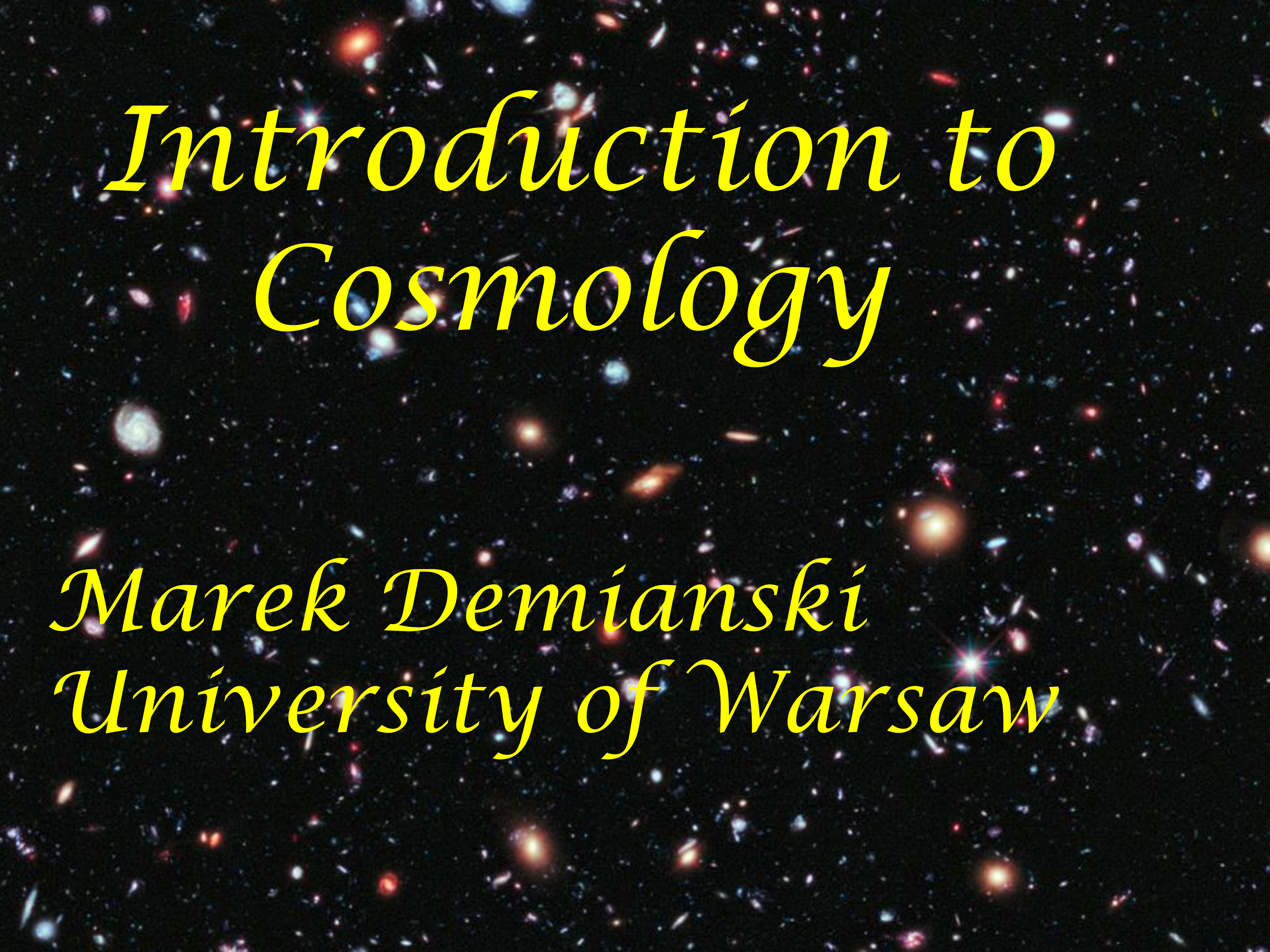
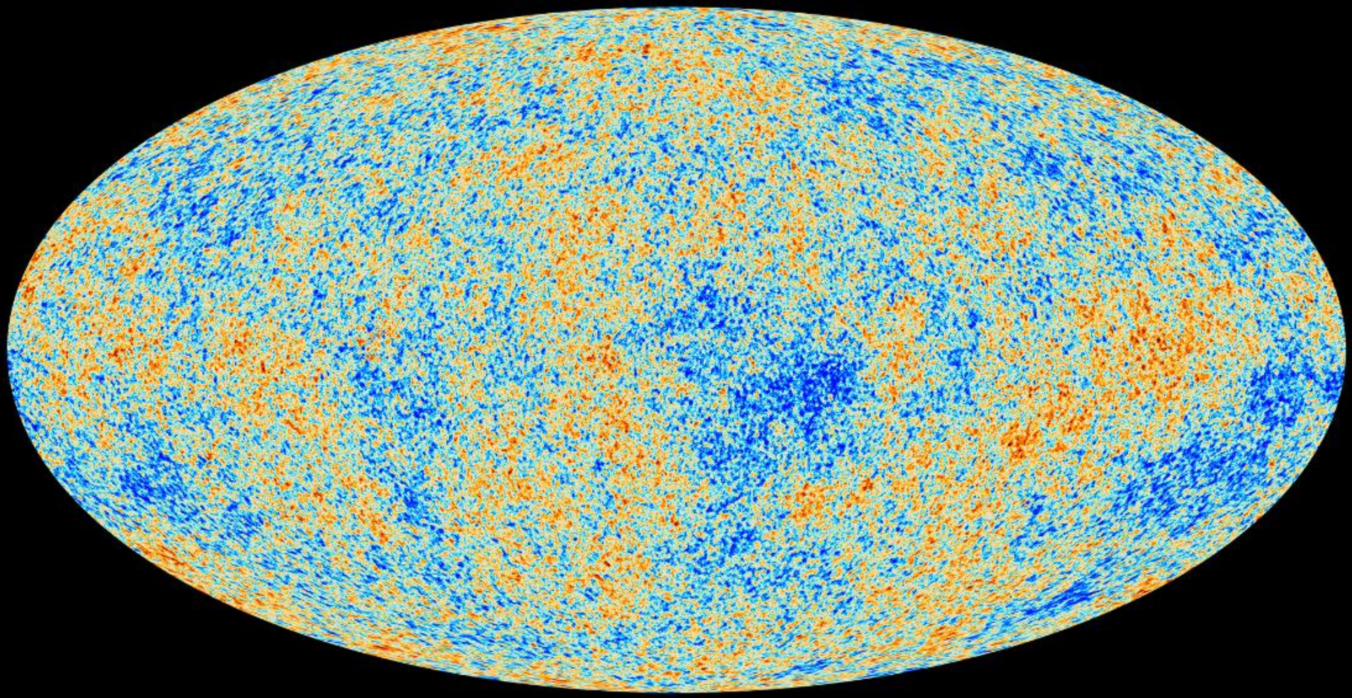


Introduction to Cosmology

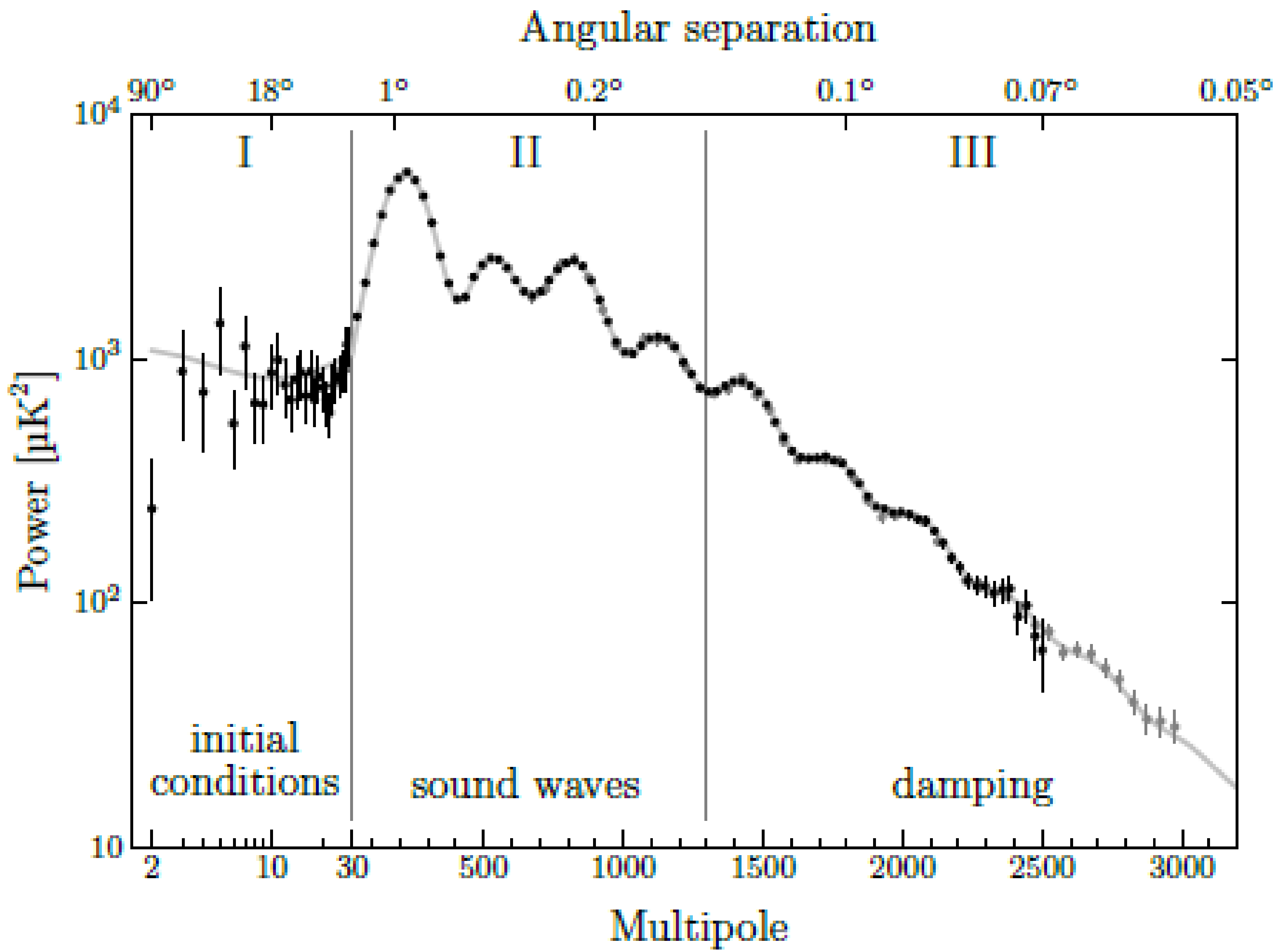
Marek Demianski
University of Warsaw

COSMIC MICROWAVE BACKGROUND

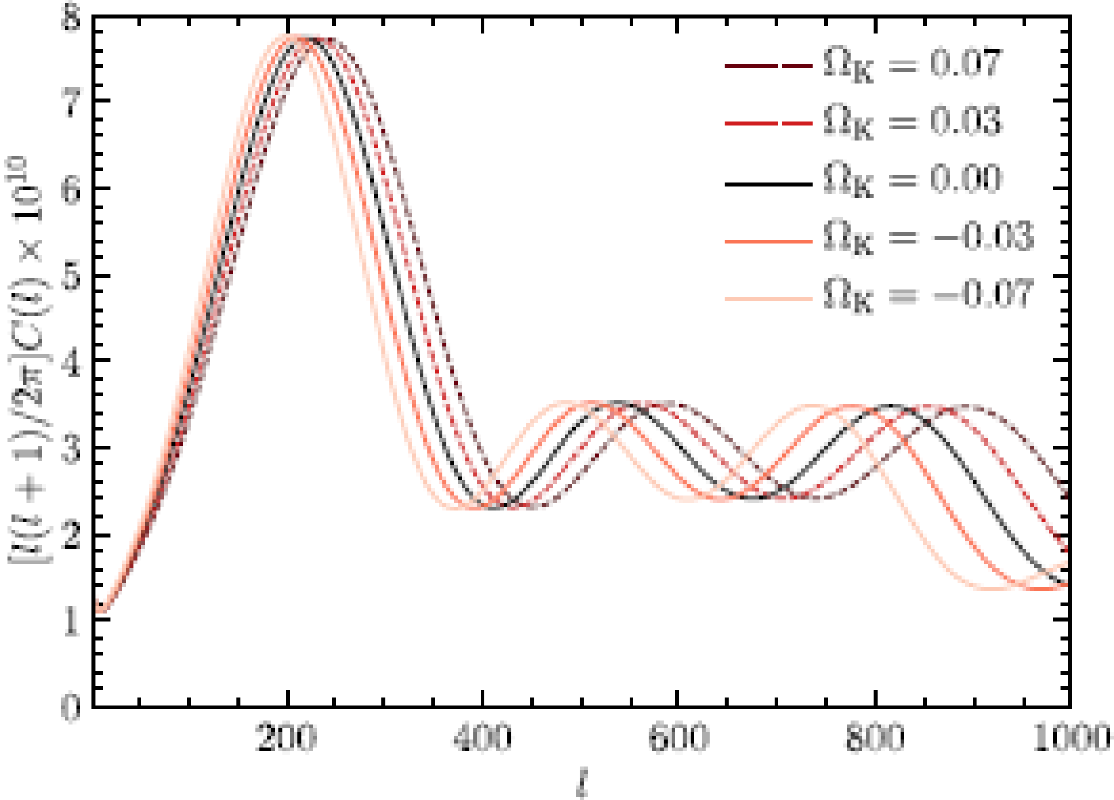


$T = 2.7255 \pm 0.0003\ \mathrm{K}$

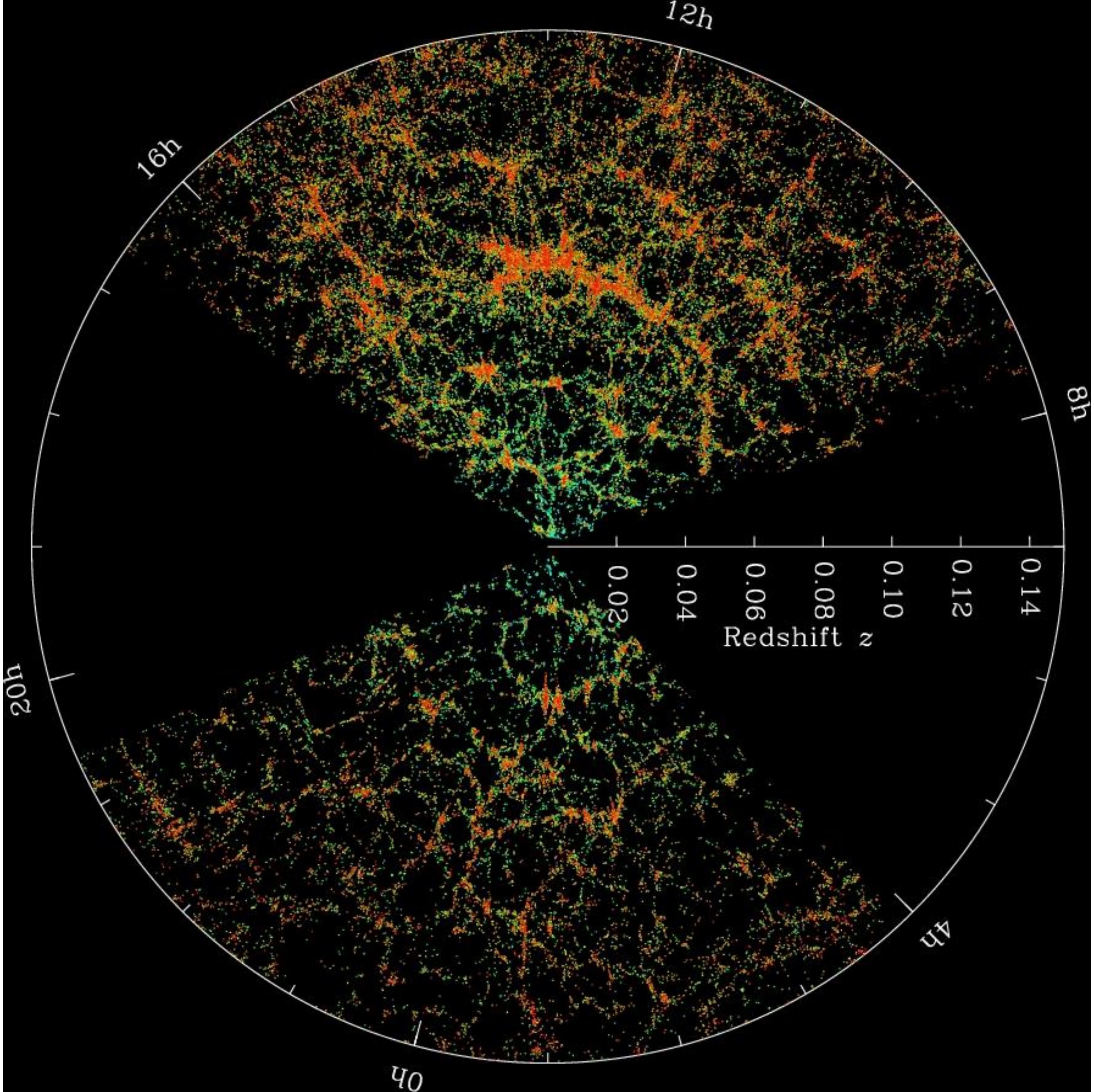
[Credits: ESA and the Planck Collaboration]



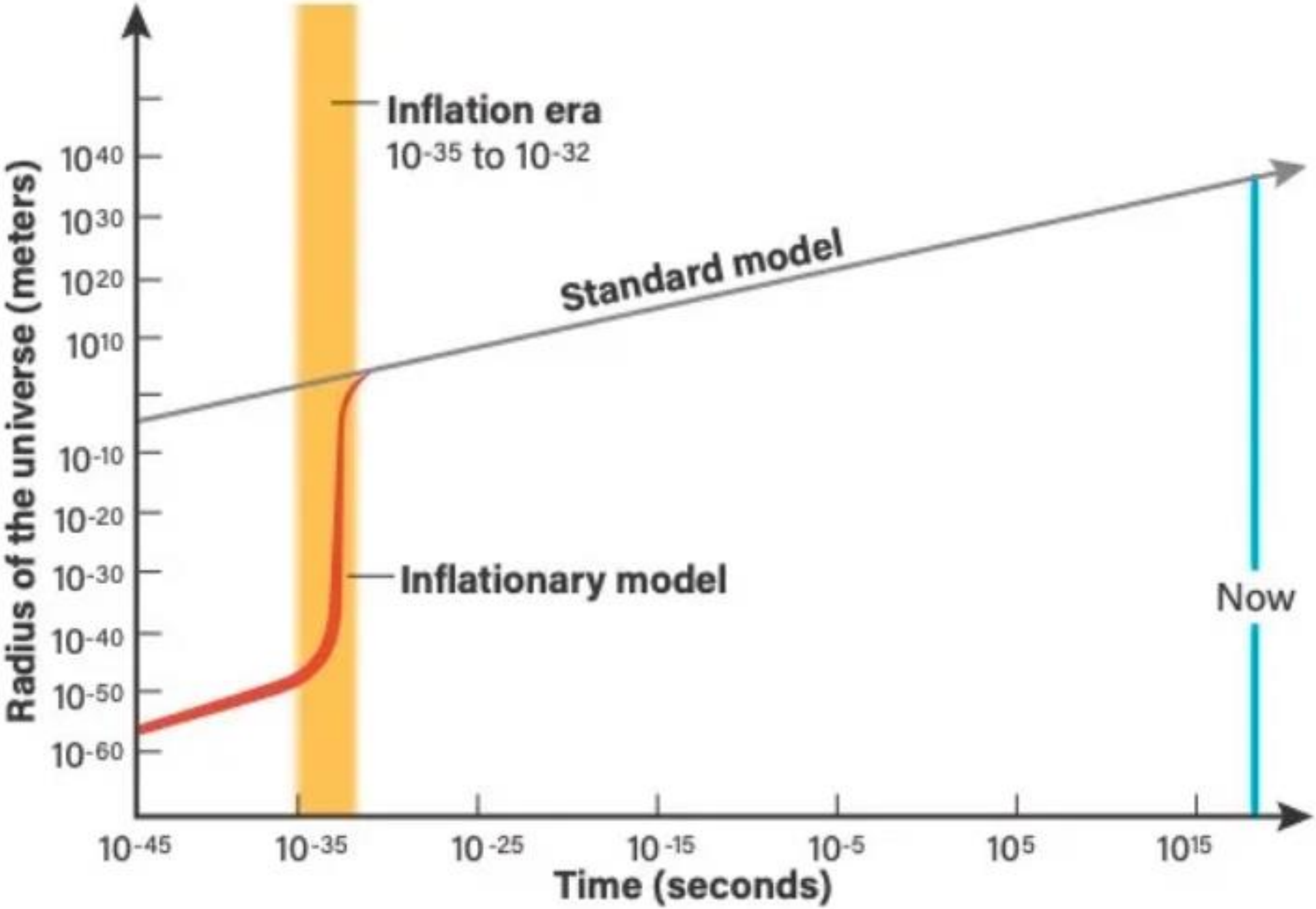
Angular separation
90°
18°
1°
0.2°
0.1°
0.07°
0.05°
I
II
III
initial
conditions
sound waves
damping
Power [μK²]
10⁴
10³
10²
10
2
10
30
500
1000
1500
2000
2500
3000
Multipole



$\Omega_K = 0.07$
$\Omega_K = 0.03$
$\Omega_K = 0.00$
$\Omega_K = -0.03$
$\Omega_K = -0.07$
$[l(l+1)/2\pi]C(l) \times 10^{10}$
l
0
1
2
3
4
5
6
7
8
200
400
600
800
1000



12h
16h
8h
20h
4h
0h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z



Inflation era
10^{-35} to 10^{-32}
Standard model
Inflationary model
Now
Radius of the universe (meters)
10^{40}
10^{30}
10^{20}
10^{10}
10^{-10}
10^{-20}
10^{-30}
10^{-40}
10^{-50}
10^{-60}
10^{-45}
10^{-35}
10^{-25}
10^{-15}
10^{-5}
10^{5}
10^{15}
Time (seconds)

Brief summary:

Inflation predicts that quantum-mechanical perturbations in the very early universe are first produced when the relevant scales are causally connected. Then these scales are whisked outside the horizon by inflation, only to re-enter much later to serve as initial conditions for the growth of structure in the universe. The perturbations are best described in terms of their Fourier modes. The mean of a given Fourier mode, for example for the gravitational potential, is zero:

$$< \Phi(\mathbf{k}) >= 0 \,.$$

Further, any given Fourier mode is uncorrelated with a different one. However, a given mode has nonzero variance, so

$$< \Phi(\mathbf{k})\Phi^*(\mathbf{k}^{'}) >= P_\Phi(\mathbf{k})(2\pi)^3\delta_D^{(3)}(\mathbf{k}-\mathbf{k}^{'}) \,,$$

the Dirac delta function is enforcing the independence of the different modes. This is the characteristic feature of a Gaussian random process.

A spectrum in which $k^3 P_{\Phi(k)}$ is constant (i.e., does not depend on k) is called a scale-invariant or scale-free spectrum.

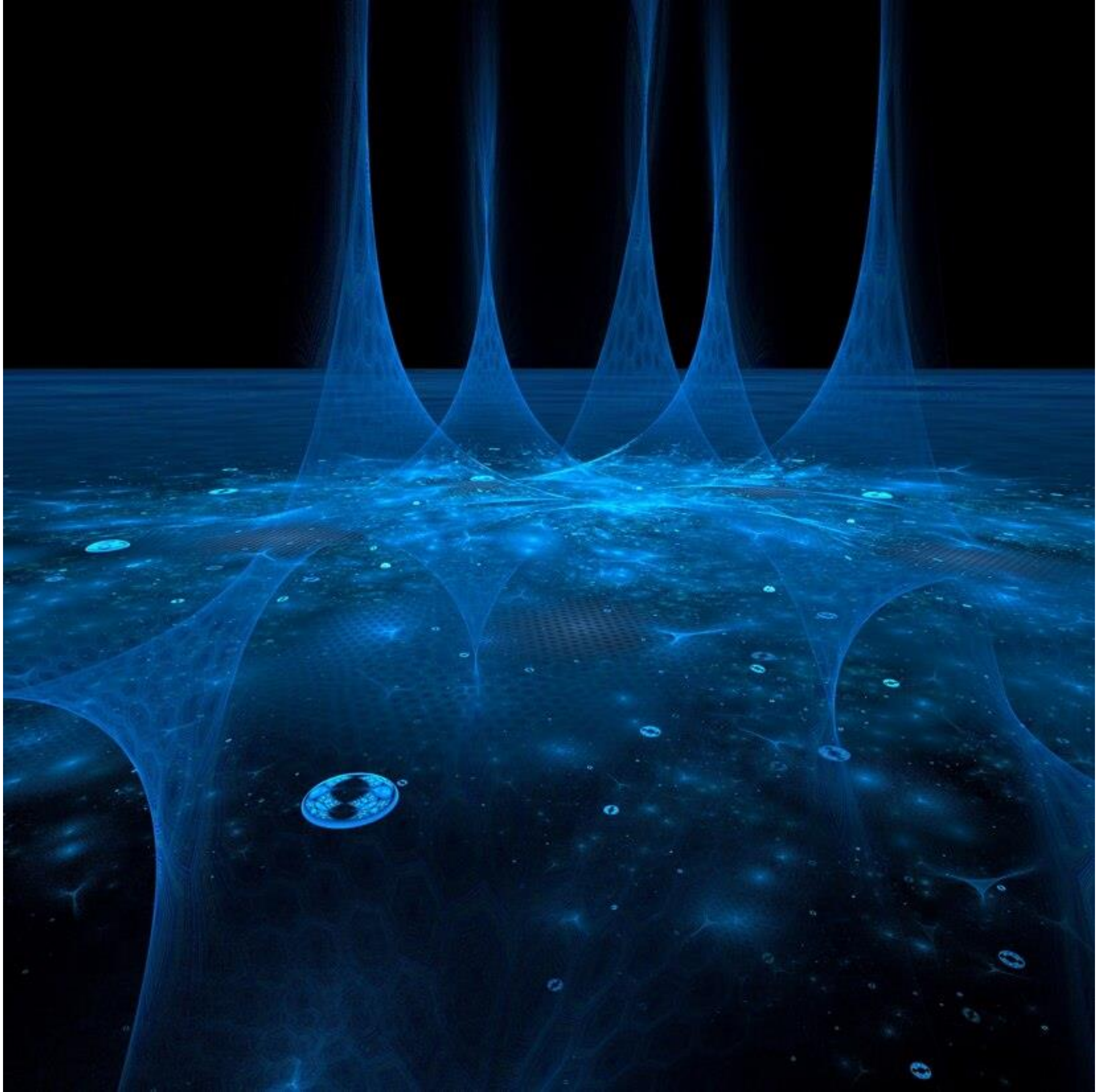
In analogy to the case of harmonic oscillator one can find the power spectrum of fluctuations in $\delta\Phi$ as

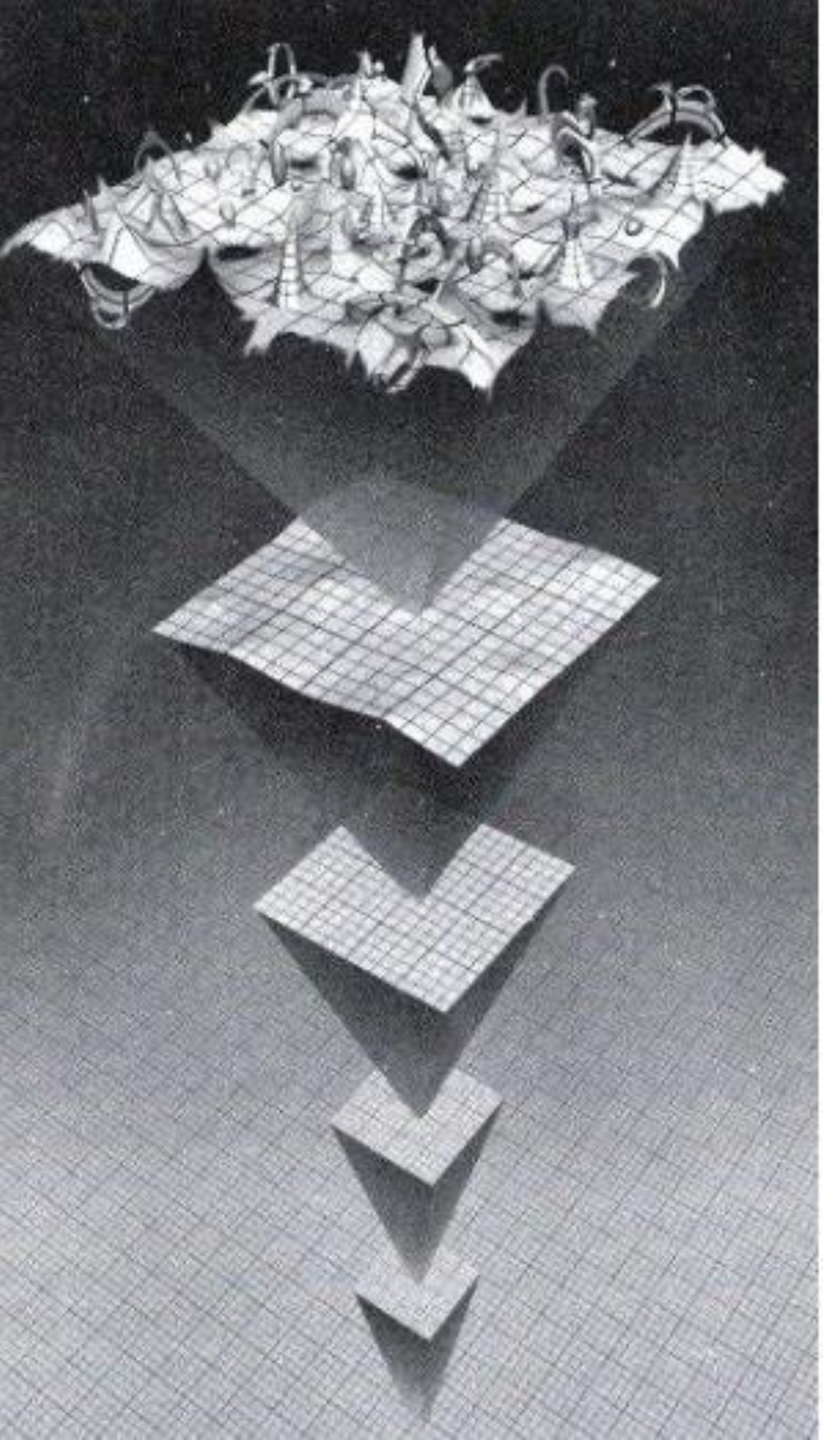
$$P_{\delta\Phi} = \frac{H^2}{2k^3} \,.$$

Since the nature of the inflaton field is not known, it is reasonable to introduce an additional parameter that describes modification of the power spectrum:

$$\mathcal{P}_{\mathcal{R}} = \frac{2k^3 P_{\delta\Phi}}{H^2}(\frac{k}{k_*})^{n_s - 1},$$

where k_* is some appropriate scale, and n_s is a constant, its current best value is $n_s = 0.9649 \pm 0.0042$.





All things we know obey the principles of quantum mechanics

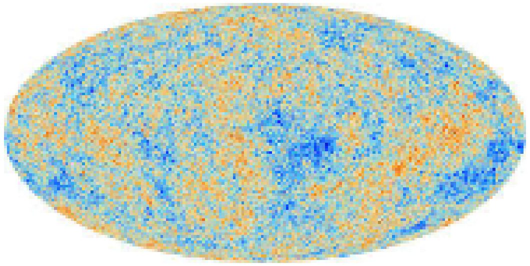
We expect that spacetime obeys quantum mechanics

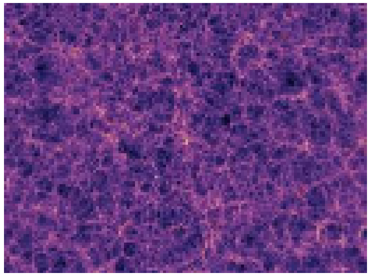
At tiny distances, spacetime must be continuously moving!

We believe that the distribution of everything originated from these tiny quantum fluctuations during inflation!

Conveniently conserved

- Remarkably, these power spectra are conserved throughout most of the history of the universe and we can measure them in the amplitude of perturbations in the CMB and galaxy distribution





- To know more about the laws of physics during inflation, physicists want to compute and observe more complicated statistical properties of these perturbations known as primordial non-Gaussianities. Despite 20 years of looking no one has discovered them yet, but the largest ever cosmological datasets are about to come online, stay tuned.

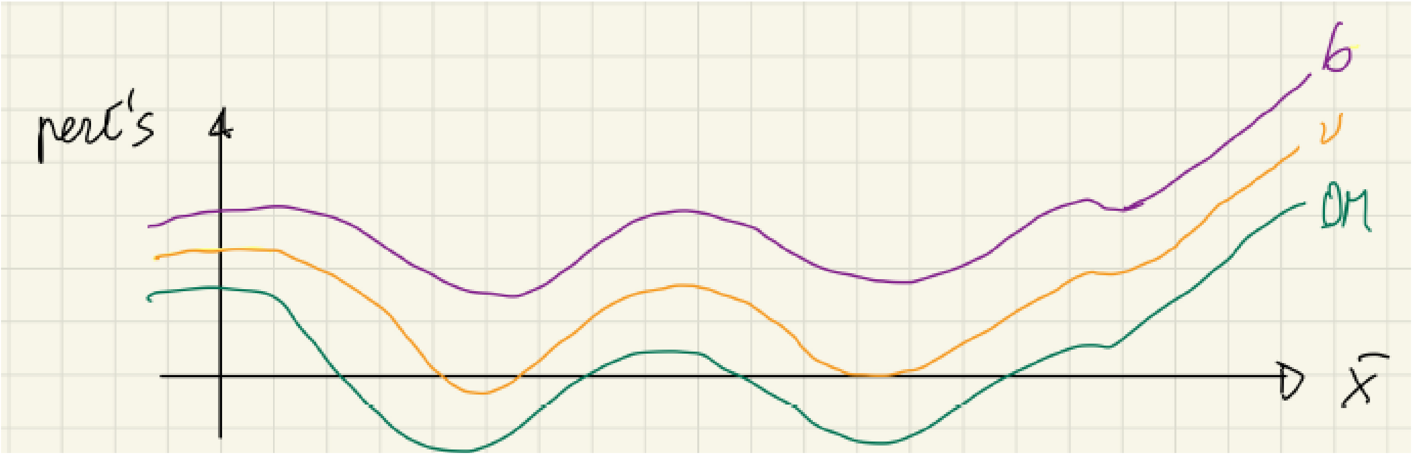


Figure 2: A cartoon depiction of the observed adiabatic nature of cosmological perturbations.

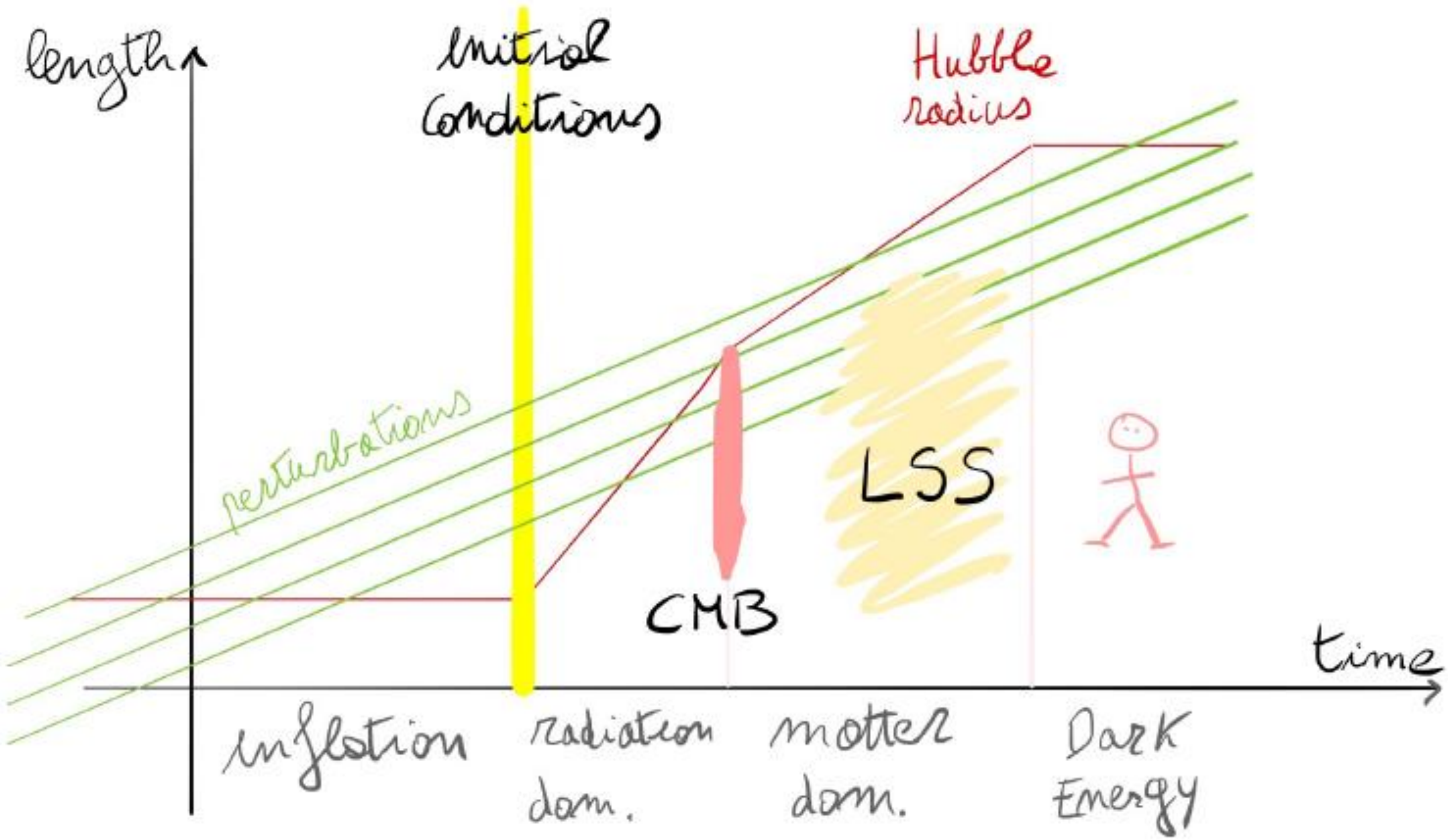
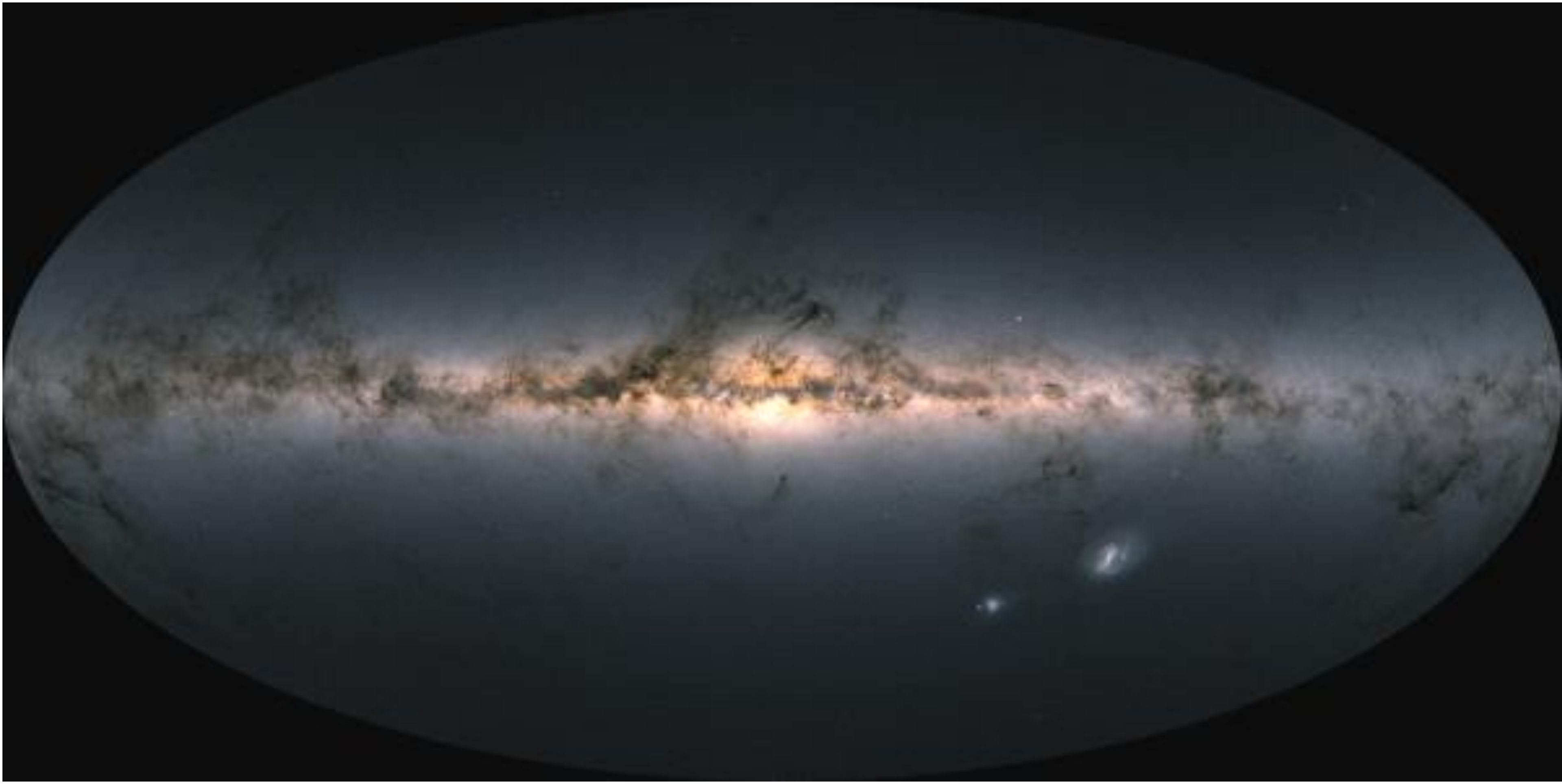
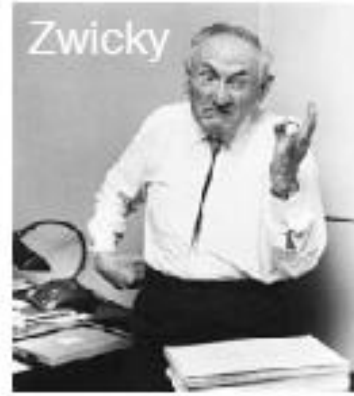
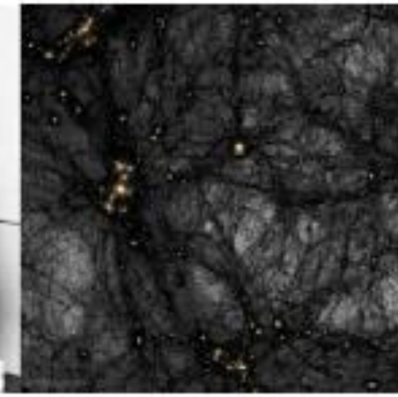


Figure 1: The big picture of cosmology. Inflation sets up the initial condition for perturbations which subsequently re-enter the Hubble radius and source perturbations in the Cosmic Microwave Background (CMB) and Large Scale Structures (LSS).



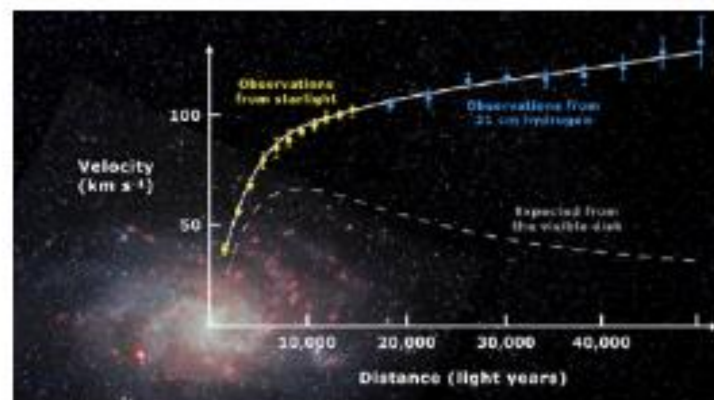
Dark Matter





- The second most abundant thing in the universe is a mysterious form of matter called *dark matter*
- It is called “dark” because it does not emit, absorb or interact with light
- We can only see dark matter through its gravitational effect on visible matter, such as stars, galaxies and light
- Dark matter was conjectured back in the 1930s by Zwicky but convincing evidence arrived only in the 70s from *galaxy rotation curves* measured by Vera Rubin and Kent Ford
- Today we detected dark matter in many different ways and we have detailed maps of where it is distributed.

Rubin
&
Ford



Vera Rubin

THE ASTROPHYSICAL JOURNAL, Vol. 159, February 1970

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

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Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡
Received 1969 July 7; revised 1969 August 21

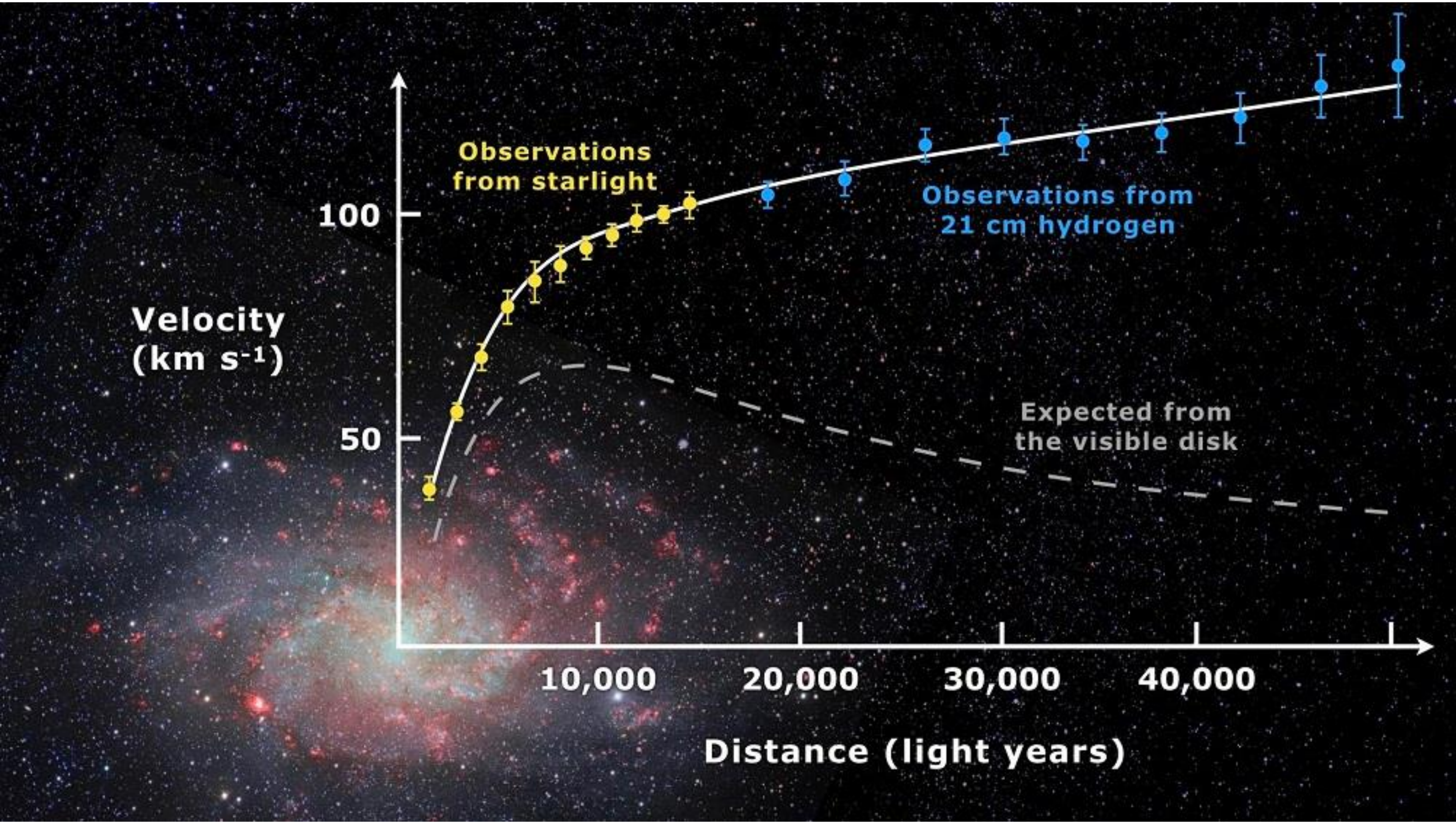
ABSTRACT

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.



Observations
from starlight
Observations from
21 cm hydrogen
100
50
Velocity
(km s-1)
Expected from
the visible disk
10,000
20,000
30,000
40,000
Distance (light years)

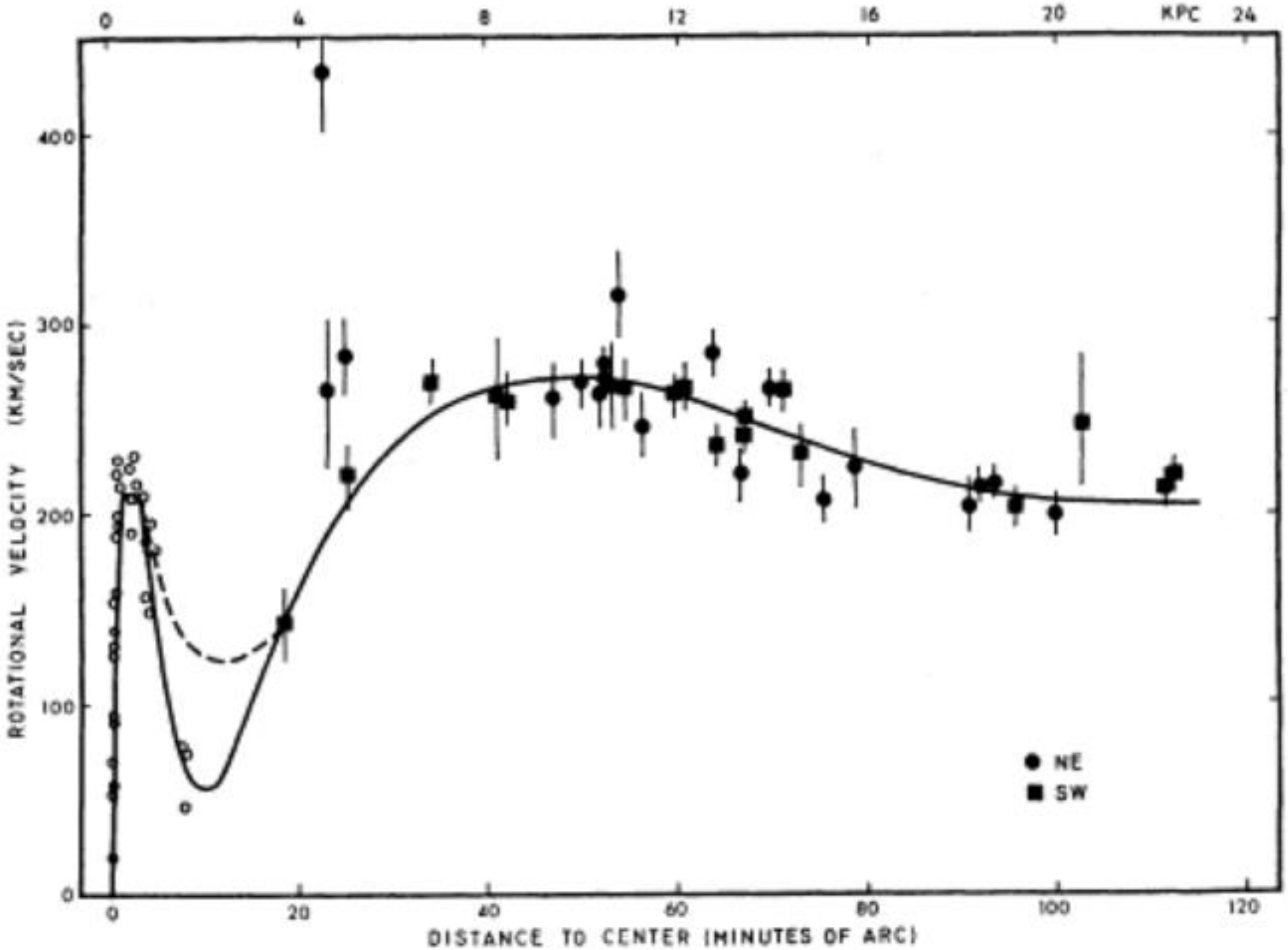
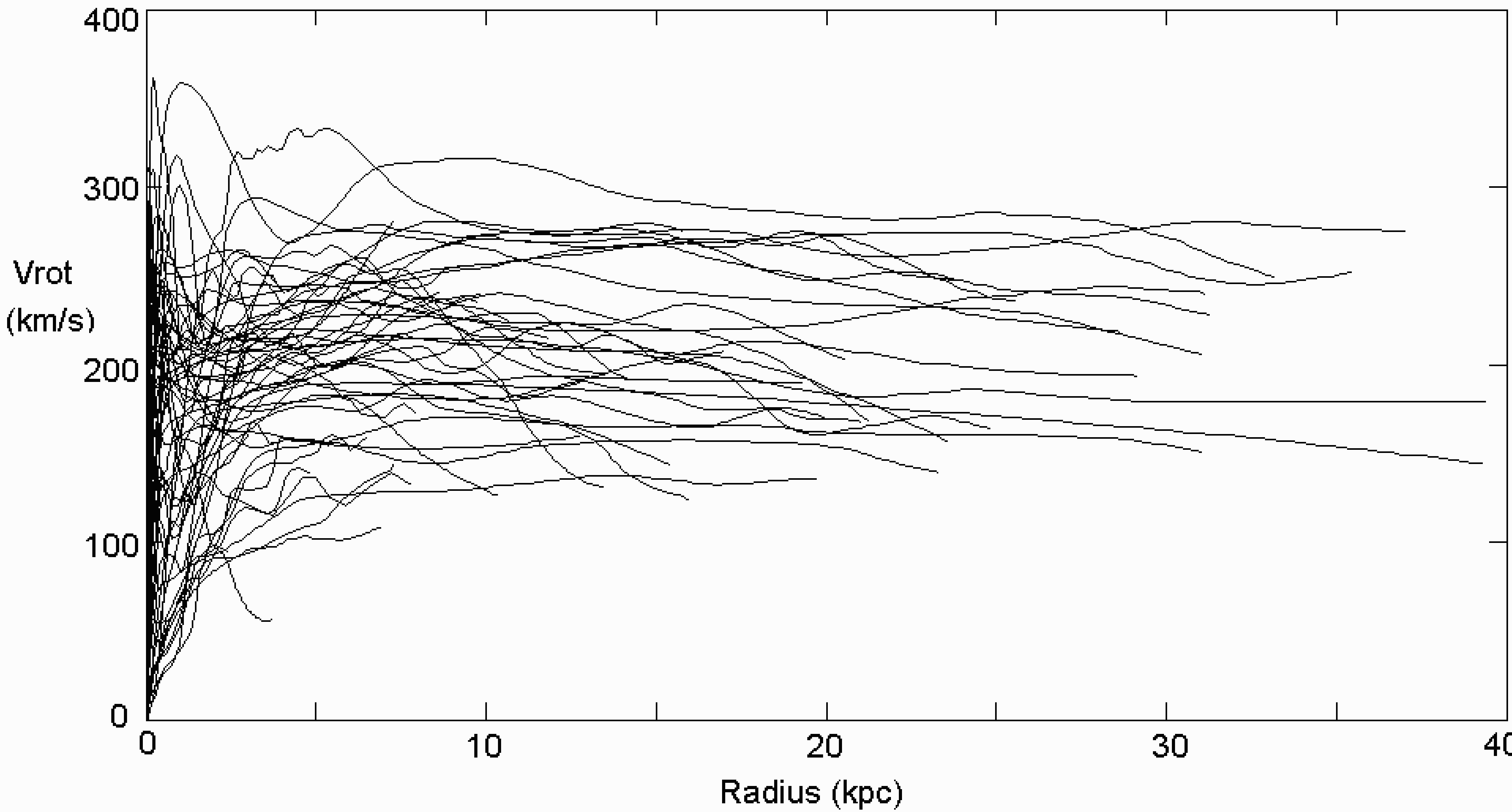
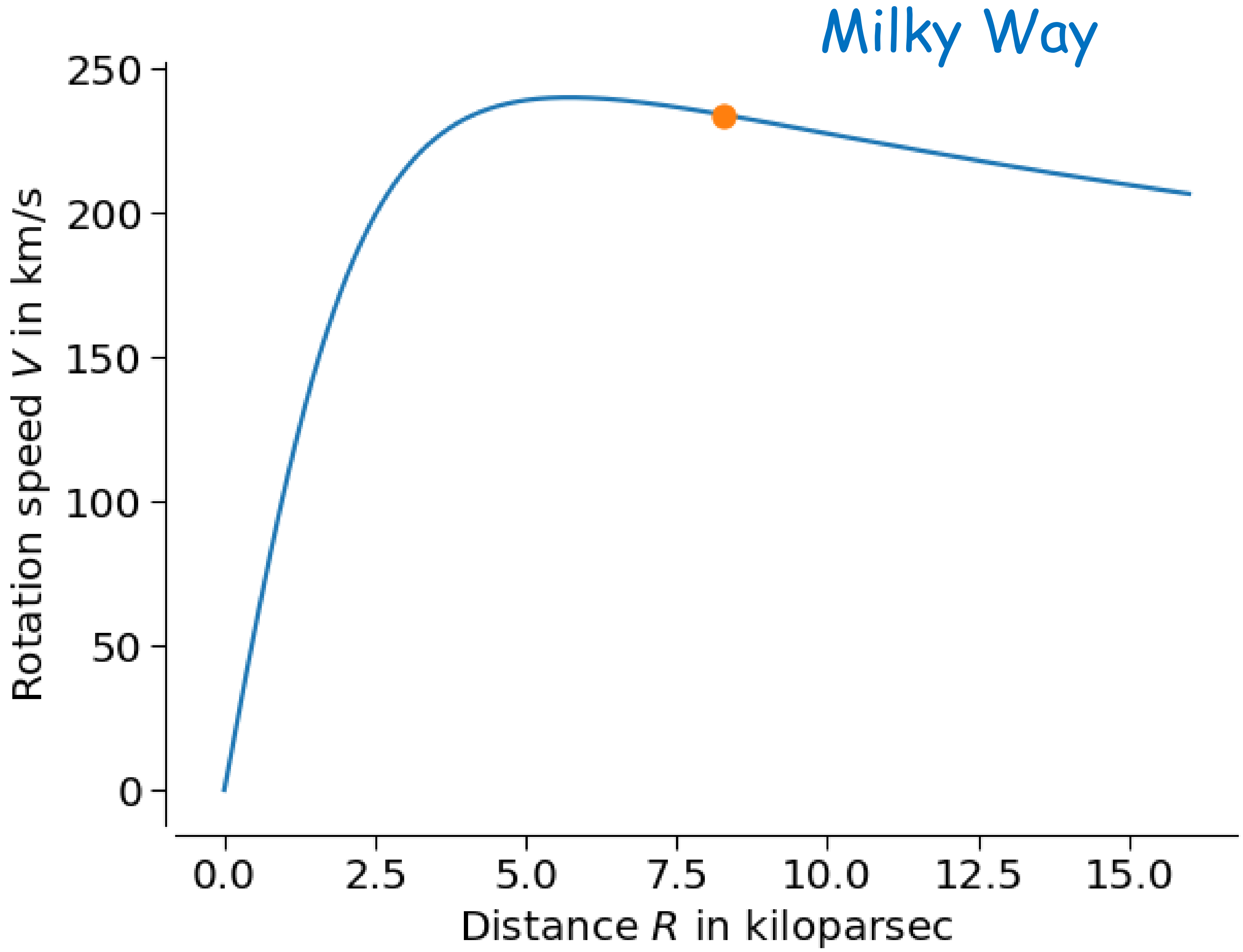


FIG. 9.—Rotational velocities for OB associations in M31, as a function of distance from the center. *Solid curve*, adopted rotation curve based on the velocities shown in Fig. 4. For $R \leq 12'$, curve is fifth-order polynomial; for $R > 12'$, curve is fourth-order polynomial required to remain approximately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


400
300
Vrot
(km/s)
200
100
0
0
10
20
30
40
Radius (kpc)



Milky Way
250
200
150
100
50
0
Rotation speed V in km/s
0.0
2.5
5.0
7.5
10.0
12.5
15.0
Distance R in kiloparsec

Rotational velocity curve

$$\frac{mv^2}{r} = \frac{GMm}{r^2}$$

$$v = \sqrt{\frac{GM}{r}}\,, \text{ but } M = \frac{4}{3}\pi r^3 \varrho\,,$$

$$\text{so } v \propto \sqrt{\varrho r^2}\,,$$

$$\text{when } v = \text{const} \Rightarrow \varrho \propto \frac{1}{r^2} \Rightarrow M(r) \propto r$$

Mass of the Milky Way is much larger than the mass of stars and gas

The additional and dominating mass component is called Dark Matter

Simple model of a dark matter halo:

Isothermal sphere with ρ(r) ≈ 1/ r^2

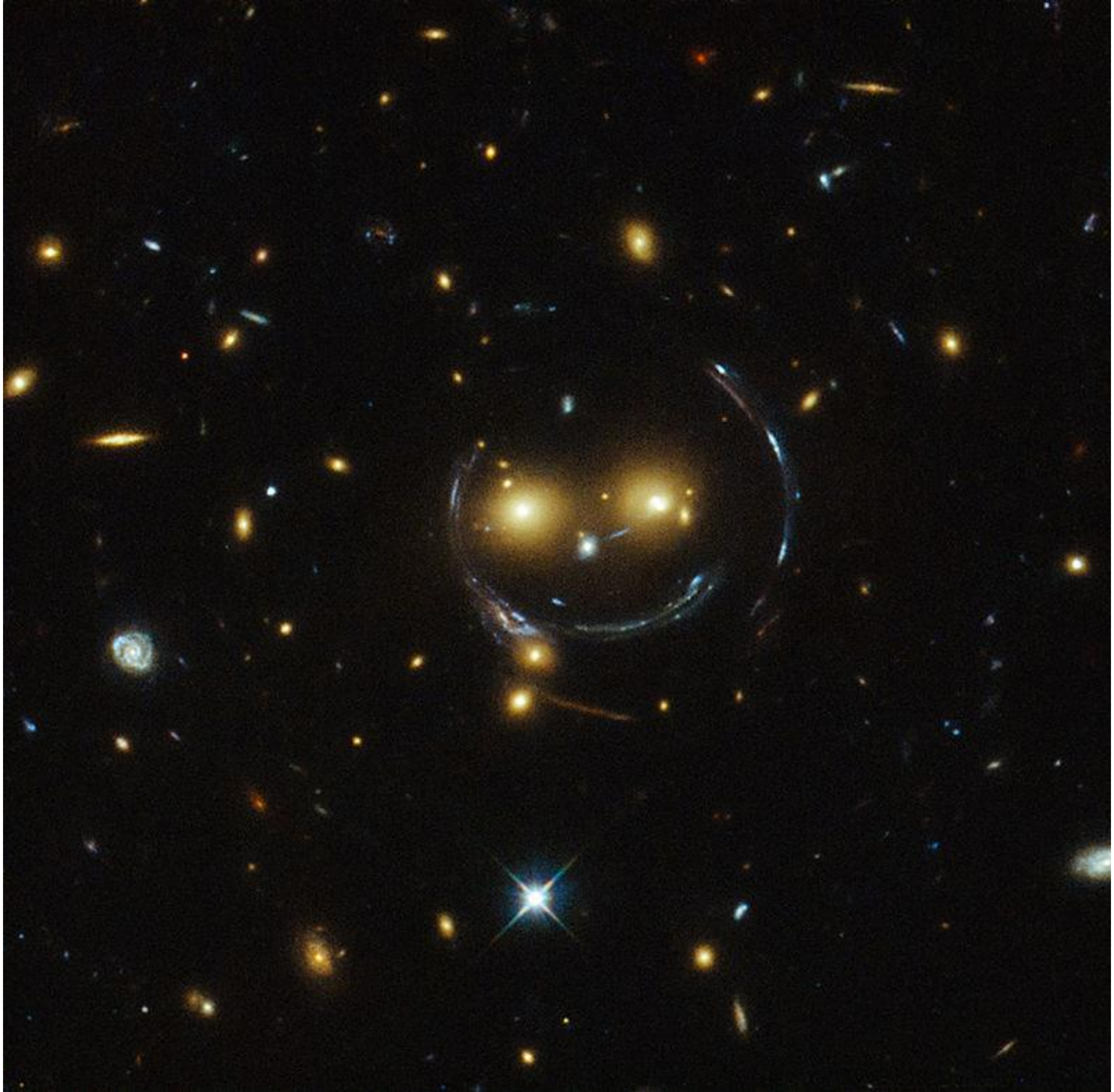
Maxwell distribution of velocities

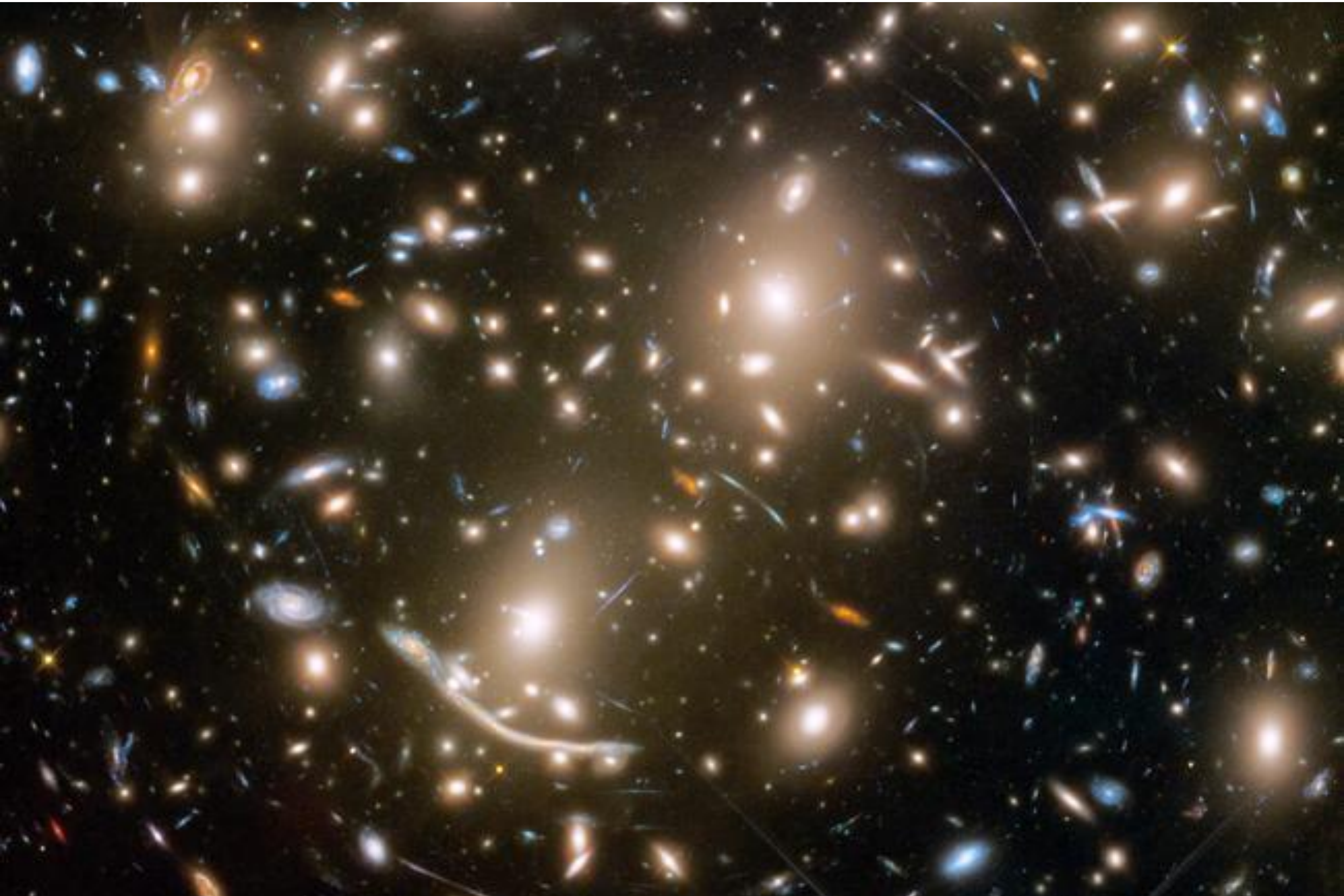
Truncated at r_* such that v(r_*) = v_{escape}

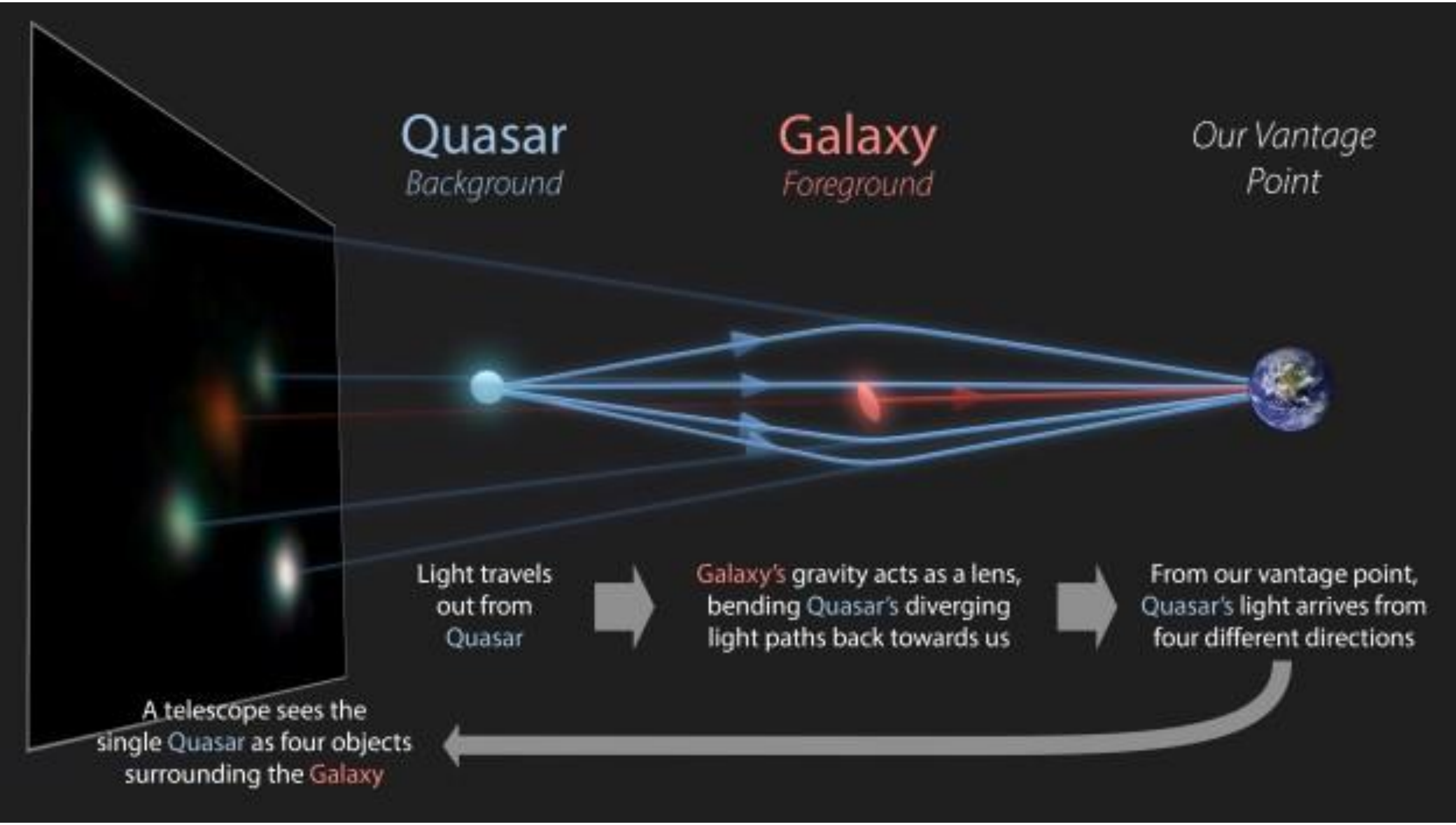
Navarro-Frenk-White halo:

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$

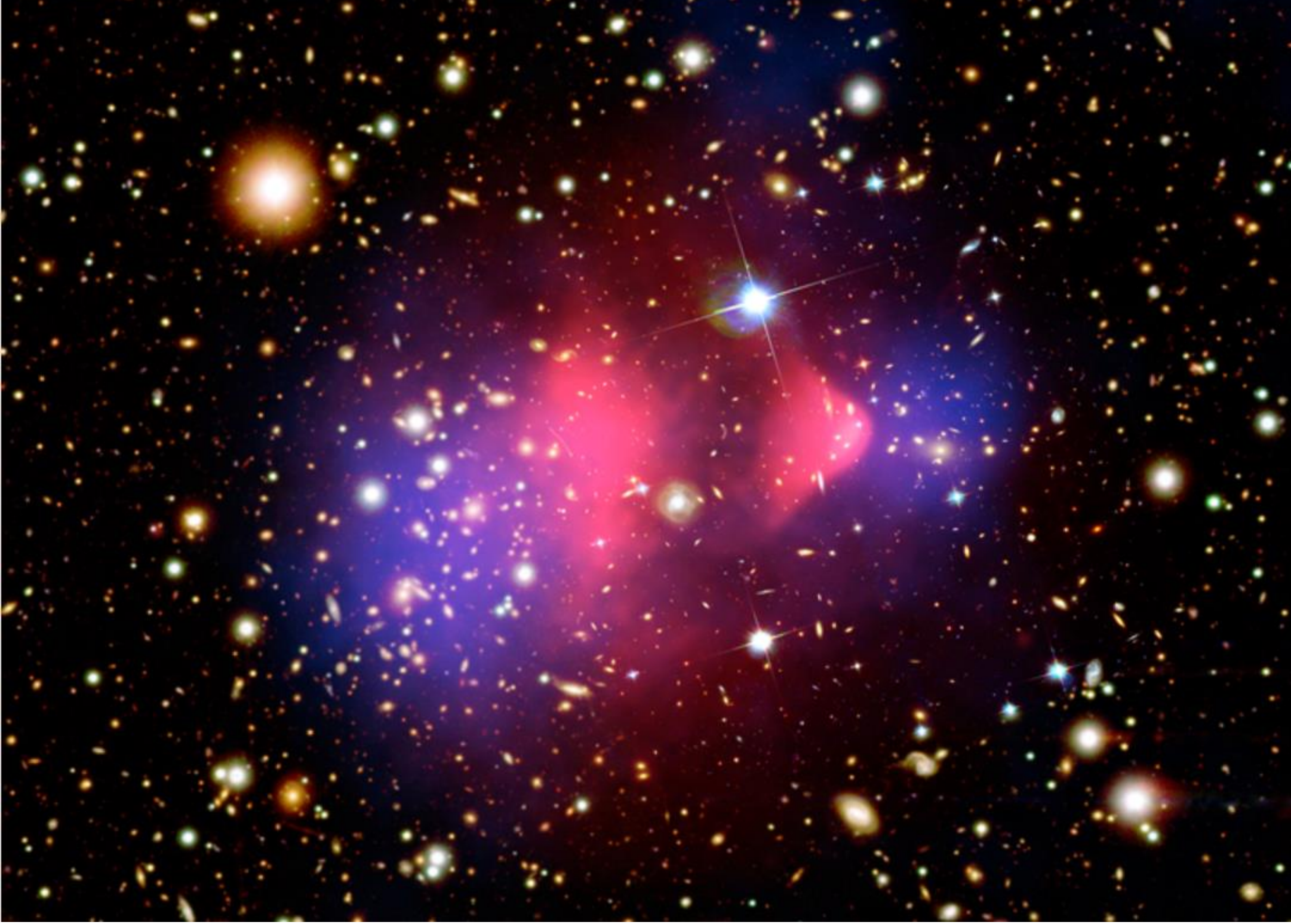
where ρ_0 and the "scale radius", R_s, are parameters which vary from halo to halo.







Quasar
Background
Galaxy
Foreground
Our Vantage Point
Light travels out from Quasar
Galaxy's gravity acts as a lens, bending Quasar's diverging light paths back towards us
From our vantage point, Quasar's light arrives from four different directions
A telescope sees the single Quasar as four objects surrounding the Galaxy



Bullet Cluster

Dark Matter in clusters of galaxies:

- Velocity dispersion
- Gravitational lensing
- X-ray observations
- Bullet cluster

Mass to light ratio :

Galaxies: 5 - 20

Clusters of galaxies: 50 - 500

Dark Matter what could it be:

WIMPs - Weakly Interacting Massive Particles

Sterile neutrinos

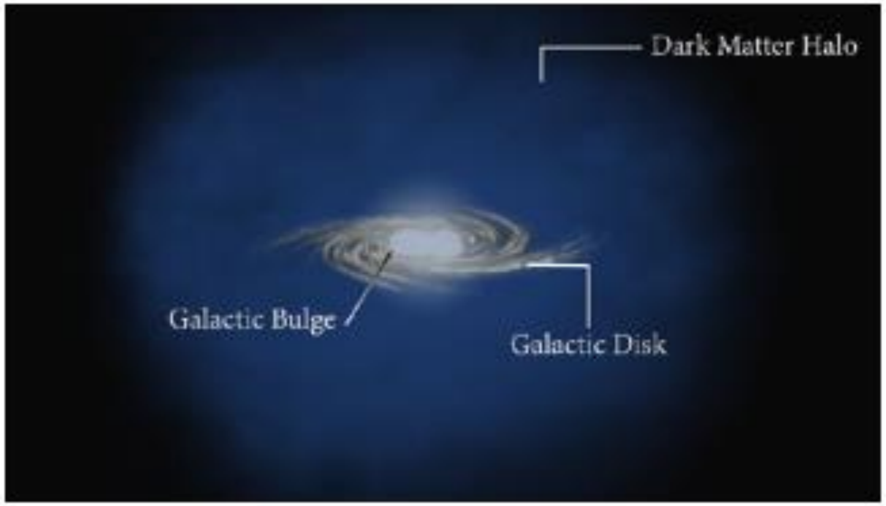
Axions

Supersymmetric particles

Primordial black holes

.....

Dark matter



- Dark matter is 6 times more abundant than ordinary matter, i.e. atoms.

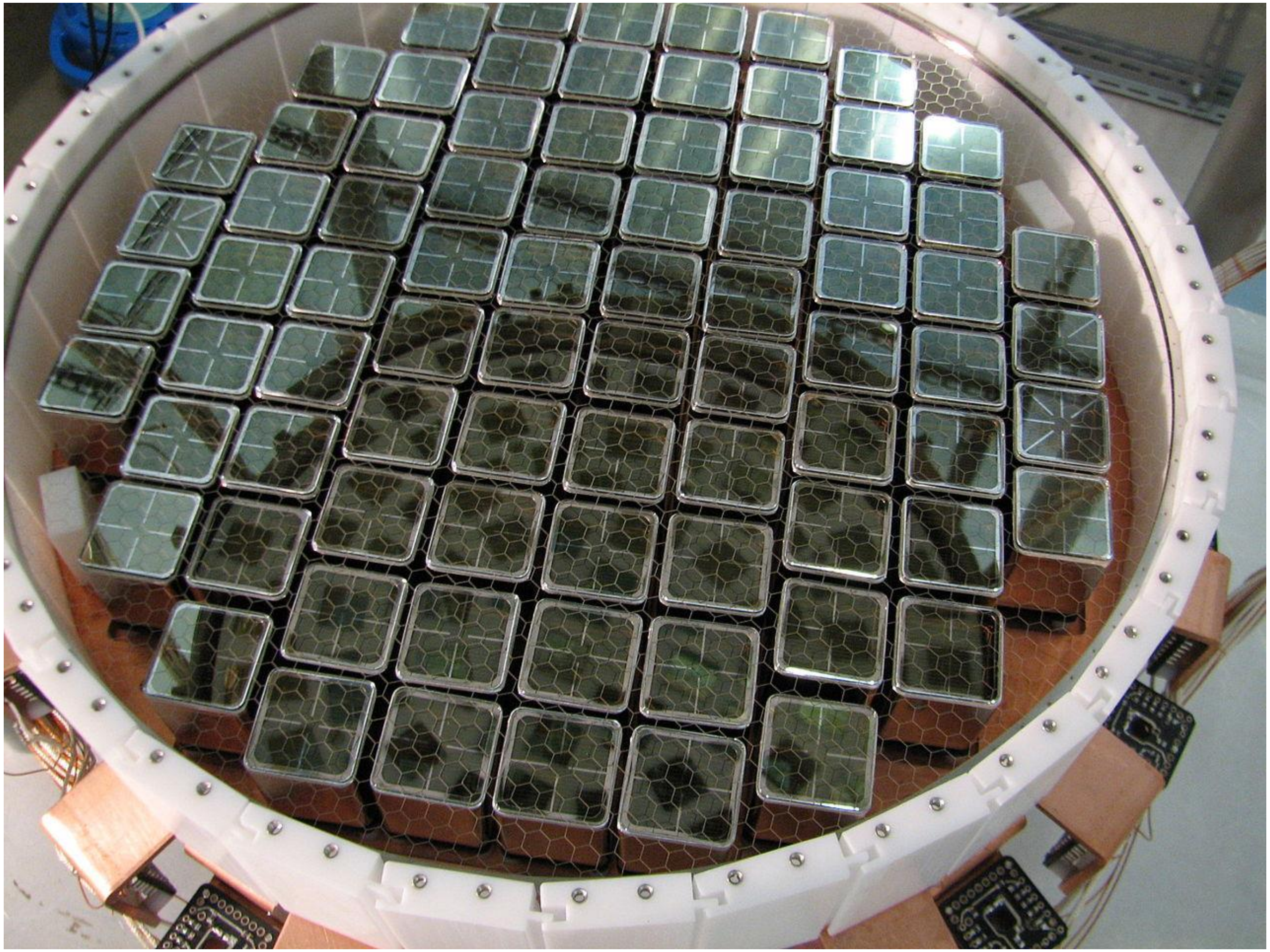
- dark matter forms much less dense regions called dark matter *halos*. All galaxies are surrounded by dark matter halos

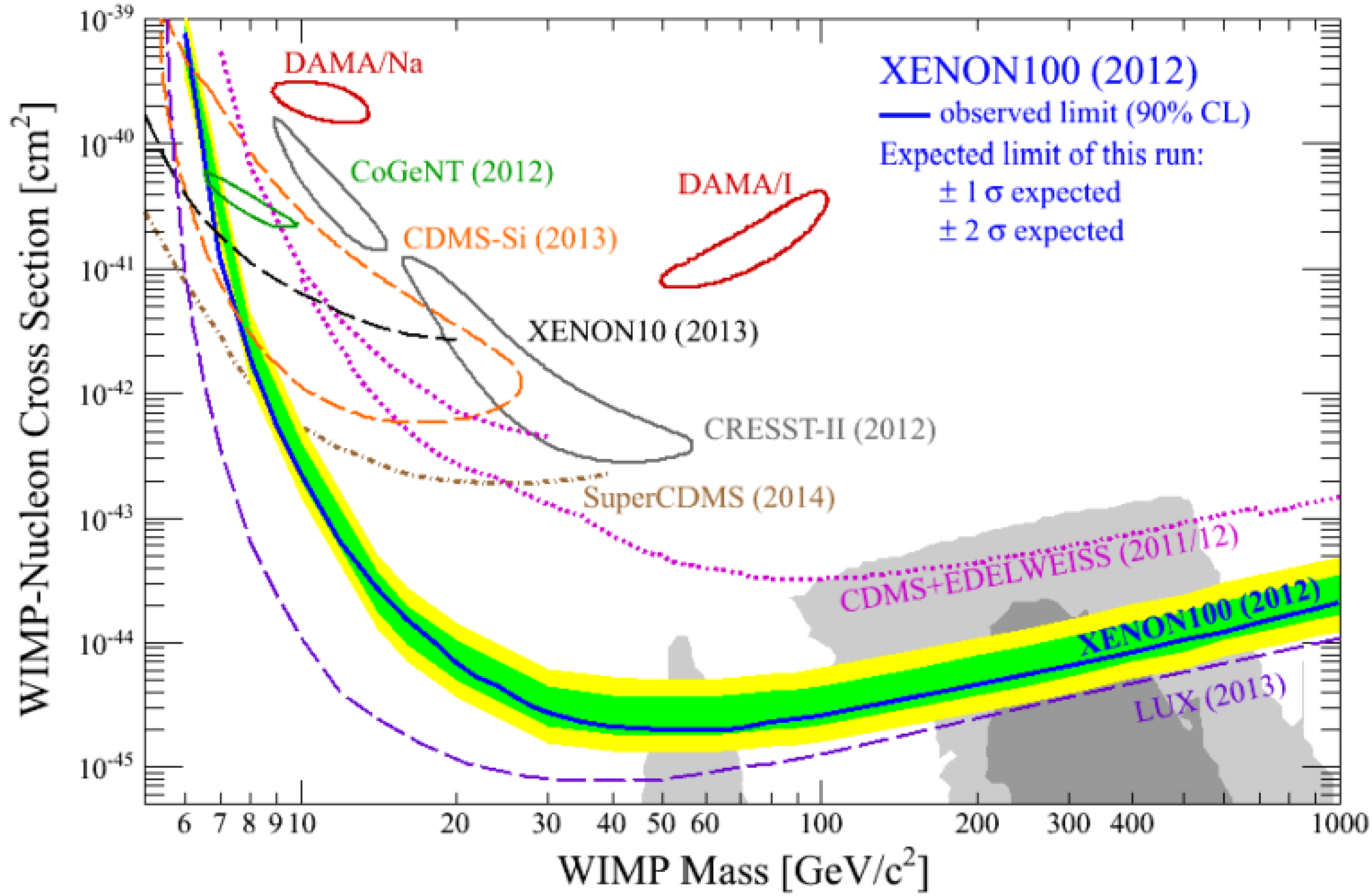
- The mass of dark matter particles is the most uncertain quantities in the history of science. It can be a

Massive neutrinos

$$\Delta m_{21}^2 = (7.9^{+1.0}_{-0.8}) \times 10^{-5} \text{ eV}^2 \qquad |\Delta m_{31}^2| = (2.2^{+1.1}_{-0.8}) \times 10^{-3} \text{ eV}^2$$

$$\sum_{i=1}^{3} m_i < 0.17\,\text{eV}$$





XENON100 (2012)
observed limit (90% CL)
Expected limit of this run:
± 1 σ expected
± 2 σ expected
DAMA/Na
DAMA/I
CoGeNT (2012)
CDMS-Si (2013)
XENON10 (2013)
CRESST-II (2012)
SuperCDMS (2014)
CDMS+EDELWEISS (2011/12)
XENON100 (2012)
LUX (2013)
WIMP-Nucleon Cross Section [cm^2]
WIMP Mass [GeV/c^2]

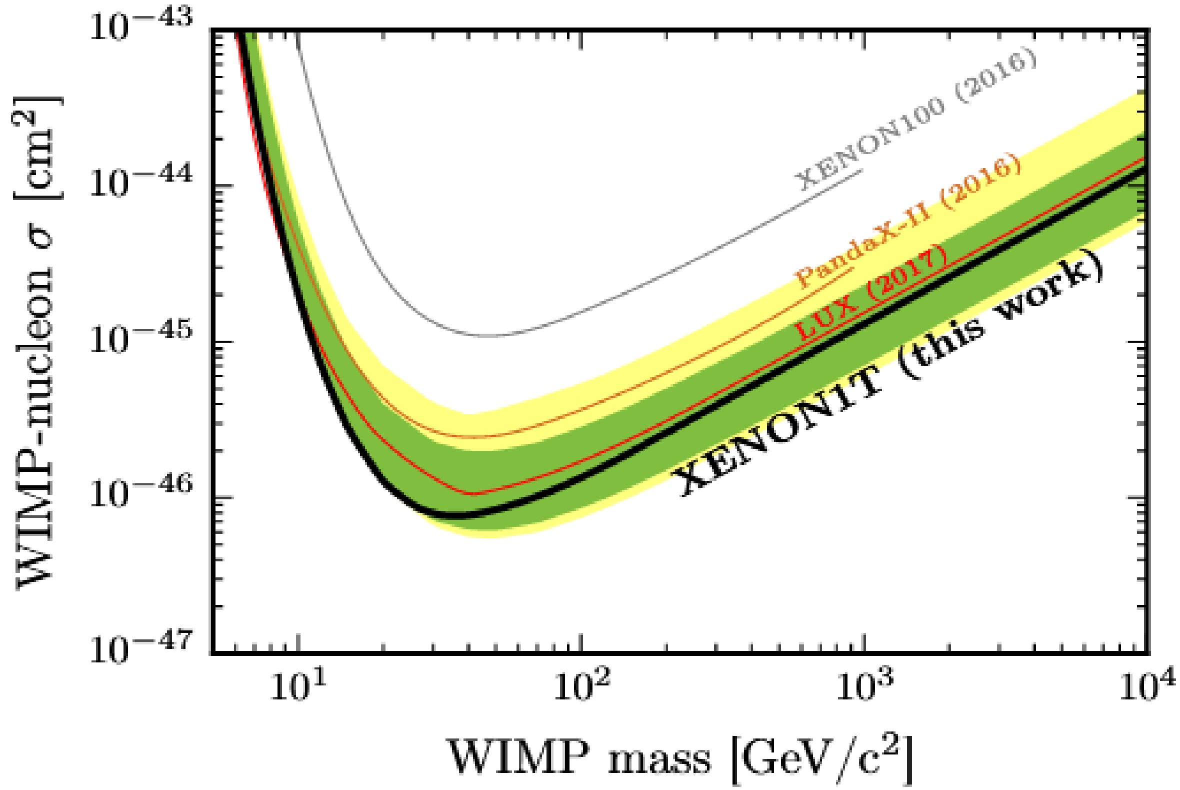
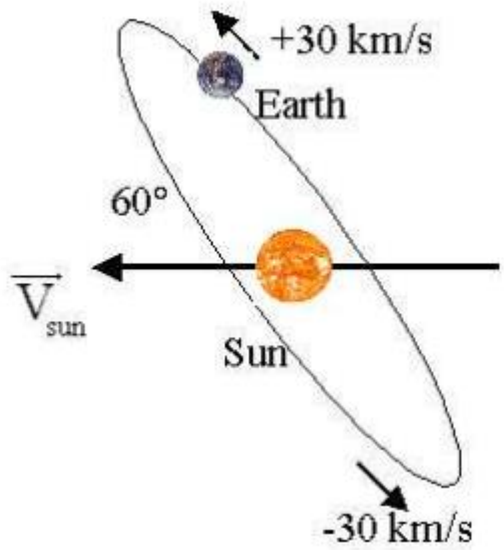
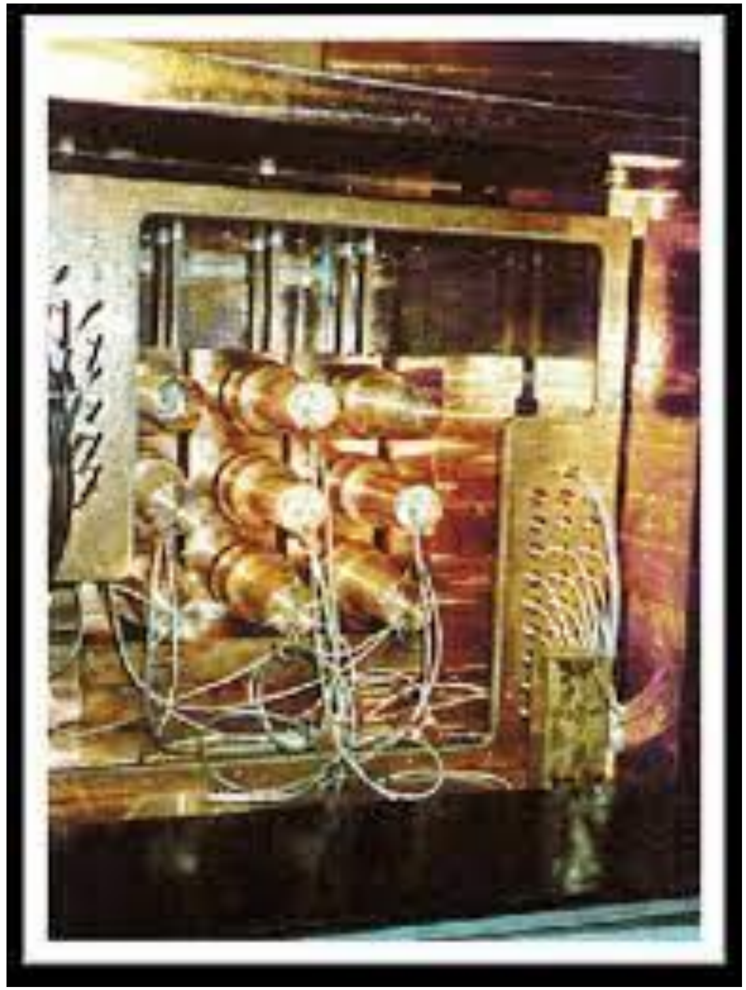
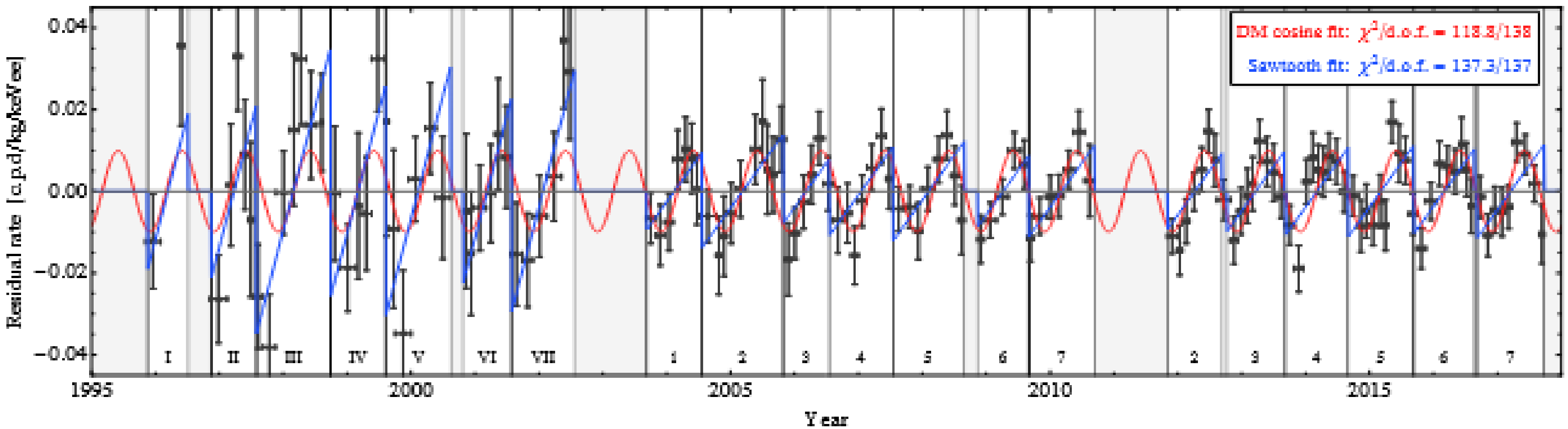


FIG. 4: The spin-independent WIMP-nucleon cross section limits as a function of WIMP mass at 90% confidence level (black) for this run of XENON1T. In green and yellow are the 1- and 2σ sensitivity bands. Results from LUX [27] (red), PandaX-II [28] (brown), and XENON100 [23] (gray) are shown for reference.


+30 km/s
Earth
60°
$\overrightarrow{V}_{sun}$
Sun
-30 km/s

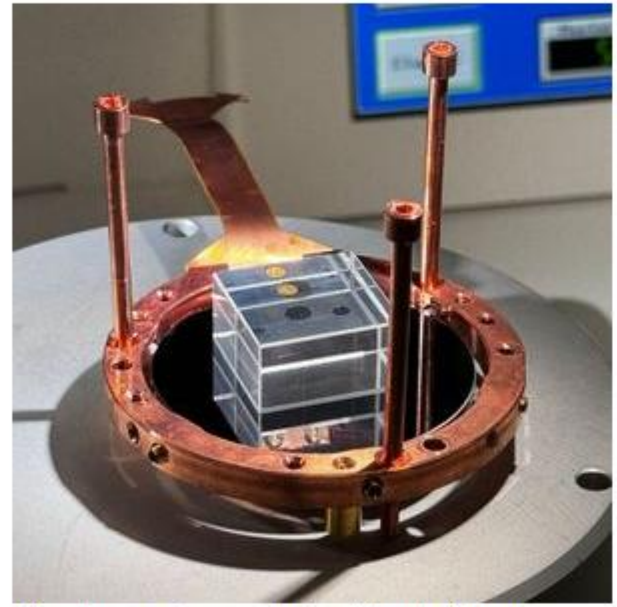


DAMA/LIBRA experiment



Known or unknown particles?

The investigation of two signals also provides clues as to which particles are involved. "This is important because not every signal that is measured in such a detector is an indication of dark matter," explains Karoline Schäffner: "For example, it could be ordinary electrons that are produced by natural radioactivity. Or neutrons produced by cosmic particles."



The detector: A crystal of sodium iodide - the same material as in the DAMA/LIBRA experiment (Photo: COSINUS Collaboration)

In order to detect dark matter signals, the researchers have to shield the crystal as effectively as possible from any background noise. This is why the experiment is well protected in a mountain massif, in the largest underground laboratory in the world: the Gran Sasso National Laboratory (Italy), around one hundred kilometers from Rome. Under 1,400 meters of rock, a tunnel system provides space for a large number of highly sensitive experiments - the DAMA/LIBRA experiment is also set up there. The detectors are also placed in a seven-metre-high tank of ultra-pure water.

The COSINUS project will open in the Gran Sasso National Laboratory on April 18, 2024. The first results of the measurements are expected in 2025/26.

At the heart of COSINUS is a cryostat - a kind of refrigerator for extremely low temperatures - in which a crystal of sodium iodide can be cooled to 1-2 hundredths of a degree above absolute zero (- 273 degrees Celsius). If this crystal is hit by dark matter particles, two reactions occur in the detector: Firstly, the atoms of the crystal are set into vibration - the crystal lattice begins to wobble and heats up. The heat energy absorbed in the process can be measured extremely accurately. Secondly, light is also produced in the crystal, which COSINUS can also "see".

Luminosity distance

d_L= (L/4πl)^(1/2) ,

L is the absolute luminosity

l is the apparent luminosity

$$d_L = \frac{1}{H_0}\left(z + \frac{1}{2}(1 - q_0)z^2 + \cdots \right)$$

H_0 – Hubble constant

q_0 - deceleration parameter

Deceleration parameter $q = -\frac{\ddot{R}R}{\dot{R}^2} = -\frac{\ddot{R}}{H^2 R}$

$$q_0 = \frac{1}{3}\Omega_m - \Omega_\Lambda \,,$$

$$q_0 = -0.6 \,.$$

Standard candles

Cepheid stars

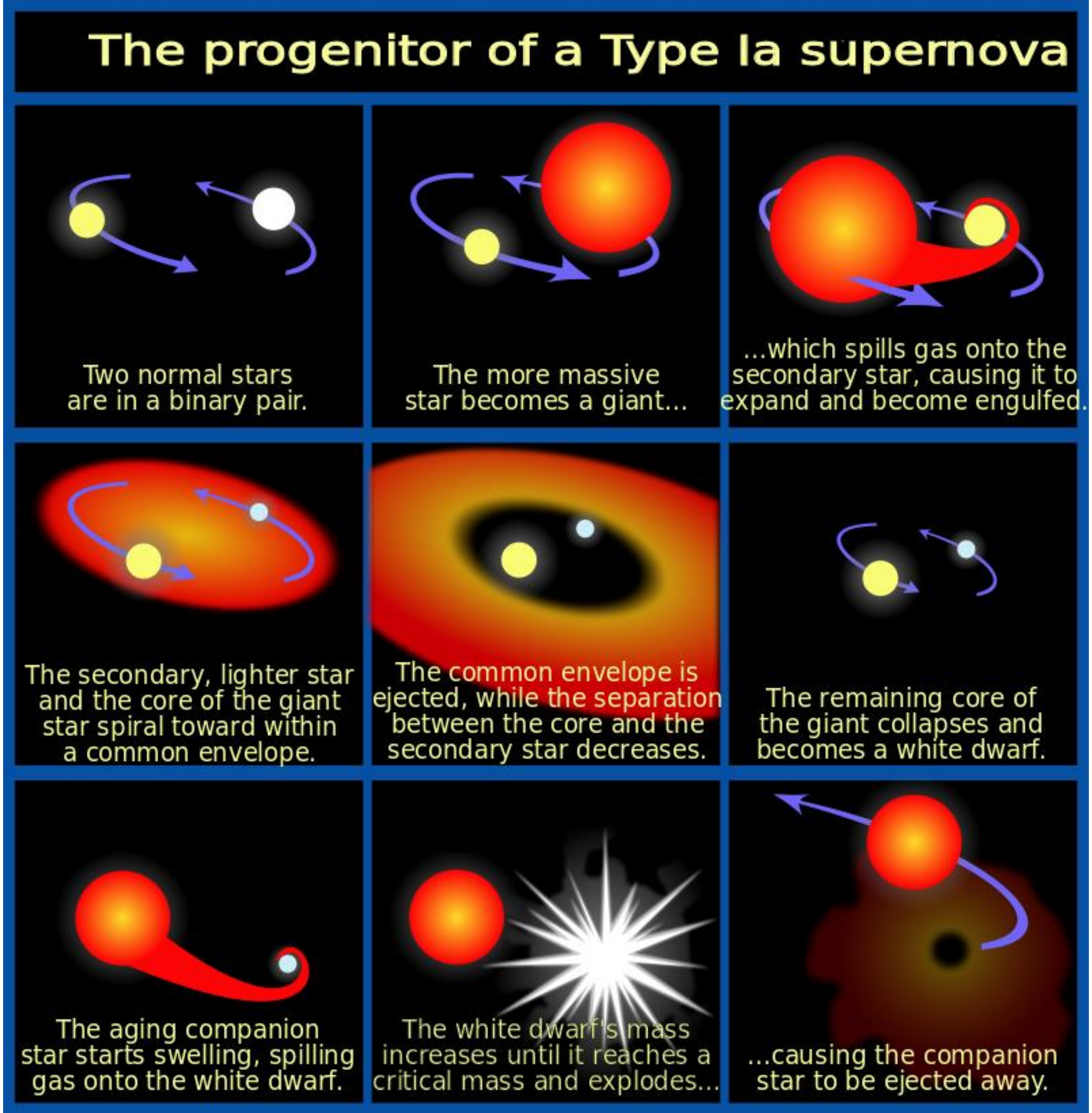
RR Lyre stars

Globular clusters

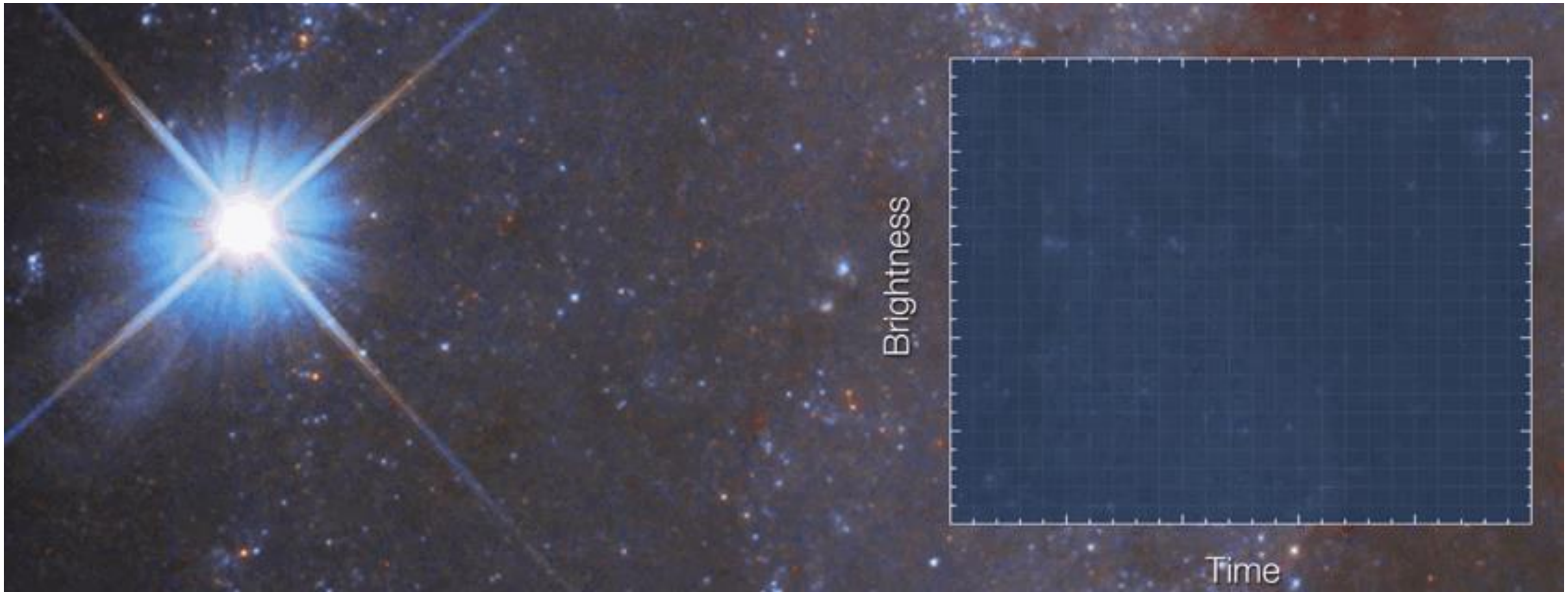
Supernovae type Ia

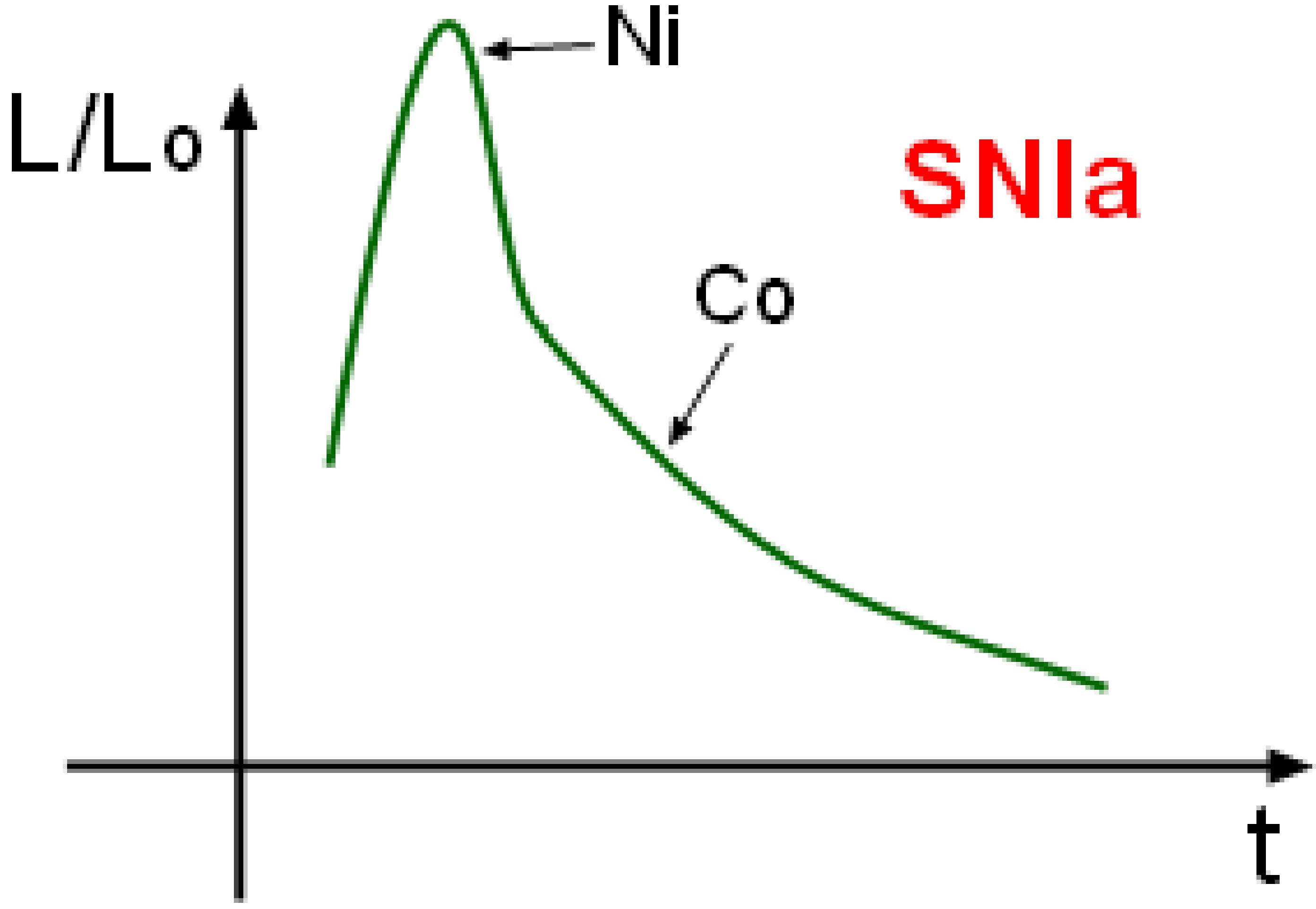
Gamma Ray Burst

Quasars



The progenitor of a Type Ia supernova
Two normal stars are in a binary pair.
The more massive star becomes a giant...
...which spills gas onto the secondary star, causing it to expand and become engulfed.
The secondary, lighter star and the core of the giant star spiral toward within a common envelope.
The common envelope is ejected, while the separation between the core and the secondary star decreases.
The remaining core of the giant collapses and becomes a white dwarf.
The aging companion star starts swelling, spilling gas onto the white dwarf.
The white dwarf's mass increases until it reaches a critical mass and explodes...
...causing the companion star to be ejected away.


Brightness
Time



Ni
L/Lo
SNIa
Co
t

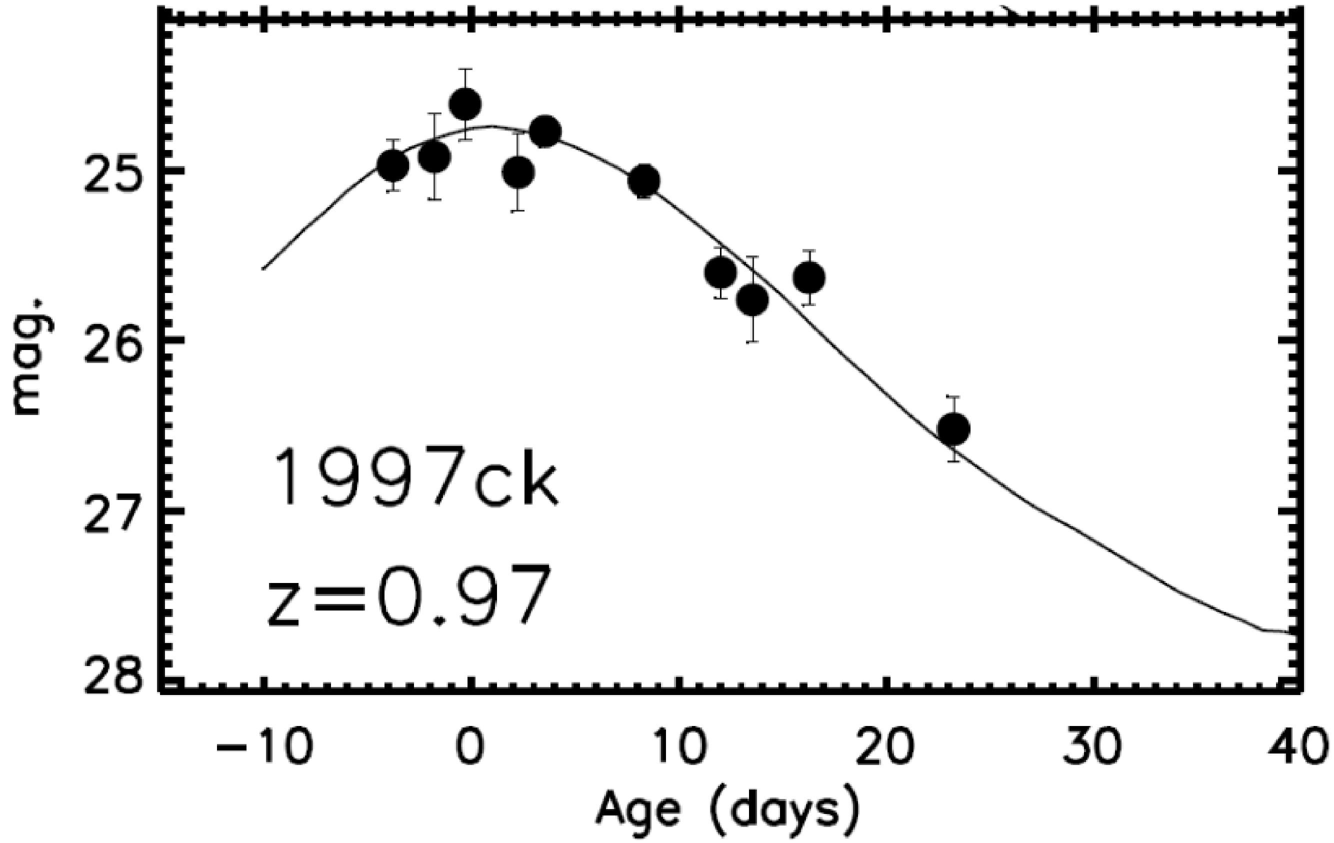


Figure 1. One of the high redshift supernovae of type Ia for which the HZT collaboration [27] could measure the magnitude, i.e., the luminosity, both before and after the peak luminosity.

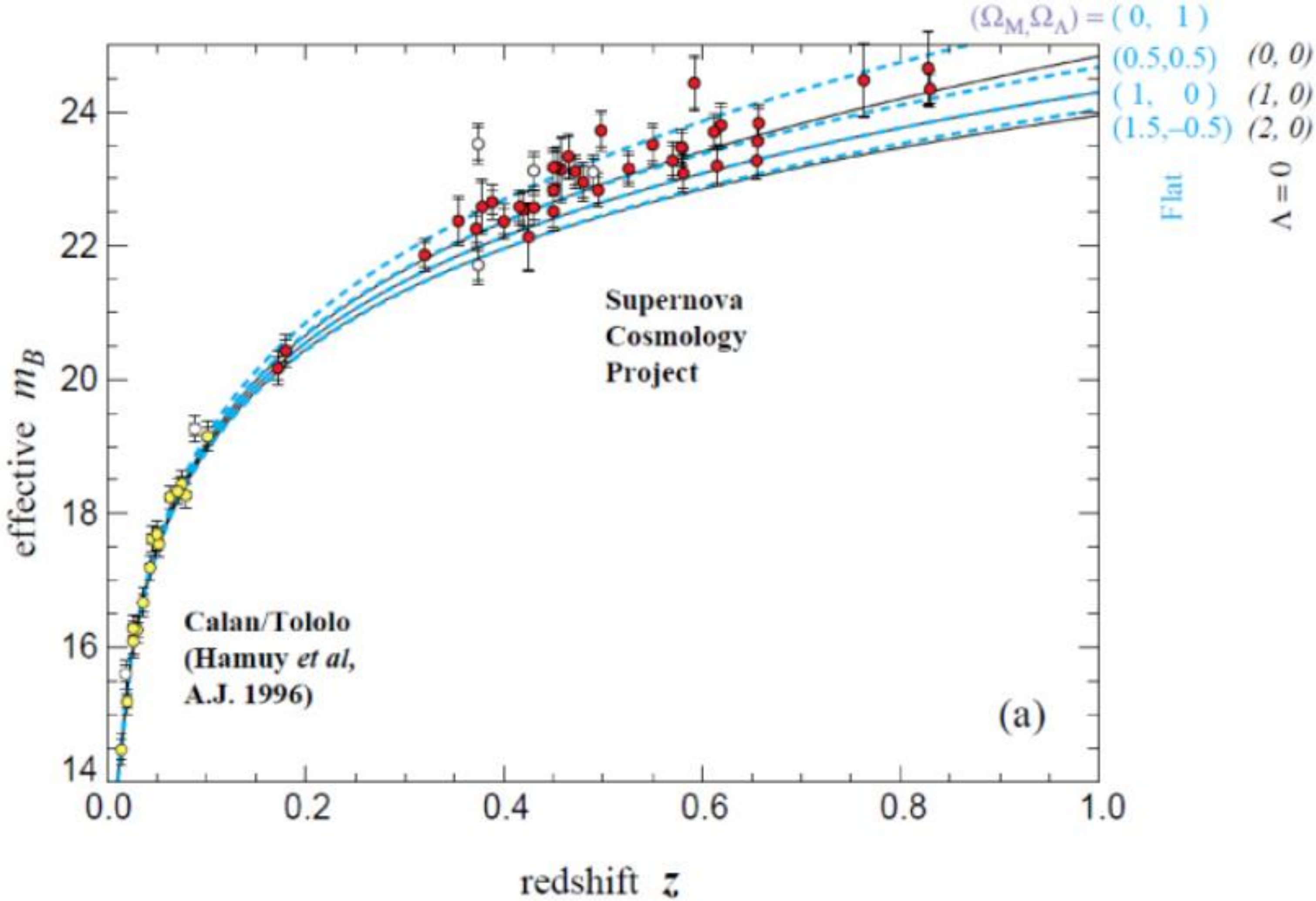


Figure 1: The Hubble diagram for 42 high redshift type Ia supernovae from SCP and 18 low redshift supernovae from the Calan/Tololo Supernova Survey. The solid curves represent a range of cosmological models with $\Lambda = 0$ and $\Omega_M = 0$, 1 and 2. The dashed curves show a range of "flat" models where $\Omega_M + \Omega_\Lambda = 1$. Note the linear redshift scale.

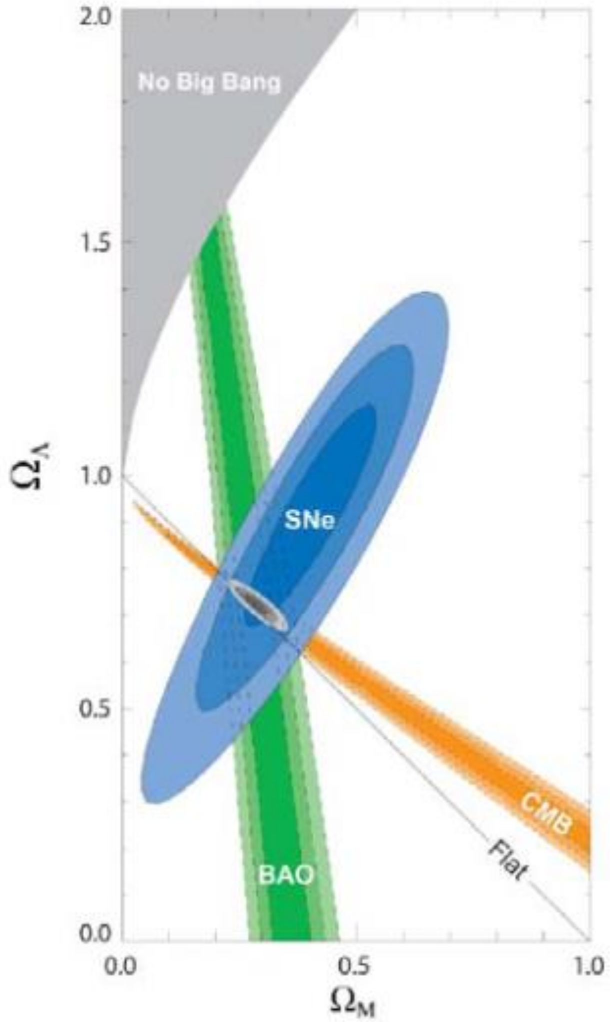


Figure 3. A summary figure from Review of Particle Properties, http://rpp.lbl.gov, showing the combination of supernova observations (SNe), the microwave background (CMB) and the spatial correlation between galaxies ("Baryon Acoustic Oscillations", *BAO).*

The Nobel Prize in Physics 2011

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Saul Perlmutter

Prize share: 1/2

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Brian P. Schmidt

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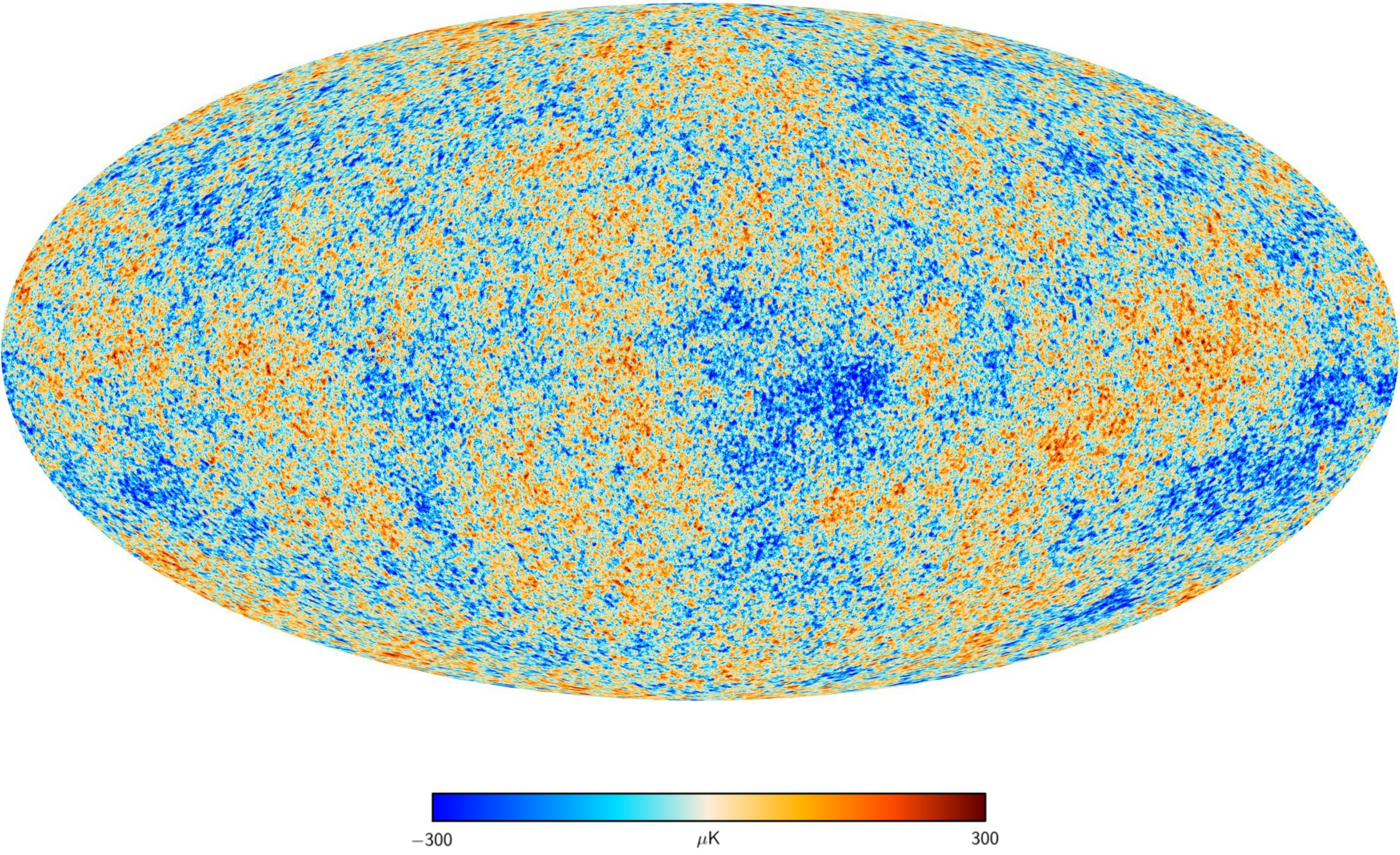
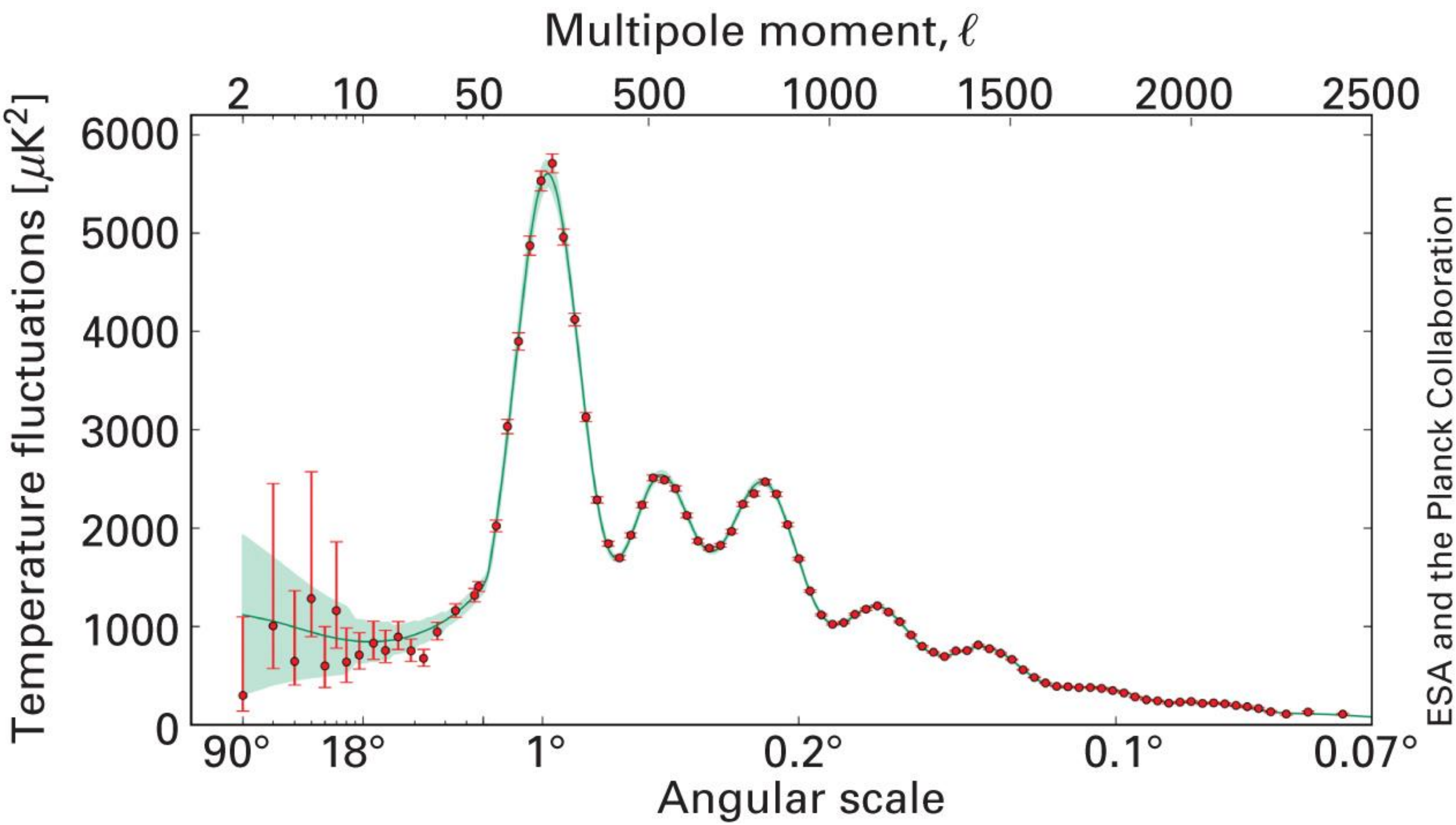
Adam G. Riess

Prize share: 1/4

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess "for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"



−300
μK
300

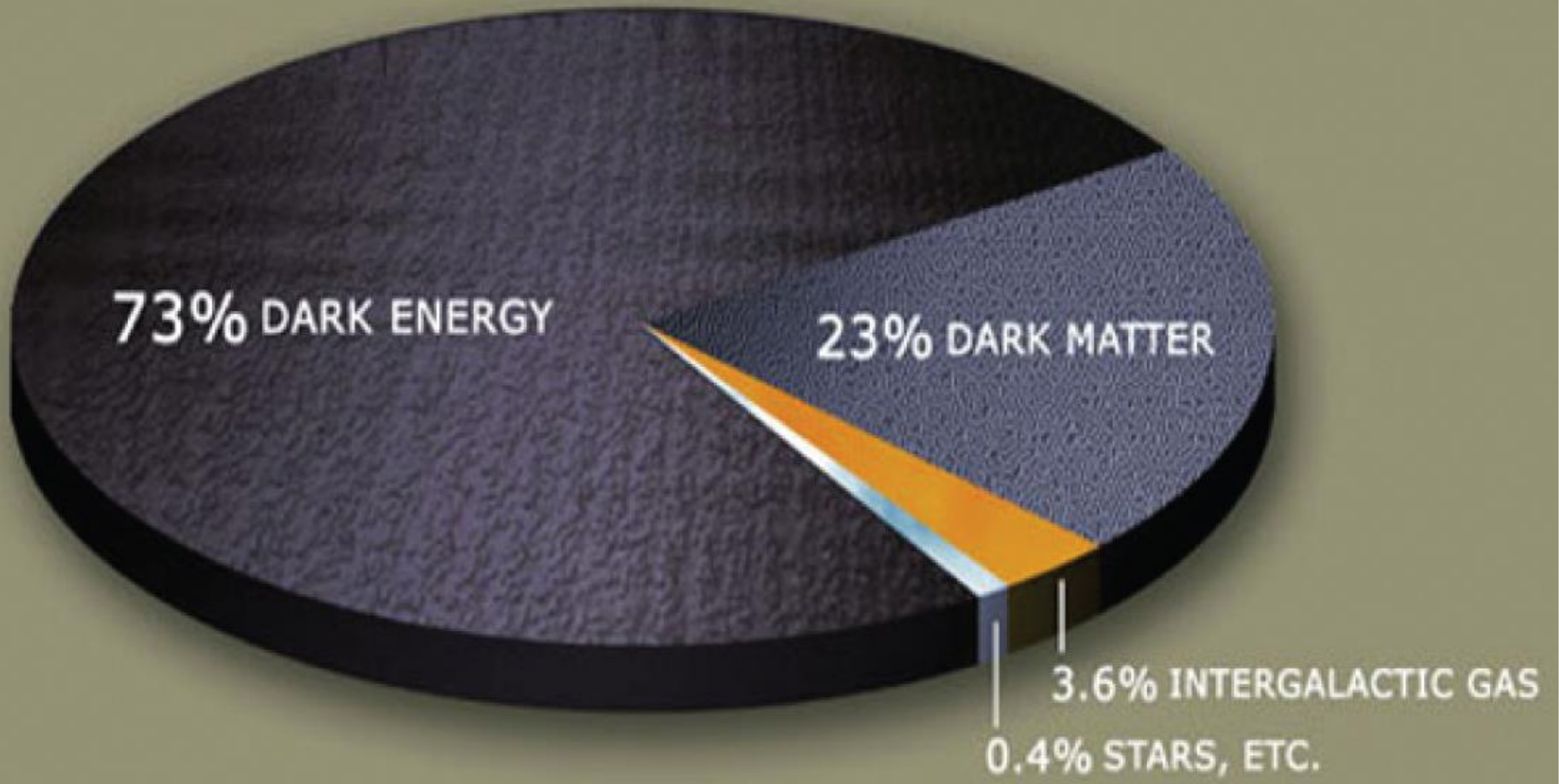


Power Spectrum from Planck

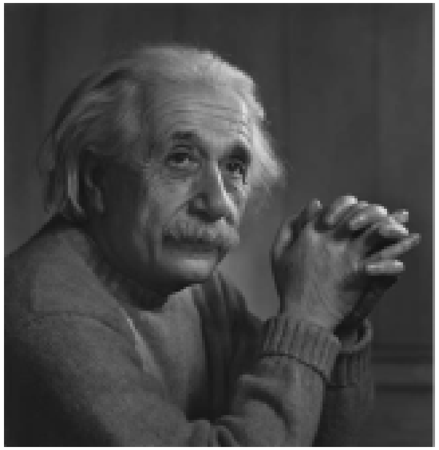
Old Universe – *New* Numbers

$\Omega_{tot} = 1.02^{+0.02}_{-0.02}$
$w < -0.78$ (95% CL)
$\Omega_\Lambda = 0.73^{+0.04}_{-0.04}$
$\Omega_b h^2 = 0.0224^{+0.0009}_{-0.0009}$
$\Omega_b = 0.044^{+0.004}_{-0.004}$
$n_b = 2.5 \times 10^{-7}{}^{+0.1\times10^{-7}}_{-0.1\times10^{-7}}$ cm^{-3}
$\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$
$\Omega_m = 0.27^{+0.04}_{-0.04}$
$\Omega_\nu h^2 < 0.0076$ (95%CL)
$m_\nu < 0.23$ eV (95% CL)
$T_{cmb} = 2.725^{+0.002}_{-0.002}$ K
$n_\gamma = 410.4^{+0.9}_{-0.9}$ cm^{-3}
$\eta = 6.1 \times 10^{-10}{}^{+0.3\times10^{-10}}_{-0.2\times10^{-10}}$
$\Omega_b \Omega_m^{-1} = 0.17^{+0.01}_{-0.01}$
$\sigma_8 = 0.84^{+0.04}_{-0.04}$ Mpc
$\sigma_8 \Omega_m^{0.5} = 0.44^{+0.04}_{-0.05}$
$A = 0.833^{+0.086}_{-0.083}$

$n_s = 0.93^{+0.03}_{-0.03}$
$dn_s/d\ln k = -0.031^{+0.016}_{-0.018}$
$r < 0.71$ (95% CL)
$z_{dec} = 1089^{+1}_{-1}$
$\Delta z_{dec} = 195^{+2}_{-2}$
$h = 0.71^{+0.04}_{-0.03}$
$t_0 = 13.7^{+0.2}_{-0.2}$ Gyr
$t_{dec} = 379^{+8}_{-7}$ kyr
$t_r = 180^{+220}_{-80}$ Myr (95% CL)
$\Delta t_{dec} = 118^{+3}_{-2}$ kyr
$z_{eq} = 3233^{+194}_{-210}$
$\tau = 0.17^{+0.04}_{-0.04}$
$z_r = 20^{+10}_{-9}$ (95% CL)
$\theta_A = 0°.598^{+0.002}_{-0.002}$
$d_A = 14.0^{+0.2}_{-0.3}$ Gpc
$l_A = 301^{+1}_{-1}$
$r_s = 147^{+2}_{-2}$ Mpc


73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.

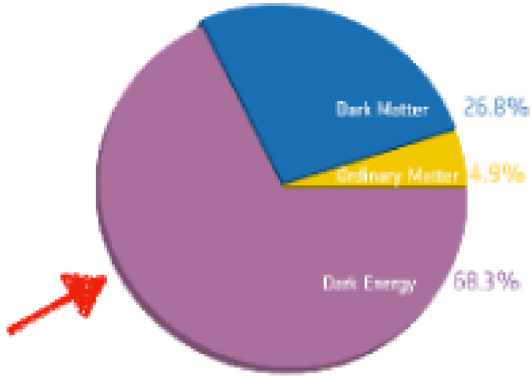
Cosmological constant



- Our best current candidate is a cosmological constant, indicated by Λ.

- Λ was originally proposed by Einstein to create an eternal universe, without a Big Bang. When Hubble and Lemaitre discovered the expansion, Einstein called the cosmological constant “the biggest blunder” of his life. But perhaps, he was right…

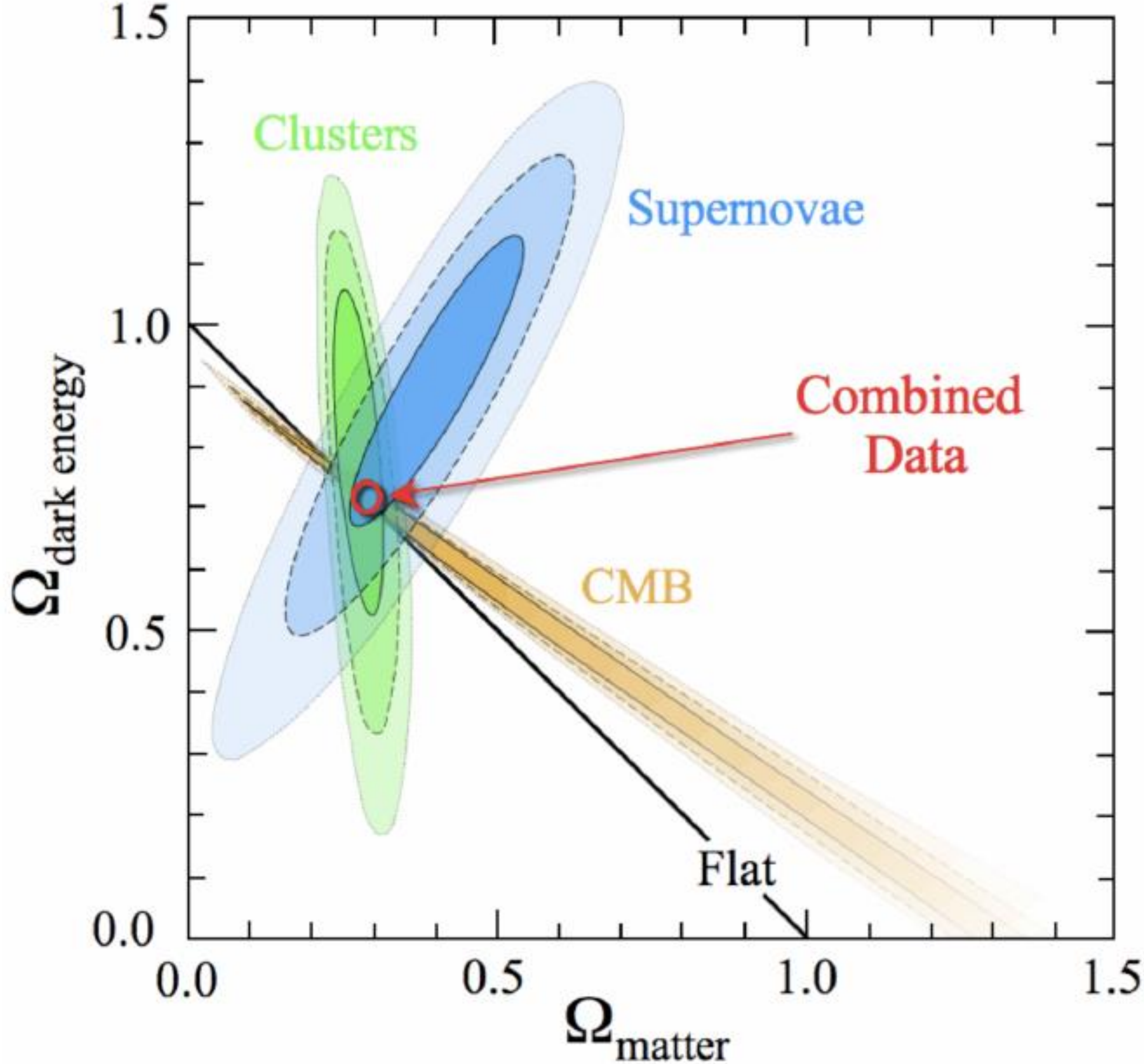
Dark Energy



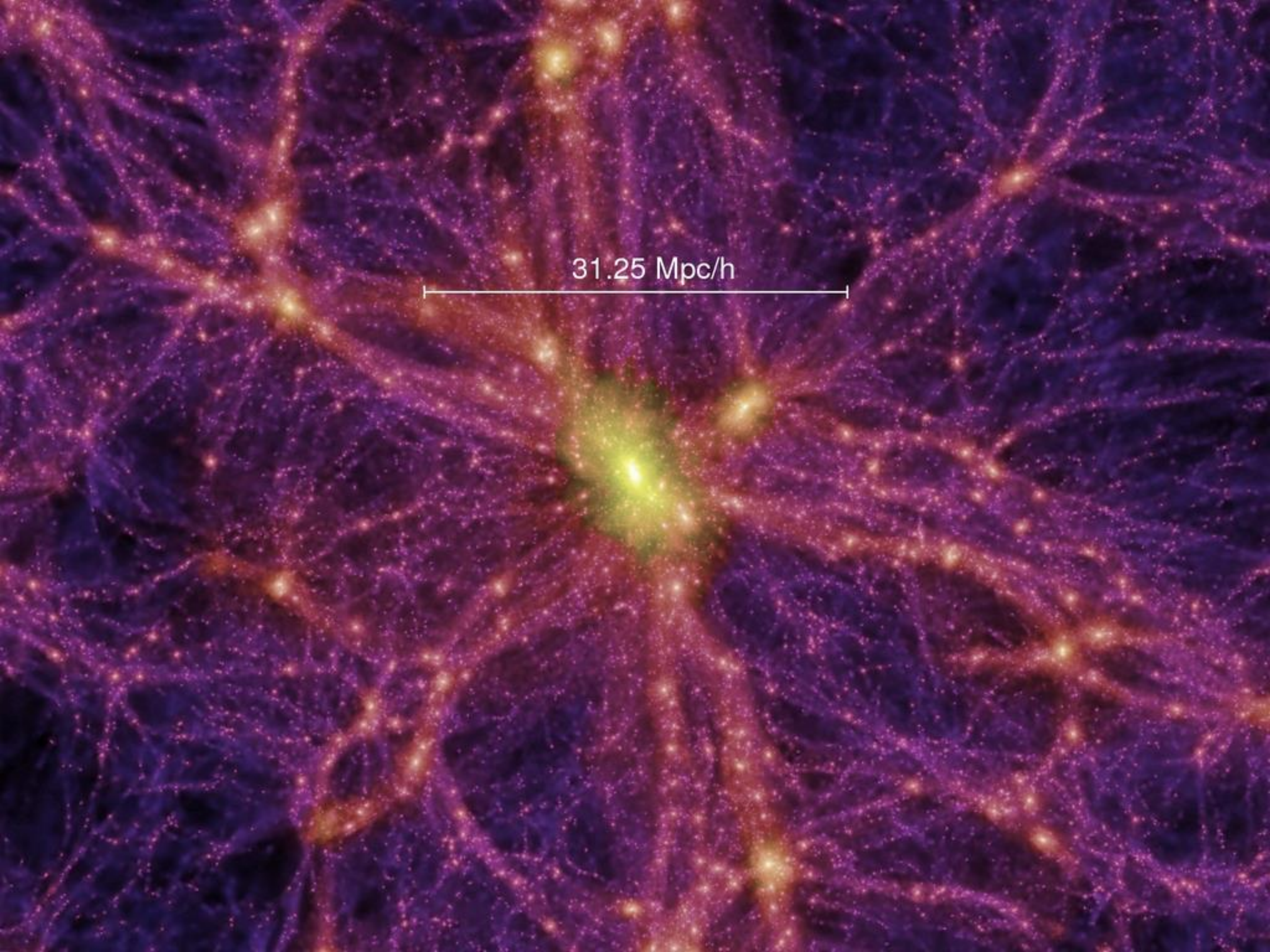
- The most abundant constituent of the universe is dark energy, 70% of today's total!
- In 1998, by looking at the distance and velocity of supernovae, astronomer realise that the universe not only expands, but it expands faster and faster every day: it accelerates!
- It is called "dark" because we can't see it using light (it doesn't emit, absorb or interact with light in any way)
- as far as we know everywhere there is space there is dark energy
- Dark energy is an incredible substance: if you put it in a closed box and make the box twice as big you find inside twice as much dark energy

Dark Energy what could it be:

- Cosmological constant
- Vacuum energy
- Quintessence - scalar field
- Modified gravity



1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
$\Omega_{\text{dark energy}}$
Ω_{matter}
Clusters
Supernovae
Combined
Data
CMB
Flat


31.25 Mpc/h