Cosmology: Facts and Problems

V.A. Rubakov

Institute for Nuclear Research
of the Russian Academy of Sciences

Department of Particle Physics and Cosmology
Physics Faculty
Moscow State University

Outline

- Introduction
- Dark matter
- Before the Hot Big Bang

Expanding Universe

- The Universe at large is homogeneous, isotropic and expanding.

  3d space is Euclidean (observational fact!)

  Sum of angles of a triangle = 180^o, even for triangles as large as the size of the visible Universe.

  All this is encoded in space-time metric (Friedmann–Lemâitre–Robertson–Walker)

$$ds^2 = dt^2 - a^2(t)\mathbf{dx}^2$$

  $\mathbf{x}$: comoving coordinates, label distant galaxies.

  $a(t)dx$: physical distances.

  $a(t)$: scale factor, grows in time; a_0: present value (matter of convention)

- The Universe at large is homogeneous, isotropic and expanding. 3d space is Euclidean (observational fact!) Space-time metric

$$ds^2 = dt^2 - a^2(t)\mathbf{dx}^2$$

$a(t)dx$: physical distances.

$a(t)$: scale factor, grows in time; a_0: present value

$$z(t) = \frac{a_0}{a(t)} - 1 : \quad \text{redshift}$$

Light of wavelength λ emitted at time t has now wavelength $\lambda_0 = \frac{a_0}{a(t)}\lambda = (1+z)\lambda$.

$$H(t) = \frac{\dot{a}}{a} : \quad \text{Hubble parameter, expansion rate}$$

- Present value

$$H_0 = (67.3 \pm 1.2)\ \frac{\text{km/s}}{\text{Mpc}} = (14 \cdot 10^9\ \text{yrs})^{-1}$$

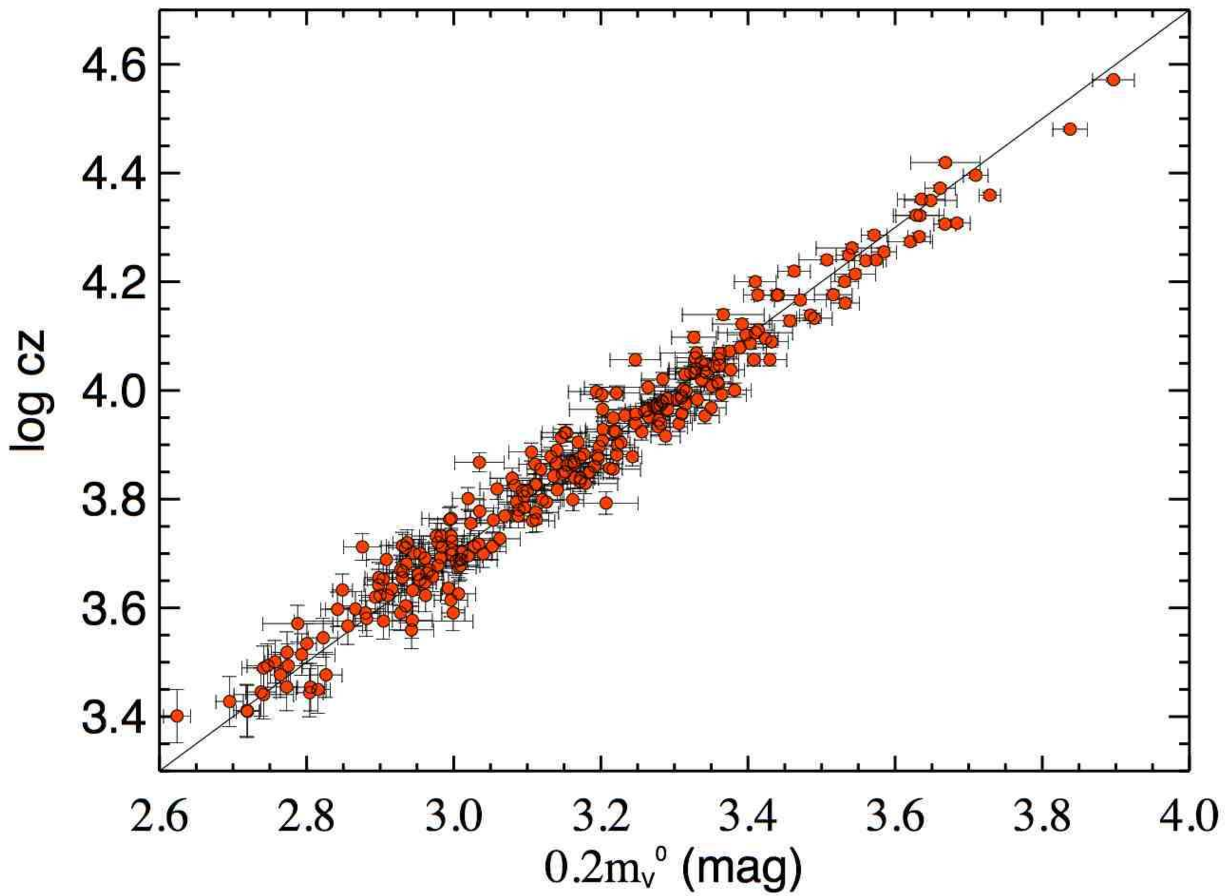
1 Mpc $= 3 \cdot 10^6$ light yrs $= 3 \cdot 10^{24}$ cm

- Hubble law (valid at $z \ll 1$)

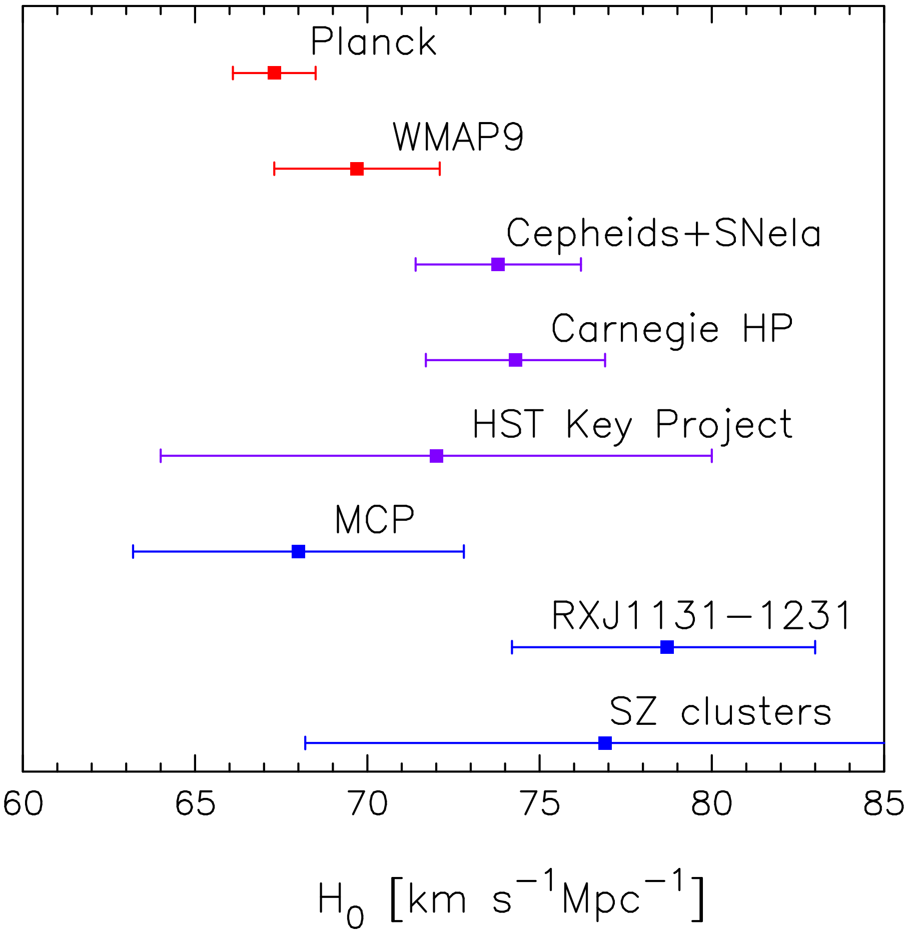
$$z = H_0 r$$

Figs. a,b

Hubble diagram, recent



Systematics still large



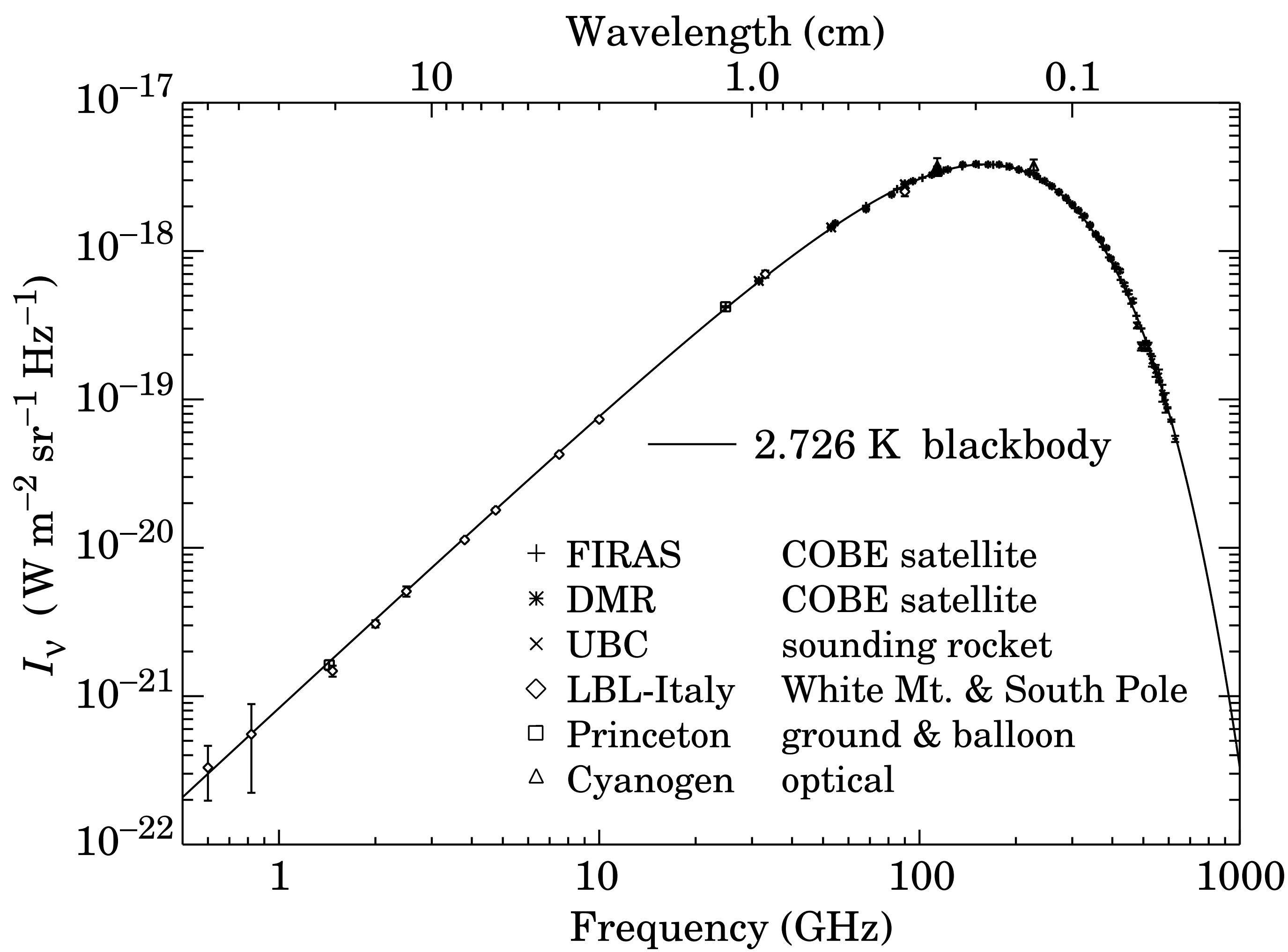
- The Universe is warm: CMB temperature today

$$T_0 = 2.7255 \pm 0.0006\ \mathrm{K}$$

Fig.

It was denser and warmer at early times.

CMB spectrum



$T = 2.726$ K

Dynamics of expansion

- Friedmann equation: expansion rate of the Universe vs total energy density ρ ($M_{Pl} = G^{-1/2} = 10^{19}$ GeV):

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi}{3M_{Pl}^2}\rho$$

Einstein equations of General Relativity specified to homogeneous isotropic space-time with zero spatial curvature

- Present energy density

$$\rho_0 = \rho_c = \frac{3M_{Pl}^2}{8\pi}H_0^2 = 5 \cdot 10^{-6}\ \frac{\text{GeV}}{\text{cm}^3}$$
$$= 5\frac{m_p}{\text{m}^3}$$

$\hbar = c = k_B = 1$ in what follows

Present composition of the Universe

$$\Omega_i = \frac{\rho_{i,0}}{\rho_c}$$

present fractional energy density of i-th type of matter.

$$\sum_i \Omega_i = 1$$

- Dark energy: $\Omega_\Lambda = 0.685$
  ρ_Λ stays (almost?) constant in time
- Non-relativistic matter: $\Omega_M = 0.315$
  $\rho_M = mn(t)$ scales as $\left(\frac{a_0}{a(t)}\right)^3$
  - Dark matter: $\Omega_{DM} = 0.265$
  - Usual matter (baryons): $\Omega_B = 0.050$
- Relativistic matter (radiation): $\Omega_{rad} = 8.6 \cdot 10^{-5}$ (for massless neutrinos)
  $\rho_{rad} = \omega(t)n(t)$ scales as $\left(\frac{a_0}{a(t)}\right)^4$

Friedmann equation

$$H^2(t) = \frac{8\pi}{3M_{Pl}^2}\left[\rho_\Lambda + \rho_M(t) + \rho_{rad}(t)\right] = H_0^2\left[\Omega_\Lambda + \Omega_M\left(\frac{a_0}{a(t)}\right)^3 + \Omega_{rad}\left(\frac{a_0}{a(t)}\right)^4\right]$$

$\ldots \Longrightarrow$ Radiation domination $\Longrightarrow$ Matter domination $\Longrightarrow$ Λ–domination

now

$$z_{eq} = 3500$$

$$T_{eq} = 9500\ \text{K} = 0.8\ \text{eV}$$

$$t_{eq} = 52 \cdot 10^3\ \text{yrs}$$

Cornerstones of thermal history

- Big Bang Nucleosynthesis, epoch of thermonuclear reactions

$$\begin{aligned} p+n &\rightarrow {}^2H \\ {}^2H+p &\rightarrow {}^3He \\ {}^3He+n &\rightarrow {}^4He \\ \text{up to} & \quad {}^7Li \end{aligned}$$

  Abundances of light elements: measurements vs theory

  $T = 10^{10} \rightarrow 10^9$ K, $\quad t = 1 \rightarrow 300$ s

  Earliest time in thermal history probed so far

- Recombination, transition from plasma to gas.

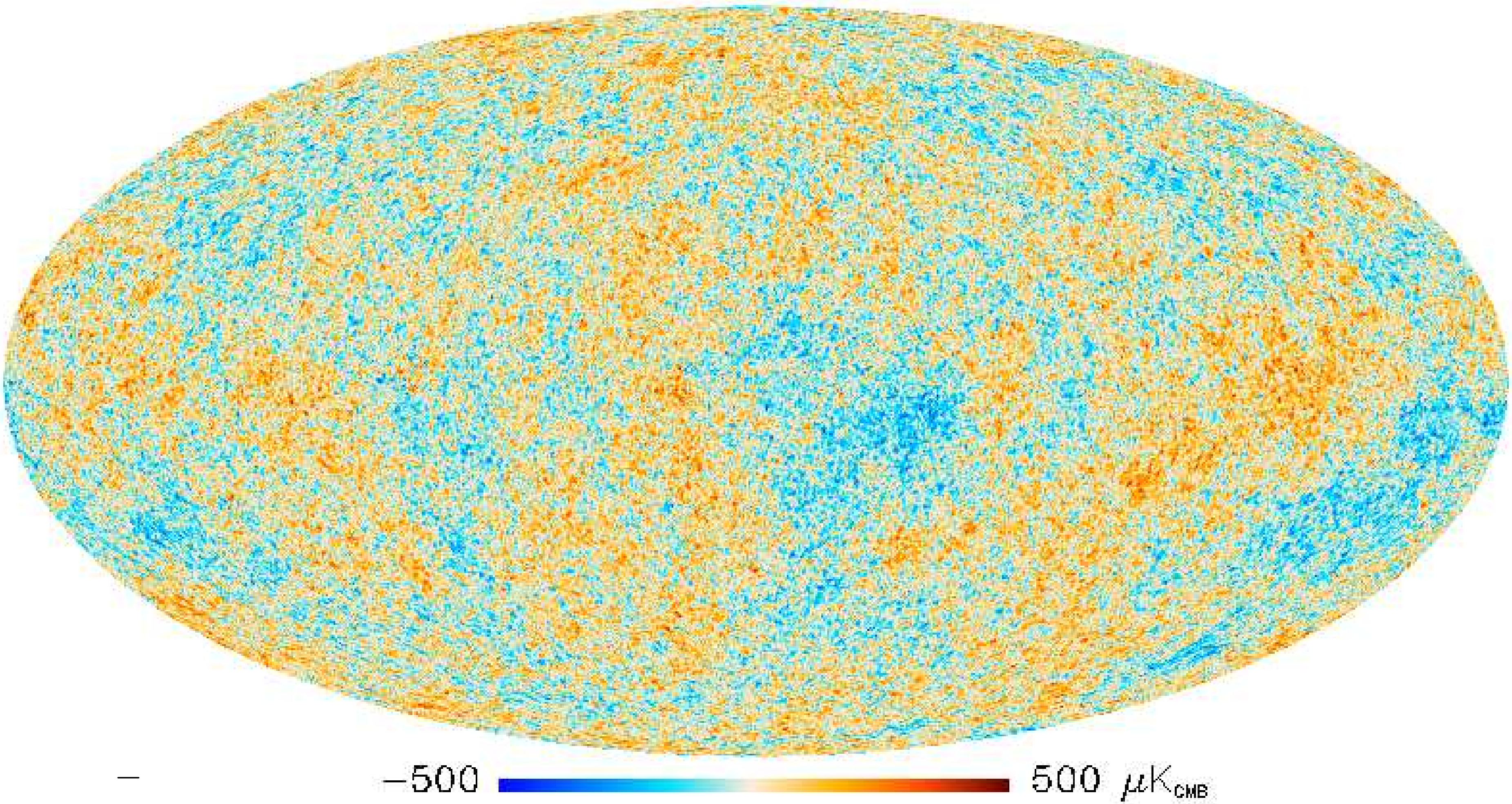
  $z = 1090$, $T = 3000$ K, $\quad t = 380\,000$ years

  Last scattering of CMB photons Fig.

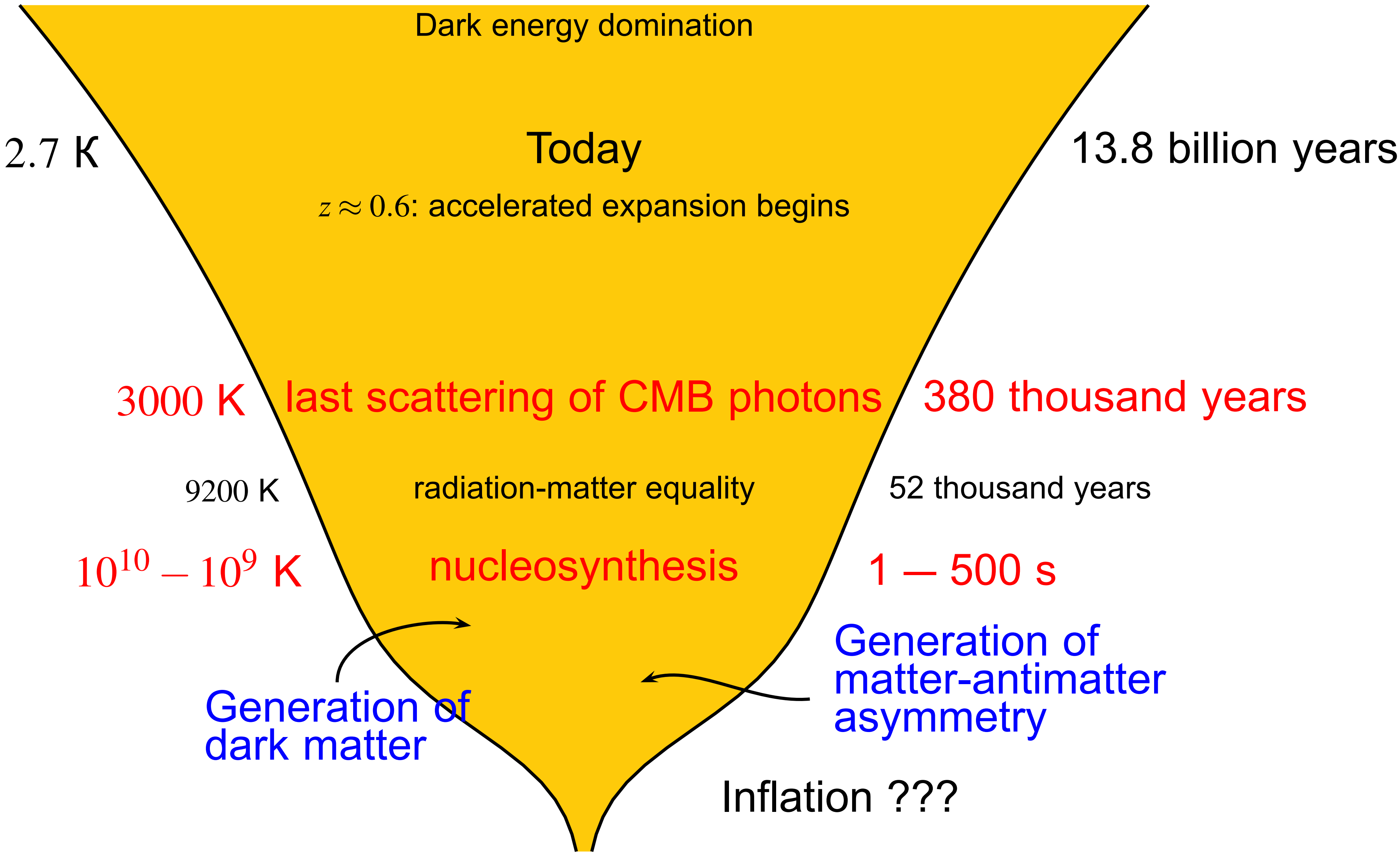
- Neutrino decoupling: $T = 2-3$ MeV $\sim 3 \cdot 10^{10}$K, $\quad t \sim 0.1 - 1$s
- Generation of dark matter*
- Generation of matter-antimatter asymmetry*

*may have happend before the hot Big Bang epoch

$$T = 2.726^\circ K, \quad \frac{\delta T}{T} \sim 10^{-4} - 10^{-5}$$

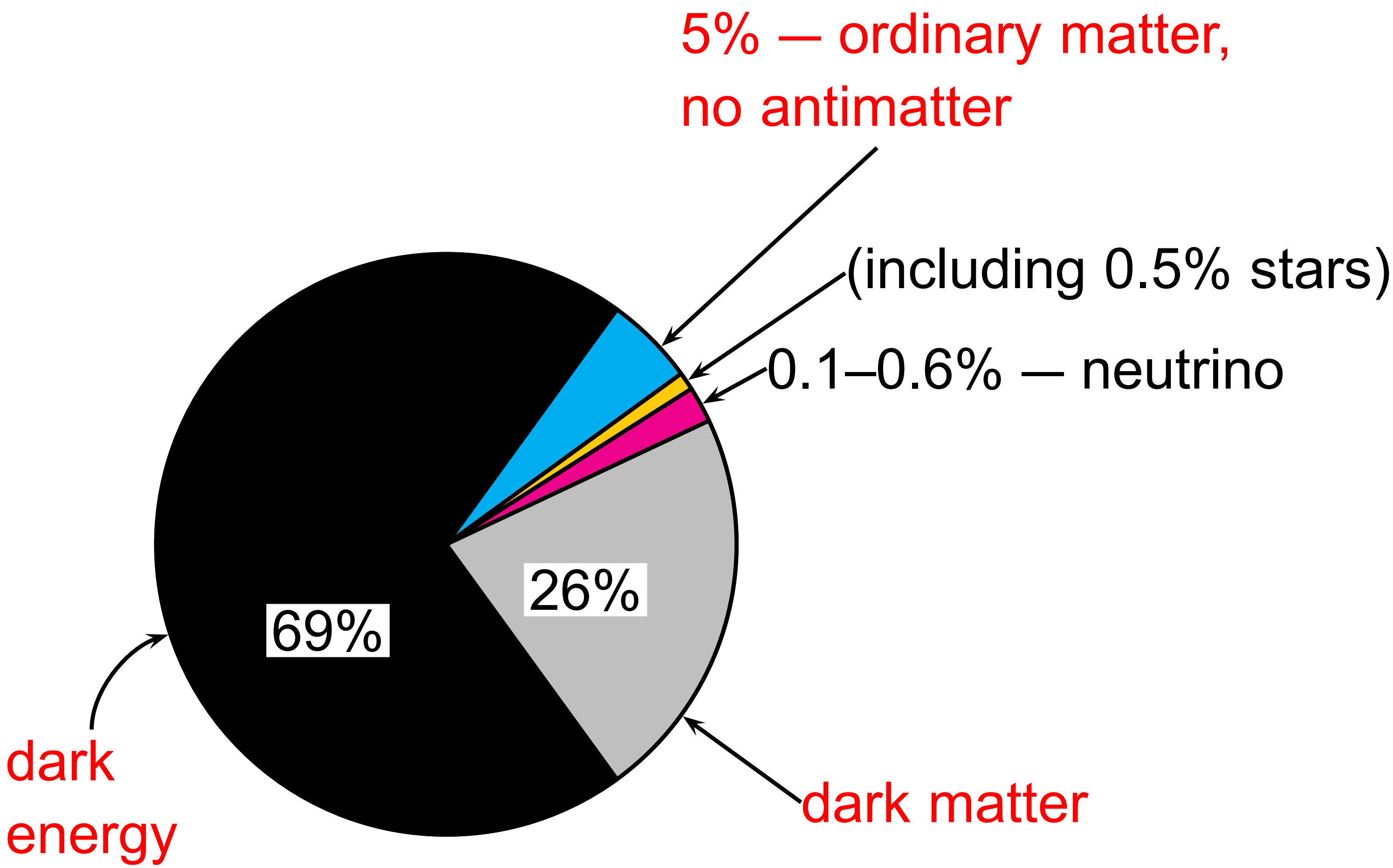


Planck



Dark energy domination
2.7 K
Today
13.8 billion years
$z \approx 0.6$: accelerated expansion begins
3000 K
last scattering of CMB photons
380 thousand years
9200 K
radiation-matter equality
52 thousand years
$10^{10} - 10^{9}$ K
nucleosynthesis
1 — 500 s
Generation of matter-antimatter asymmetry
Generation of dark matter
Inflation ???

Unknowns


5% — ordinary matter,
no antimatter
(including 0.5% stars)
0.1–0.6% — neutrino
26%
69%
dark
energy
dark matter

Dark matter

- Massive, stable, electrically neutral particles with ordinary gravitational interactions.
- No candidates among known particles
- Astrophysical evidence: measurements of gravitational potentials in galaxies and clusters of galaxies
  - Velocity curves of galaxies

    Fig.
  - Velocities of galaxies in clusters

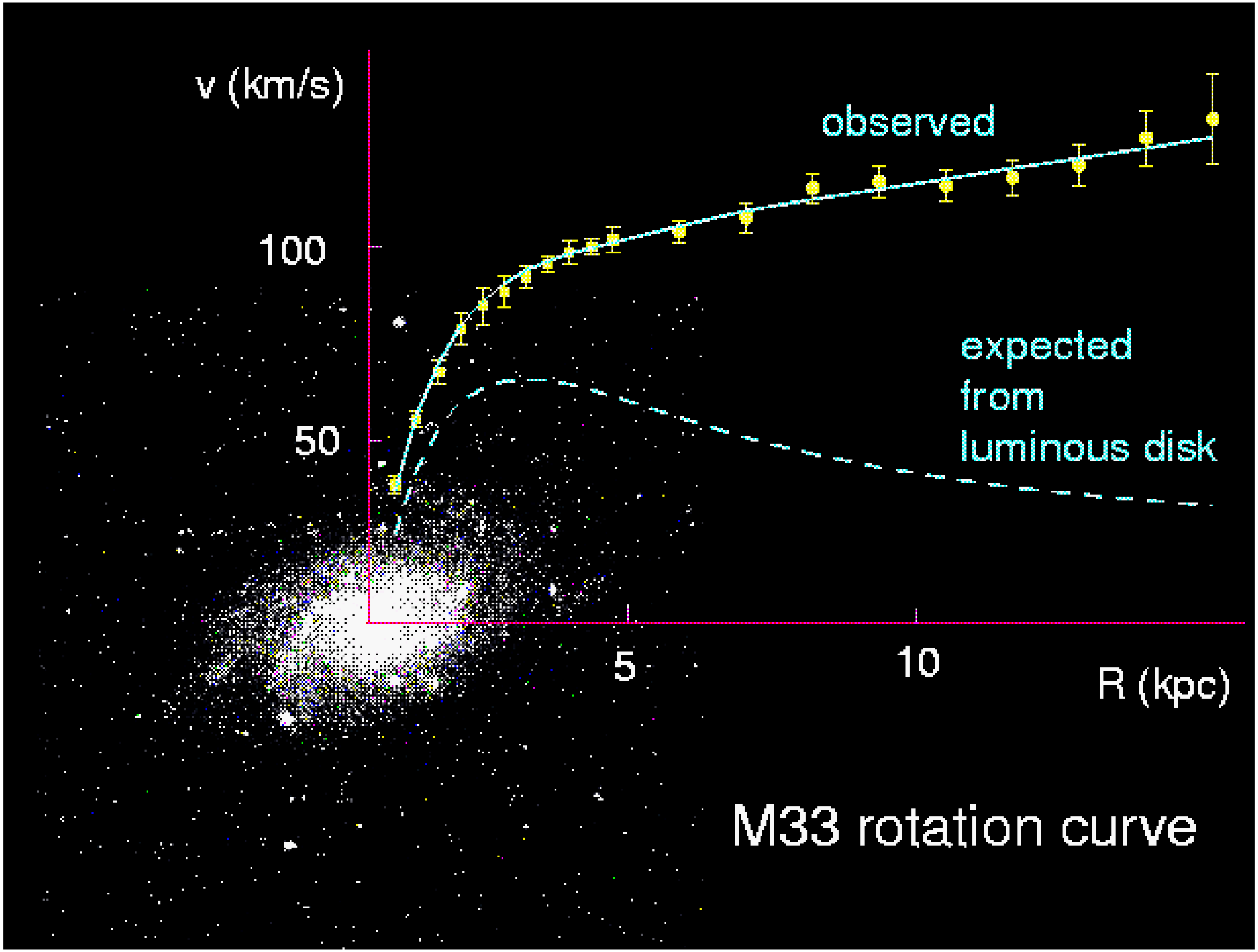
    Original Zwicky's argument, 1930's

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

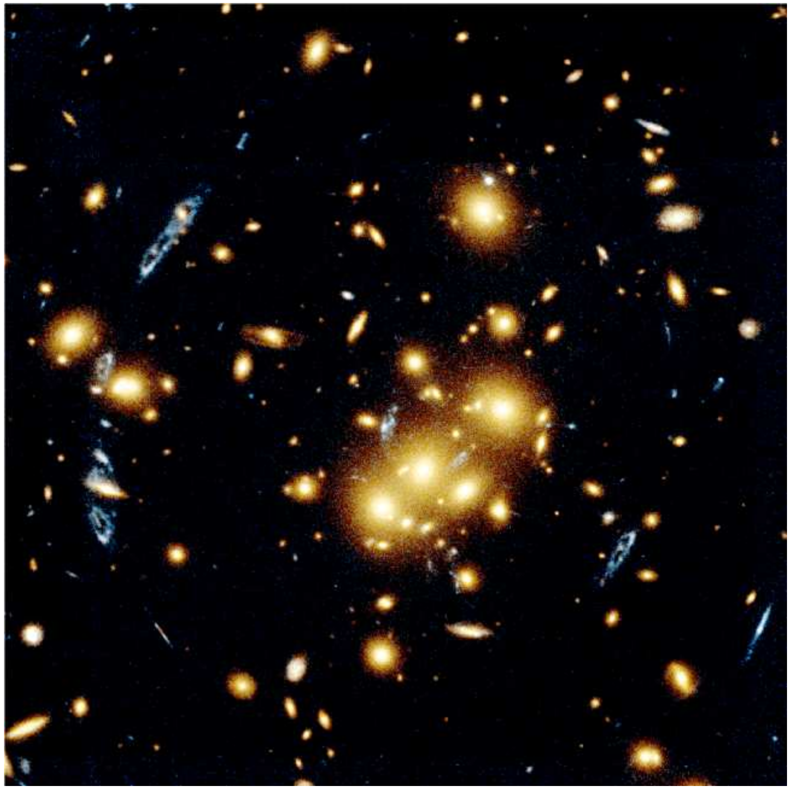
  - Temperature of gas in X-ray clusters of galaxies
  - Gravitational lensing of clusters

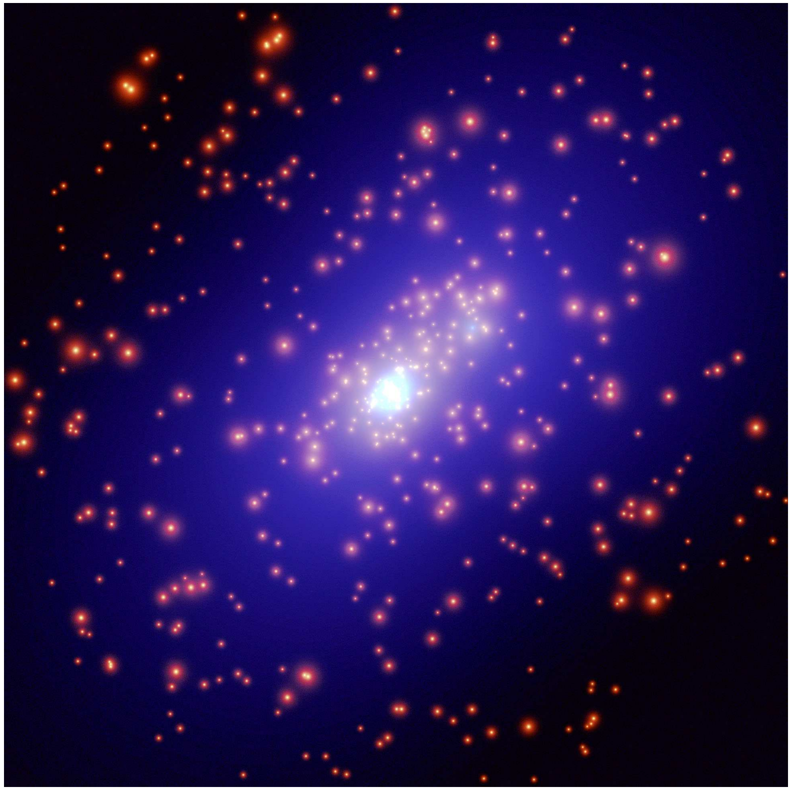
    Fig.
  - Etc.

Rotation curves

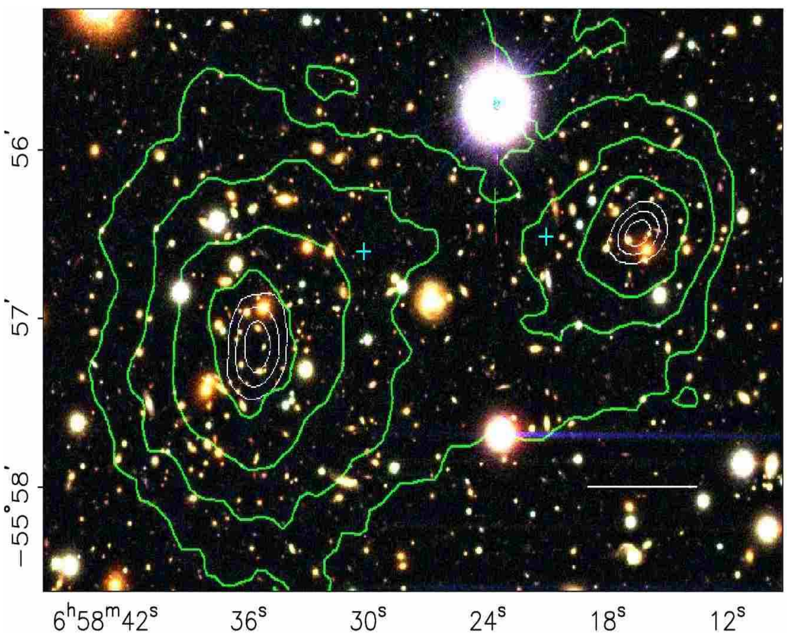


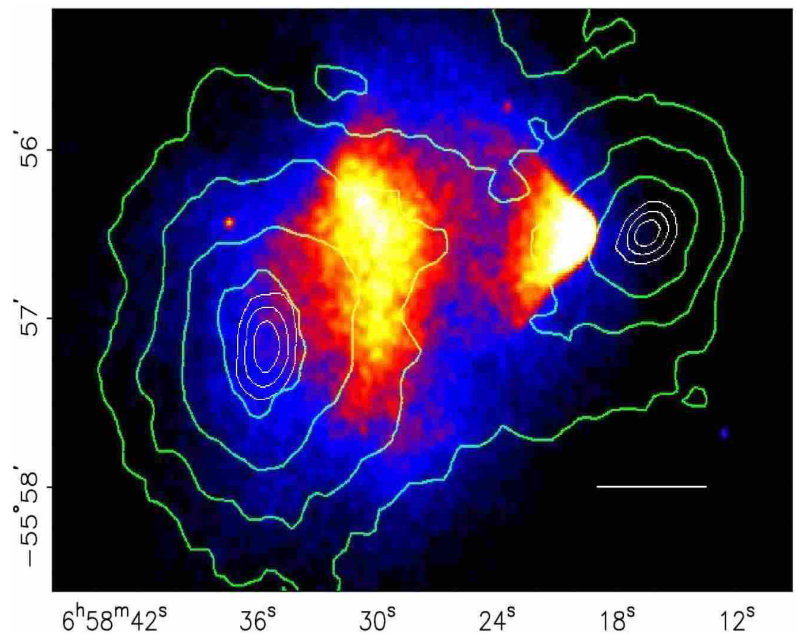
Gravitational lensing





Bullet cluster





Outcome

$$\Omega_M \equiv \frac{\rho_M}{\rho_c} = 0.2 - 0.3$$

Assuming mass-to-light ratio everywhere the same as in clusters

NB: only 10 % of galaxies sit in clusters

Nucleosynthesis, CMB:

$$\Omega_B = 0.05$$

The rest is non-baryonic, $\Omega_{DM} \approx 0.26$.

Cosmological evidence: growth of structure

CMB anisotropies: baryon density perturbations at recombination
$\approx$ photon last scattering, $T = 3000$ K, $z = 1100$:

$$\delta_B \equiv \left(\frac{\delta\rho_B}{\rho_B}\right)_{z=1100} \simeq \left(\frac{\delta T}{T}\right)_{CMB} \sim 10^{-4}$$

In matter dominated Universe, matter perturbations grow as

$$\frac{\delta\rho}{\rho}(t) \propto a(t)$$

Perturbations in baryonic matter grow after recombination only
If not for dark matter,

$$\left(\frac{\delta\rho}{\rho}\right)_{today} = 1100 \times 10^{-4} \sim 0.1$$

No galaxies, no stars...
Perturbations in dark matter start to grow much earlier
(already at radiation-dominated stage)

NB: Need dark matter particles non-relativistic early on.

Neutrinos are not considerable part of dark matter
(way to set cosmological bound on neutrino mass,
$m_\nu \lesssim 0.1$ eV for every type of neutrino)

UNKNOWN DARK MATTER PARTICLES ARE
CRUCIAL FOR OUR EXISTENCE

If thermal relic:

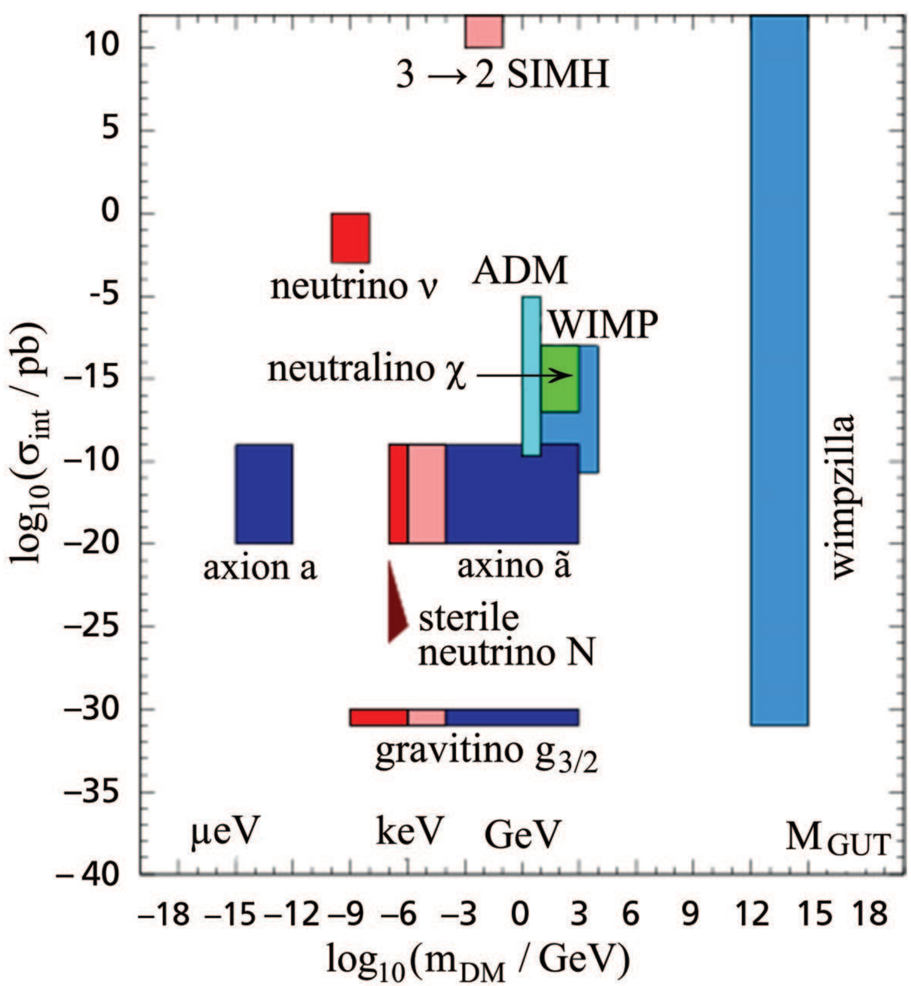
Cold dark matter, CDM

$$m_{DM} \gtrsim 100 \text{ keV}$$

Warm dark matter

$$m_{DM} \simeq 1 - 30 \text{ keV}$$

Canidates for Dark Matter particles are numerous



WIMPs

Simple but very suggestive scenario

- Assume there is a new heavy stable particle X
  - Interacts with SM particles via pair annihilation (and crossing processes)

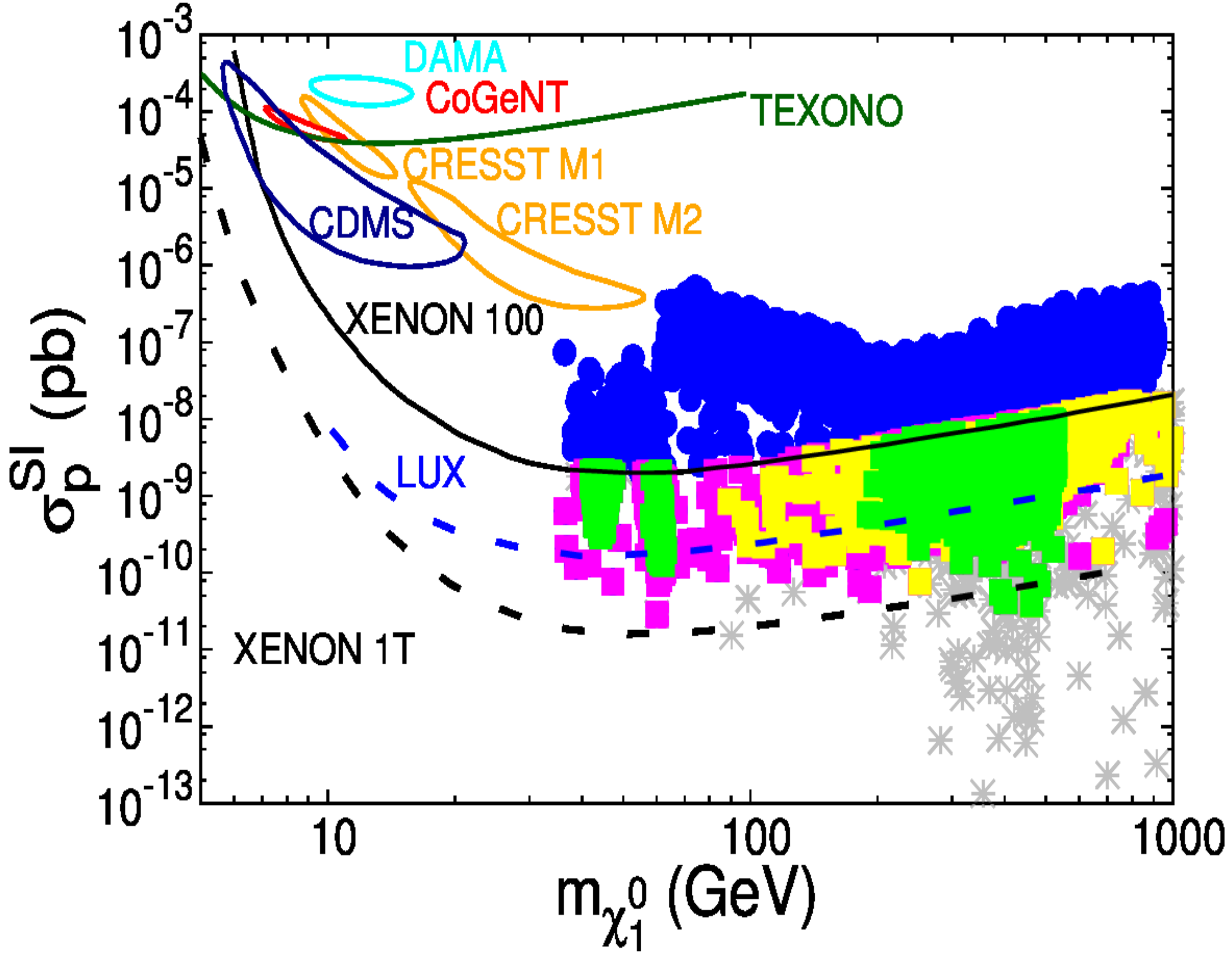
$$X + X \leftrightarrow q\bar{q} \text{ , etc}$$

  - Parameters: mass M_X; annihilation cross section at non-relativistic velocity σ
- Assume that maximum temperature in the Universe was high, $T \gtrsim M_X$
- Correct present mass density $\Longleftrightarrow M_X \sim 10 - 1000$ GeV,

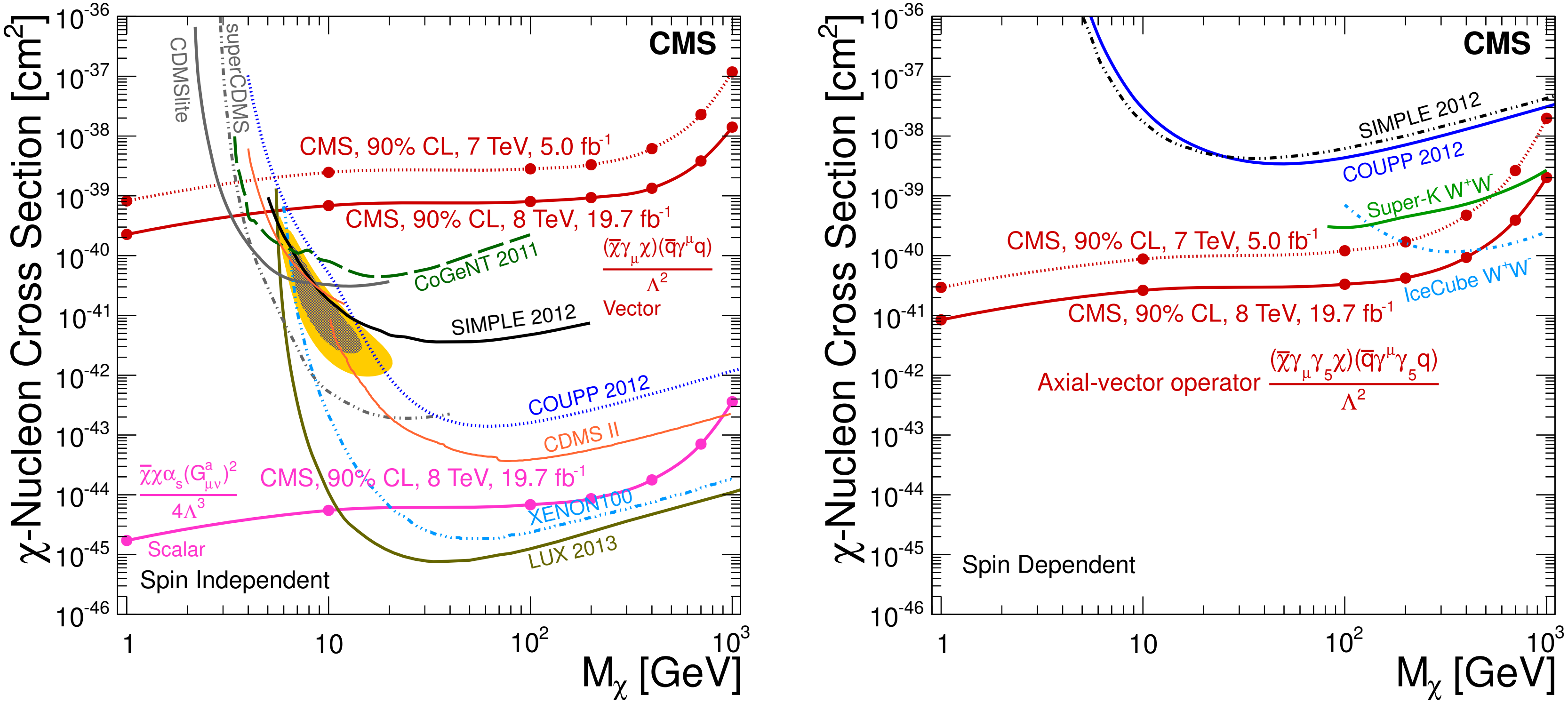
$$\sigma_0 \equiv \langle \sigma v \rangle = (1 \div 2) \cdot 10^{-36} \text{ cm}^2 = (1 \div 2) \text{ pb}$$

Weak scale cross section. Weakly interacting massive particles, WIMPs. Cold dark matter candidates.

Direct searches



The LHC becomes sensitive too



Indirect searches

- Detection of annihilation products of X-particles in centers of Sun, Earth

$$X + \bar{X} \to \pi^{\pm}\,,\ K^{\pm} + \ldots \to \nu\,,\ \bar{\nu} + \ldots$$

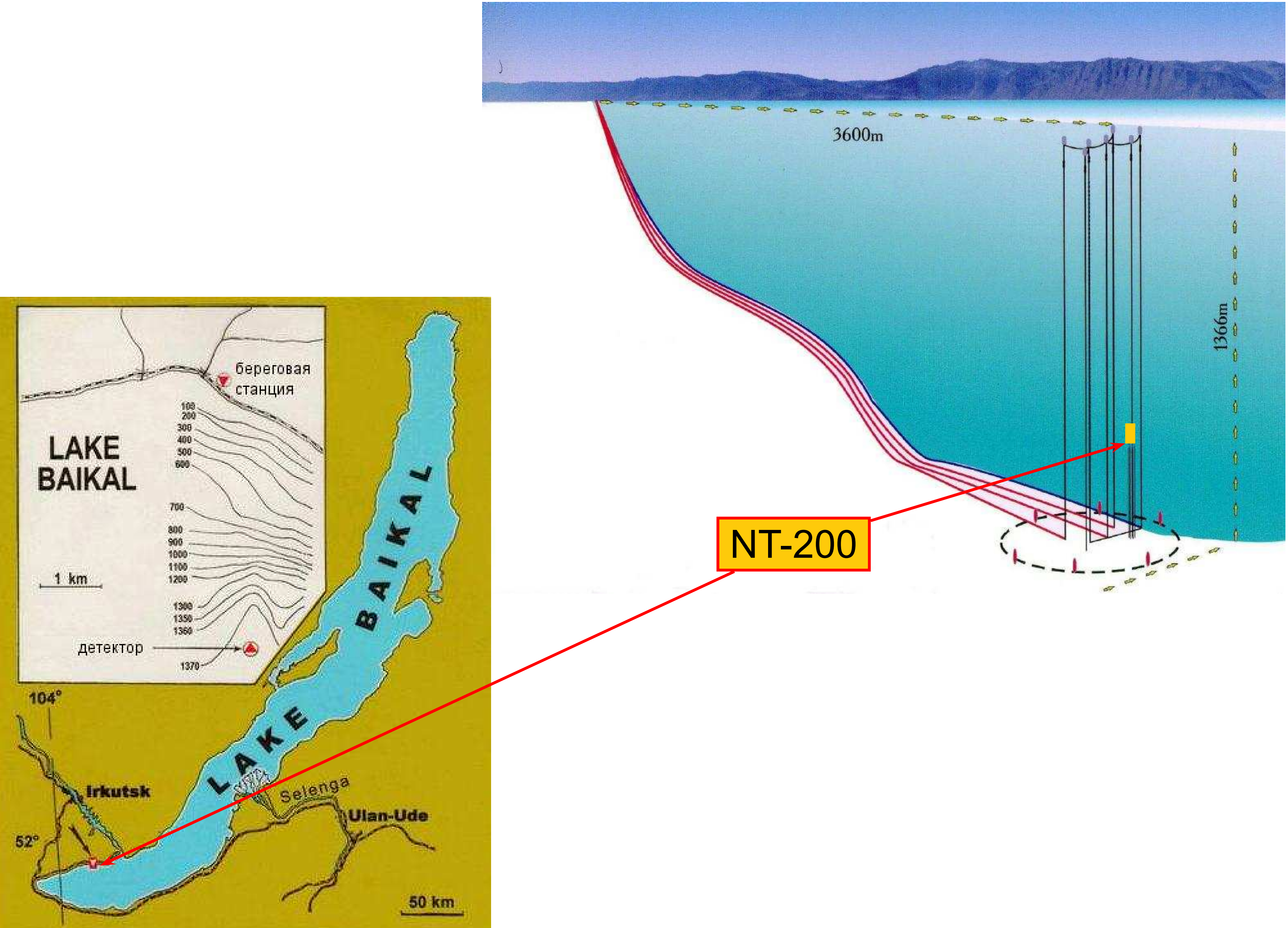
High energy neutrinos $\Longrightarrow$

- Underground neutrino detectors (e.g., Baksan)
- Baikal Neutrino Telescope, IceCUBE

- Detection of ennihilation products in space

  Searc for e^+, $\bar{p}$ in cosmic rays; photons from e^+e^--annihilation in space

  Pamela (Italy – Russia), AMS at Intl. Space Station.


3600m
1366m
NT-200
LAKE BAIKAL
береговая станция
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1350
1360
1370
1 km
детектор
104°
Irkutsk
52°
LAKE BAIKAL
Selenga
Ulan-Ude
50 km

TeV SCALE PHYSICS MAY WELL BE RESPONSIBLE FOR GENERATION OF DARK MATTER

Is this guaranteed?

By no means. Other good DM candidates:

axion, sterile neutrino, gravitino.

Plus a lot of exotica...

Crucial impact of particle physics to cosmology via direct and indirect dark matter searches

Axions

Hypothetical particles introduced for solving strong CP problem. Single parameter f_{PQ}. Axion mass

$$m_a = 0.6 \text{ eV} \cdot \left(\frac{10^7 \text{ GeV}}{f_{PQ}} \right)$$

and $a\gamma\gamma$ interaction

$$C_{a\gamma\gamma} \frac{\alpha}{2\pi} \frac{a(x)}{f_{PQ}} (\vec{E} \cdot \vec{H})$$

where $C_{a\gamma\gamma} \sim 1$ is model-dependent. Larger $f_{PQ} \Longrightarrow$ smaller m_a, weaker interactions.

Why is this interesting for cosmology?

- Axion is practically stable:

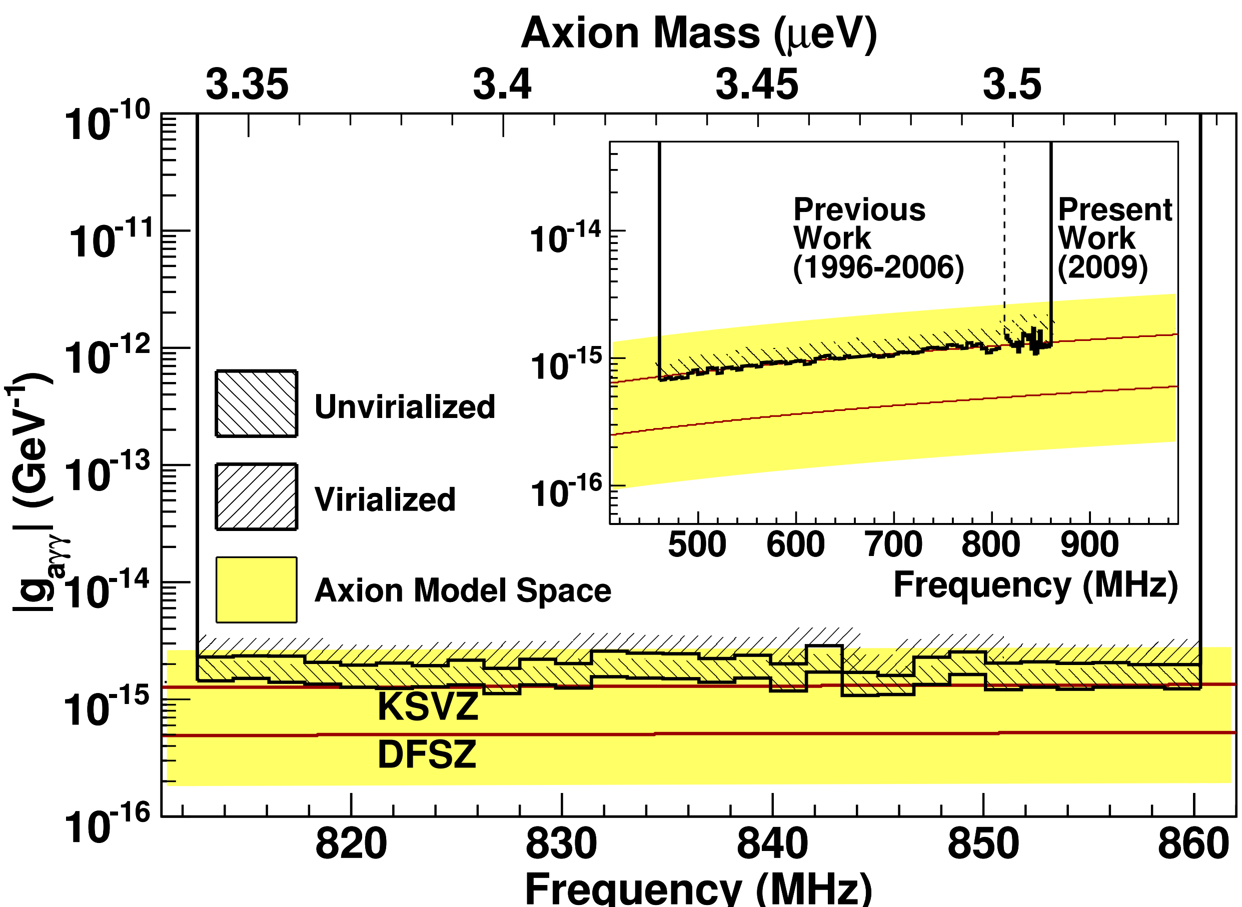
$$\Gamma(a \to \gamma\gamma) = C_{a\gamma\gamma}^2 \left(\frac{\alpha}{8\pi}\right)^2 \frac{m_a^3}{4\pi f_{PQ}^2} \quad \Longrightarrow \quad \tau_a = 10^{17} \left(\frac{\text{eV}}{m_a}\right)^5 \text{ yrs}$$

- Interacts very weakly $\Longrightarrow$ dark matter candidate
- May never be in thermal equilibrium $\Longrightarrow$ cold dark matter if momenta are negligibly small.
- Simple production mechanism: correct abundance for axions of mass $(1 - 10)\ \mu$eV

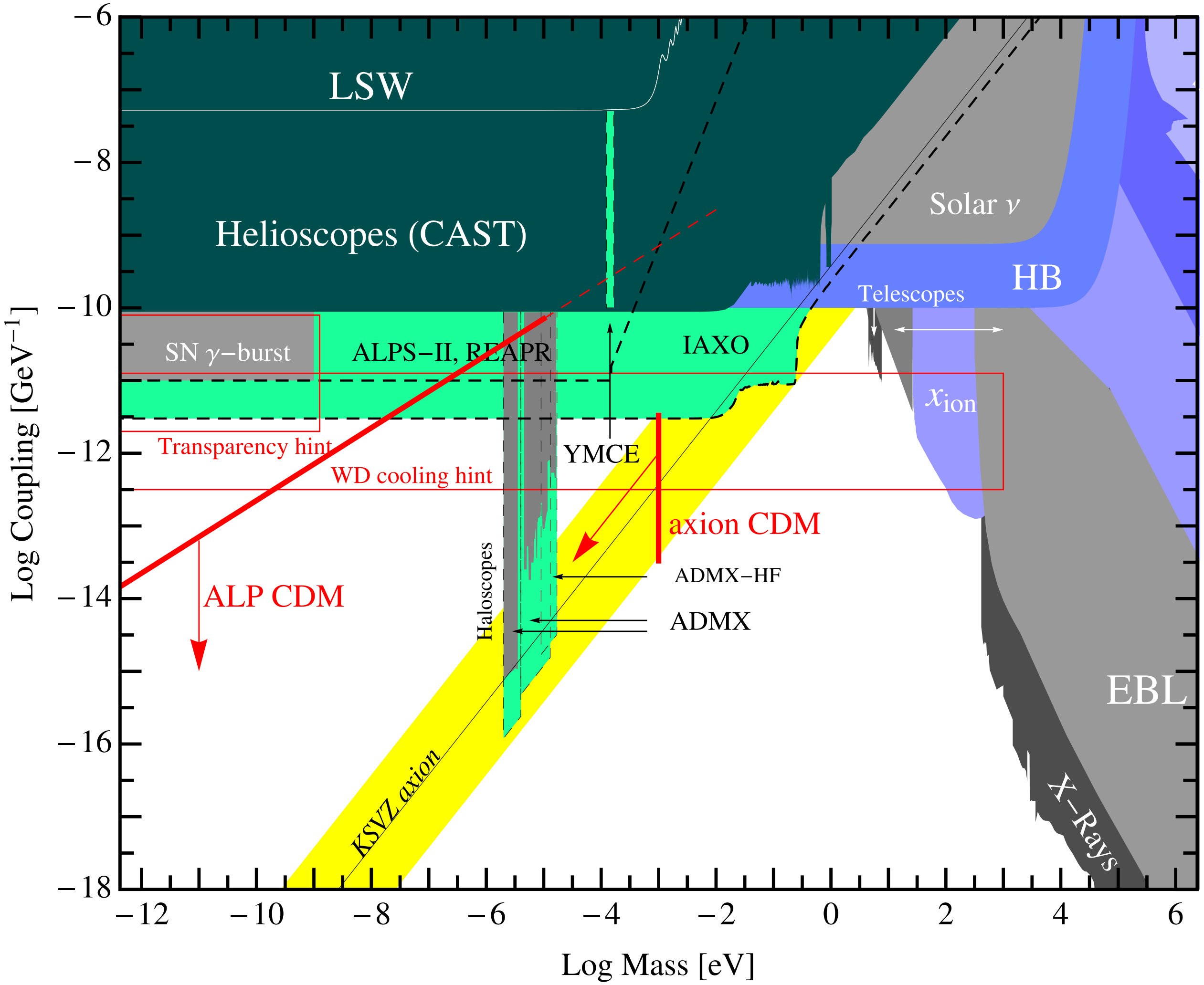
Search

$a\gamma\gamma$ interaction $\qquad C_{a\gamma\gamma}\dfrac{\alpha}{2\pi}\dfrac{a(x)}{f_{PQ}}(\vec{E}\cdot\vec{H})$

Conversion of DM axion into photon in magnetic field in a resonant cavity. 10^{-6} eV/2π = 240 MHz. Need high Q resonator to collect photons, narrow bandwidth, go small steps in m_a. Long story.



Stay tuned ... and stay ... and stay ...



Sterile neutrinos

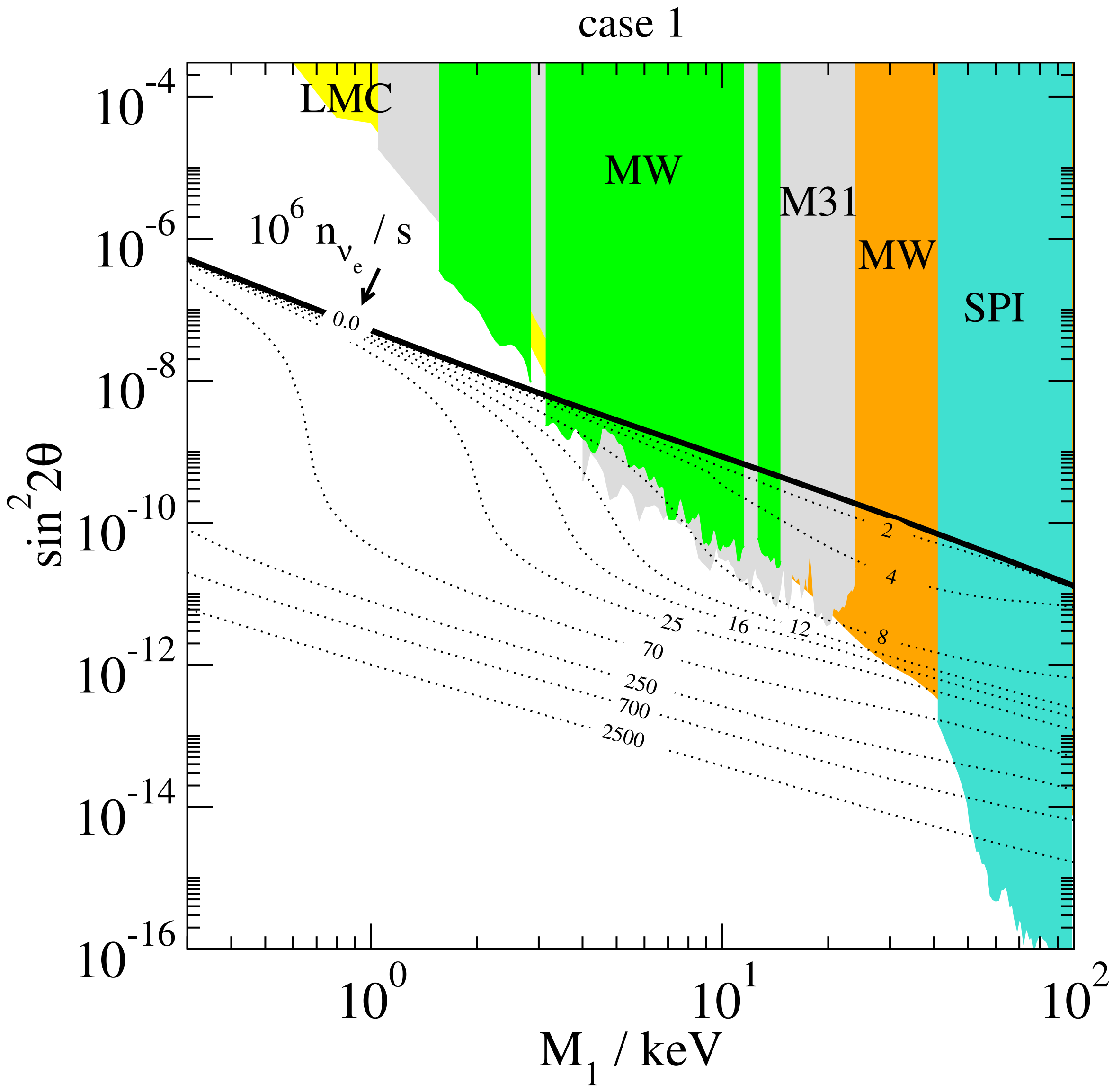
- Needed to give masses to ordinary neutrinos
- Nothing wrong with $m_{\nu_s} \gtrsim 3$ keV
- Created in early Universe at $T \sim 200$ MeV.
- Long lifetime: $\tau_{\nu_s} \gg 10^{10}$ yrs for $m_{\nu_s} = 3 - 10$ keV
- $\nu_s \to \nu\gamma \Longrightarrow$ Search for photons with $E = m_{\nu_s}/2$ from sky.

  Fig.

  Straightforward version of scenario ruled out
  But more contrived (assuming lepton asymmetry) does not

- Direct search in ^3H decay: Troitsk ν-mass experiment.

Search for for photons with $E = m_{\nu_s}/2$



Dedicated searches for even more exotic candidates:

- Decays of hadrons (K-mesons, B-mesons)
- Beam dump experiments. SHiP project at CERN.
- Shining light through wall
- ETC.

Dark matter summary

- WIMP, signal at the LHC:
  - Strongest possible motivation for direct and indirect detection
    - Inferred interactions with baryons $\Longrightarrow$ strategy for direct detection
  - A handle on the Universe at

$$T = (\text{a few}) \cdot 10 \text{ GeV} \div (\text{a few}) \cdot 100 \text{ GeV}$$

$$t = 10^{-11} \div 10^{-8} \text{ s}$$

cf. $T = 1$ MeV, $t = 1$ s at nucleosynthesis

- No signal at the LHC
  - Good guesses: axion, sterile neutrino
  - If not, need more hints from cosmology and astrophysics

Changing geers

What was the Universe before the hot Big Bang?

With Big Bang nucleosynthesis theory and observations
we are confident of the theory of the early Universe
at temperatures up to $T \simeq 1$ MeV, age $t \simeq 1$ second

With the Large Hadron Collider, we hope to be able to go
up to temperatures $T \sim 100$ GeV, age $t \sim 10^{-10}$ second

Are we going to have a handle on even earlier epoch?

Key: cosmological perturbations

Our Universe is not exactly homogeneous.

Inhomogeneities: ⊙ density perturbations and associated gravitational potentials (3d scalar), observed;

⊙ gravitational waves (3d tensor), not observed (yet? – what about BICEP-2?).

Today: inhomogeneities strong and non-linear

In the past: amplitudes small,

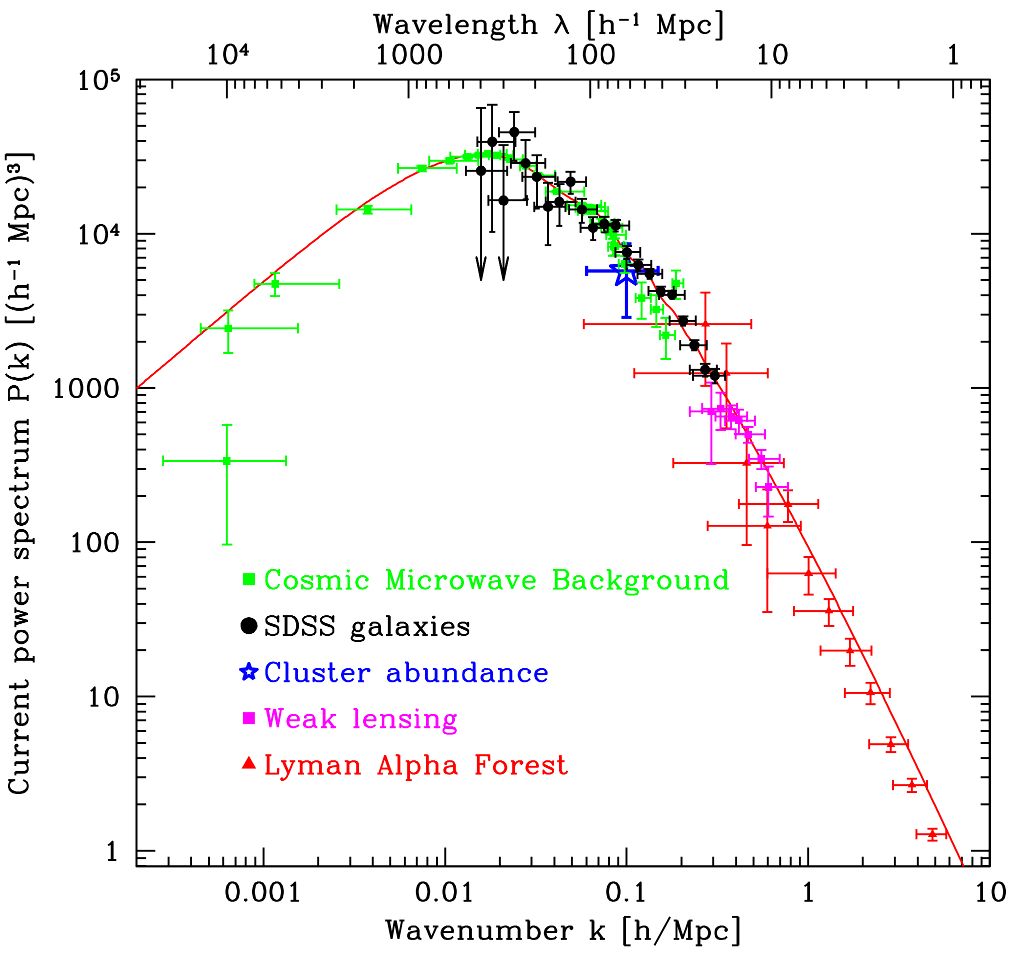
$$\frac{\delta\rho}{\rho} = 10^{-4} - 10^{-5}$$

Linear analysis appropriate.

Wealth of data

- Cosmic microwave background: photographic picture of the Universe at age 380 000 yrs, $T = 3000$ K
  - Temperature anisotropy
  - Polarization
- Deep surveys of galaxies and quasars
- Gravitational lensing, etc.

Overall consistency



NB: density perturbations = random field.
k = wavenumber
$P(k)$ = power spectrum transfered to present epoch using linear theory

We have already learned a number of fundamental things

Extrapolation back in time with known laws of physics and known elementary particles and fields $\Longrightarrow$ hot Universe, starts from Big Bang singularity (infinite temperature, infinite expansion rate)

We now know that this is not the whole story.

Key point: causality

Friedmann–Lemaître–Robertson–Walker metric:

$$ds^2 = dt^2 - a^2(t) d\vec{x}^{\,2}$$

Expanding Universe:

$a(t) \propto t^{1/2}$ at “radiation domination epoch”, before $T \simeq 1$ eV, $t \simeq 50$ thousand years

$a(t) \propto t^{2/3}$ later, until recently.

Cosmological horizon (assuming that nothing preceeded hot epoch): length that light travels from Big Bang moment,

$$l_H(t) = (2-3)ct$$

Wavelength of perturbation grows as $a(t)$.
E.g., at radiation domination

$$\lambda(t) \propto t^{1/2} \quad \text{while} \quad l_H \propto t$$

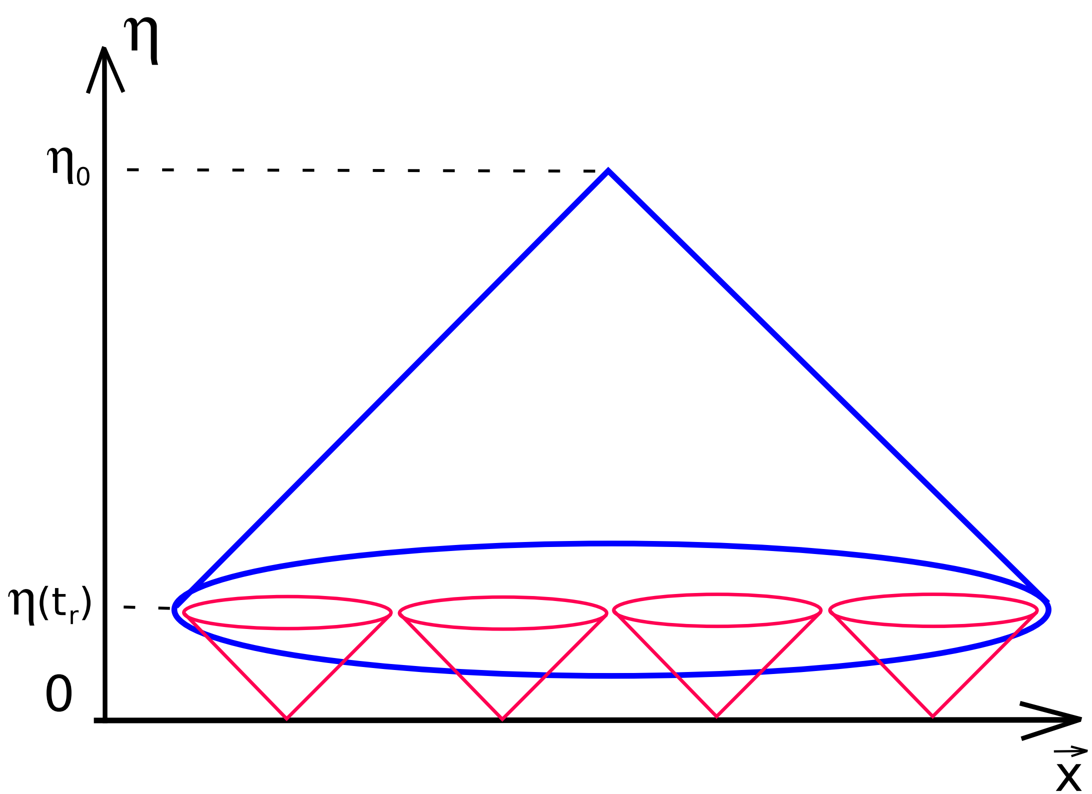
Today $\lambda < l_H$, subhorizon regime

Early on $\lambda(t) > l_H$, superhorizon regime.

NB: Horizon entry occured after Big Bang Nucleosynthesis for perturbations of all relevant wavelengths $\Longleftrightarrow$ no guesswork.

Causal structure of space-time in hot Big Bang theory (i.e., assuming that the Universe started right from the hot epoch)

$$\eta = \int \frac{dt}{a(t)} \, , \quad \text{conformal time}$$



Angular size of horizon at recombination $\approx 2^o$.

Horizon problem

Today our visible Universe consists of $50^3 \sim 10^5$ regions which were causally disconnected at recombination.

Why are they exacly the same?

May sound as a vague question.

But

Properties of perturbations make it sharp.

Major issue: origin of perturbations

Causality $\Longrightarrow$ perturbations can be generated only when they are subhorizon.

Off-hand possibilities:

- Perturbations were never superhorizon, they were generated at the hot cosmological epoch by some causal mechanism.

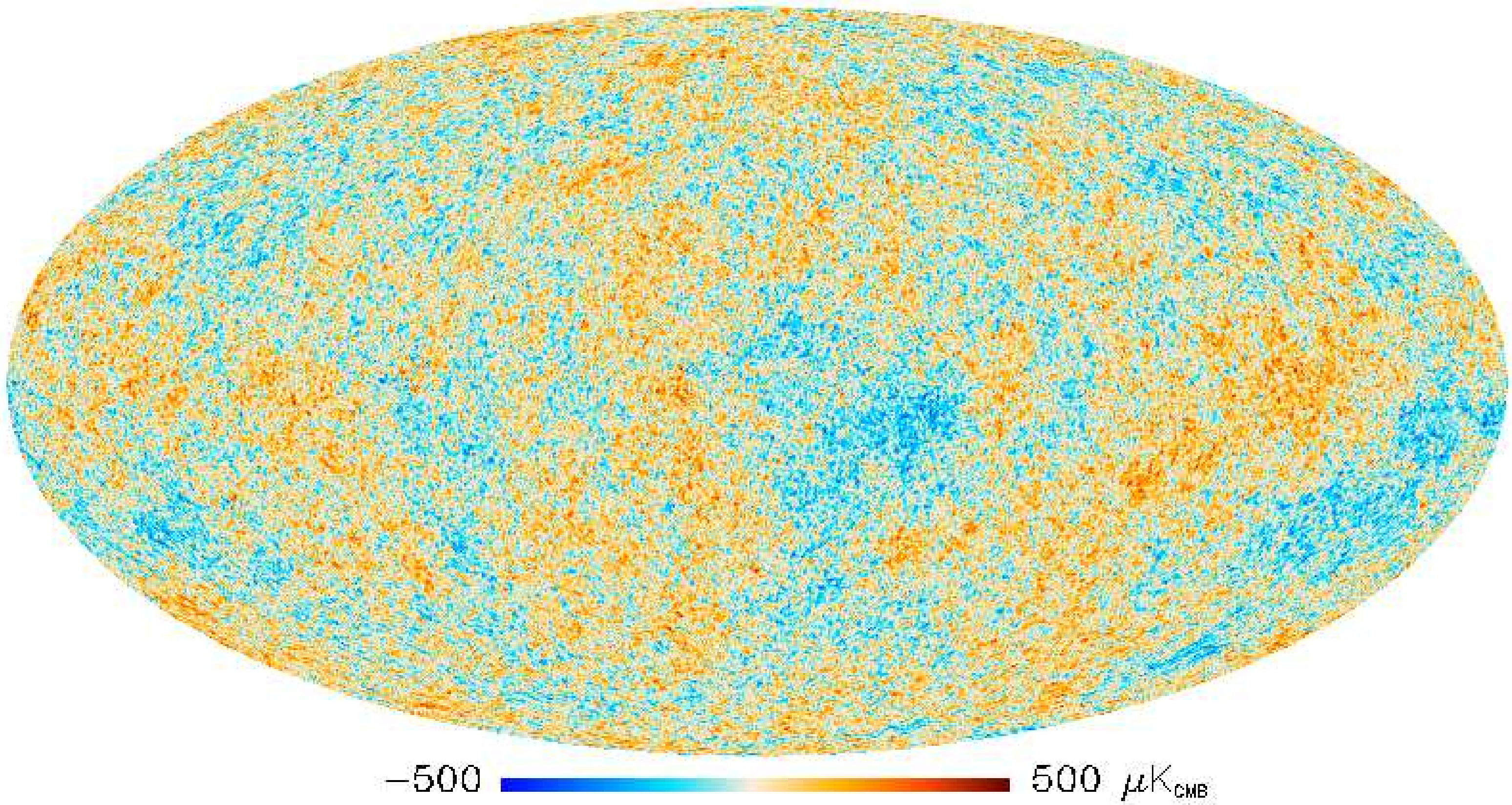
  E.g., seeded by topological defects (cosmic strings, etc.)

  N. Turok et.al.' 90s

  The only possibility, if expansion started from hot Big Bang.

  Not an option

- Hot epoch was preceeded by some other epoch. Perturbations were generated then.



There are perturbations which were superhorizon at the time of recombination, angular scale $\gtrsim 2^o$. Causality: they could not be generated at hot epoch!

Shorter wavelengths: perturbations in baryon-photon plasma = sound waves.

If they were superhorizon, they started off with one and the same phase.

Reason: solutions to wave equation in superhorizon regime in expanding Universe

$$\frac{\delta\rho}{\rho} = \text{const} \qquad \text{and} \qquad \frac{\delta\rho}{\rho} = \frac{\text{const}}{t^{3/2}}$$

Assume that modes were superhorizon. Consistency of the picture: the Universe was not very inhomogeneous at early times, the initial condition is (up to amplitude),

$$\frac{\delta\rho}{\rho} = \text{const} \implies \frac{d}{dt}\frac{\delta\rho}{\rho} = 0$$

Acoustic oscillations start after entering the horizon at zero velocity of medium $\implies$ phase of oscillations well defined.

Perturbations develop different phases by the time of photon last scattering (= recombination), depending on wave vector:

$$\frac{\delta\rho}{\rho}(t_r) \propto \cos\left(\int_0^{t_r} dt\ v_s\ \frac{k}{a(t)}\right)$$

(v_s = sound speed in baryon-photon plasma)

cf. Sakharov oscillations' 1965

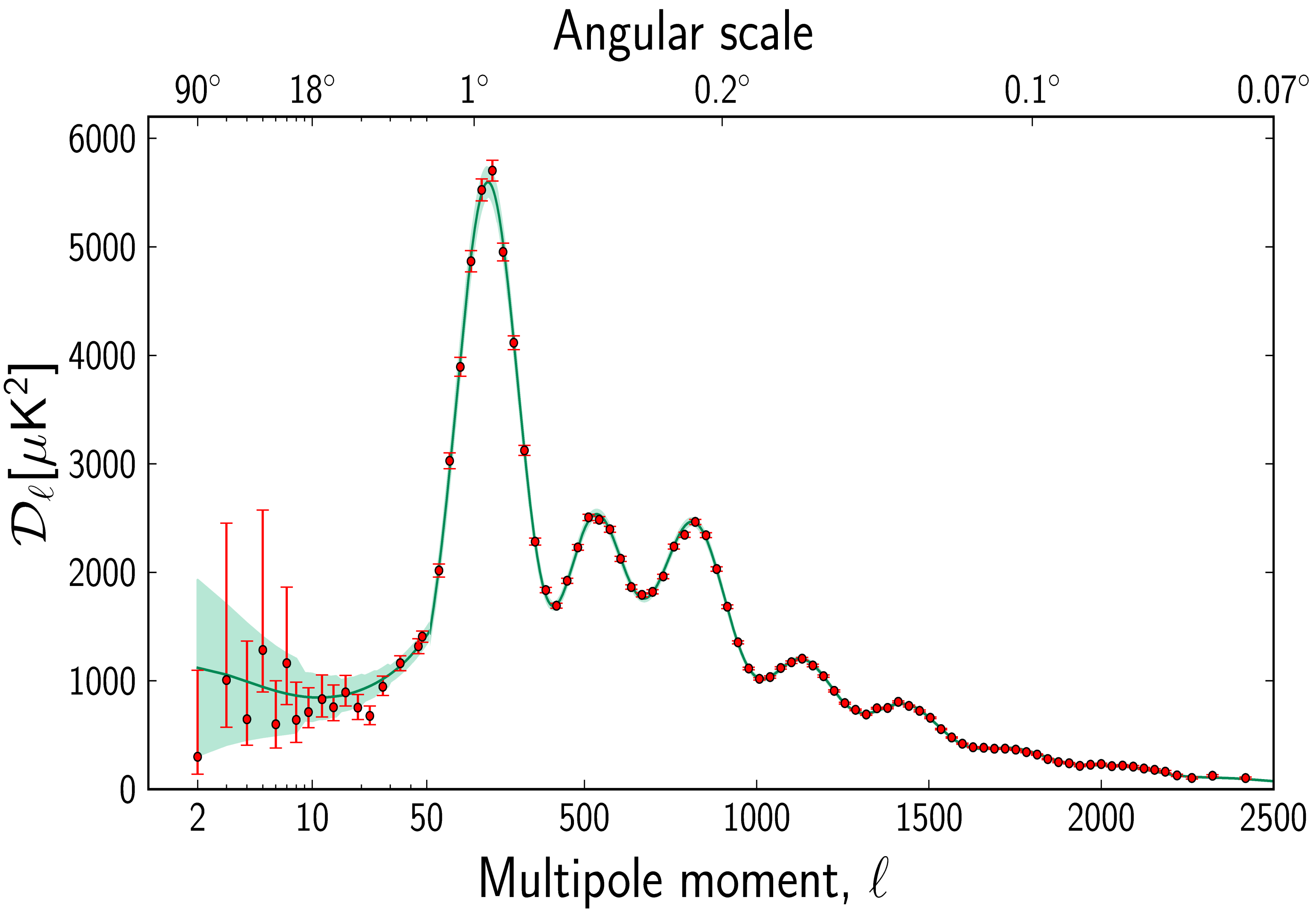
Oscillations in CMB temperature angular spectrum

Fourier decomposition of temperatue fluctuations:

$$\delta T(\theta,\varphi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\varphi)$$

$\langle a^*_{lm} a_{lm}\rangle = C_l$, temperature angular spectrum;

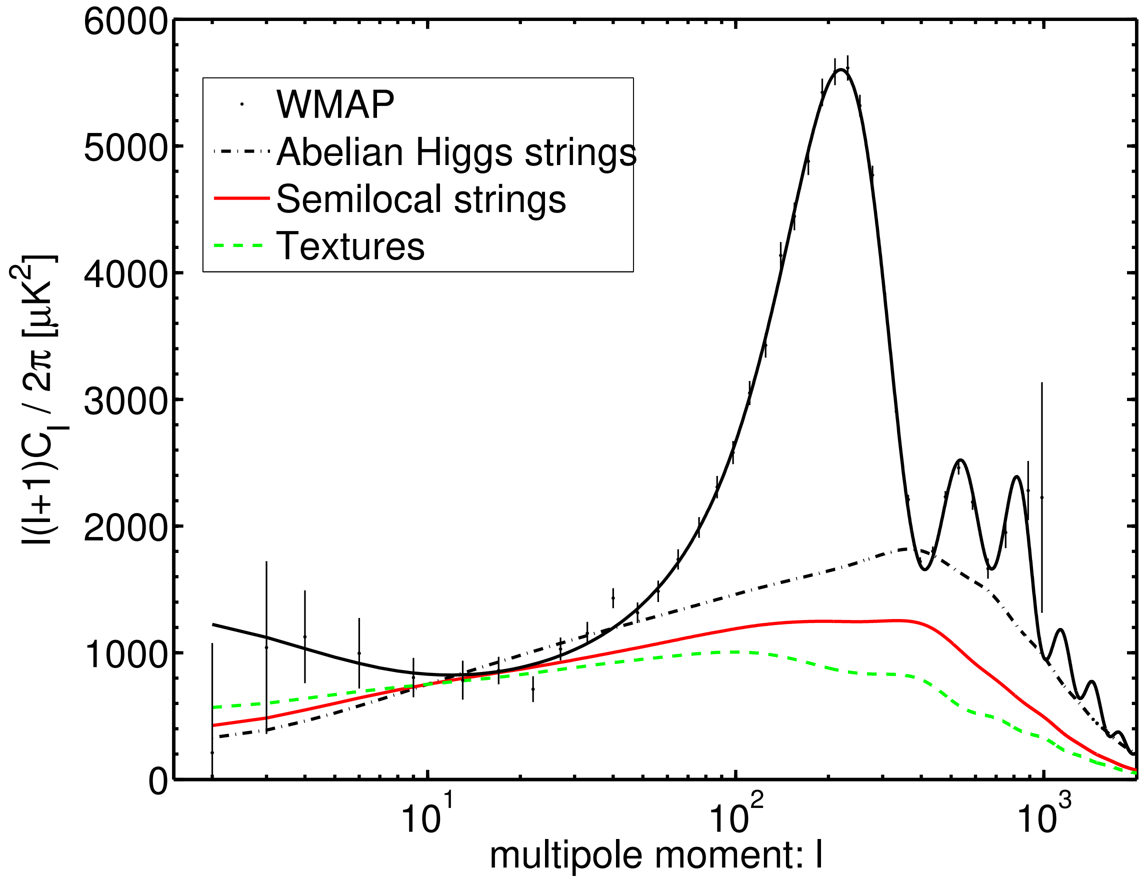
larger $l \Longleftrightarrow$ smaller angular scales, shorter wavelengths



Planck

$$\mathscr{D}_l = \frac{l(l+1)}{2\pi} C_l$$

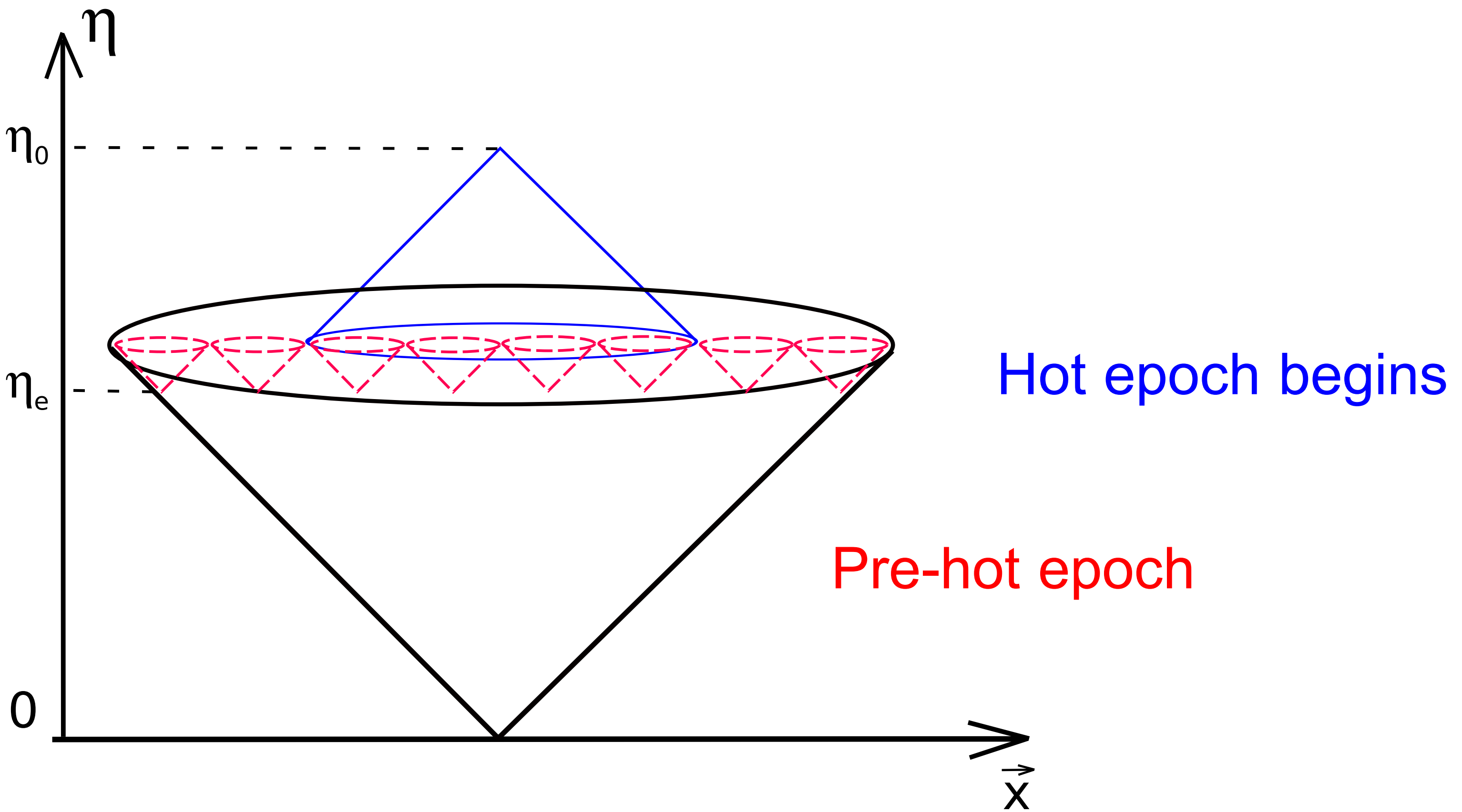
These properties would not be present if perturbations were generated at hot epoch in causal manner.



Primordial perturbations were generated at some yet unknown epoch before the hot expansion stage.

This is true also for perturbations of smaller wavelengths/angular scales (acoustic peaks in CMB angular spectrum)

That epoch must have been long (in conformal time) and unusual: perturbations were subhorizon early at that epoch, our visible part of the Universe was in a causally connected region.



Excellent guess: inflation

Starobinsky'79; Guth'81; Linde'82; Albrecht and Steinhardt'82

Exponential expansion with almost constant Hubble rate,

$$a(t) = \mathrm{e}^{\int H dt}\,, \qquad H \approx \text{const}$$

- Initially Planck-size region expands to entire visible Universe in $t \sim 100\ H^{-1} \Longrightarrow$ for $t \gg 100\ H^{-1}$ the Universe is VERY large
- Perturbations subhorizon early at inflation:

$$\lambda(t) = 2\pi \frac{a(t)}{k} \ll H^{-1}$$

since $a(t) \propto \mathrm{e}^{Ht}$ and $H \approx$ const;
wavelengths gets redshifted, the Hubble parameter stays constant

Alternatives to inflation:

- Bouncing Universe: contraction — bounce — expansion
- “Genesis”: start up from static state

Creminelli et.al.’06; ’10

Difficult, but not impossible. Einstein equations (neglecting spatial curvature)

$$H^2 = \frac{8\pi}{3} G\rho$$

$$\frac{dH}{dt} = -4\pi(\rho + p)$$

$\rho = T_{00}$ energy density, $p = T_{11} = T_{22} = T_{33}$ effective pressure.

Bounce, start up scenarios $\Longrightarrow$ $\frac{dH}{dt} > 0$ $\Longrightarrow$ $\rho > 0$ and $p < -\rho$

Very exotic matter or modified General Relativity.
Yet there are examples (e.g., galileon field theories) with no obvious pathologies like ghosts, gradient instabilities.

Other suggestive observational facts about density perturbations

(valid within certain error bars!)

- Primordial perturbations are Gaussian. Gaussianity = Wick theorem for correlation functions

  This suggests the origin: enhanced vacuum fluctuations of weakly coupled quatum field(s)

  NB: Linear evolution does not spoil Gaussianity.

  - Inflation does the job very well: vacuum fluctuations of all light fields get enhanced greatly due to fast expansion of the Universe.

    Including the field that dominates energy density (inflaton) $\Longrightarrow$ perturbations in energy density.

    Mukhanov, Chibisov'81; Hawking'82; Starobinsky'82;
    Guth, Pi'82; Bardeen et.al.'83

  - Enhancement of vacuum fluctuations is less automatic in alternative scenarios

- Primordial power spectrum is almost flat: no length scale

Homogeneity and anisotropy of Gaussian random field:

$$\langle\frac{\delta\rho}{\rho}(\vec{k})\frac{\delta\rho}{\rho}(\vec{k}')\rangle = \frac{1}{4\pi k^3}\mathscr{P}(k)\delta(\vec{k}+\vec{k}')$$

$\mathscr{P}(k) =$ power spectrum, gives fluctuation in logarithmic interval of momenta,

$$\langle\left(\frac{\delta\rho}{\rho}(\vec{x})\right)^2\rangle = \int_0^\infty \frac{dk}{k}\,\mathscr{P}(k)$$

Flat spectrum: $\mathscr{P}$ is independent of k

Harrison' 70; Zeldovich' 72, Peebles,Yu' 70

Parametrization

$$\mathscr{P}(k) = A\left(\frac{k}{k_*}\right)^{n_s-1}$$

$A =$ amplitude, $(n_s-1) =$ tilt, $k_* =$ fiducial momentum (matter of convention). Flat spectrum $\Longleftrightarrow n_s = 1$.
Experiment: $n_s = 0.96\pm 0.01$

There must be some symmetry behind flatness of spectrum

- Inflation: symmetry of de Sitter space-time $SO(4,1)$

$$ds^2 = dt^2 - \mathrm{e}^{2Ht} d\vec{x}^{\,2}$$

Relevant symmetry: spatial dilatations supplemented by time translations

$$\vec{x} \to \lambda \vec{x}\,, \quad t \to t - \frac{1}{2H} \log \lambda$$

- Alternative: conformal symmetry $SO(4,2)$

Conformal group includes dilatations, $x^\mu \to \lambda x^\mu$.
$\Longrightarrow$ No scale, good chance for flatness of spectrum

First mentioned by Antoniadis, Mazur, Mottola' 97
Concrete models: V.R.' 09;
Creminelli, Nicolis, Trincherini' 10.

NB: (Super)conformal symmetry has long been discussed in the context of Quantum Field Theory and particle physics.

Large and powerful symmetry behind, e.g., adS/CFT correspondence and a number of other QFT phenomena

It may well be that ultimate theory of Nature is (super)conformal

What if our Universe started off from or passed through an unstable (super)conformal state and then evolved to much less symmetric state we see today?

Exploratory stage: toy models + general arguments so far.

Can one tell?

More intricate properties of cosmological perturbations

Not detected yet.

- Primordial gravitational waves predicted by simplest hence plausible) inflationary models, but not alternatives to inflation

  Huge wavelengths, from 100 Mpc to size of visible Universe

  Sizeable amplitudes, $h \sim 10^{-5} - 10^{-6}$
  (cf. $h \lesssim 10^{-22}$ for gravity waves of astrophysical origin)

  Almost flat power spectrum

  May make detectable imprint on CMB temperature anisotropy

  V.R., Sazhin, Veryaskin' 82; Fabbri, Pollock' 83; ...

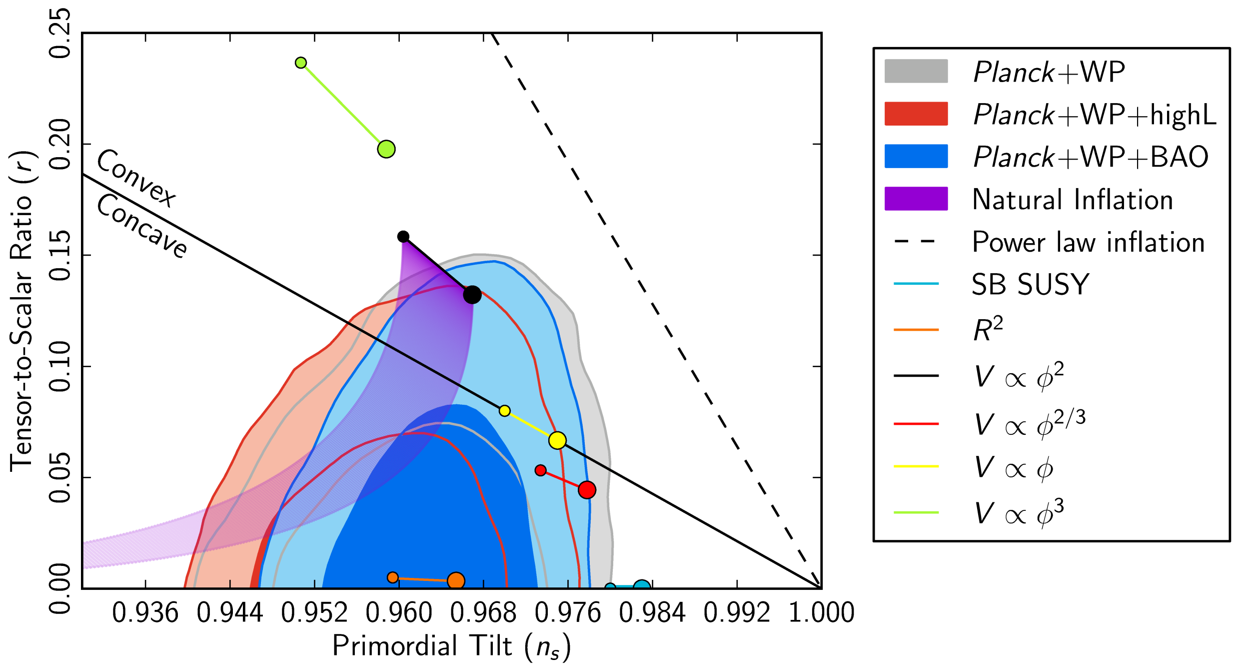
  and especially on CMB polarization

  Basko, Polnarev' 1980; Polnarev' 1985; Sazhin, Benitez' 1995
  Kamionkowski, Kosowsky, Stebbins' 96; Seljak, Zaldarriaga' 96; ...

Smoking gun for inflation

Planck + everybody else

Scalar spectral index vs. power of tensors



$$r = \left(\frac{\text{amplitude of gravity waves}}{\text{amplitude of density perturbations}} \right)^2$$

- Non-Gaussianity: hot topic
  - Very small in the simplest inflationary theories
  - Sizeable in more contrived inflationary models and in alternatives to inflation. Often begins with bispectrum

$$\langle \frac{\delta\rho}{\rho}(\mathbf{k_1})\frac{\delta\rho}{\rho}(\mathbf{k_2})\frac{\delta\rho}{\rho}(\mathbf{k_3})\rangle = \delta(\mathbf{k_1}+\mathbf{k_2}+\mathbf{k_3})G(k_i^2,\mathbf{k_1}\mathbf{k_2},\mathbf{k_1}\mathbf{k_3})$$

    Shape of $G(k_i^2,\mathbf{k_1}\mathbf{k_2},\mathbf{k_1}\mathbf{k_3})$ different in different models $\Longrightarrow$ potential discriminator.
  - Sometimes bispectrum vanishes, e.g., due to some symmetries. But trispectrum (connected 4-point function) may be measurable.
  - Very specific shape of trispectrum in conformal models

Libanov, Mironov, V.R.' 10, 11

- Statistical anisotropy

$$\mathscr{P}(\mathbf{k}) = \mathscr{P}_0(k)\left(1 + w_{ij}(k)\frac{k_i k_j}{k^2} + \dots\right)$$

  - Anisotropy of the Universe at pre-hot stage
  - Possible in inflation with strong vector fields (rather contrived)

    Ackerman, Carroll, Wise' 07; Pullen, Kamionkowski' 07; Watanabe, Kanno, Soda' 09

  - Natural in conformal models

    Libanov, V.R.' 10; Libanov, Ramazanov, V.R.' 11

To summarize:

- No doubt there was an epoch preceding the hot Big Bang. The question is what was that epoch?
- Inflation is consistent with all data. But there are competitors: the data may rather point towards (super)conformal beginning of the cosmological evolution.

More options:

Matter bounce, Finelli, Brandenberger' 01.

Negative exponential potential, Lehners et. al.' 07;
Buchbinder, Khouri, Ovrut' 07; Creminelli, Senatore' 07.

Lifshitz scalar, Mukohyama' 09

- Only very basic things are known for the time being.
- To tell, we need to discover

more intricate properties of cosmological perturbations

- Primordial tensor modes = gravitational waves

  Sizeable amplitude, (almost) flat power spectrum predicted by simplest (and hence most plausible) inflationary models
  but not alternatives to inflation

  - Together with scalar and tensor tilts $\Longrightarrow$ properties of inflaton

- Non-trivial correlation properties of density perturbations (non-Gaussianity) $\Longrightarrow$ potential discriminator between scenarios
  Very small in single field inflation.

  - Shape of non-Gaussianity: function of invariants $(\vec{k}_1 \cdot \vec{k}_2)$, etc.

- Statistical anisotropy $\Longrightarrow$ anisotropic pre-hot epoch.

  - Shape of statistical anisotropy $\Longrightarrow$ specific anisotropic model

At the eve of new physics

LHC $\Longleftrightarrow$ Planck,
dedicated CMB polarization experiments,
data and theoretical understanding
of structure formation ...

chance to learn
what preceeded the hot Big Bang epoch

Barring the possibility that Nature is dull