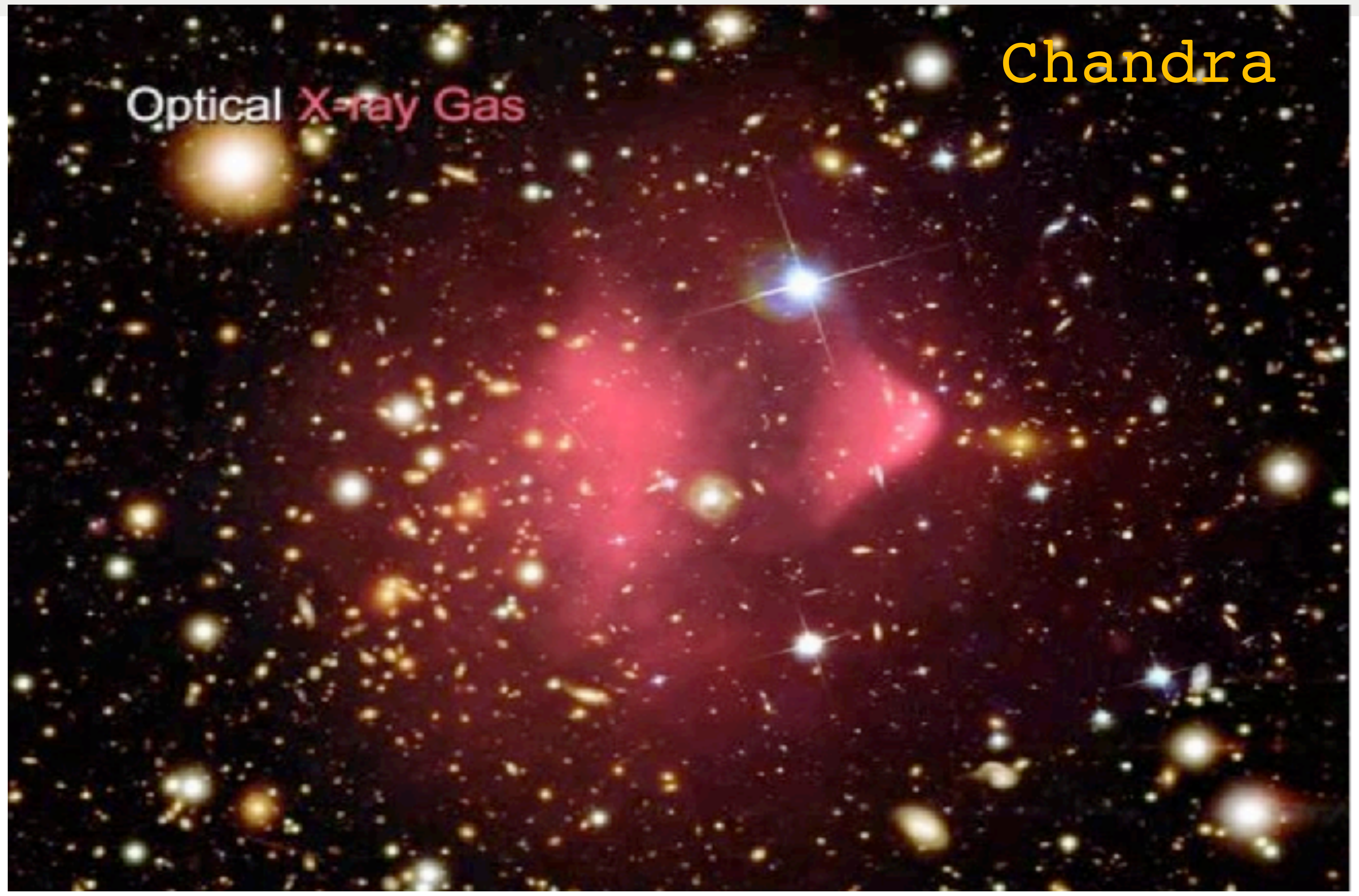
Carousel Lens



- système de **lentille gravitationnelle** induite par la matière noire
- **alignement** d’un amas de galaxies à 5 milliards d’années-lumière et de 7 galaxies jusqu’à 12 milliards d’années-lumière

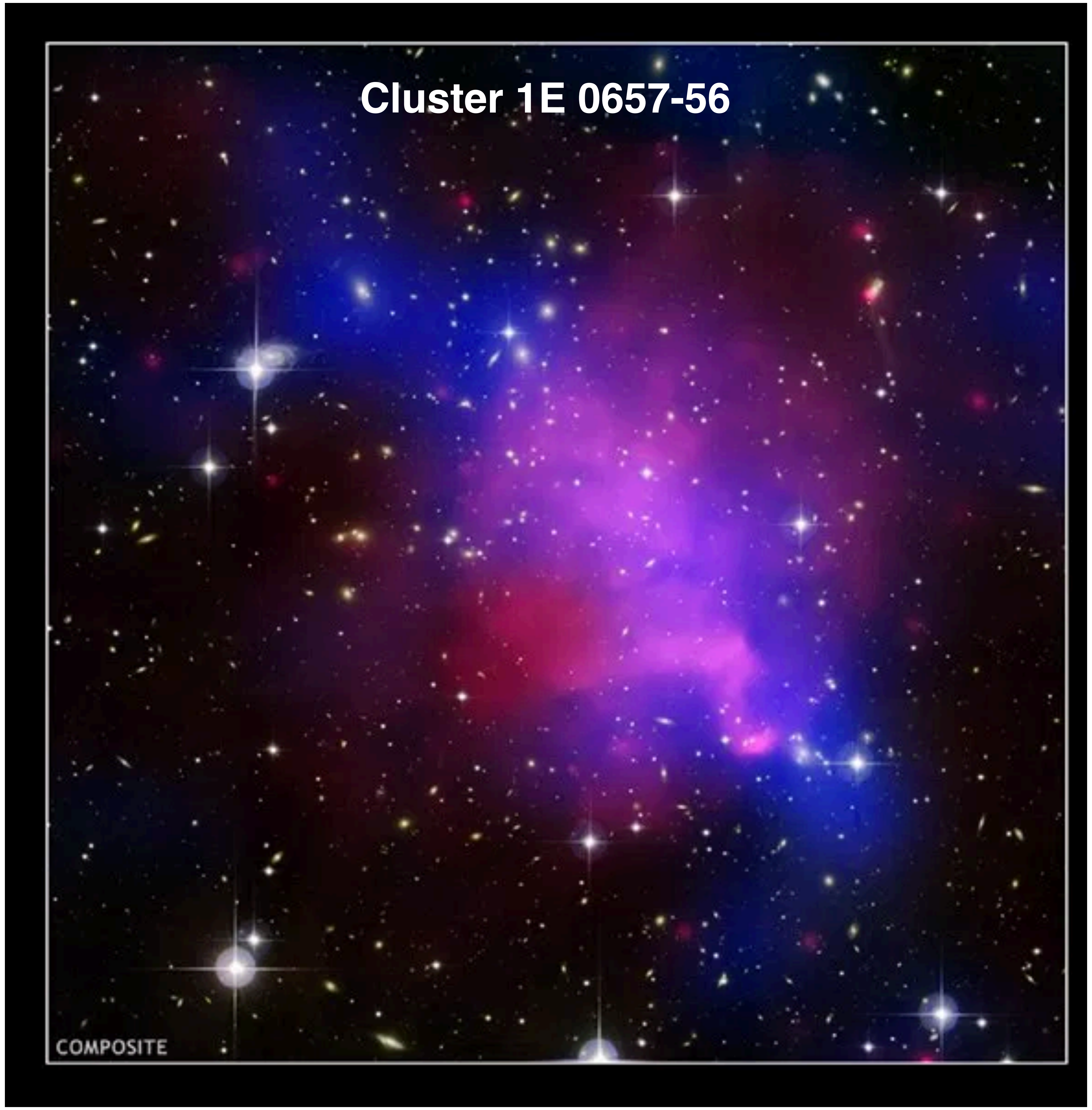
Bullet Cluster





Cluster 1E 0657-56. X-rays detected by Chandra. Optical image from Magellan and the Hubble Space Telescope

Bullet Cluster



Average distance between galaxies: 1 Mpc or 3.3×10^6 light-years → virtually **no collisions between galaxies**

Dark matter **does not interact** and passes through gas.

Most of the baryonic matter is found in the hot gas between galaxies.

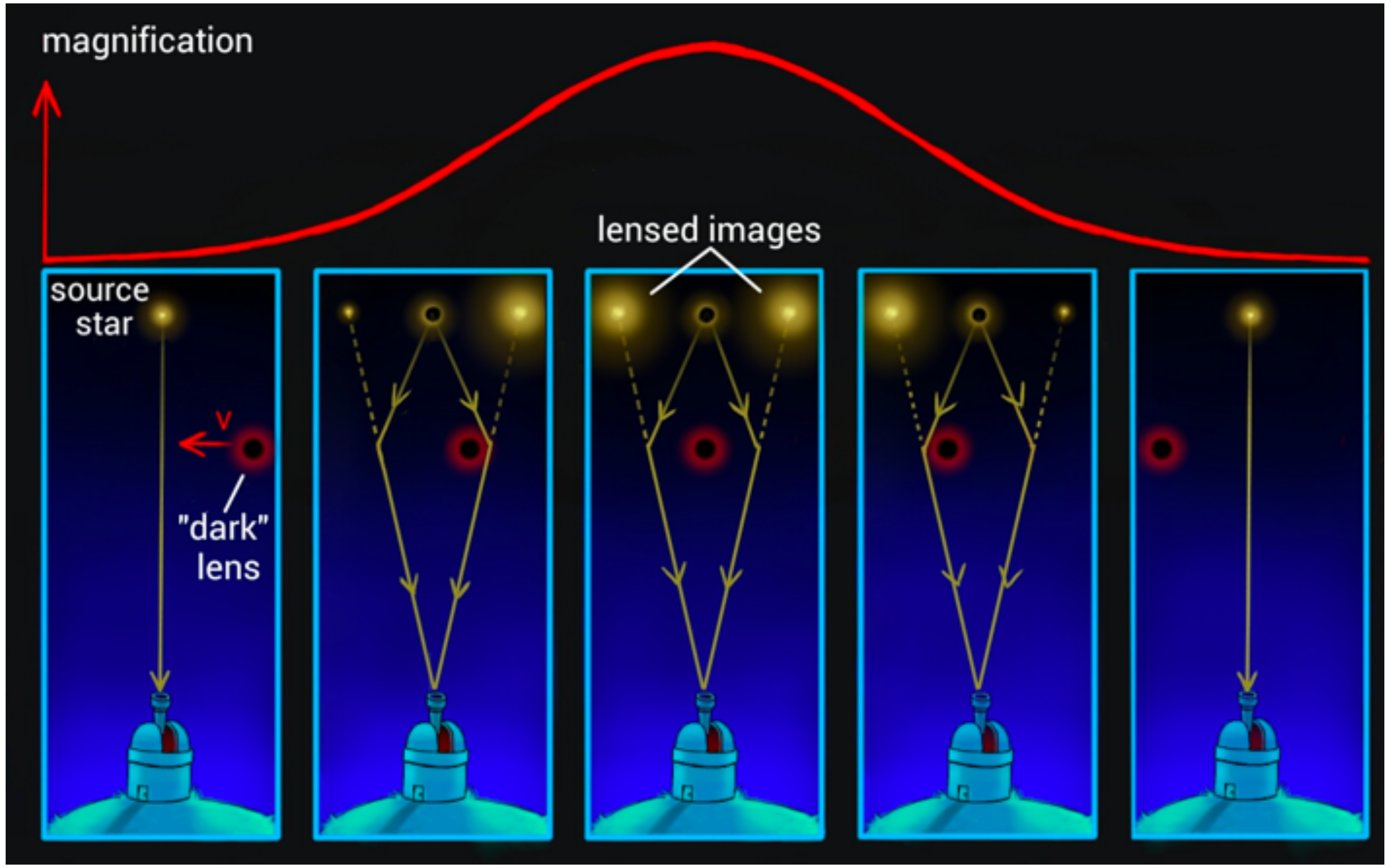
Galaxy clusters collide at ~10^7 km/h, compressing the gas and creating shock waves.

→ This results in X-ray emission.

Baryonic matter: maybe but…

Possible candidates for ordinary (**baryonic**) matter include massive astrophysical objects such as brown dwarfs, neutron stars, black holes, and planets; all of these can be classified as **MACHOs** (Massive Compact Halo Objects).

Microlensing effect



The MACHO and EROS-2 collaborations carefully monitored and statistically analyzed the sky for such an effect.

They studied **11.9 and 7 million stars** respectively, detecting only **13-17 and 1 candidates**.

This small number of MACHO candidates can account for only a very small fraction of the non-luminous mass in our galaxy.

→ Most dark matter cannot be strongly concentrated into or consist of baryonic astrophysical objects.

Microlensing

In the case of the Large Magellanic Cloud and a galactic halo full of solar mass dark objects, one **expects** about **1.5 magnification per million stars monitored and per year for an ideal, 100% efficient observing program**

It can only be **detected** when the monitored source star and the dark object have an **angular separation smaller than a milli-arcsecond.**

The phenomenon **duration** is called the Einstein timescale, which depends on the speed, position and mass of the deflector. For dark objects of our galactic halo, the Einstein timescale **varies between a half-hour to about two month**s for objects in the mass range between that of the Moon and that of the Sun (7 orders of magnitude in mass, 3.5 in timescale).

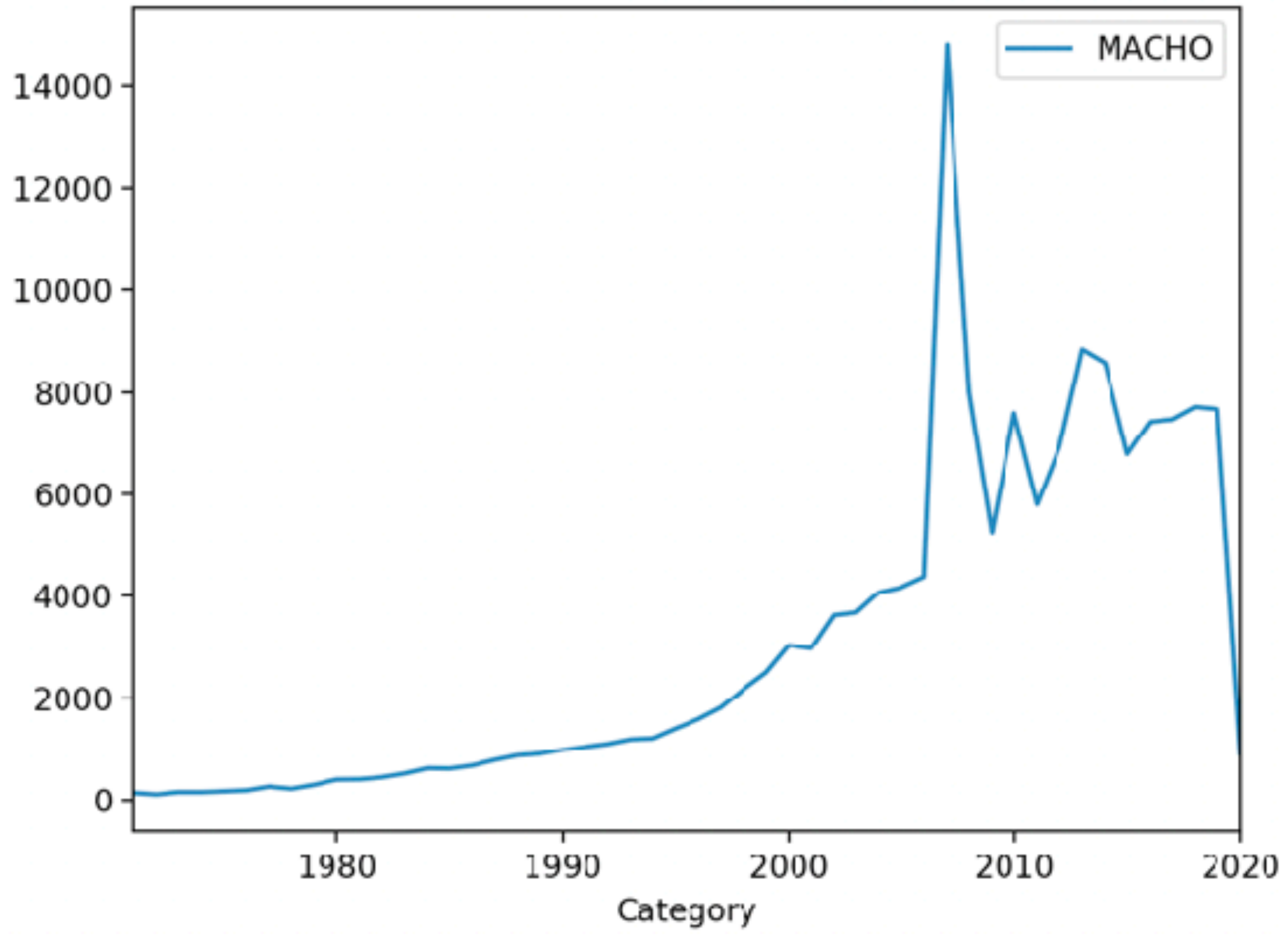
To separate a microlensing effect from **other transient phenomena** encountered in stellar evolution, one uses the **achromaticity**: the phenomenon should be identical in two distinct wavelength ranges.

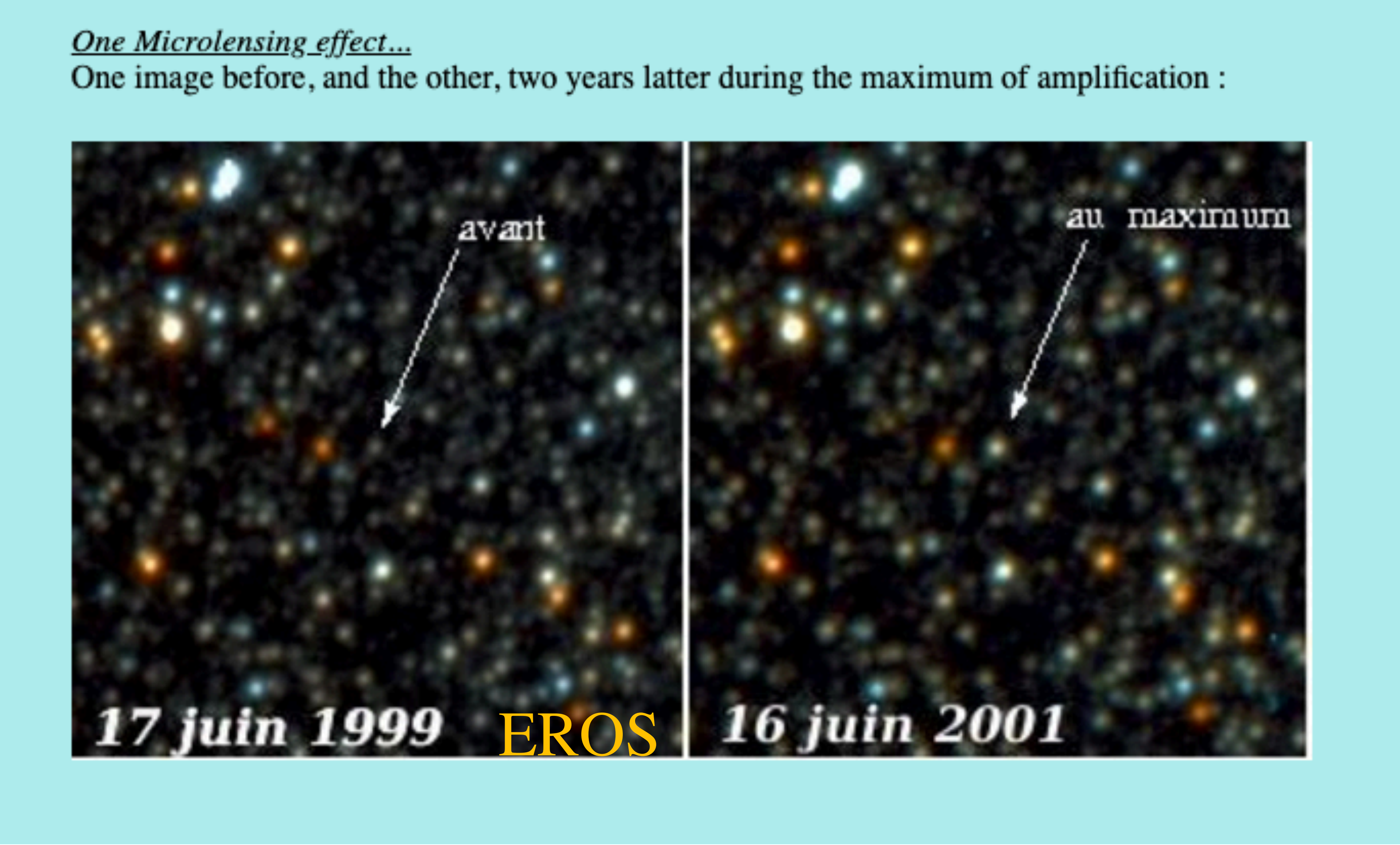
Microlensing

The MACHO Collaboration painstakingly observed and statistically analyzed the skies for such lensing; **11.9 million stars** were studied, with only **13-17 possible lensing events detected**.

In April of 2007, the EROS-2 Survey reported even fewer events, observing a sample of **7 million bright stars** with only **one lensing candidate found**.

This low number of possible **MACHOs can only account for a very small percentage of the non-luminous mass** in our galaxy, revealing that most dark matter cannot be strongly concentrated or exist in the form of baryonic astrophysical objects.





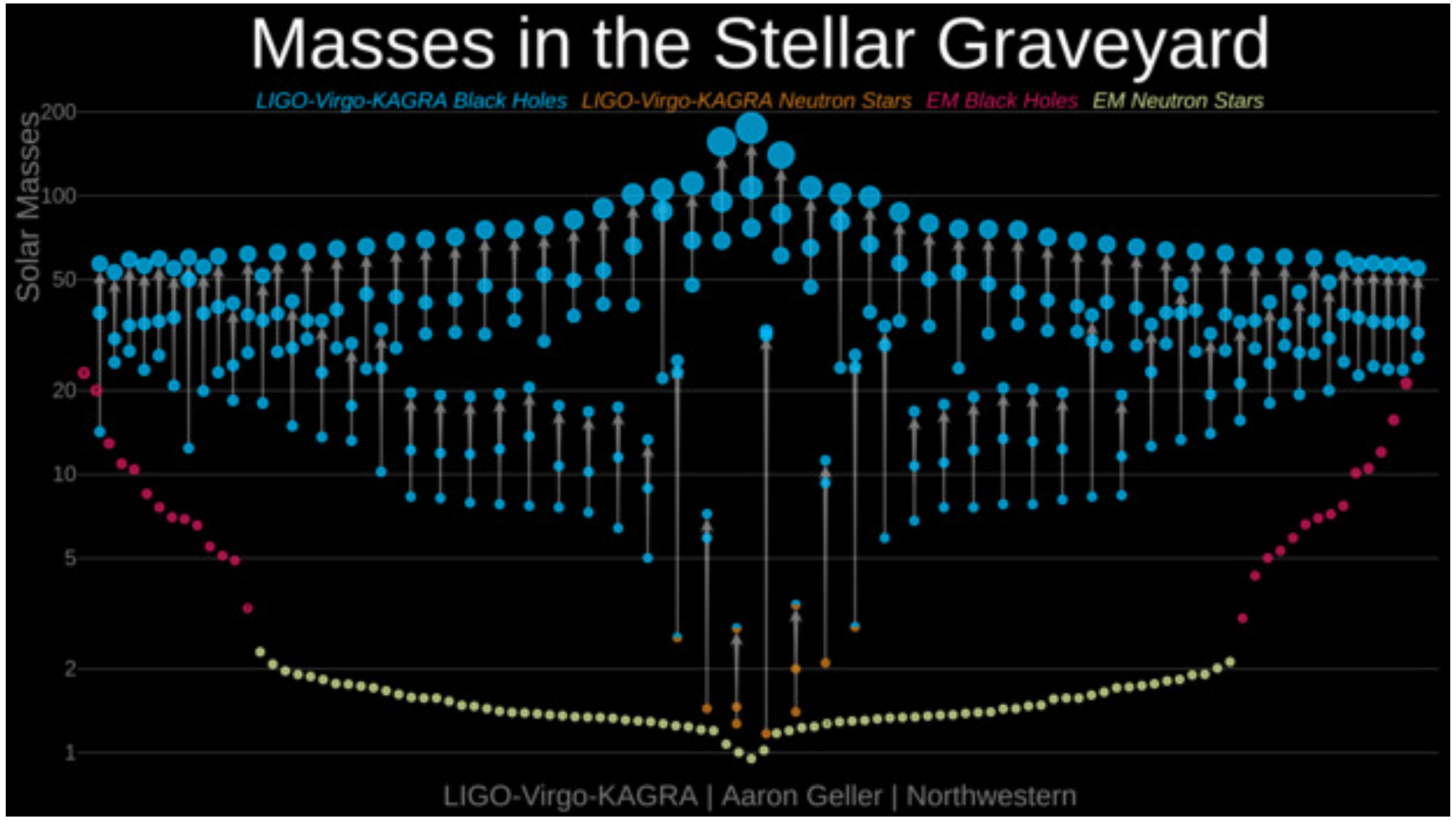
One Microlensing effect...

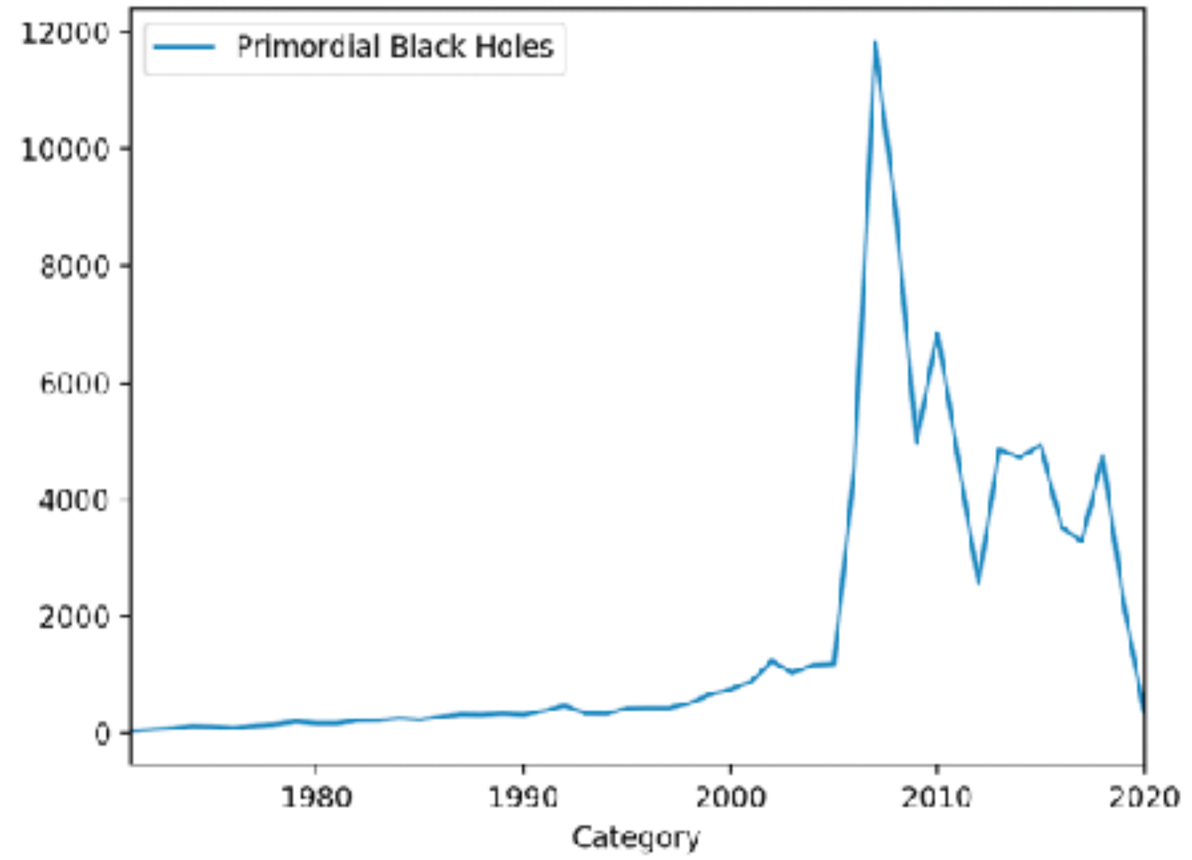
One image before, and the other, two years latter during the maximum of amplification :

Primordial Blackholes?

in 2016, when the LIGO-Virgo collaboration reported the **first detection of gravitational waves**, and the source was a binary black hole merger. The sizes of these black holes were slightly larger—and their rotation rates were slower—than expected from stellar models, so many theorists began considering a primordial origin.

Masses of confirmed black hole mergers observed by LIGO and Virgo.





Number of publications mentioning ‘Primordial Black Holes’

Primordial Blackholes?

The basic recipe for making primordial black holes is actually pretty simple: all you need is a **region in the very early Universe with a density that is roughly twice the average density**, and gravity will do the rest.

Of course, the most exciting possibility is that primordial black holes are **numerous enough to account for the dark matter (?)**

Problem 1: **how to make over-dense region?** the early Universe appears to have been very uniform—at least on the large scales from CMB. If all density fluctuations are as small as those in the CMB, **then any black holes could not be produced in the early Universe**.

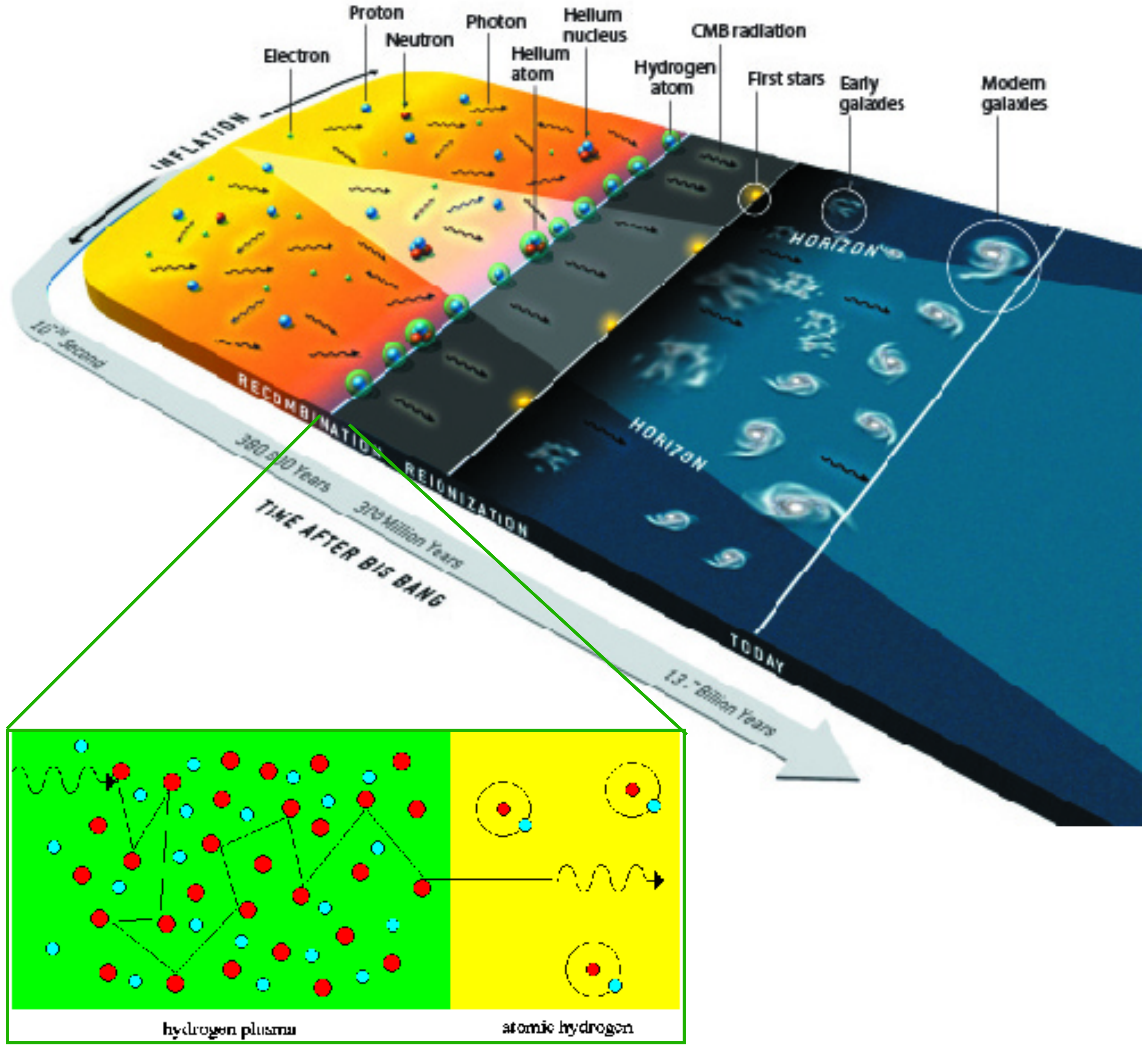
Problem 2:

- the Milky Way Galaxy should be **swimming in a sea of roughly a trillion black holes** => these black holes should occasionally run into things, in particular, each other.
- The LIGO-Virgo detections of black hole mergers are evidence of a **large population of black holes in the 10 solar-mass range**.
- Recent calculations have shown that if dark matter were made up of black holes weighing between 10 and 300 solar masses, then **LIGO should have detected hundreds more** mergers in its first run.
- Turning the argument around: **multi-solar-mass black holes can only account for about 1% of the dark matter.**

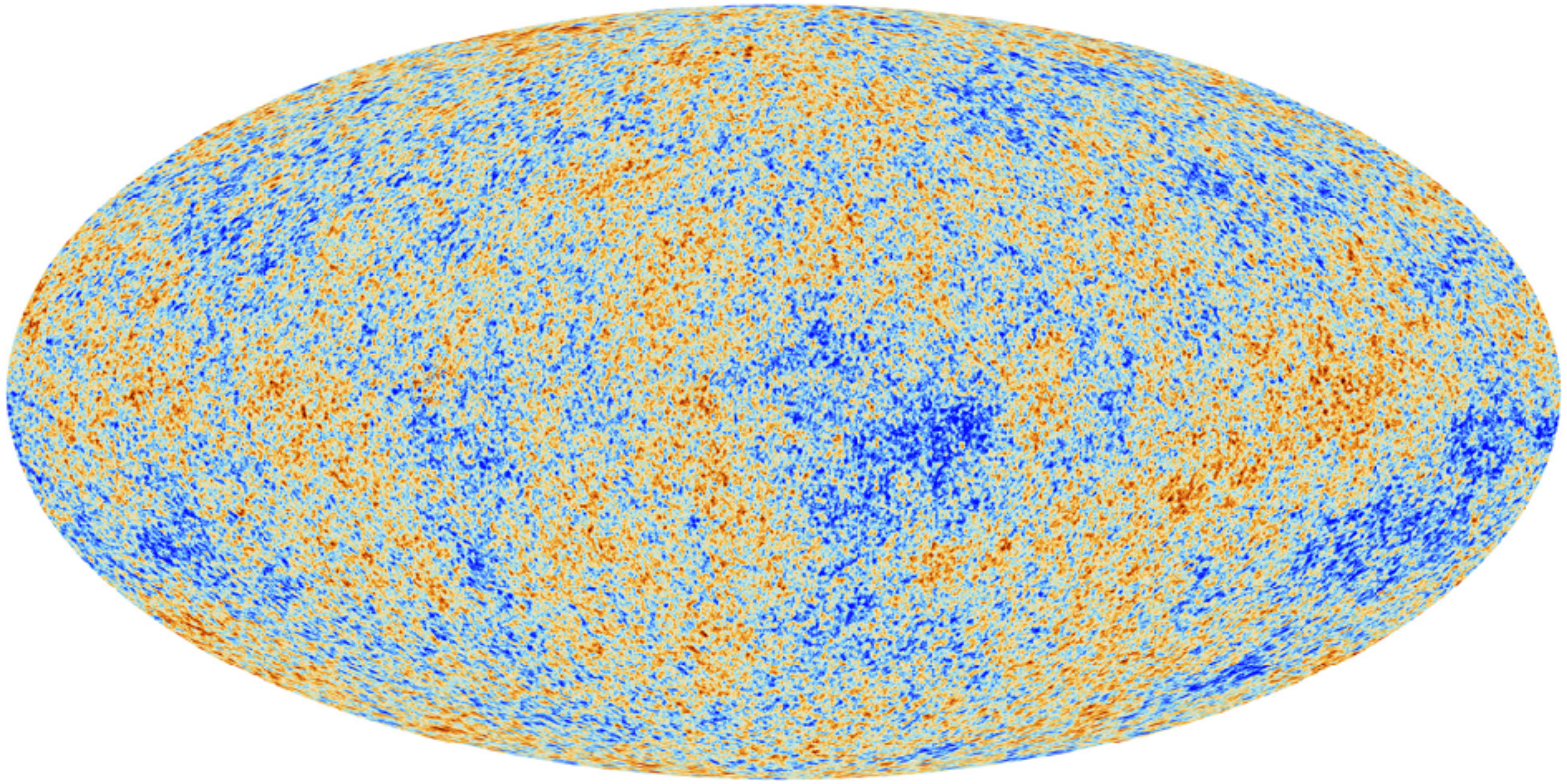
Cosmic Microwave Background

- Big Bang: dense plasma (particles + photons)
- 380,000 years later: expansion and cooling
- Recombination: formation of neutral atoms

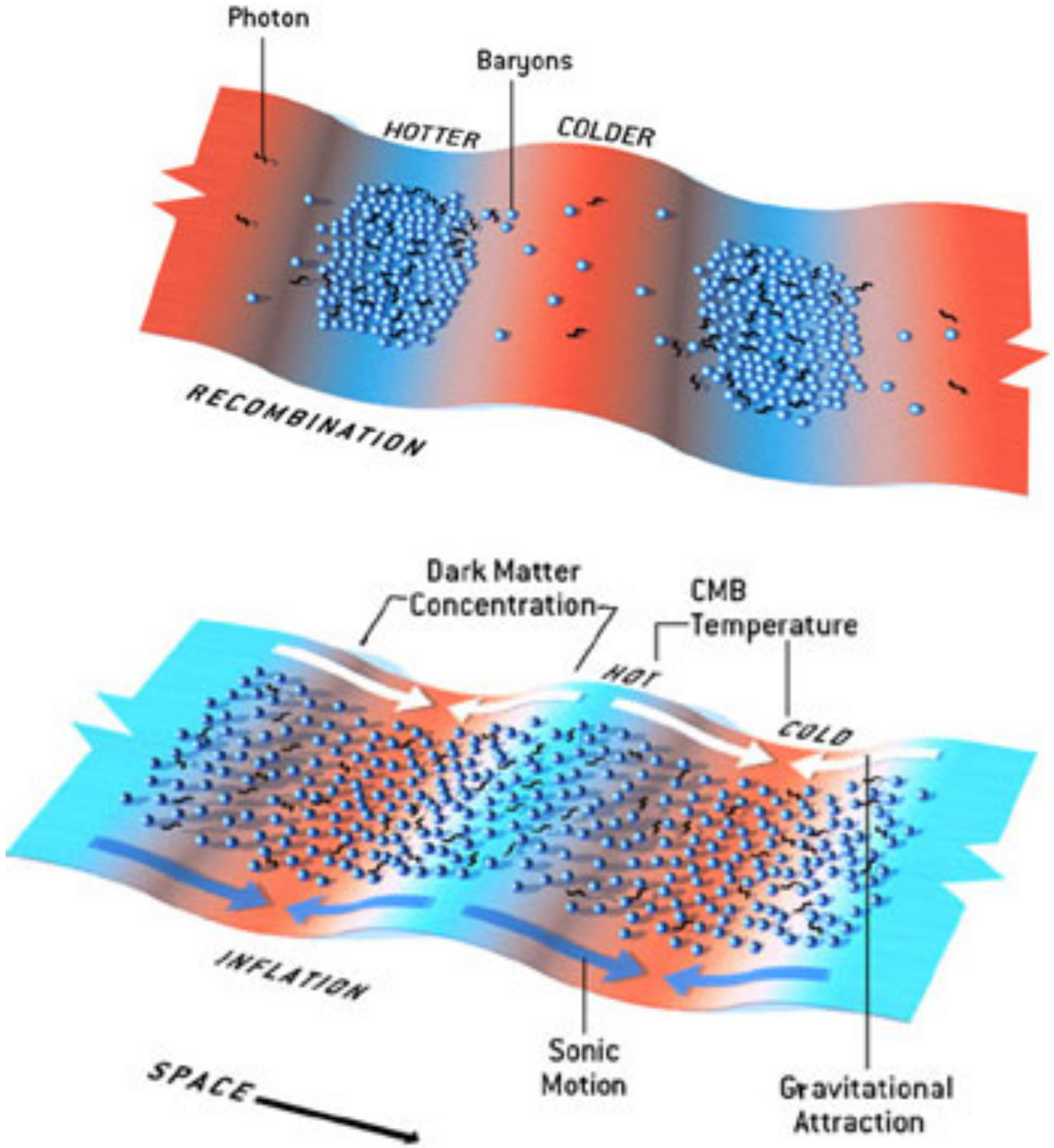
→ Universe becomes transparent

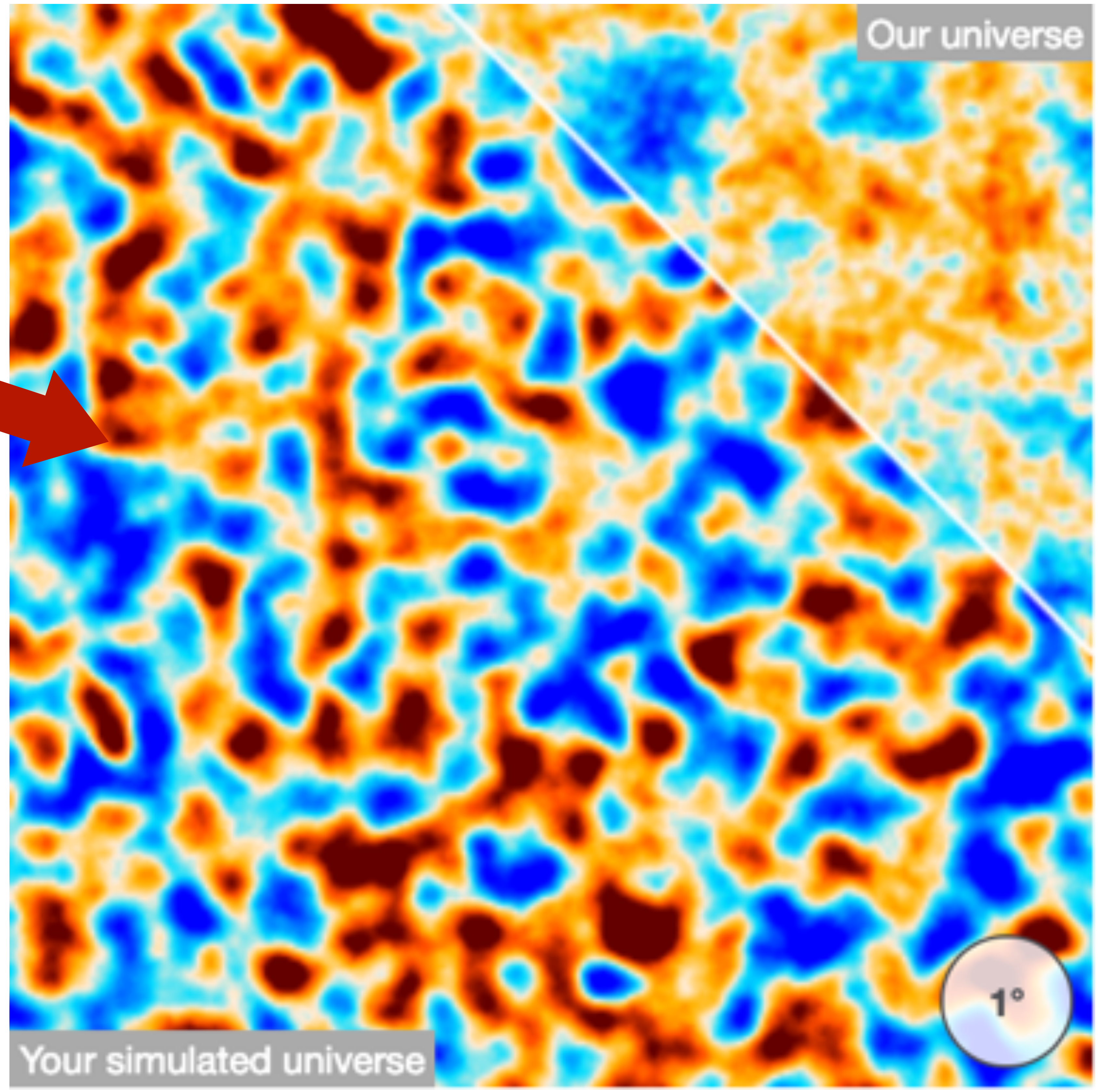


- CMB: photons released → Cosmic Microwave Background
- Blackbody spectrum with temperature: 2.725 K
- Anisotropies: temperature fluctuations of order 10^{-5}, related to density variations in the early Universe

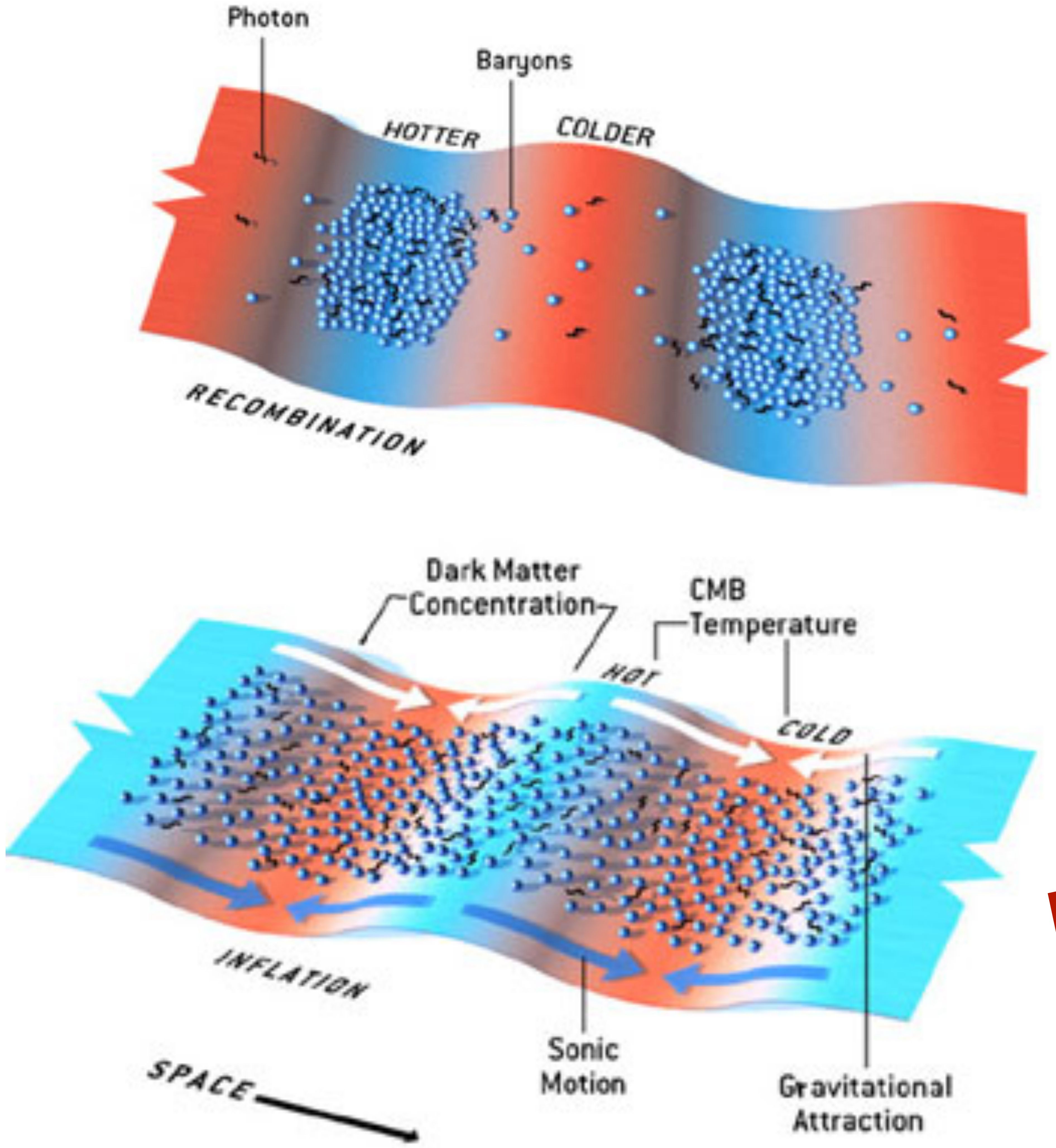


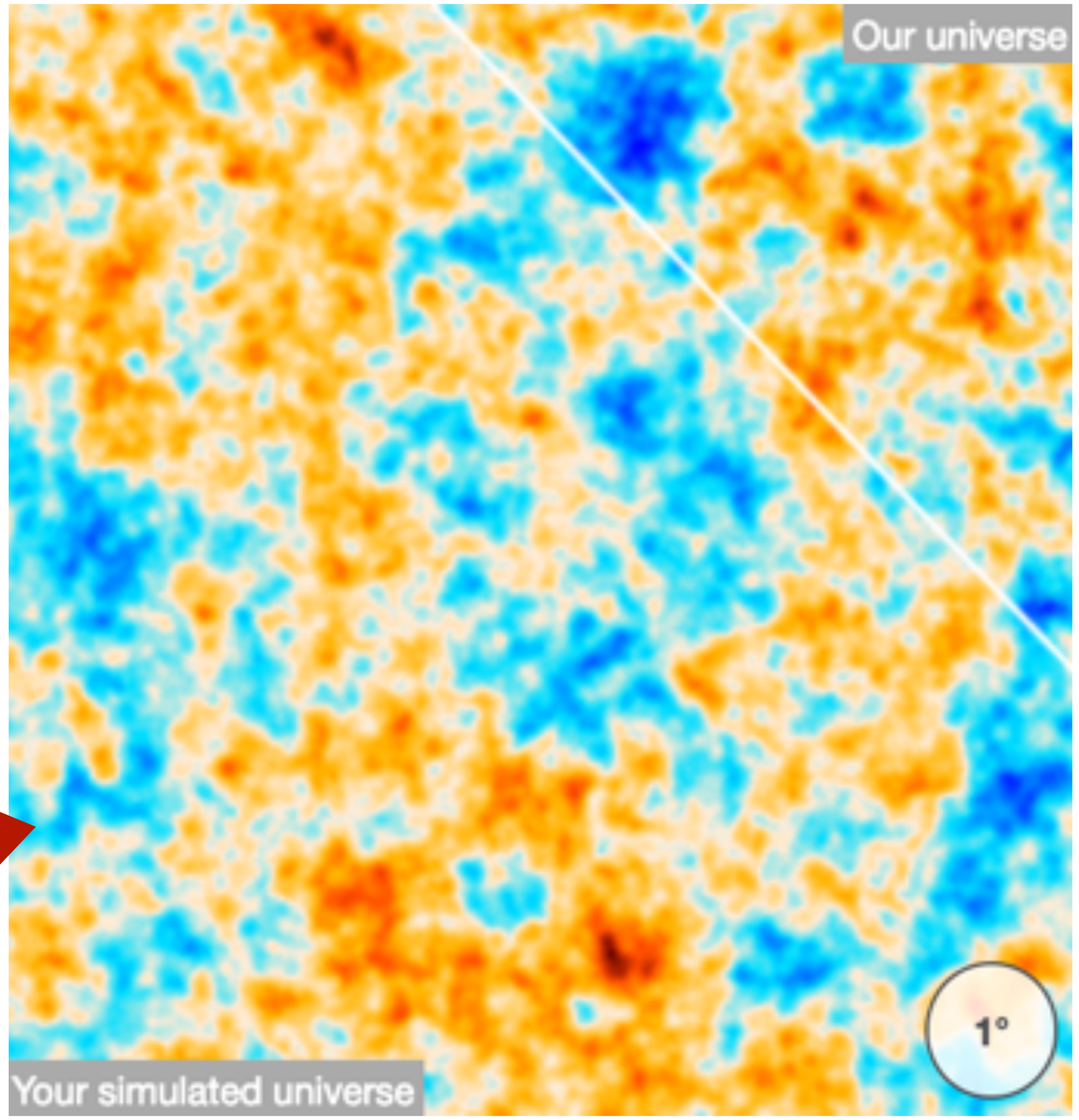
CMB: anisotropies and matter density





CMB: anisotropies and matter density





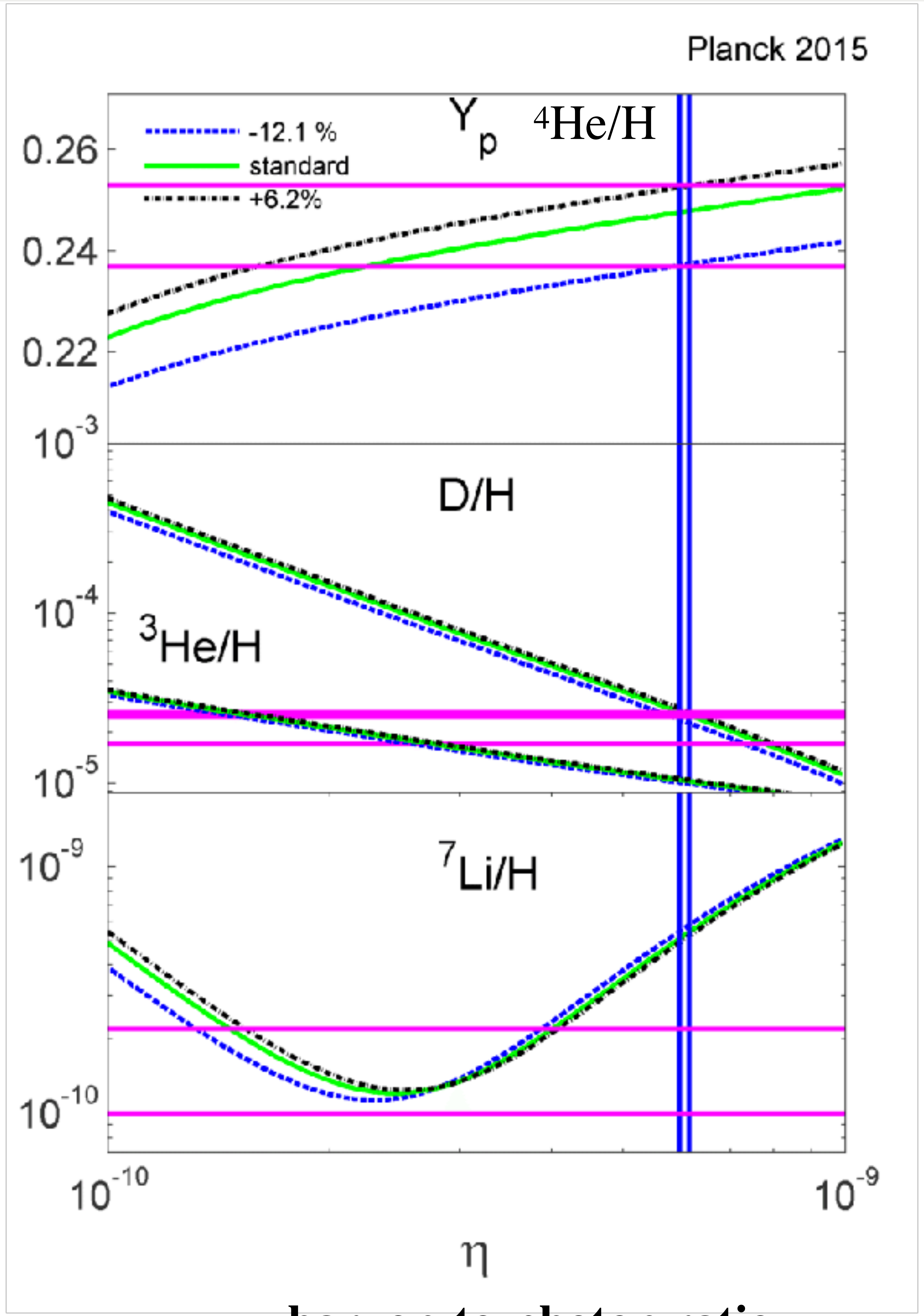
Deuterium-to-Hydrogen (D/H) ratio

BBN (from a few seconds to a few minutes from BB), when neutrons and protons fused together to form D, He, and a small amount of Li or heavier elements
=> **largest source of D**

In fact, if D is found or produced in stars it is destroyed by fusing into ^{4}He:
⇒ abundance of D in the early universe is lower limit of amount of D created by BBN

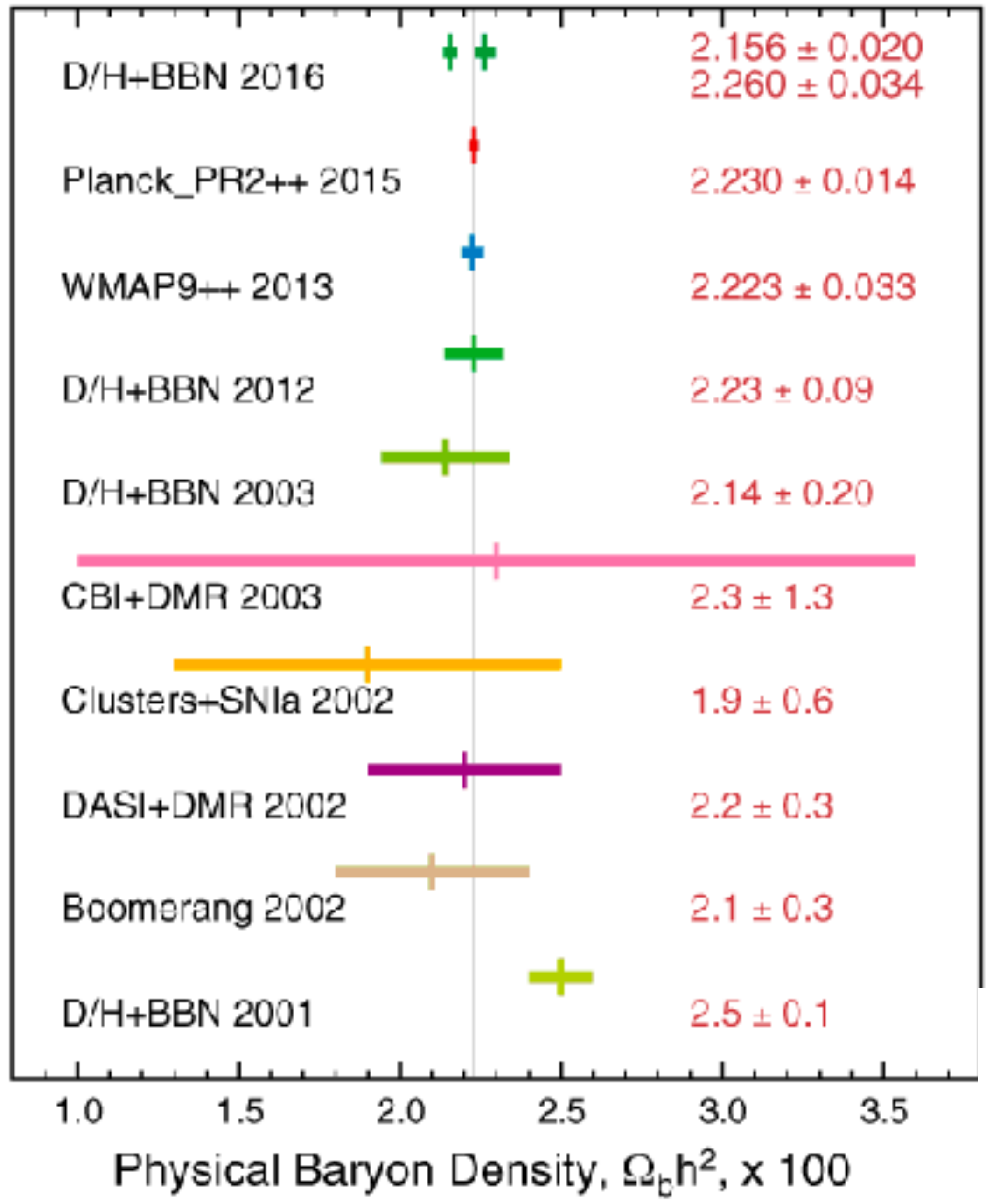
Look for D/H in far and primordial areas of universe (selected by looing at low concentrations of elements heavier than Li)

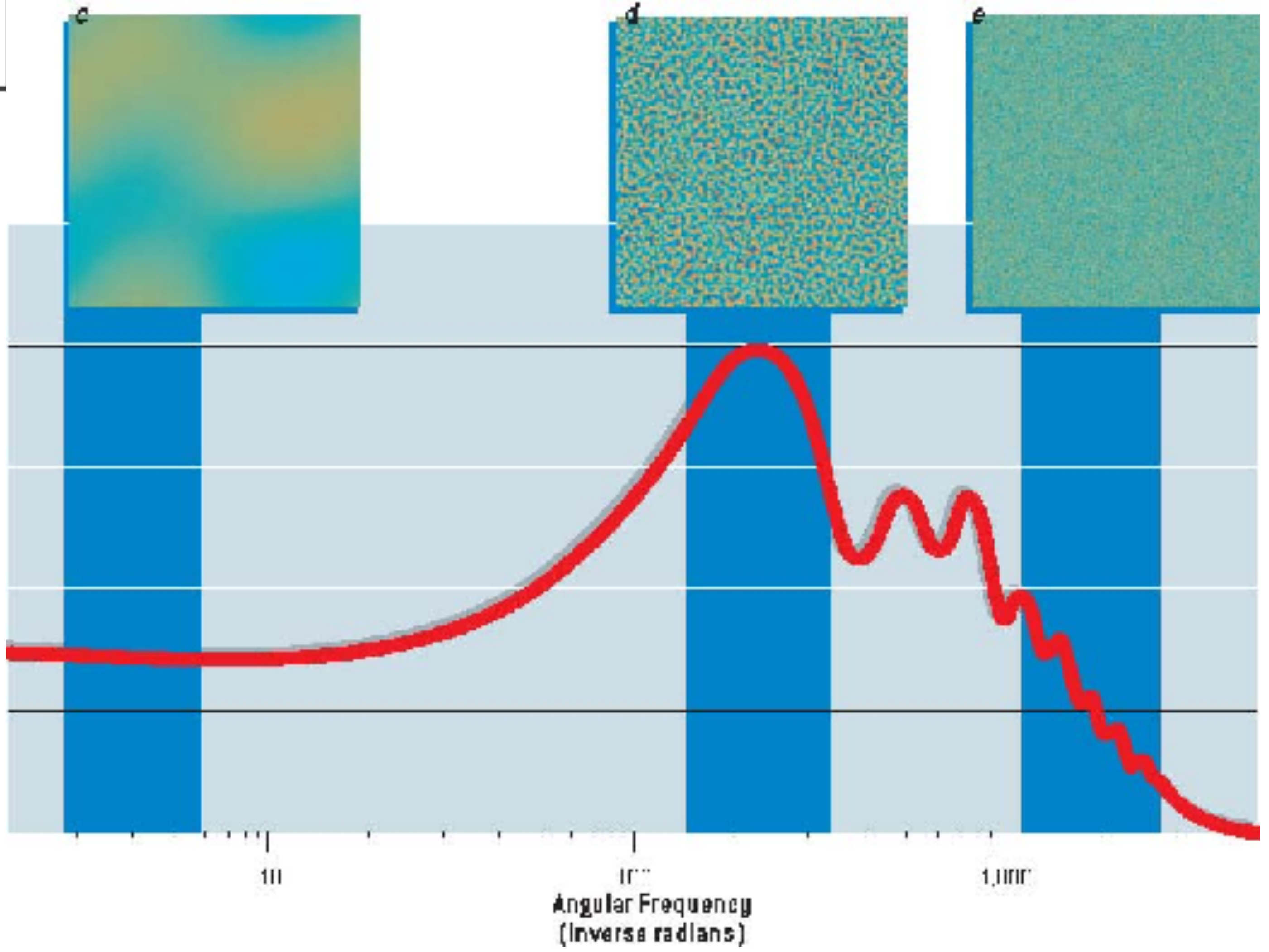
D/H is strongly dependent on baryon relative density. From models and comparing to matter density from CMB (see next slides), **baryons account only for 20% of total matter**

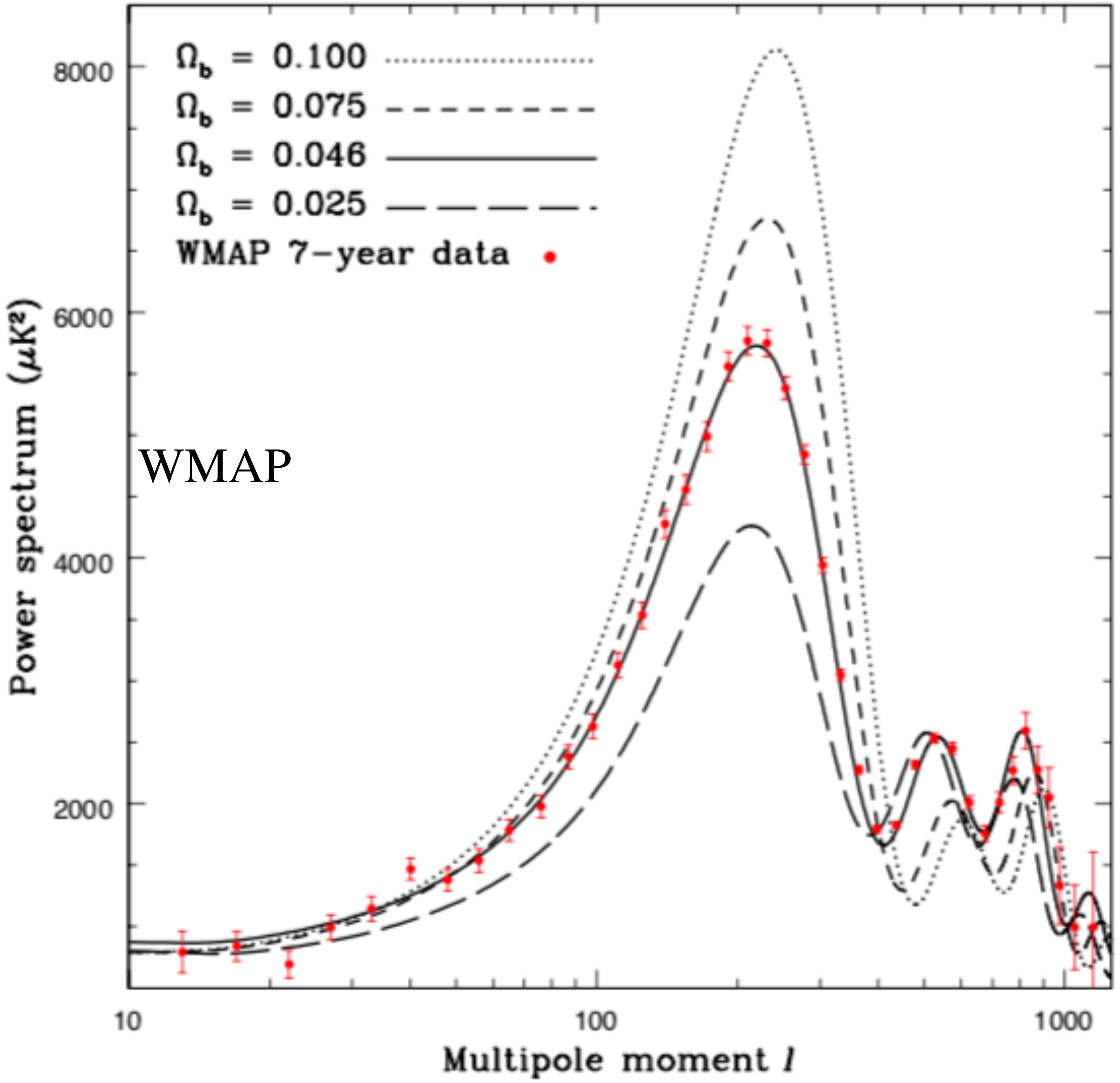


η = baryon-to-photon ratio

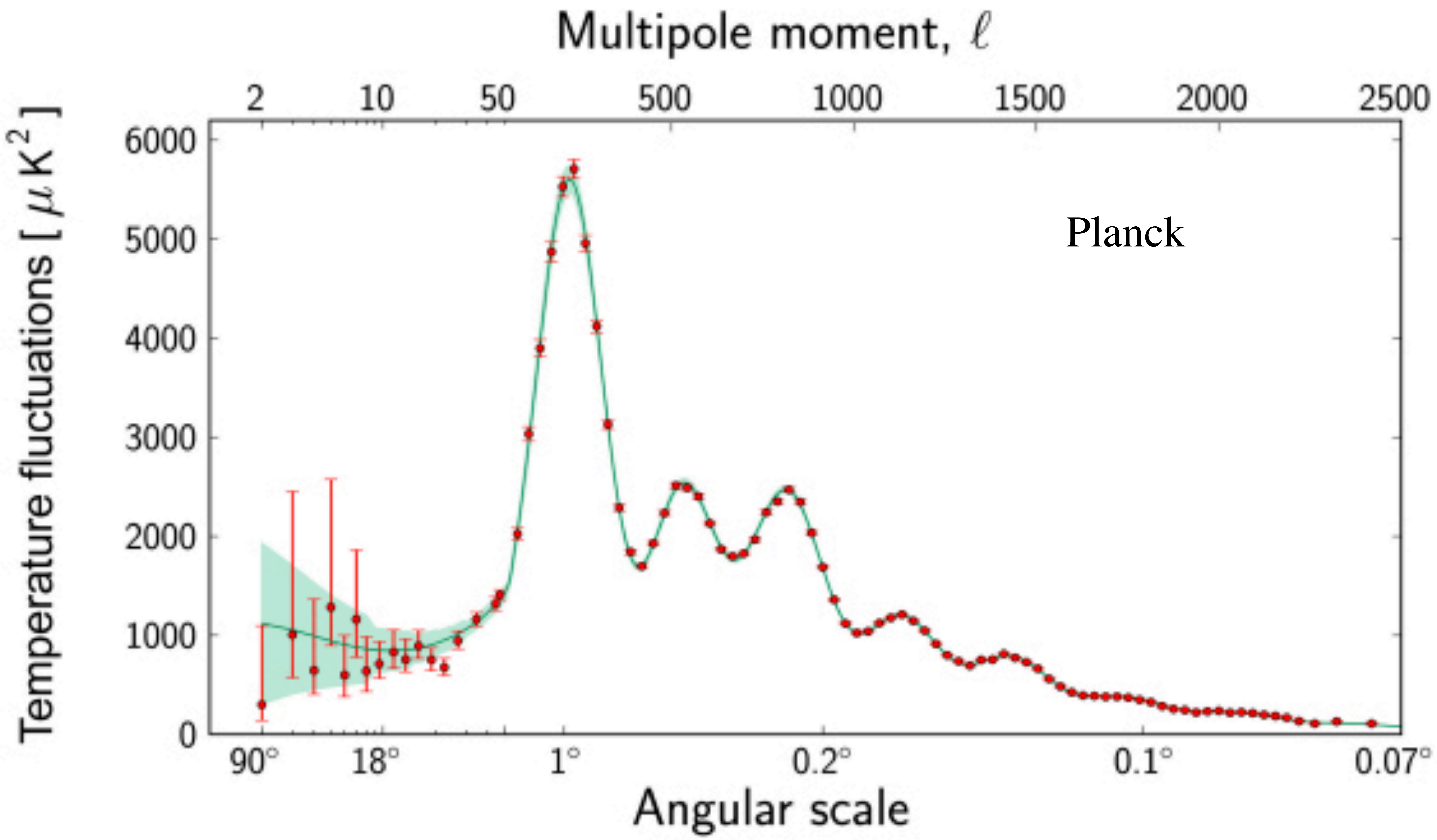
CMB and baryon density

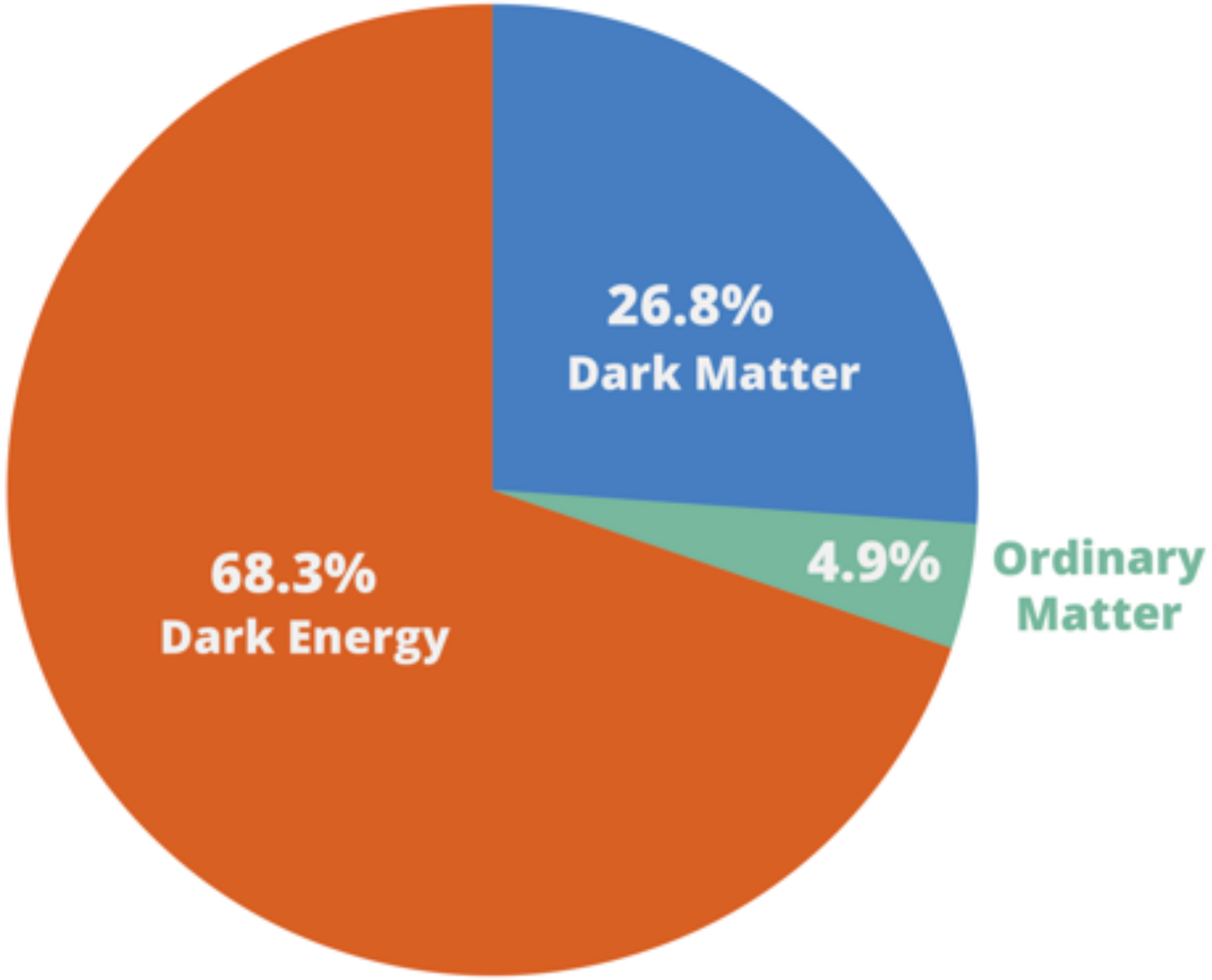






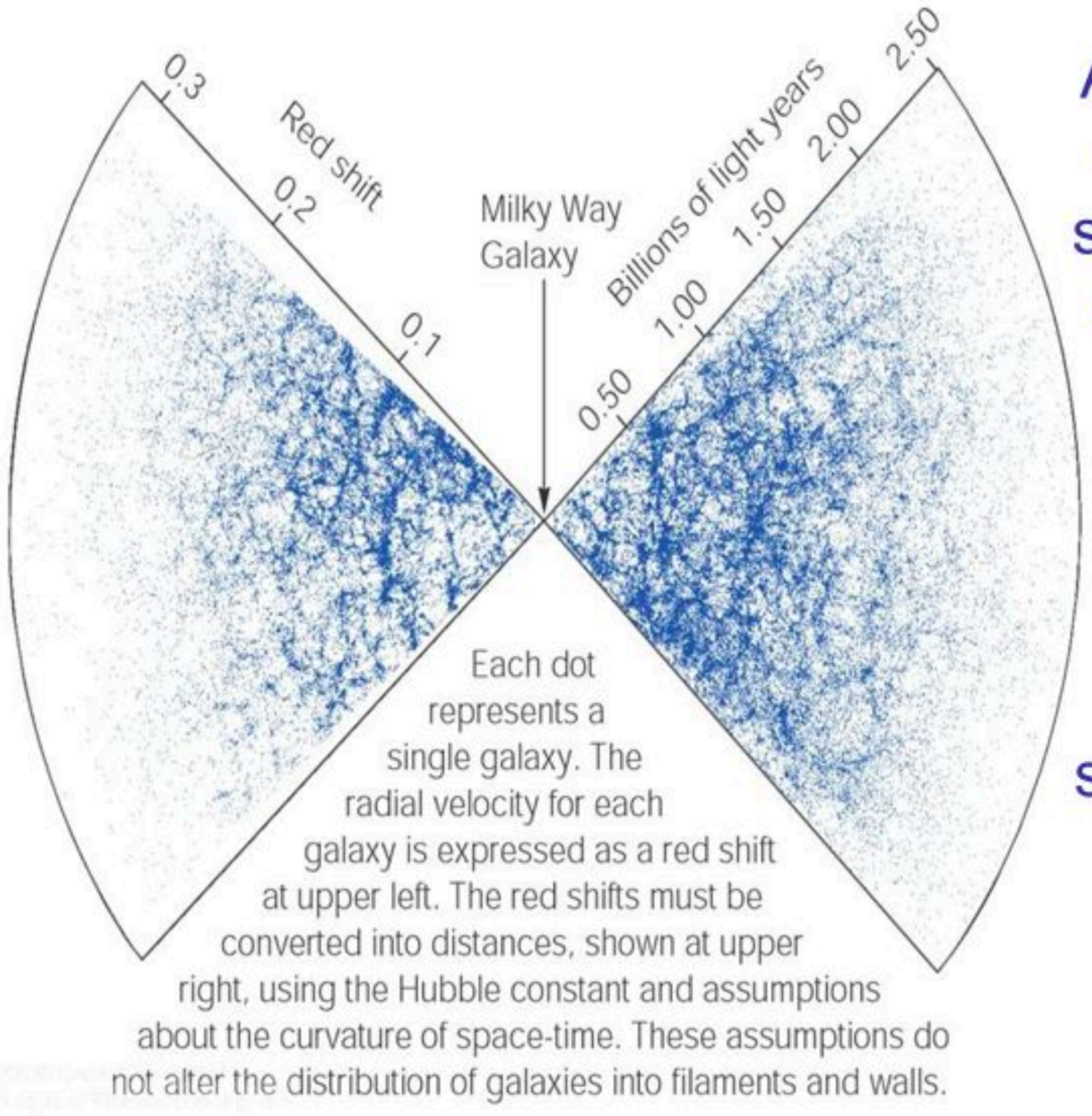
CMB and dark matter





Large Scale Structures

Measurements of matter distribution from CMB maps, spectroscopic surveys, gravitational lensing and Lyman-α line of quasars



Each dot represents a single galaxy. The radial velocity for each galaxy is expressed as a red shift at upper left. The red shifts must be converted into distances, shown at upper right, using the Hubble constant and assumptions about the curvature of space-time. These assumptions do not alter the distribution of galaxies into filaments and walls.

A large survey of distant galaxies shows the largest structures in the universe:

Filaments and *walls* of galaxy superclusters, and *voids*, basically empty space.

Hot, warm, or cold dark matter?

Hot Dark Matter

Relativistic

HDM particles moving fast => can escape from small mass density fluctuations.

Since HDM mass makes the density fluctuation, HDM can escape from small mass density fluctuations
⇒ small fluctuations will dissolve
⇒ baryons won't collapse into small lumps
⇒ only the big surviving lumps will collapse
⇒ after collapse, fragmentation can occur

Direct consequences:
⇒ structure forms slowly
⇒ structure forms "top down”
⇒ galaxies form very late in the Universe's history

Note: calculations for neutrinos suggest that any density fluctuation smaller than about $10^{15}\ M_{sun}$ *will dissolve away before recombination*

Hot, warm, or cold dark matter?

Cold Dark Matter

Non-relativistic

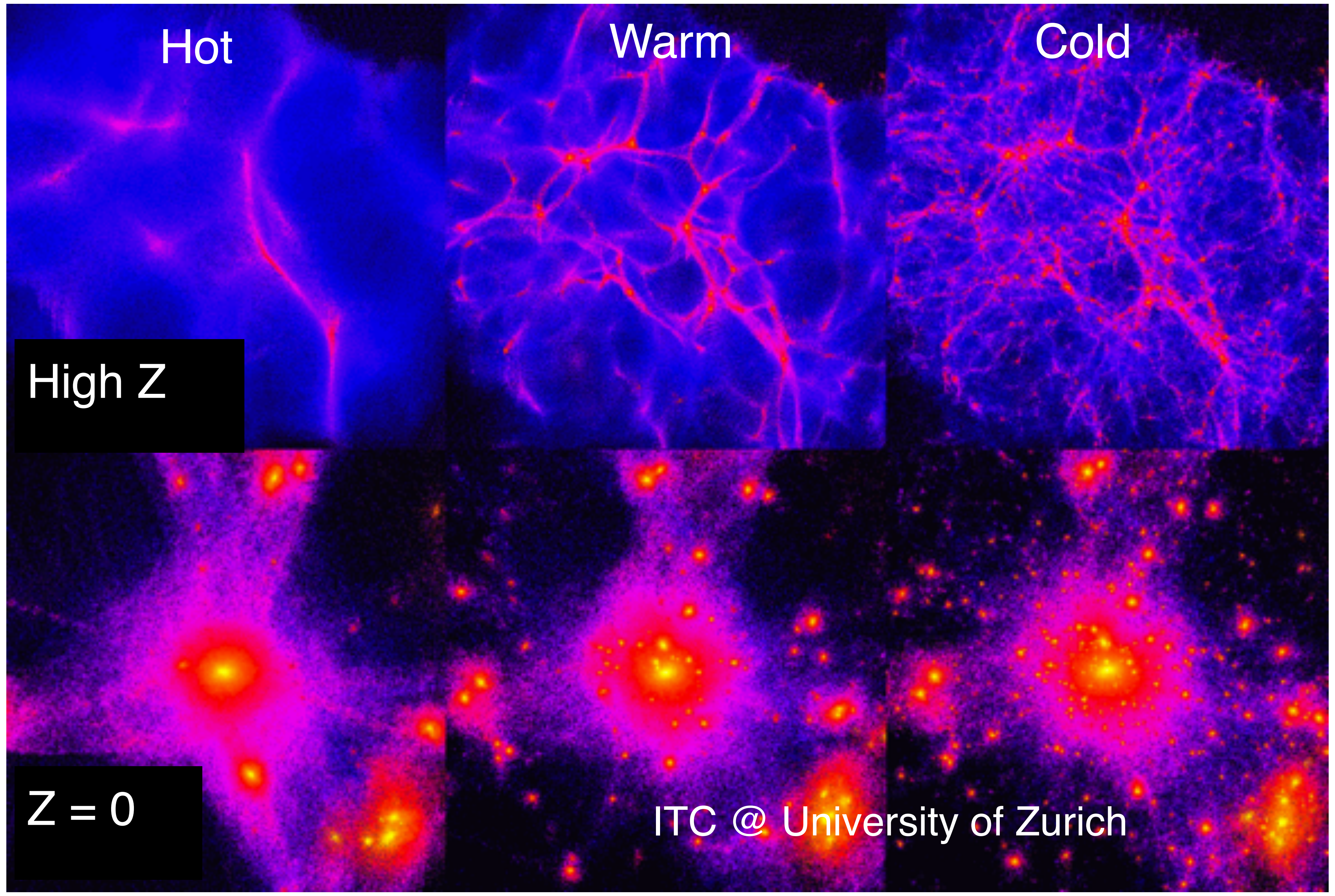
CDM particles do not diffuse out of small lumps:
⇒ lumps exist on all scales -- small and large.
⇒ little things collapse first
⇒ big things collapse later, incorporating the little things in as they collapse

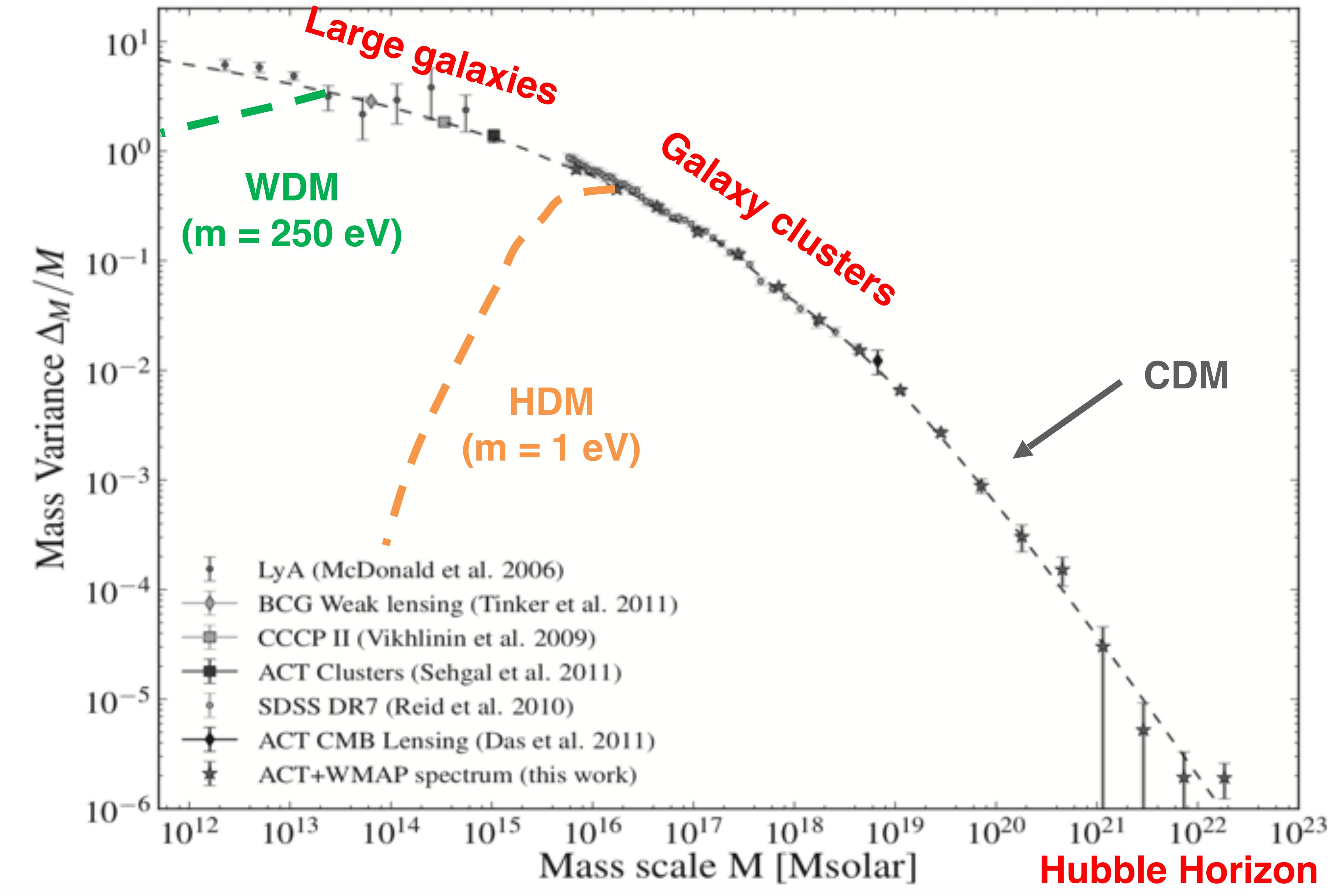
Direct consequences:
⇒ structure begins to form early
⇒ structure forms "bottom up”
⇒ galaxies form before galaxy clusters.

Another way to classify cold/hot DM is based on velocity dispersion larger or lower than escape velocity

Hot, warm, or cold dark matter?

How change the universe structure by changing the dark matter “temperature”?



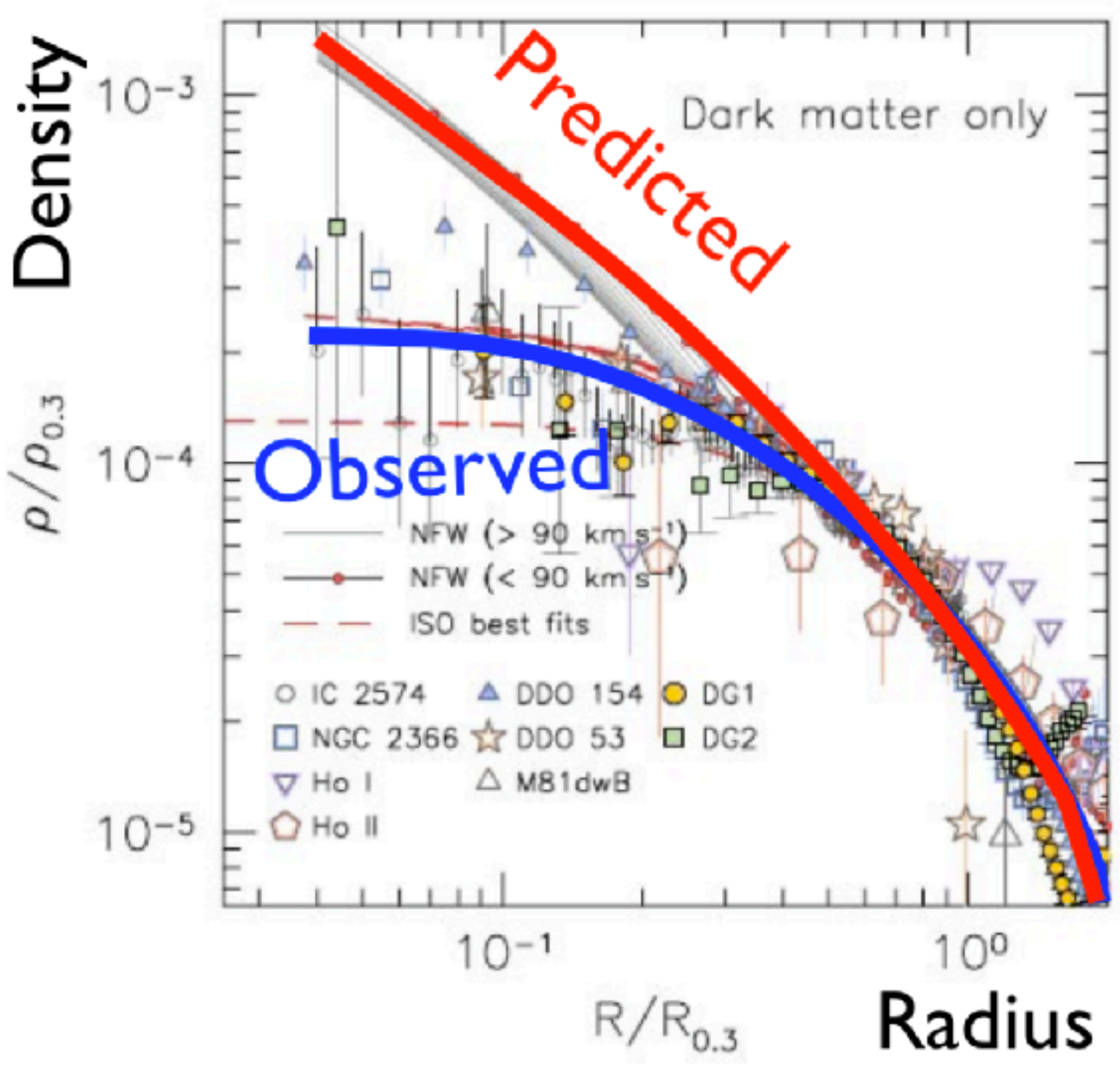


Hot, warm, or cold dark matter?

An example

Observed density profiles in dwarf galaxies are shallower than predicted with DM only

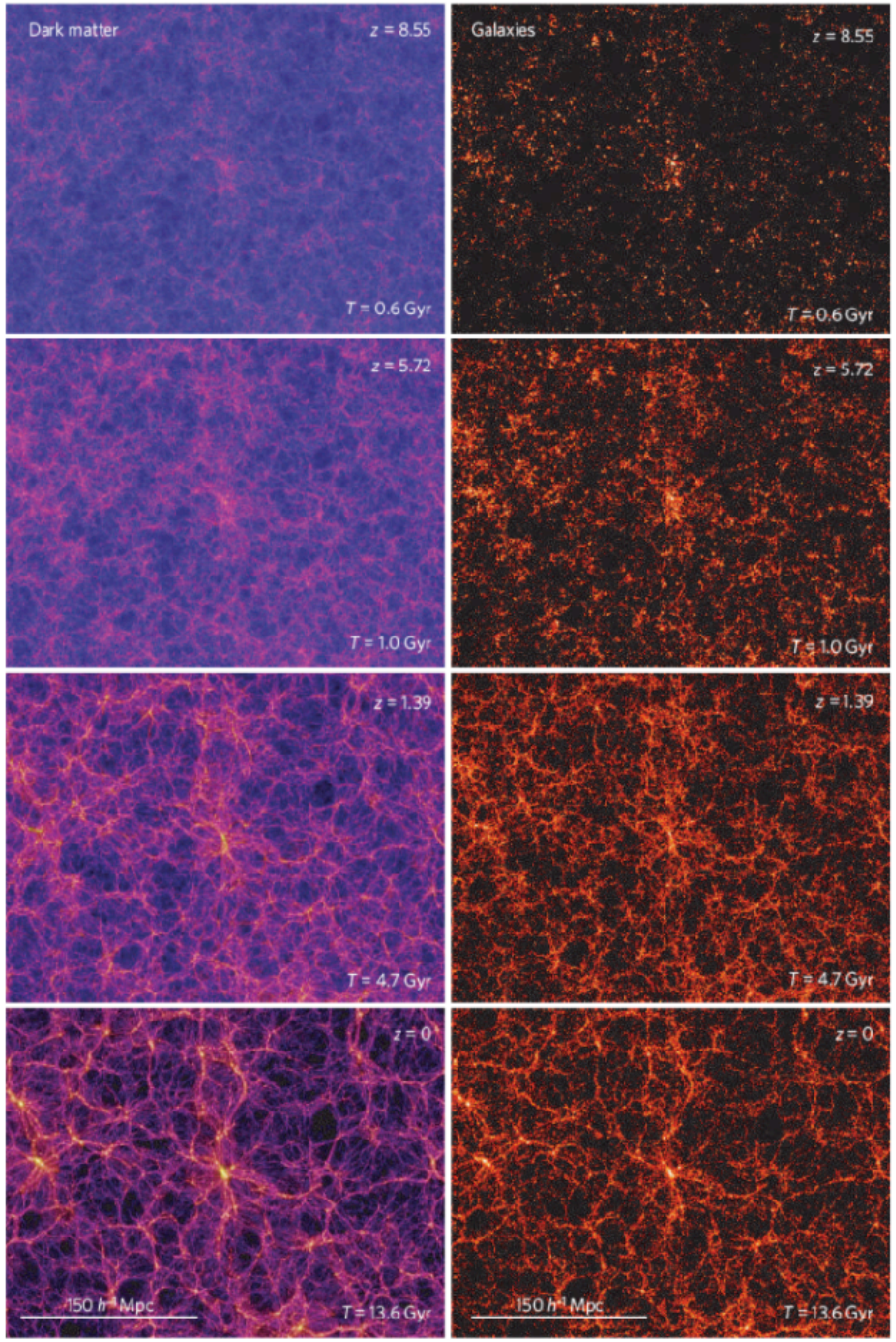
With baryons, density profiles appear to match observations



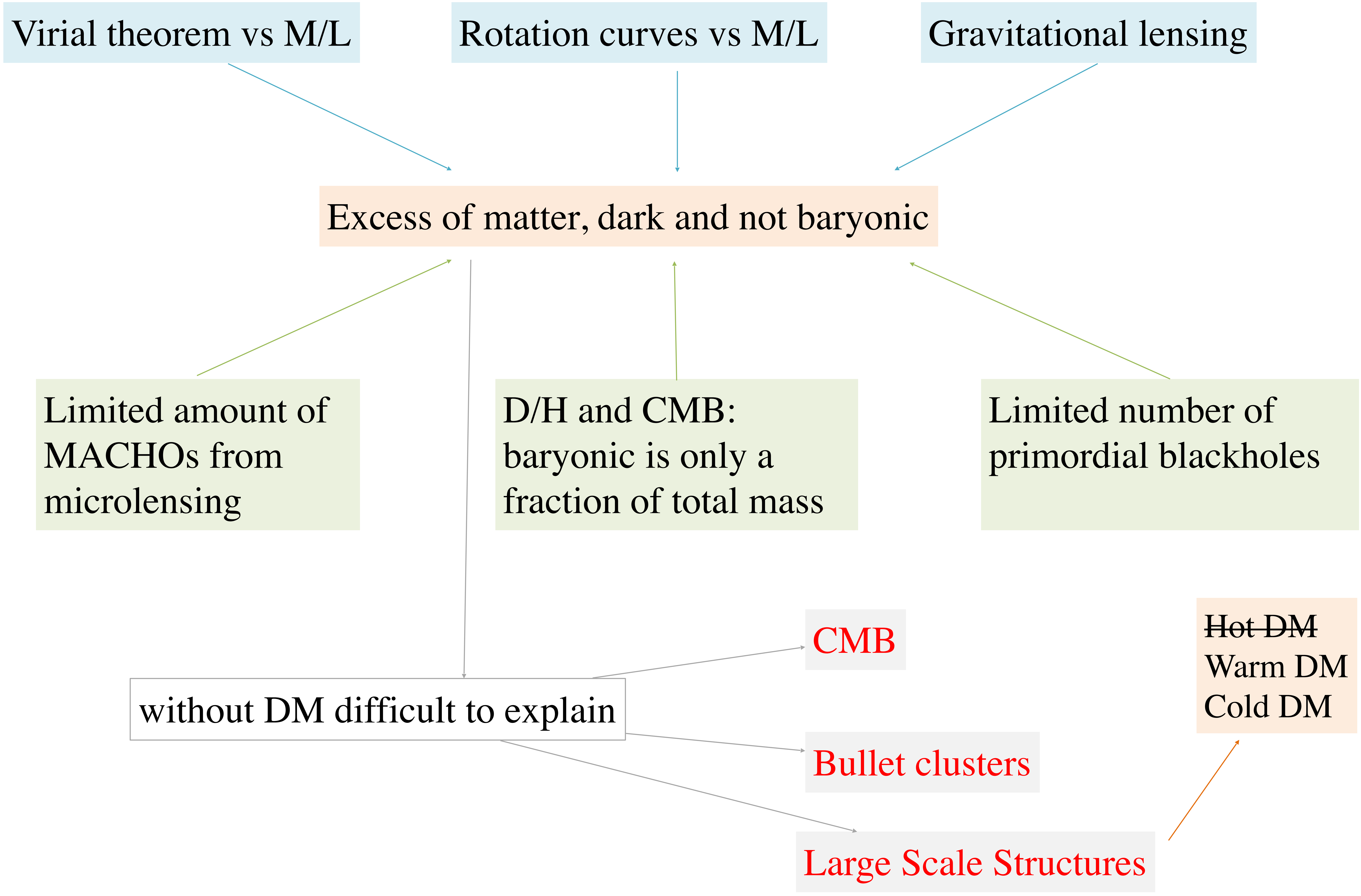
Large Scale Structures

Left: **Projected dark matter distributions from Millennium N-body simulations**. The epochs displayed correspond to times of 600 million, 1 billion, 4.7 billion and 13.6 billion years after the Big Bang, respectively. The dark matter evolves from a smooth, nearly uniform distribution into a highly clustered state, quite unlike the galaxies, which are strongly clustered from the start. From Springel, Frenk & White, Nature 440 (2006)

Right: **predicted distribution of galaxies in the same region at the corresponding times** obtained by applying semi-analytic techniques to simulate galaxy formation in the Millennium simulation



In summary…



Virial theorem vs M/L

Rotation curves vs M/L

Gravitational lensing

Excess of matter, dark and not baryonic

Limited amount of MACHOs from microlensing

D/H and CMB: baryonic is only a fraction of total mass

Limited number of primordial blackholes

without DM difficult to explain

CMB

Bullet clusters

Large Scale Structures

~~Hot DM~~
Warm DM
Cold DM

Dark matter production

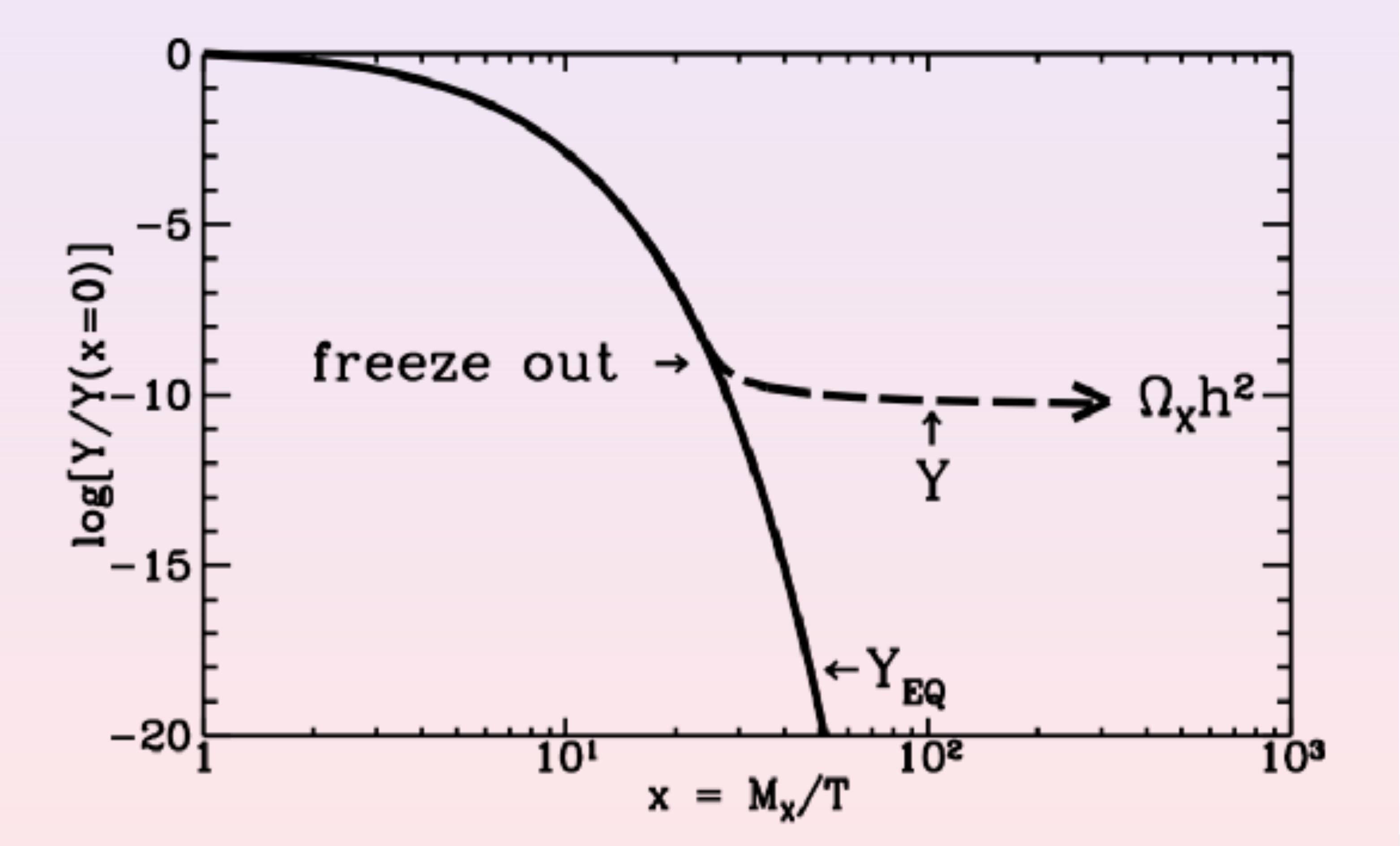
Thermal

(1) DM is a stable particle in thermal **equilibrium with the thermal bath of SM** particles in the Early Universe

(2) Temperature of the Universe drops below the DM mass:
⇒ **annihilation processes DM DM ⟷ SM SM**, try to maintain the thermal equilibrium

(3) DM density becomes so small that the DM DM **annihilation rate is slower** than the expansion rate
⇒ the thermal equilibrium can no longer be maintained

(4) At this point DM stops annihilating and its abundance "**freezes-out**"



Dark matter production

Non-Thermal

(1) DM particle is **absent** in the thermal bath of the Early Universe

(2) Particle is **coupled to the SM** particles by reactions like: SM SM ⟷ DM DM, SM SM ⟷ DM, SM ⟷ DM DM

(3) The coupling entering these reactions is assumed to be extremely feeble, so that **DM is slowly but steadily produced**

(4) Production will stop and the DM abundance is ‘**frozen-in**’ when:
- either because the temperature of the thermal bath drops below the DM mass
- or because the temperature drops below the mass of the SM particle from which DM is produced

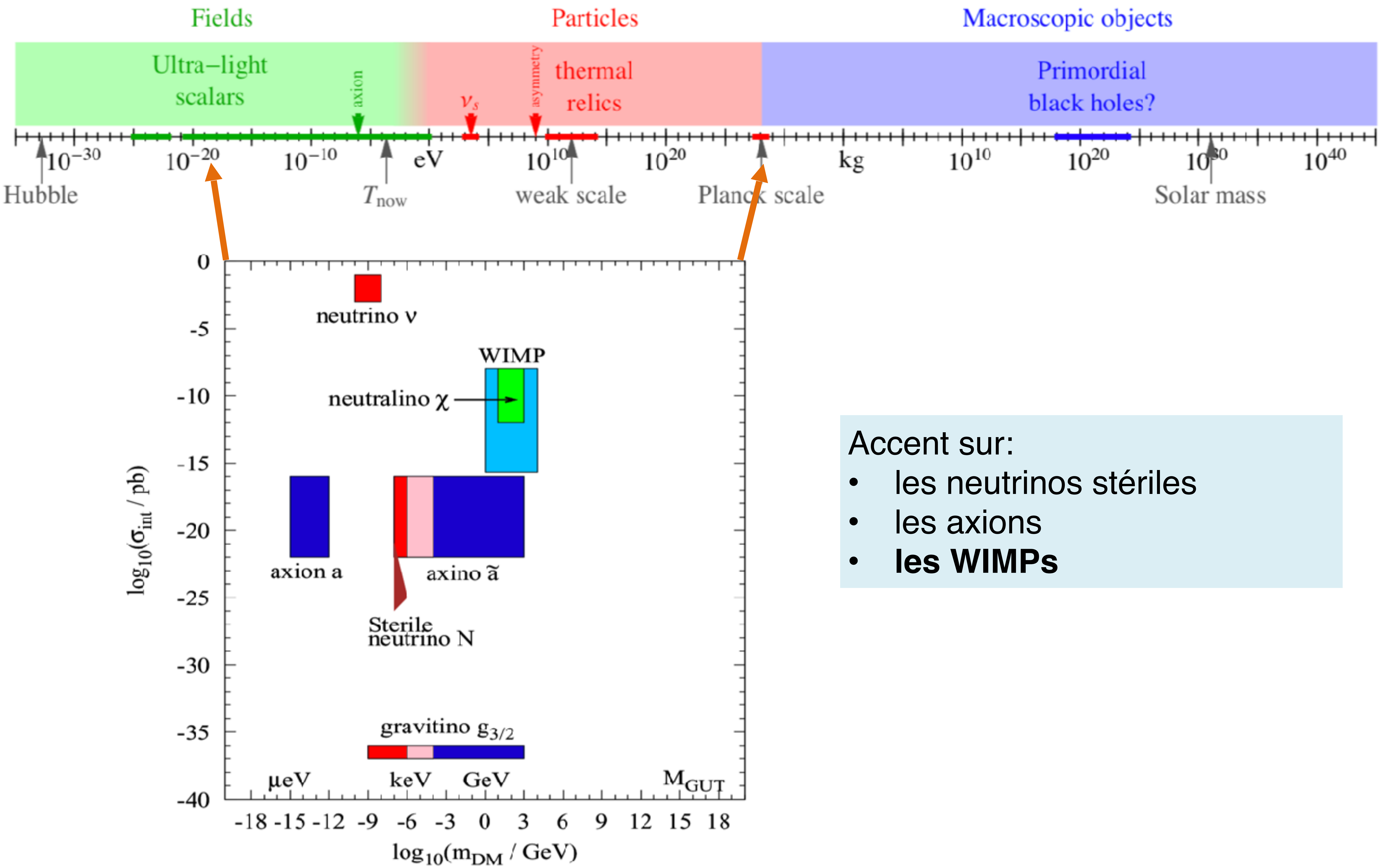
Note: both thermal and non-thermal DM productions requires some coupling with SM particles!

What about the dark matter particle?

Dark matter… exists

- A new, unknown particle (no Standard Model particle fits the evidence)
- Makes up 23% of the total energy or 80% of the total mass of the Universe
- It is **neutral** (dark)
- It is **stable** or long-lived
- Possibly a relic from the early Universe
- Does not interact via the strong or electromagnetic forces
- Does interact via gravity
- May interact via a “**weak**” force
- …and what about its mass?

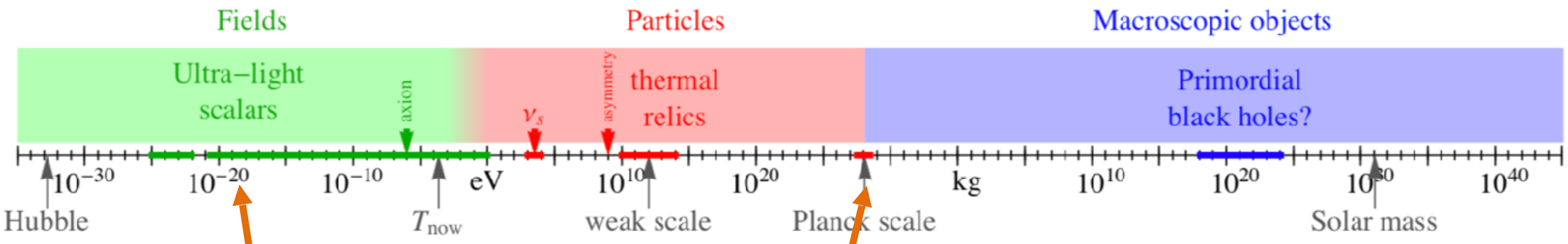
The particle zoo

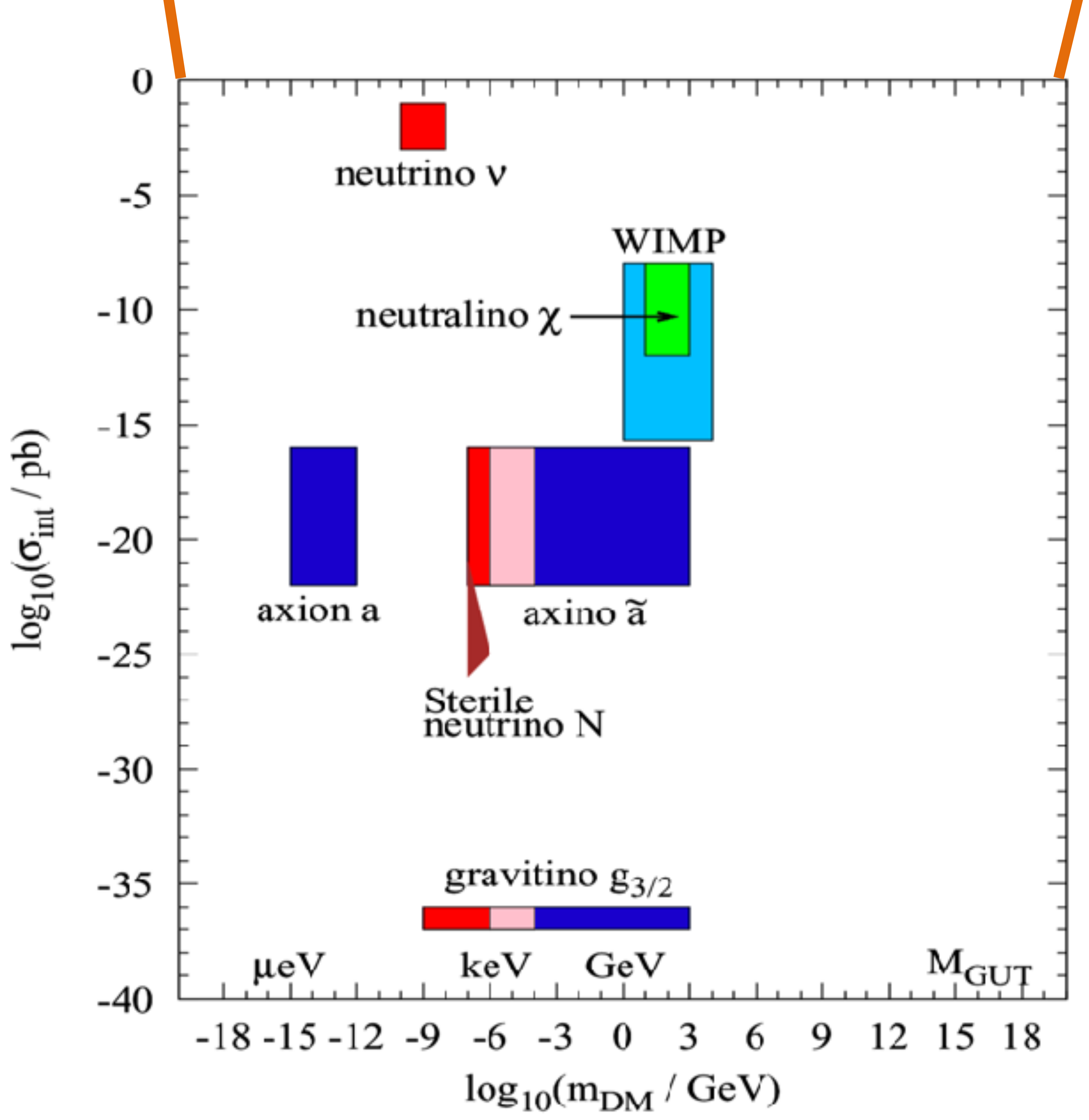


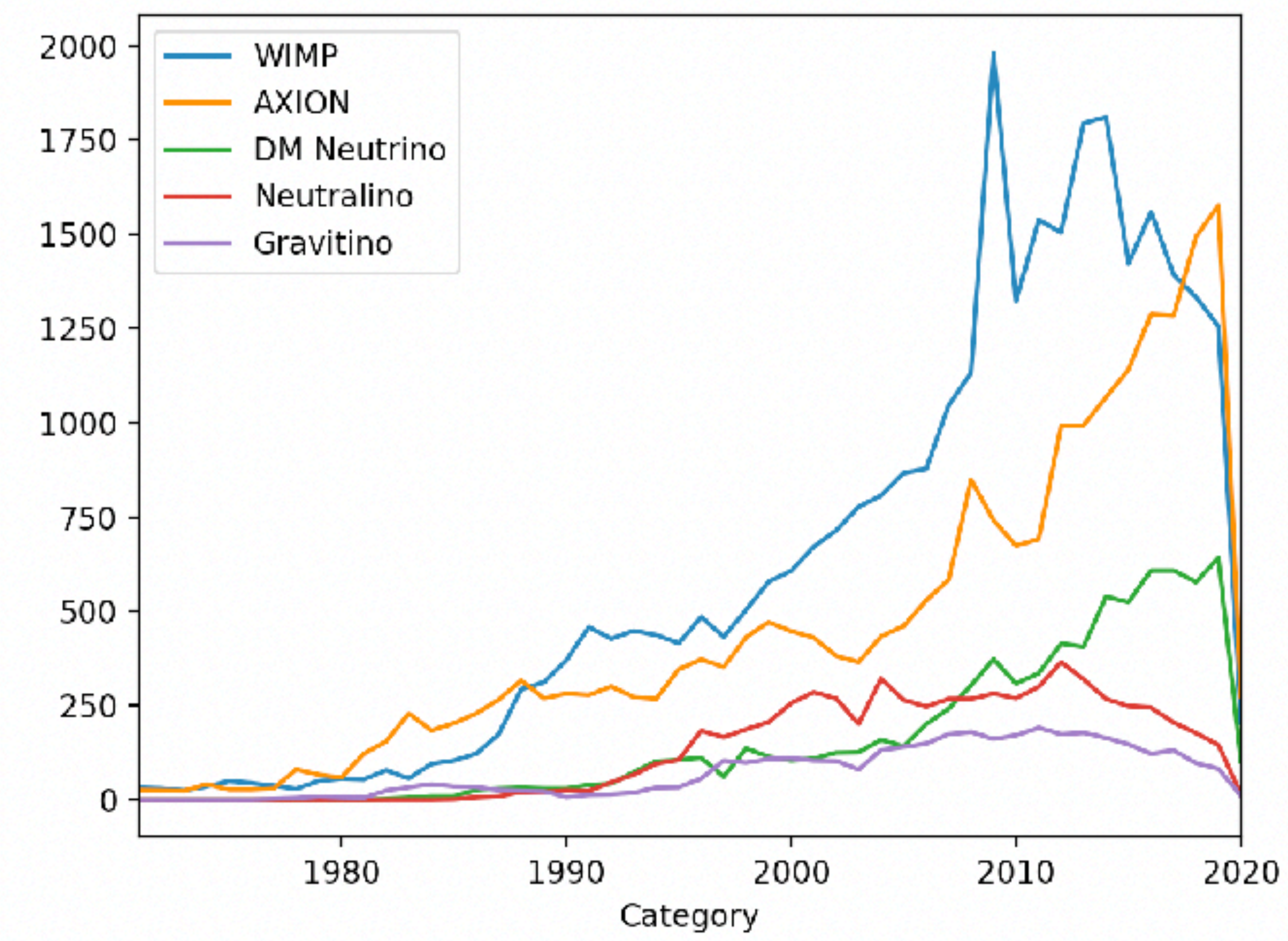
Accent sur:

- les neutrinos stériles
- les axions
- **les WIMPs**

The particle zoo







Active Neutrinos

Neutrinos represent the only kind of **non-baryonic** matter which contributes non-negligibly to the cosmic energy density and is actually known to exist.

$$\gamma \leftrightarrow e^+ + e^- \leftrightarrow \bar{\nu} + \nu$$

Not enough mass:

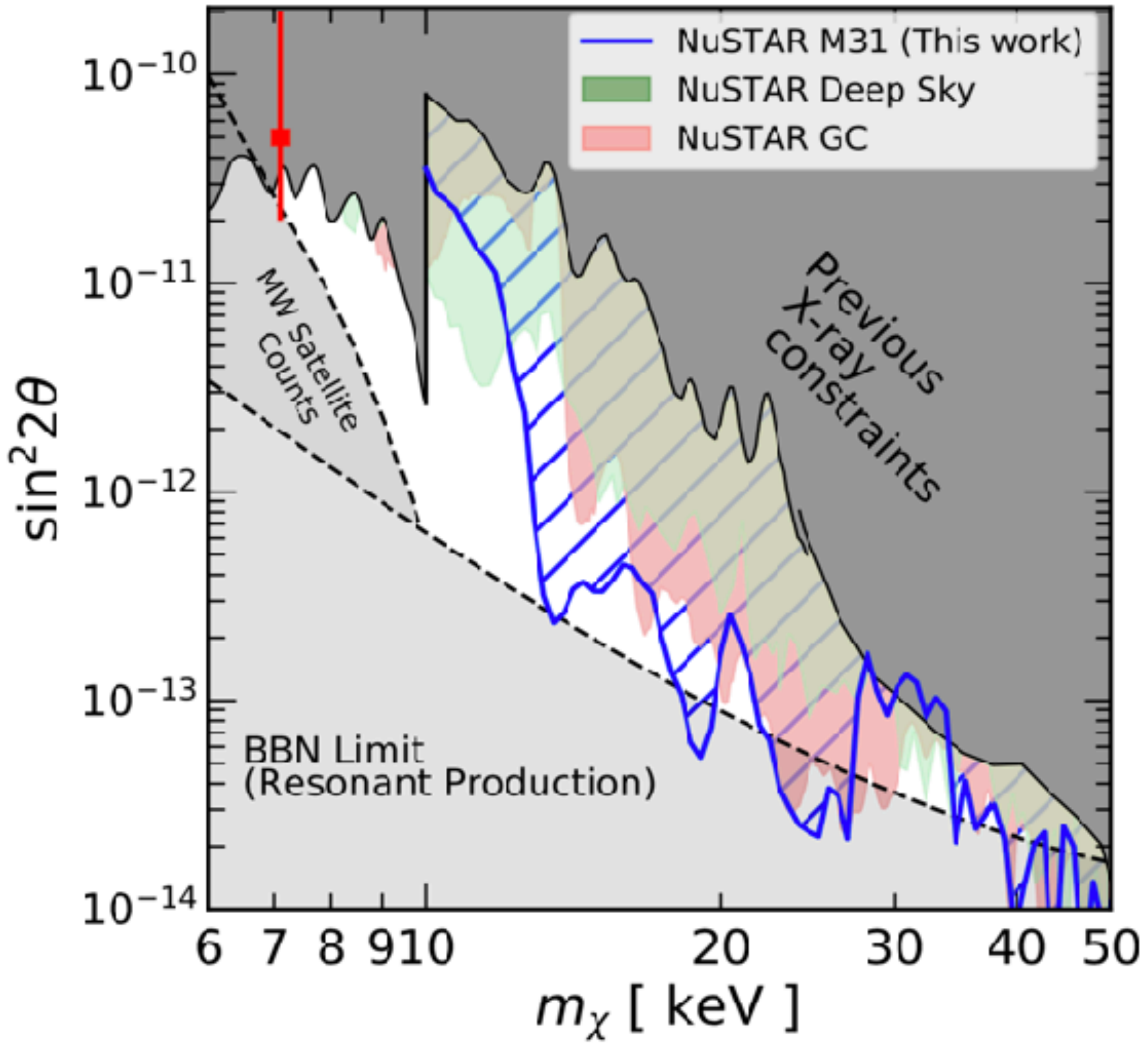
- The three known neutrino species (ν_e, ν_τ and ν_μ) are however constrained by laboratory bounds and the CMB to be very light ($\Sigma\, m_\nu \leq 0.7$ eV), corresponding to a contribution to the cosmic energy budget of $0.001 \leq \Omega\nu \leq 0.014$.

HDM:

- Standard neutrinos in this mass range would act as HDM and are therefore not suitable candidates for the dark matter of the Universe.

Sterile Neutrinos

A fourth, so-called sterile neutrino – which could act as CDM – has been postulated from time to time to solve various problems in neutrino physics, but does not seem to be favored by the most recent experiments



From PDG:

Relic keV neutrinos ν_s can only be detected if they mix with the ordinary neutrinos. This mixing leads to radiative $\nu_s \rightarrow \nu\gamma$ decays, with lifetime

$$\tau_{\nu s} \simeq 1.8 \;\; 10^{21} \text{ s} \cdot (\sin\theta)^{-2} \cdot (1 \text{ keV}/m_{\nu s})^5,$$

where θ is the mixing angle. This gives rise to a **flux of mono-energetic photons with $E\gamma = m_{\nu s}/2$**, which might be observable by X-ray satellites.

Axions

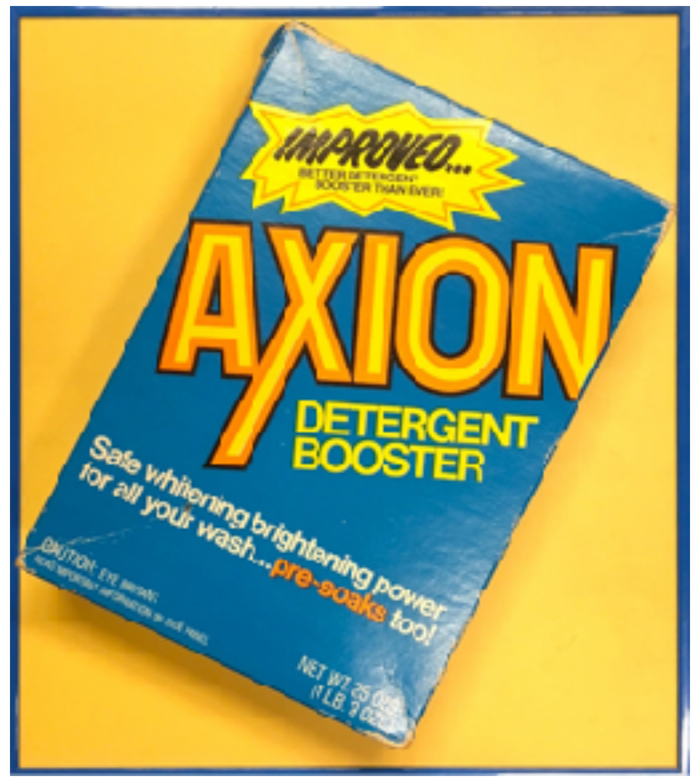
The axion, named after a laundry detergent, was proposed in the late 1970s to solve the “strong CP problem”: the absence of CP violation in strong interactions, predicted by QCD.

$$\mathscr{L}_{\mathrm{QCD}} = \sum_q \bar{\psi}_q \left(\mathrm{i}D - m_q \right) \psi_q - \frac{1}{4} G_{\mu\nu a} G_a^{\mu\nu} - \overline{\Theta} \frac{\alpha_{\mathrm{s}}}{8\pi} G_{\mu\nu a} \tilde{G}_a^{\mu\nu}$$

$G_{\mu\nu a}\tilde{G}_a^{\mu\nu}$ violates T reversal AND Parity → CP violating term

$\Rightarrow$ induces electric dipole moment of neutron (EDM): $d \sim \bar{\Theta} \cdot 10^{-16}$ e cm

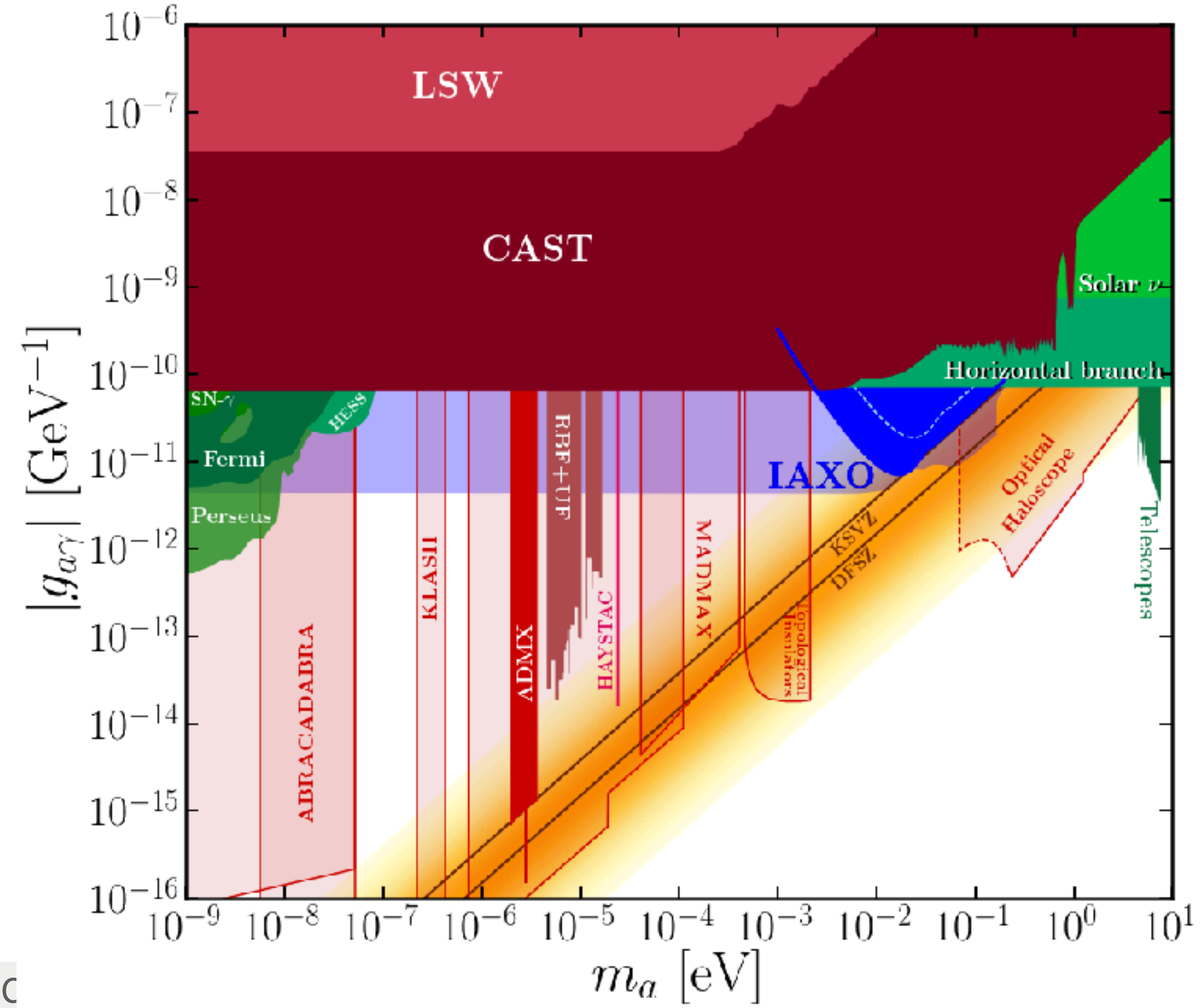
But experimentally: $d < 10^{-26}$ e cm → $\bar{\Theta} < 10^{-10}$



Axions

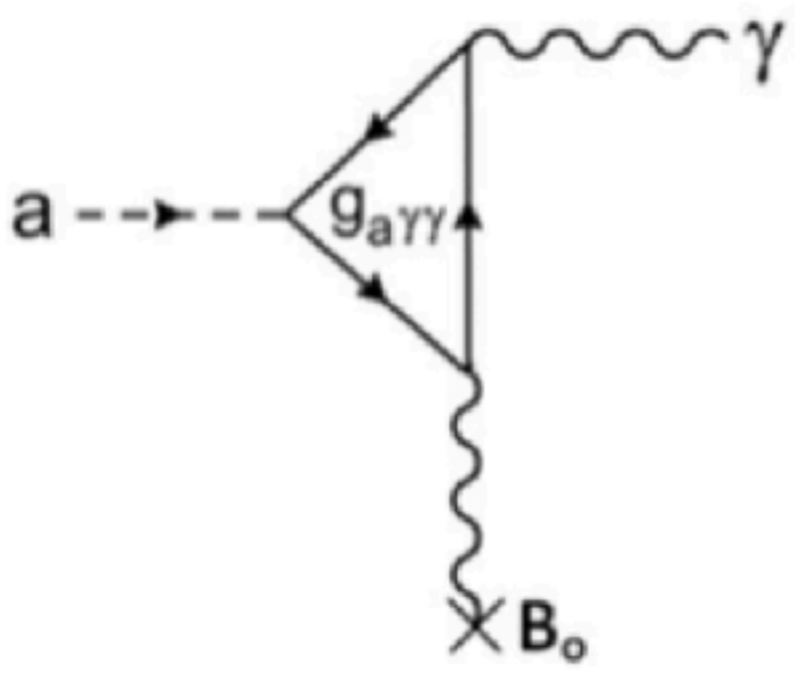
$$m_a \sim \frac{\Lambda^2_{\rm QCD}}{F_a} \sim 6 \times 10^{-5}{\rm eV}\left(\frac{10^{11}{\rm GeV}}{F_a}\right)$$

$$\Lambda_{\rm QCD} \simeq \mathcal{O}(100){\rm MeV}$$

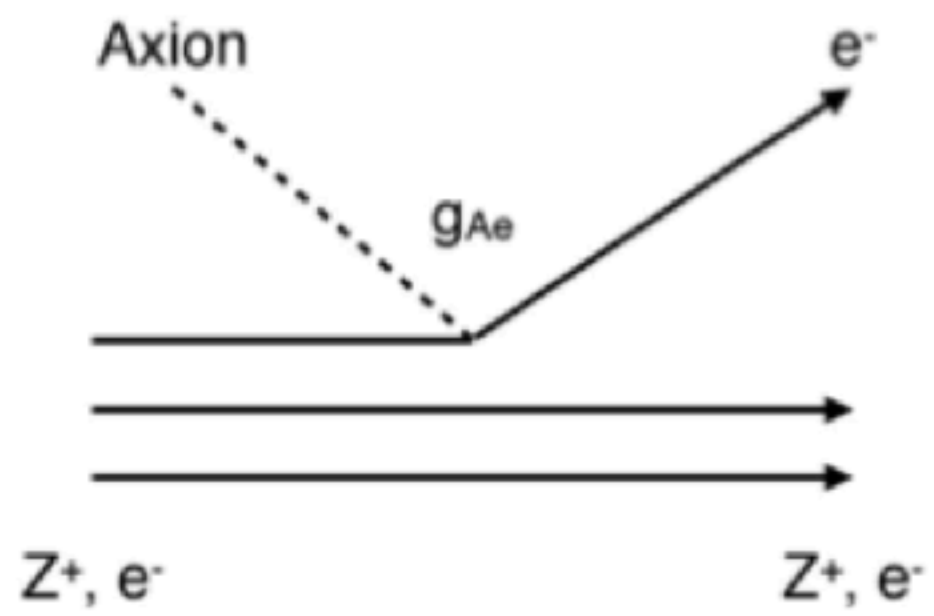


Axion Decay

Primakoff Effect



Axio-electric effect



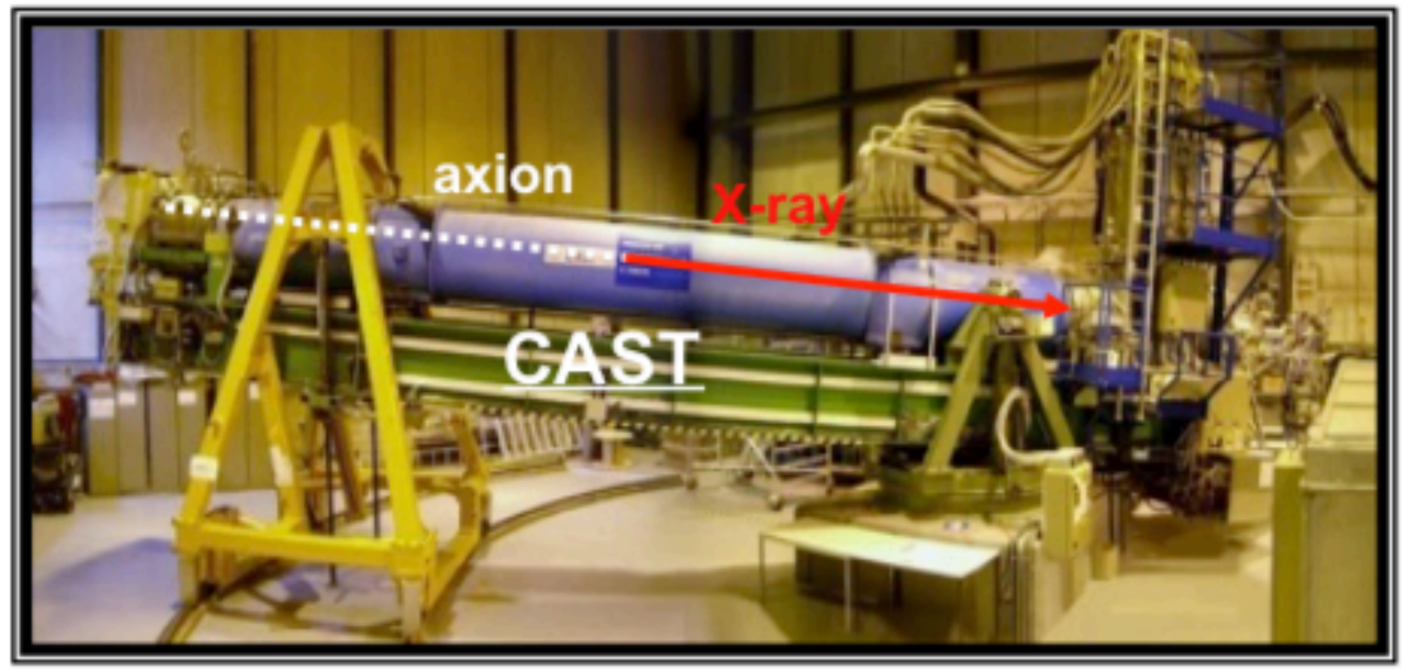
Axion search

Variety of experiments

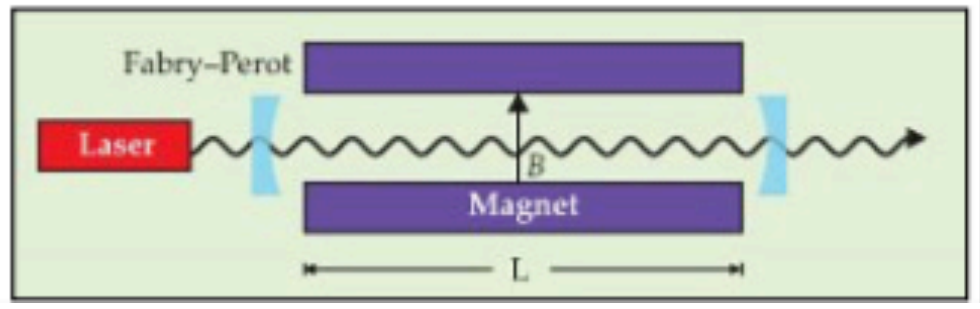
- **Axions as Dark Matter**
  - Haloscopes: Microwave cavities in solenoid magnet
  - Look for dark matter axions (low mass) converting to photons in B-Field
    - Sikivie PRL 51:1415 (1983)
  - **New techniques being explored: NMR, LC-circuit, Axion Wind**

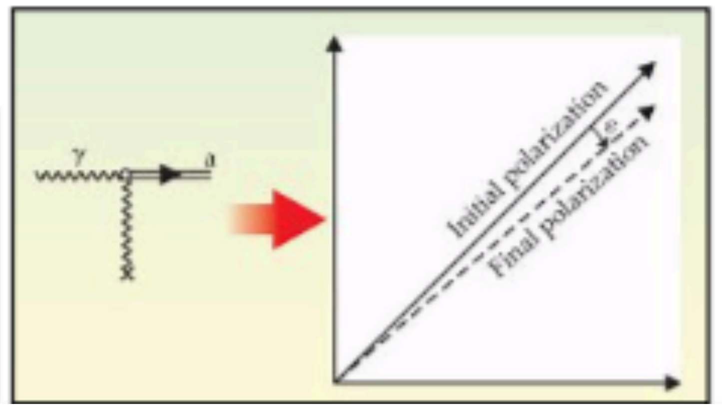
Pierre Sikivie

- Axions from the Sun
  - Helioscopes: Axions generated from the sun
    - Sikivie PRL 51:1415 (1983)
    - Van Bibber et al. PhysRevD 39:2089 (1989)
    - CAST, IAXO
  - Bragg scattering, noble liquids (g_{ae})

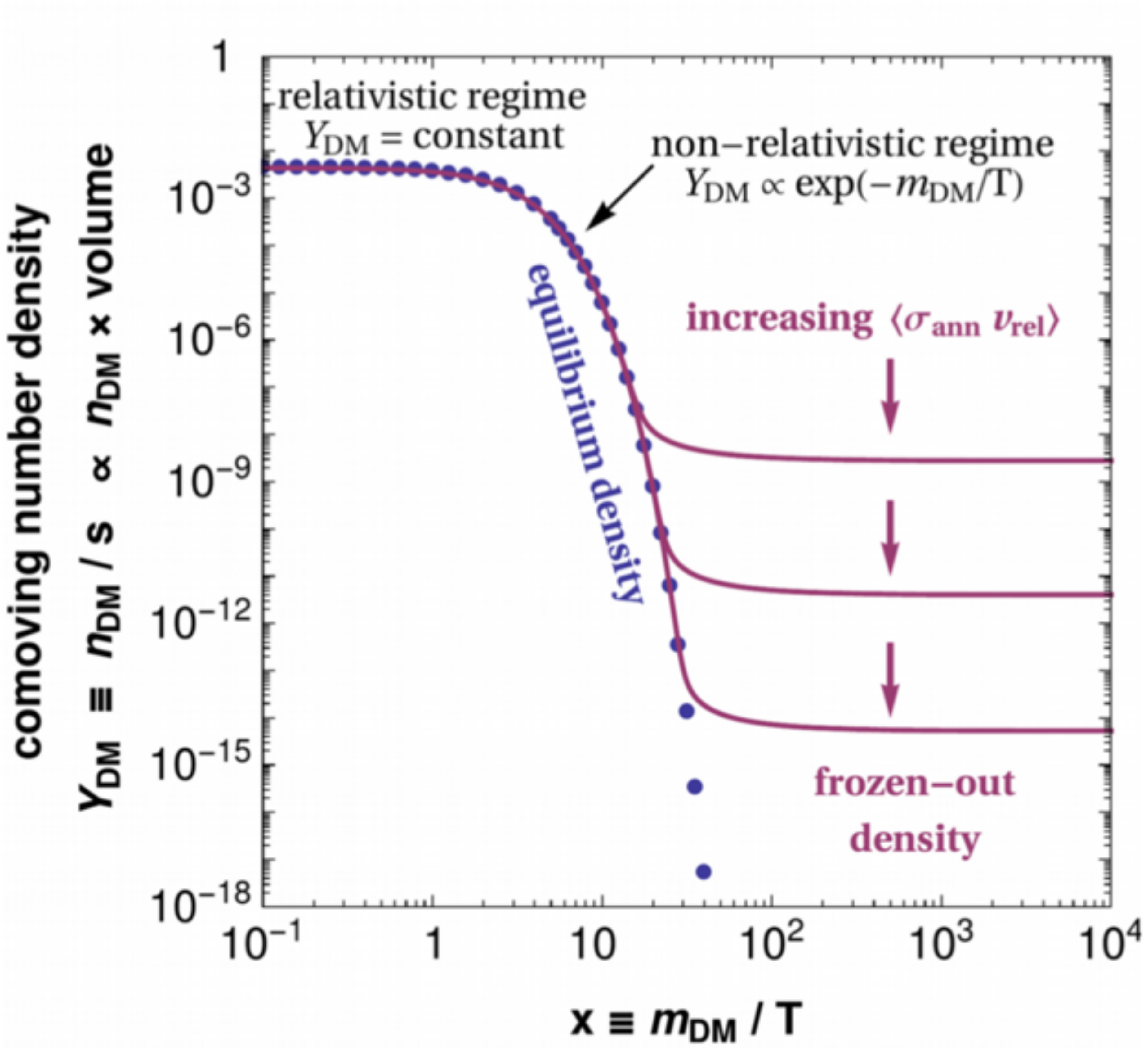


- Axions in the Lab
  - Photon regeneration and polarization changes
    - **PVLAS, ALPS**
  - Modifications to short range forces
    - **ARIADNE, Torsion-balance**





The WIMP miracle



- Fermi's constant G_F introduced in 1930s to describe beta decay

$$n \rightarrow p\, e^- \bar{\nu}$$

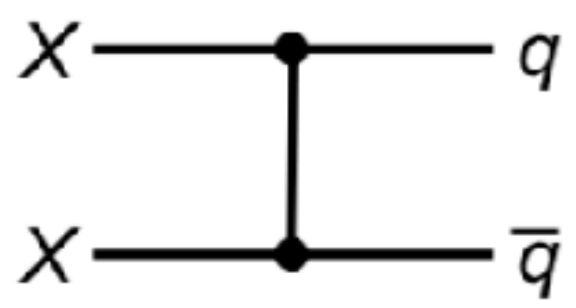
- $G_F \sim 10^{-5}$ GeV^{-2} → a new mass scale in nature

$$m_{weak} \sim 100 \text{ GeV}$$

- We still don't understand the origin of this mass scale, but every attempt so far introduces new particles at the weak scale

- The relation between Ω_X and annihilation strength is wonderfully simple:

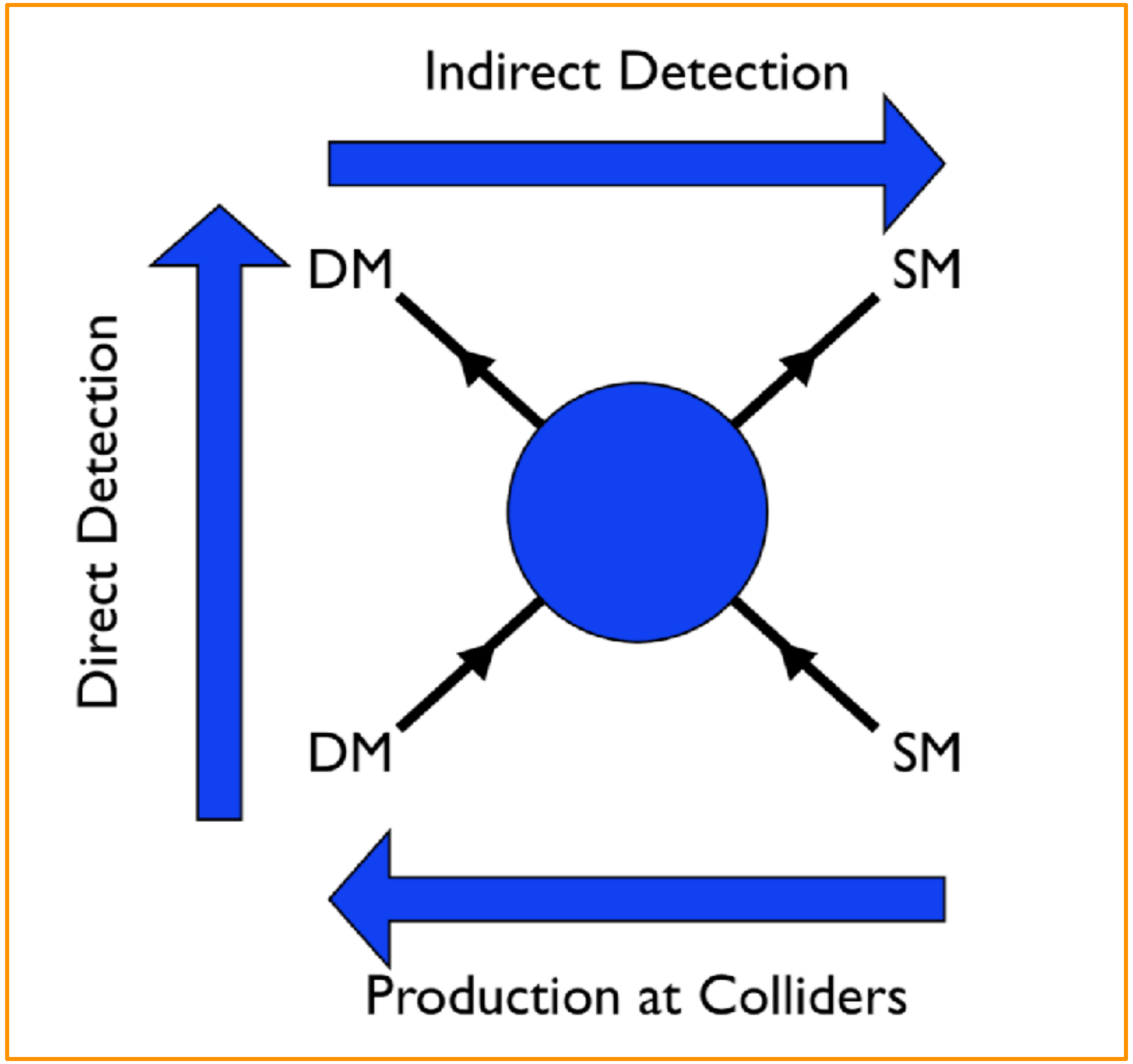
$$\Omega_X \propto \frac{1}{\langle\sigma v\rangle} \sim \frac{m_X^2}{g_X^4}$$



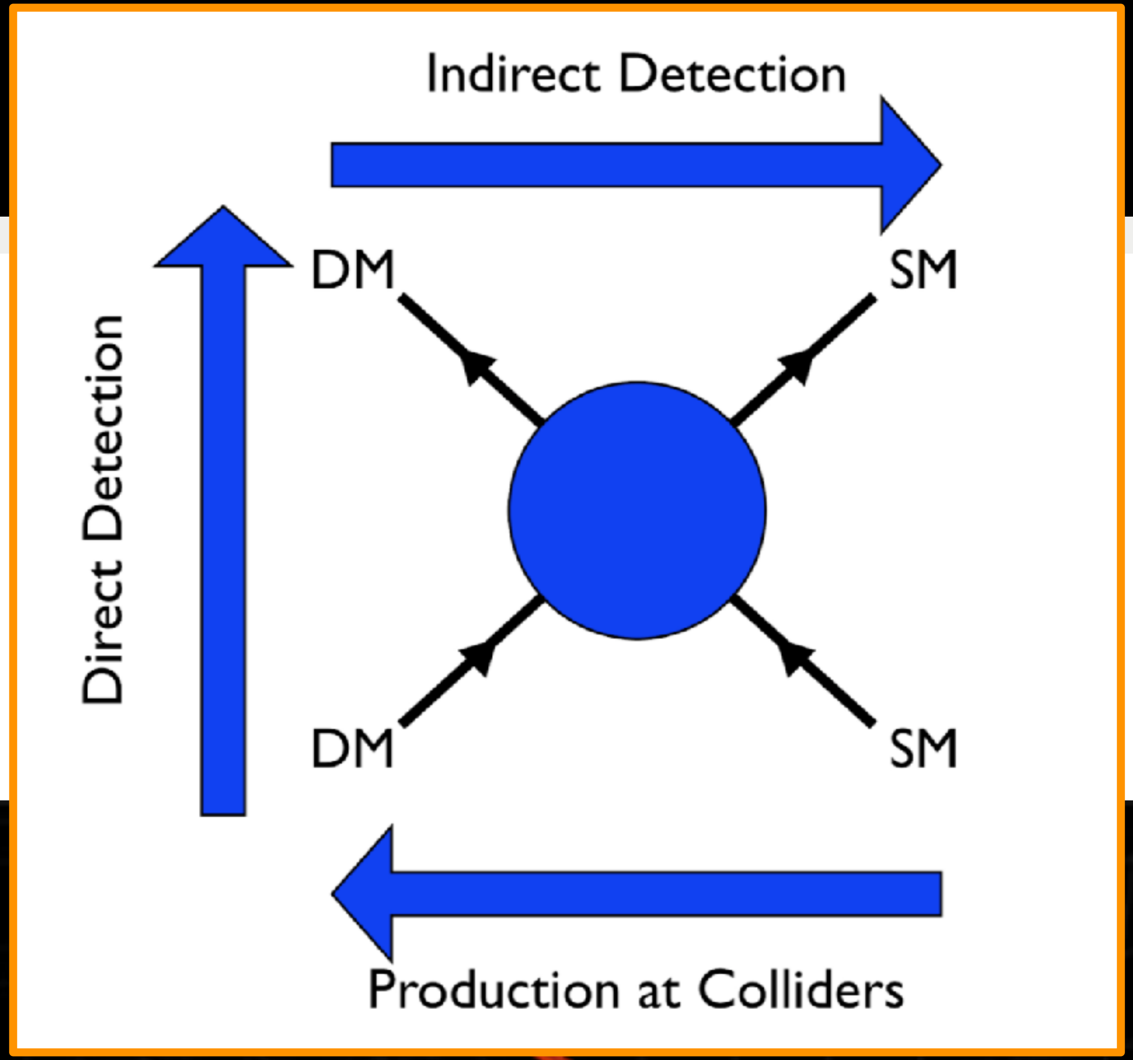
- $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

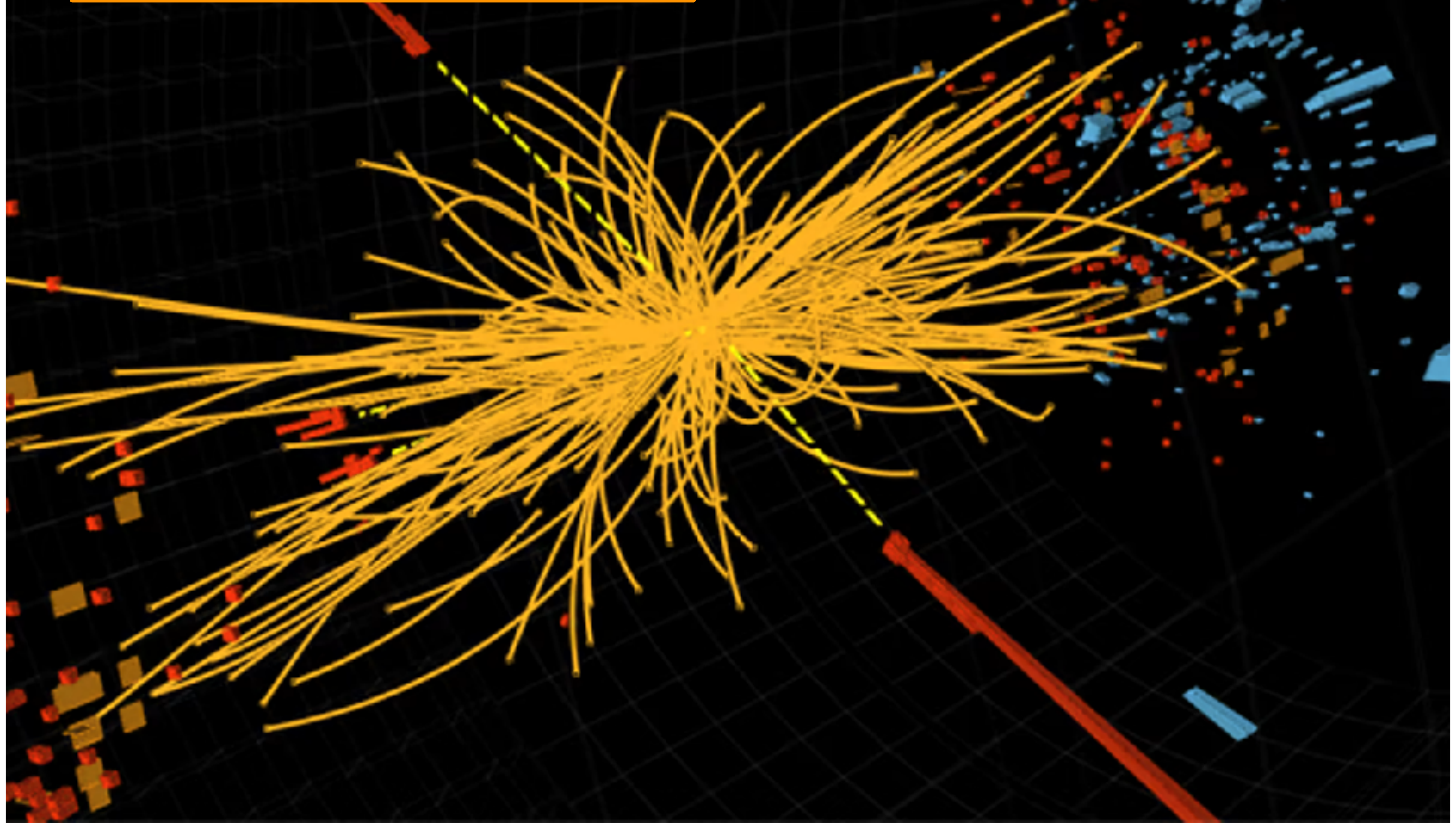
Remarkable coincidence: particle physics independently predicts particles with the right density to be dark matter

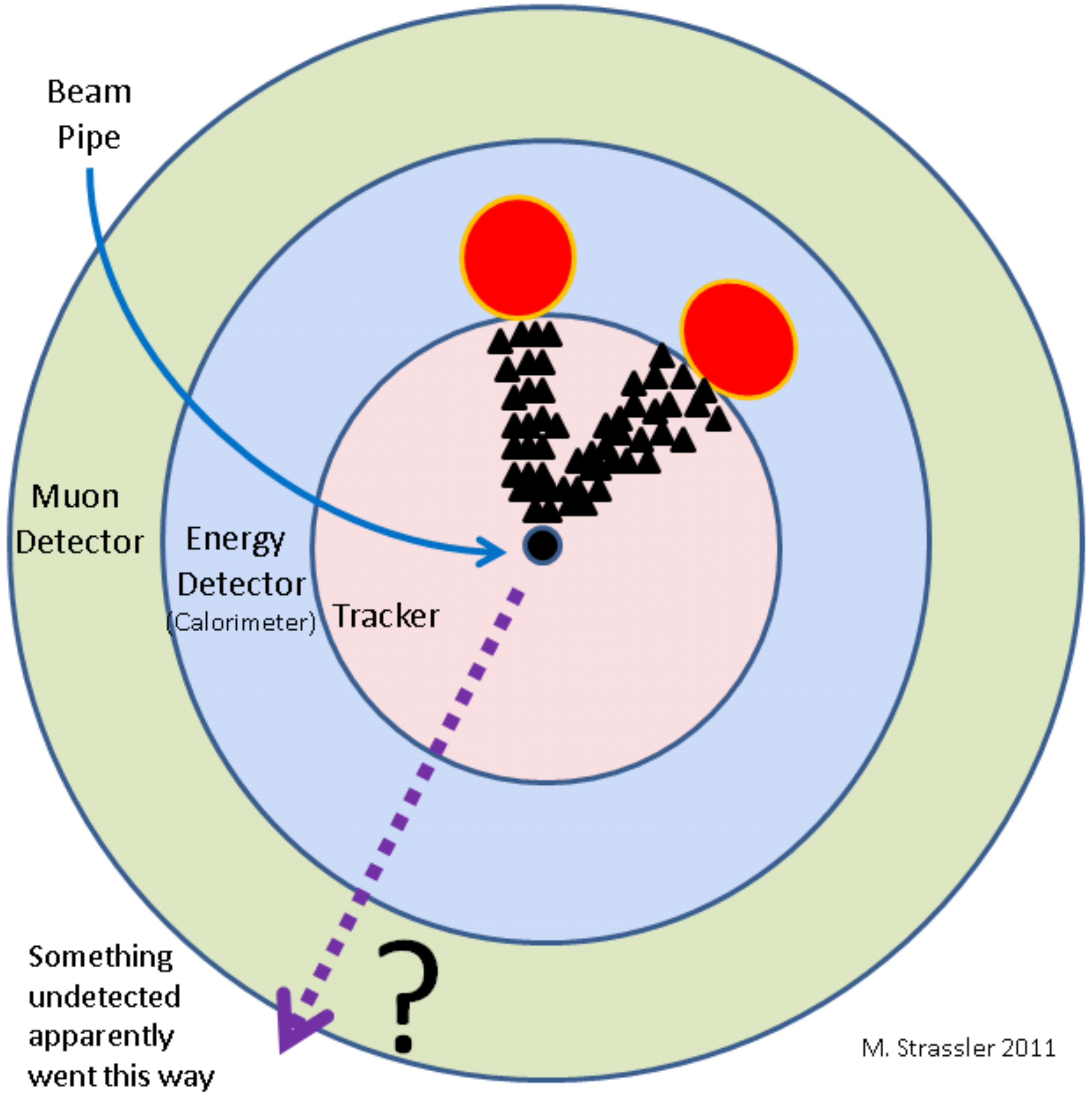
Detecting dark matter



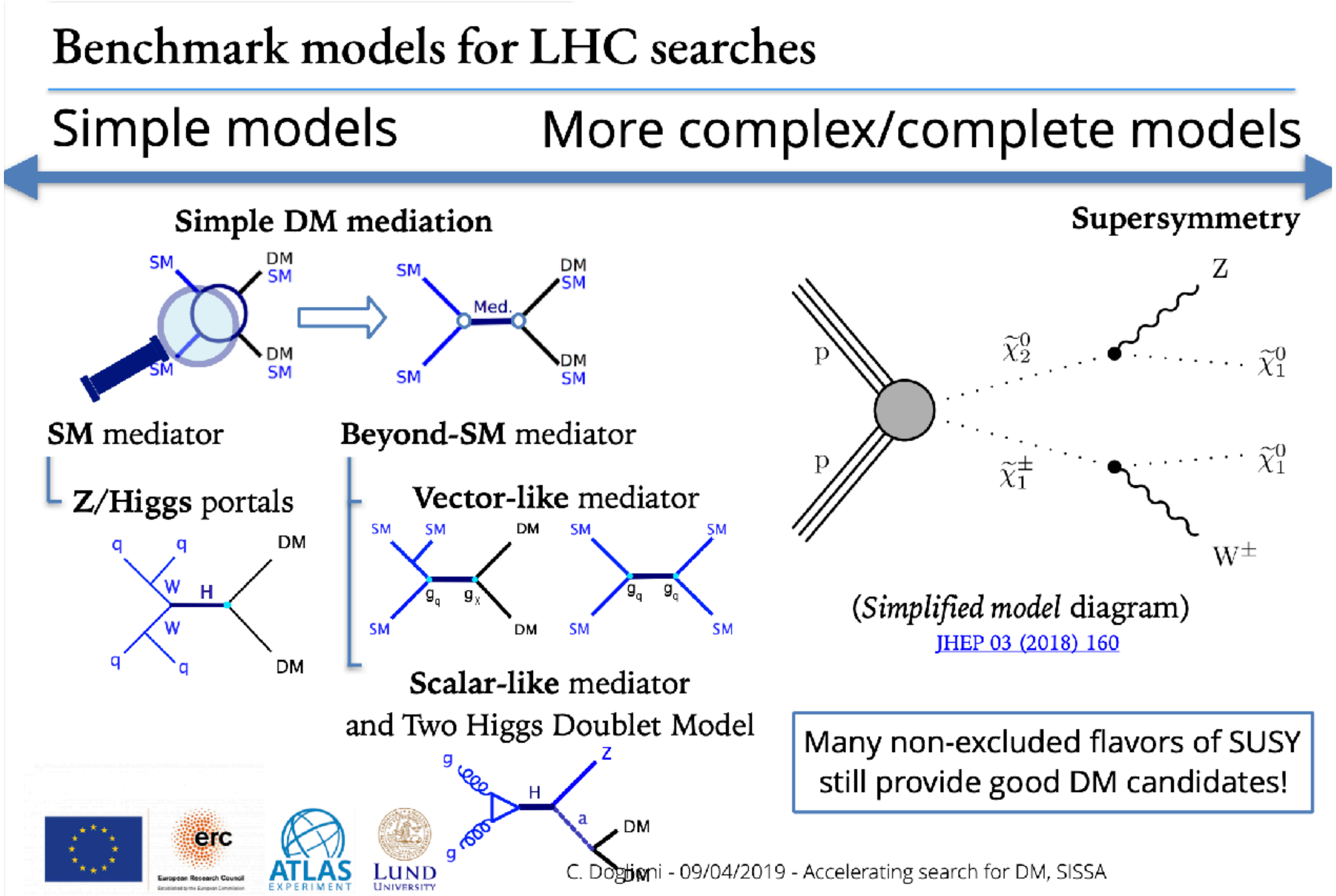
Production at accelerators







Dark matter searches at LHC



Benchmark models for LHC searches

Simple models ⟷ More complex/complete models

Simple DM mediation

SM mediator

Z/Higgs portals

Beyond-SM mediator

Vector-like mediator

Scalar-like mediator and Two Higgs Doublet Model

Supersymmetry

(*Simplified model* diagram)

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Many non-excluded flavors of SUSY still provide good DM candidates!

C. Doglioni - 09/04/2019 - Accelerating search for DM, SISSA

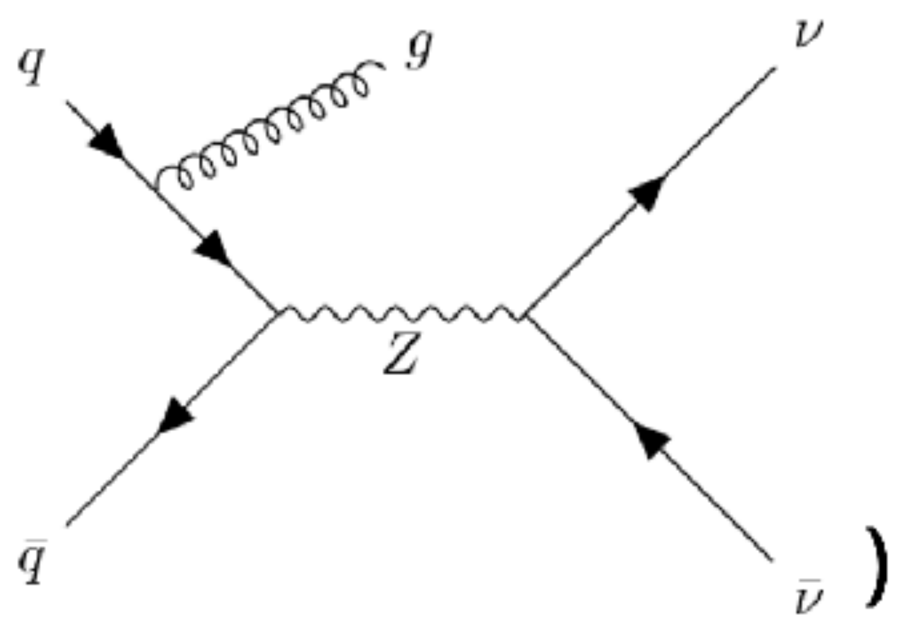
Dark matter searches at LHC

Mono-jet at the LHC

10.1103/PhysRevD.97.092005

Ingredients:

- Jets (and everything else)
- Precise background estimations (main bkg:

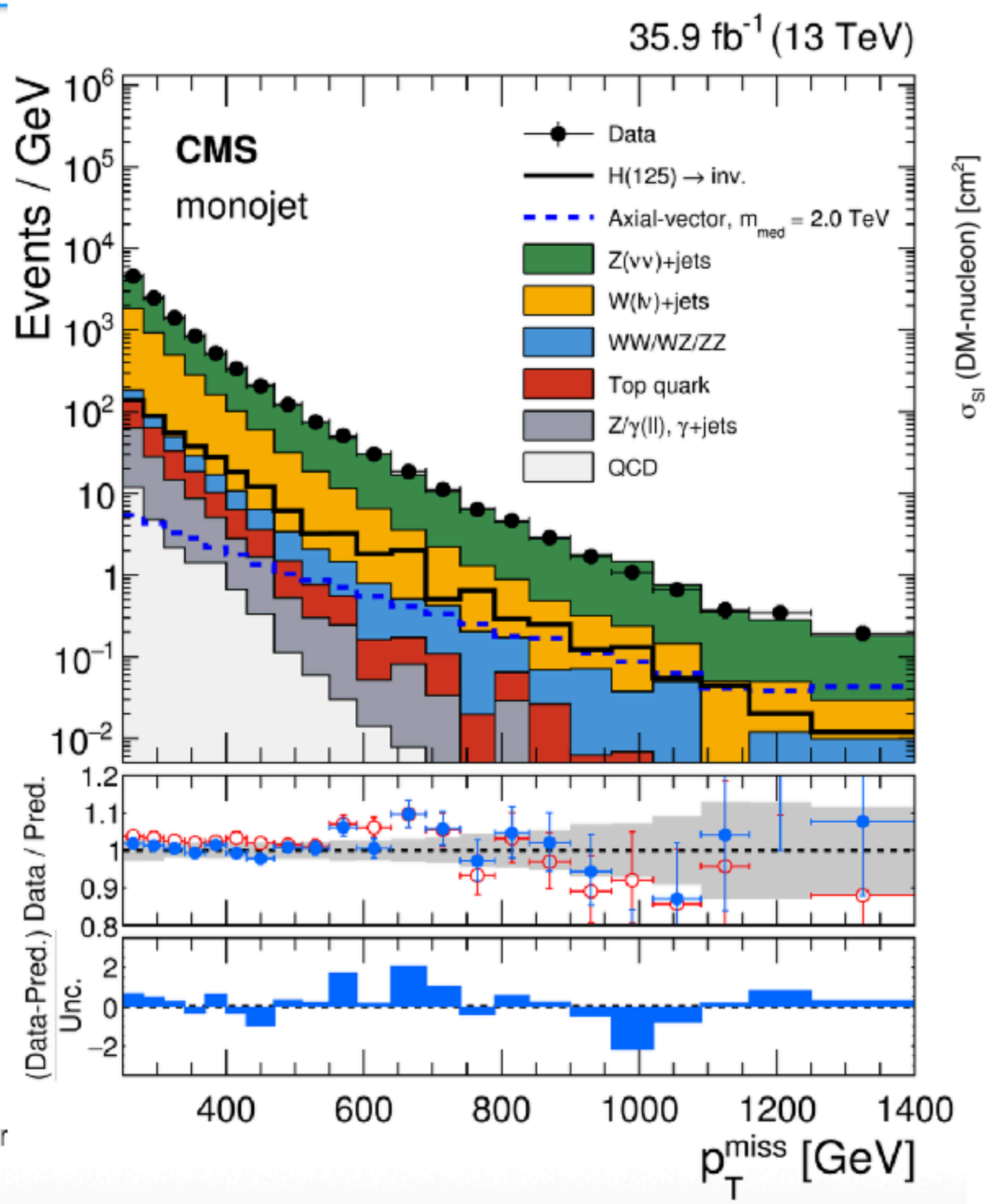


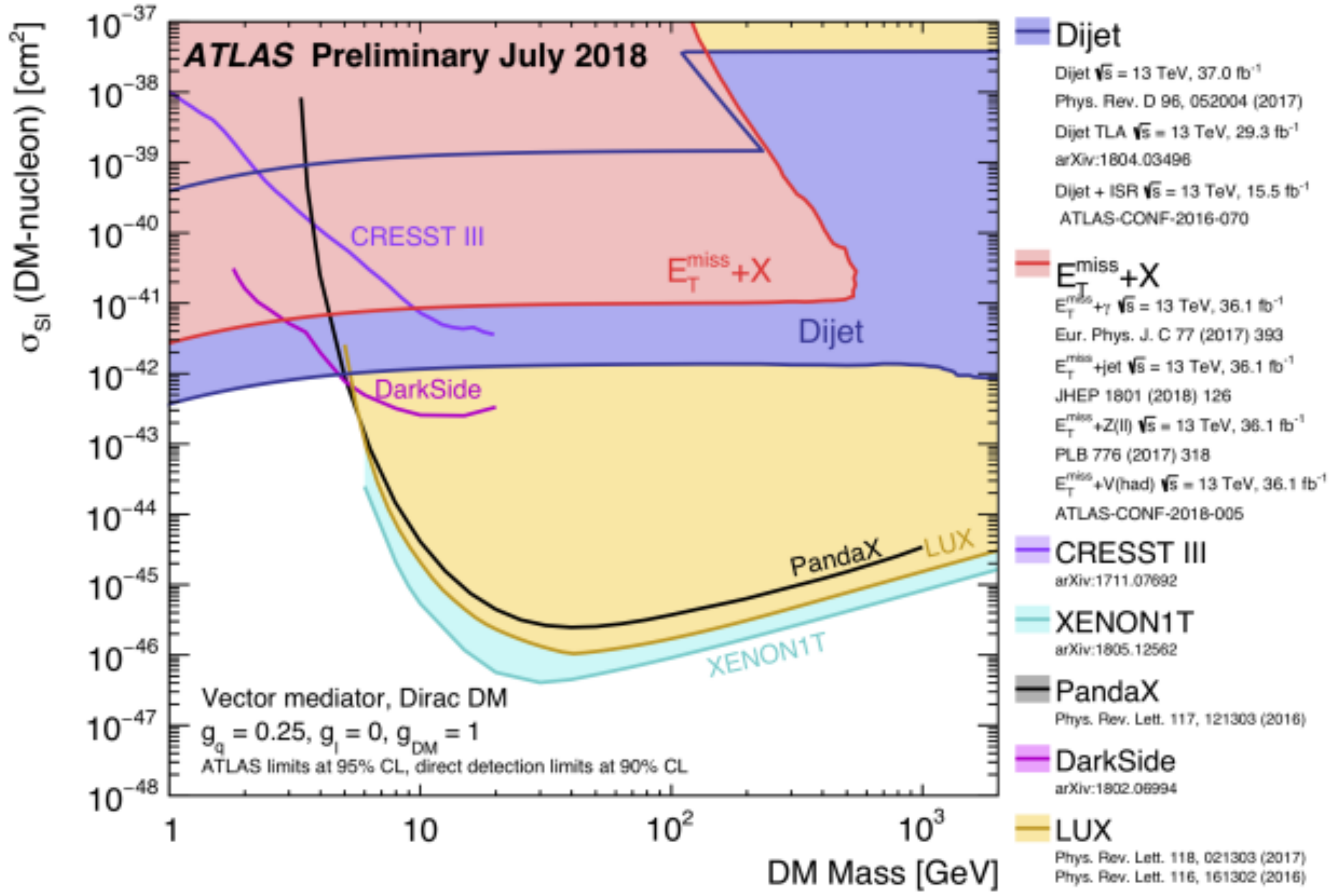
)

Method:

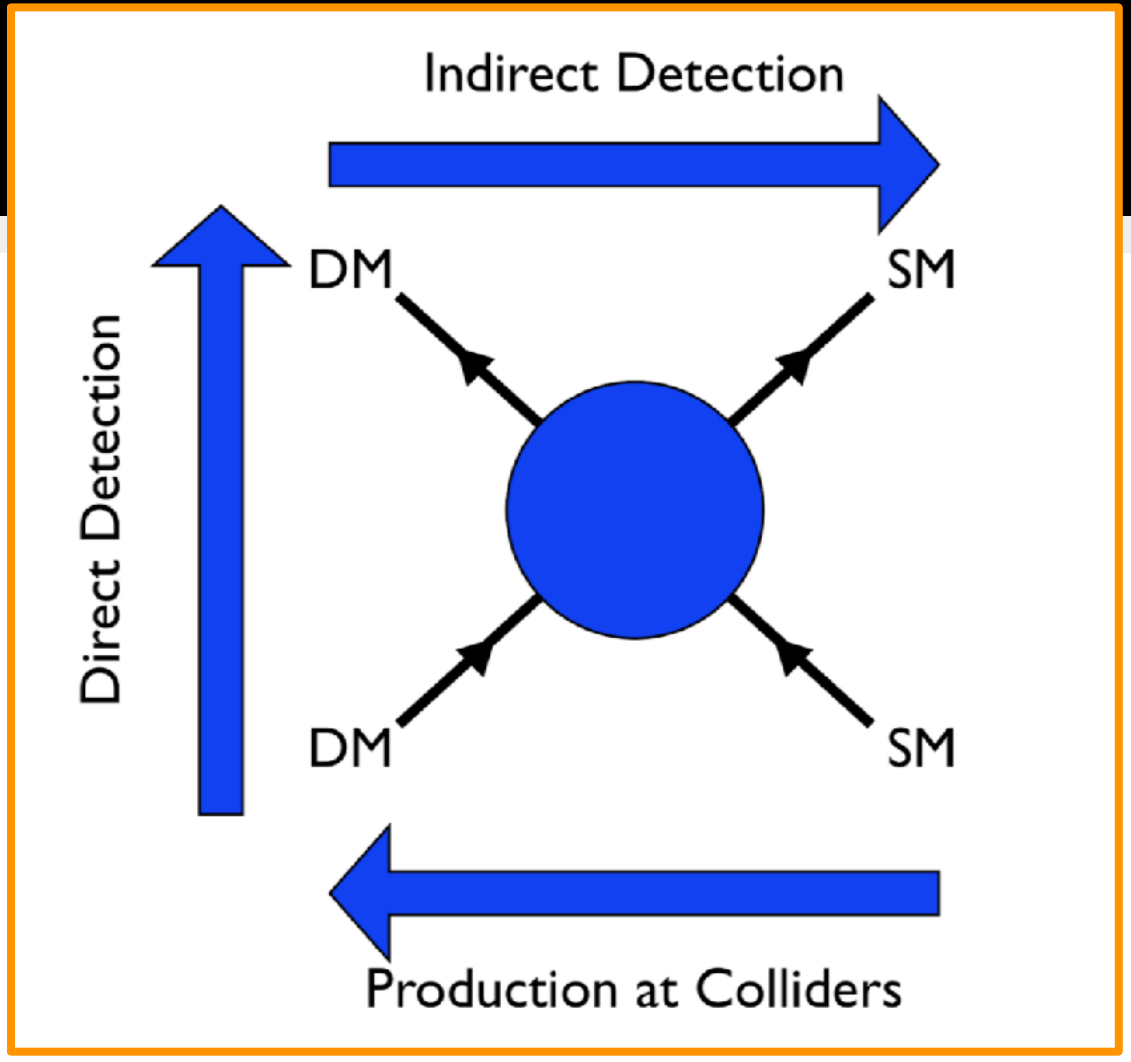
- Estimate backgrounds in signal-free regions
- Look for discrepancies between bkg prediction & data

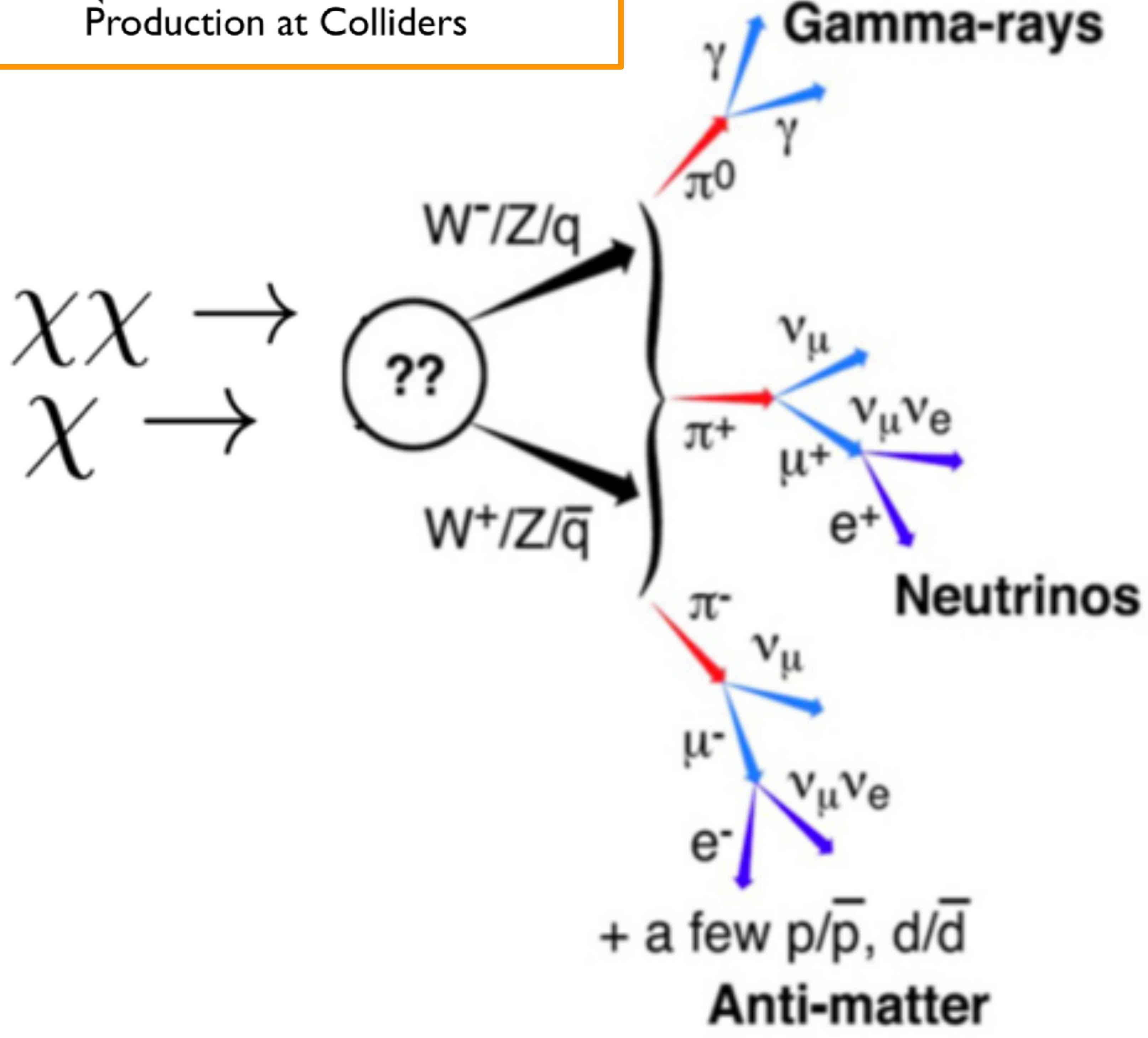
oglior

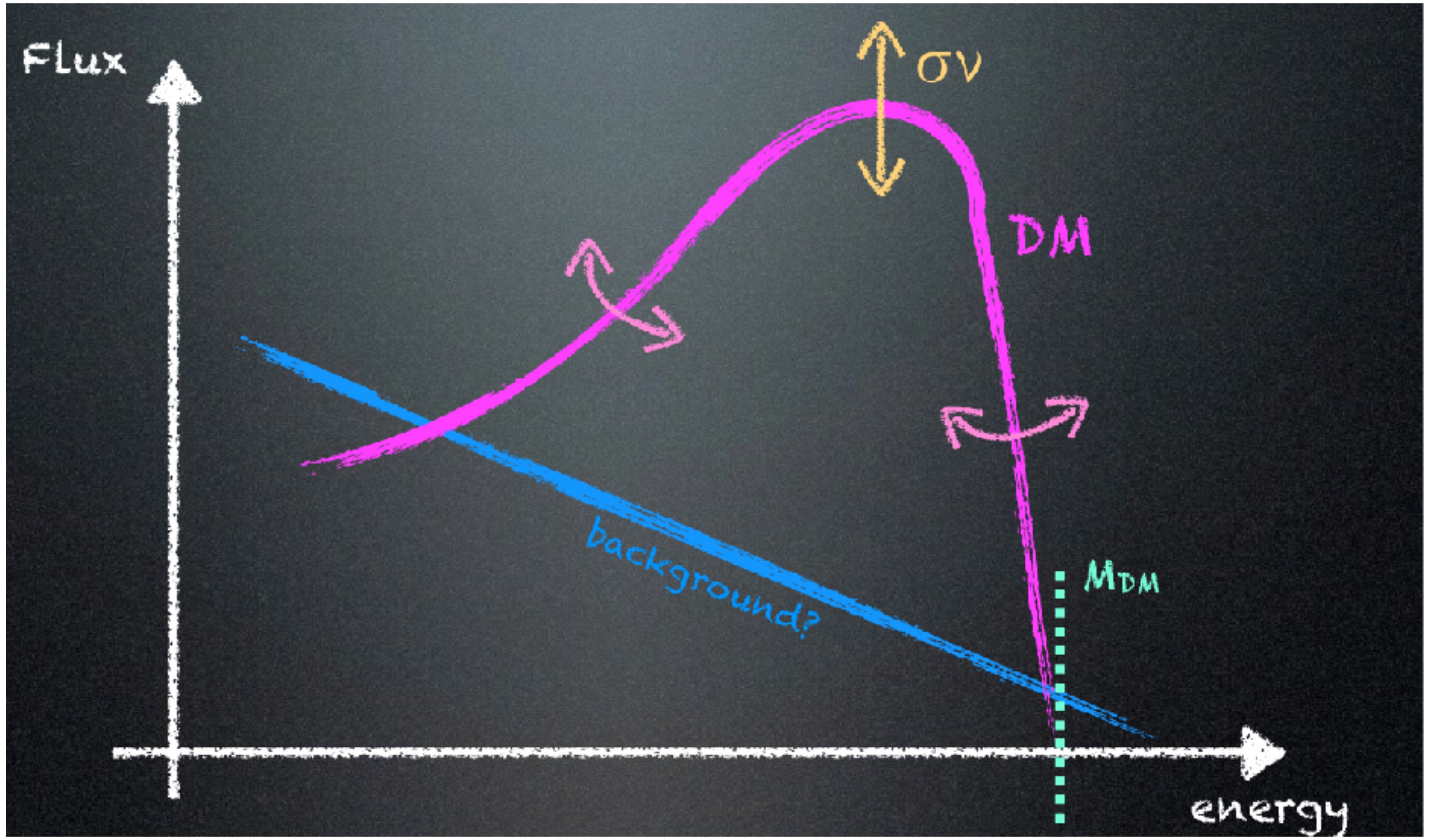




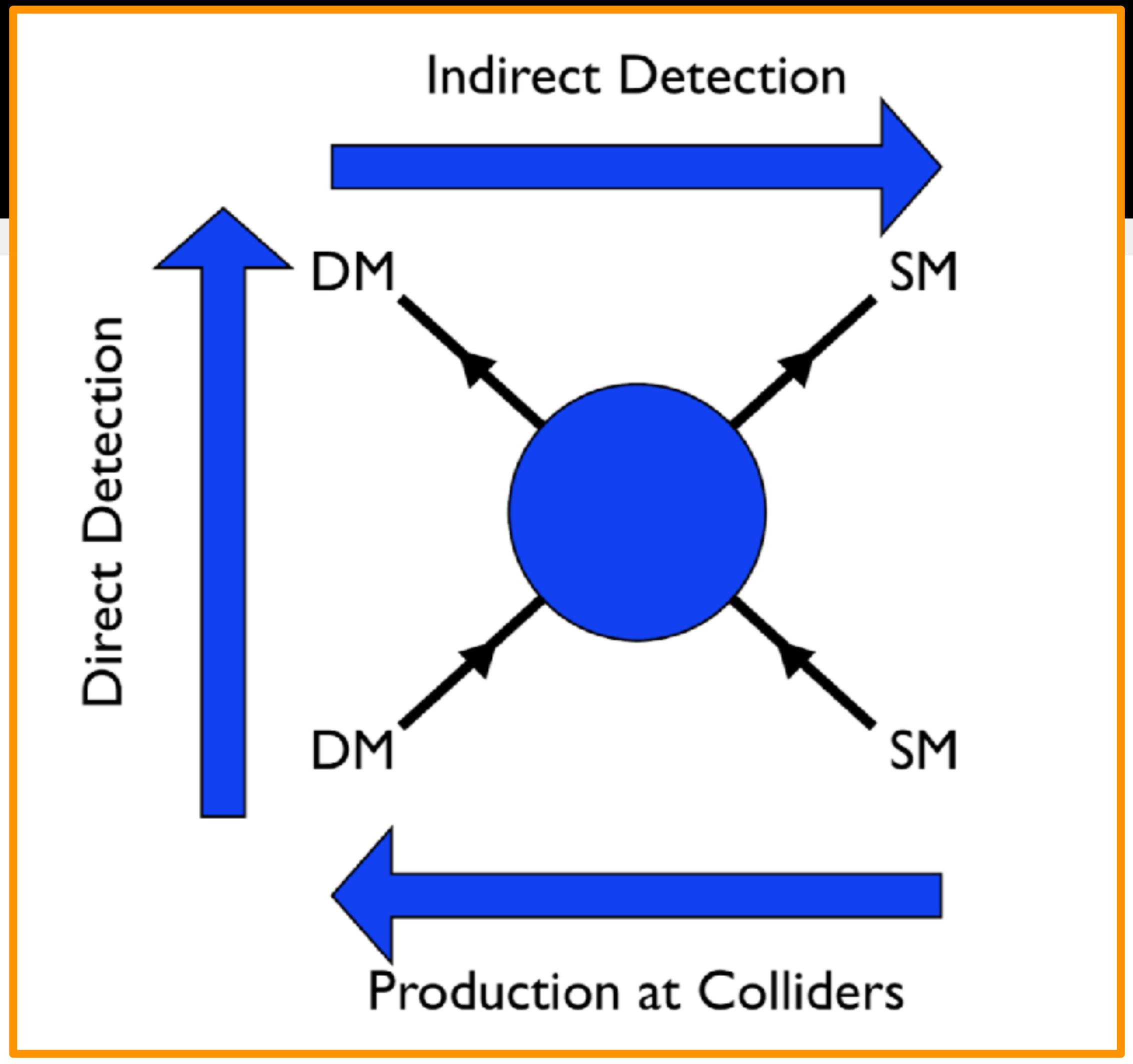
Indirect detection

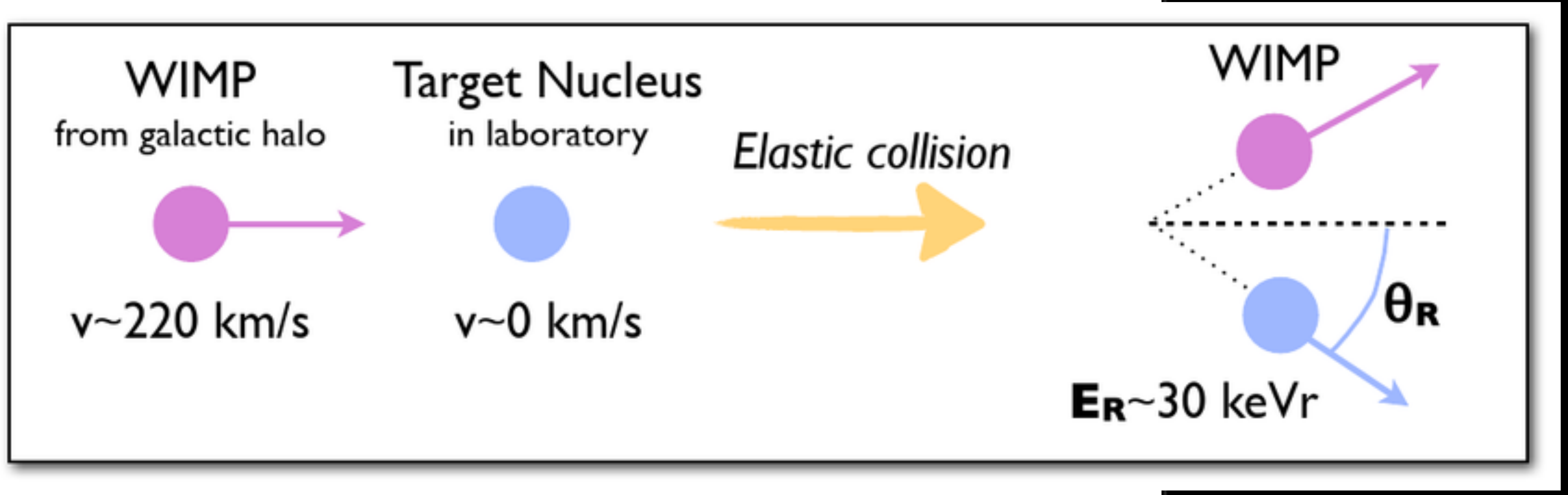




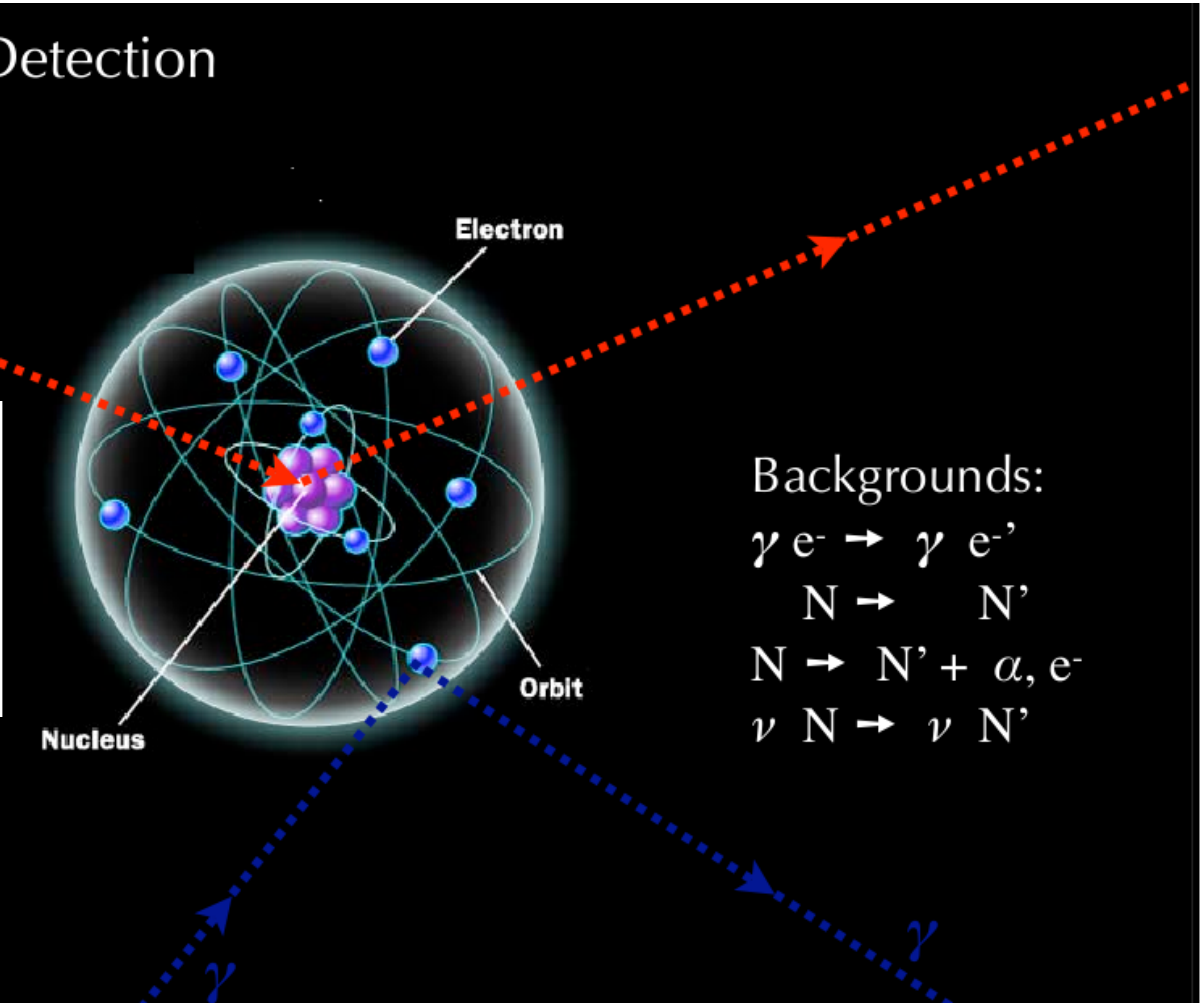


Direct detection





Direct Detection



Backgrounds:

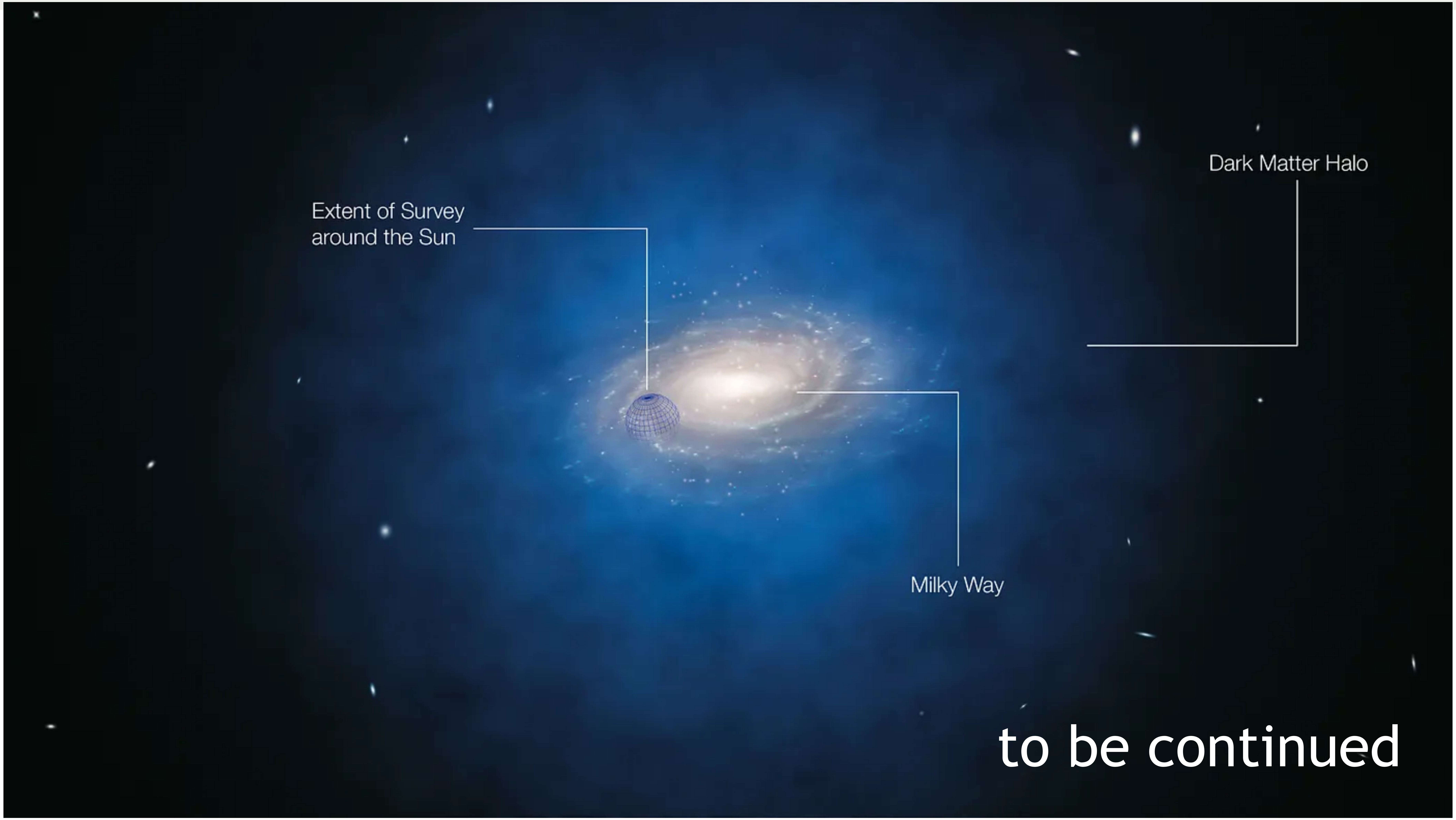
γ e$^-$ → γ e$^{-'}$

N → N’

N → N’ + α, e$^-$

ν N → ν N’

WIMP Halo



to be continued