1^{st} *Summer School for young researchers*
of the Norwegian Centre for CERN-related Research

Introduction to Cosmology

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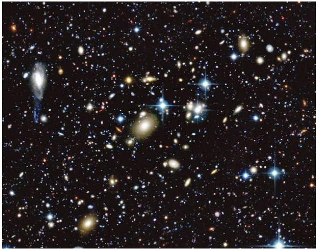
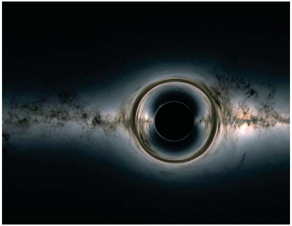


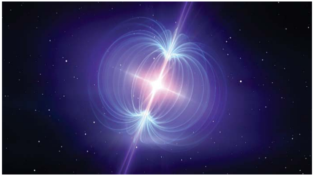
Why the Universe is interesting for physicists?

In the Universe, matter is in **extreme conditions**, often unattainable in the laboratory:

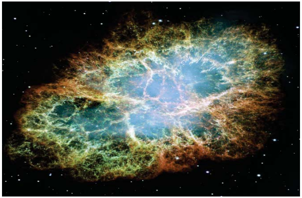


Superstrong gravitational fields

Superdense states of matter



Superstrong electromagnetic fields



Superhigh energies of particles

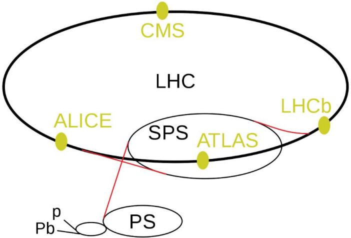
Why the Universe is interesting for particle physicists?

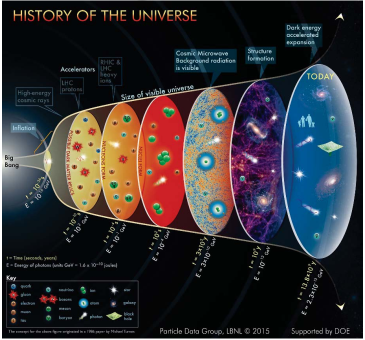
- SPS (Super Proton-Antiproton Synchrotron, 1981 – 1991)
  900 GeV — **∼$ 1 billion**
- LHC (Large Hadron Collider, 2010 – now)
  13 TeV — **∼$ 9 billion**
- FCC (Future Circular Collider, planned)
  50 TeV — **∼$ 20 billion (?)**

Ya. B. Zel'dovich

"The Universe is the poor man's particle accelerator."

Energies as high as 10^{16} **GeV** could be reached there!
We receive cosmic rays with energies up to $\sim 10^{11}$ **GeV** from the Universe!



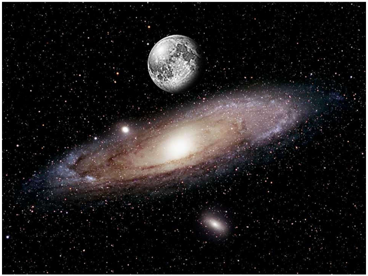


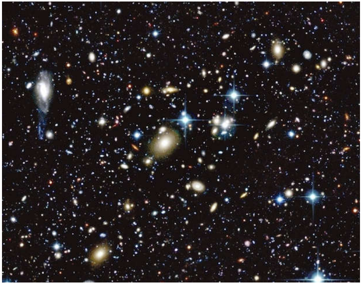
Characteristic sizes and distances in the Universe

Distance Earth–Sun: $1.5 \cdot 10^{13}\text{cm} \equiv 1\text{a.u.}$ Nearest star: $4 \cdot 10^{18}$ cm

$$1 \text{ light year (ly)} = 0.95 \cdot 10^{18} \text{ cm}, \;\; 1 \text{ parsec (pc)} = 3.1 \cdot 10^{18} \text{ cm}$$

Sizes of visible parts of galaxies are of order ≈ 10 kiloparsec (kpc).
Dark halos of galaxies extend to distances of order ≈ 100 kpc and larger.
Clusters of galaxies have sizes of order $\approx 1 - 3$ megaparsec (Mpc).



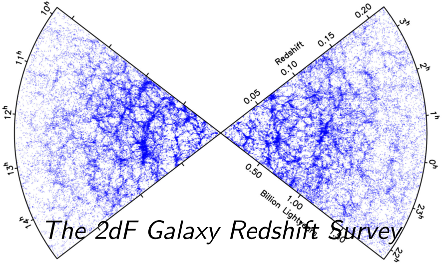


Characteristic cosmic voids distance: more than 10 Mpc $\sim 3.1 \times 10^{25}$ cm
The size of the visible Universe is 14 gigaparsec (Gpc) $\sim 10^{28}$ cm

Cosmological principle

Cosmological principle - at large scales ($\gtrsim$ 100 Mpc) the (visible part of) the Universe is **homogeneous and isotropic**: **all regions of the Universe are the same, and no direction is preferred.**

This feature ensures that observations made from our single vantage point are representative of the Universe as a whole and can therefore be legitimately used to test cosmological models. Also one has well developed inhomogeneous structure on smaller scales;



The 2dF Galaxy Redshift Survey

The Universe is expanding

- **Vesto M. Slipher** discovers **redshifts** of the spectral lines in the nearby galaxies (1912-1913). **Willem de Sitter** speculates for the first time that this can be due to cosmological expansion
- **Edwin Hubble** discovers in 1925 that spiral "nebulae" are far from us (they are galaxies M31, M33)
- **Edwin Hubble** and **Milton Humason** estimate the distances to the nearby galaxies and establish redshift-distance relation (1926)

  $$\boxed{cz = c\frac{\lambda-\lambda_0}{\lambda_0} = H_0 r}$$

  which they interpreted using the Doppler effect as

  $$v = H_0 r$$

  where H_0 is the Hubble constant.
- Velocity is proportional to the distance to the object, **the Universe expands!**

The Universe's expansion is accelerated today

Big collaborations of scientists (**Supernova Cosmology Project**, **High-z Supernova Search Team**) in 1990 – 2000 collect a large number of supernovae type 1a observations and plot the Hubble diagram for large distances.

2011 Nobel Prize in physics:

Photo: Roy Kaltschmidt. Courtesy: Lawrence Berkeley National Laboratory

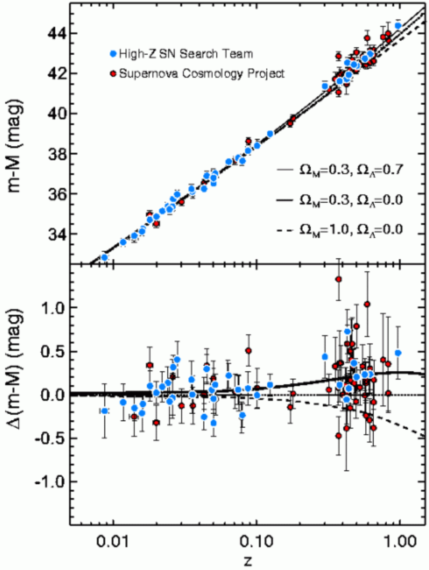
Saul Perlmutter

Photo: Belinda Pratten, Australian National University

Brian P. Schmidt

Photo: Homewood Photography

Adam G. Riess



The Universe is hot today: $\boxed{T_0 = 2.7255 \pm 0.0006 \text{ K}}$

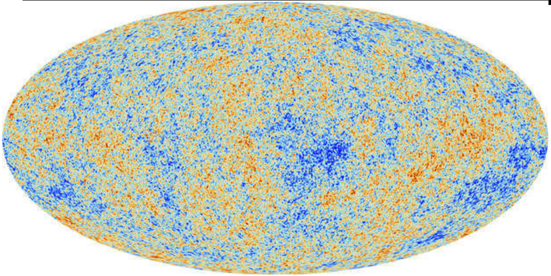
One of the fundamental discoveries (1964) was cosmic microwave background (CMB) – these are photons with black-body spectrum with $T = 2.7255 \pm 0.0006$ K

Measurements of spectrum show almost **ideal Planck spectrum**.

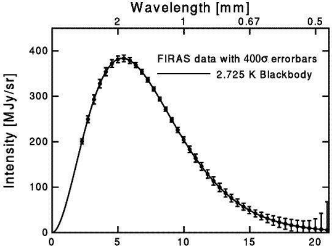
The energy densities of CMB photons: $\rho_{\gamma,0} = \frac{\pi^2}{15} T_0^4 = 2.7 \cdot 10^{-10} \frac{\mathrm{GeV}}{\mathrm{cm}^3}$

The number density of CMB photons: $n_{\gamma,0} = 410 \frac{1}{\mathrm{cm}^3}$

The discovery of CMB has shown that the Universe is hot today.



Planck spectrum of CMB



The Universe is baryon-asymmetric

- Current mean number density of antibaryons and baryons: $n_{\bar{b}}(t_0) = 0$, $n_b(t_0) = 2.7 \times 10^{-7}\,\text{cm}^{-3}$, $\boxed{\text{the Universe is baryon-asymmetric}}$
- the time independent characteristic of the baryon abundance is the baryon-to-entropy ratio: the present entropy density in the Universe with the prescription that neutrinos are relativistic $s(t_0) = 3000\,\text{cm}^{-3}$

$$\boxed{\Delta_b = \frac{n_b}{s} \simeq 0.86 \times 10^{-10}}$$

What is the origin of this number? What is the nature of baryon asymmetry of the Universe? This is one of open questions

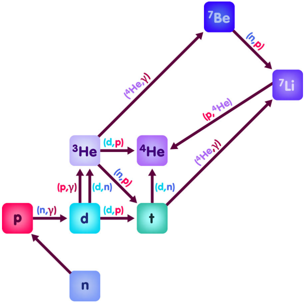
- Another time independent parameter, which characterizes the baryon asymmetry of Universe, is baryon-to-photon ratio: mean concentration of relic CMB photons with $T_\gamma = 2.7255 \pm 0.0006$ K: $n_\gamma(t_0) = \frac{2\,\zeta(3)}{\pi^2}\,T_\gamma^3 \approx 410\,\text{cm}^{-3}$

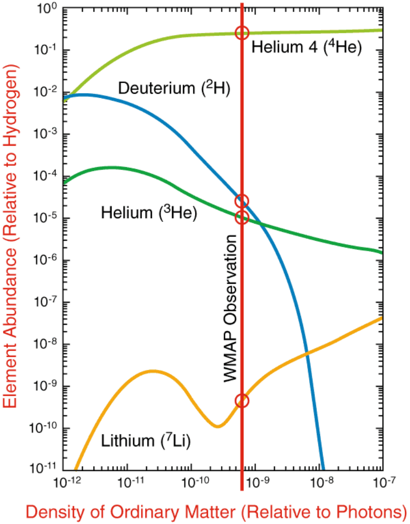
$$\boxed{\eta_b = \frac{n_b}{n_\gamma} \simeq 6 \times 10^{-10}}$$

$$\Delta_b = 0.14\eta_b$$

Chemical composition of the Universe

- Usual (baryonic) matter consists mostly from Hydrogen (75%) and Helium (25%)
- Such a big amount of Helium cannot be created in stars
- The lightest nuclei were generated in the early Universe:



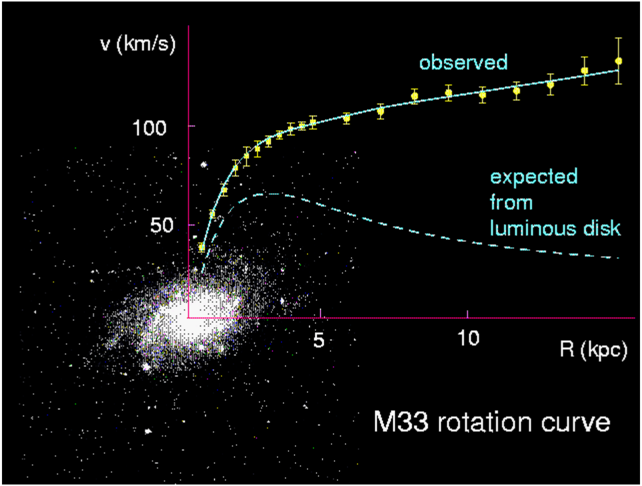


NASA/WMAP Science Team
WMAP101087

Element Abundance graphs: Steigman, Encyclopedia of Astronomy and Astrophysics (Institute of Physics) December, 2000

Evidence of dark matter

Galactic rotation curves

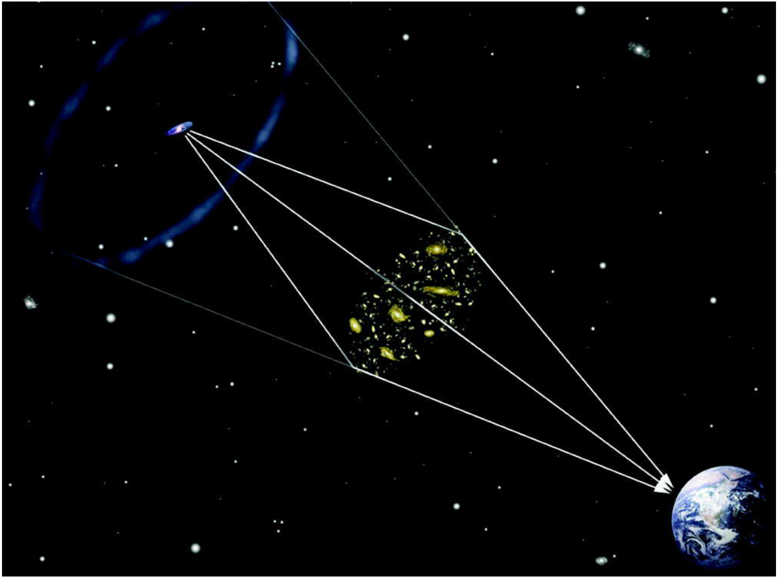


$$\frac{v^2}{r} = \frac{GM(r)}{r^2}$$

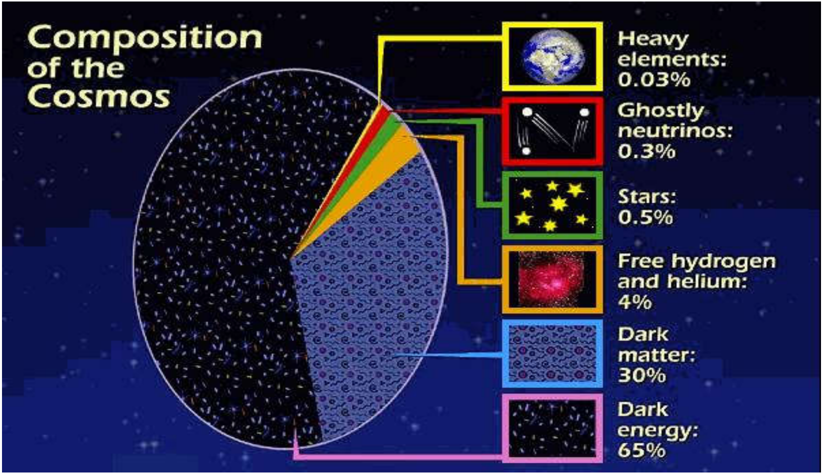
$$v^2 = \frac{GM(r)}{r}$$

Total mass in a galaxy is 6 to 7 times its “visible” mass

Gravitational lensing



Current composition of the Universe



The nature of the Dark Energy and the Dark Matter are still unknown!!!

Metric of the expanding Universe

A basic property of Universe is that it expands: space stretches out. This is encoded in the space-time metric (FLRW):

$$ds^2 = dt^2 - a^2(t)\,d\vec{x}^2 \;=\; dt^2 - a^2(t)\,[\frac{dr^2}{1-\kappa r^2} + r^2(d\theta^2 + sin^2\theta d\phi^2)]$$

where $d\vec{x}^2 = \gamma_{ij}dx^i dx^j$ – the distance on unit three-sphere ($\kappa = 1$) or Euclidean space ($\kappa = 0$) or hyperboloid ($\kappa = -1$),

$a(t)$ - the scale factor.

The coordinates x are comoving – they label positions of free, static particles in space (one has to check that world lines of free static particles obey $x =$ const: as an example, distant galaxies stay at fixed x).

The Universe is expanding remaining homogeneous and isotropic!

In expanding Universe, the scale factor $a(t)$ increases in time, so the distance between free masses of fixed spatial coordinates $x = r_0$ grows, $r(t) = a(t)\, r_0 \Longrightarrow$ the galaxies run away from each other.

Hubble law and Hubble parameter:

$$\boxed{\dot{r} = Hr, \quad H = \frac{\dot{a}}{a}}$$

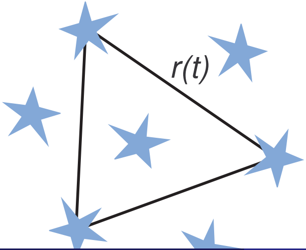
Hubble constant:

$$\boxed{H_0 \approx 67.7 \pm 0.4 \text{ km/s Mpc}}$$

Age of Universe:

$$t_0 \sim H_0^{-1} \simeq 1.44 \cdot 10^{10} \text{ yr}$$

Velocity $v = \dot{r}$ is measured by redshift of spectral lines in remote galaxies



H_0 tension

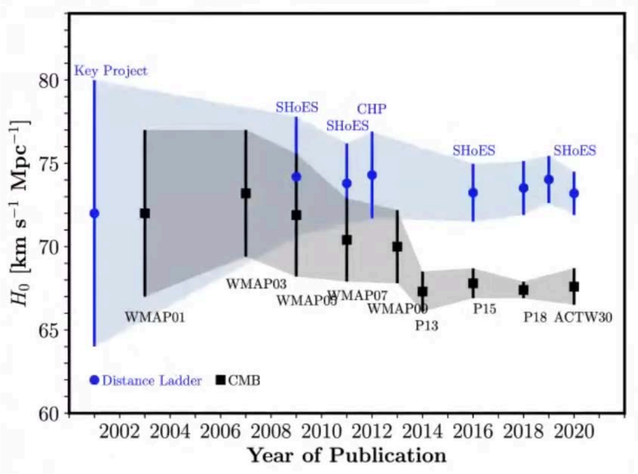
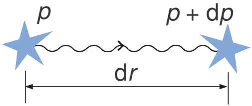


Figure: Evolution of the Hubble tension (determinations of H_0) in the last 20 years using direct measurements from the distance ladder (in **blue**) and CMB-based measurements (in **black**). Credit: Prof. Wendy Freedman.

Cosmological redshift

Since the space stretches out, so does the wavelength of a photon – photon experiences redshift $\lambda_{\rm obs} = (1+z)\lambda_{emit}$, $\quad 1+z = \dfrac{a_0}{a}$



Performing Lorentz transformation with $v_{\rm rel} \ll c$, we have (*exercise*)

Relative velocity:
$v_{\rm rel} = Hdr \ll c = 1$

$$dp = -\frac{Ev_{\rm rel}}{c^2} = -pHdt$$

$$\boxed{\frac{dp}{p} = -Hdt = -\frac{da}{a} \quad \Rightarrow \quad p \propto \frac{1}{a}}$$

For photons, $p = \hbar\omega/c$, which determines redshift z:

$$\boxed{(1+z) \equiv \frac{\omega_{\rm em}}{\omega_{\rm obs}} = \frac{a_0}{a}}$$

High redshift sources are far away from us both in space and in time.

Dynamics of cosmological expansion

Einstein equation (with two fundamental constants):

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

Using FLRW metric

$$ds^2 = dt^2 - a^2(t)\, d\vec{x}^2 = dt^2 - a^2(t)[\frac{dr^2}{1-\kappa r^2} + r^2(d\theta^2 + \sin^2\theta\, d\phi^2)]$$

get the Friedman equations, related $H = \frac{\dot{a}}{a}$, ρ, Λ and p (presure):

$$\boxed{H^2 + \tfrac{\kappa}{a^2} = \tfrac{8\pi G}{3}\rho + \tfrac{\Lambda}{3}, \qquad \dot{\rho} + 3H(\rho + p) = 0, \quad p = f(\rho). \quad \Longrightarrow}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}.$$

Currently accepted model is called ΛCDM ($\Lambda +$ Cold Dark Matter)

$\boxed{\text{this model runs into a singularity since } \ddot{a} < 0 \text{ in the past}}$

The Ω parameters

The Friedmann equation can be recast in the form

$$H^2 = \frac{8\pi G}{3}\rho - \frac{\kappa}{a^2} + \frac{\Lambda}{3} = \frac{8\pi G}{3}\sum_i \rho_i$$

determines the critical density

$$\rho_c = \frac{3H_0^2}{8\pi G} \approx 10^{-29}\ \mathrm{g/cm^3} = 10^{-5}\ \mathrm{GeV/cm^3} = 10^{-46}\ \mathrm{GeV^4}\,, \qquad \Omega_i = \frac{\rho_i}{\rho_c}$$

$$H^2(t) = H_0^2\Big[\Omega_r(\tfrac{a_0}{a(t)})^4 + \Omega_m(\tfrac{a_0}{a(t)})^3 + \Omega_\kappa(\tfrac{a_0}{a(t)})^2 + \Omega_\Lambda\Big]$$

$$= H_0^2\Big[\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_\kappa(1+z)^2 + \Omega_\Lambda\Big]$$

$$\Omega_r + \Omega_m + \Omega_\kappa + \Omega_\Lambda = 1$$

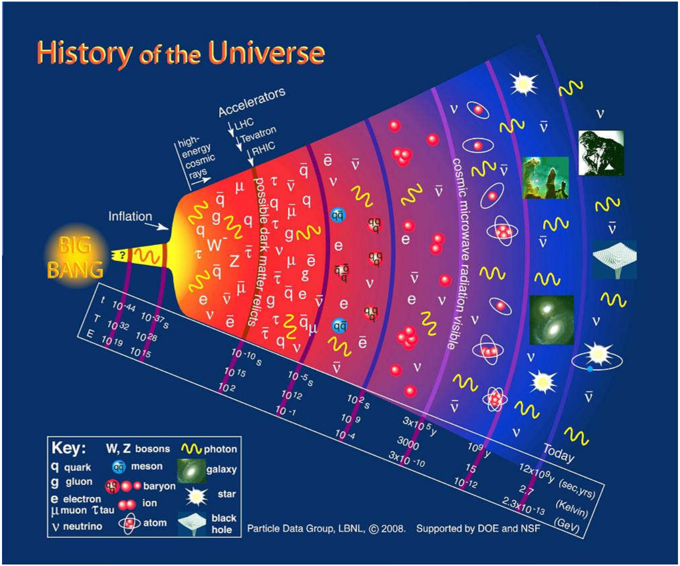
$$\Omega_\Lambda \approx 0.69\,, \quad \Omega_m \approx 0.31\,, \quad \Omega_r \approx 8.6\times 10^{-5}\,, \quad \Omega_\kappa = 0.001 \pm 0.002$$

Ω_m consists of baryons and dark matter: $\Omega_b = 0.049$, $\Omega_{DM} = 0.26$

Thermodynamic history of the Universe - I

- $T \sim 200$ GeV: symmetric electroweak phase, $g = 106.75$
- $T \sim 120$ GeV: electroweak symmetry breaking (cross-over), annihilation of $t\bar{t}$ quarks, $g = 96.25$
- $T < 80$ GeV: annihilation of $W^{\pm}$, Z^0, H^0, $g = 86.25$
- $T < 4$ GeV: $b\bar{b}$ annihilation, $g = 75.75$
- $T < 1$ GeV: $\tau^-\tau^+$ annihilation, $g = 72.25$
- $T \sim 150$ MeV: epoch of QCD; quarks and gluons are confined, forming baryons and mesons. Light hadrons (pions), leptons and photons give $g = 17.25$
- $T < 100$ MeV: annihilation of pions $\pi^{\pm}$, π^0 and muons $\mu^{\pm}$. Remaining particles $e^{\pm}$, γ and ν give $g_\epsilon = 10.75$
- $T \sim 1$ MeV: decoupling of neutrinos
- $T < 500$ keV: annihilation of e^+e^-, $g = 3.36$

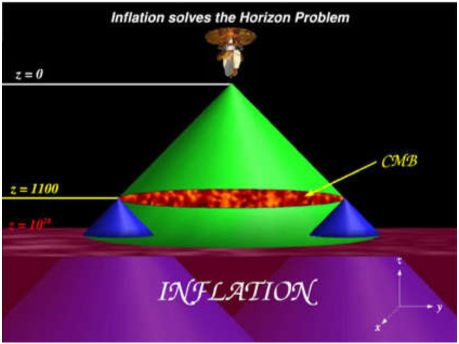
Thermodynamic history of the Universe - II



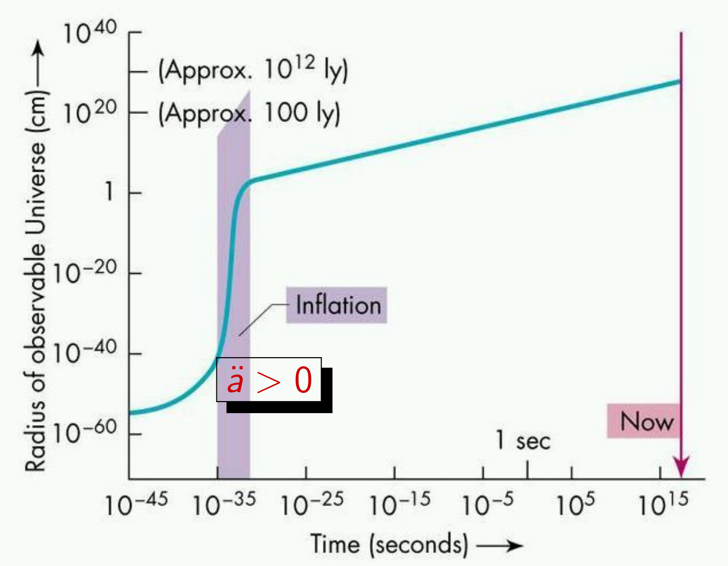
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Problems of the hot Big Bang Theory

- Horizon problem
- Flatness problem
- Entropy problem
- Origin of inhomogeneities



Cosmological inflation



$\ddot{a} > 0$

Magnetic fields in Universe

Magnetic fields exist in all astrophysical objects on all observable scales of the visible Universe:

- **Neutron stars**: $10^{12} - 10^{15}$ G
- **Stars**: $1 - 10^{3}$ G
- **Planets**: ~ 1 G
- **Galaxies**: $\sim 10^{-5} - 10^{-6}$ G
- **Galaxy clusters**: $\sim 10^{-6} - 10^{-7}$ G

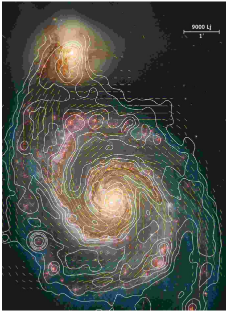


Figure: Optical and radio image of the Whirlpool galaxy M51 with MF configuration. Credit MPIfR Bonn

Since 2010, there is evidence of MF detection also on a cosmological scale — **in the cosmic voids**: $10^{-16}\,\mathrm{G} \lesssim B_0 \lesssim 10^{-10}$ G

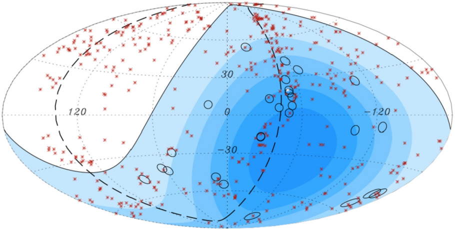
Ultra-High-Energy Cosmic Rays deflection - I

UHECR ($E \sim 10^{20}\,$eV!!!) are deflected by cosmic magnetic fields. If the correlation length of the magnetic field λ_B is less than the distance D to the source of CR, the deflection angle reads as:

$$\theta = \frac{ZeB\sqrt{D\lambda_B}}{E_{UHECR}} \simeq 4^o Z \left[\frac{E_{UHECR}}{10^{20}\,\mathrm{eV}}\right]^{-1} \left[\frac{B}{10^{-9}\,\mathrm{G}}\right] \left[\frac{D}{50\,\mathrm{Mpc}}\right]^{1/2} \left[\frac{\lambda_B}{1\,\mathrm{Mpc}}\right]^{1/2}$$

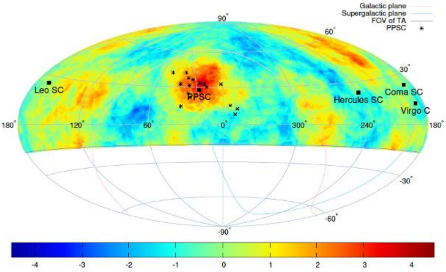
Observations of 27 UHECR with $E > 57$ EeV, Pierre Auger Observatory (Argentina).

[Pierre Auger Collaboration, Science **318**, 938 (2007)]

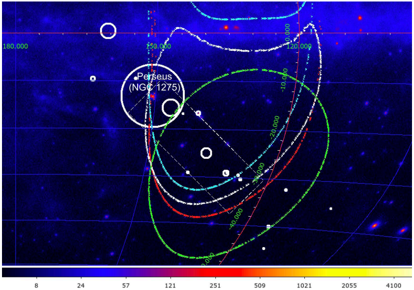


Correlation length $\lambda_B = \frac{1}{\rho_B}\int \frac{2\pi}{k}\rho_B(k)\,dk$ – characteristic spatial scale on which the MF changes.

Ultra-High-Energy Cosmic Rays deflection - II



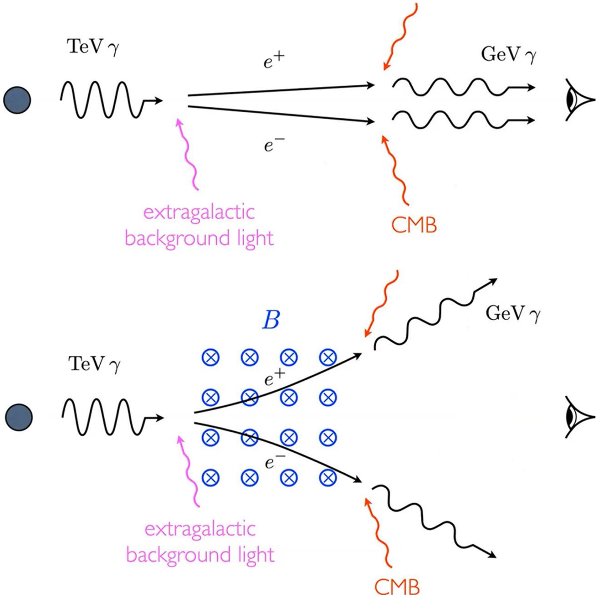
[TA Collaboration, arXiv:2110.14827]



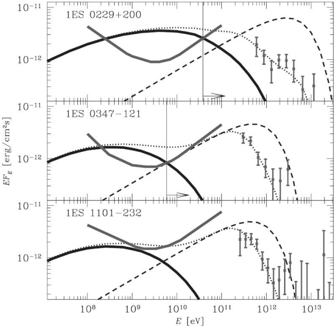
[A. Neronov et al., arXiv:2112.08202]

- Probably, we can connect one of the "hot spots" in UHECR with Perseus-Pisces Supercluster of galaxies.
- Characteristic angular size of this area on the sky $\sim 10^o$.
- Distance to the source $\sim 70\,\mathrm{Mpc}$.
- Constraint from above for the MF strength $B \lesssim 10^{-10}\,\mathrm{G}$.

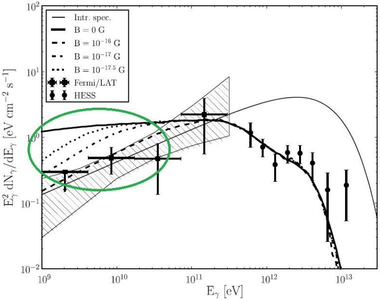
γ-rays from distant blazars - I



γ-rays from distant blazars - II



(Neronov & Vovk '10)



(Vovk *et al.* '12)

There is a lack of secondary (GeV range) γ-rays!

Existing constrains on MF

- Constraint from below is from the analysis of γ-radiation of blazars: $B \geq 10^{-16}$ G.

  [Tavecchio *et al.*, MNRAS **406**; Ando & Kusenko, Astrophys. J. Lett. **722**; Neronov & Vovk, Science **328**]

- Constrains from **above** follow from the analysis of the anisotropy spectrum of CMB and UHECR deviation: $B \leq 10^{-10}$ G.

  [Neronov et al., arXiv:2112.08202]

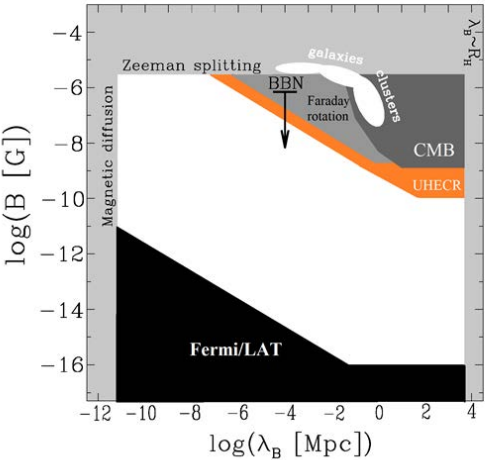
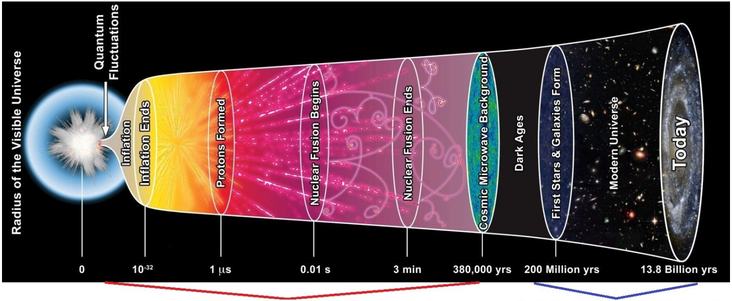


Figure: Summary of constrains on B and λ_B [Neronov&Vovk, Science **328**, 73 (2010)] and [Neronov et al., arXiv:2112.08202]

When and how could MFs arise in the Universe?

There are two different hypotheses for the generation of seed MF:

- **Astrophysical** — generation during the structures formation: Biermann battery, adiabatical contraction, dynamos, ...
- **Cosmological** — generation in a very early Universe: phase transitions, reheating, inflation, ...



Cosmological mechanisms

Astrophysical mechanisms

Sources of our knowledge about the Early Universe

If MF were generated before the BBN, we get a new source of information about a very early Universe:

- Abundances of light elements in the Universe
- CMB spectrum
- Large-scale structure of the Universe
- Primordial gravitational waves (???)
- Relic neutrinos (???)
- **Magnetic fields in voids!!!**

Thank you for your attention!