Radio and mm astronomy

Wintersemester 2012/2013

Henrik Beuther & Hendrik Linz

16.10 Introduction & Overview	*(HL & HB)*
23.10 Emission mechanisms, physics of radiation	**(HB)**
30.10 Telescopes – single-dishs	(HL)
06.11 Telescopes – interferometers	(HB)
13.11 Instruments – continuum radiation	(HL)
20.11 Instruments – line radiation	(HB)
27.11 Continuous radiation (free-free, synchrotron, dust, CMB)	(HL)
04.12 Line radiation	(HB)
11.12 Radiation transfer	(HL)
18.12 Effelsberg Excursion	
Christmas break	
08.01 Molecules and chemistry	(HL)
15.01 Physics and kinematics	(HB)
22.01 Applications	(HL)
29.01 Applications	(HB)
05.02 last week, no lecture	

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws1213.html

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Literature

- Rohlfs & Wilson: Tools of Radioastronomy, Spinger Verlag
- Synthesis imaging in radio astronomy II, edited Taylor, Carilli, Perley, ASP Conference Series 180
- Condon & Ransom: Essential radio astronomy, online notes: http://www.cv.nrao.edu/course/astr534/ERA.shtml

Excursion to Effelsberg, 18.12.2012, 11:00

Topics today

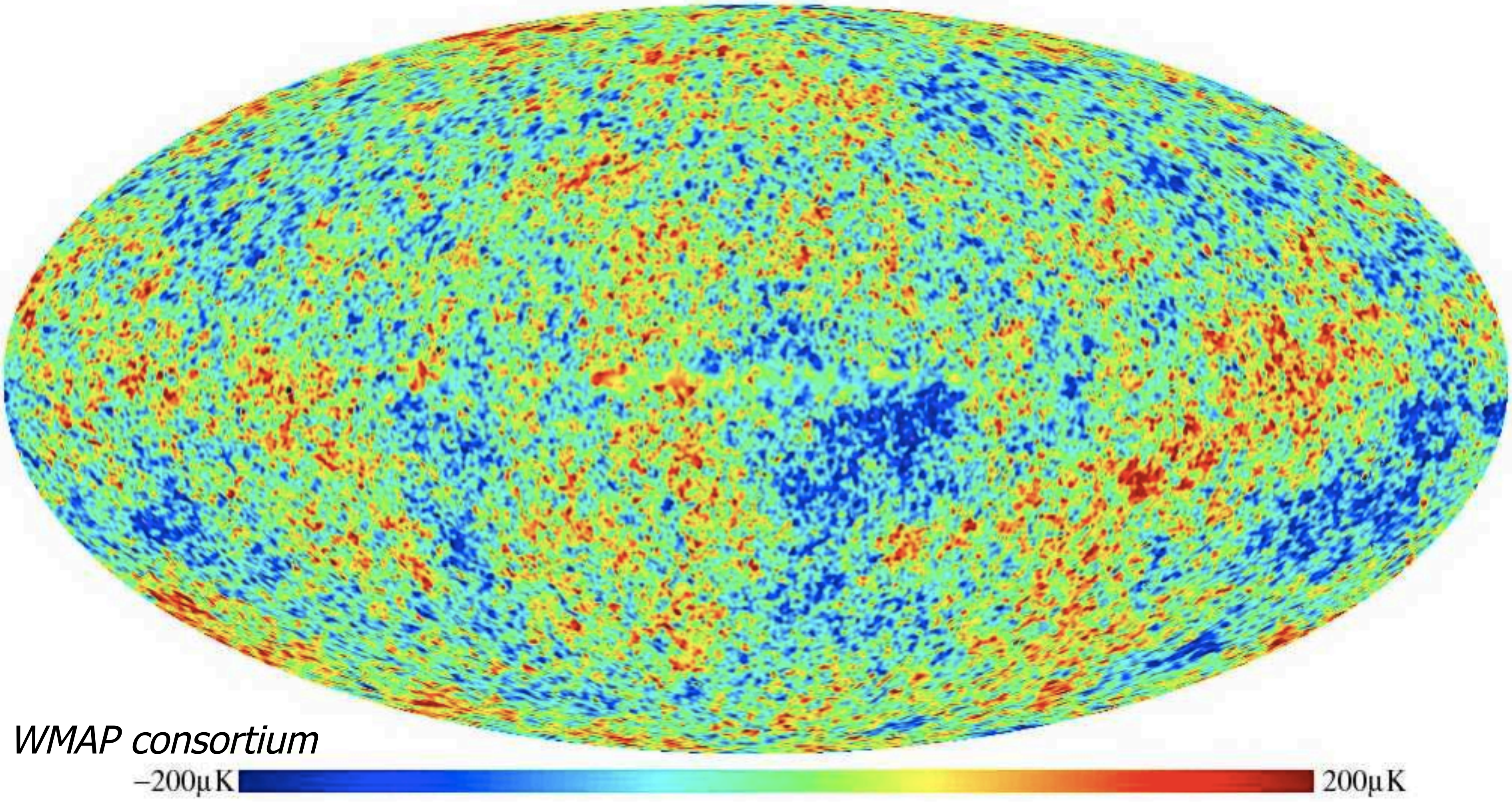
- What kind of phenomena do we see at radio/mm wavelength?

- Some initial defintions, basic properties of the sun

- Interaction of radiation with matter

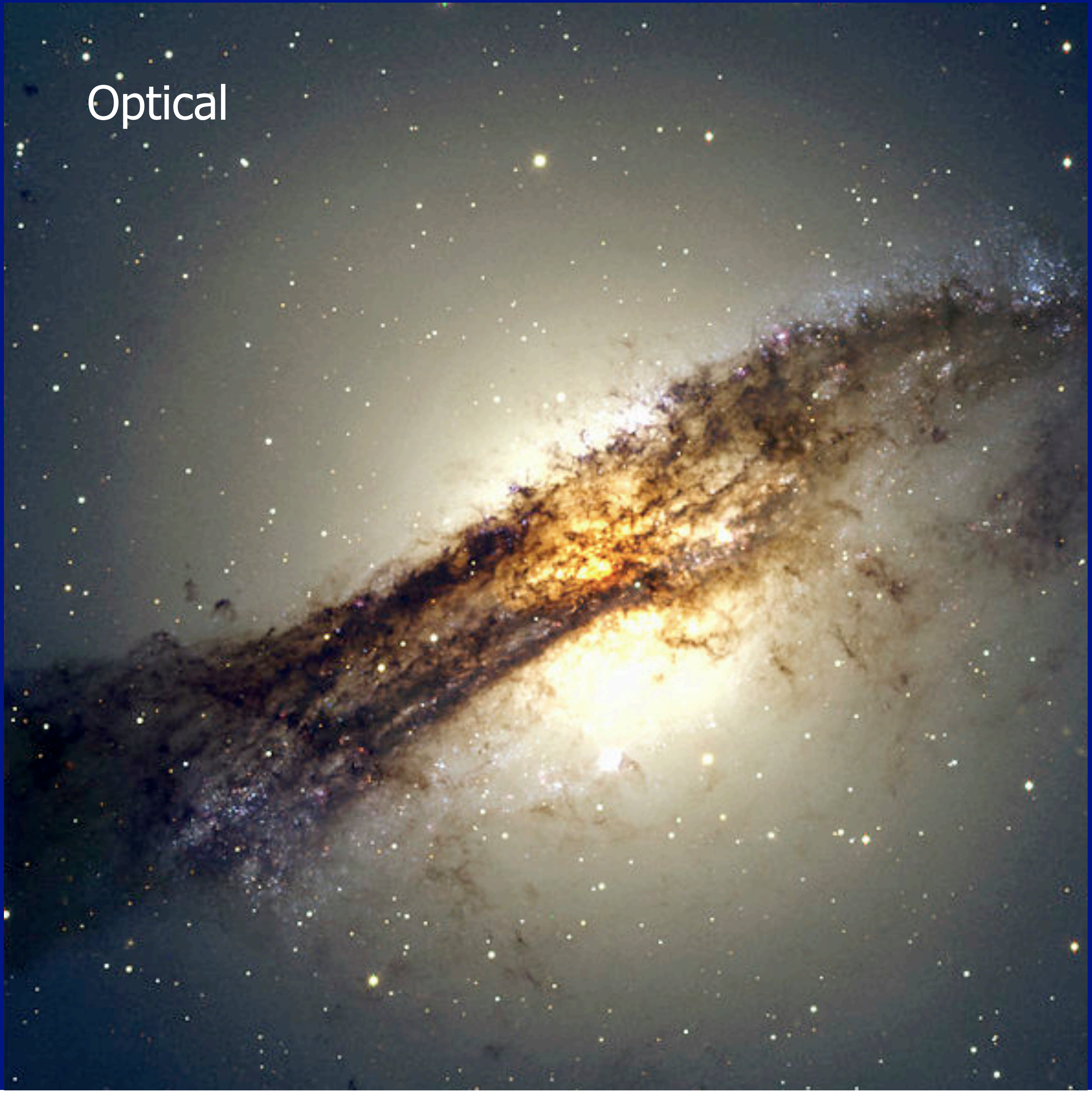
- Basic continuum radiation processes

Cosmic mircowave background (CMB)

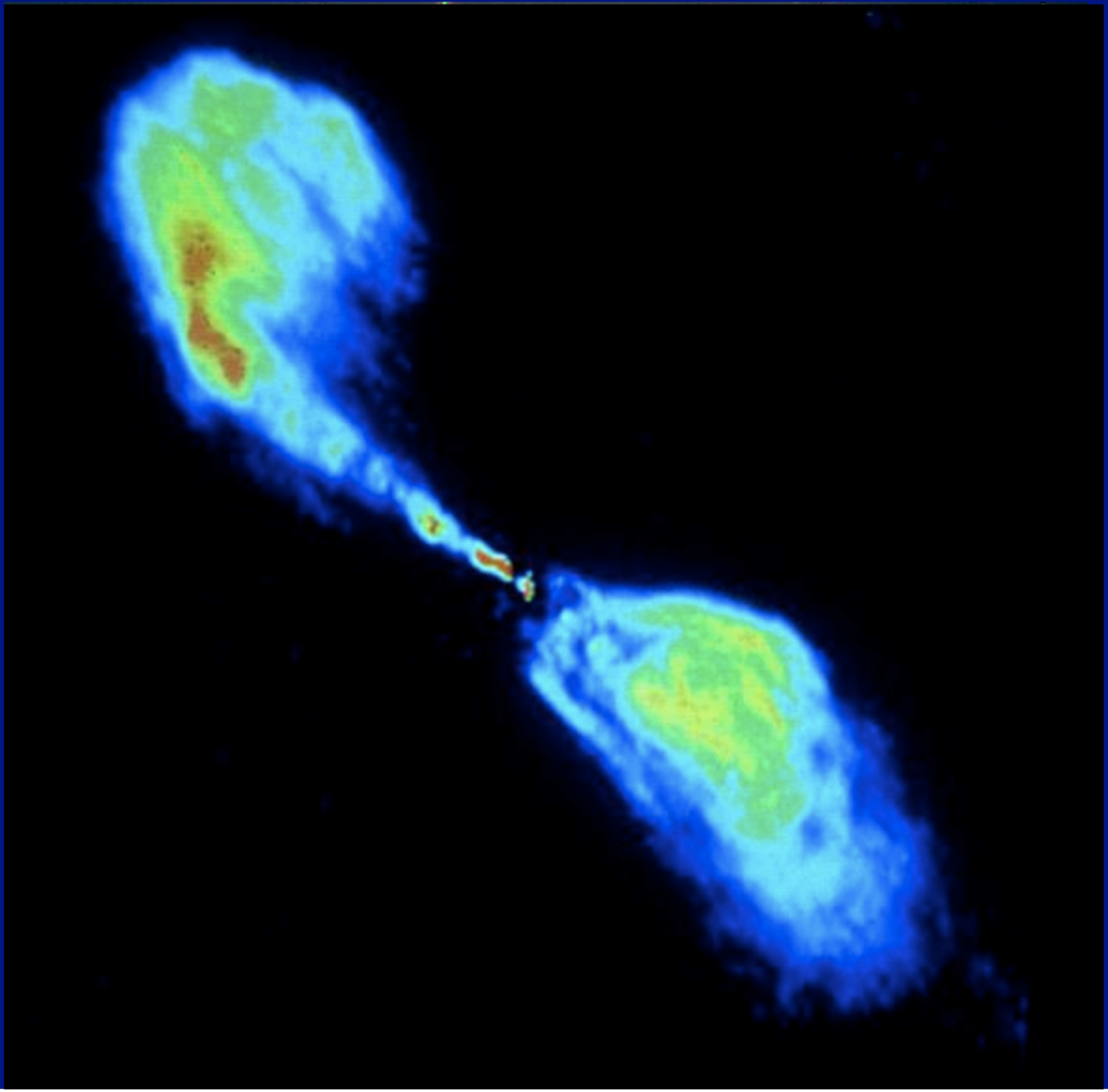


WMAP consortium

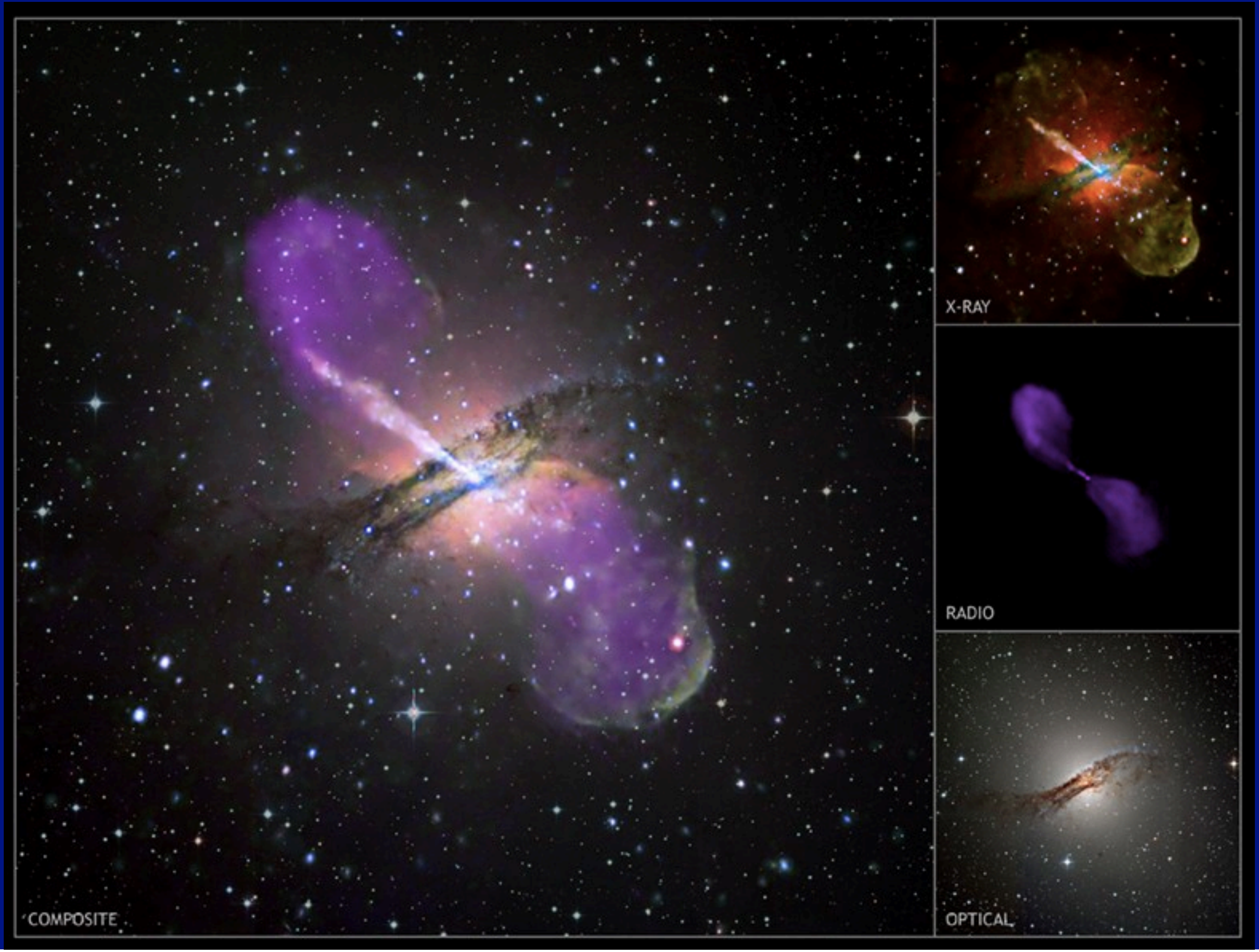
Radio Galaxy Centaurus A



Radio Galaxy Centaurus A

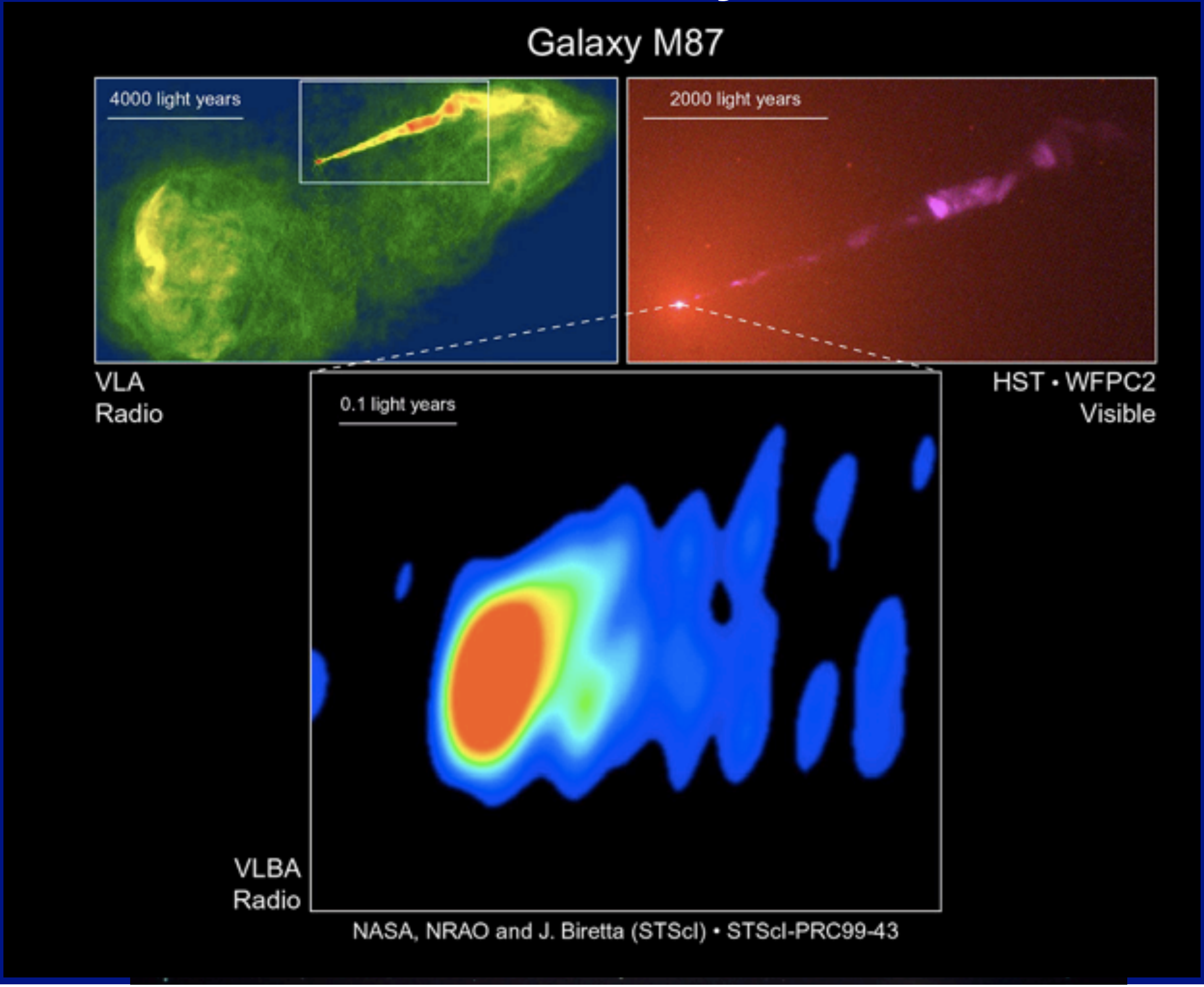


Radio Galaxy Centaurus A



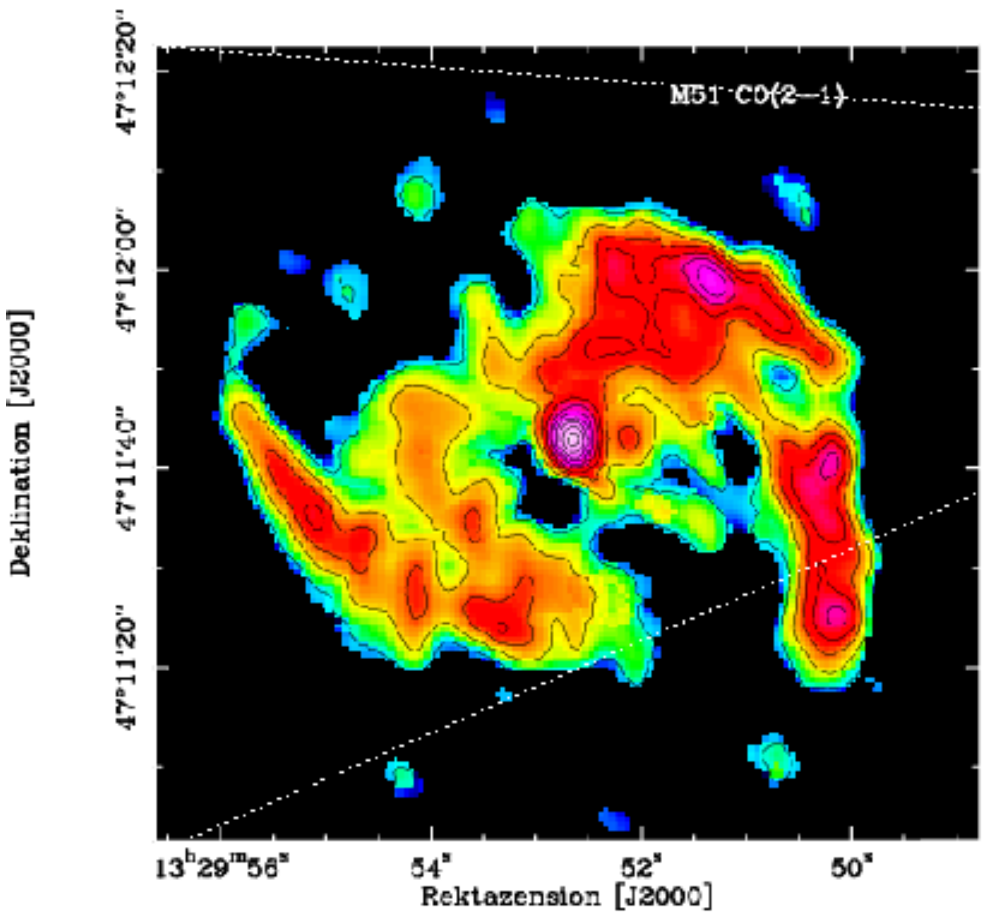
The relativistic jet in M87

The relativistic jet in M87



NASA, NRAO and J. Biretta (STScI) • STScI-PRC99-43

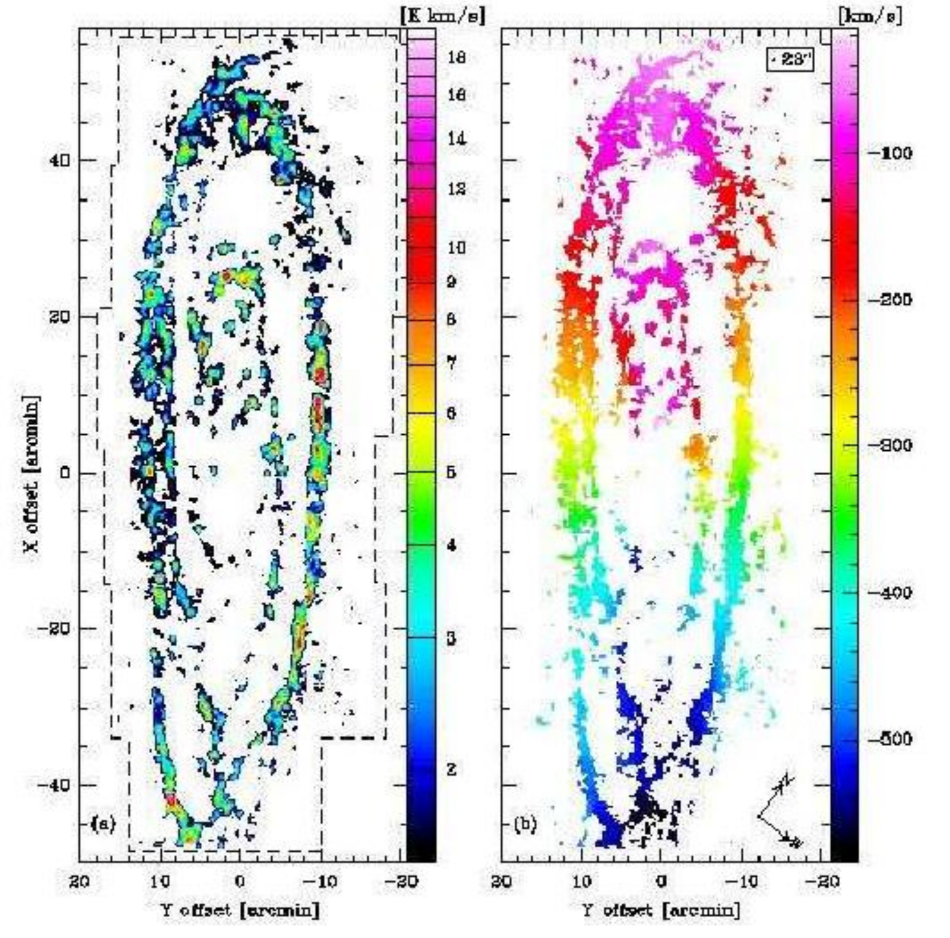
M51: The Whirlpool Galaxy



CO(2-1)

Optical

Andromeda



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Optical

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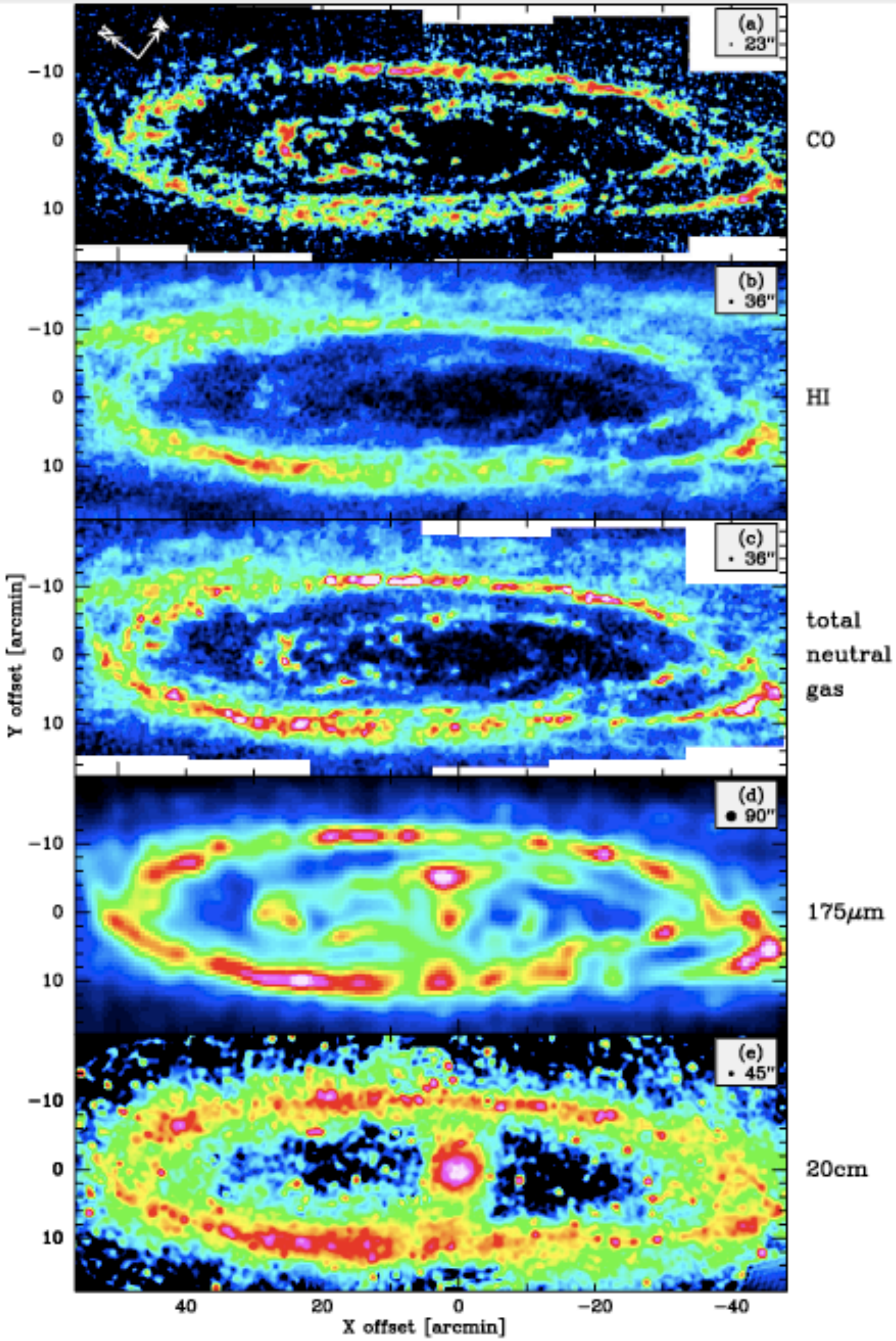
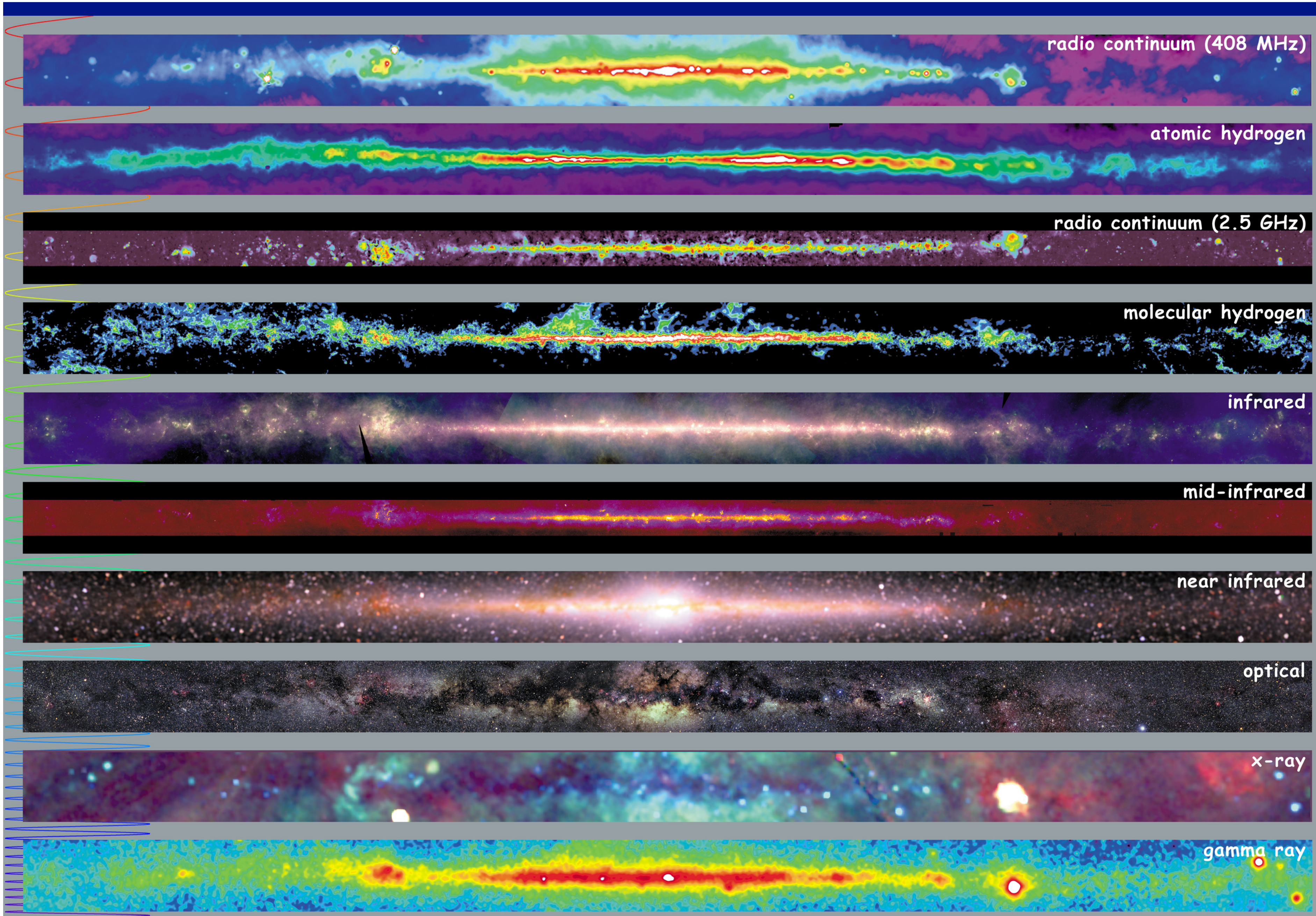


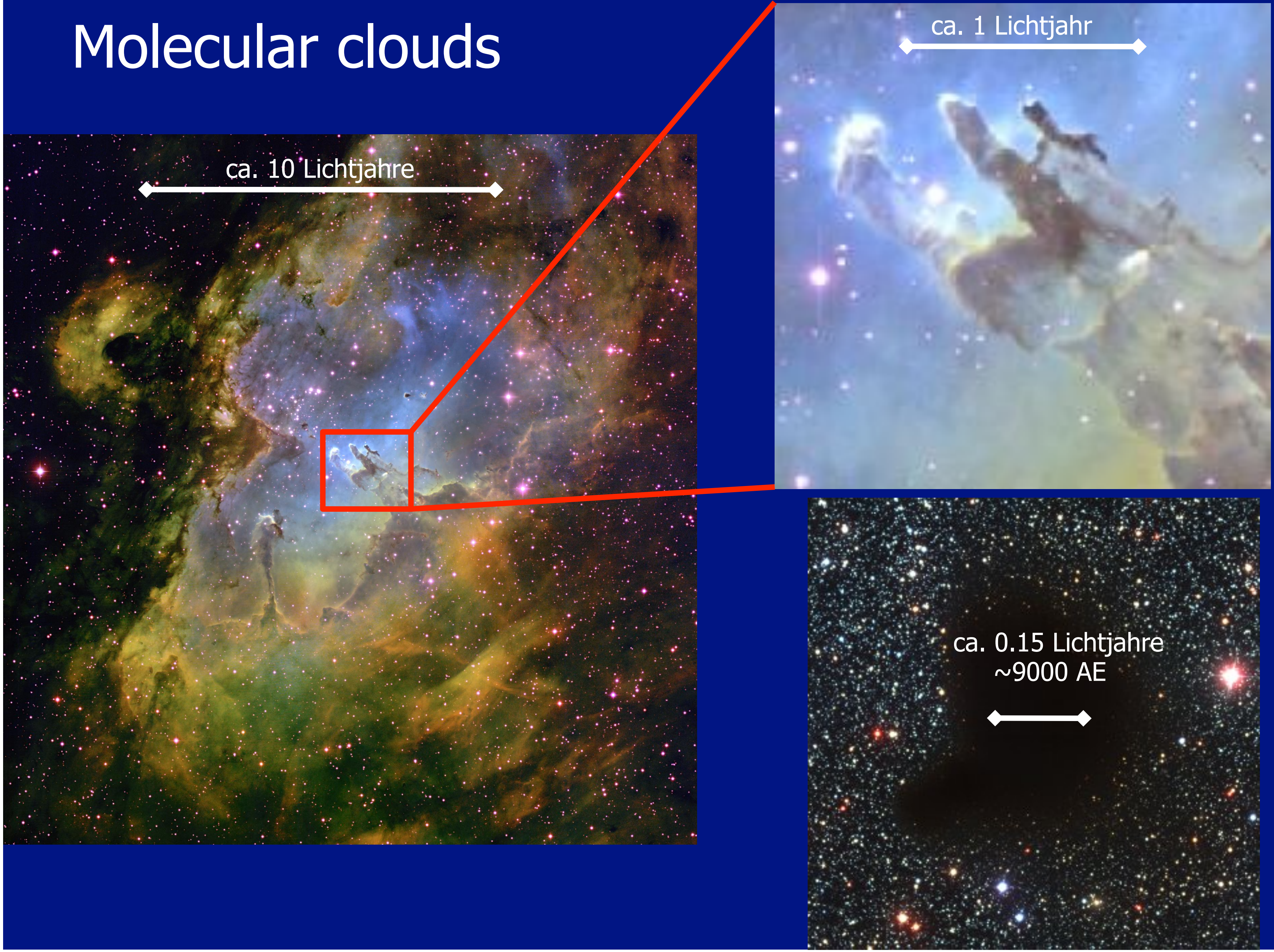
Optical



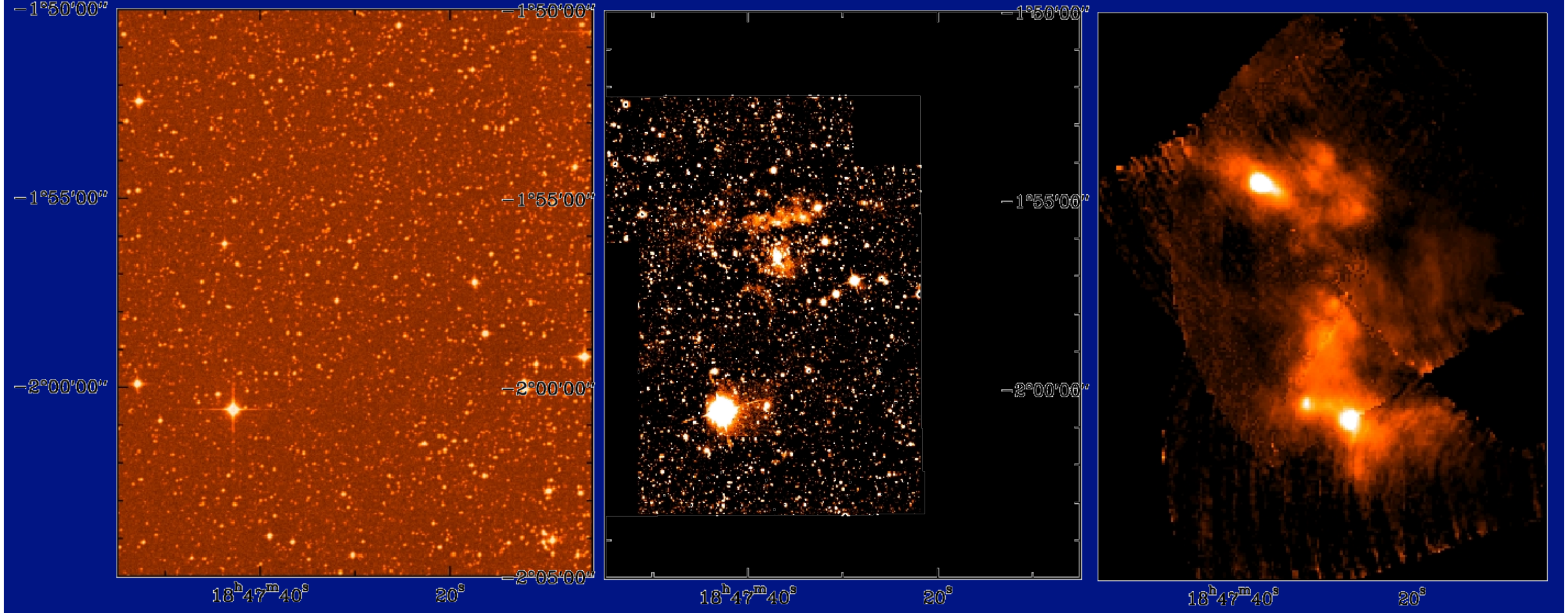
Multiwavelength Milky Way

http://adc.gsfc.nasa.gov/mw

Molecular clouds



The star-forming region W43

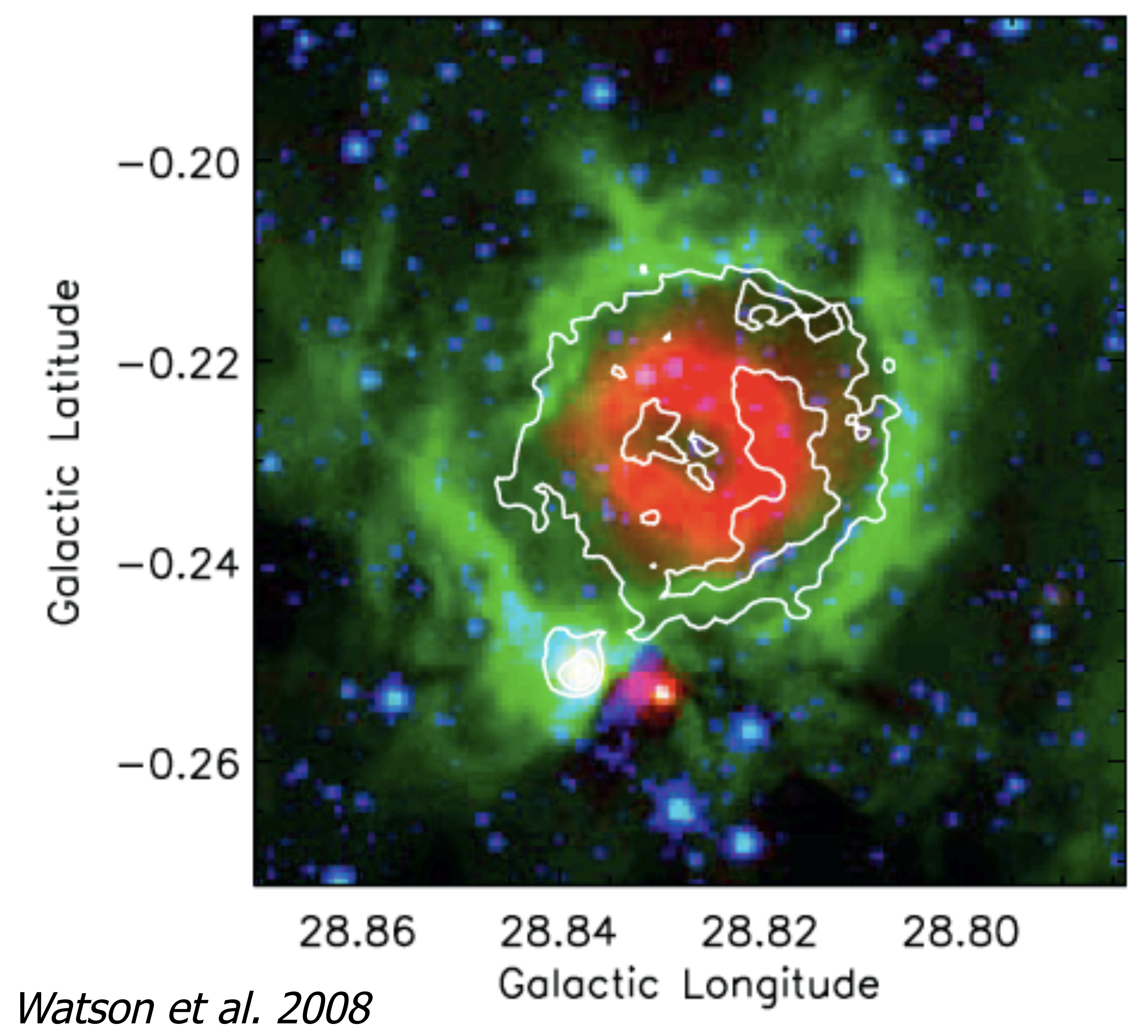


Optical

Near infrared

1.2 mm cold dust

Galactic HII region (N49)

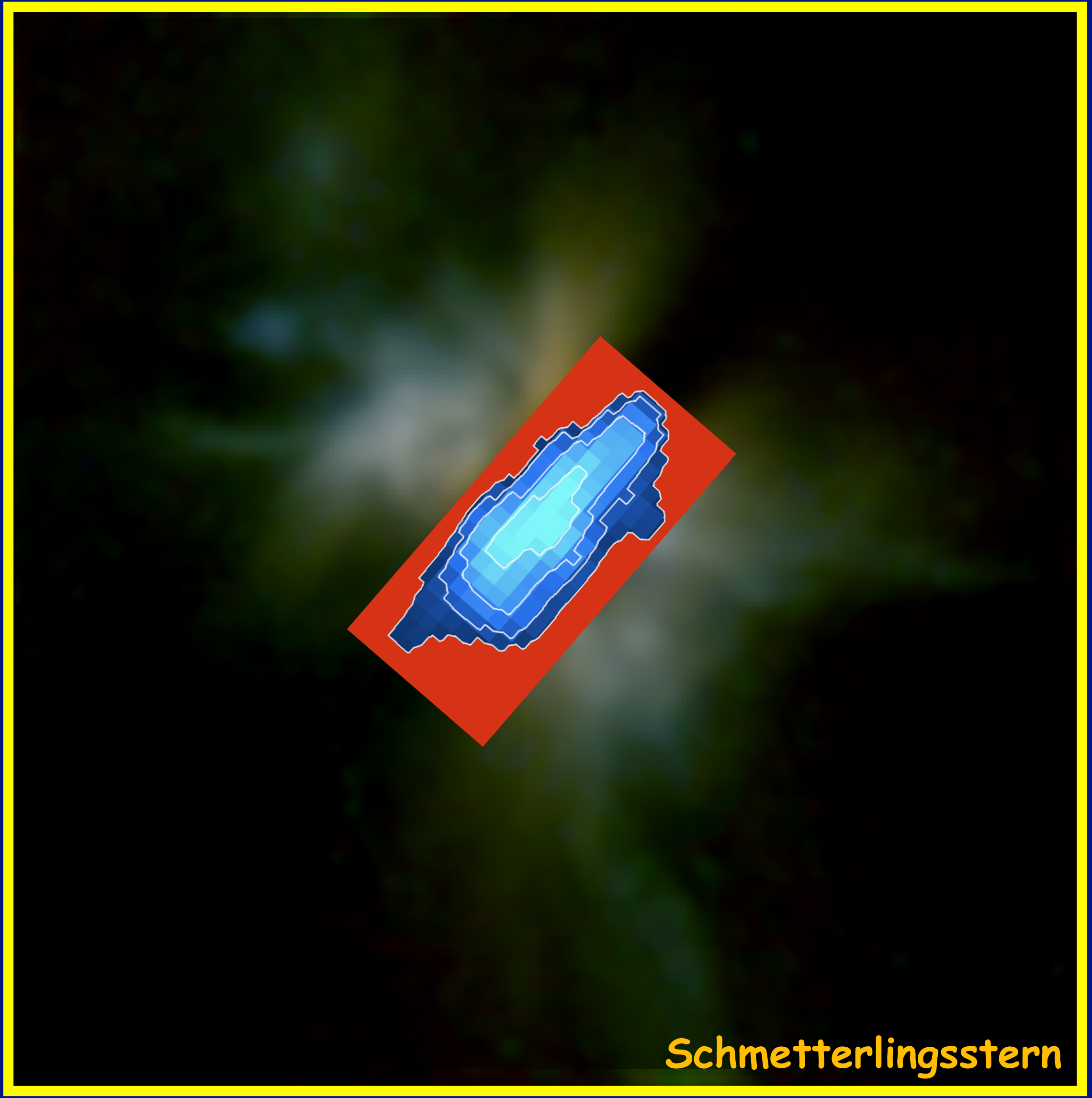


Watson et al. 2008

Red: 24μm
warm dust
Green: 8μm
PAH
Blue: 4.5μm
Stars

Contours: 20cm
free-free

The Butterfly star



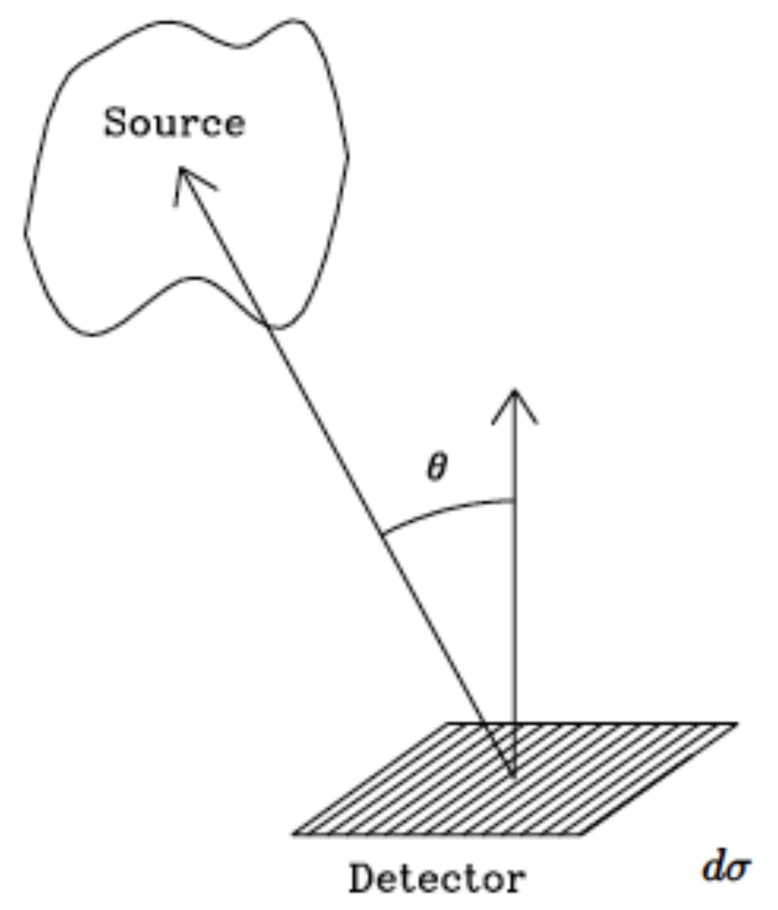
Wolf et al. 2003

Topics today

- What kind of phenomena do we see at radio/mm wavelength?
- Some initial defintions, basic properties of the sun
- Interaction of radiation with matter
- Basic continuum radiation processes

Brightness and intensity

$$dE_\nu = I_\nu \cos\theta d\sigma d\Omega dt d\nu$$



Energy dE received in the surface element $d\sigma$, under the angle $d\Omega$, in the time dt and the frequency range $d\nu$.
Since Power is dP=dE/dt

→ $$dP = I_\nu \cos\theta d\sigma d\Omega d\nu$$ (eq. 1)

Or the specific intensity or brightness:

$$\boxed{I_\nu \equiv \frac{dP}{\cos\theta d\sigma\, d\nu\, d\Omega}}$$

Units: $\mathrm{W\ m^{-2}\ Hz^{-1}\ sr^{-1}}$

Brightness is independent of distance as long as the source is resolved.

Total intensity $I \equiv \int_0^\infty I_\nu d\nu$ is conserved.

Andromeda (M31) appears only bright because the detector has accumulated the light.

Flux density and luminosity

Spectral power received by detector per frequency (eq. 1): $$\frac{dP}{d\sigma d\nu} = I_\nu \cos\theta d\Omega$$

Integrating over the solid angle of the source gives the flux density:

$$S_\nu \equiv \int_{\rm source} I_\nu(\theta,\phi)\cos\theta d\Omega$$

Since sources are usually small $\theta \sim 0$ → cos $\theta \sim 1$

→ $$S_\nu \approx \int_{\rm source} I_\nu(\theta,\phi) d\Omega$$ unit: $$1~\mathbf{Jansky} = 1~\mathbf{Jy} \equiv 10^{-26}~\mathbf{W~m^{-2}~Hz^{-1}}$$

In contrast to brightness, the flux density is distance dependent:

$$\int_{\rm source} d\Omega \propto 1/d^2 \rightarrow S_\nu \propto d^{-2}$$

Spectral luminosity: $$L_\nu = 4\pi d^2 S_\nu$$ (d=distance)

→ intrinsic source property and not distance dependent (d cancels out).

Bolometric luminosity: $$L_{\rm bol} \equiv \int_0^\infty L_\nu d\nu$$

Brightness, flux density and luminosity of sun I

Sun at about 5800K → Rayleigh-Jeans approximation valid:

$$\frac{h\nu}{kT} = \frac{6.63 \times 10^{-27}\mathrm{erg\ s} \times 10^{10}\ \mathrm{Hz}}{1.38 \times 10^{-16}\ \mathrm{erg\ K}^{-1} \times 5800\ \mathrm{K}} = 8 \times 10^{-5} \ll 1$$

Specific intensity: $I_\nu = B_\nu \approx \frac{2kT\nu^2}{c^2}$

At 10GHz

$$\rightarrow \quad I_\nu \approx \frac{2 \times 1.38 \times 10^{-16}\ \mathrm{erg\ K}^{-1}\ 5800\ \mathrm{K}\ (10^{10}\ \mathrm{s}^{-1})^2}{(3 \times 10^{10}\ \mathrm{cm\ s}^{-1})^2} \approx 1.78 \times 10^{-13}\ \frac{\mathrm{erg}}{\mathrm{cm}^2\ (\mathrm{sr})} \left(\frac{\mathrm{s}^{-1}}{\mathrm{Hz}}\right)$$

Using $1\ \mathrm{W} = 1\ \mathrm{J\ s}^{-1} = 10^7\ \mathrm{erg\ s}^{-1}$ we get → $I_\nu \approx 1.78 \times 10^{-16}\ \frac{\mathrm{W}}{\mathrm{m}^2\ \mathrm{sr\ Hz}}$

→ Property of the sun, does not depend on distance.

Brightness, flux density and luminosity of sun II

Flux density: radius sun R ~ 7.0e10 cm & r = 1AU = 1.496e13 cm

→ Angular size of sun: sin(θ) ~ θ ~ R/r ~ 4.7e-3 rad

→ $$S_\nu \approx \int_{\mathrm{Sun}} I_\nu d\Omega \approx I_\nu \Omega_\odot \approx \pi I_\nu \theta_\odot^2 \approx 1.78 \times 10^{-16} \frac{\mathrm{W}}{\mathrm{m^2\ Hz\ sr}} \times \pi (4.7 \times 10^{-3}\ \mathrm{rad})^2$$

→ $$S_\nu \approx 1.24 \times 10^{-20} \frac{\mathrm{W}}{\mathrm{m^2\ Hz}} = 1.24 \times 10^{6}\ \mathrm{Jy}$$

→ varies with distance

Spectral luminosity: Convert flux density to cgs units:

$$S_\nu = 1.24 \times 10^{-17}\ \mathrm{erg\ s^{-1}\ cm^{-2}\ Hz^{-1}}$$

$$L_\nu = 4\pi r_\odot^2 S_\nu = 4\pi (1.5 \times 10^{13}\ \mathrm{cm})^2 \times 1.24 \times 10^{-17}\ \mathrm{erg\ s^{-1}\ cm^{-2}\ Hz^{-1}}$$

→ $$L_\nu = 3.5 \times 10^{10}\ \mathrm{erg\ s^{-1}\ Hz^{-1}}$$

→ Again a distance independent property of the sun.

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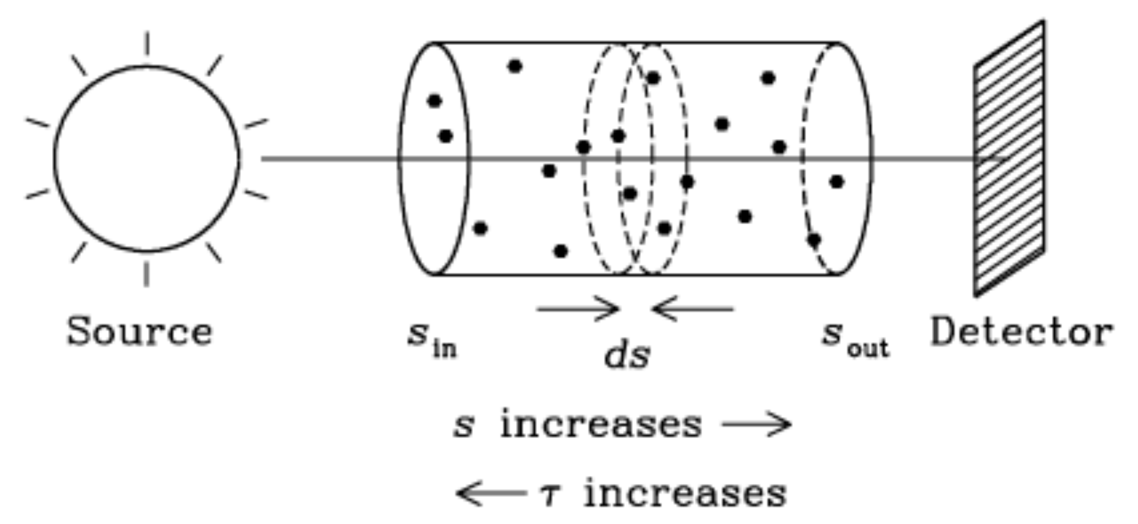
Interaction of radiation with matter I



Absorption coefficient: $\kappa = dp_\nu/ds$

dp_ν = absorption probability
ds = path length

Fraction of lost emission in ds:

$$\frac{dI_\nu}{I_\nu} = -dp_\nu = -\kappa_\nu ds$$

Integration:

$$\int_{s_{\mathrm{in}}}^{s_{\mathrm{out}}} \frac{dI_\nu}{I_\nu} = -\int_{s_{\mathrm{in}}}^{s_{\mathrm{out}}} \kappa_\nu(s')ds'$$

→ Optical depth:

$$\tau_\nu \equiv \int_{s_{\mathrm{out}}}^{s_{\mathrm{in}}} -\kappa_\nu(s')ds'$$

Interaction of radiation with matter II

Emission coefficient: $\epsilon_\nu \equiv \frac{dI_\nu}{ds}$

Combining emission and absorption → radiative transfer equation:

$$\frac{dI_\nu}{ds} = -\kappa_\nu I_\nu + \epsilon_\nu$$

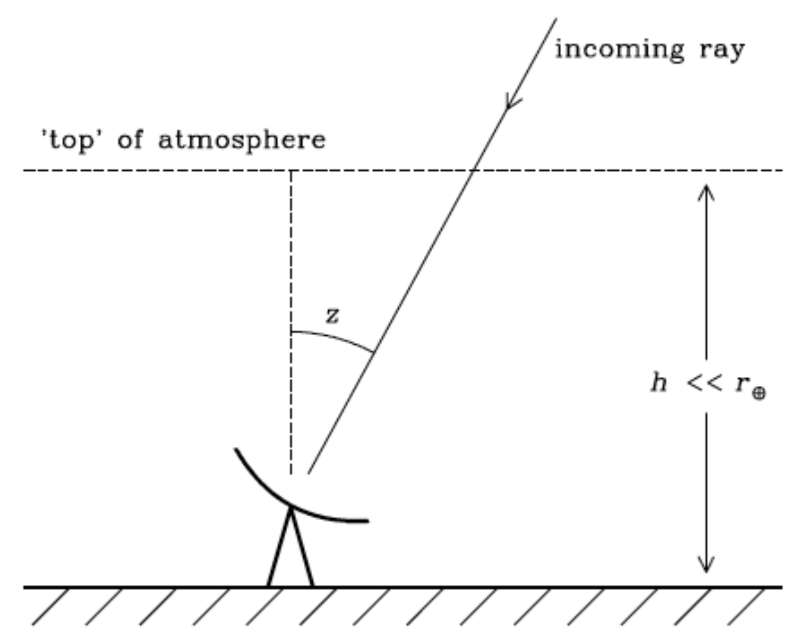
In thermodynamic equilibrium, emission and absorption are coupled:

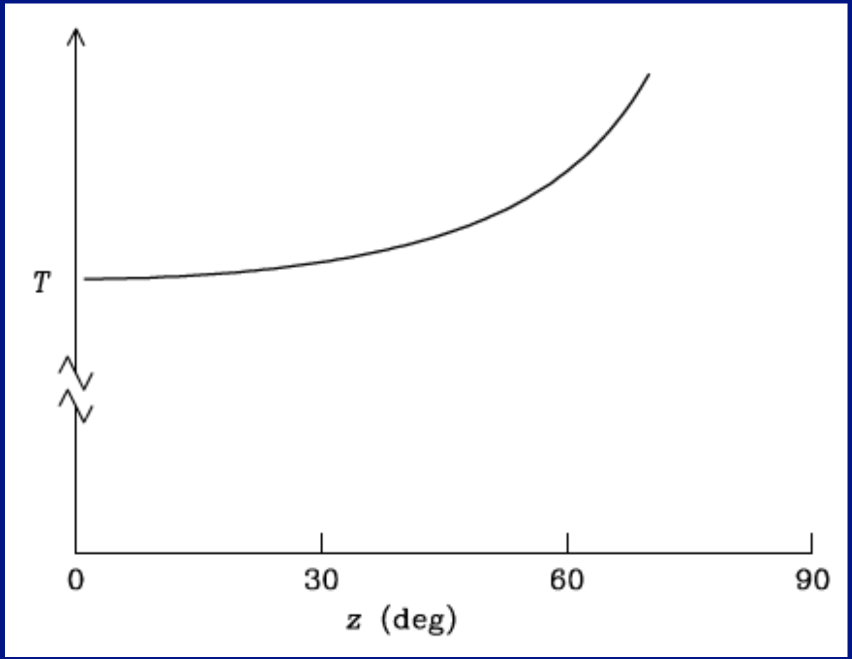
$$\frac{dI_\nu}{ds} = 0 \text{ and } I_\nu = B_\nu(T)$$

→ $$\frac{dI_\nu}{ds} = 0 = -\kappa_\nu B_\nu(T) + \epsilon_\nu$$

→ $$\frac{\epsilon_\nu(T)}{\kappa_\nu(T)} = B_\nu(T)$$ (Kirchhoff’s law)

Example: Measuring the atmospheric abs. I





In Rayleigh-Jeans limit: $$B_\nu \approx \frac{2kT\nu^2}{c^2}$$

Radio astronomers often define specific intensity in terms of equivalent brightness temperature: $$I_\nu = \frac{2kT_b(\nu)\nu^2}{c^2}$$ even if $I_\nu \neq B_\nu$

→ T_b not necessarily kinetic gas T.

→ $$T_b(\nu) \equiv \frac{I_\nu c^2}{2k\nu^2}$$

Example: Measuring the atmospheric abs. II

Start with radiative transfer equation: $\frac{dI_\nu}{ds} = -\kappa_\nu I_\nu + \epsilon_\nu$

And Kirchhoff's law $\epsilon_\nu = \kappa_\nu B_\nu(T_\mathrm{A})$ → $\frac{1}{\kappa_\nu}\frac{dI_\nu}{ds} = \frac{-dI_\nu}{d\tau} = -I_\nu + B_\nu(T_\mathrm{A})$

(T_A is now (isothermal) kinetic temperture of the atmosphere)

Multiplication with $\exp(-\tau)$ and integration along the ray with $\tau_\mathrm{A}(z)$ the optical depth along the ray at given zenith angle z:

→ $$\int_0^{\tau_\mathrm{A}} e^{-\tau}\frac{dI_\nu}{d\tau}d\tau = \int_0^{\tau_\mathrm{A}} [I_\nu - B_\nu(T_\mathrm{A})]e^{-\tau}d\tau$$

After (partial) integration, we get: $I_\nu(\tau = 0) = (1 - e^{-\tau_\mathrm{A}})B_\nu(T_\mathrm{A})$

with $\tau_\mathrm{A} = \tau_\mathrm{Z} \sec z$ and $\tau_\mathrm{Z} \equiv \tau_\mathrm{A}(z = 0)$

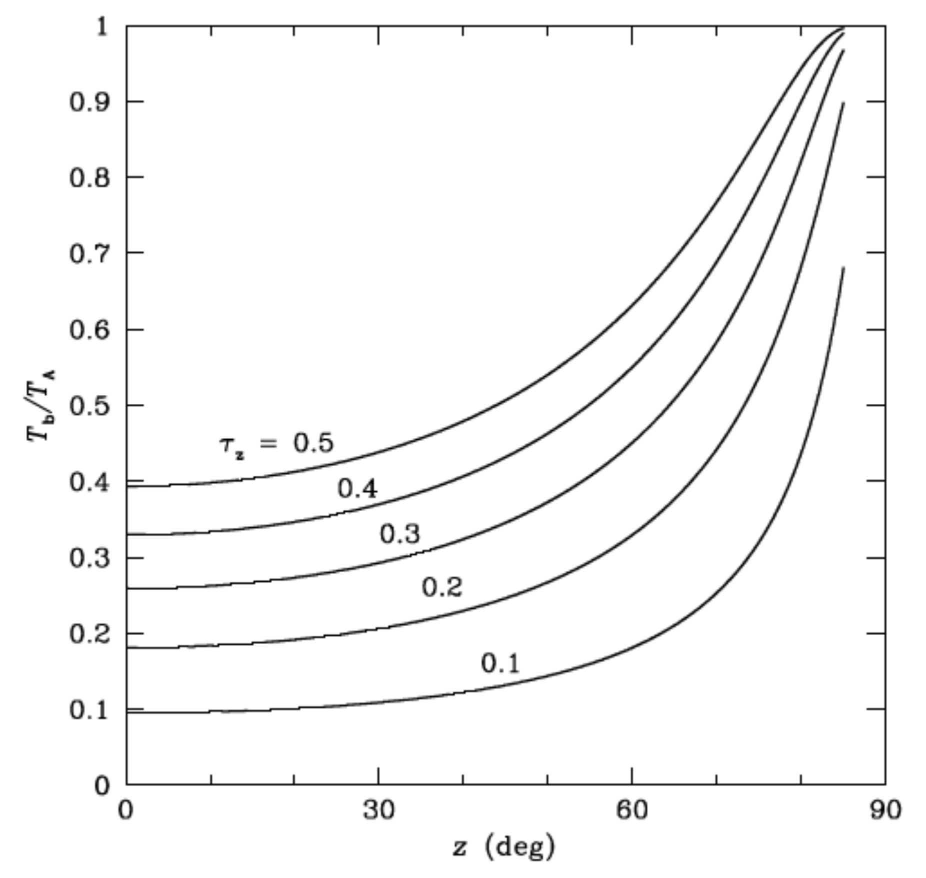
Example: Measuring the atmospheric abs. III

We then get:

$$I_\nu = [1 - \exp(-\tau_Z \sec z)] \frac{2kT_A\nu^2}{c^2}$$

Or in terms of brightness temperature:

$$T_b = \frac{I_\nu c^2}{2k\nu^2} = T_A \left[1 - \exp(-\tau_Z \sec z)\right]$$



By fitting the observed curve to this function, we can derive the zenith opacity as well as the opacities at all zenith angles.

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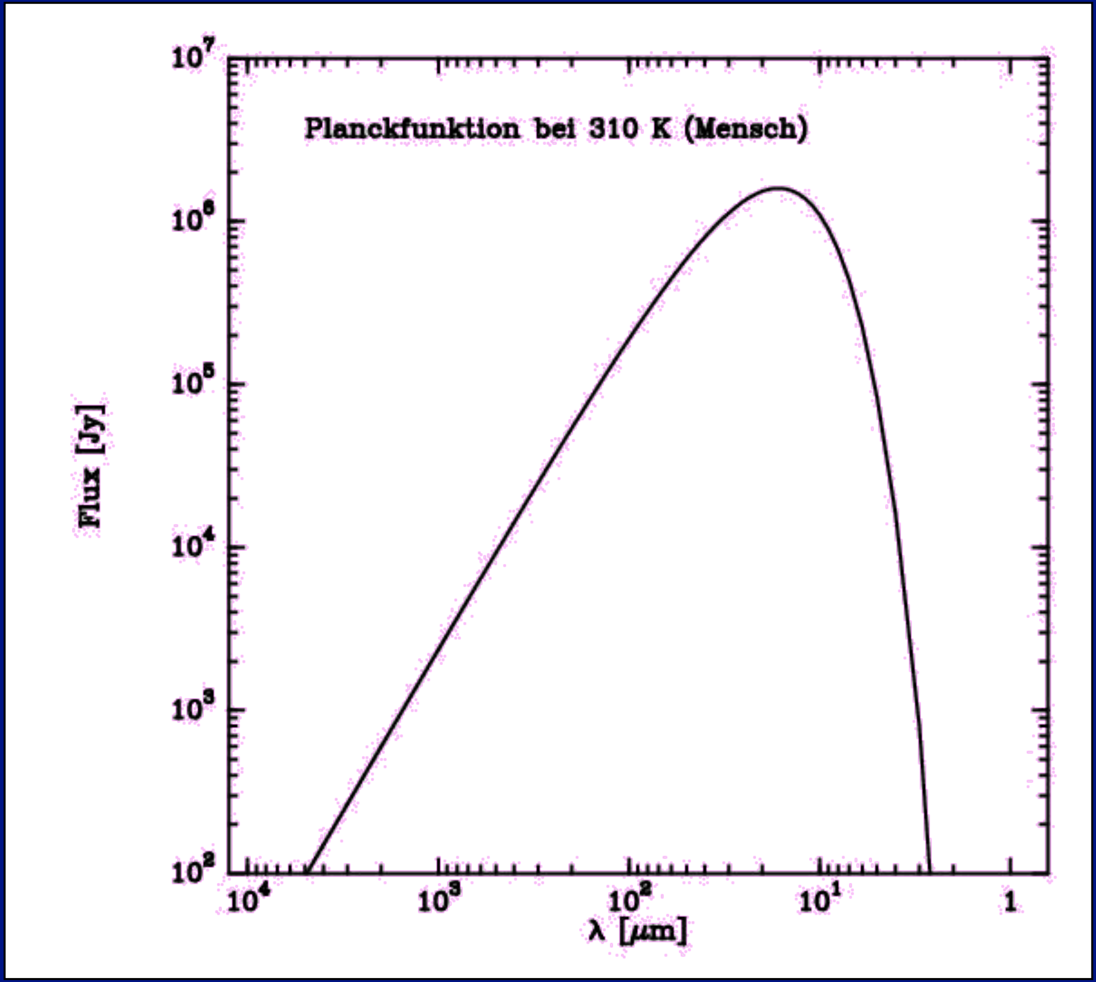
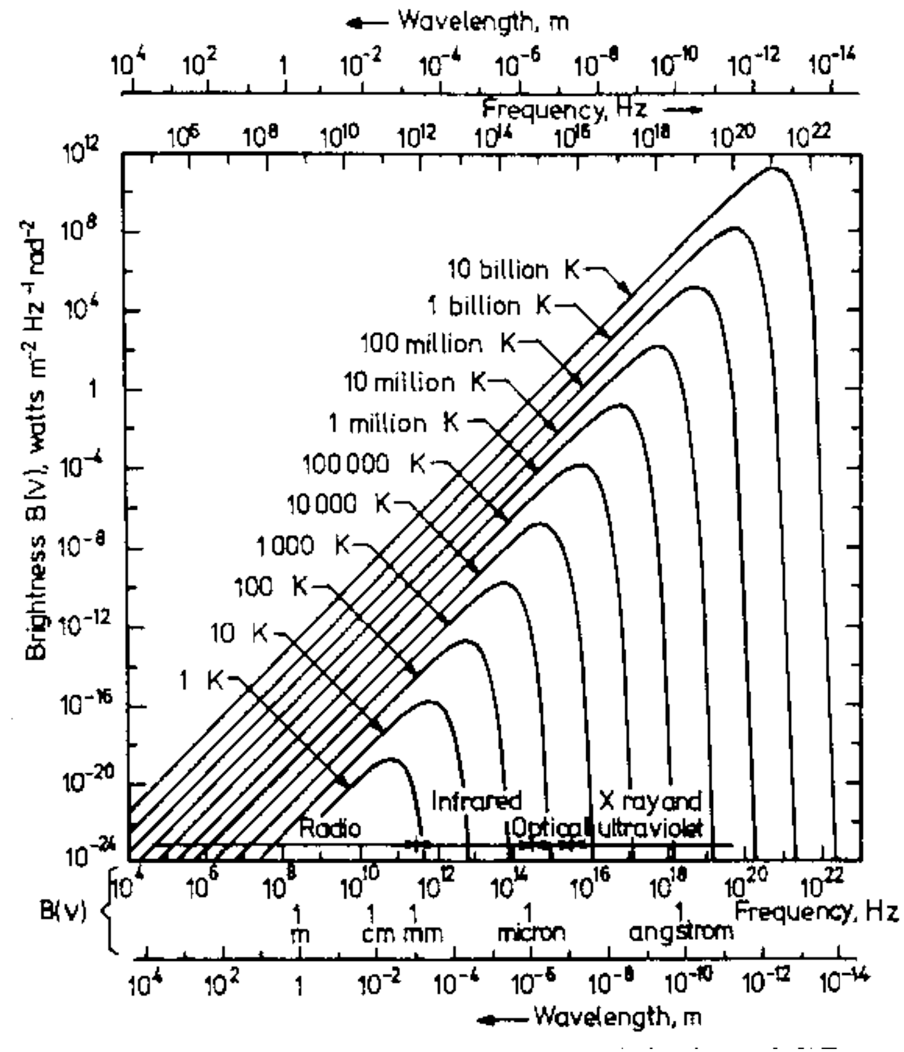
Planck's Black Body



$B_\nu(T) = 2h\nu^3/c^2 * 1/(\exp(h\nu/kT)-1)$

Planck's Black Body



$B_\nu(T) = 2h\nu^3/c^2 * 1/(\exp(h\nu/kT)-1)$

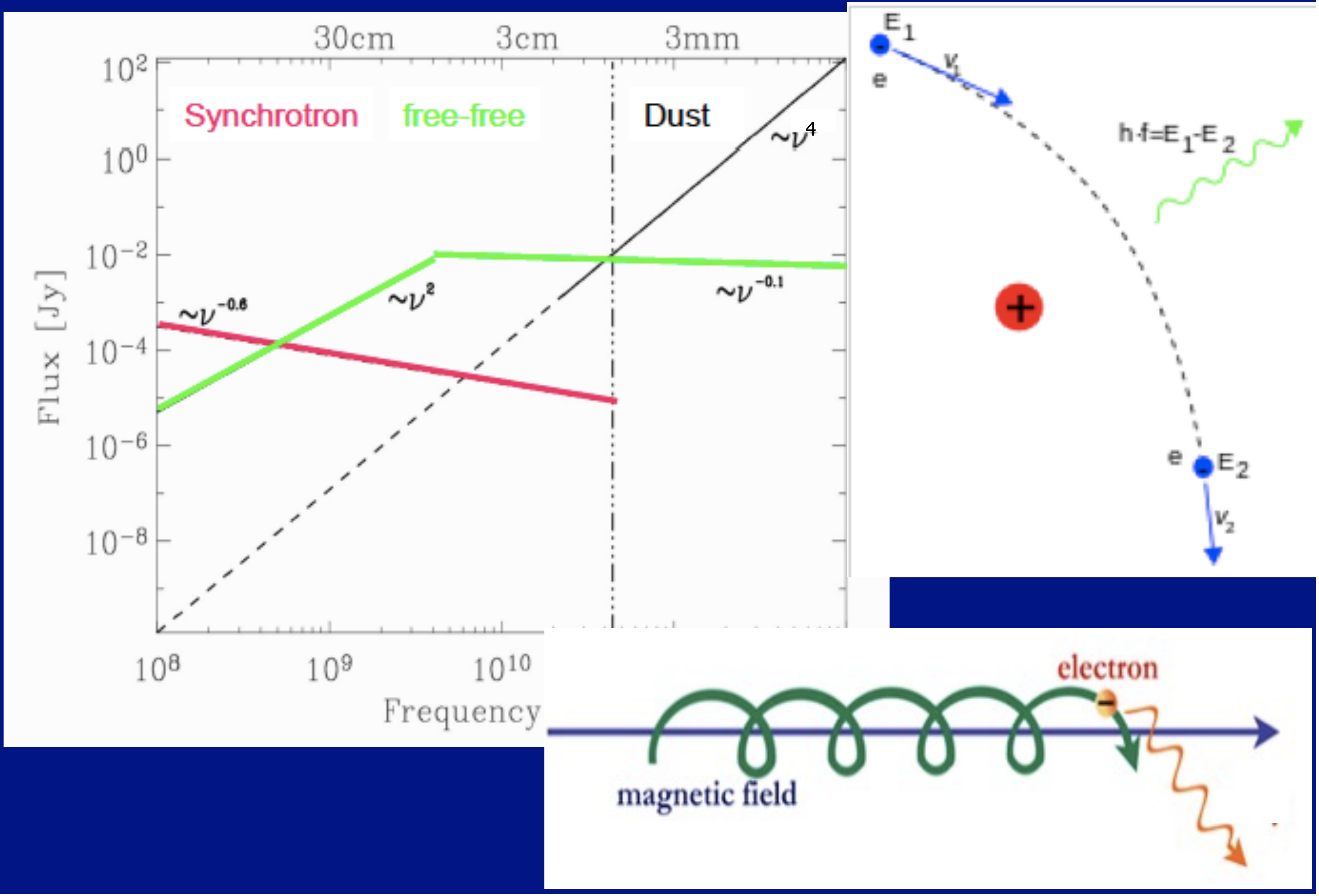
Wien's Law

$$\lambda_{max} = 2.9/T \text{ [mm]}$$

Examples:

The Sun	$T \sim 6000$ K $\Rightarrow \lambda_{max} = 480$ nm (optical)
Humans	$T \sim 310$ K $\Rightarrow \lambda_{max} = 9.4\ \mu$m (MIR)
Molecular Clouds	$T \sim 20$ K $\Rightarrow \lambda_{max} = 145\ \mu$m (FIR/submm)
Cosmic Background	$T \sim 2.7$ K $\Rightarrow \lambda_{max} = 1.1$ mm (mm)

Different continuum radiation mechanisms



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