Astroparticle Theory

Francesca Calore
calore@lapth.cnrs.fr

Lecture 1

1. A short introduction to cosmology
2. The early Universe thermal history
3. Boltzmann equations for thermal relics

Main reference:

Kolb & Turner, "The Early Universe" (1988)

Chapters 1-3, 5

Lecture 2

1. Observational evidence for dark matter
2. Fundamental properties of dark matter
3. The dark matter landscape

References in the slides

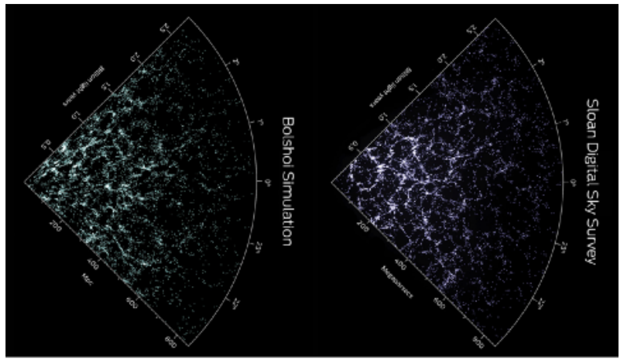
1. Observational evidence for dark matter

Dark matter gravitational evidence

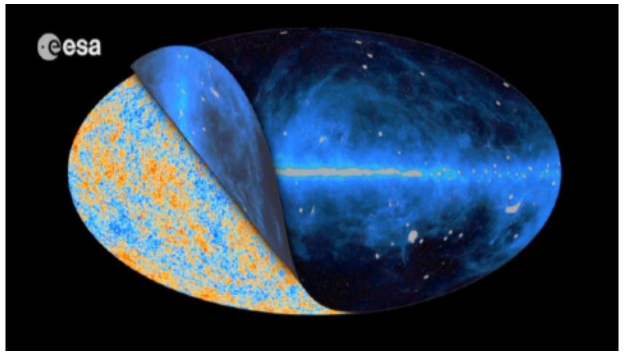
Rotation curves

Galaxy clusters

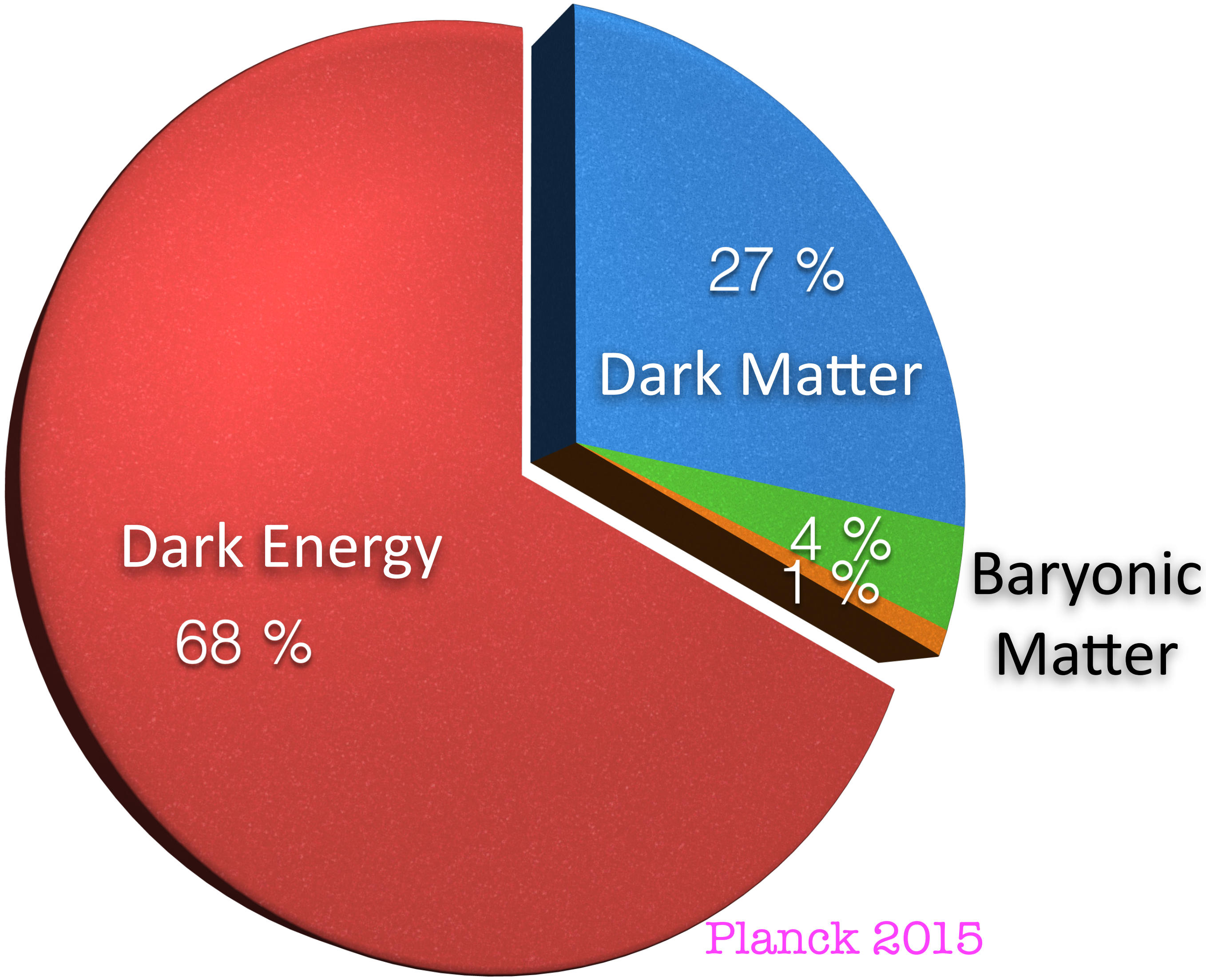
Large Scale structures



Cosmic microwave background

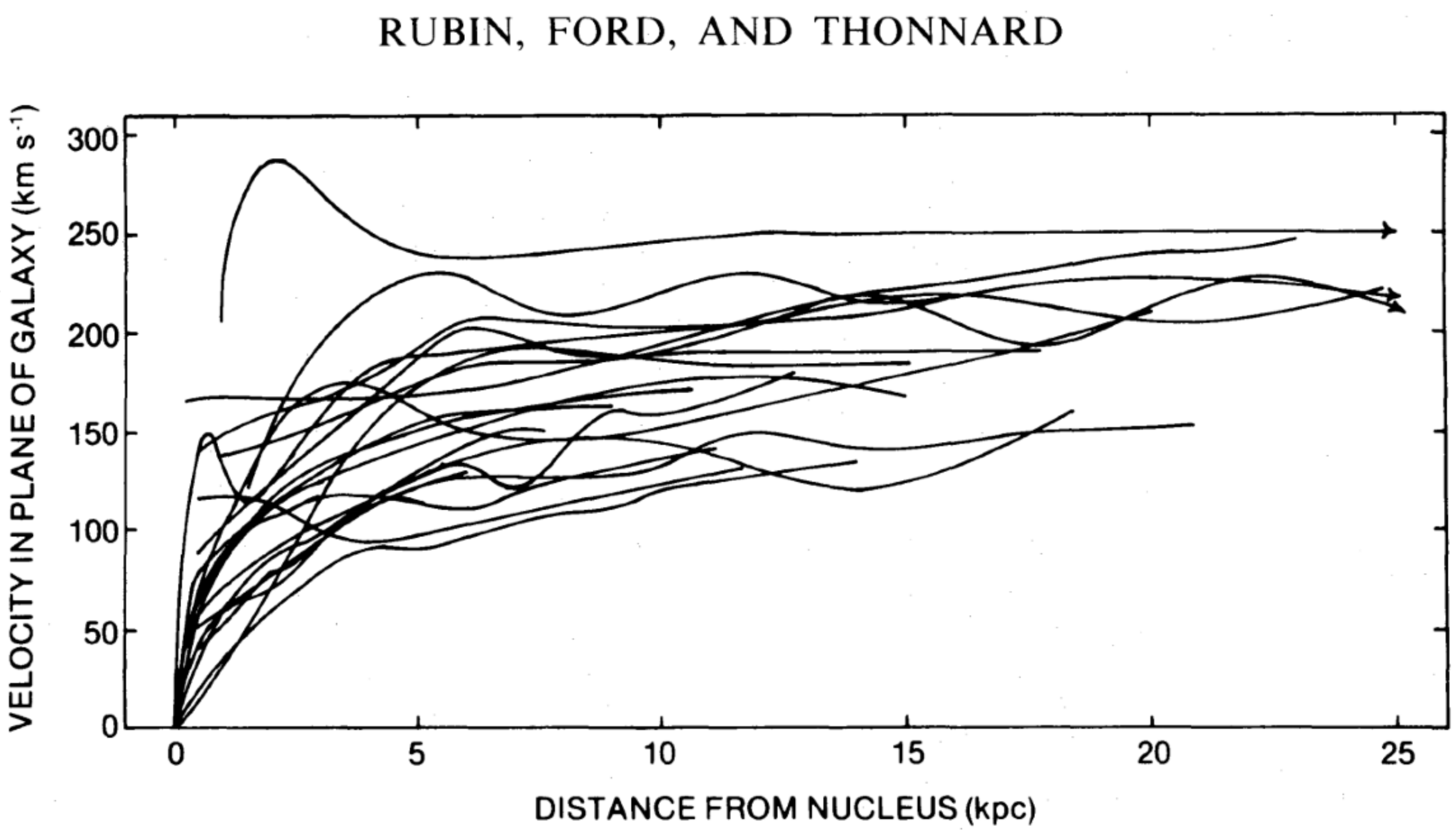


We do not know what most of the Universe is made of!



Dark matter constitutes about 85% of the matter content of the Universe.

Flat galactic rotation curves



'70/'80: observation of spiral galaxies,
rotation supported systems like the Milky Way

V. C. Rubin and W. K. Ford, Jr., ApJ 159, 379 (1970); V. C. Rubin, N. Thonnard and W. K. Ford, Jr., ApJ 238, 471 (1980)

$$v_c^2(<R) = R\frac{d\phi_{\rm tot}}{dR} = \frac{GM(<R)}{R}$$

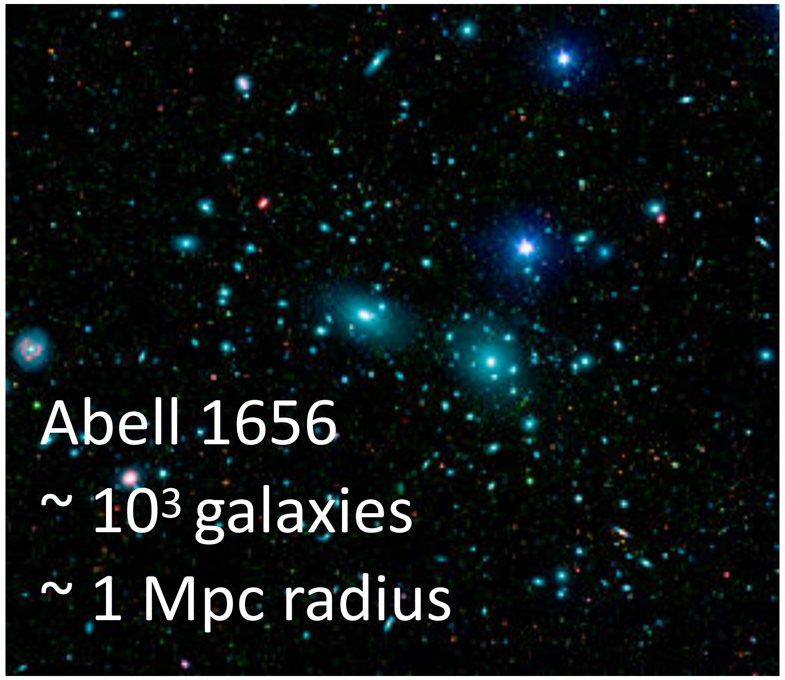
$$M(<R) \equiv 4\pi \int_0^R r^2 \rho(r) dr$$

Predicted from visible light: $v_c^2 \propto \frac{1}{R}$

Observed: $v_c^2 \sim constant$ → $\rho(r) \propto \frac{1}{r^2}$

Data are well described by an additional "matter" component, but also **MOND** works at these scales

Dark matter in the Coma Cluster



Pioneering application of the **virial theorem** in astronomy

F. Zwicky, Helvetica Physica Acta (1933) 6, 110–127; ApJ (1937) 86, 217

$$2\langle T\rangle + \langle U_{\rm tot}\rangle = 0 \qquad U(r) \propto r^{-1}$$

$$T = N\frac{m}{2}\langle v^2\rangle$$

$$\langle U_{\rm tot}\rangle \sim -\frac{3}{5}\frac{G_N M^2}{R}$$

gravitational potential of a self-gravitating homogeneous sphere of radius R

$$\longrightarrow \quad M \sim \mathcal{O}(1)\frac{R\langle v^2\rangle}{G_N} \sim 3\times M_{\rm visible}$$

X-rays and gravitational lensing

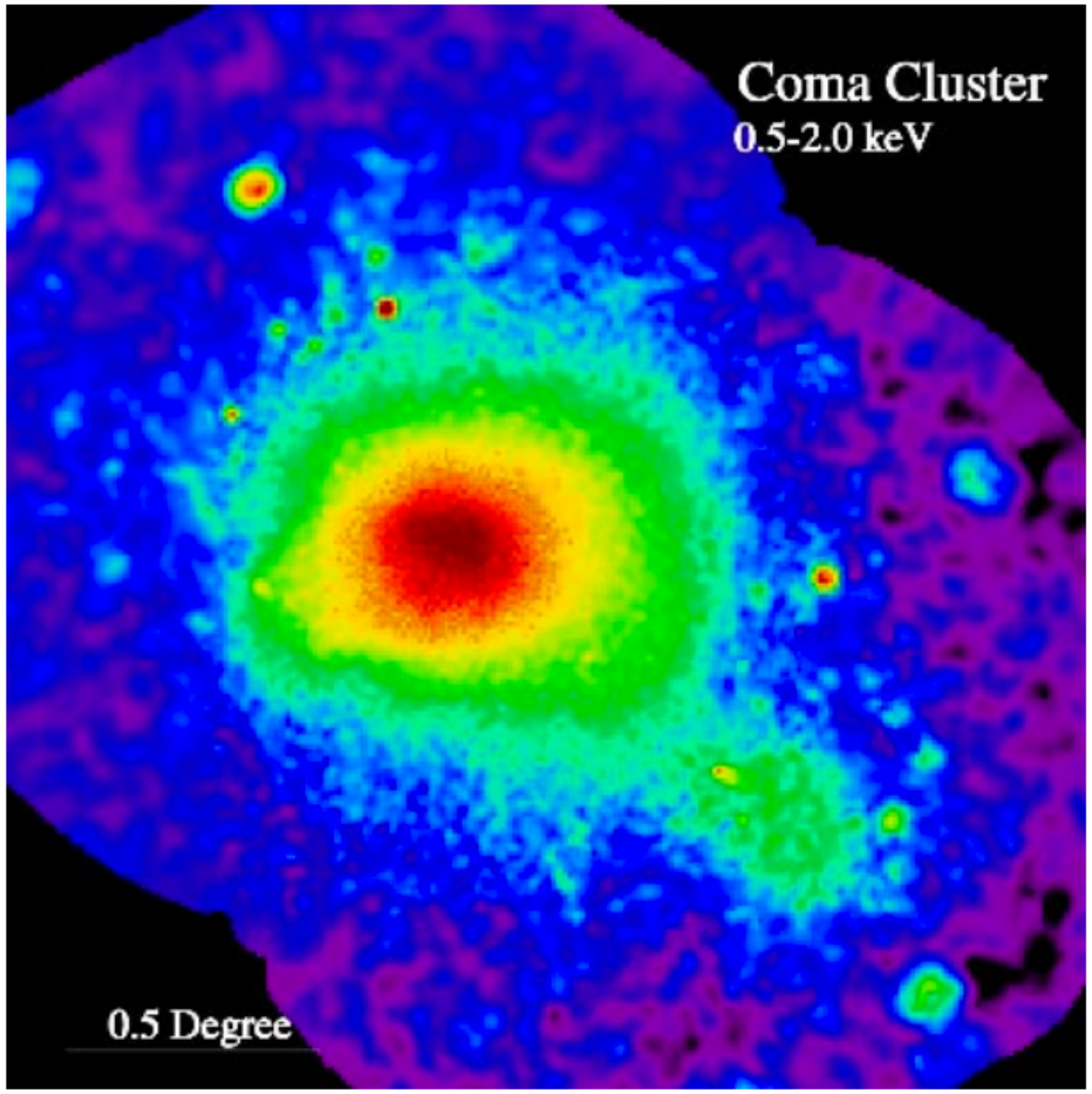
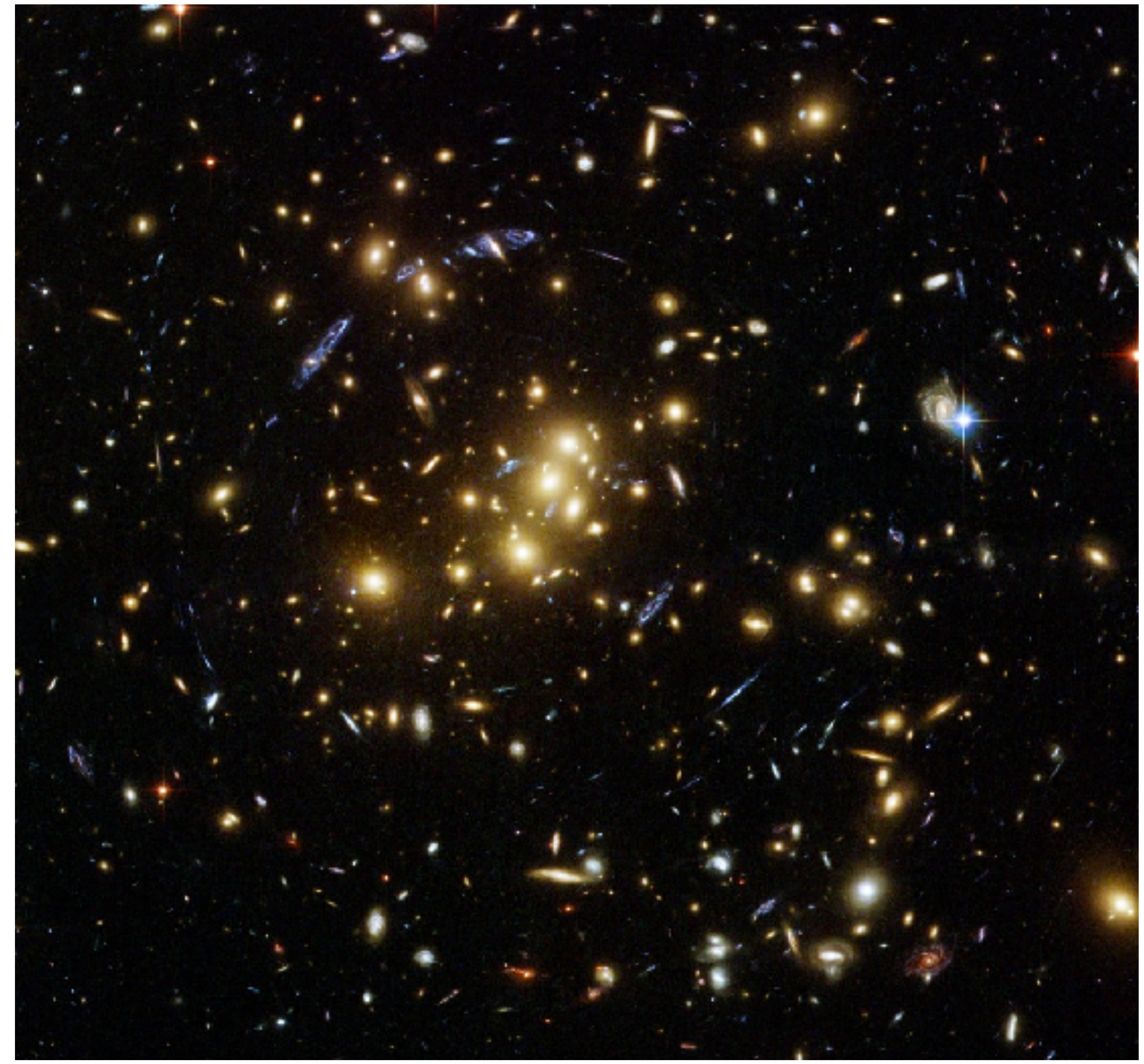


Figure 2. An x-ray image of the Coma cluster obtained with the ROSAT satellite, showing both the main cluster and the NGC4839 group to the south-west. (Credit: S L Snowden, High Energy Astrophysics Science Archive Research Center, NASA.)

Mass in clusters is in the form of hot, intergalactic gas, which can be traced via X rays: X-luminosity and spectrum constrain the mass profile

Lewis, Buote & Stocke, ApJ (2003), 586, 135



Strong gravitational lensing around galaxy cluster CL0024+17, demonstrating at least three layers projected onto a single 2D image.

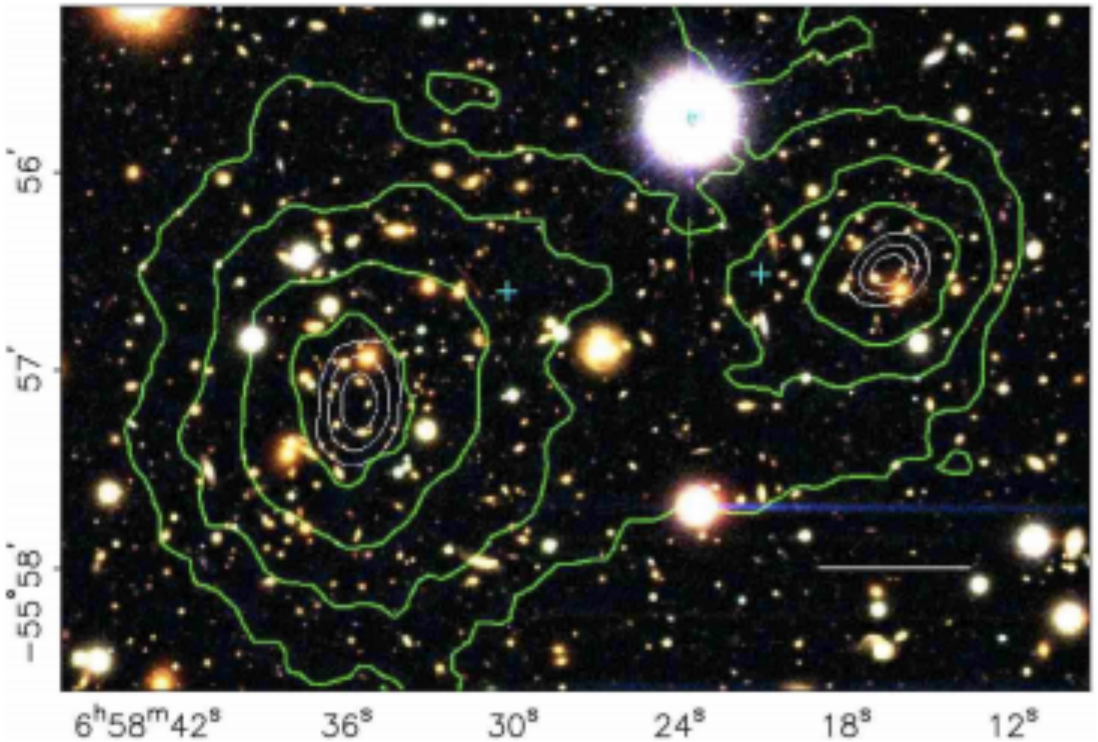
Massey, Kitching & Richard, Rept.Prog.Phys. 73 (2010)

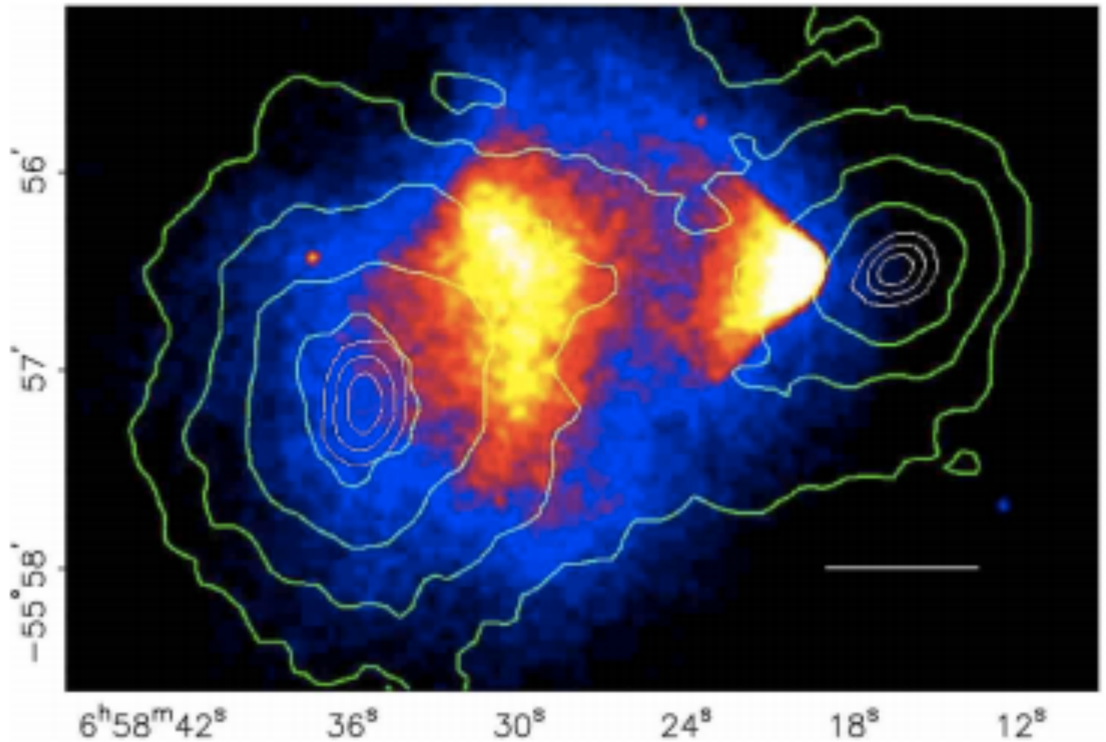

James Webb Space Telescope
JWST
NASA • ESA • CSA

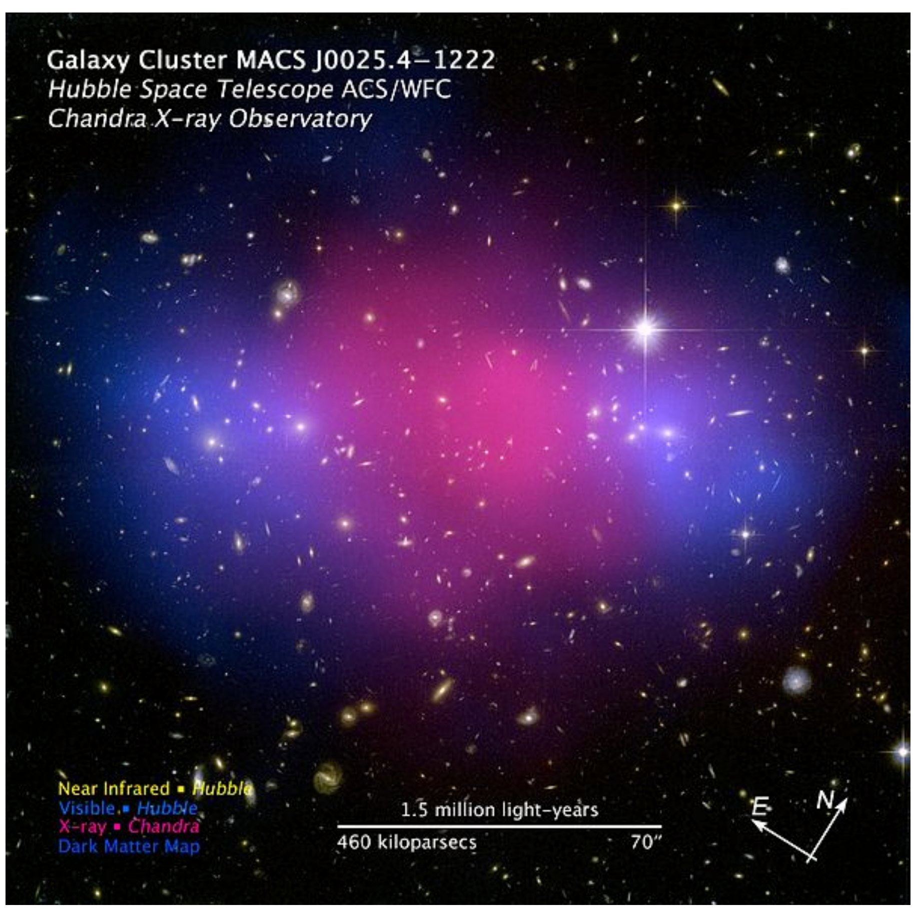
Segregation of matter in clusters

Bullet Cluster (1E 0657-56)

Clowe+, ApJ 604 (2004) 596-603; Clowe+ ApJ, 648 (2006) L109

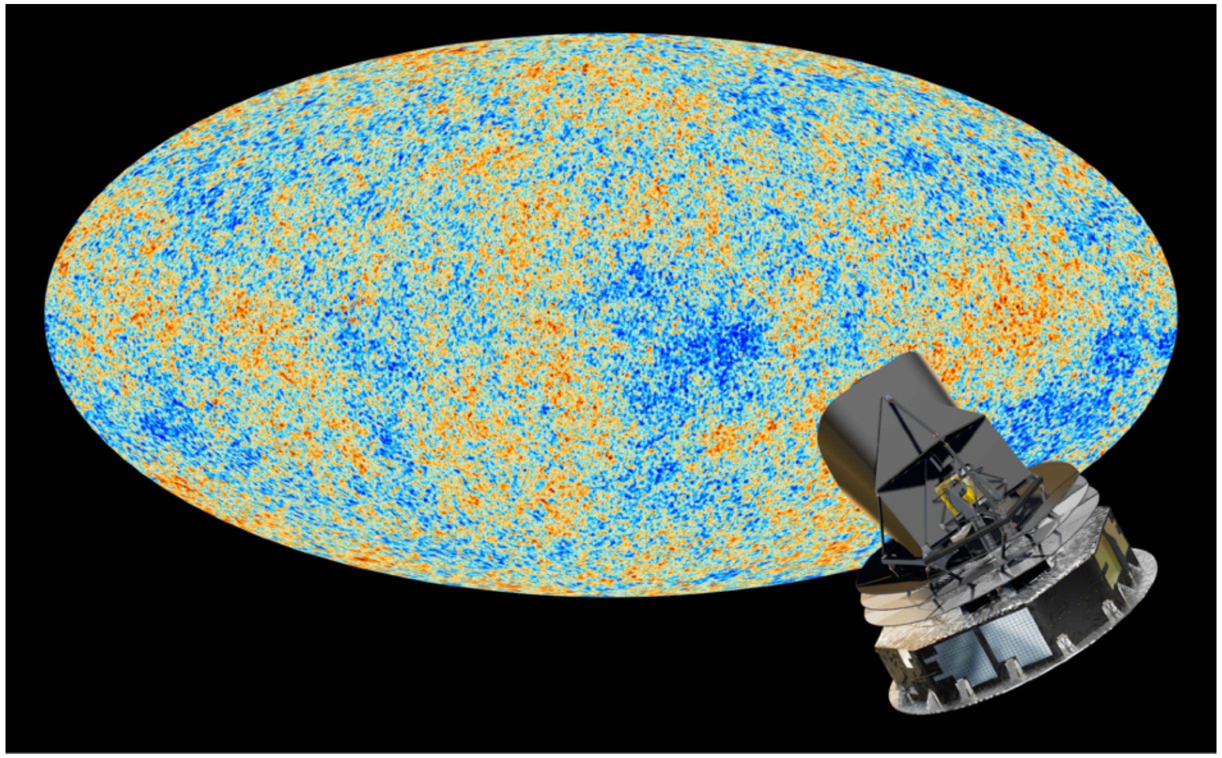






James Jee+, ApJ 783 (2014) 78

Cosmic Microwave Background



$$\Omega_i \equiv \frac{\bar{\rho}_i}{\rho_c}$$ Abundance species *i*

Critical density
(average density of a flat Universe)

$$\rho_c \equiv \frac{3H_0^2}{8\pi G_N}$$

10 protons per **cubic meter**
[1 GeV ~ 10^{-24} g]

$$\bar{\rho}_{\rm DM} \simeq 0.3\rho_c \longrightarrow \bar{\rho}_{\rm DM} \sim 10^{10}\,\frac{\rm M_\odot}{\rm Mpc^3} \sim 10^{-6}\,\frac{\rm GeV}{\rm cm^3}$$

Galaxy clusters: 10^5 denser!
Galaxies: 10^6 denser!

$$\frac{\delta\rho}{\rho} \gg 1$$

The Universe today is highly **non-linear**!

Cosmic Microwave Background

$T > T_{CMB}$ tight coupling between photons and baryons
and presence of primordial overdensities $\delta > 0$

Gravitational vs radiation pressure => acoustic oscillations

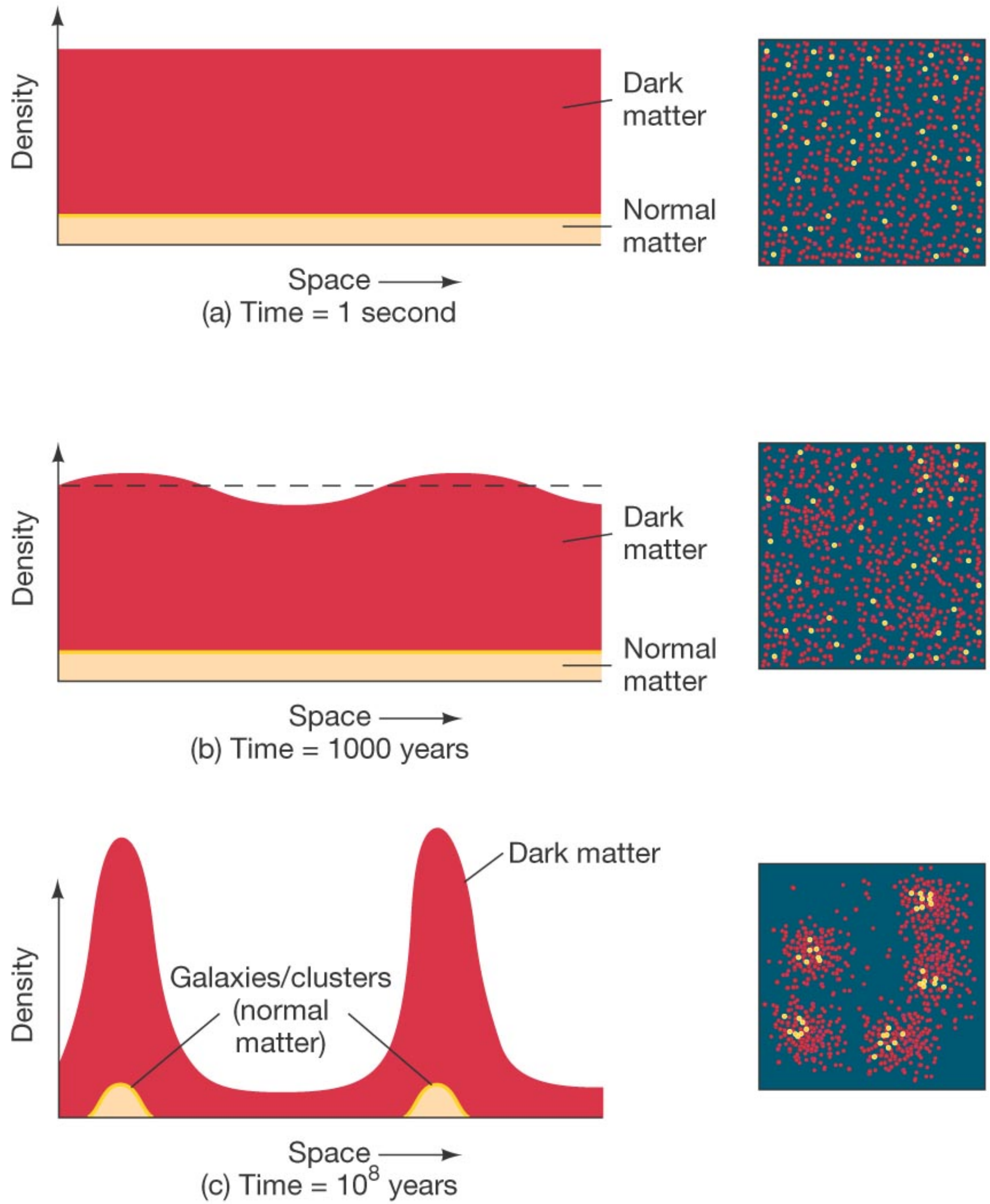
$$\frac{\delta n_\gamma}{n_\gamma} \sim 3\frac{\delta T}{T} \sim \frac{\delta n_b}{n_b} \equiv \delta \qquad n_\gamma \propto T^3$$

$$\frac{\Delta T}{T} \sim 10^{-5}$$ on Mpc scales @ z_{CMB}~ 1100

$$\frac{\Delta n_b}{n_b} \sim 10^{-5}(1+z_{\mathrm{CMB}})^{-1} \sim 0.01$$ in a matter dominated Universe

→ With baryonic matter only, structure formation would be very different! We need a **non-baryonic** component that decouples from photons early enough to create deep potential wells.

Growth of structures: cartoon



2. Fundamental properties of dark matter

Properties of dark matter

What fundamental properties can we infer from this astro/cosmo evidence?

How much dark matter at cosmological scales?

$$\Omega_{\rm CDM} \sim 0.26$$

Planck 2015, 68% CL

The dominant component of dark matter in the Universe should be:

1. Non-relativistic at decoupling, i.e. **cold**
2. **Stable** or long-lived
3. **Sufficiently heavy**, to behave "classically"
4. Smoothly distributed at cosmological scales
5. Dark and **dissipationless**
6. **Collisionless**, i.e. not very collisional

DM evidence requires new physics, beyond current theories
=> **new d.o.f., appealing from a particle physics perspective**

1. Non-relativistic @ decoupling (CDM)

Primordial density fluctuations modified by non-linear effects: gravitation, pressure, dissipation, etc. => N-body simulations are needed to follow the growth in non-linear regime.

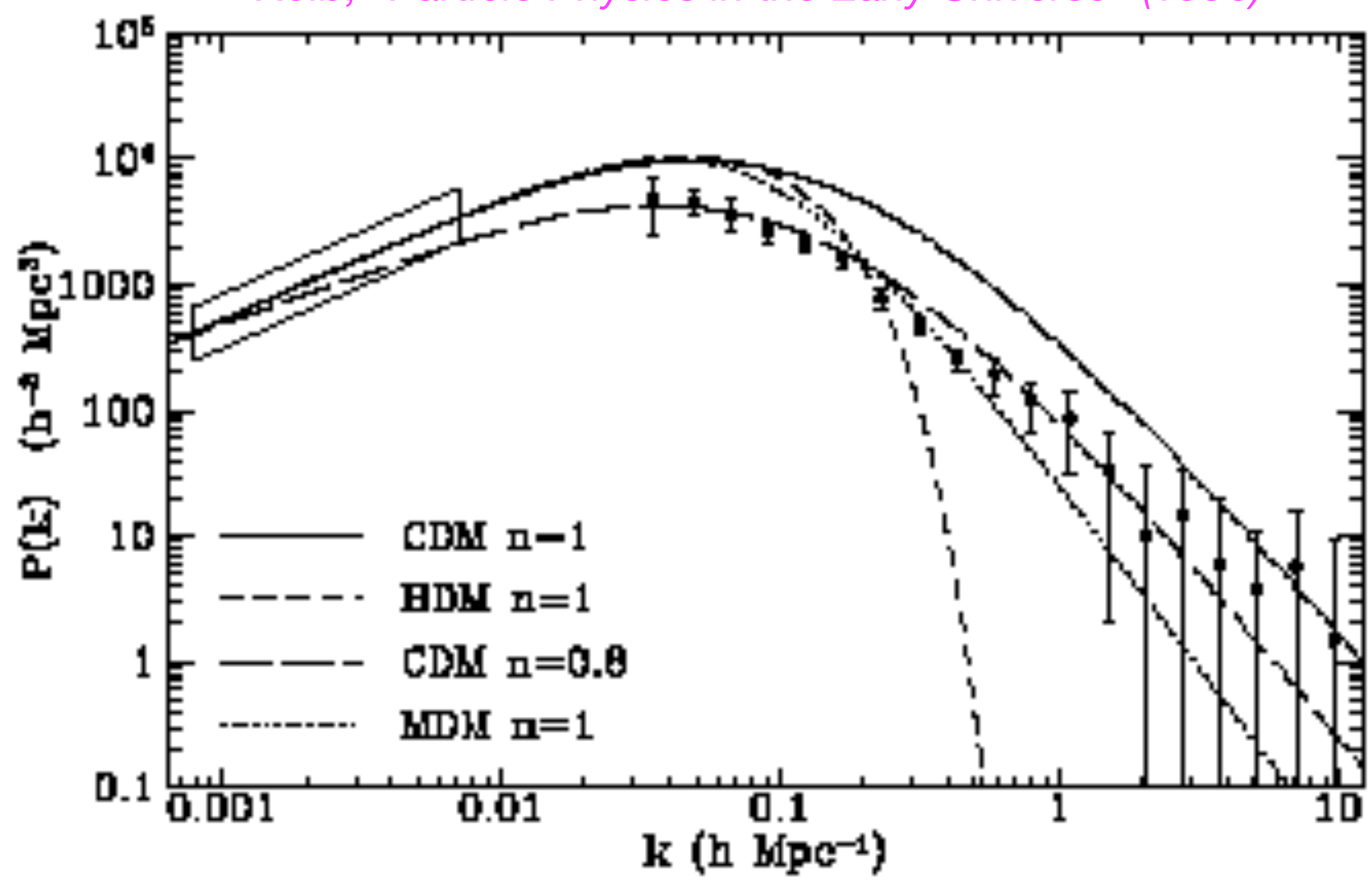
Collisions-less species (neutrinos, DM): free stream from overdense to underdense regions and wash out perturbations => damping of small scale density perturbations

$$\lambda_{\rm phys} \lesssim \lambda_{\rm fs}$$

$$\lambda_{\rm fs} \sim \frac{\nu(t_{\rm eq})}{H(t_{\rm eq})}$$

Characteristic imprint in the matter power spectrum and galaxy distribution

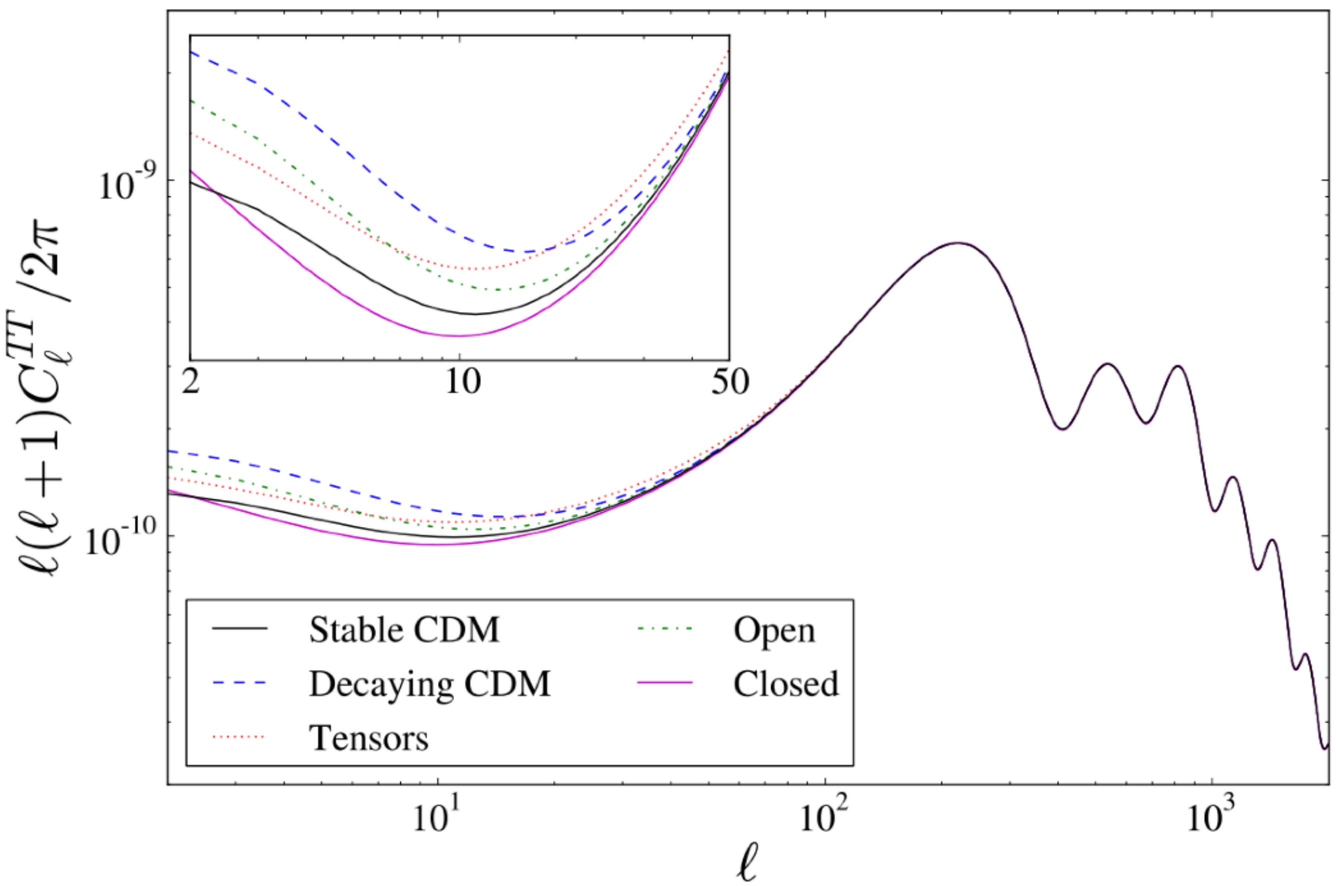
Kolb, "Particle Physics in the Early Universe" (1998)



2. Stable or long-lived

Model independent bounds exist from CMB & Large Scale structures if decay into invisible species

Audren+, JCAP 12 (2014) 028; Poulin+, JCAP 1608 (2016) no.08, 036



$\tau \gtrsim 160\,\mathrm{Gyr}$ CMB only

$\tau \gtrsim 170\,\mathrm{Gyr}$ + other consistent data

More stringent bounds from astrophysics and CMB if decaying into “visible” species ($e^{\pm}$,γ)

$$\tau \gtrsim 10^{26}\,\mathrm{sec}$$

3. Sufficiently massive (LL from localisation)

Evidence of DM at astrophysical scales => Localised therein and behave classically

Dark matter gravitationally bound on scales at least as large as dSph

$$\lambda_{\rm De\,Broglie} = \frac{h}{mv} \lesssim {\rm kpc} \longrightarrow m \gtrsim 10^{-22}\,{\rm eV}\;({\rm v} \sim 100\,{\rm km/s})$$

If DM is a fermion: Pauli exclusion principle holds and the phase space density is further constrained

Tremaine-Gunn bound

$$\bar{f} \lesssim \frac{g}{h^3}$$

$$m > \mathcal{O}(10 - 100\,{\rm eV})$$

Tremaine & Gunn, PRL 42 (1979) 407;
Boyarsky, Ruchayskiy & Iakubovskyi, JCAP 0903 (2009) 005

[From conservation of phase space density of a non-interacting fluid (Liouville equation)]

4. Smoothly distributed (not "granular")

On galaxy scales, we do not detect any "granularity" of dark matter; should have a continuum "fluid" limit

➡ Granular distribution would provide time-dependent gravitational potentials, which might disrupt bound systems of different sizes => heat the galactic disk or disrupt globular clusters

Lacey & Ostriker, ApJ 299 (1985) 633; Moore, ApJ 413 (1993) L93; Rix & Lake, ApJ 417 (1993) L1

➡ Additional Poisson noise into matter power spectrum

Afshordi+, ApJ 594 (2003) L71

$$m \lesssim 10^{3-4}\, M_\odot \sim 10^{70-71}\, \mathrm{eV}$$

5. Optically dark and dissipationless

Very weak e.m. interaction

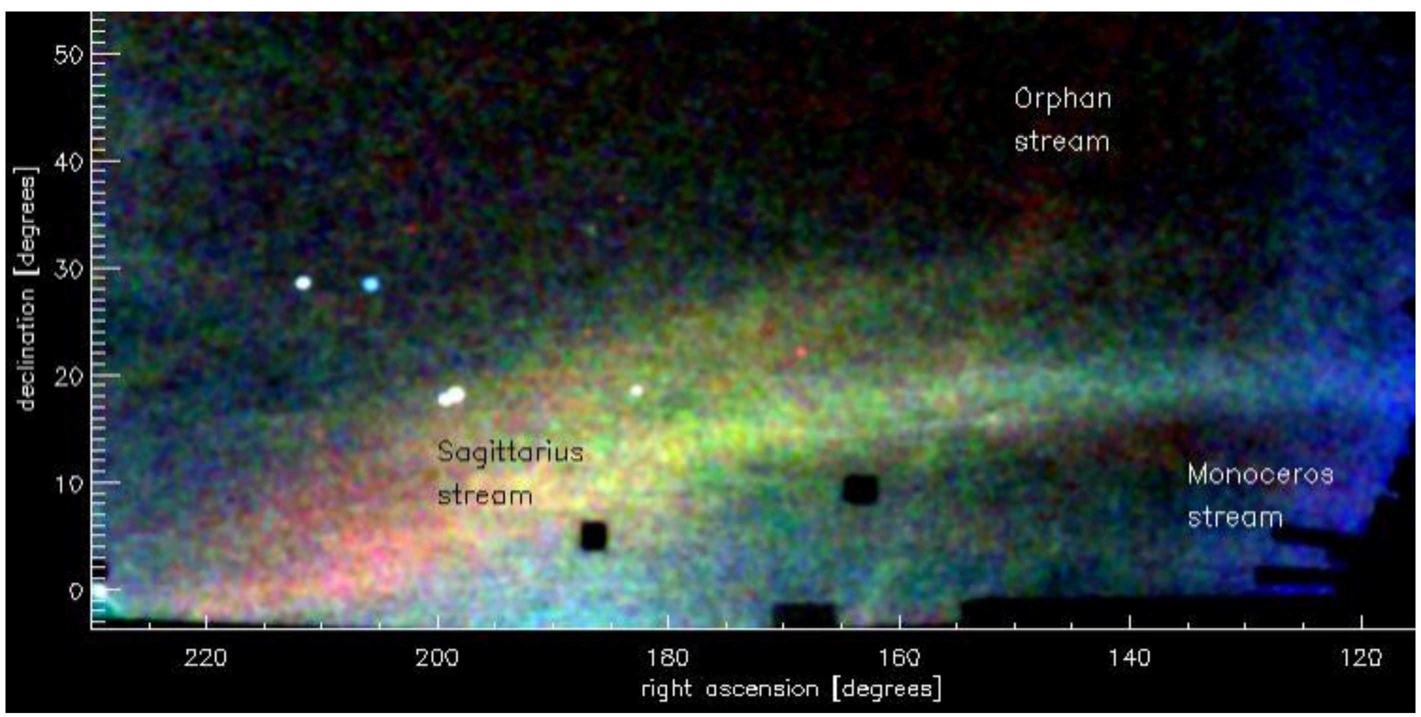
$$\sigma_{\rm DM-\gamma} \leq 8 \times 10^{-31} \, (m_{\rm DM}/{\rm GeV}) \; {\rm cm}^2$$

Wilkinson+, JCAP 04 (2014) 026

Dark matter can not cool by radiating photons => Strong constraints of the fraction of dissipative dark matter (e.g. through cooling into a rotationally-supported disk)

$$\epsilon_{\rm disk} \lesssim 0.05$$

J. Fan+, PRL 110, 211302 (2013)



e.g. Law+, ApJ 703 (2009) L67 (2009) & refs. to it

If dissipation and cooling occurs, there may be the consequent formation of a dark disk

NB: Subdominant component

6. Collisionless (or not very collisional)

DM-DM interaction too strong, spherical structures would be obtained rather than triaxial:

$$\sigma \sim \frac{m}{\mathrm{GeV}} \frac{\mathrm{Mpc}}{\lambda} \,\mathrm{barn} \qquad\qquad \lambda \sim \frac{1}{\sigma/m\,\rho} > 1\,\mathrm{Mpc}$$

From clusters: $\sigma/m<0.02\ \mathrm{cm}^2/\mathrm{g}$

Miralda-Escudé ApJ 564 60 (2002)

From Bullet cluster: $\sigma/m<0.7\text{-}1.3\ \mathrm{cm}^2/\mathrm{g}$

Randall+, ApJ 679,1173(2008); Buckley & Fox, Phys.Rev.D 81,083522(2010)

.....much less than atomic or molecular cross sections!

$$\frac{\mathrm{cm}^2}{\mathrm{g}} = 1.78 \frac{\mathrm{barn}}{\mathrm{GeV}}$$

DM should **not** have **self-interactions exceeding the barn/GeV** level; **slightly smaller σ could also be beneficial**

Kaplinghat+ PRL 116, 041302 (2016)

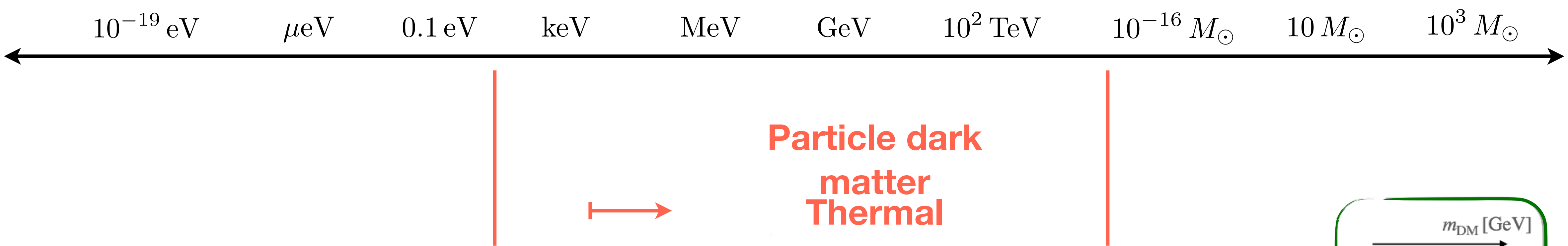
3. The dark matter landscape

The dark matter landscape

Vast parameter space in mass and interaction strength

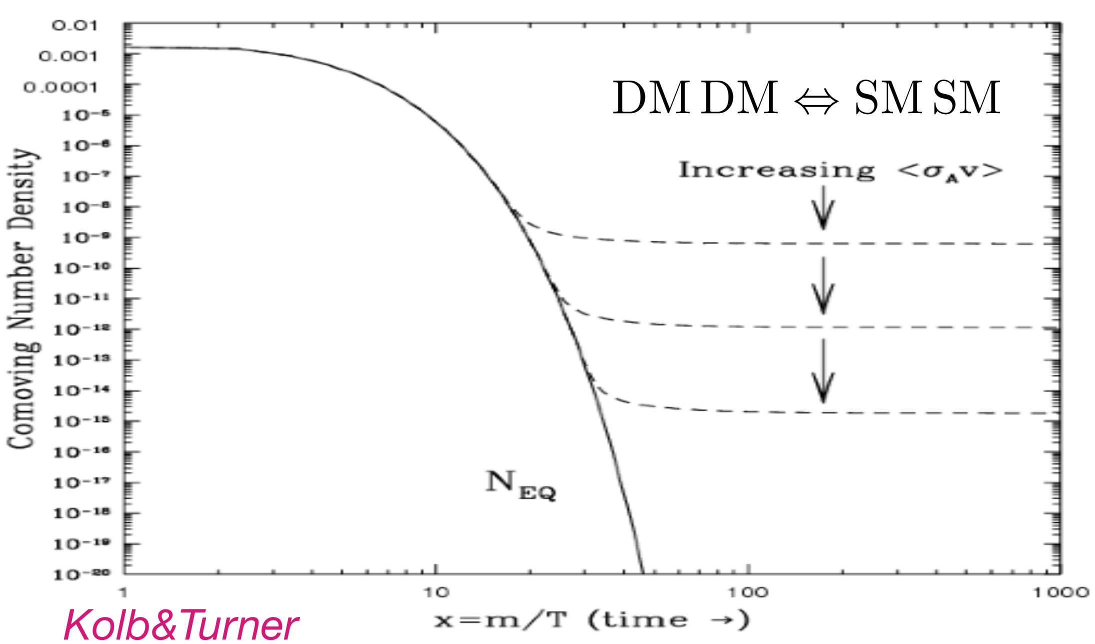
The dark matter landscape

The dark matter landscape



Weakly interacting massive particles (WIMPs)

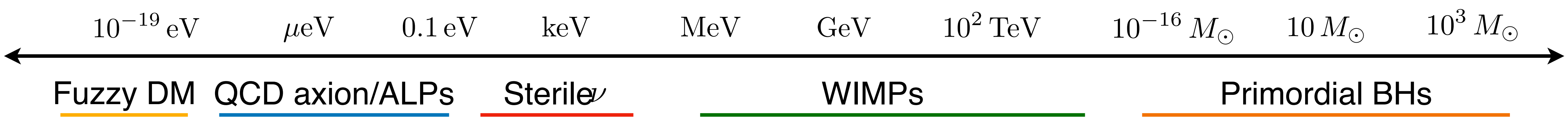
- Freeze-out production mechanism



Kolb&Turner

$$\Omega_{\rm DM} h^2 \sim \frac{10^{-27}{\rm cm}^3/{\rm s}}{\langle \sigma({\rm DM\,DM} \to {\rm SM\,SM}){\rm v}\rangle}$$

The dark matter landscape



The quest for dark matter is colourful and very broad!!
It leverages on model signatures and available data