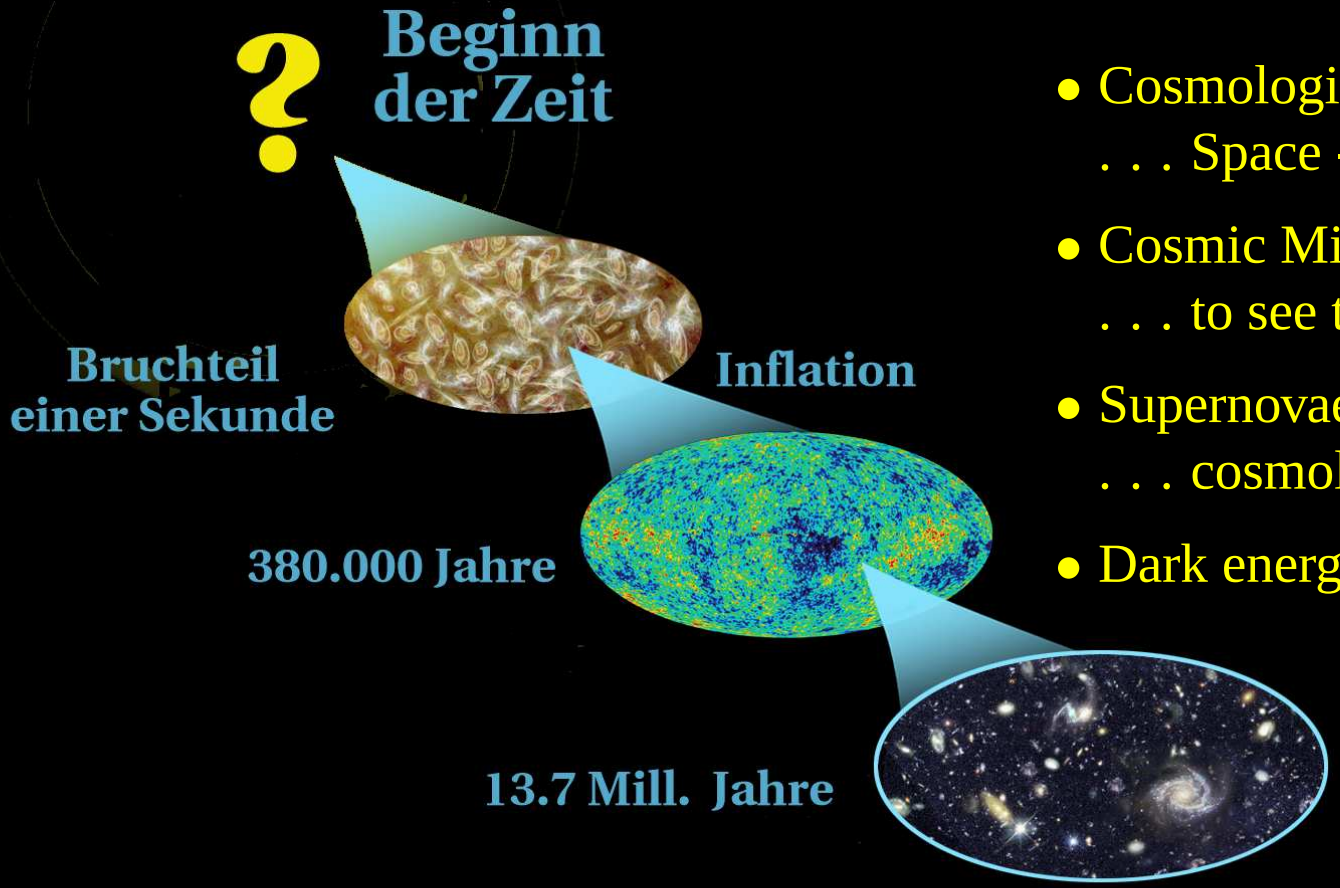
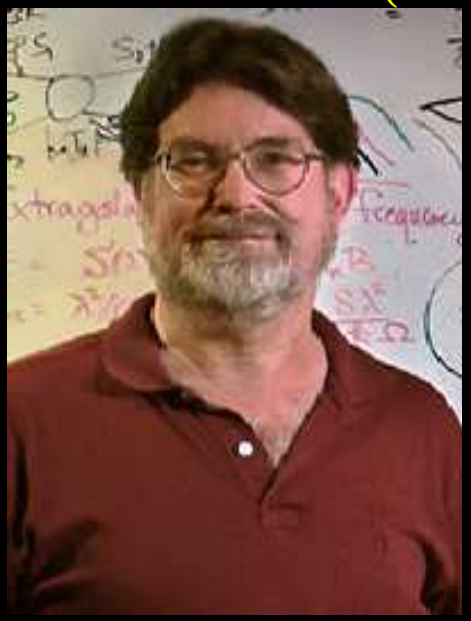
Evolution of the Universe: Standard concepts and new ideas



- Cosmological Evolution
  . . . Space - Time - Matter
- Cosmic Microwave Background
  . . . to see the Echo of the Big Bang
- Supernovae Ia
  . . . cosmological Standard candles
- Dark energy - Puzzle and Perspective

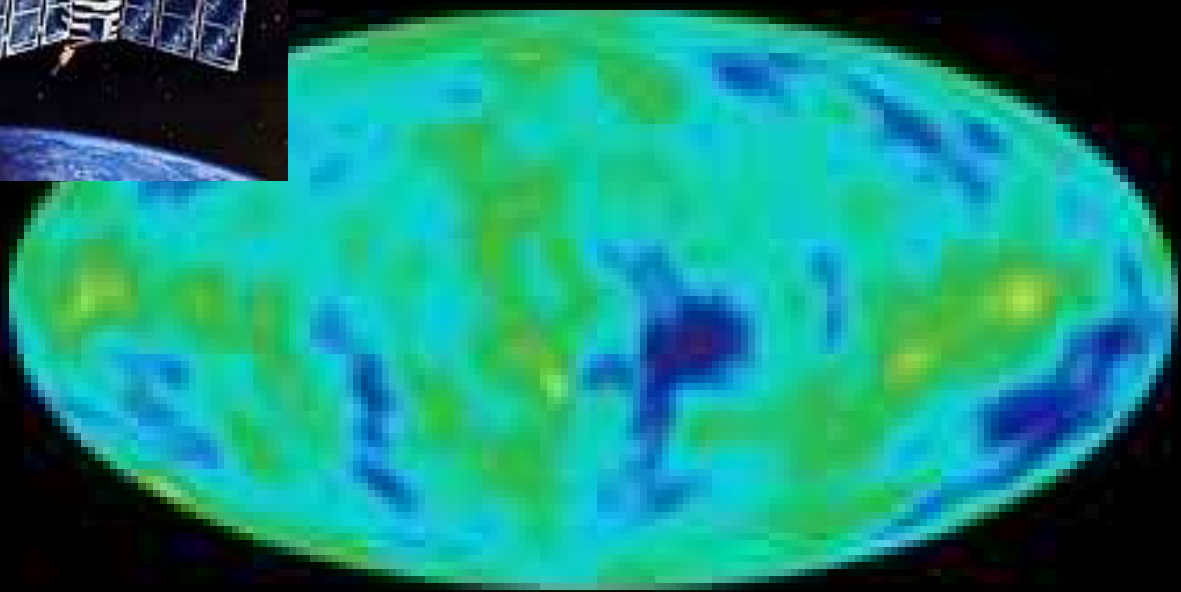
John C. Mather (NASA)



George F. Smoot (Berkeley)

Nobel Prize in Physics 2006

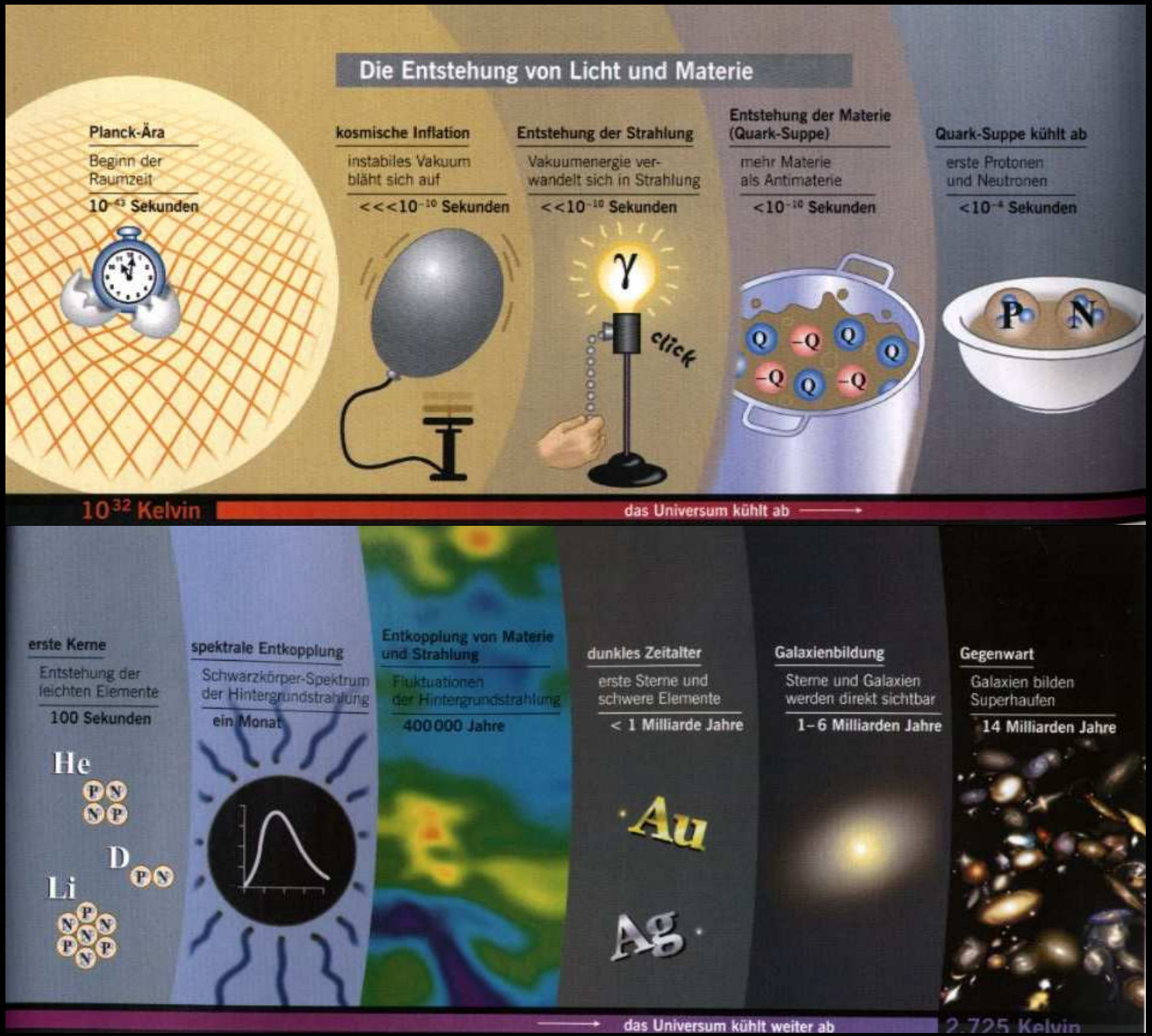
"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"



Myths of Creation: Division of Light and Darkness

Cupola of San Marco, Venice, 13. century

Sequence of Phase transitions → Structure formation



Mathematical Basis for Modern Cosmology

Einstein's Field Equations of General Relativity Theory (1916)

$$(\text{Space} - \text{Time}) \quad G_{\mu\nu} = 8\pi G\, T_{\mu\nu} \quad (\text{Matter})$$

Friedmann-Robertson-Walker Metric for isotropic Mass Distribution

$$ds^2 = -dt^2 + a^2(t)[dr^2 + r^2 d\Omega^2]\ , \ \ \text{ScaleFactor}\ a(t)$$

(Quasi-)Static Universe for positive Cosmological Constant Λ

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$
$$T_{\mu\nu} = -p g_{\mu\nu} + (p + \varrho) u_\mu u_\nu; \ \ u = (1,0,0,0)$$

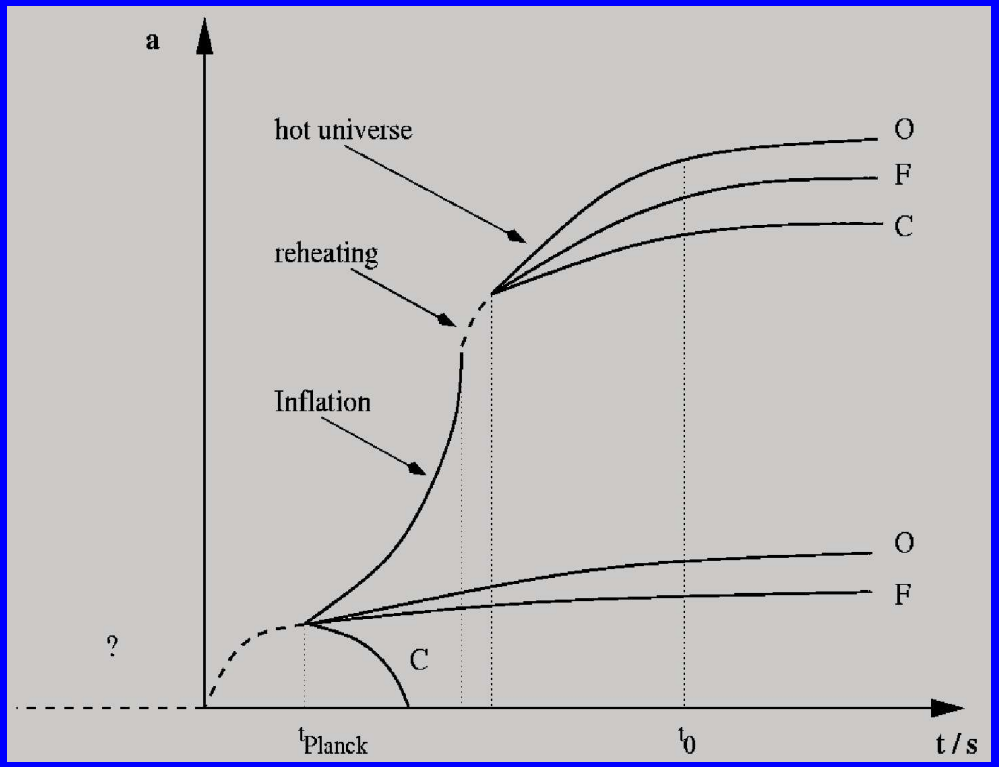
Einstein: *... die größte Eselei meines Lebens!*

Today: Renaissance of the Cosmological Constant as 'Dark Energy': ϱ^{vac}

$$G_{\mu\nu} = 8\pi G\, (T_{\mu\nu} + T^{\text{vac}}_{\mu\nu}); \ \ -p^{\text{vac}} = \varrho^{\text{vac}} = \Lambda/(8\pi G)$$

Strong Experimental Evidence!

Cosmic Expansion of Space – Scale factor $a(t)$



Evolution of the Scale factor

$$\frac{\dot{a}}{a} = H(t) = \sqrt{\frac{8\pi G}{3}\,\rho}$$

$$\frac{\dot{a}}{a} = H_0\sqrt{\Omega_M a^{-3} + (1-\Omega_M-\Omega_\Lambda)a^{-2} + \Omega_\Lambda}$$

Cosmological Parameters, $a(t_0) = 1$

$$H_0 = H(t = t_0)$$

$$\Omega_M = \frac{8\pi G}{3H_0^2}\,\rho_M$$

$$\Omega_\Lambda = \frac{c^2}{3H_0^2}\,\Lambda$$

Flat Space: $\Omega_M + \Omega_\Lambda = 1$

Attention: Space can expand with superluminal velocity!

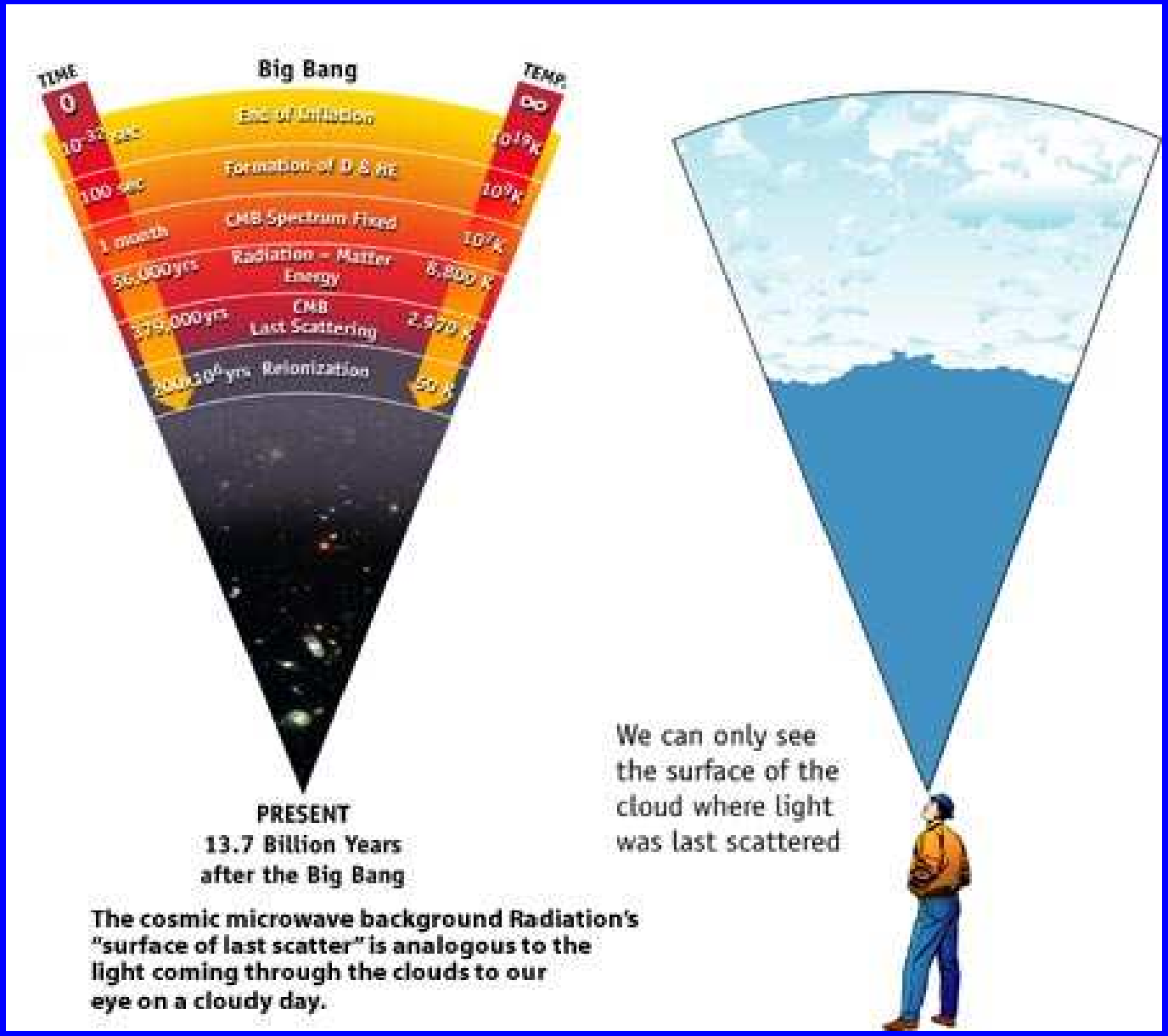
Time and Distance: Thunder and Lightning

$$\begin{aligned} \text{Distance L} &= \text{RetardationofSignal} \\ &\quad \times \text{VelocityofSound} \\ &= 3\,\text{s} \times 330\,\text{m/s} \\ &= 1\,\text{km} \end{aligned}$$

Distance and Time: Sun and Earth

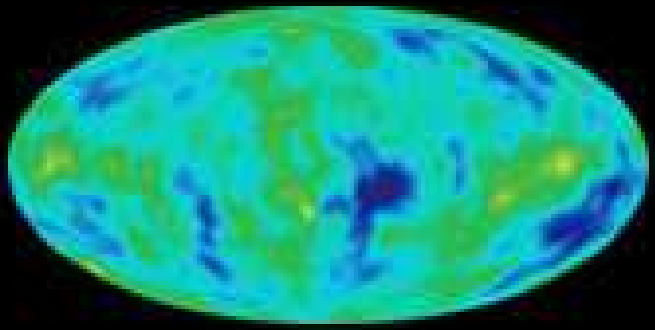
$$\begin{aligned} \text{Traveltime } t &= \frac{1 \text{ Astronomical Unit}}{\text{VelocityofLight}} \\ &= \frac{150\,000\,000 \text{ km}}{300\,000 \text{ km/s}} \\ &= 500 \text{ s} = 8.3 \text{ Minutes} \end{aligned}$$

Cosmology: Background Radiation as "Echo" of the Big Bang

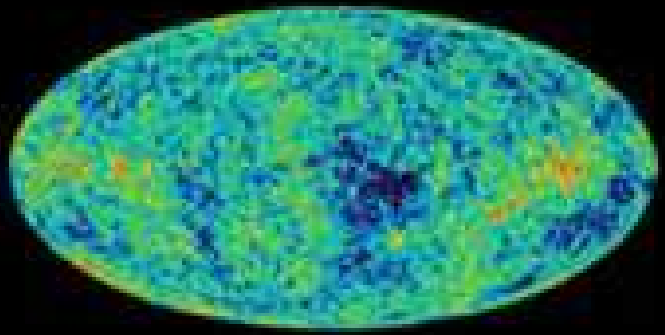


WMAP: A view onto the "Surface of Last Scattering"

Sharp Pictures of the Baby-Universe: COBE vs. WMAP



COBE



WMAP

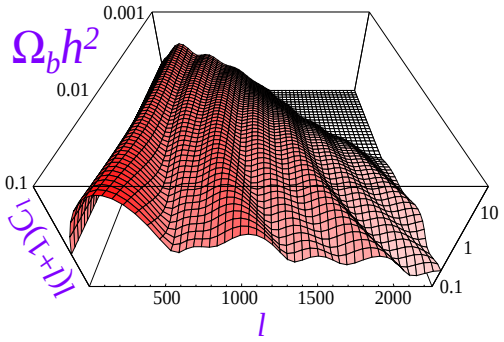
Only 380 000 Jahre old !

Evolution of Large Scale Structures

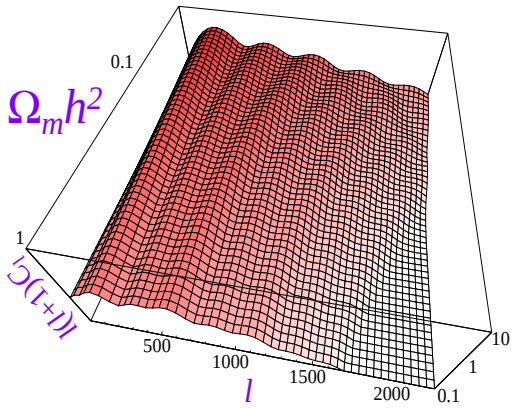
CMB Fluctuations $\Longrightarrow$ First Stars $\Longrightarrow$ Galaxy Clusters

Cosmological Parameters in the CMB

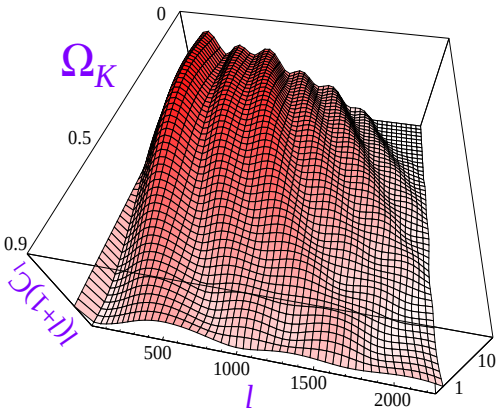
Baryon–Photon Ratio



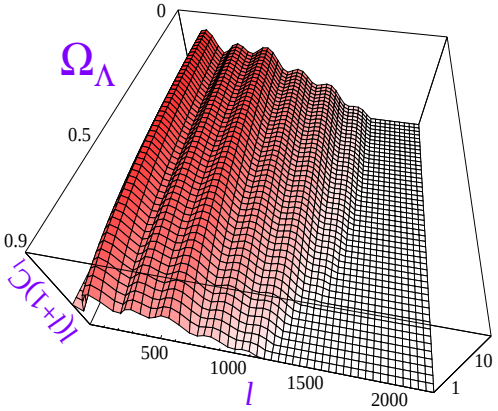
Matter–Radiation Ratio



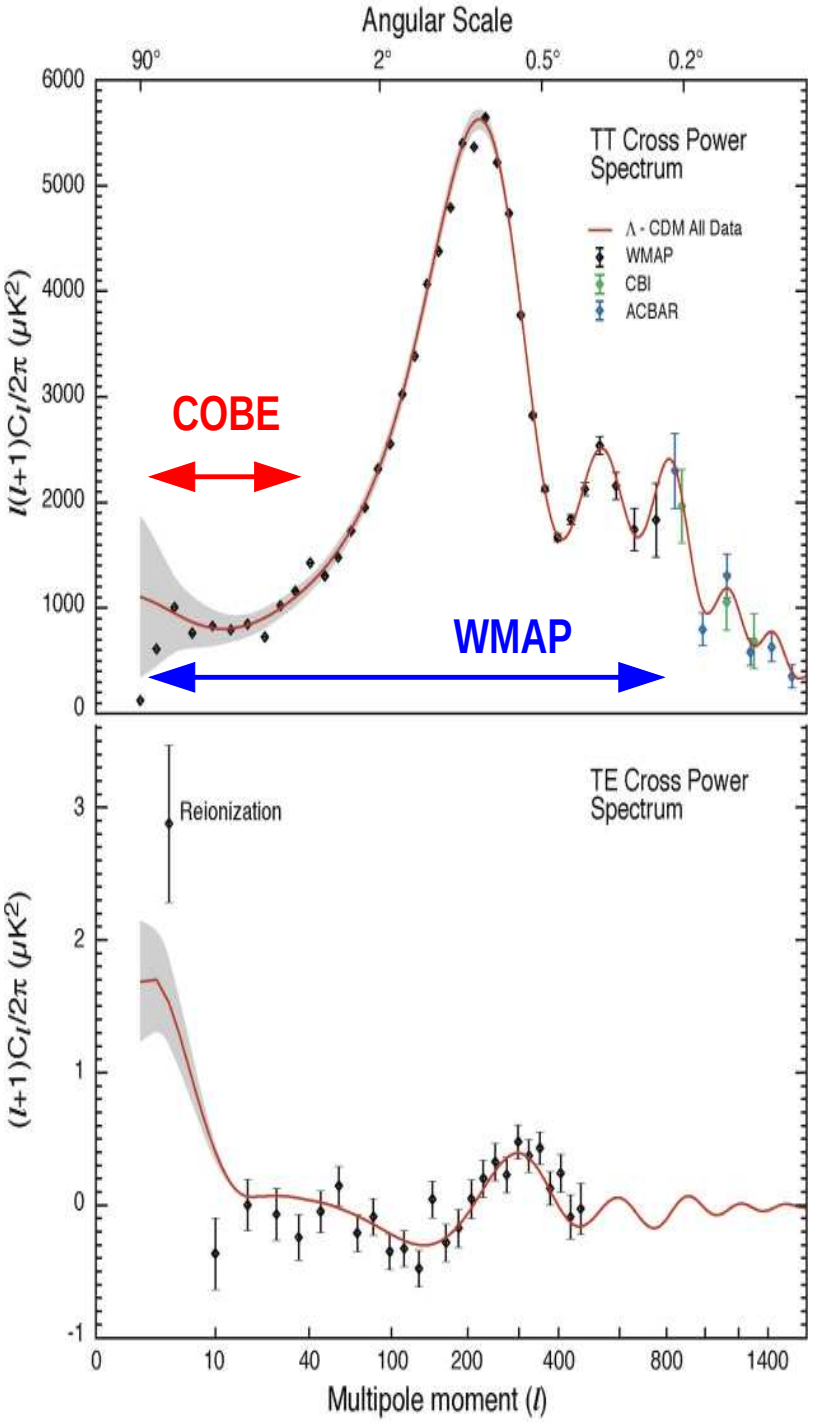
Curvature



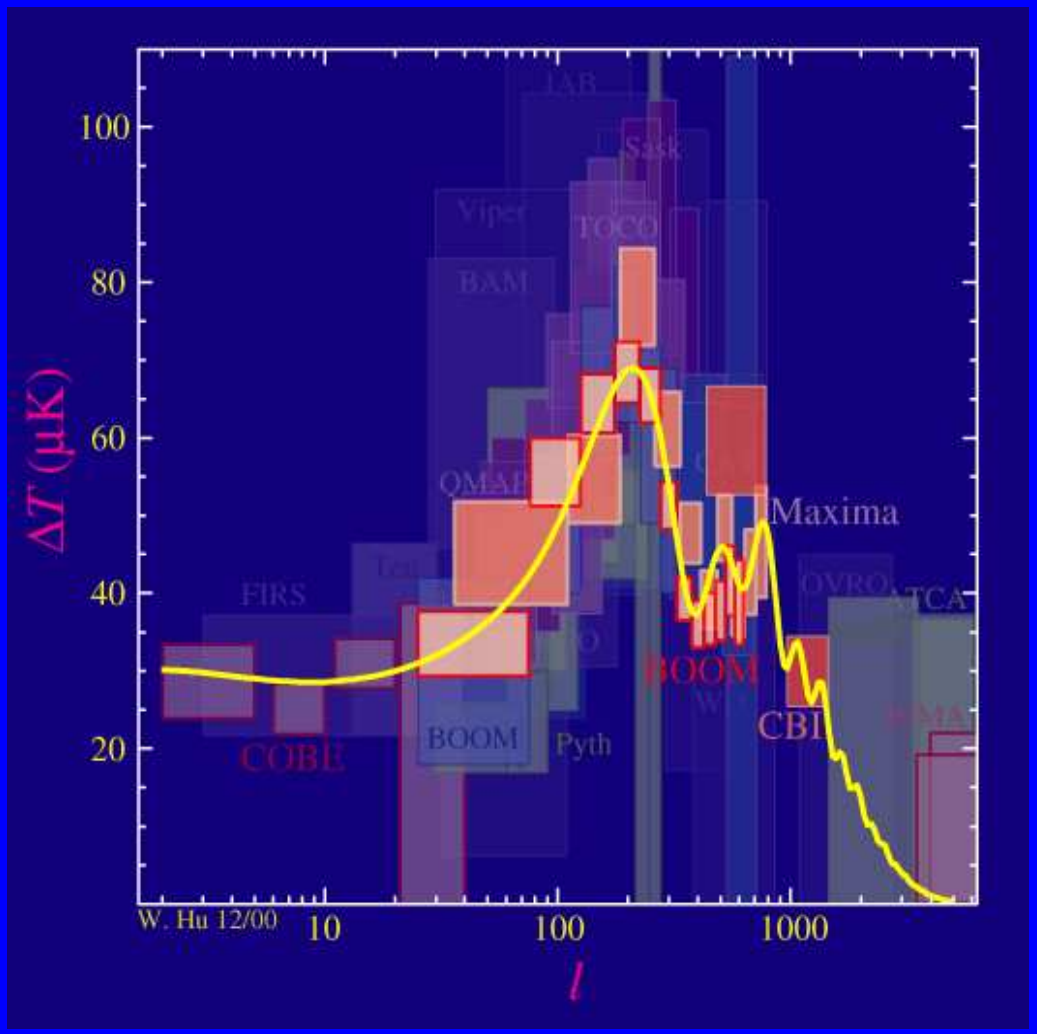
Cosmological Constant



W.Hu 2/98



Cosmological Parameters and Fluctuation Spectrum

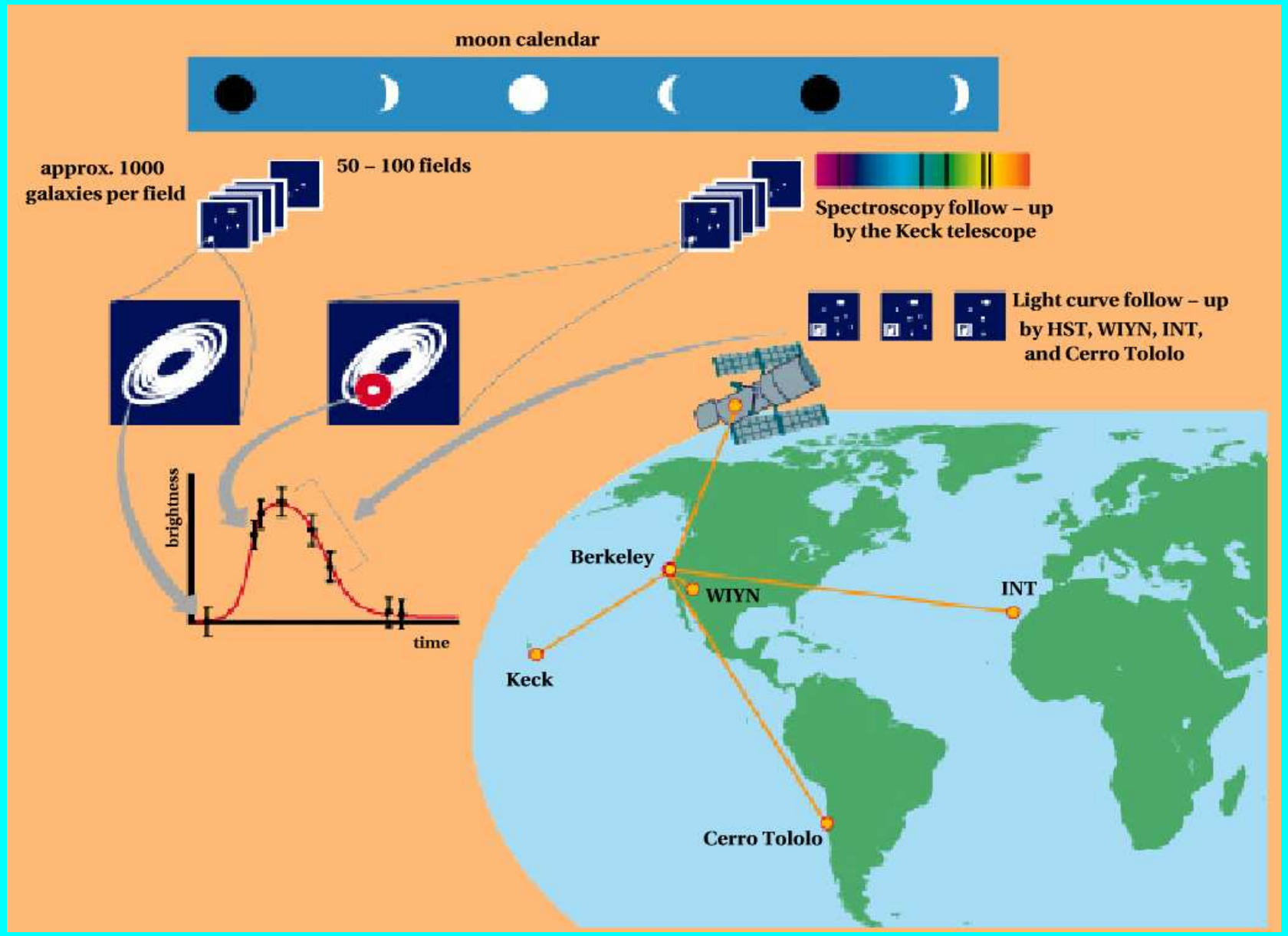


Boxes: 1 sigma errors x band window width.
Upper limits are plotted as 2 sigma constraints.
$\Omega_m = 0.28$,
$\Omega_\Lambda = 0.72$,
$\Omega_b\, h^2 = 0.024$,
$n_s = 1$, $\tau = 0.17$, $h = 0.72$.

Physics of CMB Fluctuations:
Homepage Wayne Hu (U Chicago)

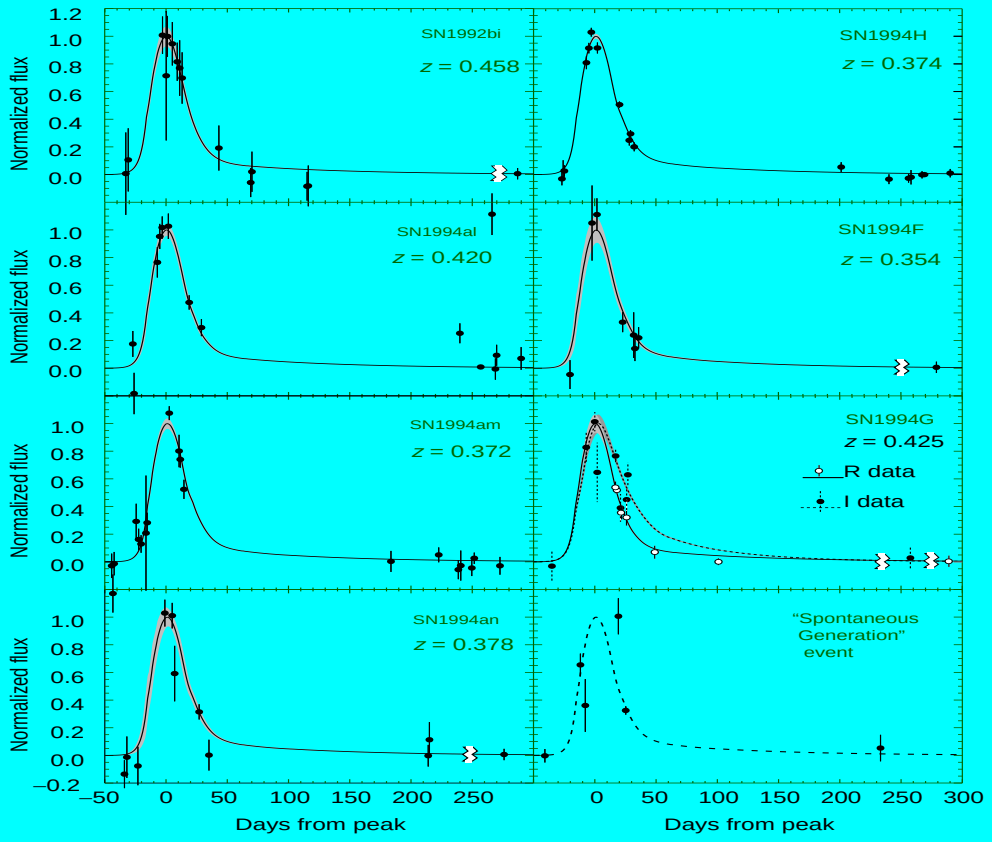
http://background.uchicago.edu/∼whu/intermediate/intermediate.html

Supernovae as Cosmological Length Scales (I)

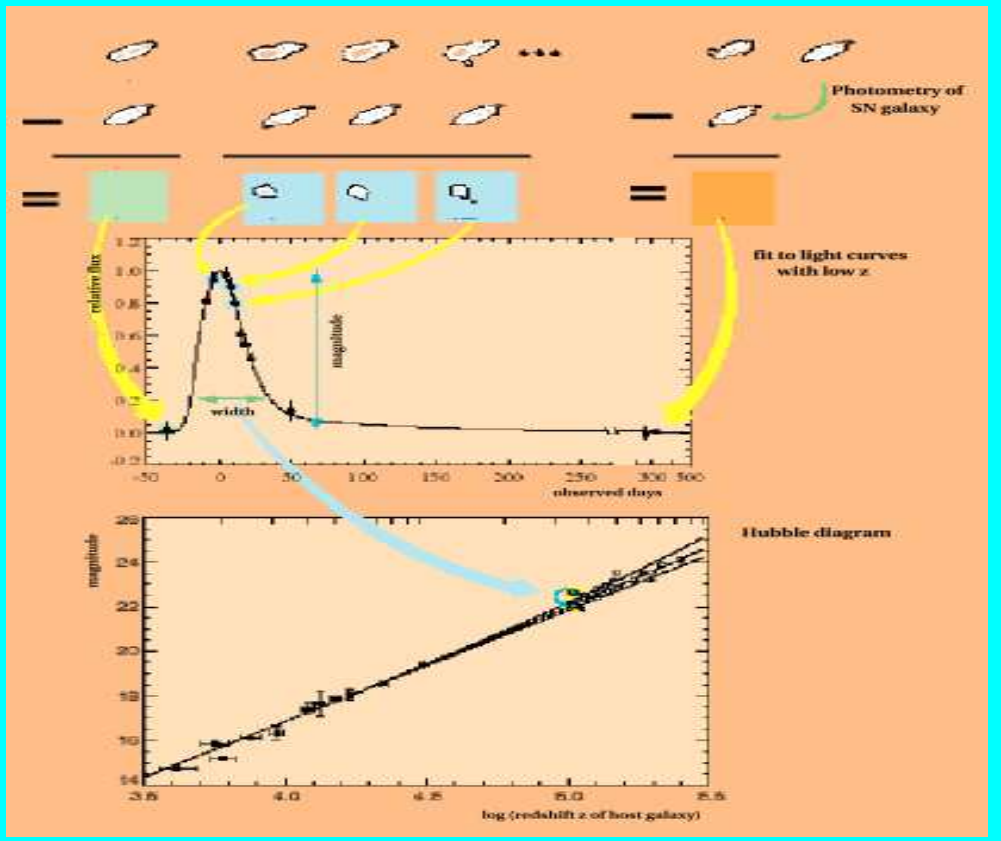


Supernovae as Cosmological Length Scales (II)

Light Curves of Type- Ia- Supernovae

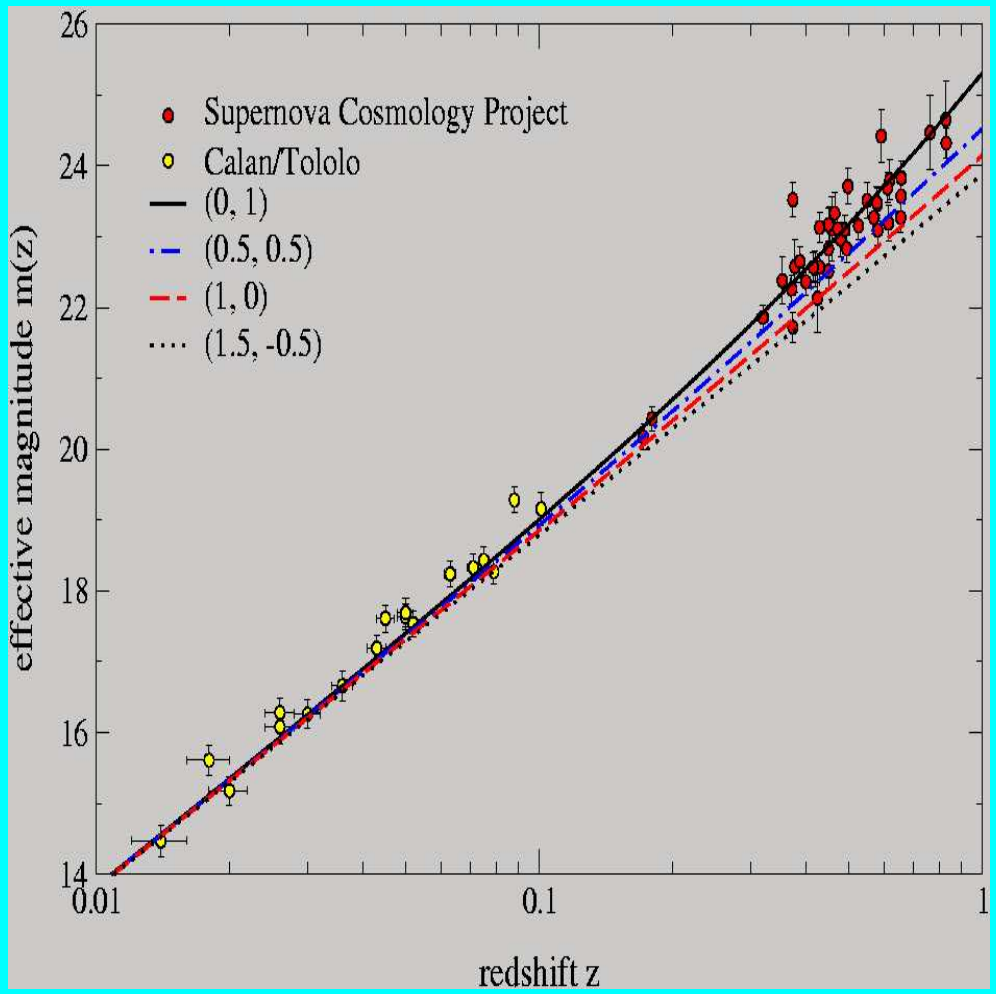


Data Analysis

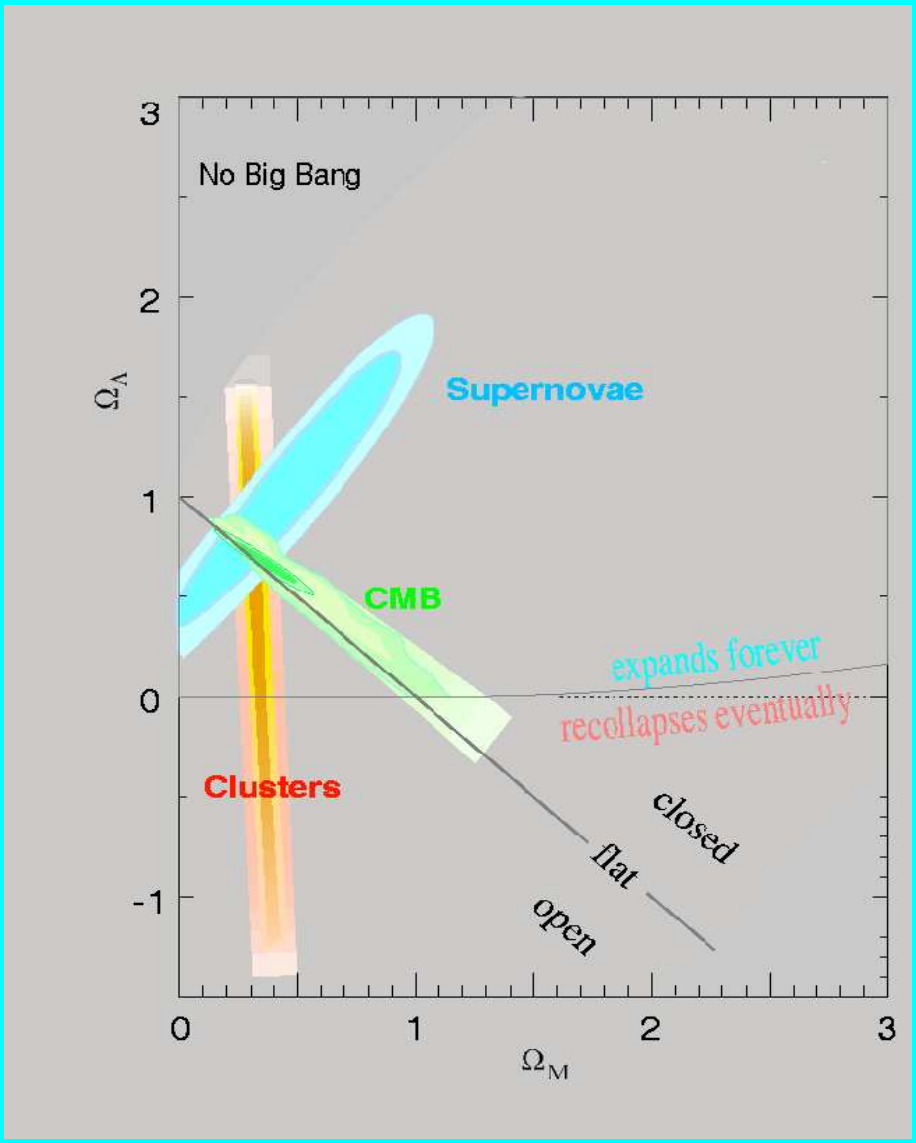


Supernovae as Cosmological Length Scales (III)

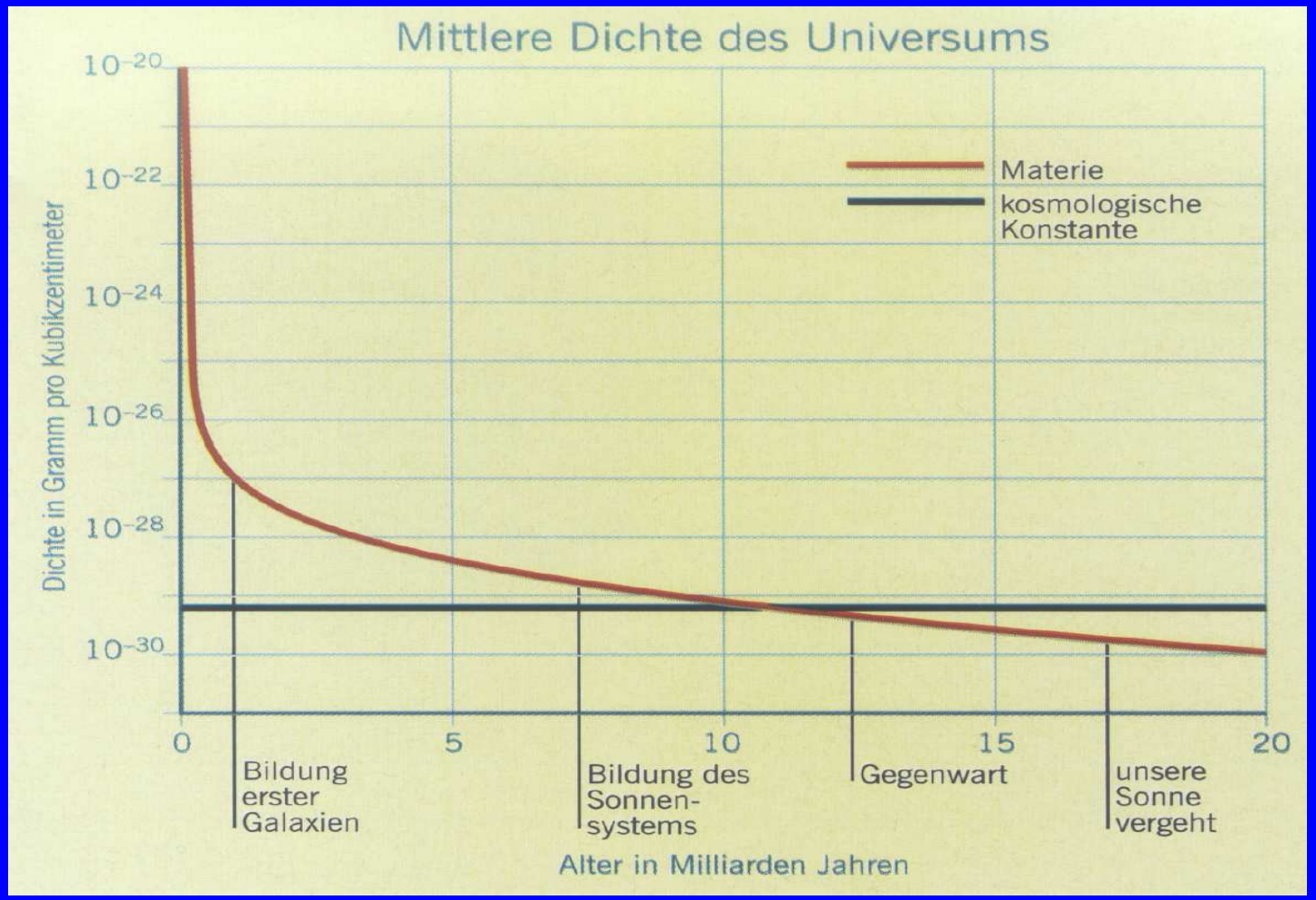
Hubble - Law



Cosmological Parameters

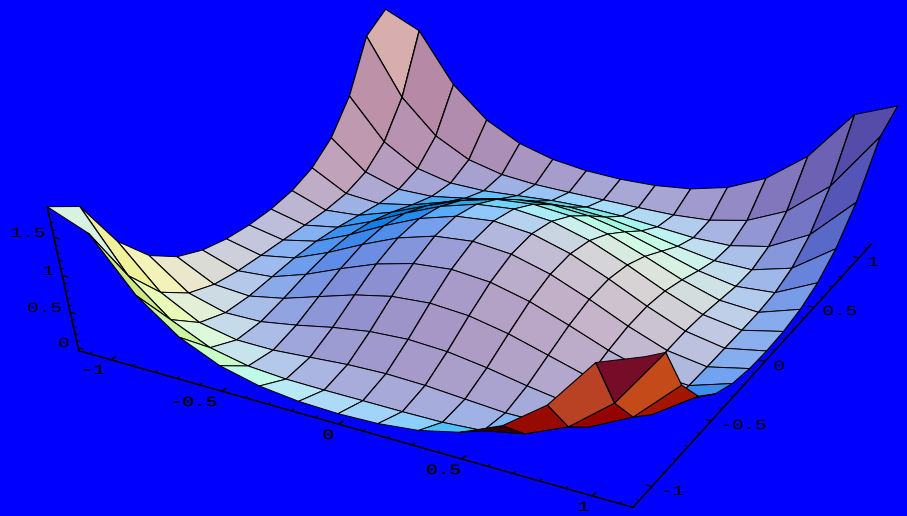


Energy Density of Matter and Vacuum



Questions: Origin of Ω_Λ? Why $\Omega_\Lambda \sim \Omega_m$ at present?

Symmetry Breaking Phase Transitions in QFT's



"Higgs-type" model field theory

$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - U(\phi)$

$U(\phi) = \frac{\lambda}{4}\phi^4 - \frac{\mu^2}{2}\phi^2$

Nontrivial Minimum of the Potential:

$|\phi_0|^2 = \mu^2/\lambda$

Gain in energy density:

$\Delta U = U(0) - U(\phi_0) = -\frac{\mu^4}{4\lambda}$

Example:

Mass scale $\mu = 200$ MeV, $\lambda = 1/2$

$\Delta U = (200\ \mathrm{MeV})^2/2 = 10^{47}$ eV cm^{-3}?

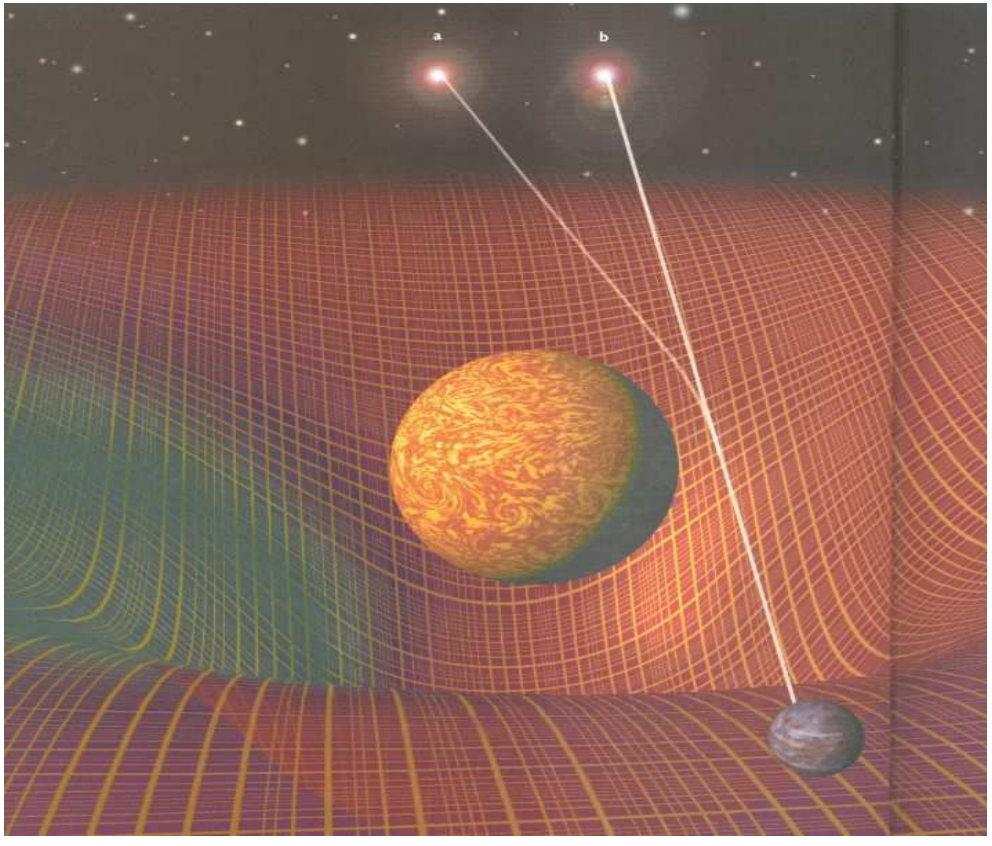
Compare:

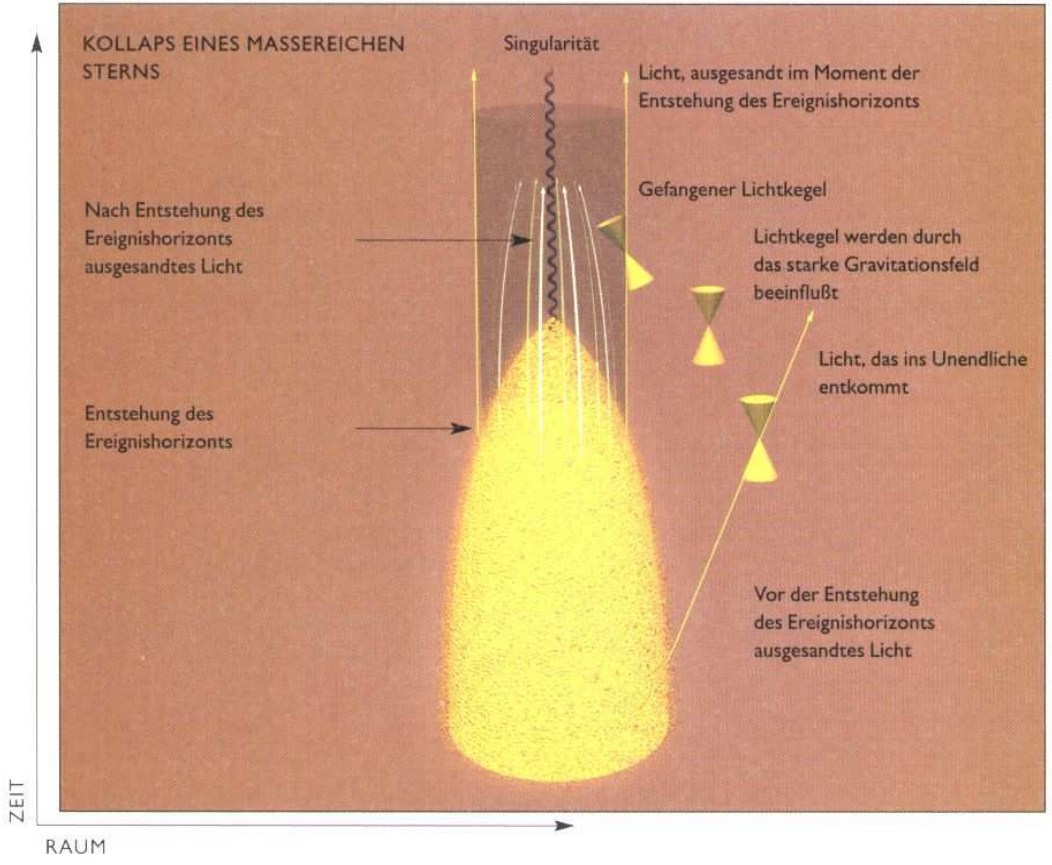
$\rho_\Lambda \sim \rho_c \sim 10^{-29}$ gcm$^{-3} \sim$ meVcm^{-3}

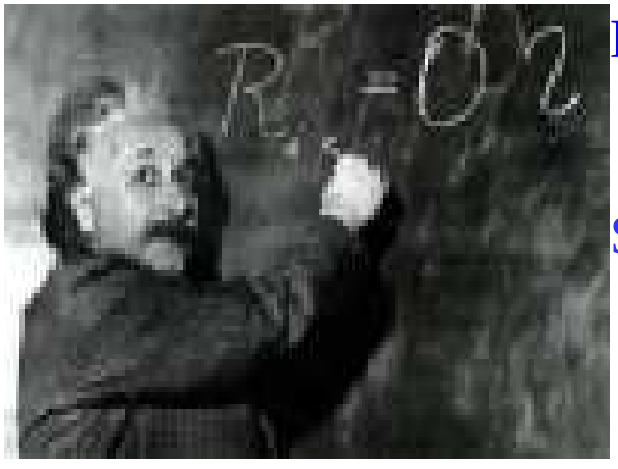
Chiral phase transition:
Quarks acquire mass!

Is there a symmetry breaking transition with the energy density scale $\mathcal{O}$ (meV cm^{-3}) ??

What lesson from Black Holes in this context ?







Einstein's Field Equations of General Relativity (1916)

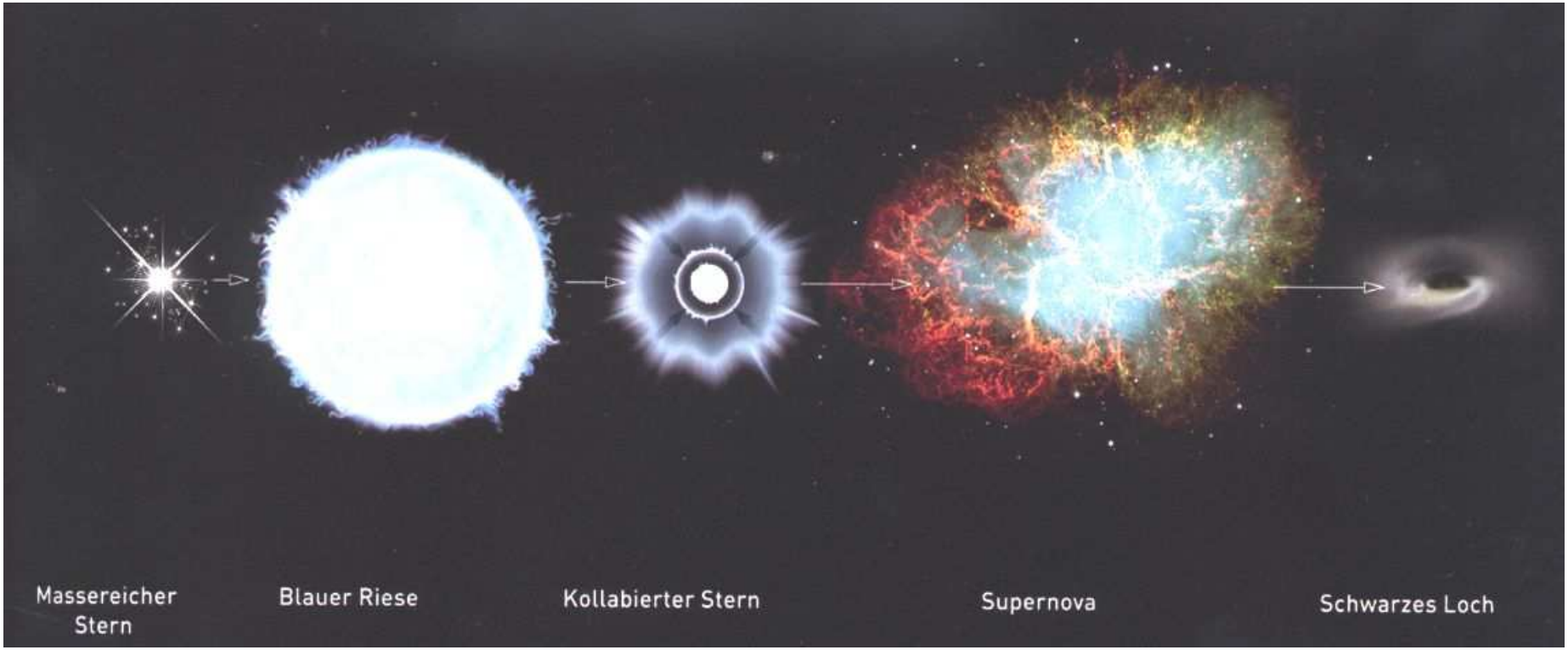
$$(\text{Space} - \text{Time}) \quad G_{\mu\nu} = 8\pi G\, T_{\mu\nu} \quad (\text{Matter})$$

Schwarzschild-Metric for Spherical Mass Distribution

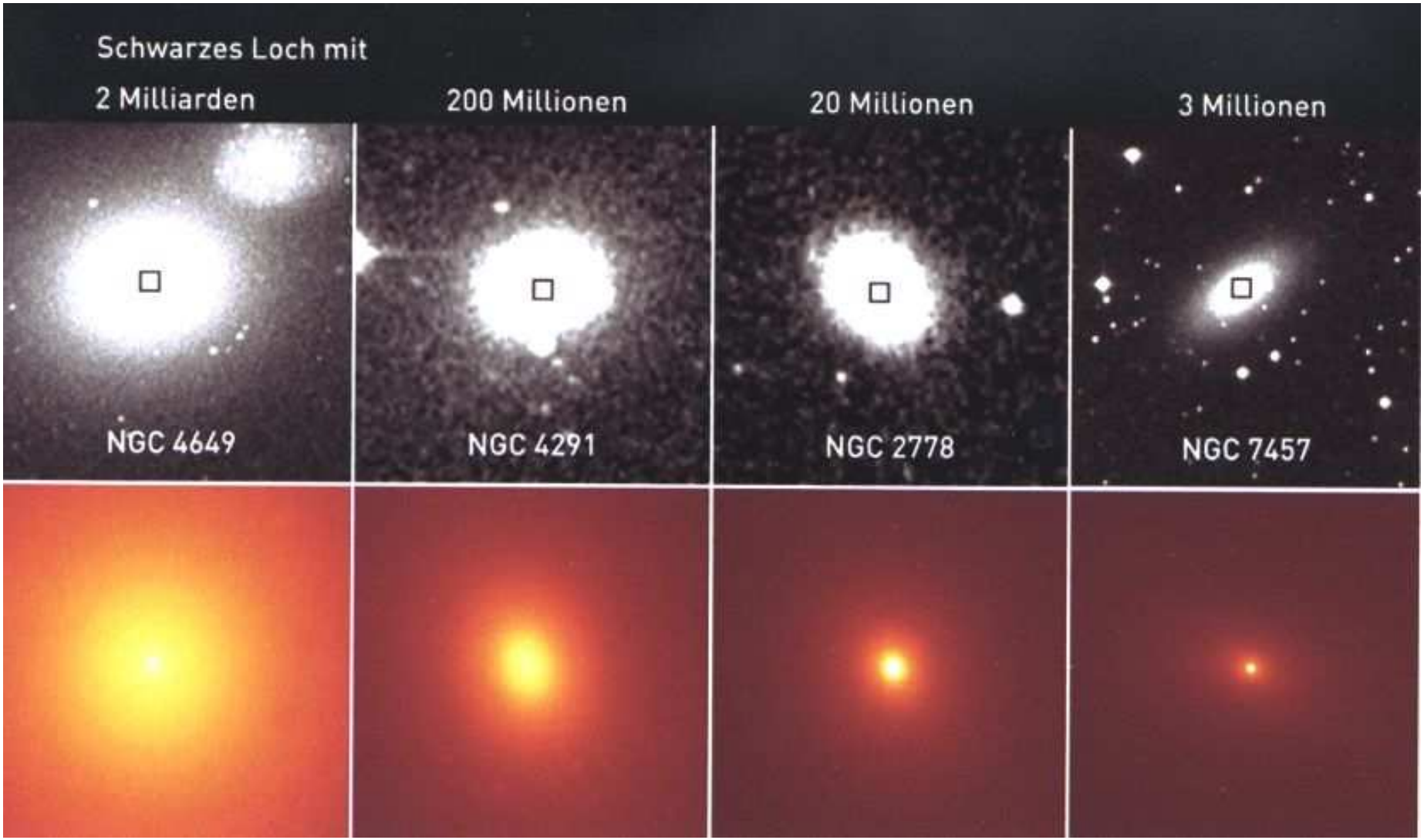
$$ds^2 = -(1 - \frac{2GM}{r})dt^2 + (1 - \frac{2GM}{r})^{-1}dr^2 + r^2 d\Omega^2$$

Where are the Black Holes ?

Stellar Black Holes - Final Stages of Stellar Evolution

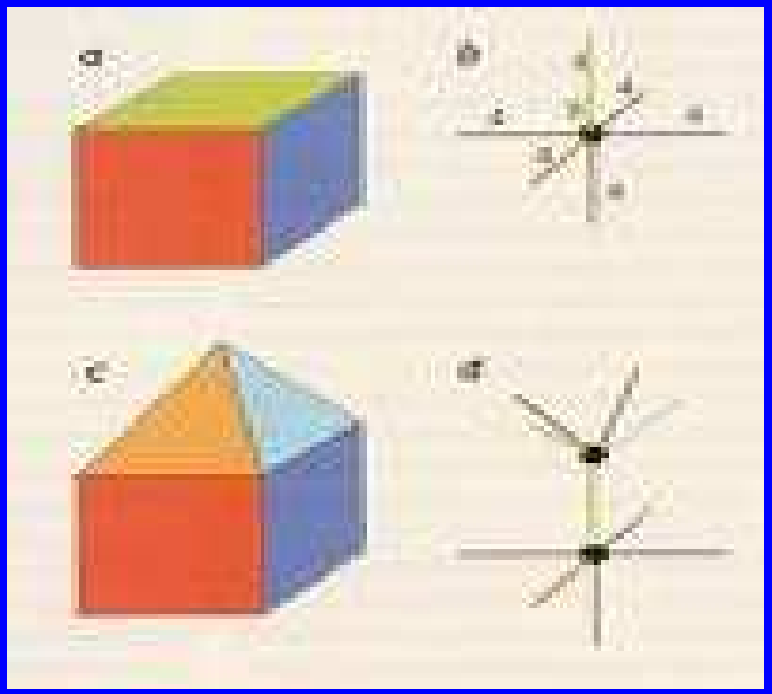


Supermassive Black Holes - Active Galactic Nuclei



... also in the Center of our Milky Way !

Quantum Gravity: Spin-Foam Networks



Mass-Information equivalence

$M = I\hbar/(6\pi\ c\ R\ k_B)$
I - number of Q-bits
R - Ricci curvature scalar

T.+B. Görnitz (Spektrum, 2002)
"Der kreative Kosmos - Geist
und Materie aus Quanteninformation"

Bekenstein-Hawking entropy:
$S_{BH} \approx 1.07 \times 10^{77} k_{\mathrm{B}} (M/M_{\odot})^2$
Black hole entropy = Information loss!

Problem: Which degrees of freedom?
Statistical, microphysical foundation?

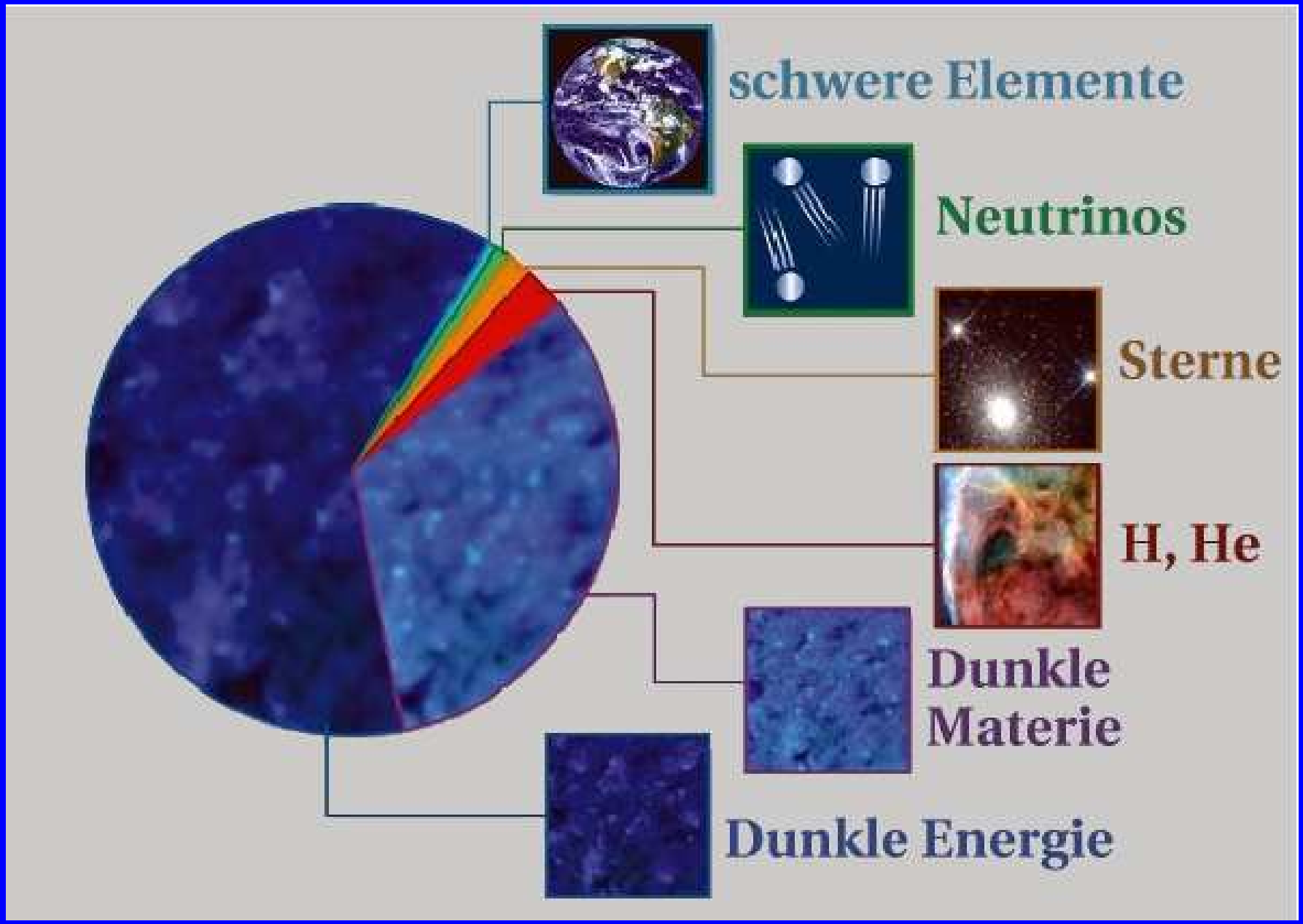
Lee Smolin, Carlo Rovelli, et al.
Holographic principle
Entropy of Black Holes reconstructed from their horizon surface A by decomposition into plaquettes of the squared Planck length $l_{\mathrm{P}} = 1.62 \times 10^{-35}$ m
$S_{BH} = k_{\mathrm{B}} A/(4 l_{\mathrm{P}}^2)$

C. Kiefer, G. Kolland: arXiv:0707.0615
Gibbs' paradox and black-hole entropy

C.F.v. Weizsäcker: Quantum Theory of Elementary Particles reconstructed from binary alternative U_r ("Qbit")

T. Görnitz: Int. J. Theor. Phys. (1988)

The Composition of the Universe



Summary of Results

- Age of the Universe: 13.7 Billion years (1% Error)
- First Stars ignite 200 Million years after the Big Bang
- Background Radiation decouples 379 000 years after the Big Bang
- Composition of the Universe:
  - 4% Atoms, 23% Cold Dark Matter, 73% Dark Energy
  - Interpretation of the Dark Energy unclear!
    Mystery: Origin of "Cosmological Constant" or "Quintessence"??
- Hubble-Constant: $H_0 = 71$ km/s/Mpc (5% Error)
- Evidence for Inflation (early and late-time exponential growth)
- Expansion of the Universe: probably eternal ...
- Falling Temperature $\rightarrow$ Interaction dominates over Kinetic Energy
  $\rightarrow$ Dark Energy dominates over everything!
- Structures form at ever-smaller Energy-Scales