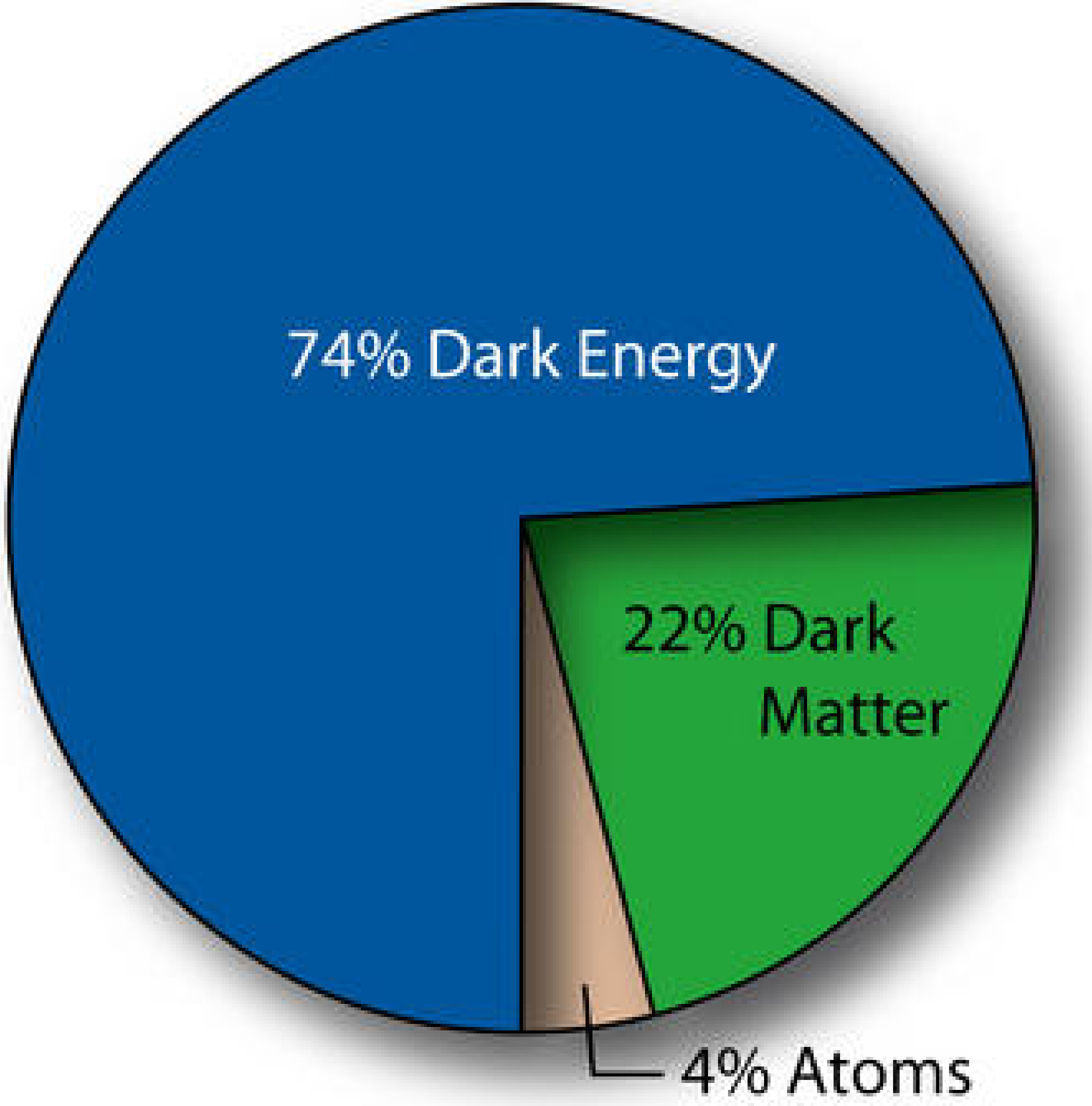
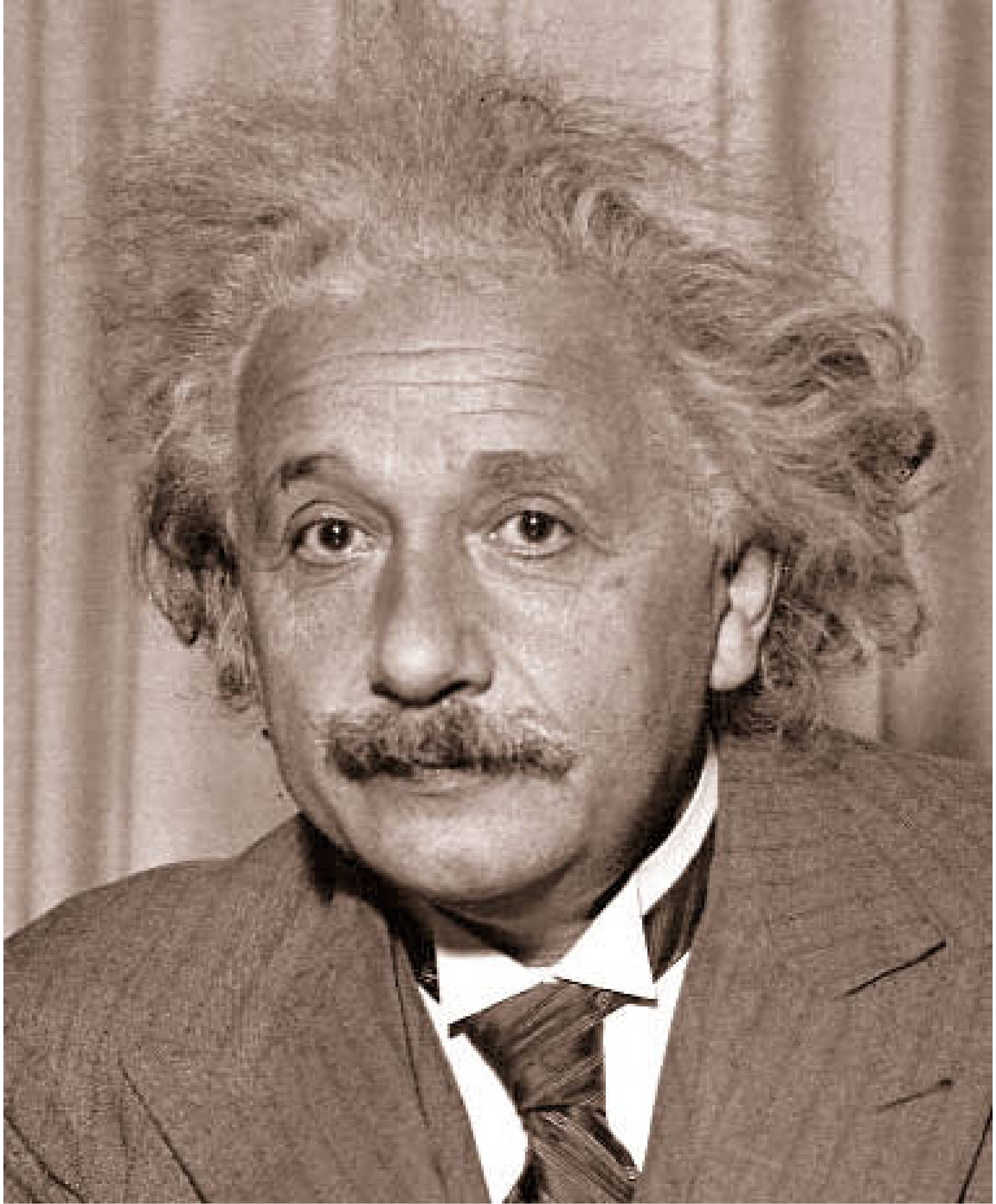
The Dark Matter Puzzle

Pierre Sikivie (U. of Florida)

Hamburg, June 19, 2008


74% Dark Energy
22% Dark Matter
4% Atoms



Albert Einstein

1987 - 1955

General Relativity, in brief

1. there is no gravity, only curved space-time

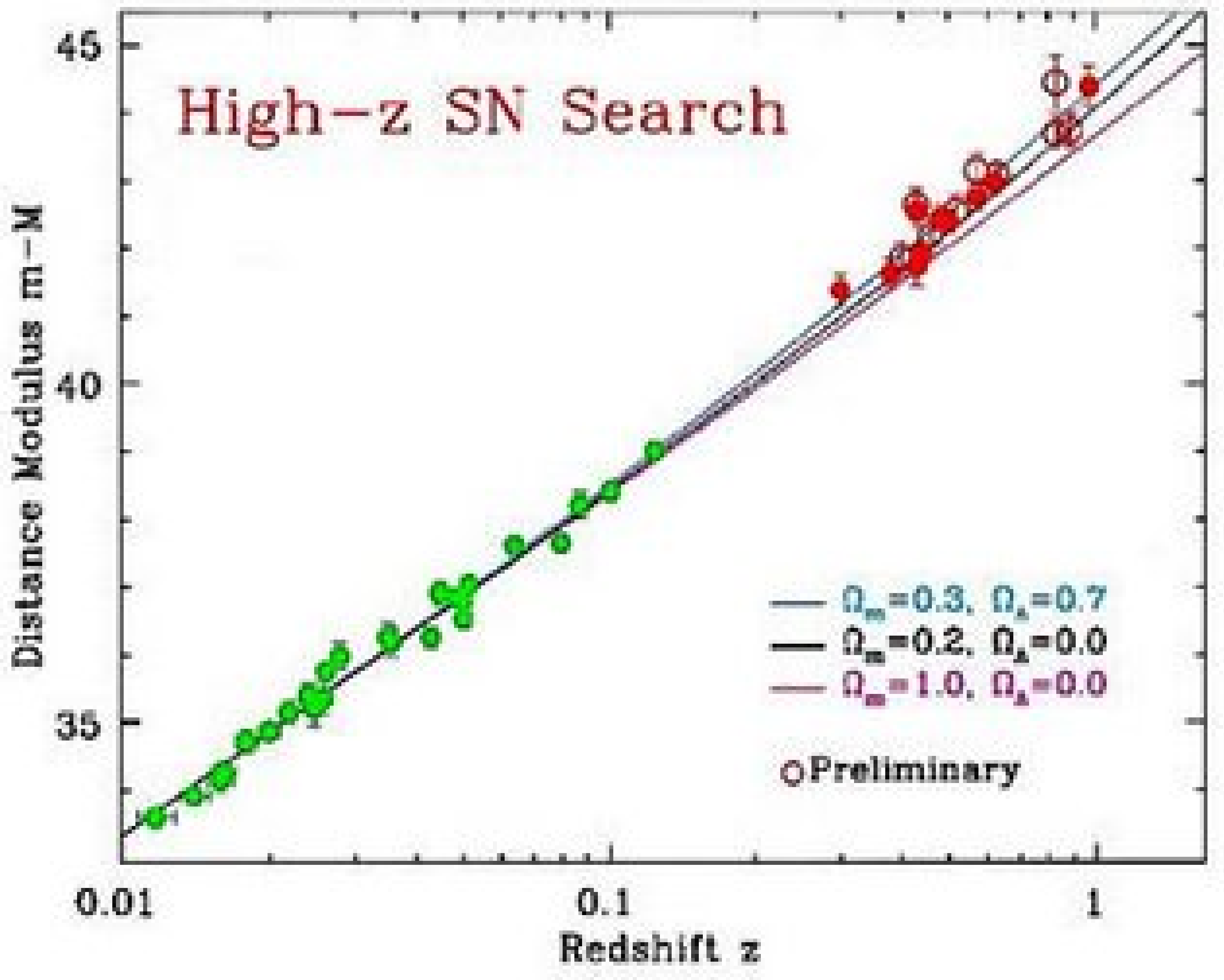
2. the source of space-time curvature is energy, momentum, and stress

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}$$

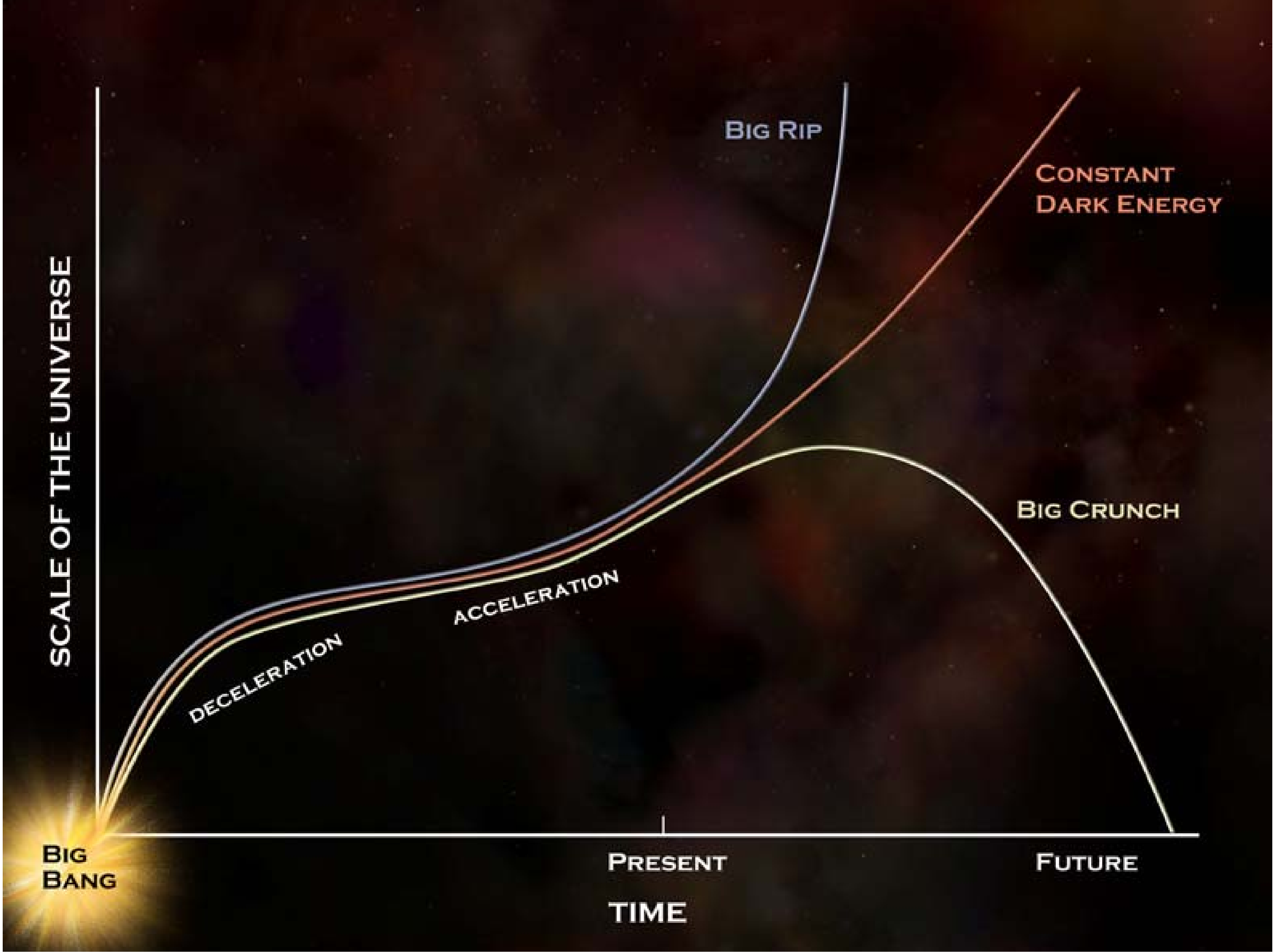
space-time
curvature

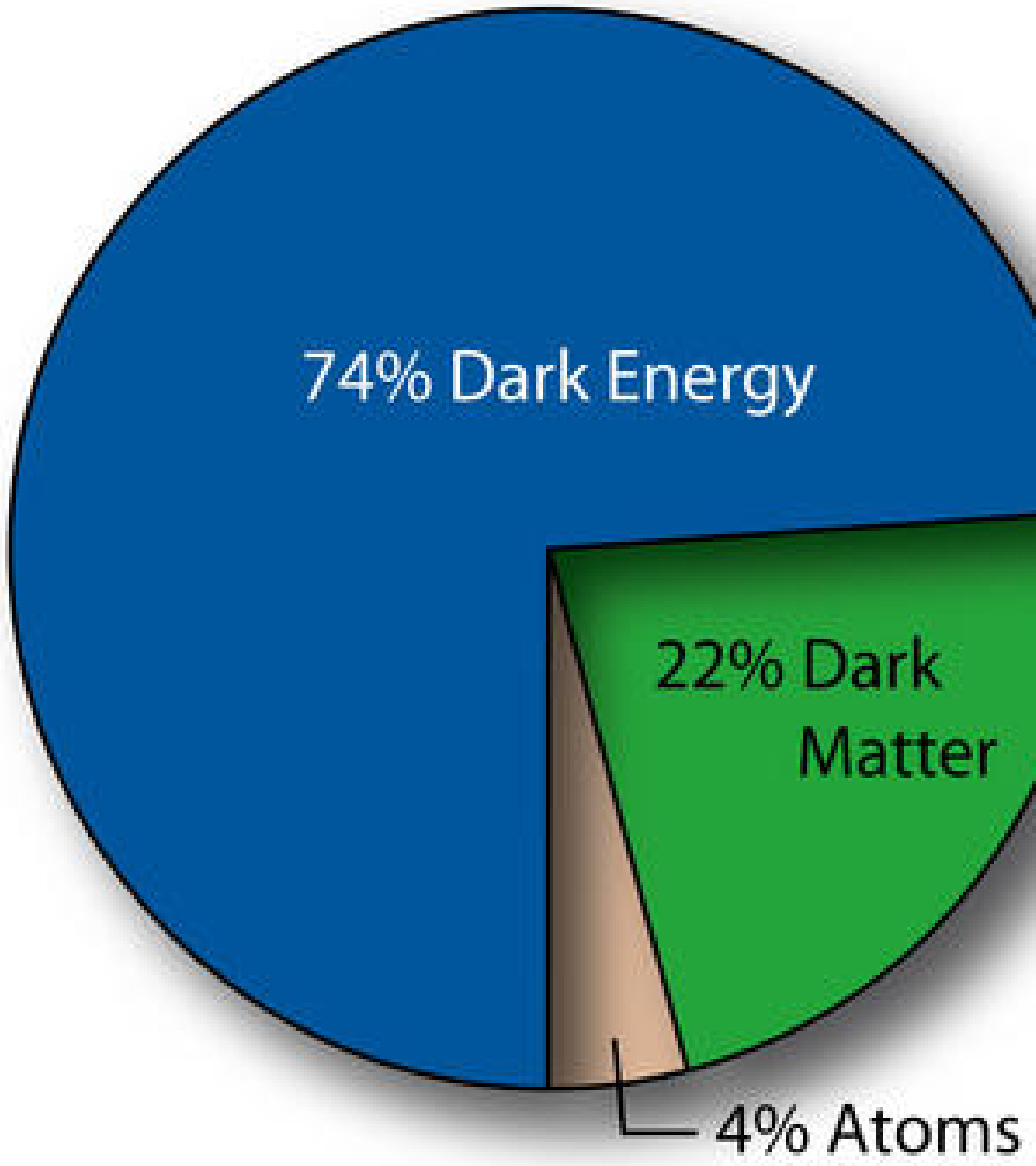
stress
energy
momentum

	Energy density	Pressure
• matter	ρ_{m}	$p_{\mathrm{m}} \approx 0$
• radiation	ρ_r	$p_r = \frac{1}{3}\rho_r c^2$
• vacuum energy	ρ_Λ	$p_\Lambda = -\rho_\Lambda c^2$



S. Perlmutter et al. '99 , A. Riess et al. '98


Big Rip
Constant
Dark Energy
Big Crunch
Scale of the Universe
Deceleration
Acceleration
Big
Bang
Present
Future
Time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Fritz Zwicky

1898 - 1974

NGC 4414, a galaxy

COMA, a cluster of galaxies

Virial Theorem

cluster mass

$$\frac{1}{2}\left\langle \mathbf{V}^2 \right\rangle = \frac{GM}{R}$$

cluster radius

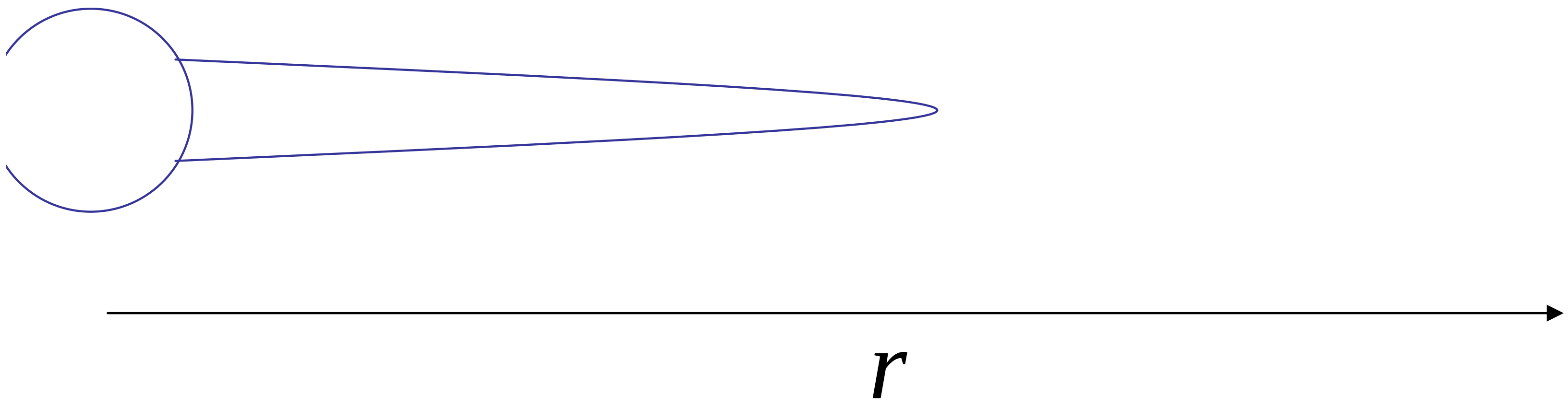
velocties of galaxies
in the cluster

Using the virial theorem, Zwicky (1933) showed that the Coma cluster contains roughly 100 times more mass than accounted for by the luminous matter in the cluster.

Vera
Rubin

Vera Rubin and Kent Ford

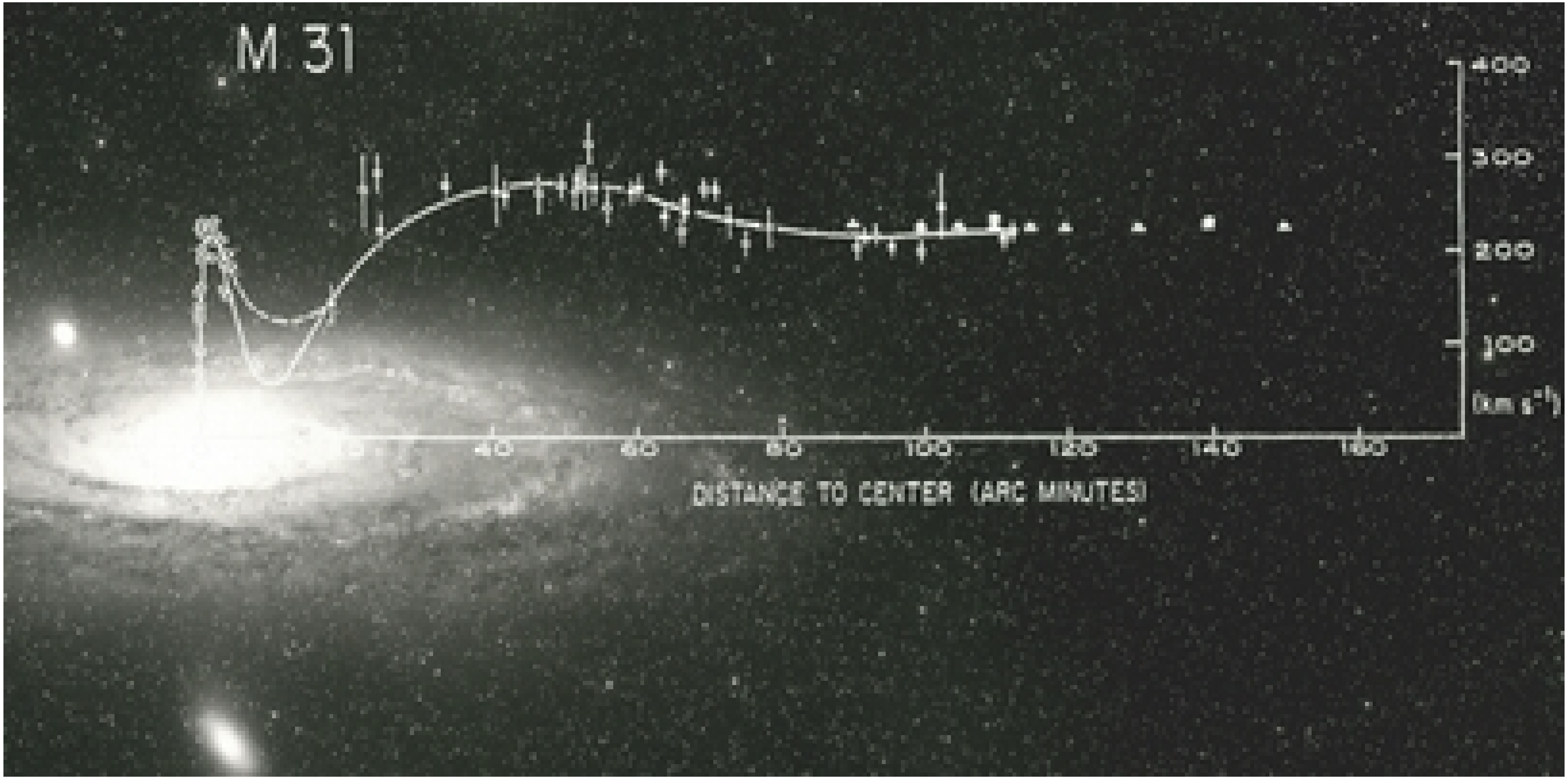
Galactic rotation curves



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

galactic mass

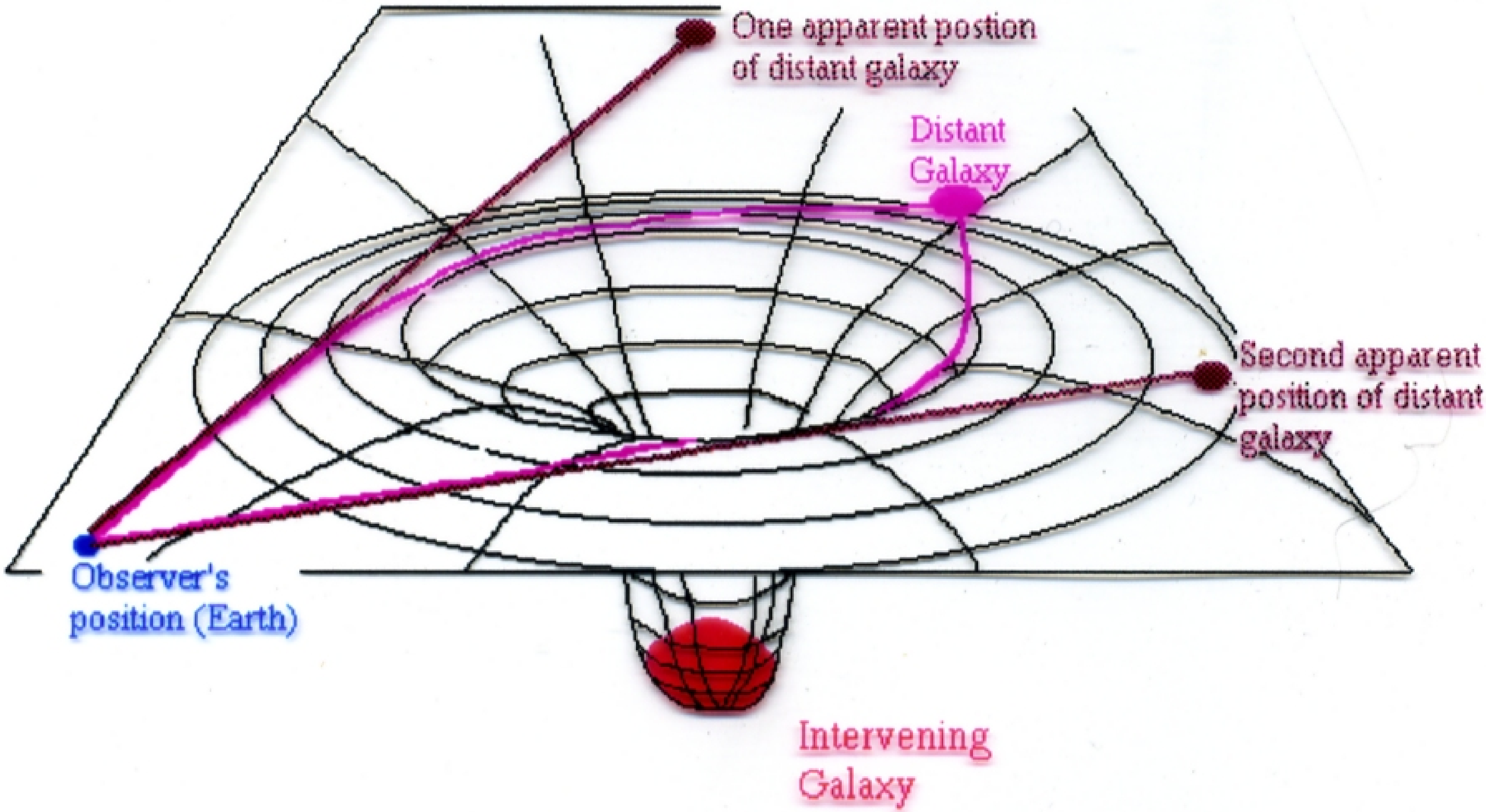
rotation speed

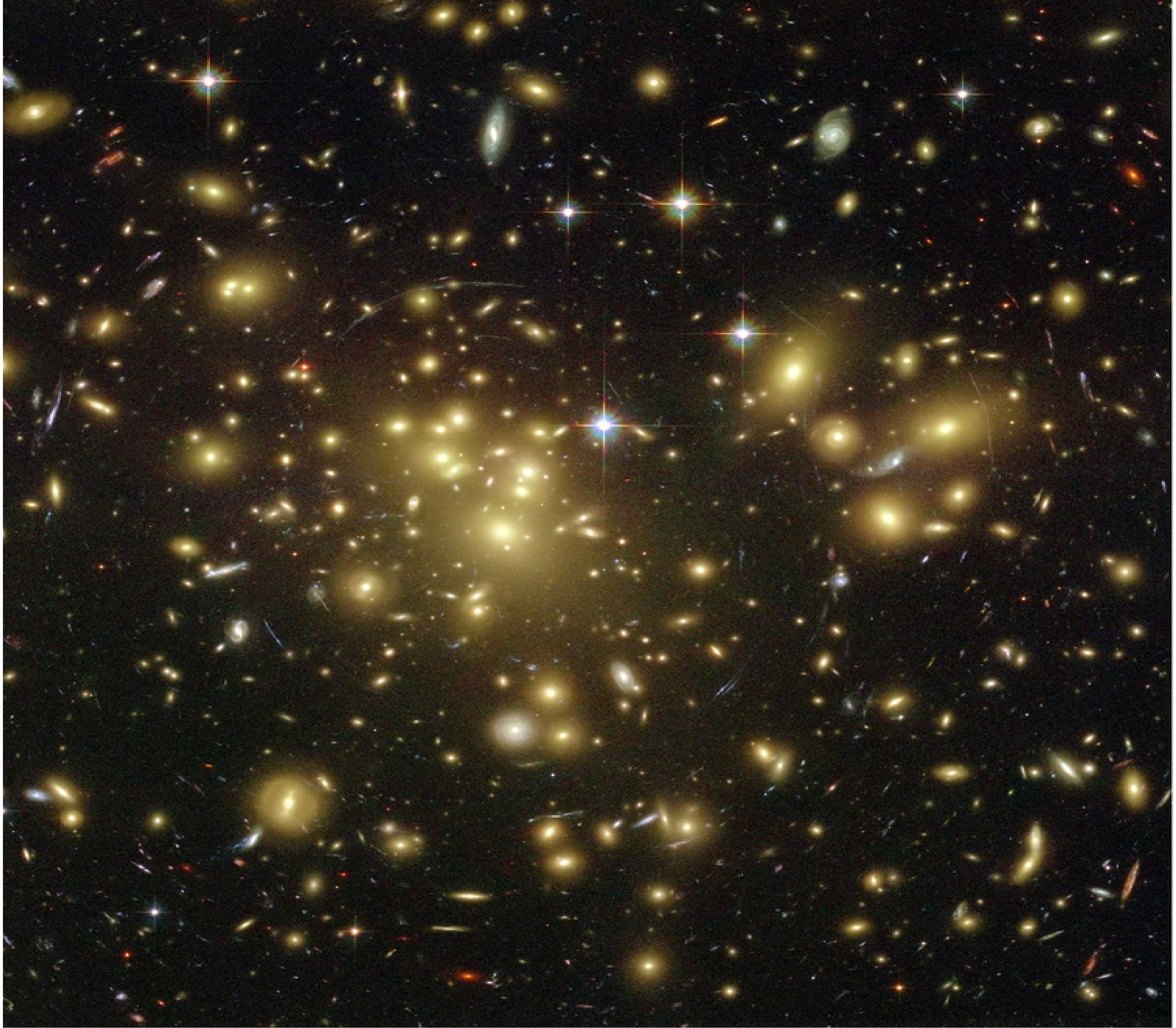


Rubin and Ford (1970) found that the rotation speed of M31 is constant at large radii implying that the total galactic mass increases proportionately to the radius.

Galaxies are surrounded by halos of dark matter.

Gravitational lensing

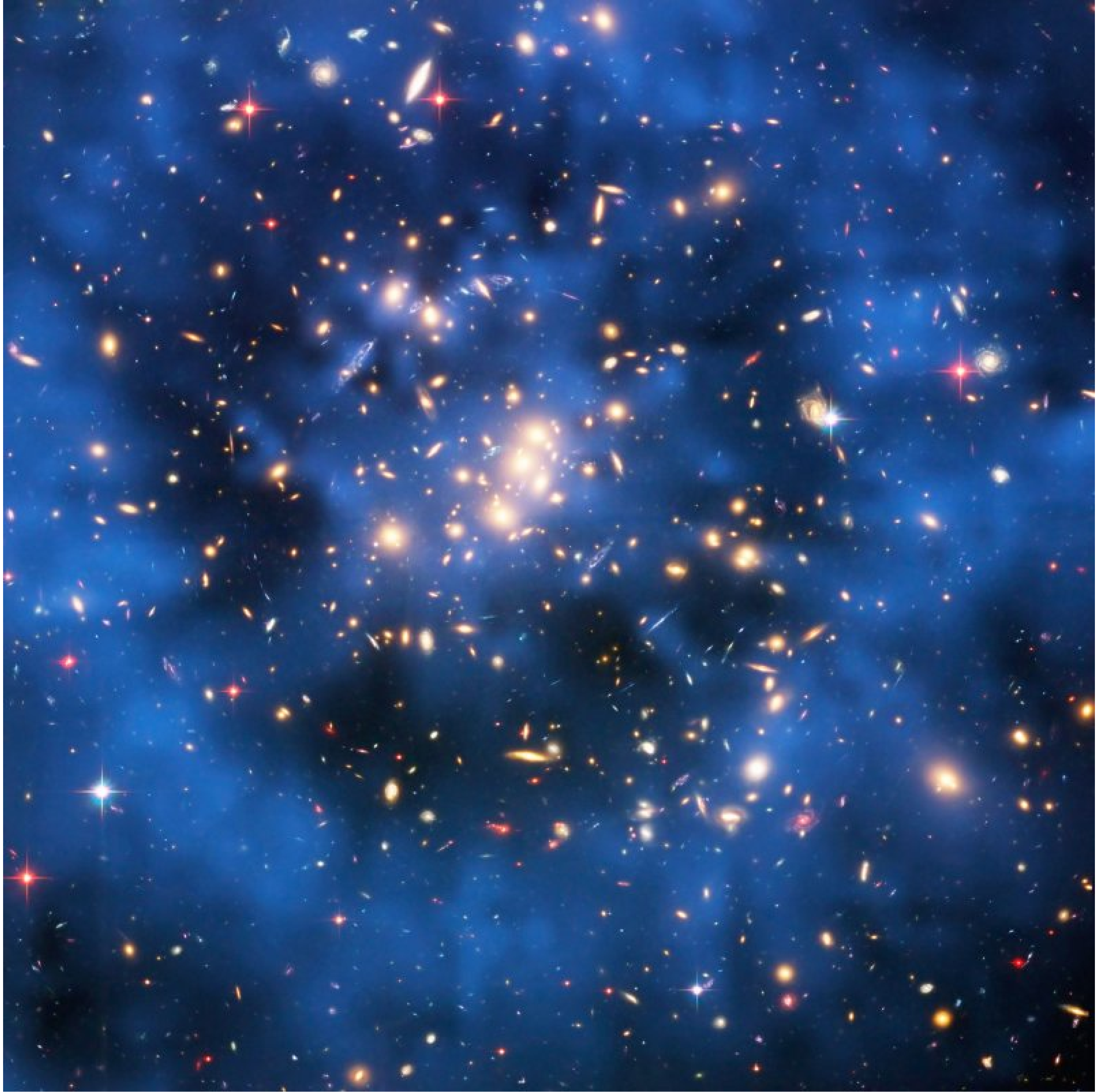




Galaxy Cluster Abell 1689

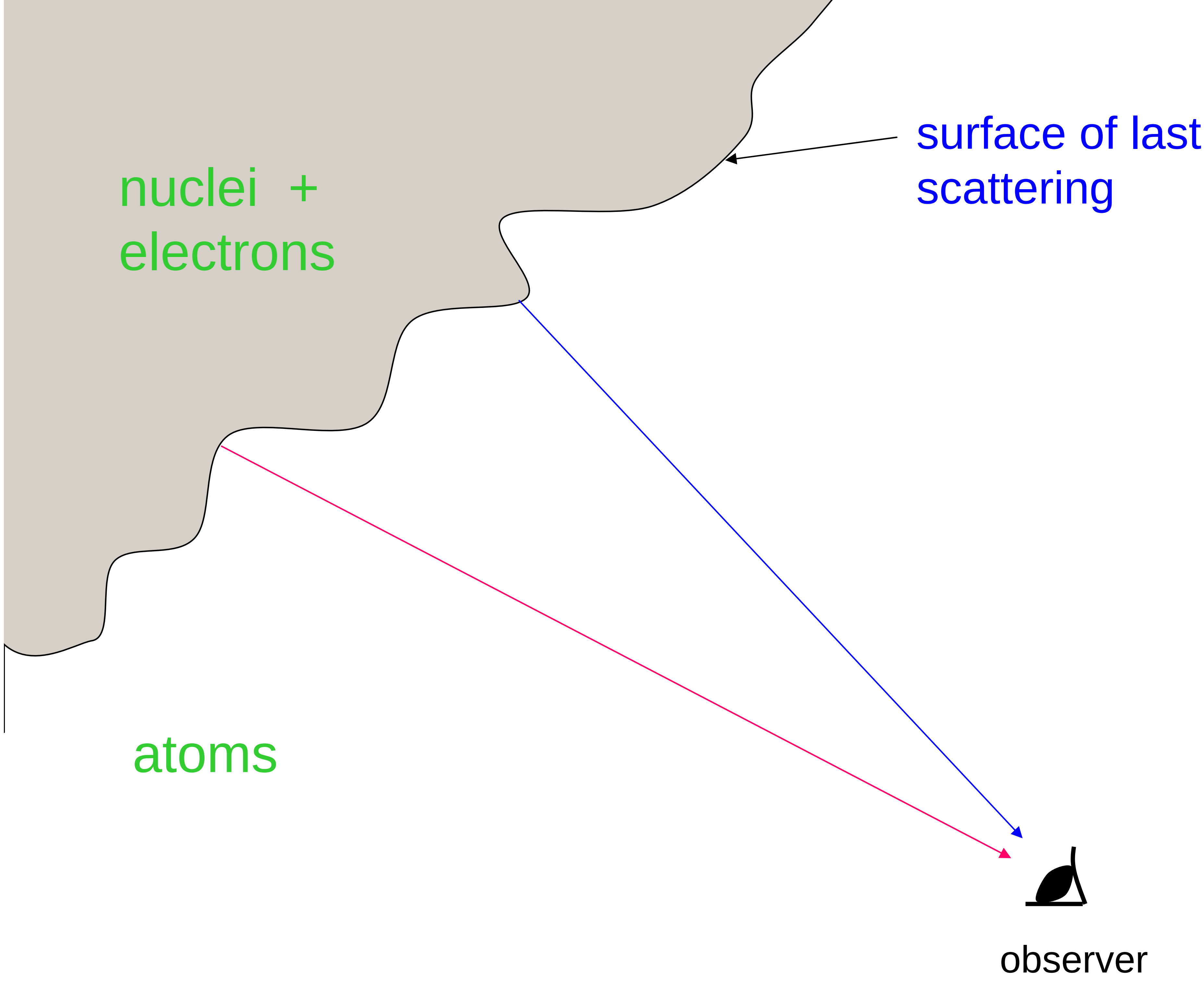
Hubble Space Telesc. ACS Science Team

the bullet cluster (D. Clowe et al. 2004)

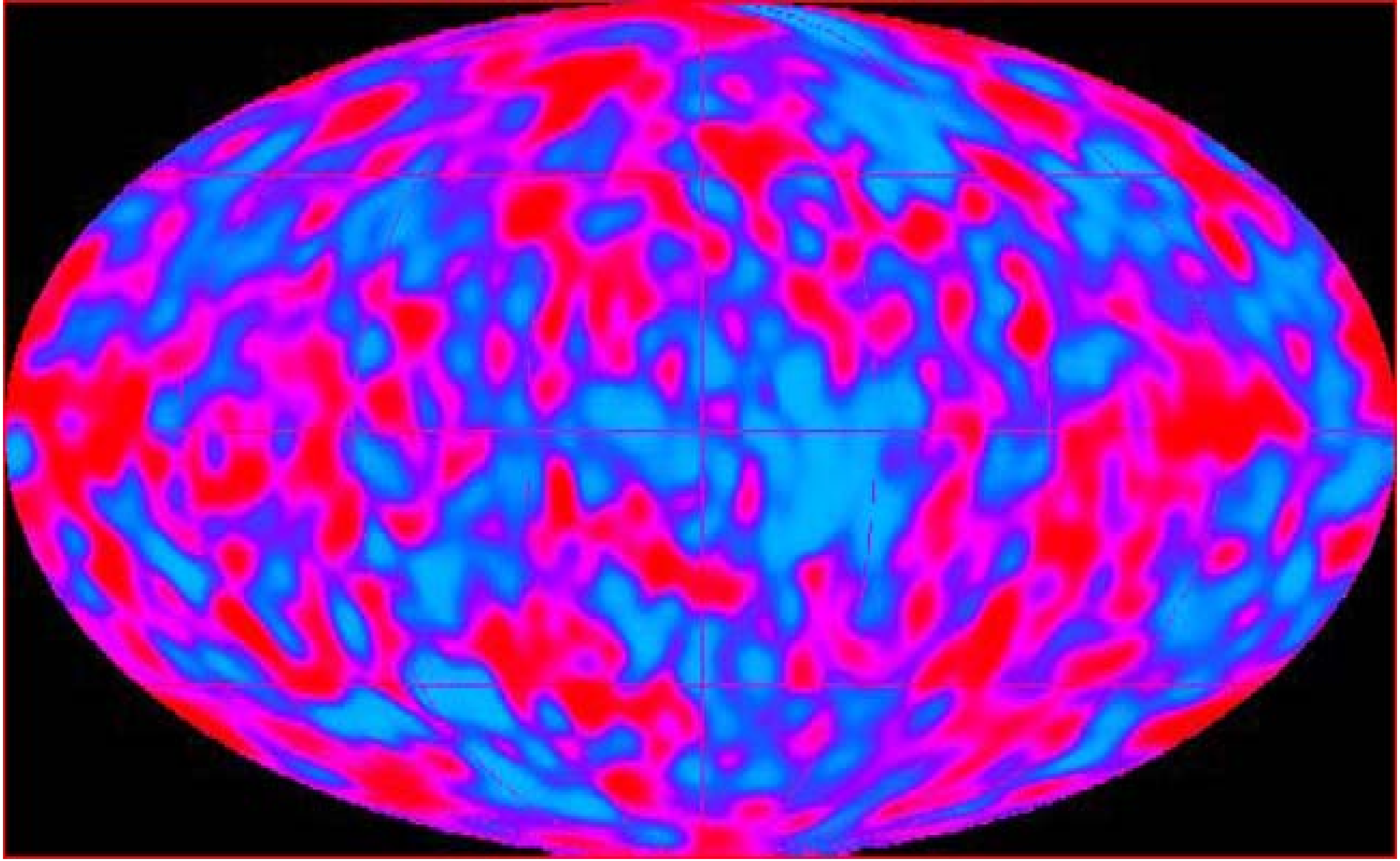


dark
matter
ring
in the
cluster
Cl 0024+1654

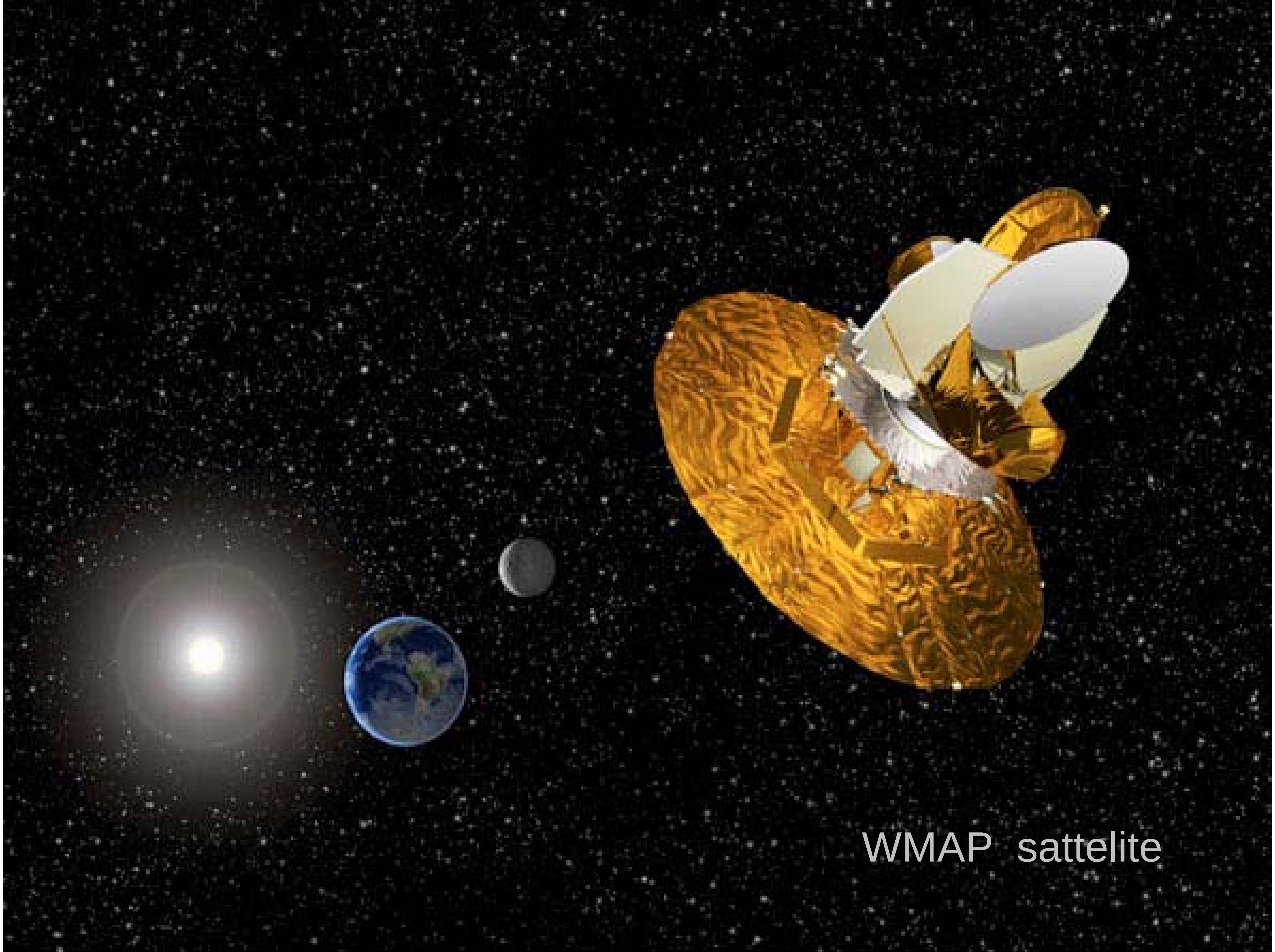
Jee et al.
2007


surface of last scattering
nuclei + electrons
atoms
observer

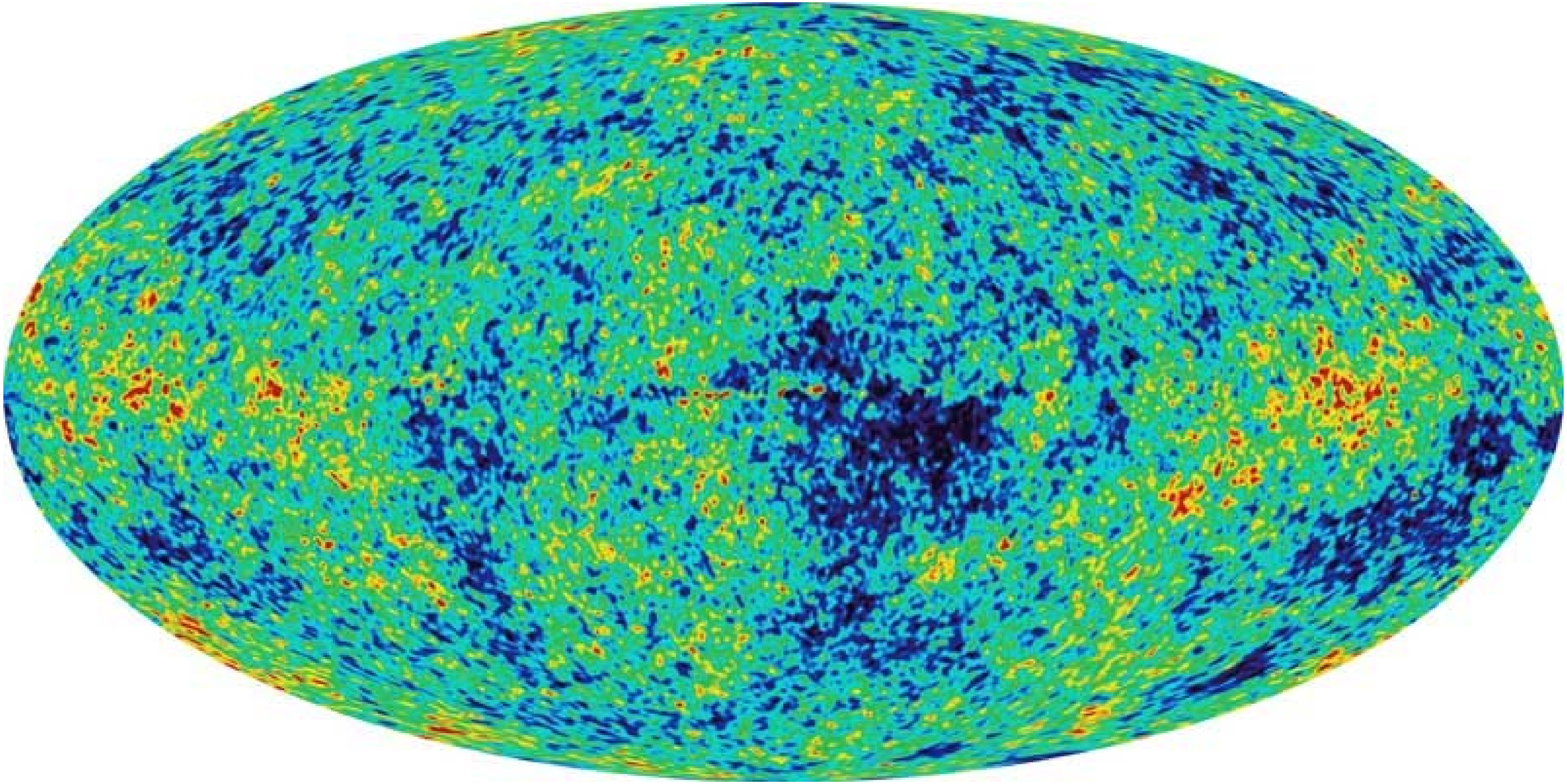
COBE sattelite



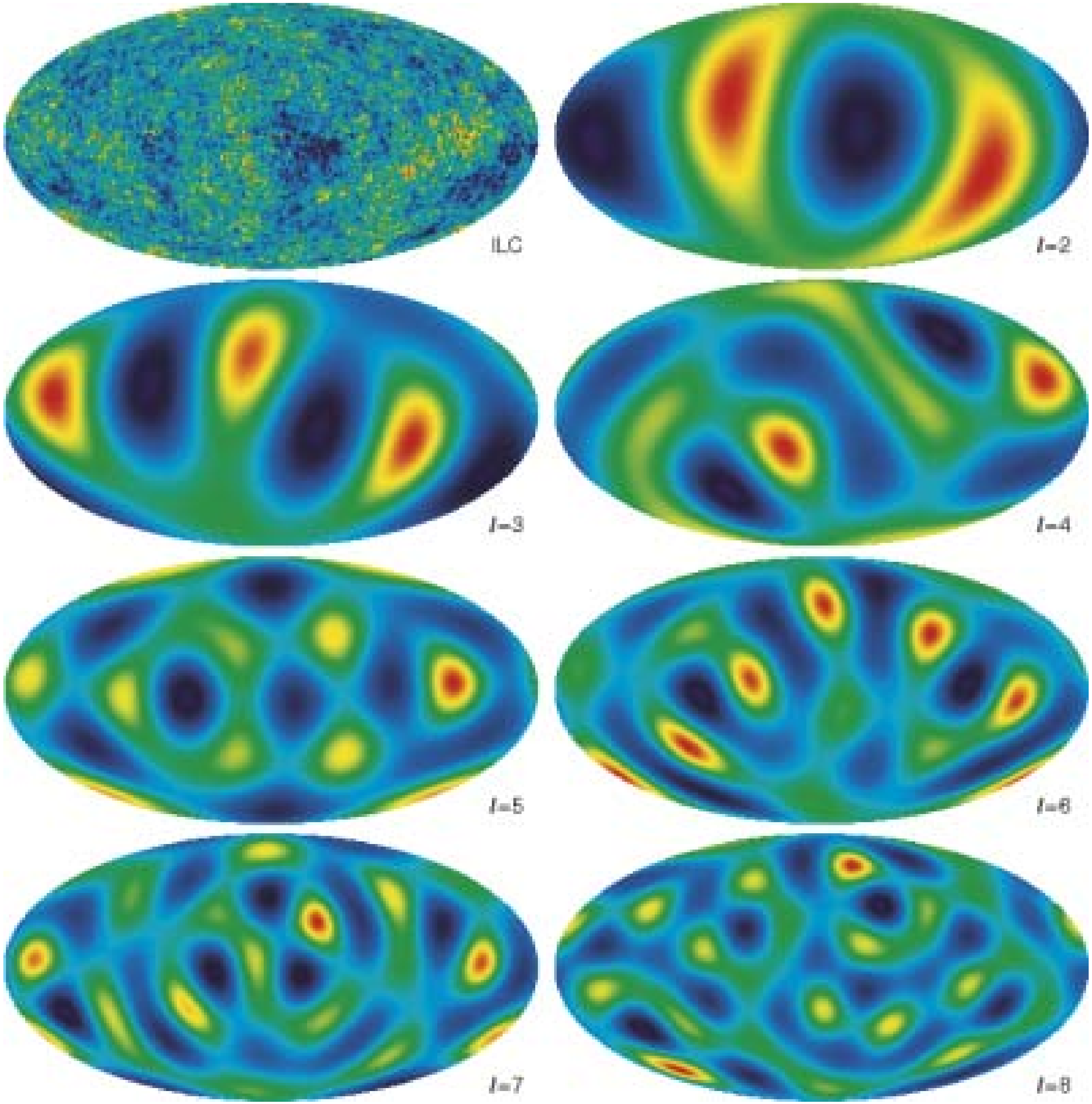
COBE skymap



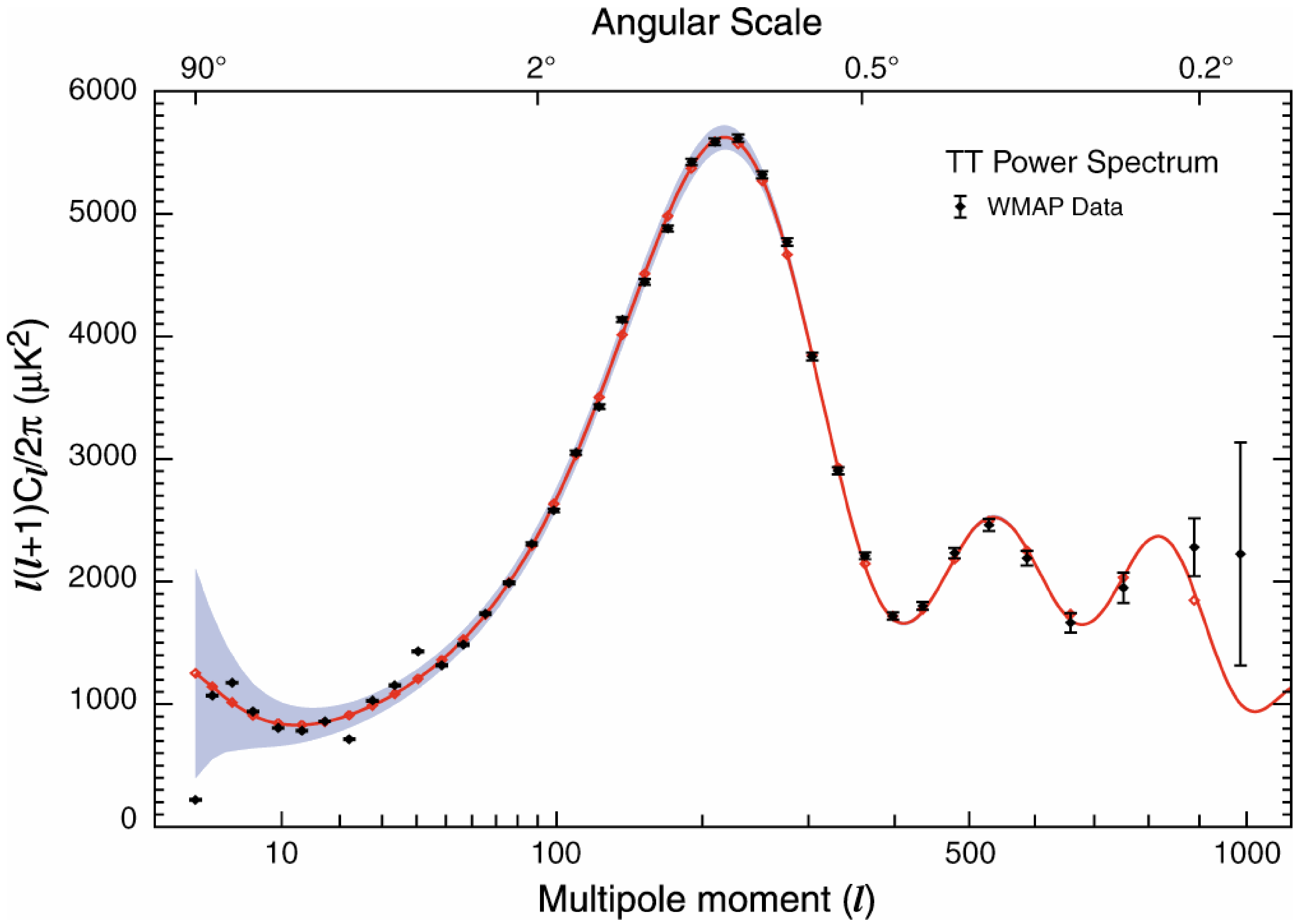
WMAP sattelite



WMAP



HARMONIC ANALYSIS



Concurring data from: Boomerang, Maxima, South Pole, Saskatoon, DASI, VSA, …

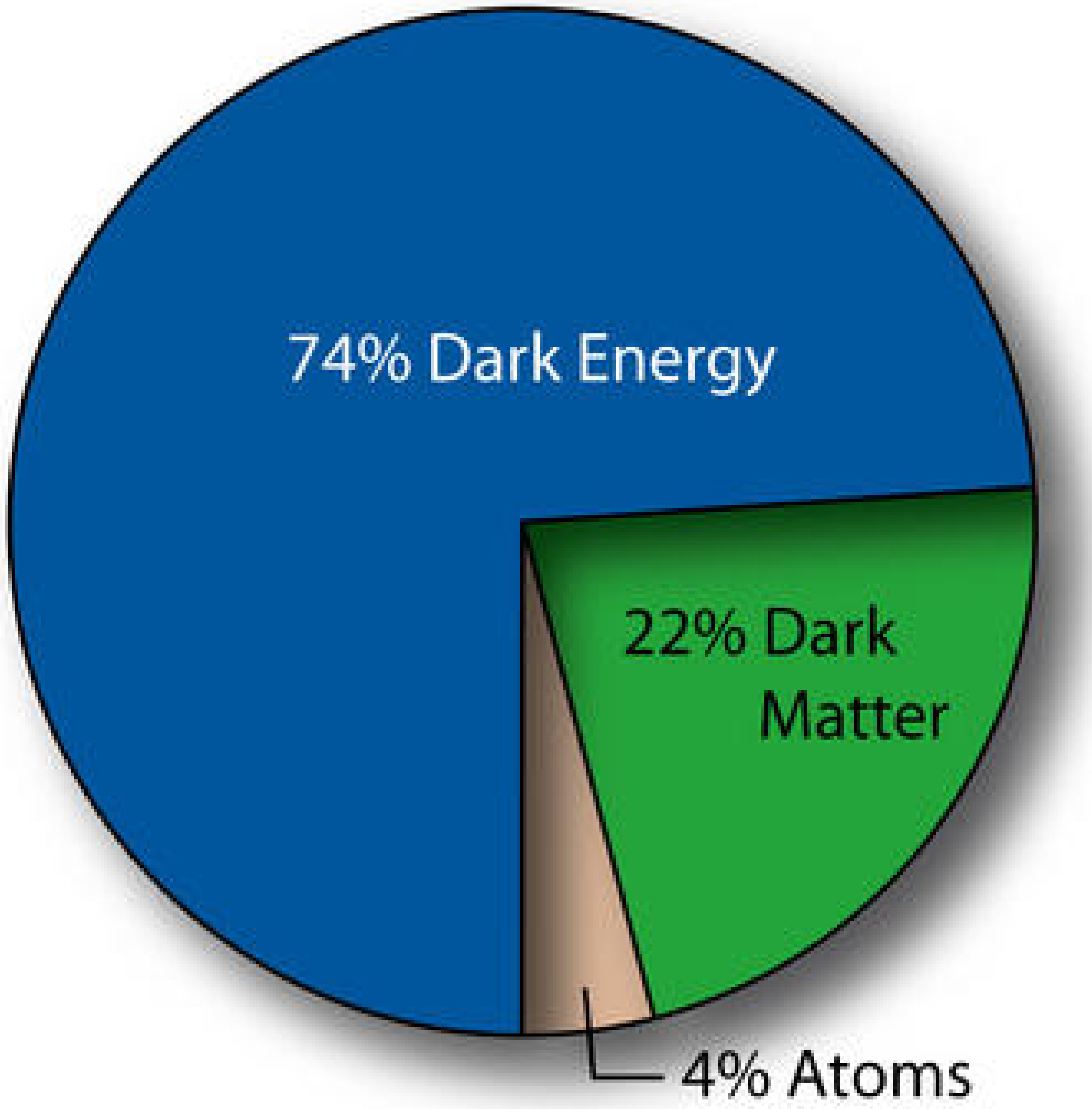
Cosmological Parameters

- Age of the universe 13.7 Gigayear
- Spatial curvature none
- Energy density $0.95\ 10^{-29}$ gr/cm^3
- Energy fractions

vacuum energy $\Omega_\Lambda = 0.74$

atoms and molecules $\Omega_b = 0.04$

dark matter $\Omega_{dm} = 0.22$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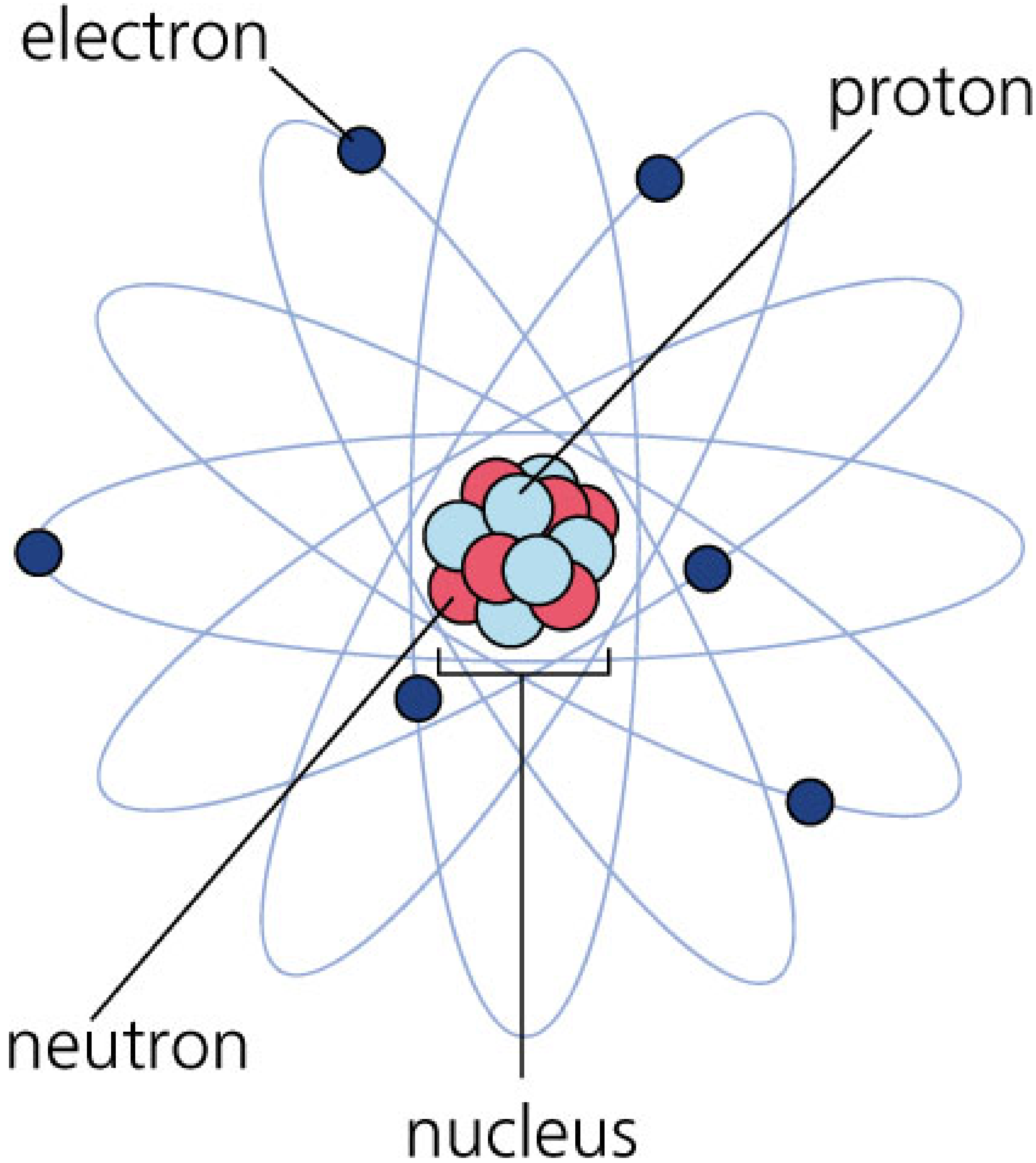
What is the dark matter ?



Why not atoms and molecules? (ordinary matter)

Why not ordinary matter?

- there is too little of it

  even before WMAP, studies of primordial nuclear synthesis (the first work was done by Gamov, Alpher and Herman, in the late 1940’s) already implied $\Omega_b < 0.05$

- ordinary matter is not collisionless

- was not found in microlensing searches

  (MACHO, OGLE, EROS …)

LIGHT

- is definitely weird
- appears and disappears
- moves fast, at $c = 2.998\ 10^5$ km/s
- is collisionless with glass and water, and with itself (makes rainbows and other caustics)

Why not Black Holes?

- subject to $\Omega_b < 0.05$ constraint
  if formed after primoridal nucleosynthesis

- no known formation mechanism before
  primordial nucleosynthesis

$$E = mc^2$$

$$E = mc^2$$

one gram

90 TeraJoules

$$E = mc^2$$

$$E = mc^2$$

for a particle at rest,

when $p = 0$

$$E = \sqrt{m^2c^4 + p^2c^2}$$

p is called momentum

Speed

$$\mathrm{v} = \frac{p\,c^2}{E} = \frac{p\,c^2}{\sqrt{m^2c^4 + p^2c^2}}$$

$= c$ when $m = 0$

Particles are quanta of field oscillation

$$E = \sqrt{m^2c^4 + p^2c^2} = h\nu$$

frequency

$$p = \frac{h}{\lambda}$$

wavelength

h is Planck's constant

the ElectronVolt (eV)

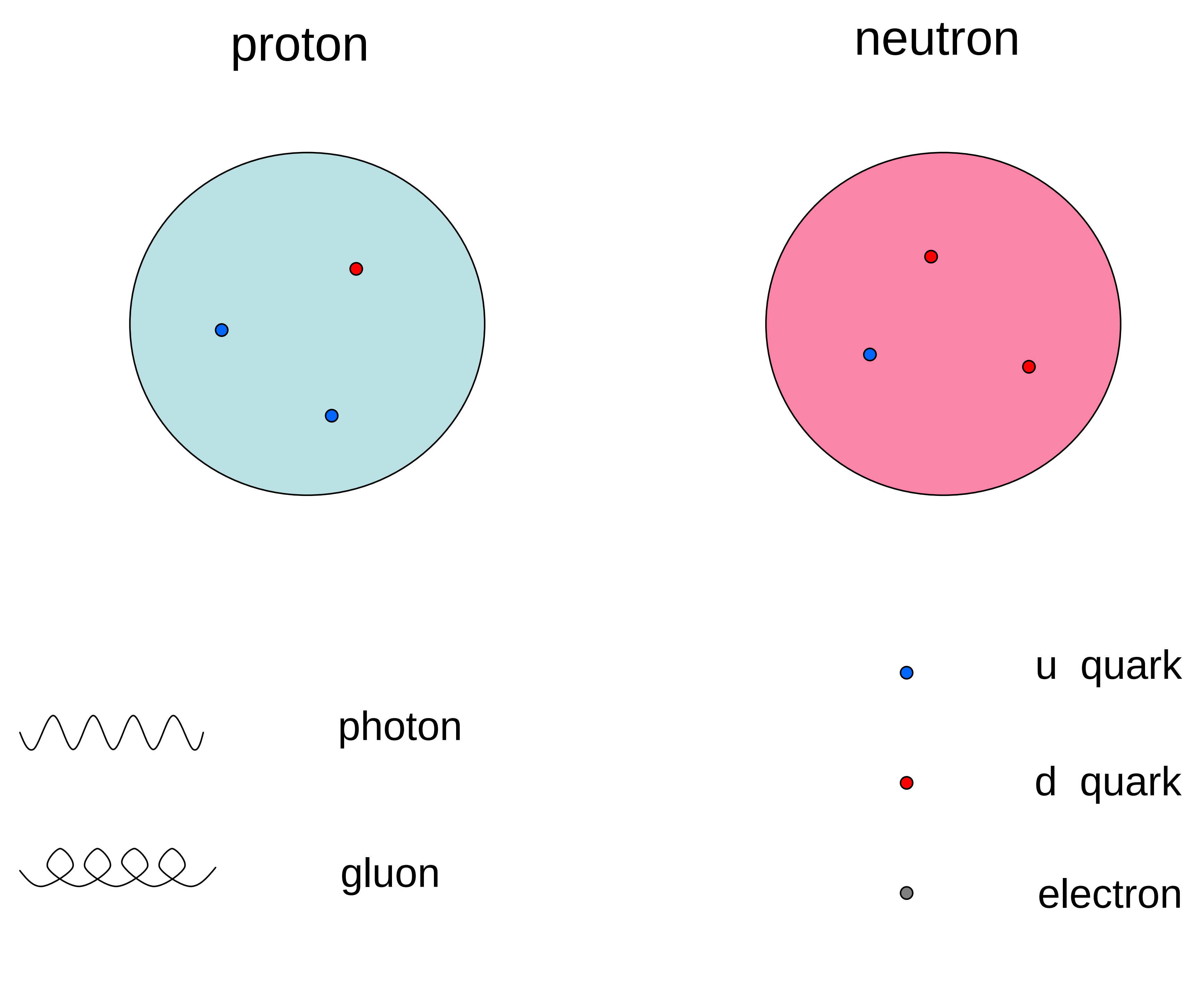
- eV is the typical energy of a quantum of visible light (photon)

- rest mass energy of the electron

$$m_e c^2 = 511 \text{ keV}$$

- rest mass energy of the proton

$$m_p c^2 = 938 \text{ MeV}$$


proton
neutron
photon
gluon
u quark
d quark
electron

The Standard Model

- quarks: u d s c b t
- charged leptons: e μ τ
- neutrinos: ν_e ν_μ ν_τ
- gauge fields: γ g W Z
- Higgs particle: h

Why not neutrinos?

- are collisionless

- are produced in the early universe $\quad n_{\nu} \approx \dfrac{115}{\mathrm{cm}^3}$

- but move too fast and too far

$$\mathrm{v}_{\nu} = \frac{p_{\nu}\, c^2}{E_{\nu}} \approx \frac{10^{-4}\ \mathrm{eV}}{m_{\nu}\, c}$$

$$\Sigma\, m_{\nu}\, c^2 < 1\,\mathrm{eV}$$

neutrinos
are
hot
dark
matter

What we need is Cold Dark Matter

- stable
- collisionless
- cold $\quad v_{\mathrm{DM}} < 10^{-8}\, c$

The candidates

- the axion $\quad m_a \sim 10^{-5}\ \mathrm{eV}/c^2 \qquad \mathrm{v}_a \sim 10^{-17}\, c$

- the WIMP $\quad m_W \sim 100\ \mathrm{GeV}/c^2 \qquad \mathrm{v}_W \sim 10^{-12}\, c$

- the sterile neutrino

$$m_\nu \sim 10\ \mathrm{keV}/c^2 \qquad \mathrm{v}_\nu \sim 10^{-8}\, c$$

- others

Weakly Interacting Massive Particles

- weakly interacting, like a neutrino
- but much more massive

$$m_W \sim 100 \ \mathrm{GeV}/c^2$$

- motivated by supersymmetric extensions of the Standard Model

WIMP cosmological energy density

$$\Omega_W \simeq \frac{2 \cdot 10^{-37}\, c\ \mathrm{cm}^2}{< \sigma_{\mathrm{ann}}\ \mathrm{v} >}$$

WIMP
annihilation
cross-section

P. Hut

B. Lee &
S. Weinberg

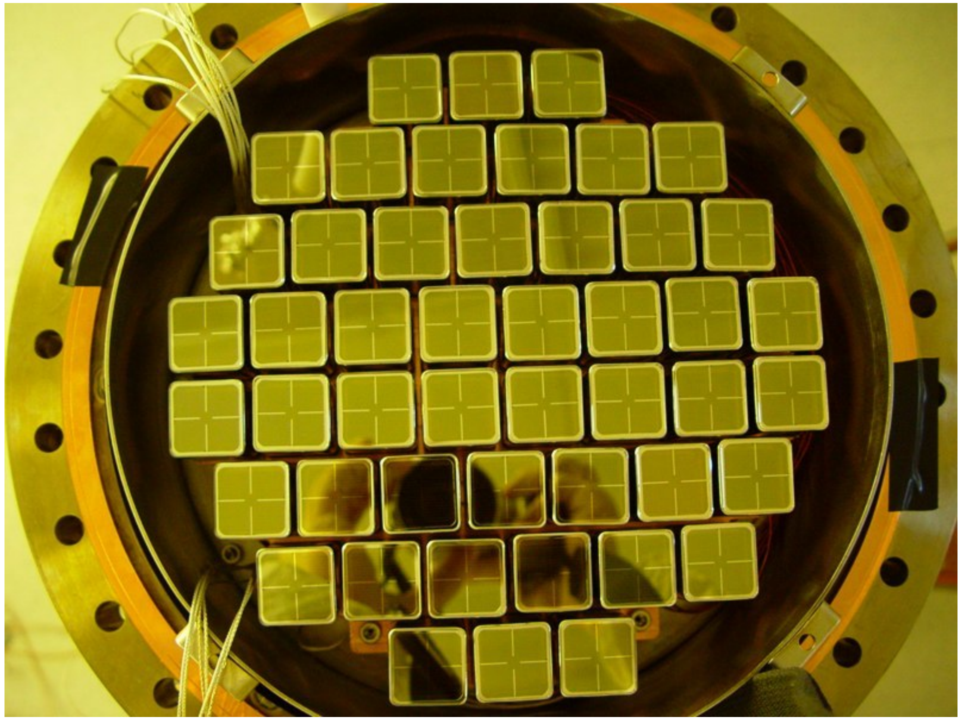
K. Sato &
H. Kobayashi

M.I. Vysotskii,
A.D. Dolgov &
Y.B. Zel'dovich

1977

WIMP detectors

CDMS



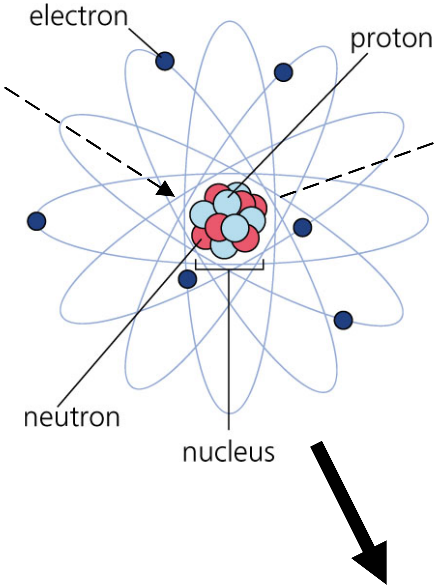
Xenon

Also: DAMA, Edelweiss, CRESST, ZEPLIN, …

WIMP – nucleus elastic scattering

WIMP

WIMP

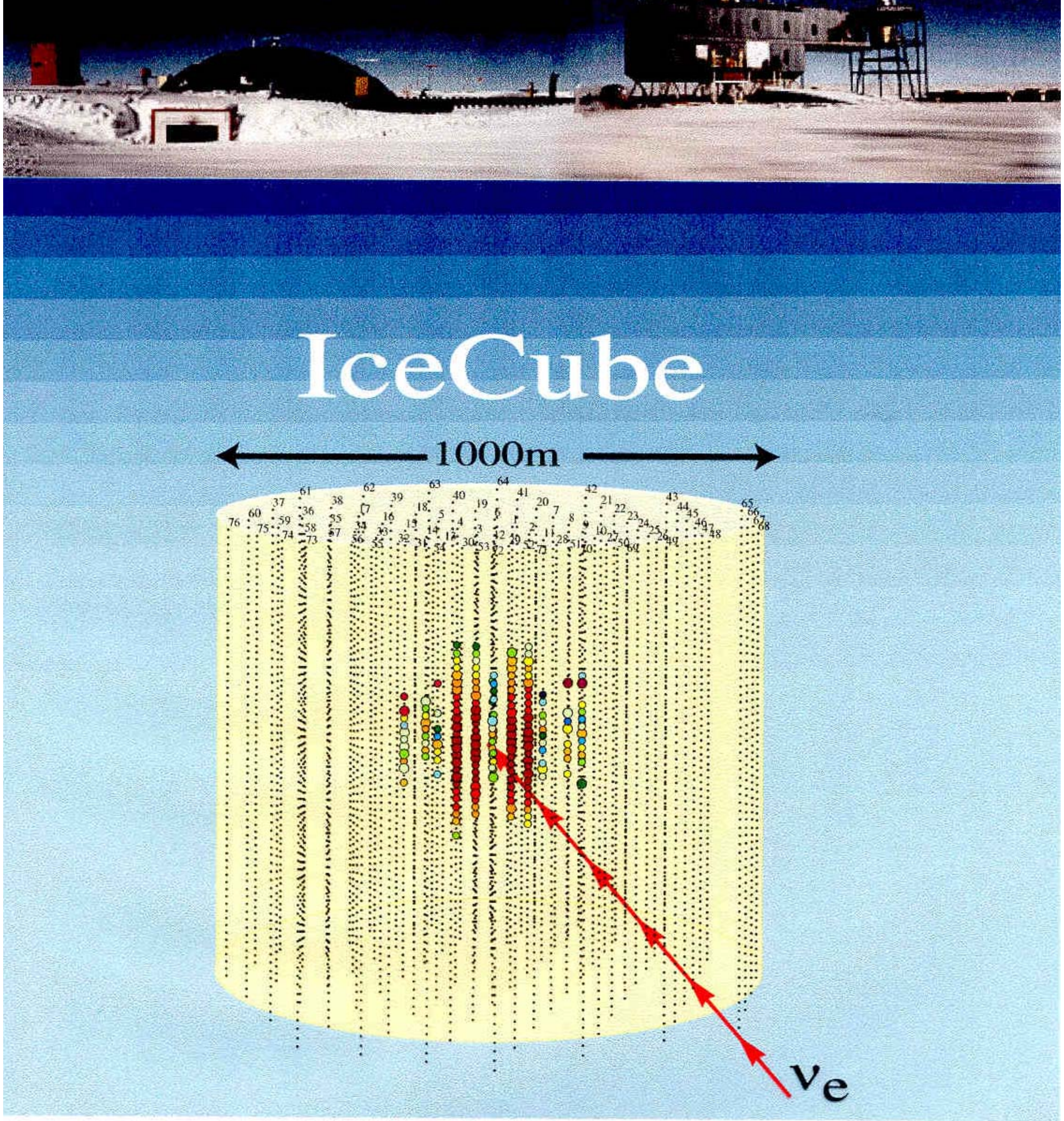


$$\sigma_{\text{elastic}} < \text{few } 10^{-43}\ \text{cm}^2$$

$$\text{for } m_W \sim 100\,\text{GeV}$$

ionization,
scintillation,
phonons …

M. Goodman &
E. Witten   1985



At the South Pole, IceCube looks for neutrinos

produced by the annihilation of WIMPs captured in the Sun.

In space, the GLAST sattelite looks for gamma rays produced by the annihilation of WIMPs in the Milky Way halo

The strong CP puzzle

- The theory of strong interactions (QCD) has a parameter θ
- If $\theta \neq 0$, QCD violates parity P and CP
- $\theta < 10^{-10}$ is required
- but θ may have any value a-priori

- Peccei and Quinn showed that the Standard Model can be modified in such a way as to make θ a dynamical variable.

- The modified theory contains a new particle, named the axion

Weinberg, Wilczek 1978

The axion cosmological energy density

Relic axion field oscillations
continue to this day

$$\Omega_a \sim \frac{10^{-5}\ \mathrm{eV}}{m_a\, c^2}$$

Abbott and PS

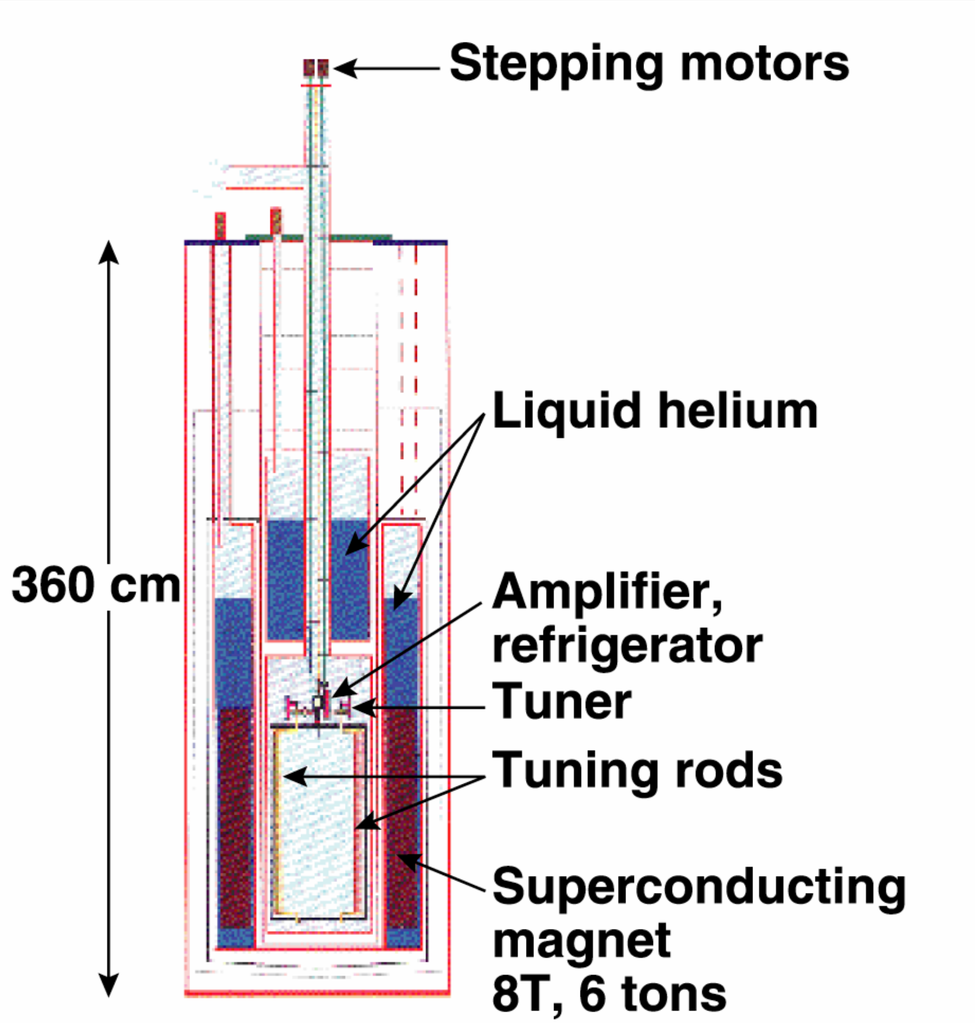
Preskill, Wilczek
and Wise

Dine and Fischler

1983

Axion Dark Matter eXperiment

Magnet with Insert (side view)



Pumped LHe → T ~ 1.5 k

Magnet

8 T, 1 m × 60 cm ∅

A parting thought …

Dark matter forms caustics
as does light

Ludwig
Boltzmann

1844 - 1906

Boltzmann's law

In thermal equilibrium

$$p\,(E) \;\square\; \exp\left(\frac{-E}{k_B T}\right)$$

probability

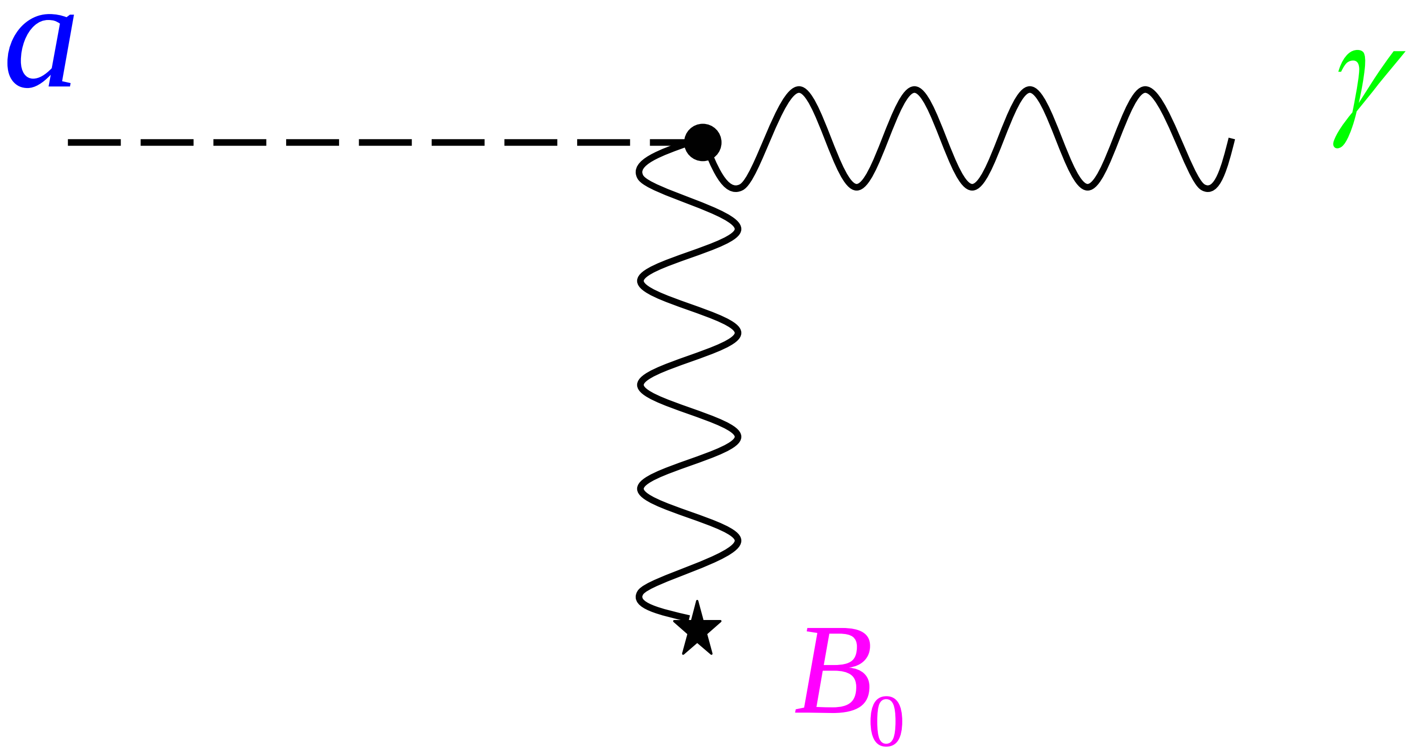
temperature

For WIMPs $\quad E = m_W\, c^2 + \ \ldots$

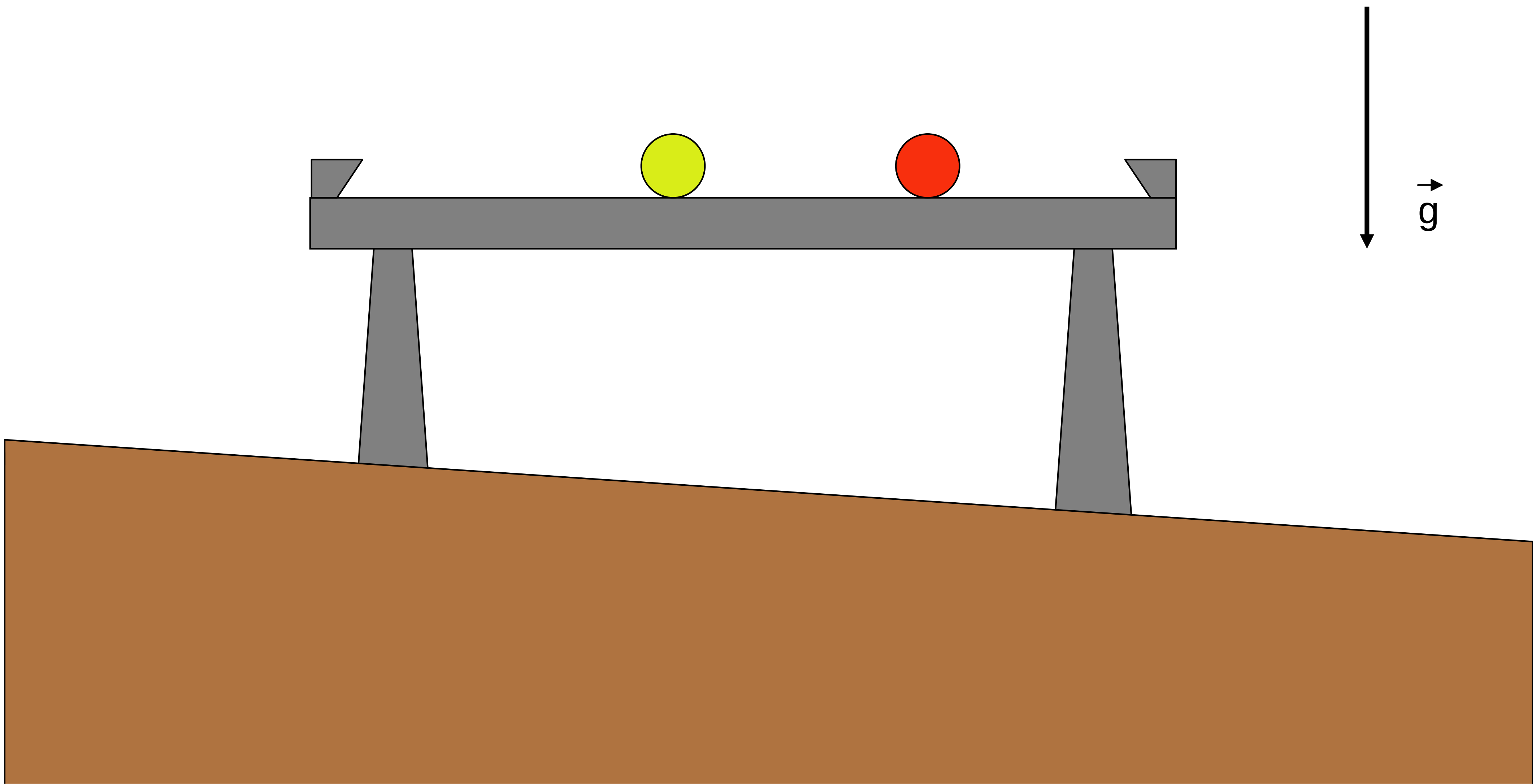
The WIMPs annihilate until $\quad k_B\, T \;\square\; \dfrac{m_W\, c^2}{20}$

Axion to photon conversion in a magnetic field

PS 83



A level pooltable on an inclined floor



A self adjusting pooltable