Rosat and Cosmology

Sergei Bobrovskyi (RB-CA)
RB-Seminar
Oberpfaffenhofen, Nov 2012

DLR

Outline

- Introduction to Cosmology
- Galaxy Clusters
- X-Ray Astronomy
- ROSAT Mission
- ROSAT Results and Cosmology
- Future Missions
- Summary

Preamble: Units and Conventions

- Theoretical cosmologists are working in the units of particle physics
- We will employ „natural units“ defined by:

$$\hbar = c = k_B = 1$$

meaning that all physical quantities can be expressed in terms of eV

- [Energy] = [Mass] = [Temperature] = eV
- [Length] = [Time] = eV^{-1}
- 1 eV of temperature is 1.16×10^4 K

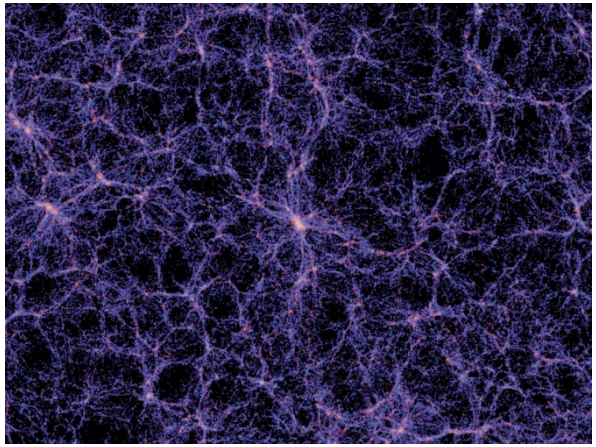
Introduction to Cosmology

Einstein‘s Field Equations (EFE)

- Study of the composition, structure, and dynamics of the whole universe
- Based upon the general theory of relativity (Einstein 1915):

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

-Cosmological Principle: *The universe is spatially homogeneous and isotropic on large scales*
(justified on scales > 100 Mpc)



Introduction to Cosmology

Friedmann-Lemaître-Robertson-Walker Metric

- Exact solution to EFE can be found assuming homogeneity and isotropy of space. A solution of EFE is called a *metric* – it describes the geometry of spacetime (tells how to measure distances)

- In FLRW universe the geometry is determined by one function of time called *scale factor* $a\,(t)$ and one constant k describing the spatial geometry (values: +1, 0, -1)

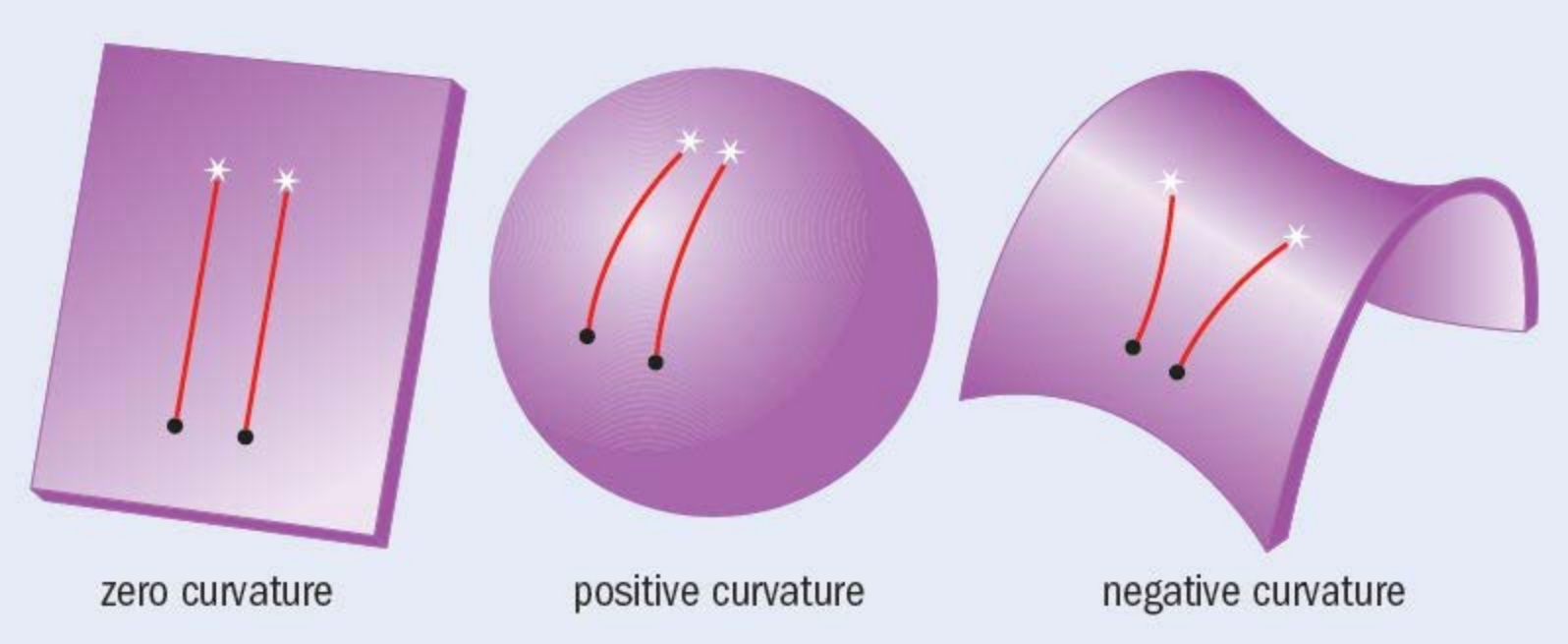
$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1 - k\,r^2} + r^2 d\Omega^2\right]$$

- $a\,(t)$ describes the expansion (contraction) of the universe (in our case: expansion discovered by Hubble in 1929)

- k can be determined from observations

Introduction to Cosmology

3-Dimensional Geometry



$k = 0$ $k = 1$ $k = -1$

Introduction to Cosmology

Friedmann Equation(s) and Cosmological Parameters

- Determination of $a\,(t)$ from: EFE + energy-momentum conservation + equation of state for all energy forms present in the Universe
- RW metric + EFE ⇨ Friedmann equation:

$$\Omega - \Omega_k = 1$$

- Ω : cosmological parameter defined as the total energy density of the universe divided by critical energy density (here function of time)

$$\Omega = \Omega_m + \Omega_r + \Omega_?$$

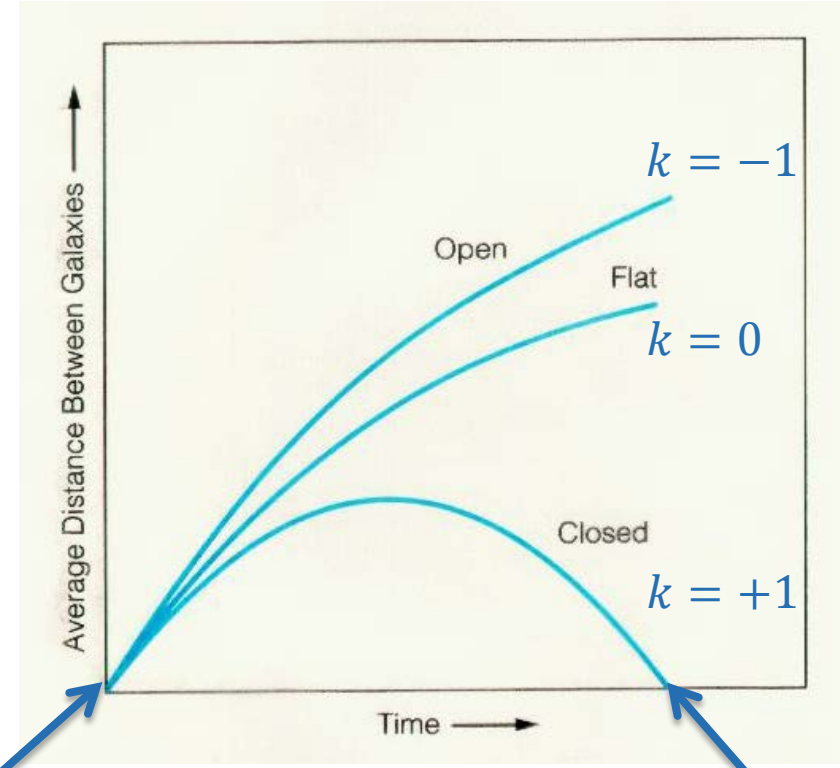
m: matter, r: radiation, ?: exotic components

- Ω_k : similar parameter proportional to the spatial curvature k

- Therefore:
  - $k = 0 \quad \Rightarrow \Omega = 1$ flat universe (Euclidean geometry)
  - $k = +1 \Rightarrow \Omega > 1$ closed universe (3d sphere)
  - $k = -1 \Rightarrow \Omega < 1$ open universe (hyperbolic geometry)

Introduction to Cosmology

The Scale Factor



Big Bang

Big Crunch

Assuming reasonable matter content – matter domination:

$$\Omega = \Omega_m$$

$$p = 0 \quad \text{(EoS)}$$

Introduction to Cosmology

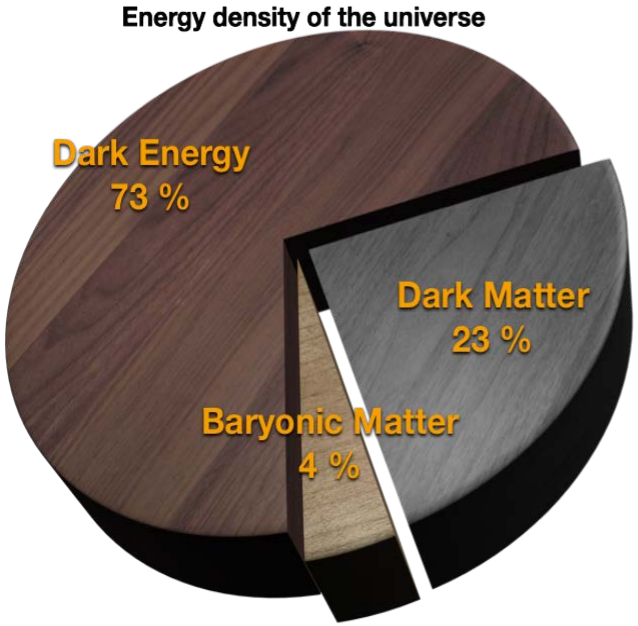
Current Status

Existence of Dark Energy (SN Ia, Nobel Prize 2011)

$\Omega_? = \Omega_\nu$

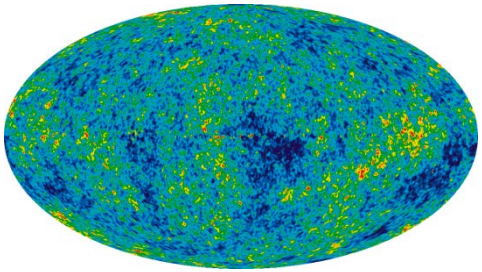
$p = w\rho$

$w < 0$!!!



Flat universe: $\Omega = 1$ (CMB)

Existence of Dark Matter



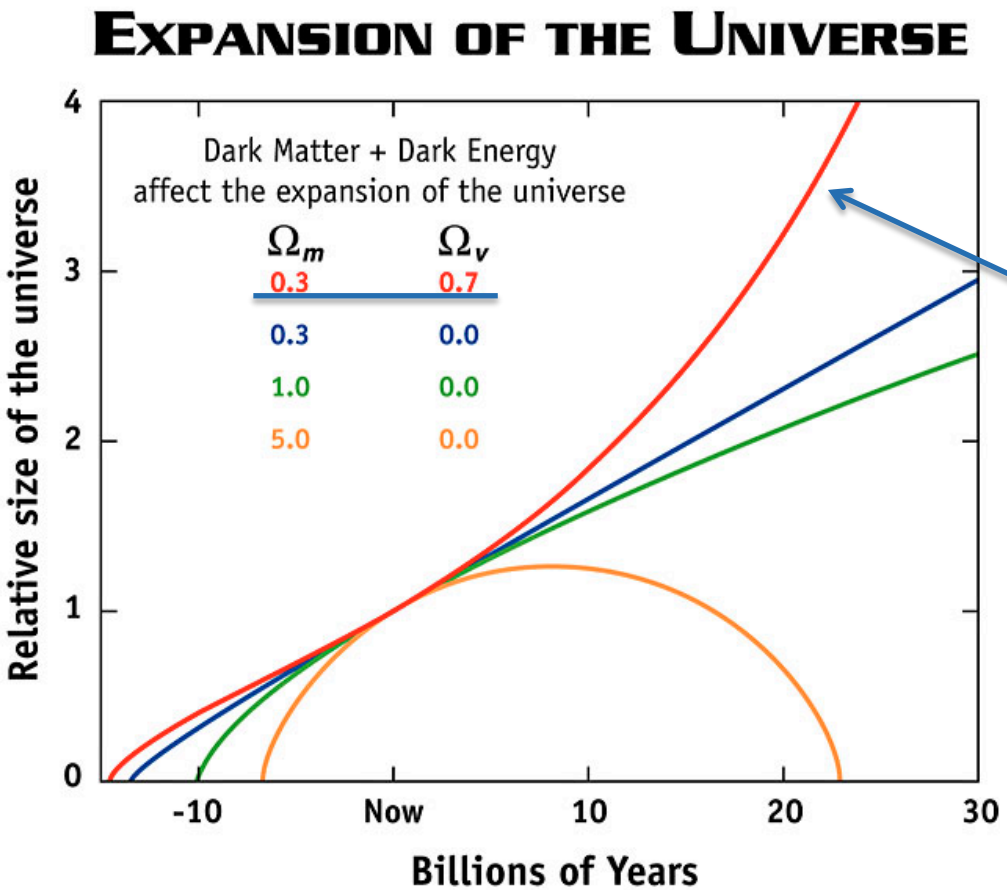
$\Omega_m \approx \Omega_{DM}$

Additional Puzzle: Matter-Antimatter asymmetry

DLR

Introduction to Cosmology

Dark Energy



Accelerated (exponential) expansion of the universe due to Dark Energy

Note that Ω_m and Ω_v from now on denote the values of parameters at current time

What is Dark Energy ?

- The nature of Dark Energy is still unknown and is one of the largest mysteries in cosmology.

- While Dark Matter could be detected in various experiments – Underground direct detection experiments, signatures at the LHC, gamma-rays from annihilation or decays – Dark Energy can probably be only accessed via its influence on the history of the Universe

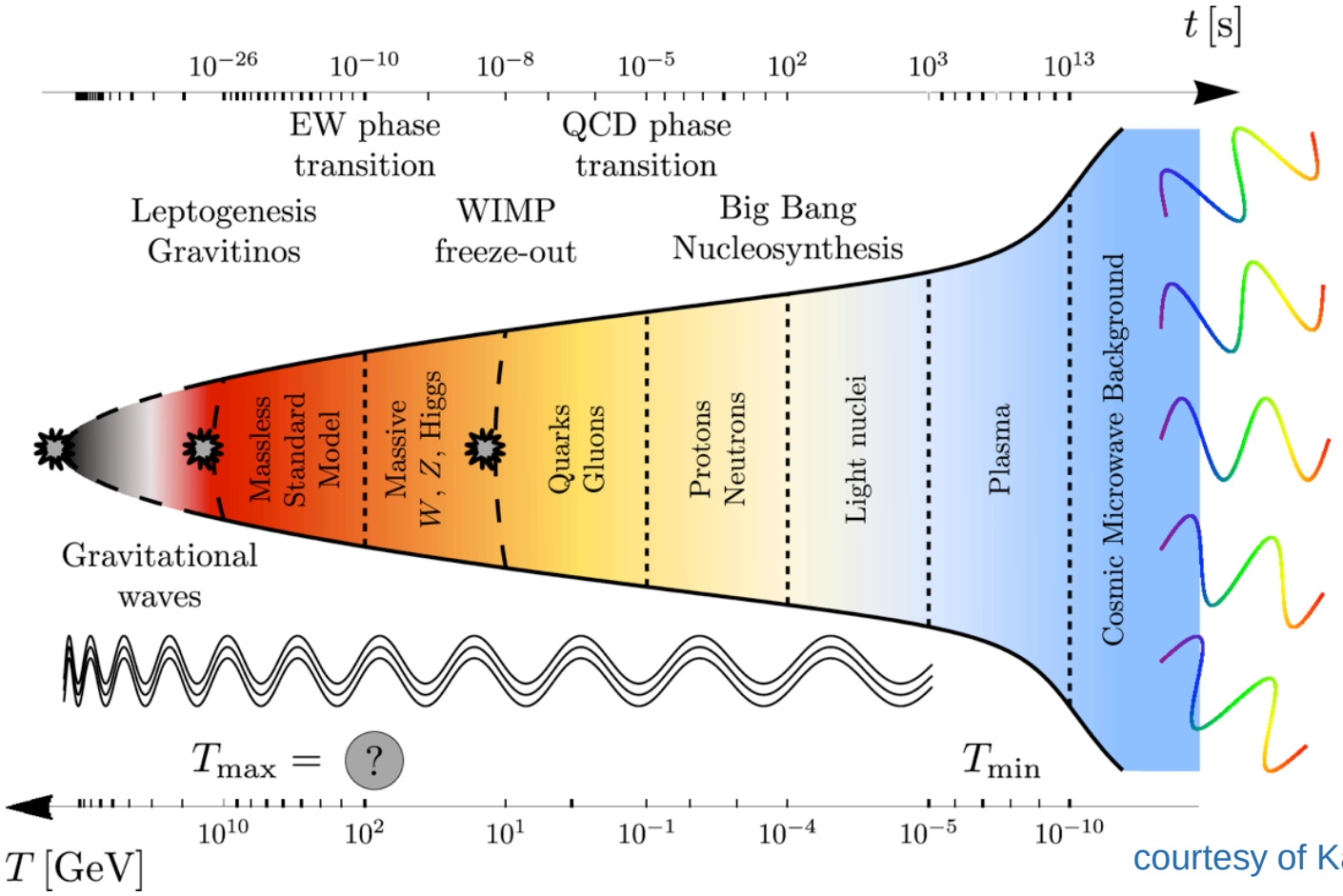
- One has to determine the value of the equation of state parameter w and to trace its evolution

- Constant value of -1 is compatible with the idea of DE as cosmological constant (proposed and later abandoned by Einstein). However, is it the energy of the vacuum?– Cosmological Constant Problem

- Evolution of w could point to a new force and the long-term future of the Universe is unknown in this case

Introduction to Cosmology

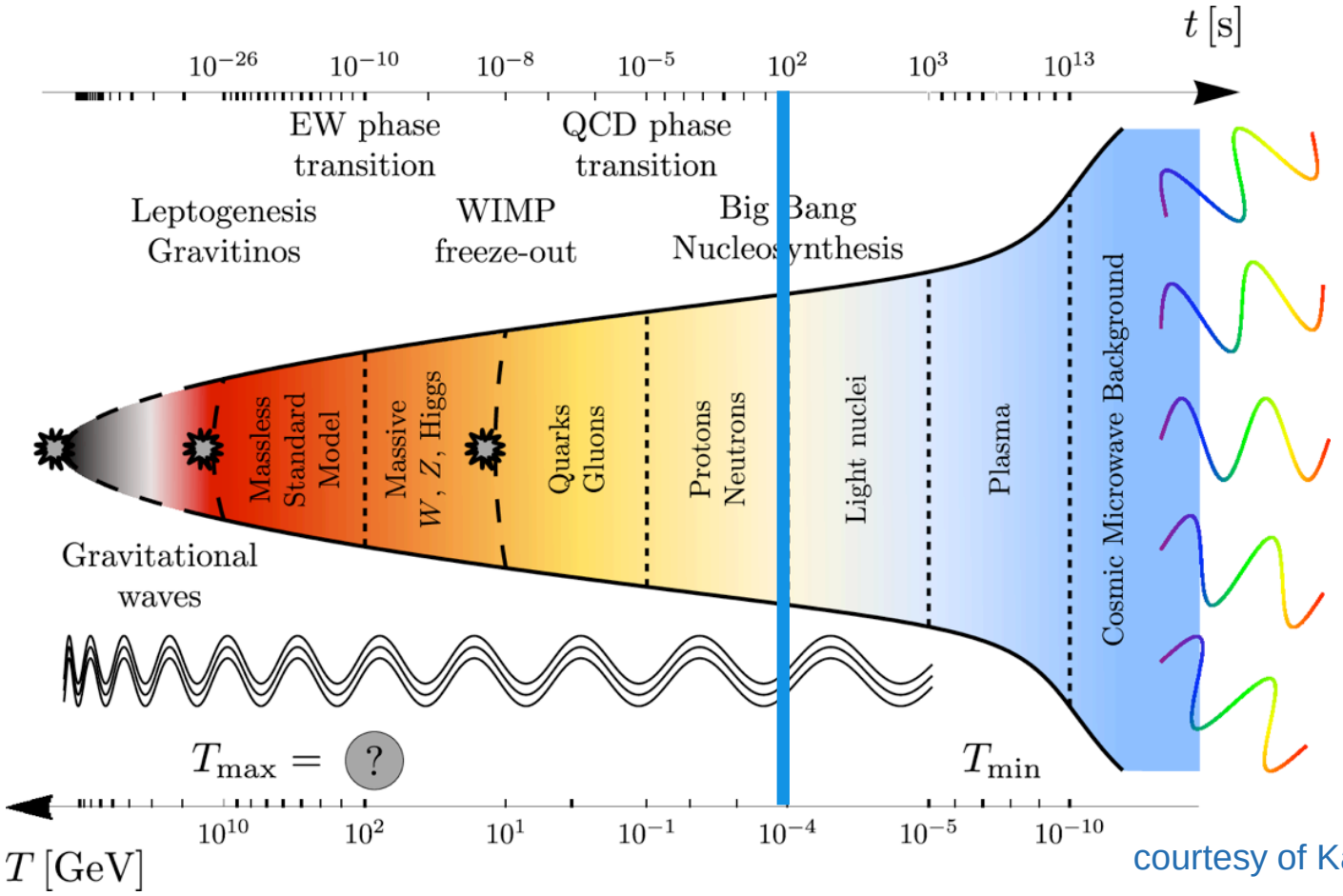
History of the Universe



courtesy of Kai Schmitz

Introduction to Cosmology

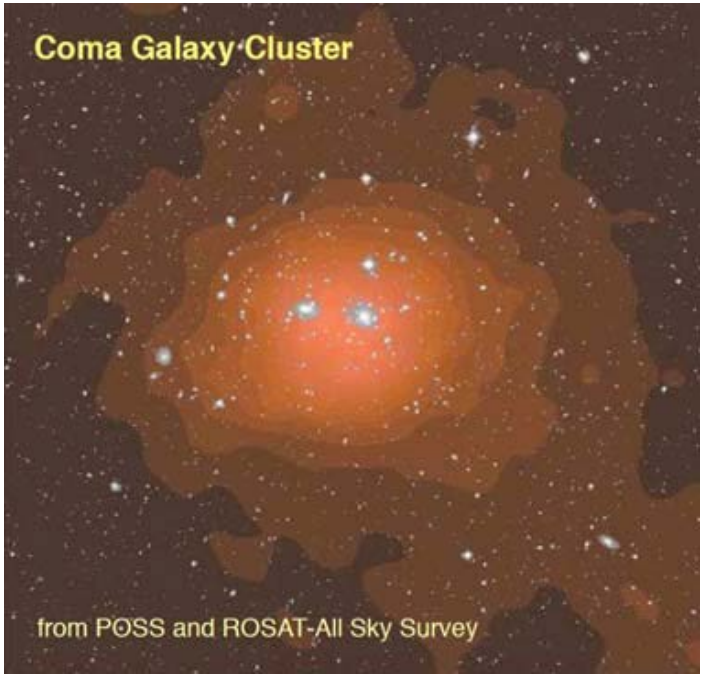
History of the Universe

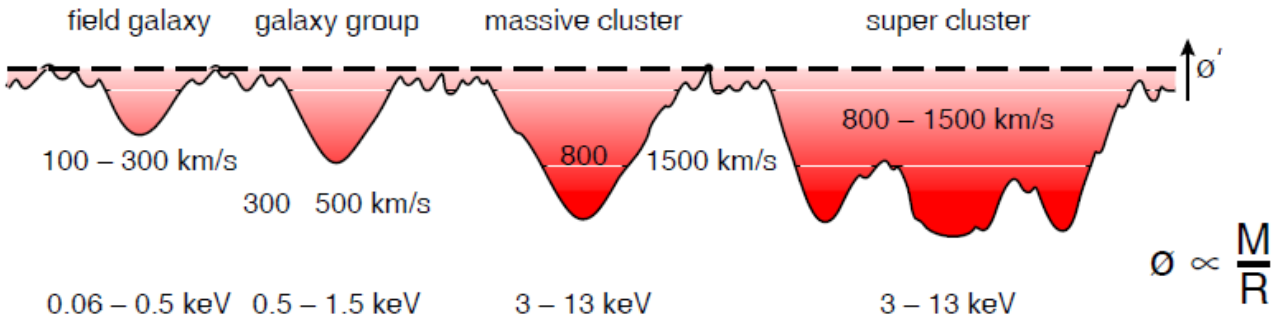


courtesy of Kai Schmitz

Galaxy Clusters

- Structural hierarchy of the Universe: Stars, Galaxies, Clusters of Galaxies
- GC are the largest objects in the Universe characterized by their own proper equilibrium structure accessible to observations and theoretical modeling





Böhringer, in The Universe in X-rays, 2008

Galaxy Clusters

Galaxy Clusters and Cosmology

- Galaxies in GC are gravitationally bound and in dynamical equilibrium. Application of the virial theorem to GC led Fritz Zwicky to the postulation of the missing mass (DM) already in the thirties

- Assessment of the cluster mass and comparison with the mass of the visible ingredients provides independent conf. of DM on the cluster scale.

- GC grew from the primordial density perturbations. Thus, their statistics is governed by the cosmological parameters.

- Constrains on cosmological models from:
    - Cluster abundance at present (Ω_m, amplitude of matter-density fluct.)
    - Statistics of the spatial distribution of clusters
    - The evolution of the cluster abundance (Access to Dark Energy)

X-Ray Astronomy

X-Rays from Galaxy Clusters

- One of the most important discovery of UHURU X-Ray observatory: X-rays from GC

- Diffuse emission from hot gas trapped inside of the grav. potential radiating away its energy in X-rays ($T \sim 2 - 15\ keV$)

- This intracluster medium (ICM) fills the whole volume and provides a contiguous picture of the cluster structure

- X-ray observations allow for determination of : ICM density, ICM temperature, shape of the spectrum and then also the full gravitating mass of the cluster (mass profile), the gas mass and thus DM

- GC : one of the main targets of X-ray astronomy

X-Ray Astronomy

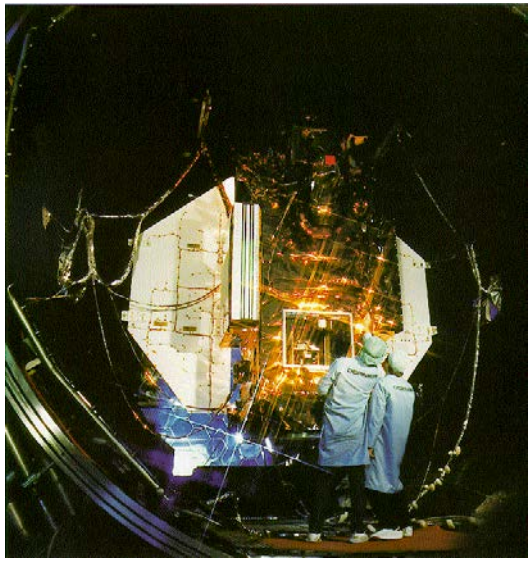
Important Missions

UHURU: 1970-1973

Einstein: 1978-1981

(first fully-imaging

X-ray telescope)



ROSAT: 1990-1999

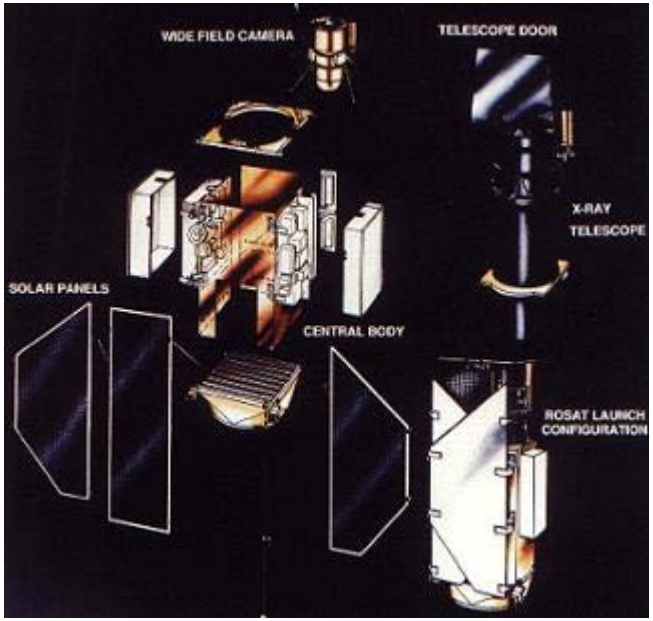
Chandra: 1999-present

XMM-Newton: 1999-present

ROSAT (ROentgenSATellit)

- German/US/UK Mission:

dimension (launch configuraion)	2,38 × 2,13 × 4,50 m³
total mass	2426 kg
payload mass	1555 kg
power consumption - sun phase - eclipse	 905 W 337 W
available power	1.000 W
data rate	700 Mbit pro 21 h

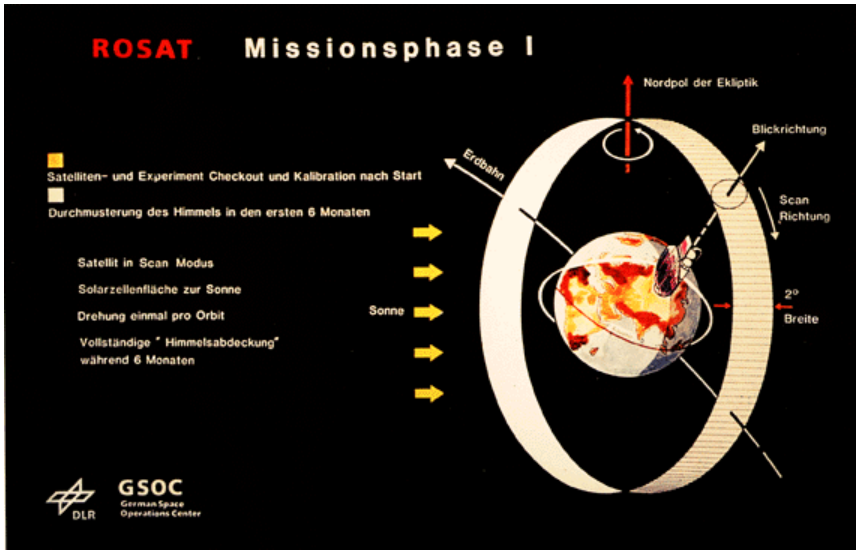


- Scientific Payload:
  - Large X-ray telescope (XRT) measuring soft X-rays 0.1: keV – 2 keV, X-ray detectors : 2 position sensitive proportion counters, 1 high resolution imager (HRI)
  - Wide Field Camera (WFC) measuring in extreme ultraviolet 0.04 keV– 0.2 keV

DLR

The ROSAT Mission

orbit	580 km circular
- inclination	53 °
- max. eclipse	36 min
ground station contacts	6 × 8 min/day
6 month all-sky survey	discovery of more than 150.000 X-ray objects
more than eight years pointed mission	detailed investigation of selected X-ray sources, guest observers programme



- ROSAT was operated by GSOC
- Carried out the first complete survey of the sky with an imaging X-ray telescope (also the last X-ray all-sky survey up to now)
- The deepest of the pointed observations could resolve the majority of the Cosmic X-ray Background (CXRB) into individual sources

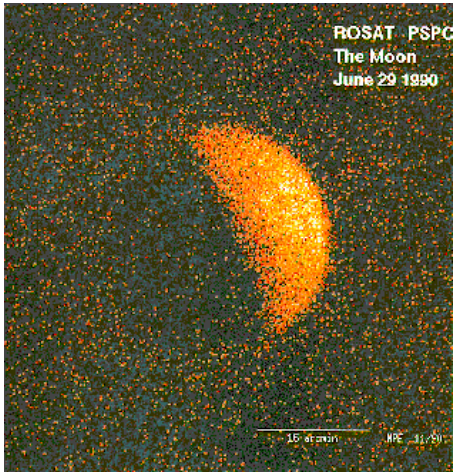
ROSAT Results

Astrophysics

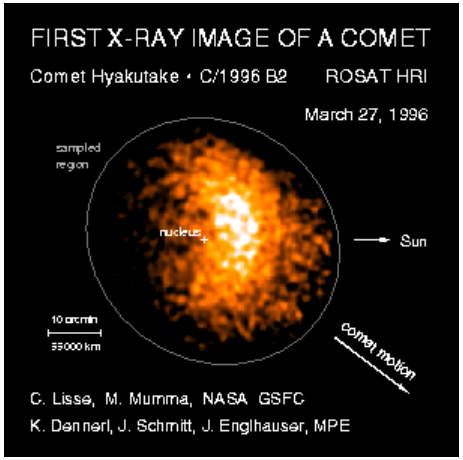
- First X-rays from the Moon, the weakest known non-terrestrial X-ray source (expected already from UHURA)

- Detection of the X-ray emission from comets for the first time (new emission mechanism)

- Classification of Geminga as pulsar due to the ROSAT detection of the 237 ms pulsation (Gemini gamma-ray source, discovered 1975)



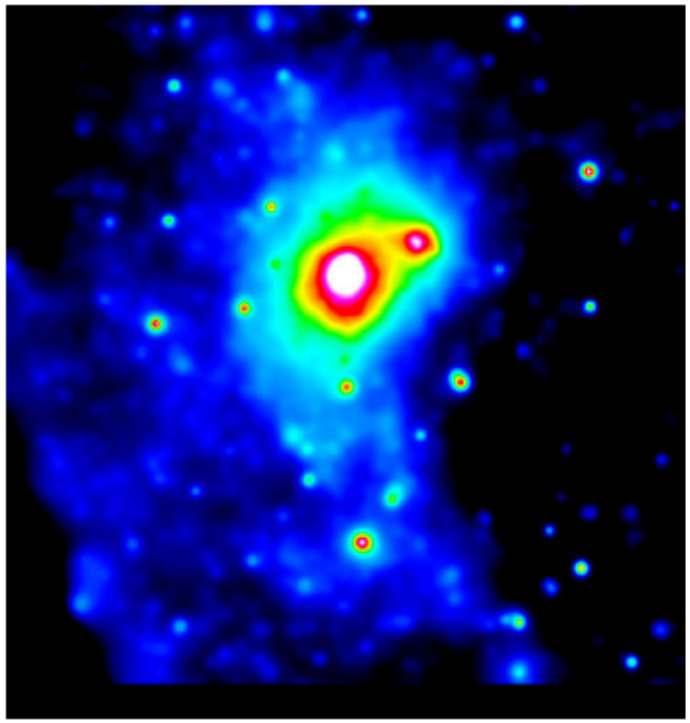
Schmitt et al., Nature, 1991

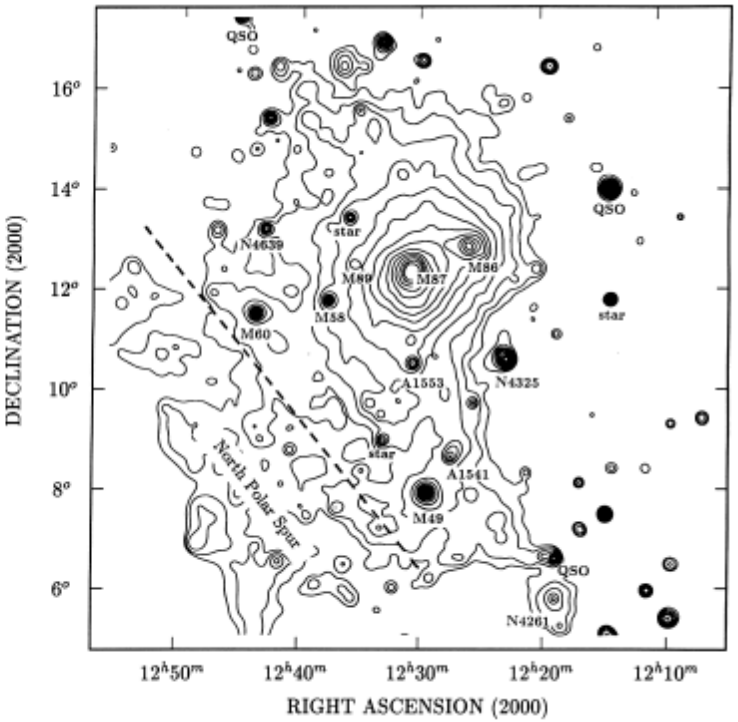


Dennerl et al., Science, 1997

ROSAT Results

The Structure of the Virgo Cluster





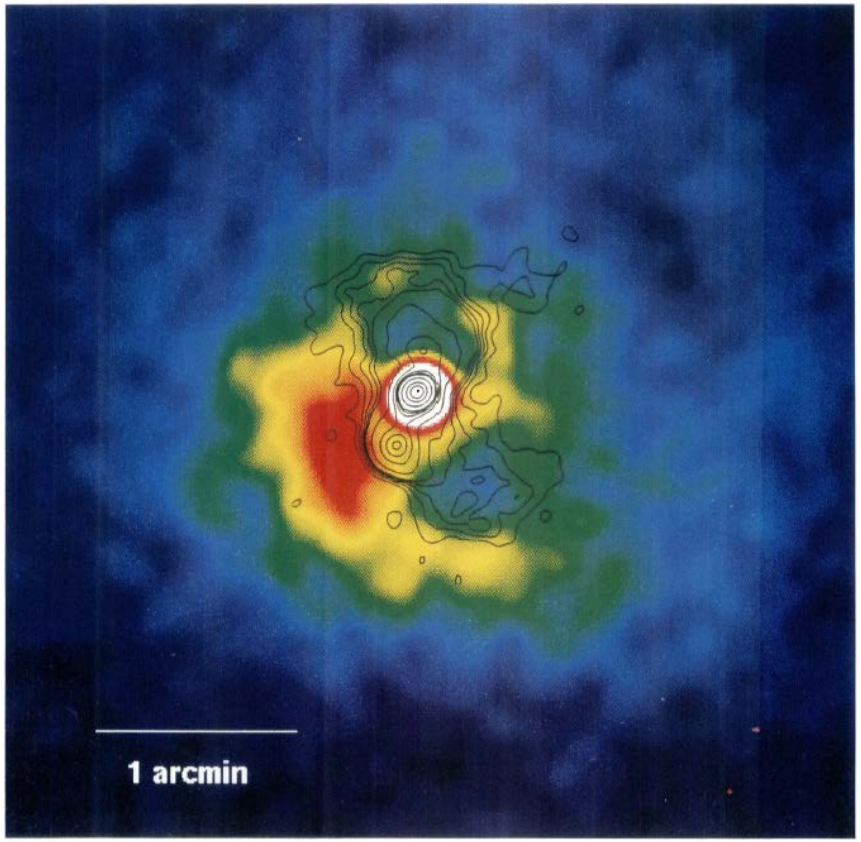
Böhringer et al., Nature, 1994

- Nearest large constellation of galaxies, gas tracing DM shows that DM is distributed like the galaxies

ROSAT Results

Radio Lobes of the Perseus Cluster

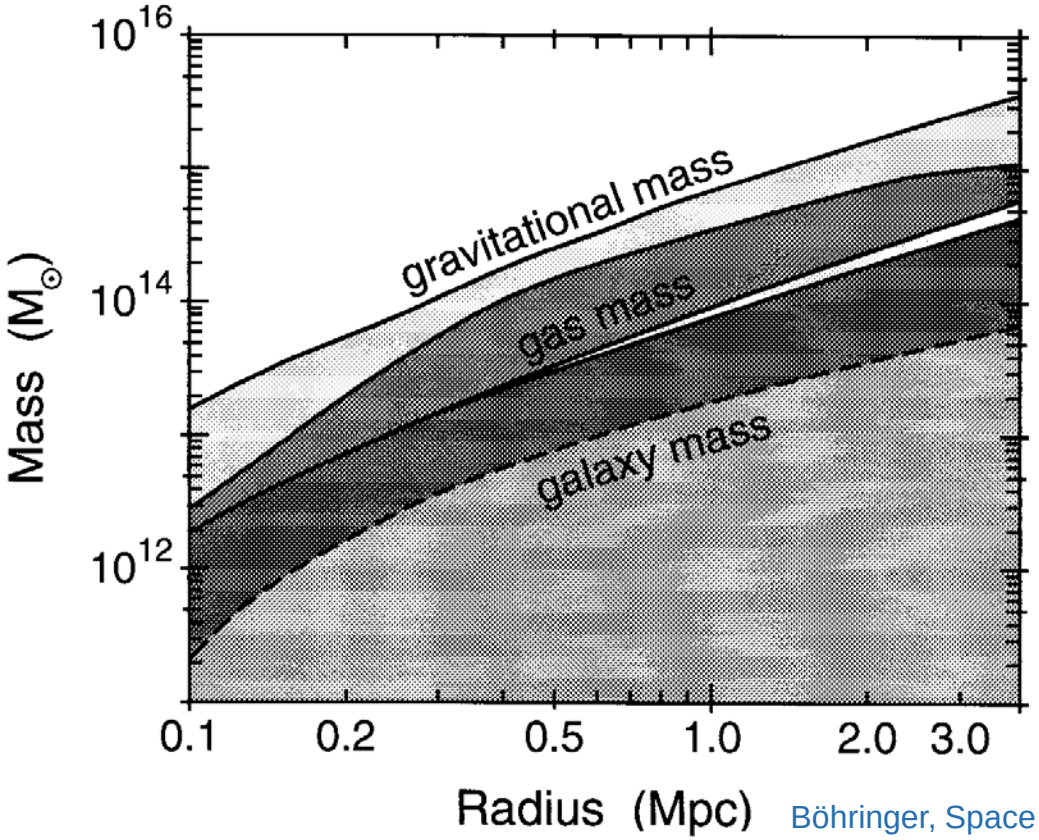
- Study using the ROSAT HRI, best X-ray imaging detector of that time
- Radio emission (black contours in the plot) from the AGN in the central galaxy has been known before
- First clear evidence for the interaction of rel. particles in the radio lobes with X-ray emitting ICM (thermal plasma displacement)
- Strange bend in the southern radio lobe explained by collision of the inner radio lobe and the dense gas



Böhringer et al., Mon. Not. R. Astron. Soc.,1993

ROSAT Results

Dark Matter in Galaxy Clusters

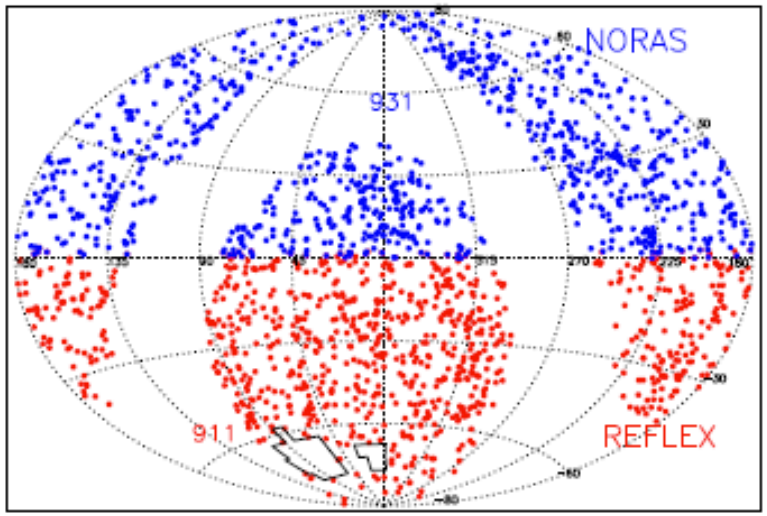


Böhringer, Space Science Review, 2002

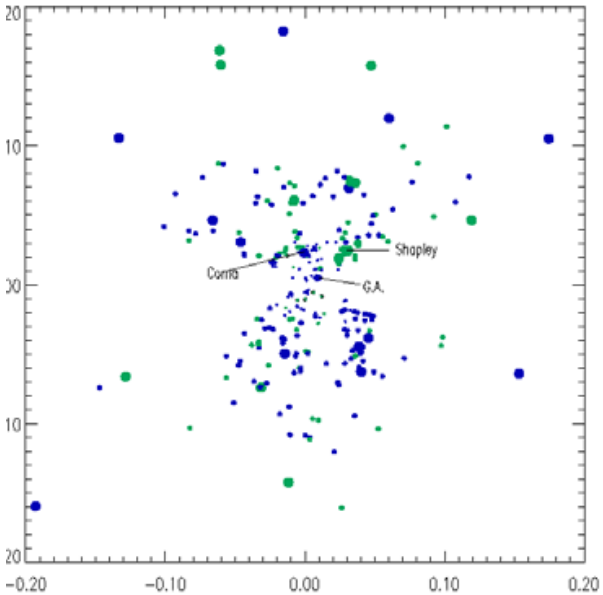
- Independent confirmation of existence of DM at cluster scales, example here: Perseus cluster

ROSAT Results

Importance of Surveys for Cosmology



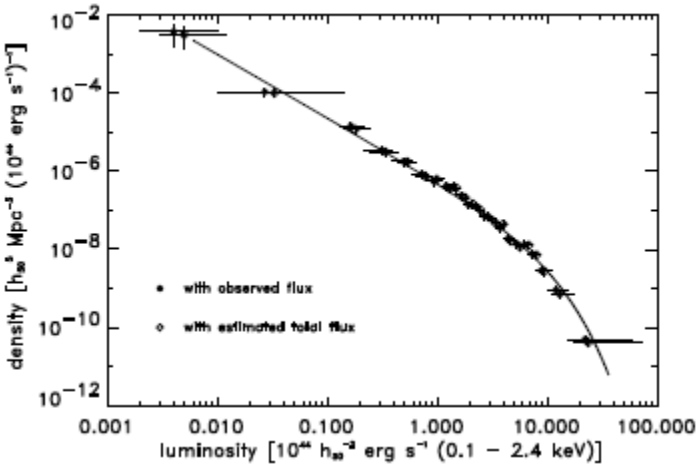
Böhringer, AIP Conf. Proc. 1381, 2011

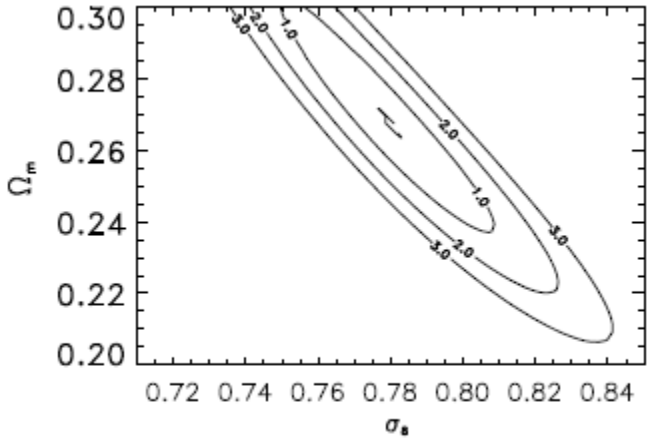


- Large samples of galaxy clusters needed for the evaluation of their statistics which provides access to cosmological parameters
- The cluster catalogues derived from ROSAT all-sky survey are the largest up to now

ROSAT Results

Cosmological Parameters I





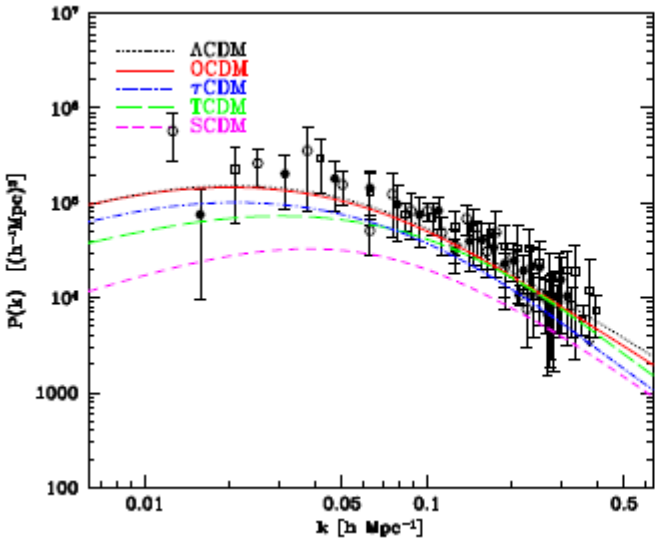
Böhringer, AIP Conf. Proc. 1381, 2011

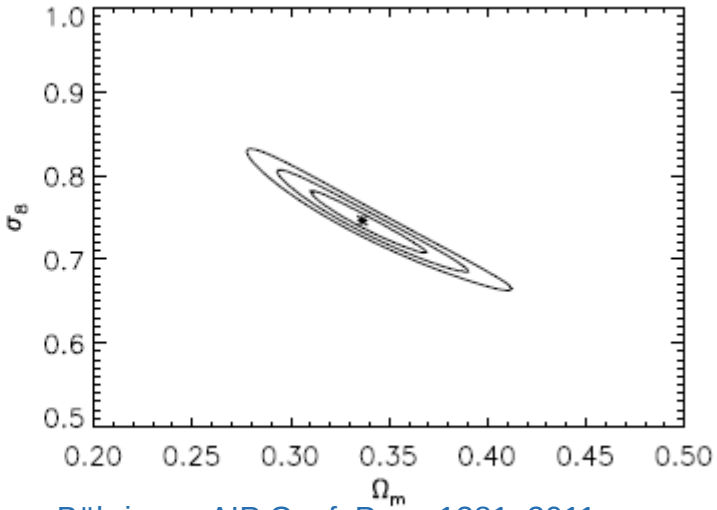
- Parameters derived from the X-ray luminosity function closely related to the mass function. We observe degeneracy in both parameters

- Note: $\Omega = 1$ (CMB first peak) and $\Omega_m < 1$ (GC) implies $\Omega_\nu \neq 0$

ROSAT Results

Cosmological Parameters II



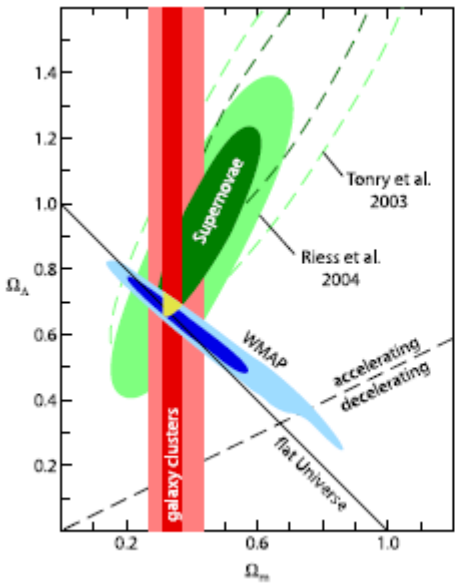


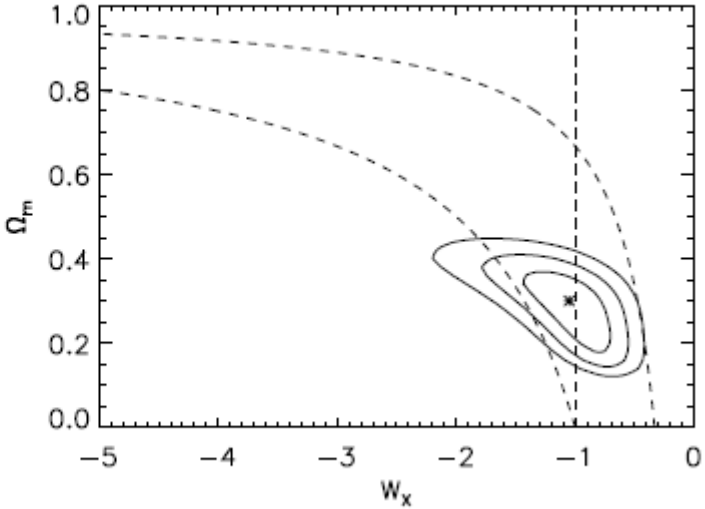
Böhringer, AIP Conf. Proc. 1381, 2011
Schuecker et al., A&A, 2001, 2003

- Parameters derived from the power spectrum of the density fluctuations
- The maximum of the PS reflects the size of the horizon when the energy densities of radiation and matter in the Universe were equal
- The degeneracy between cosmological parameters has been reduced

ROSAT Results

Combined Results on Cosmology



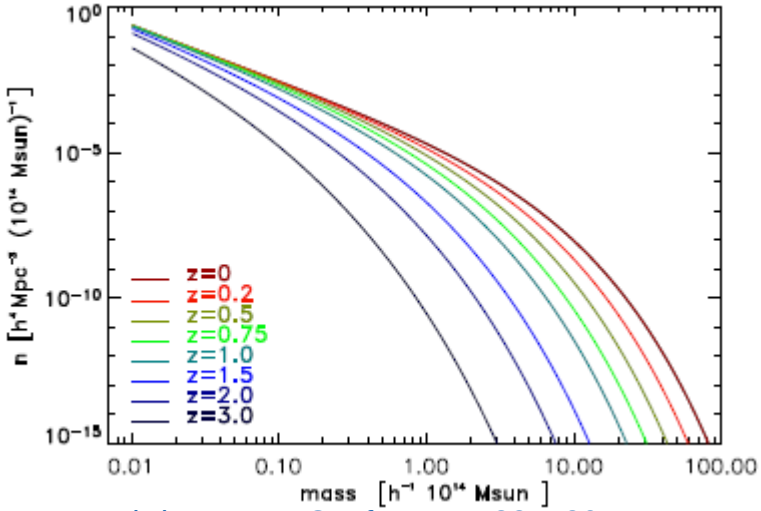


Böhringer, in The Universe in X-rays, 2008
Schuecker et al., A&A, 2003

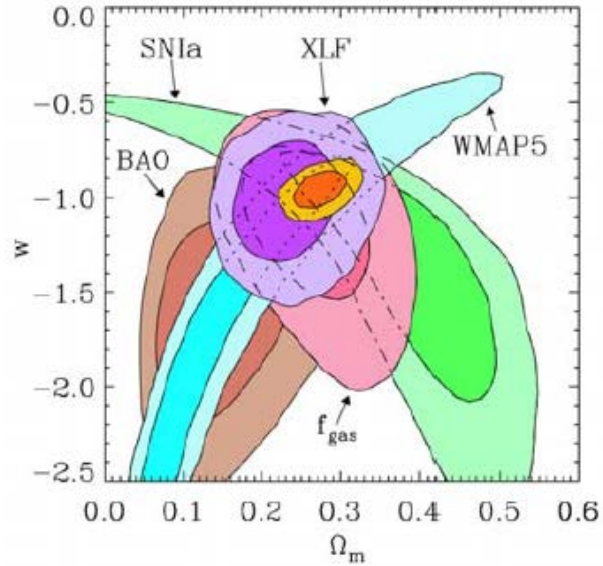
- Only clusters in a narrow redshift range (0-0.2) have been used – a snapshot of the present epoch
- Constraints obtained from different methods meet in a single region.
- Clusters + Supernovae alone can provide constraints on cosmological parameters

ROSAT Results

Combined Results on Cosmology: Dark Energy



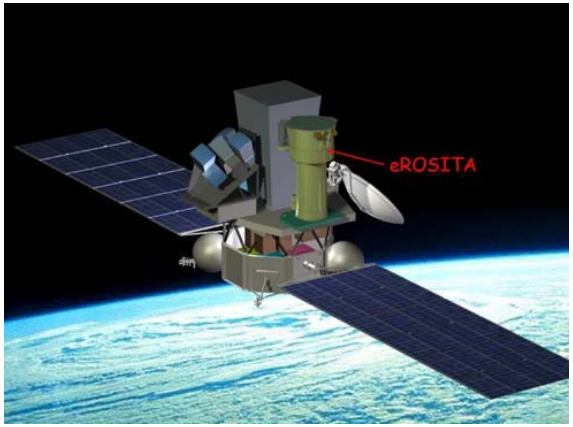
Böhringer, AIP Conf. Proc. 1381, 2011
Mantz et al., MNRAS, 2010



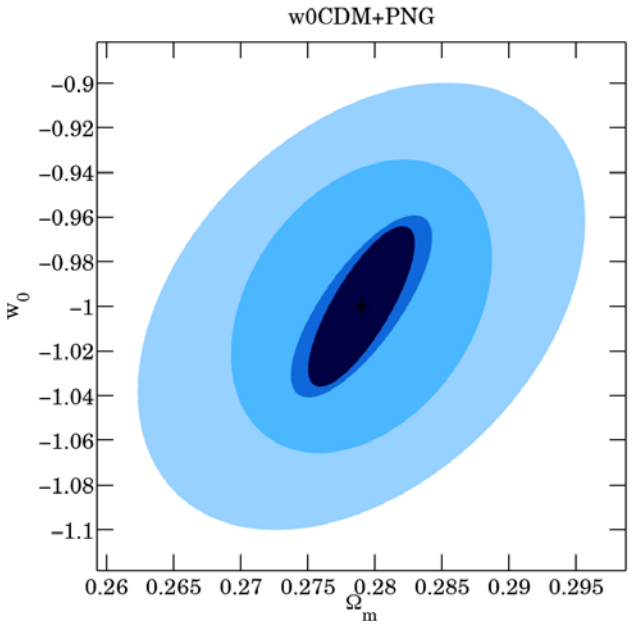
- Redshift evolution of the cluster population needed for a study of Dark Energy

- One could use some very luminous clusters from RASS at z=0.3 - 0.5 but the number of clusters is very small

Future Projects



Böhringer, AIP Conf. Proc. 1381, 2011



Merloni et al.,arXiv:1209.3114, 2012

- ROSAT follow-up mission using modern mirror design from XMM-Newton, ABRIXAS, failed in 1999 because of design failure in power supply
- Sample of 100 000 clusters needed for stringent constraints on the cosmological model - modification of ABRIXAS design - eROSITA project
- German eROSITA instrument on the Russian Spektrum-Roentgen-Gamma satellite – expected launch in 2014

Summary

- We are living in the age of precision cosmology
- Observations point to a flat universe filled with 70 % Dark Energy and 30% Dark Matter
- The German-led ROSAT mission was an incredibly successful X-ray telescope providing independent information on cosmological parameters
- The German eROSITA instrument will be the first next generation mission for the exploration of Dark Energy

Acknowledgements

I would like to thank Prof. Dr. Hans Böhringer from the Max Planck institute for extraterrestrial physics for providing me many useful references for this talk and for giving me the opportunity to do an internship at MPE in 2007.

Literature

- Steven Weinberg - *The First Three Minutes* (very good on popular level but outdated)

- Malcolm Longair – *Galaxy Formation* (Emphasis on observations, galaxy clusters and other astrophysical themes also discussed)

- Steven Weinberg – *Gravitation and Cosmology* (a canonical text with non-geometrical view of GR)

- Viatcheslav Mukhanov - *Physical Foundations of Cosmology* (theoretical cosmology on advanced level)

- H. Böhringer – *Testing Cosmological Models with the Properties of the Galaxy Cluster Population* (Overview over Cosmology with GC) see references

- Stefano Borgani – Cosmology with Clusters of Galaxies (technical introduction) arXiv: astro-ph/0605575

References

- Böhringer, H., X-ray Studies of Clusters of Galaxies In: Trümper, J.E, Hasinger, G, ed. The Universe in X-rays, Springer, 395-434 (2008)
- Schmitt, J. H. M. M., B. Aschenbach, G. Hasinger, E. Pfeffermann, and S. L. Snowden. A soft x-ray image of the moon. Nature, **349**, 583-587, (1991)
- Dennerl, K., J. Englhauser, J. Trümper, X-ray Emissions from Comets Detected in the Röntgen X-ray Satellite All-Sky Survey, Science **277**, 1625-1630 (1997)
- H. Böhringer, U. G. Briel, R. A. Schwarz, W. Voges, G. Hartner & J. Trümper, The structure of the Virgo cluster of galaxies from Rosat X-ray images, Nature, **368**, 828-831, (1994)
- Boehringer, H., Voges, W., Fabian, A. C., Edge, A. C., & Neumann, D. M., A ROSAT HI study of the interaction of the X-ray-emitting gas and radio lobes of NGC 1275, Mon. Not. R. Astron. Soc., **264**, L25-L28 (1993)
- H. Böhringer, Galaxy Clusters as Probes for Matter in the Universe, Space Science Review, **100**, 49-60 (2002)
- H. Böhringer, Testing Cosmological Models with Properties of the Galaxy Cluster Population, AIP Conf. Proc., **1381**, 137-149 (2011) and references therein
- P. Schuecker, H. Böhringer, L. Guzzo, et al., The ROSAT-ESO Flux-Limited X-Ray (REFLEX) galaxy cluster survey (III), A&A, **368**, 86-106 (2001)
- P. Schuecker, H. Böhringer, C. A. Collins, L. Guzzo, et al., The REFLEX galaxy cluster survey (VII), A&A, **398**, 867-877 (2003)
- P. Schuecker, R.R. Caldwell, H. Böhringer, C. A. Collins, et al., Observational constraints on general relativistic energy conditions, cosmic matter density and dark energy from X-ray clusters of galaxies and type-Ia supernovae, A&A, **402**, 53-63 (2003)
- Mantz, A., Allen, S. W., Rapetti, D. and Ebeling, H., The observed growth of massive galaxy clusters – I. Statistical methods and cosmological constraints. Mon. Not. R. Astron. Soc., 406: 1759–1772 (2010)
- Merloni, A., eROSITA Science Book: Mapping the Structure of the Energetic Universe, arXiv:1209.3114 [astro-ph.HE], (2012)

Credits: Figures

- **Andromeda Galaxy:** messier.seds.org
- **Large Scale Structure:** Springel et al, the Millennium simulation, MPA Garching
- **3d Geometry:** physicsworld.com
- **BigBang Picture 1:** University of Oregon Homepage
- **CMB Sky:** WMAP team (Wikimedia Commons)
- **Bullet Cluster:** X-ray: NASA/CXC/CfA/ M.Markevitch et al.
- **Expansion of the universe:** NASA
- **UHURU:** NASA
- **Einstein Observatory:** NASA
- **ROSAT:** MPE
- **Chandra:** NASA
- **XMM-Newton:** Wikimedia Commons
- **ROSAT Astrophysics Results, Mission and Data Sheets:** MPE ROSAT Website (# of discovered objects taken from NASA)