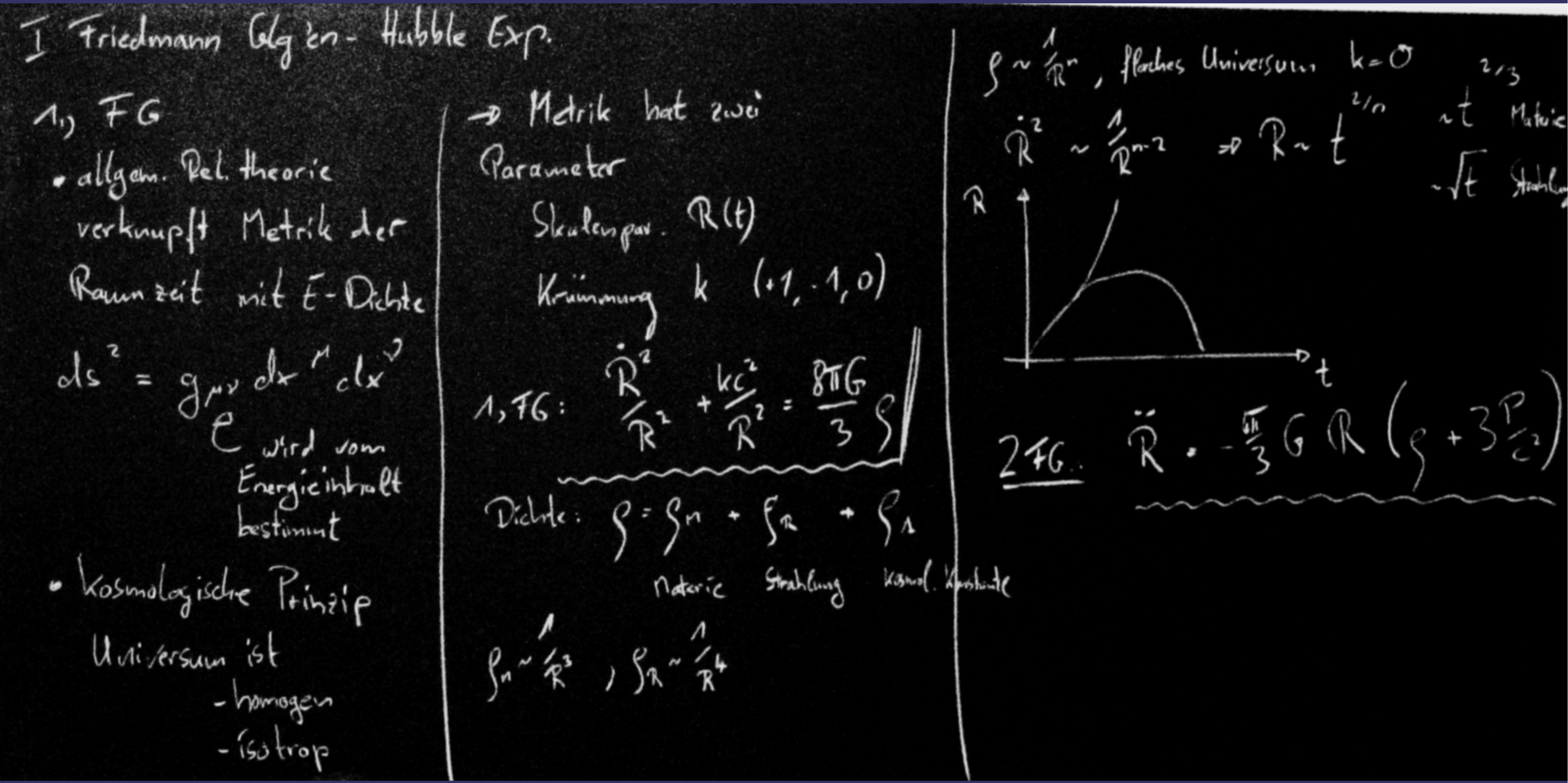
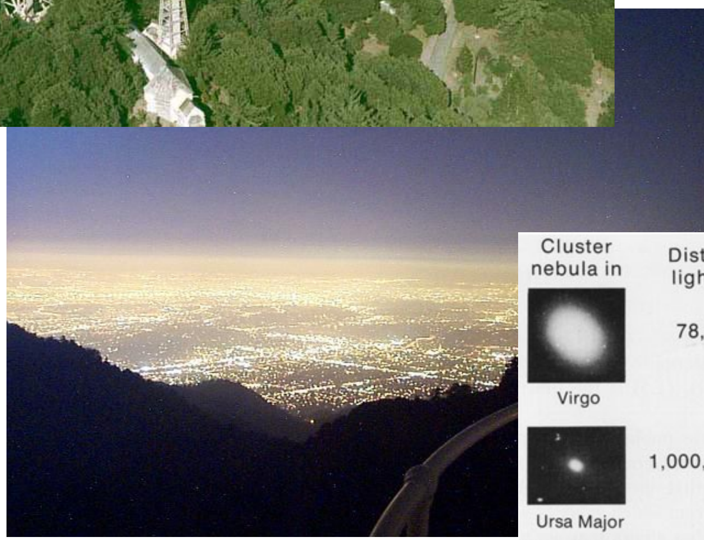
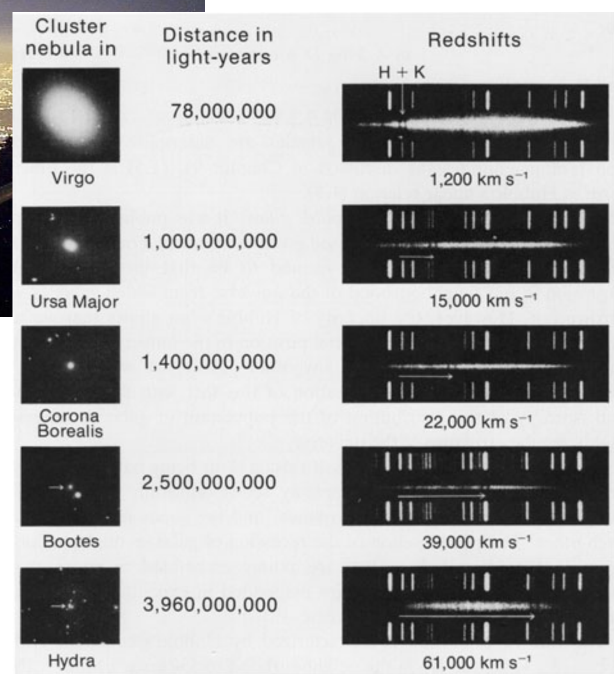
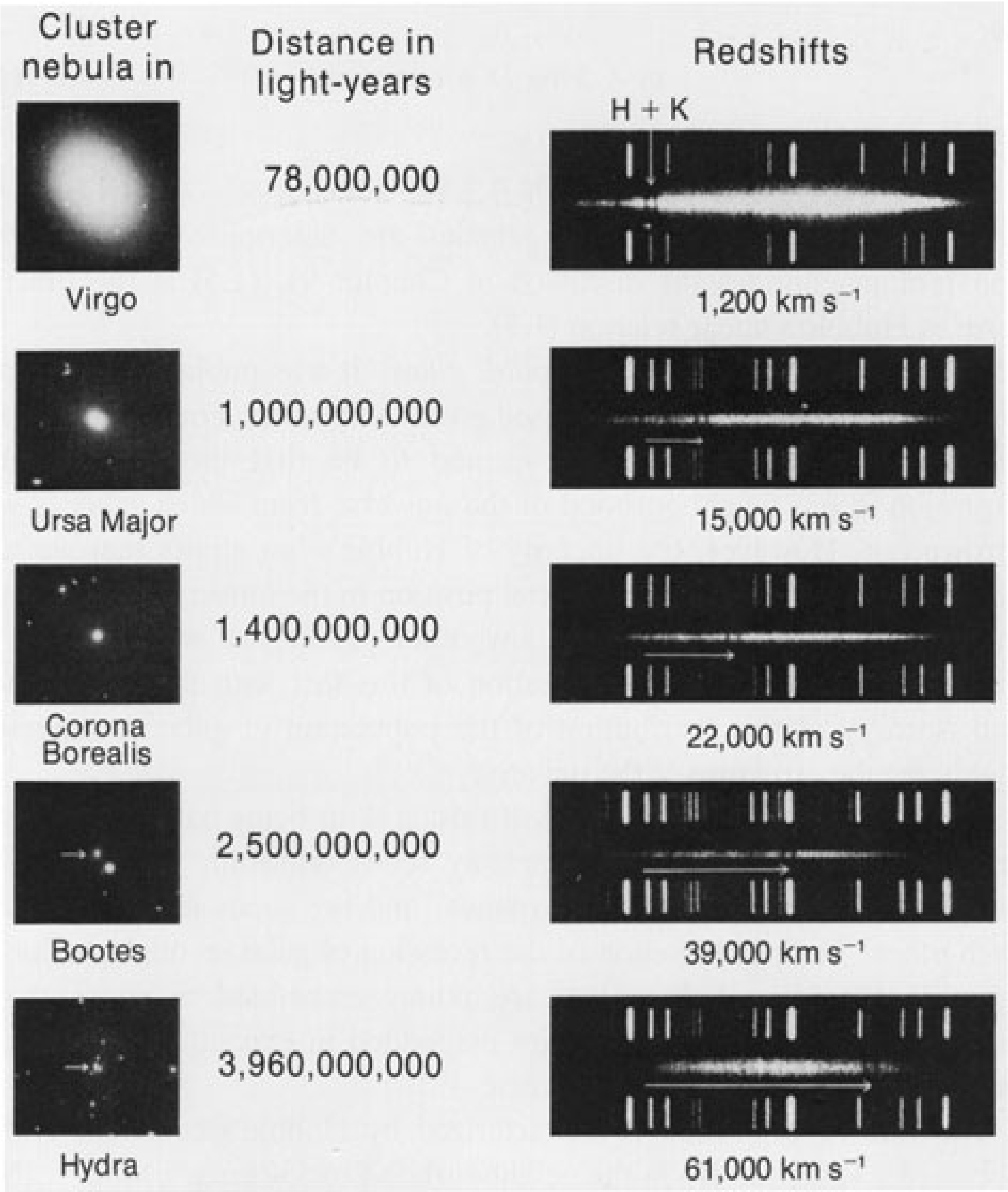

I Friedmann Glg'en - Hubble Exp.
1.) FG
• allgem. Rel. theorie verknüpft Metrik der Raumzeit mit E-Dichte
$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$
g wird vom Energieinhalt bestimmt
• kosmologische Prinzip
Universum ist
- homogen
- isotrop
→ Metrik hat zwei Parameter
Skalenpar. $R(t)$
Krümmung k $(+1, -1, 0)$
1. FG: $\frac{\dot{R}^2}{R^2} + \frac{kc^2}{R^2} = \frac{8\pi G}{3}\rho$
Dichte: $\rho = \rho_M + \rho_R + \rho_\Lambda$
Materie
Strahlung
kosmol. Konstante
$\rho_M \sim \frac{1}{R^3}$, $\rho_R \sim \frac{1}{R^4}$
$\rho \sim \frac{1}{R^n}$, flaches Universum $k=0$
$\dot{R}^2 \sim \frac{1}{R^{n-2}} \Rightarrow R \sim t^{2/n}$
$\sim t^{2/3}$ Materie
$\sim \sqrt{t}$ Strahlung
R
t
2. FG. $\ddot{R} = -\frac{4\pi}{3} G R \left(\rho + 3\frac{P}{c^2}\right)$



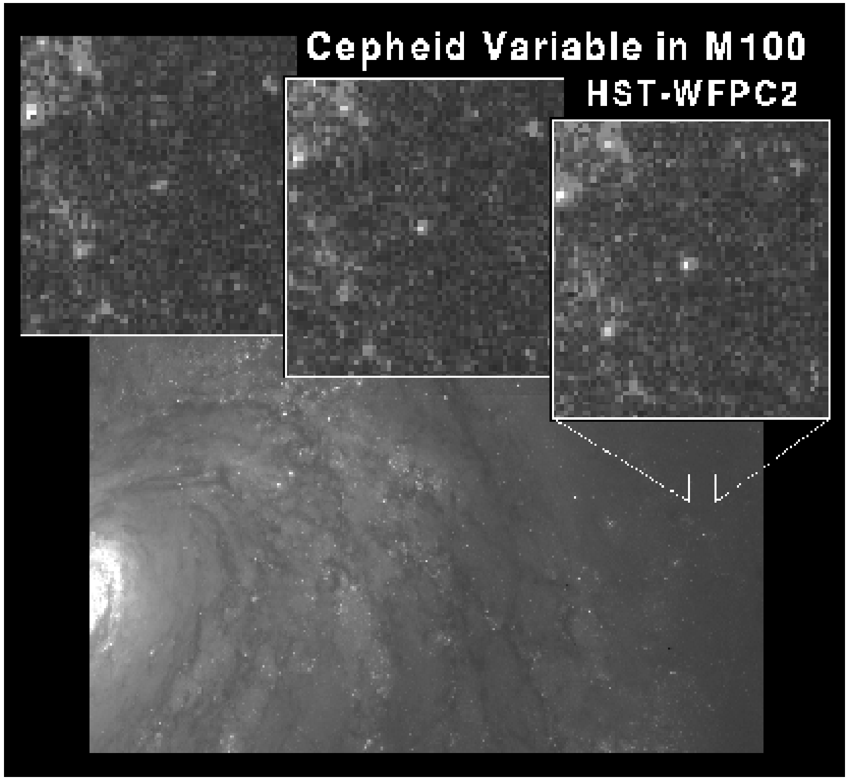
Mt.Wilson
Observatory

E.Hubble
1929

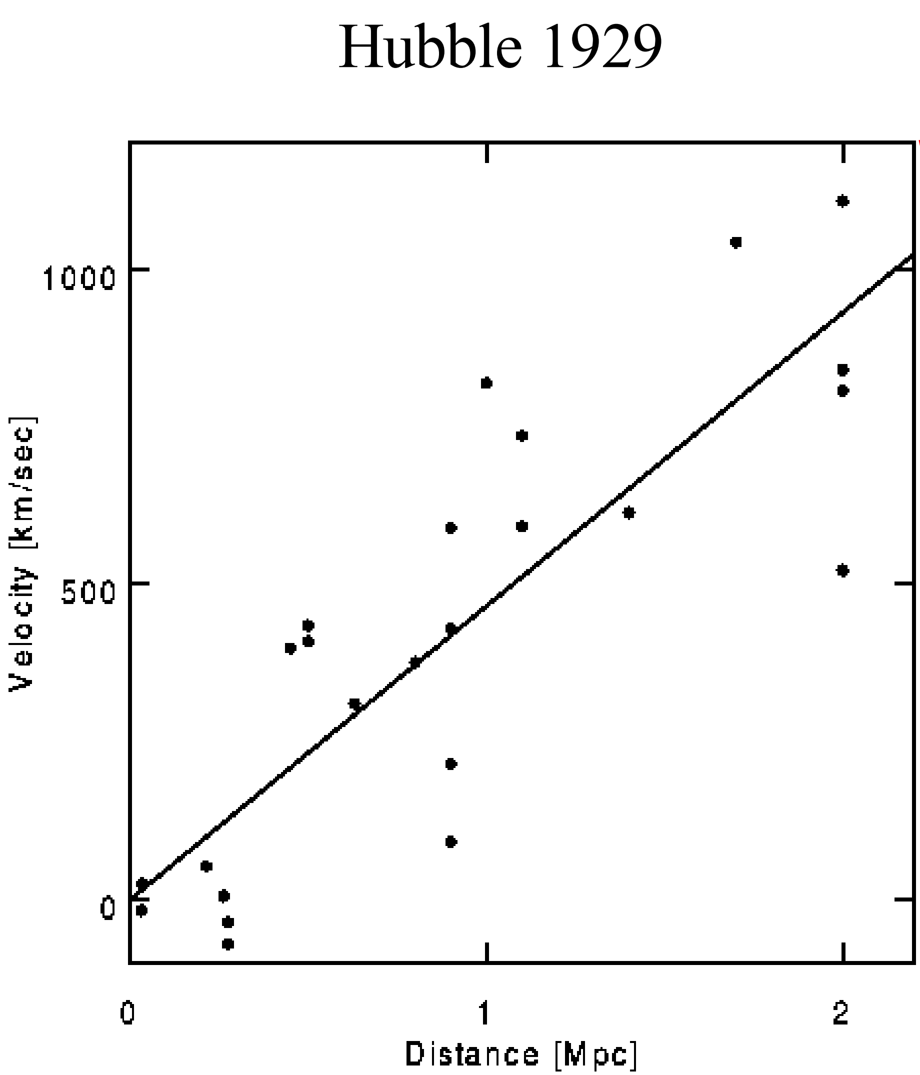




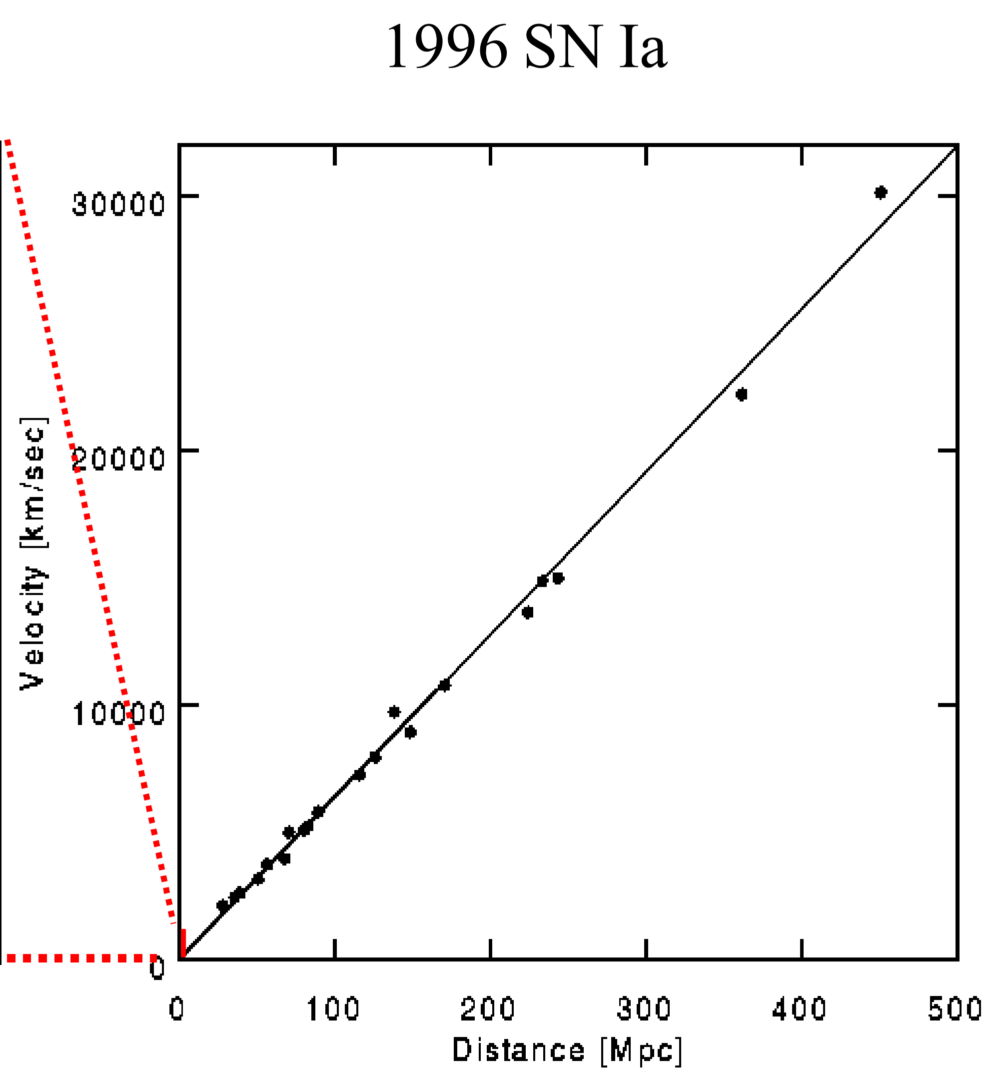
Cluster nebula in
Distance in light-years
Redshifts
H + K
Virgo
78,000,000
1,200 km s⁻¹
Ursa Major
1,000,000,000
15,000 km s⁻¹
Corona Borealis
1,400,000,000
22,000 km s⁻¹
Bootes
2,500,000,000
39,000 km s⁻¹
Hydra
3,960,000,000
61,000 km s⁻¹



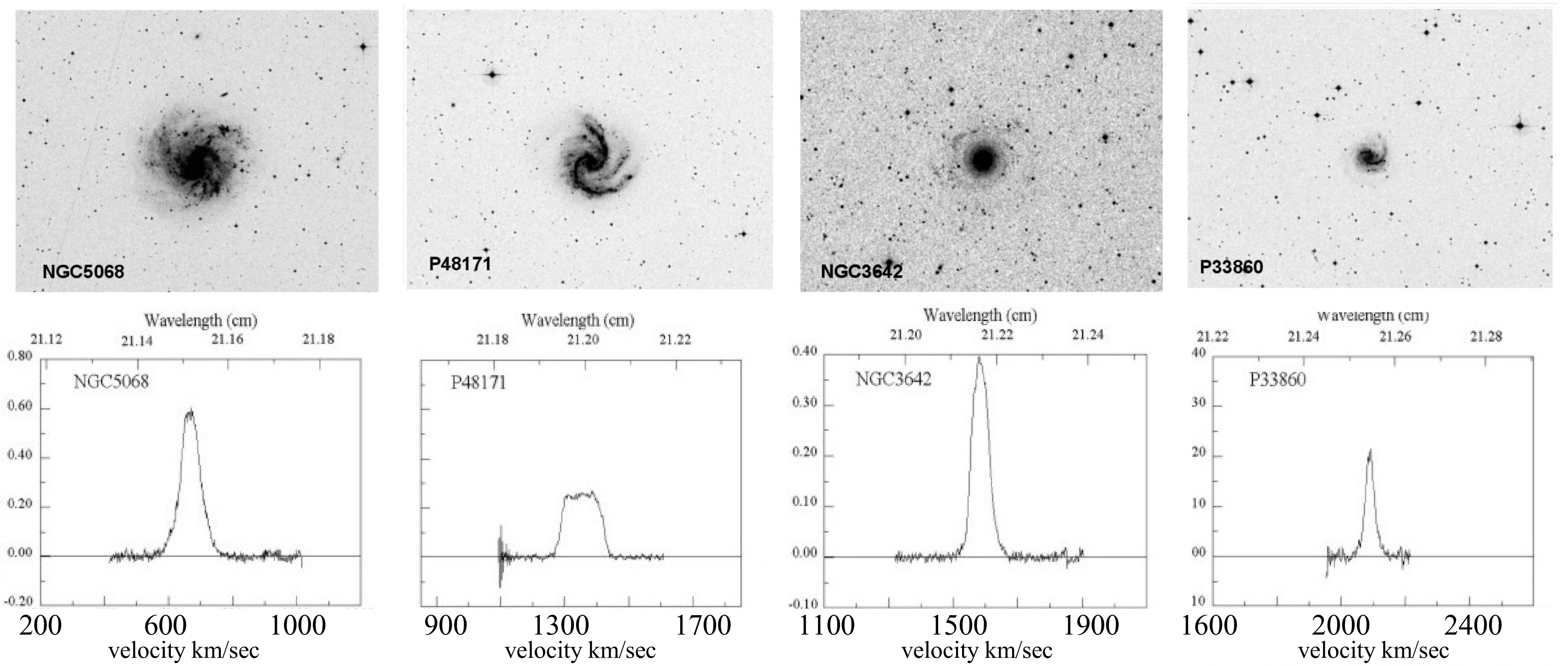
Cepheid Variable in M100
HST-WFPC2

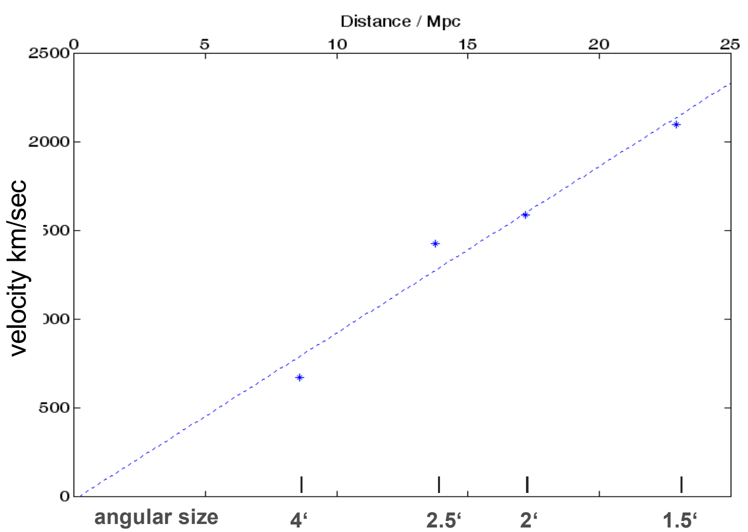


H ~ 500 km/s/Mpc



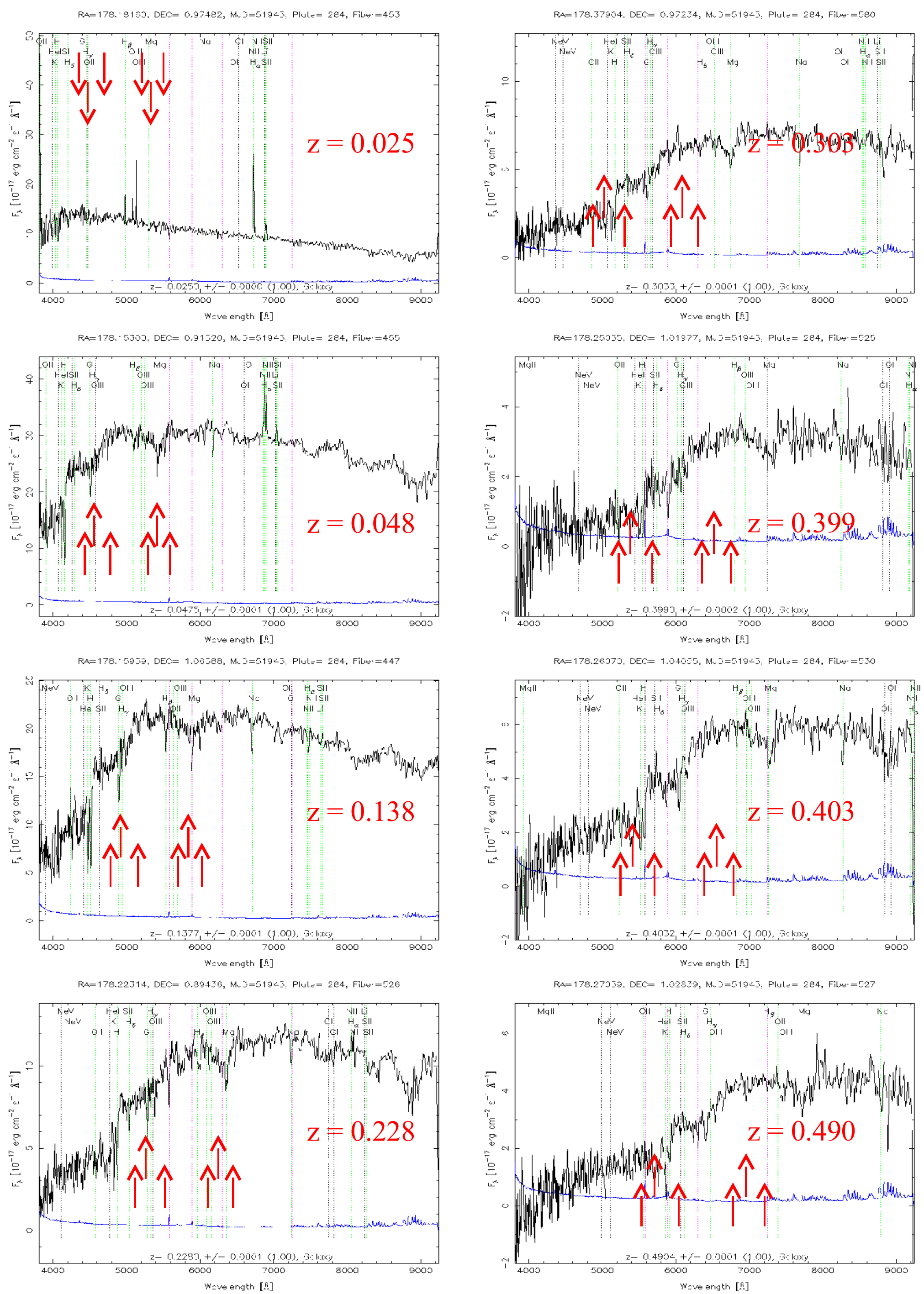
H ~ 70 km/s/Mpc

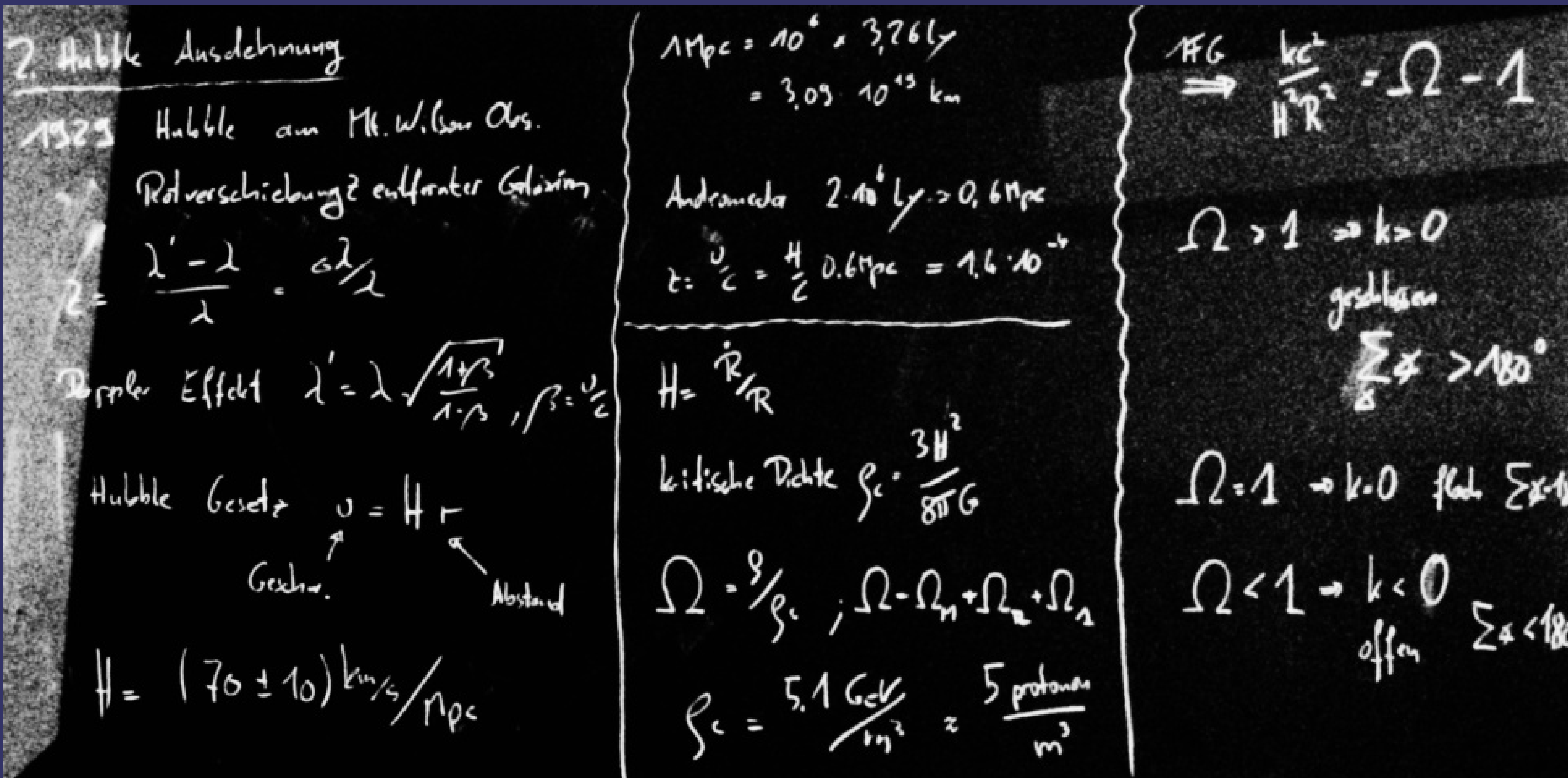




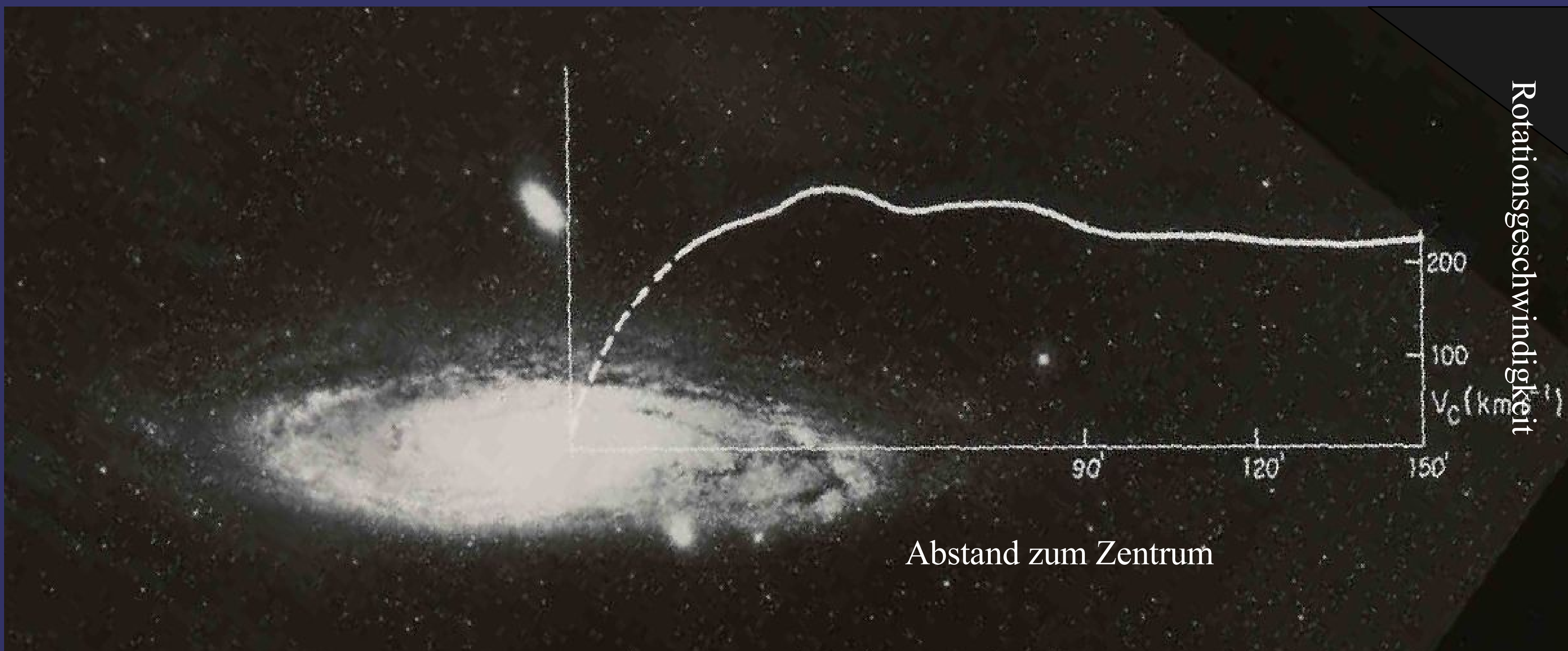
21 cm Radio- Linie
scheinbare Größe der Galaxie
=> je kleiner (weiter) desto mehr rotverschoben

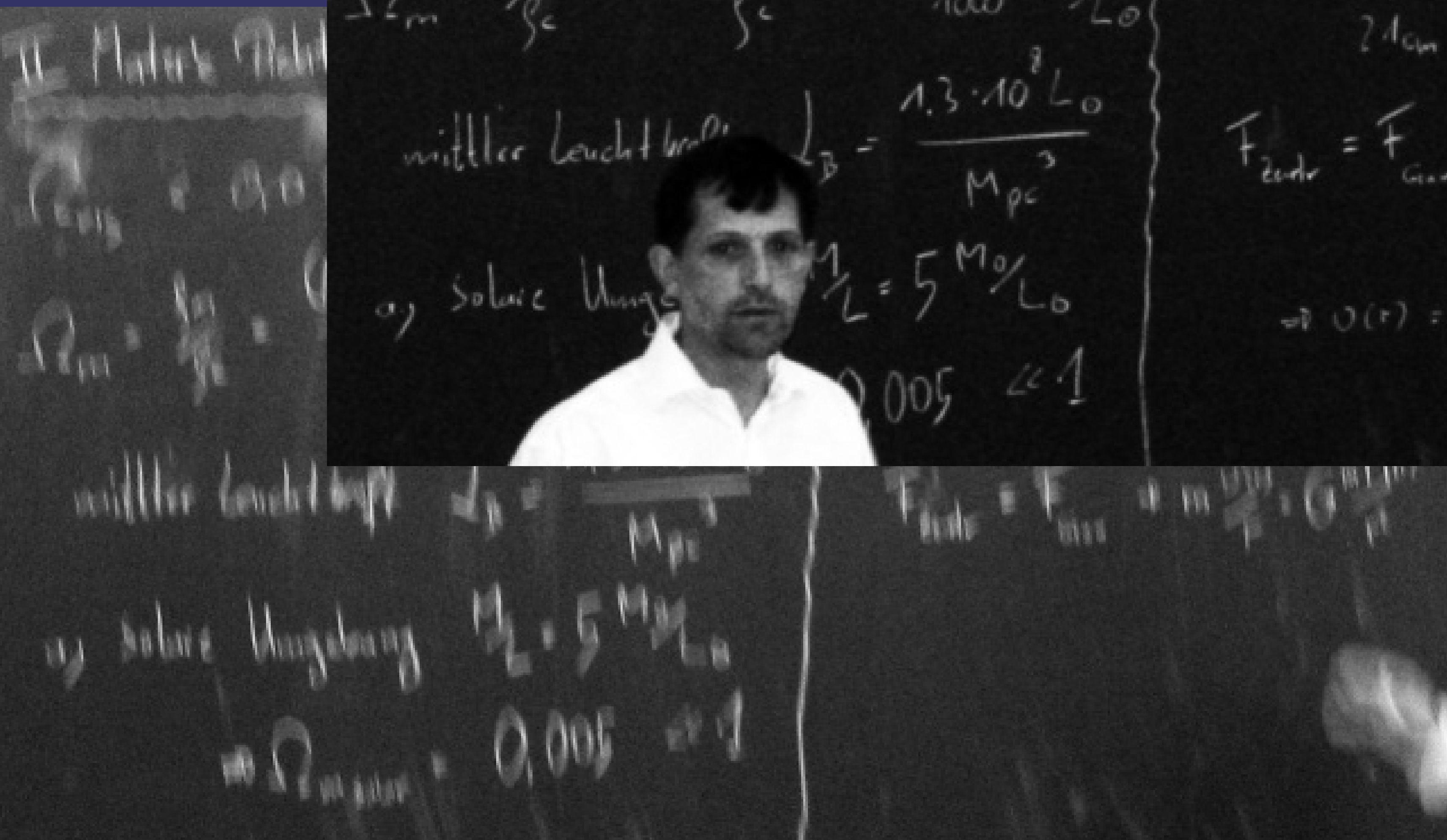
aus Annahme Galaxienradius = 10kpc
⇒ Abstand
⇒ Steigung ~ Hubble Parameter ~ 90 km/s/Mpc

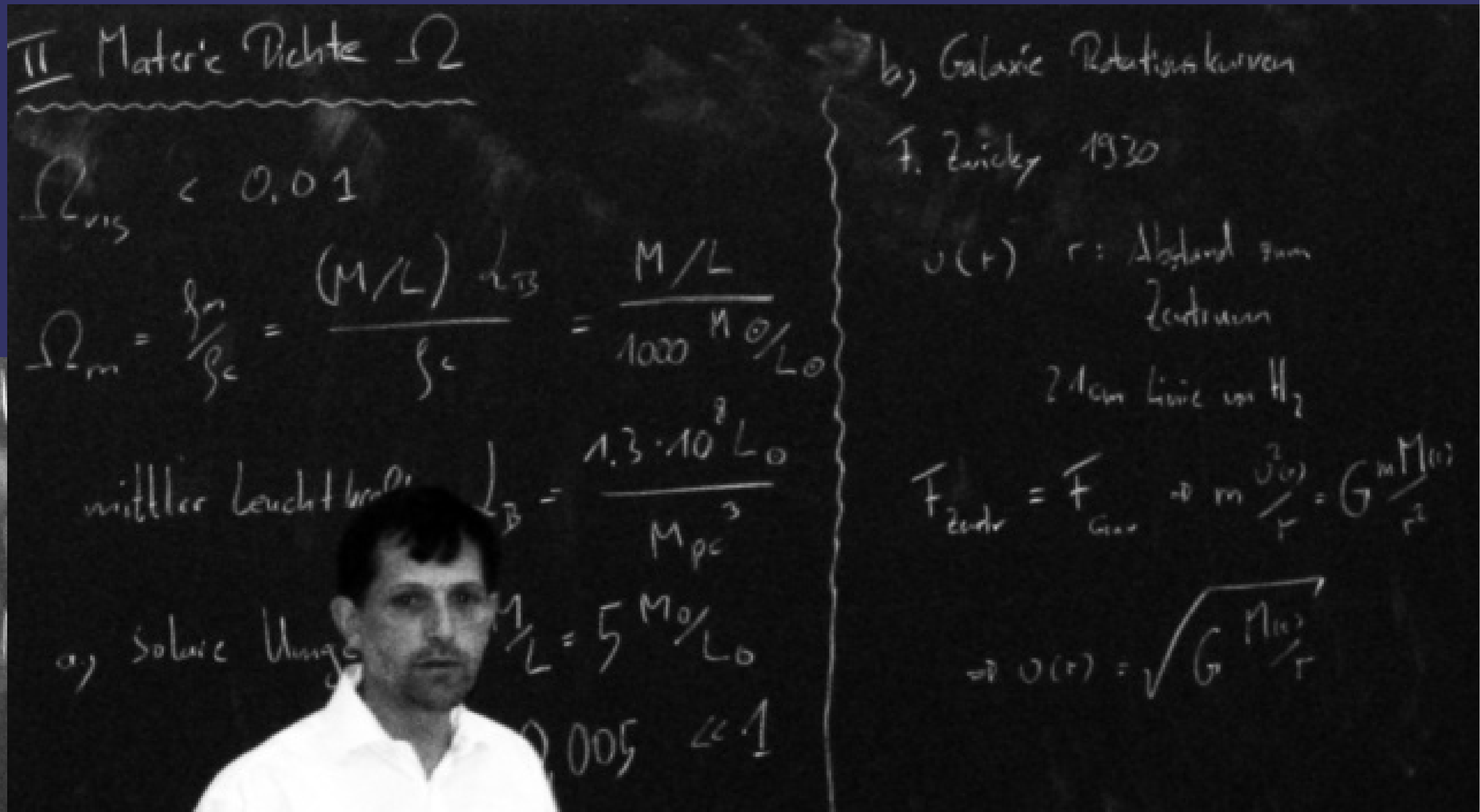

z = 0.025
z = 0.303
z = 0.048
z = 0.399
z = 0.138
z = 0.403
z = 0.228
z = 0.490
Wavelength [Å]

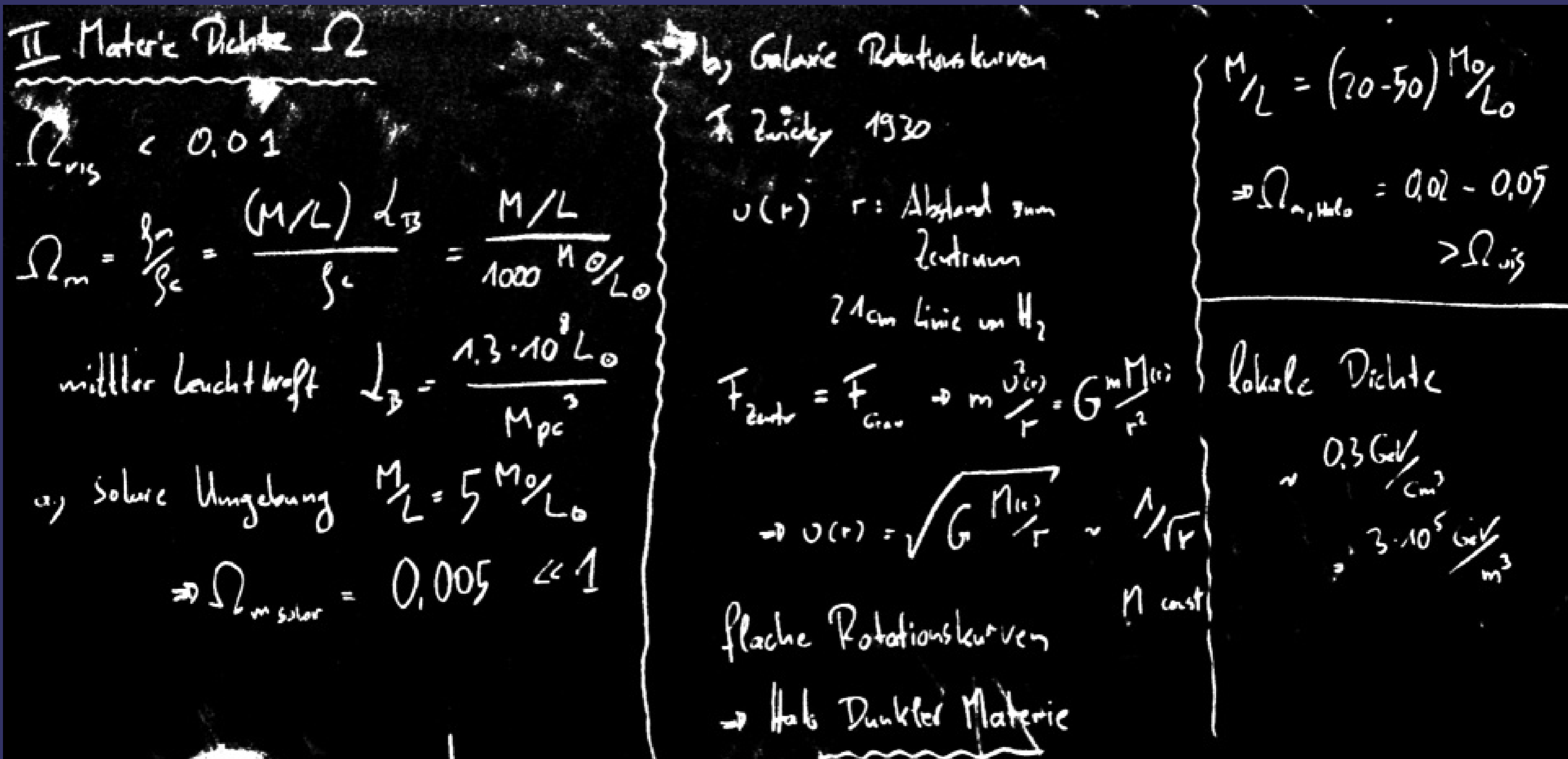


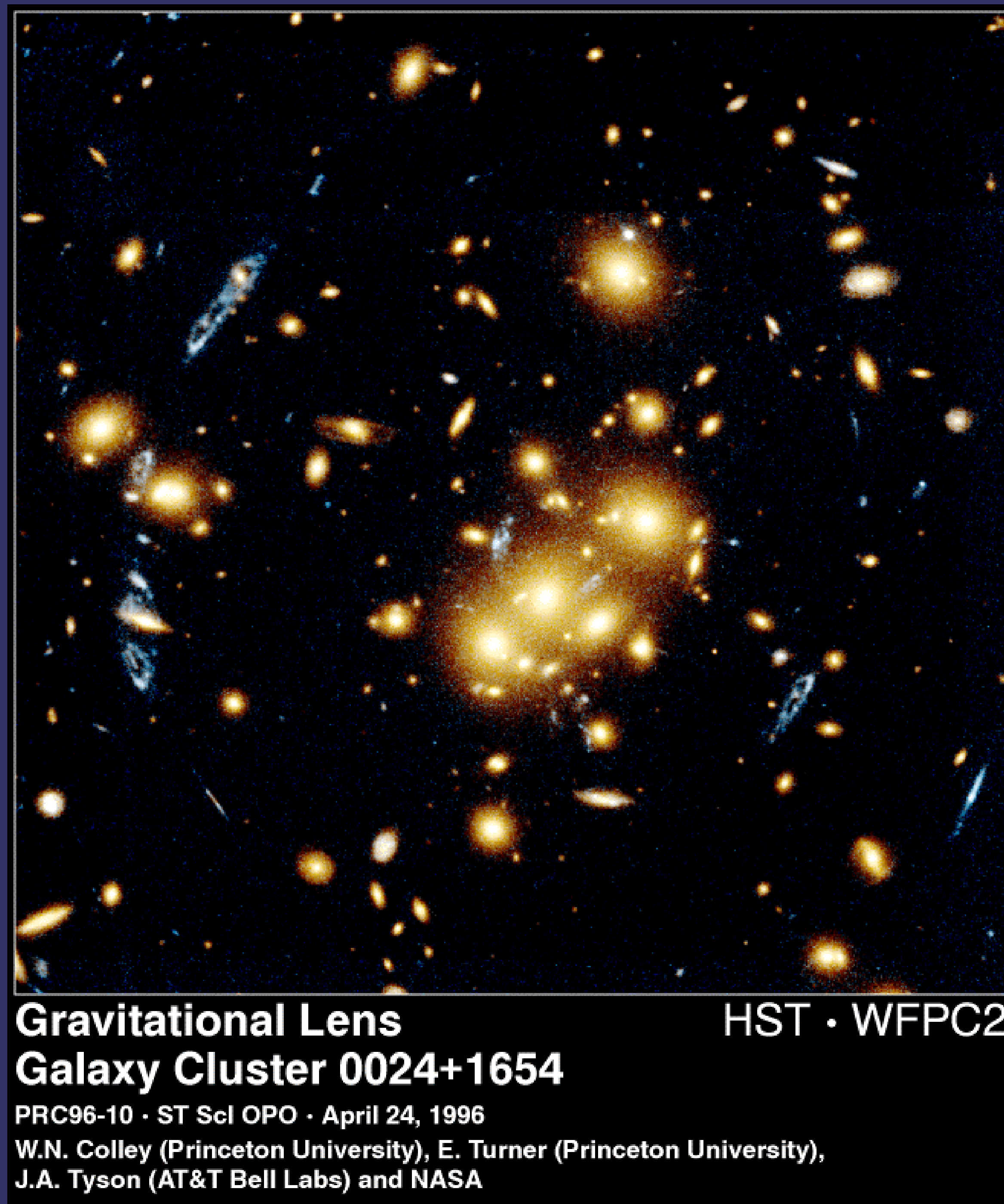
2. Hubble Ausdehnung
1929 Hubble am Mt. Wilson Obs.
Rotverschiebung? entfernter Galaxien
Doppler Effekt
Hubble Gesetz
Geschw.
Abstand
H = (70 ± 10) km/s/Mpc
1 Mpc = 10^6 · 3,26 ly
= 3.09 · 10^19 km
Andromeda 2·10^6 ly -> 0,6 Mpc
kritische Dichte
geschlossen
flach
offen

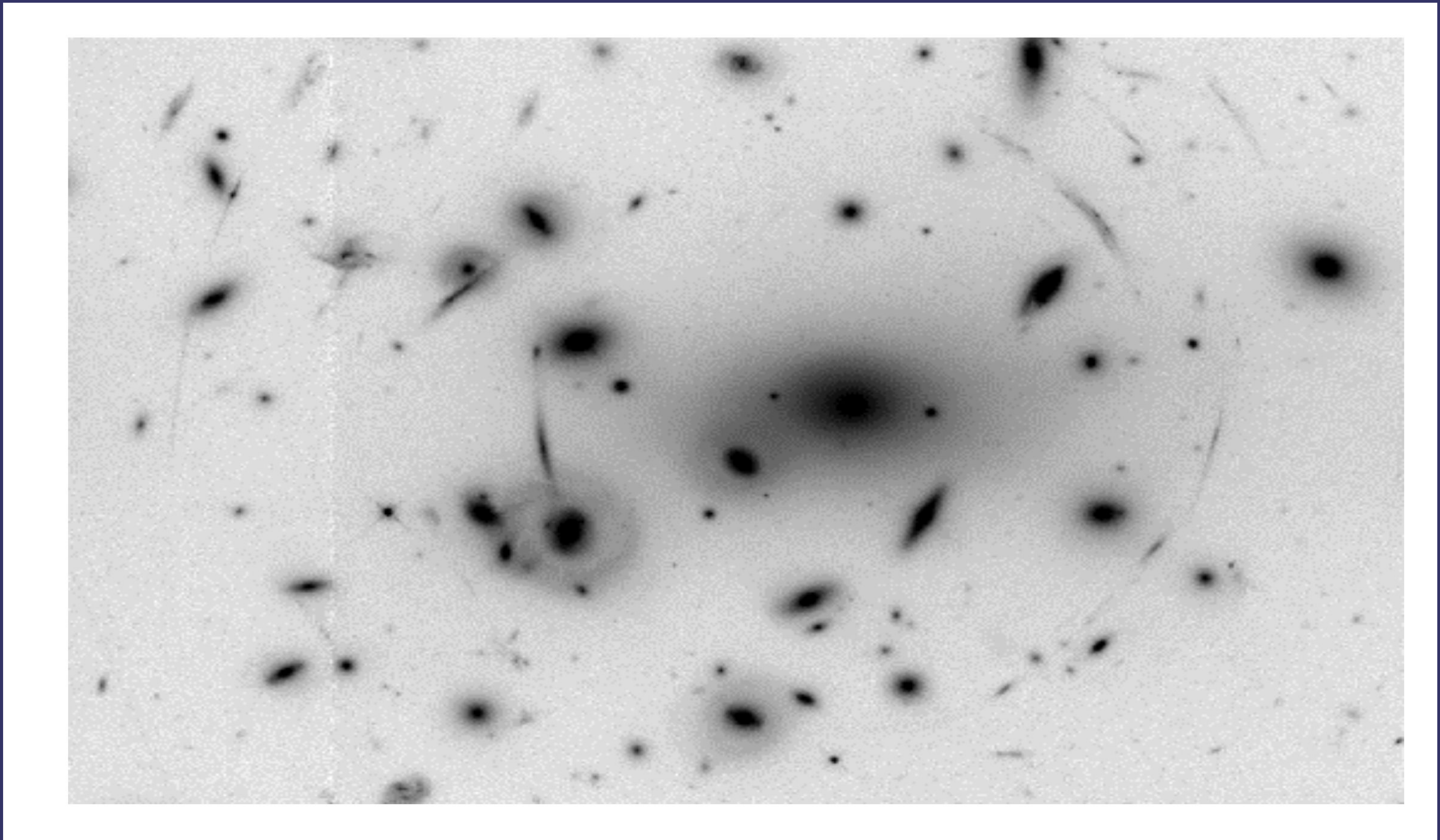

Rotationsgeschwindigkeit
200
100
V_c (km s^{-1})
90'
120'
150'
Abstand zum Zentrum

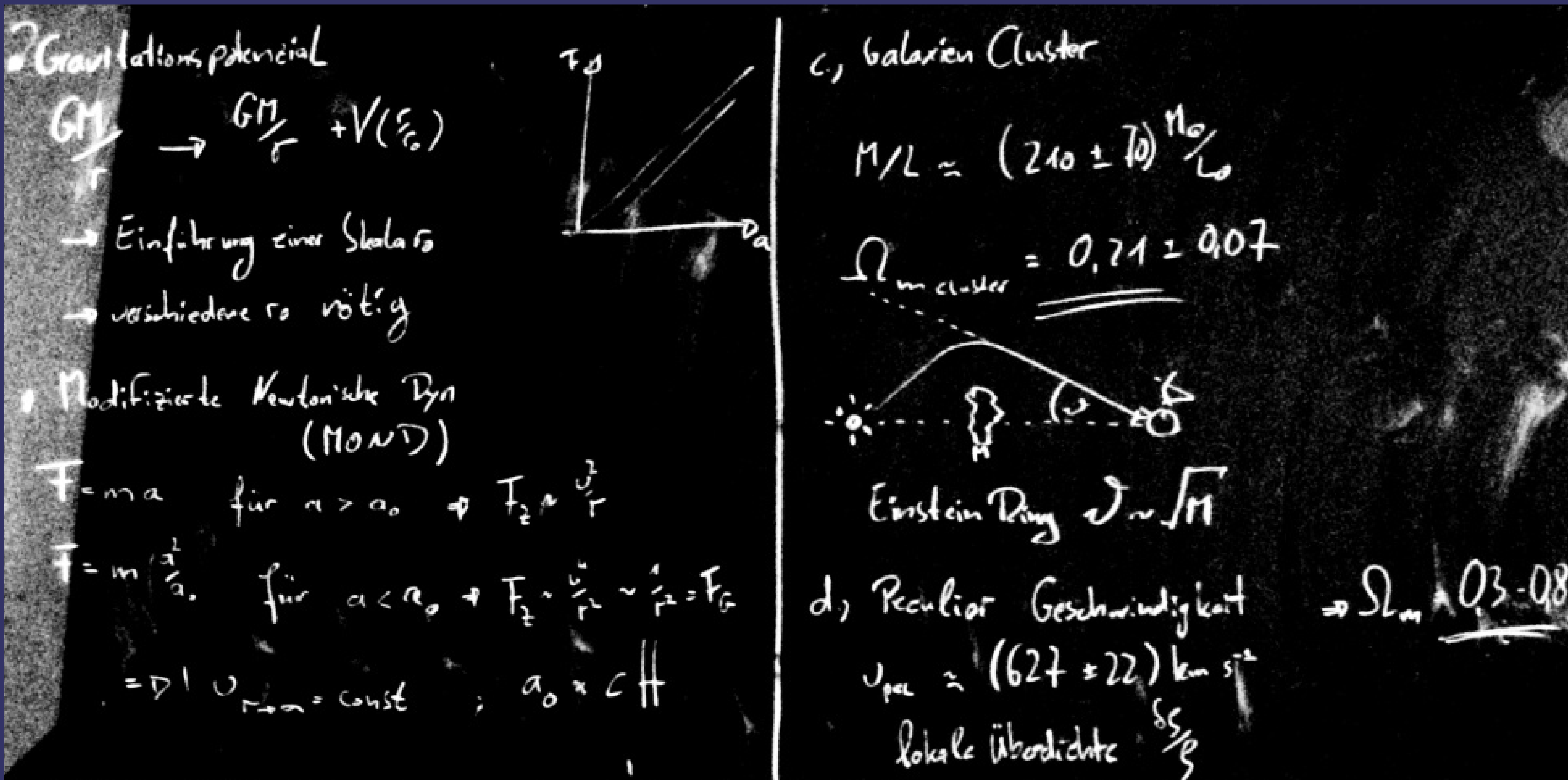


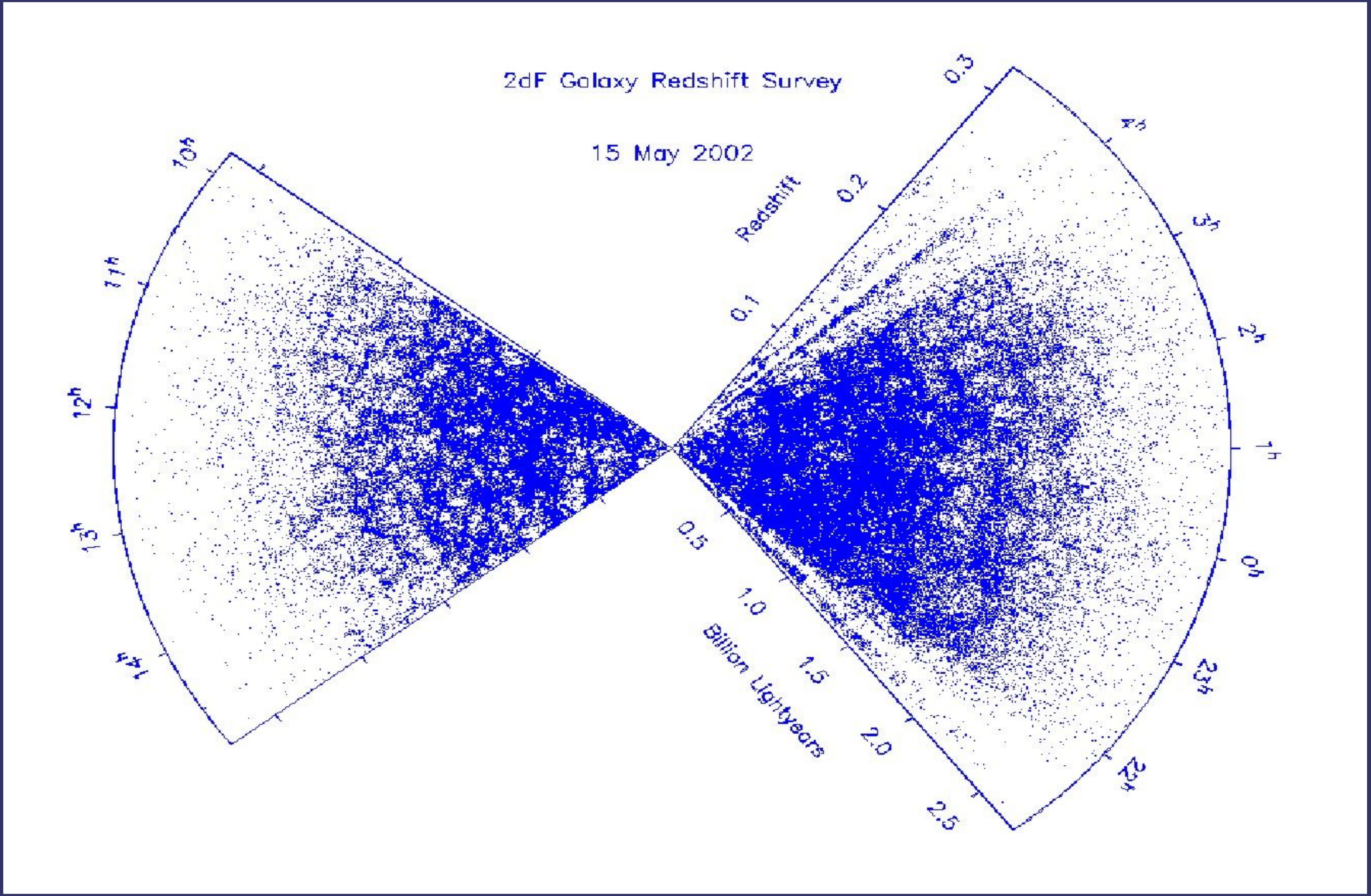

II Materie Dichte Ω
$\Omega_{vis} < 0.01$
$\Omega_m = \rho_m / \rho_c = \frac{(M/L)\, \mathcal{L}_B}{\rho_c} = \frac{M/L}{1000\, M_\odot / L_\odot}$
mittler Leuchtkraft
$\mathcal{L}_B = \frac{1.3 \cdot 10^8 L_\odot}{Mpc^3}$
a, solare Umgebung
$M/L = 5\, M_\odot / L_\odot$
$0.005 \ll 1$
b, Galaxie Rotationskurven
F. Zwicky 1930
v(r) r: Abstand zum Zentrum
21cm Linie von H_2
$F_{Zentr} = F_{Grav} \Rightarrow m\frac{v^2(r)}{r} = G\frac{m M(r)}{r^2}$
$\Rightarrow v(r) = \sqrt{G\, M(r)/r}$


II Materie Dichte Ω
$\Omega_{vis} < 0.01$
$\Omega_m = \rho_m/\rho_c = \frac{(M/L)\,\mathcal{L}_B}{\rho_c} = \frac{M/L}{1000\, M_\odot/L_\odot}$
mittlere Leuchtkraft $\mathcal{L}_B = \frac{1.3\cdot 10^8 L_\odot}{Mpc^3}$
a) solare Umgebung $M/L = 5\, M_\odot/L_\odot$
$\Rightarrow \Omega_{m\,solar} = 0{,}005 \ll 1$
b) Galaxie Rotationskurven
F. Zwicky 1930
$v(r)$ r: Abstand zum Zentrum
21cm Linie von H_2
$F_{Zentr} = F_{Grav} \Rightarrow m\frac{v^2(r)}{r} = G\frac{m M(r)}{r^2}$
$\Rightarrow v(r) = \sqrt{G\frac{M(r)}{r}} \sim 1/\sqrt{r}$
M const
flache Rotationskurven
$\Rightarrow$ Halo Dunkler Materie
$M/L = (20\text{-}50)\, M_\odot/L_\odot$
$\Rightarrow \Omega_{m,Halo} = 0{,}02 - 0{,}05$
$> \Omega_{vis}$
lokale Dichte
$\sim 0.3\, GeV/cm^3$
$\approx 3\cdot 10^5\, GeV/m^3$

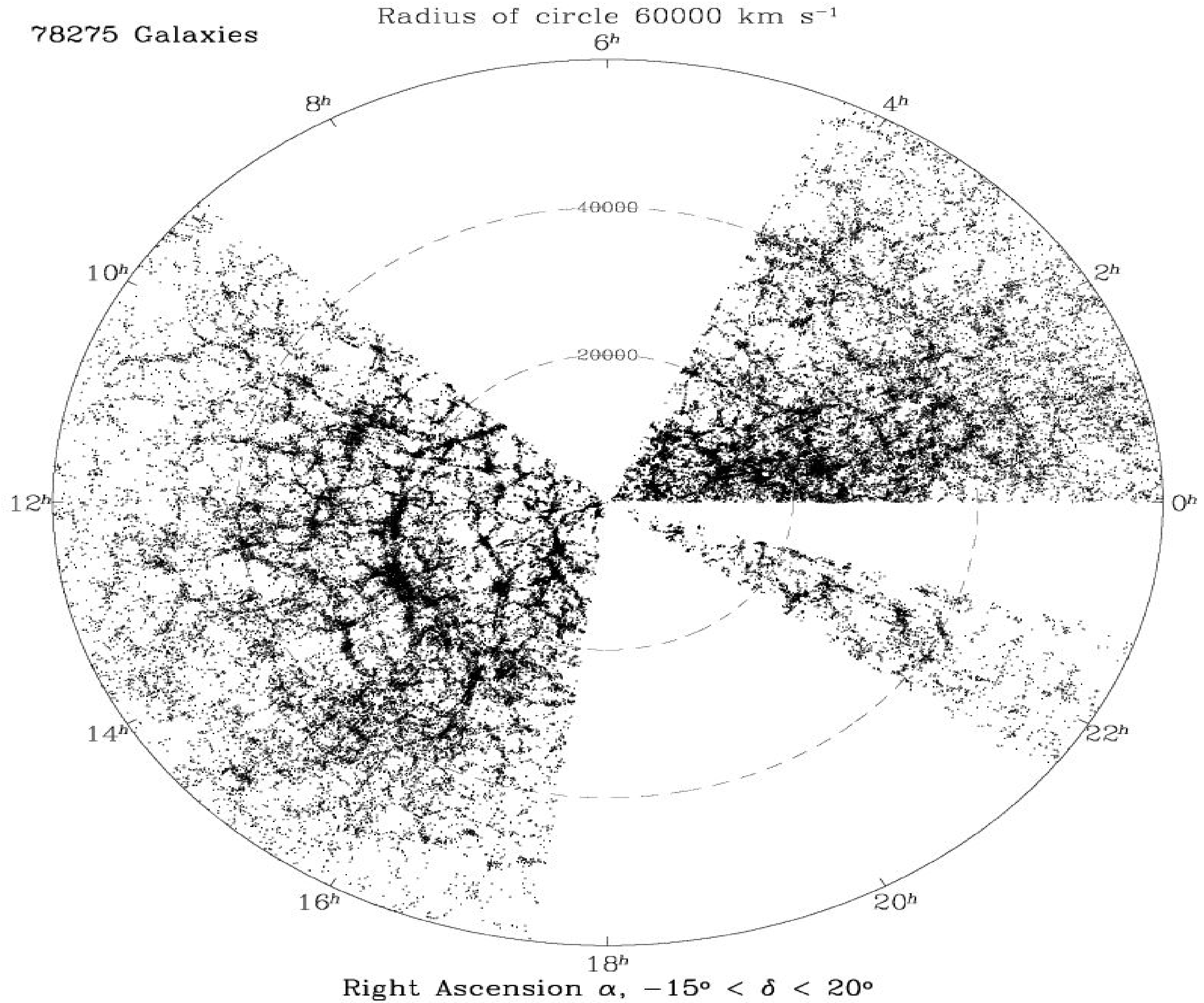

Gravitational Lens
Galaxy Cluster 0024+1654
HST • WFPC2
PRC96-10 • ST ScI OPO • April 24, 1996
W.N. Colley (Princeton University), E. Turner (Princeton University),
J.A. Tyson (AT&T Bell Labs) and NASA



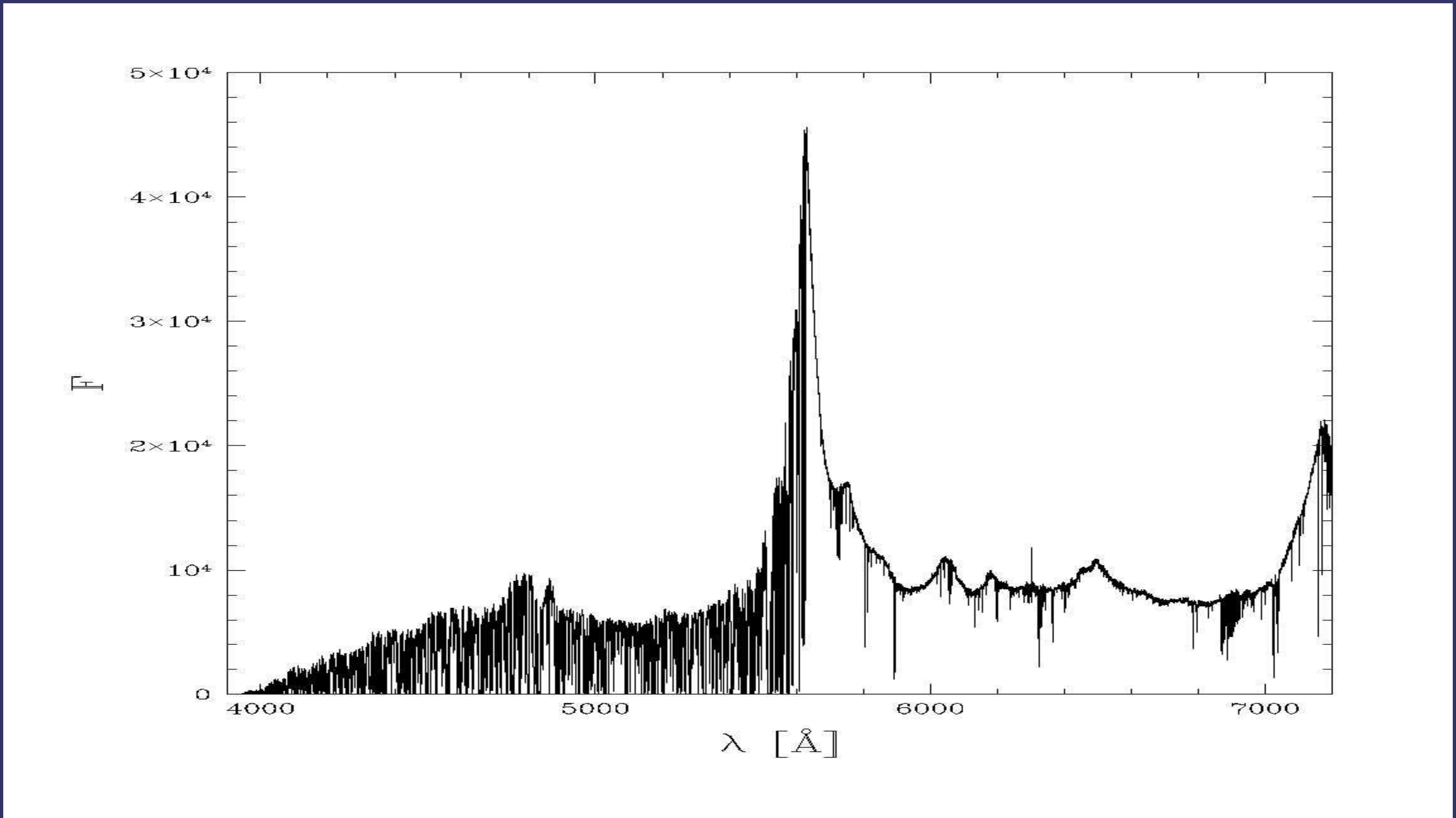

Gravitationspotential
Einführung einer Skala r0
verschiedene r0 nötig
Modifizierte Newtonische Dyn
(MOND)
F = m a für a > a0
F = m a²/a0 für a < a0
a0 ≈ c H
c) Galaxien Cluster
M/L ≈ (210 ± 70) M⊙/L⊙
Ωm cluster = 0,21 ± 0,07
Einstein Ring
d) Peculiar Geschwindigkeit
Ωm 0.3-0.8
vpec ≈ (627 ± 22) km s⁻¹
lokale Überdichte δρ/ρ

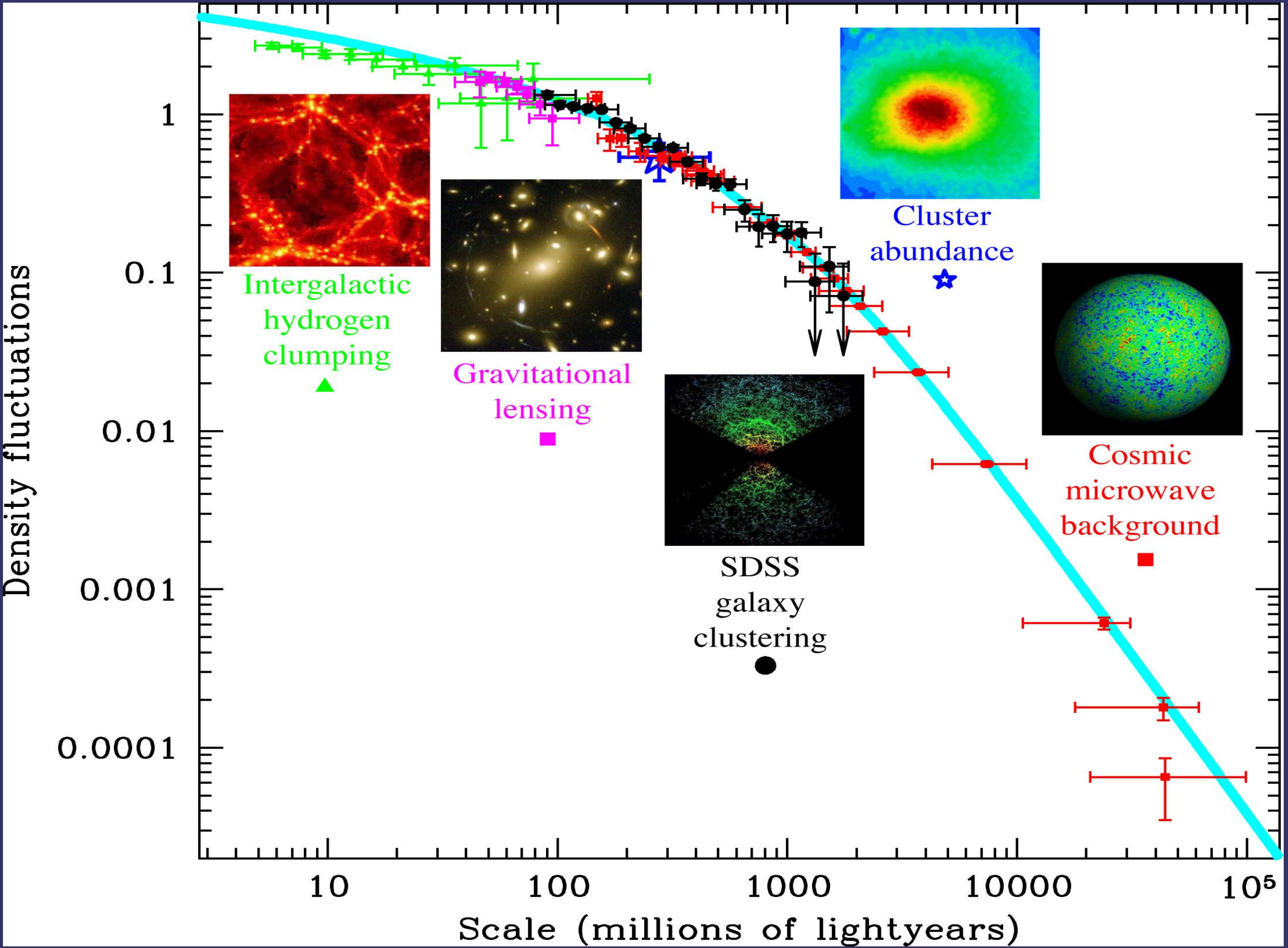

2dF Galaxy Redshift Survey
15 May 2002
Redshift
0.1
0.2
0.3
0.5
1.0
1.5
2.0
2.5
Billion Lightyears
10h
11h
12h
13h
14h
4h
3h
2h
1h
0h
23h
22h

Sloan Digital Sky Survey

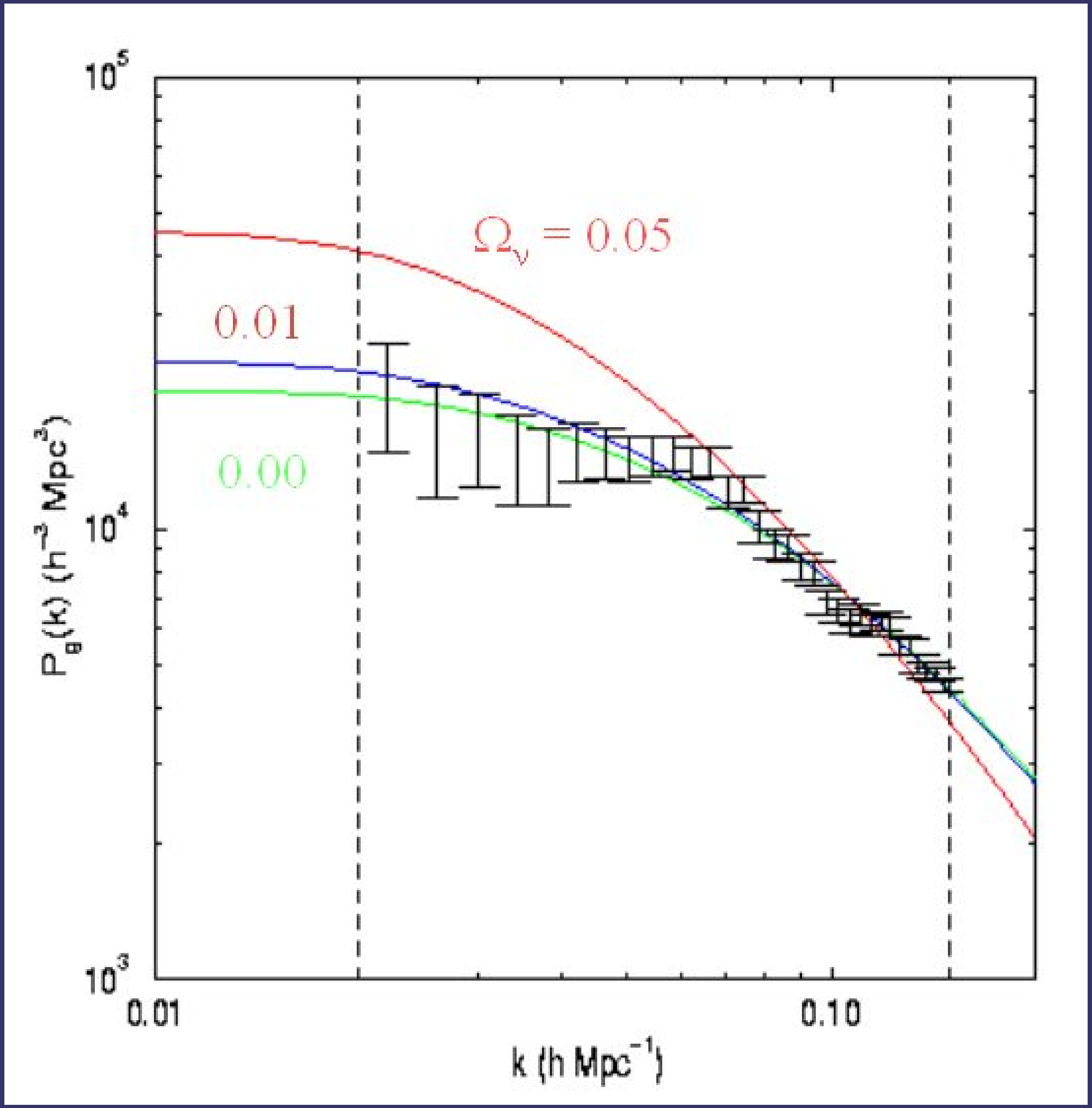


Lyman α Forest

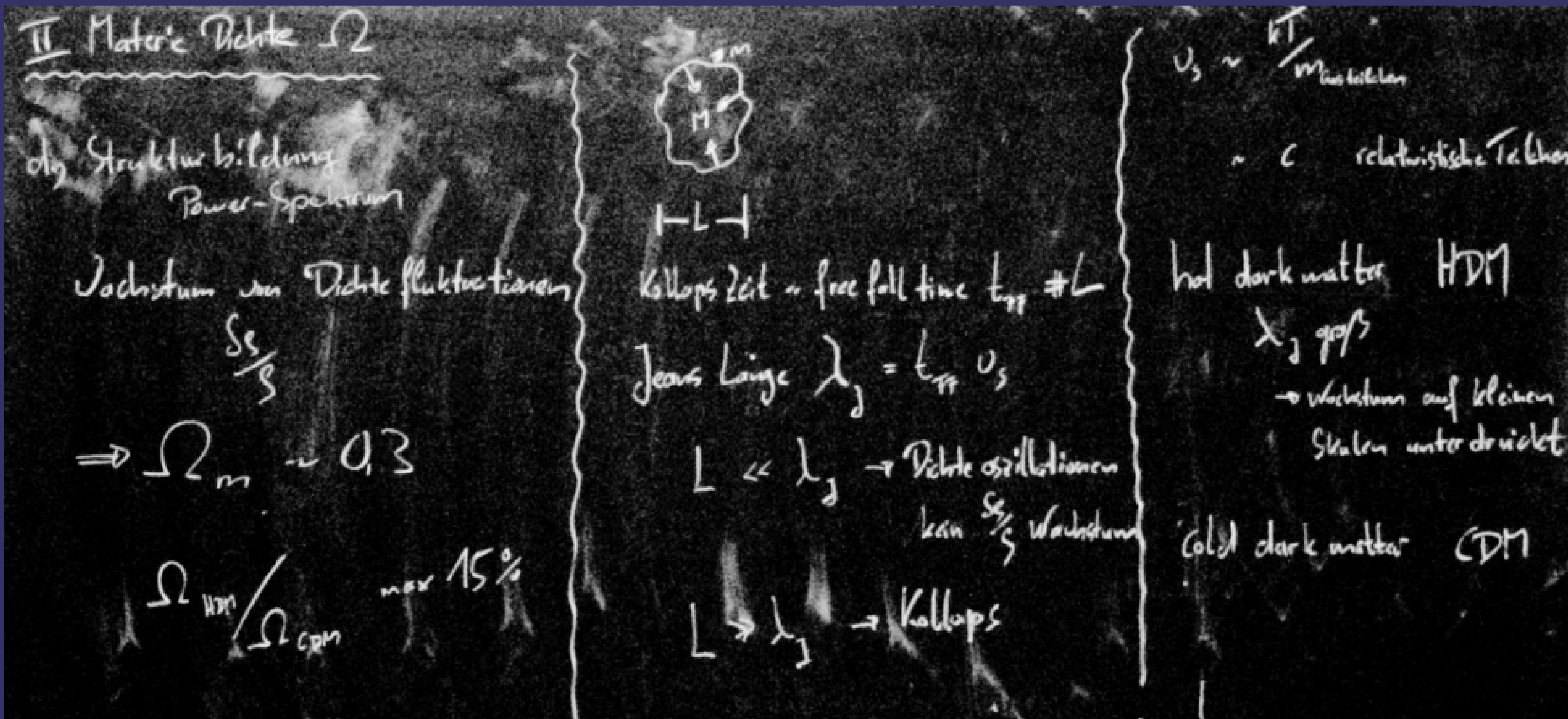


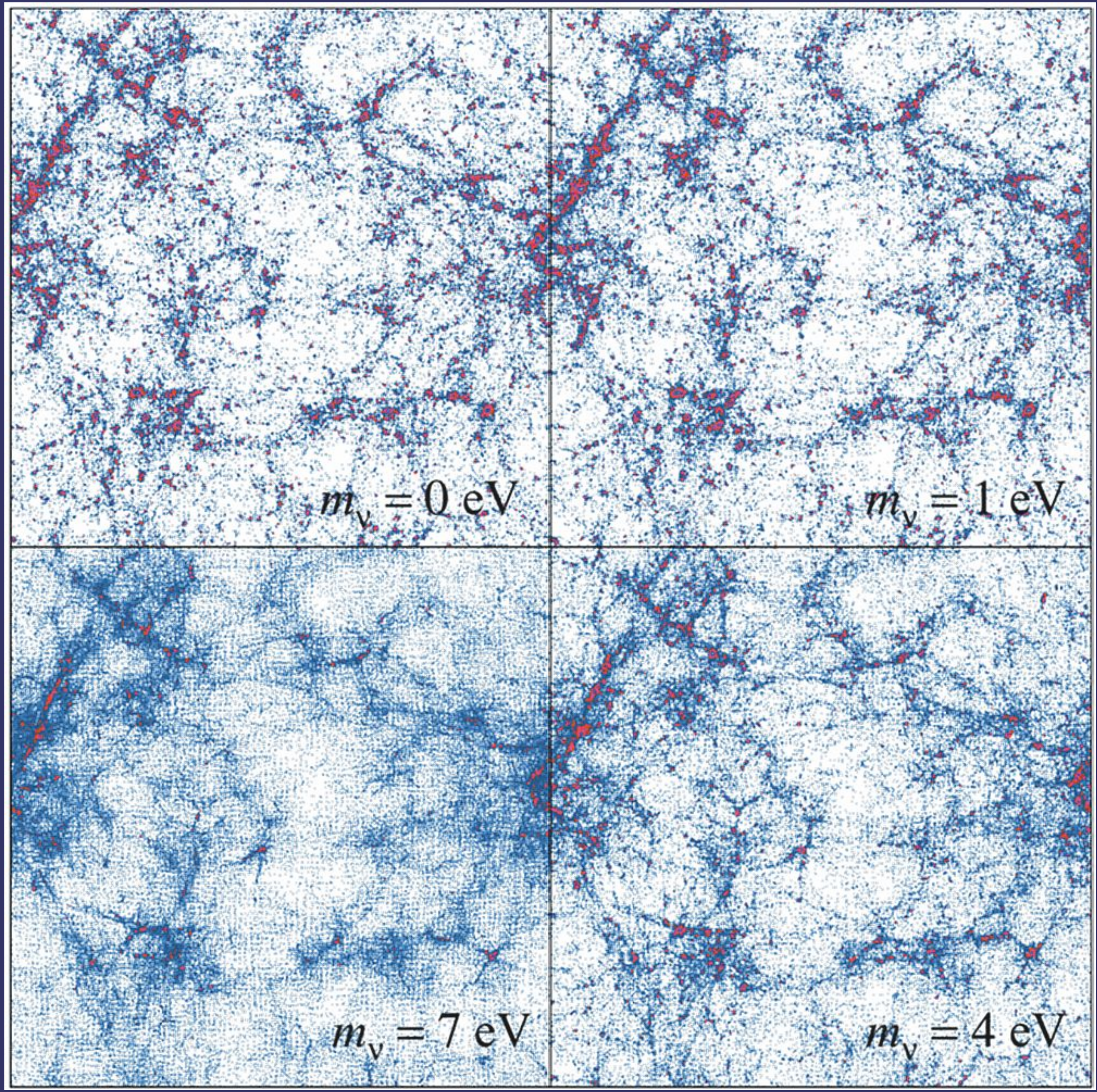


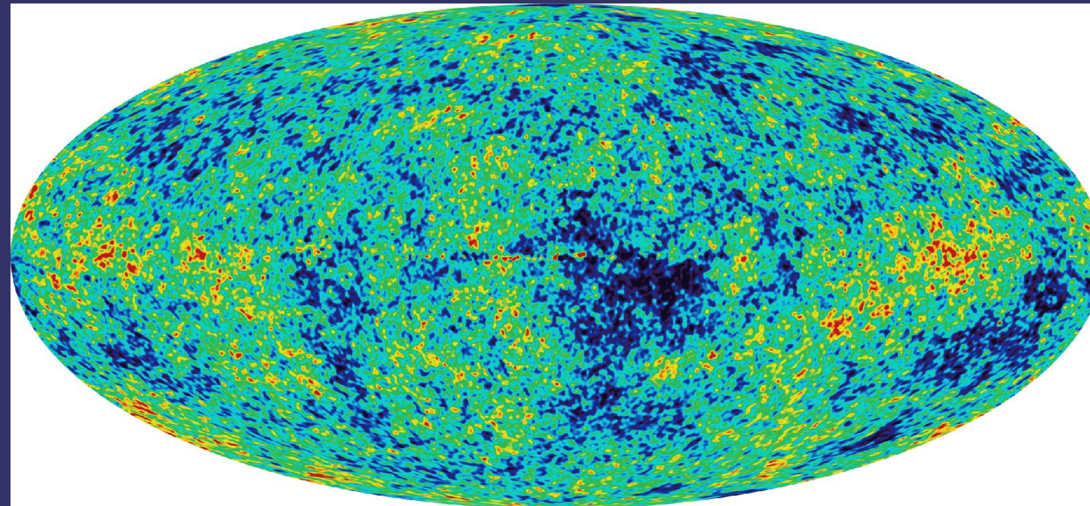
Density fluctuations
1
0.1
0.01
0.001
0.0001
10
100
1000
10000
10⁵
Scale (millions of lightyears)
Intergalactic
hydrogen
clumping
Gravitational
lensing
SDSS
galaxy
clustering
Cluster
abundance
Cosmic
microwave
background

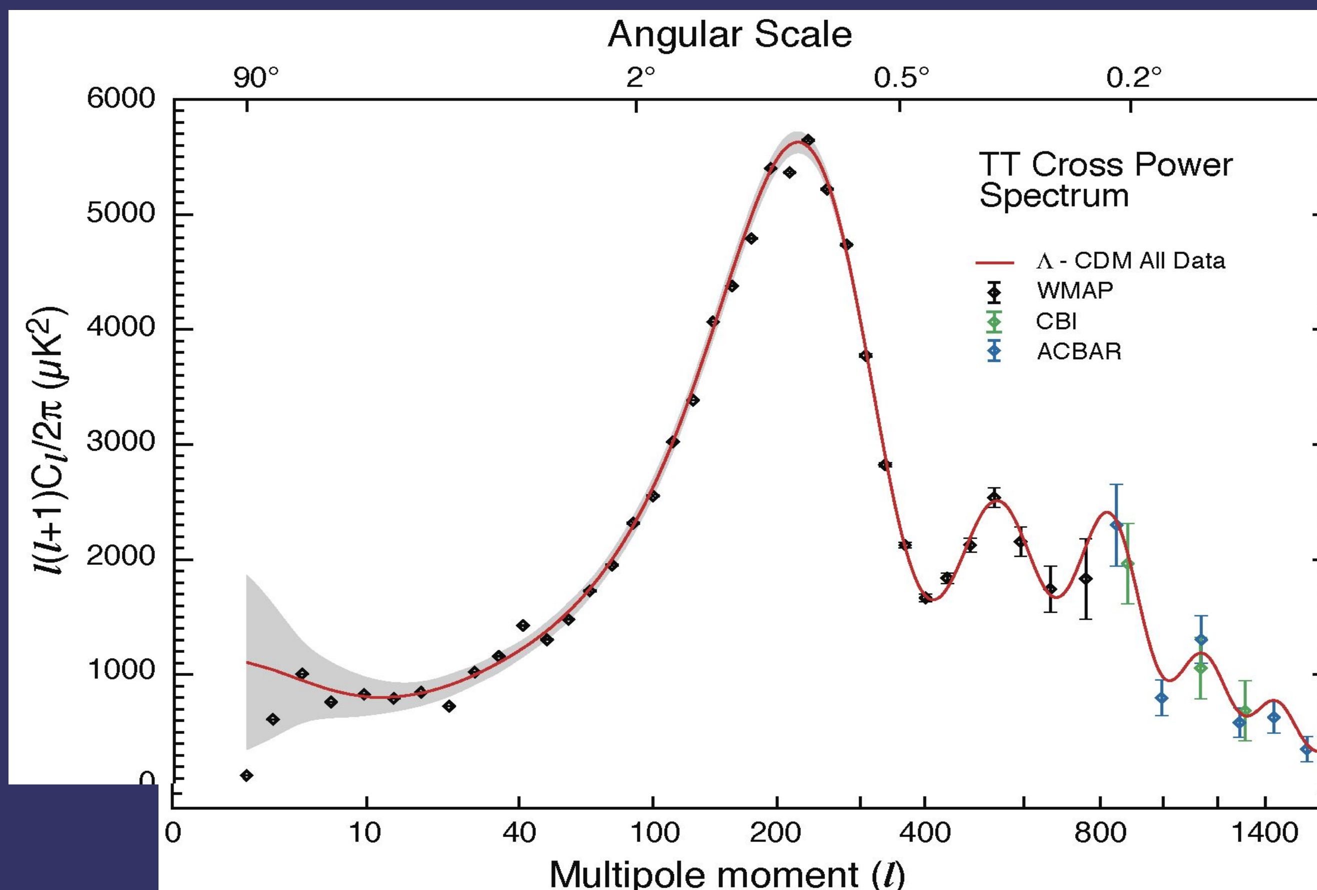


$\Omega_\nu = 0.05$
0.01
0.00
10^5
10^4
10^3
0.01
0.10
$P_g(k)$ (h^{-3} Mpc^3)
k (h Mpc^{-1})


II Materie Dichte Ω
d) Strukturbildung
Power-Spektrum
Wachstum von Dichtefluktuationen
δρ/ρ
⇒ Ω_m ~ 0,3
Ω_HDM/Ω_CDM max 15%
m
M
L
Kollaps Zeit ~ free fall time t_ff ≠ L
Jeans Länge λ_J = t_ff v_s
L << λ_J → Dichte oszillationen
kein δρ/ρ Wachstum
L > λ_J → Kollaps
v_s ~ kT/m_Teilchen
~ c relativistische Teilchen
hot dark matter HDM
λ_J groß
→ Wachstum auf kleinen Skalen unterdrückt
cold dark matter CDM


$m_\nu = 0$ eV
$m_\nu = 1$ eV
$m_\nu = 7$ eV
$m_\nu = 4$ eV




Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ (μK^2)
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
0
10
40
100
200
400
800
1400
Multipole moment (l)

Neutrinos als DM

$N_\nu = 113\ \mathrm{cm}^{-3}$

$\Rightarrow \Omega_\nu = \frac{\sum m_\nu c^2}{47\,\mathrm{eV}}$

ν sind HDM

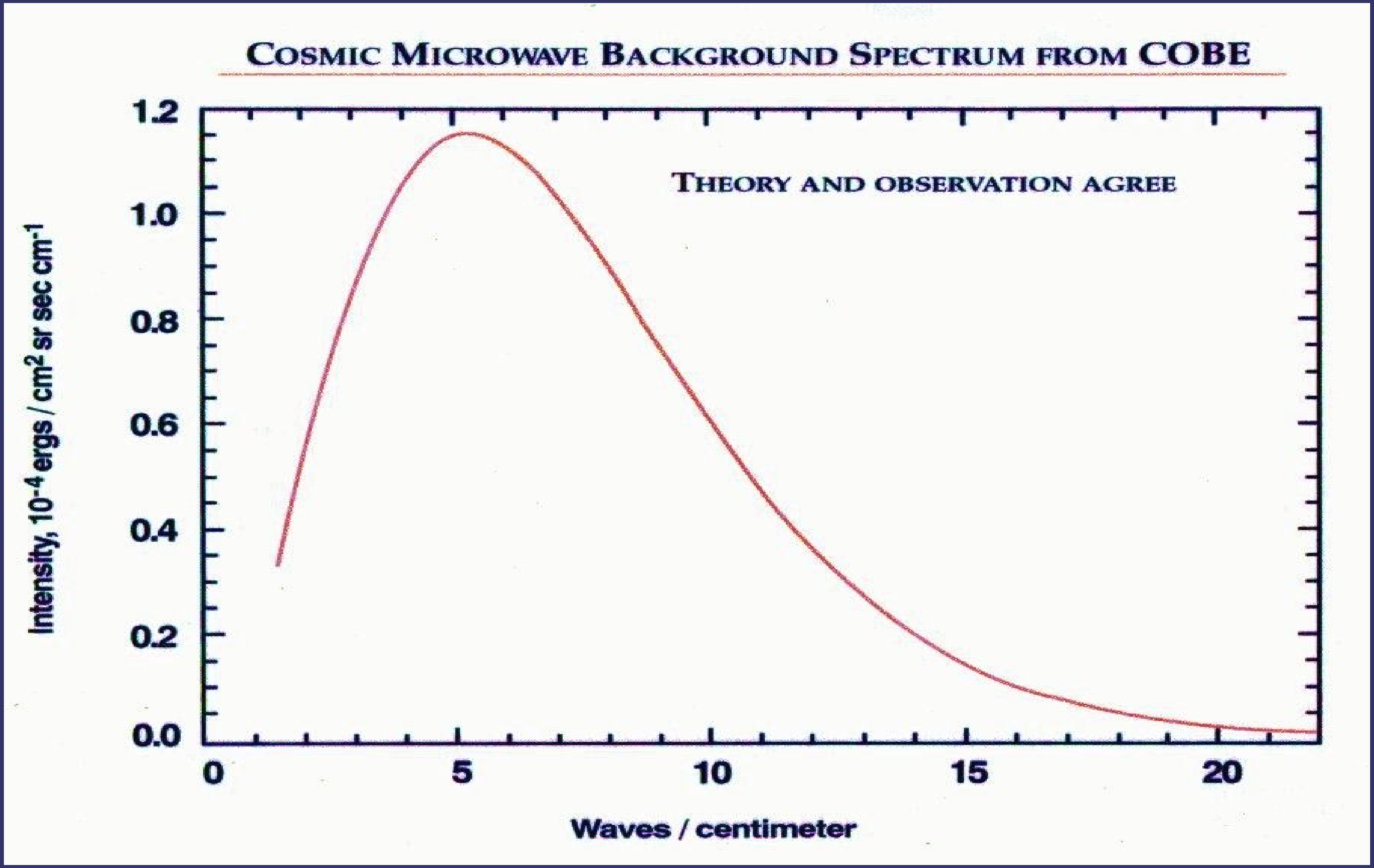
$\Omega_m \cong 0{,}3$

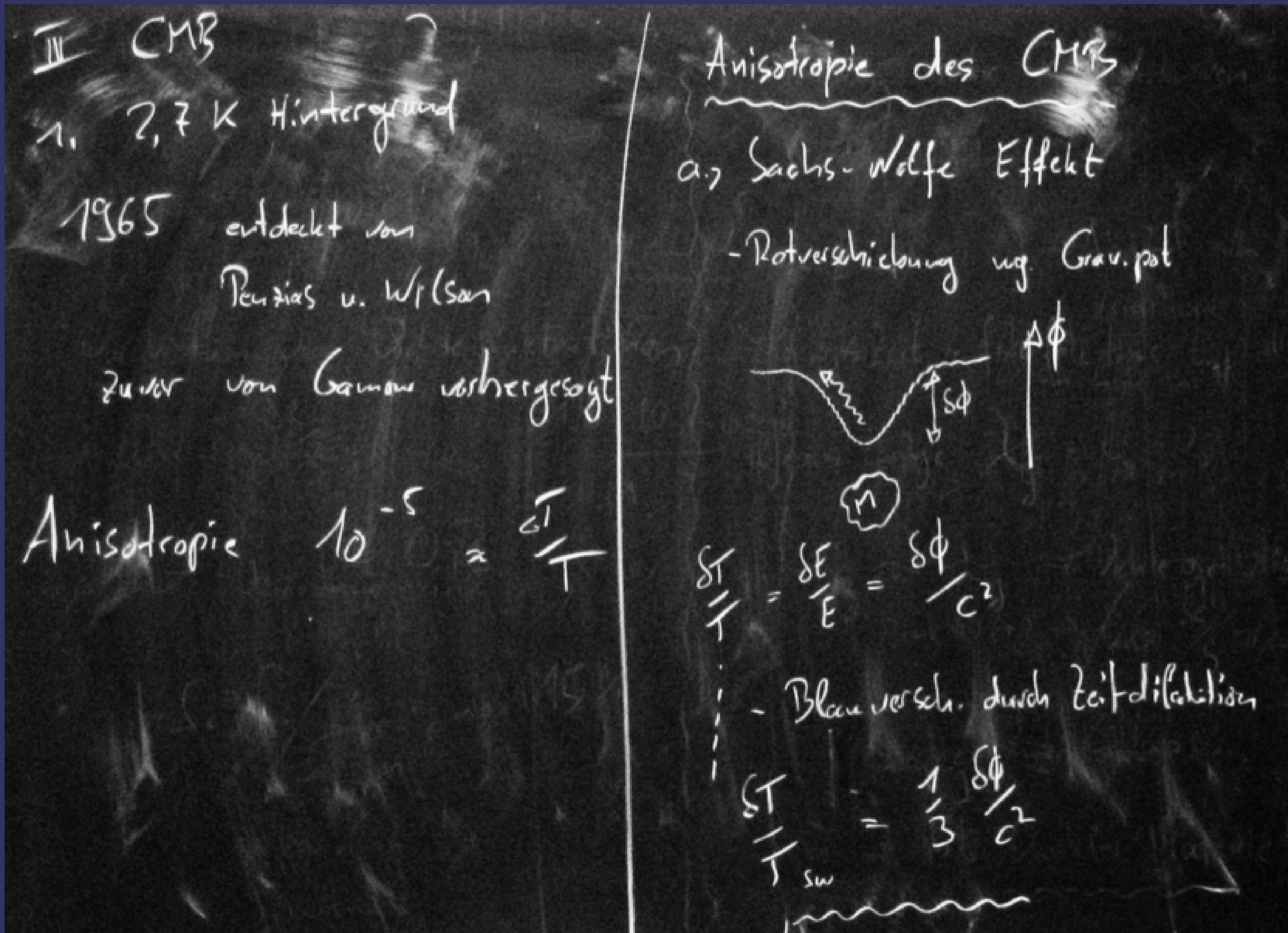
hauptsachlich CDM

$\Rightarrow$ max 15% HDM

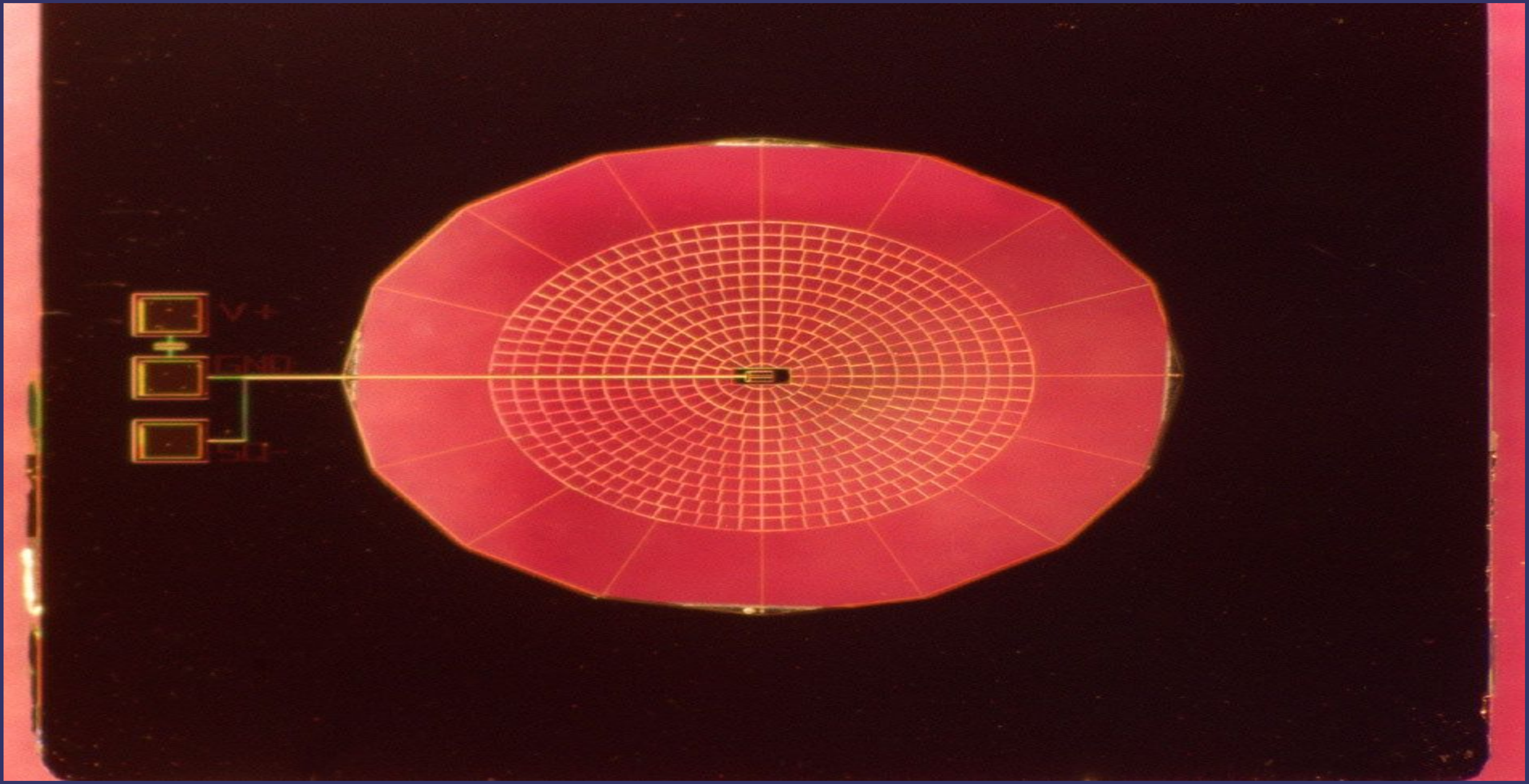
COBE - FIRAS

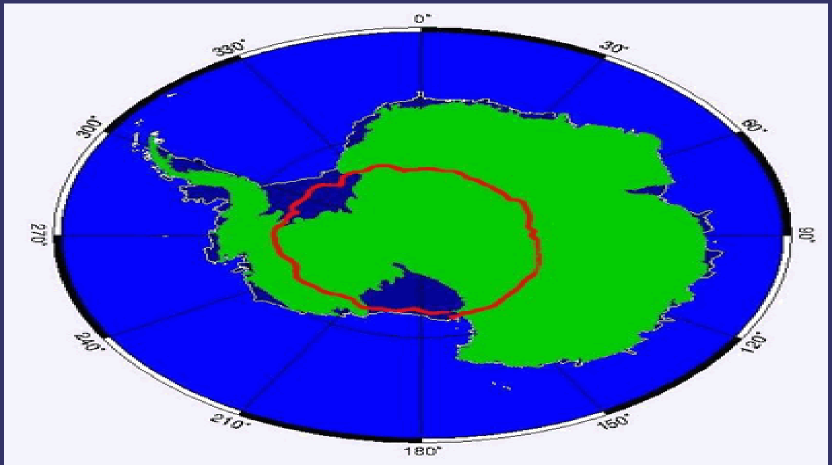

ONE CENT

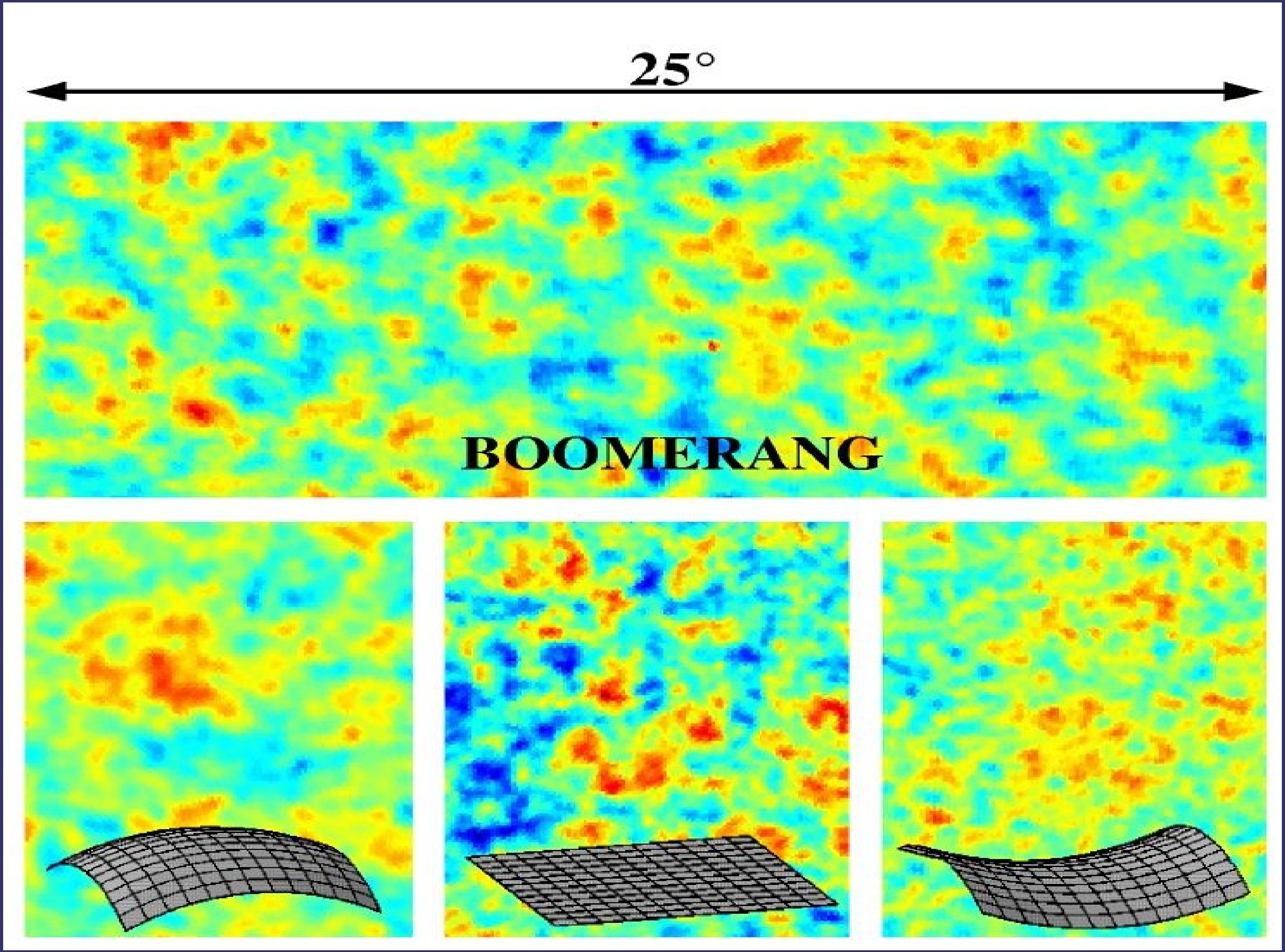

COSMIC MICROWAVE BACKGROUND SPECTRUM FROM COBE
THEORY AND OBSERVATION AGREE
Intensity, 10^{-4} ergs / cm^2 sr sec cm^{-1}
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
Waves / centimeter

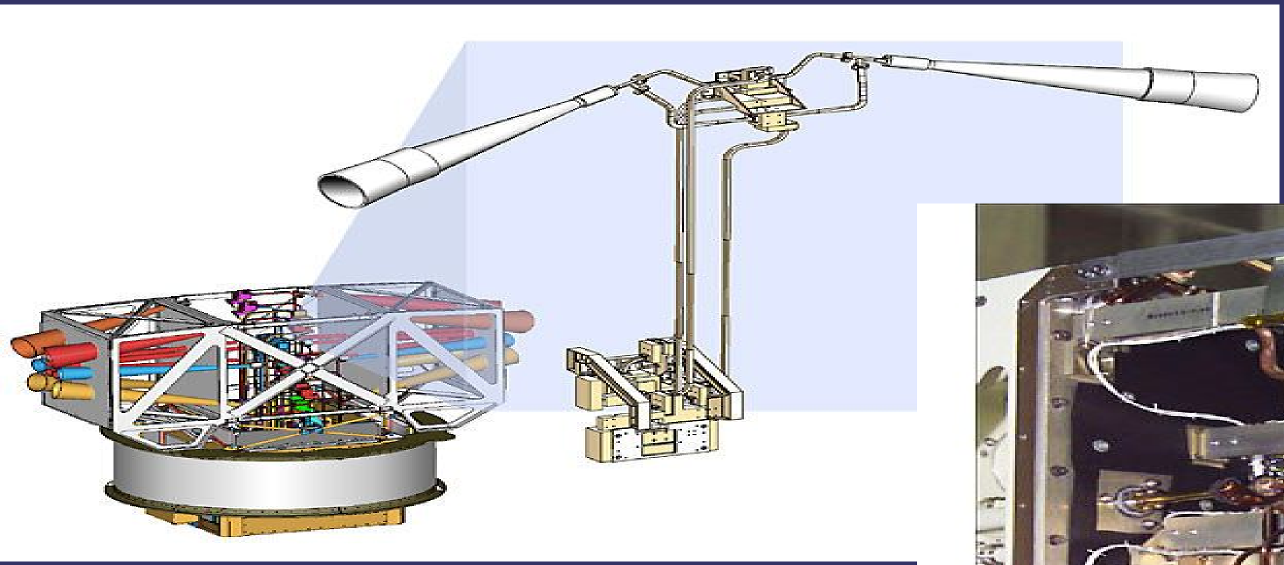

IV CMB
1. 2,7 K Hintergrund
1965 entdeckt von
Penzias u. Wilson
zuvor von Gamow vorhergesagt
Anisotropie $10^{-5} \approx \delta T / T$
Anisotropie des CMB
a.) Sachs-Wolfe Effekt
- Rotverschiebung wg. Grav.pot
$\Delta\phi$
$\delta\phi$
M
$\delta T / T = \delta E / E = \delta\phi / c^2$
- Blauversch. durch Zeitdilatation
$\delta T / T_{SW} = \frac{1}{3} \, \delta\phi / c^2$

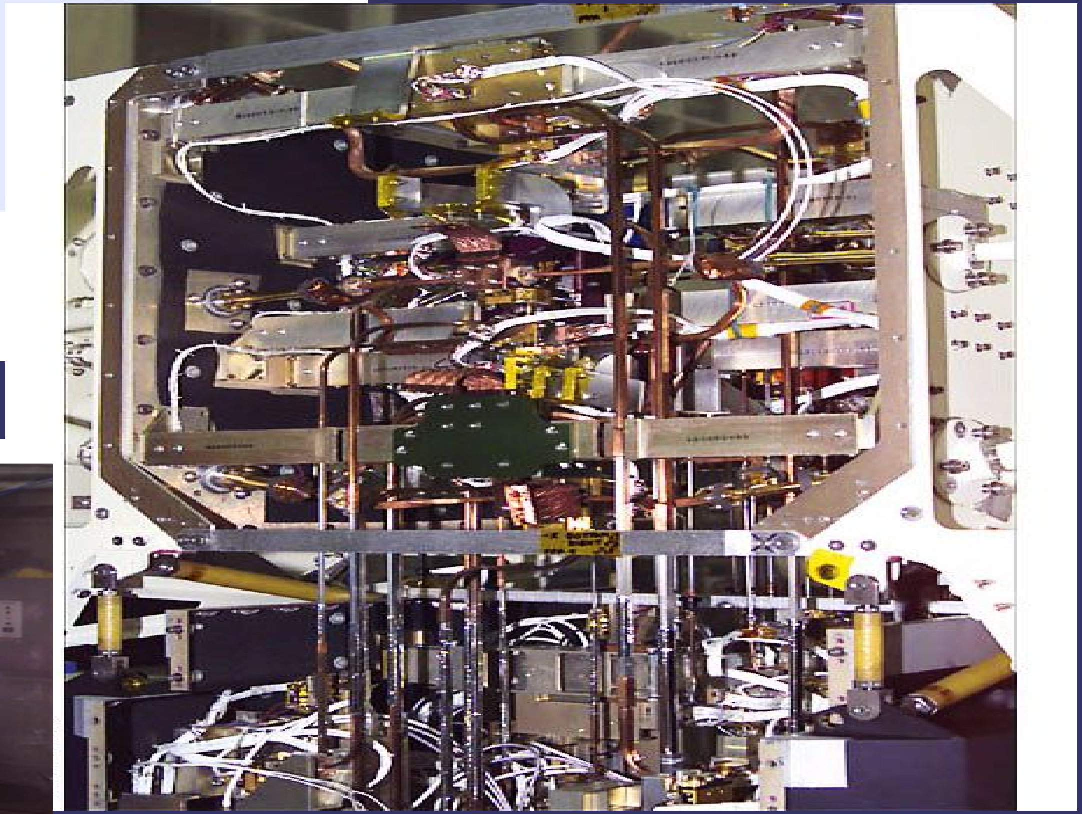
Boomerang

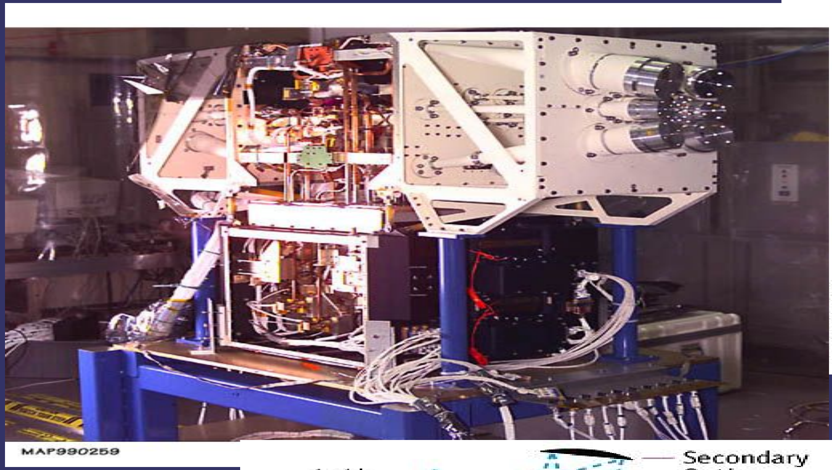


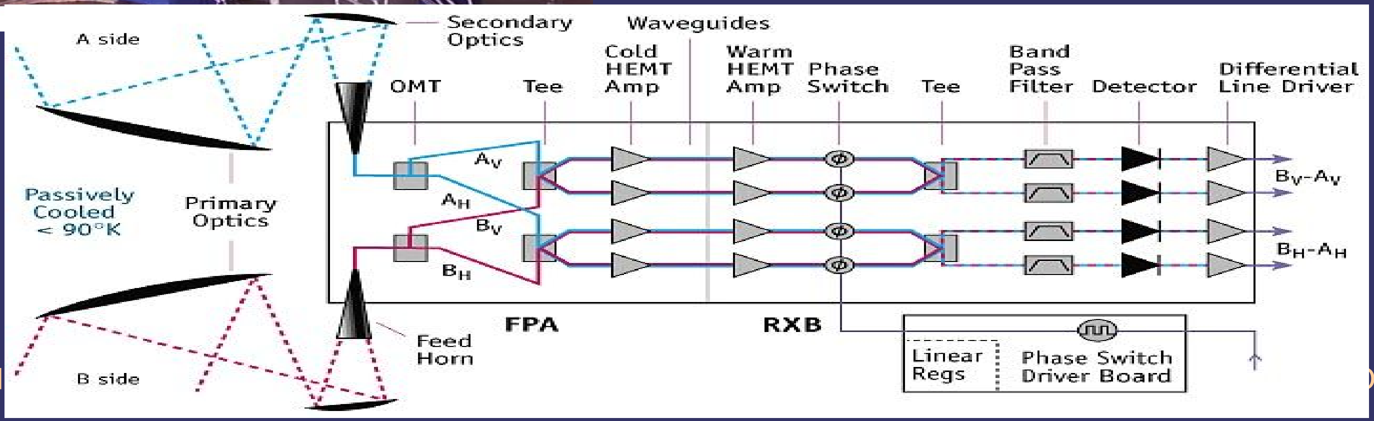

0°
30°
60°
90°
120°
150°
180°
210°
240°
270°
300°
330°

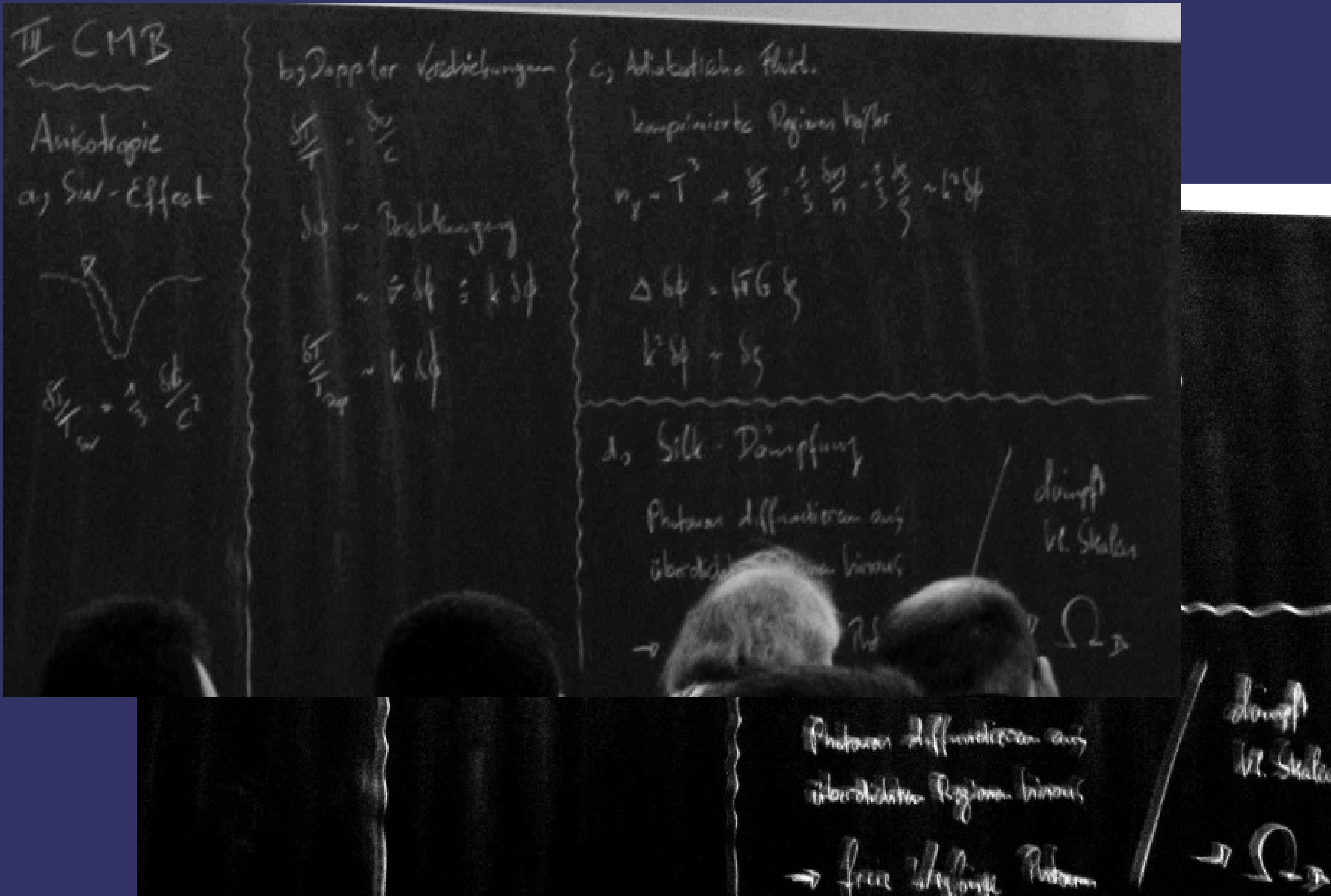

25°
BOOMERANG

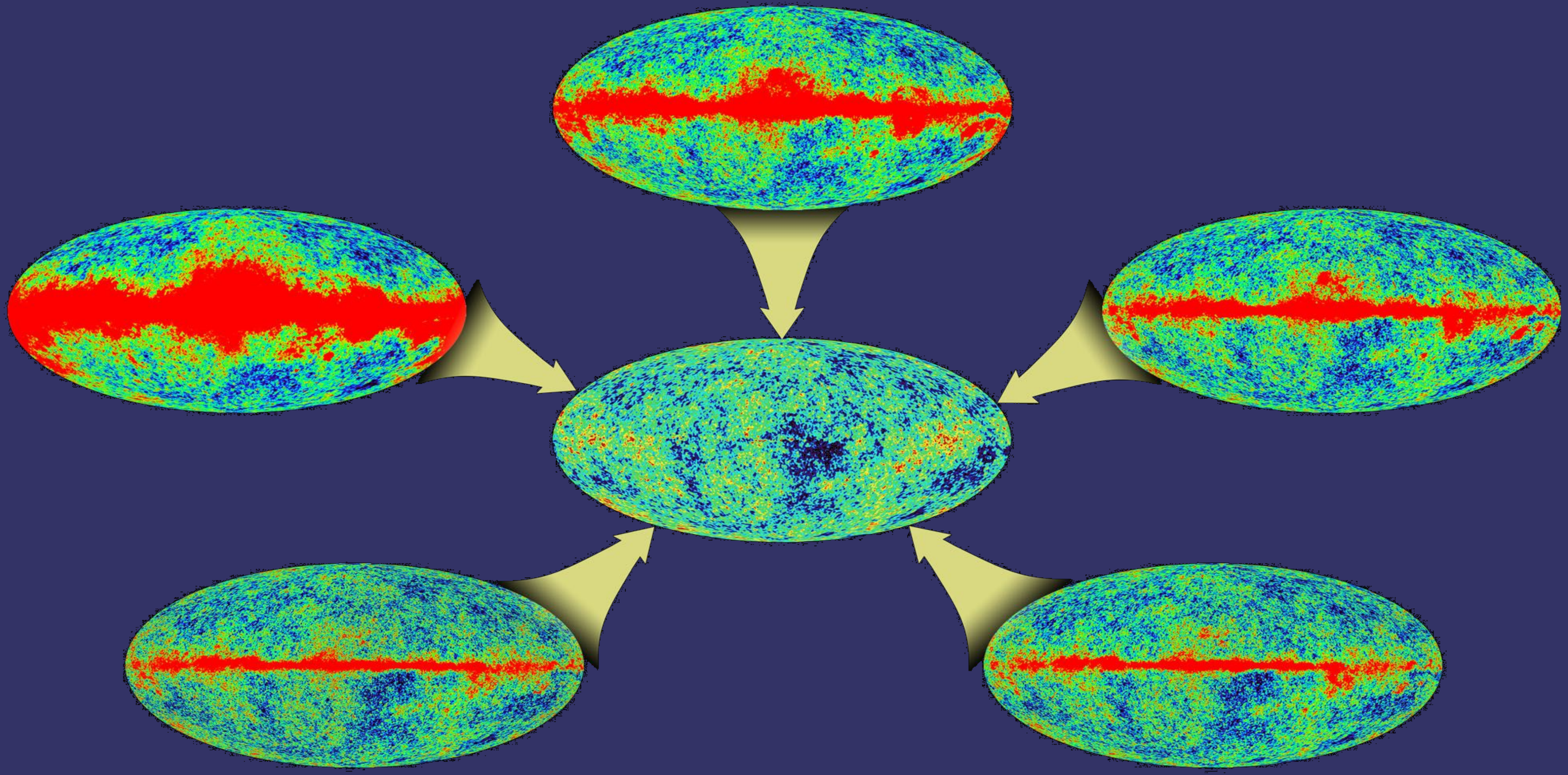


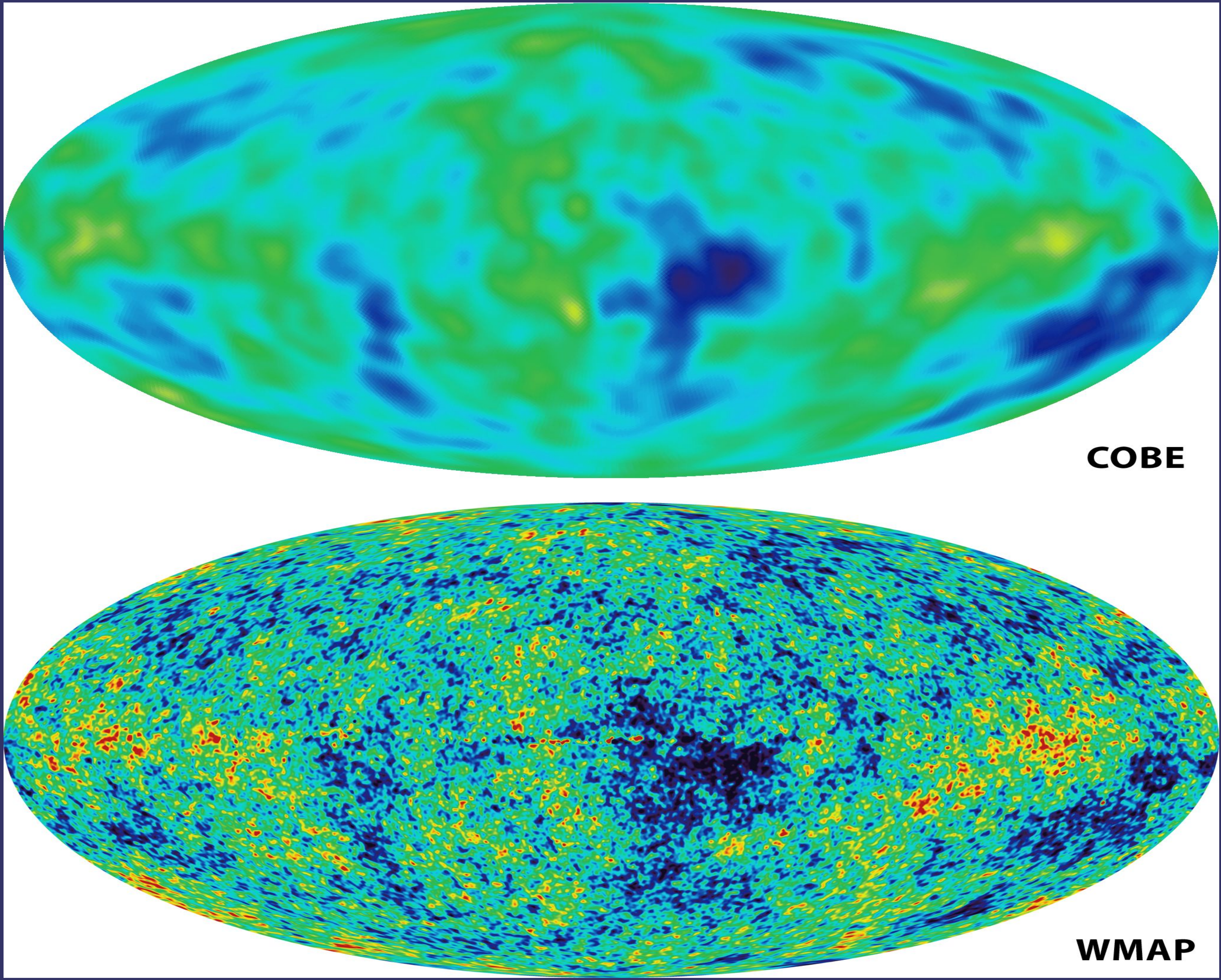


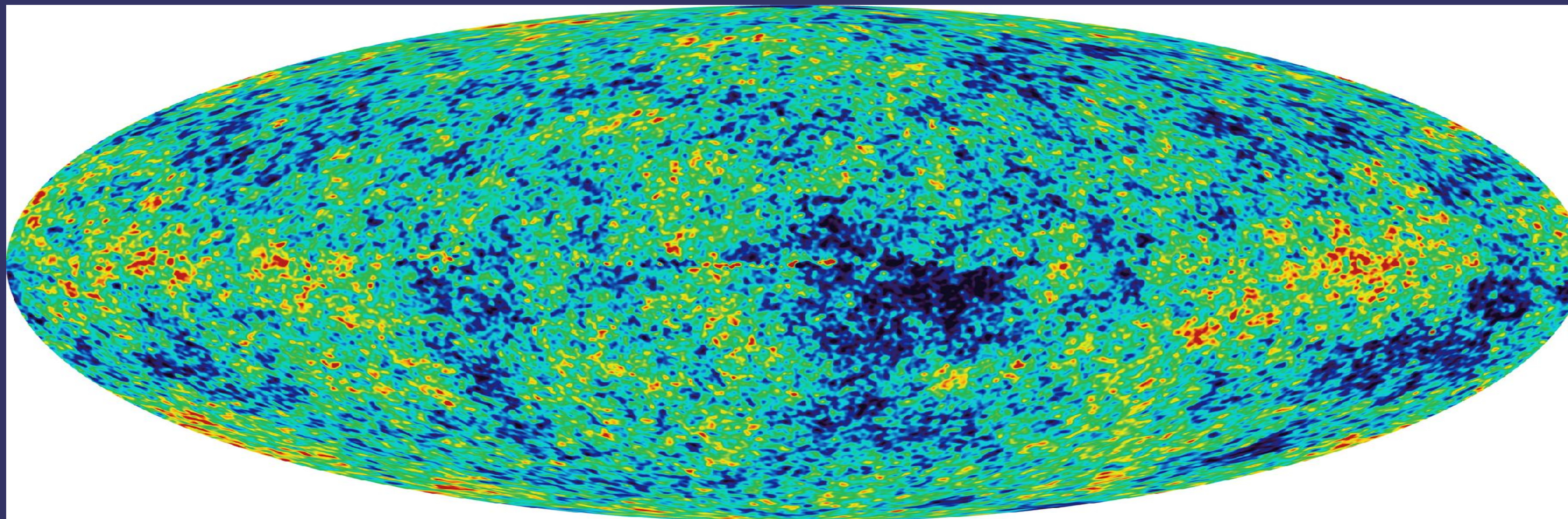

MAP990259

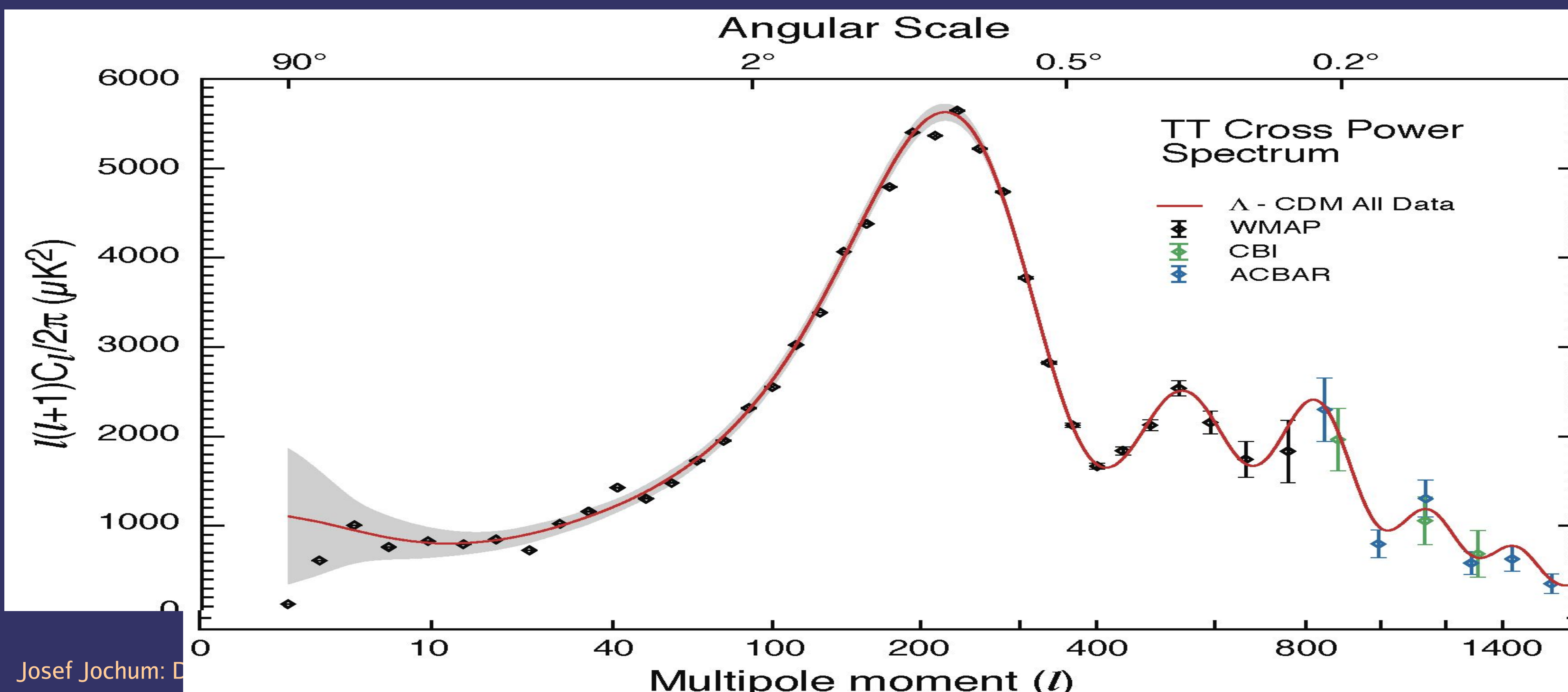

A side
Secondary Optics
Waveguides
Cold HEMT Amp
Warm HEMT Amp
Phase Switch
Band Pass Filter
Detector
Differential Line Driver
OMT
Tee
Tee
A_V
A_H
B_V
B_H
$B_V - A_V$
$B_H - A_H$
Passively Cooled < 90°K
Primary Optics
FPA
RXB
Feed Horn
Linear Regs
Phase Switch Driver Board
B side


III CMB
Anisotropie
a) SW-Effect
b) Doppler Verschiebungen
c) Adiabatische Fluct.
d) Silk-Dämpfung
Photonen diffundieren aus überdichteten Regionen hinaus
→ freie Weglänge Photonen
dämpft kl. Skalen




COBE
WMAP





Angular Scale
90°
2°
0.5°
0.2°
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
$l(l+1)C_l/2\pi\ (\mu K^2)$
6000
5000
4000
3000
2000
1000
0
0
10
40
100
200
400
800
1400
Multipole moment (l)