NCTS SSP Lectures 2026 —Dark Matter

Sut-Ieng Tam 譚雪瑩 (National Yang Ming Chiao Tung University; NYCU)

Outline

- 1. The Dark Matter Problem
  - —Missing mass in galaxies and clusters
  - —Why dark matter is needed
- 2. Astrophysical Evidence for Dark Matter
  - —Rotation curves; Galaxy clusters; Gravitational lensing
- 3. Cold Dark Matter and Structure Formation
  - —Growth of perturbation; Halo formation
- 4. Challenges to the CDM Paradigm; alternative DM models
  - —Growth of perturbation; Halo formation; different DM models

The Dark Matter Problem

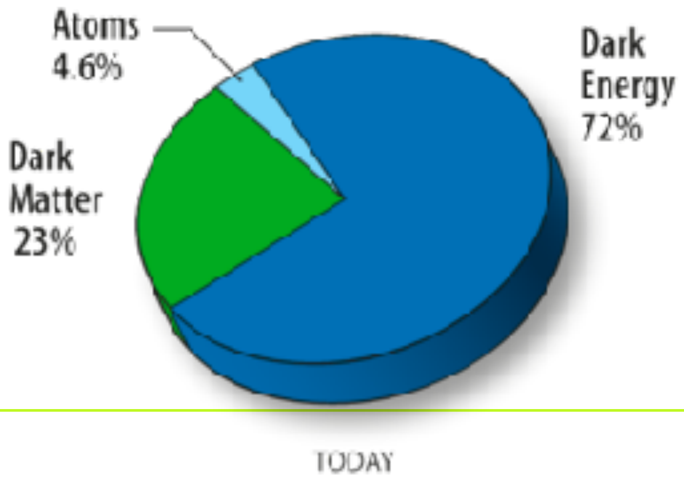
- Density parameter in matter, $\Omega_{m,0}$
—> important to determine the spatial curvature, expansion rate, the rate of structure formation

- What the universe is made of?
—> Baryonic matter: stars, gas
—> Dark matter

- What is fraction of baryons and dark matter?

$$\Omega_m + \Omega_r + \Omega_\Lambda + \Omega_k = 1$$

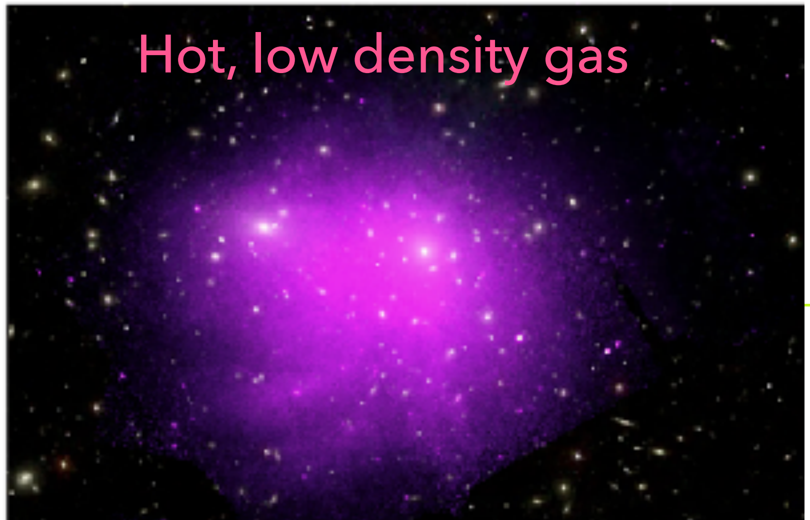
What is Ωm? $$\Omega_m = \Omega_b + \Omega_{\rm DM}$$



Visible Matter

- Stars —> emit the infrared, visible, and ultraviolet light —> convert to their mass by assumption of Mass-to-light ratio $\langle M/L \rangle$
- $\Omega_{\star,0}$ only makes up 0.004=0.4% to flatten the Universe
- low-mass, low-luminosity stars, brown dwarfs and stellar remnants
- Interstellar medium (ISM): gas in galaxy, ~10% of the mass of stars.
- Intergalactic medium (IGM): hot, low-density gas between galaxies
- $\Omega_{bary,0} = 0.04 \pm 0.01$ (from BBN)> $\Omega_{\star,0}$

$$p + n \rightarrow D,\ {}^3He,\ {}^4He,\ {}^7Li$$



Dark Matter

- The majority of matter is non-baryonic dark matter, which doesn't absorb, emit, or scatter light of any wavelength.
- Not EM interaction, but they interact through via gravity
- How to detect them?
  —> gravitational influence on visible matter
- Kinematic study for the stars in spiral galaxies
  —> stars are on nearly circular orbits around the center of the galaxy with an orbital speed; For Sun, v = 220 km s^{-1} at R=8.5kpc.

From observation $$v = \sqrt{\frac{GM(R)}{R}}$$

Expectation from Newtonian Physics

From Newton's law of gravitation and circular motion:

$$F = \frac{GM(r)m}{r^2} = m\frac{v^2}{r} \quad \Rightarrow \quad v(r) = \sqrt{\frac{GM(r)}{r}}$$

— If most mass is concentrated near the center (as in solar system), then M(r) becomes roughly constant at large r.
— Thus, velocity should decrease as $v \propto \frac{1}{\sqrt{r}}$. Keplerian decline ~same as what we observe in the solar system.

Observed Rotation Curves

— **Velocity stays flat or even increases slightly** at large distances from the galactic center.

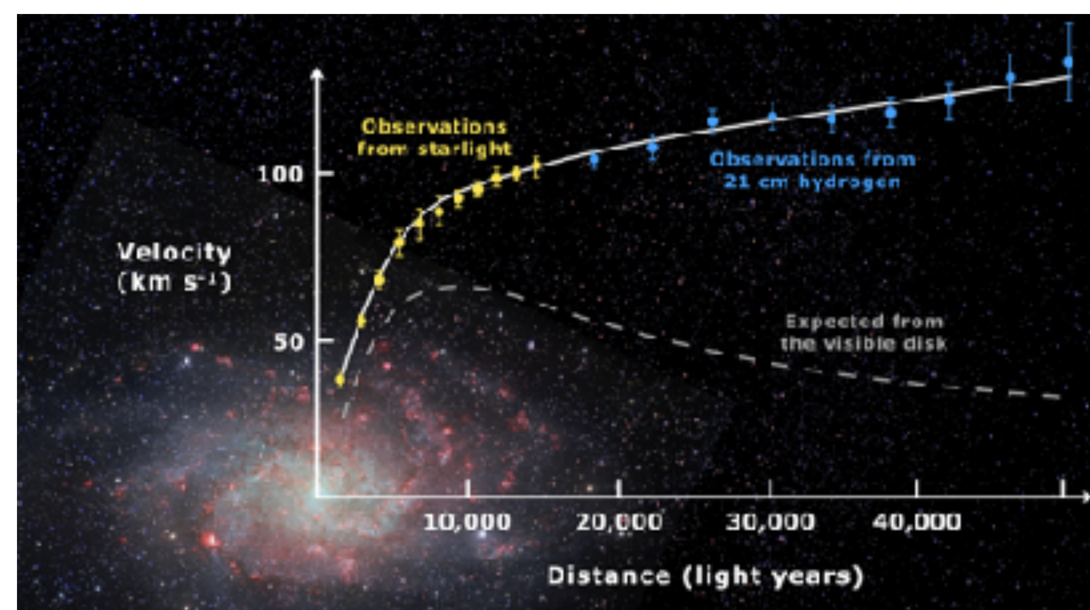
$v(r) \approx \text{constant} \Rightarrow M(r) \propto r$ $\quad \rho(r) \propto r^{-2}$. isothermal density profile

—> **mass continues to increase with radius, but there is no visible matter exists!**

—> There Must Be Unseen Mass

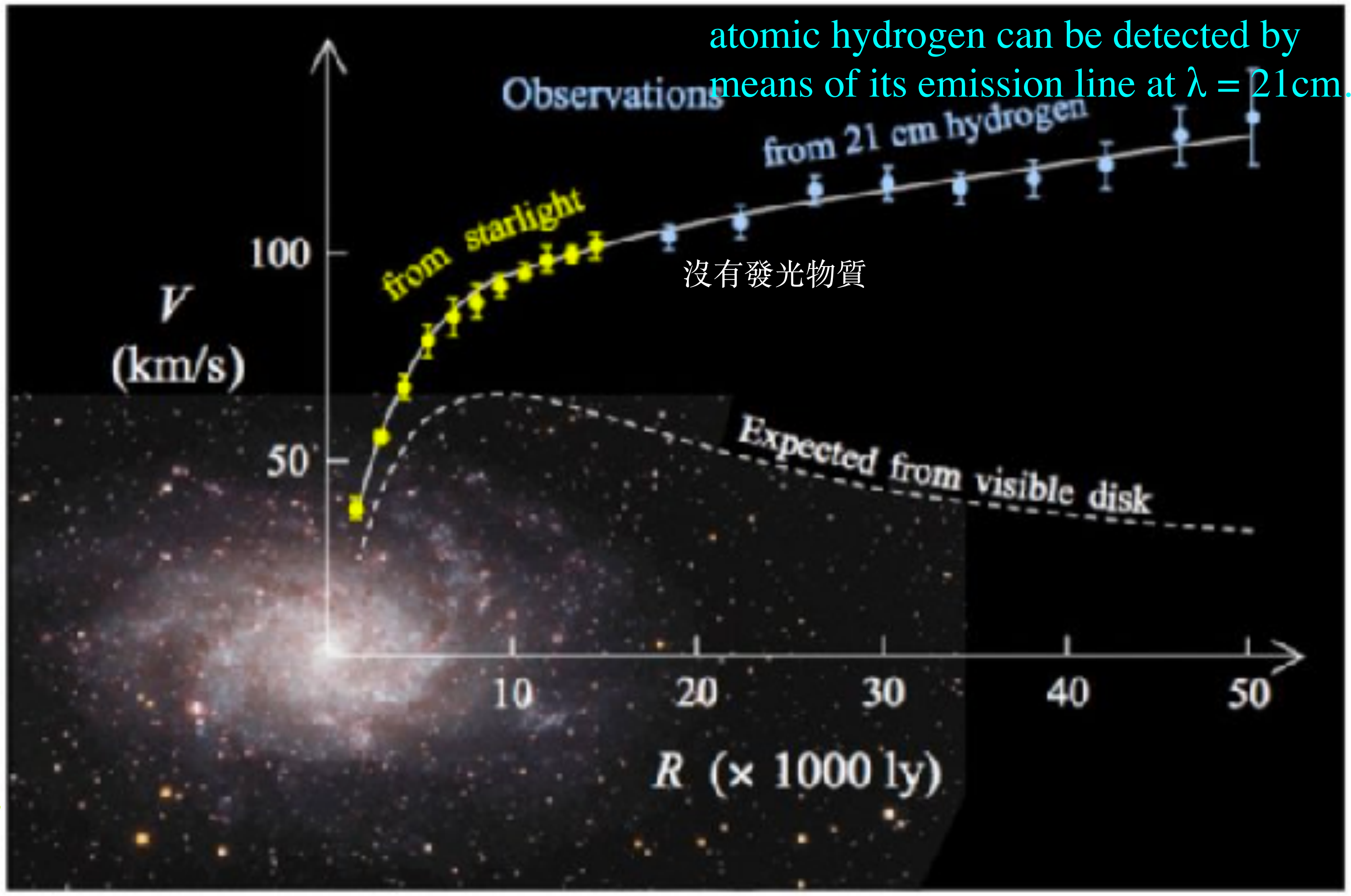
—> invisible matter —Dark Matter

Galaxies are embedded in **massive, extended halos** of non-luminous matter.



First detection of rotation of M31

- In 1970, Vera Rubin and Kent Ford looked at emission lines from regions of hot ionized H gas in M31 out to R = 24 kpc = $4R_s$
- No Keplerian decrease in the orbital speed.
- The orbital speed of the stars and gas at large radii is greater than expected (only stars and gas present)
- Dark halo! —> in order to offer an extra gravitational potential to keep the high-speed stars and gas from being threw away into intergalactic space.



Rotation curve of M33 (Yahalom 2019)

M31 is not a special case, all spiral gals have comparable dark halos

Galaxies are embedded in extended dark matter halos.

1970 ApJ 159, 379

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

VERA C. RUBIN† AND W. KENT FORD, JR.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡
Received 1969 July 7; revised 1969 August 21

ABSTRACT

Spectra of sixty-seven H II regions from 3 to 24 kpc from the nucleus of M31 have been obtained with the DTM image-tube spectrograph at a dispersion of 135 Å mm^{-1}. Radial velocities, principally from $H\alpha$, have been determined with an accuracy of ± 10 km sec^{-1} for most regions. Rotational velocities have been calculated under the assumption of circular motions only.

For the region interior to 3 kpc where no emission regions have been identified, a narrow [N II] λ6583 emission line is observed. Velocities from this line indicate a rapid rotation in the nucleus, rising to a maximum circular velocity of $V = 225$ km sec^{-1} at $R = 400$ pc, and falling to a deep minimum near $R = 2$ kpc.

From the rotation curve for $R \leq 24$ kpc, the following disk model of M31 results. There is a dense, rapidly rotating nucleus of mass $M = (6 \pm 1) \times 10^9 M_\odot$. Near $R = 2$ kpc, the density is very low and the rotational motions are very small. In the region from 500 to 1.4 kpc (most notably on the southeast minor axis), gas is observed leaving the nucleus. Beyond $R = 4$ kpc the total mass of the galaxy increases approximately linearly to $R = 14$ kpc, and more slowly thereafter. The total mass to $R = 24$ kpc is $M = (1.85 \pm 0.1) \times 10^{11} M_\odot$; one-half of it is located in the disk interior to $R = 9$ kpc. In many respects this model resembles the model of the disk of our Galaxy. Outside the nuclear region, there is no evidence for noncircular motions.

The optical velocities, $R > 3$ kpc, agree with the 21-cm observations, although the maximum rotational velocity, $V = 270 \pm 10$ km sec^{-1}, is slightly higher than that obtained from 21-cm observations.

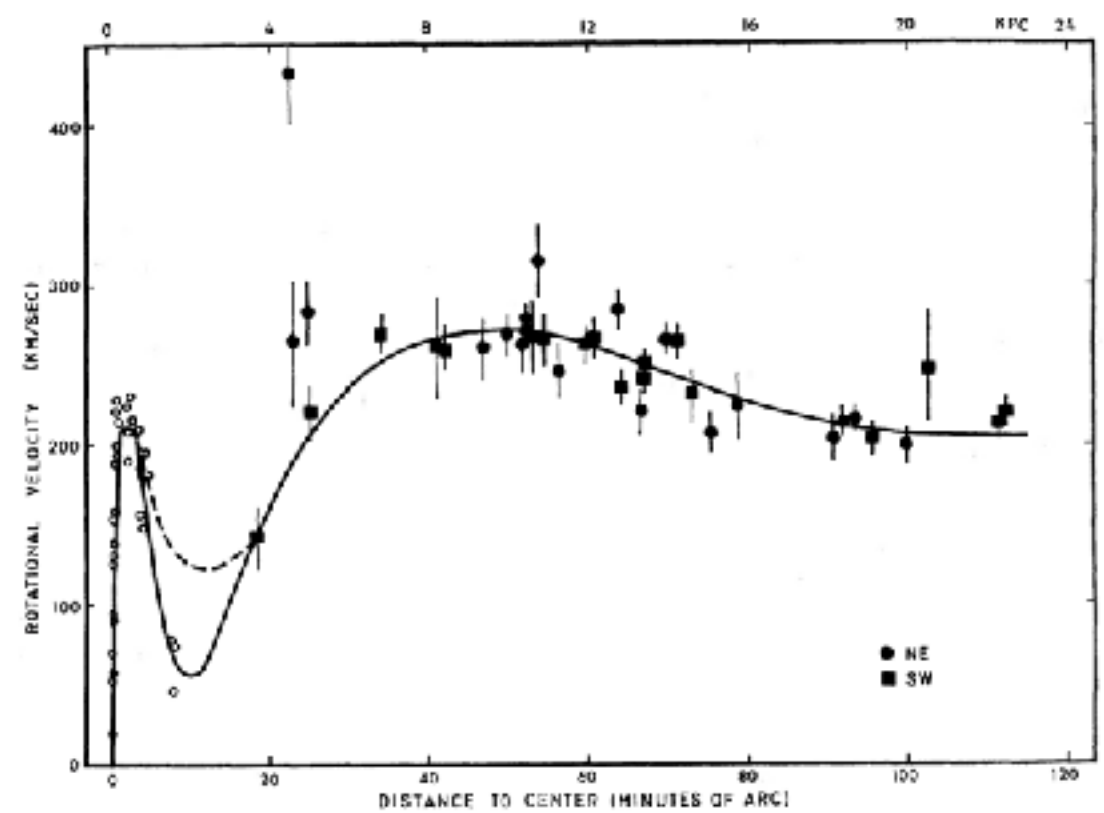


FIG. 9.—Rotational velocities for OB associations in M31, as a function of distance from the center. *Solid curve*, adopted rotation curve based on the velocities shown in Fig. 4. For $R \leq 12'$, curve is fifth-order polynomial; for $R > 12'$, curve is fourth-order polynomial required to remain approximately flat near $R = 120'$. Dashed curve near $R = 10'$ is a second rotation curve with higher inner minimum.

Rough Estimate the Milky Way's Dark Matter Halo

- Observations of stellar kinematics imply:

$$M_{\text{halo}} \sim 10^{12} M_{\odot}$$

- Local dark matter density:

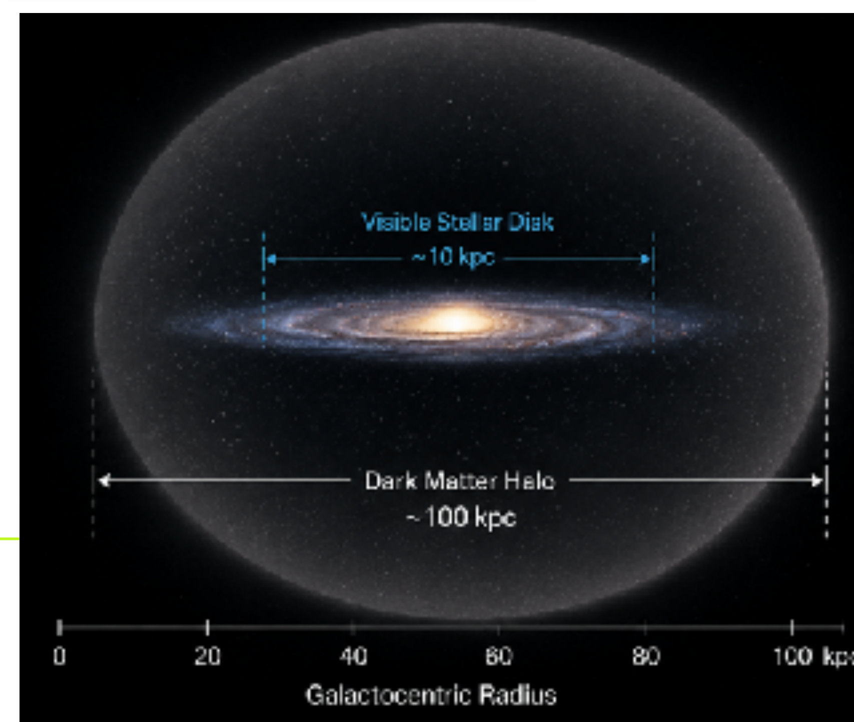
$$\rho_0 \sim 0.3\ \text{GeV cm}^{-3}$$

- By assuming spherically symmetric density distribution:

$$M_{\text{halo}} = 4\pi \int_0^{R_{\text{halo}}} \rho(r)\, r^2\, dr \qquad \rho(r) \propto r^{-2}.$$

$$\Rightarrow \quad R_{\text{halo}} \sim 100\ \text{kpc}$$

The dark matter halo extends roughly an order of magnitude beyond the visible stellar disk (~10kpc).



Other solution? MOND?

Is it possible if Newtonian physics is not corrected?
— Alternative Explanation: MOND (Modified Newtonian Dynamics)
— Instead of adding invisible matter, MOND **modifies Newton's second law** for very low accelerations (like those at galaxy outskirts).
— Instead of F=ma, MOND suggests:

$$F = m\mu\left(\frac{a}{a_0}\right)a$$

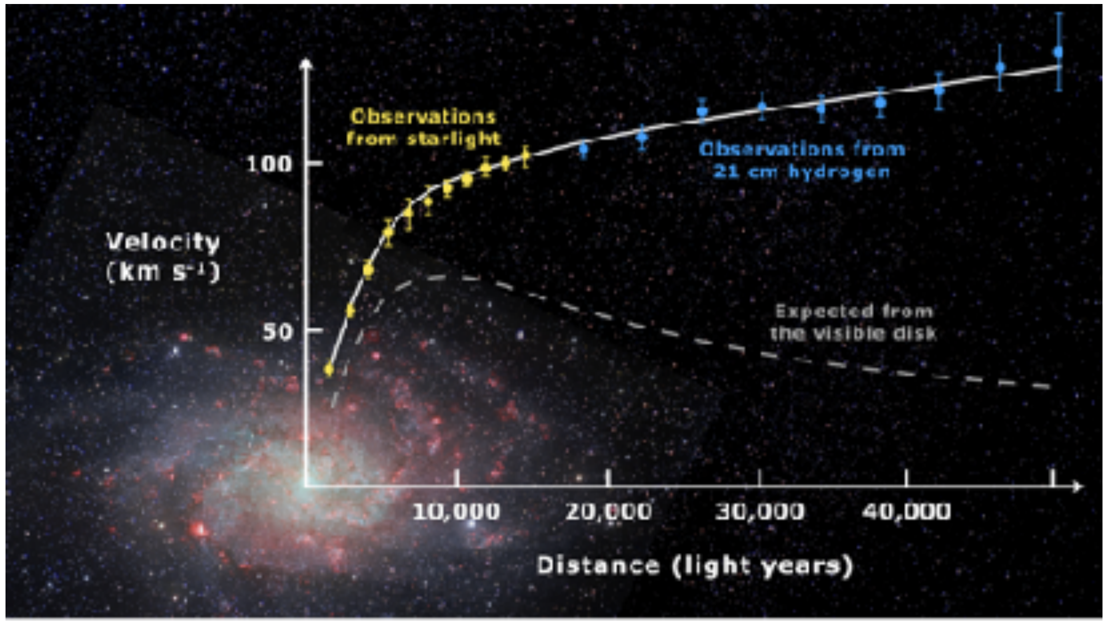
$\mu(x) \approx 1$ for $x \gg 1$; $a > a_0$, high-acceleration regime
$\mu(x) \approx x$ for $x \ll 1$; $a < a_0$, low-acceleration regime

At the galaxy outskirts:

$$a \cdot \mu\left(\frac{a}{a_0}\right) = \frac{GM}{r^2}$$

$$a \cdot \left(\frac{a}{a_0}\right) = \frac{GM}{r^2} \Rightarrow \frac{a^2}{a_0} = \frac{GM}{r^2}$$

$$a = \sqrt{\frac{GMa_0}{r^2}}$$



Since $a = \frac{v^2}{r}$, $\frac{v^2}{r} = \sqrt{\frac{GMa_0}{r^2}} \Rightarrow v^2 = \sqrt{GMa_0}$

Prediction of flat rotational curve without needing dark matter.

$a0 \sim 1.2 \times 10^{-10} m/s^2$

Which one is correct?

MOND can not explain cluster-scale object

More Missing Mass in Galaxy Cluster

Zwicky (1937) measured velocities of galaxies in the Coma Cluster and found that galaxies were moving **too fast** to be gravitationally bound by the **visible matter** (stars and gas). The velocity dispersion of radial direction is so large~1000 km/s. The stars and IGM (gas) can not provide enough gravitational attraction to hold the cluster together.

> "If these galaxies were only held together by visible matter, the cluster should have flown apart."
>
> — There must be some unseen mass — coined the term "dark matter", that holds the cluster together.

Limitation of MOND:

— It underestimates the total gravitational mass; same a0 does **not provide enough effective gravity** to explain cluster-scale dynamics.

- **additional undetected mass**
- Or, MOND needs to introduce a second acceleration scale, which undermines its simplicity and elegance.

Fritz Zwicky

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

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

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

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

Overestimated

$$\gamma = 500 , \tag{37}$$

1937 ApJ 86, 217

What is Dark Matter?

Not ordinary matter (atoms, stars, gas, from BBN), doesn't emit, absorb or reflect light.

What we know about it

- **Massive** — It exerts gravity (rotational curve).
- **Invisible** — Does not emit or scatter light.
- **Non-baryonic** — Not made of protons, neutrons, electrons.
- **Cold** (in most models) — Dark matter particles are slow-moving compared to the speed of light, which helps in galaxy formation. (Why? Structure formation)
- **Weakly interacting** (why? Bullet Cluster)

How to search for them?

→ Two Frontiers: Particle Physics and Astronomy

—Collider Searches

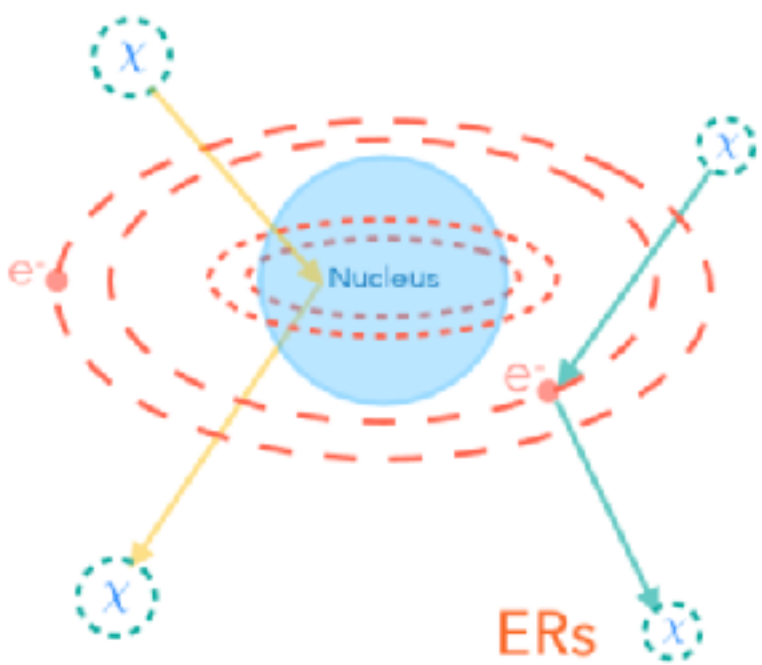
—Search for high-energy particles from **dark matter annihilation or decay**.

—Gravitational Signatures

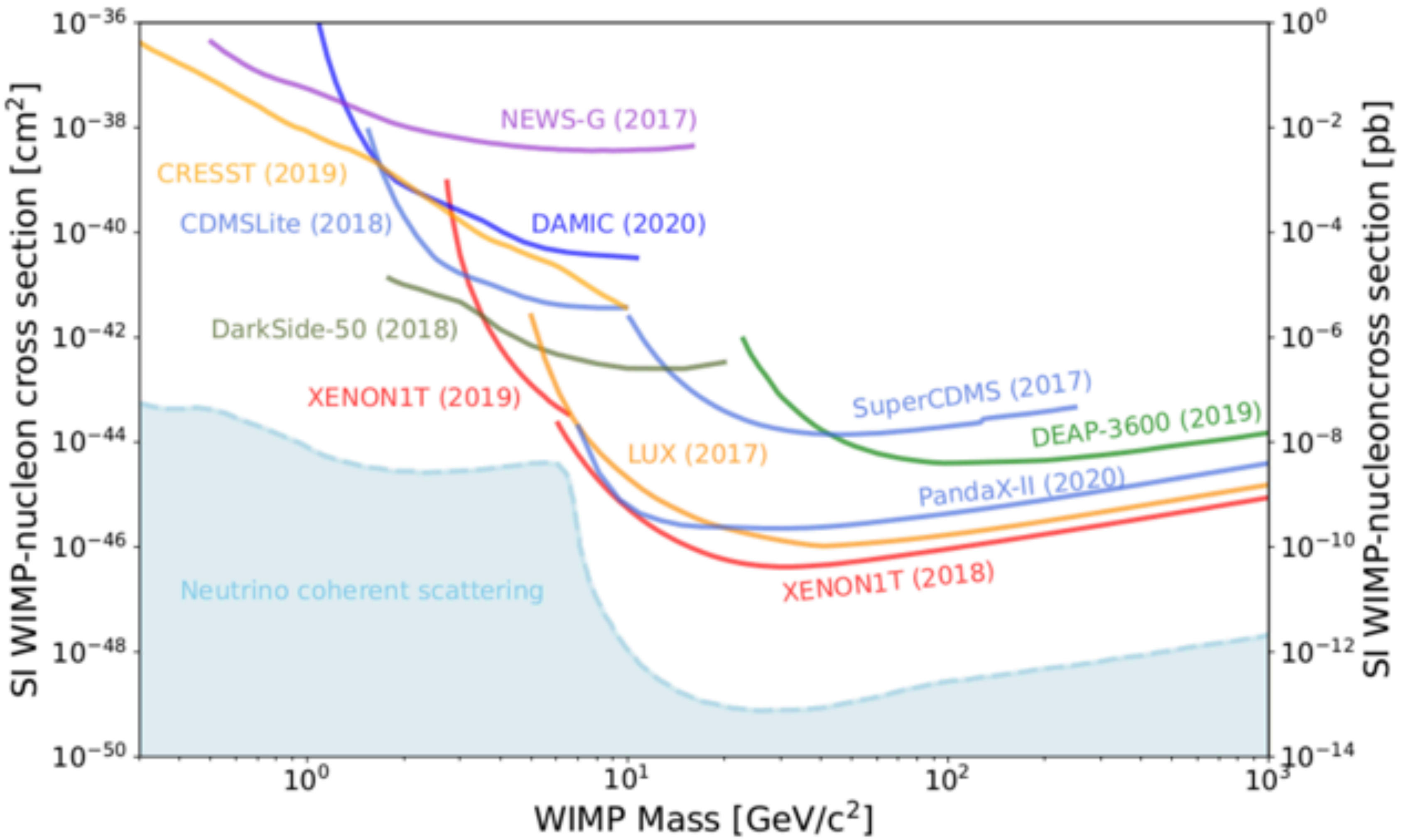
Particle physics perspective

- Direct Detection Experiments
  — Using ultra-sensitive detectors deep underground to detect the rare interaction of dark matter particles from Universe with normal matter—nucleus.

- Low recoil energy (~keV)—Scintillation light, Ionization, Heat



Laura Baudis 2025



Misiaszek & Rossi 2023

Particle physics perspective

- Indirect Detection:
  — Looking for the decay or annihilation products of dark matter particles, such as **gamma rays**, **positrons**, or **antiprotons**.

- Annihilation: χ+χ→SM particles

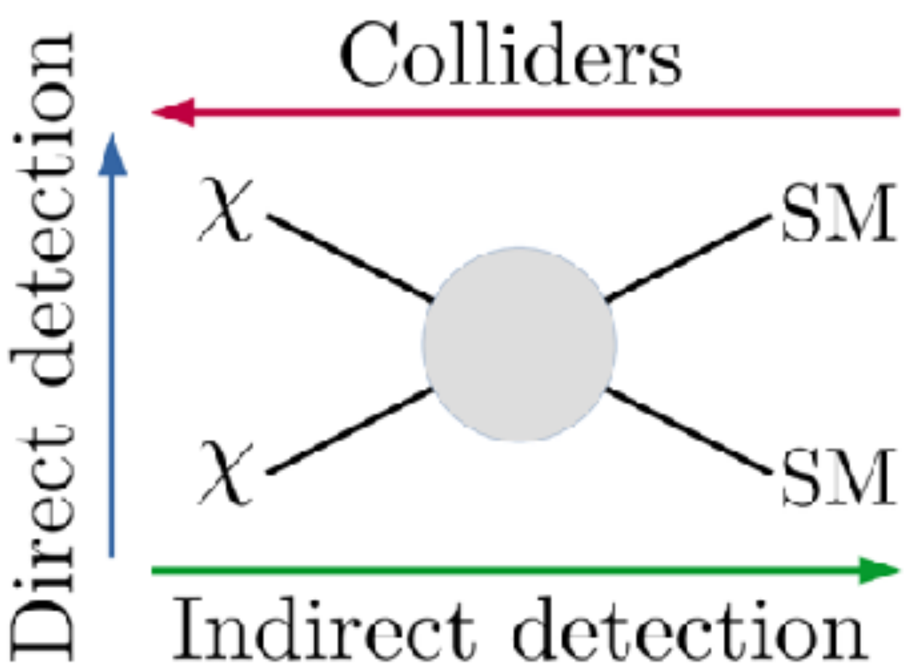
$$\Gamma_{\rm ann} \sim \langle \sigma v \rangle n_\chi^2 \sim \langle \sigma v \rangle \left(\frac{\rho_\chi}{m_\chi} \right)^2 .$$

focus on regions where dark matter is most concentrated (e.g. the Galactic Center, dwarf spheroidal galaxies, galaxy clusters)

- Decay: χ→SM particles

$$\Gamma_{\rm decay} \sim \frac{\rho_\chi}{m_\chi \tau_\chi} .$$

Constraints on lifetime



A. Arbey and F. Mahmoudi 2021

Particle physics perspective

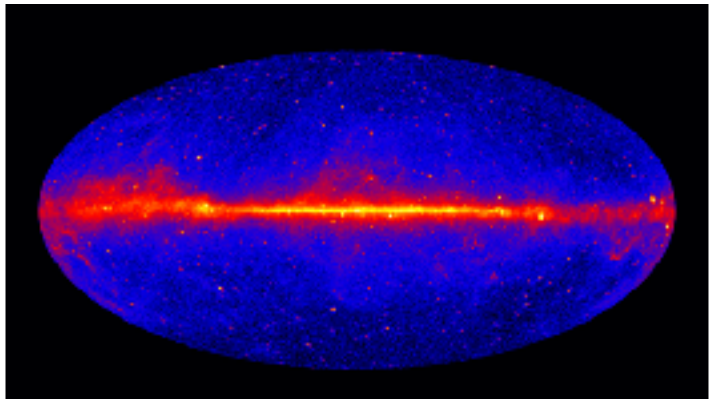
- Indirect Detection:

$$\chi + \chi \to \gamma,\ e^{+},\ \bar{p},\ \nu,\ \dots$$

- Gamma rays—Fermi-LAT (space), H.E.S.S. (ground)
  Neutrinos—IceCube, ANTARES
  cosmic rays: positrons and antiprotons—AMS

- Where Do We Look?

  —Galactic Center; Dwarf spheroidal galaxies; Galaxy clusters

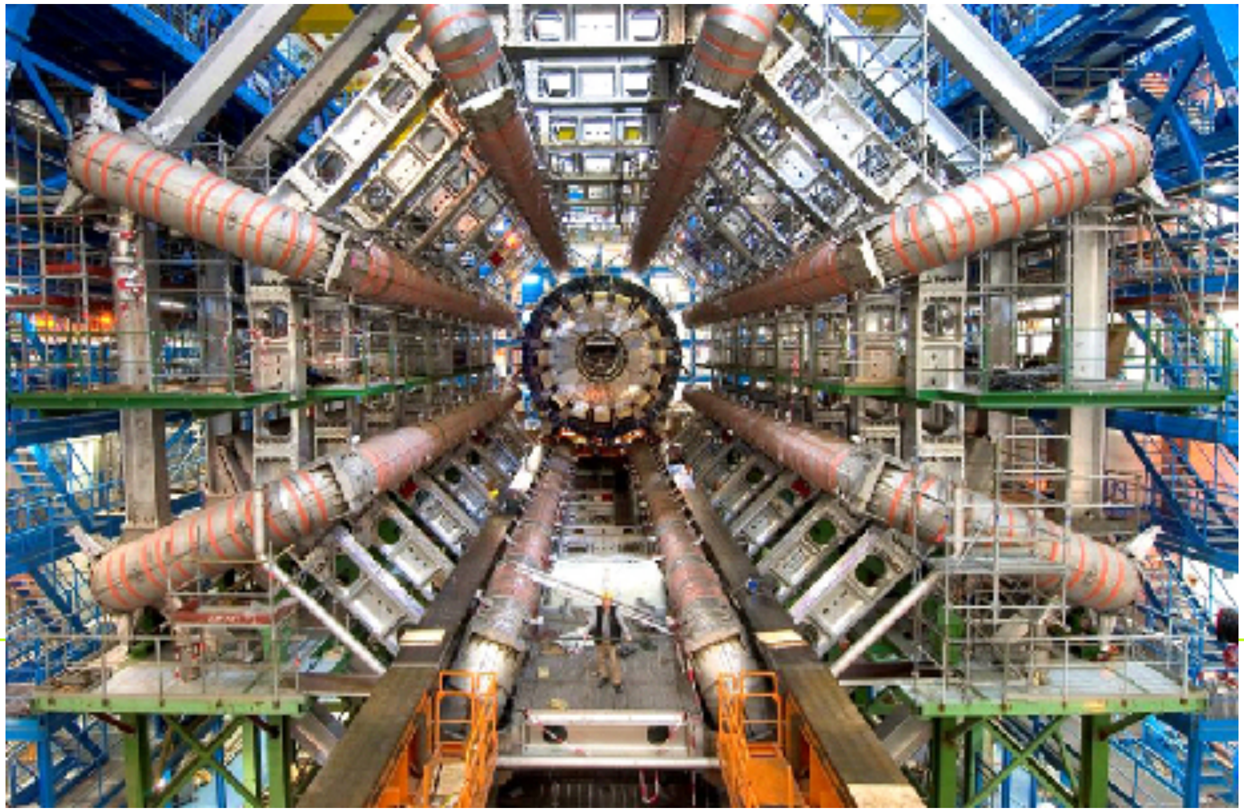


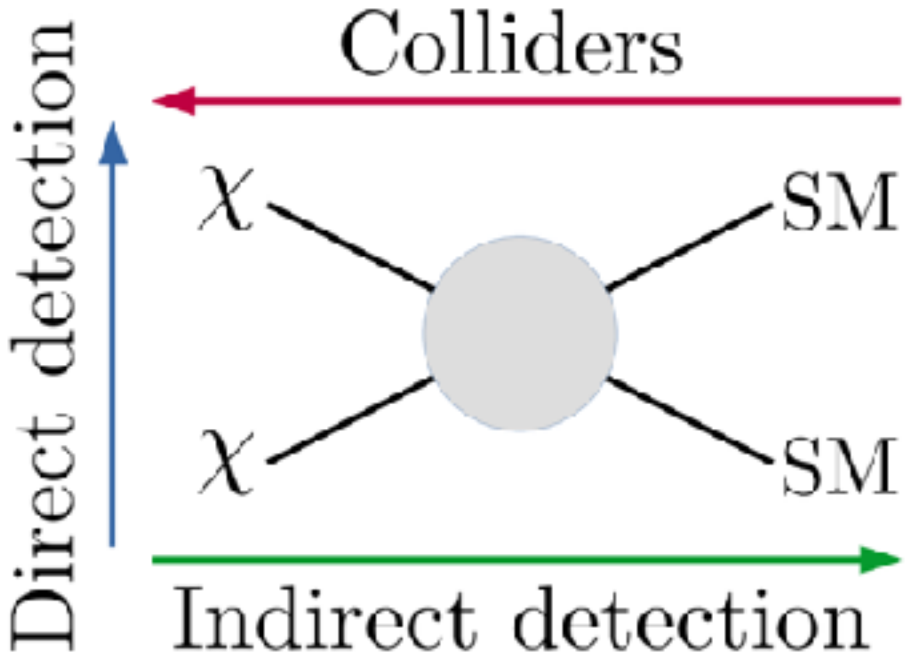
Particle physics perspective

- Collider Experiments:
  — Searching for dark matter signatures at particle accelerators (e.g., the **Large Hadron Collider (LHC)**).

- pp→χχ+j
  Mono-jet; missing transverse momentum

- Decay products of heavy beyond SM particles produced in collisions





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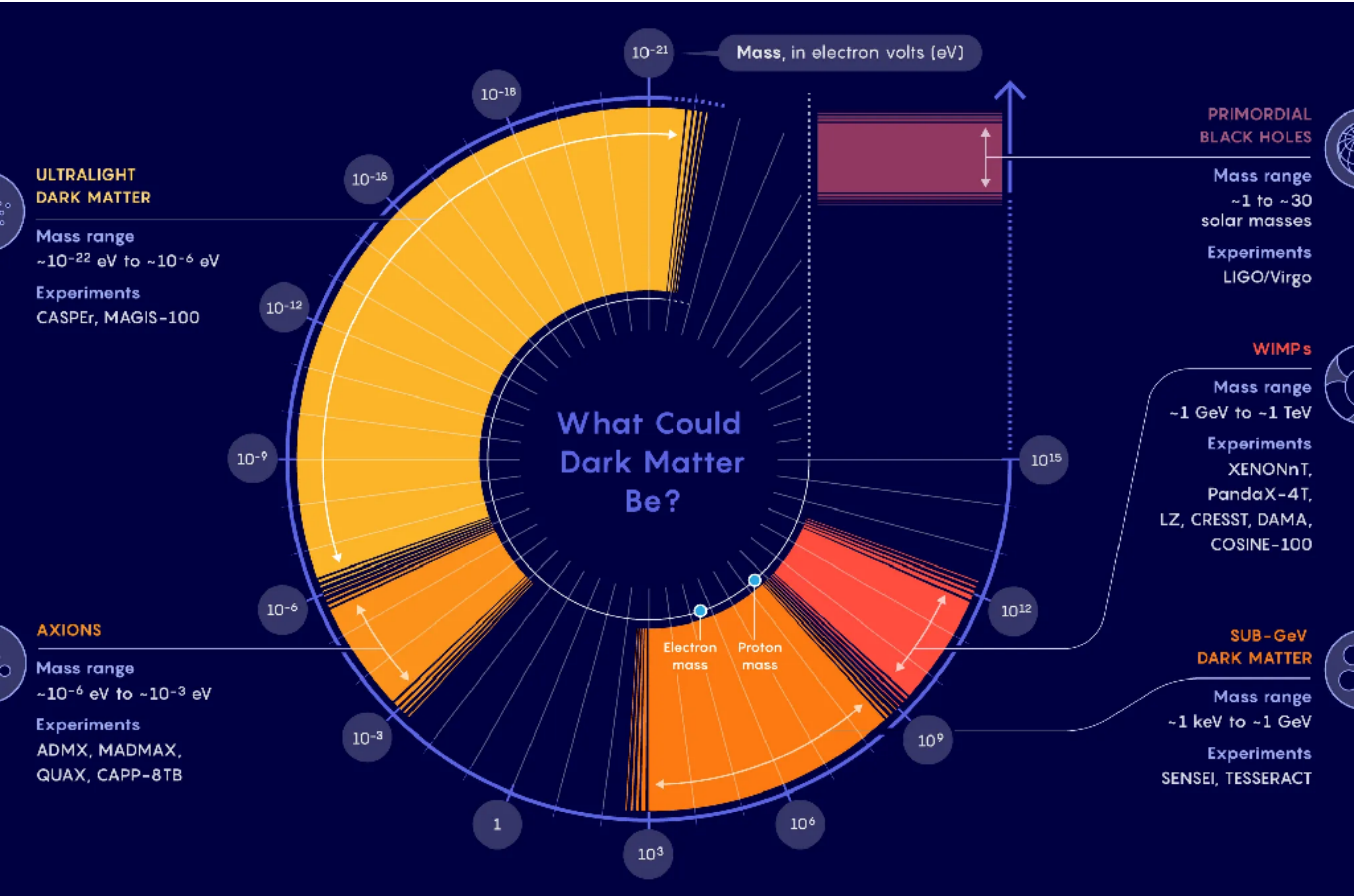


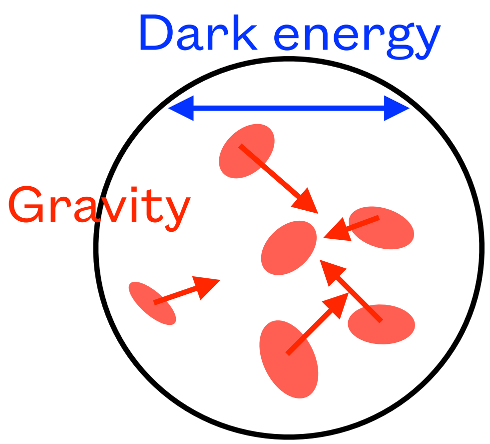
ILLUSTRATION: SAMUEL VELASCO/QUANTA MAGAZINE

Astrophysical perspective

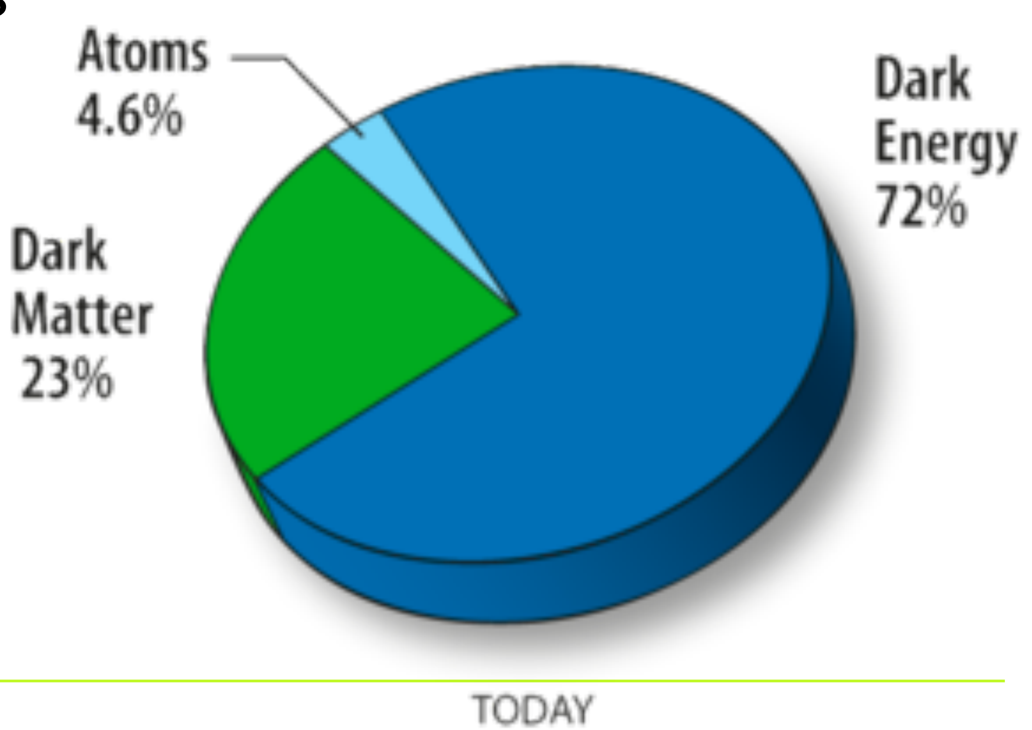
- Look for gravitational signatures
- **Galaxy rotation curves**
  Stars orbit too fast to be explained by visible matter alone.
- **Galaxy clusters**
  The total mass inferred from galaxy motions greatly exceeds the luminous mass.
- **Gravitational lensing—tomorrow**
  Dark matter bends light and reveals the mass distribution directly.
- **Large-scale structure formation**
  Dark matter provides the gravitational seeds for galaxies and clusters to form.

Lambda CDM Universe

- Composition: Dark Energy, Dark Matter, Normal matter



- What determine the dynamical evolution of the Universe?
  -Expansion vs contraction;
  -Dark energy vs matter density (gravity)
- The amount of energy density determines the curvature and expansion of the Universe
- Energy density changes with time —> causing different evolution stage of the Universe
- Current standard model: ΛCDM
  - Λ: cosmological constant, which is associated with dark energy—accelerating expansion
  - CDM: cold dark matter, "cold" refers to slow-moving, a form of matter that interacts only weakly with regular matter and radiation



FLRW models

- Friedmann-Lemaître-Robertson-Walker (FLRW) model

$$ds^2 = -c^2dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta\, d\phi^2)\right].$$

a(t):expansion of the Universe;
k: geometry of space, k=0: flat; k>0: closed; k<0: open

- Friedmann equations:

Matter, radiation

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}.$$

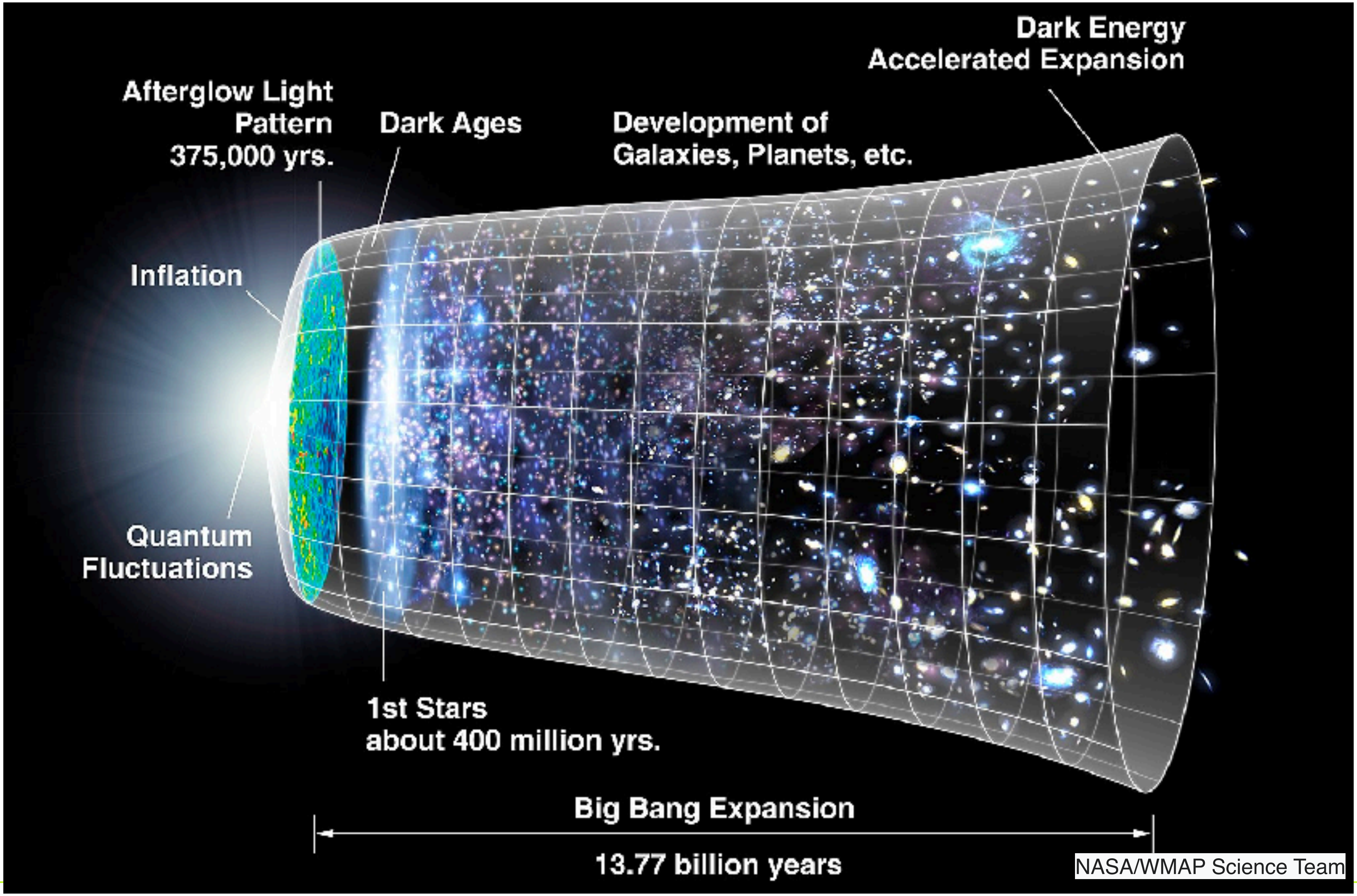
Expansion rate Curvature Dark energy

$$H^2(a) = H_0^2\left[\Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda\right]$$

Density parameter: $\Omega_i = \frac{\rho_i}{\rho_c}$

$$\Omega_m + \Omega_r + \Omega_\Lambda + \Omega_k = 1.$$

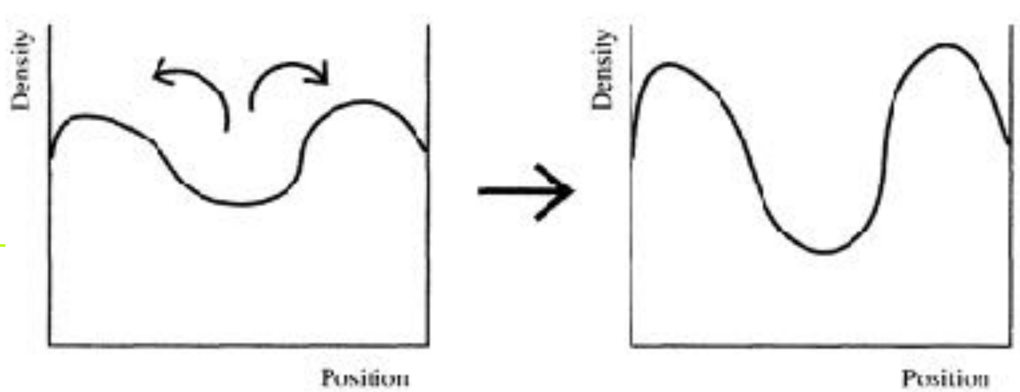
Evolution of the Universe



The Role of Dark Matter in Cosmology

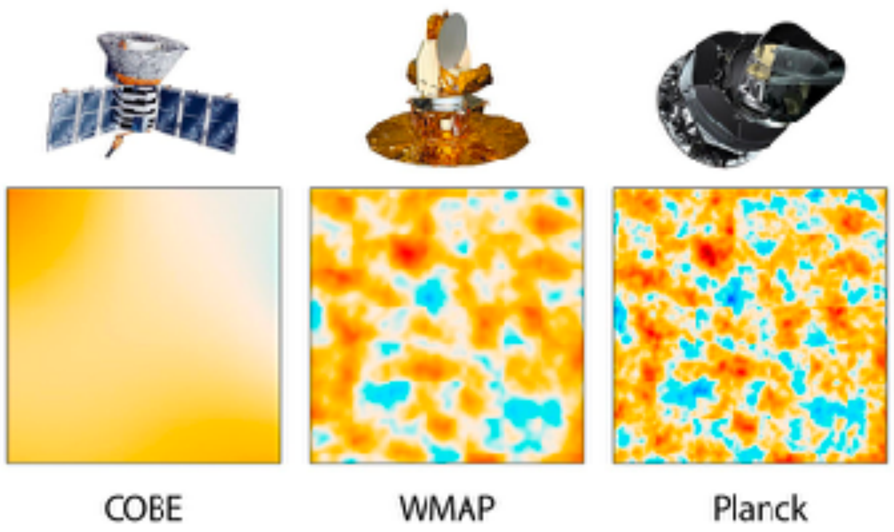
Gravitational Backbone of Structure Formation

- Dominates the Matter Content of the Universe ~ 85% of all matter
- Tiny density fluctuations observed in the CMB provide the seeds of today's large-scale structure.
- Basic mechanism for growing LSS: gravitational instability
- Before recombination, baryons are tightly coupled to photons and cannot collapse efficiently.
- DM does not interact with radiation and begins clustering much earlier.
- After recombination ($z \approx 1100$), baryons into pre-existing DM potential wells.

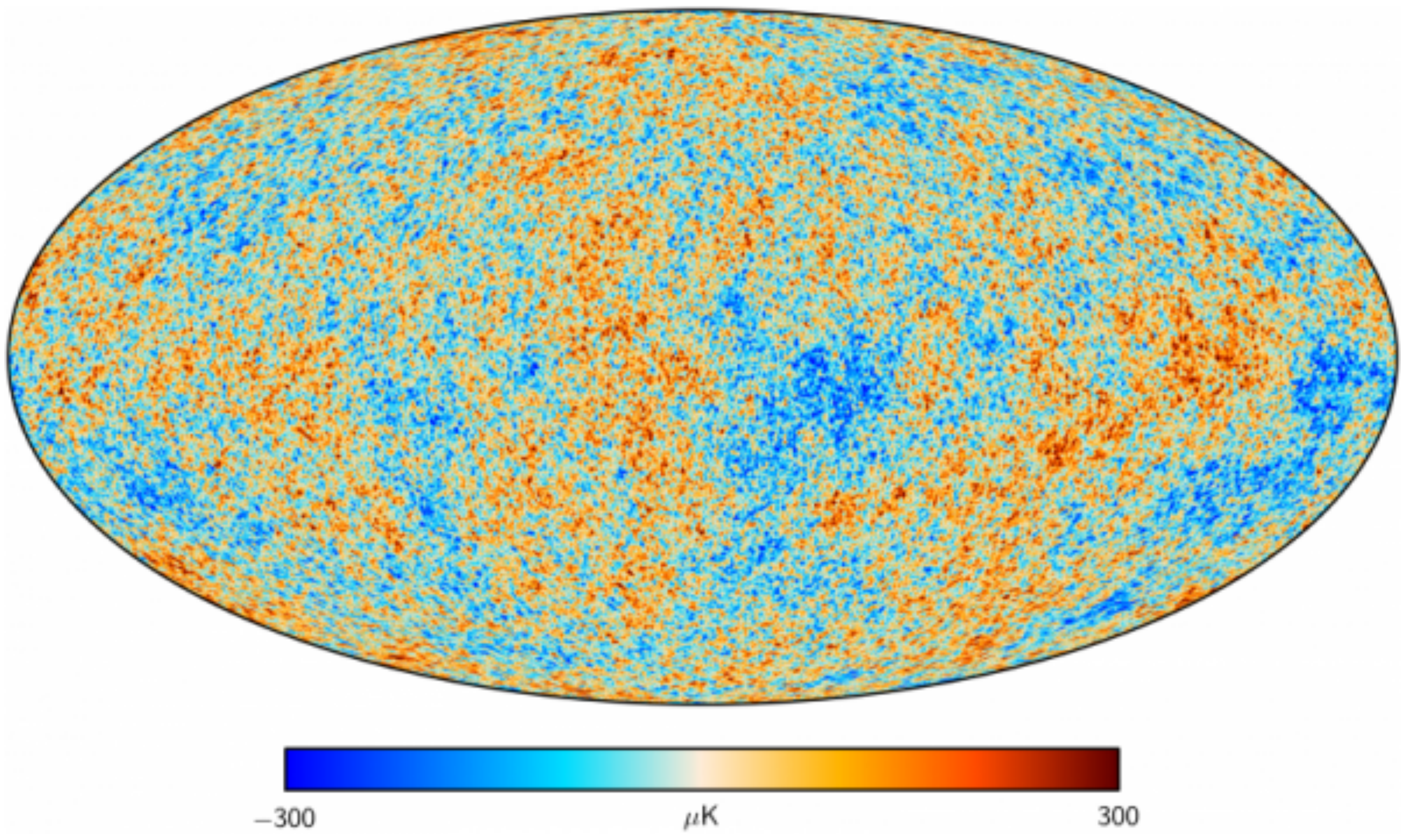


FULL-SKY CMB

- Homogeneous and isotropic
- Tiny anisotropies ($\Delta T/T \sim 10^{-5}$)

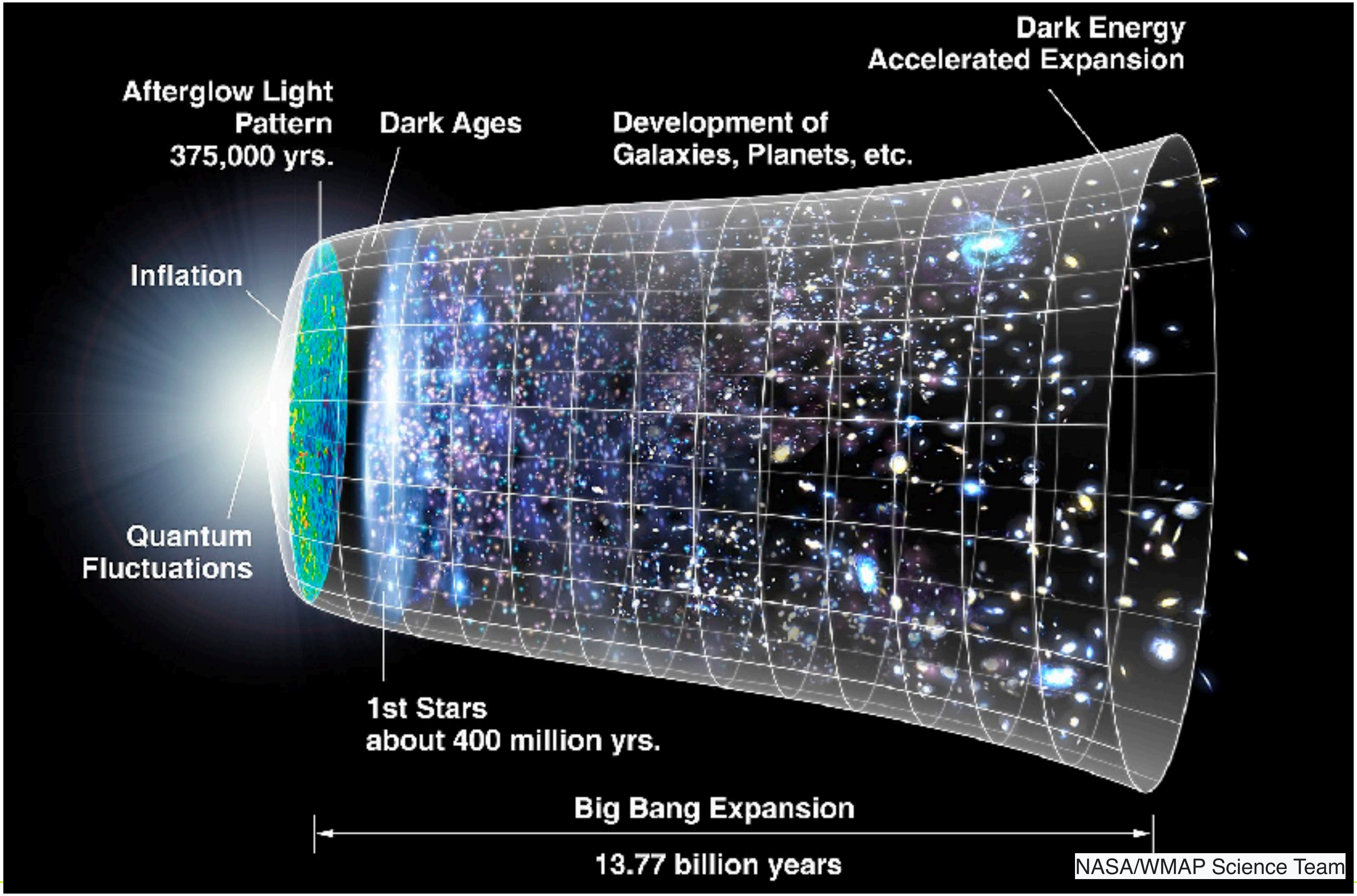


(Image credit: NASA/JPL-Caltech/

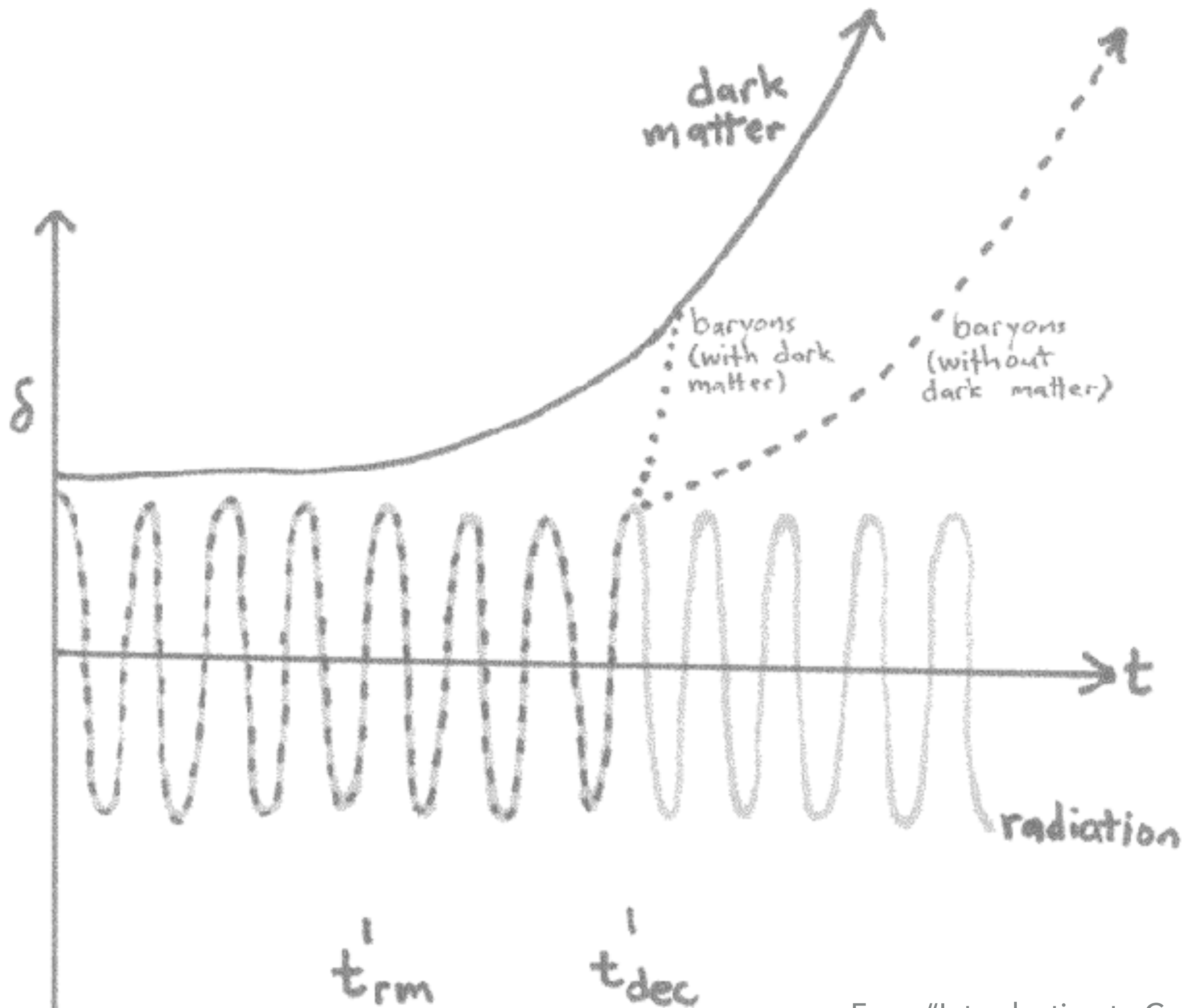


Credit: ESA/Planck Collaboration

Evolution of the Universe



- Dark matter provides the gravitational scaffolding for galaxy and cluster formation.



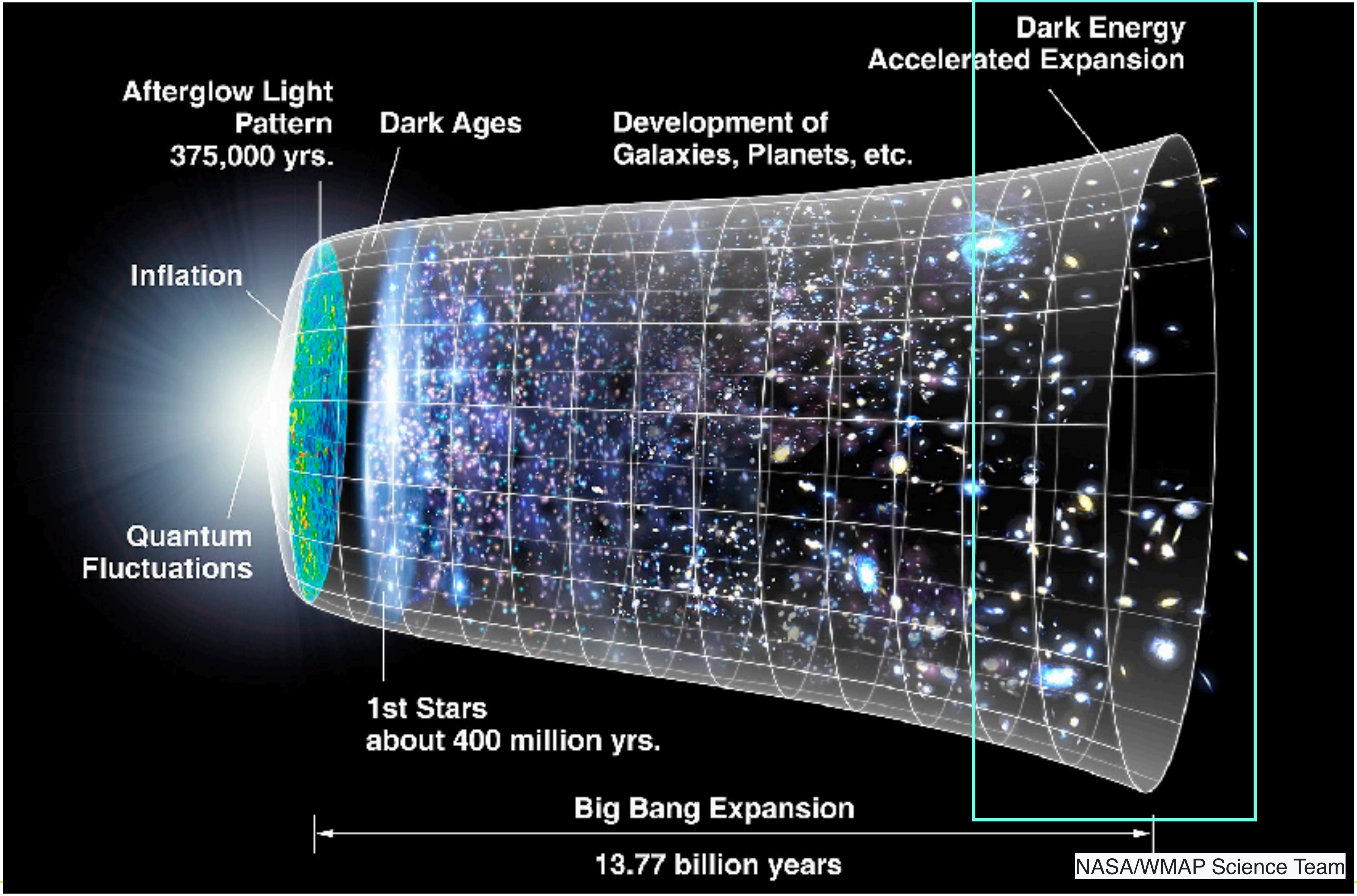
From "Introduction to Cosmology", Barbara Ryden

If dark matter is responsible for structure formation, what properties must it have?

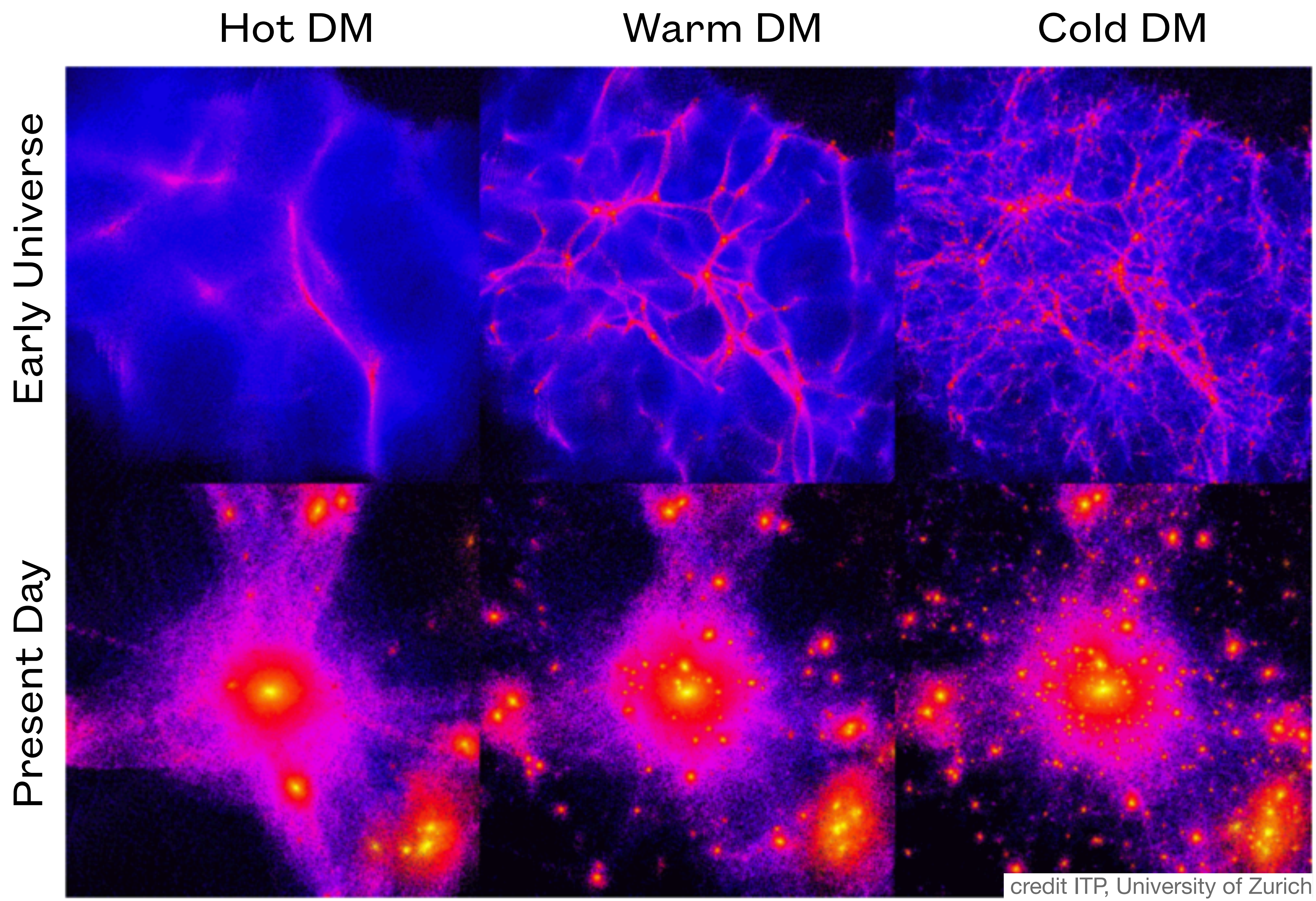
Why CDM?

- Cold and collision-less?
- Cold: non-relativistic $v \ll c$, in the early Universe; no free stream, allowing small-scale density fluctuations to survive and grow into structures.
  —> Bottom-Up formation: Small structures form first and merge into larger ones.
- Free stream: particle moves freely through space without being trapped by gravity.
- Hot DM: remain relativistic v~c for a long time after decoupling, e.g. Neutrinos—> high speed motion escape small overdense regions and wash out density perturbation
  —> Top-Down Structure Formation: Large structures form first and small-scale structures form later by fragmentation
- Warm DM: $v_{HDM} > v_{WDM} > v_{CDM}$.
  —> Still bottom-up, but with fewer very small halos.

Evolution of the Universe



NASA/WMAP Science Team



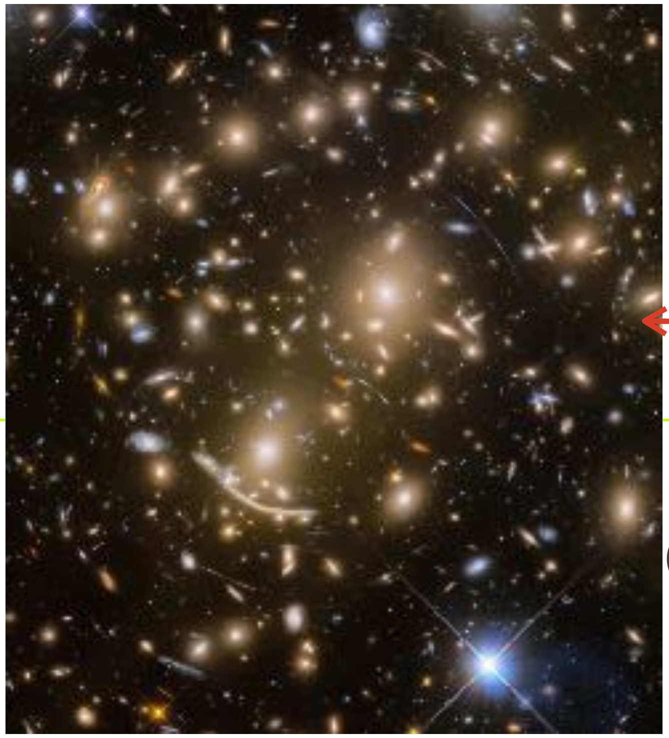
- Top-down structure formation: largest structures form first

- Bottom-up structure formation

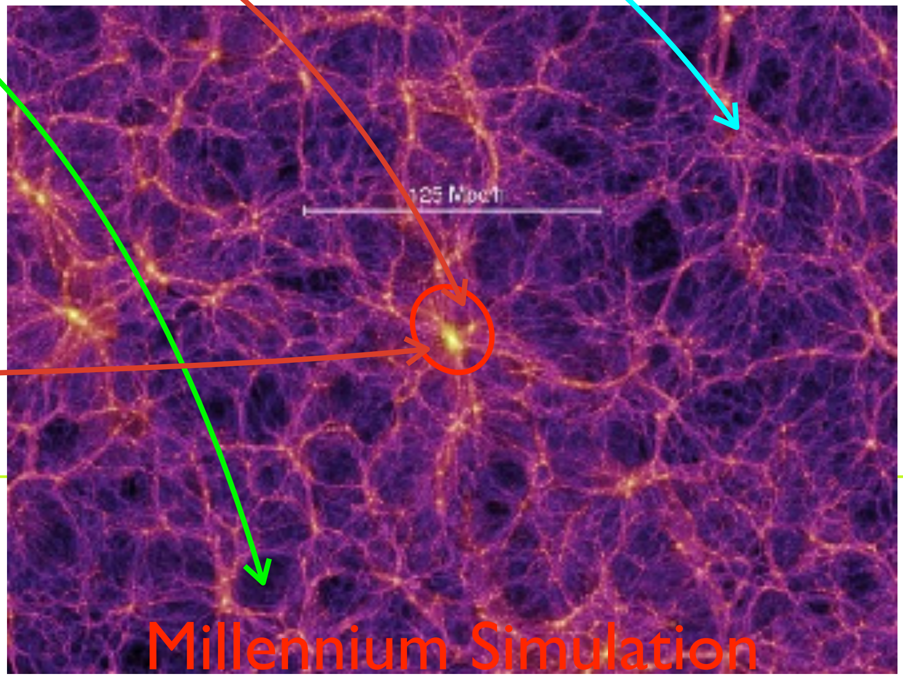
- More small-scales objects compare with HDM

Non-linear Gravitational Growth

- Non-linear regime: $$\delta \equiv \frac{\rho - \bar{\rho}}{\bar{\rho}} \gtrsim 1$$
- Numerical Simulations
- (cosmic web):
  filament structures
  Node: galaxy clusters
  voids: empty region

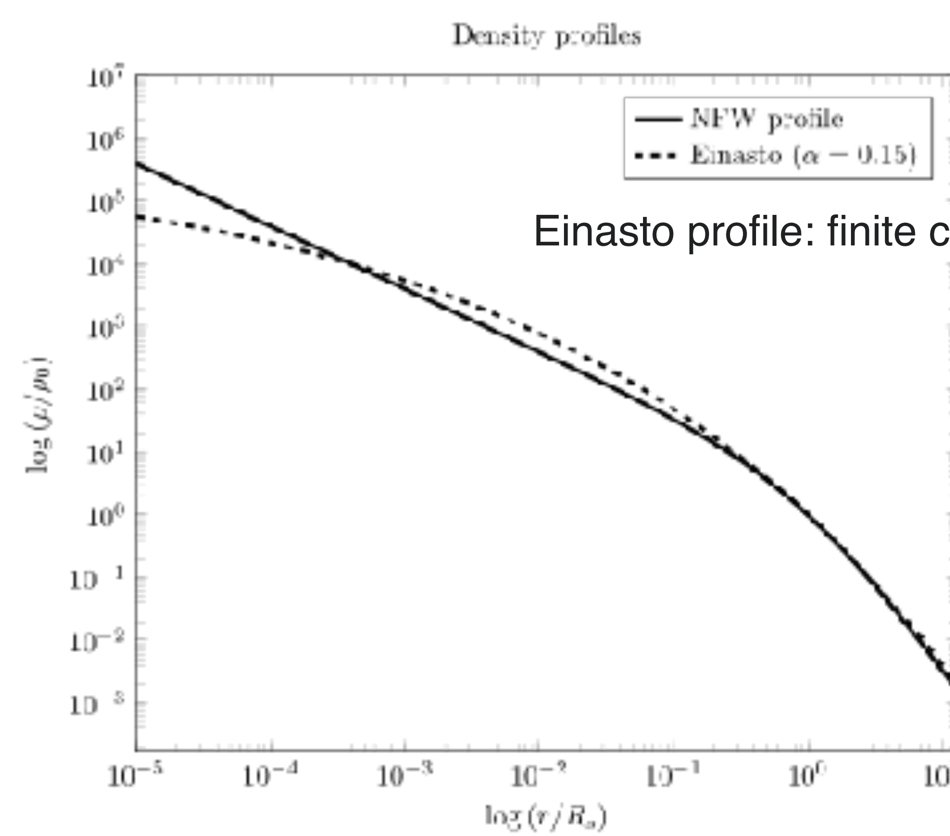


Galaxy cluster



DARK MATTER HALO

- Navarro–Frenk–White (NFW) profile:how dark matter density (ρ) varies with distance (r) from the center of a gravitational halo $$\rho(r) = \frac{\rho_0}{(\frac{r}{r_s})(1+\frac{r}{r_s})^2}$$
- Self-similar model predicted by LCDM: retains the same functional form regardless of the size or mass of the dark matter halo.
- Relaxed/ virialized objects follow NFW model, while unrelaxed (merging) objects deviates from it



Einasto profile: finite central density

Small-Scale Challenges with CDM

- Cusp-Core Problem:
  — CDM simulations predict steep central density profiles in galaxy halos (cusps).
  — Observations show **flatter density profiles** (cores) in galaxy centers, especially in dwarf galaxies

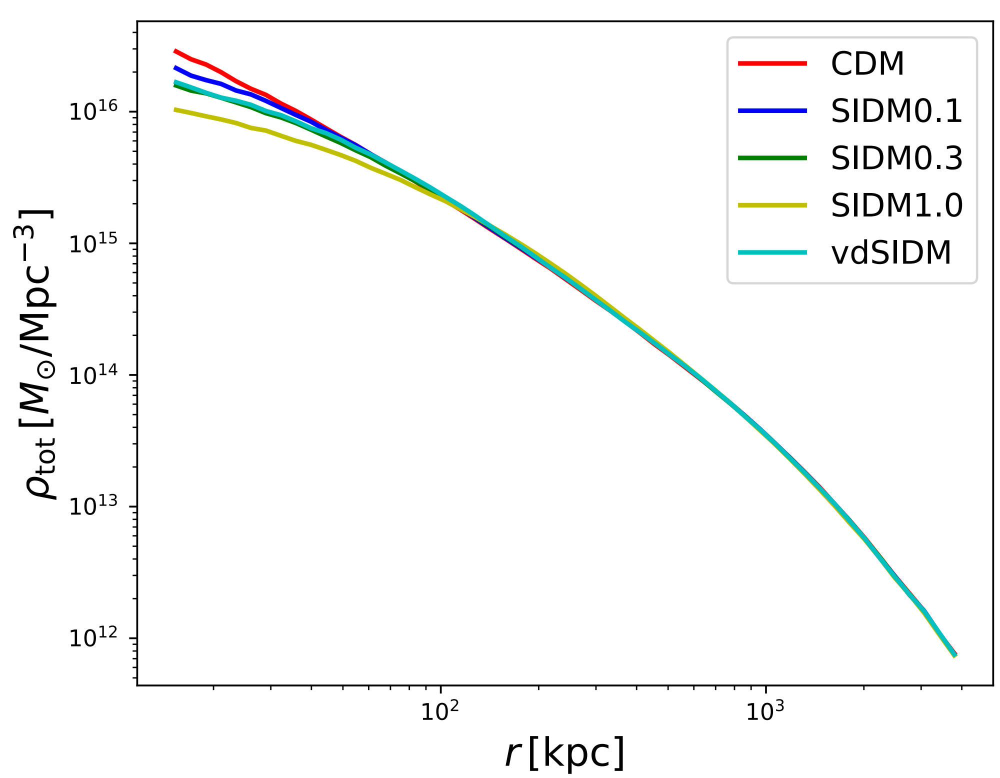
- Missing Satellites Problem:
  — CDM predicts a large number of small satellite galaxies orbiting large galaxies like the Milky Way.
  — Fewer satellites are observed than expected, suggesting discrepancies in the formation of small galaxies.

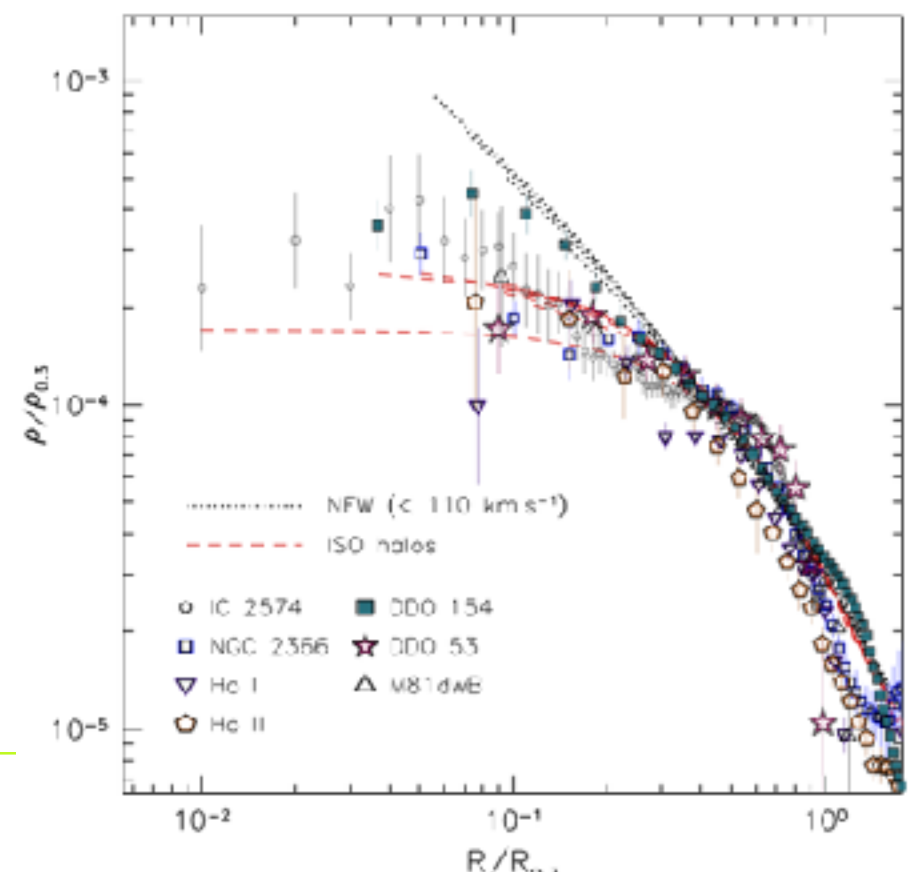
- Too Big to Fail Problem:
  — Massive subhalos in CDM simulations should host observable dwarf galaxies.
  — These massive subhalos are **too dense** and do not match the properties of actual observed galaxies.

Cusp-Core Problem

- CDM simulations predict steep central density profiles in galaxy halos (cusps). Observations show **flatter density profiles** (cores) in galaxy centers, especially in dwarf galaxies

- Possible solutions:
  — Baryonic Feedback: redistribute the dark matter particle
  — Self-Interacting Dark Matter: exchange energy in the core and scatter out the DM particles to outer regions



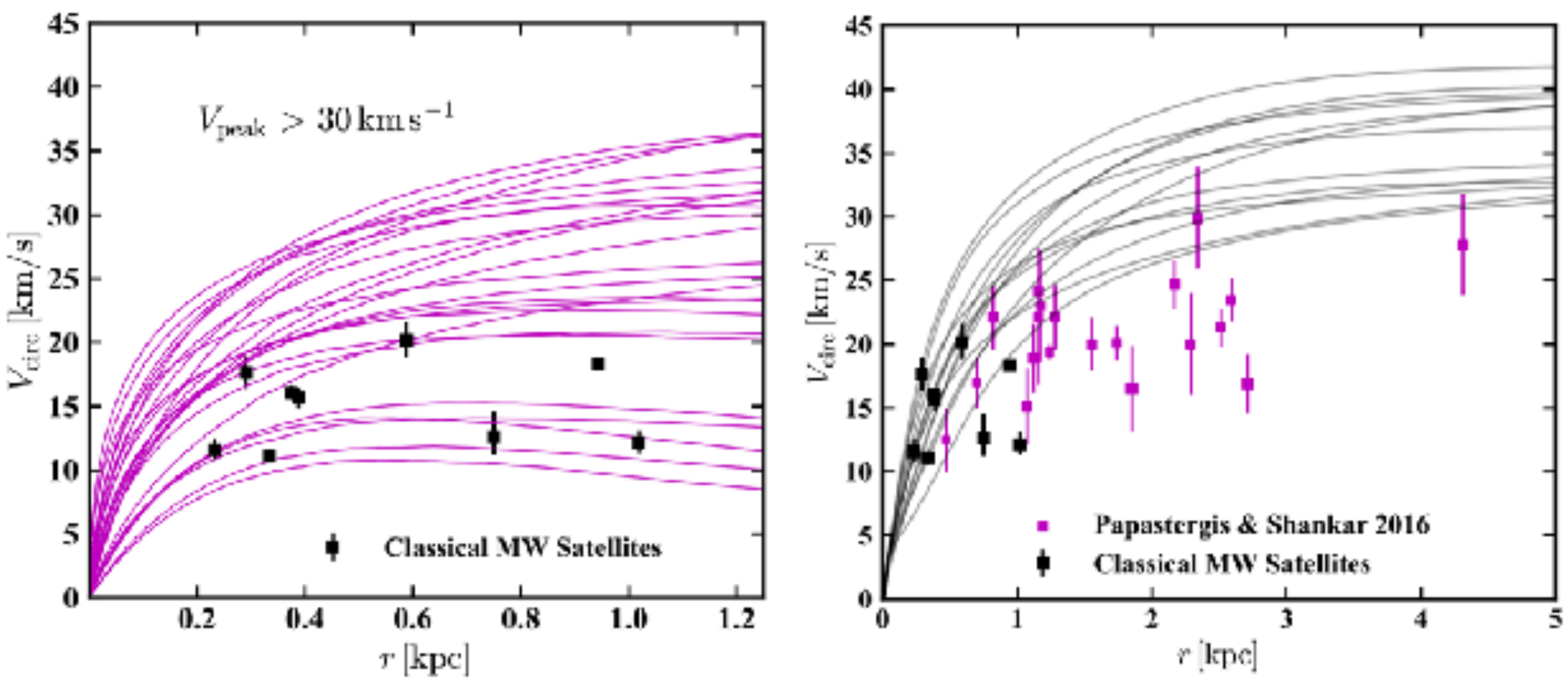


Oh et al. 2011

Too Big to Fail Problem

- From simulations, higher number of massive subhalos with denser halo centers than observed, and these massive subhalos should be able to host visible galaxies if they existed

- Possible solutions:
  — Baryonic Feedback: Feedback from supernovae, stellar winds, and AGN often produce galaxies that are less luminous
  — SIDM: DM with self-interactions can reduce the central density —>shallow cores



All have M too small compared to predictions

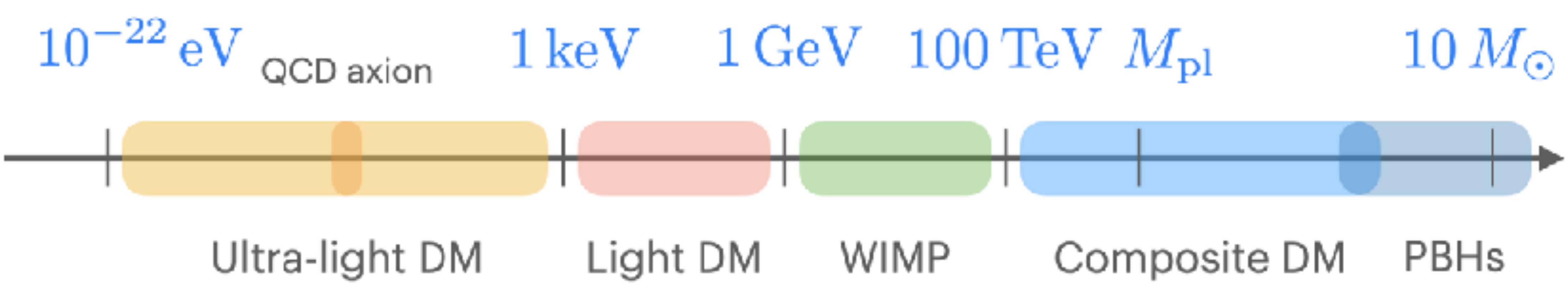
Dark matter models

- CDM:
  — **WIMPs (Weakly Interacting Massive Particles):** The most well-known dark matter candidate, which interacts weakly with normal matter.
  — mass with 1 GeV to several TeV and interact via the weak nuclear force

- Self-Interacting Dark Matter (SIDM): CDM particles with self-interaction

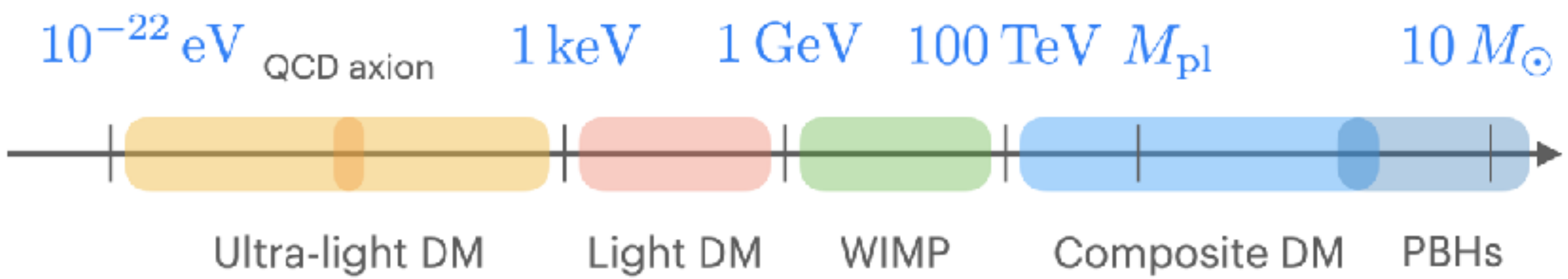
- Neutrinos are no longer a good candidate (hot dark matter)

- Warm dark matter



Dark matter models

- Axions: Ultra-light particles
- Fuzzy (wave) Dark Matter: ultra-light bosonic particles, leading to wave-like behaviour on cosmic scales.
- Massive compact objects (MACHOs): massive, compact, and dark, e.g. Black Holes, Neutron Stars, Brown Dwarfs…
—> From microlensing analyses, MACHOs cannot account for all the dark matter in the universe, their density is too low



SIDM model

- SIDM was proposed to solve the small-scale problems while preserving the successful predictions on large-scales in the ΛCDM model.

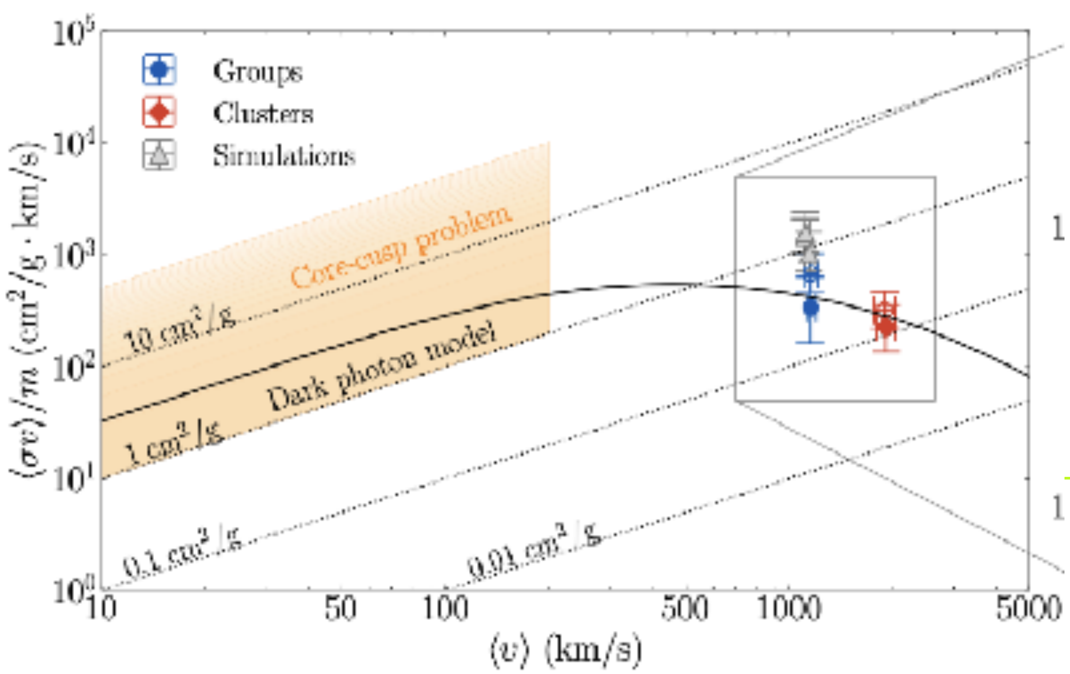
- Dark matter particles in halos elastically scatter with other dark matter particles. (Spergel & Steinhardt 2000)

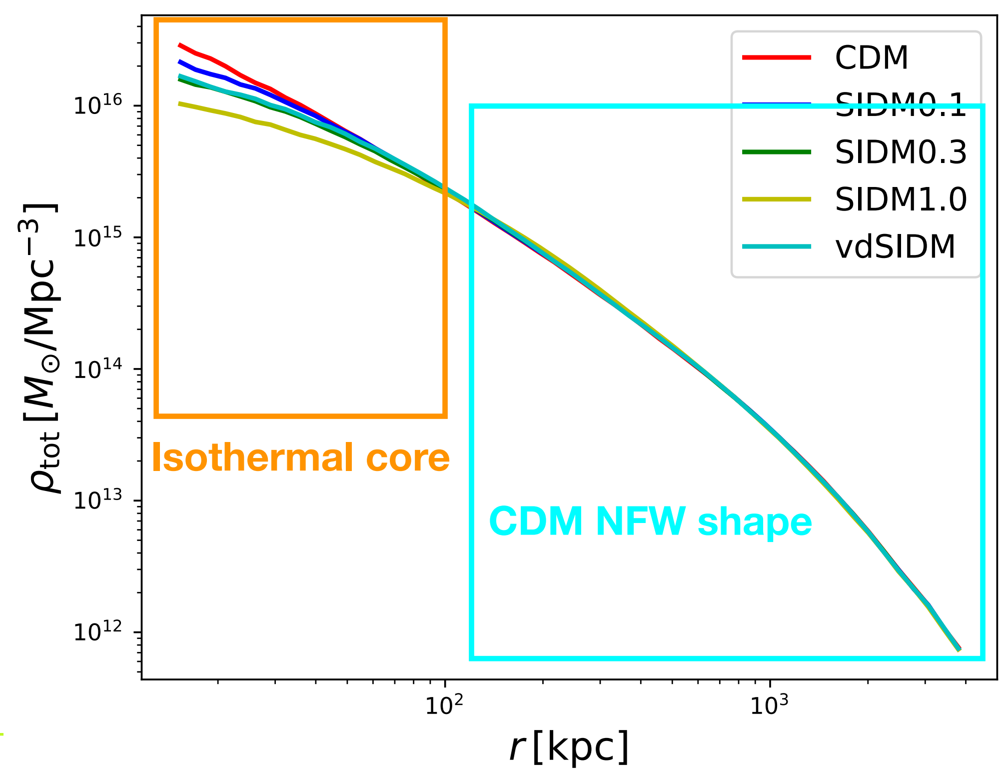
scattering rate = σ (ρ/m) velocity

$$\Gamma t_{age} \sim 1$$

Cross-section σ/m of interest: 0.1~1 cm^2/g from galaxy clusters;
0.5-10 cm^2/g from dwarf galaxy—> velocity dependent SIDM model
σ(v) with light mediator

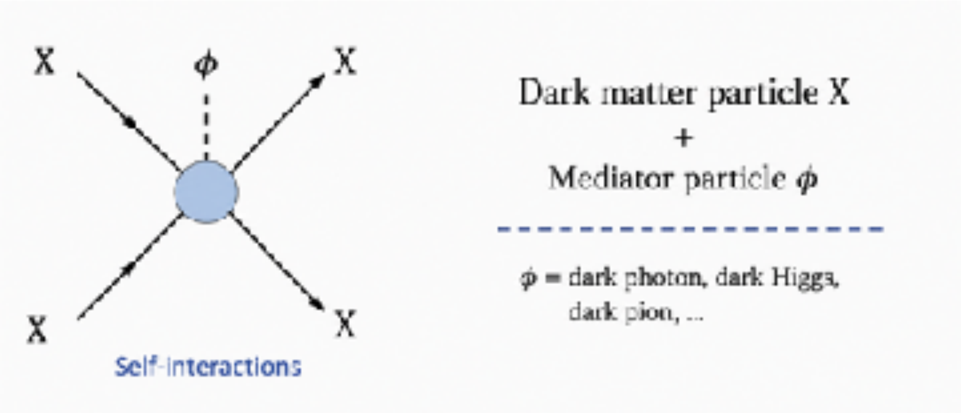
e.g. 15 GeV dark matter interacting through an 11 MeV dark photon yields σ/m ~ O(1) cm2 g−1 in low-velocity systems and ~ 0.1 cm2 /g in galaxy clusters





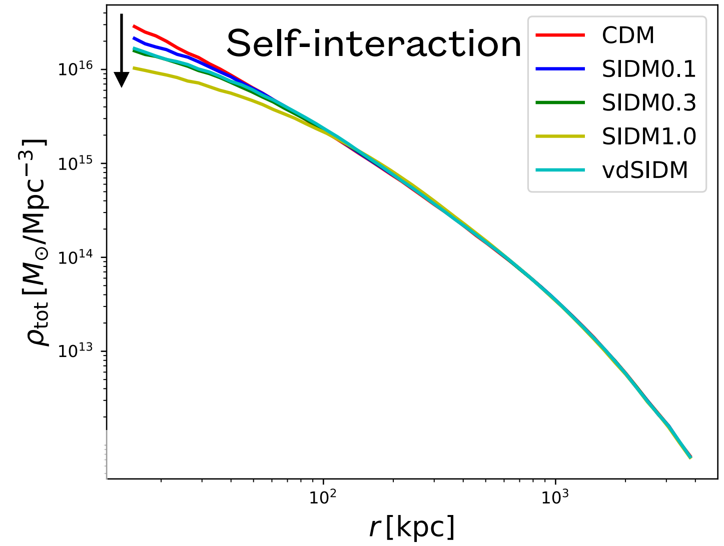
Sagunski et al. (2021).

Particle Physics Realizations of SIDM



- DM may possess a hidden sector containing new mediator particles, such as dark photons or dark scalars.
- Yukawa potential: $$V(r) = \pm \frac{\alpha_\chi}{r} e^{-m_\phi r}$$
- By using Born approximation, the differential cross section can be expressed by $$\frac{d\sigma}{d\Omega} = \frac{\alpha_\chi^2}{\left(m_\phi^2 + m_\chi^2 v^2 \sin^2\left(\frac{\theta}{2}\right)\right)^2}$$
- Heavy mediator mϕ ≫ mχv—> short-range force and isotropic
- Light mediator mϕ ≪ mχv—> long-range force and velocity-dependent σ(v) and anisotropic scattering.

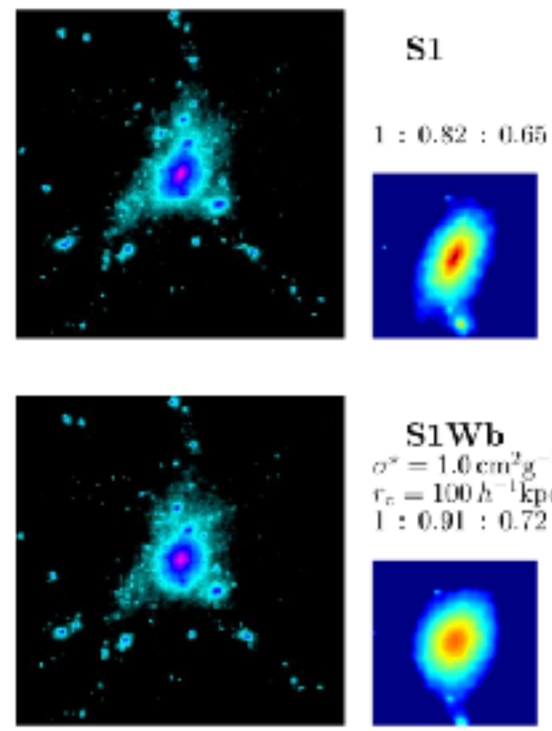
Halo structure affected by self-interaction



- Particles exchange energy through scattering —> Heat flows inward; Central density becomes shallower and expands —> isothermal cores

$$\rho(r) \propto r^{-1} \quad \rightarrow \quad \rho(r) \approx \text{const.}$$

- Self-scattering isotropizes orbits—>DM halos become rounder and less triaxial than in CDM.



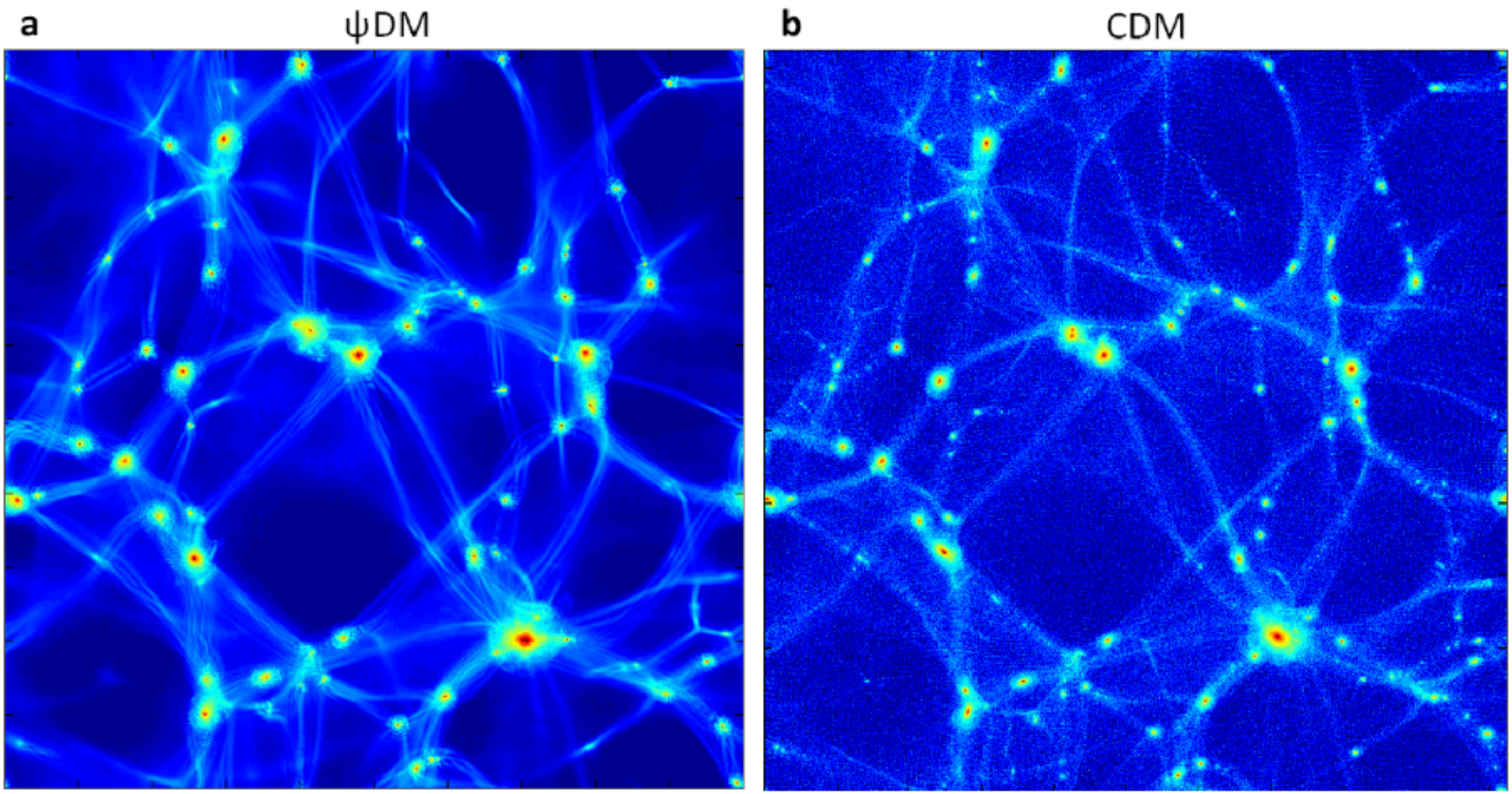
Yoshida et al. 2000

In merging clusters, SIDM behaves more like a collisional fluid than collisionless CDM.

Wave (Fuzzy) DM —ψDM/FDM

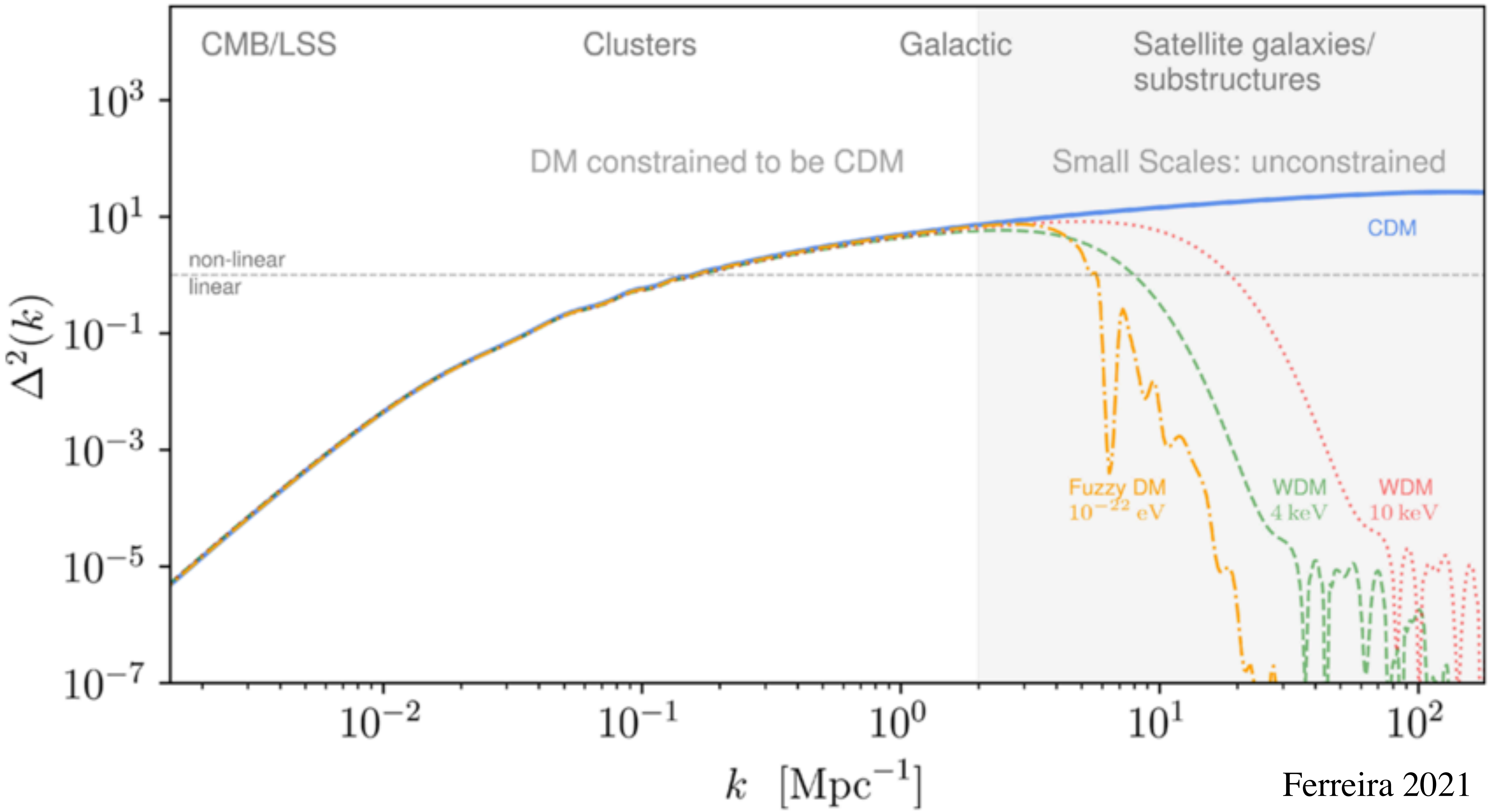
- Extremely light bosons with mass ~10^{-22}eV without interaction
- Why wave? de Broglie wavelength: $\lambda_{\rm dB} = \frac{h}{mv}. \sim {\rm kpc.}$
- The wavelength is comparable to the size of a galaxy —> DM behaves as a coherent quantum wave (e.g., interference) rather than classical particles.
- Solve the cusp-core problem: On large length scales, gravity dominates; on small length scales, quantum pressure ("Heisenberg uncertainty principle") wins—> smooth out the central density —> cored density profile —> solitonic core
- Missing Satellites Problem: Wave-like dark matter suppresses small-scale structure formation—>Reduces the abundance of low-mass halos —> Naturally predicts fewer dwarf satellites
- Delay structure formation:
  Suppression of small-scale density perturbations—> Formation of low-mass halos is delayed relative to CDM—> Fewer dwarf galaxies form at early times (still buttom-up formation)

On scales larger than the quantum Jeans scale, fuzzy dark matter behaves almost identically to collisionless CDM.



Schive, Chiueh, & Broadhurst 2014, Nature Physics, 10, 496

Suppression in small-scales



Ferreira 2021

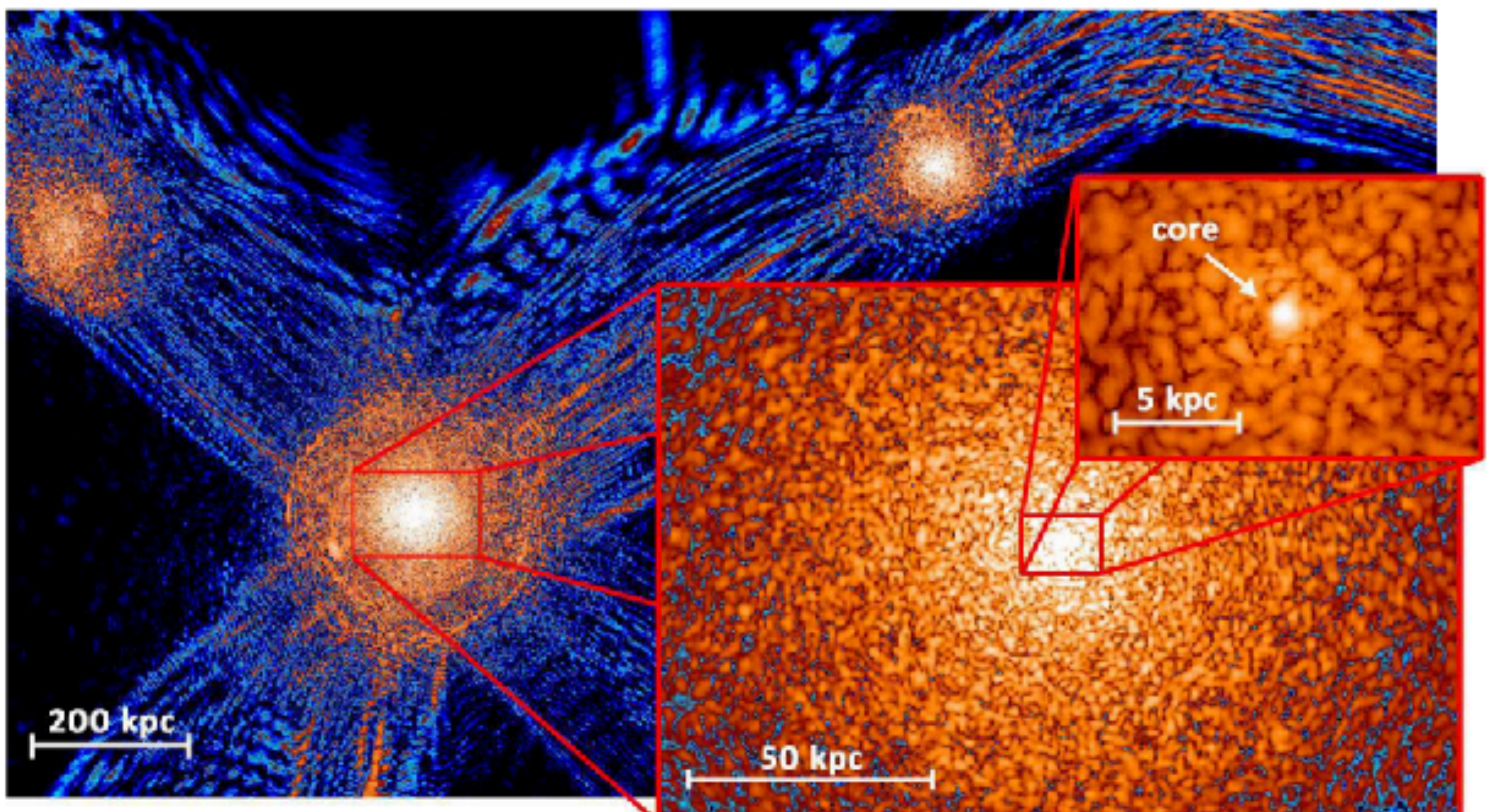
For higher FDM particle masses, smaller cut-off scales.

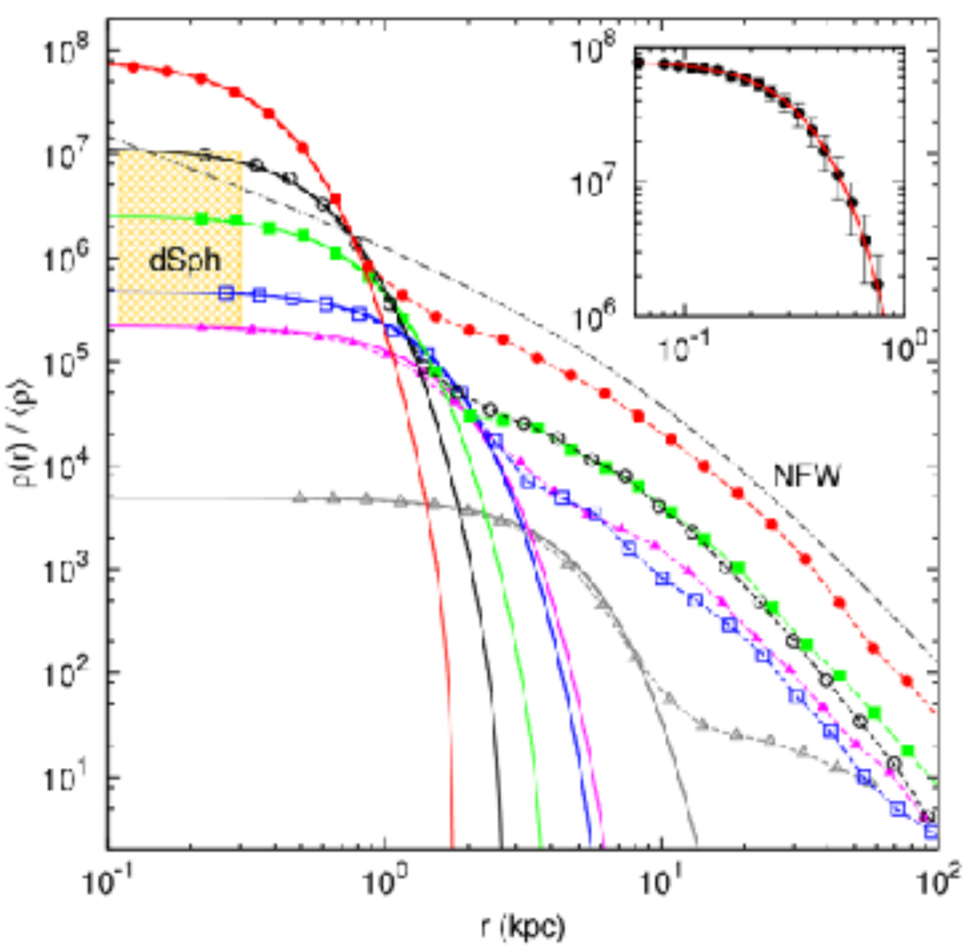
Predicted Astrophysical Signatures

- Soliton cores: spherical, constant-density cores form at the centers of FDM halos

$$r_{\text{core}} \propto \frac{1}{m}.$$

- Quantum Interference—> density granules, and central cores

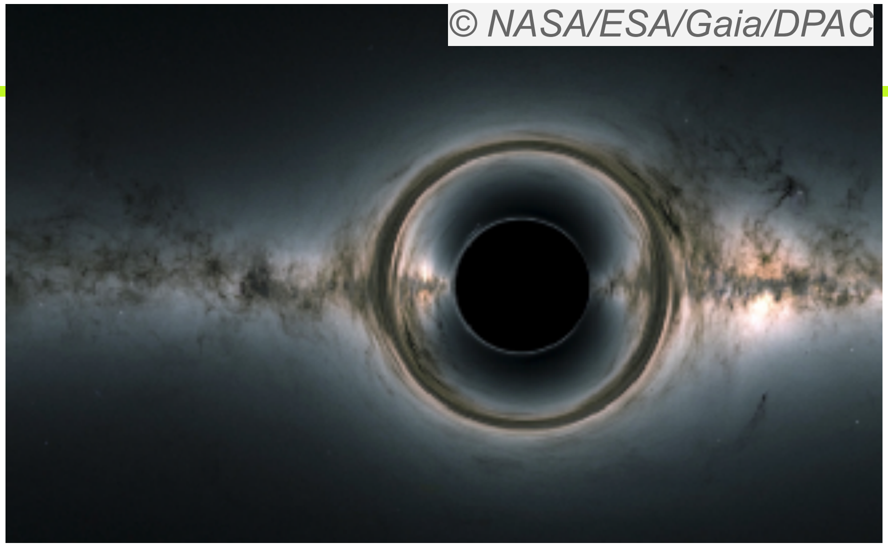




Schive, Chiueh, & Broadhurst 2014, Nature Physics, 10, 496

Constraints on FDM mass scale

MACHOs



- Non-particle candidate: Could dark matter simply be ordinary matter that is difficult to see?
- Massive Astrophysical Compact Halo Objects: Brown dwarfs; White dwarfs; Neutron stars; Black holes
- Search for their Gravitational microlensing signals
- Microlensing events were detected, but far fewer than expected if MACHOs made up the entire dark matter halo—> Most dark matter must be non-baryonic.
- The Standard Model contains no viable dark matter candidate—>DM provides evidence for physics beyond the SM

Conclusion —DM

- Dark matter exists from evidence:
  —Galaxy rotation curves; Galaxy clusters; Gravitational lensing; Cosmic Microwave Background

$$\Omega_{\mathrm{DM}} \approx 0.26$$

- Possible dark matter candidates include:
  WIMPs, SIDM, Axions, Fuzzy DM, and Primordial Black Holes
- No dark matter particle has yet been conclusively detected.
- Astrophysical observations probe dark matter through its gravitational effects.
- Tomorrow: Gravitational Lensing — Seeing the Invisible Universe