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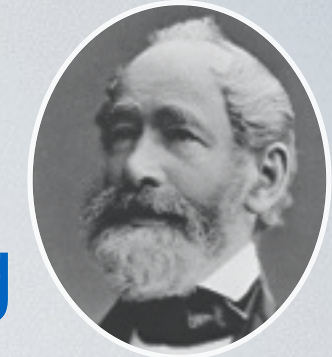


INTRODUCTION TO DARK MATTER

Susanne Westhoff

2nd Colima Winter School on High Energy Physics
January 8-19, 2018 — Colima, Mexico

GALAXY VELOCITIES IN CLUSTERS

Redshift measurements of galaxies: large velocity dispersions

Velocities of nebulae in Coma cluster

$v =$ 8500 km/sek	6900 km/sek
7900	6700
7600	6600
7000	5100 (?)

virial theorem: $\langle v_{\rm rad}^2 \rangle = \alpha \frac{GM}{R}$

Fritz Zwicky, 1898 - 1974

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

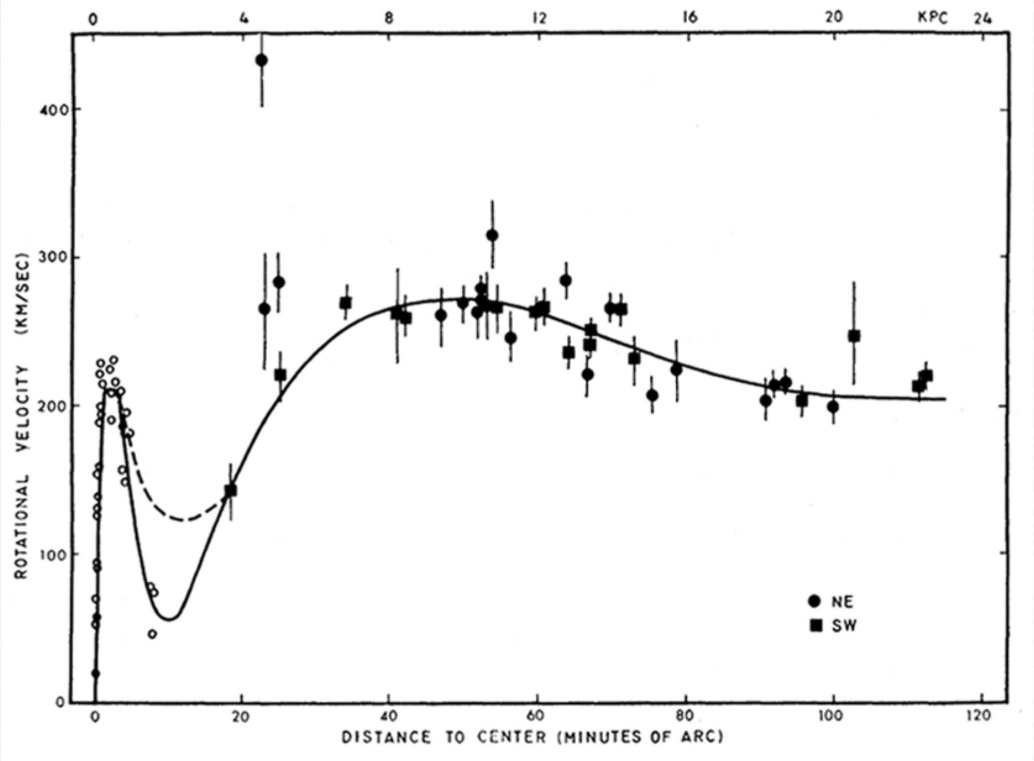
Zwicky, 1933

GAS ROTATION IN GALAXIES

Radio astronomy:

measurements of rotational velocity of hydrogen in galaxies

velocity distribution in Andromeda Nebula



[Rubin, Ford, 1970]

Vera Rubin, 1928 - 2016

Observation: rotational velocity distributions are mostly flat

$$v(r) \sim \text{const.} \quad \neq \quad v(r) = \sqrt{\frac{GM}{r}} \text{ (Newton)}$$

A CLOSED UNIVERSE?

Philosophical considerations:
The expansion of the universe must be decelerating, $\Omega_{\rm tot} \geq 1$.

However, the observed energy density of visible matter was

$$\Omega_{\rm baryons} = \rho/\rho_c \approx 10^{-2} \ll 1$$

„If one tentatively accepts a closed universe, then one is forced to the conclusion that the mass density of $\rho_c \approx 10^{-29} {\rm g/cm}^3$ *must be found outside the normal galaxies. But where?"*

adapted from Stephen Weinberg, 1972

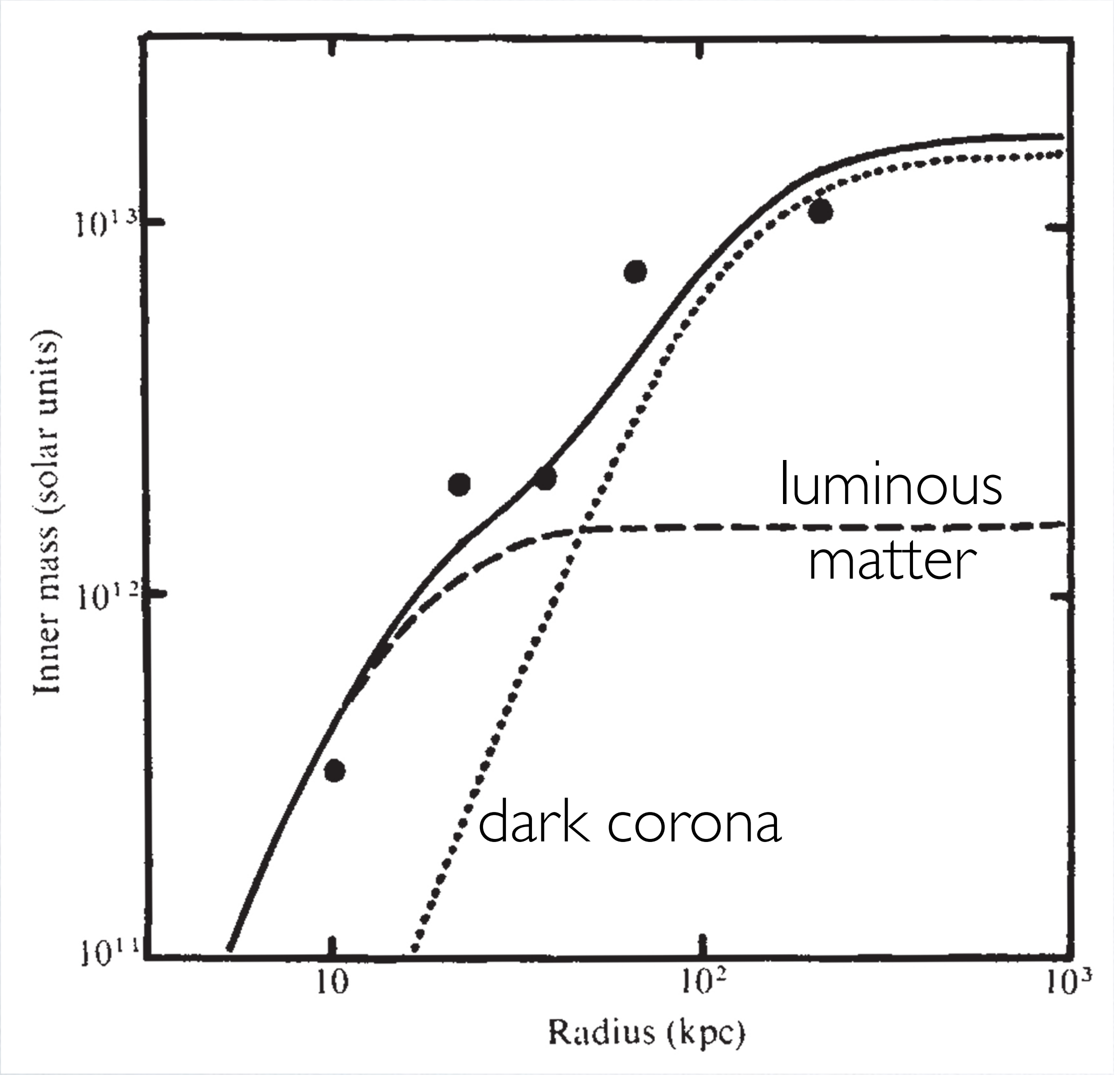
EVIDENCE OF MISSING MATTER

Determining the average mass of the universe

by combining velocity distributions of clusters and galaxies

$$M(r) \sim r$$

Ostriker, Peebles, Yahil, 1974
Einasto, Kaasik, Saar, 1974



[Einasto, Kaasik, Saar, 1974]

Peebles, Abell, Longair, Einasto (l.t.r.)
Tallinn 1977

PART I
DARK MATTER IN THE UNIVERSE

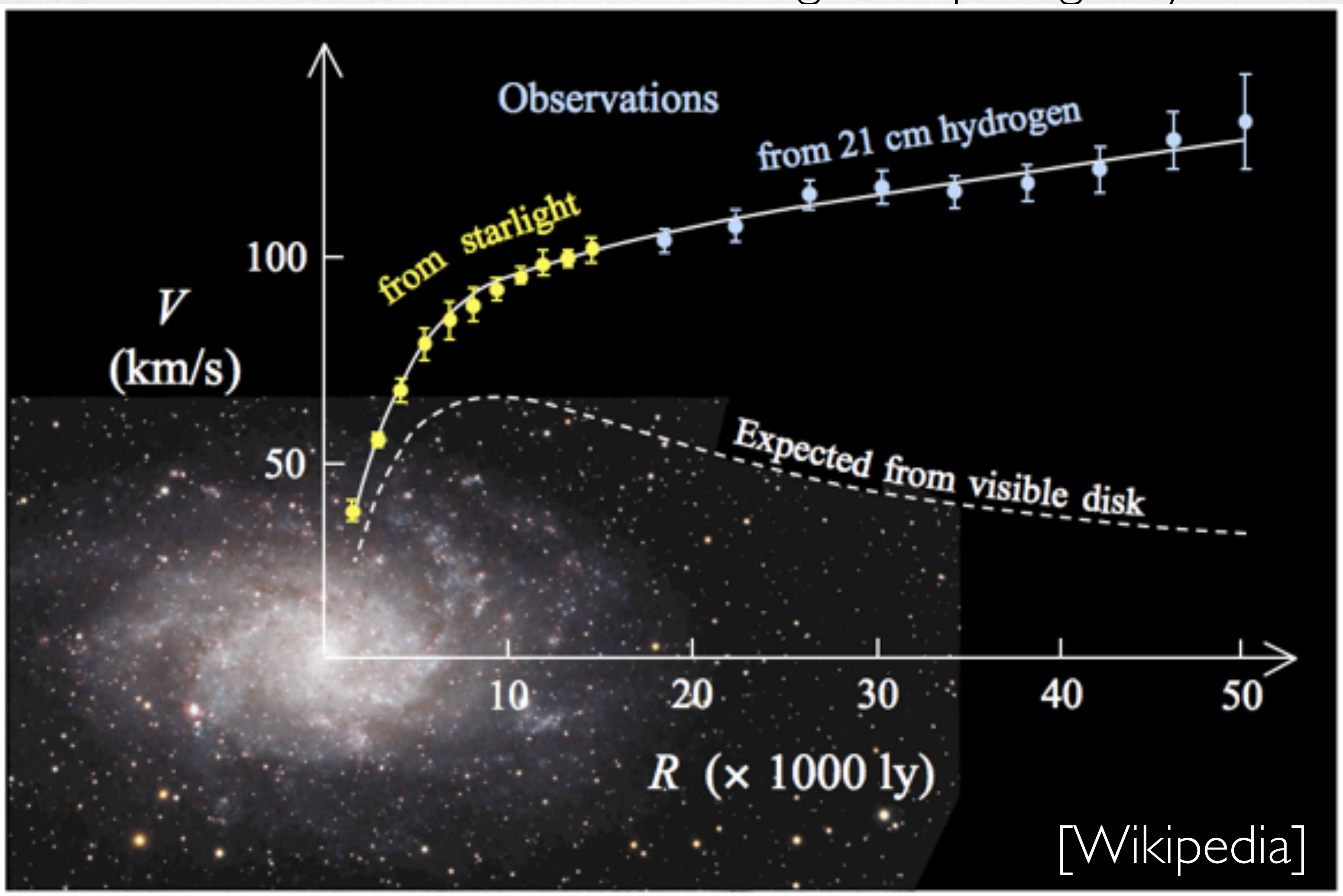
- Experimental evidence today
- Particle dark matter
- The relic abundance

ROTATION CURVES TODAY

Density distribution of DM halo: $\rho(r) \sim \frac{M(r)}{r^3} \sim \frac{1}{r^2}$

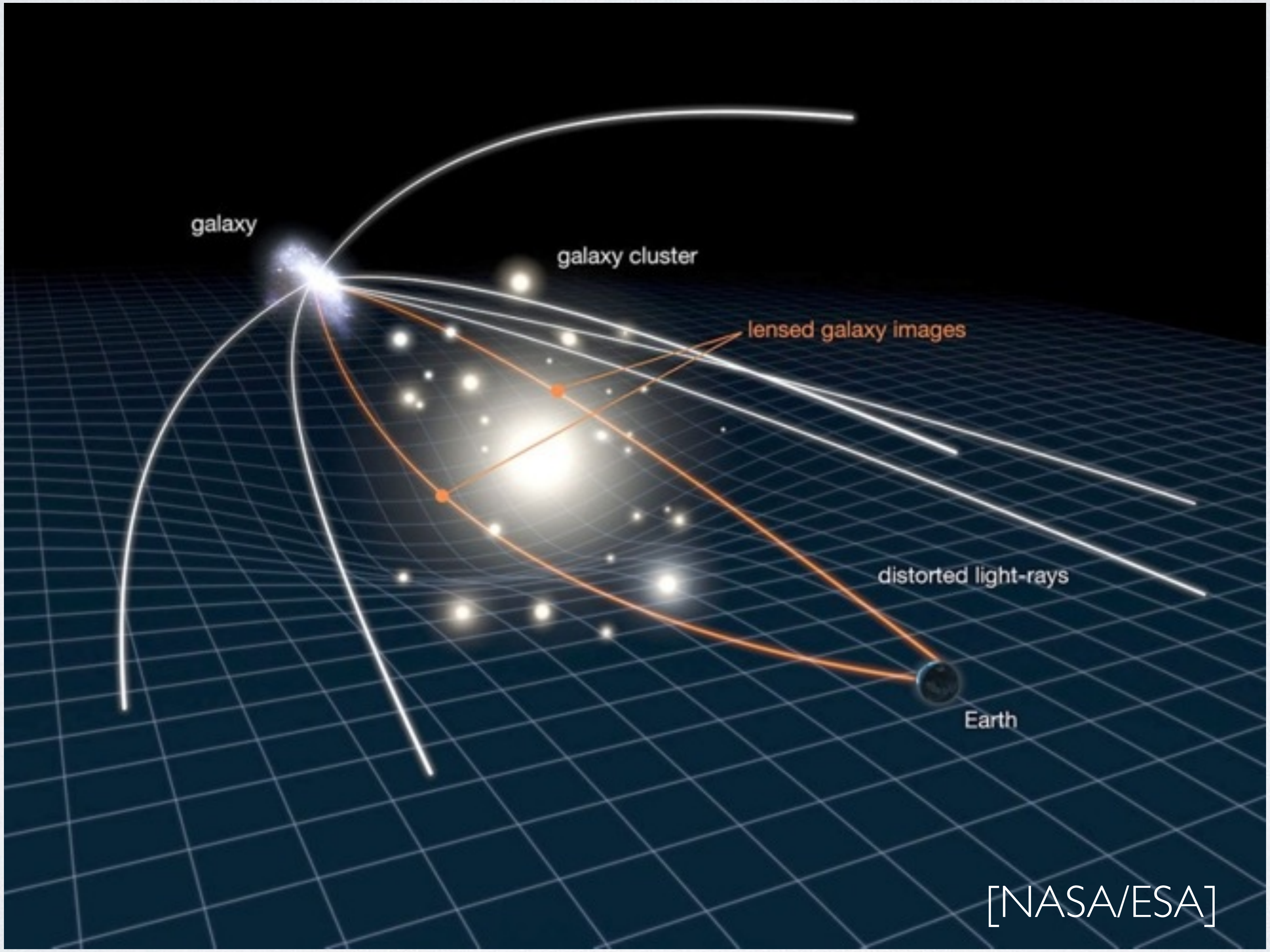
Average velocity: $\langle v \rangle = \sqrt{\frac{GM_{\text{halo}}}{R_{\text{halo}}}} \approx 200\,\text{km/s} \ll c$

Rotation curve of visible stars and gas in spiral galaxy M33

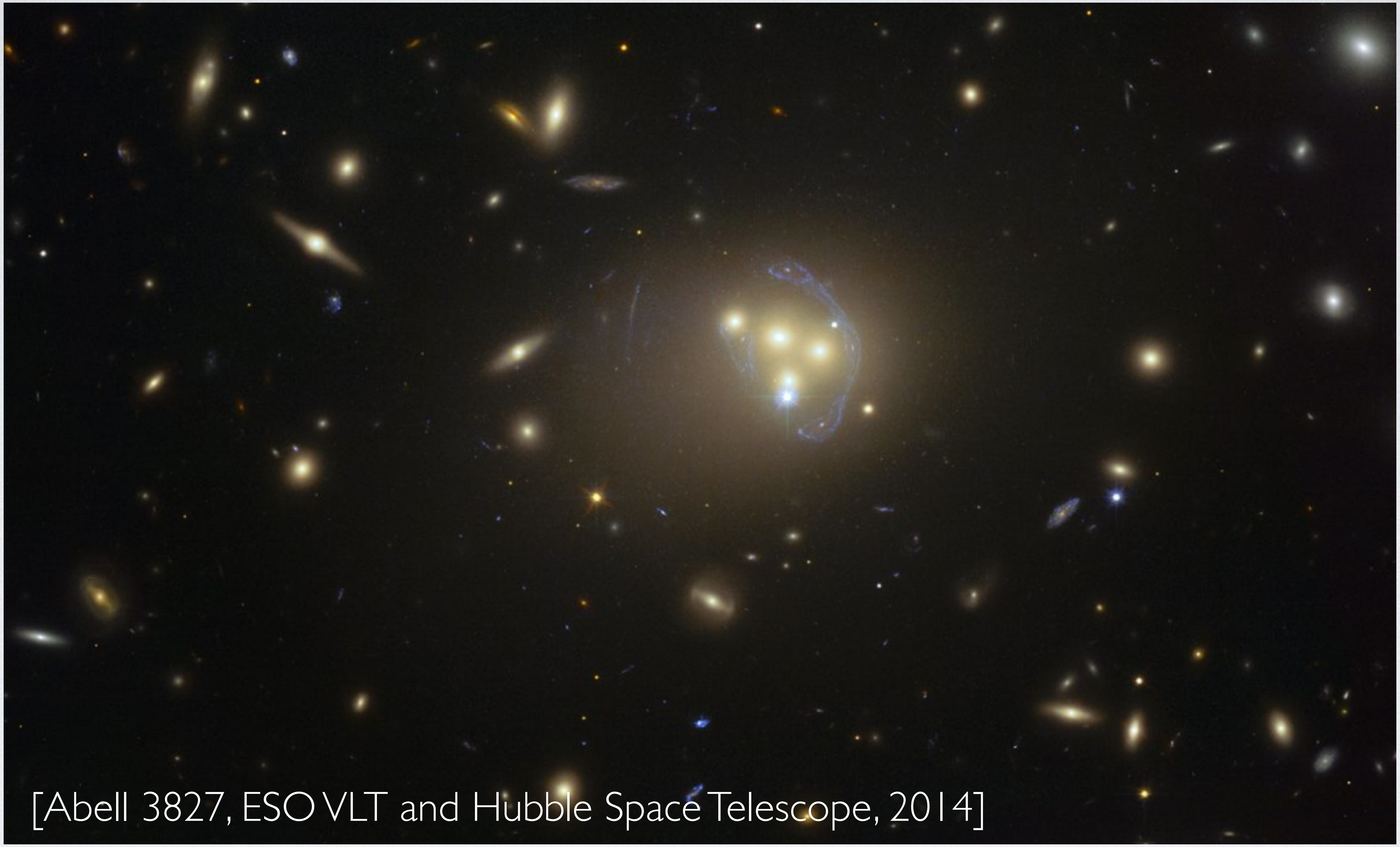


GRAVITATIONAL LENSING

Light is bent when traveling
through the distorted space-time around massive objects



SELF-INTERACTING DARK MATTER?

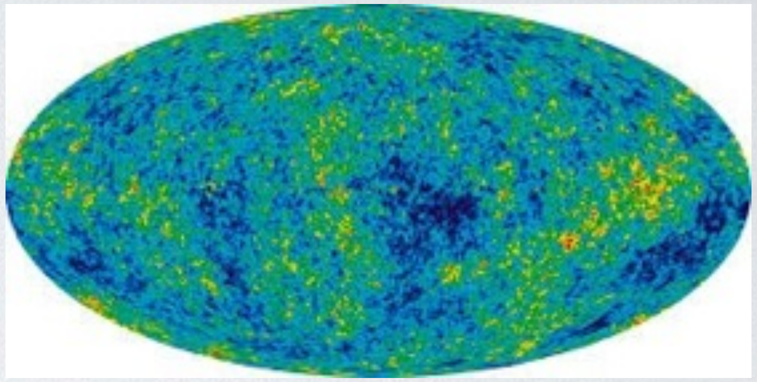


Dark matter seems to lag behind in this collision of galaxies.

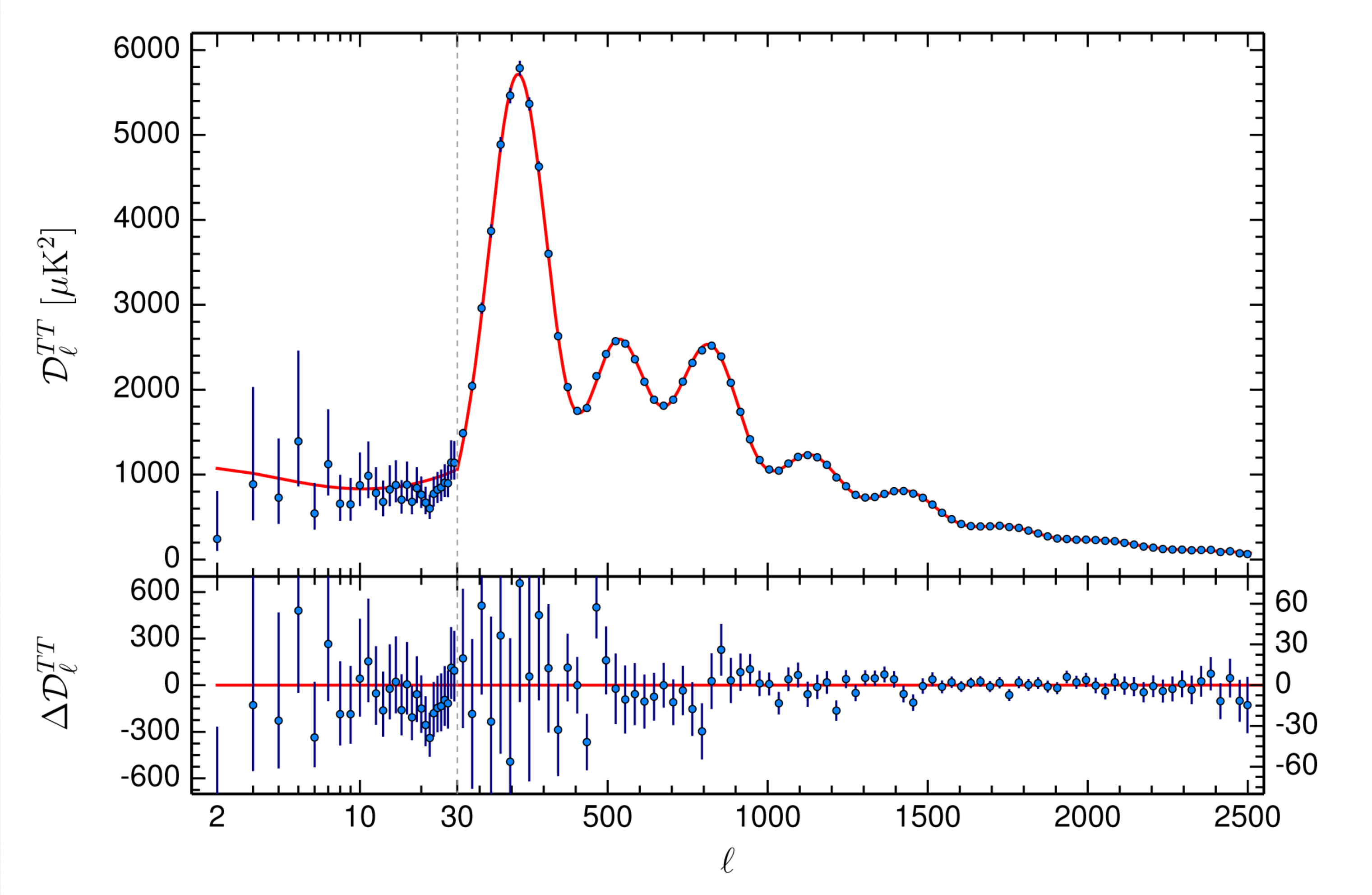
Lag not observed in collisions of galaxy clusters.

COSMOLOGICAL EVIDENCE

- cosmological microwave background anisotropies
- large-scale structure of the universe
- galaxy formation
- baryonic acoustic oscillations

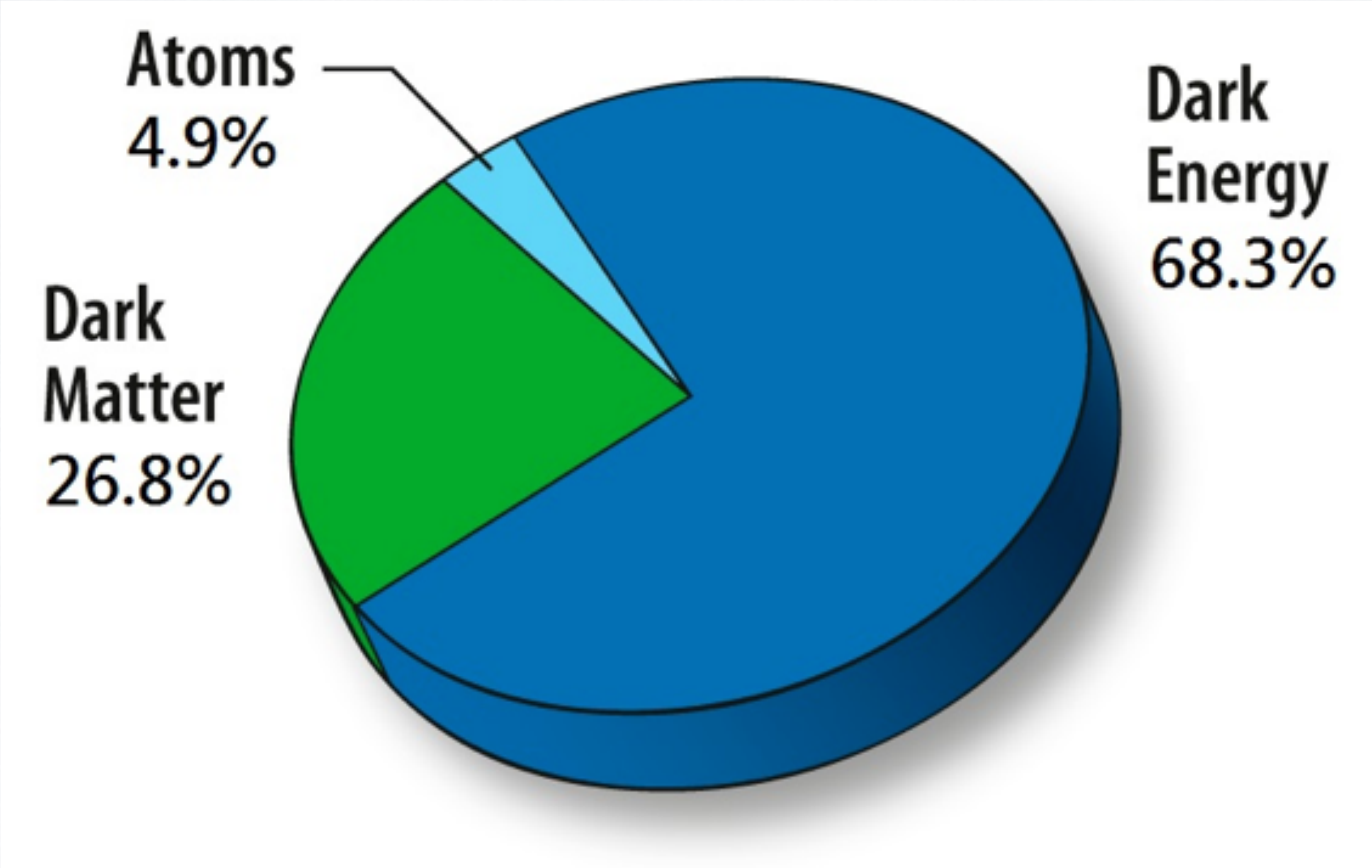


Acoustic peaks of the CMB power spectrum



[Planck+WMAP]

ENERGY BUDGET OF OUR UNIVERSE



[NASA / WMAP Science Team, after Planck 2013]

Density of non-relativistic, non-baryonic matter:

$$\Omega_\chi h^2 = 0.1198 \pm 0.0015$$

[Planck coll., 2015]

WHAT WE KNOW ABOUT DARK MATTER

It exists in **abundance** in the universe today.

It interacts **gravitationally**.

It must be **stable** on cosmological time scales.

It should be mostly non-relativistic („**cold**“).

It cannot be baryonic (primordial black holes are an option).

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WHAT WE DON’T KNOW

Is dark matter a **particle**?

If so, what are its **properties**: mass, spin, interactions?

Does it have **self-interactions**?

Is there maybe an entire **dark sector**?

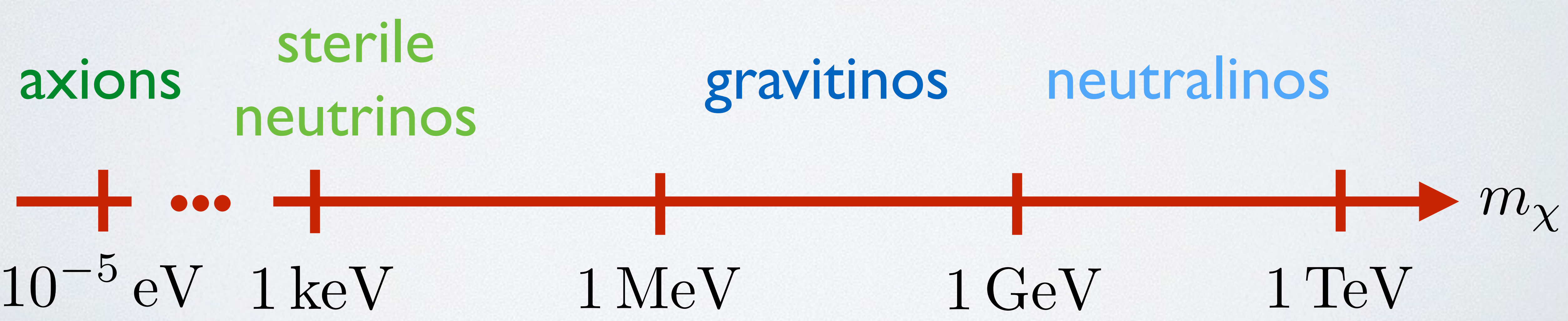
PARTICLE DARK MATTER

Requiring that DM form halos, it should be heavier than

scalar: $m_\chi \gtrsim 10^{-22}\,\mathrm{eV}$ (uncertainty principle)

fermion: $m_\chi \gtrsim 0.7\,\mathrm{keV}$ (Pauli exclusion)

Possible candidates:



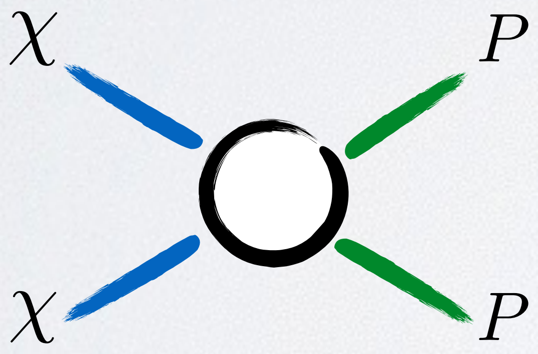
THERMAL DARK MATTER

Dark matter number density in **thermal equilibrium**:

$$n_\chi \sim (m_\chi T)^{3/2} e^{-m_\chi/T}$$ (non-relativistic, „cold")

$$n_\chi \sim T^3$$ (relativistic, „hot")

Dark matter decouples from **chemical equilibrium** when



$$\Gamma_{\chi\chi\to PP} = n_\chi \langle \sigma v \rangle \approx H$$

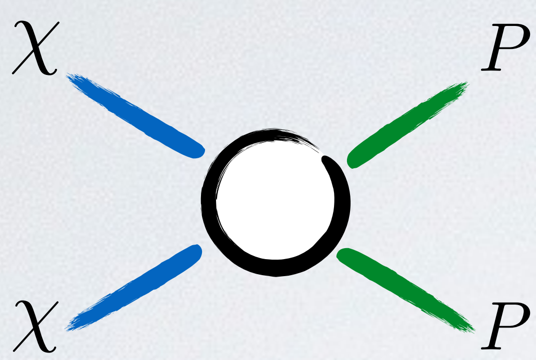
Cold dark matter decouples earlier than hot dark matter.

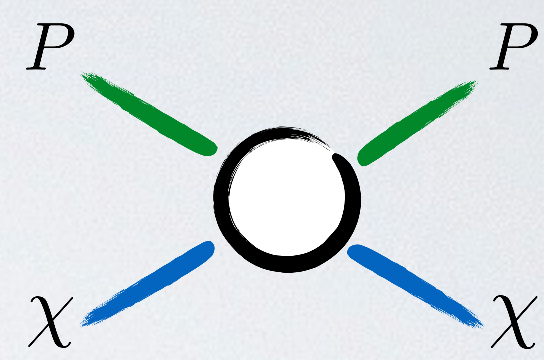
FREEZE-OUT

[Gondolo, Gelmini, 1991]

After chemical decoupling,

cold DM is still in kinetic equilibrium with the SM particle P:





$n_P \sim T^3$

decoupling from chemical equilibrium → decoupling from kinetic equilibrium

$n_\chi \langle \sigma v \rangle \approx H$

$n_P \langle \sigma_{\text{scatt.}} v \rangle \approx H$

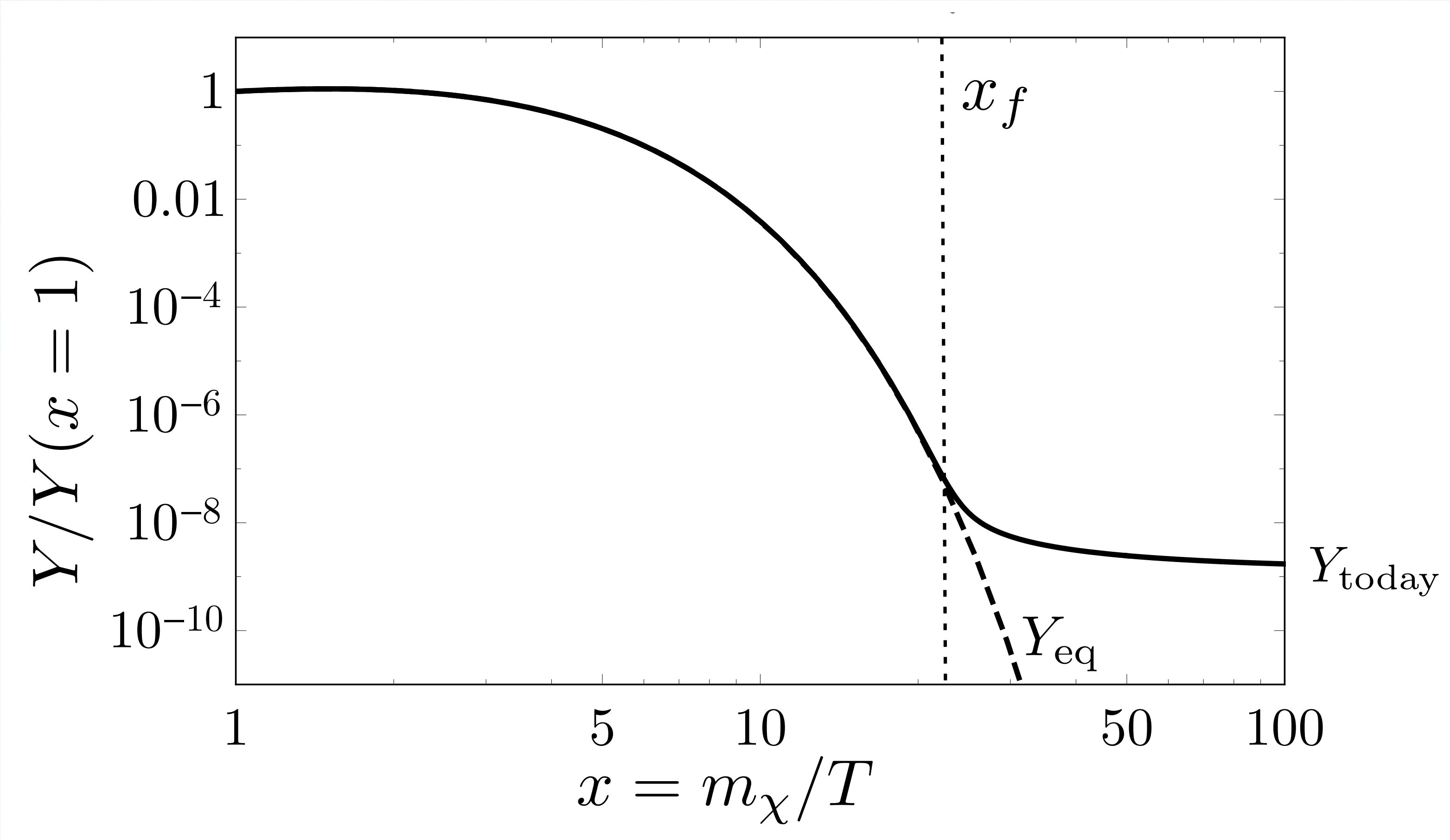
The DM **number density** changes over time as (**Boltzmann**):

$$\frac{dn_\chi}{dt} + 3H(t)n_\chi = -\langle \sigma v \rangle (n_\chi^2 - n_{\chi,\text{eq}}^2)$$

COMOVING NUMBER DENSITY

Scaling out the **Hubble expansion**: $Y = n_\chi/s,\ x = m_\chi/T$

$$\frac{dY}{dx} = -\frac{xs\langle\sigma v\rangle}{H(m_\chi)}(Y^2 - Y_{\rm eq}^2)$$



[Lisanti, TASI 2016]

Non-relativistic limit: $\langle\sigma v\rangle = b_0 + \frac{3}{2}\frac{b_1}{x} + \ldots \longrightarrow Y_{\rm today} \sim x_f$

RELIC DARK MATTER ABUNDANCE

Dark matter density in the universe today:

$$\Omega_\chi = \frac{m_\chi s_{\rm today} Y_{\rm today}}{\rho_c}$$

For a weakly interacting massive particle (**WIMP**):

$$\Omega_\chi h^2 \approx \frac{10^{-26}{\rm cm}^3/{\rm s}}{\langle \sigma v \rangle} \approx 0.1 \left(\frac{0.01}{\alpha}\right)^2 \left(\frac{m_\chi}{100\,{\rm GeV}}\right)^2$$

Observed: $\Omega_\chi h^2 = 0.1198 \pm 0.0015$ [Planck coll., 2015]

Freeze-out temperature: $T_f = 4\,{\rm GeV}\,(x_f = 25, m_\chi = 100{\rm GeV})$

Thermal DM could be much lighter: $\langle \sigma v \rangle \sim \alpha^2/m_\chi^2$

NEUTRINOS AS DARK MATTER?

The cross section for neutrino annihilation is small:

$$\langle \sigma v \rangle \approx 10^{-32} \mathrm{cm}^3/\mathrm{s} \quad \longrightarrow \quad \Omega_\nu h^2 \approx 0.1 \left(\frac{m_\nu}{9\,\mathrm{eV}} \right)$$

From cosmology (e.g., impact on structure formation):

$$\sum_i m_{\nu_i} \lesssim 1\,\mathrm{eV}$$

[e.g. Lesgourges, Pastor, 2012]

Neutrino dark matter would be **relativistic** at freeze-out:

$$T_f / m_\nu \sim \mathrm{MeV}/\mathrm{eV} \gg 1$$

hot dark matter

SM neutrinos can only contribute a small amount of hot DM.

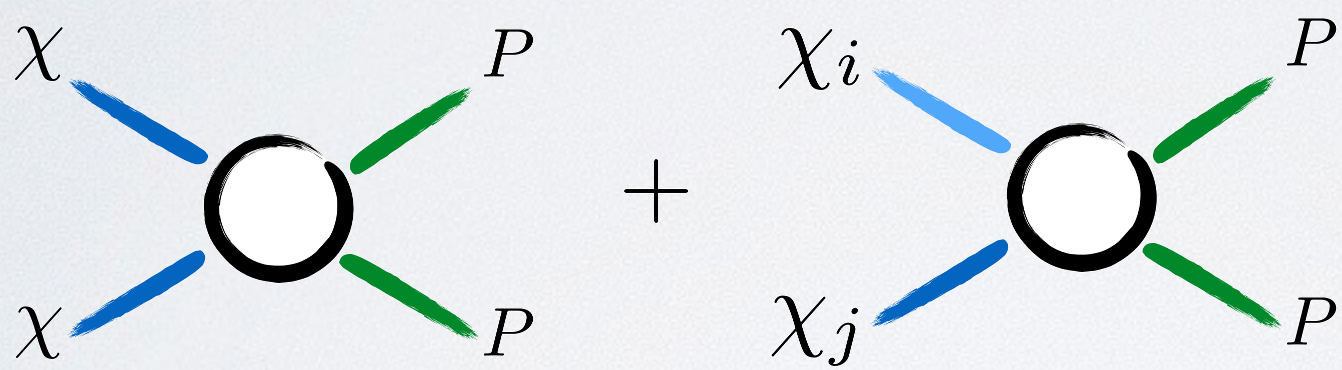
CO-ANNIHILATION

[Griest, Seckel, 1991]

Relative abundance of two non-relativistic particles at freeze-out:

$$\frac{n_i}{n_j} \sim \frac{e^{-m_i/T_f}}{e^{-m_j/T_f}}$$

For $\Delta_i = (m_i - m_\chi)/m_\chi \approx 10\%$: $\quad n_i/n_j \approx 0.1$

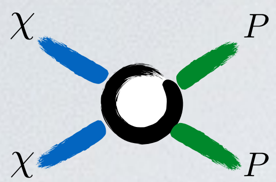


$$\langle \sigma v \rangle \to \langle \sigma_{\text{eff}}(x) v \rangle$$

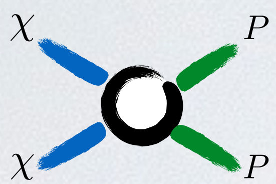
$$\sigma_{\text{eff}}(x) = \sum_{i,j} \sigma_{ij} \frac{g_i g_j}{g_{\text{eff}}^2(x)} (1+\Delta_i)^{3/2} (1+\Delta_j)^{3/2} e^{-x(\Delta_i + \Delta_j)}$$

For $\sigma_{i\chi} \gg \sigma_{\chi\chi}$, co-annihilation sets the relic abundance.

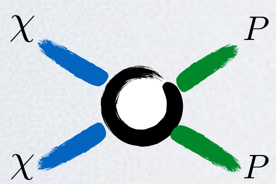
SUMMARY PART I



We have strong evidence for dark matter based on gravitation.



Particle dark matter is a tempting hypothesis, but so far without positive hints from experiment.



Thermally produced dark matter points towards interaction rates that can be tested at colliders.

LITERATURE

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