

„Frontiers of extragalactic astrophysics“

SoSe 2009

Silke Britzen

Max-Planck-Institut für Radioastronomie
Bonn

Tel.: 0228 525 280

E-mail: sbritzen@mpifr-bonn.mpg.de

Internet: <http://www.mpifr-bonn.mpg.de/staff/sbritzen/>

Programm SoSe 09

03.04.	Überblick über die Themen des Semesters
17.04.	Die Konstanz der Naturkonstanten
08.05.	Aus aktuellem Anlass: Planck & Herschel
22.05.	Äquivalenzprinzip & Schleifen-Quantengravitation
05.06.	Zeitreisen
19.06.	Gibt es Extraterrestrisches Leben?
03.07.	

The background of the slide is a colorful map of the Cosmic Microwave Background (CMB) radiation. It shows a complex pattern of temperature fluctuations across the sky, with colors ranging from dark blue (cooler) to red and yellow (warmer). The map is centered on the Earth, with the Milky Way galaxy visible as a bright, curved band of light.

Nachtrag zur letzten Vorlesung:

- Dunkle Energie (m^2)
- Dunkle Materie & das Sonnensystem
- Frame dragging

Heute:

- Planck & Herschel



Nachtrag zur letzten Vorlesung:

- Dunkle Energie (m^2)
- Dunkle Materie & das Sonnensystem
- Frame dragging

Grundlegende Probleme der Physik

- Um nur einige zu nennen:
 - Dunkle Energie (74% der Gesamtenergie, Natur völlig unklar, möglicherweise kosmologische Konstante aus den Einsteinschen Feldgleichungen; aus Beobachtungen von Supernovae Ia und der kosmischen Hintergrundstrahlung erhält man einen Wert von ca. 10^{-52}m^2)
 - Dunkle Materie (22% der Gesamtenergie; Natur unbekannt; Feldgleichungen für die Gravitation abändern?)
 - Pioneer-Anomalie (Beschleunigung der Pioneer-Sonden, deren beobachtete Daten eine Anomalie zeigen)

Kosmologische Konstante

Die **kosmologische Konstante** (gewöhnlich durch das große griechische Lambda Λ abgekürzt) ist eine physikalische Konstante in Albert Einsteins Gleichungen der allgemeinen Relativitätstheorie, welche die Gravitationskraft als geometrische Krümmung der Raumzeit beschreibt. Die Einheit von Λ ist $1/\text{m}^2$, ihr Wert kann a priori positiv, negativ oder null sein.



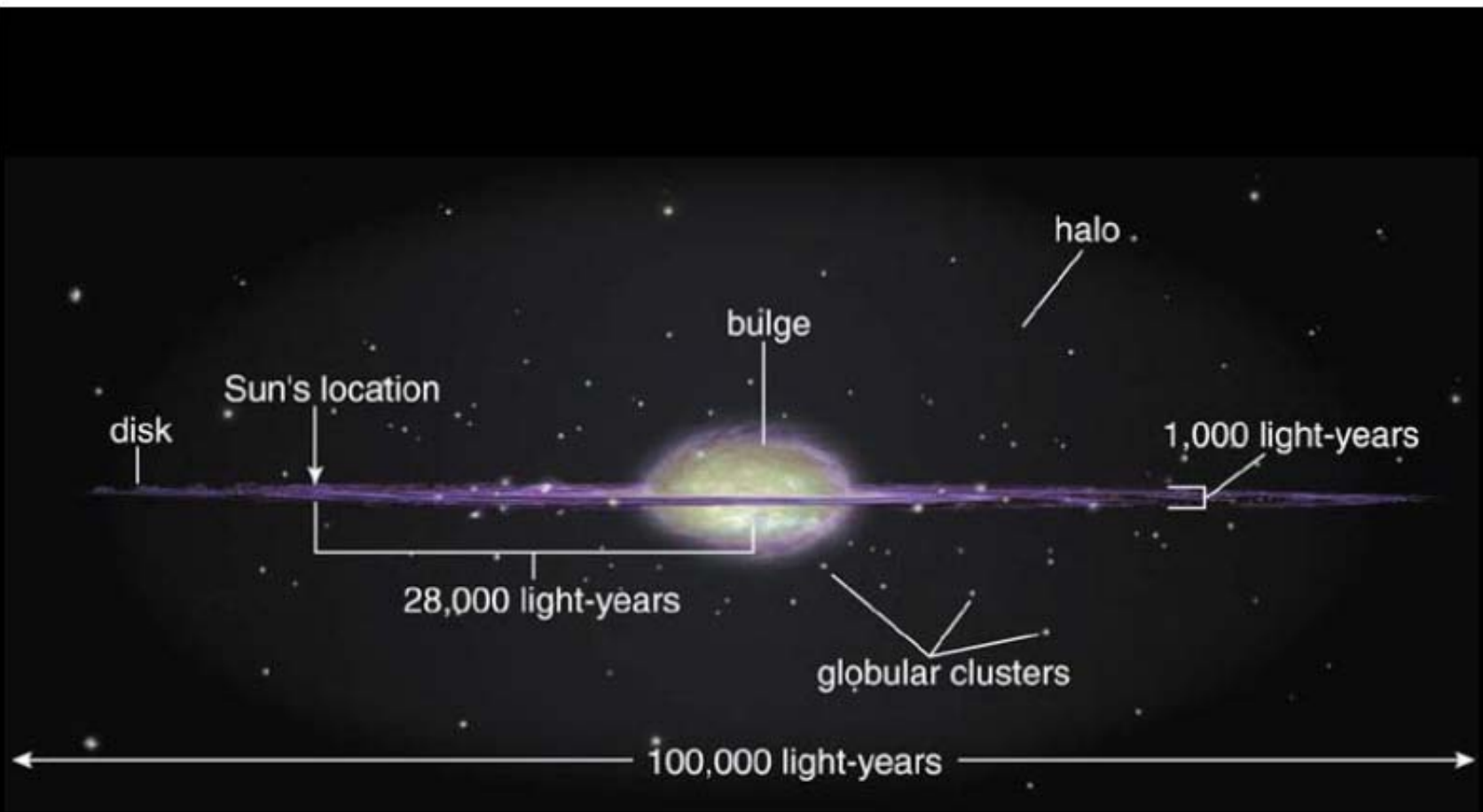
Nachtrag zur letzten Vorlesung:

- Dunkle Energie (m^2)
- Dunkle Materie & die Milchstraße
- Frame dragging

Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

Aus diesen Überlegungen geht hervor, dass die grosse Streuung der Geschwindigkeiten im Comasystem (und in anderen dichten Nebelhaufen) ein noch nicht geklärtes Problem in sich birgt.

Fritz Zwicky (1933)

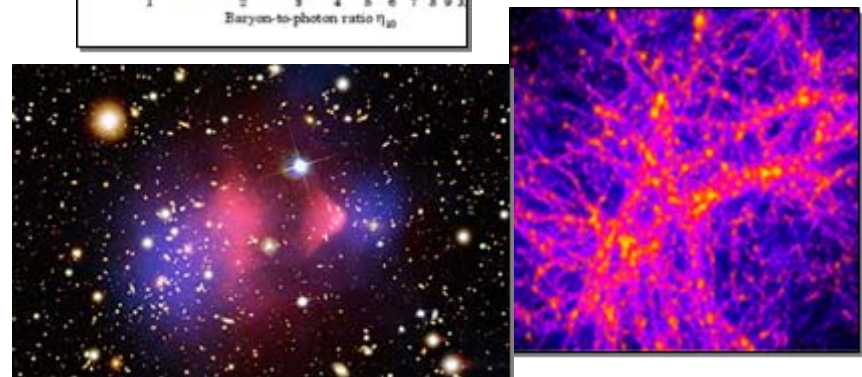
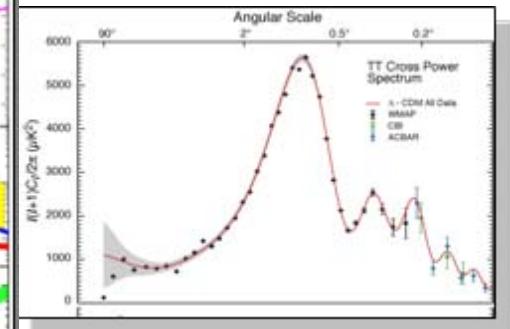
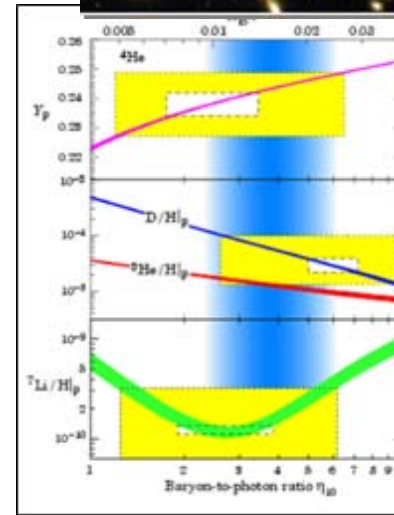


Edge-On View

Evidence For Dark Matter

- Galactic rotation curves
- Gravitational lensing
- Light element abundances
- CMB anisotropies
- Large scale structure
- Etc...

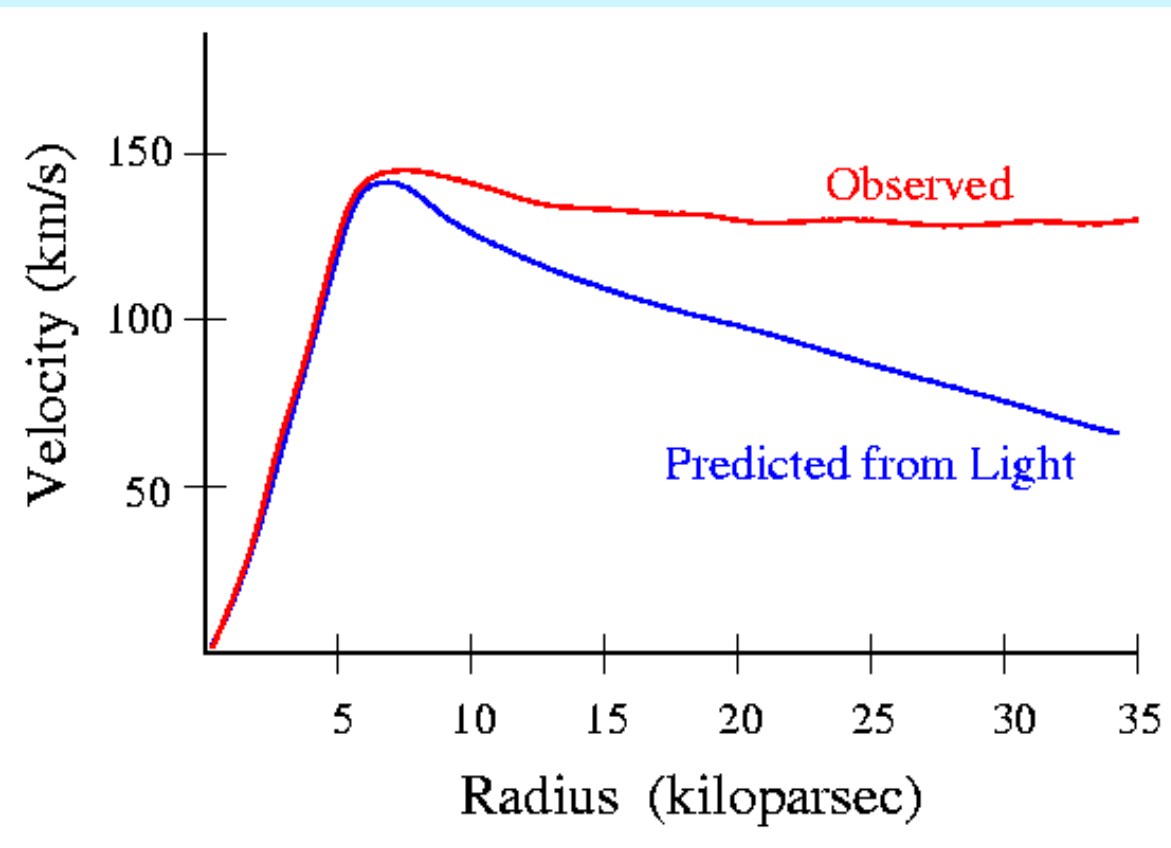
-Cold,
-Non-baryonic,
-Collisionless



Dynamically Estimating Galaxy Masses

According to Newton's laws, once outside a galaxy, the rotation velocity of gas should decrease with distance, but that's not observed.

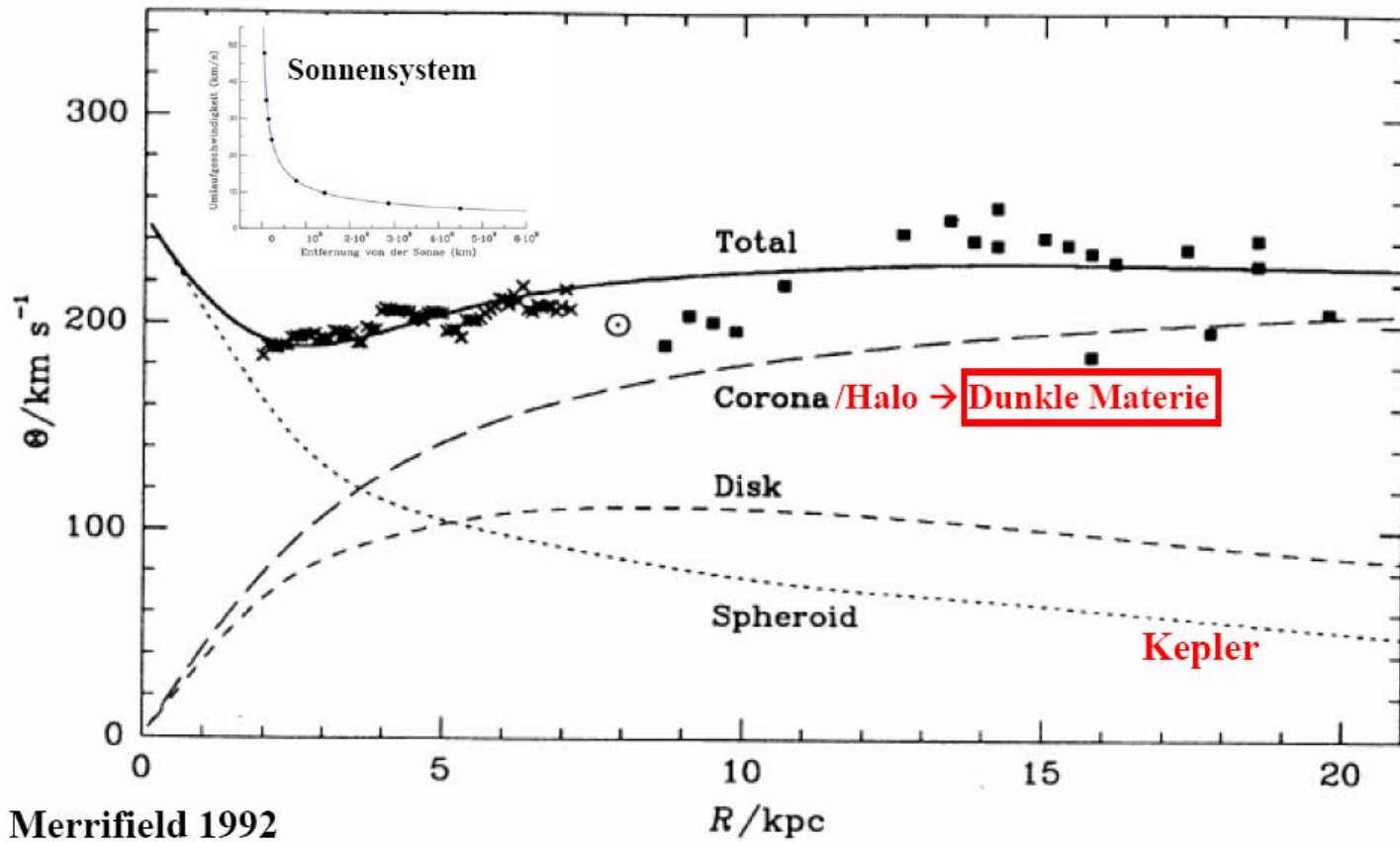
$$v = 2\pi\sqrt{M} \cdot \frac{1}{\sqrt{r}}$$



There must be a lot of mass in the outer regions of galaxies that we are not observing.

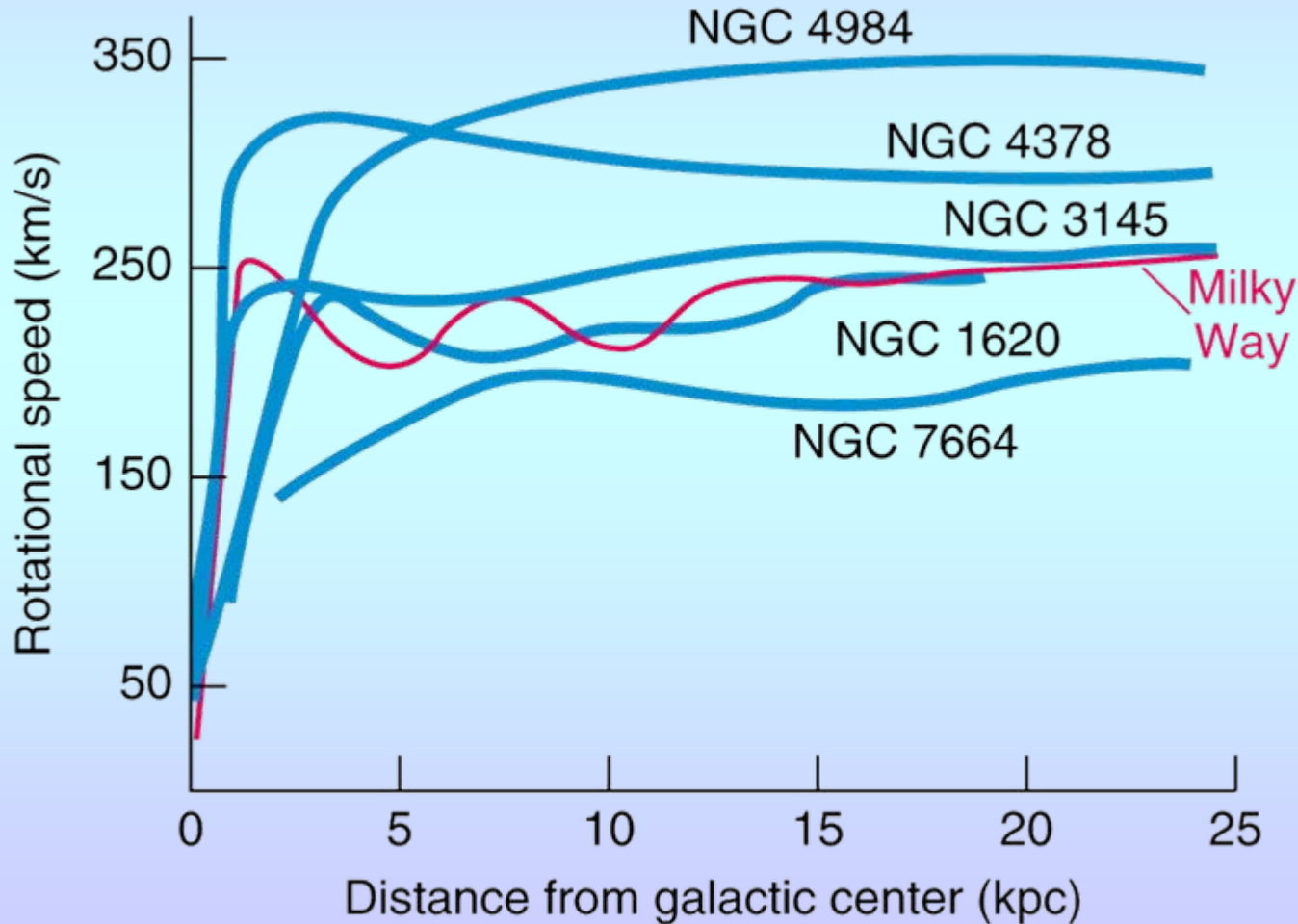
This is the galactic **dark matter**.

Rotationskurve der Milchstrasse



Dynamically Estimating Galaxy Masses

Virtually all spiral galaxies have these “flat” **rotation curves**. The outer regions of spirals are dominated by **dark matter**.



Constituents of the Galaxy

- Interstellar Medium
 - Atomic Hydrogen – **H I**
 - Molecular Hydrogen – **H₂**
 - ▶ Traced by the molecule **CO**
 - Ionized Hydrogen – **H II**
 - Dust
- Stars
 - Population I
 - Population II
- **Dark Matter**

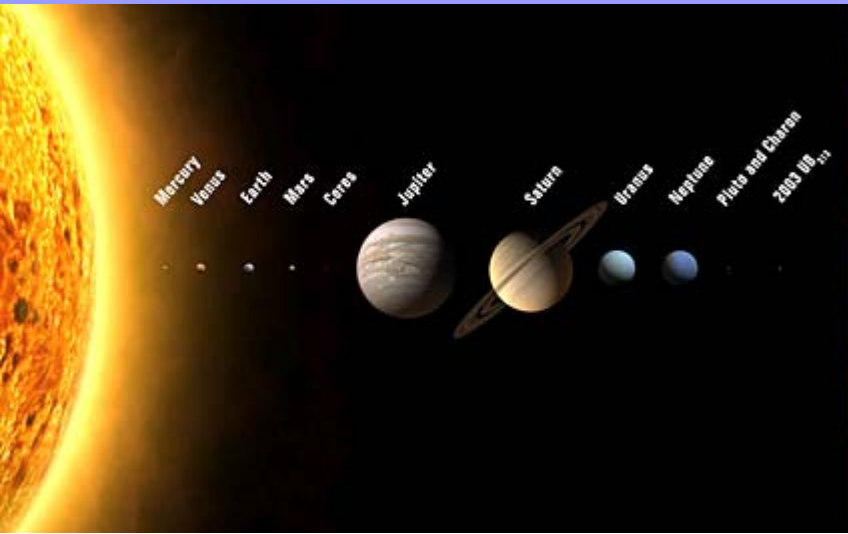
In fact, ~85% of the Milky Way's mass is **DARK!**



Nachtrag zur letzten Vorlesung:

- Dunkle Energie (m^2)
- Dunkle Materie & die Milchstraße
 - Wo sollte sie zu finden sein?
- Frame dragging

Dunkle Materie & das Sonnensystem



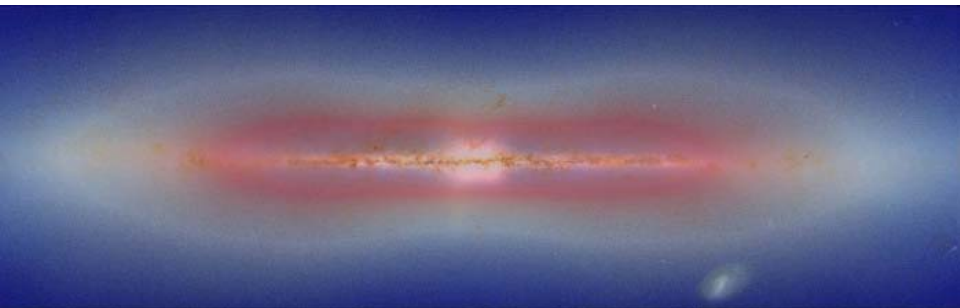
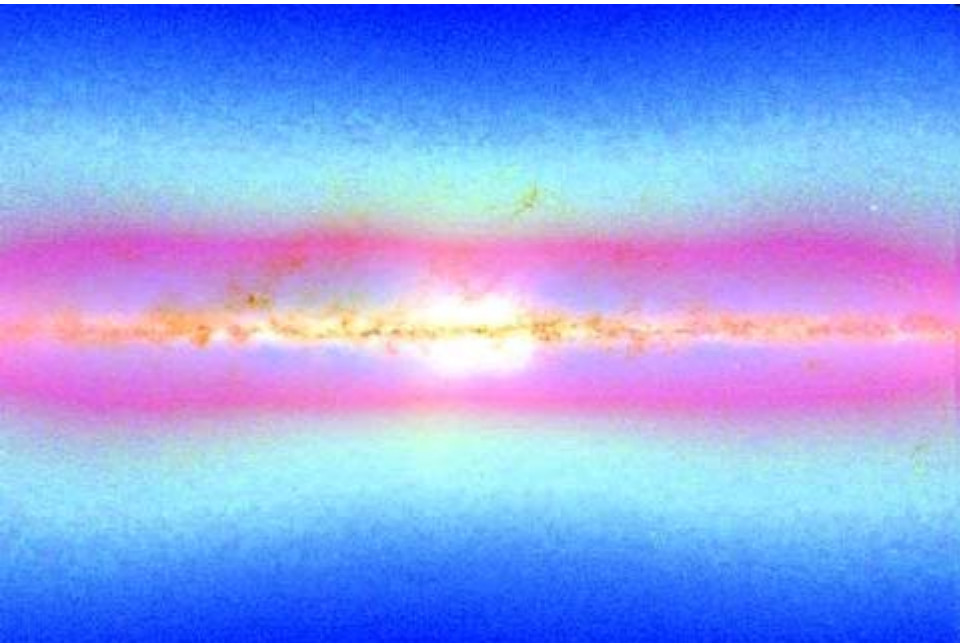
- Sonnensystem beinhaltet laut Forschung von Siegel und Xu 300mal mehr Dunkle Materie als das galaktische Halo-Mittel, 16000 mal dichter als der Hintergrund an Dunkler Materie
- Modellrechnungen
- Vergleich mit Autofahrt durch Schneefall – Schnee bleibt nicht überall liegen
- Dunkle Materie auch im Sonnensystem nicht gleichmäßig verteilt – einige Planeten haben mehr Dunkle Materie um sich herum als andere
- Kein großer Effekt auf Planetenbewegung und erklärt nicht die Pioneer Anomalie

Dunkle Materie in der Milchstraße



- Computersimulationen: Strukturen Dunkler Materie in der Milchstraße detektiert, Dunkle-Materie Sub-Halos, Ströme Dunkler Materie, Dunkle-Materie Klumpen, viele in der Nähe des Sonnensystems
- Jede Galaxie sitzt in einem Halo aus Dunkler Materie, Halos sind nicht gleichförmig sondern haben interne Struktur
- Simulation mit einer Milliarde an Teilchen vom Urknall bis heute verfolgt
- 40 000 Sub-Halos wurden aufgelöst
- WIMPs (weakly interacting massive particles) würden miteinander wechselwirken, sich auslöschen und Gammastrahlung aussenden – sollte mit FERMI detektierbar sein

Scheibe aus Dunkler Materie



- Die Scheibe der Dunklen Materie (lila) und die darin eingebettete Milchstrasse
- Scheibe dreht sich synchron mit den Spiralarmen und Sternen um das Galaxienzentrum
- Simulationsrechnungen
- Scheibe besitzt nur die Hälfte der Dichte der im Halo angehäuften Dunklen Materie
- Sterne und Gas sollen sich in der Frühzeit des Universums in Scheiben angesammelt haben und damit auch beeinflusst haben, wie sich kleine Halos aus Dunkler Materie bilden. Die meisten Klumpen versammelten sich in unserer Nähe, rund um die Milchstraße (Halo); die größten Klumpen bevorzugt in Richtung galaktischer Ebene und wurden auseinander gerissen (Scheibe)



Nachtrag zur letzten Vorlesung:

- Dunkle Energie (m^2)
- Dunkle Materie & die Milchstraße
 - Wie kann man sie detektieren?
 - Wie läßt sich die Natur der Dunklen Materie entschlüsseln?
- Frame dragging

The Indirect Detection of Dark Matter

1. WIMP Annihilation

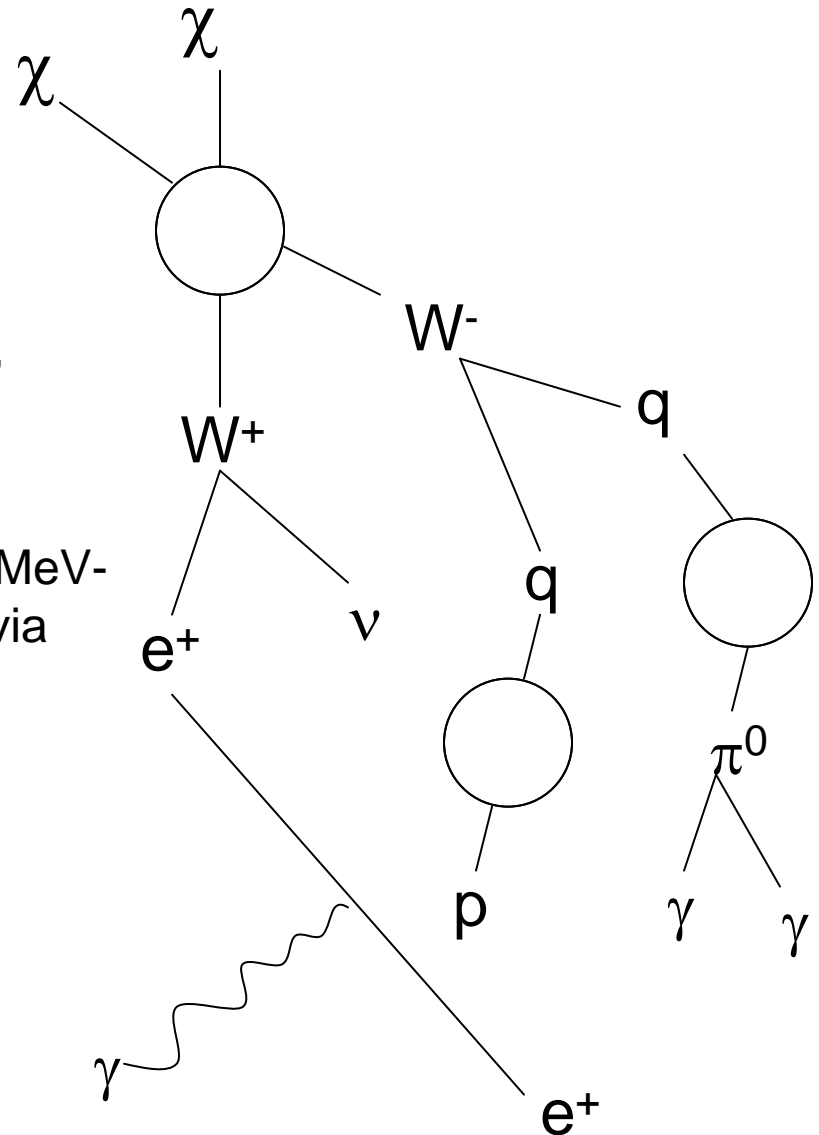
Typical final states include heavy fermions, gauge or Higgs bosons

1. Fragmentation/Decay

Annihilation products decay and/or fragment into combinations of electrons, protons, deuterium, neutrinos and gamma-rays

1. Synchrotron and Inverse Compton

Relativistic electrons up-scatter starlight/CMB to MeV-GeV energies, and emit synchrotron photons via interactions with magnetic fields





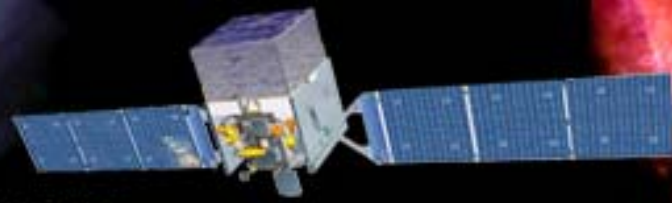
Fermi-Gamma-ray Space Telescope



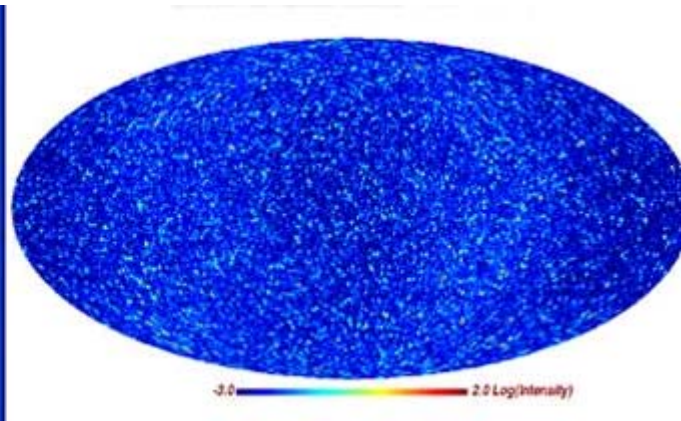
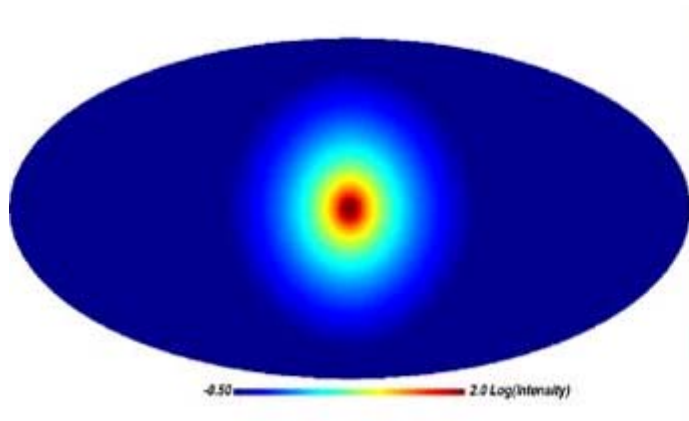
Fermi-GST launched on June 11, 2008

Fermi

Gamma-ray Space Telescope



- Mehr als eine Milliarde Teilchen in einer Dunkle-Materie Simulation, Annihilation im Halo sollte einen diffusen Hintergrund im Gamma-Bereich erzeugen, der mit Fermi nachgewiesen werden könnte – Hinweis auf die Natur der Dunklen Materie
- Wie intensiv wird die Strahlung sein?
- Wo wird sie zuerst entdeckt werden?
 - Zentrum der Milchstraße ungünstig (Störung durch Supernovae oder Gaswolken)
 - Innerhalb der Sonnenbahn
 - Zwerggalaxien?



Where To Look For Dark Matter With Fermi?

The Galactic Center

- Brightest spot in the sky
- Considerable astrophysical backgrounds

The Galactic Halo

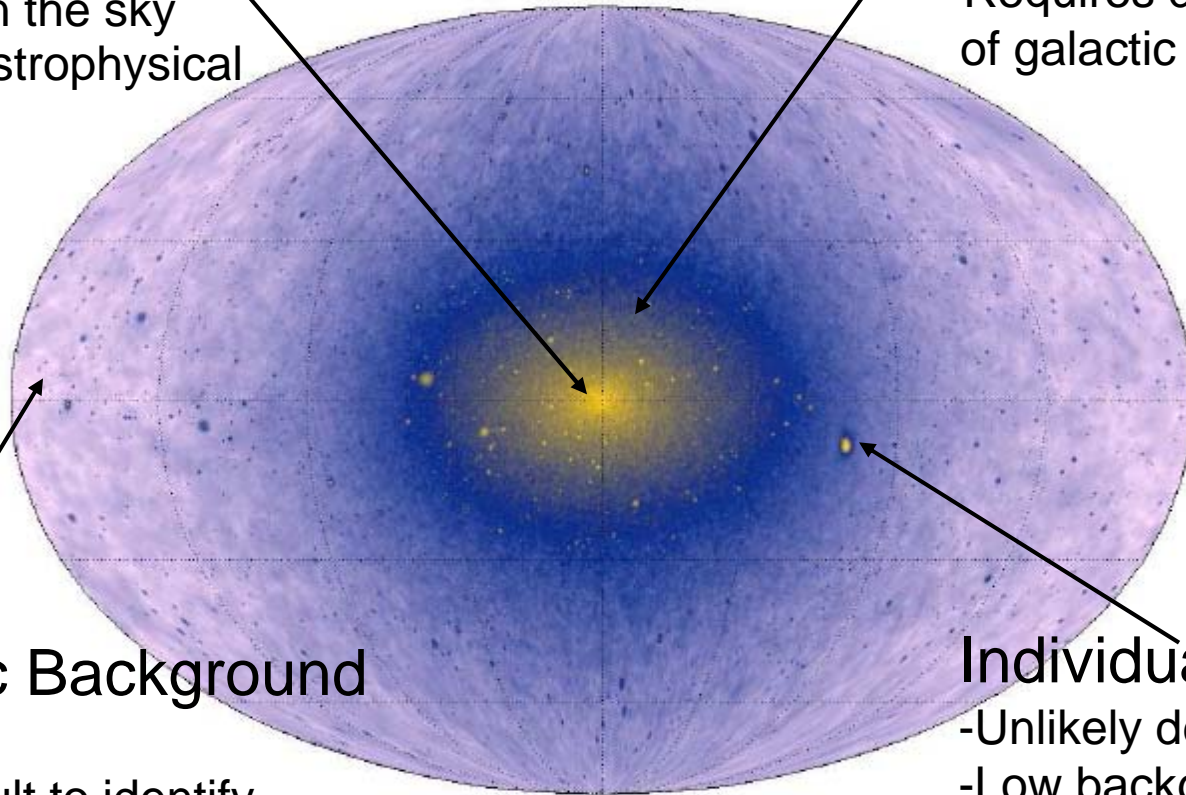
- High statistics
- Requires detailed model of galactic backgrounds

Extragalactic Background

- High statistics
- potentially difficult to identify

Individual Subhalos

- Unlikely detectable
- Low backgrounds





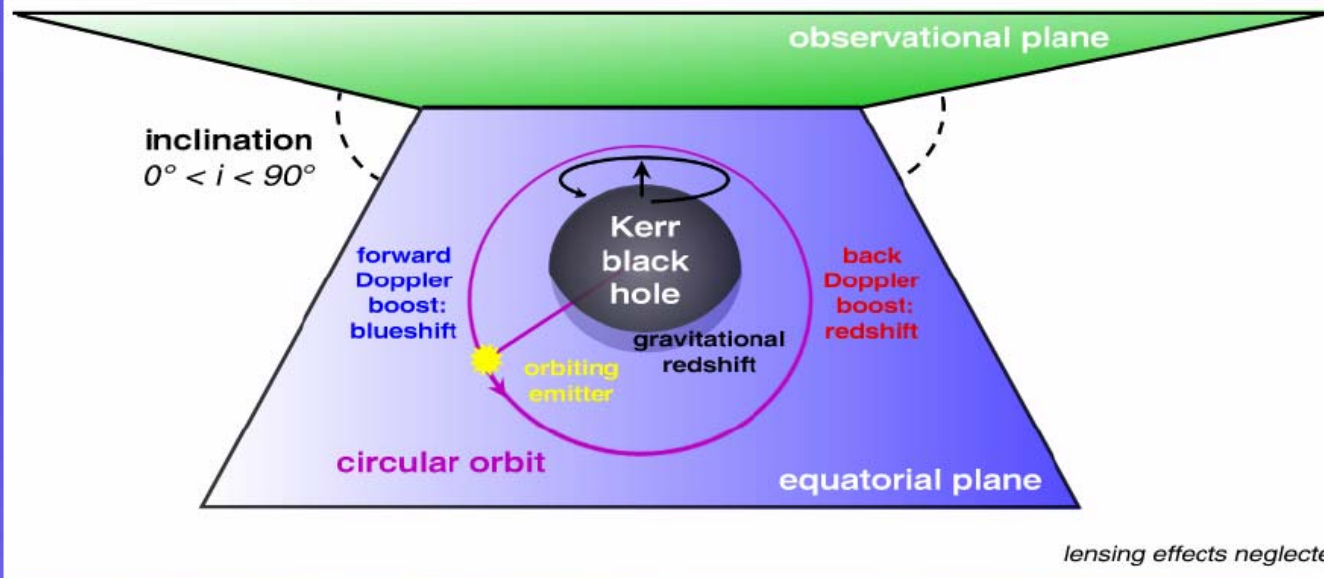
Nachtrag zur letzten Vorlesung:

- Dunkle Energie (m^2)
- Dunkle Materie & das Sonnensystem
- Frame dragging

Einsteins Doppler-Effekt

Orbiting a rotating black hole

generalized relativistic Doppler factor



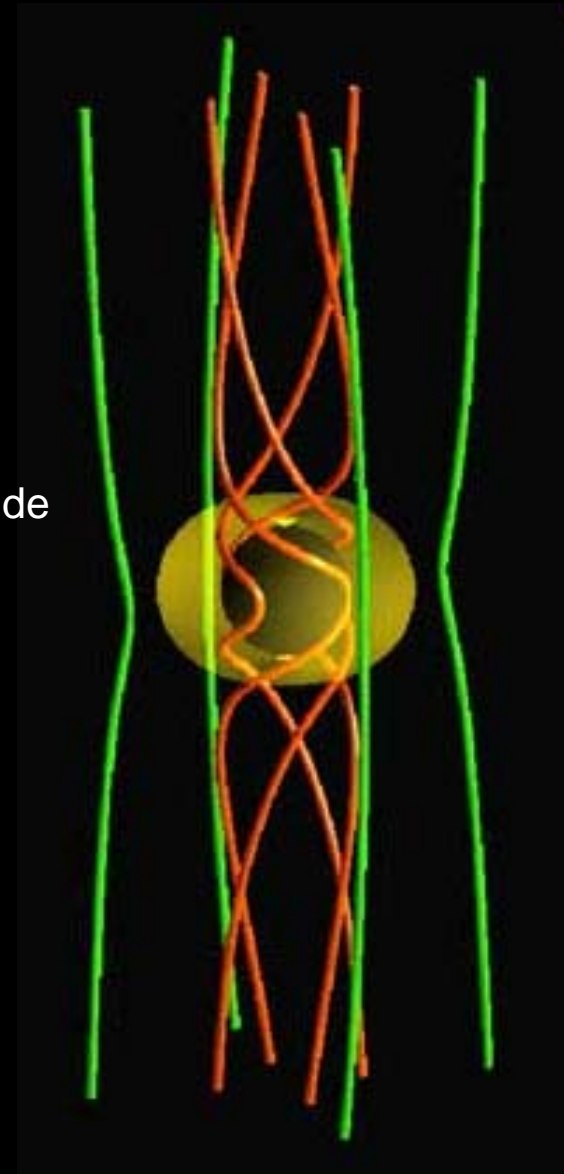
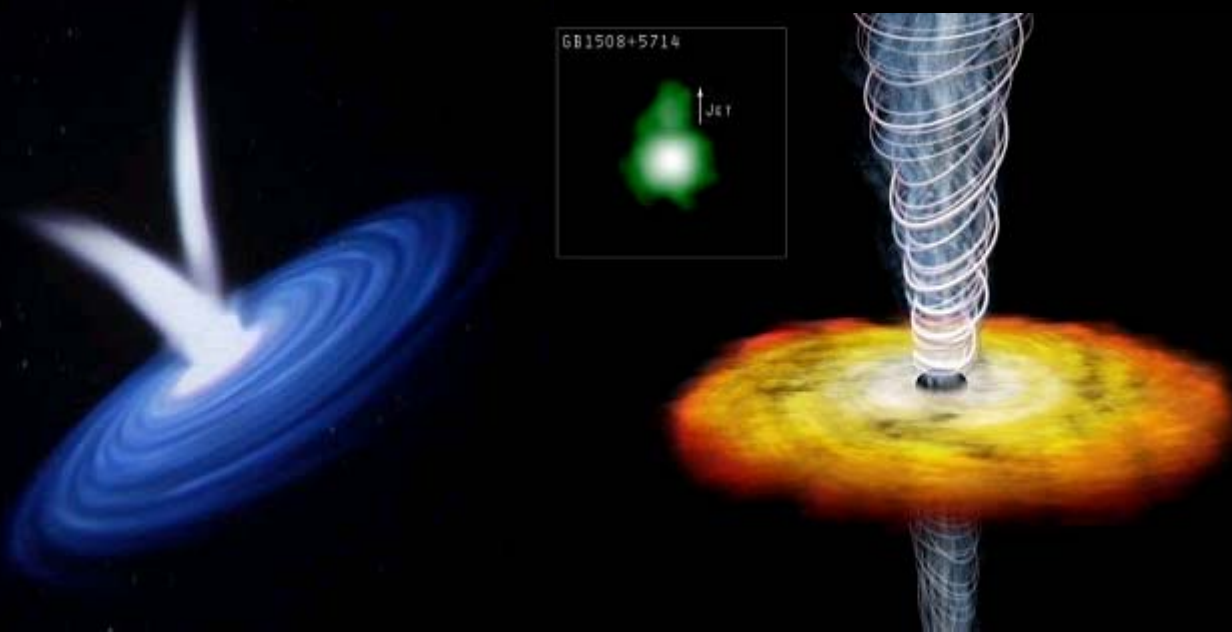
- Keplerbahnen bis zum Radius marginaler Stabilität
- Neigung ist Parameter mit stärkstem Einfluss

Rotierende Schwarze Löcher

Mikroquasar (sonnenähnlicher Stern + Schwarzes Loch)
dreht sich 950mal pro Sekunde



Neutronensterne rotieren mit maximal 1000 Umdrehungen pro Sekunde

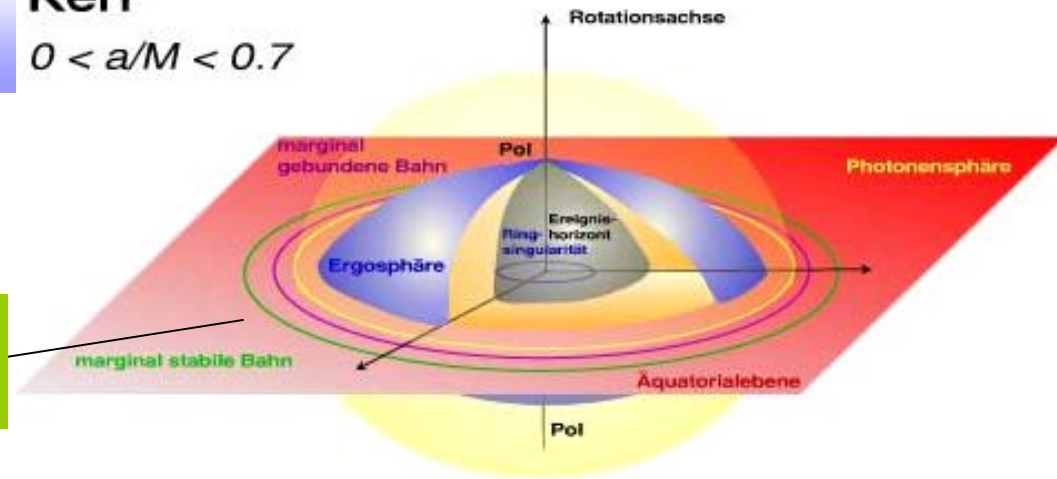


Maximale Rotation Schwarzer Löcher

- Für ein rotierendes Schwarzes Loch gibt es eine maximale Geschwindigkeit: wenn es mit halber Lichtgeschwindigkeit rotiert ($a=1$, Maximal-Kerr) lassen es die Zentrifugalkräfte nicht mehr zu, dass Materie ins Loch fällt. Sie wird vom Horizont fortgeschleudert
- Würde allerdings Maximal-Kerr tatsächlich erreicht werden, könnten die Zentrifugalkräfte die Gravitation aufheben. Wir hätten dann ein Schwarzes Loch ohne Horizont geschaffen, denn der würde jetzt zerplatzen und wir könnten direkt auf die Singularität sehen! Nach Roger Penrose (1969) gibt es die „**Kosmische Zensur**“ – demnach kann kein außenstehender Beobachter zu keiner Zeit und an keinem Ort des Universums eine Singularität ohne Ereignishorizont sehen. Ein Beobachter kann eine Singularität nur sehen, wenn er sich in das Schwarze Loch begibt.
- In der Praxis kann **kein** Schwarzes Loch mit maximaler Geschwindigkeit rotieren.

Kerr

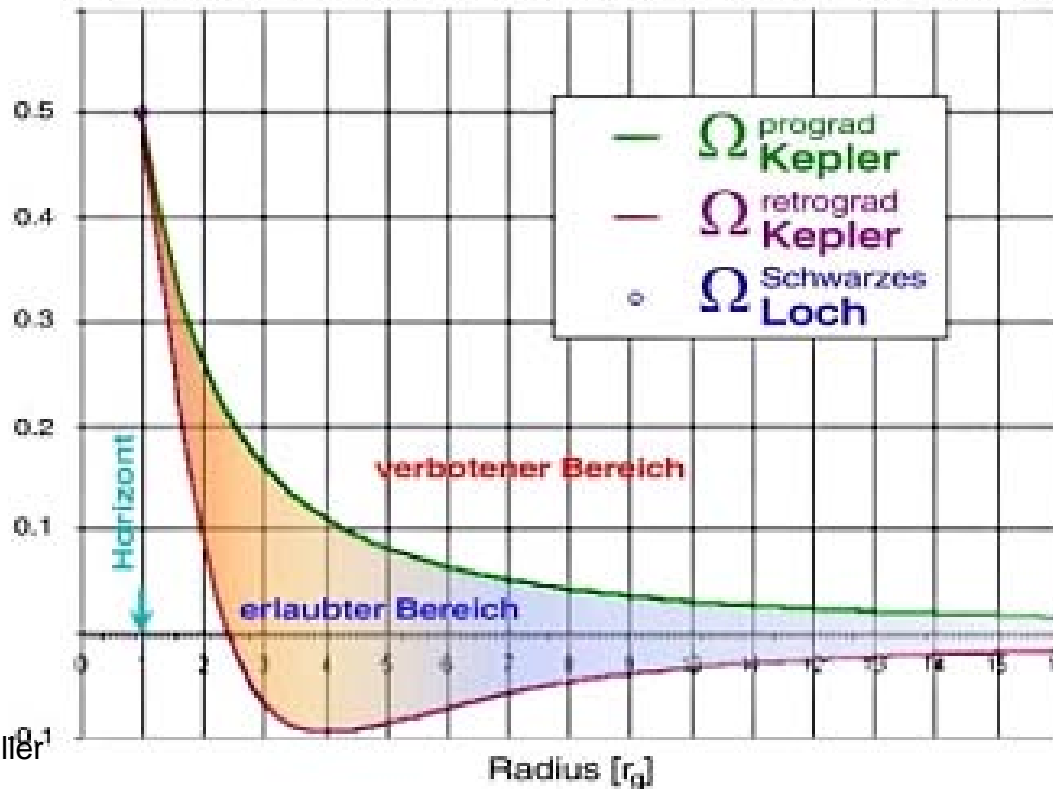
$$0 < a/M < 0.7$$



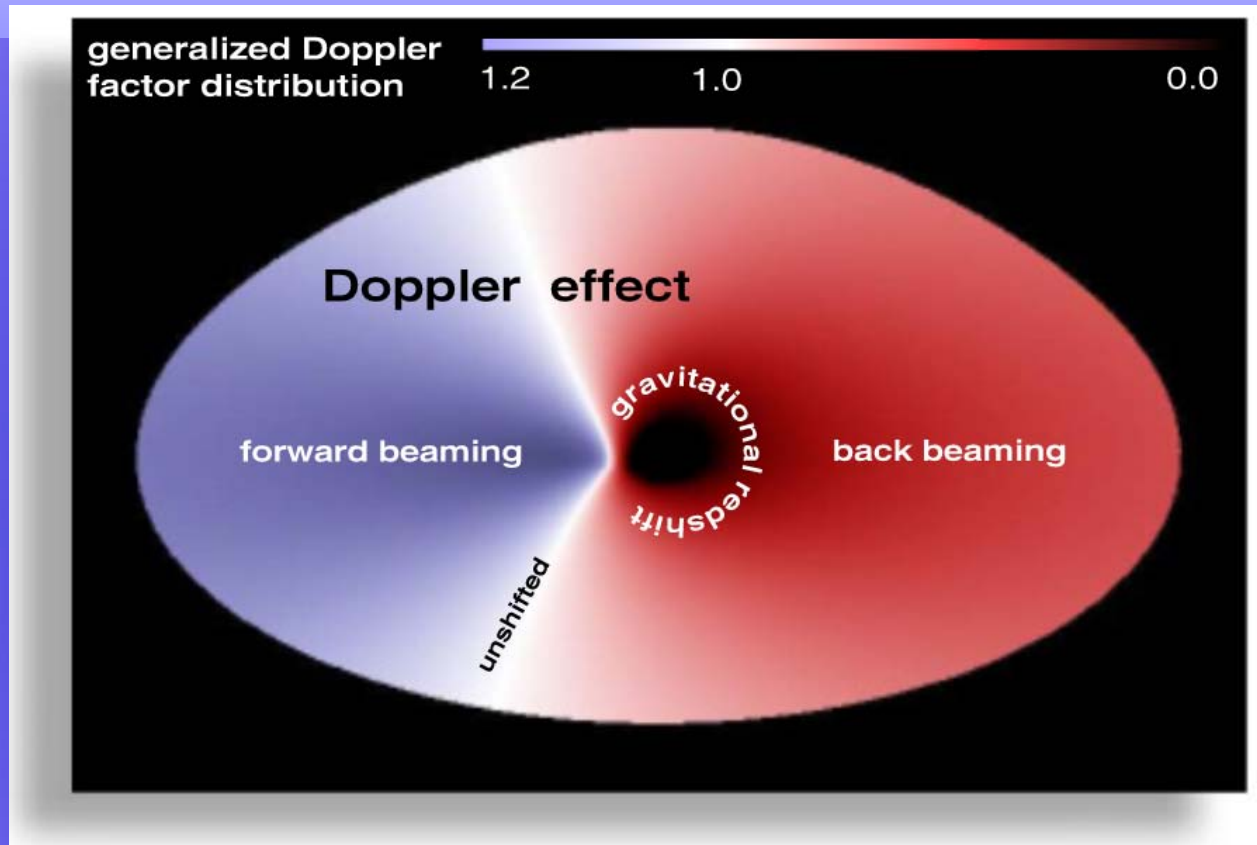
Bis hierher stabile Kepler-Rotation auf Kreisbahn möglich

prograde und retrograde Winkelfrequenzen Ω

eines maximal rotierenden Schwarzen Loches $a = 1.0$



Relativistischer Dopplerfaktor

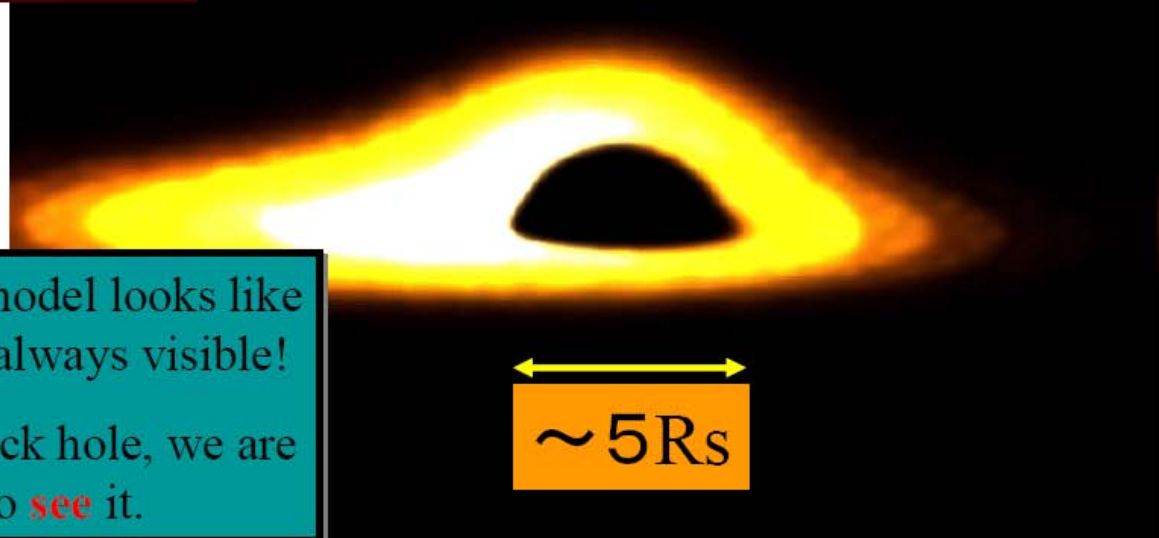
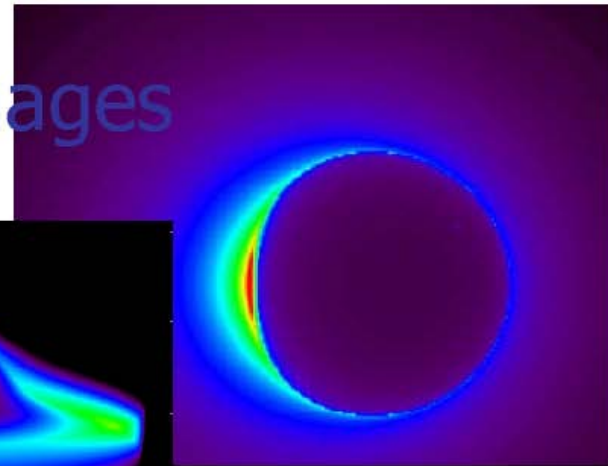
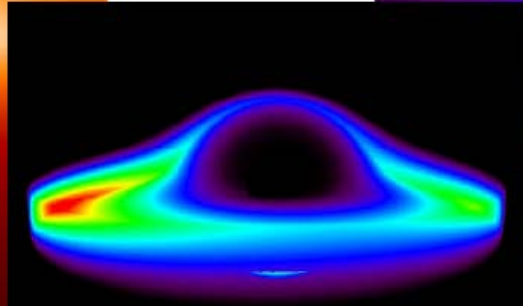
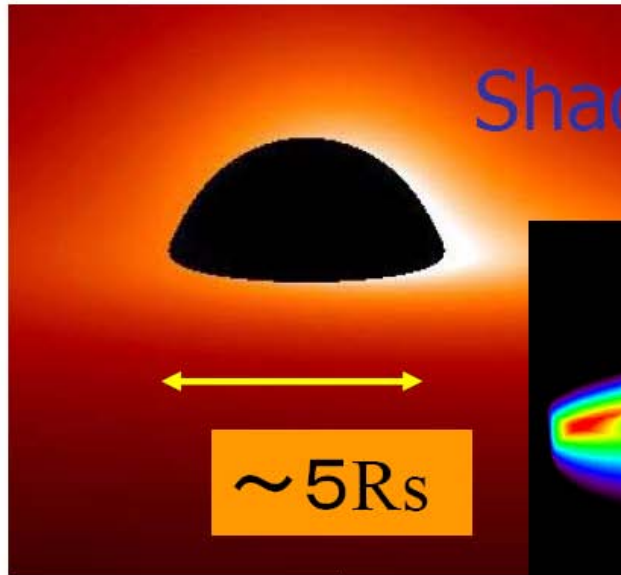


$$\begin{aligned}i &= 60^\circ \\ a &= 0.99 \\ r_{\text{in}} &= r_{\text{H}} \\ r_{\text{out}} &= 30.0\end{aligned}$$

Kepler-
Kinematik

- klassischer Doppler-Effekt signifikant modifiziert!
- relativistisch: Beaming und Gravitationsrotverschiebung
- beeinflusst jede Emission in der Nähe Schwarzer Löcher!

Shadow Images



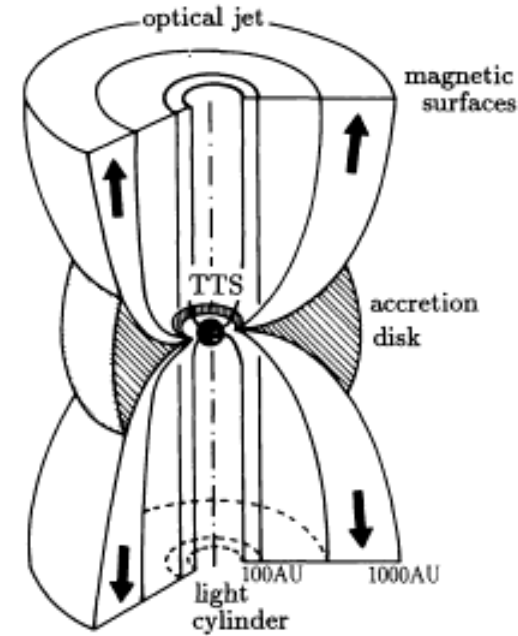
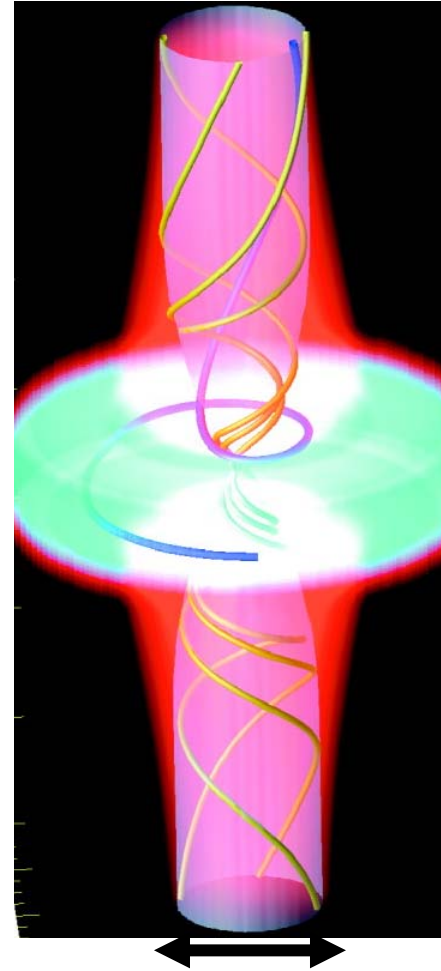
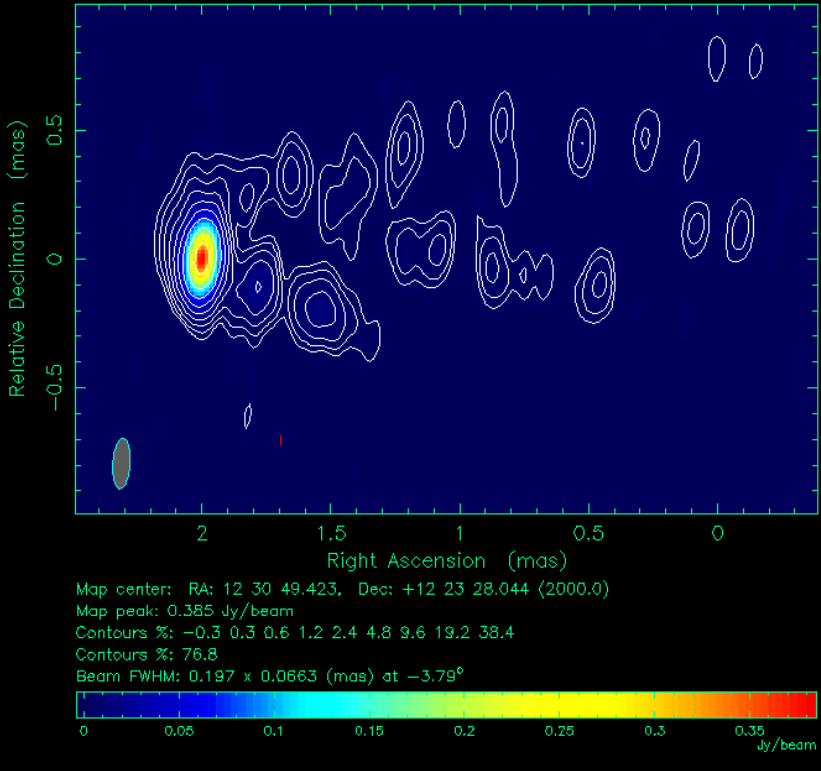
Whatever the model looks like
the shadow is always visible!

If there is a black hole, we are
going to **see** it.



M87 with 3mm-VLBI

Clean LL map. Array: ESPPVfHhNIOvPtKpMkLa
3C274 at 86.254 GHz 2004 Apr 19



Size of the jetbase:

197 x 54 mas = 21 x 6 Lichttage
= 69 x 19 Rs

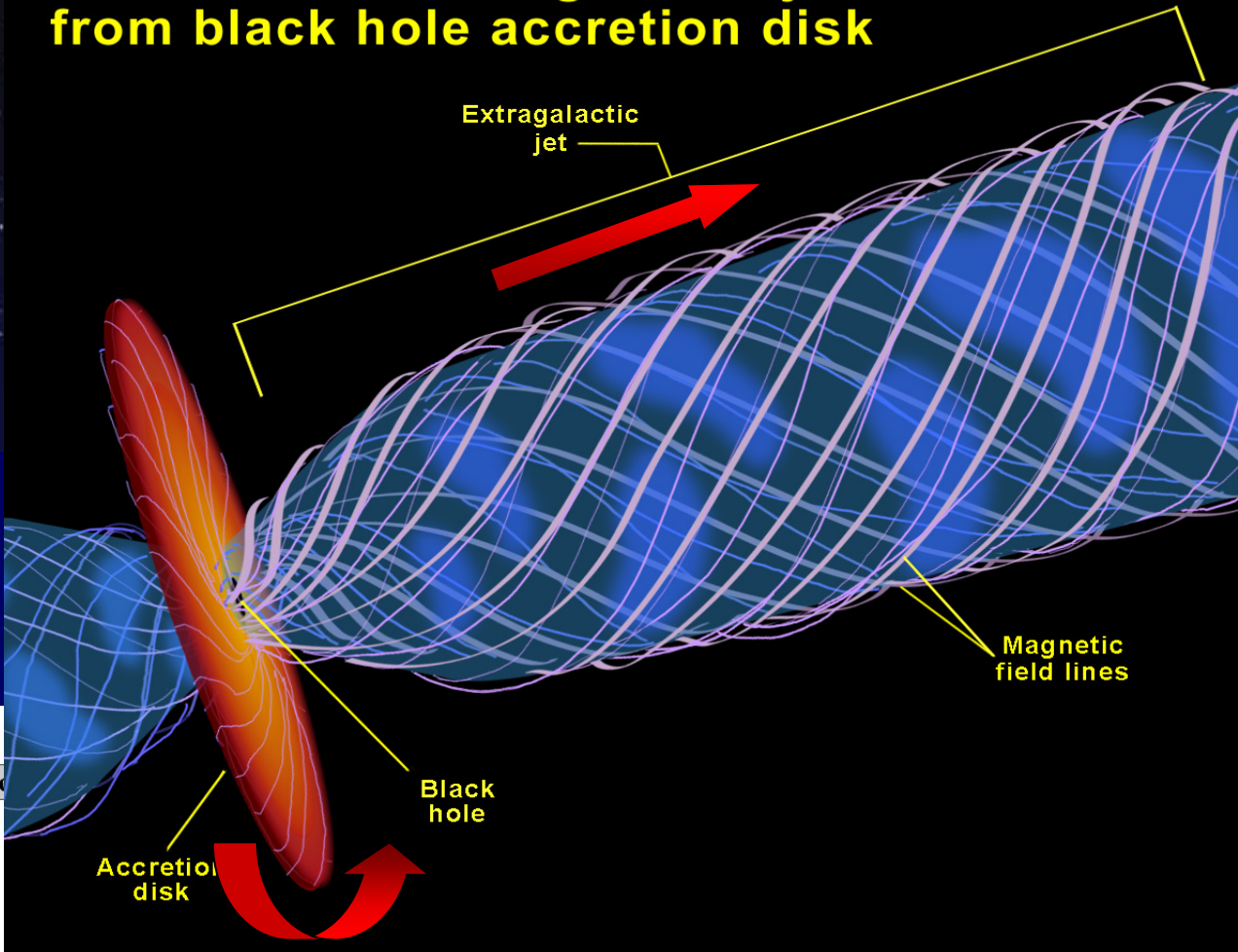
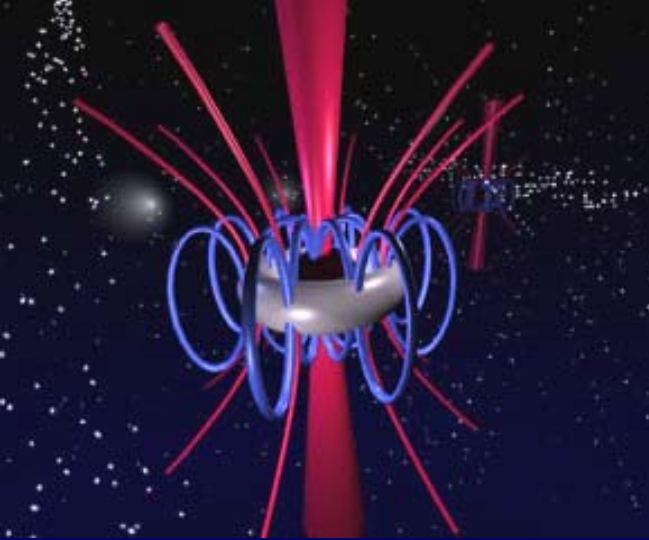
Krichbaum et al. 2006

> 40 R_s

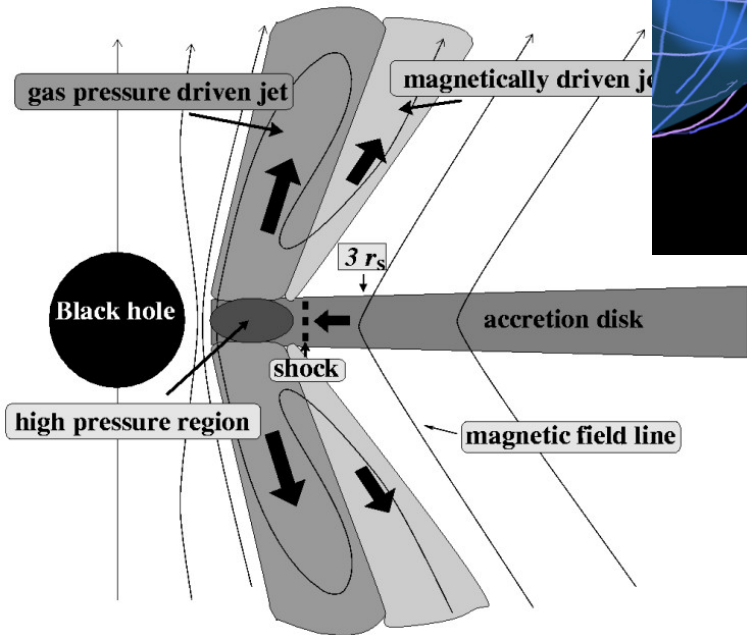
Casse & Keppens 2004

Camenzind, 1990

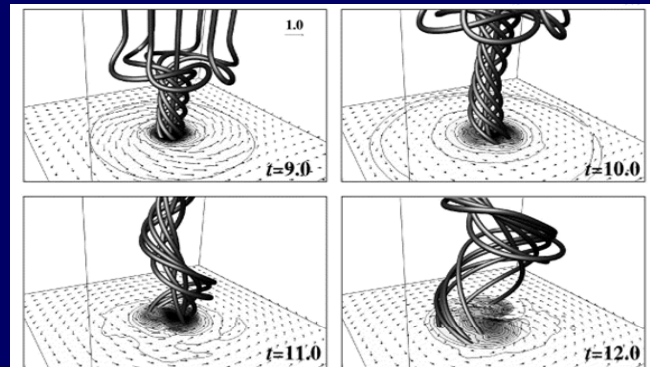
Formation of extragalactic jets from black hole accretion disk




The central engine – a MHD dynamo ?
















MHD simulation of a confining B-field anchored in a rotating disk





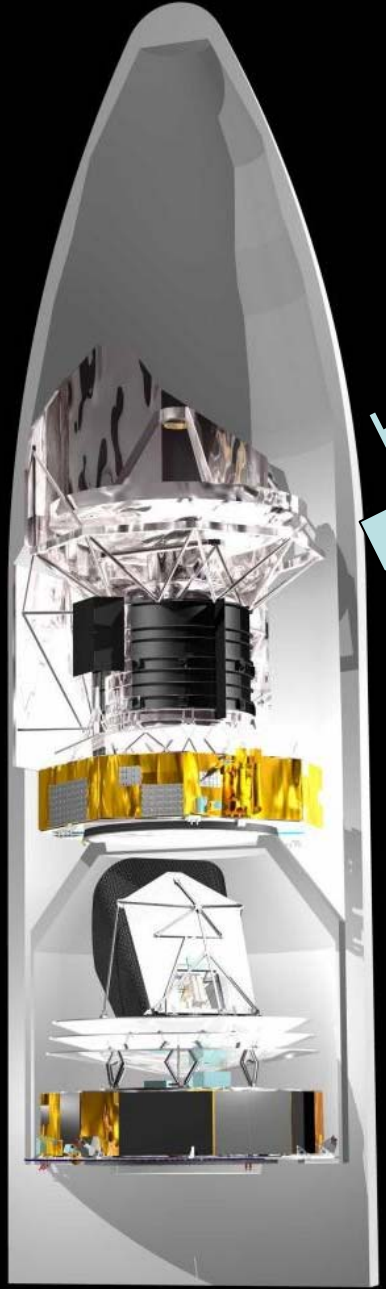
Planck & Herschel

Herschel and Planck - From Conception to Flight

Cornerstone in ESA longterm Programme Horizon 2000	- 1984		
Technical Feasibility of mission (several studies)	- 1986...		
Selection as fourth Cornerstone (Rosetta CS3)	- 1993		
Selection of payloads	- 1999		
Start Spacecraft Design	- 2001		
Start Qualification	- 2004		
Completion of Flight Satellite Assembly	- 2007		
Completion of Flight Verification	- 2008		
Launch from Kourou	14. Mai 2009		

Launch & orbit

Herschel: 7.5m hoch, 4x4m,, 3.4 Tonnen, Teleskopdurchmesser 3.5m

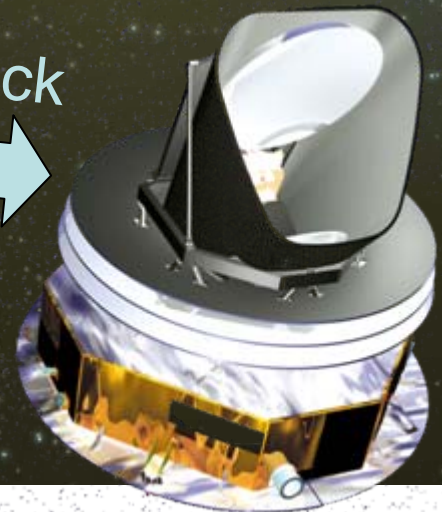


Herschel



Nach 26 Minuten

Planck



Nach 28.5 Minuten

Common launch with Herschel
from Kourou by Ariane V
~~Scheduled for summer 2009~~

to the L2 Lagrange point
in the Earth shadow



Planck: 4.2m hoch, 4.2m Durchmesser, 1.9 Tonnen, Teleskop 1.9x1.5m



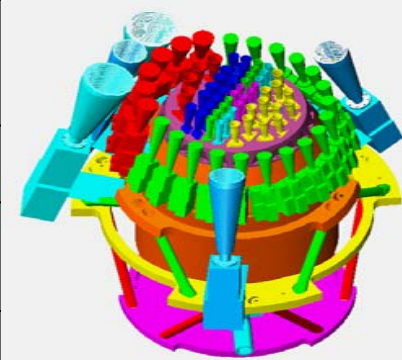
Planck

Planck, the third space CMB mission after *COBE* and *WMAP*, is designed to extract essentially all of the information in the CMB temperature anisotropies.

***Planck* will image the the whole sky with an unprecedented combination of sensitivity ($\Delta T/T \sim 2 \times 10^{-6}$), angular resolution (to 5'), and frequency coverage (30–857 GHz).**

- Planck will operate for 14 months
- Its lifetime strongly depends on cryogenic system
- From L2 *Planck* will sweep the sky in large swaths, and cover it fully at least twice (hopefully 4!!!!!!).

Estimated Planck Instrument Performance Goals



<u>Instrument</u>	<u>LFI[^]</u>			<u>HFI</u>					
Center Frequency (GHz)	30	44	70	100	143	217	353	545	857
Detector Technology	<u>HEMT radio receiver arrays</u>			<u>Bolometer arrays</u>					
Detector Temperature	20 K			0.1 K					
Cooling Requirements	<u>H₂ sorption cooler</u>			<u>H₂ sorption + 4K J-T stage + Dilution</u>					
Number of Unpolarised Detectors	0	0	0	0	4	4	4	4	4
Number of Linearly Polarised Detectors	4	6	12	8	8	8	8	0	0
<u>Angular Resolution (arcmin)</u>	33	24	14	9.5	7.1	5.0	5.0	5.0	5.0
Bandwidth (GHz)	6	8.8	14	33	47	72	116	180	283
Average $\Delta T/T$ per pixel *	2.0	2.7	4.7	2.5	2.2	4.8	14.7	147	6700
Average $\Delta T/T$ per pixel	2.8	3.9	6.7	4.0	4.2	9.8	29.8		

* Sensitivity (1) to intensity (Stokes I) fluctuations observed on the sky, in thermodynamic (x10-6) temperature units, relative to the average temperature of the CMB (2.73 K), achievable after two sky surveys (14 months).

The High Frequency Instrument

The [High Frequency Instrument \(HFI\)](#) is an array of 48 bolometric detectors which will be placed in the focal plane of the Planck telescope, and will image the sky in six frequency channels between 100 and 857 GHz. The HFI is being designed and built by a Consortium of scientists led by Jean-Loup Puget (PI) of the [Institut d'Astrophysique Spatiale](#) in Orsay (France), and Francois Bouchet (Deputy PI) of the Institut d'Astrophysique de Paris. The other main institutes involved in the HFI Consortium are:

[California Institute of Technology](#), in Pasadena (USA)

[Canadian Institute for Theoretical Astrophysics](#), in Toronto (Canada)

[Cardiff University](#), in Cardiff (UK)

[Centre d'Etudes Spatiales des Rayonnements](#), in Toulouse (F)

[Centre de Recherche sur les tres Basses Temperatures](#), in Grenoble (F)

[College de France](#), in Paris (F)

[Commissariat a l'Energie Atomique](#), in Gif-sur-Yvette (F)

[Danish Space Research Institute](#), in Copenhagen (DK)

[Imperial College](#), in London (UK)

[Institut d'Astrophysique de Paris](#), in Paris (F)

[Institut des Sciences Nucleaires](#), in Grenoble (F)

[Institute of Astronomy](#), in Cambridge (UK) - [[Planck page](#)]

[Jet Propulsion Laboratory](#), in Pasadena (USA)

[Laboratoire de l'Accelerateur Lineaire](#), in Orsay (F)

[Laboratoire d'Etude du Rayonnement et de la Matiere en Astrophysique](#), in Paris, (F)

[Max-Planck-Institut fuer Astrophysik](#), in Garching (D) - [[Planck Page](#)]

[Mullard Radio Astronomy Observatory](#), in Cambridge (UK)

[National University of Ireland](#), in Maynooth (IR)

[Rutherford Appleton Laboratory](#), in Chilton (UK)

[Space Science Dpt of ESA](#), in Noordwijk (NL)

[Stanford University](#), in Stanford (USA)

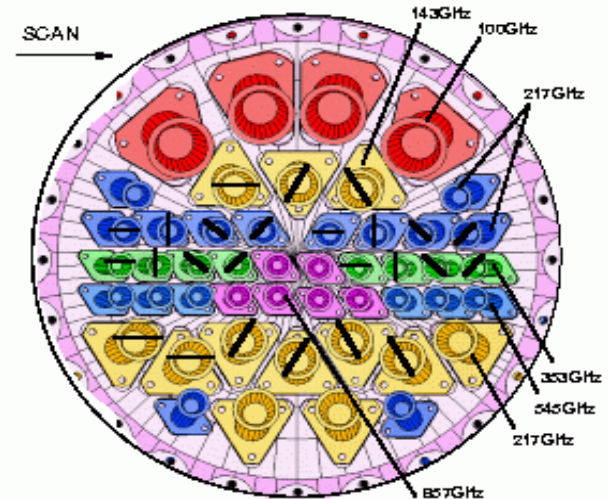
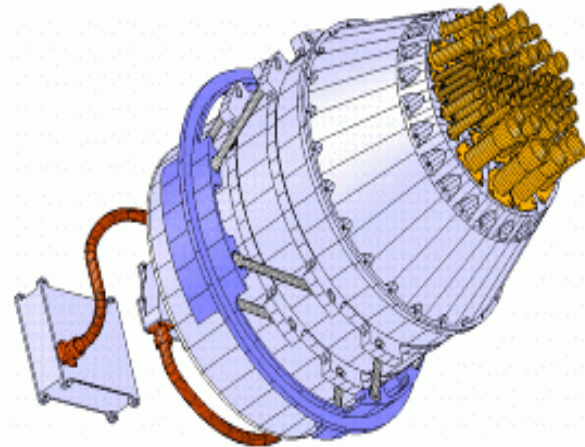
[Universite de Geneve](#) , in Geneva (CH)

[Universidad de Granada](#), in Granada (E)

[University La Sapienza](#), in Rome (I)

The High Frequency Instrument or HF

- 48 bolometers sensitive to 100-850 GHz (split into 6 channels)
- Actively cooled to 0.1K
- Best angular resolution $\sim 5'$ and temperature sensitivity ~ 5 microK



The Low Frequency Instrument

The [Low Frequency Instrument \(LFI\)](#) is an array of 56 tuned radio receivers which will be placed in the focal plane of the Planck telescope, and will image the sky in three frequency channels between 30 and 70 GHz. The LFI will be designed and built by a Consortium of scientists led by Reno Mandolesi of the [Istituto Fisica Spaziale e Fisica Cosmica](#) (IASF) in Bologna (Italy) - [[Planck Page](#)].

The other main institutes involved in the LFI Consortium are:

- [Chalmers University of Technology](#), in Goteborg (S)
- [Danish Space Research Institute](#), in Copenhagen (DK) - [[Planck Page](#)]
- [Instituto de Astrofisica de Canarias](#), in La Laguna (E)
- [Instituto de Fisica de Cantabria](#), in Santander (E)
- Istituto CAISMI, in Firenze (I)
- [Istituto IASF \(CNR\)](#), in Milano (I)
- [Istituto di Fisica del Plasma IFP \(CNR\)](#), in Milano (I)
- [Istituto IFSI](#), in Roma (I)
- [Jet Propulsion Laboratory](#), in Pasadena (USA)
- [Max-Planck-Institut fuer Astrophysik](#), in Garching (D) -
- [Millimetre Wave Laboratory, in Espoo \(FI\)](#)
- [Jodrell Bank Observatory](#), in Macclesfield (UK)
- [Osservatorio Astronomico di Padova](#), in Padova (I)
- [Osservatorio Astronomico di Trieste](#), in Trieste (I) - [[LFI](#)]
- [SISSA](#), in Trieste (I)
- [Space Science Dpt of ESA](#), in Noordwijk (NL)
- [Theoretical Astrophysics Center](#), in Copenhagen (DK)
- [University of California \(Berkeley\)](#), in Berkeley (USA)
- [University of California \(Santa Barbara\)](#), in Santa Barbara (USA)
- [Universite de Geneve](#), in Geneva (CH)
- [University of Oslo](#), in Oslo (N)
- [Universita Tor Vergata](#), in Roma (I)

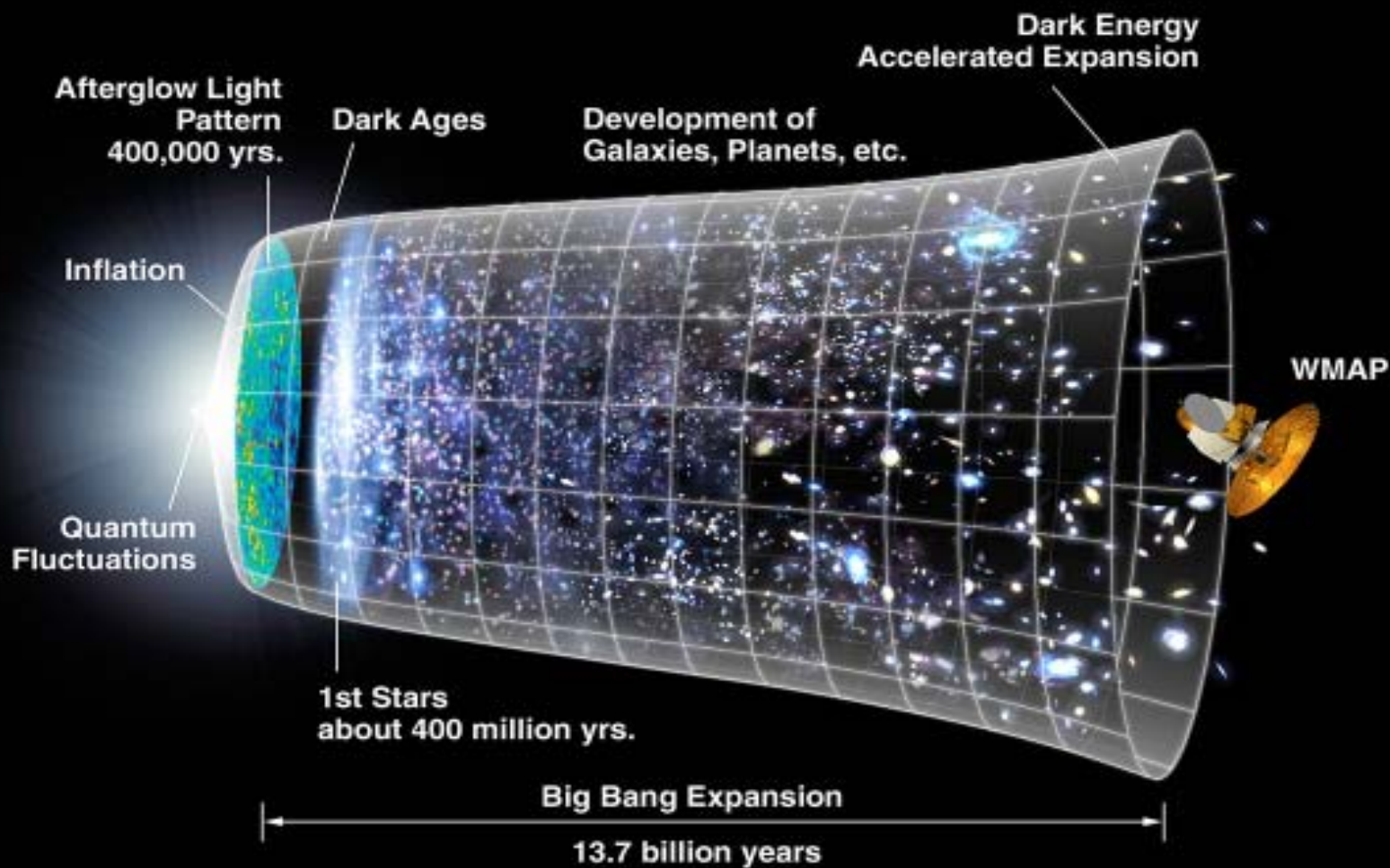
The LFI team, a great international collaboration: **about 300 people contributing to the instrument and the data processing development**



The image shows a collection of logos for the LFI consortium members. At the top, there is a row of national flags: Italy, Finland, Norway, Spain, Switzerland, United Kingdom, United States, Canada, and Germany. Below the flags is a large yellow-bordered box containing numerous logos of the participating institutions and agencies, such as IASF Bologna, IFP-CNR Milano, Dipartimento di Fisica Università di Milano, ASI Agenzia Spaziale Italiana, Alcatel Alenia Space, DAT, The University of Manchester Jodrell Bank Observatory, MilliLab, VTT, JPL, UCSB, YINEN, Univ. Cantabria, Dpto. Ing. Comunicaciones, Mier, and the Instituto de Astrofísica de Canarias.

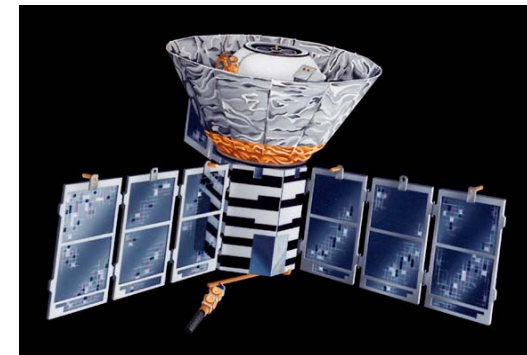
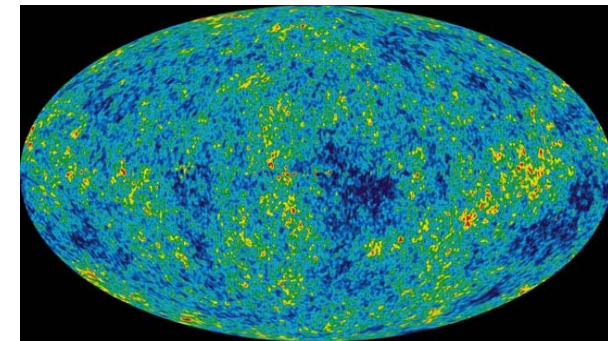
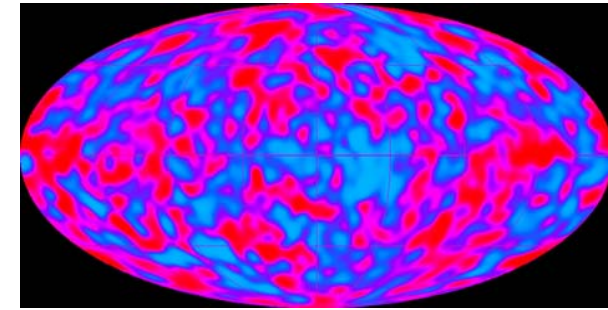
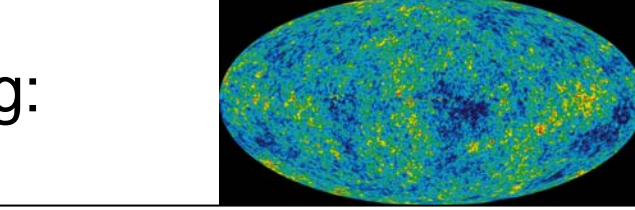
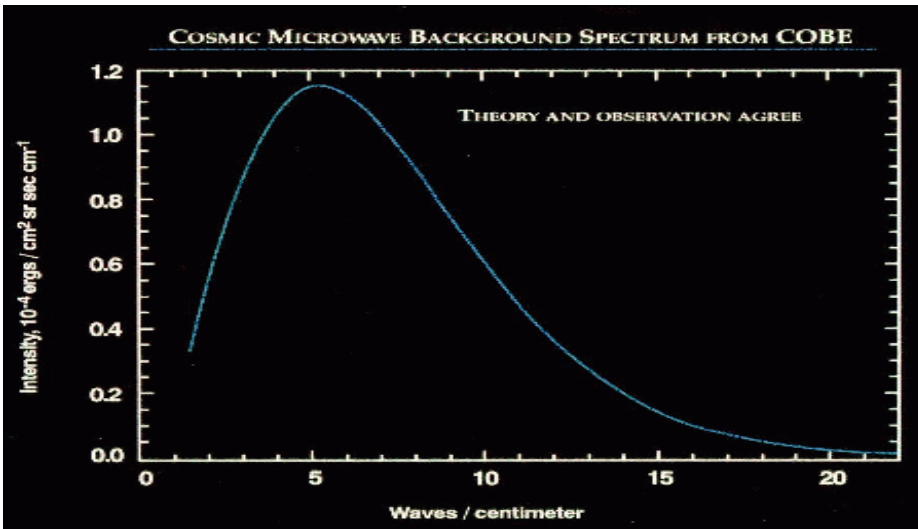


Wissenschaft mit **Planck**



Die weitere Erforschung:

- Suborbitale Erforschung:
 - Bodengebunden: Antennen
 - Atmosphärisch: Wetterballons, Raketen
- Satellitenmissionen:
 - Cobe (1989-1992) $T=2,728\pm 0,002$ K
 - WMAP (ab 2002)
 - Planck (Start 2007)



Wilkinson Microwave Anisotropy Probe

*A partnership between
NASA/GSFC and Princeton*

Science Team:

NASA/GSFC

Chuck Bennett (PI)

Michael Greason

Bob Hill

Gary Hinshaw

Al Kogut

Michele Limon

Nils Odegard

Janet Weiland

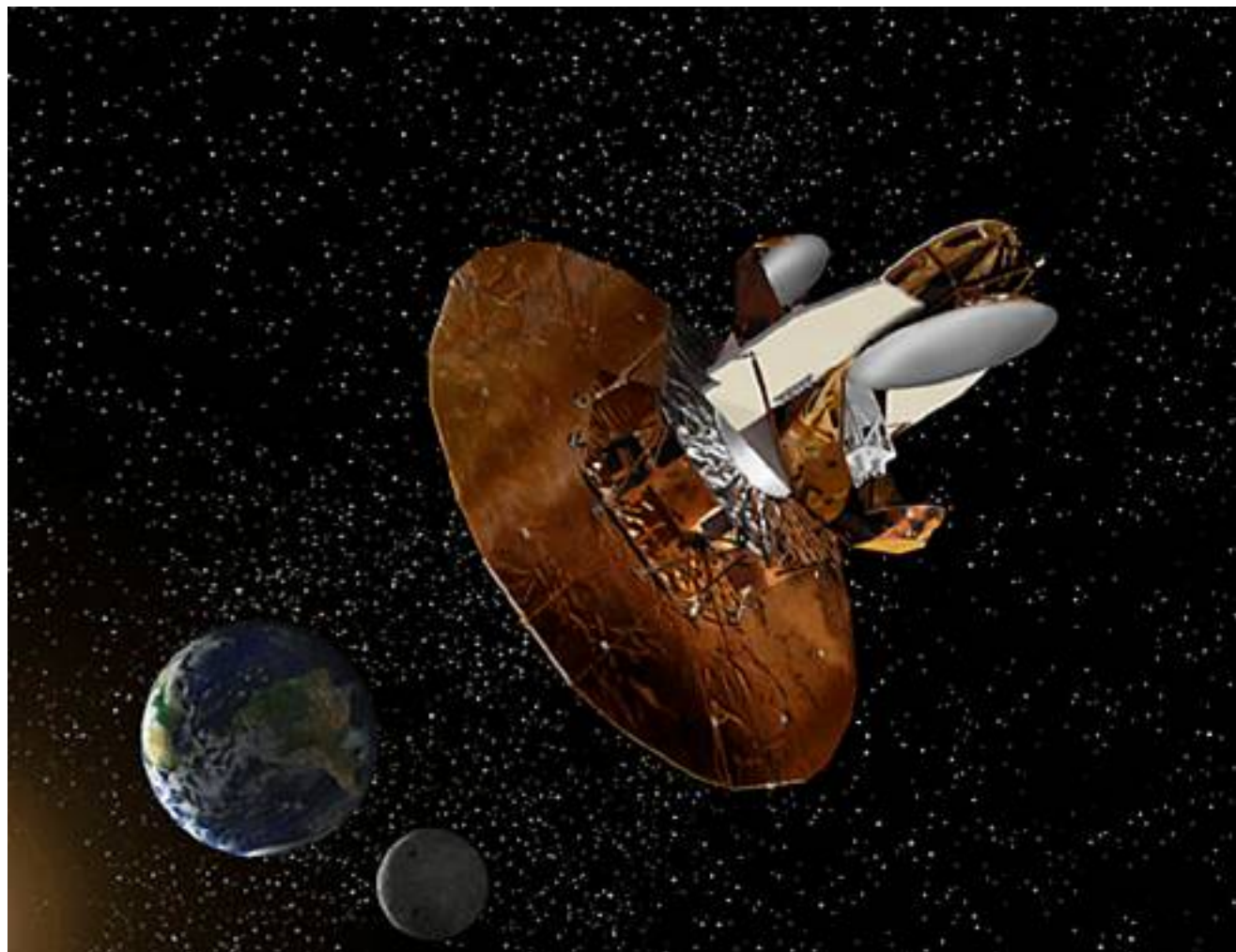
Ed Wollack

Brown

Greg Tucker

UCLA

Ned Wright



UBC

Mark Halpern

Chicago

Stephan Meyer

Princeton

Chris Barnes

Norm Jarosik

Eiichiro Komatsu

Michael Nolte

Lyman Page

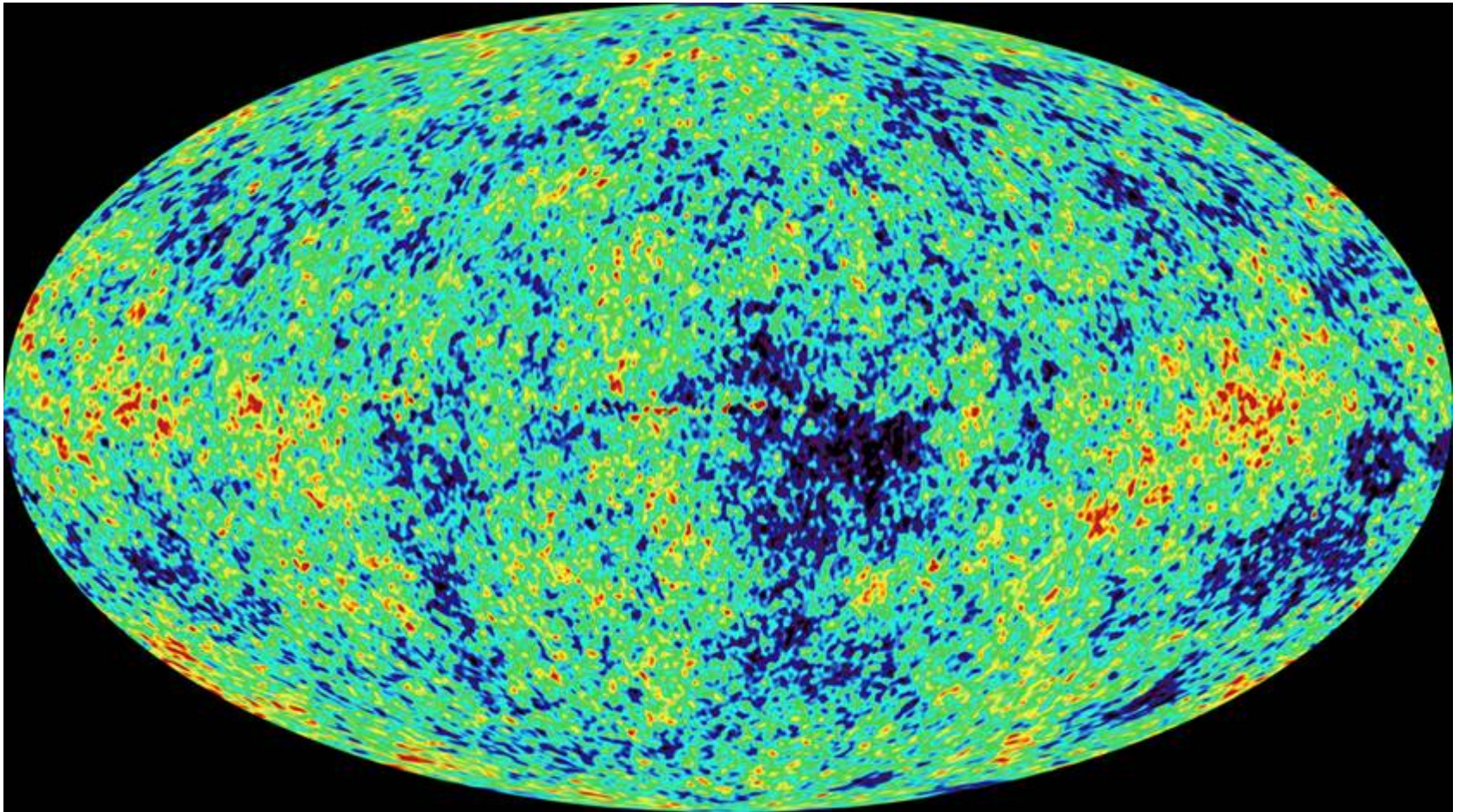
Hiranya Peiris

David Spergel

Licia Verde

WMAP

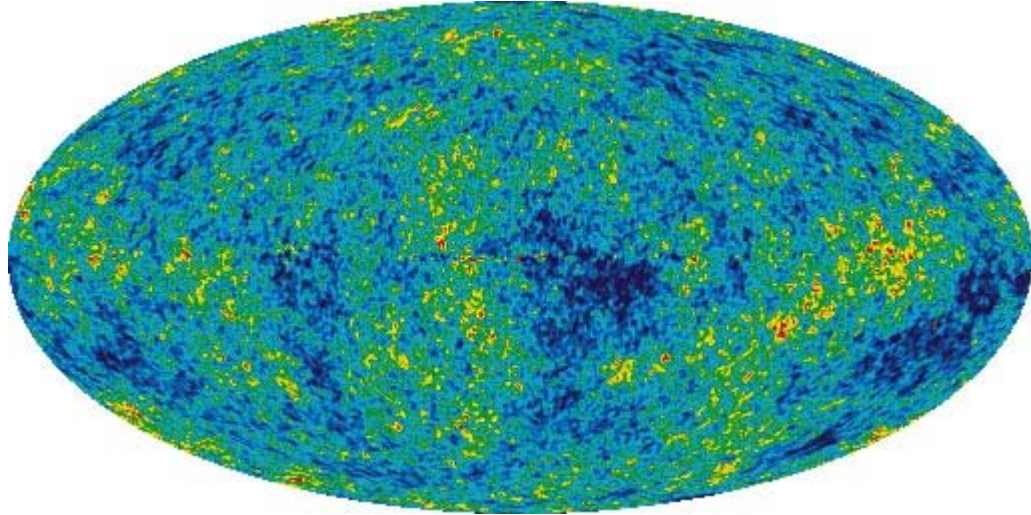
Foto des Urknalls



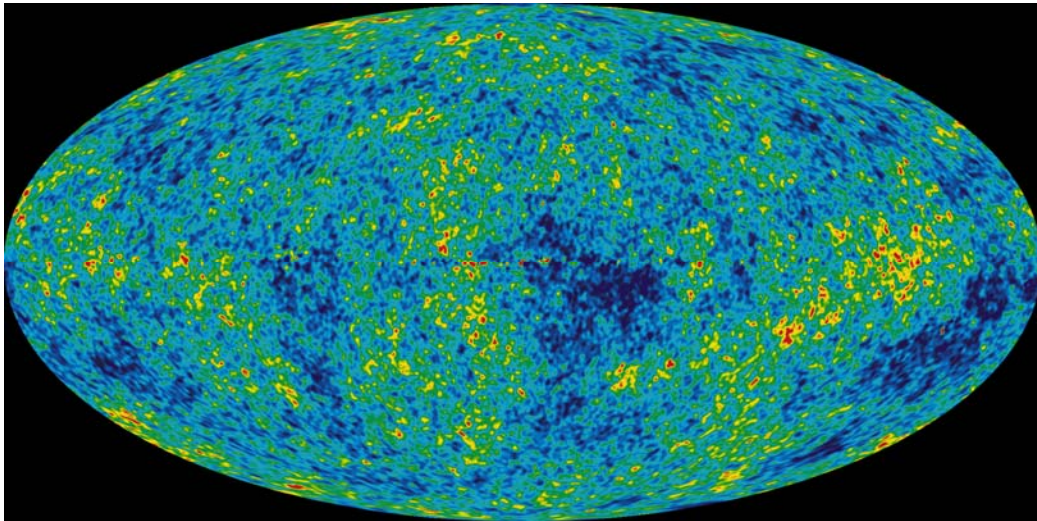
Die Hintergrundstrahlung ist isotrop mit Temperatur 2.726 K!
Schwankungen sind kleiner als $1/100000$!



WMAP: Neue Daten

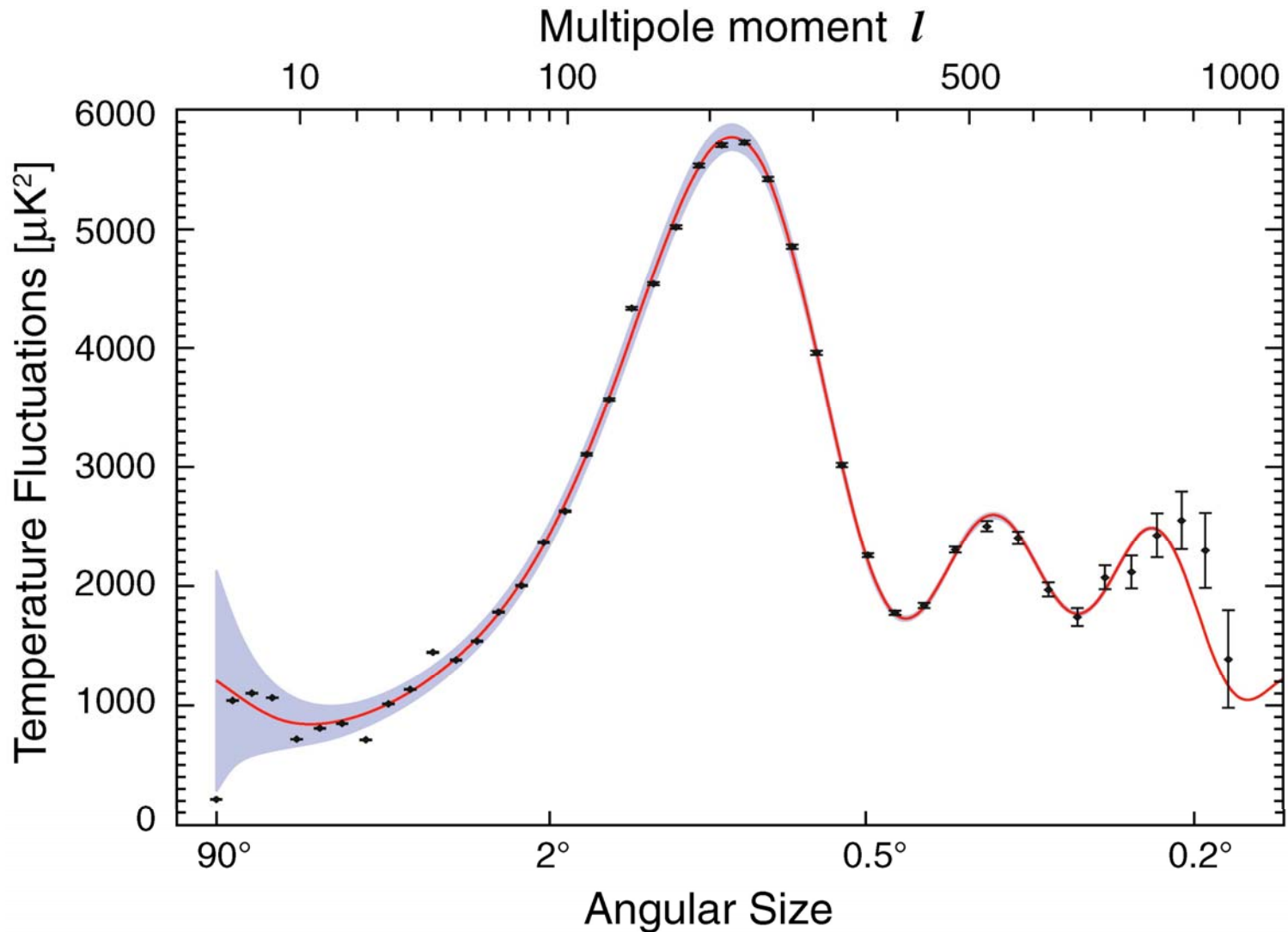


- 3 Jahre Daten

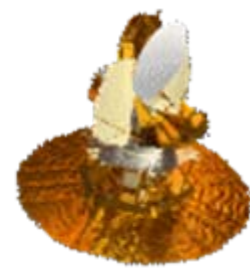


- 5 Jahre Daten

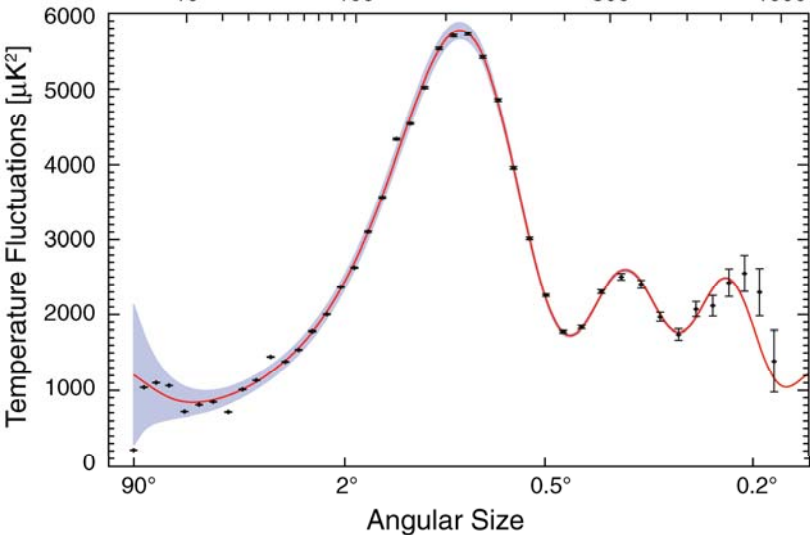
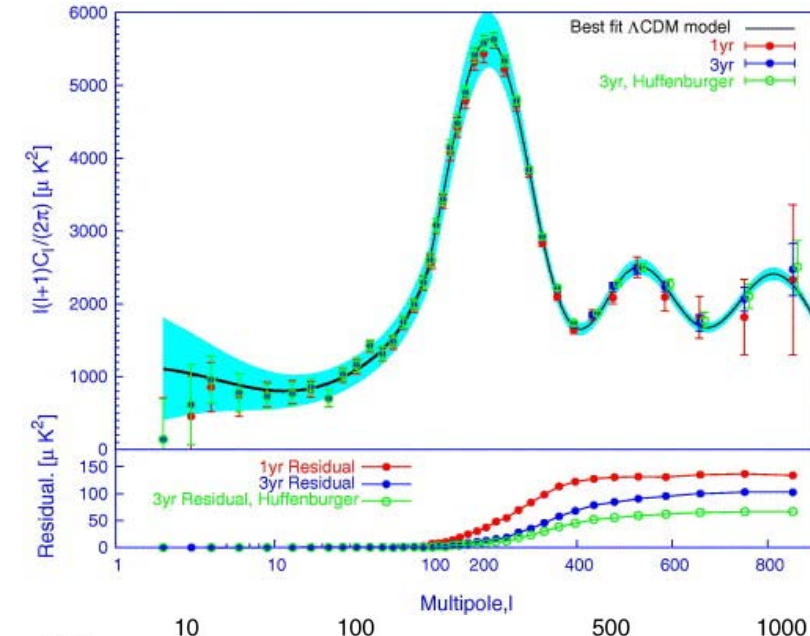
WMAP: Neue Daten



WMAP: Neue Daten

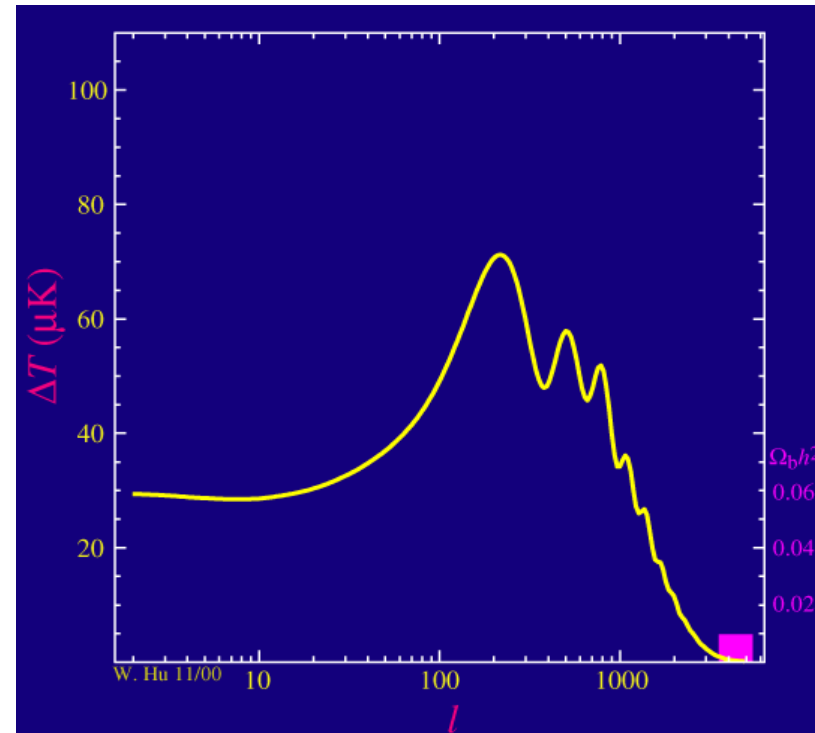


- WMAP-3Jahre



- Temperaturfluktuationen als Funktion der Winkelausdehnung – links: große Winkel
- 3. Maximum gibt Auskunft über die Neutrinos in den Frühphasen des Universums

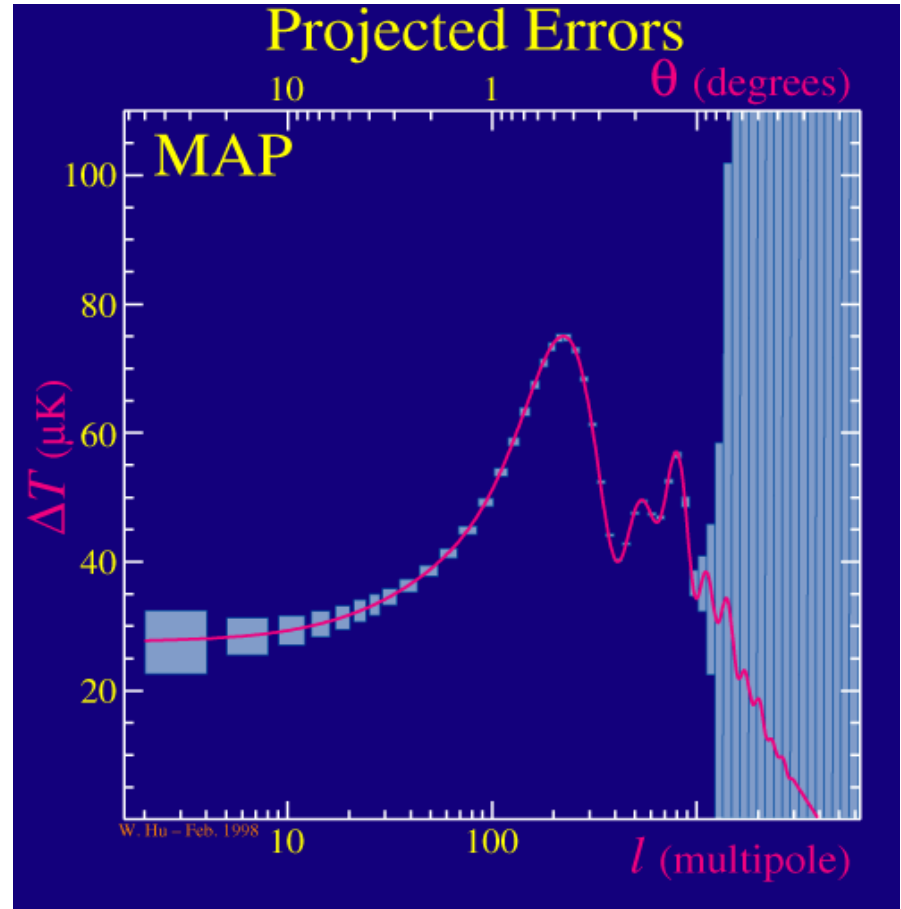
- The shape of the angular power spectrum is very sensitively dependent on fundamental cosmological parameters
- First peak (position) shows the universe is close to spatially flat =total energy density
- First peak (height) depends upon the matter and baryon density (both depend on the Hubble constant)
- Constraints on the second peak indicate substantial amounts of dark baryons
- Third peak will measure the physical density of the dark matter
- Damping tail will provide consistency checks of underlying assumptions
- curvature of the universe the position of the peaks
- $l < 100$ plateau indicate Scale-invariant density fluctuations, tilting the primordial power spectrum raising the right side relative to the left side



(W. Hu's web page)

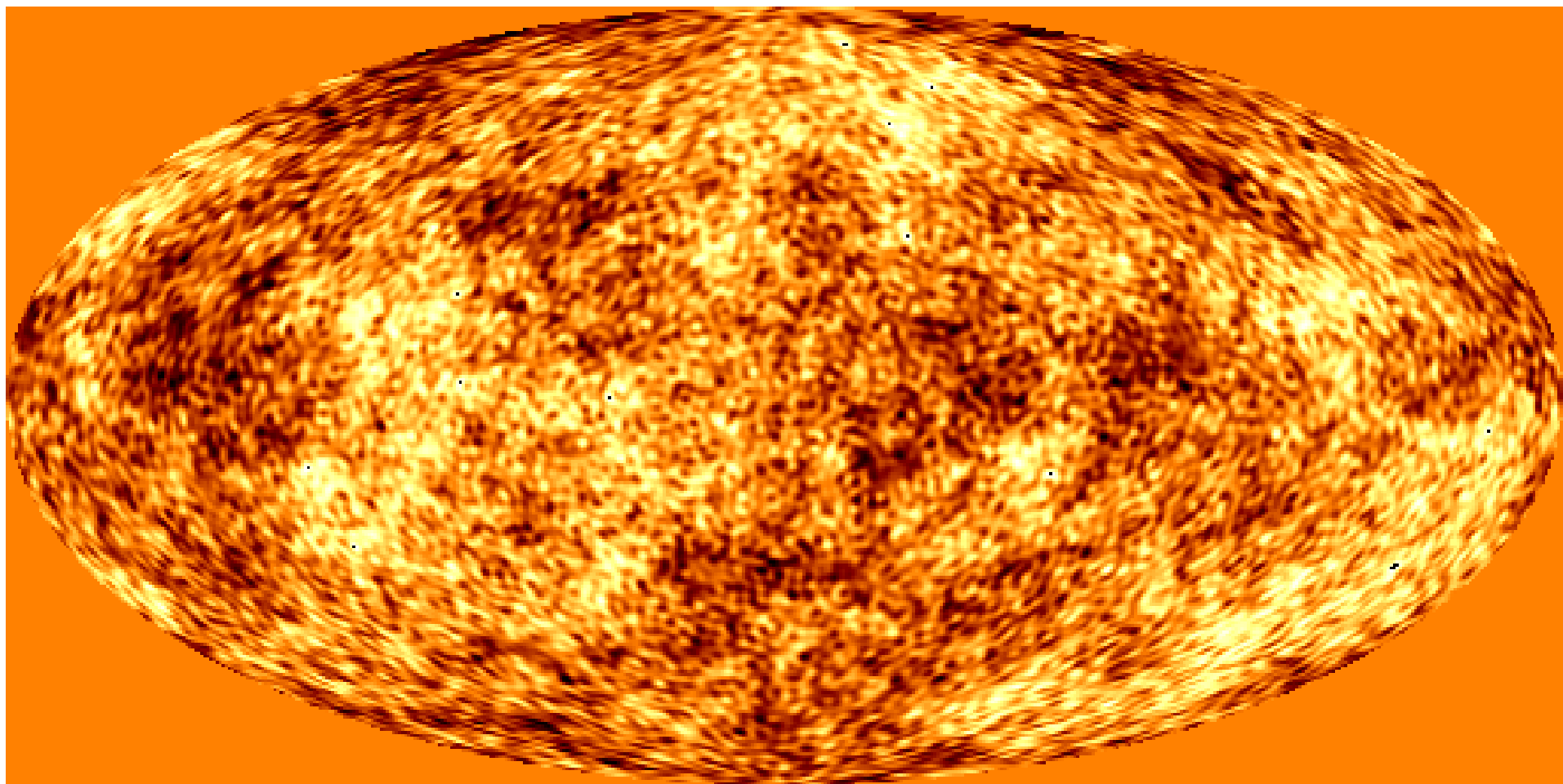
→ Precision cosmology

- Planck has the ability :
 - Detect much smaller temperature variations (about ten times WMAP) in the CMB than previous missions
 - Perform CMB measurements with a higher angular resolution than ever before (about twice better than WMAP)
 - Measure over a wider band of frequencies to enhance the separation of the CMB from interfering foreground signals (*frequency coverage about ten times larger than WMAP*)

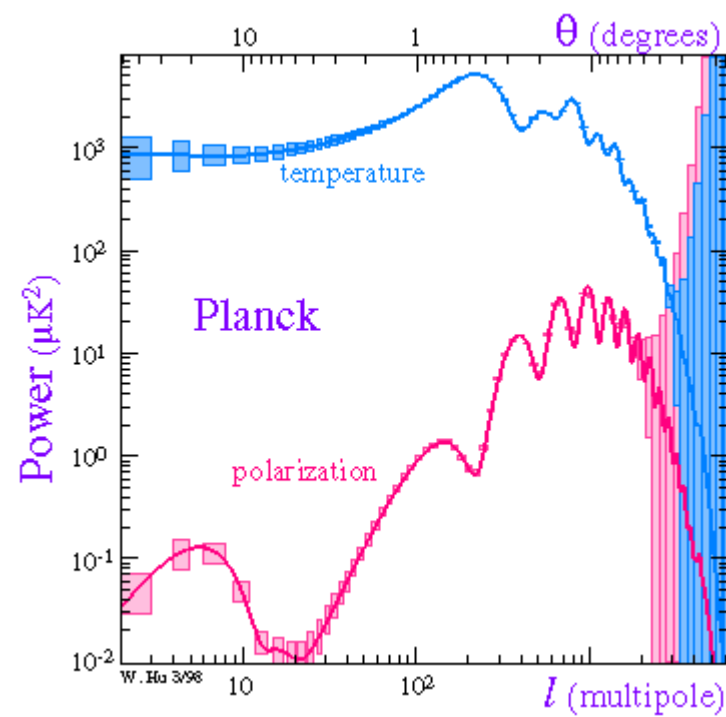
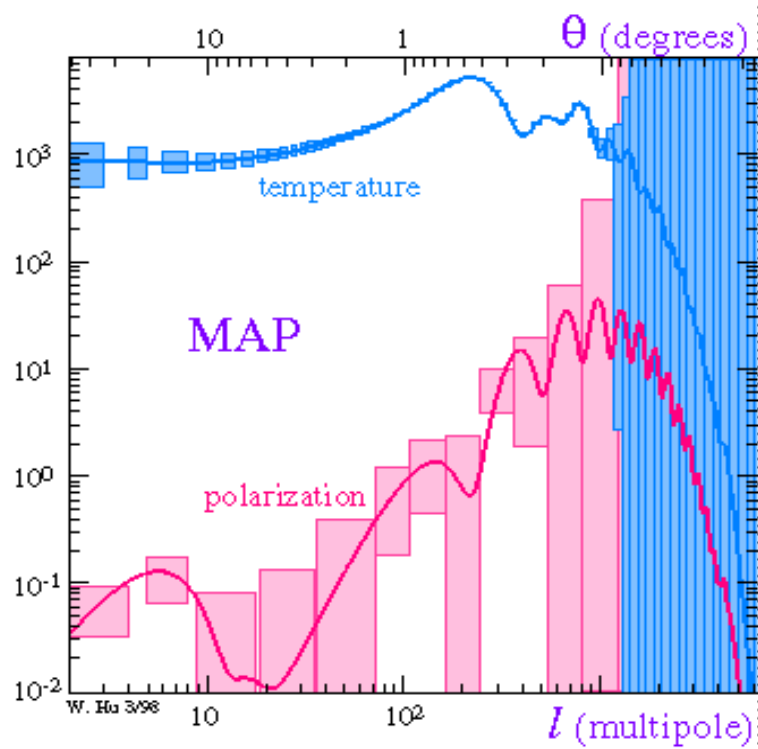


(taken from [W. Hu's web page](#))

Foto des Urknalls



A simulation of the CMB anisotropies at an angular resolution and sensitivity level typical of what can be achieved by Planck (1 MikroKelvin)

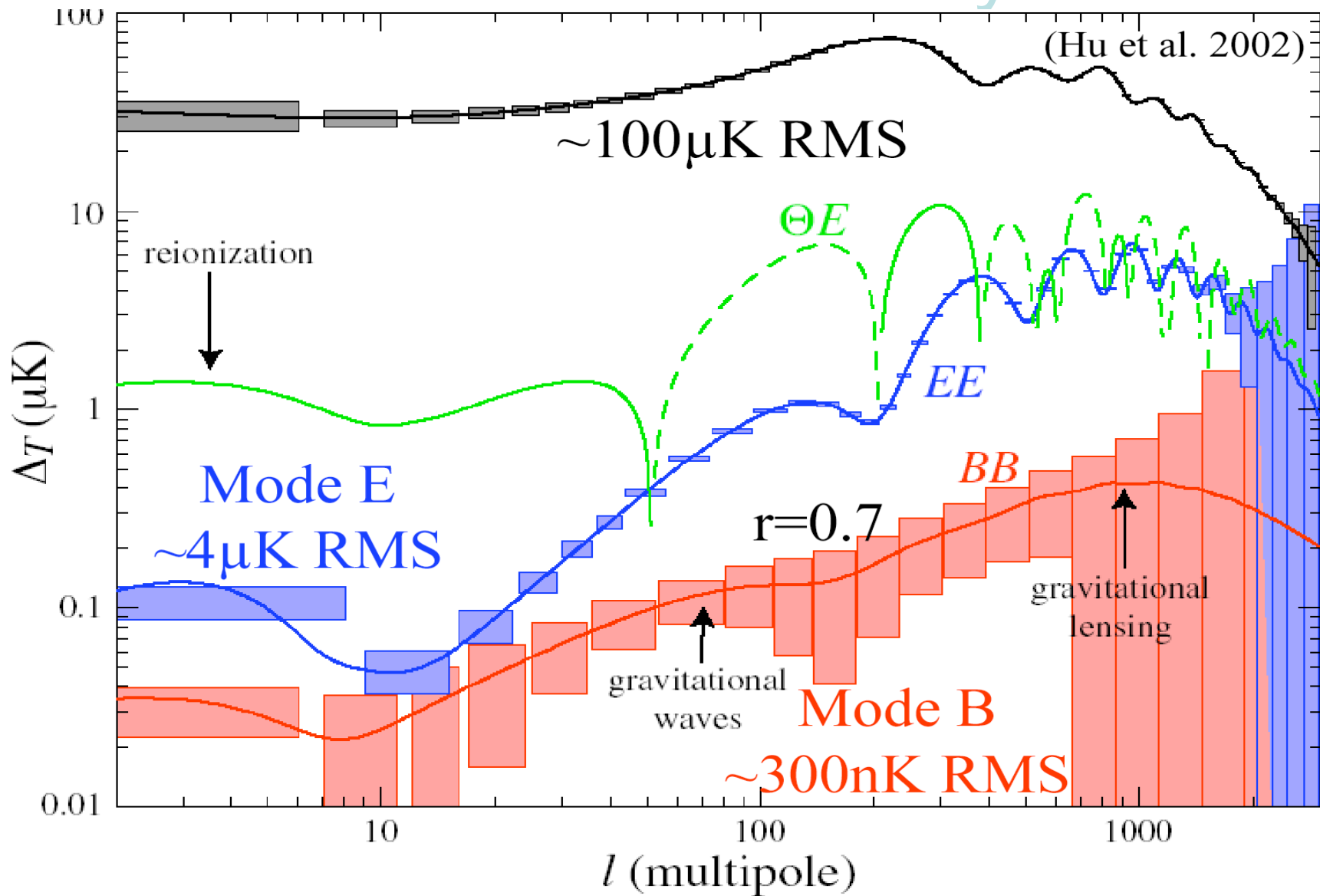


- The main difference between Planck and MAP lies in the quality of the CMB data taken, and therefore, in the accuracy with which the cosmological parameters can be determined + polarization properties

Parameter	Meaning	Status	Use	Definition
τ	Reionization optical depth	Not optional		
ω_b	Baryon density	Not optional	MCMC	$\omega_b = \Omega_b h^2 = \rho_b / (1.88 \times 10^{-26} \text{kg/m}^3)$
ω_d	Dark matter density	Not optional	MCMC	$\omega_d = \Omega_d h^2 = \rho_d / (1.88 \times 10^{-26} \text{kg/m}^3)$
f_ν	Dark matter neutrino fraction	Well motivated	MCMC	$f_\nu = \rho_\nu / \rho_d$
Ω_Λ	Dark energy density	Not optional	MCMC	
w	Dark energy equation of state	Worth testing	MCMC	p_Λ / ρ_Λ (approximated as constant)
Ω_k	Spatial curvature	Worth testing		
A_s	Scalar fluctuation amplitude	Not optional		Primordial scalar power at $k = 0.05/\text{Mpc}$
n_s	Scalar spectral index	Well motivated	MCMC	Primordial spectral index at $k = 0.05/\text{Mpc}$
α	Running of spectral index	Worth testing	MCMC	$\alpha = d \ln n_s / d \ln k$ (approximated as constant)
r	Tensor-to-scalar ratio	Well motivated	MCMC	Tensor-to-scalar power ratio at $k = 0.05/\text{Mpc}$
n_t	Tensor spectral index	Well motivated	MCMC	
b	Galaxy bias factor	Not optional	MCMC	$b = [P_{\text{galaxy}}(k)/P(k)]^{1/2}$ (assumed constant for $k < 0.2h/\text{Mpc}$)
z_{ion}	Reionization redshift (abrupt)			$z_{\text{ion}} \approx 92(0.03h\tau/\omega_b)^{2/3}\Omega_m^{1/3}$ (assuming abrupt reionization; [37])
ω_m	Physical matter density		Fits	$\omega_m = \omega_b + \omega_d = \Omega_m h^2$
Ω_m	Matter density/critical density			$\Omega_m = 1 - \Omega_\Lambda - \Omega_k$
Ω_{tot}	Total density/critical density			$\Omega_{\text{tot}} = \Omega_m + \Omega_\Lambda = 1 - \Omega_k$
A_t	Tensor fluctuation amplitude			$A_t = rA_s$
M_ν	Sum of neutrino masses			$M_\nu \approx (94.4 \text{ eV}) \times \omega_d f_\nu$ [38]
h	Hubble parameter			$h = \sqrt{(\omega_d + \omega_b)/(1 - \Omega_k - \Omega_\Lambda)}$
β	Redshift distortion parameter			$\beta \approx [\Omega_m^{4/7} + (1 + \Omega_m/2)(\Omega_\Lambda/70)]/b$ [39, 40]
t_0	Age of Universe			$t_0 \approx (9.785 \text{ Gyr}) \times h^{-1} \int_0^1 [(\Omega_\Lambda a^{-(1+3w)} + \Omega_k + \Omega_m/a)]^{-1/2} da$ [38]
σ_8	Galaxy fluctuation amplitude			$\sigma_8 = \{4\pi \int_0^\infty [\frac{3}{x^3}(\sin x - x \cos x)]^2 P(k) \frac{k^2 dk}{(2\pi)^3}\}^{1/2}$, $x \equiv k \times 8h^{-1}\text{Mpc}$
Z	CMB peak suppression factor		MCMC	$Z = e^{-2\tau}$
A_p	Amplitude on CMB peak scales		MCMC	$A_p = A_s e^{-2\tau}$
Θ_s	Acoustic peak scale (degrees)		MCMC	$\Theta_s(\Omega_k, \Omega_\Lambda, w, \omega_d, \omega_b)$ given by [25]
H_2	2nd to 1st CMB peak ratio		Fits	$H_2 = (0.925\omega_m^{0.18} 2.4^{n_s-1})/[1 + (\omega_b/0.0164)^{12\omega_m^{0.52}}]^{0.2}$ [25]
H_3	3rd to 1st CMB peak ratio		Fits	$H_3 = 2.17[1 + (\omega_b/0.044)^2]^{-1}\omega_m^{0.59} 3.6^{n_s-1}/[1 + 1.63(1 - \omega_b/0.071)\omega_m]$
A_*	Amplitude at pivot point		Fits	$A_* = 0.82^{n_s-1} A_p$

B-mode sensitivity

From pure CMB maps



Polarization

- Thomson scattering of temperature anisotropies on the last scattering surface generates a linear polarization pattern on the sky. Polarisation pattern can be separated into 'electric' (E) and 'magnetic' (B) components.

-

USEFUL BECAUSE:

- As polarization is generated only at last scattering, it probes last scattering in a more direct way than anisotropies alone
- Observations of polarization provide an important tool for reconstructing the model of the fluctuations from the observed power spectrum → breaking the degeneracy between certain parameter combinations
- Different sources of temperature anisotropies (scalar, vector and tensor) give different patterns in the polarization: both in its intrinsic structure and in its correlation with the temperature fluctuations themselves.
- Polarization power spectrum provides information complementary to the temperature power spectrum. This can be of use in breaking parameter degeneracies and thus constraining cosmological parameters more accurately.
- Timing of reionization

Reionization

The absence of a Lyman alpha absorption trough in the spectra of high redshift quasars $z > 6$ shows that the intergalactic medium must have been reionized

BUT: The re-ionization could not have been earlier than $z \sim 30$, or there would be a suppression of the first Doppler peak in the angular fluctuation spectrum of the Cosmic Microwave Background (Tegmark & Zaldarriaga 2000; De Bernardis et al. 2000).

WMAP led to the estimate $\tau \sim 0.17 \pm 0.04$. WMAP accuracy is not enough for discrimination between models (Naselsky, Chiang 2004). Double reionization models [Cen 2003, Wythe, Loeb 2003], period of extended reionization [Haiman, 2003], but more complex pictures are possible

Constraining **inflation**: Initial perturbations comprise a contribution from tensor modes (gravity waves) in addition to scalar modes (density perturbations) → contribute on large scales ($r=T/S$).

Differentiating between tensor and scalar modes:

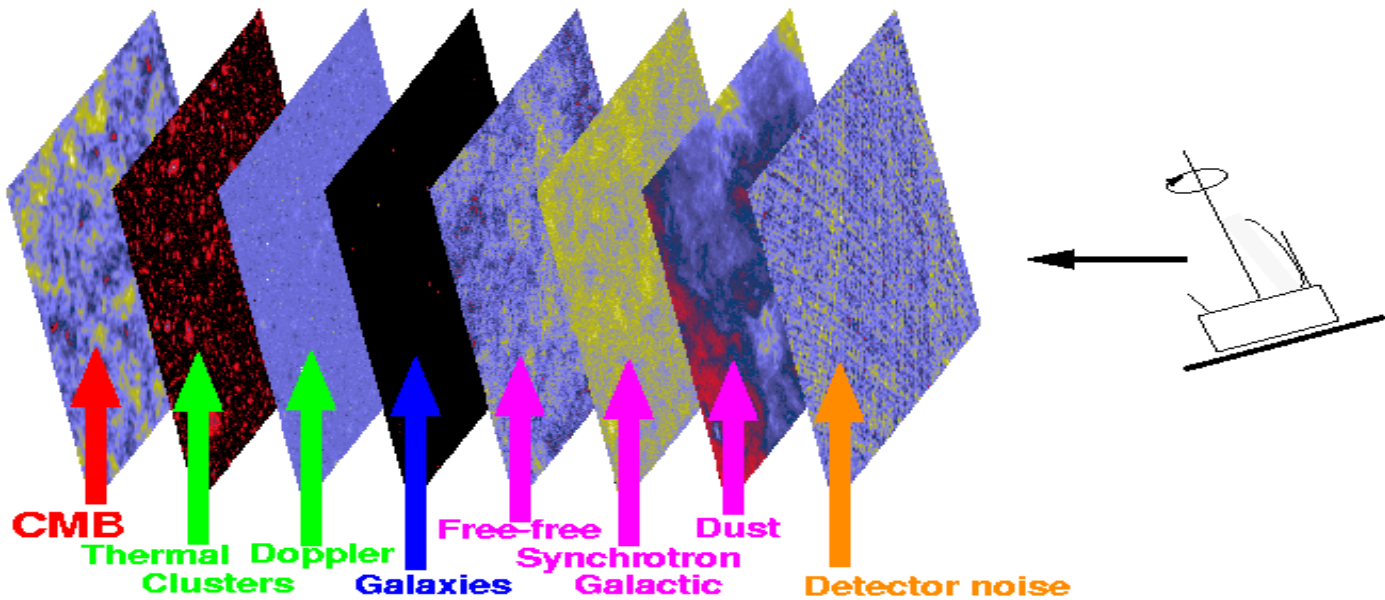
Scalar perturbations produce a pure E-mode polarisation pattern

Vector perturbations (generated in topological defect models) generate mainly a B-mode polarisation pattern

Tensor modes (gravity wave) generate an admixture of E- and B-modes

Secondary effects

Broad frequency coverage (from 30 to about 900 GHz) → detailed nature of various astrophysical foregrounds → must be corrected → but also byproducts



- Cluster of galaxies: kSZ-effect and tSZ-effect
- Extragalactic sources
- Galactic studies: dust properties, magnetic field, distrb. Of the ionized vs. interstellar medium

1. In the low frequency channels (30 to 90 GHz), are expected to detect mainly radio-loud, flat-spectrum **radiogalaxies and QSOs, blazars,** and possibly some inverted-spectrum radiosources.

2. In the millimetre channels (90 to 300 GHz), the predominant extragalactic sources will be rich **clusters of galaxies** detected via the SZ effect.

3. In the sub-millimetre channels (300 to 900 GHz), are expect to detect many thousands of **infra-red luminous galaxies** (both normal and starbursting) and (mostly radio-quiet) AGNs, and a few high-redshift galaxies and QSOs.

4. In sub-mm and mm wavelengths maps of the emission from Galactic

Some scientific areas addressed by Planck

Component

Area

Highlights

CMB

Cosmology & origin of structure

- Initial conditions for structure evolution
 - Origin of primordial fluctuations
 - Testing and characterizing inflation
 - Testing and characterizing topological defects
- Constraints on the nature and amount of dark matter
- Determination of fundamental parameters:

Sunyaev-Zeldovich

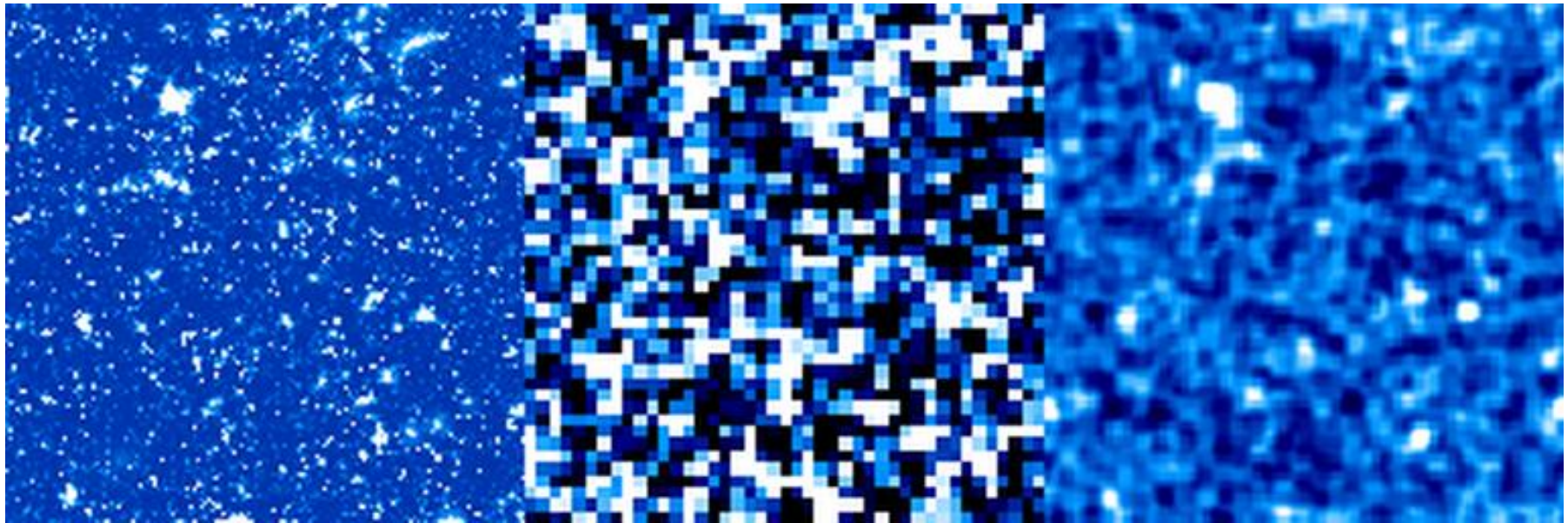
Cosmology & structure evolution

- Measurement of y in $>10^4$ clusters
- Estimate of H_0 from y and X-ray measurements
- Cosmological evolution of clusters
- Bulk velocities (scales >300 Mpc) out to $z \sim 1$ with $v \sim 50$ km/s

The Thermal SZ effect

High signal to noise and angular resolution are essential to studying higher order effects and cross-correlating CMB maps with observations at other wavelengths.

← 3 deg →



Input SZ simulation

WMAP 4yr

Planck 1yr

Some scientific areas addressed by Planck

Component

Area

Highlights

[Extragalactic sources](#)

Cosmology & structure formation

- Source catalogues of
 - [IR and radio galaxies](#)
 - [AGNs, QSOs, blazars](#)
 - [Inverted-spectrum radio sources](#)
- [Far-infrared background fluctuations](#)
- Evolution of galaxy counts

[Dust emission](#)

[Galactic studies](#)

- Dust properties
- Cloud and cirrus morphology
- Systematic search for cold cores

[Free-free and synchrotron](#)

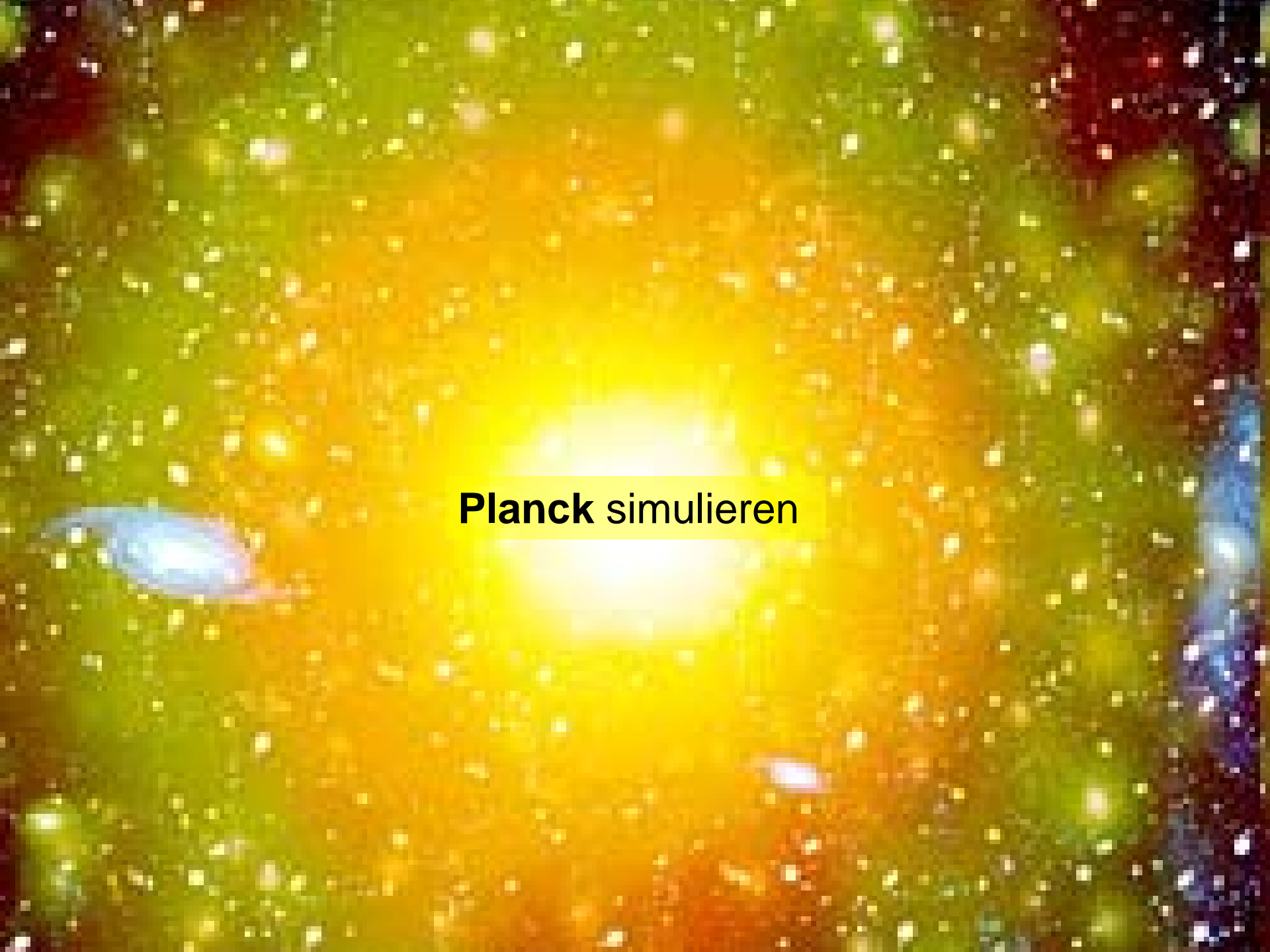
[Galactic studies](#)

- Determination of spectral indices
- Cosmic ray distribution
- Magnetic field mapping

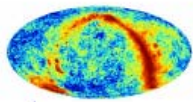
All Channels

Solar System studies

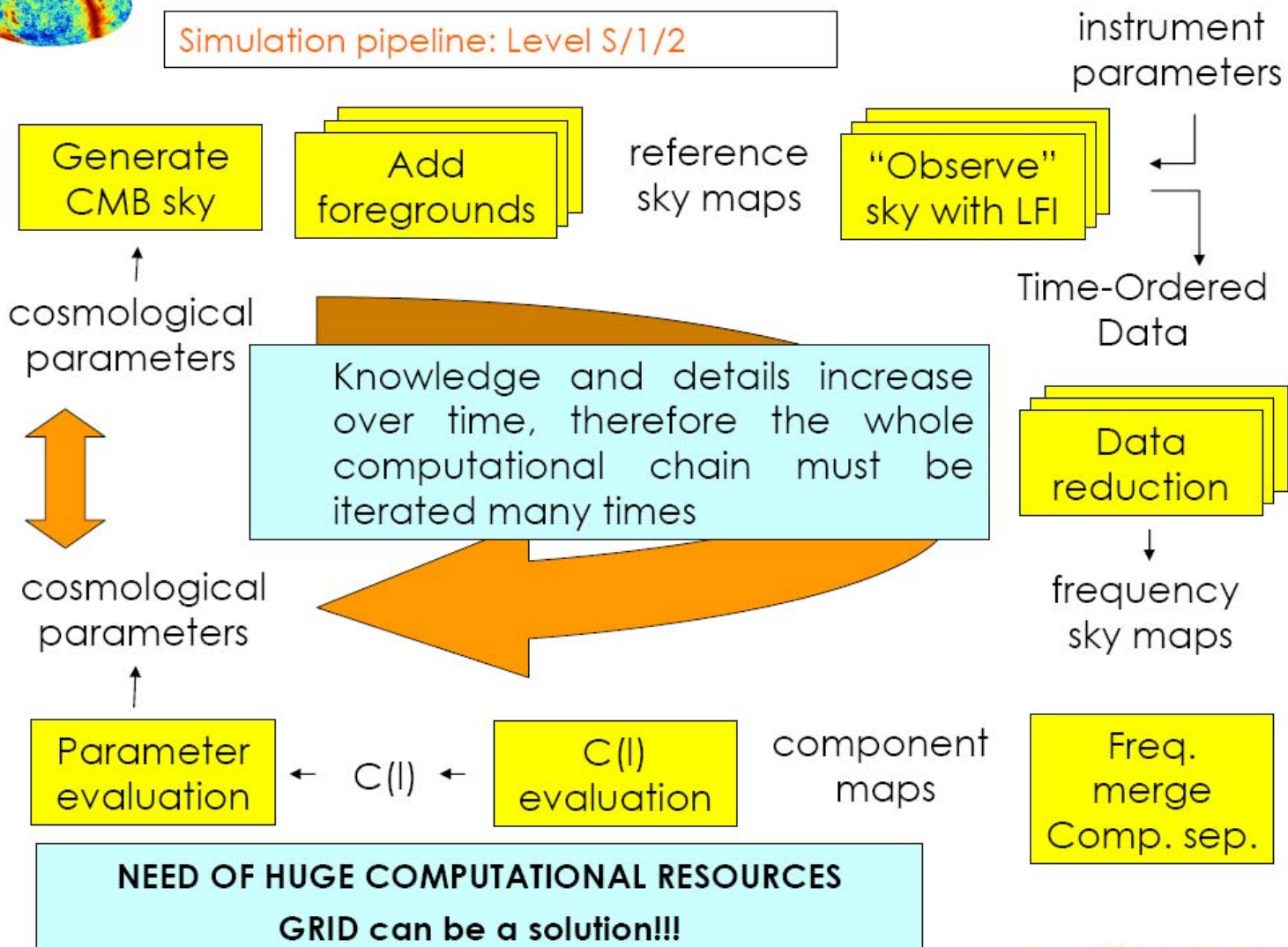
- Asteroids
- Planets
- Comets
- Zodiacal emission

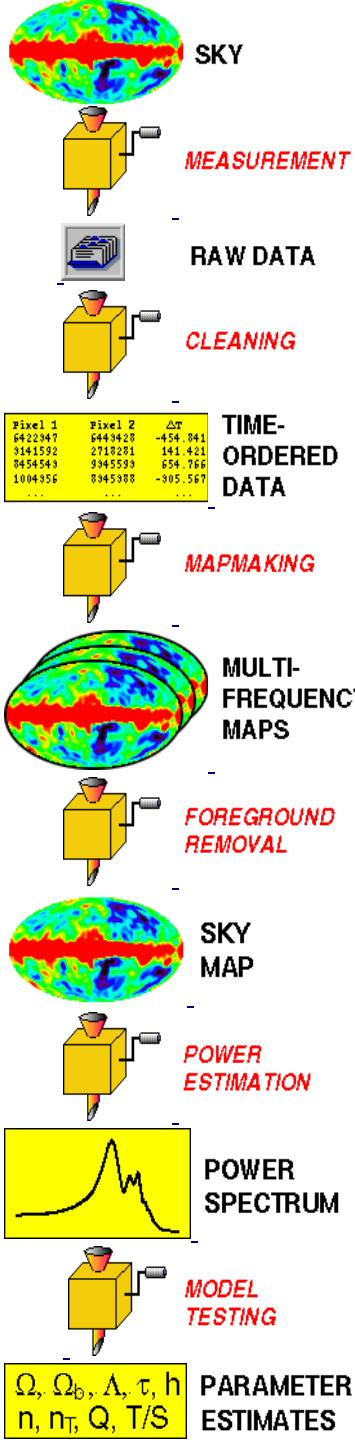


Planck simulieren



Simulation pipeline: Level S/1/2



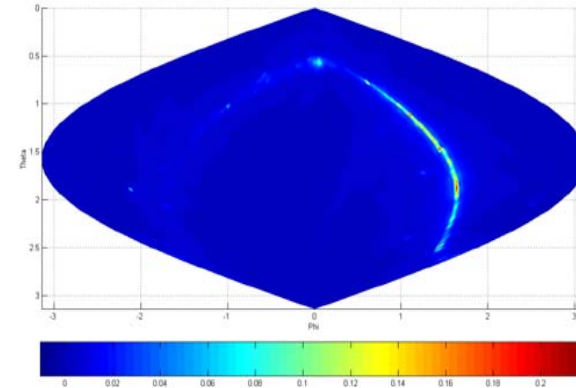


→ Maximize the ability to: discriminate between different cosmological models, subtract foregrounds & minimize the susceptibility to systematic errors: pointing strategy, frequency coverage...

→ Instrument noise etc.

=TOD

→ HEALPIX



also "electric" and "magnetic" parts of the the polarization field
 → To remove contaminating foreground signals

Secondary anisotropies!

Show how much T varies from to point to point on the sky
 → Values of cosmological parameters can be determined by comparing model and observed temperature power spectra

German Astrophysical Virtual Observatory



- **The Planck Simulator**
- The Planck Simulator provides synthetic sky maps of the Cosmic Microwave Background. The Planck Simulator allows to enter a variety of parameters which describe the assumed cosmology and allows to include a number of foreground emission processes. A detailed description of the available options can be found here.

<http://www.g-vo.org/portal/tile/products/services/planck/index.jsp>

- WOMBAT is dedicated to understanding sources of microwave foreground emission and providing the cosmology community with estimates of foreground emission as well as uncertainties in those estimates.

<http://astron.berkeley.edu/wombat/>



Hierarchical Equal Area isoLatitude Pixelisation of the sphere

Analysis Packages:

- [HEALPix](#)
- [SpICE](#)
- [MADCAP](#) Microwave Anisotropy Dataset Computational Analysis Package
- [CMBFit](#) CMBfit is a software package for ultra-fast calculation of likelihoods from the Wilkinson Microwave Anisotropy Probe (WMAP) data
- [GLESP](#) Gauss-Legendre Sky Pixelization for CMB analysis

C(l) Computation:

- [CMBFAST](#) The [CMBfast](#) software can be used for the computation of the theoretical spectra of CMB anisotropy. The HEALPix synfast program reads in the output of this routine to allow one to generate random realisations of the observable CMB sky.
- [CAMB](#) Code for Anisotropies in the Microwave Background
- [CMBEASY](#) CMBEASY is a software package for calculating the evolution of density fluctuations in the universe
- [DASh](#) CMBEASY is a software package for calculating the evolution of density fluctuations in the universe
- [RECFAST](#) A code to calculate the recombination history of the Universe



Herschel

Wilhelm Herschel entdeckt das Infrarot (1800)



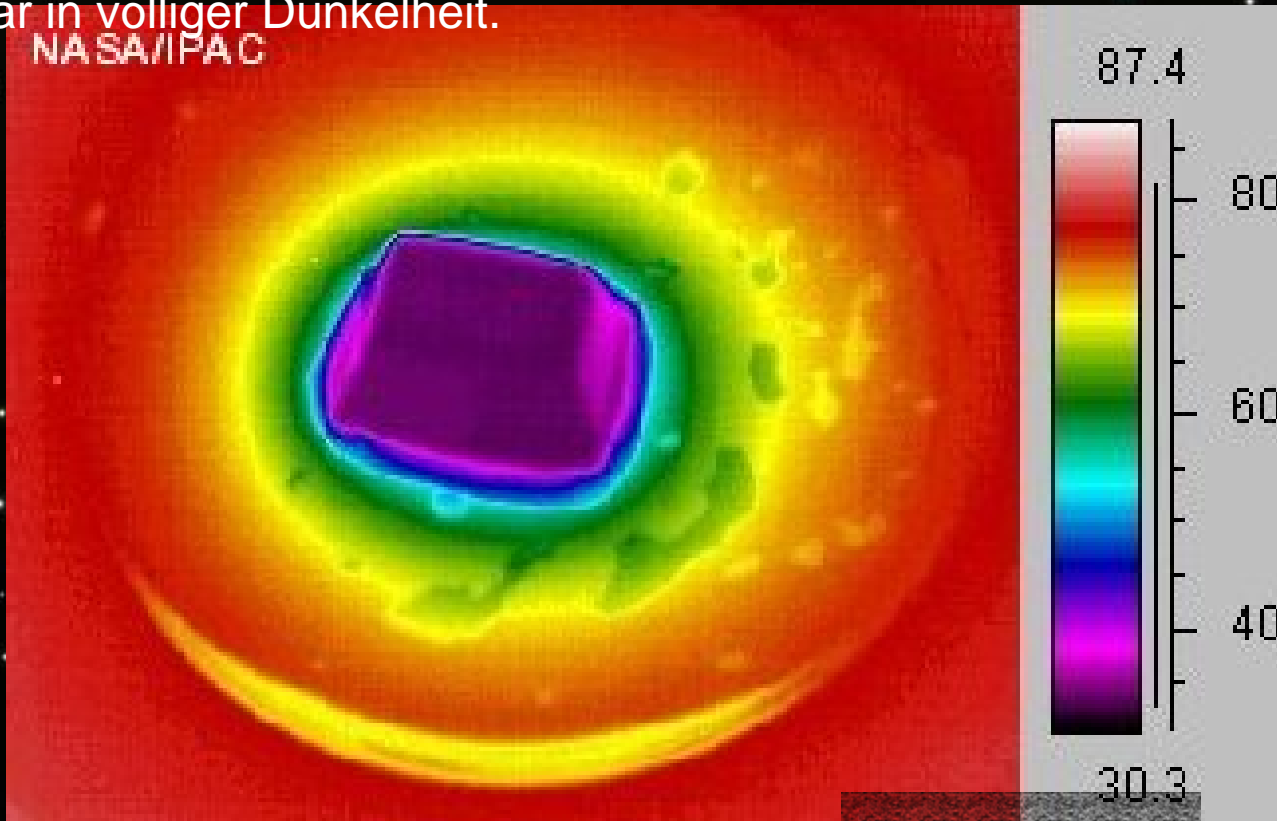
Sturm

Beschreibung des Experiments:

http://coolcosmos.ipac.caltech.edu/cosmic_classroom/classroom_activities/herschel_experiment.html

Die primäre Quelle infraröter Strahlung ist Wärme (*thermische* oder *Wärme-Strahlung*). Jeder Körper hat eine gewisse Temperatur und sendet elektromagnetische Strahlen aus. Je kühler ein Objekt ist, desto weiter liegt seine Strahlung im Infraroten. Eiswürfel, zum Beispiel, sind Infrarotquellen. Gegenstände, die nicht heiß genug sind, um sichtbares Licht abzustrahlen, senden Infrarotstrahlen ab, die wir nicht sehen können, aber als Wärme empfinden.

Einige Lebewesen haben aber tatsächlich so etwas wie Infrarot-Augen. Grubenottern wie die Klapperschlange, z.B., können mit ihrem Grubenorgan warmblütige Tiere lokalisieren, sogar in völliger Dunkelheit.



Sturm





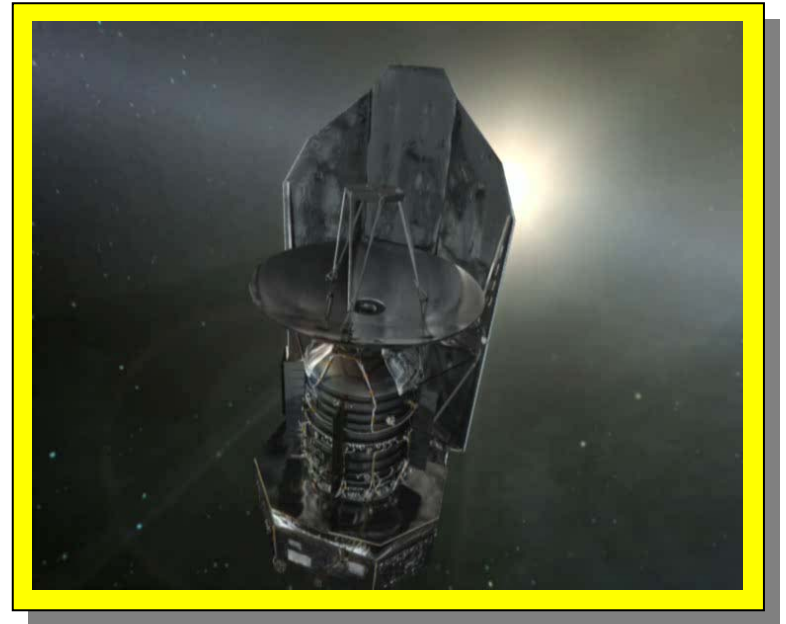
Infrarotstrahlung wird von den Körpern selber abgestrahlt,
während der größte Teil des sichtbaren Lichts reflektiertes Tages- oder Kunstlicht ist.



Aufgrund ihrer langwelligigen Natur kann Infrarotstrahlung Hindernisse durchdringen, die sichtbares Licht vollständig blockieren.

Herschel

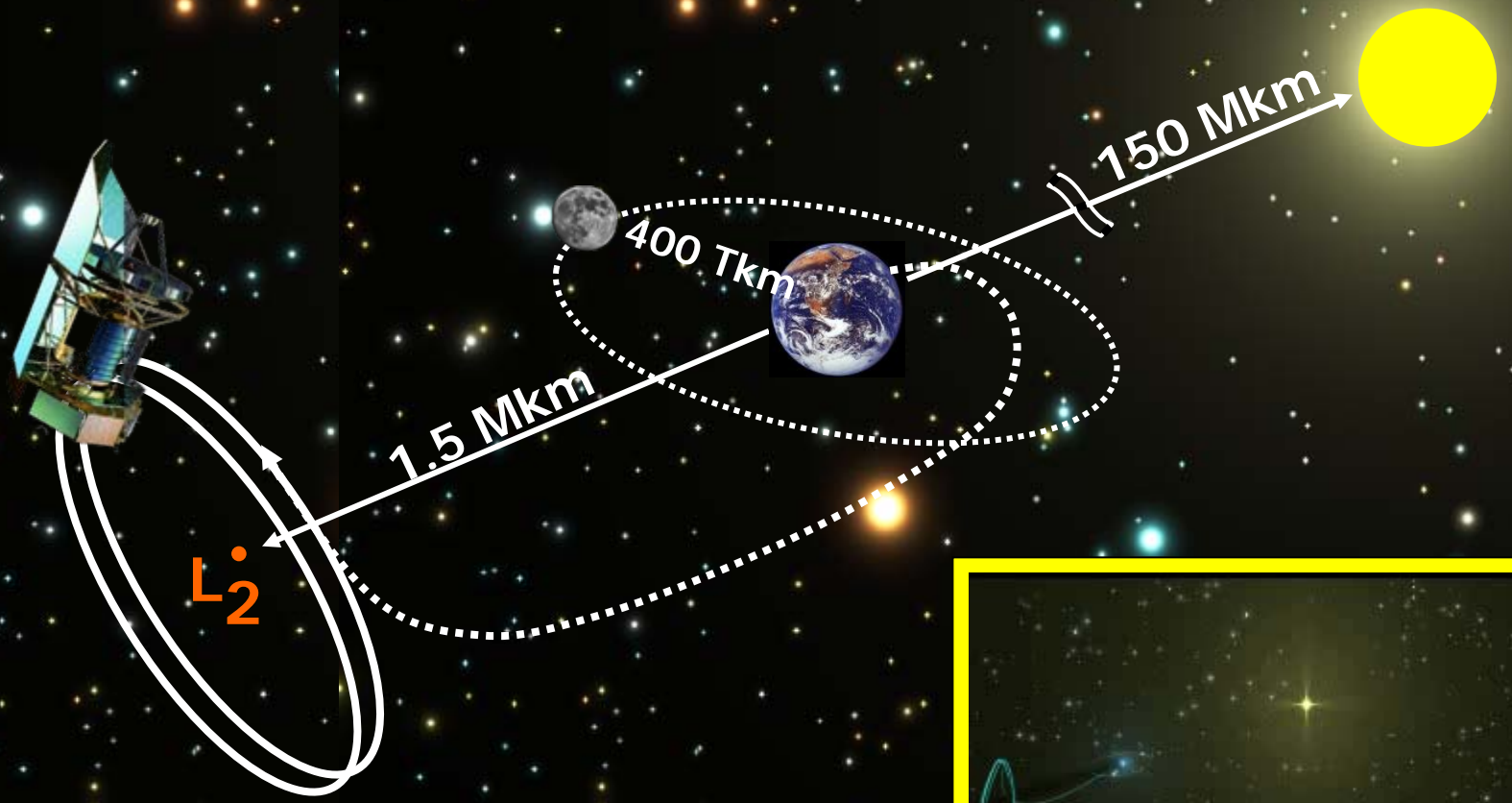
- **Zentrale ESA-Mission** (“Cornerstone Observatory”)
- **Observatorium im All zur astronomischen Forschung im Infraroten (57 - 670 μm)**
 - 3.5 m Teleskop (größtes Weltraumteleskop aller Zeiten)
 - 3 wissenschaftliche Instrumente (HIFI, PACS und SPIRE)
 - 3 Jahre Beobachtungsbetrieb
- **Start im Mai 2009 (zusammen mit Planck)**



World's largest space mirror polished at Tuorla

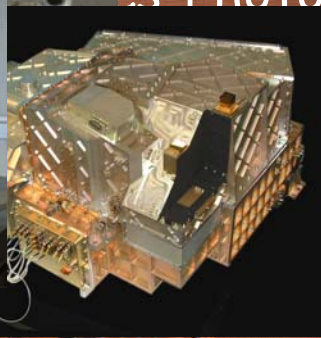


The mirror will be unique in many ways. When the mission is launched in 2009, it will be the largest ever sent to space. It will be the first SiC mirror used in a telescope, and of course the first to be used in space as well. It will be the first mirror polished to operate at both short radio wavelengths and long infra-red wavelengths. Herschel will be the first entirely European space telescope.



Herschels 3 Messinstrumente

- **PACS** ist eine Kamera und ein Spektrometer (niedriger bis mittlerer Auflösung) für den Wellenlängenbereich 5-210 μm . Es arbeitet entweder als Photometer oder als Spektrometer (mit "wide field") Linienspektrometer.

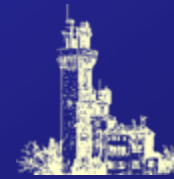


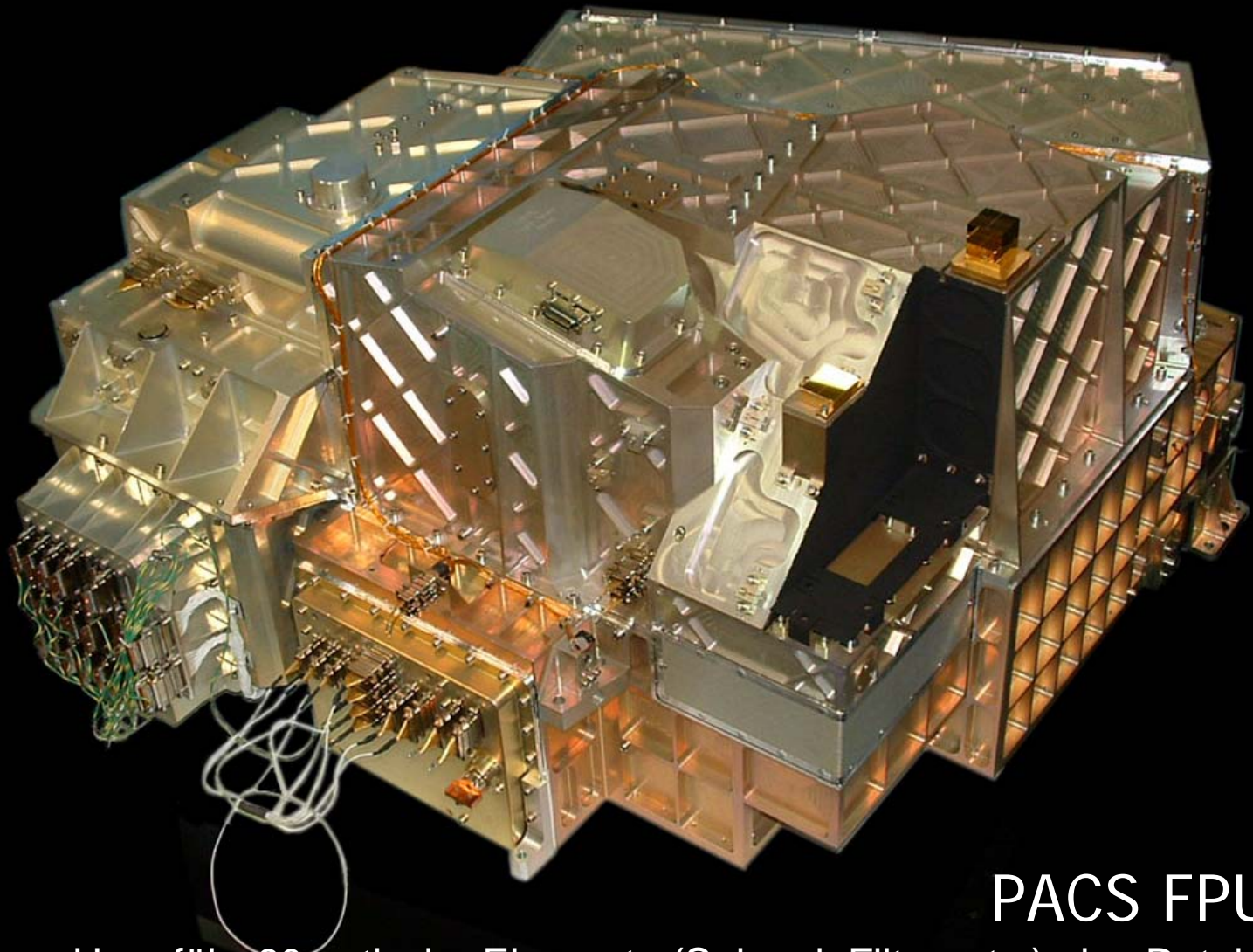
- **SPIRE** ergänzt PACS als Spektrometer im Wellenlängenbereich 194-672 μm .

- **HIFI** ist ein Heterodyn-Spektrograph sehr hoher spektraler Auflösung für Frequenzen zwischen 490 - 1250 GHz und 1410 - 1910 GHz (625-236 μm und 213-157 μm).

→ http://herschel.esac.esa.int/science_instruments.shtml

Das PACS Konsortium: 15 Institute in 6 Ländern



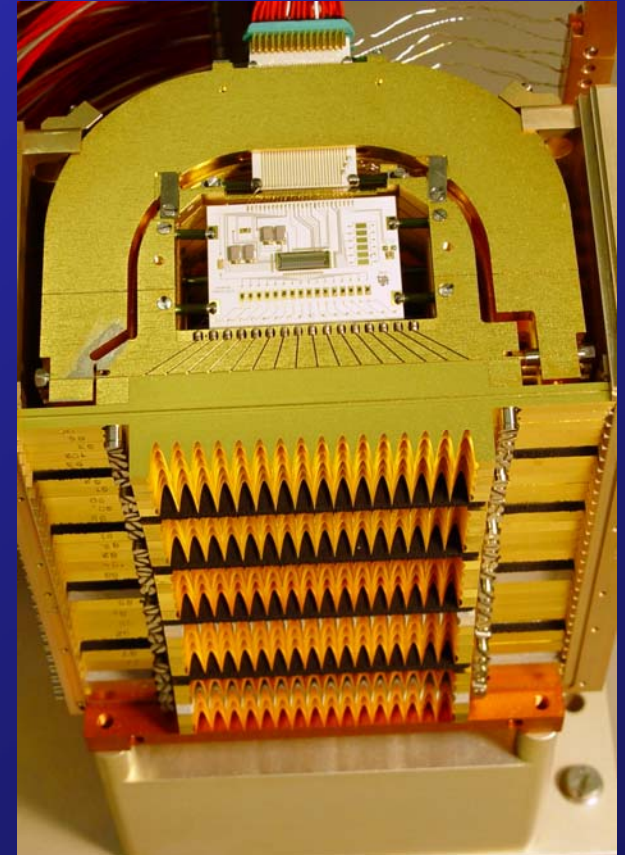
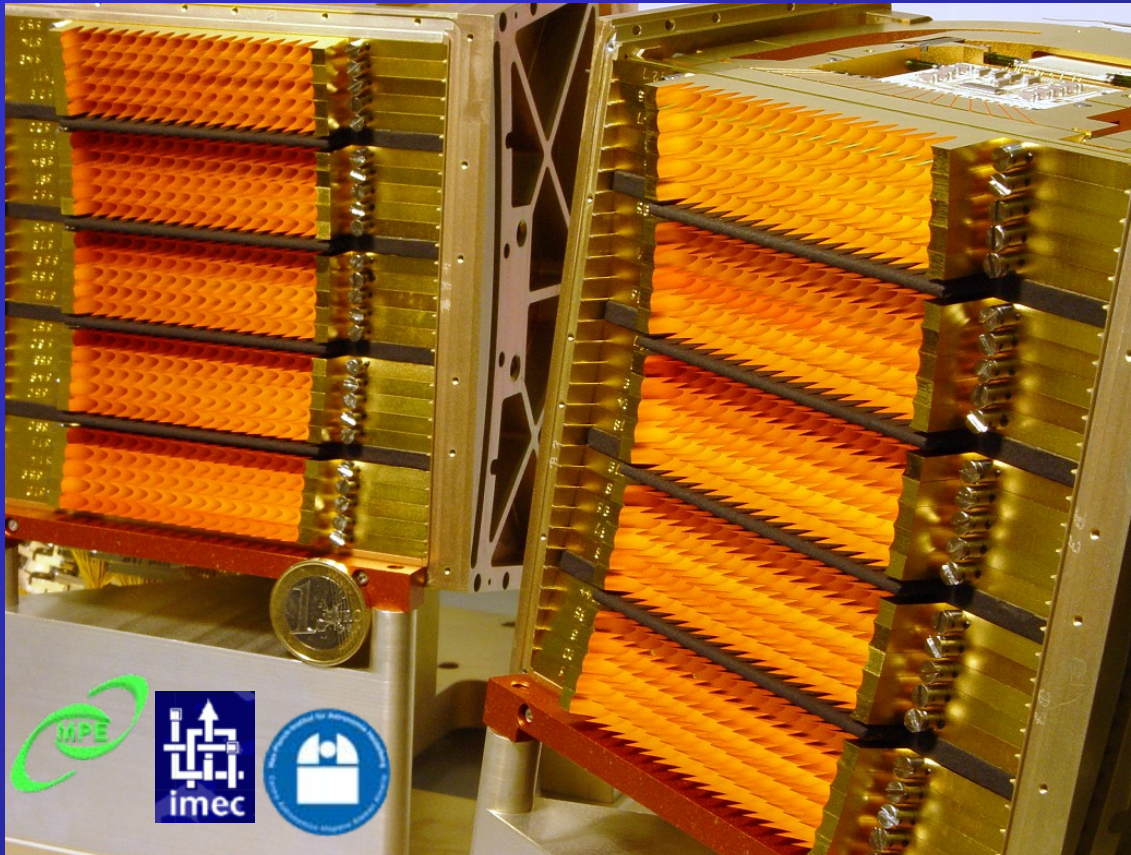


PACS FPU

Ungefähr 60 optische Elemente (Spiegel, Filter, etc.) plus Detektoren und Mechanismen auf engstem Raum!

PACS Ge:Ga Lichtleiter-Detektoren (Spektrometer)

- Zwei Chips mit je 25x16 pixel, teilweise unter Druck, für 55 - 210 μm
- Betriebstemperatur der Detektoren: $\sim 2\text{ K}$ (-271° C), 4 K für die Auslese-Elektronik



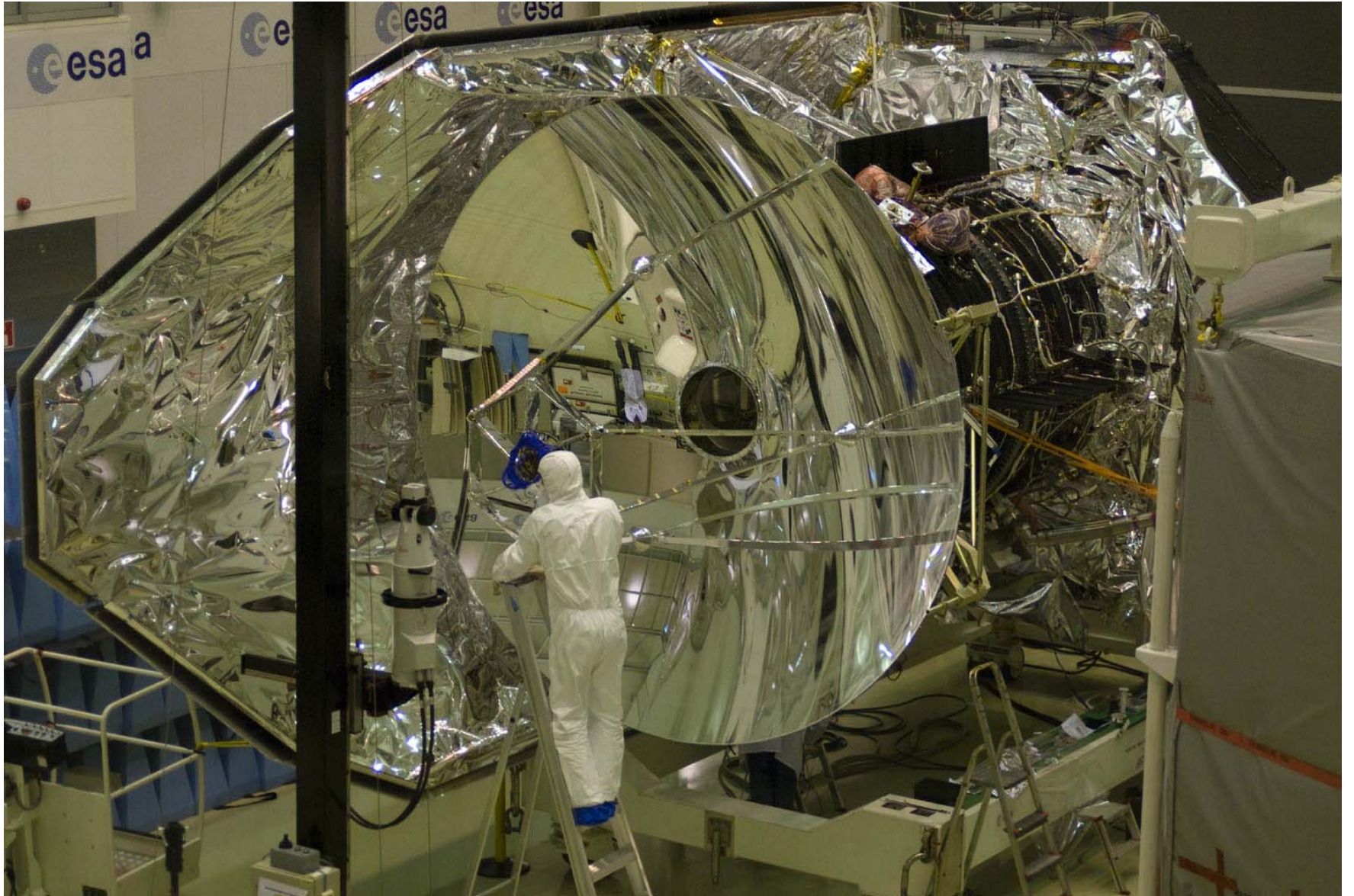
Transport des Teleskopspiegels

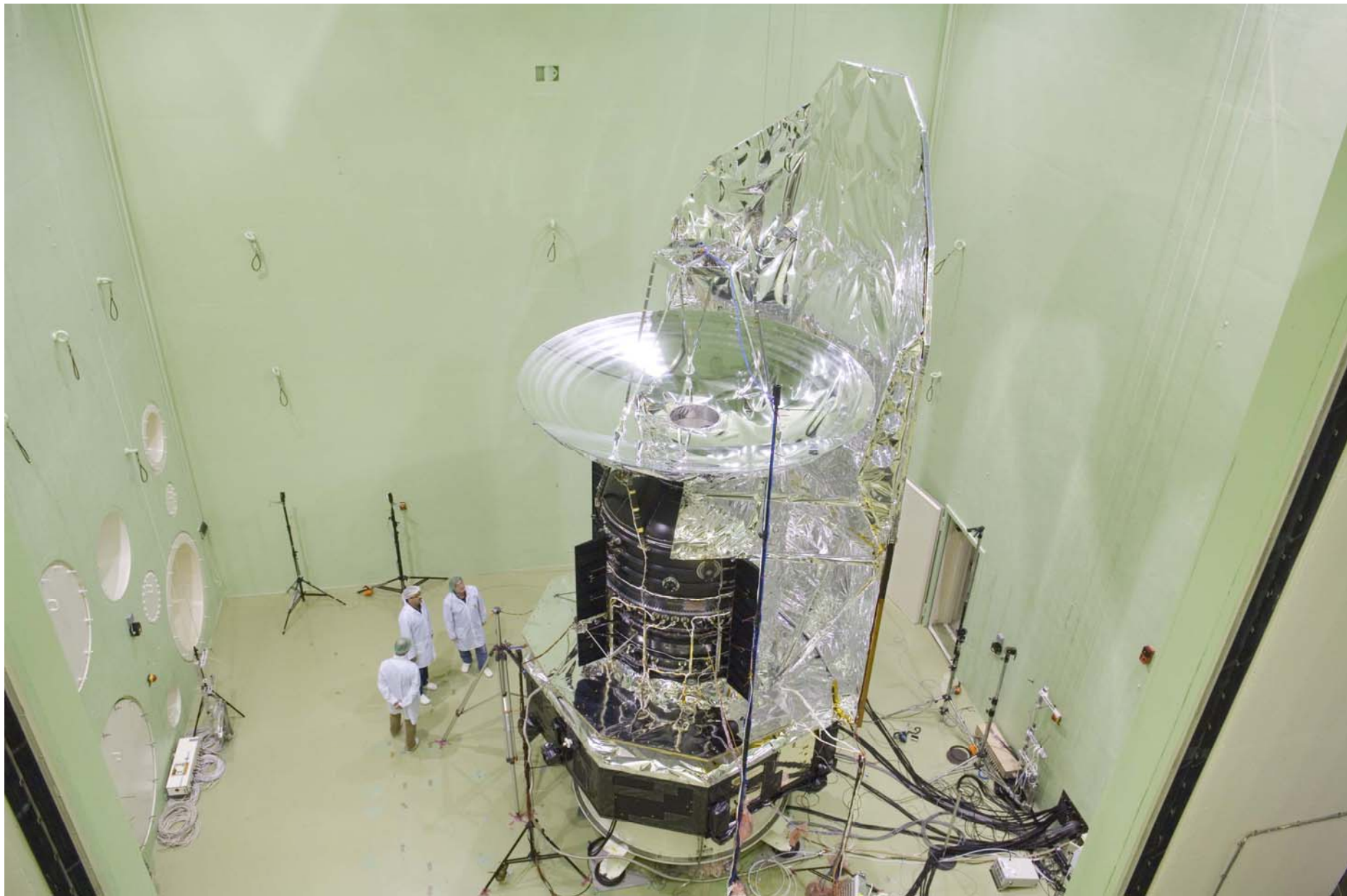




Satelliten-Integration beim Technologiezentrum der ESA (ESTEC) in Noordwijk, Holland

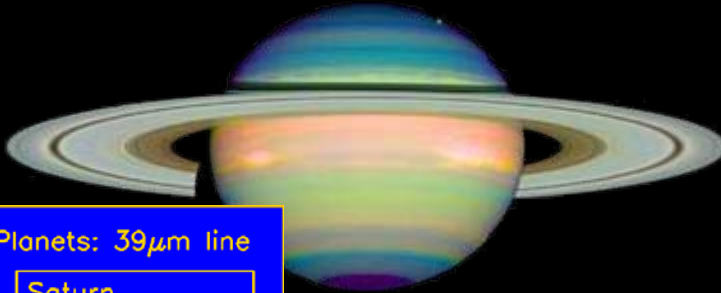
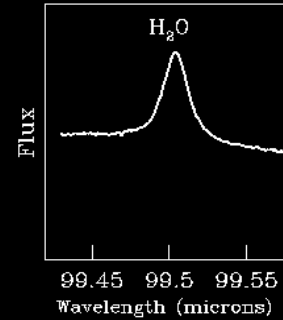
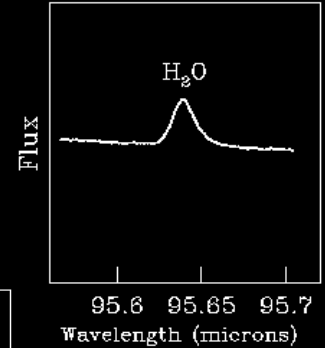
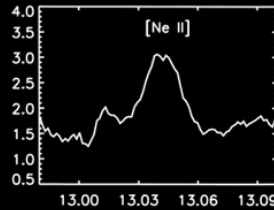
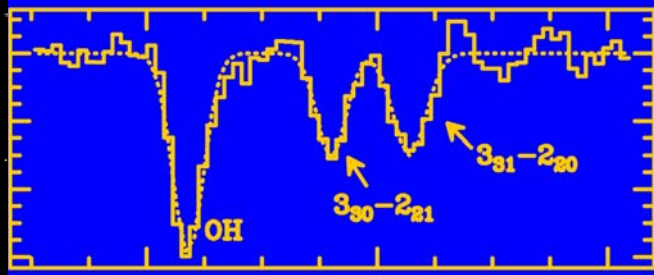
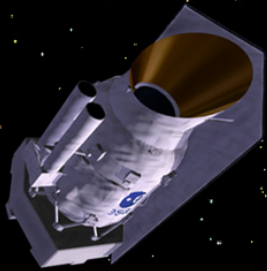




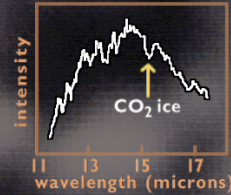
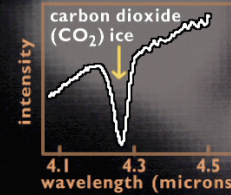
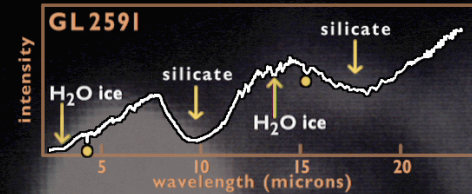
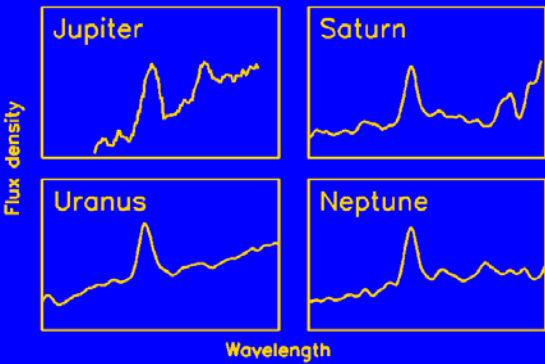


<http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=42984>

Wasser - Segen und Fluch der Infrarot Astronomy

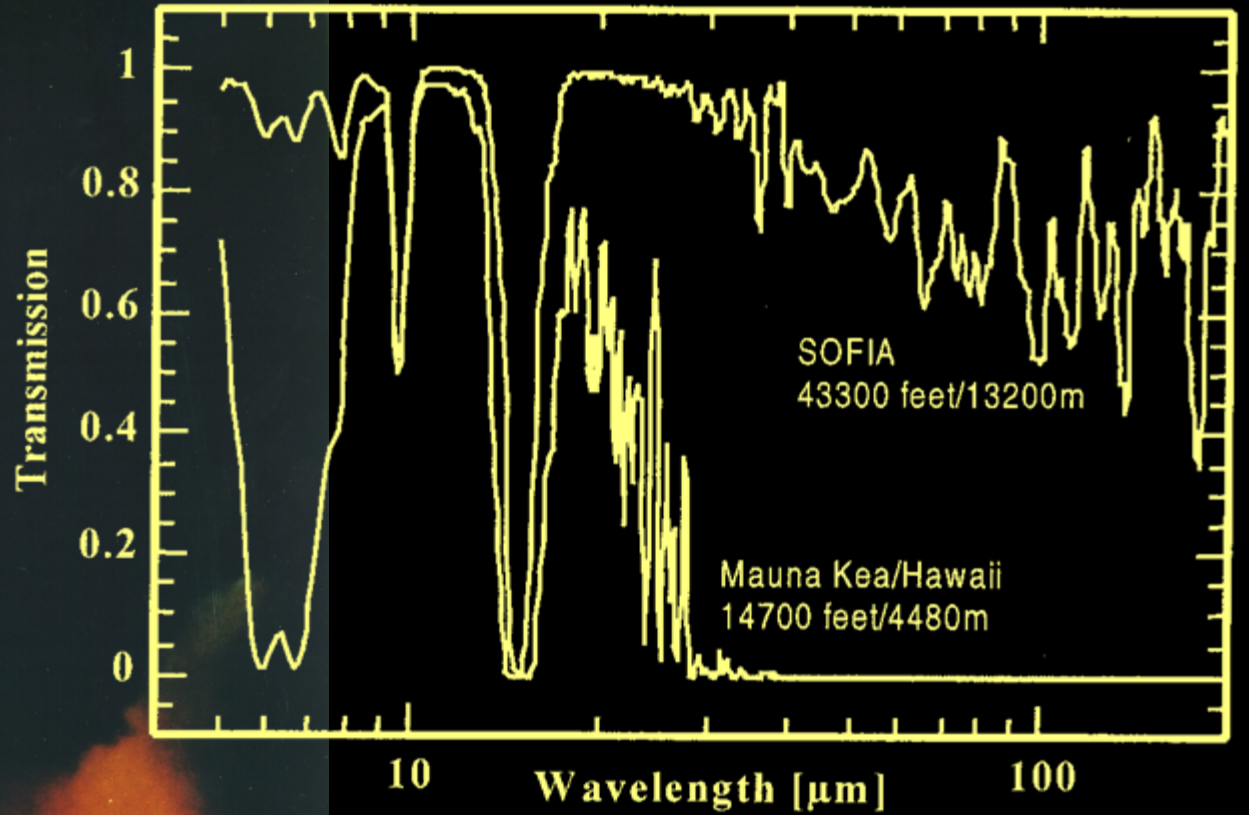
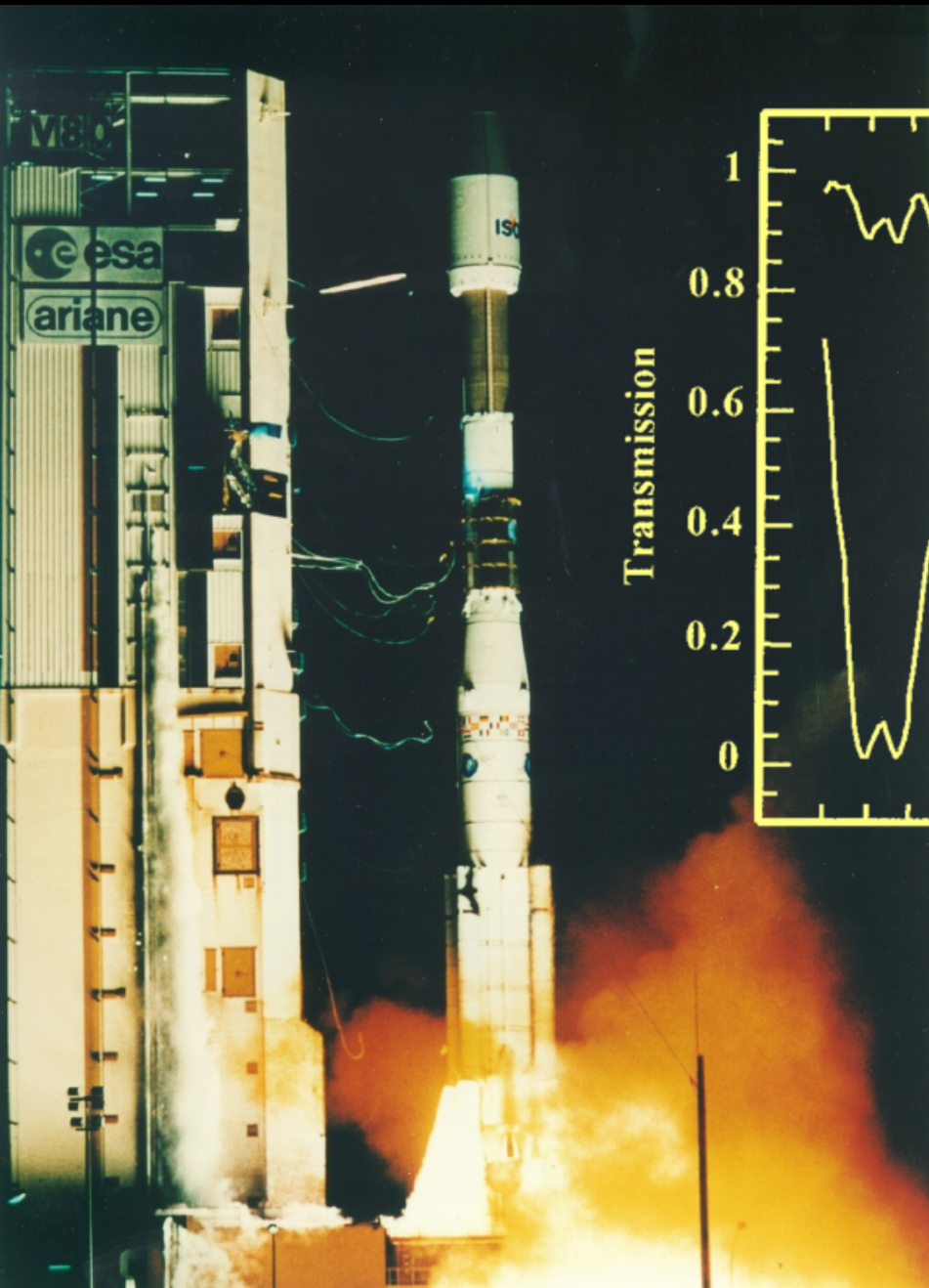


Water on the Giant Planets: 39 μ m line

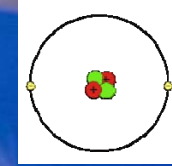


ESA/ISO and SWS Consortium

Wasser - Segen und Fluch der Infrarot Astronomy



Die He-Krise



Knapp & teuer



Heliumkrise:

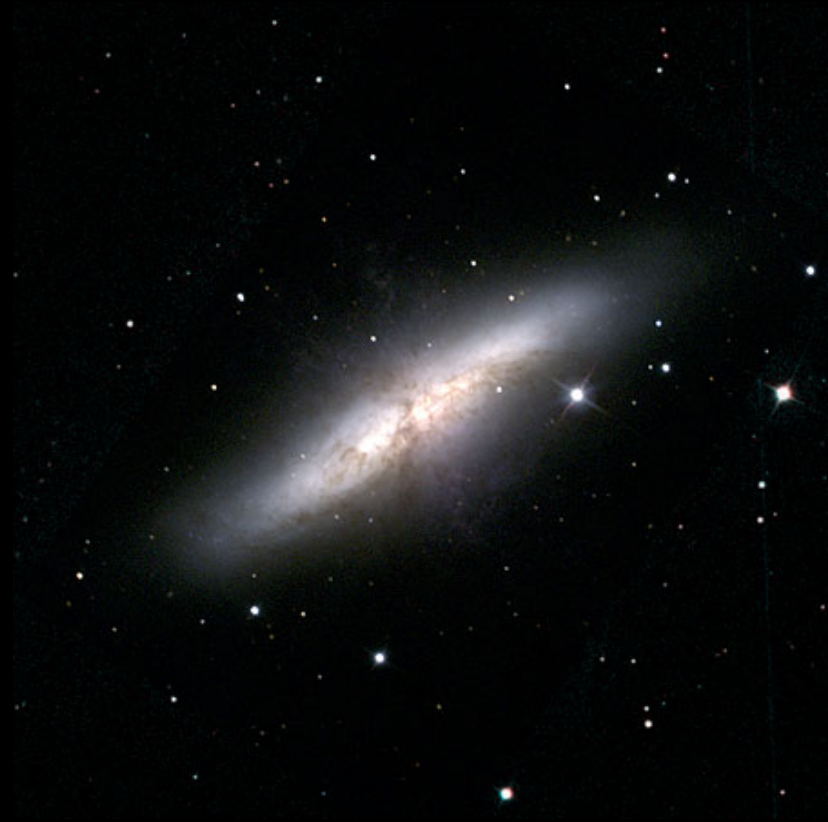
http://scitation.aip.org/journals/doc/PHTOAD-ft/vol_60/iss_6/31_1.shtml



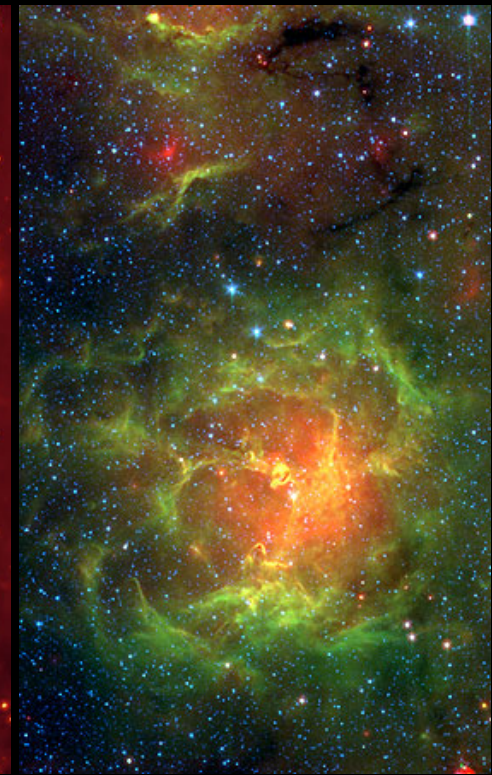
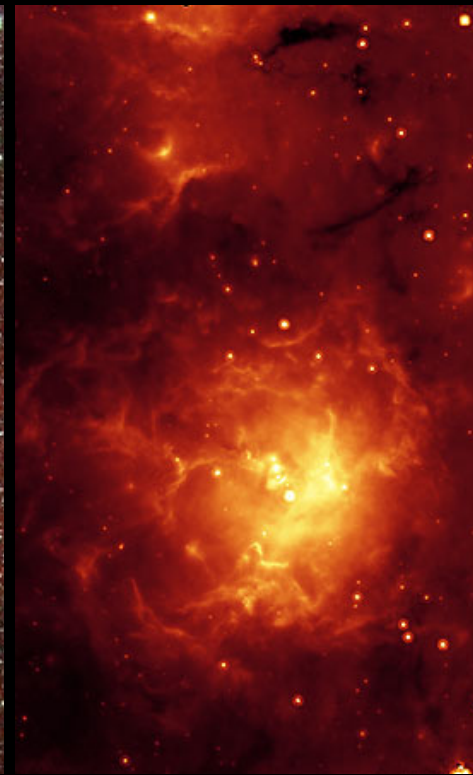


Wissenschaft mit **Herschel**

M82 im sichtbaren (links) und infraroten Licht (rechts)



Trifidnebel im sichtbaren Licht (links), im nahen (Mitte) und im mittleren Infrarot



Kühle Sterne

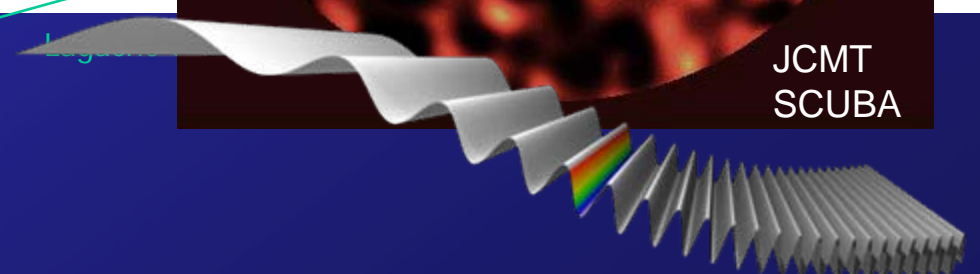
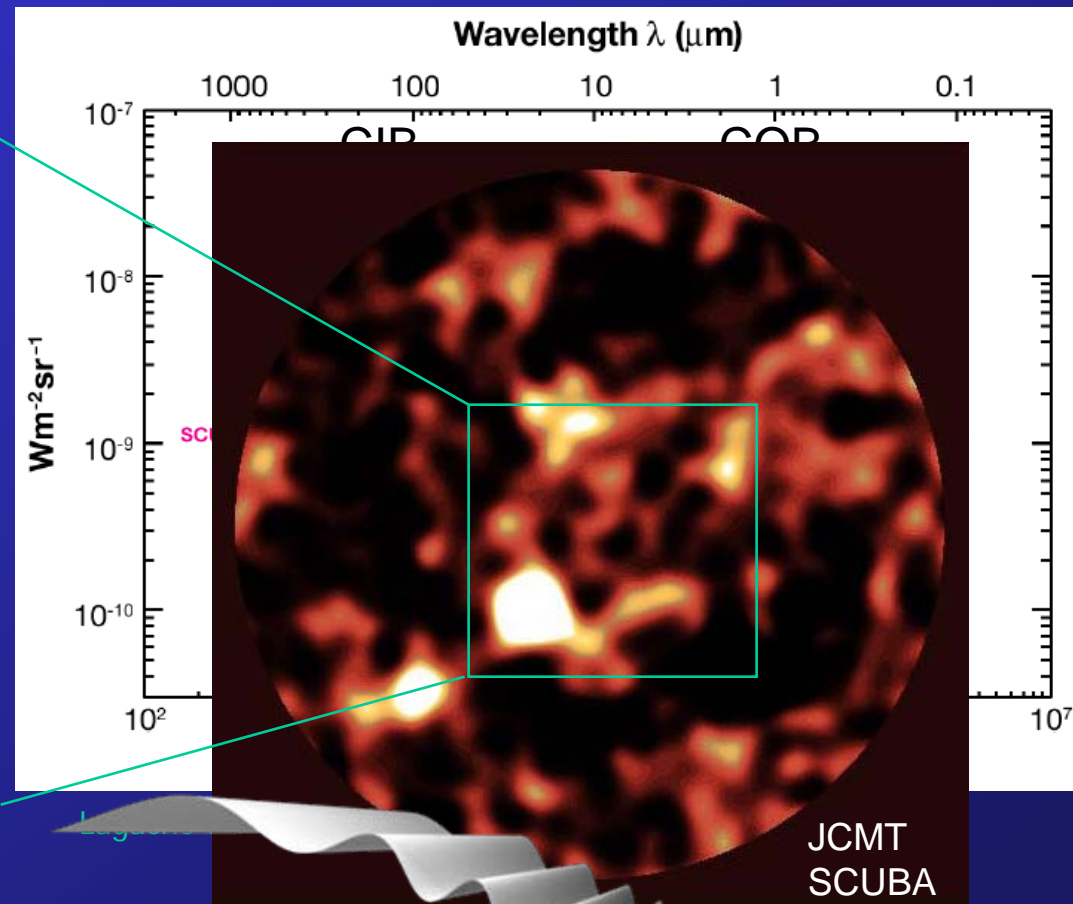
Kalter Staub strahlt

Herschels Forschungsziele (Auswahl)

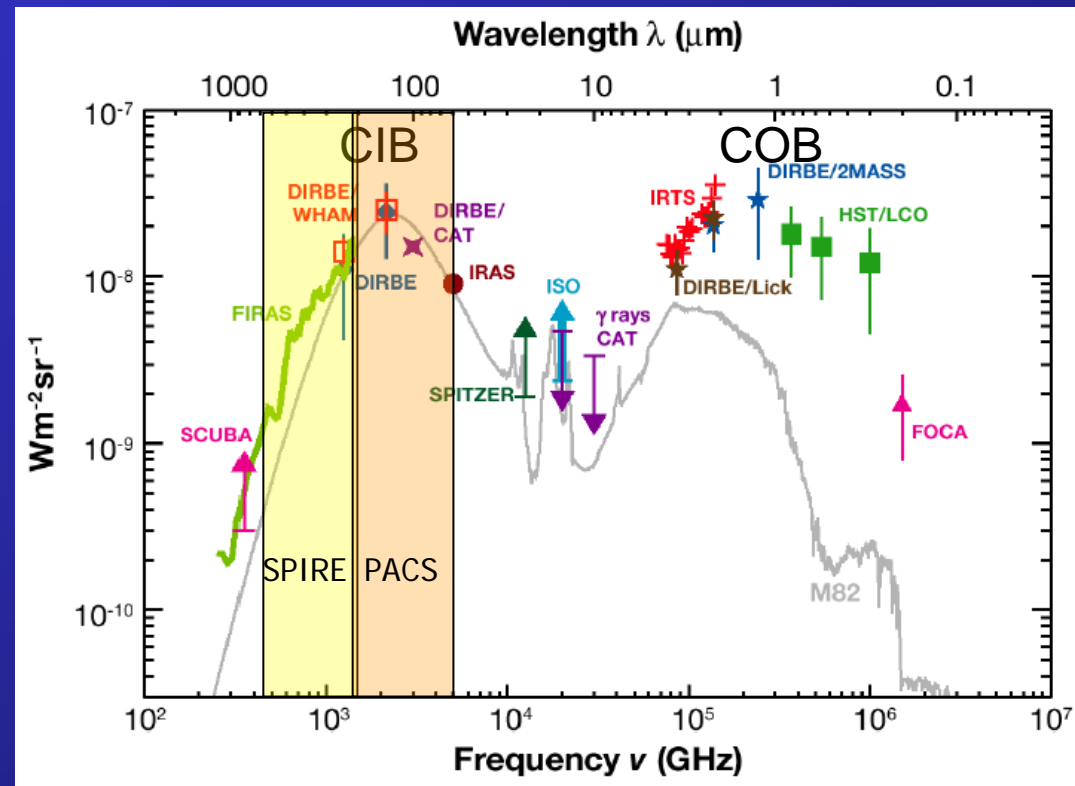
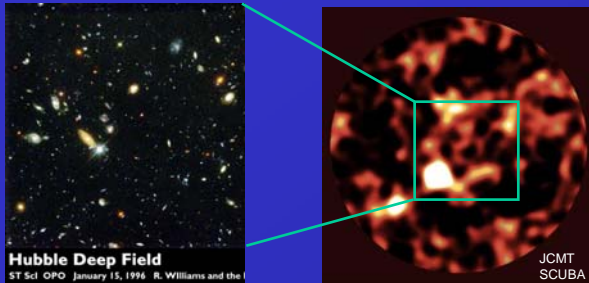


Hubble Deep Field

ST ScI OPO January 15, 1996 R. Williams and the I



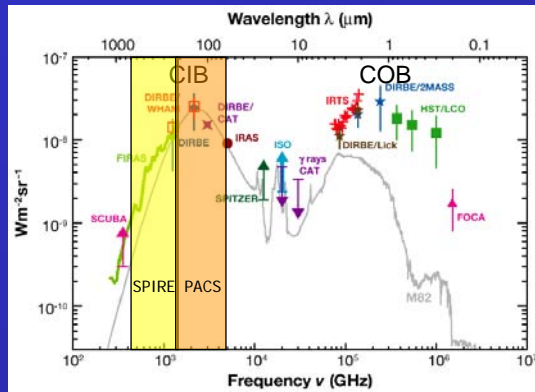
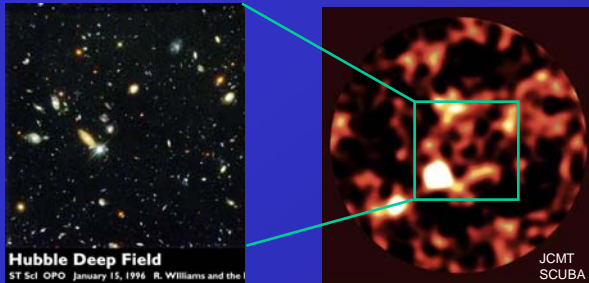
Herschels Forschungsziele (Auswahl)



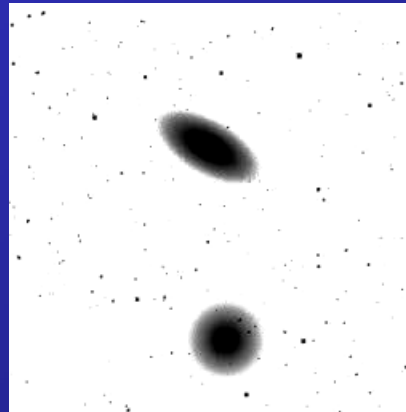
Lagache et al. 2005 ARAA

Auflösung des kosmischen Infrarot-Hintergrunds in einzelne Quellen:
Photometrie und Spektroskopie des
Höhepunktes der Galaxienentstehung.

Herschels Forschungsziele (Auswahl)

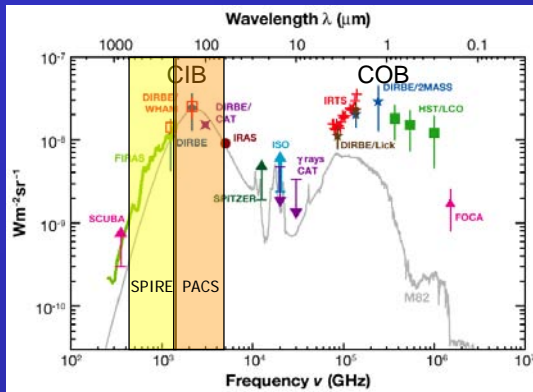
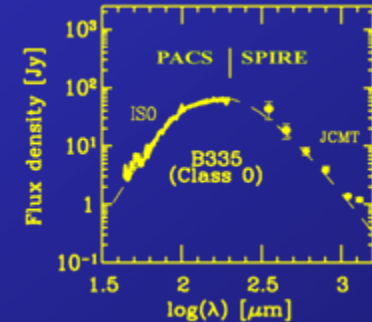
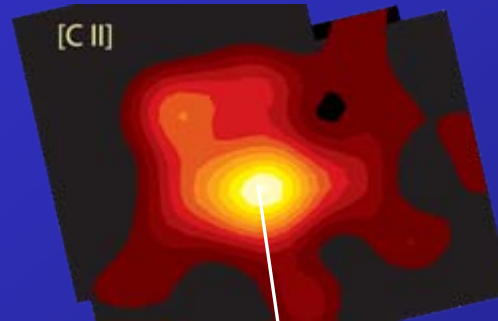
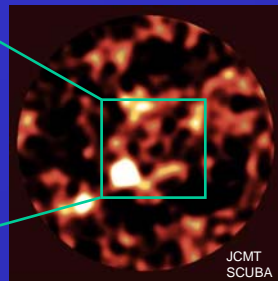


Lagache et al. 2005 ARAA



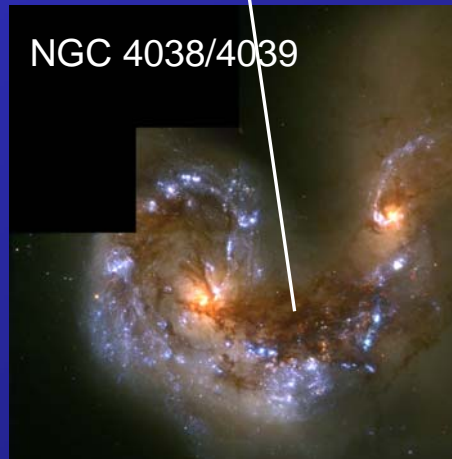
Auflösung des kosmischen Infrarot-Hintergrunds in einzelne Quellen:
Photometrie und Spektroskopie des
Höhepunktes der Galaxienentstehung.

Herschels Forschungsziele (Auswahl)



Lagache et al. 2005 ARAA

Auflösung des kosmischen Infrarot-Hintergrunds in einzelne Quellen: Photometrie und Spektroskopie des Höhepunktes der Galaxienentstehung.

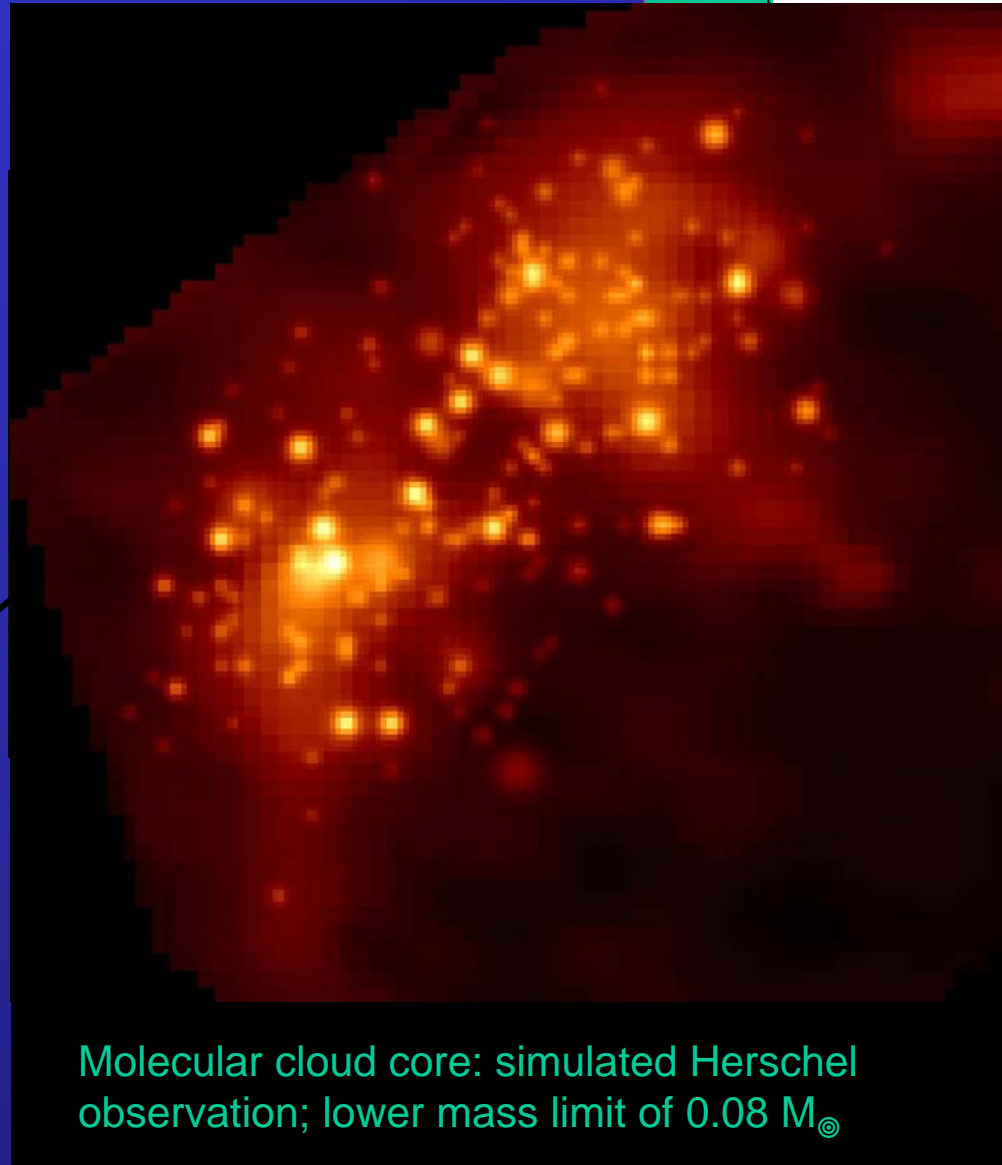
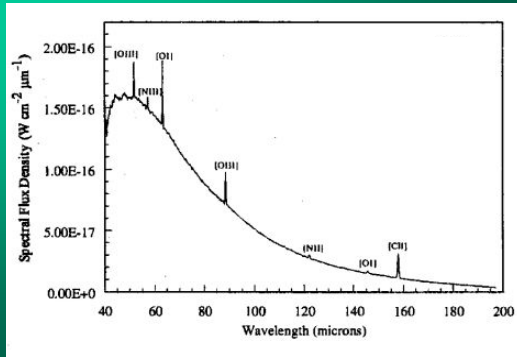
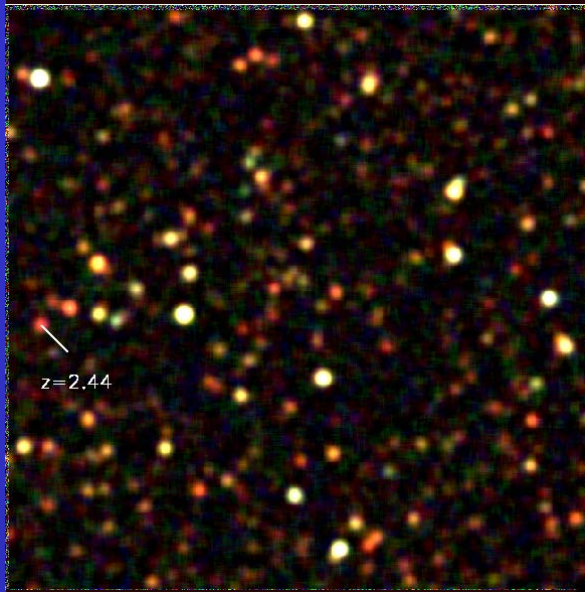


Sternentstehung unter verschiedenen Bedingungen in unterschiedlichen Galaxientypen: räumlich aufgelöste photometrische und spektroskopische Abbildung.



Bildung von Sternen und Planetensystemen in der Milchstraße und der Ursprung der stellaren Massenverteilung: Photometrie und Spektroskopie.

Die Rolle von PACS



Molecular cloud core: simulated Herschel observation; lower mass limit of $0.08 M_{\odot}$

on prestellaren
Protosternen,
sich der Früh-
Zwerg

Starttermin:

14. Mai 2009, nächste Woche !!



ESA / CNES
Arianespace / CSG



Programm SoSe 09

03.04.	Überblick über die Themen des Semesters
17.04.	Die Konstanz der Naturkonstanten
08.05.	Aus aktuellem Anlass: Planck & Herschel
22.05.	Äquivalenzprinzip & Schleifen-Quantengravitation
05.06.	Zeitreisen
19.06.	Gibt es Extraterrestrisches Leben?
03.07.	