Dark Matter

Lesson 1: Evidence and Candidates

Alexandre Lindote, 8th March 2024

Outline

Lesson 1: Evidence and Candidates

- **Evidence**
  - First hints
  - More evidence
  - The Big Picture
- **DM Candidates**
  - Candidates
  - The WIMP paradigm
  - Supersymmetry
- **Our Dark Milky Way**
  - The Standard Halo Model

Outline

Lesson 2: Detection Methods

- **Production in colliders**
- **Indirect detection**
- **Direct detection**
    - Principles
    - Kinematics and expected rates
    - Corrections
    - Nucleon scattering cross sections
    - Expected WIMP signal and background sources
- **Direct detection technologies**
    - Cryogenic experiments
    - Directional detectors
    - Room temperature detectors
    - Bubble chambers
    - Liquid noble element experiments

Outline

Lesson 3: Direct detection experimental overview

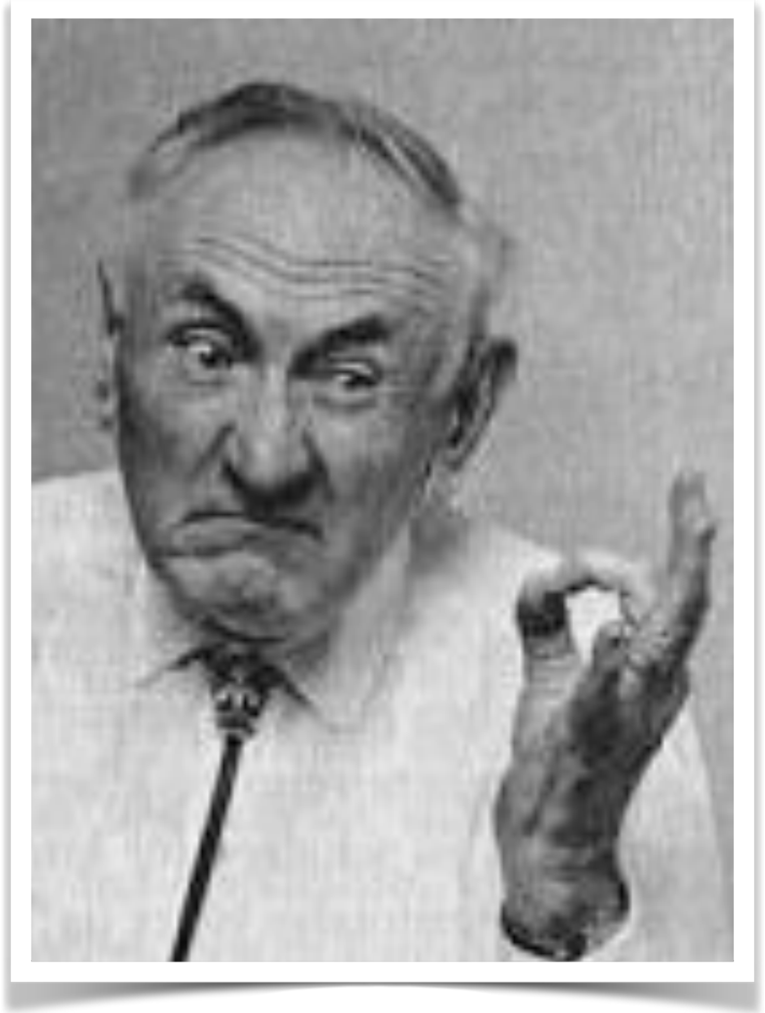
- 2-phase xenon TPC experiments in detail

Lesson 4: Exercises

Evidence for Dark Matter

First hints — Galaxy cluster dynamics

Fritz Zwicky (1933)



- Compared the velocity distribution of galaxies in the Coma cluster to what would be expected given the observed mass (estimated from the luminosity) — using the virial theorem

Virial theorem

$$\langle KE \rangle = -\frac{1}{2}\langle PE \rangle$$

$$\frac{1}{2}Mv^2 \qquad\qquad G\frac{Mm}{R}$$

Coma cluster (image from SDSS)

Note: The existence of some form of invisible matter was not new, and had been suggested by other authors in the previous decades. See “A History of Dark Matter”, by G. Bertone and D. Hooper

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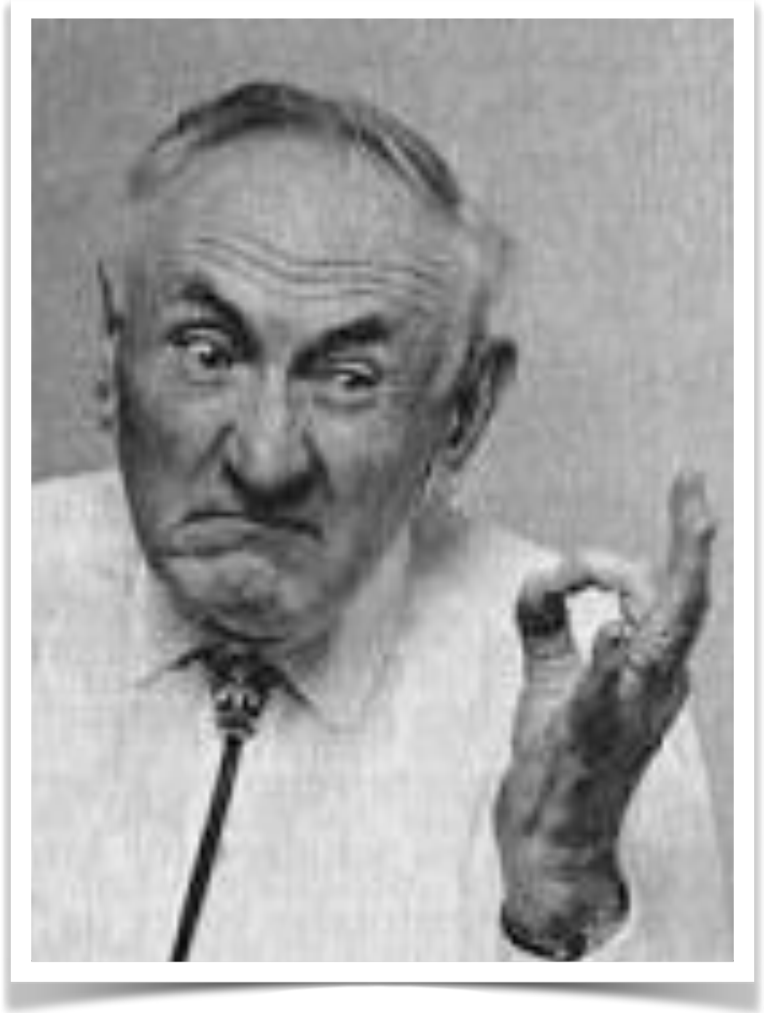

- Compared the velocity distribution of galaxies in the Coma cluster to what would be expected given the observed mass (estimated from the luminosity) — using the virial theorem
  - galaxies moved much faster than expected
  - visible matter only **0.5 %** of the total!
  - he named the invisible matter as ***dunkle materie*** (dark matter)

Virial theorem

$$\langle KE \rangle = -\frac{1}{2}\langle PE \rangle$$

$$\langle KE \rangle \leftarrow \frac{1}{2}Mv^2 \qquad \langle PE \rangle \leftarrow G\frac{Mm}{R}$$

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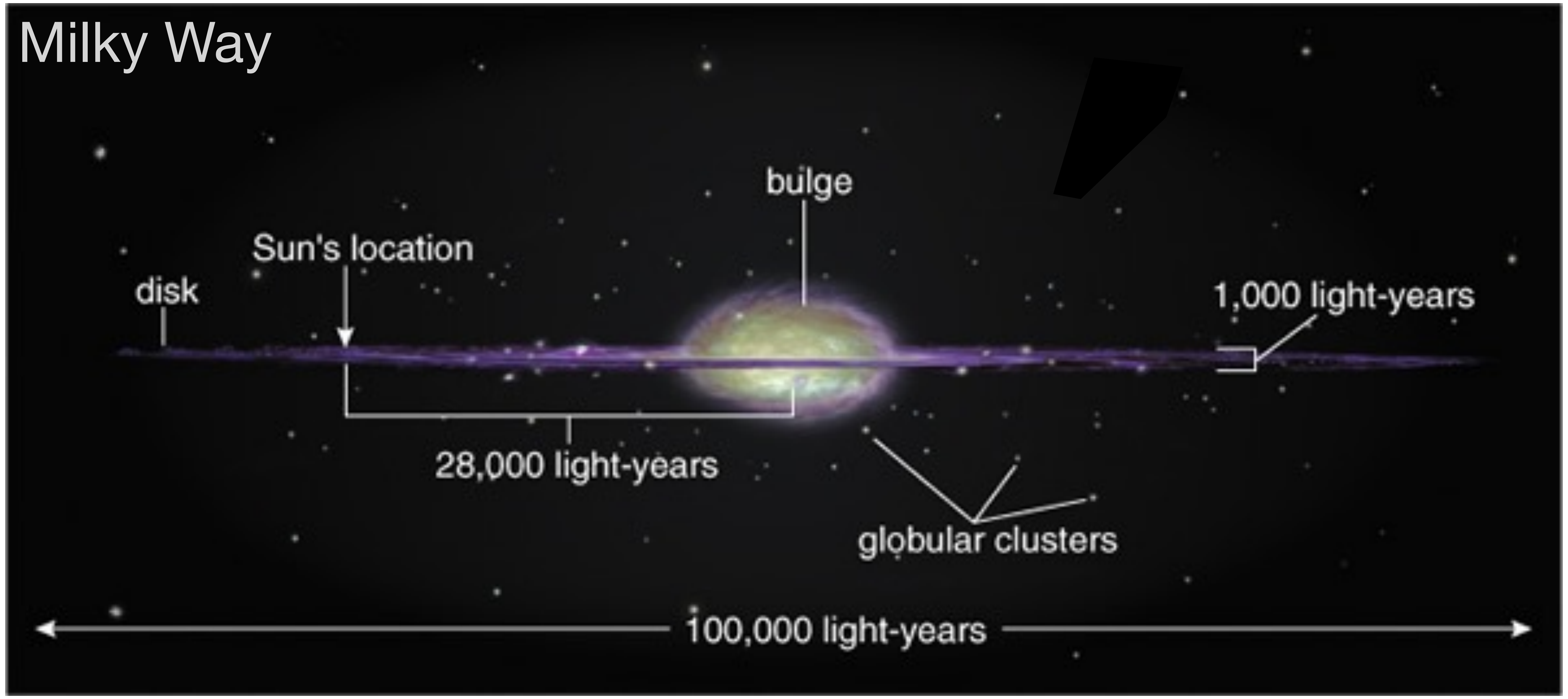
First hints — Galaxy dynamics (rotation curves)

Vera Rubin (1970s)

- During her PhD, she measured the rotation velocities of stars and dust in the outer regions of galaxies

Most of the mass is in the central region of galaxies. We expect that the rotation velocity of stars and gas clouds decreases rapidly with the distance to the center.



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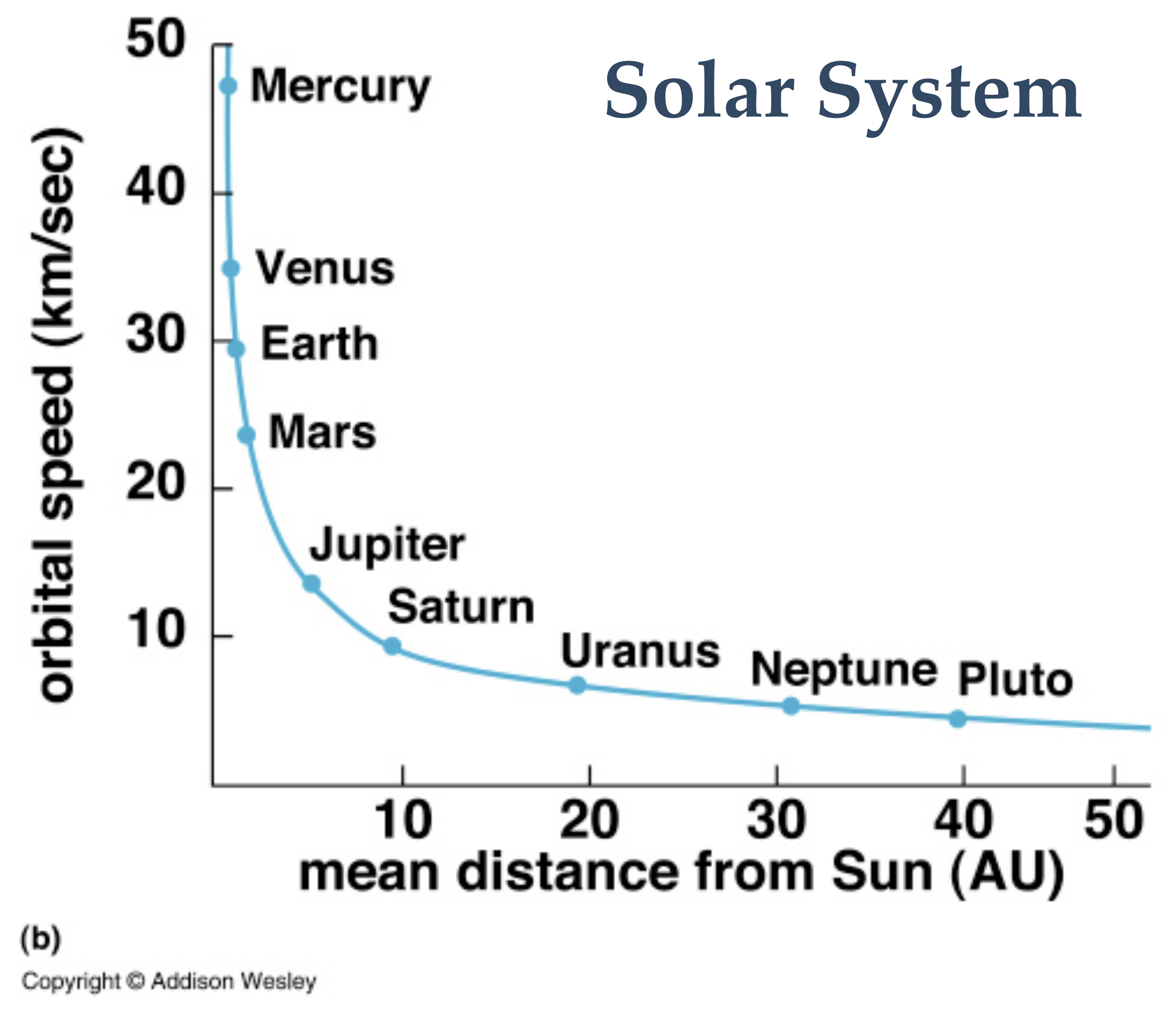
- Considering the distribution of luminous matter only, we expect the velocity to fall as we get further away from the center
(as in the Solar System):



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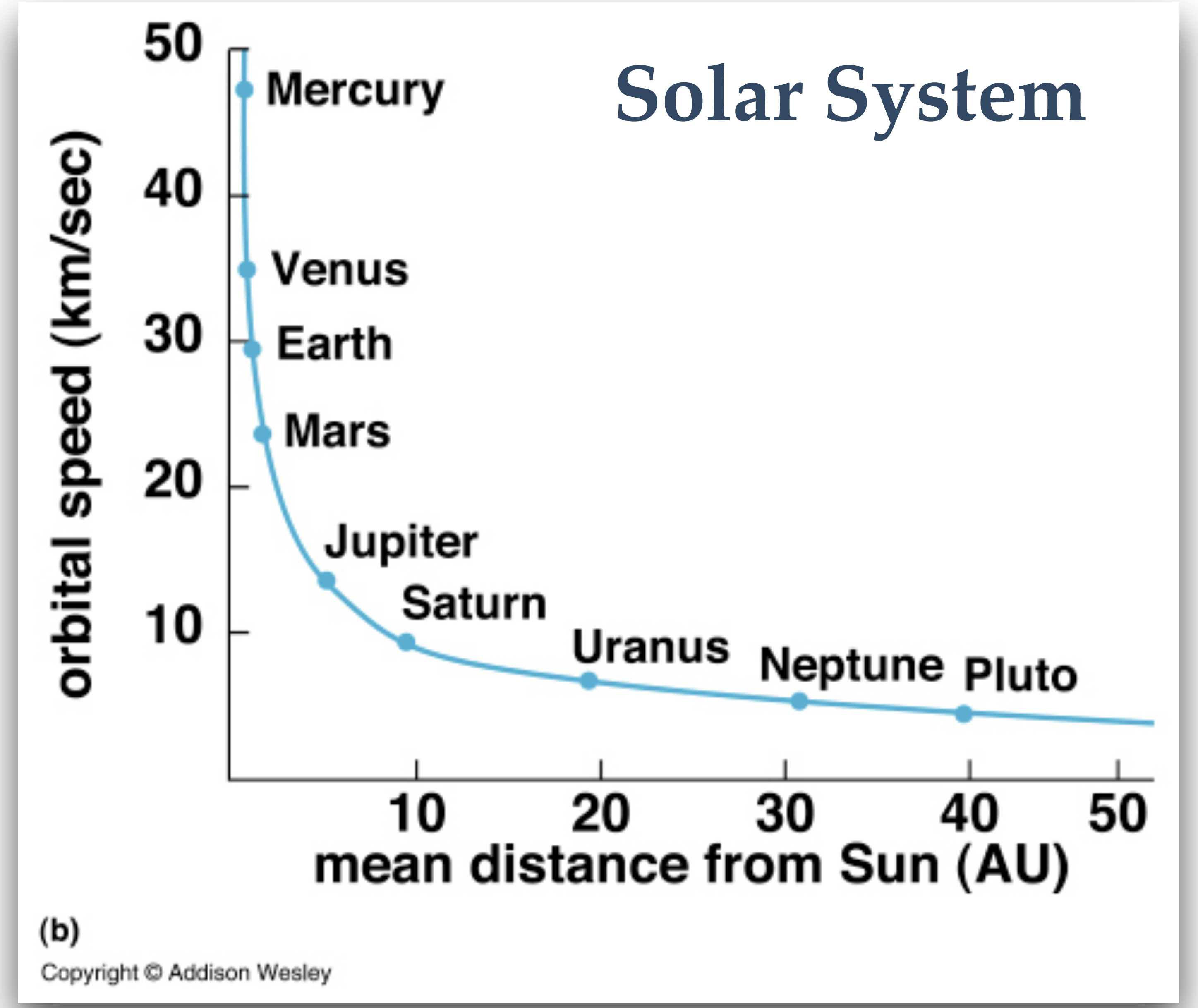

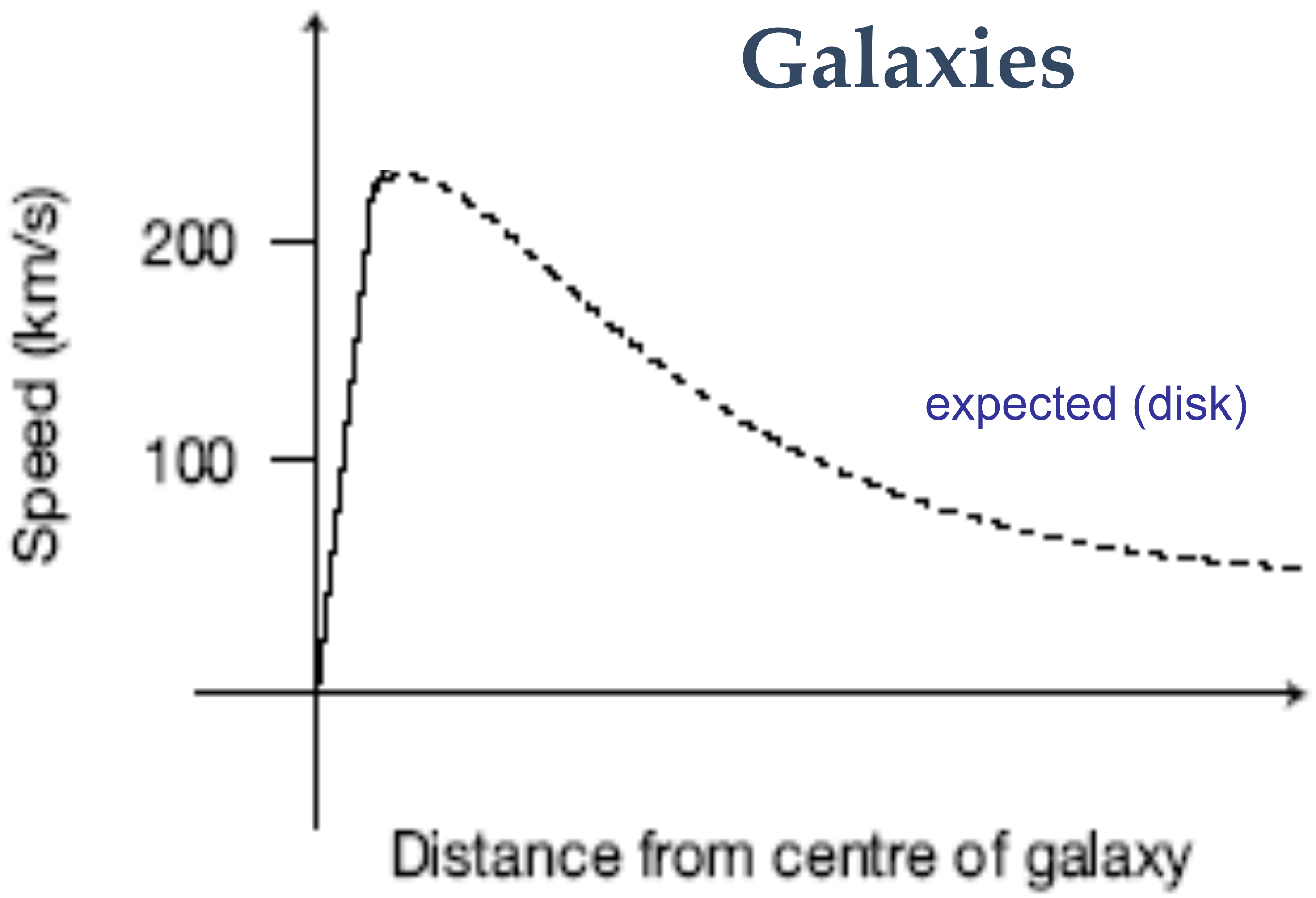

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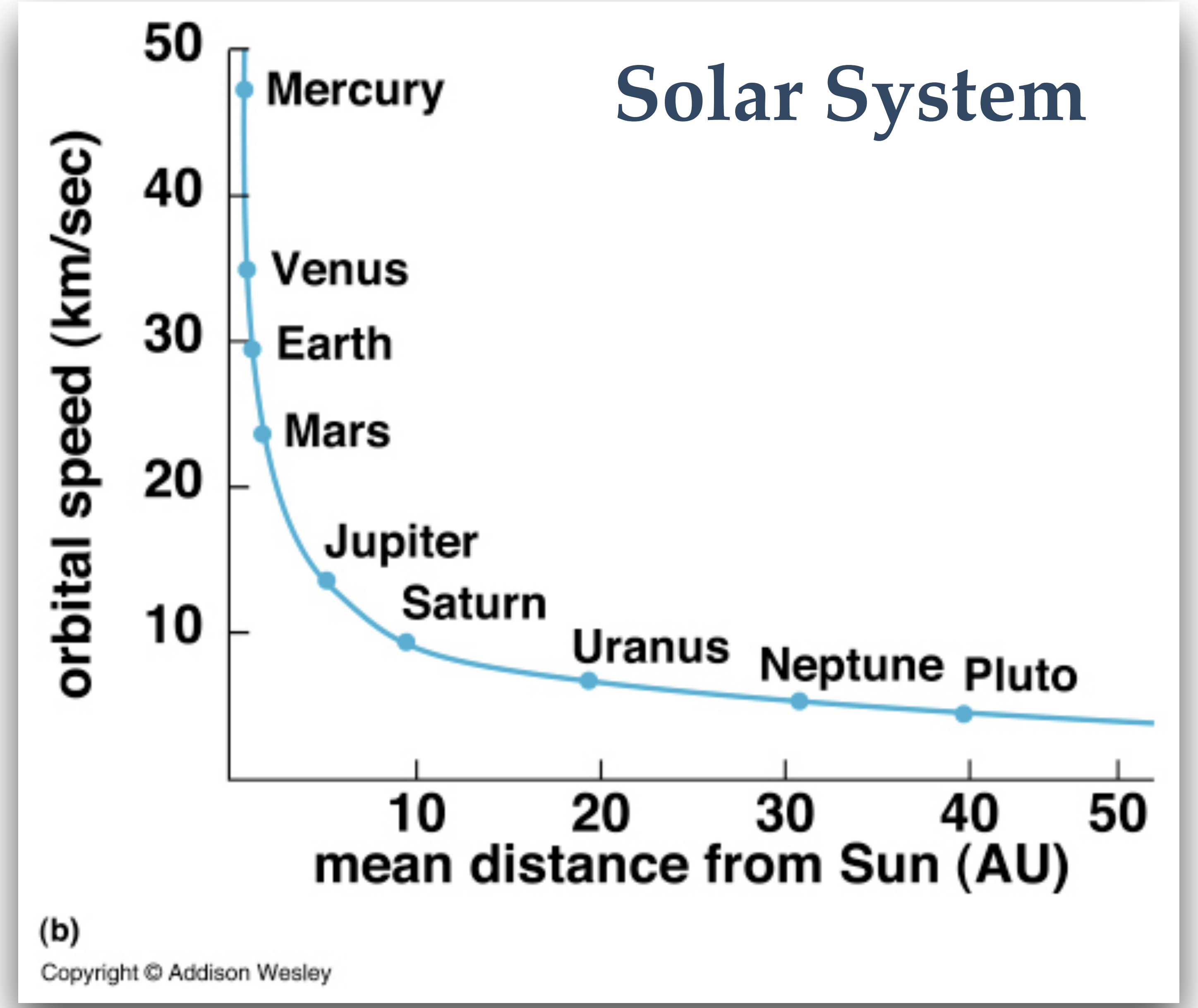

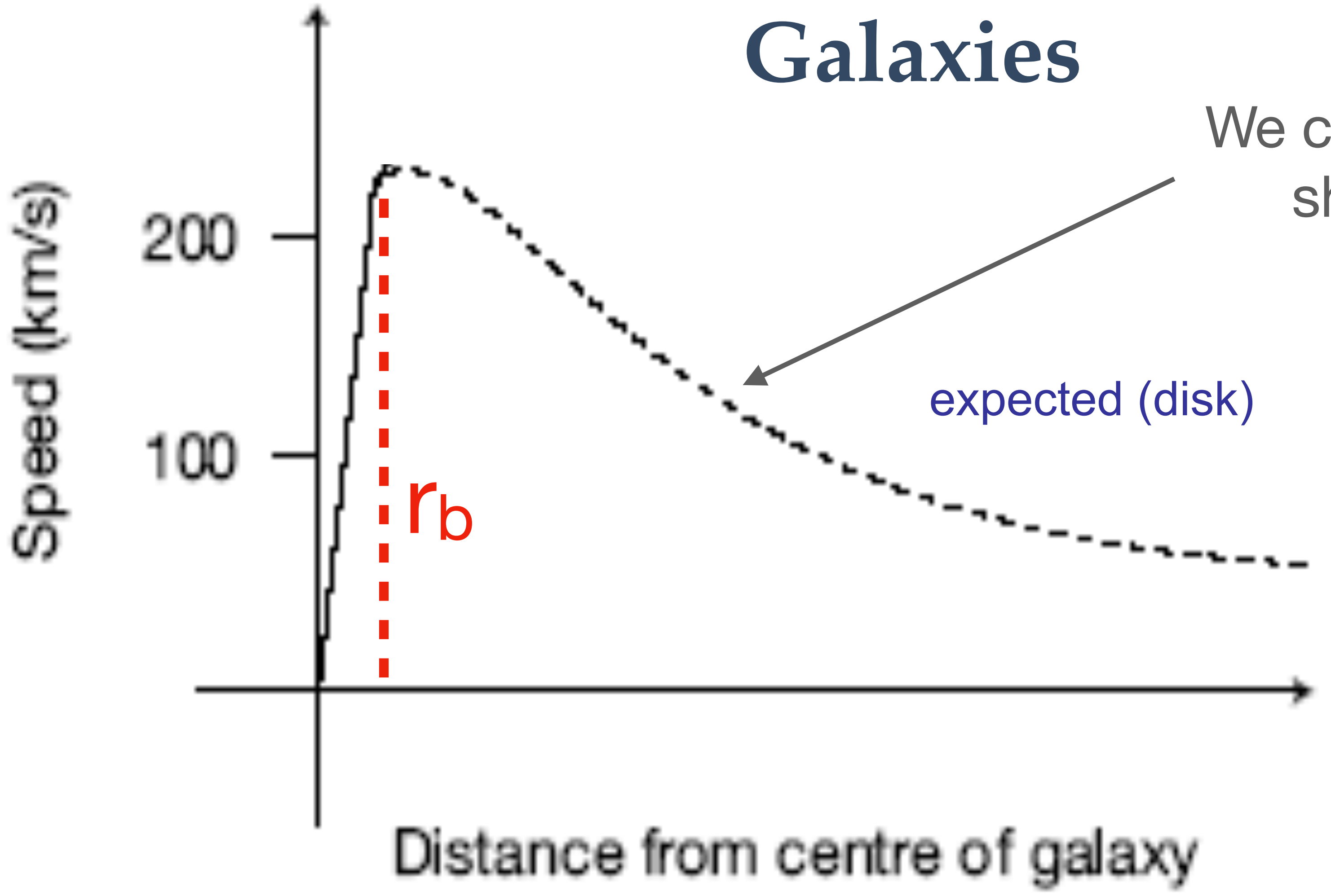

We can even estimate the shape of this curve

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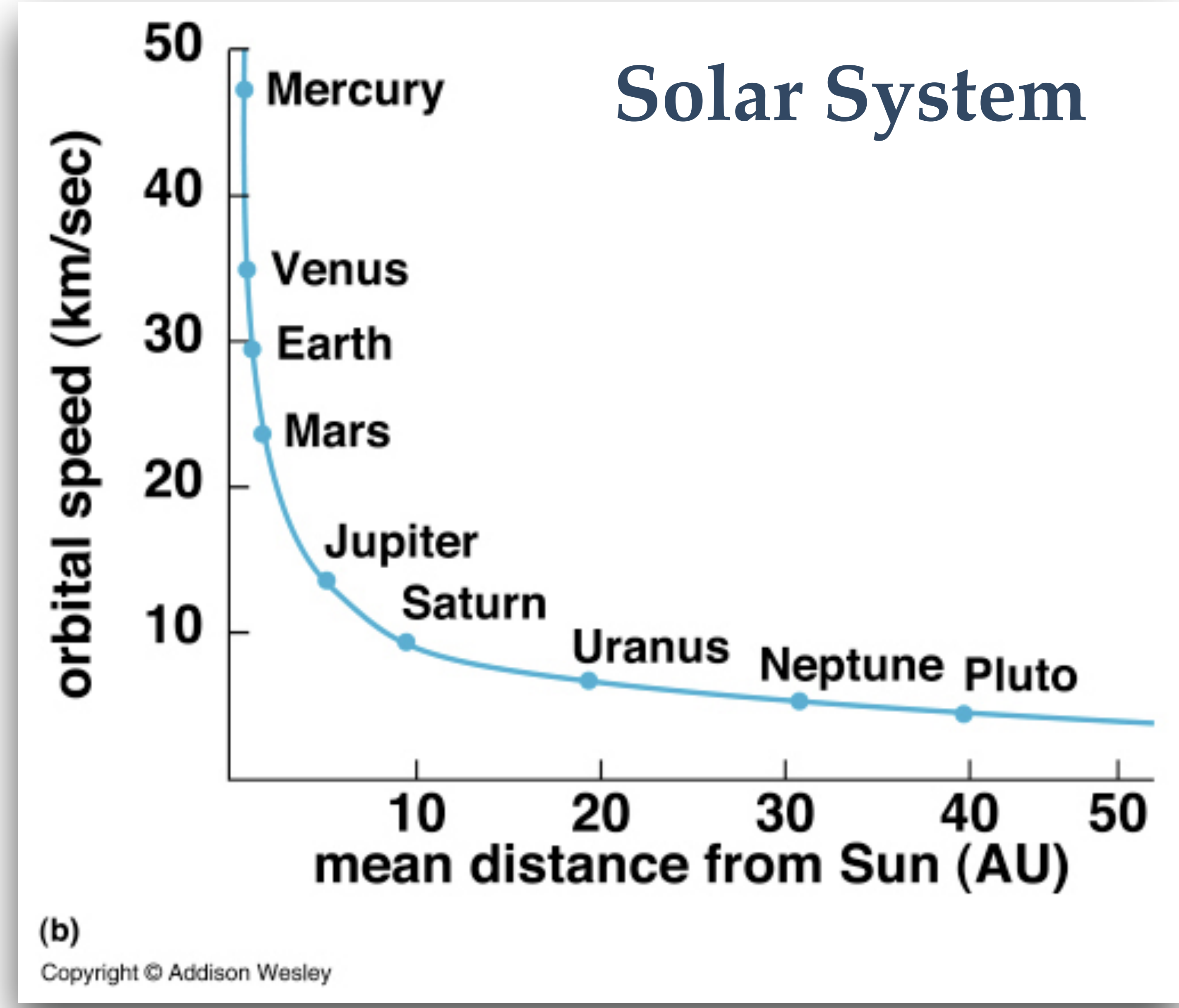
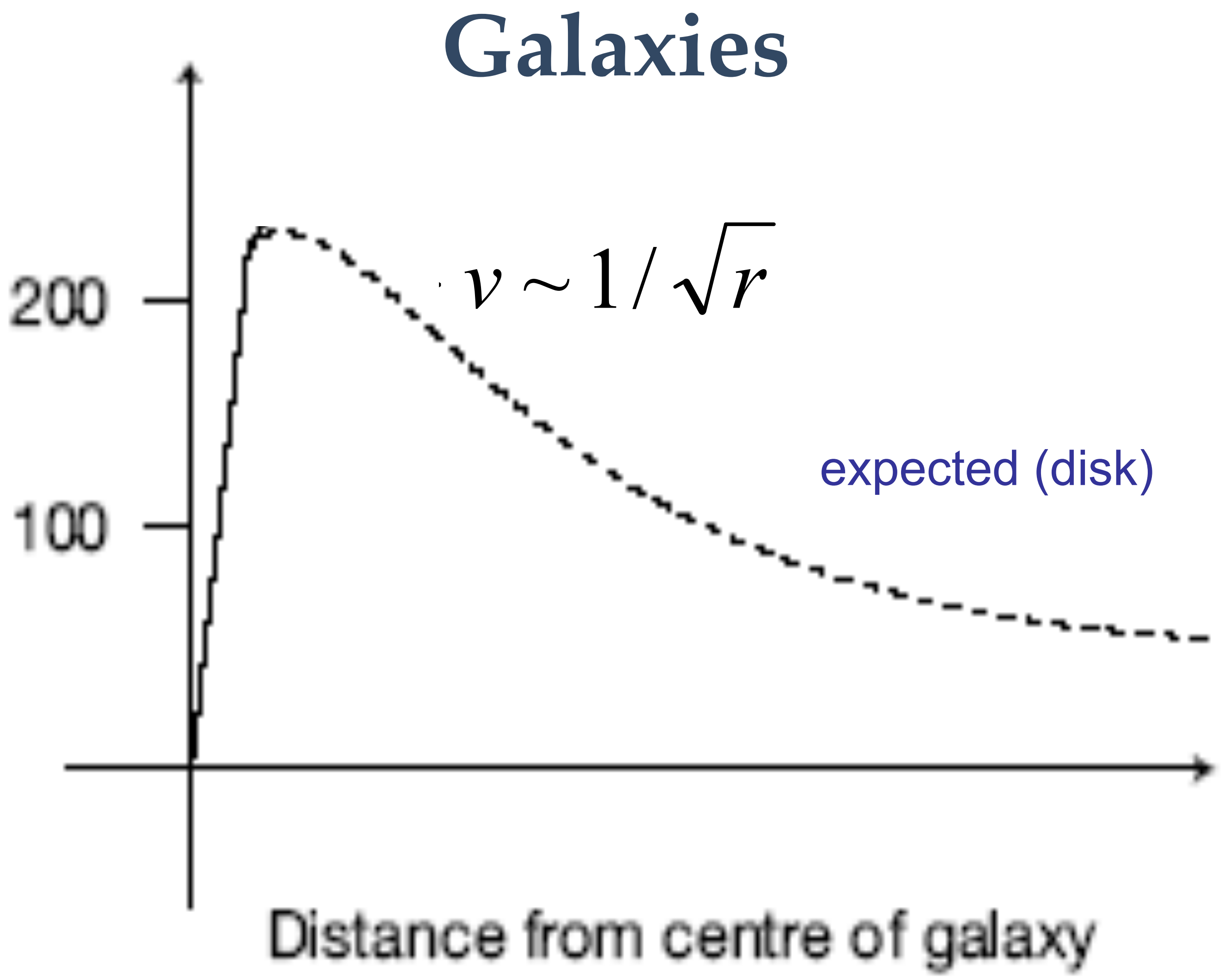




$$\frac{m v_r^2}{r} = G\frac{M_r m}{r^2}$$

$$v_r^2 = G\frac{M_r}{r}$$

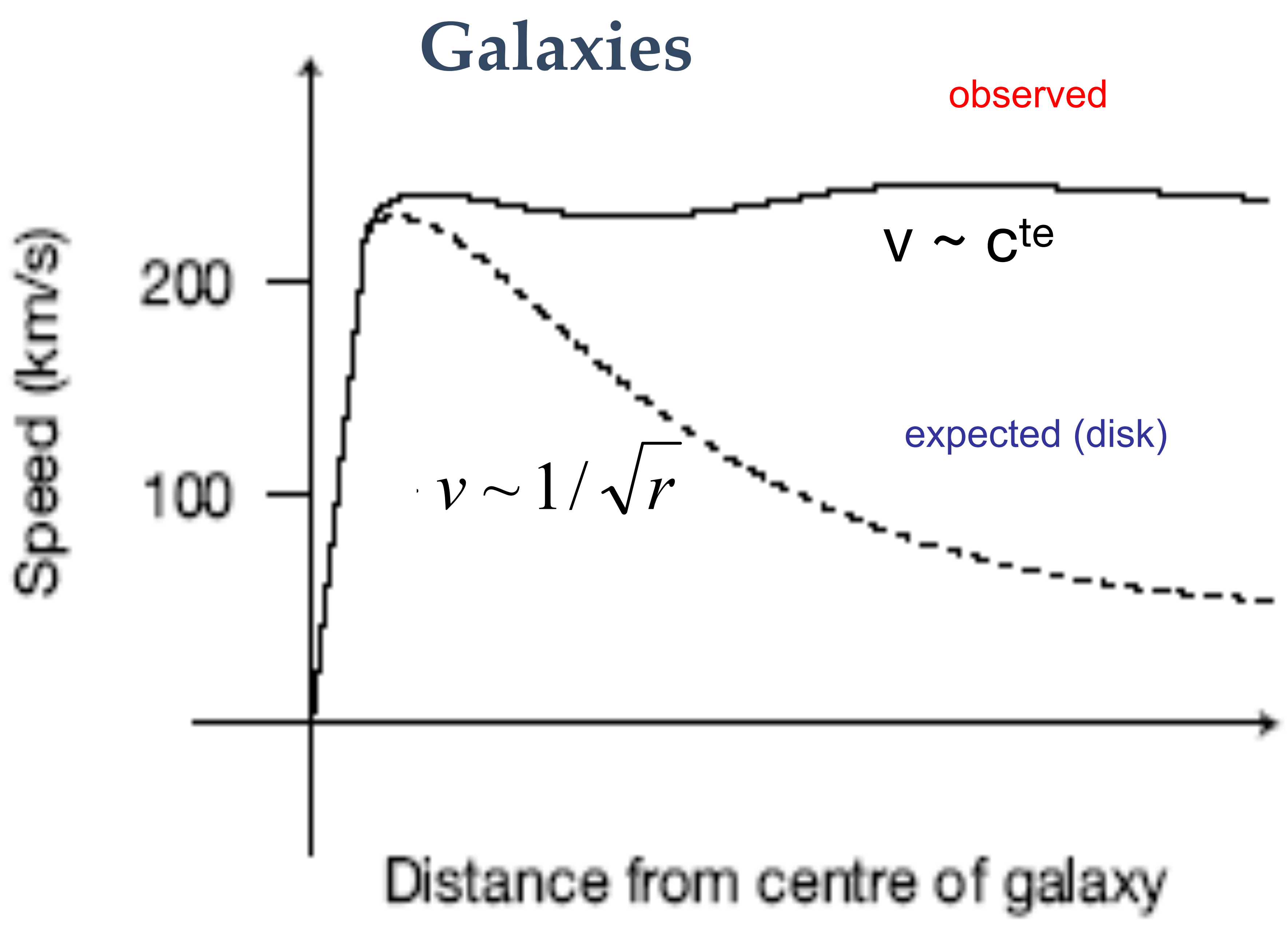
$$v_r = \sqrt{\frac{G M_r}{r}}$$

$$\Rightarrow v_r \propto \frac{1}{\sqrt{r}}$$

First hints — Galaxy dynamics (rotation curves)

Vera Rubin (1970s)

- **Actually she observed that stars (and dust) in the outer regions move approximately as fast as the inner ones!**



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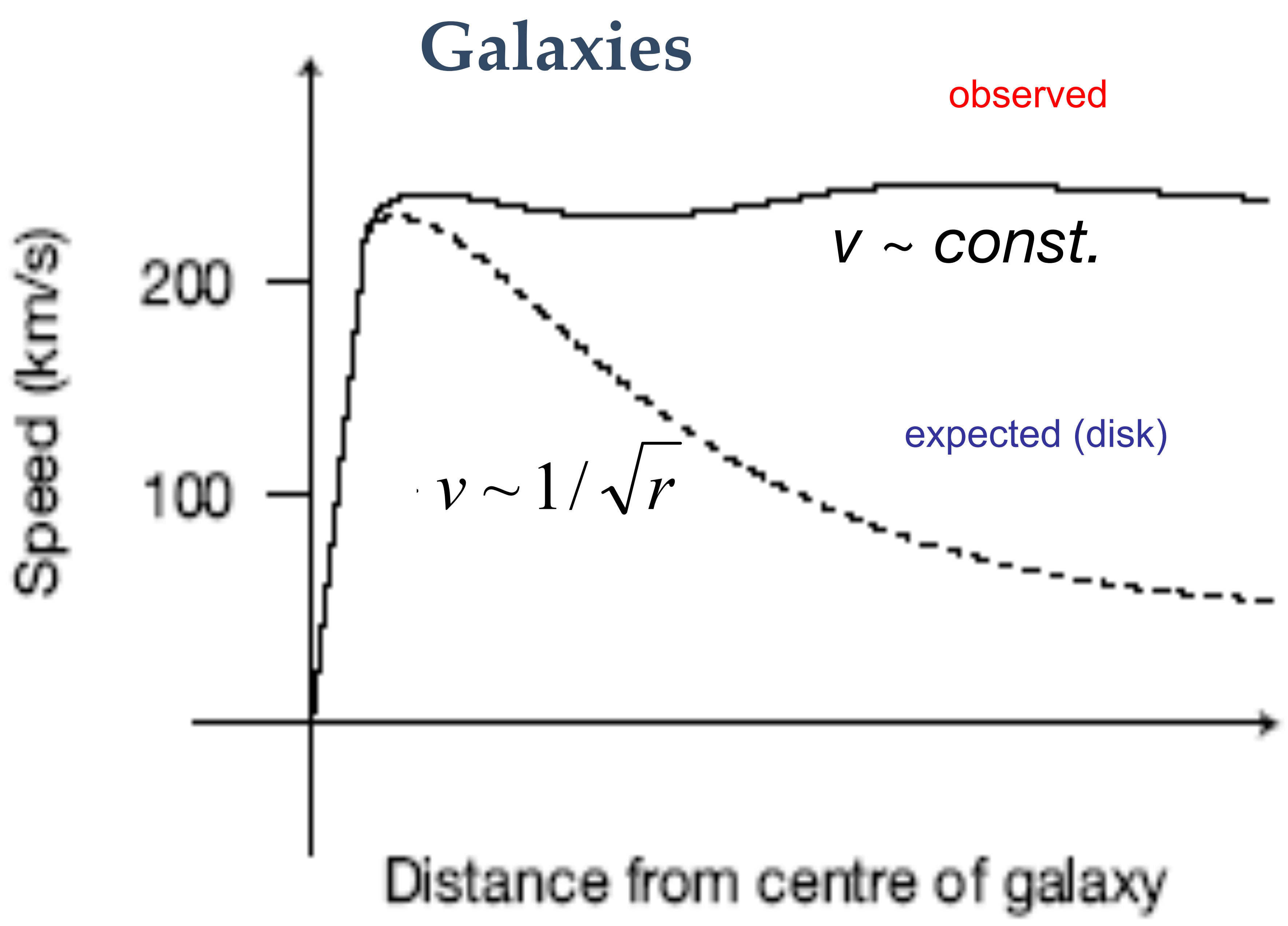

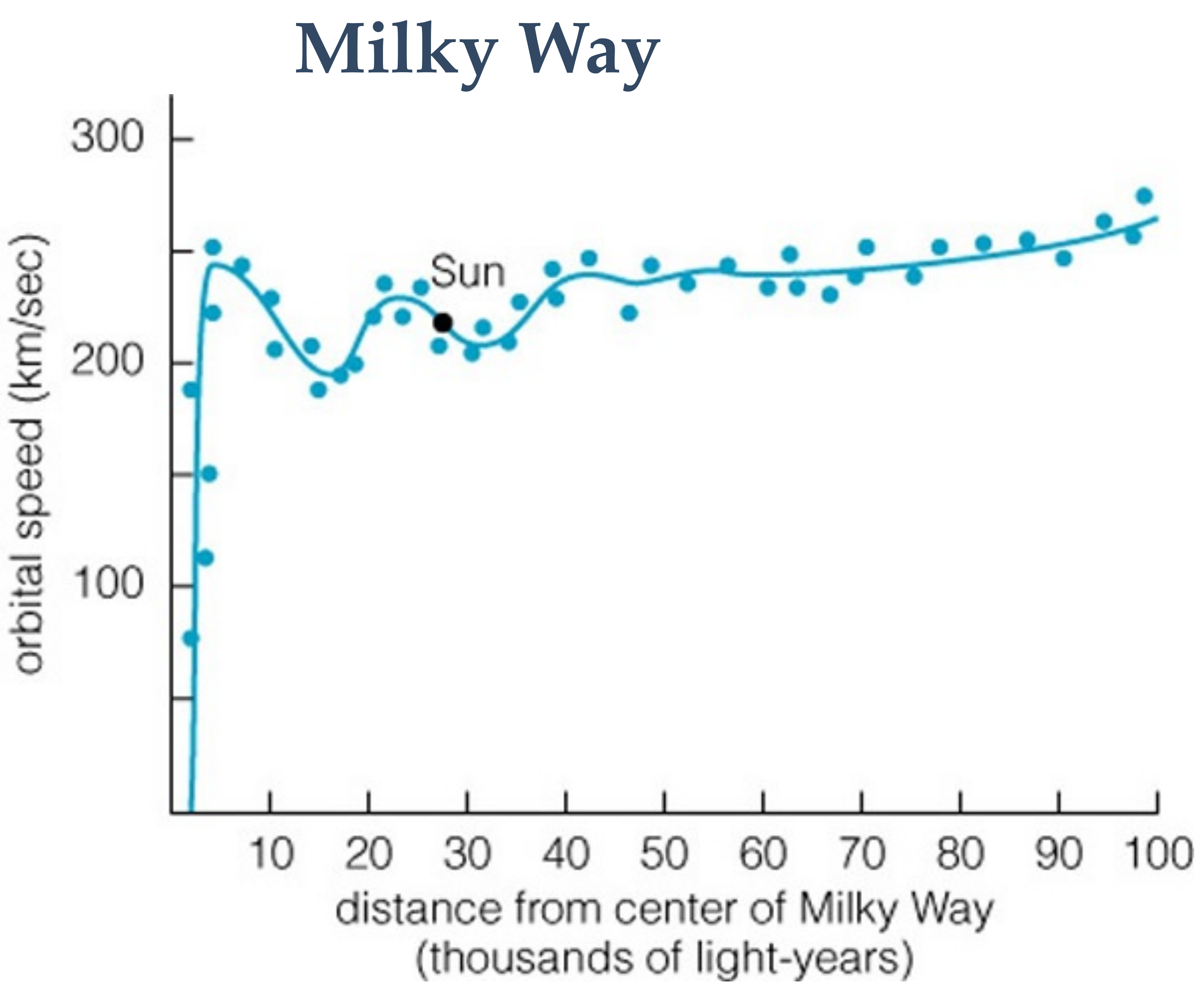

First hints — Galaxy dynamics (rotation curves)

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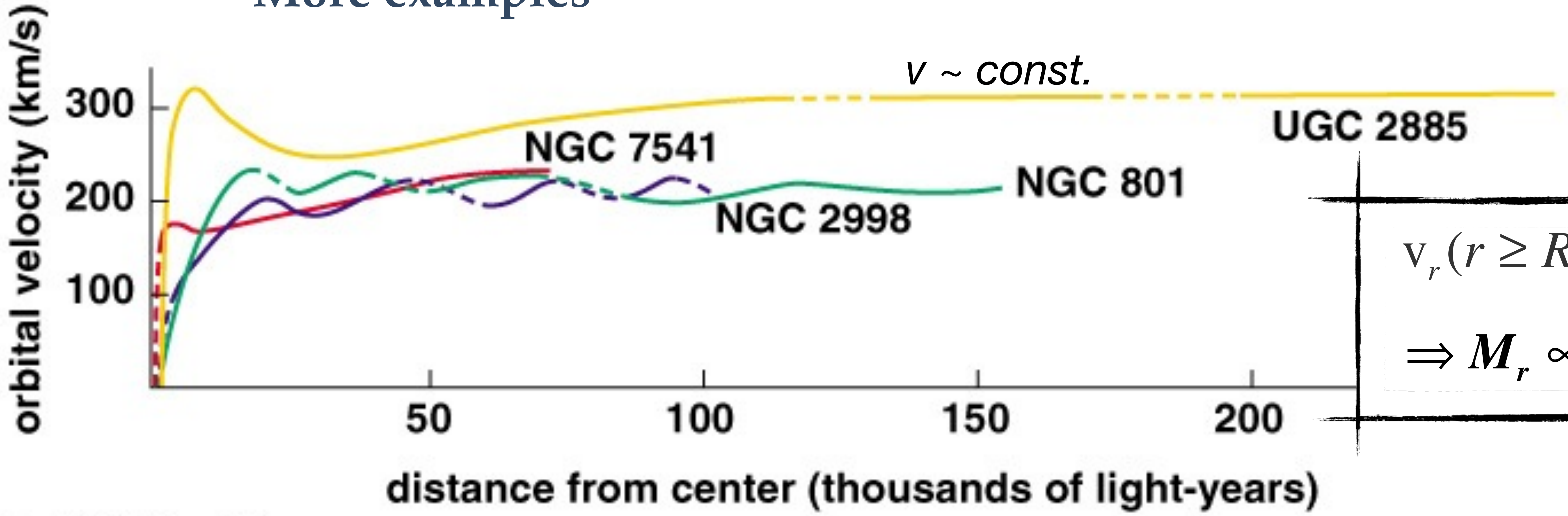
More examples

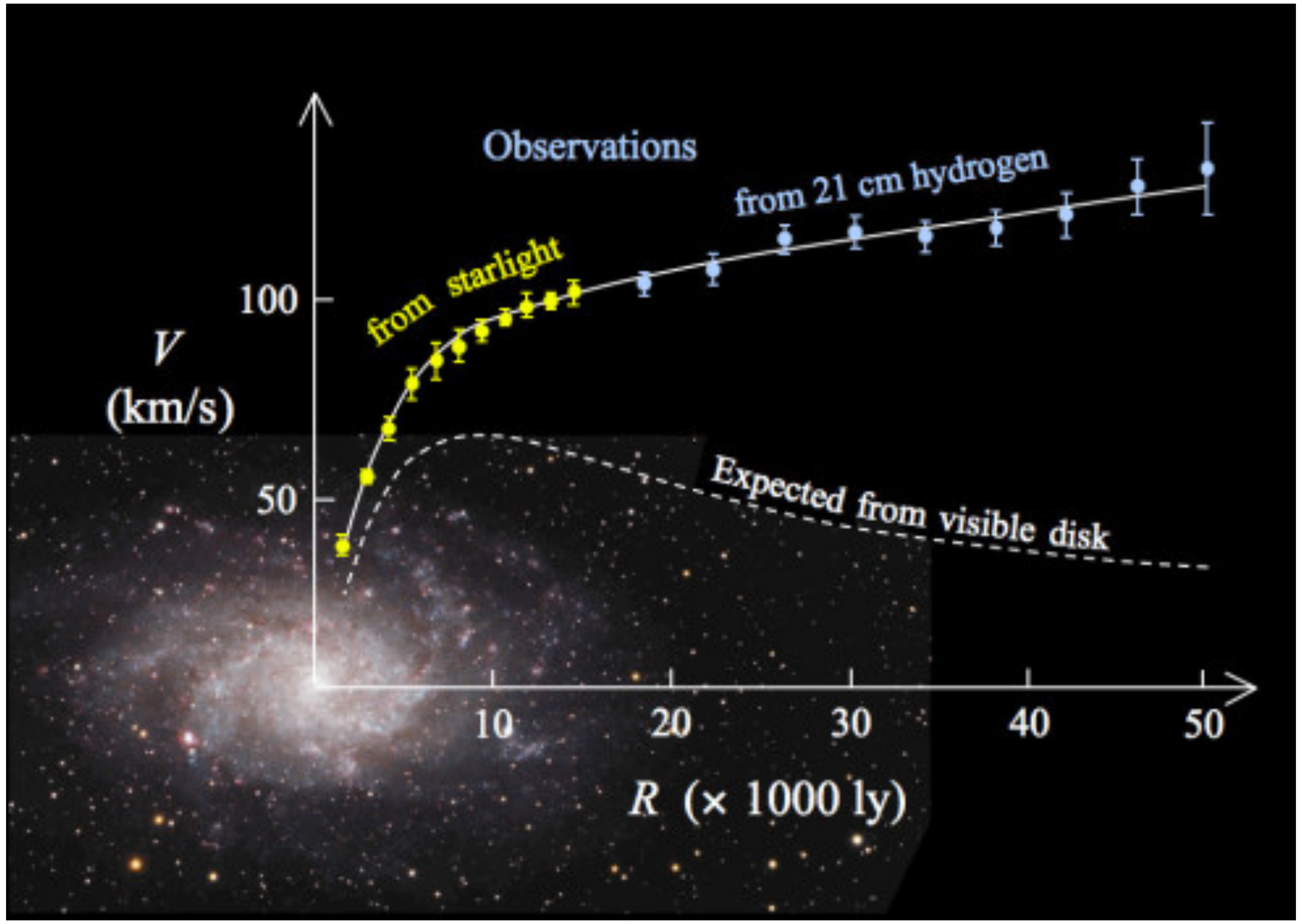


$$v_r(r \geq R_0) \approx const.$$

$$\Rightarrow \boldsymbol{M_r \propto r}$$

First hints — Galaxy dynamics (rotation curves)

Gas (hydrogen)

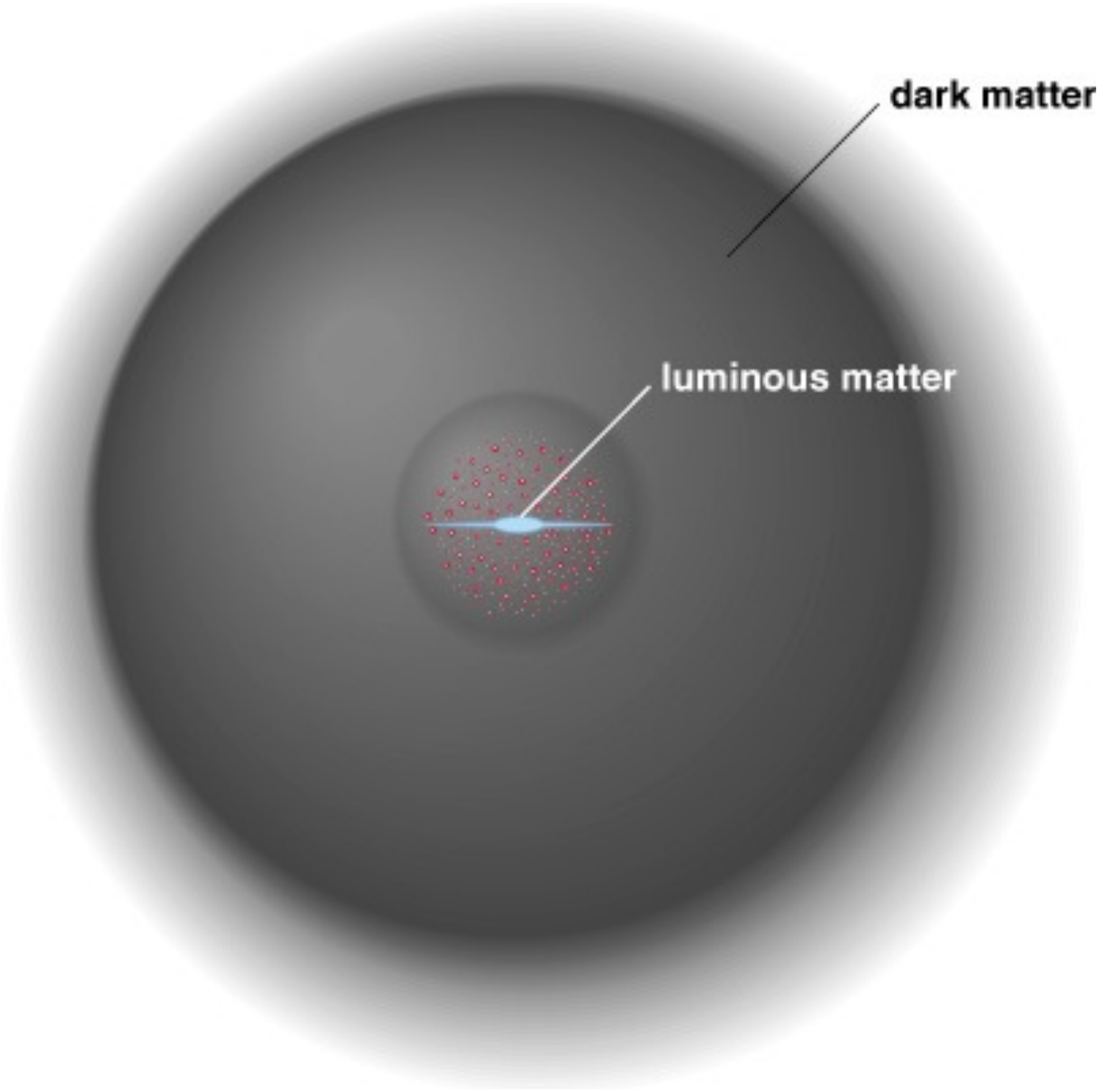


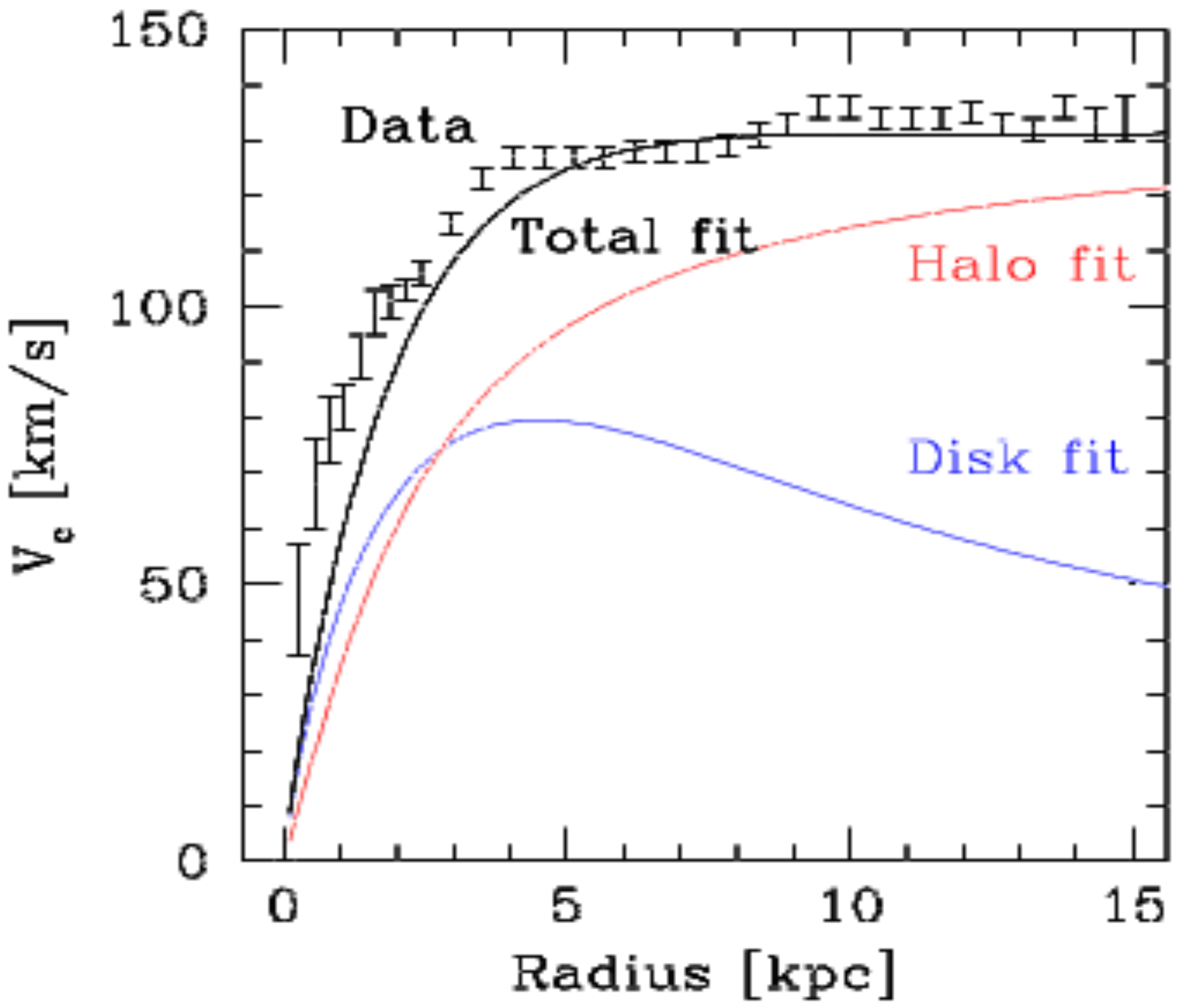
Even at very large distances from the center:

- rotation speed **of the gas** is ~ constant
  - measured using the 21 cm line from hydrogen
- this **cannot** be explained by the mass of the stars or the mass of the gas
- evidence that there is a **large amount of dark matter** well beyond the limits of the galaxy disk

First hints — Galaxy dynamics (rotation curves)

- A non-visible mass component, which increases linearly with radius, must exist!
- The rotation curve depends on the distribution of this mass





First hints — Galaxy dynamics (rotation curves)

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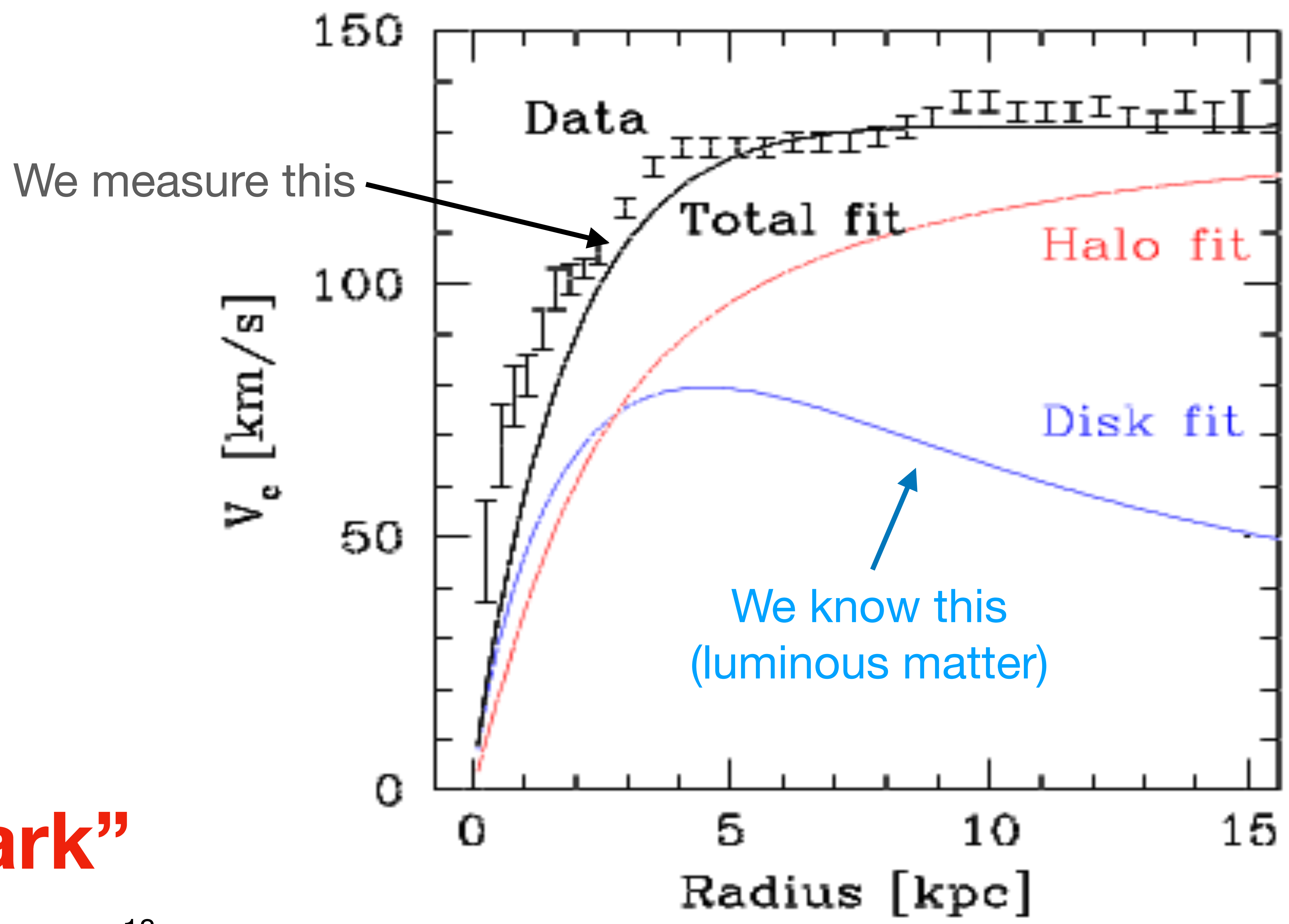
- The rotation curve depends on the distribution of this mass
  => we can use the measured rotation curve to learn about the dark matter distribution

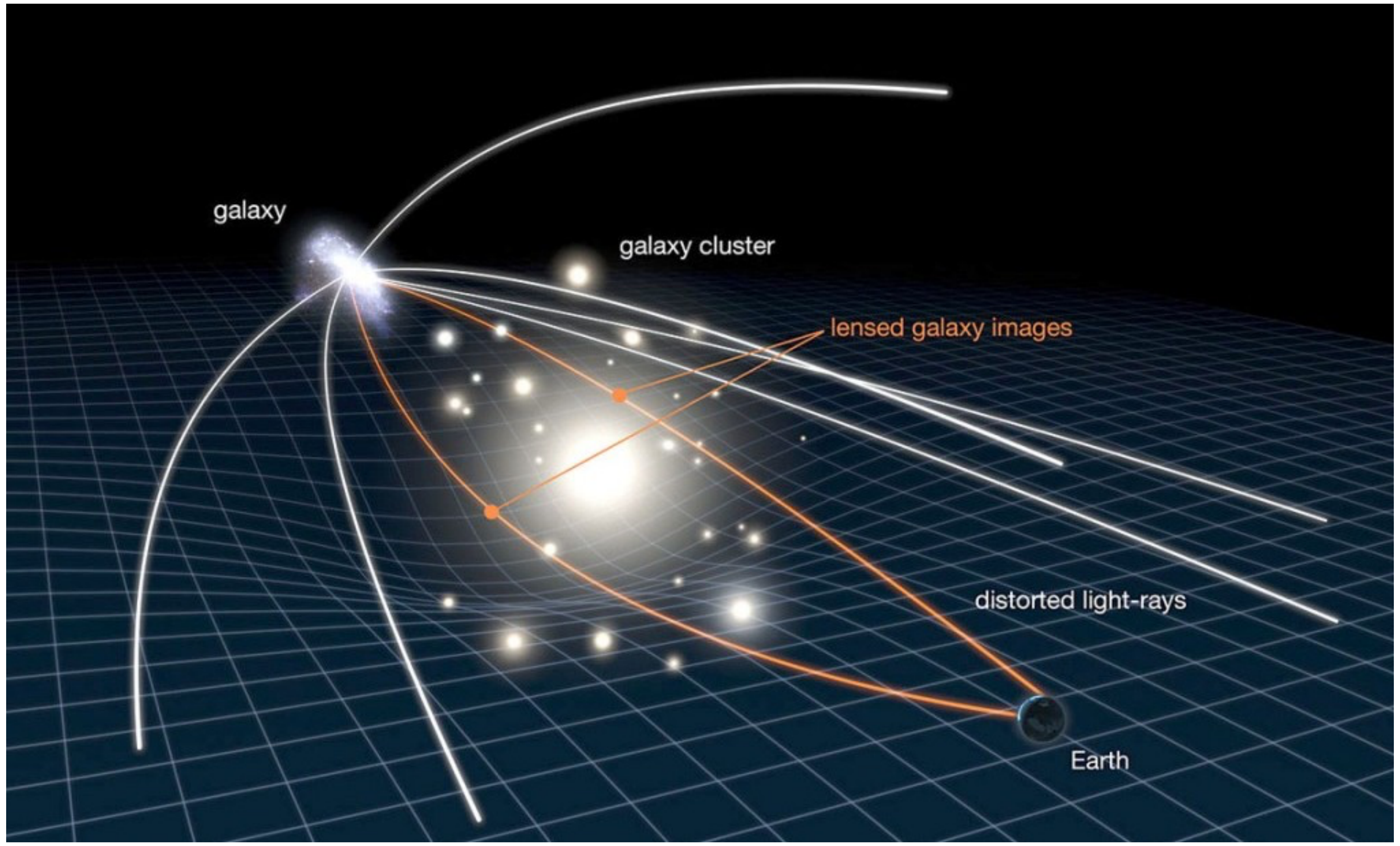


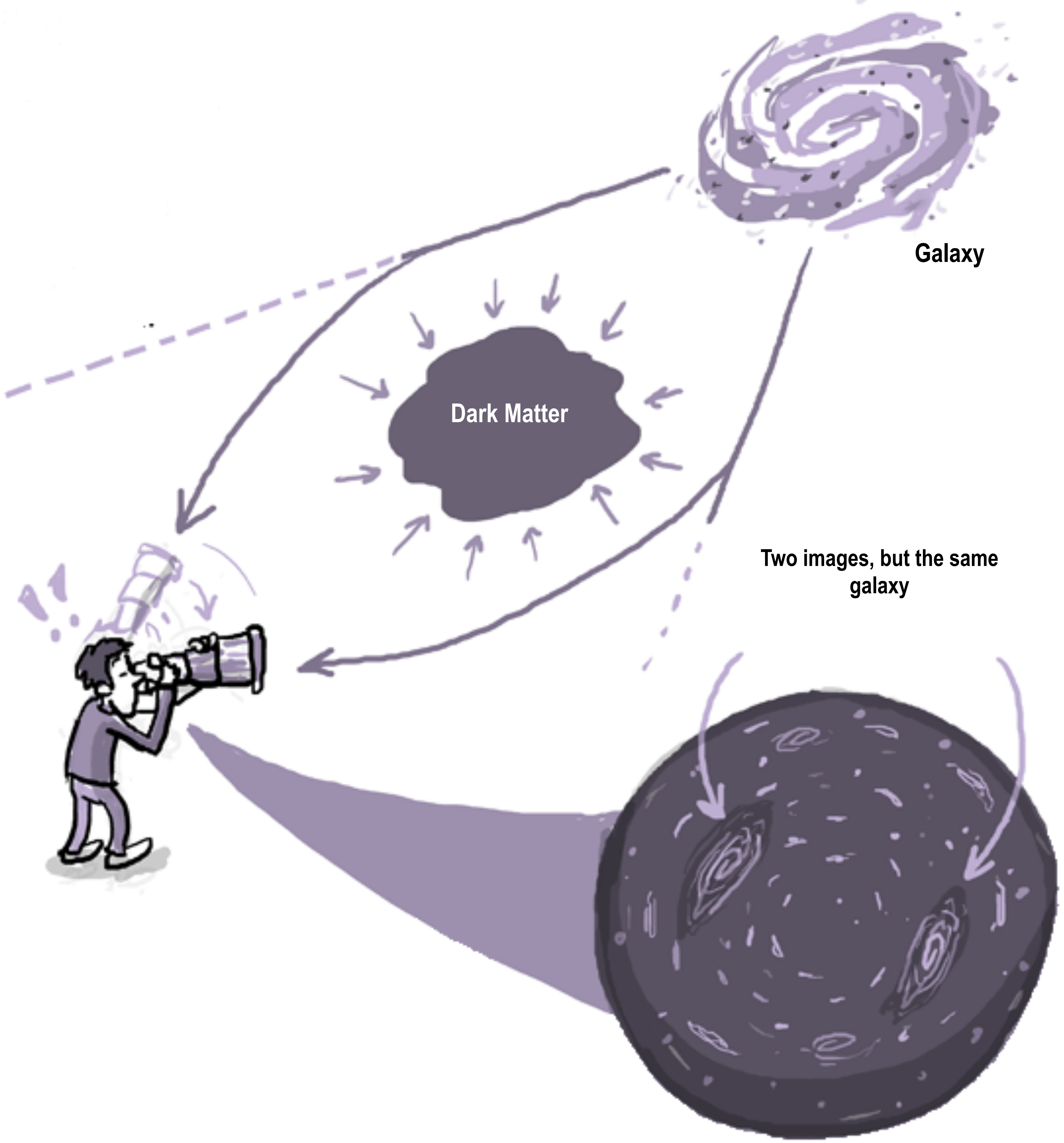
~90% of the mass in galaxies is "dark"

More evidence

Gravitational lensing

- General Relativity:
  - Space-time is distorted by large masses
  - The light path is distorted (lens effect)



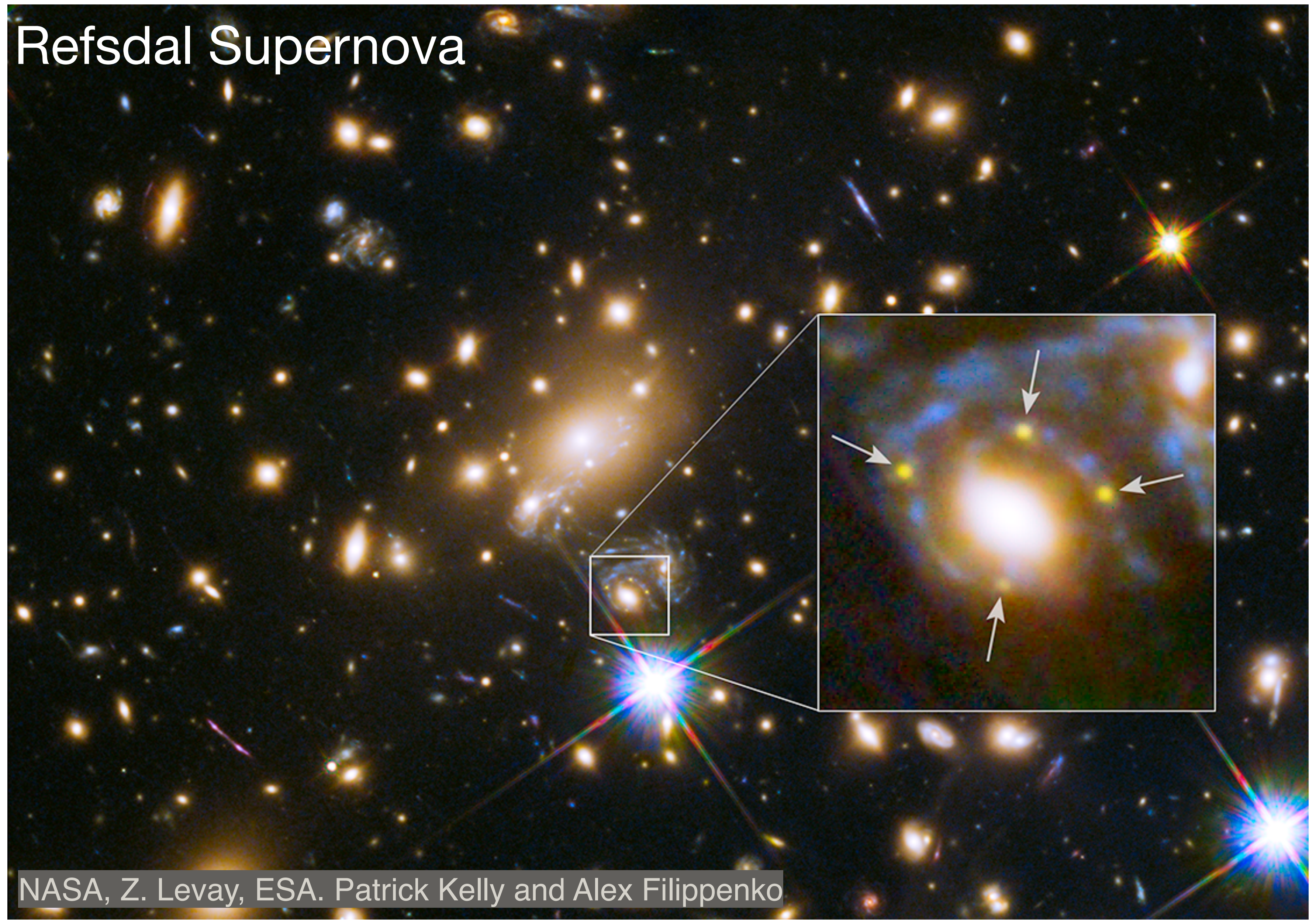


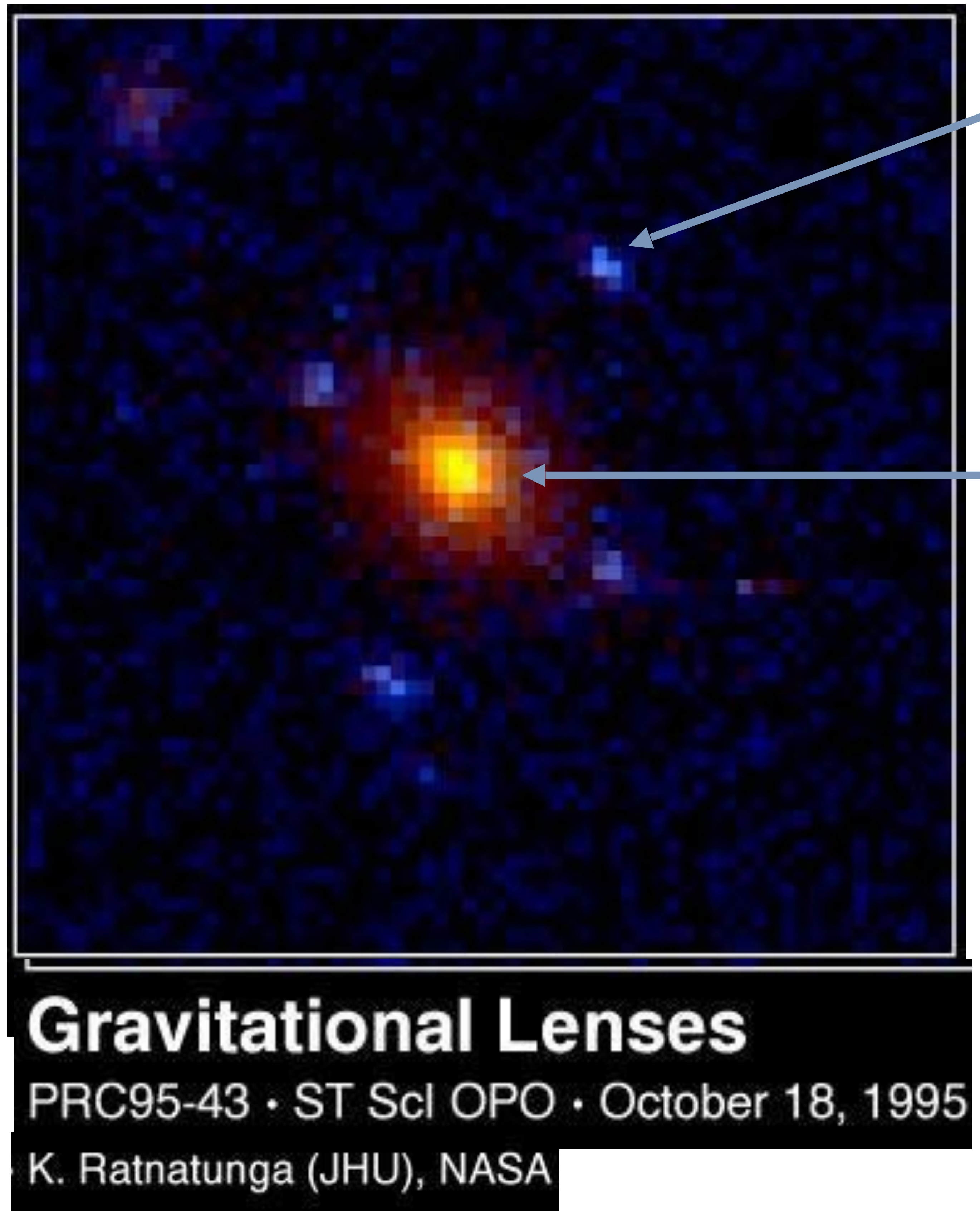
More evidence

Gravitational lensing

- Weak lenses:
  - Small masses ⇒ slight distortion of the image
- Strong lenses:
  - Large masses ⇒ big distortion and multiple images

Remember: this is not a smooth lens





One of four images created by the gravitational lens

Galaxy responsible for the lens effect

- ➡ A galaxy or galaxy cluster creates the gravitational lens
- ➡ Using the position and distortion of the four images, the mass distribution responsible for creating the lens can be estimated

Estimated mass >> visible mass!

More evidence

Gravitational lensing

- Weak lenses:
  - Small masses ⇒ slight distortion of the image
- Strong lenses:
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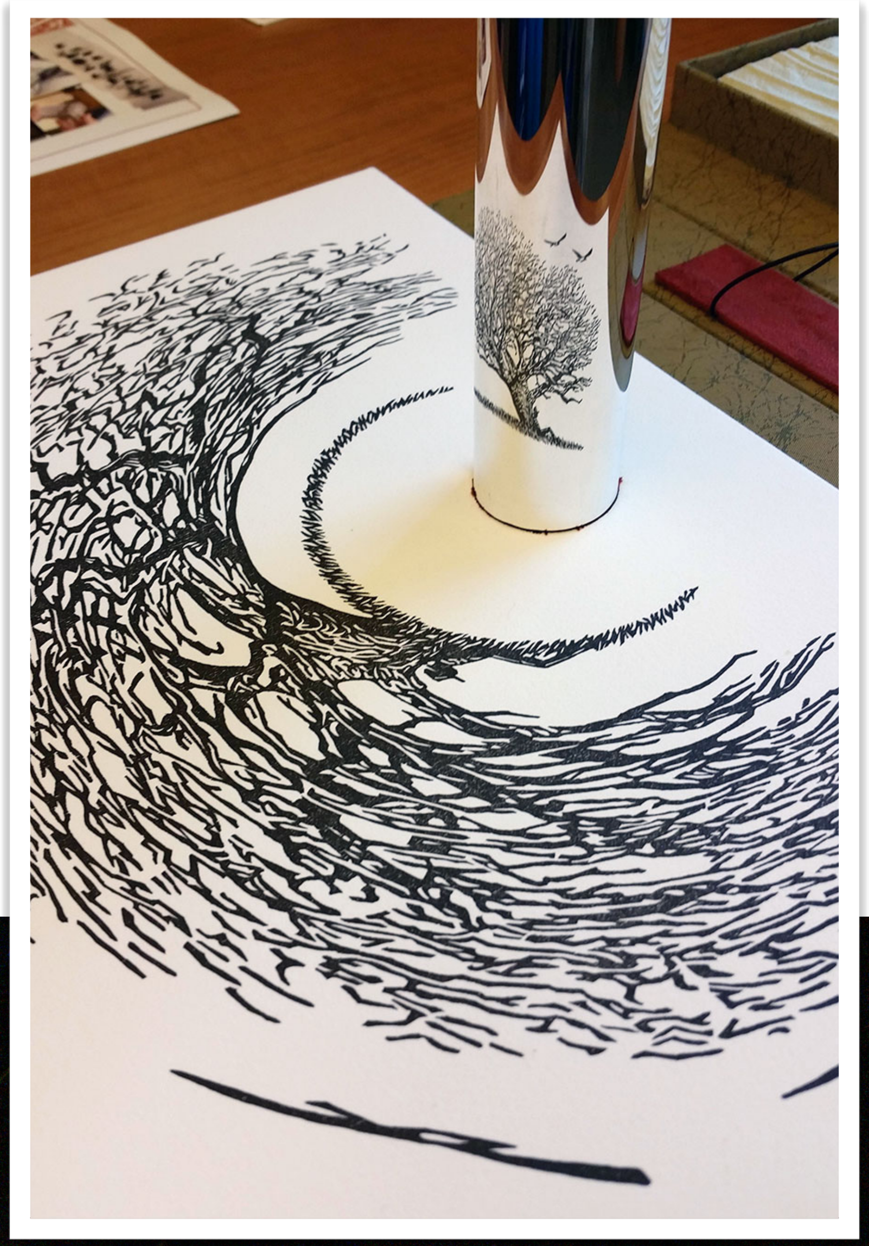
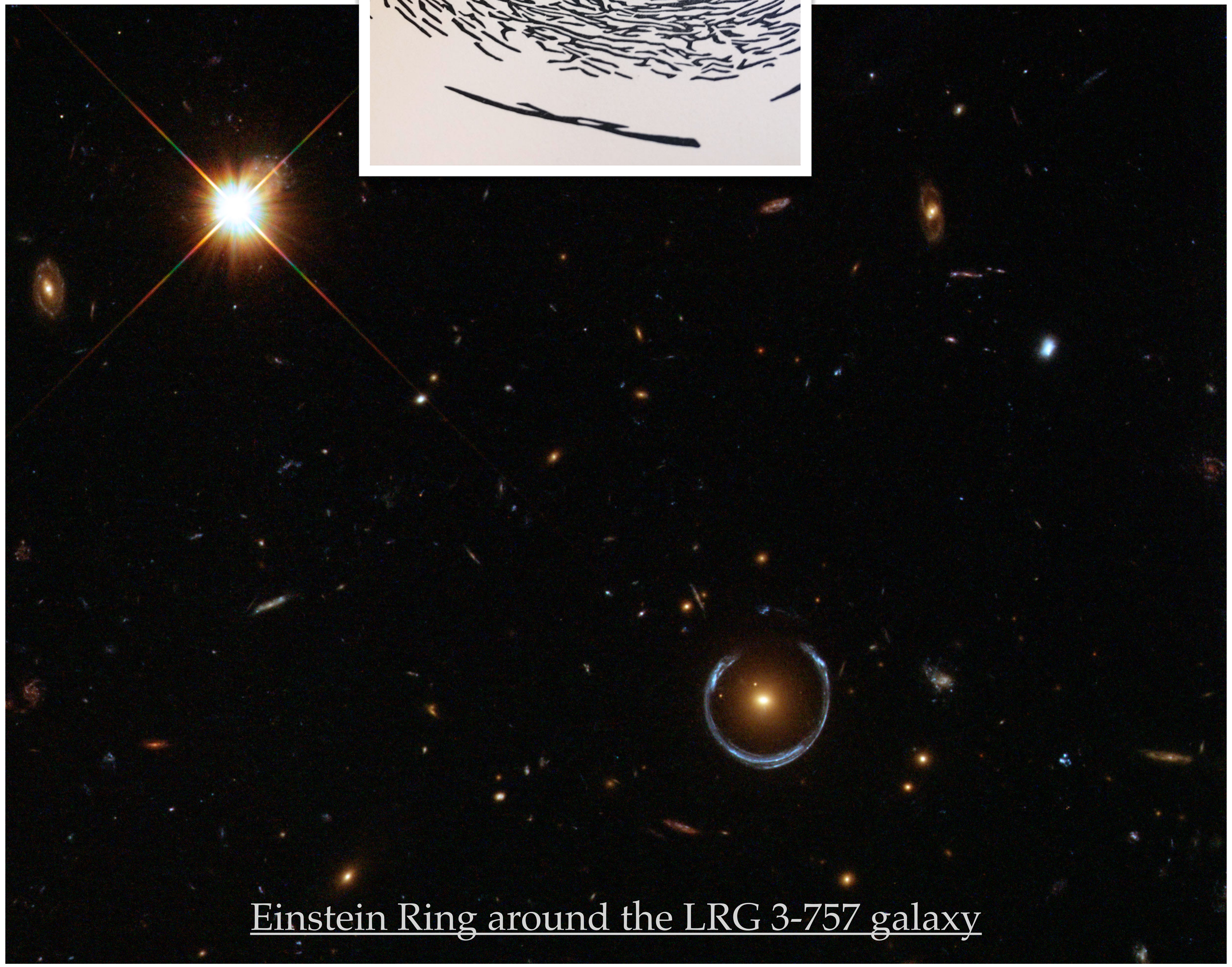




Einstein Ring around the LRG 3-757 galaxy

More evidence

The Bullet Cluster — the “smoking gun” of dark matter

- Shows the potential of using gravitational lensing for reconstruction of the mass distributions
- Two galaxy clusters collided
150 million years ago

More evidence

The Bullet Cluster — the “smoking gun” of dark matter

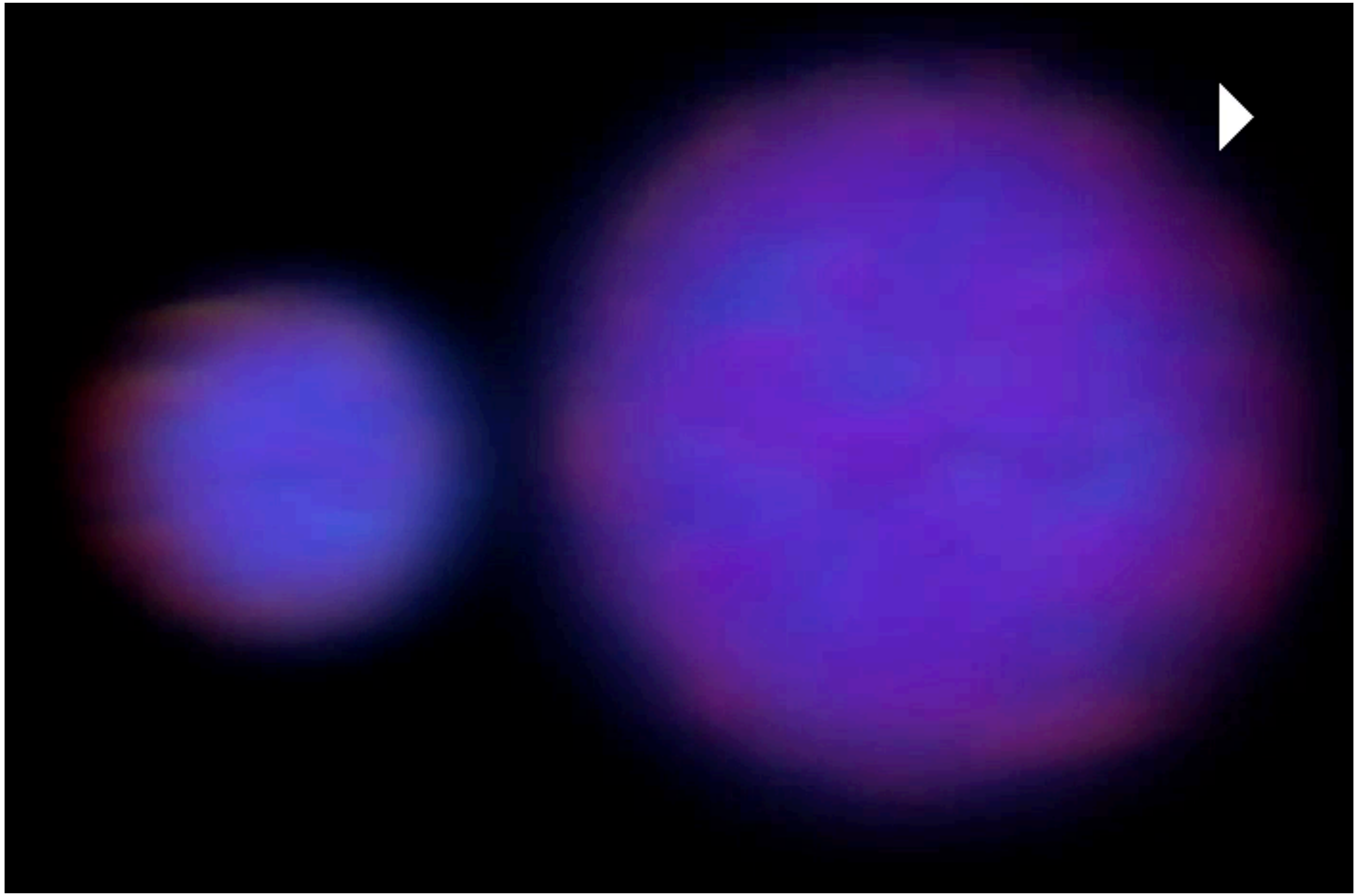
- Shows the potential of using gravitational lensing for reconstruction of the mass distributions
- Two galaxy clusters collided 150 million years ago
- While the gas clouds (red) interacted strongly and got distorted during the collision, the galaxies and the dark matter halos (blue) just passed by each other

Gas distribution (red) measured using an X-ray telescope

Mass distribution (blue) determined using the gravitational lens effect

More evidence

The Bullet Cluster



More evidence

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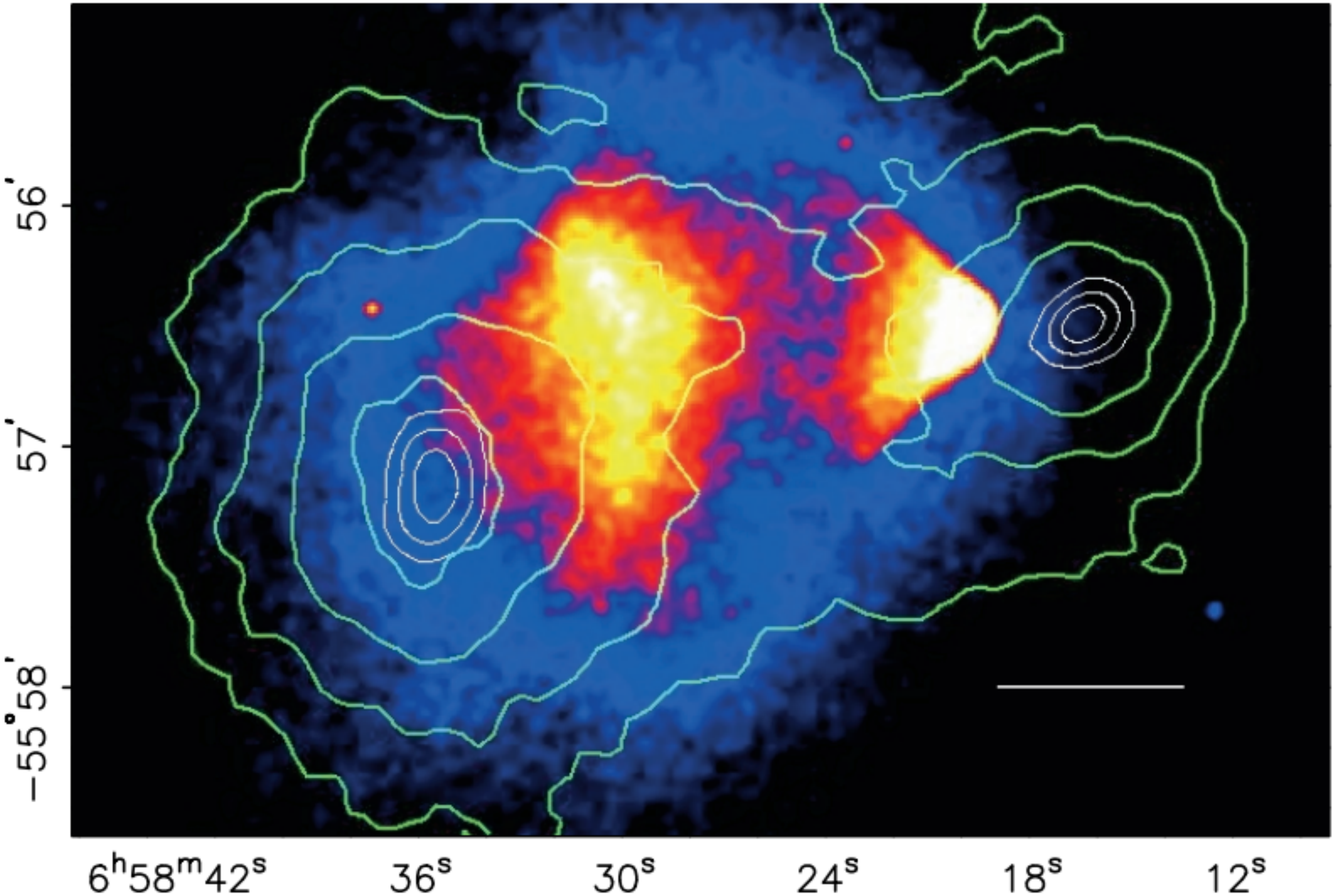

Cosmological evidence

Cosmic Background Radiation (CMB)

- 380 thousand years after the Big Bang, the temperature of the Universe gets too low for the radiation to have enough energy to ionise atoms
- Protons and electrons combine, and make the first stable hydrogen atoms
- Matter and radiation “**decouple**”
- This radiation is still visible, and is a snapshot of the Universe at that age
- As the Universe expands, the radiation gets colder (currently 2.73 K)

1948 Predicted by **George Gamow**, Ralph Alpher and Robert Herman

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1948 Predicted by **George Gamow**, Ralph Alpher and Robert Herman

Never won the Nobel Prize!

1965 Accidentally discovered by **Penzias and Wilson**

They thought it was just background noise

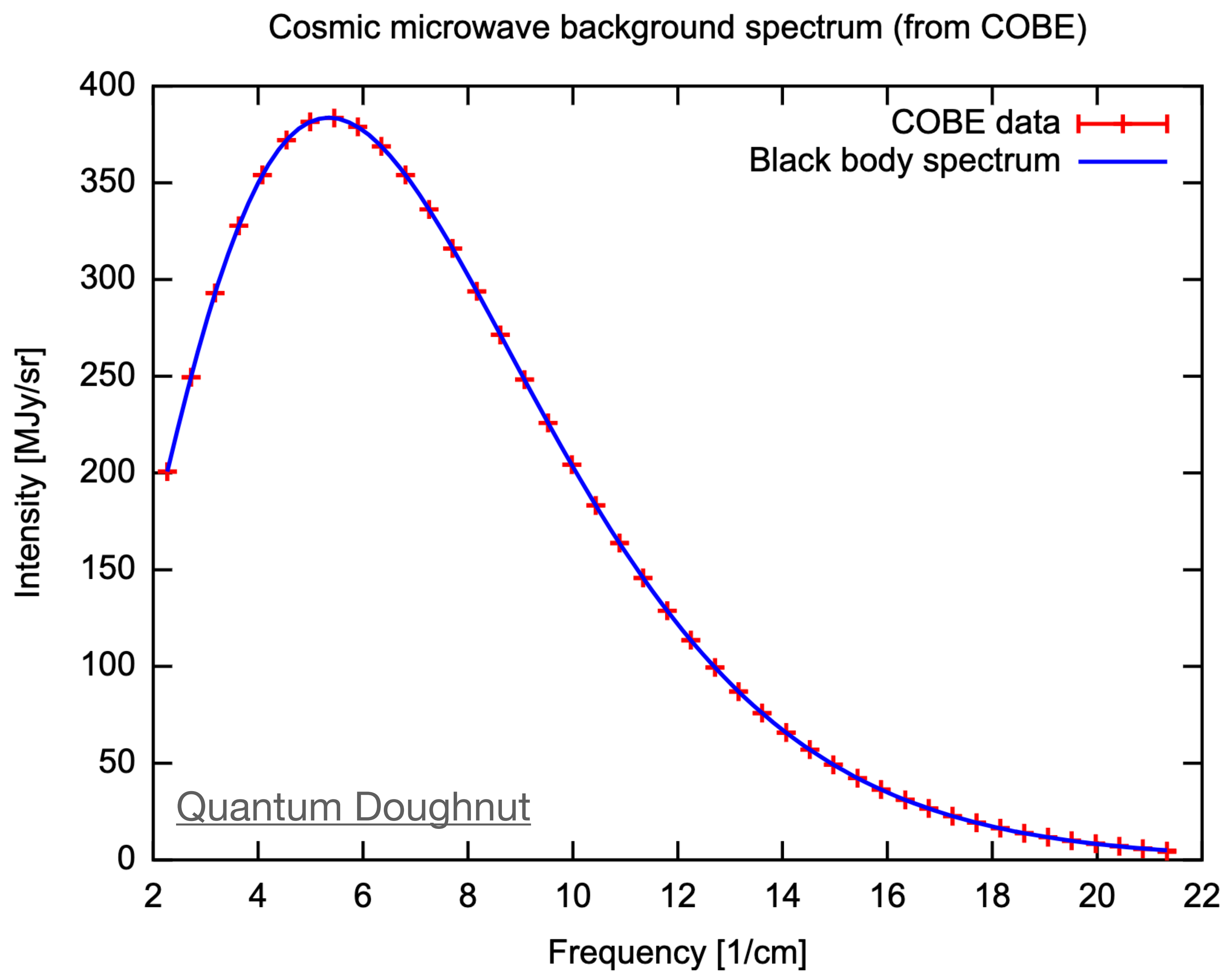
Won the Nobel Prize in 1978!

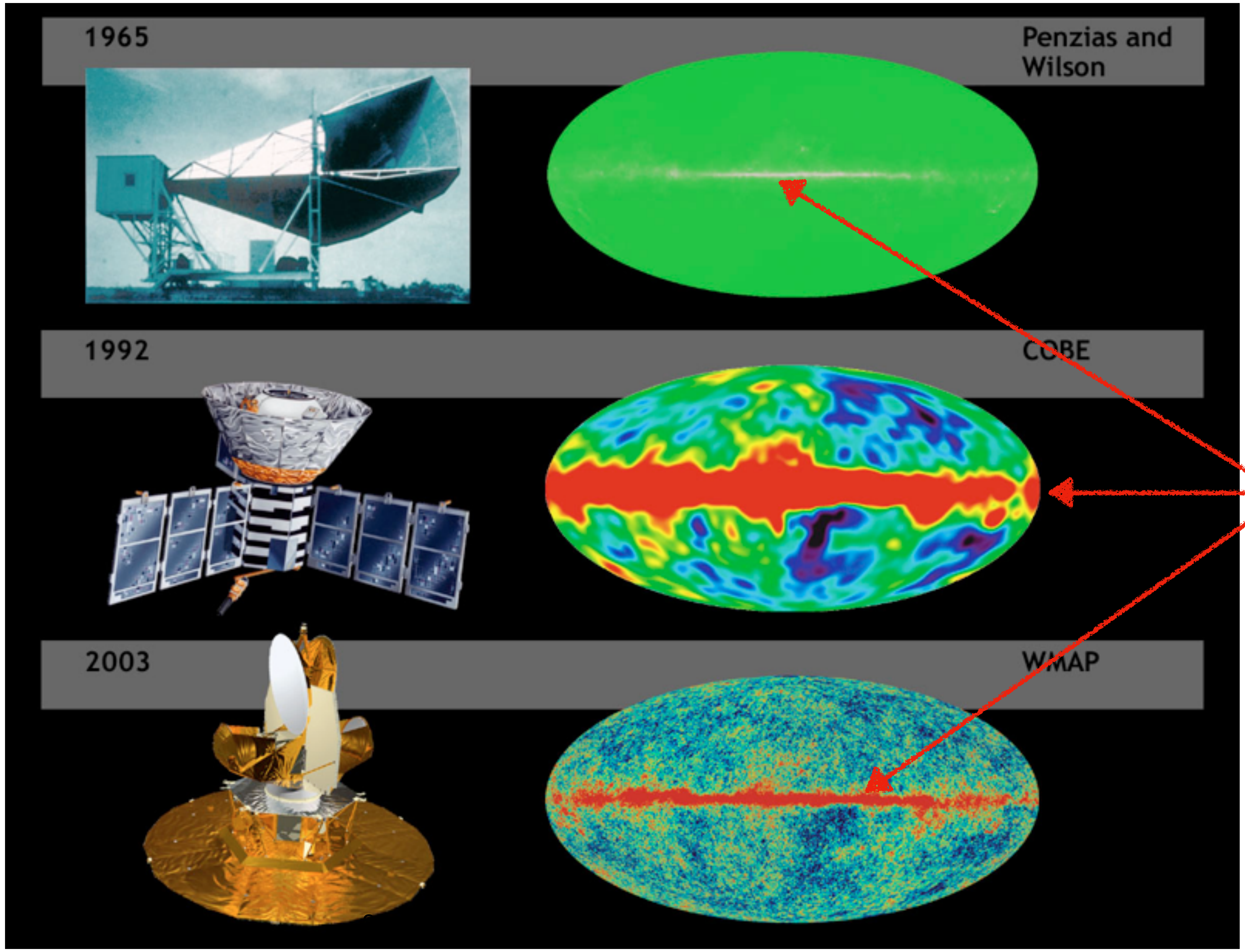
Cosmological evidence

Cosmic Background Radiation (CMB)

- Measured with increasing precision since its discovery

The most precisely measured black body radiation spectrum



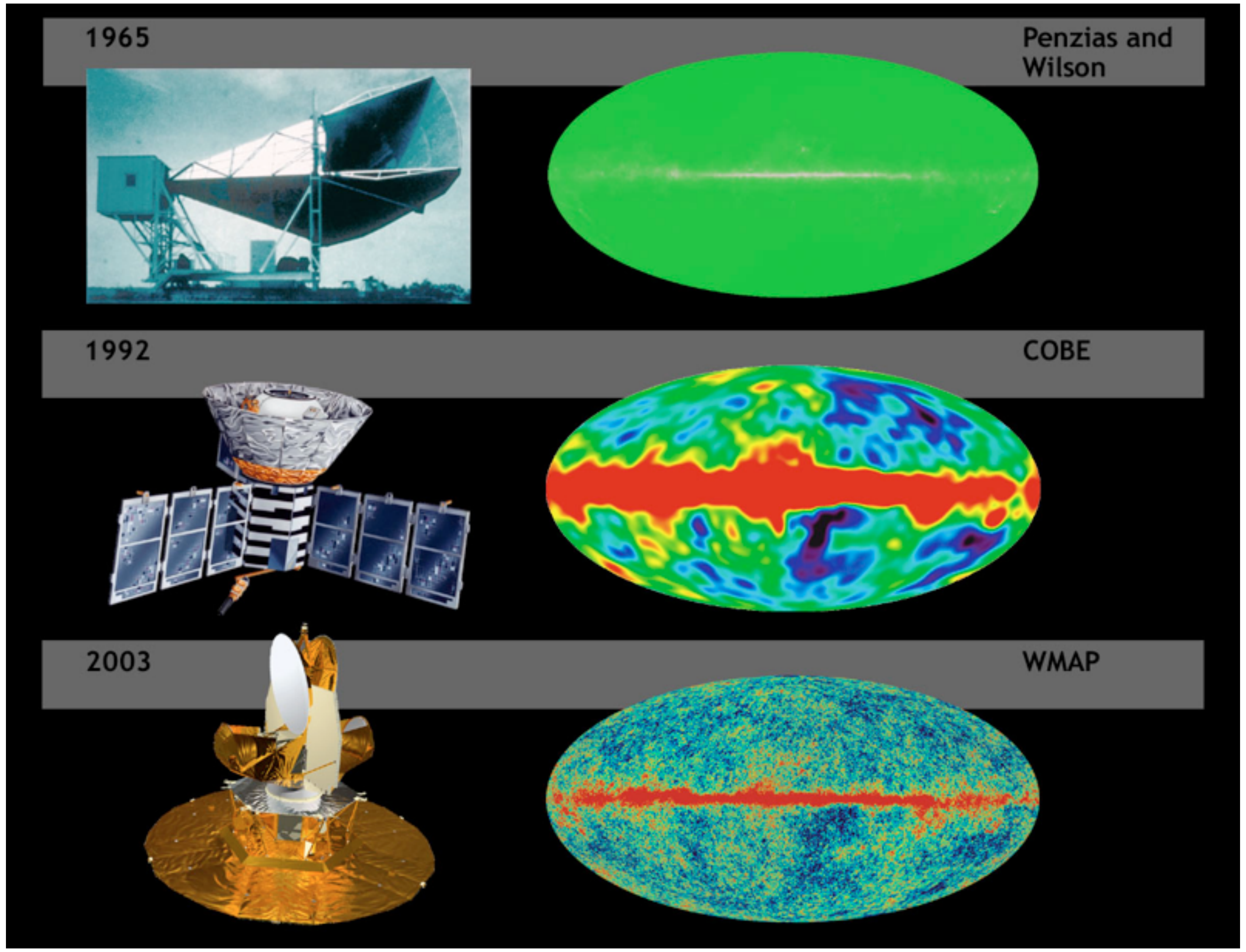


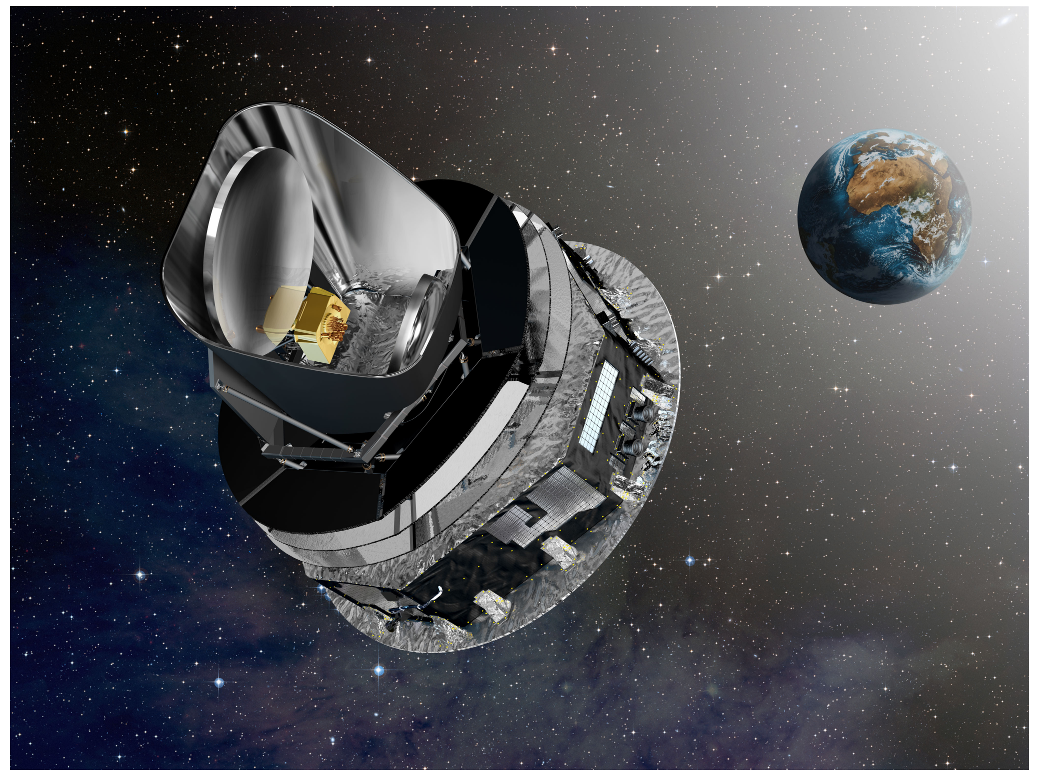
Milky Way plane “foreground”

Cosmological evidence

Cosmic Background Radiation (CMB)

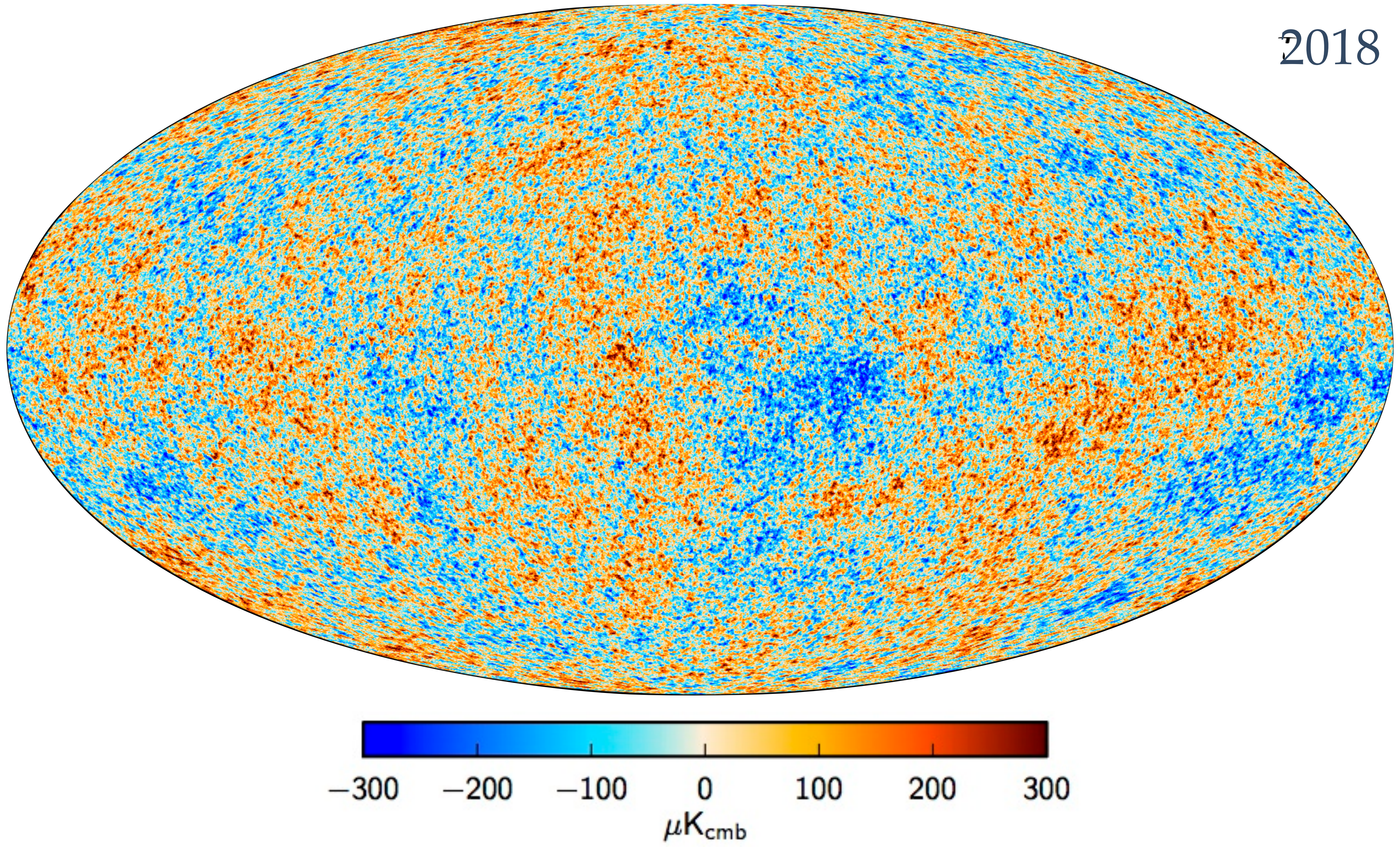
- Measured with increasing precision since its discovery
- It is not uniform as initially thought — **anisotropies**





Planck satellite:
www.esa.int/Our_Activities/Space_Science/Planck

These small anisotropies of the early universe acted as gravitational seeds for the structures observed today

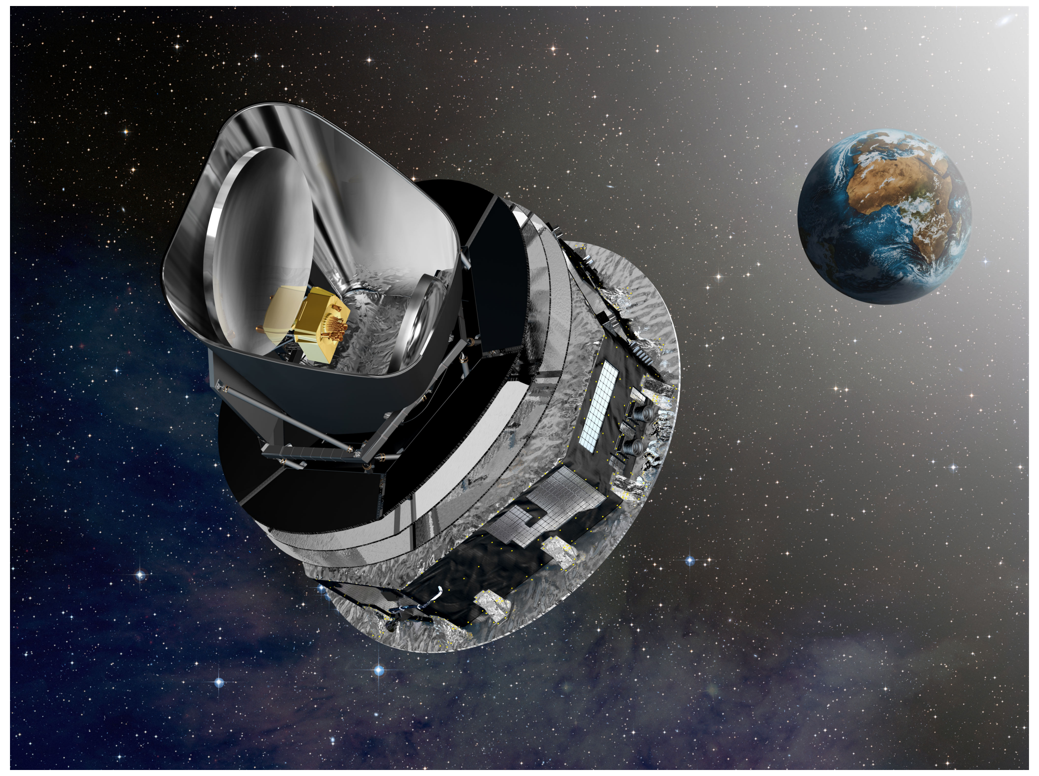


Temperature fluctuations in the **micro-Kelvin scale**

Cosmological evidence

Cosmic Background Radiation (CMB)

- Measured with increasing precision since its discovery
- Analysis of anisotropies and power spectrum consistent with Λ-CDM model, including a large fraction of Dark Matter in the Universe



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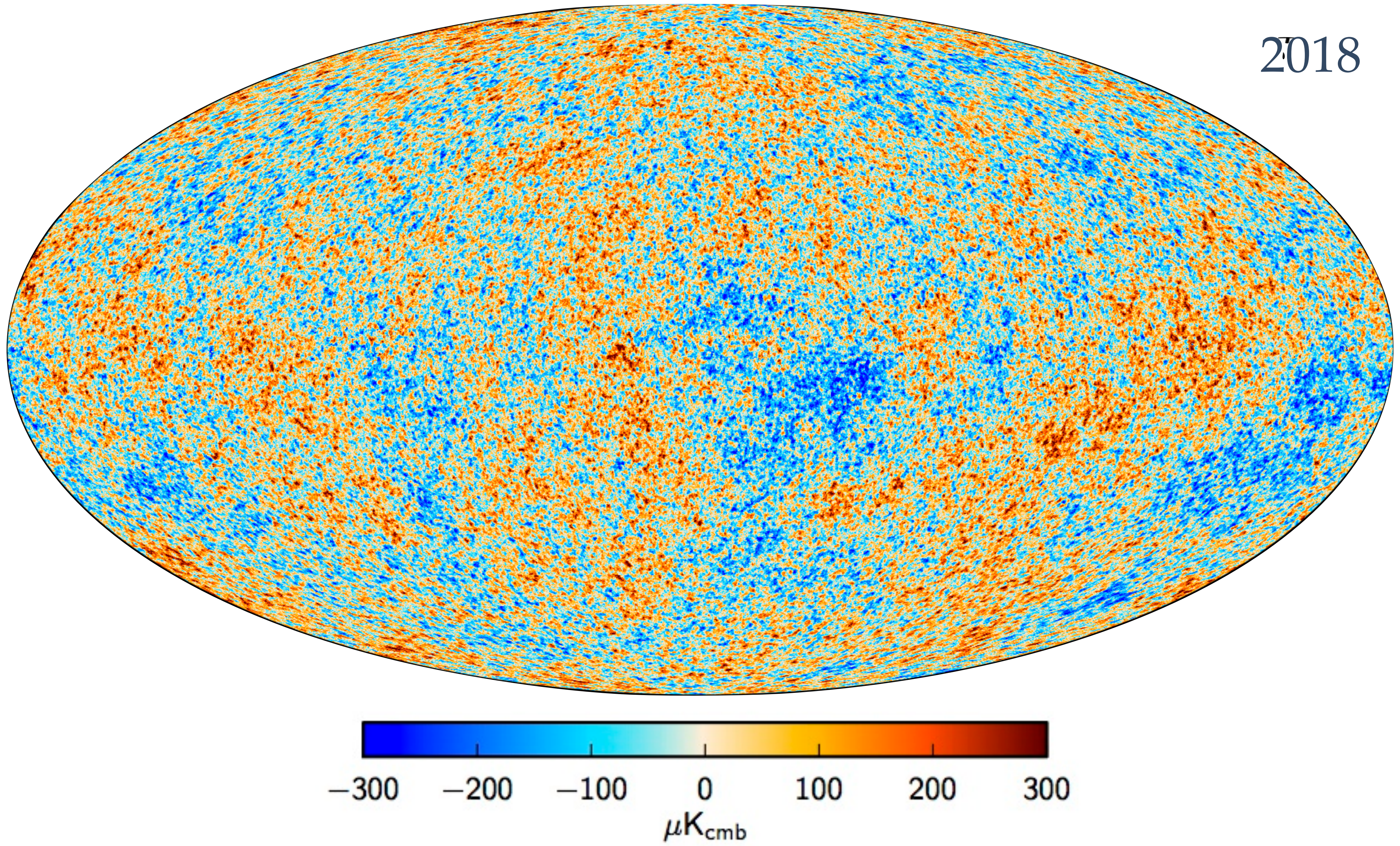

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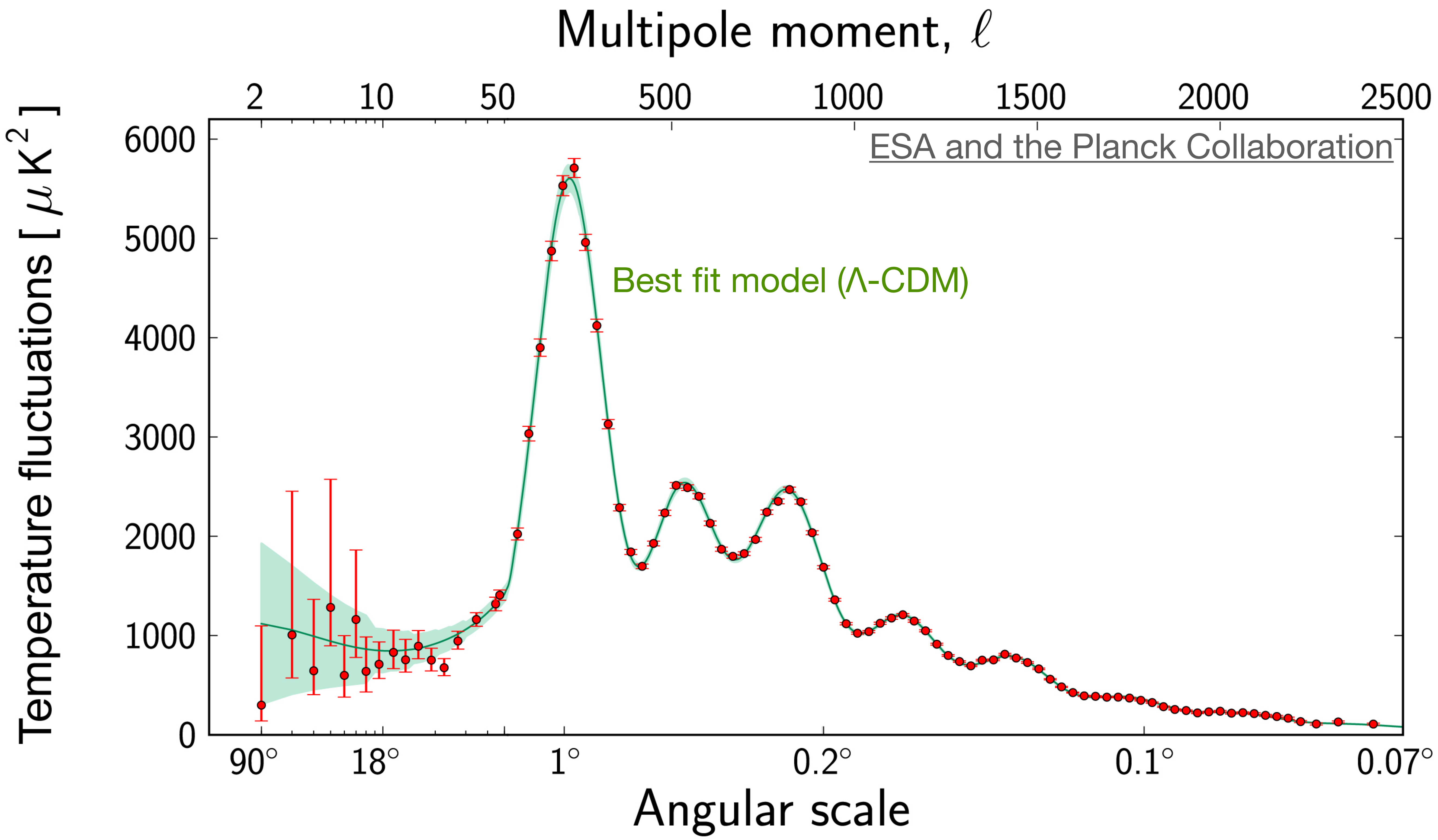
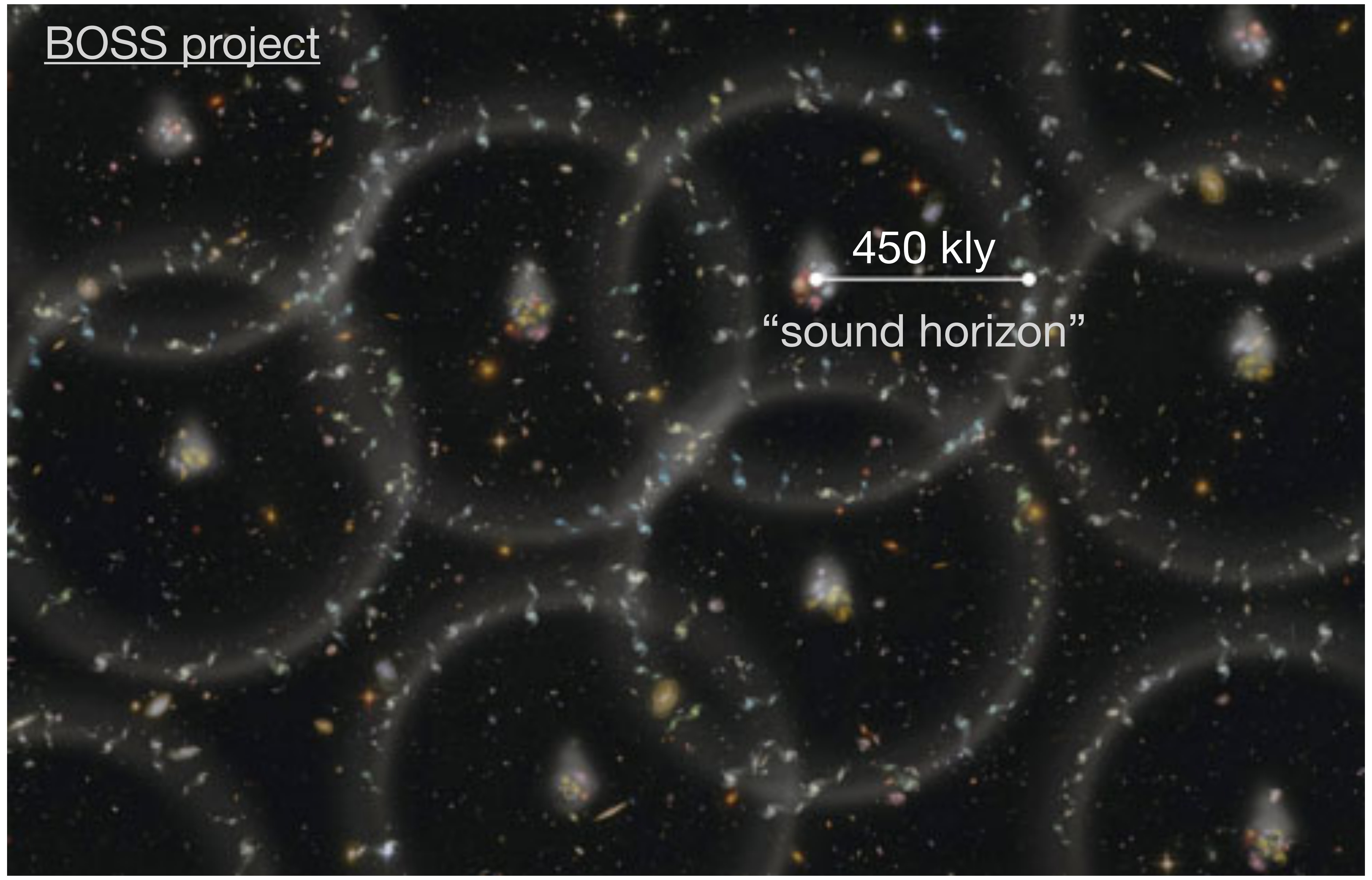


Baryon Acoustic Oscillations

A reflection of the early Universe

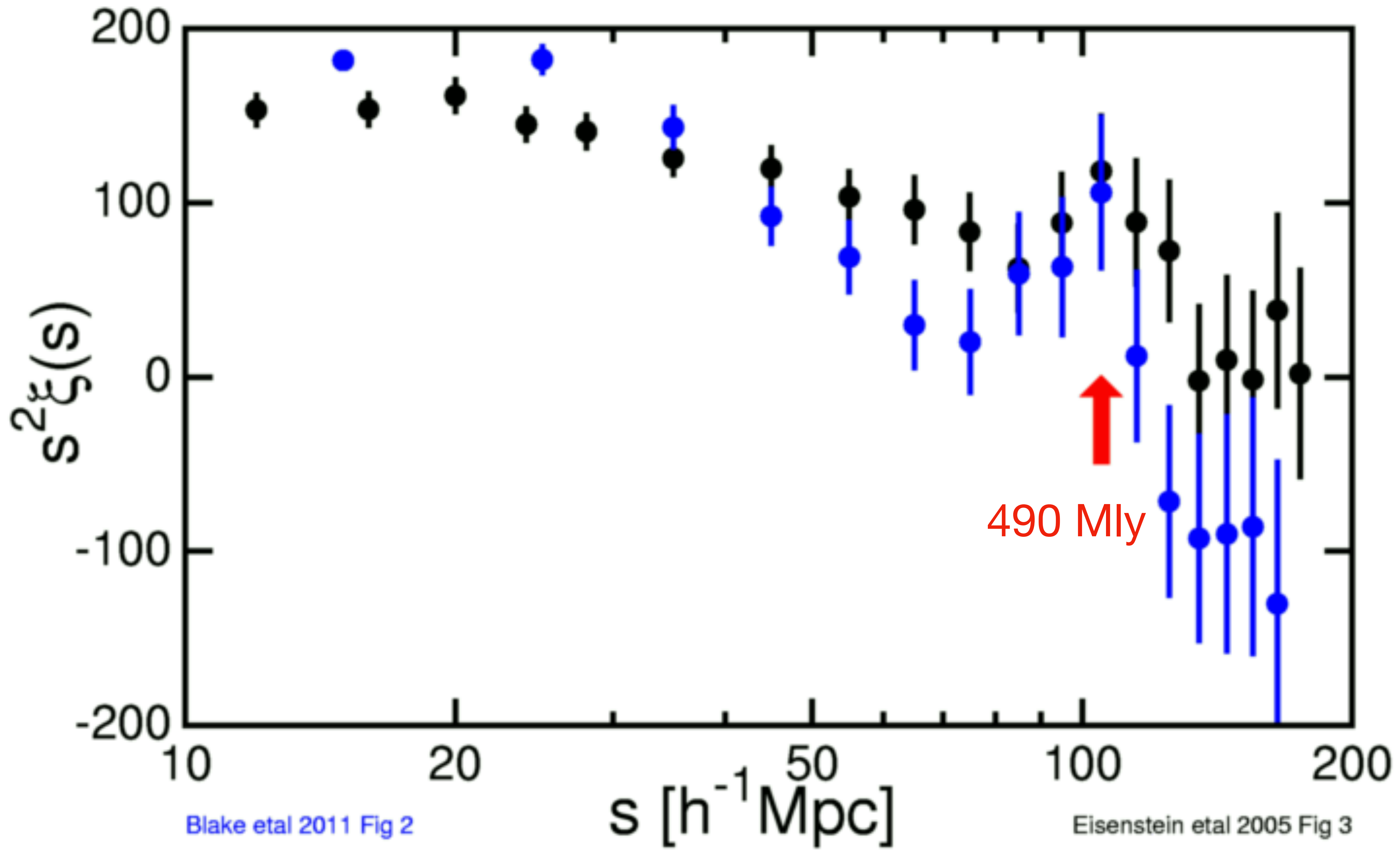


- In the plasma of the early Universe, gravity was higher in higher density regions (anisotropies)
- As particles (and light) got closer due to gravity, the temperature of baryonic matter increases and radiation creates an outward pressure wave
- This creates density waves in the baryonic matter, while dark matter remains at the center of the anisotropies
- When matter and radiation decoupled (t~380k yr) the “shells” of these waves remained imprinted in the matter distribution, creating overdensities, which later led to the formation of galaxies
- The size of these oscillations is determined by the properties of the early Universe and the abundance of its components: the normal (baryonic) matter, dark matter and dark energy.

Baryon Acoustic Oscillations

A reflection of the early Universe

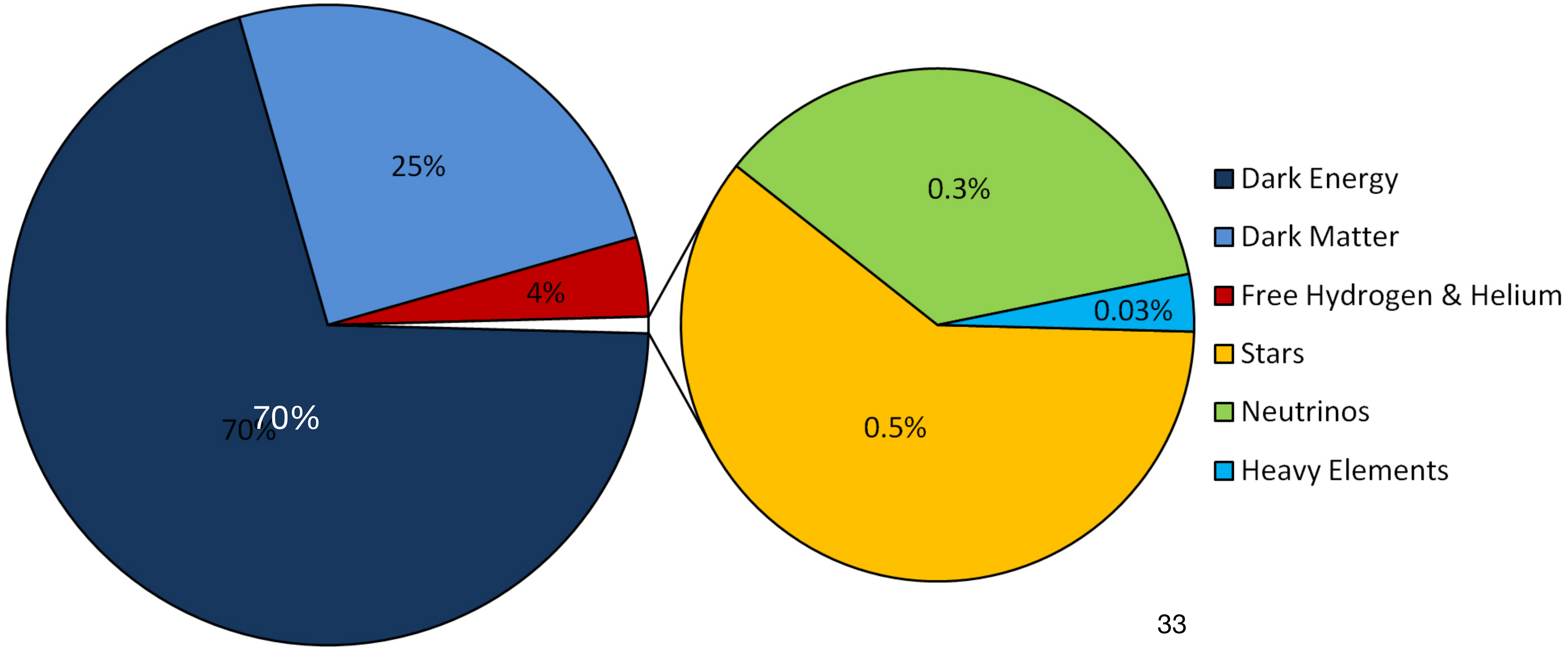
- Still visible today, as a bump in the distribution of distances between galaxies and in the CMB power spectrum



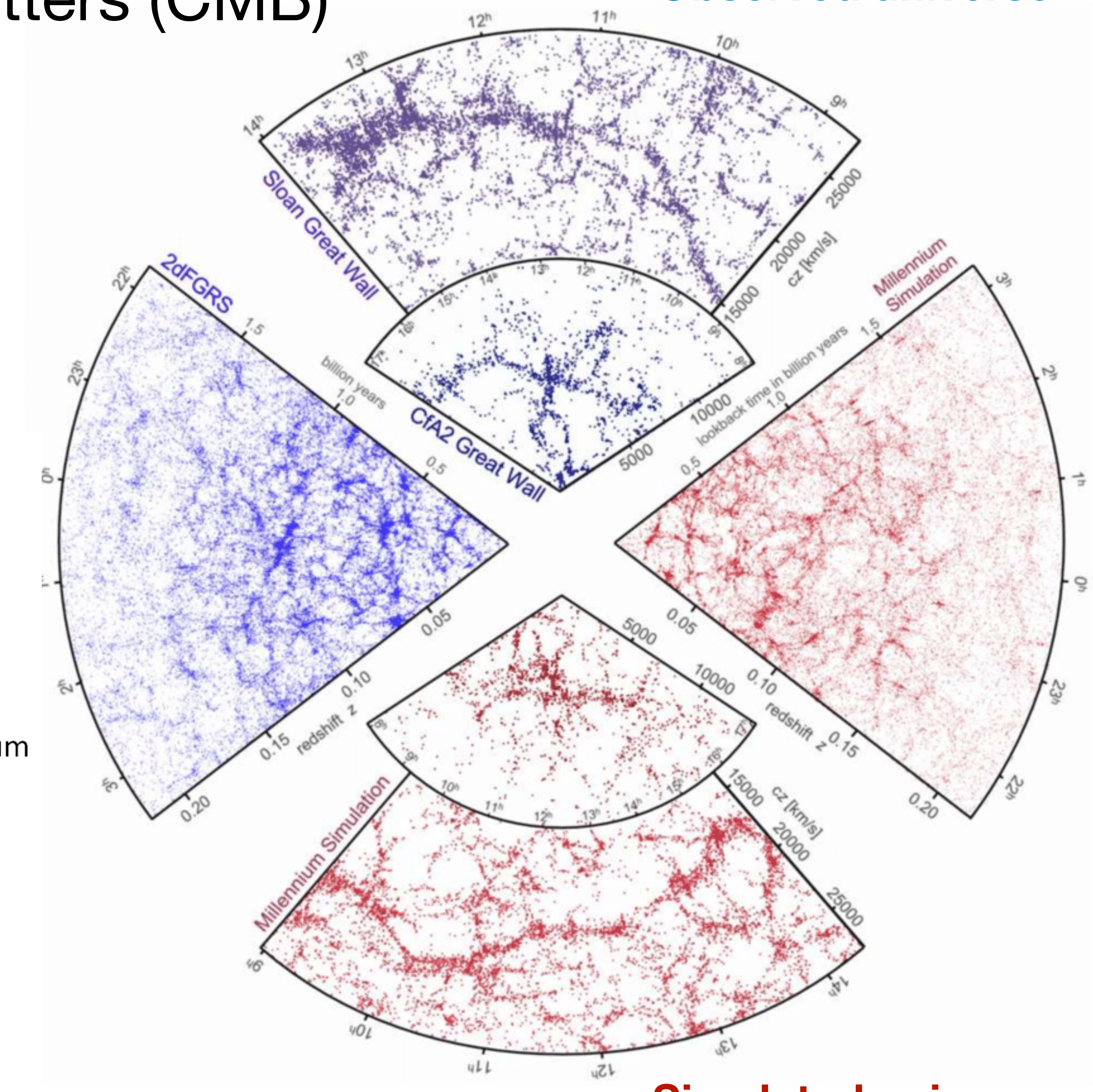
The Big Picture

The Standard Model of Cosmology (Λ-CDM) is remarkably successful

- Initial conditions photographed at the surface of last scatters (CMB)
- Left to evolve for 13.7 Gyr under two dark ‘fluids’:
  – dark energy (Λ) and (cold) dark matter (CDM)
- To produce what we see today
  – ordinary matter (almost) does not matter...



Observed universe

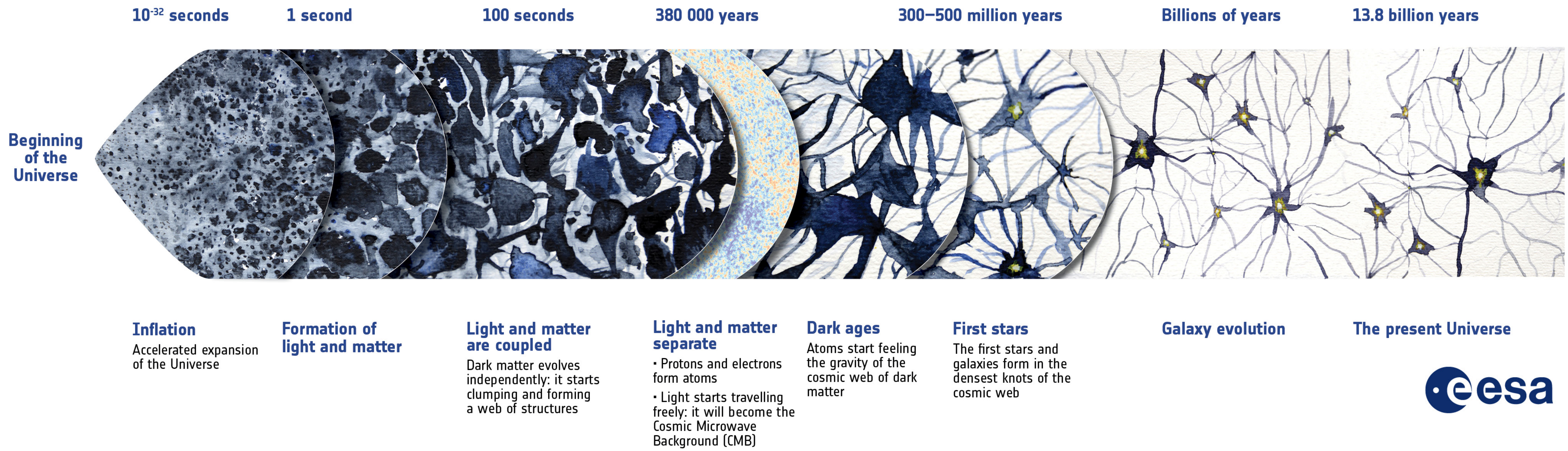


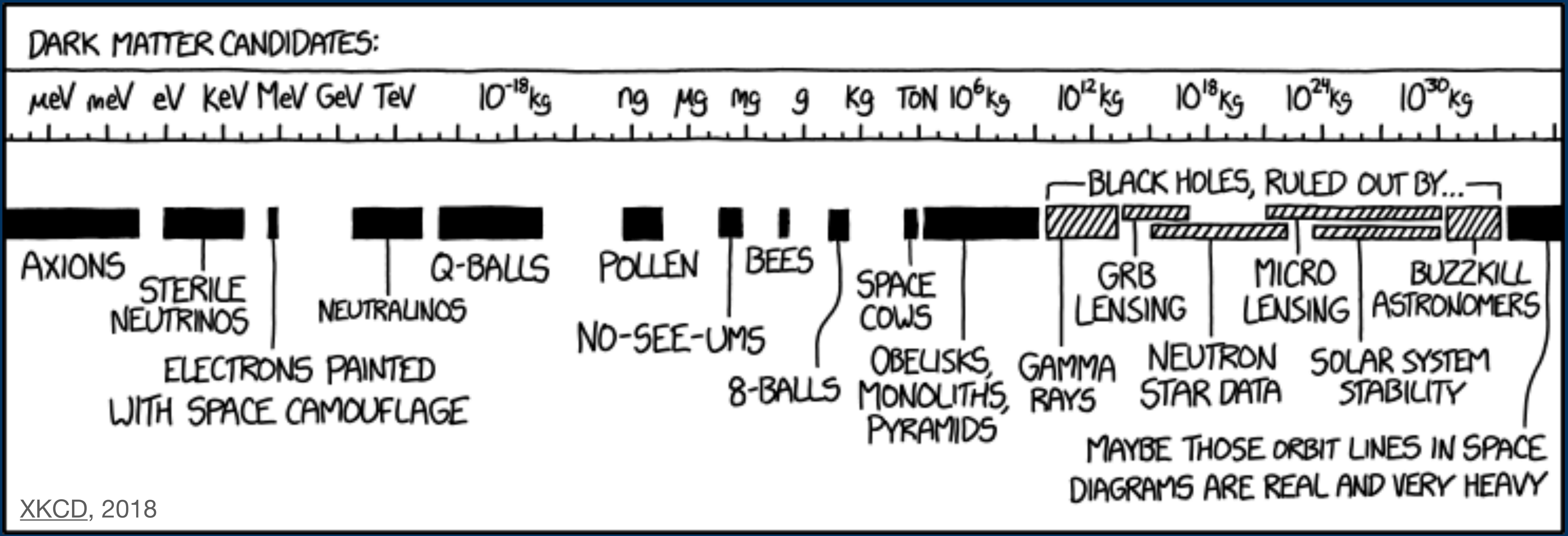
Simulated universe

The Big Picture

Plenty of evidence for dark matter at all scales

- Fluctuations in the Cosmic Microwave Background
  - Large-scale structure of galaxies and clusters
    - Motion of individual galaxies within clusters
      - How stars move within galaxies





XKCD, 2018

Dark Matter Candidates

Nothing new

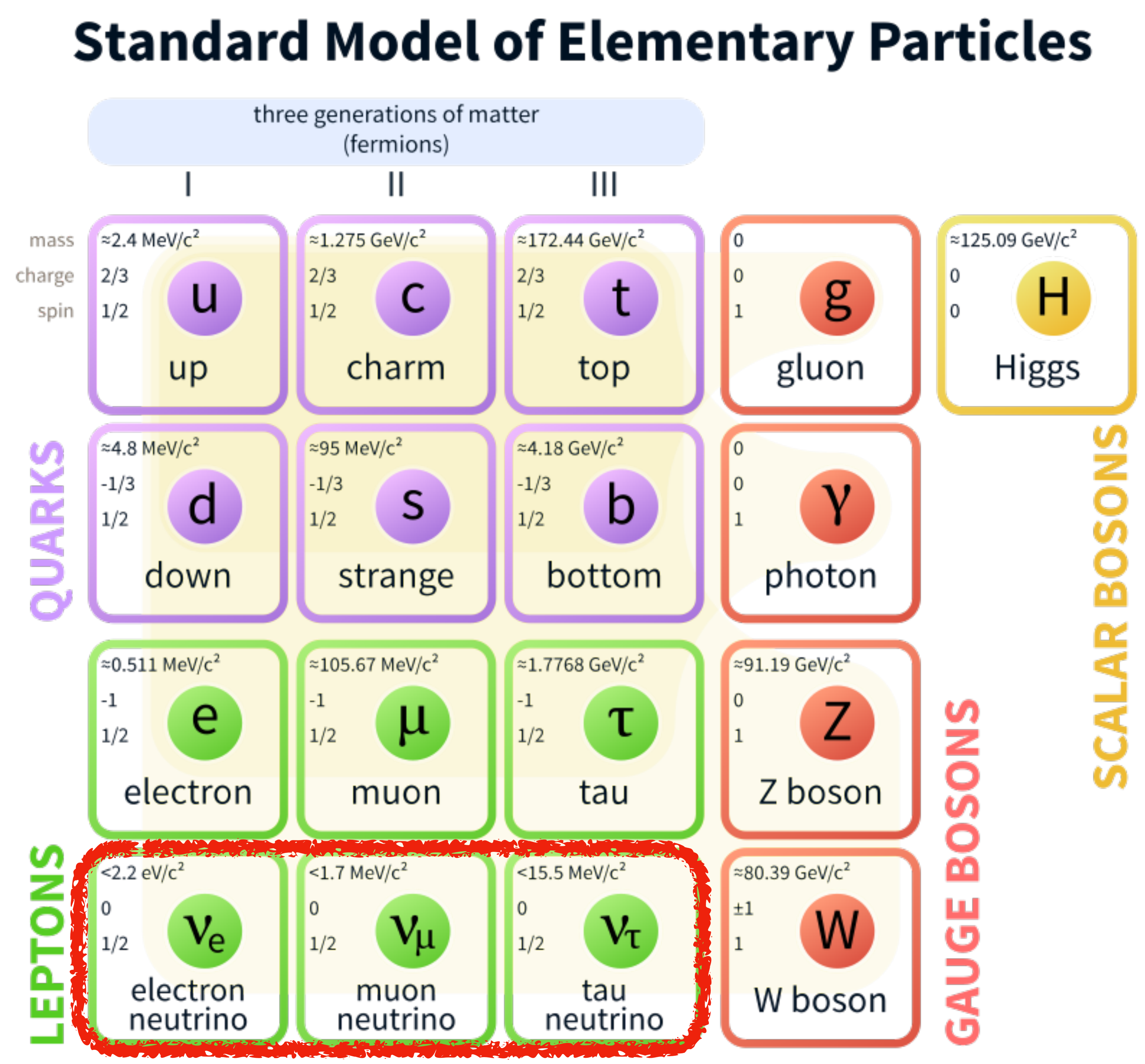
Maybe there is no “dark matter”

- Modified Newtonian Dynamics (MOND)
  - Assumes that gravity behaves differently at large distances (when the gravitational force is very small)
  - Simplest models modify the r^{-2} dependency of gravity with an additional parameter ($r^{-(2+\alpha)}$)
  - Successful at explaining galaxy rotation curves (although α is not universal, different for each galaxy) and cluster dynamics
  - Cannot properly explain gravitational lensing — in particular the Bullet Cluster —, and CMB fluctuations
- Non-luminous baryonic matter
  - MACHOs: Massive Astrophysical Compact Halo Objects
    - Planets, brown dwarfs, neutron stars, etc.
  - Dedicated surveys searched for these using the microlensing effect, with little success
  - And we know that the total amount of baryonic matter is limited by the CMB measurements!

Neutrinos

Hot Dark Matter

- Sub-atomic particles with extremely small masses
- We know there are plenty of them
- Number density: similar to photons
  - ~ 10^9 neutrinos/proton!
  - 113 neutrinos/cm^3 ! (411/cm^3 for photons)
- Probability of interaction with normal matter is very small, but known

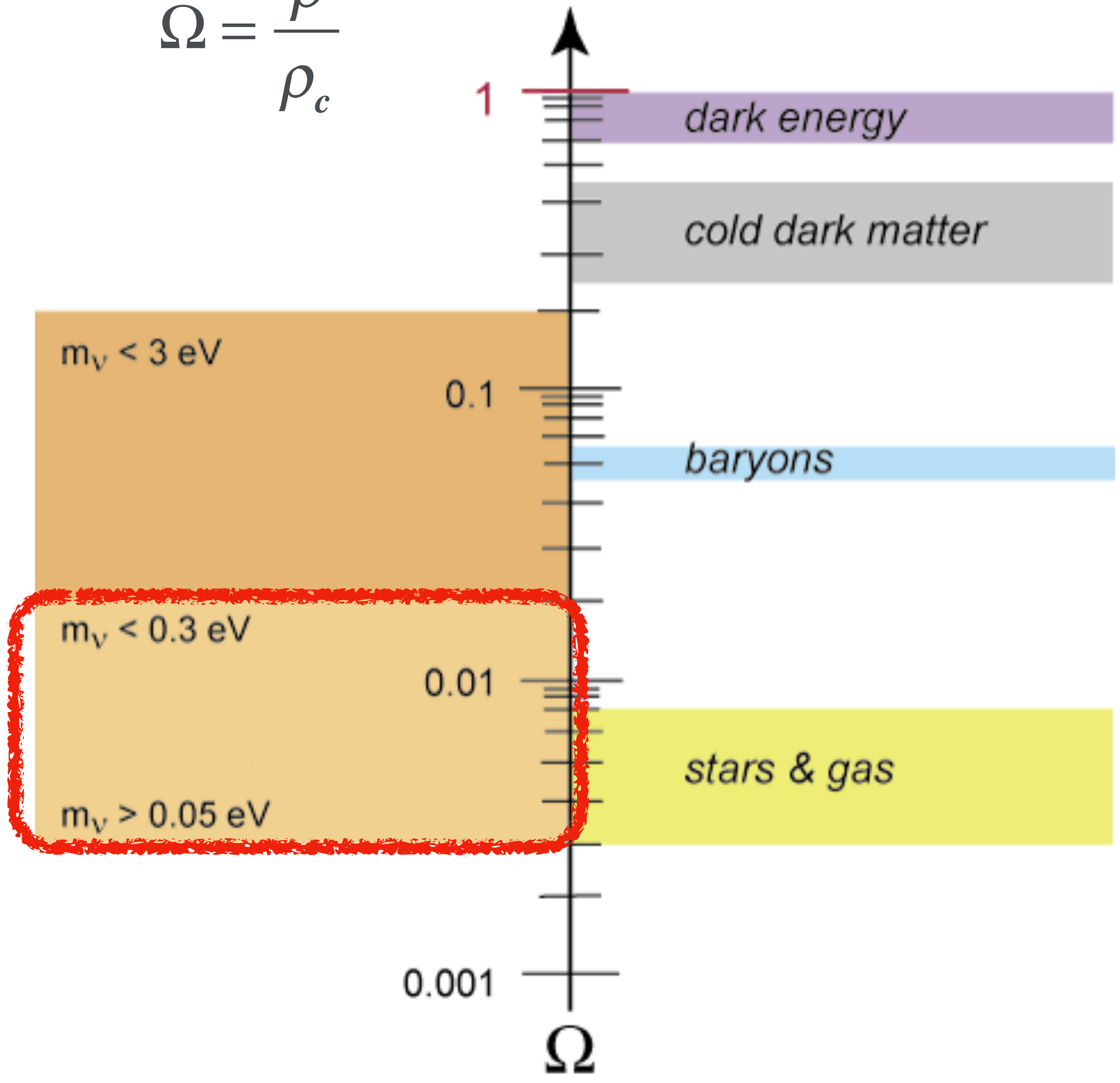


Neutrinos

Hot Dark Matter

- Neutrinos can make a small fraction of the dark matter
- Contribution depends on their mass
- We don’t know what their mass is, but existing upper limits indicate the possible extent of neutrino contribution
- Also, neutrinos are **Hot Dark Matter (HDM)**:
    - relativistic at the time of decoupling
    - would not form halos, so no galaxies or clusters would form
    - cannot reproduce the large-scale structures in the Universe

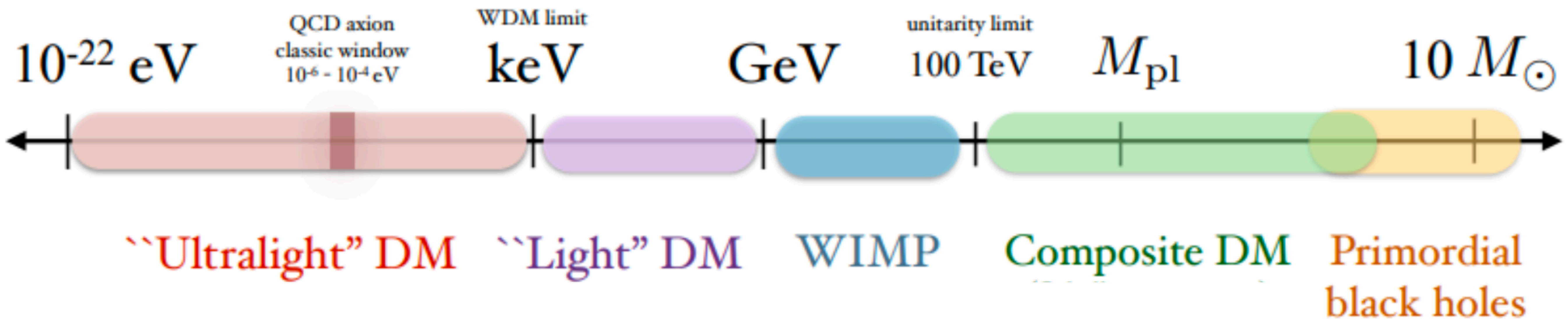
$$\Omega = \frac{\rho}{\rho_c}$$



Total density Ω in units of the critical density

Something new

- Elementary particles that may have been produced in the early Universe
- They must either be stable or very long lived ($\tau \gg t_U$)
- Many candidates!



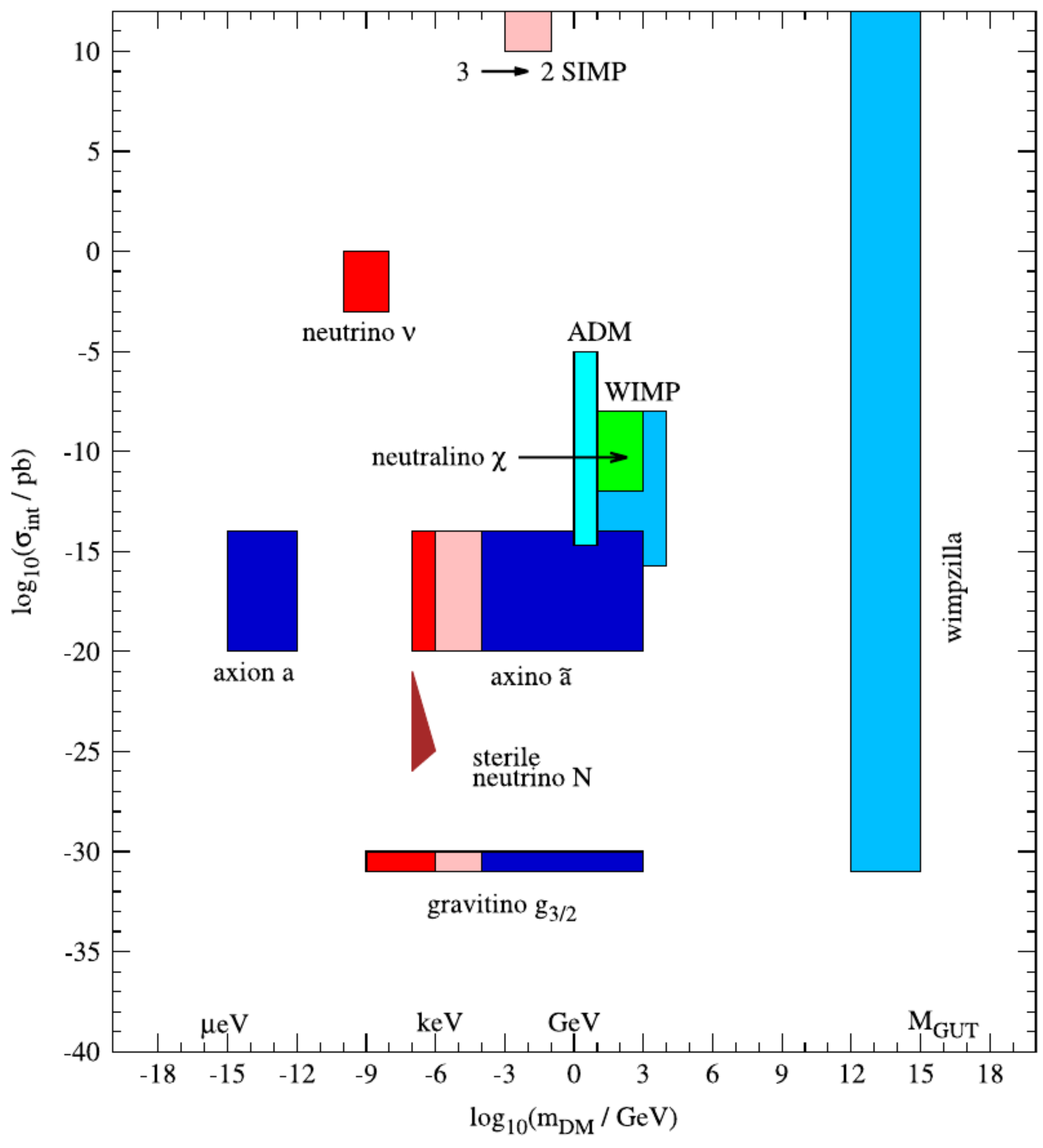
arXiv:1904.07915

- **Axions:** m ≈ 10^{-5} eV
  - light pseudo-scalar particle postulated in connection with the absence of CP violation in QCD
- **WIMPs** (Weakly Interacting Massive Particles): m ~ 1 GeV — 100 TeV
- **Superheavy dark matter:** m ~ 10^{12} - 10^{16} GeV
  - SIMPzillas, WIMPzillas, DM “nuggets", etc.

Something new

- Many candidates!
- And a lot of (phase) space to look for them!
- See reference for more details on each of these (and more) candidates

H. Baer et al. / Physics Reports 555 (2015) 1–60

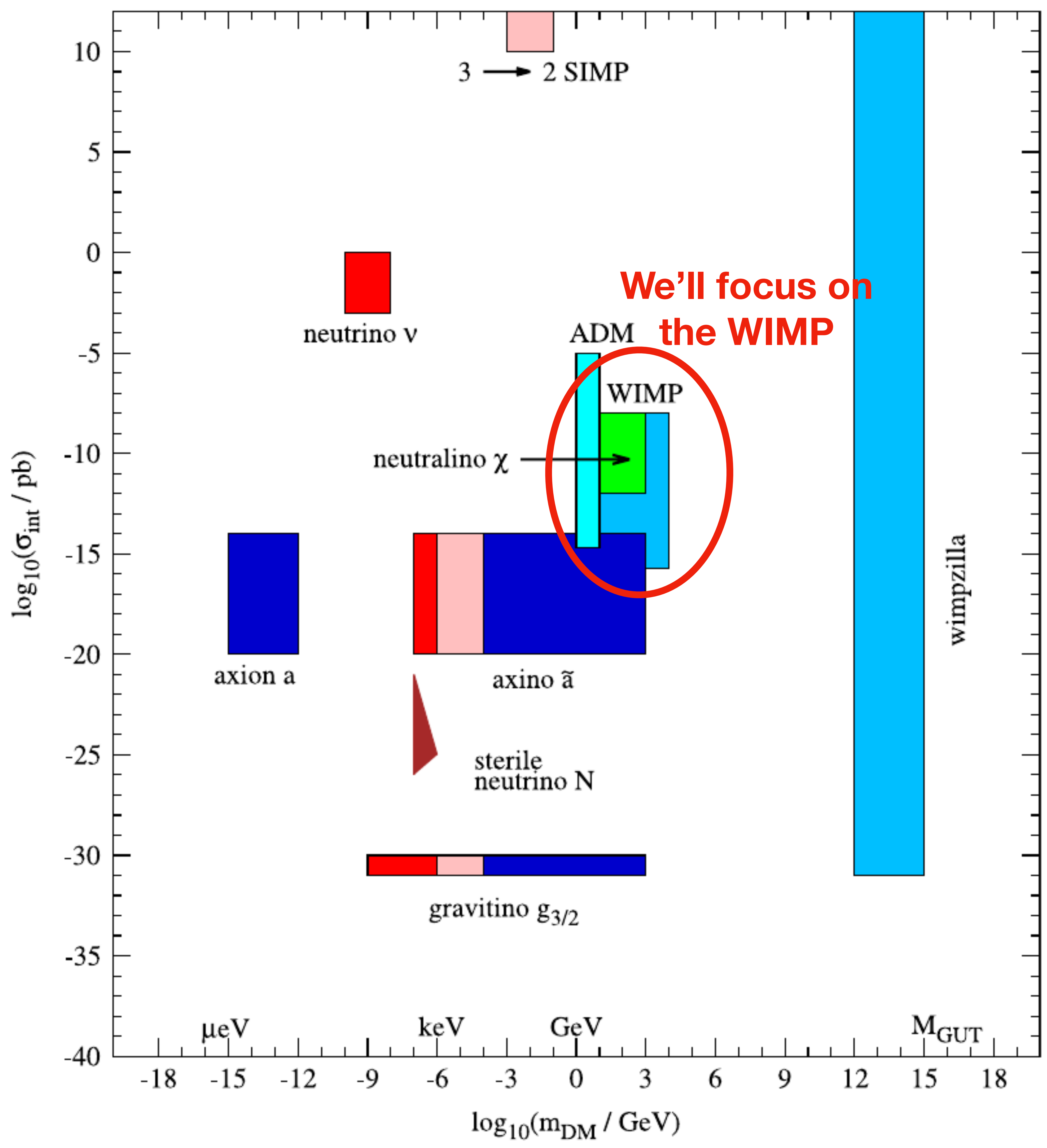


Something new

- Many candidates!
- And a lot of (phase) space to look for them!

- See reference for more details on each of these (and more) candidates

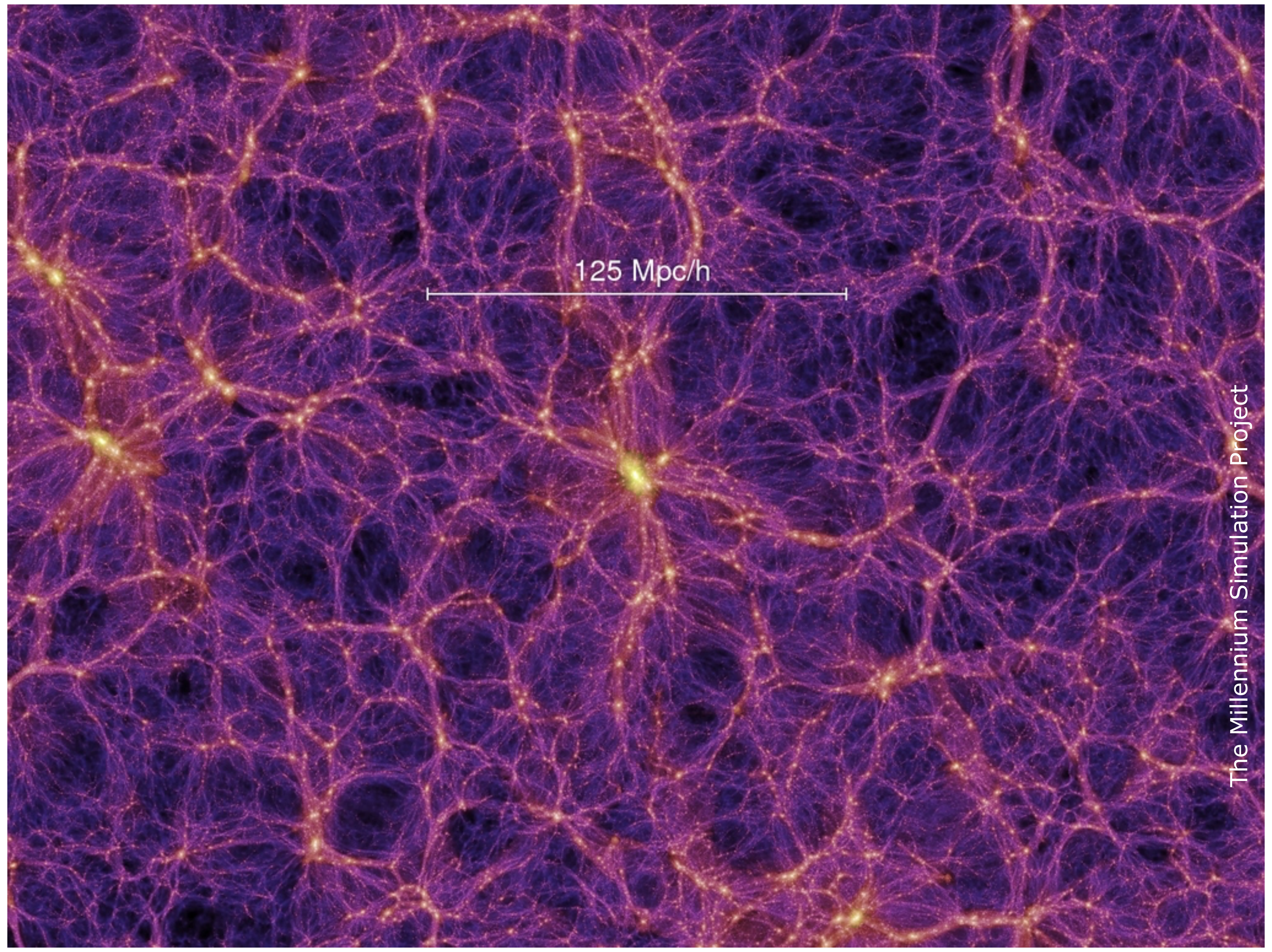
H. Baer et al. / Physics Reports 555 (2015) 1–60



WIMPs

Weakly Interacting Massive Particles

- Stable heavy particles produced in the early Universe (half-life at least comparable to the age of the universe)
- Non-baryonic (no room for more baryons)
- Slow (*i.e.* non-relativistic at freeze out)
  - **Cold Dark Matter** — required for n-body simulations to match the observed Universe
- Neutral (no electromagnetic/strong interactions)
  - Or we would have “seen” them or “found” them in nuclei
- Only feel the gravitational force and (possibly) the weak nuclear force
- Mass in the ~1 GeV — ~100 TeV range
  - Thermal production fails to explain DM abundance beyond this range
- WIMP-like candidates from supersymmetry (neutralinos), from theories with universal extra dimensions (UED) (lightest Kaluza-Klein particle), and from most other theories beyond the SM



Computer simulation of large structure formation in the Universe using Cold Dark Matter

WIMP “Miracle”

The Weak Scale

- The Fermi constant (G_F) was introduced to describe beta decay

$$n \rightarrow p + e^- + \nu$$

- Its measured value, $G_F \sim 10^{-5}\ \mathrm{GeV}^{-2}$, introduced a new mass in nature: the weak scale

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

- We still don’t understand the origin of this mass scale, but could be linked to new particles at the weak scale

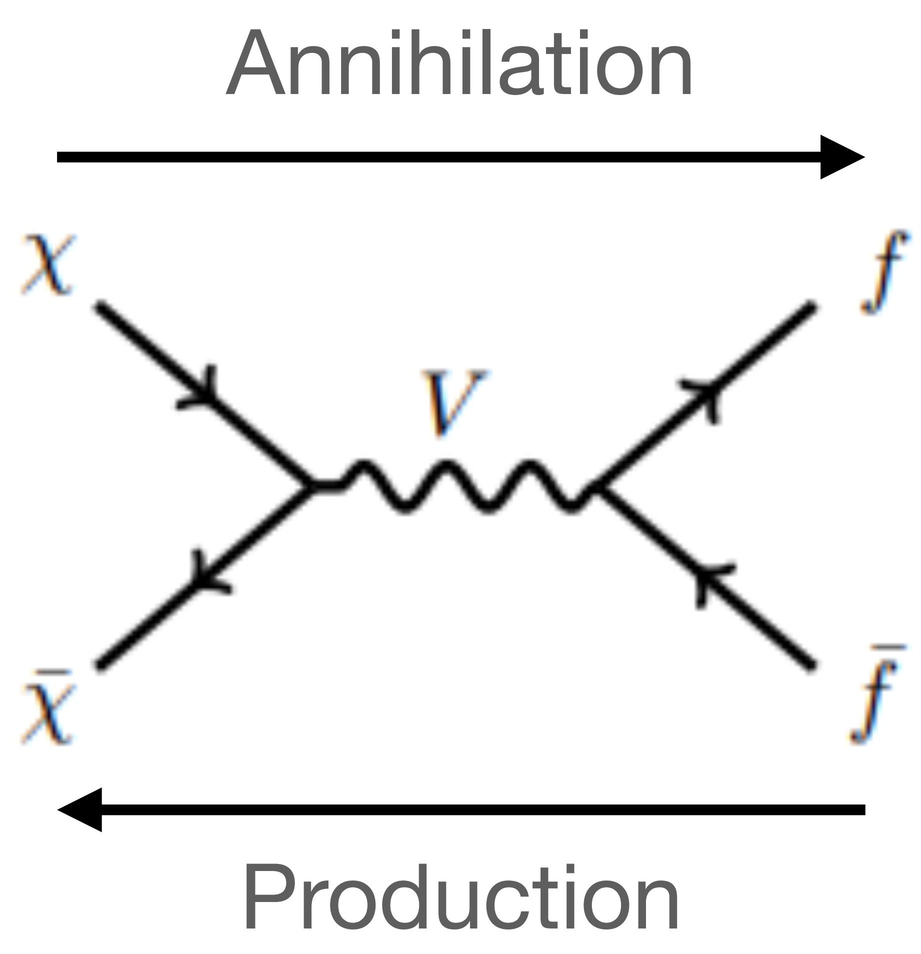
WIMP "Miracle"

Thermal freeze-out

- Local thermodynamic equilibrium in the primordial universe:
  - production rate = annihilation rate ($\boldsymbol{\Gamma}$)
- As the Universe expanded, temperature decreases
  - when the temperature drops below m_χ, no more WIMPs are created
  - their number density drops until the annihilation rate falls below the expansion rate (Hubble parameter)

$$\Gamma = n \langle \sigma_A v \rangle \leq H$$

- At this point WIMPs cease to annihilate and we are left with a relic abundance ("*freeze-out*")



n – comoving number density
σ_A – $\chi\bar{\chi}$ annihilation XS
v – relative velocity
H – Hubble parameter at freeze-out

WIMP "Miracle"

Thermal freeze-out

- If we **assume** that the unknown annihilation cross section is of the order of the **weak interaction**
  - We can write, for a non-relativistic WIMP:

$$\langle \sigma_A v \rangle \sim G_F^2 m_\chi^2$$

  - From cosmology in the radiation era (first few 10^5 years):

$$H = 1.66 \sqrt{g*} \frac{T^2}{m_{Pl}}$$

  - The freeze-out condition can thus be written as:

$$(m_\chi T)^{3/2} \exp\left(-\frac{m_\chi}{T}\right) G_F^2 m_\chi^2 = \frac{\sim 100\, T^2}{m_{Pl}}$$

  - Solving this equation numerically for m_χ/T,

$$T_f \simeq \frac{m_\chi}{20}$$ for a 1 — 100 GeV WIMP

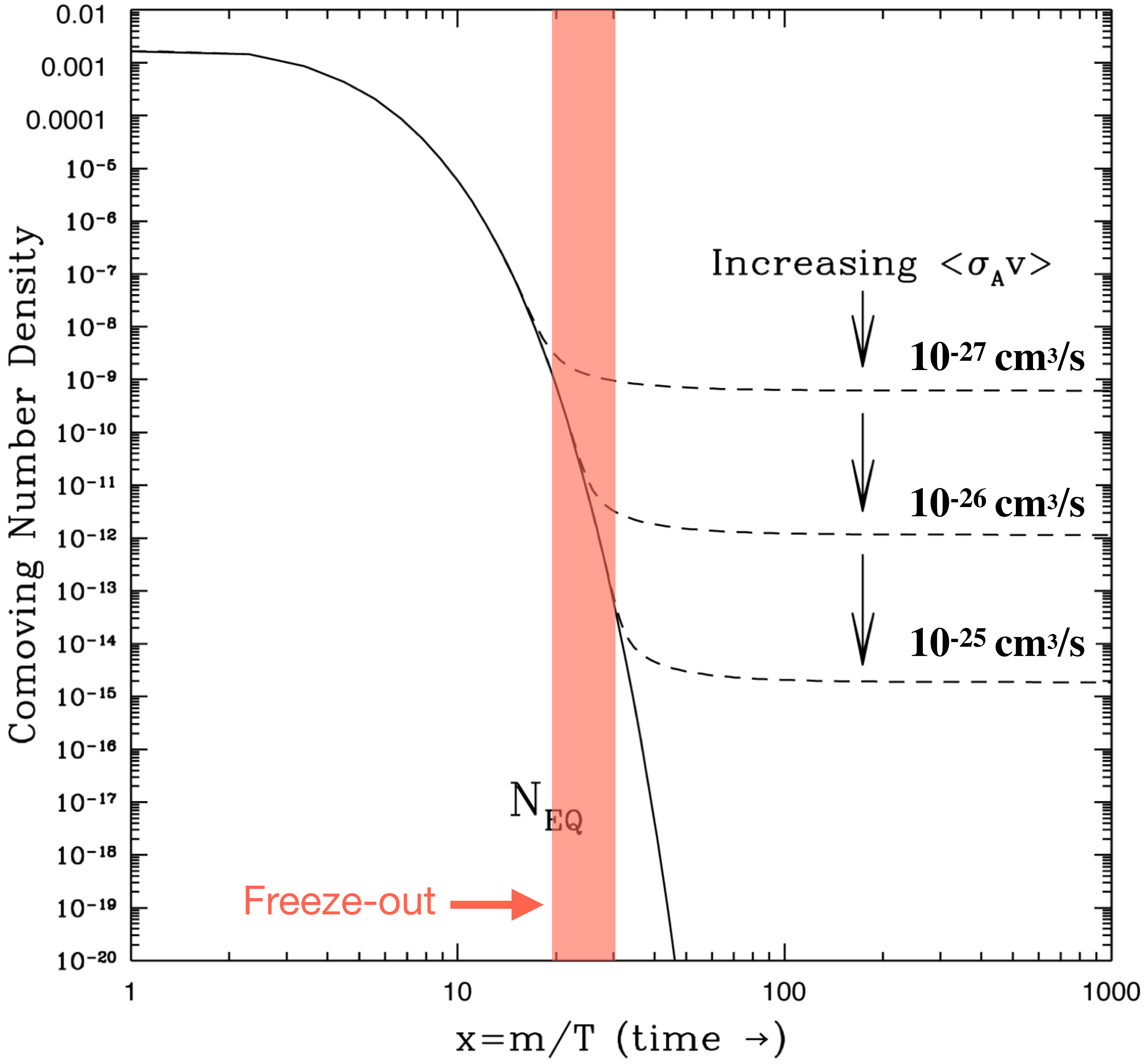
Equilibrium number density when T << m_χ
(Boltzmann equation)

$$n_\chi^{eq} \approx g \left(\frac{m_\chi T}{2\pi}\right)^{3/2} e^{-m_\chi/T}$$

n – comoving number density
σ_A – $\chi\bar{\chi}$ annihilation XS
v – relative velocity
H – Hubble parameter at freeze-out
m_χ – WIMP mass
m_{Pl} – Planck mass
T – temperature
g – internal dof of particle
$g*$ – effective relativistic dof
G_F — Fermi constant (weak interaction coupling)

See, e.g., Tongyan Lin

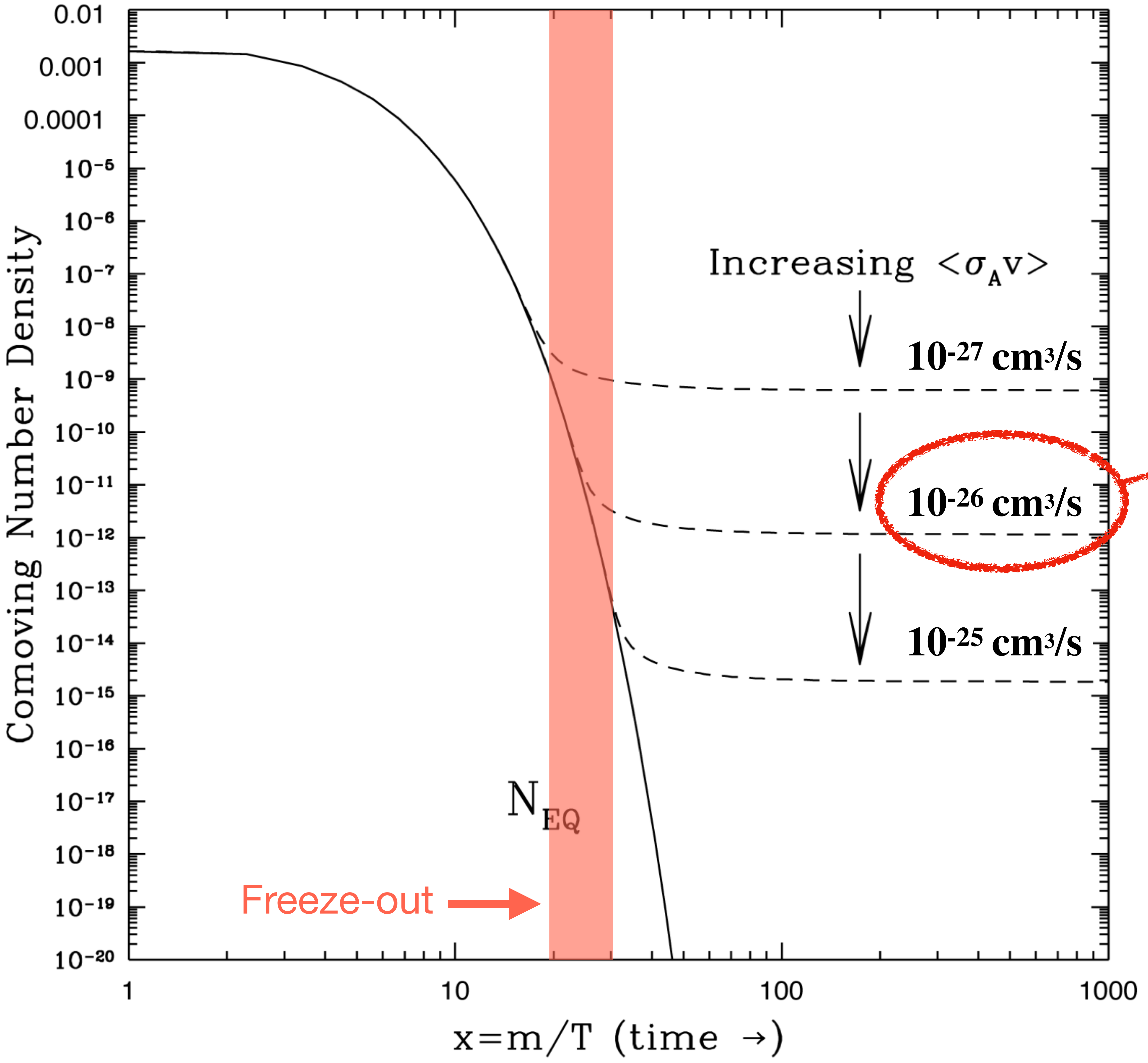
WIMP critical density



$$\Omega_\chi = \frac{\rho_\chi}{\rho_c} = \frac{m_\chi n(0)}{\rho_c}$$

$$\Omega_\chi \sim \frac{10^{-25}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma_A v \rangle}$$

WIMP critical density



$$\Omega_\chi = \frac{\rho_\chi}{\rho_c} = \frac{m_\chi n(0)}{\rho_c}$$

$$\Omega_\chi \sim \frac{10^{-25}\ \mathrm{cm^3/s}}{\langle \sigma_A v \rangle}$$

$$\langle \sigma_A v \rangle \sim 10^{-26}\ \mathrm{cm^3/s}$$

$$\boxed{\Omega_\chi \sim 0.1 - 1}$$

WIMPs are indeed enough to close the Universe

This is known as the "WIMP miracle"!

A remarkable coincidence?

- There is no *a-priori* relationship between the weak interaction (particle physics) and the closure density of the Universe (cosmology)
- The energy scales involved are staggeringly different!
  - $H \sim 10^{-42}$ GeV
  - $T_0 \sim 10^{-13}$ GeV
  - $m_\chi \sim 10^{1\text{-}3}$ GeV
  - $m_{Pl} \sim 10^{19}$ GeV
- But we conclude that if there is a new stable particle associated with the electroweak scale, then its relic density would be enough to close the Universe!
- **That particle <u>is</u> the dark matter!**

Supersymmetry

SUSY

- Every standard model particle has a corresponding ‘sparticle’ with 1/2 spin difference
- SM fermions have bosonic SUSY superpartners, and vice-versa

Ordinary Particles		Supersymmetric Partners	
Higgs Boson (spin 0)		Higgsino (spin 1/2)	
Fermions (spin 1/2)		Bosons (spin 0)	
Quarks	Leptons	Squarks	Sleptons
Gauge Bosons (spin 1)		Gauginos (spin 1/2)	
$W^{\pm}$	Z, B gluons, photons	Winos	Zinos, Binos gluinos, photinos
charged	*neutral*	*charginos*	*neutralinos*
Graviton (spin 2)		Gravitino (spin 3/2)	

Supersymmetry

SUSY

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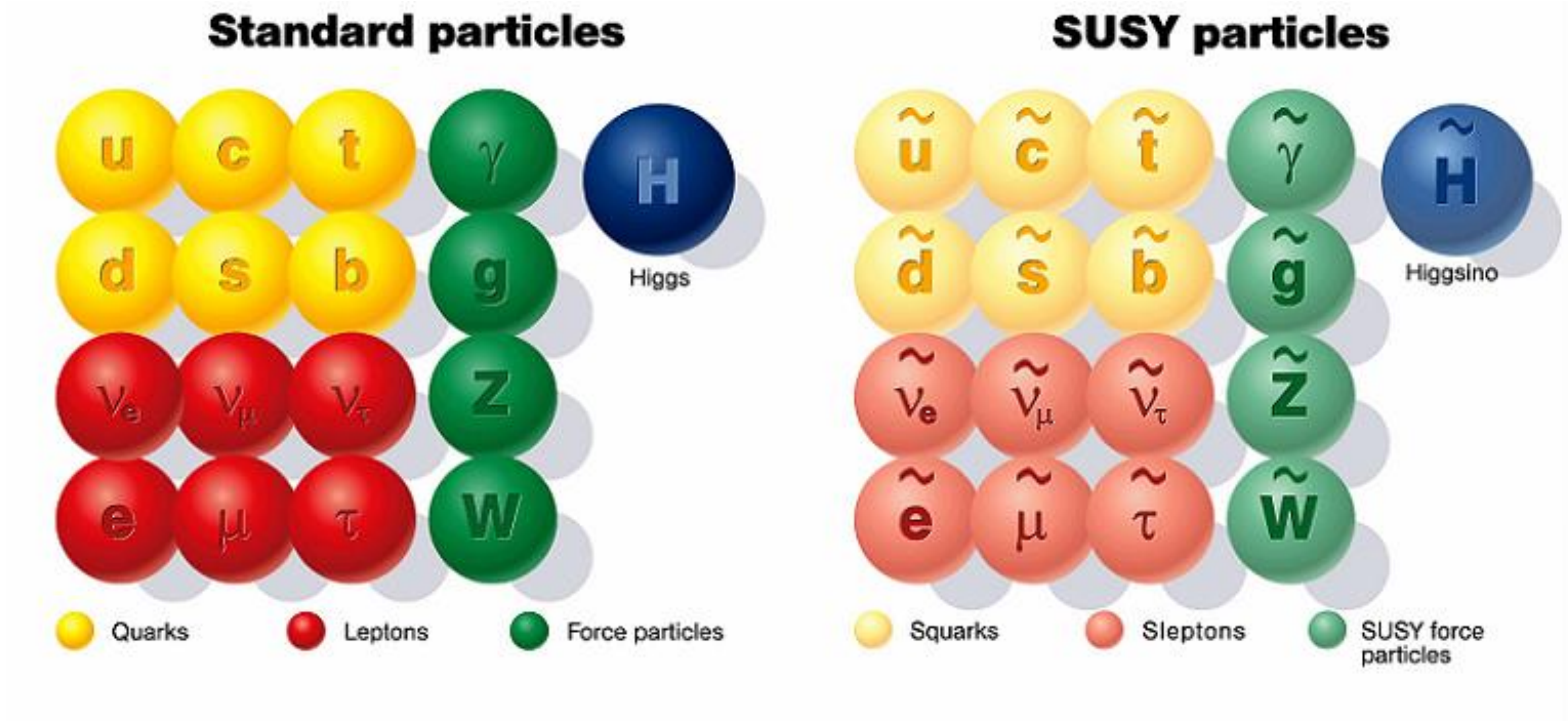


Supersymmetry

SUSY

- Introduced to
  - solve the hierarchy problem of quadratically-divergent quantum corrections to the Higgs mass
  - unification of the strong and electroweak interactions at (10^{16} GeV) GUT scale (if the super-partner masses are in the range 100 GeV - 10 TeV)
- If SUSY was an exact symmetry, squarks and sleptons would have the same mass as the quarks and leptons
  - But SUSY particles have never been observed, so the symmetry must be broken
  - SUSY models require more than 100 parameters! (Including the masses of the super-partners)
    - For practical applications, the number of parameters needs to be reduced using theoretically motivated assumptions

Supersymmetry

SUSY

- SUSY was <u>not intended</u> to solve the dark matter problem
  - But it predicts new, **stable**, elementary particles with M ~ 1 TeV
  - Which should interact **weakly** with ordinary matter
  - The **neutralinos are great WIMP candidate!**

- The super-partners of the SM gauge bosons and Higgs bosons mix into 4 fermionic eigenstates: these are **the neutralinos.** The lightest neutralino is:

$$\chi_1^0 = \alpha_1 \tilde{\boldsymbol{B}} + \alpha_2 \tilde{\boldsymbol{W}} + \alpha_3 \tilde{\boldsymbol{H}}_{\boldsymbol{u}}^0 + \alpha_4 \tilde{\boldsymbol{H}}_{\boldsymbol{d}}^0$$

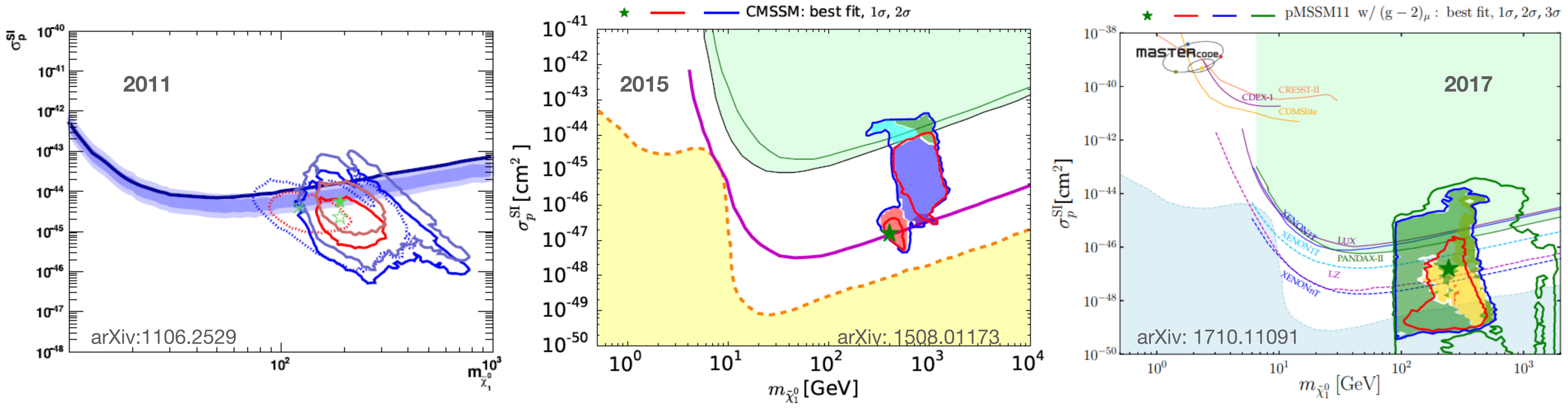
Supersymmetry

SUSY models are used to calculate neutralino properties

- They are expected to be non-relativistic
- Most relevant interactions for DM search:
  - self-annihilation and co-annihilation
  - elastic scattering off nucleons
- At low velocities, the leading annihilation channels are: (relevant for indirect searches)
  - fermion/anti-fermion pairs (e.g., e^-/e^+)
  - gauge boson pairs (e.g. photons)
  - final states containing the Higgs boson

Where are the neutralinos?

- The “canonical” WIMP has already been ruled out
- But there are always new SUSY models around the corner
- There is still a significant, well motivated, parameter space to be explored
- And remember: not all WIMPs come from SUSY!



Should we get discouraged?

- Recent WIMP search results have failed to find any evidence of their existence
- No need to get discouraged, there is still plenty of parameter space to explore
- And good reasons to extend the thermal DM paradigm to lower masses and cross sections, *e.g.*
    - Scattering with nuclei only occurs through highly suppressed loop diagrams
    - Dark matter that is lighter than a few GeV

Our Dark Milky Way

The dark Milky Way

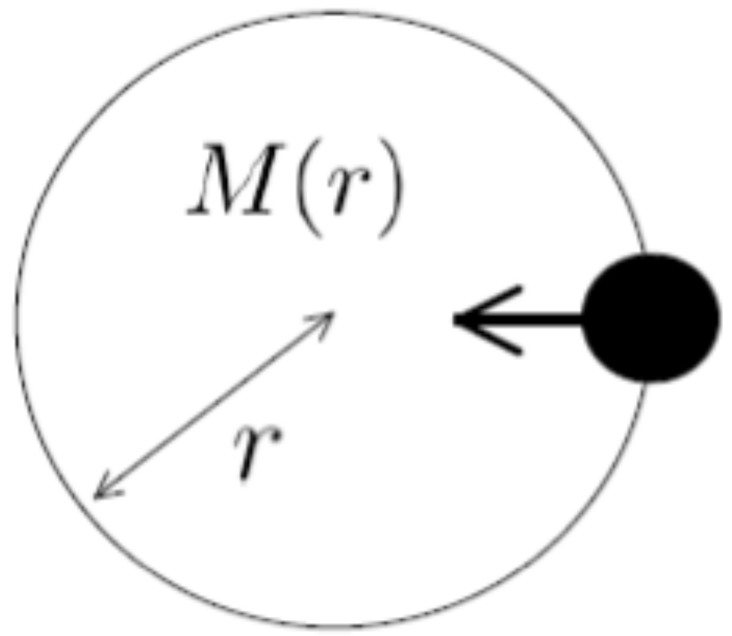
N-body simulation of a Milky Way like halo

The Aquarius Project (https://wwwmpa.mpa-garching.mpg.de/aquarius/)

Dark matter density profile

Let’s consider an isothermal smooth spherical halo (no overdensities)

- At radius *r*, the mass inside the sphere is *M(r)*



Dark matter density profile

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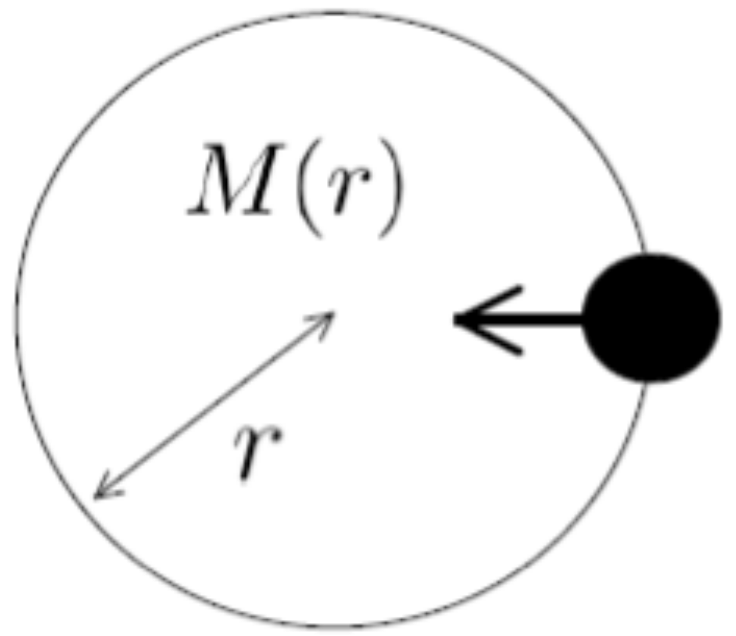


- At radius *r*, the mass inside the sphere is *M(r)*
- Using Newton's laws, an orbiting body of mass *m* will follow:

$$G\frac{M(r)m}{r^2} = \frac{mv^2}{r} \longrightarrow M(r) = \frac{v^2 r}{G} \propto r$$

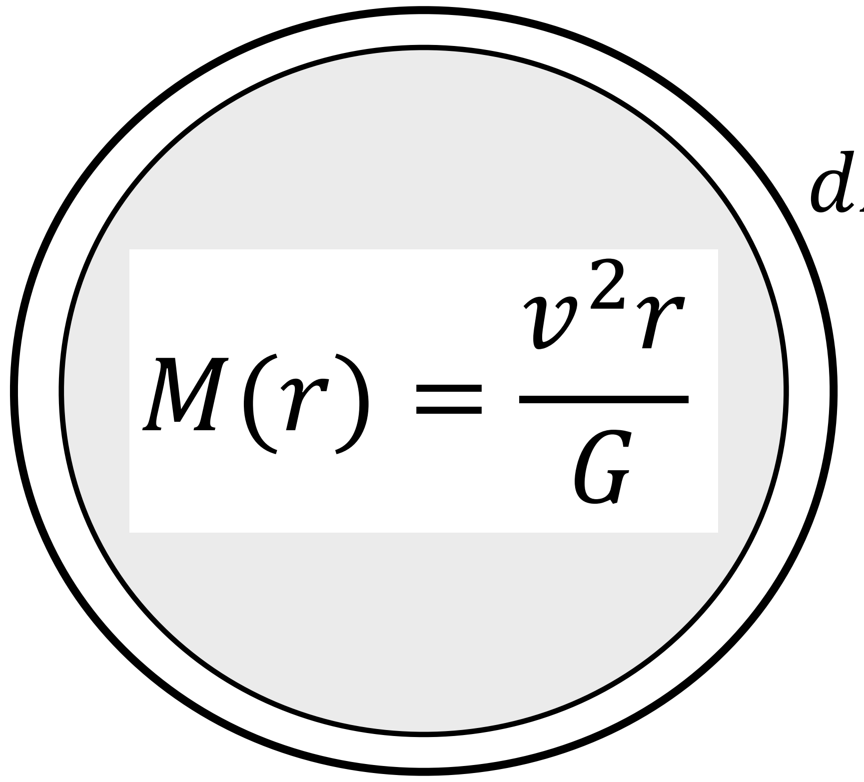
- Where *v* is the orbiting velocity at radius *r* (which we know is ~constant)
- As our halo is spherical, we can write

$$\frac{dM(r)}{dr} = \frac{v^2}{G} = 4\pi r^2 \rho(r)$$

- From where we can obtain the density distribution: $\boldsymbol{\rho(r) = \frac{v^2}{4\pi r^2 G} \propto r^{-2}}$

Dark matter velocity profile

Potential energy
contained in the halo up to radius R



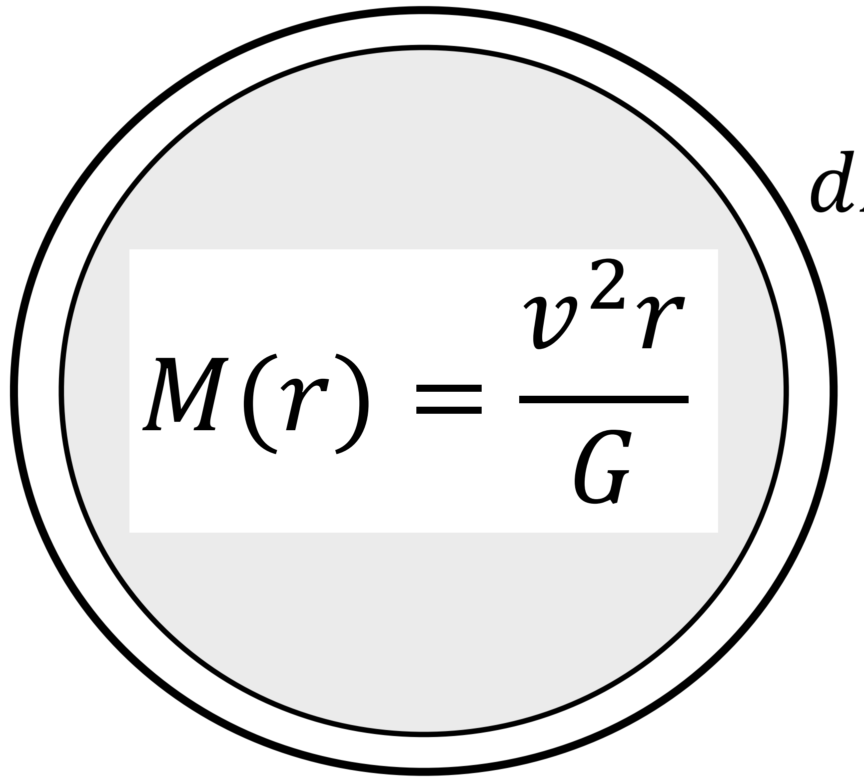
$$dM(r) = 4\pi r^2 \rho(r) dr$$

$$M(r) = \frac{v^2 r}{G}$$

Kinetic energy
contained in the halo up to radius R

Dark matter velocity profile

Potential energy
contained in the halo up to radius R



$$dM(r) = 4\pi r^2 \rho(r) dr$$

$$M(r) = \frac{v^2 r}{G}$$

$$V = -\int_0^R \frac{GM(r) 4\pi r^2 \rho(r)}{r} dr$$

$$= -\boldsymbol{\frac{v^4 R}{G}}$$

Kinetic energy
contained in the halo up to radius R
($\overline{v_H^2}$ is the average velocity of halo particles)

$$T = \frac{1}{2}\int_0^R 4\pi r^2 \rho(r) \overline{v_H^2}\, dr = \boldsymbol{\frac{v^2\, \overline{v_H^2}\, R}{2G}}$$

Using the viral theorem (V = -2T)

$$\frac{v^4 R}{G} = \frac{v^2\, \overline{v_H^2} R}{G}$$

$$\boxed{\boldsymbol{\overline{v_H^2} = v^2}}$$

The average velocity of halo particles is the same as the orbital velocity

Local dark matter density

In the Solar System region

- Simple exercise: Calculate the WIMP density in the Solar System
  - Distance to galactic center: 8.1 kpc
  - Orbiting velocity of the Sun around the center of the galaxy: 220 km/s

$G = 6.674 \times 10^{-11}$ $m^3/kg/s^2$

1 $GeV/c^2 = 1.79 \times 10^{-27}$ kg

1 kpc $= 3.09 \times 10^{19}$ m

Local dark matter density

In the Solar System region

- As we saw previously

$$\rho(r) = \frac{v^2}{4\pi r^2 G}$$

- Now use our distance to the galactic center: r ~ 8.1 kpc = 2.5×10^{20} m
- And the orbiting velocity of the Sun around the center of the galaxy: v ~ 220 km/s
- We get our local dark matter density:

$$\boxed{\rho_0 \sim 0.3 \text{ GeV/cm}^3}$$

Local dark matter density

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- And the orbiting velocity of the Sun around the center of the galaxy:
  v ~ 220 km/s

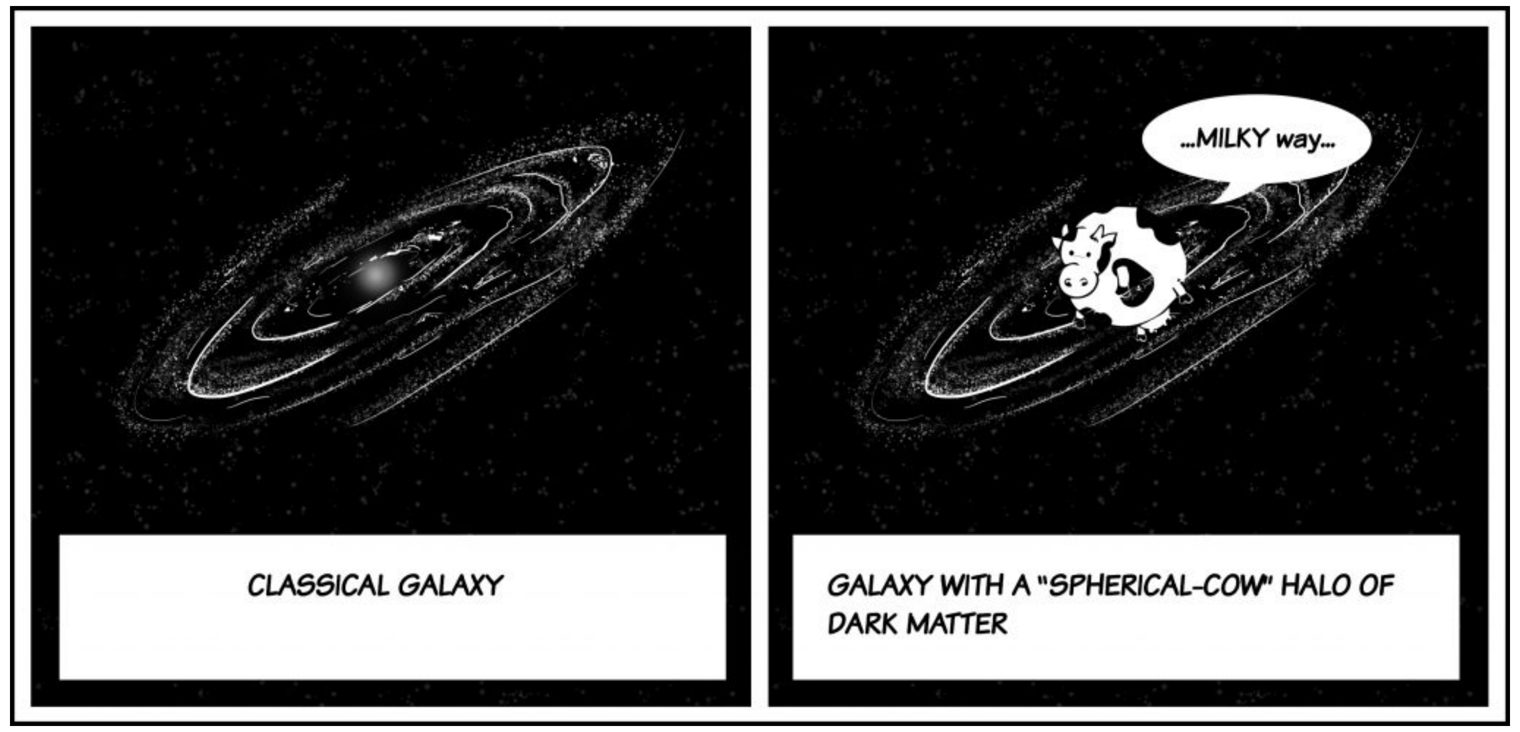
- We get our local dark matter density:

$$\boxed{\rho_0 \sim 0.3\ \text{GeV/cm}^3}$$

= One 100 GeV WIMP per litre!

Standard Halo Model

aka Canonical Model, aka Spherical Cow Model



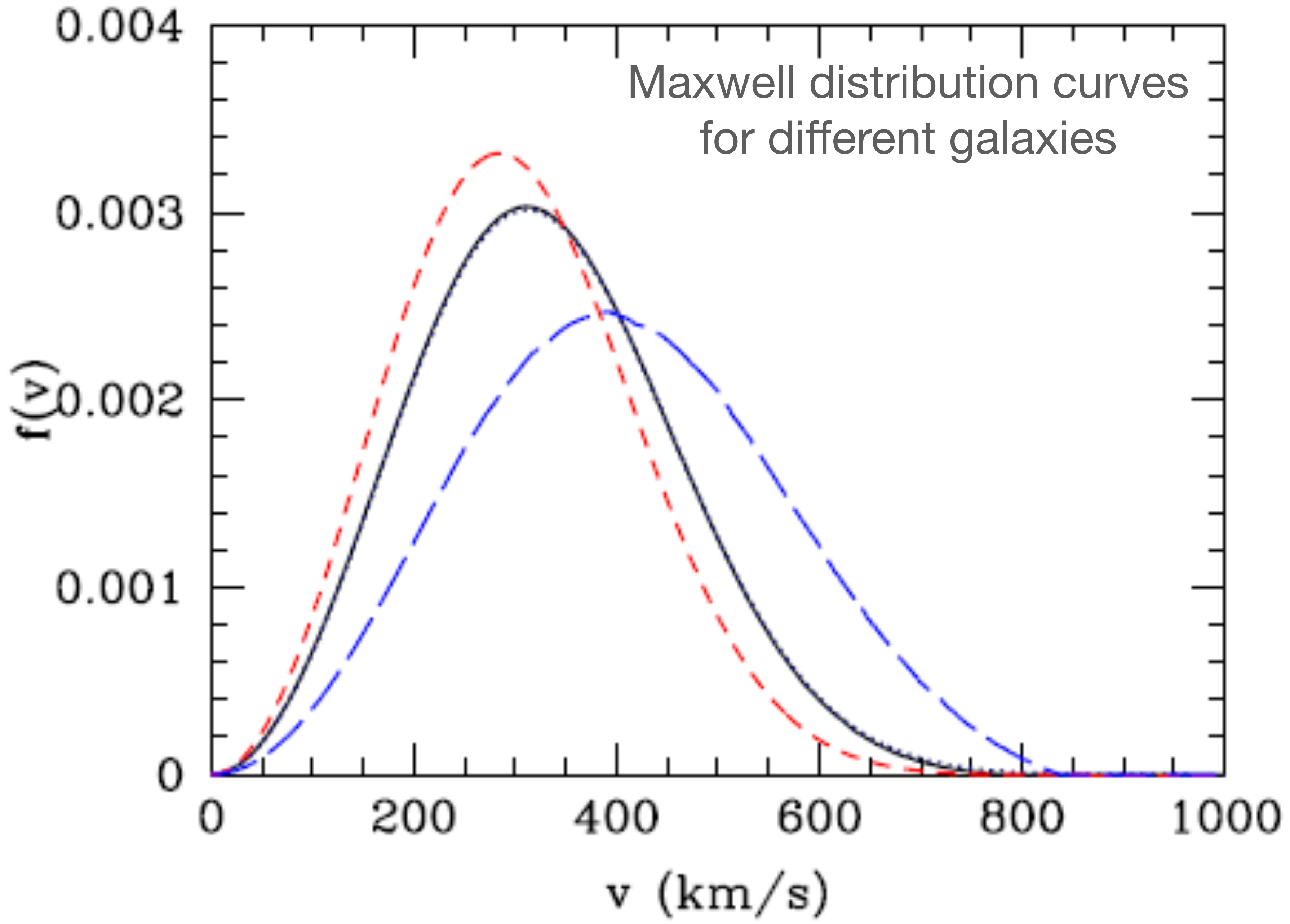
- Isothermal smooth spherical halo, containing a Maxwell-Boltzmann gas

$$\rho_{\mathrm{Iso}}(r) = \frac{\rho_0}{(1 + r/r_c)^2}$$

- DM particles follow a Maxwellian velocity distribution truncated at the escape velocity

$$v_{esc} \approx 544 \text{ km/s}$$

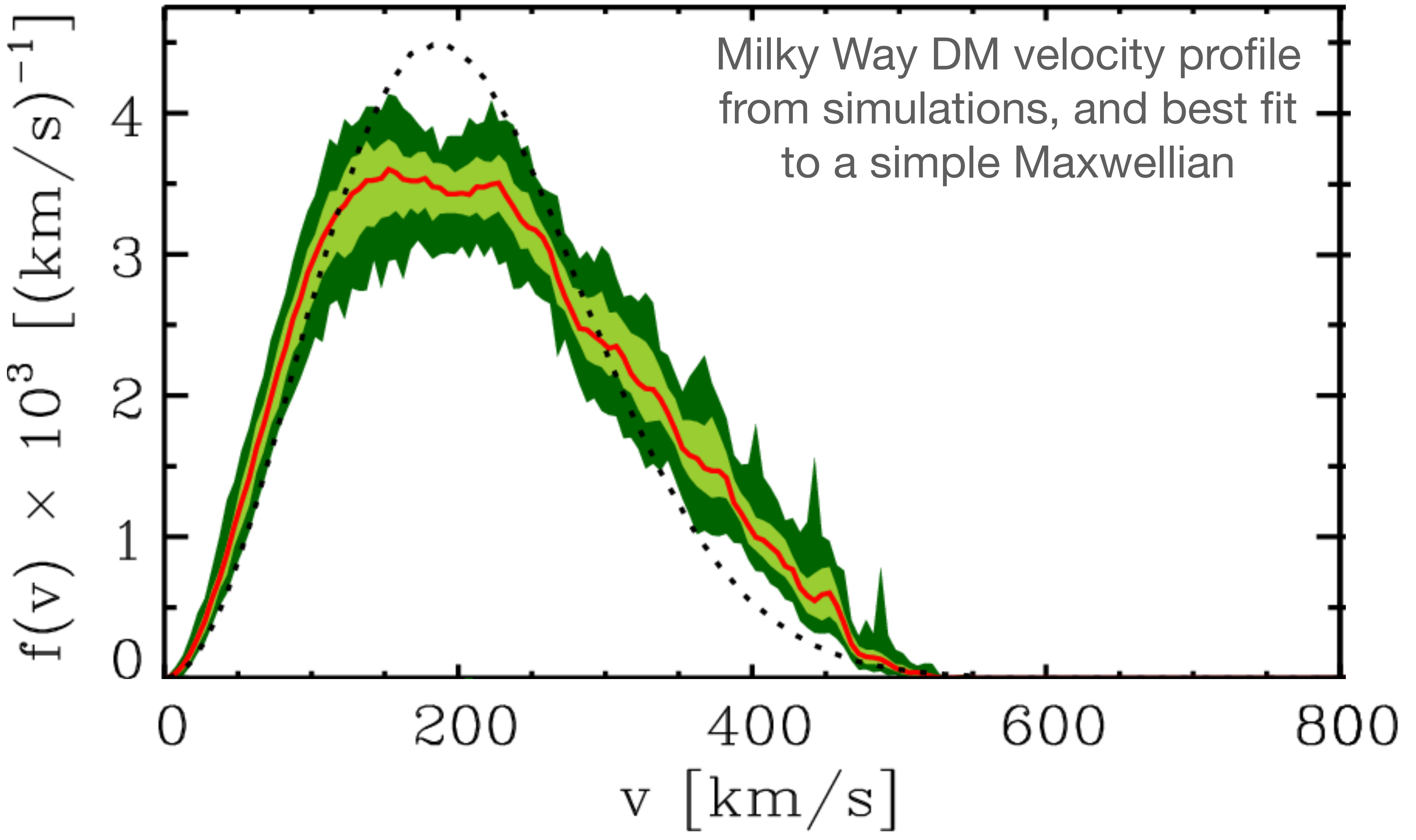
- Local density: $\rho_0 \sim 0.3$ GeV/cm^3



Despite its simplicity, the Canonical Model is still used by experimentalists to present results from direct detection experiments

Other halo models

- We will not go into details about these, just to let you know there are more realistic models, *e.g.*
  - Navarro-Frenk-White (NFW) $\rho_{\mathrm{NFW}}(r) = \frac{\rho_0}{(r/r_s)[1+r/r_s]^2},$
  - Moore
  - Einasto



- Typically obtained from n-body simulations
  - First these included only DM
  - Now baryons are considered too
    (these may lead to a DM disk in the plane of the galaxy, in addition to the halo)

Conclusions

from today

- Clear gravitational and cosmological evidence of “missing” mass at all scales, including in our own Milky Way galaxy
- The case for the existence of Dark Matter seems irrefutable, but no direct observation has been made
- Many candidates to explain Dark Matter, but so far the most popular are still the WIMPs: thermal relics with weak scale interactions
- Models of the dark matter halo in our Milky Way
  - DM halos are much larger than the visible galaxies
  - Local DM density ~0.3 — 0.6 GeV
  - Average velocity of DM particles ~220 km/s
  - Can be used to make predictions for direct detection experiments (next class)

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- "Dark Matter Searches", Laura Baudis, BND School 2009, http://bnd-graduateschool.org/2009/?Lecture_Notes

Combined constraints