A taste of radio astronomy

Fundamentals of Radio Interferometry

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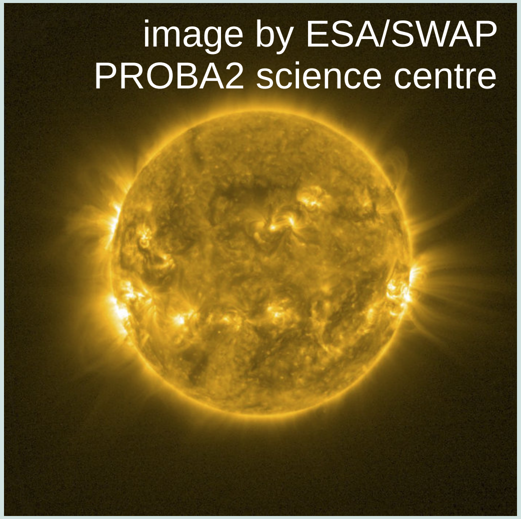
Astrophysics

Astrophysics is a discipline of physics or astronomy which tries to explain extraterrestrial phenomena by means of fundamental physical principles, and, with that, to test fundamental theories of physics.

- Disadvantage: (half the) laboratory setup pre-determined
- Advantage: testing different parameter space

x 2200

x 110



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Kilimanjaro, image by Gary Craig

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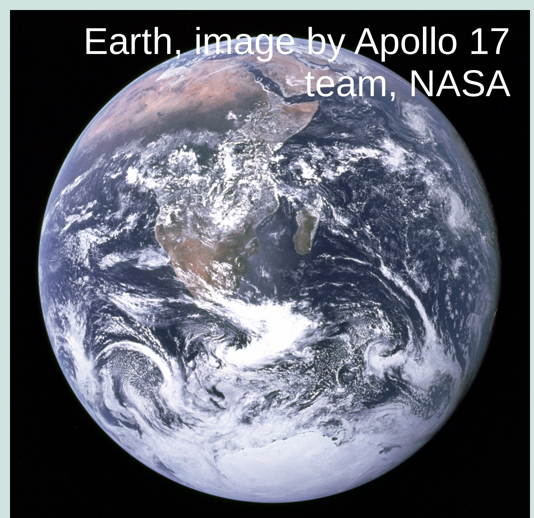
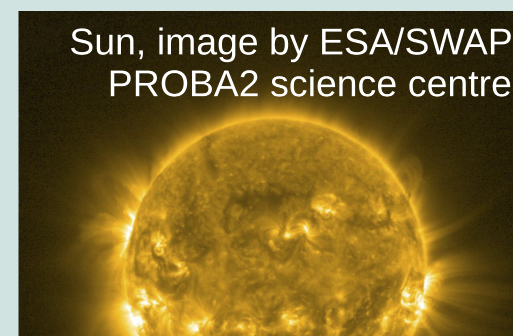
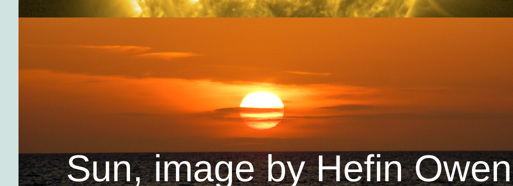

Earth, image by Apollo 17 team, NASA

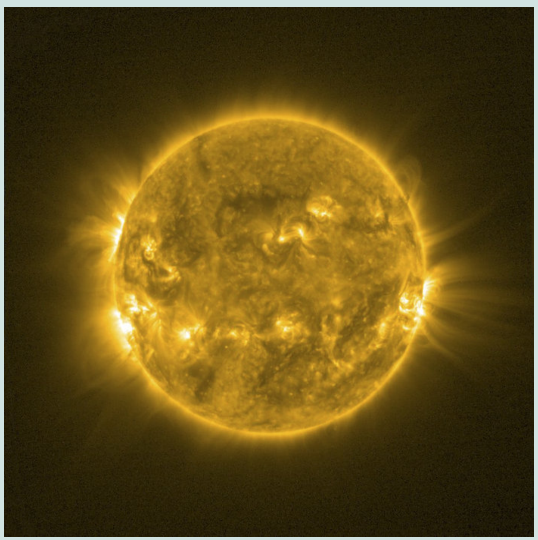
x 110


Sun, image by ESA/SWAP PROBA2 science centre

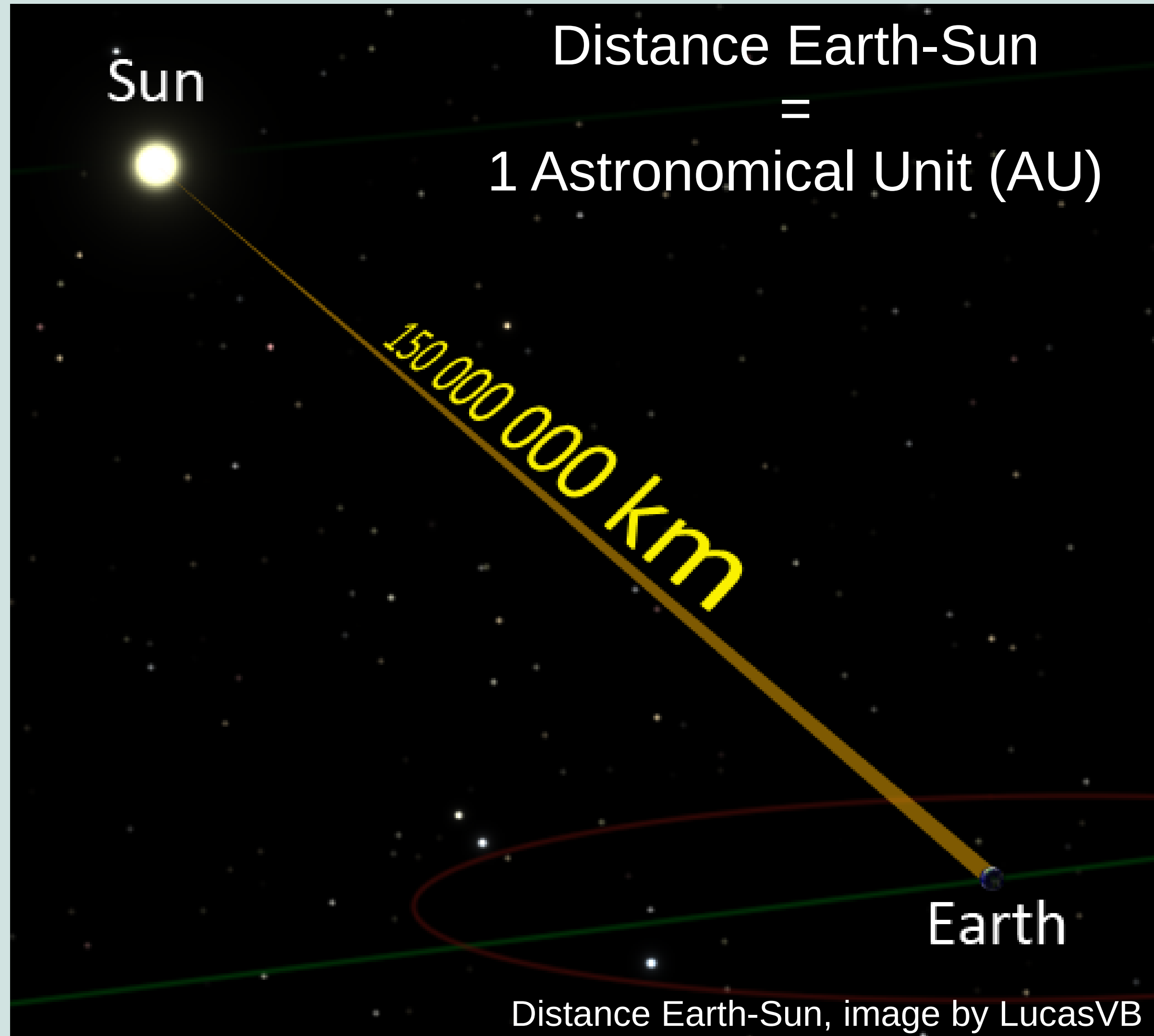

Sun, image by Hefin Owen

Astrophysics

- Advantage: testing different parameter space: scales



x
110
=



Distance Earth-Sun, image by LucasVB

Astrophysics

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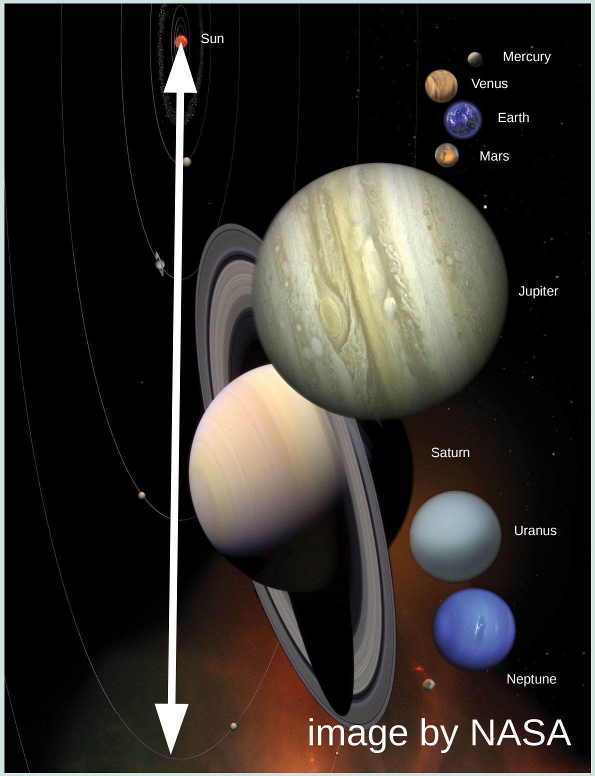
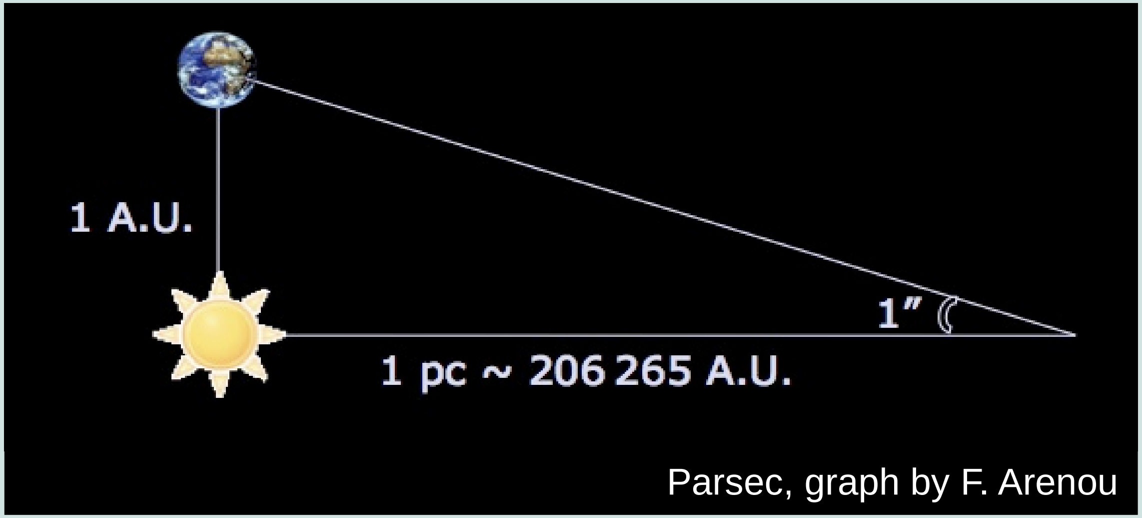


x
6800
=

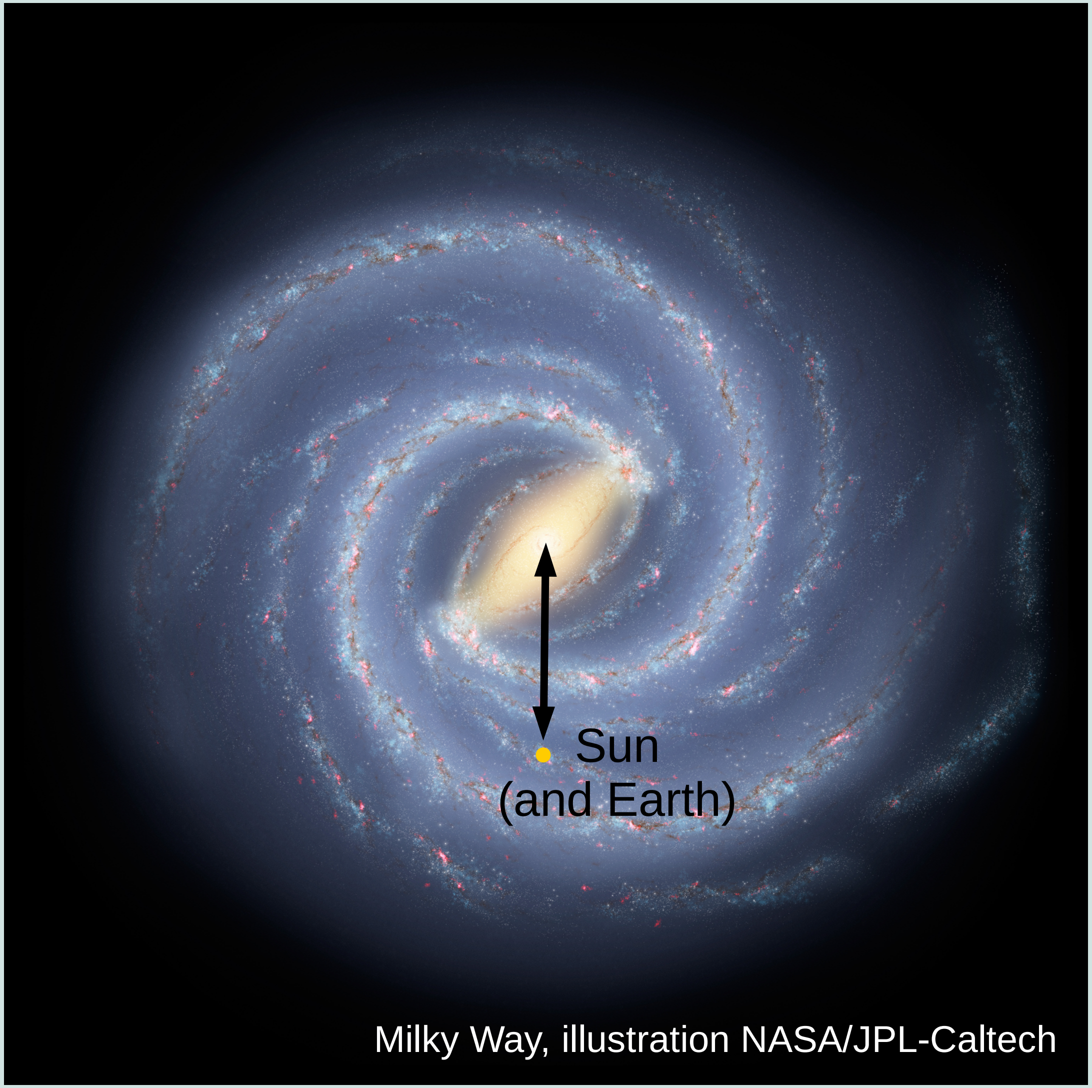


1 parsec (parallactic second)
=
3.26 ly
=
30 857 000 000 000 km

Astrophysics

- Advantage: testing different parameter space: scales

Distance to next neighbouring star Proxima Centauri:
1.3 pc
4.2 light years



Milky Way, illustration NASA/JPL-Caltech

Astrophysics

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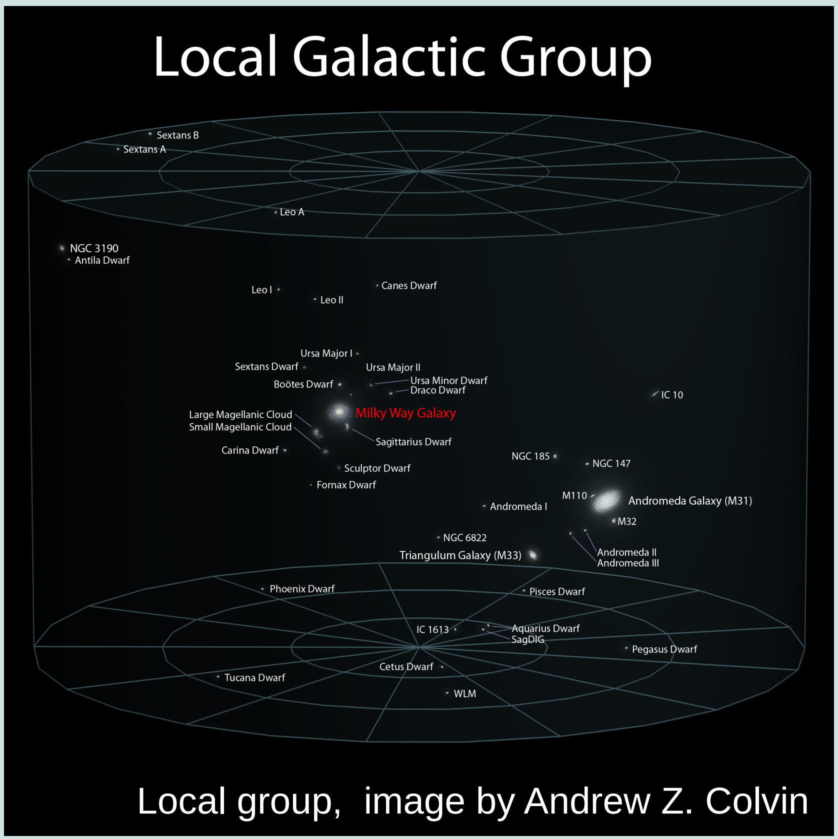
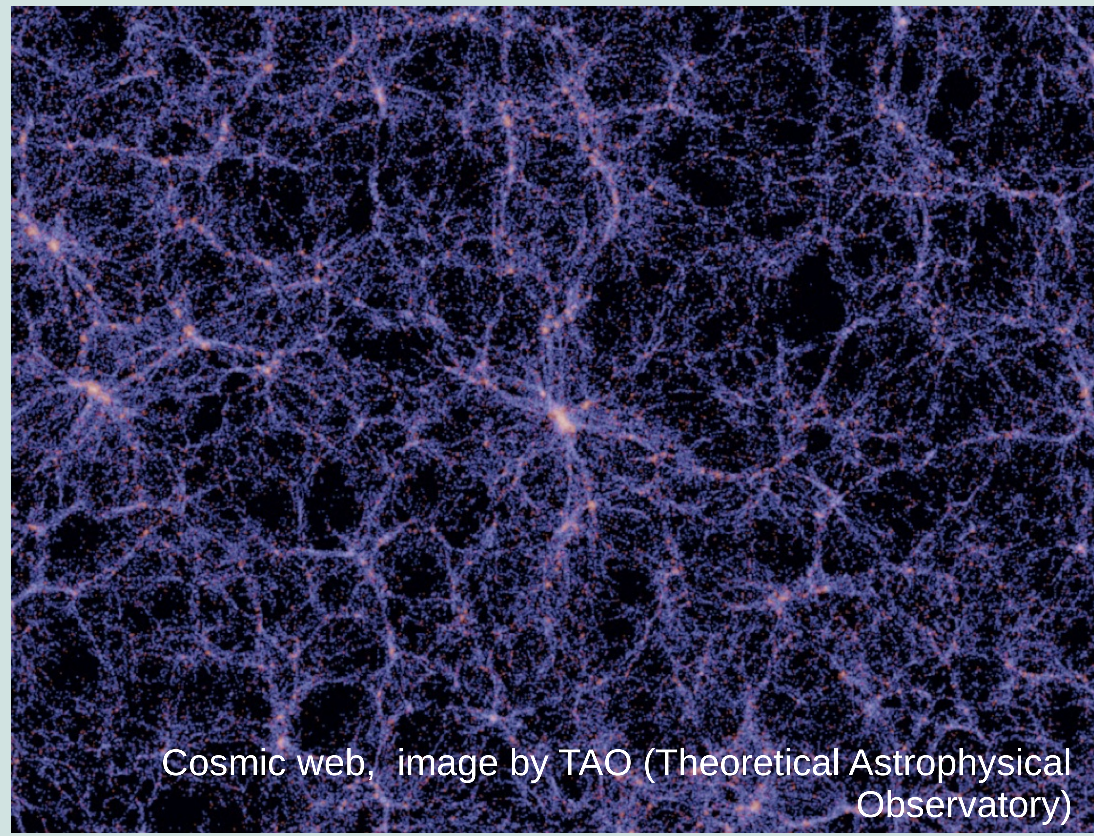


Local group, image by Andrew Z. Colvin


Cosmic web, image by TAO (Theoretical Astrophysical Observatory)

Astrophysics

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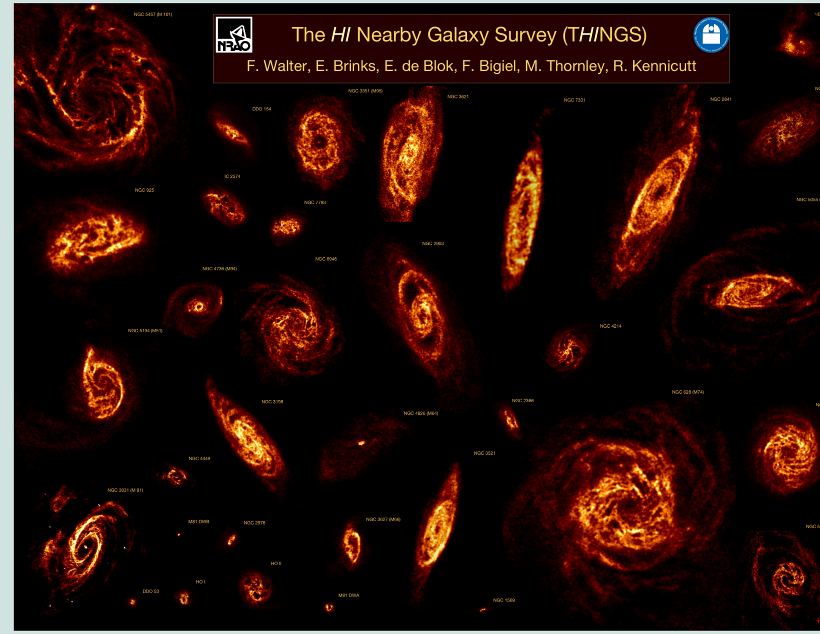
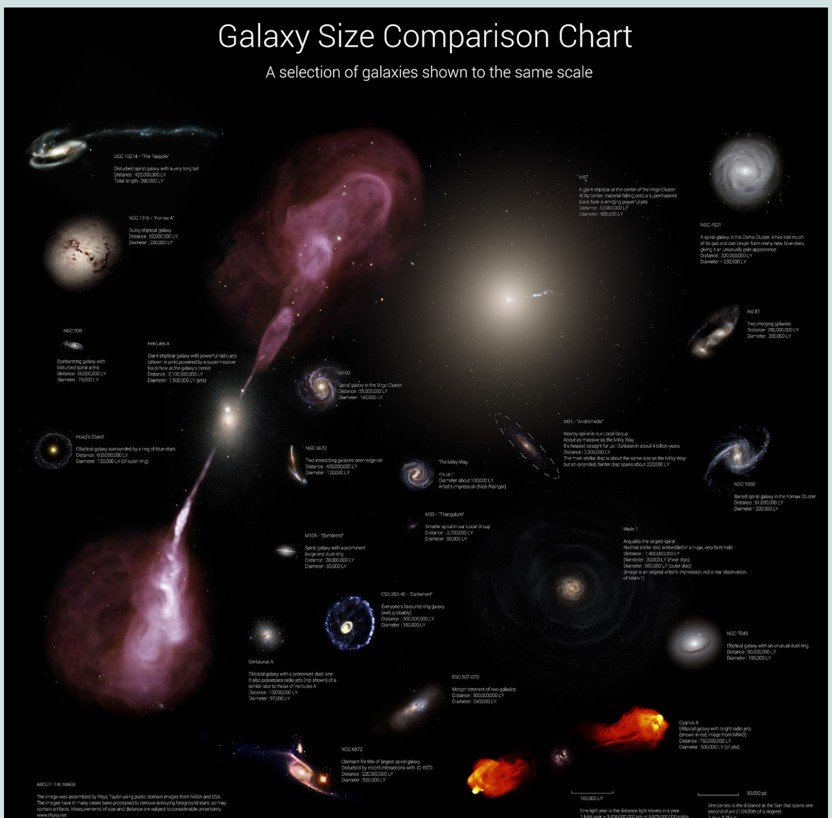
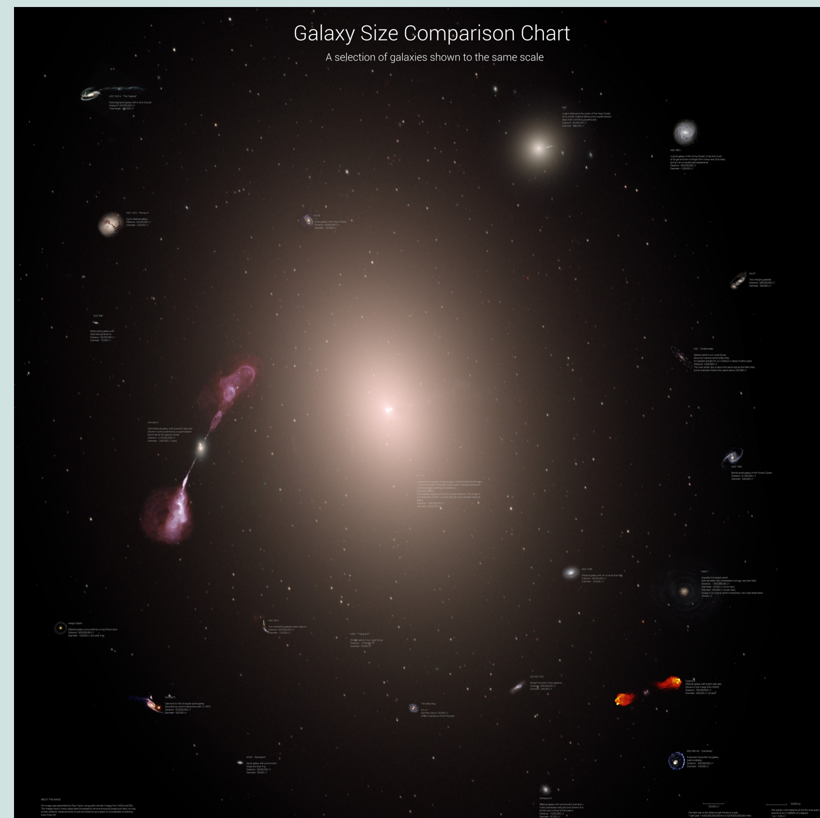


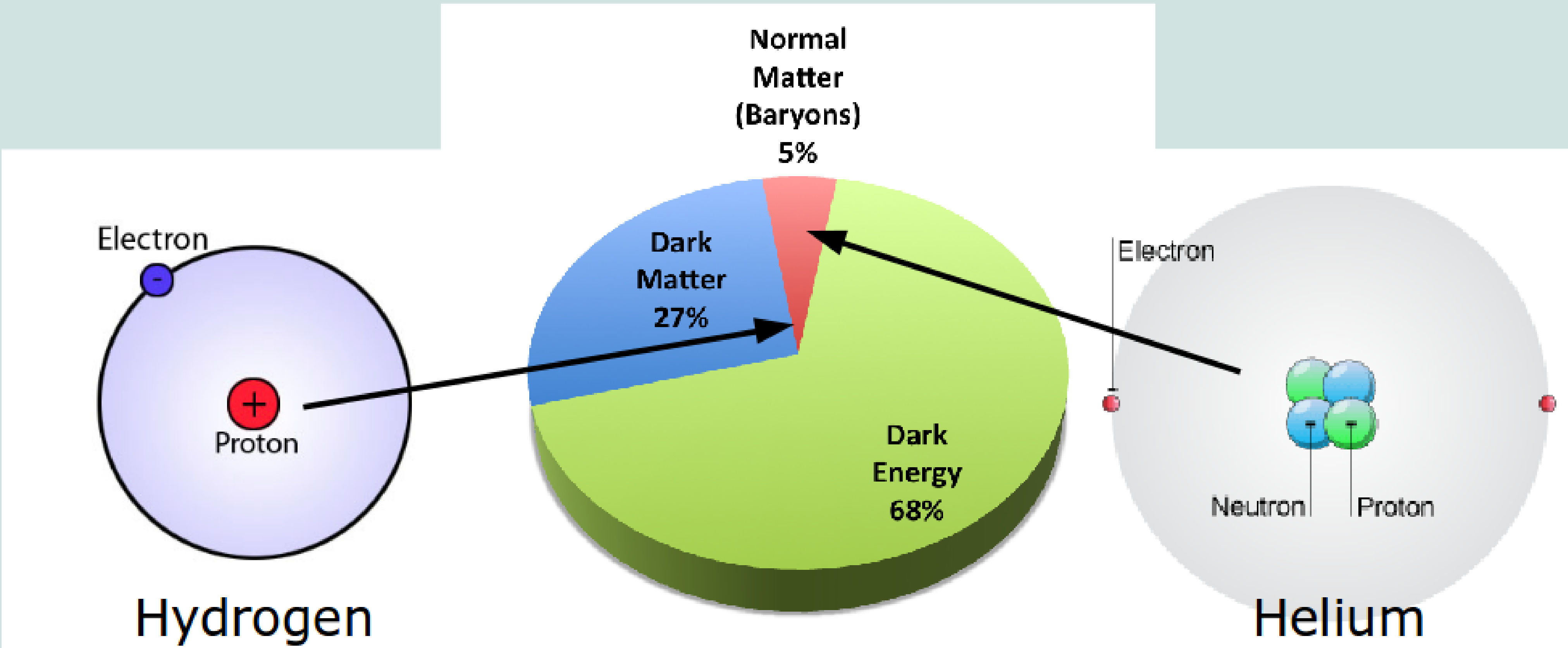




Galaxy sizes, image by Rhys Taylor

Astrophysics

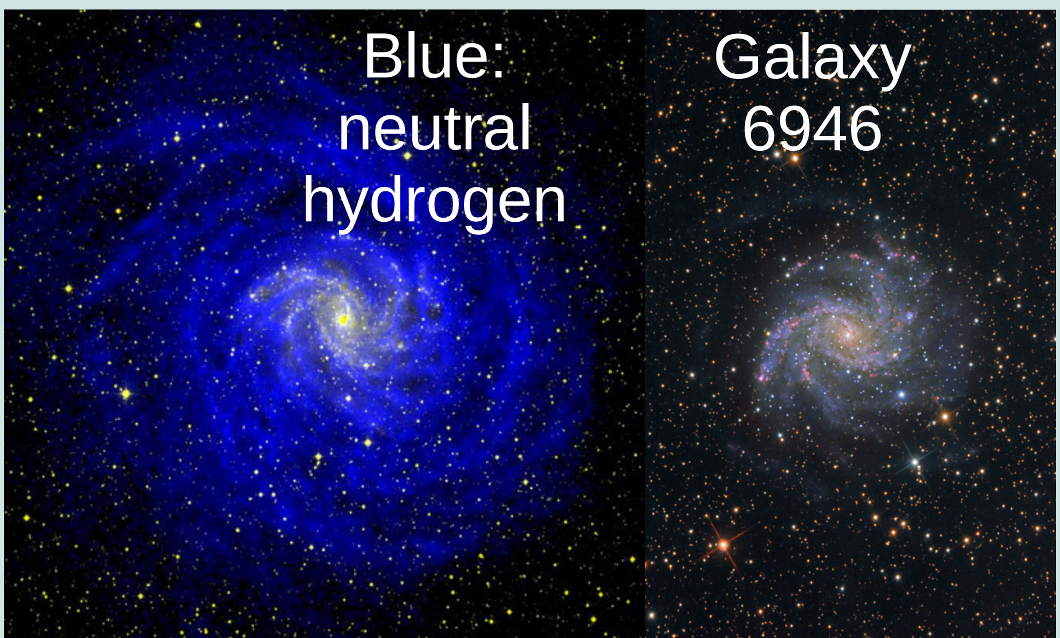
- Advantage: testing different parameter space: physics

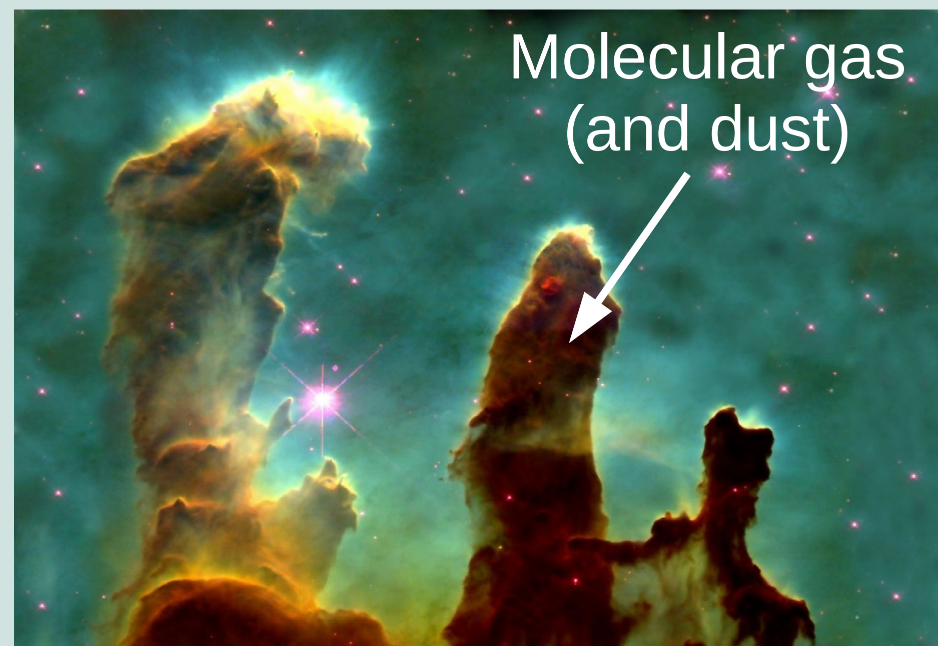


- Most detectable matter in the universe consists of the simplest atoms, hydrogen (75%) and helium (25%)
- 50% of the detectable matter we have not yet seen

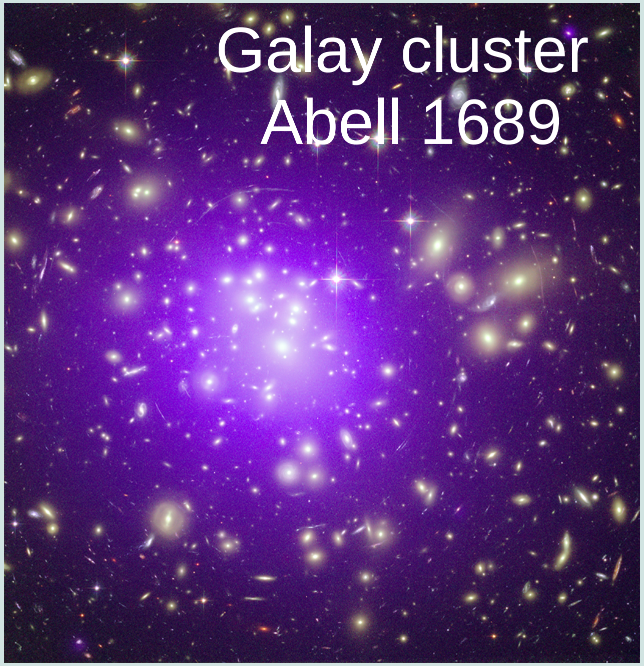
Astrophysics

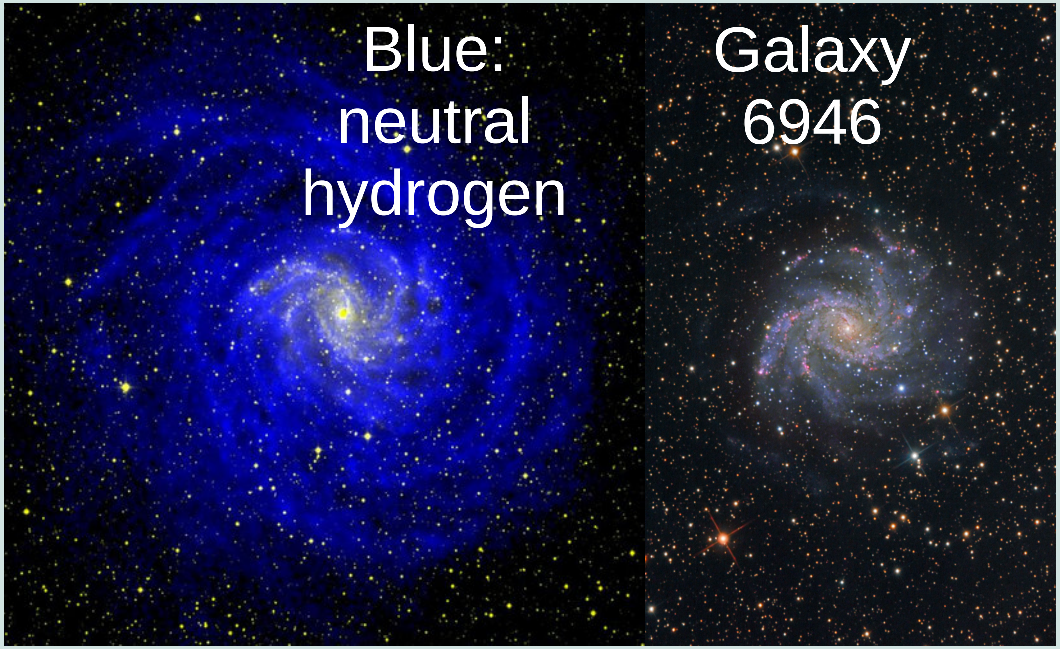
- Advantage: testing different parameter space: physics
- Most detectable matter is hot: few 10^3 K (surface of stars) to 10^8 K (gal. clusters)
- Some of it is cold: neutral gas (100 K) and molecular gas (20 K)
- Cold gas density 1 atoms cm^{-2} (neutral) to 10^4 - 10^6 atoms cm^{-2} (molecular)

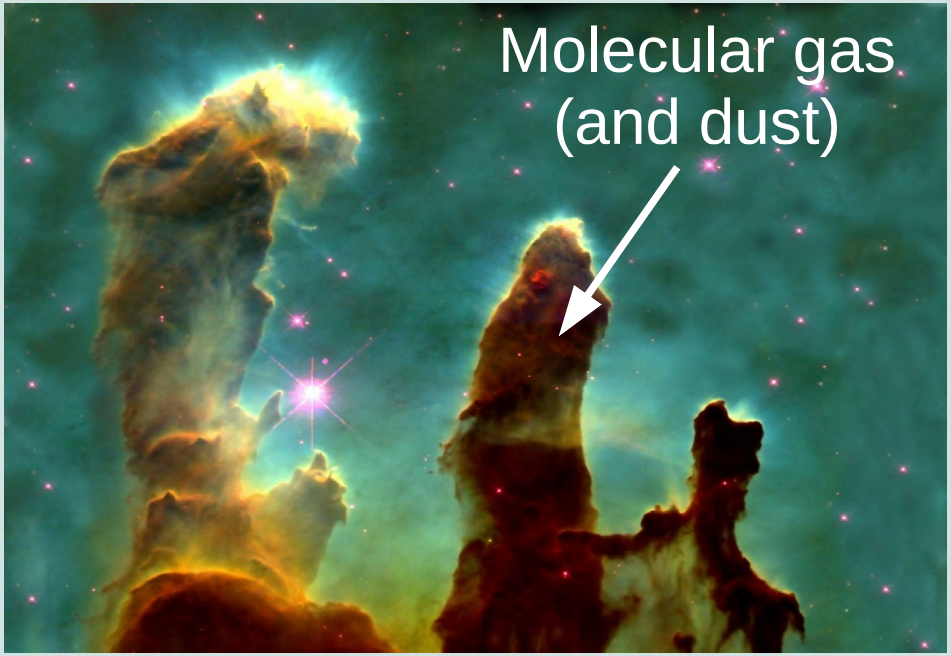




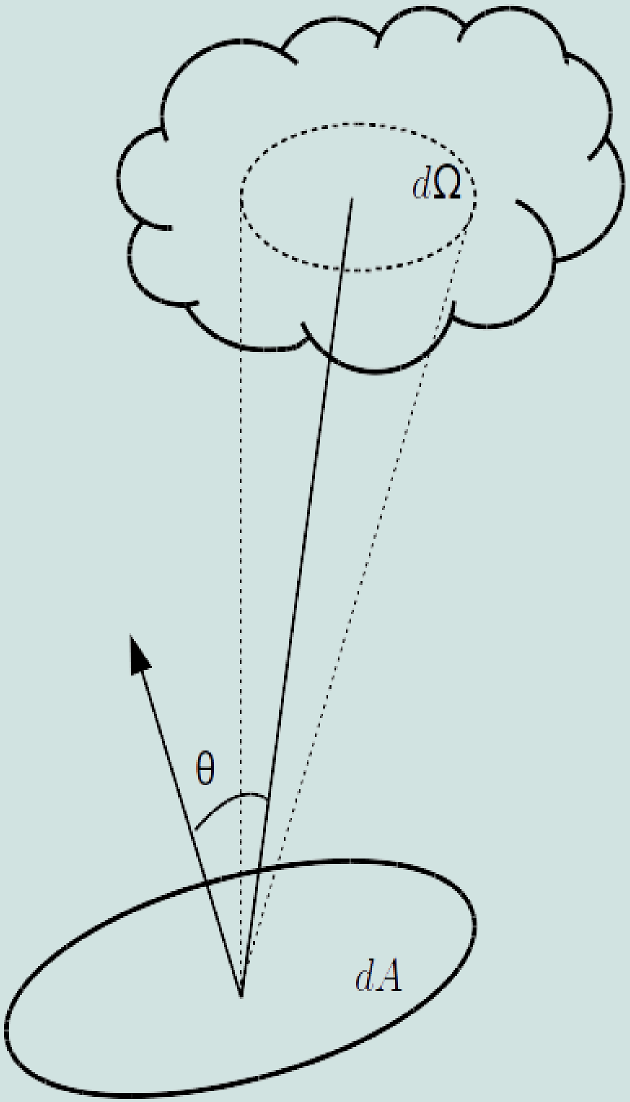
Most information comes from the detection of electromagnetic radiation







Electromagnetic radiation and astronomical quantities



$$dP = I_\nu(\theta,\,\phi)\,dA_{\rm eff}\,d\nu\,d\Omega$$
$$= I_\nu(\theta,\,\phi)\,\cos\theta\,dA\,d\nu\,d\Omega$$

dP: (infinitesimal) Power

dA_{eff}: effective (infinitesimal) Area

dA: (infinitesimal) Area

dν: (infinitesimal) frequency range

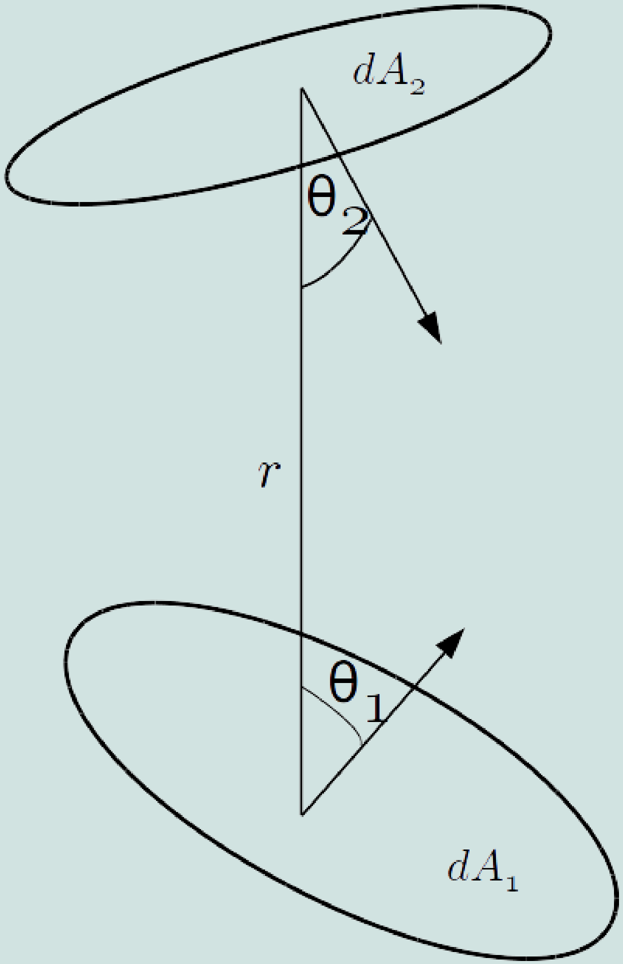
$d\Omega$: (infinitesimal) solid angle

I_ν: (Specific) Intensity / Brightness

[W m^{-2} Hz^{-1} $sterad^{-1}$ or W m^{-2} Hz^{-1} $beam^{-1}$ or Jy $sterad^{-1}$ or Jy $beam^{-1}$]

$$1\,{\rm Jy} = 10^{-26}\,{\rm W\,m^{-2}\,Hz^{-1}}$$

Electromagnetic radiation and astronomical quantities



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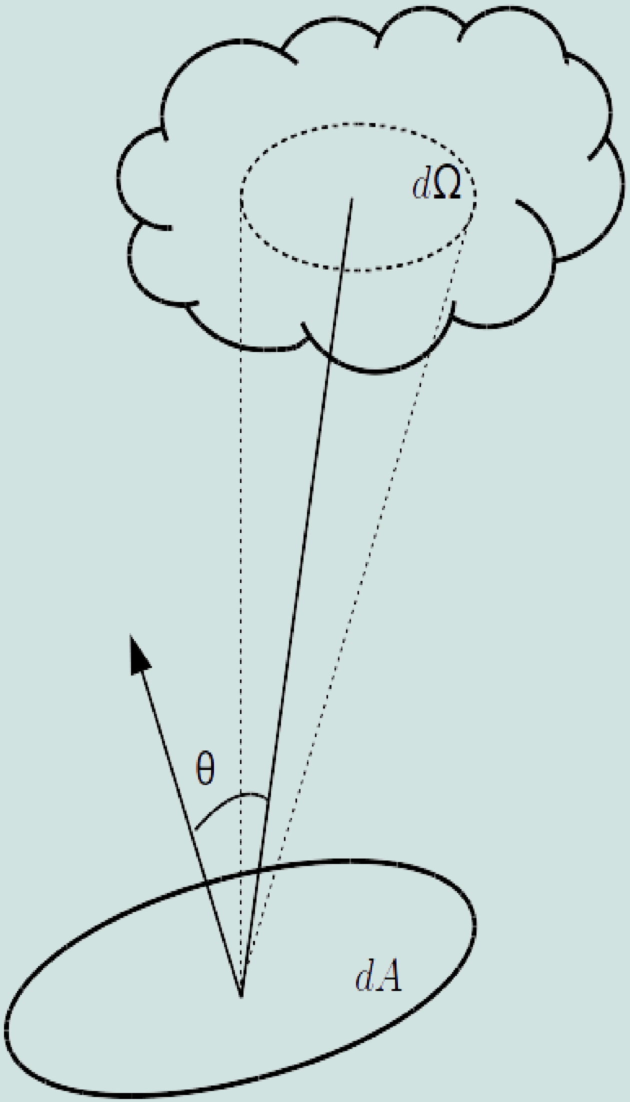
$$d\Omega_1 = \frac{cos\theta_2\,dA_2}{r^2}$$

$$d\Omega_2 = \frac{cos\theta_1\,dA_1}{r^2}$$

$$\begin{aligned} dP &= I^1_\nu\,\cos\theta_1\,dA_1\,d\Omega_1\,d\nu \\ &= I^1_\nu\,r^2\,d\Omega_2\,d\Omega_1\,d\nu \\ &= I^2_\nu\,r^2\,d\Omega_2\,d\Omega_1\,d\nu \\ &= I^2_\nu\,\cos\theta_2\,dA_2\,d\Omega_2\,d\nu \end{aligned} \quad ,$$

- Intensity is independent of the distance to the source (without emission or absorption)

Electromagnetic radiation and astronomical quantities



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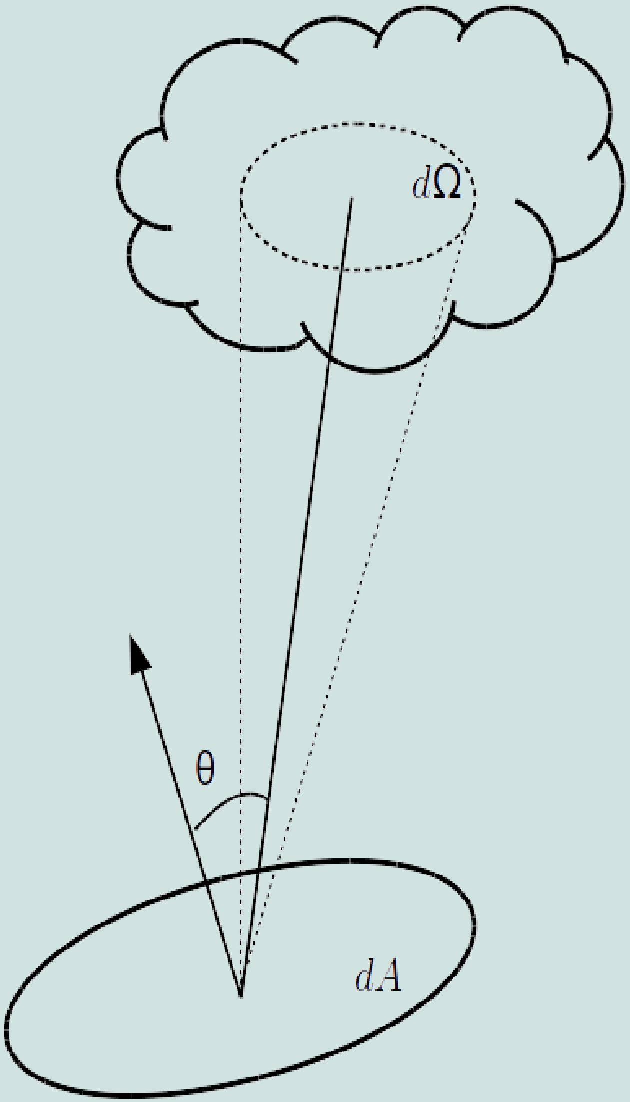
$$S_\nu = \int I_\nu(\theta,\, \phi)\, \cos\theta\, d\Omega$$ (Integrate over all directions)

S_ν: Flux density [W m^{-2} Hz^{-1} or Jy]

$$1\,\text{Jy} = 10^{-26}\,\text{W}\,\text{m}^{-2}\,\text{Hz}^{-1}$$

- Flux density is proportional to the inverse of the square of the distance

Electromagnetic radiation and astronomical quantities



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$$S_\nu = \int I_\nu(\theta,\, \phi)\, \cos\theta\, d\Omega$$

S_ν: Flux density [W m^{-2} Hz^{-1} or Jy]

Integrate over sphere with radius R

$$L_\nu = \int S_\nu(R, \theta, \phi)\, R^2\, d\Omega$$

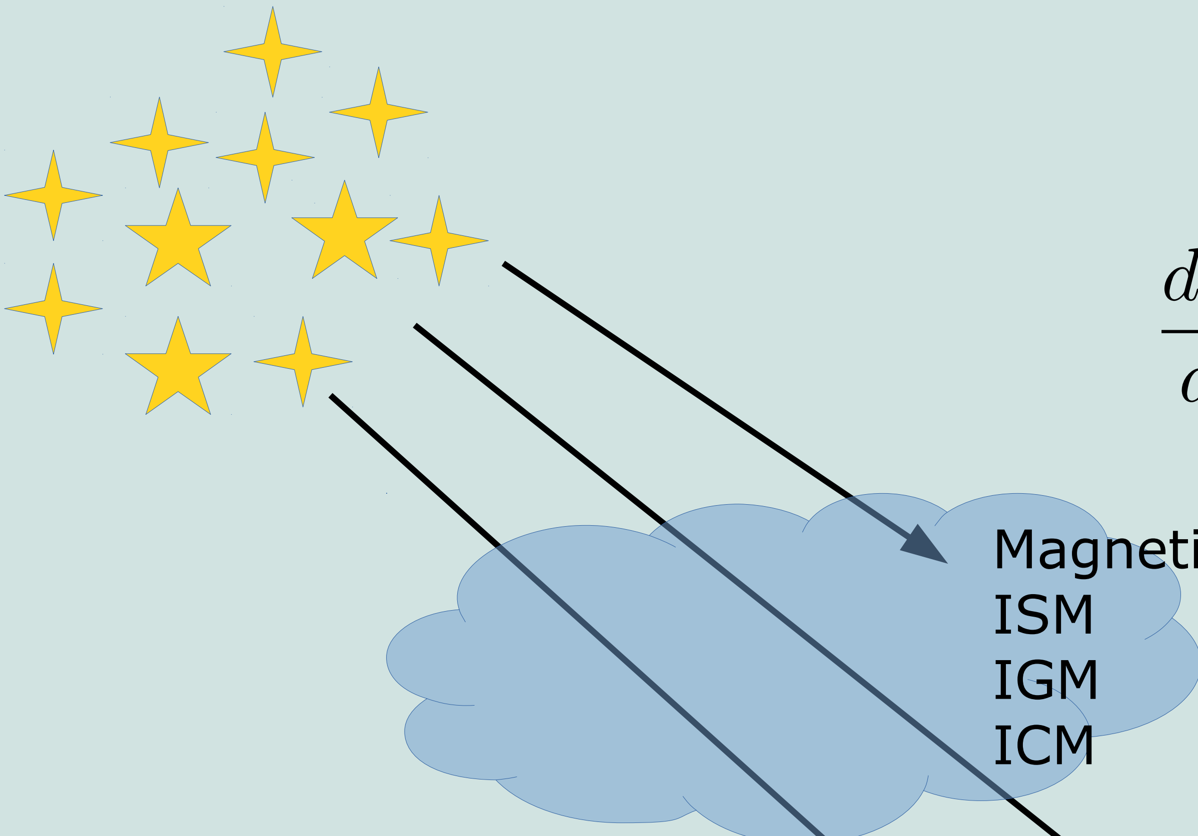
L_ν: Specific Luminosity [W Hz^{-1}]

$$L = \int L_\nu\, d\nu$$

L_ν: Bolometric Luminosity [W Hz^{-1}]

- Bolometric and specific luminosity are intrinsic to a source

Radiative transfer



Change in specific intensity

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

Absorption coefficient

Emission coefficient

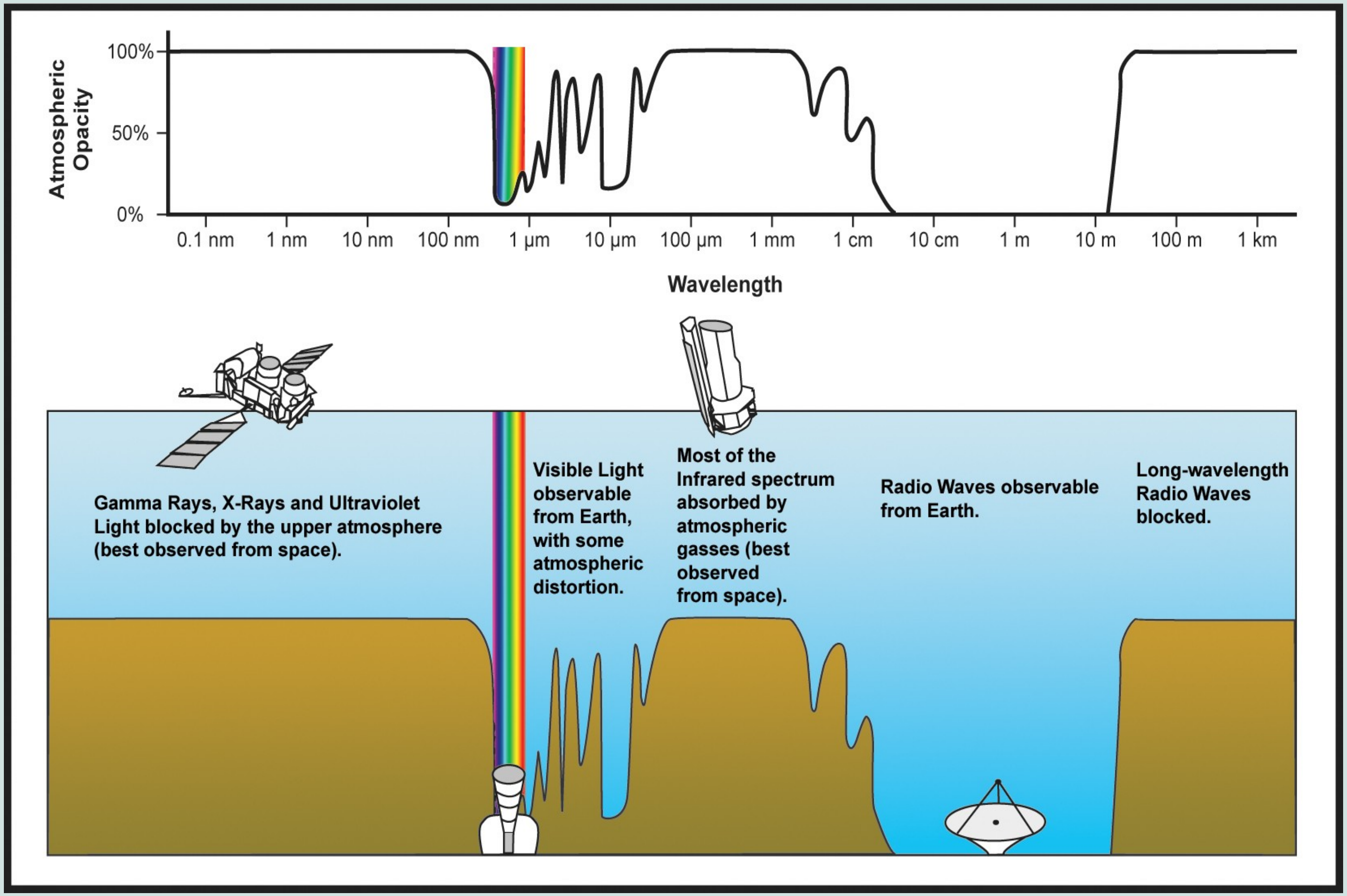
$d\tau_\nu \underset{def}{=} -\kappa_\nu \, dt$ Optical depth

$s_\nu \underset{def}{=} \dfrac{\varepsilon_\nu}{\tau_\nu}$ Source function (efficiency)

$$I_\nu(0) = I_\nu(s_0) = I_\nu\left(\tau_\nu(s)\right) e^{-\tau_\nu(s)} + \int_0^{\tau_\nu(s)} s_\nu \, e^{-\tau_\nu} \, d\tau_\nu$$

$$\varepsilon_\nu \underset{LTE}{=} \kappa_\nu \, B(T)$$

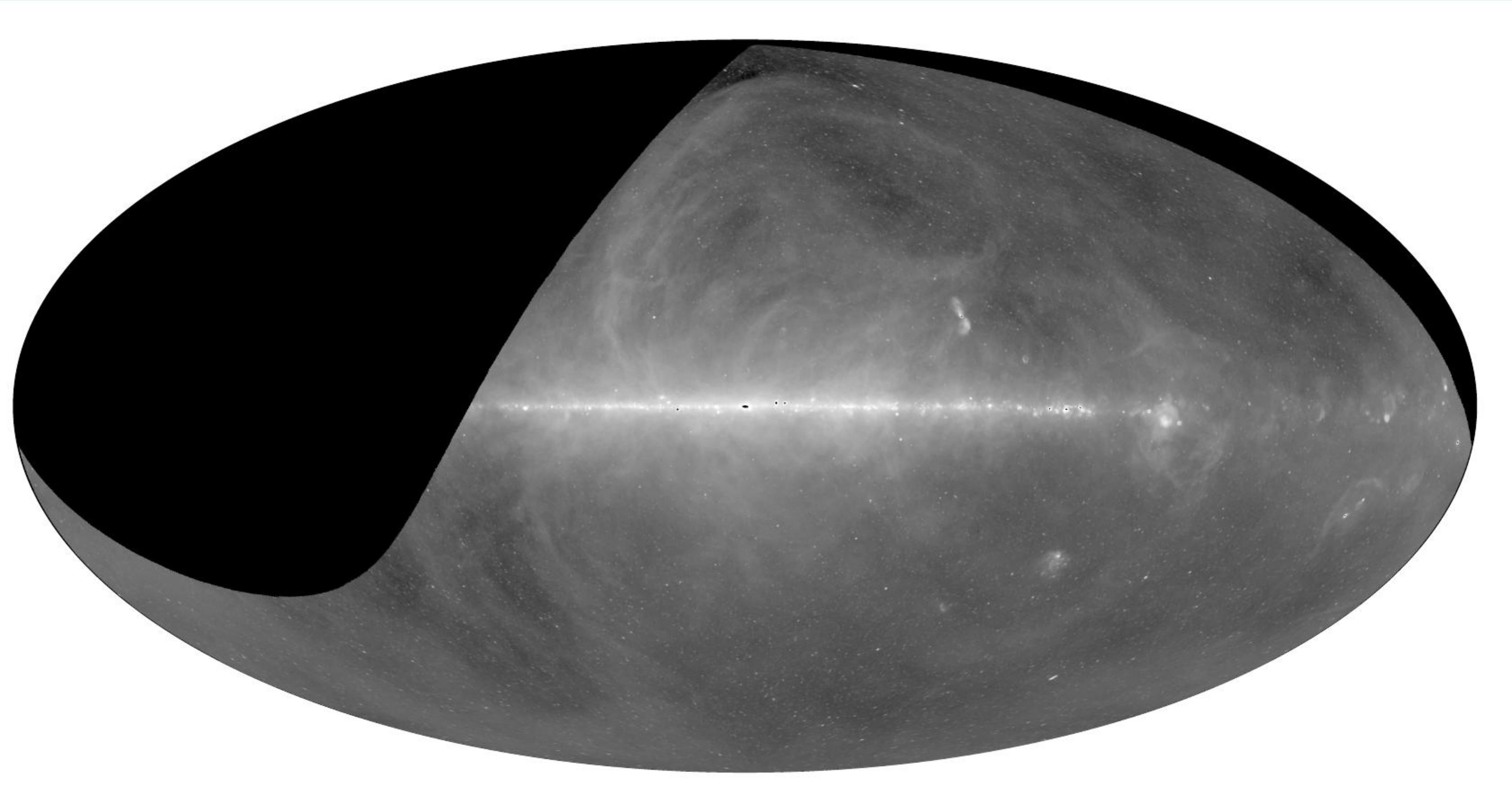
The radio window



Radio regime: 10 MHz – 1000 GHz

Band	Frequency (GHz)
P	0.23 - 0.47
L	1 - 2
S	2 - 4
C	4 - 8
X	8 - 12
Ku	12 - 18
K	19 - 26.5
Ka	26.5 - 40.0
Q	40.0 - 50.0

The radio sky



Radio Continuum Image of the Sky at 1.4 GHz, Calabretta et al. 2013

Radio sources

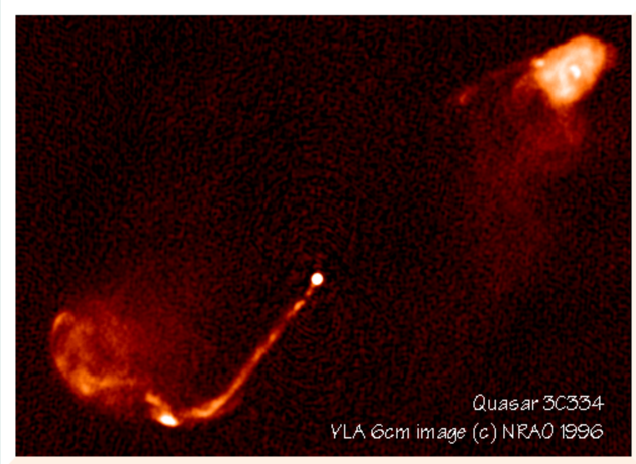
AGN (active galactic nucleus)

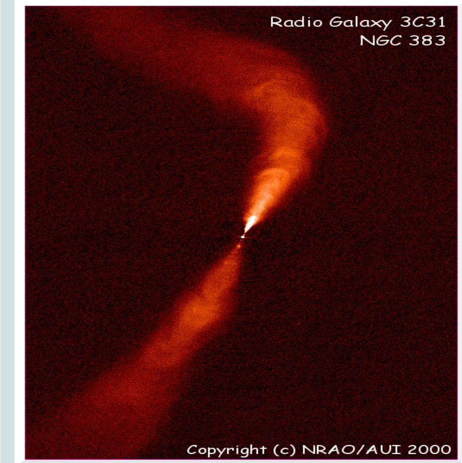
- powered Radio Sources

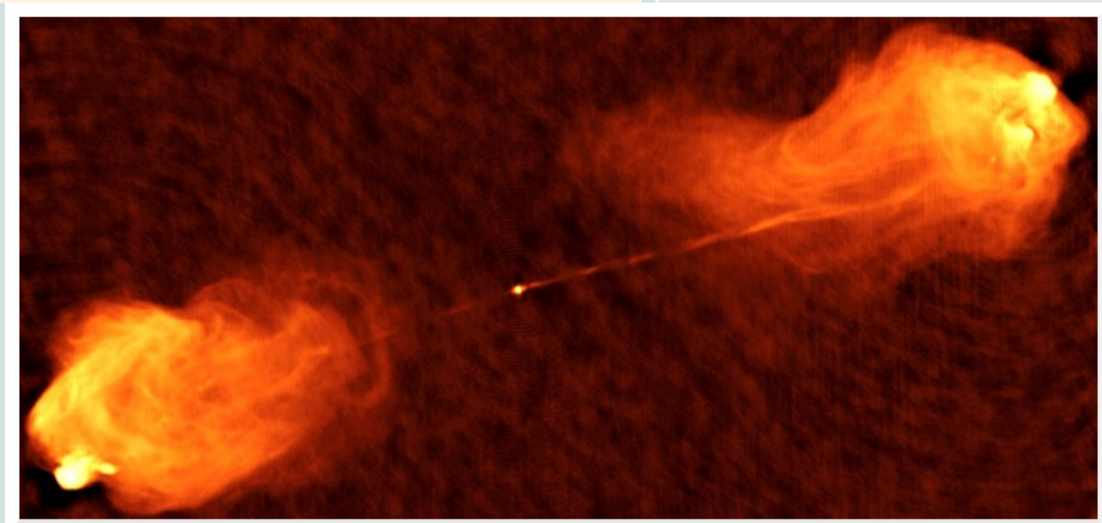
- Radio Quasars
- FRII/FRI Radio Galaxies

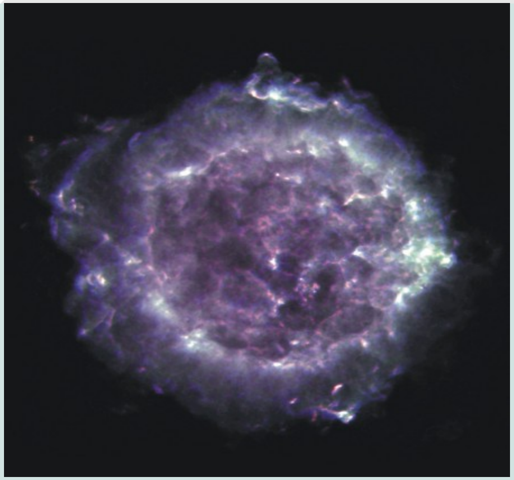
Non-AGN powered radio sources

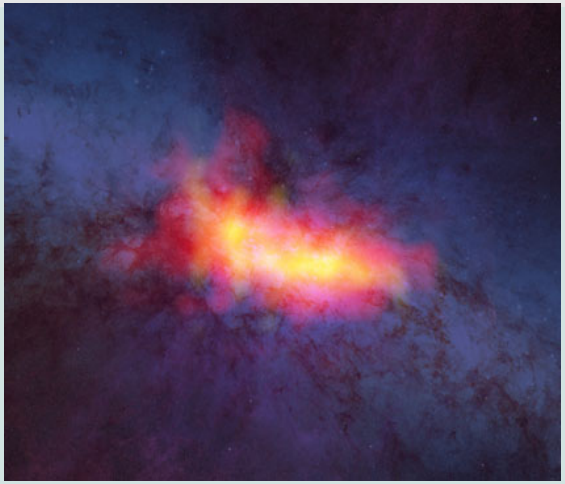
- Supernova Remnants
- Star-forming Galaxies
- H I gas (neutral hydrogen)
- Molecular Clouds
- HII regions
- Sun
- Planets and moons



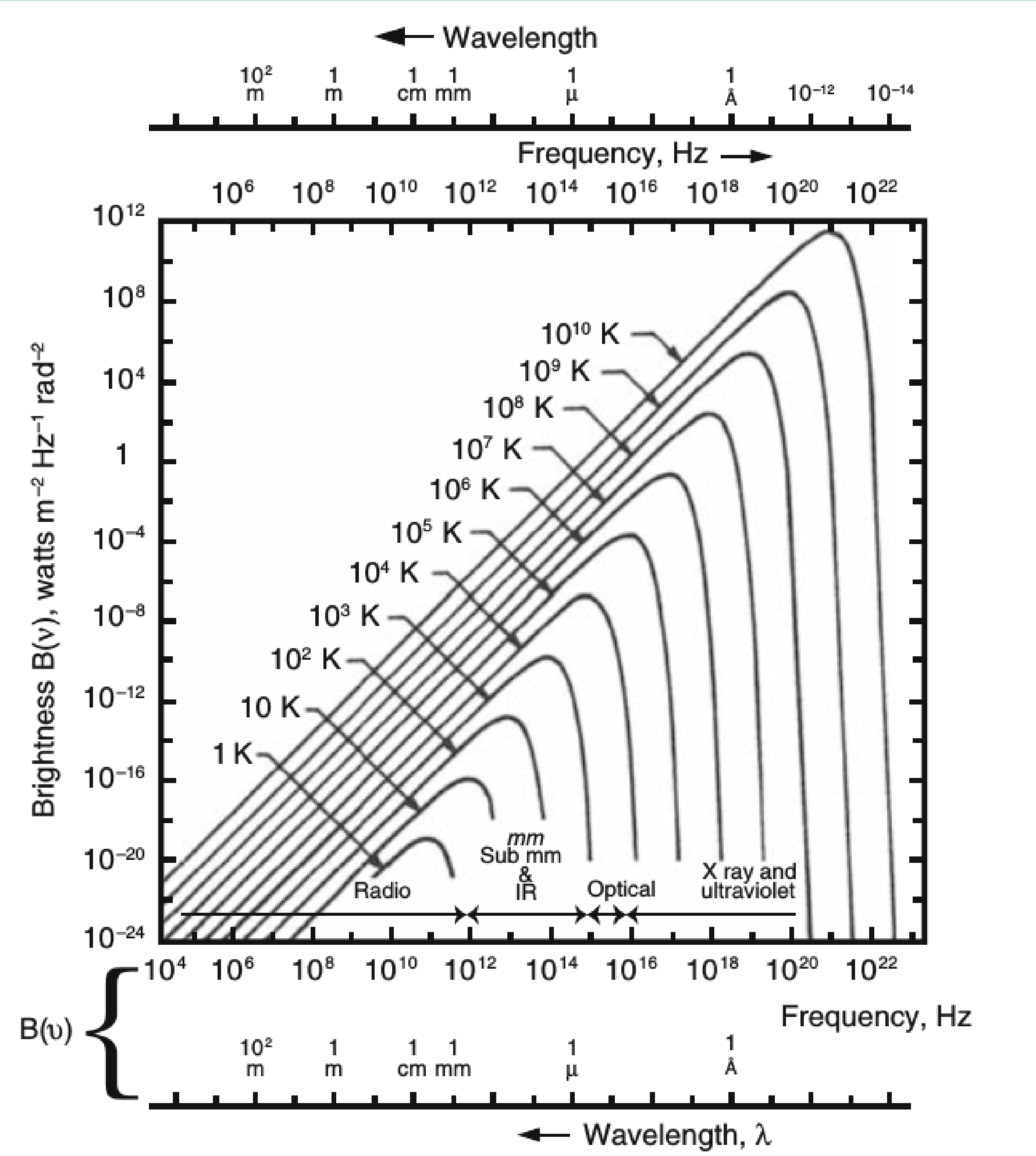








Black body radiation



Planck's law, in local thermodynamic equilibium or black body:

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{k_B T}} - 1},$$

Maximum given by Wien's displacement law:

$$\nu_{max} = 58.789\frac{\mathrm{GHz}}{\mathrm{K}}T$$

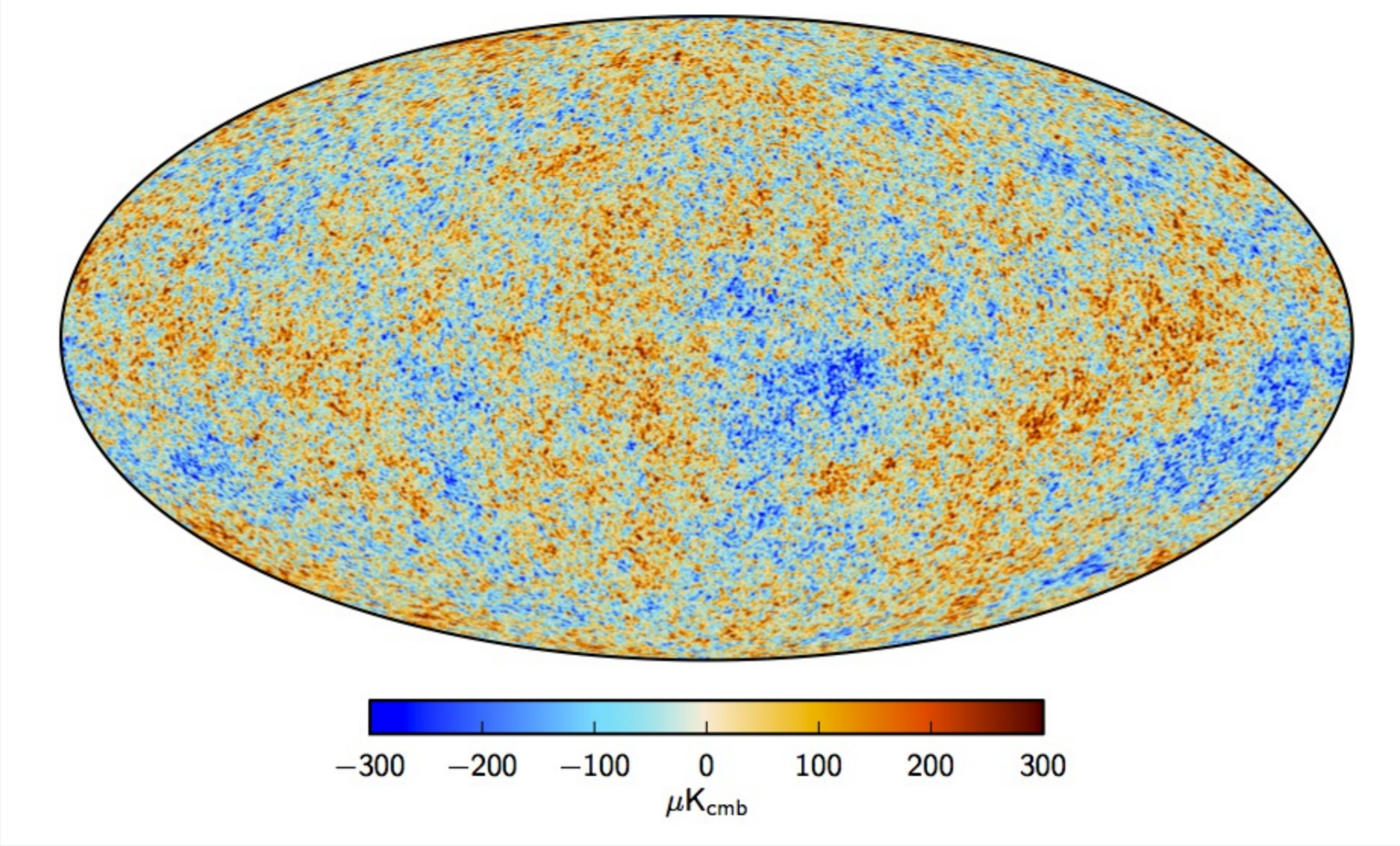
For low temperatures the Rayleigh-Jeans approximation applies:

$$B_\nu(T) = \frac{2\nu^2}{c^2}k_B T$$

Brightness temperature T_B:

$$T_B \underset{def}{=} \frac{c^2 I_\nu}{2k_B\nu^2}$$

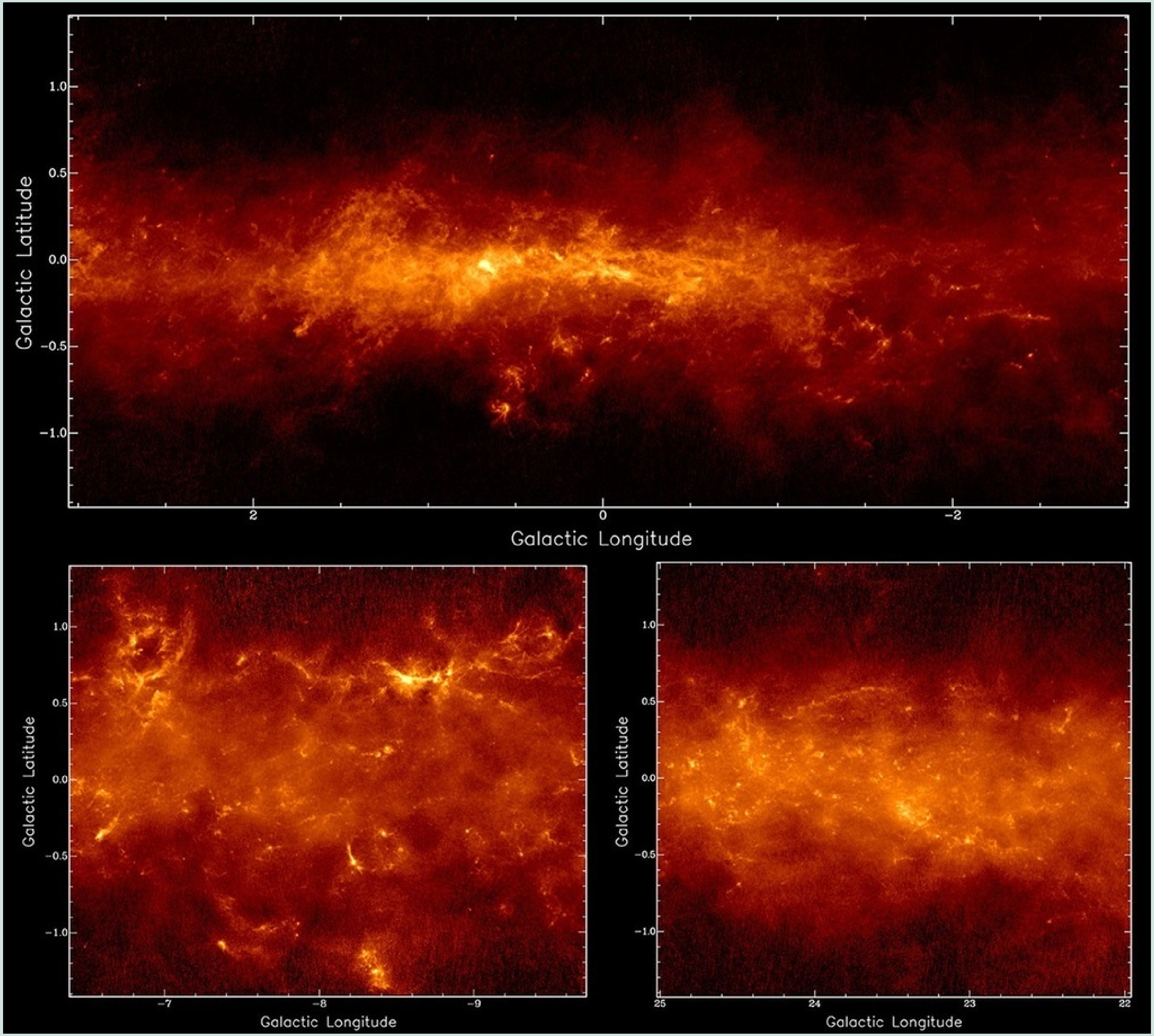
The Cosmic Microwave Background



- 2.725 K (ν_{max}=160 GHz, λ_{max}=1.9 mm)
- Variations at a level of 1:10^5

Black body radiation

- Planets, Moon
- Cold dust



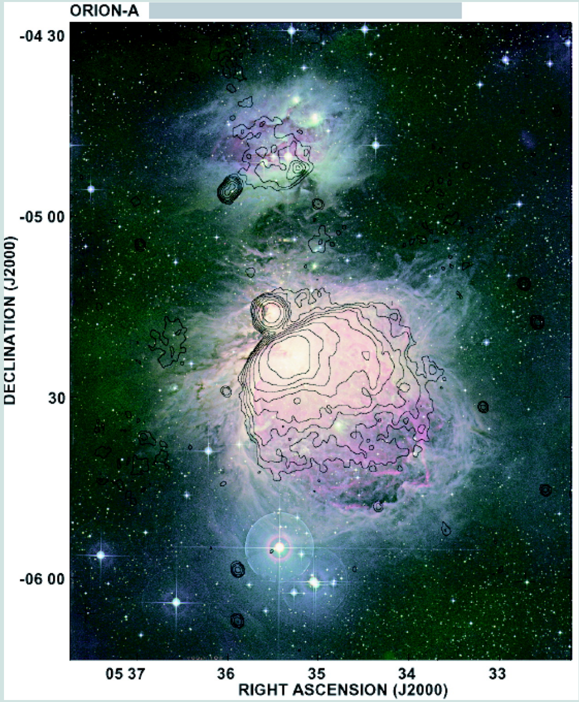
Galactic plane, APEX LABOCA sub-mm camera and Planck satellite. (ATLASGAL-Konsortium/Csengeri et al. 2016)

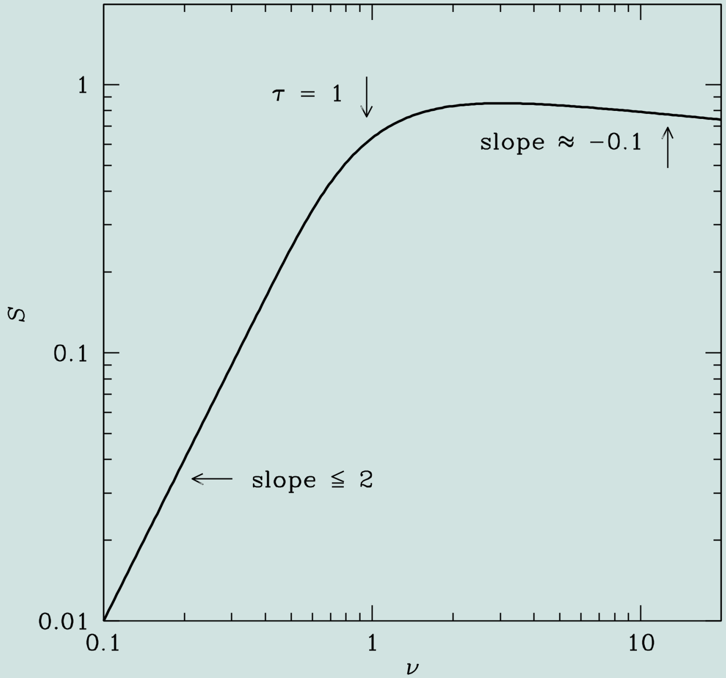
Bremsstrahlung

- Emission produced by accelerating a charge
- (Non-relativistic) Larmor formula: $P = \frac{2}{3}\frac{q^2 a^2}{c^3}$
- Electrostatic Bremsstrahlung mostly thermal (free-free thermal plasma)
- Magnetobremsstrahlung mostly non-thermal
- Total spectrum determined by velocity distribution

Thermal (free-free) Bremsstrahlung

- Nonrelativistic charged particles in thermodynamic equilibrium
- Velocity distribution of charged particles given by Mawellian distribution
- H II-regions around bright, young stars
- Spectrum of blackbody below a break frequency v_0 (dependent of e$^-$ temperature) and flat (S_v proportional to v) beyond.
- Parameters: emission measure (e$^-$ density integrated along path), e$^-$ temperature, frequency



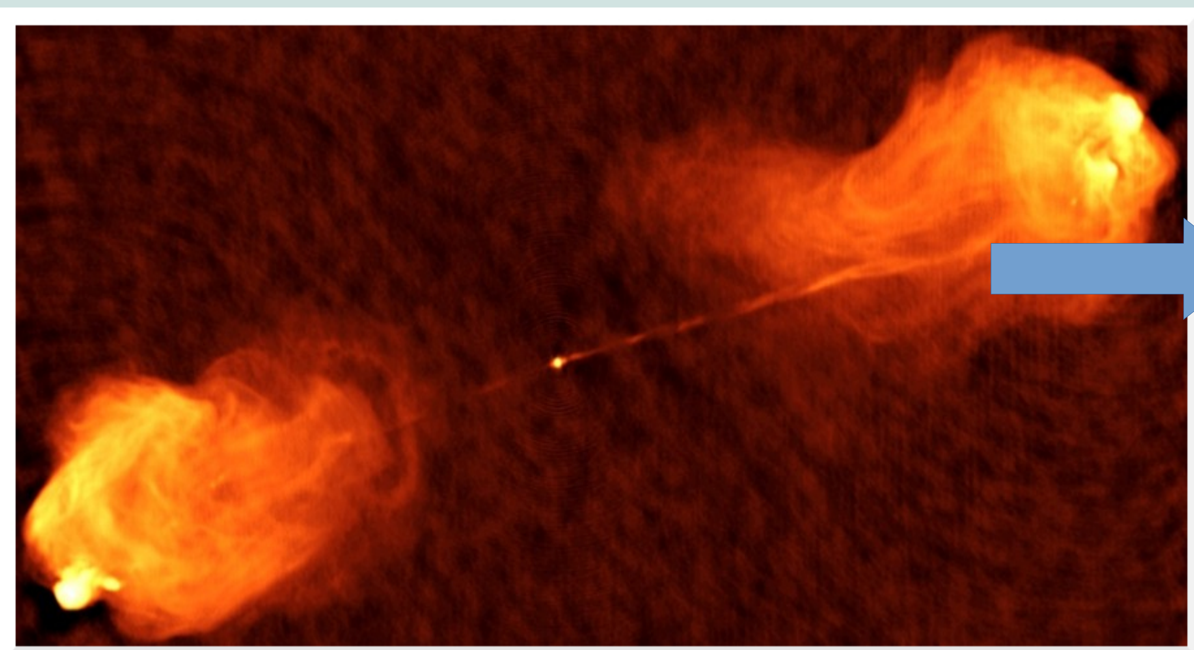


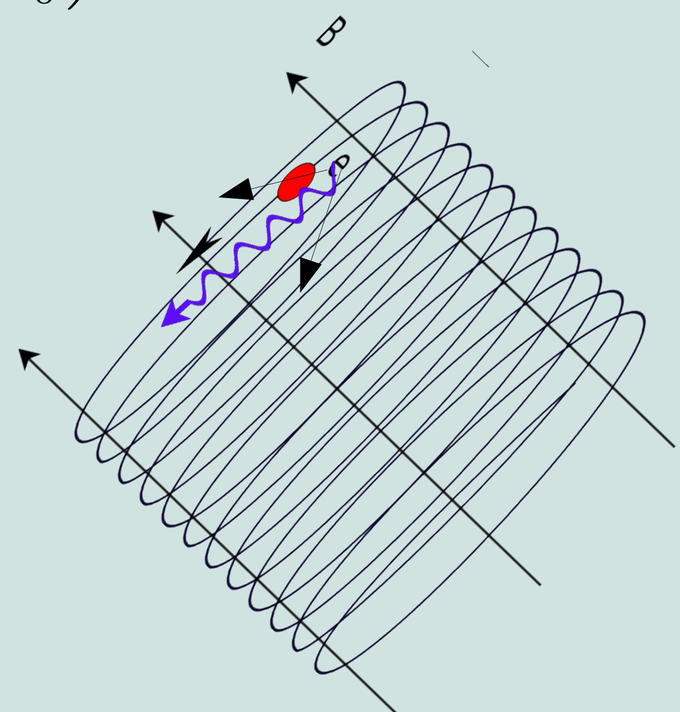
From: Essential Radio Astronomy
James J. Condon and Scott M. Ransom

Nonthermal (relativistic) synchrotron emission

- Charged particles (e^+, e^-) in magnetic field
- Gyro-frequency (orbital if non-relativistic): $\omega_\mathrm{G} = \frac{qB}{mc}$
- Power-law distribution of energy density: $N(E)dE = E^{-\delta}dE$
- Connected to power-law spectrum: $\frac{I_\nu}{I_0} = \left(\frac{\nu}{\nu_0}\right)^{-\alpha}$
- Lifetime:

$$t(\nu) = 3 \cdot 10^4\,\mathrm{y}\,\frac{B}{\mathrm{Gauss}}\left(\frac{\nu}{\mathrm{Hz}}\right)^{-\frac{1}{2}} \qquad = \left(\frac{\nu}{\nu_0}\right)^{-\frac{\delta-1}{2}}$$





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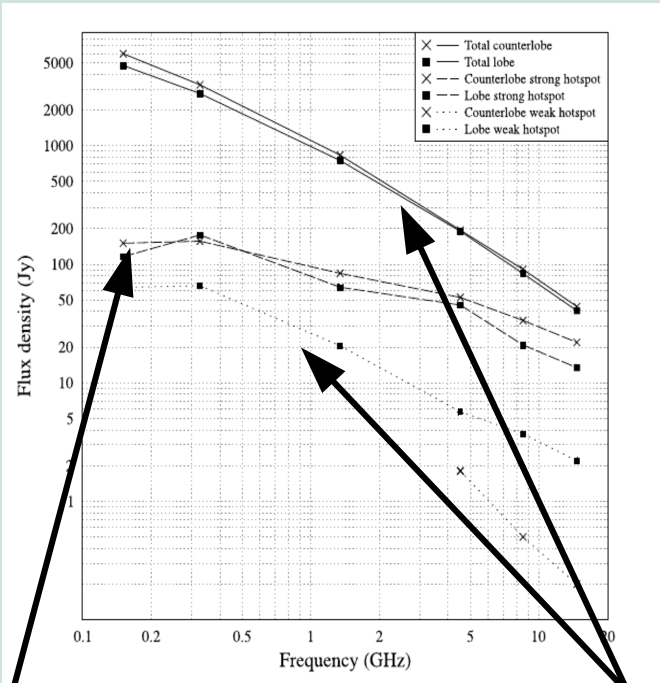
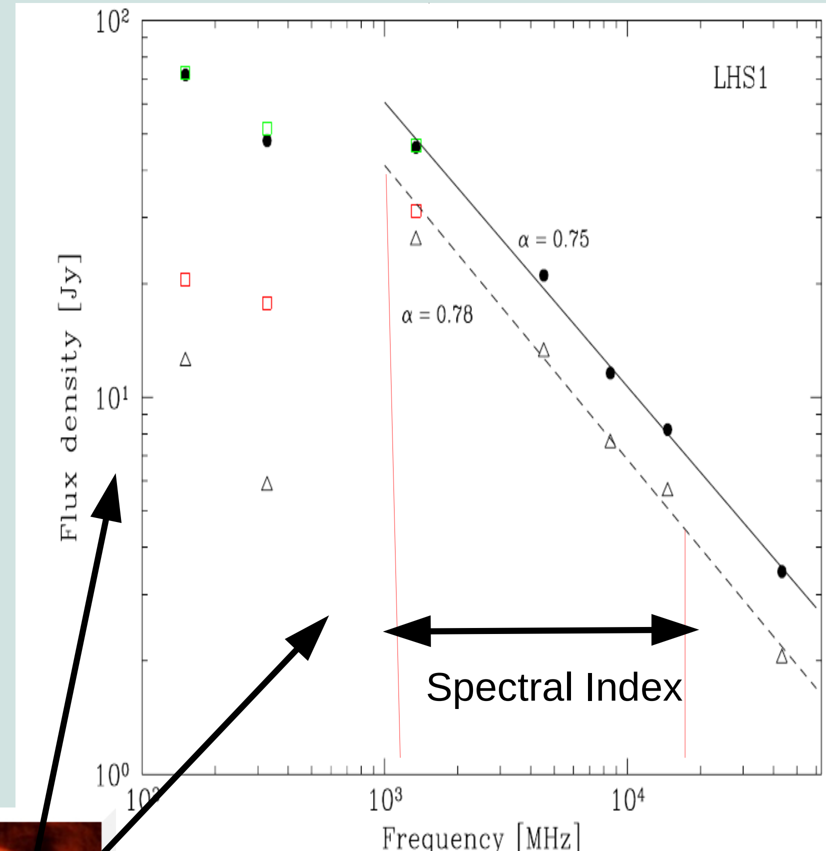
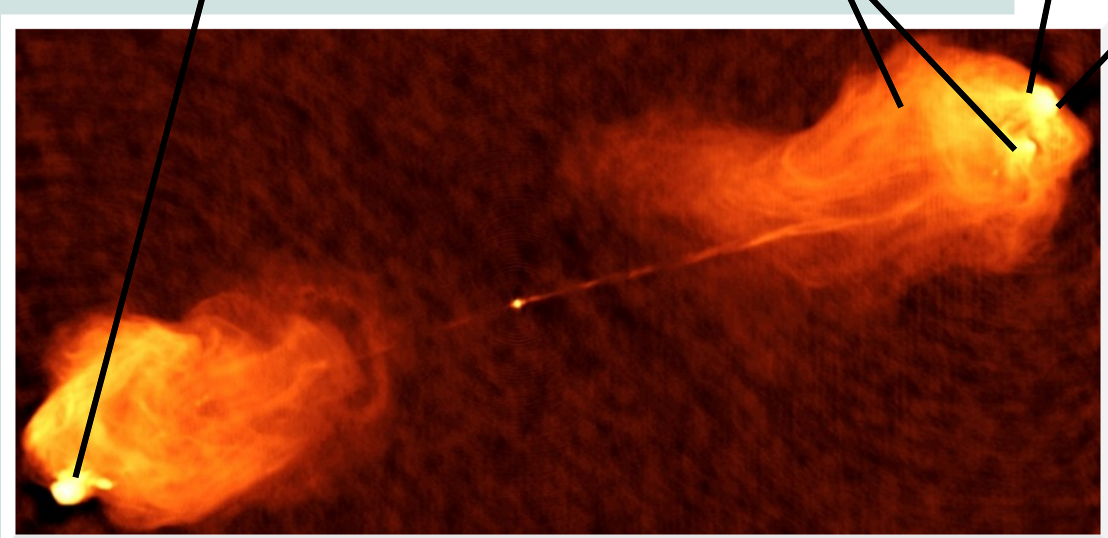




Synnchrotron Spectum



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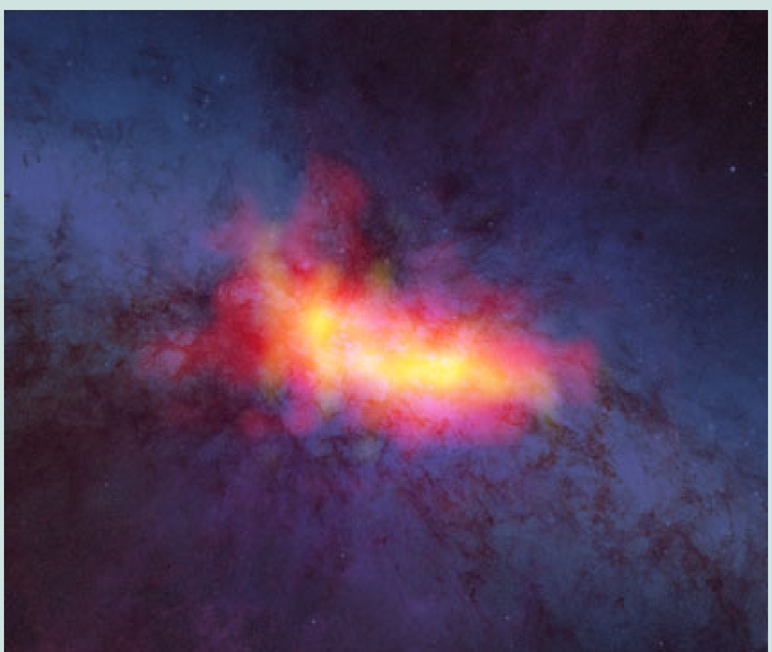
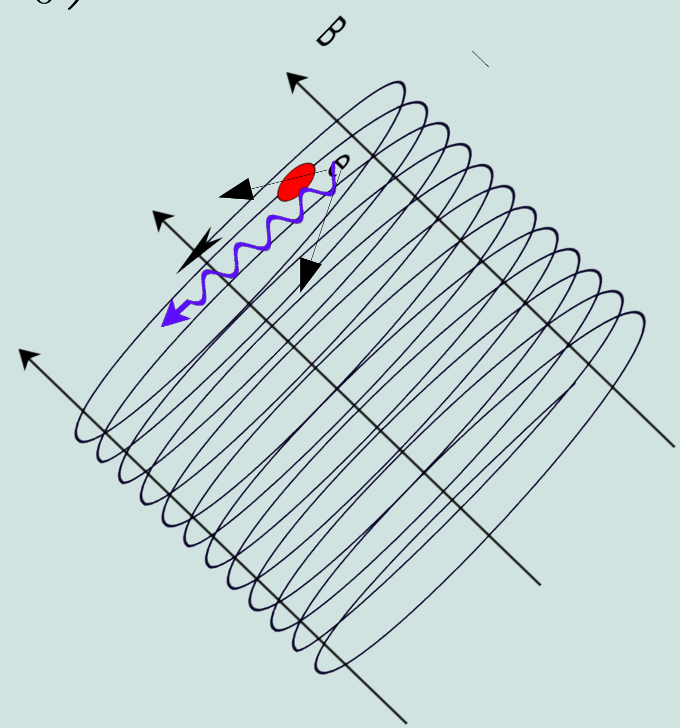
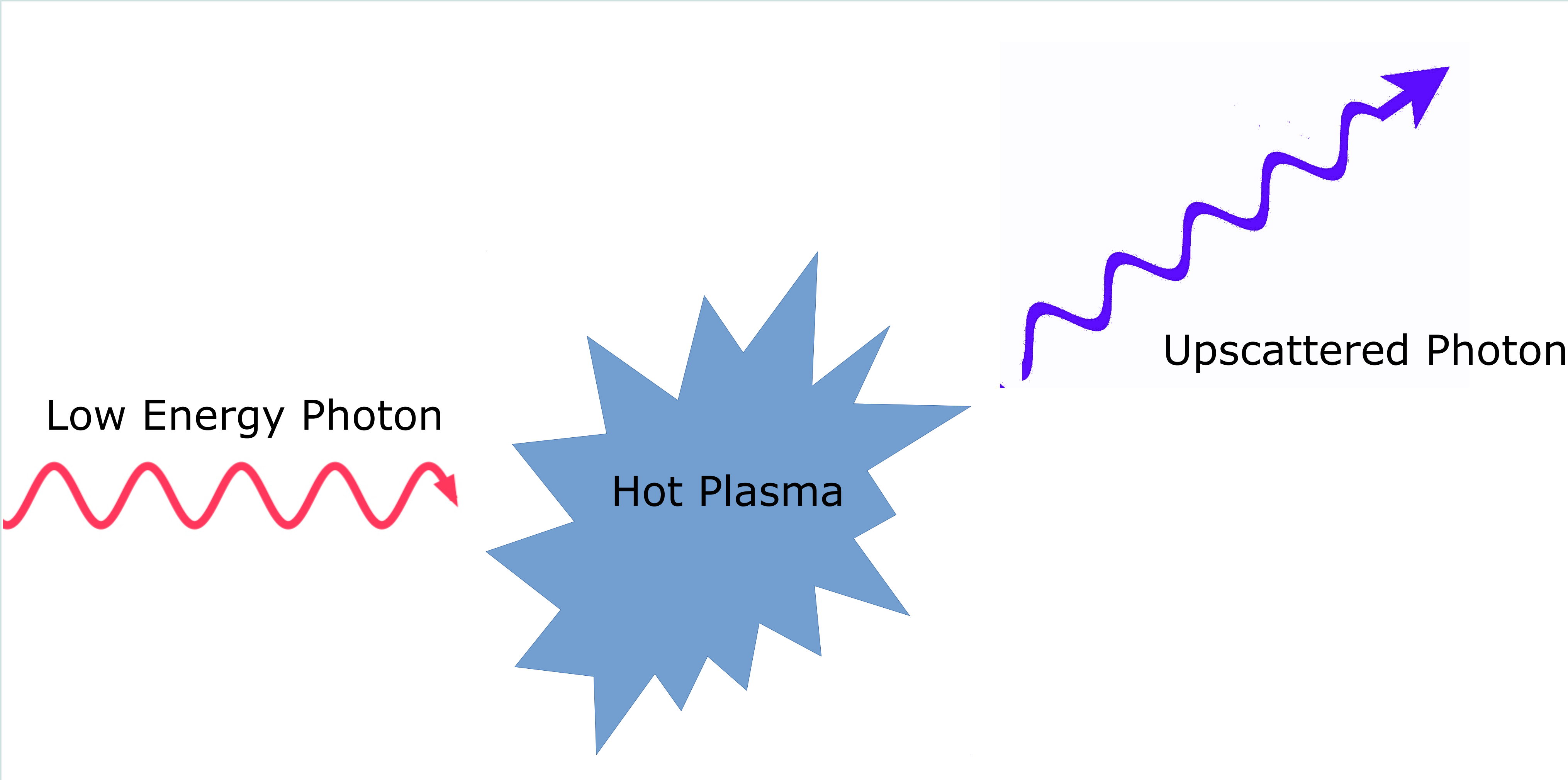




Inverse Compton Effect



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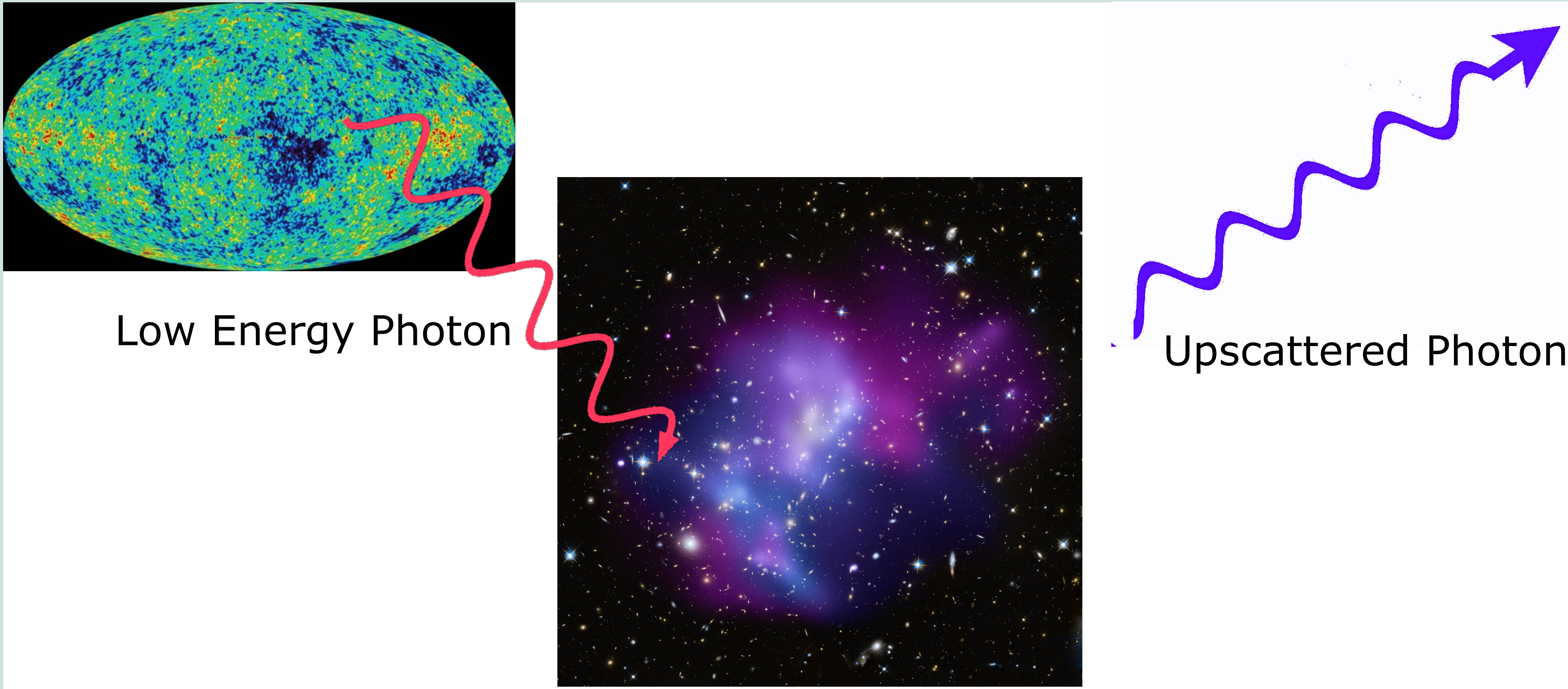
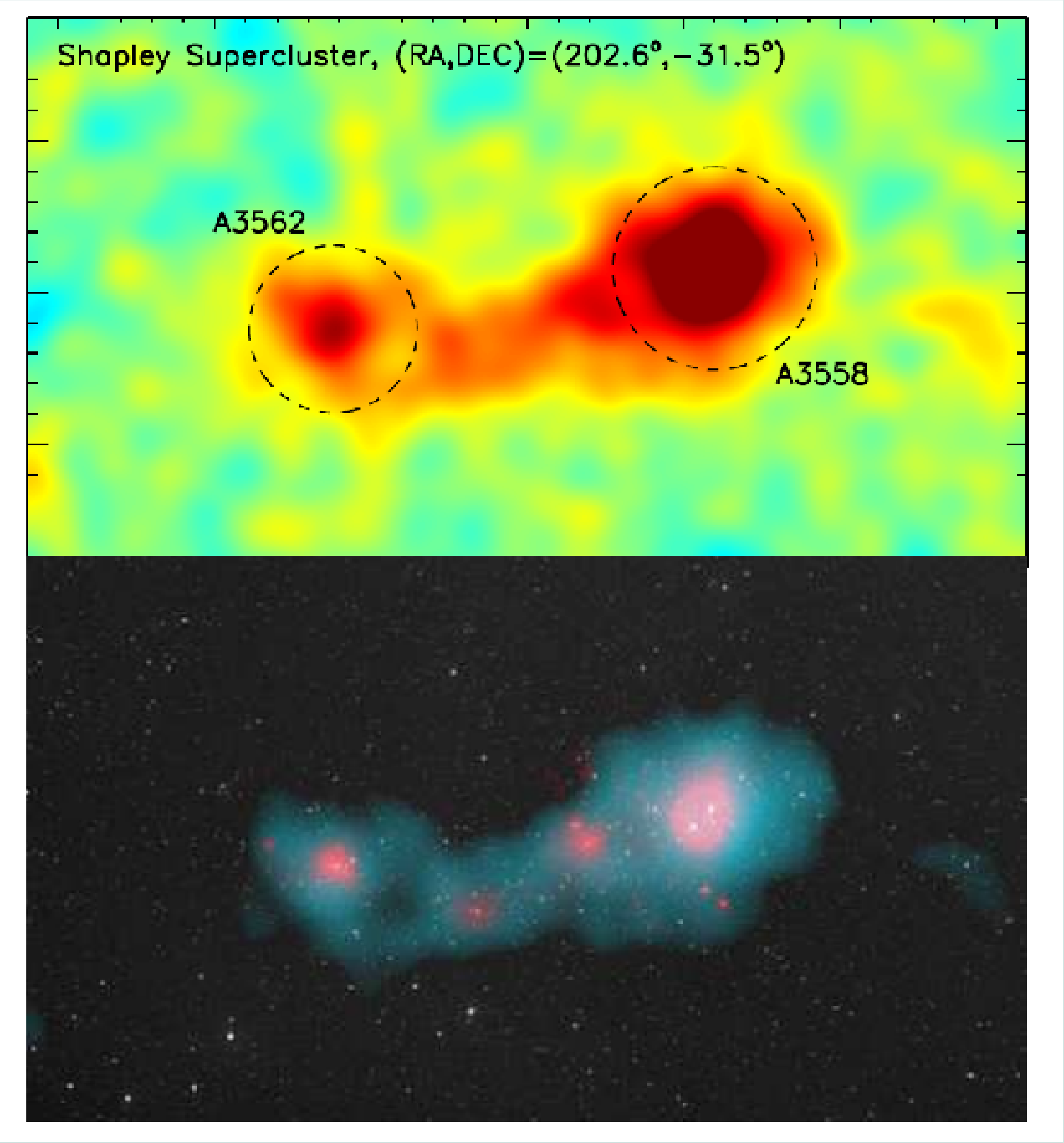


MACS J0717.5+3745 (, HST, Chandra, NASA/ESO)

Inverse Compton Effect

- Galaxy clusters and CMB

$$\frac{\Delta T_{\text{CMB}}}{T_{\text{CMB}}} \propto T_e N_e$$



Line emission basics

- Photons from sharp transitions between atomic energy levels
- Einstein coefficients A_{21} B_{21} B_{12} can be calculated from each other

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

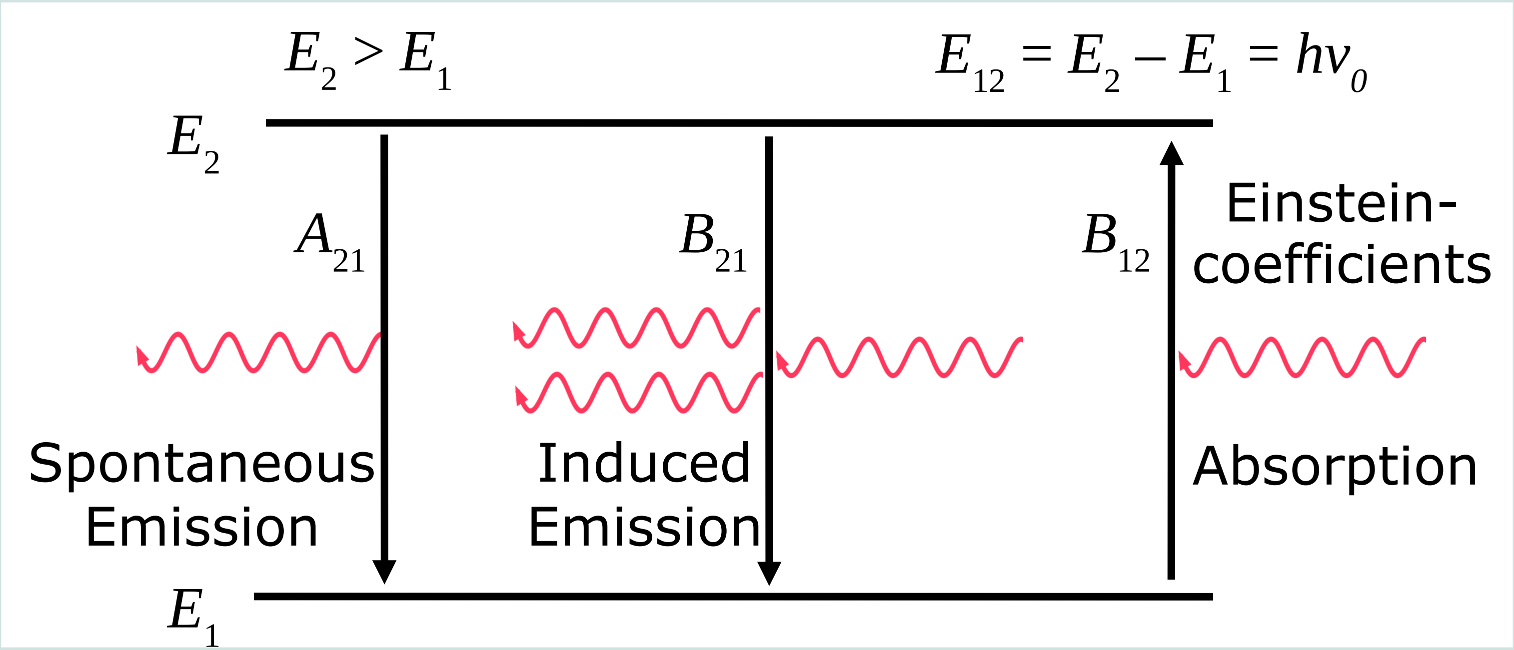
$$\int \nu \varphi \, d\nu = \nu_0$$

$$\kappa_\nu = \frac{h\nu_0}{c} N_1 B_{12} \left(1 - \frac{g_1 N_2}{g_2 N_1}\right) \varphi(\nu)$$

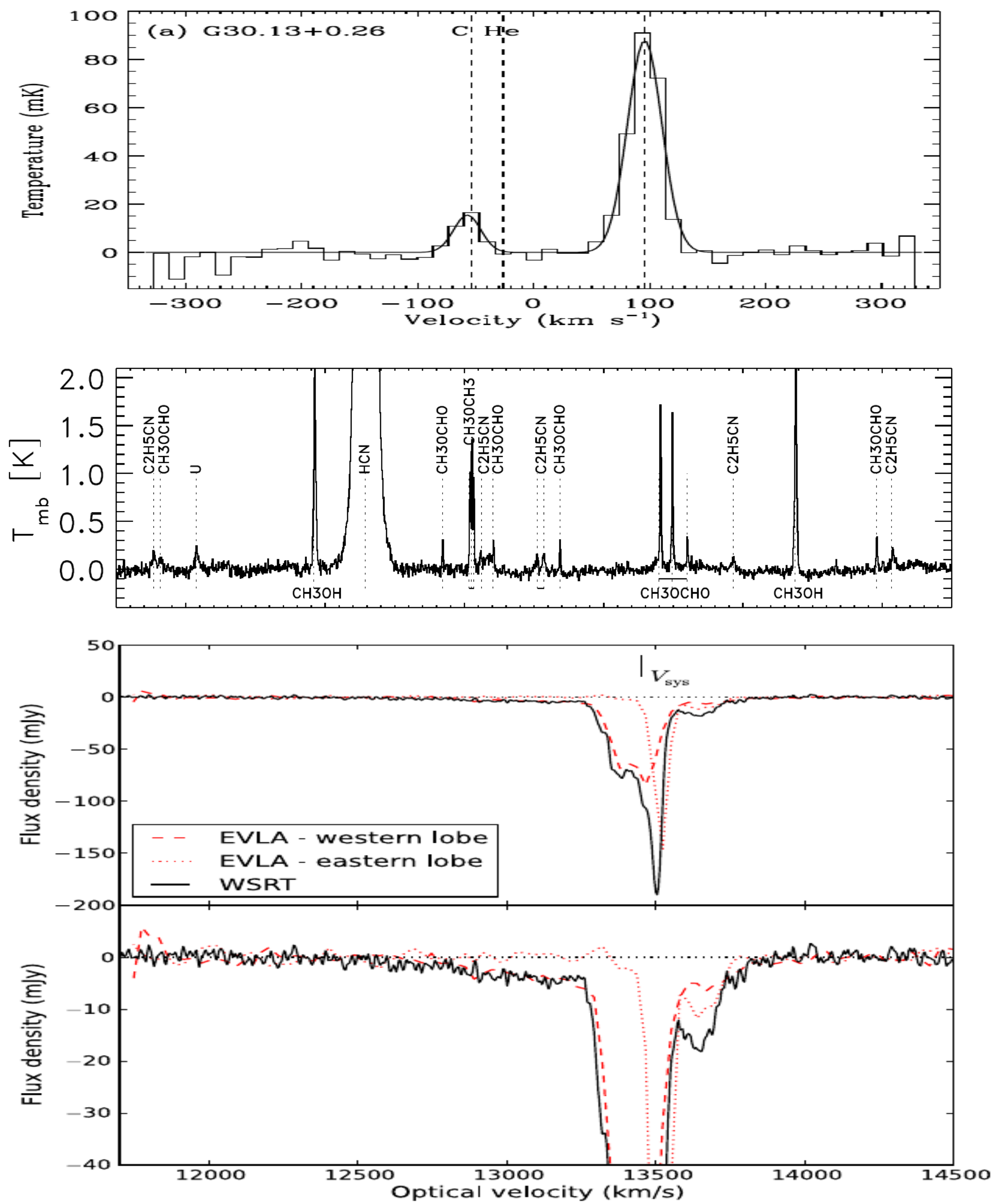
$$\int \varphi \, d\nu = 1$$

$$\varepsilon_\nu = \frac{h\nu_0}{4\pi} N_2 A_{21} \varphi(\nu)$$

$$\frac{N_2}{N_1} \underset{LTE}{=} \frac{g_2}{g_1} e^{-\frac{h\nu}{kT}}$$



Line emission mechanisms



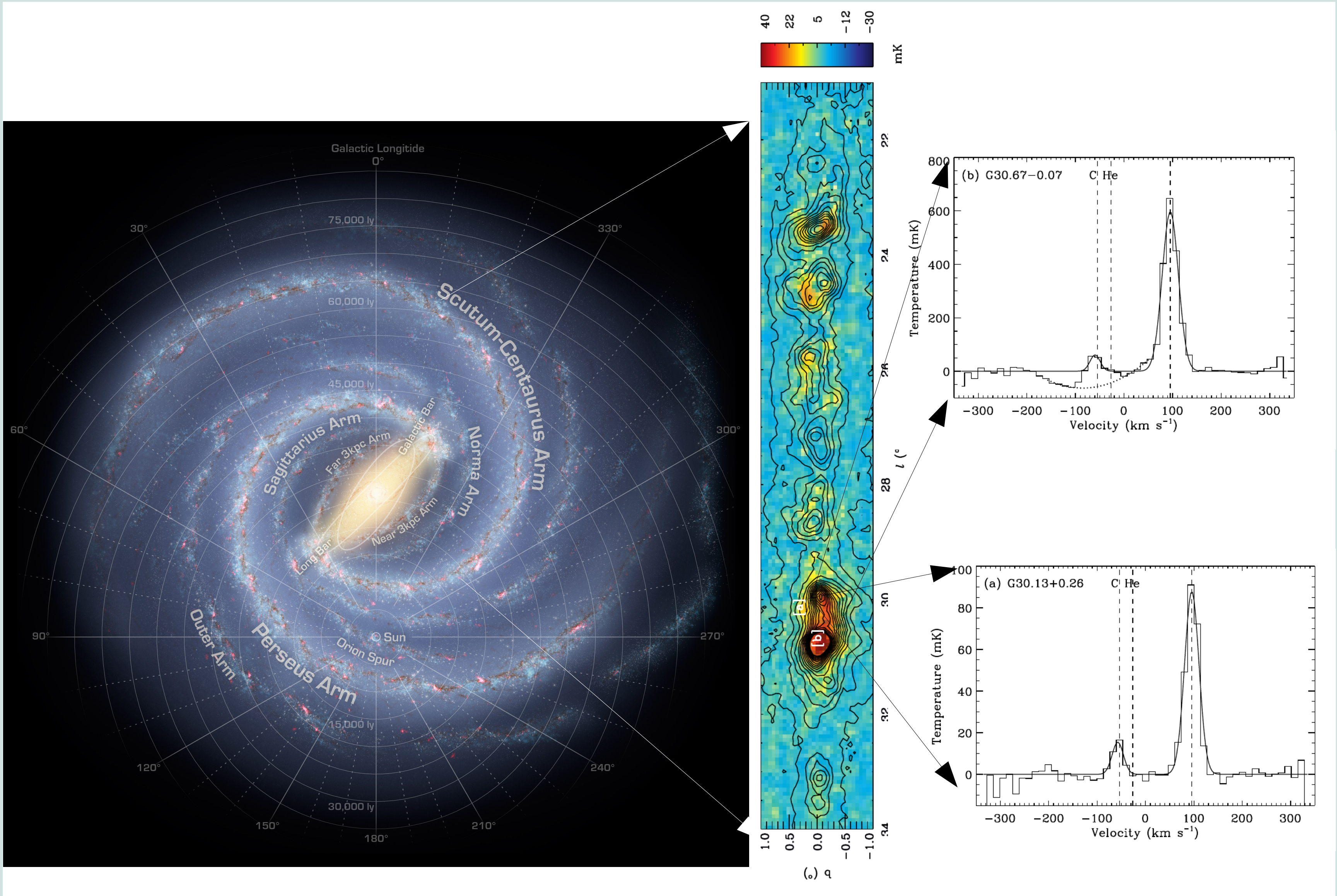
Recombination Lines

Molecular Lines

Hyperfine Lines

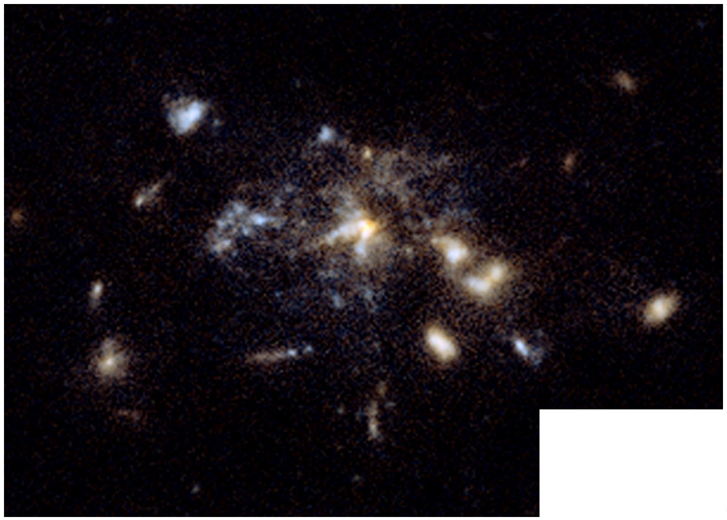
Radio recombination lines

- Capture of electrons and high-order transition
- Useful as temperature tracer

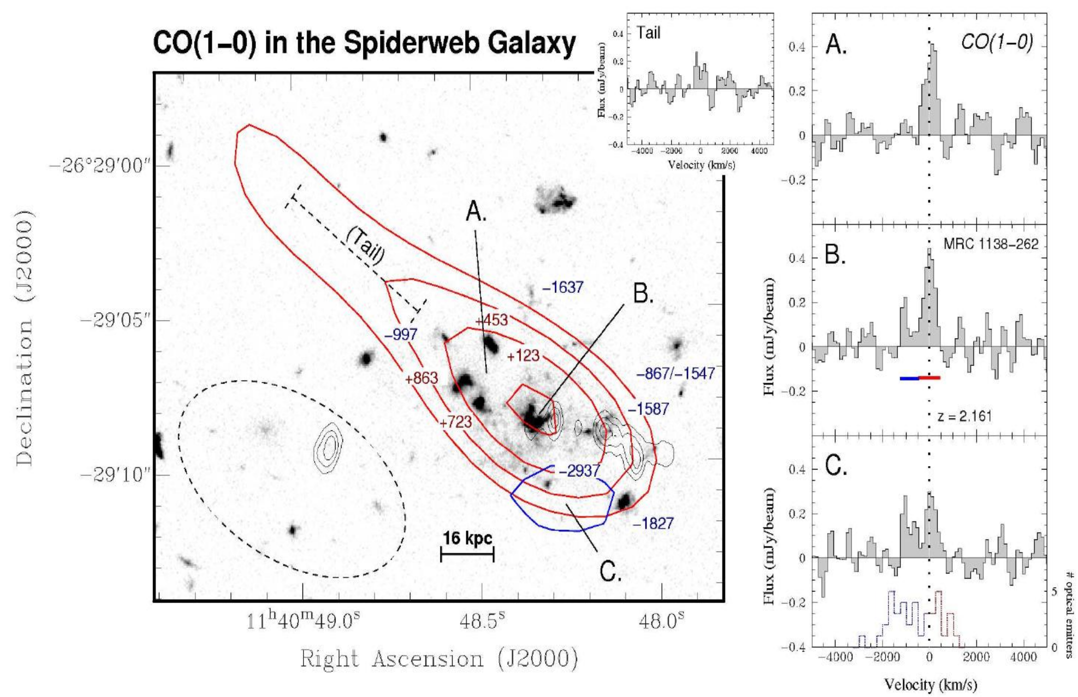


Molecular lines

- Rotational modes, maser
- Tracing different domains (optical depth), temperatures



Spiderweb Galaxy

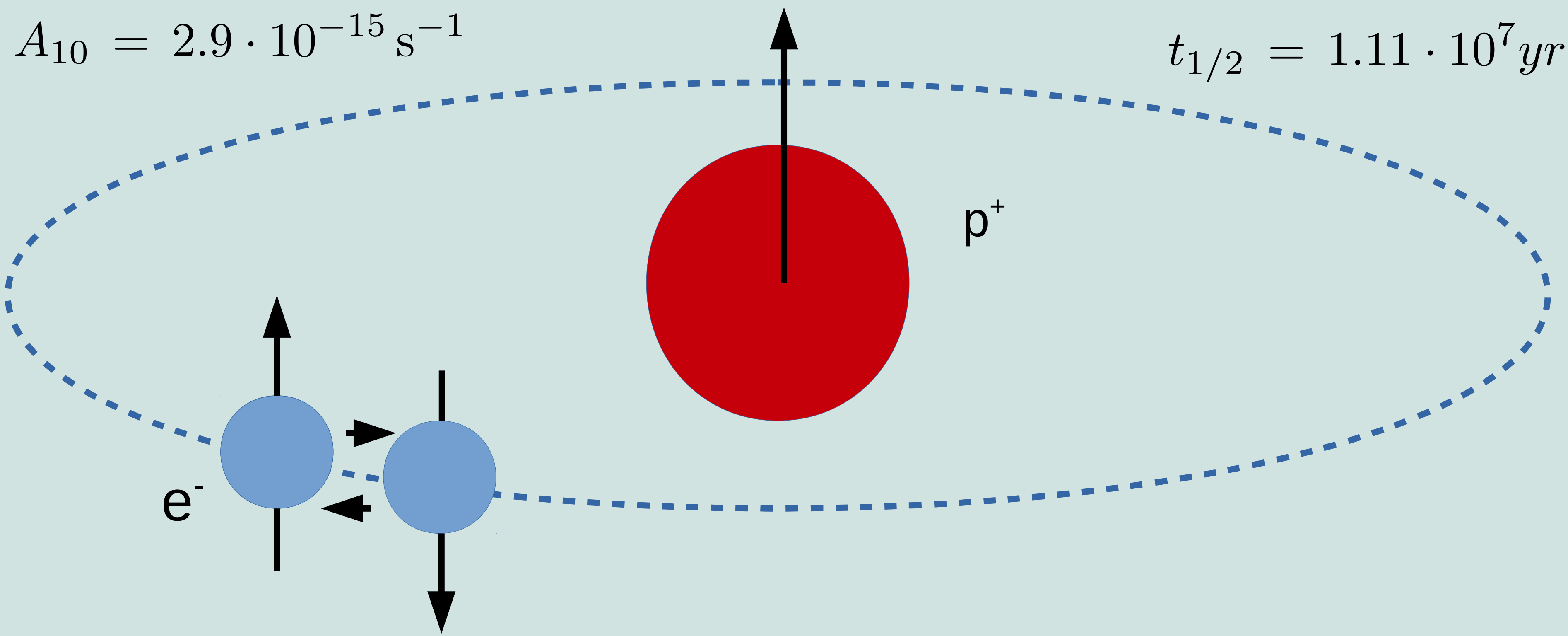


Neutral hydrogen (H I)

- Hyperfine transition (n = 1, l = 0, S = ½, J = ½, I = ½, F = 1 or F = 0
- 1420.405751786 MHz
- 21.1 cm

$$A_{10} = 2.9 \cdot 10^{-15}\,\mathrm{s}^{-1}$$

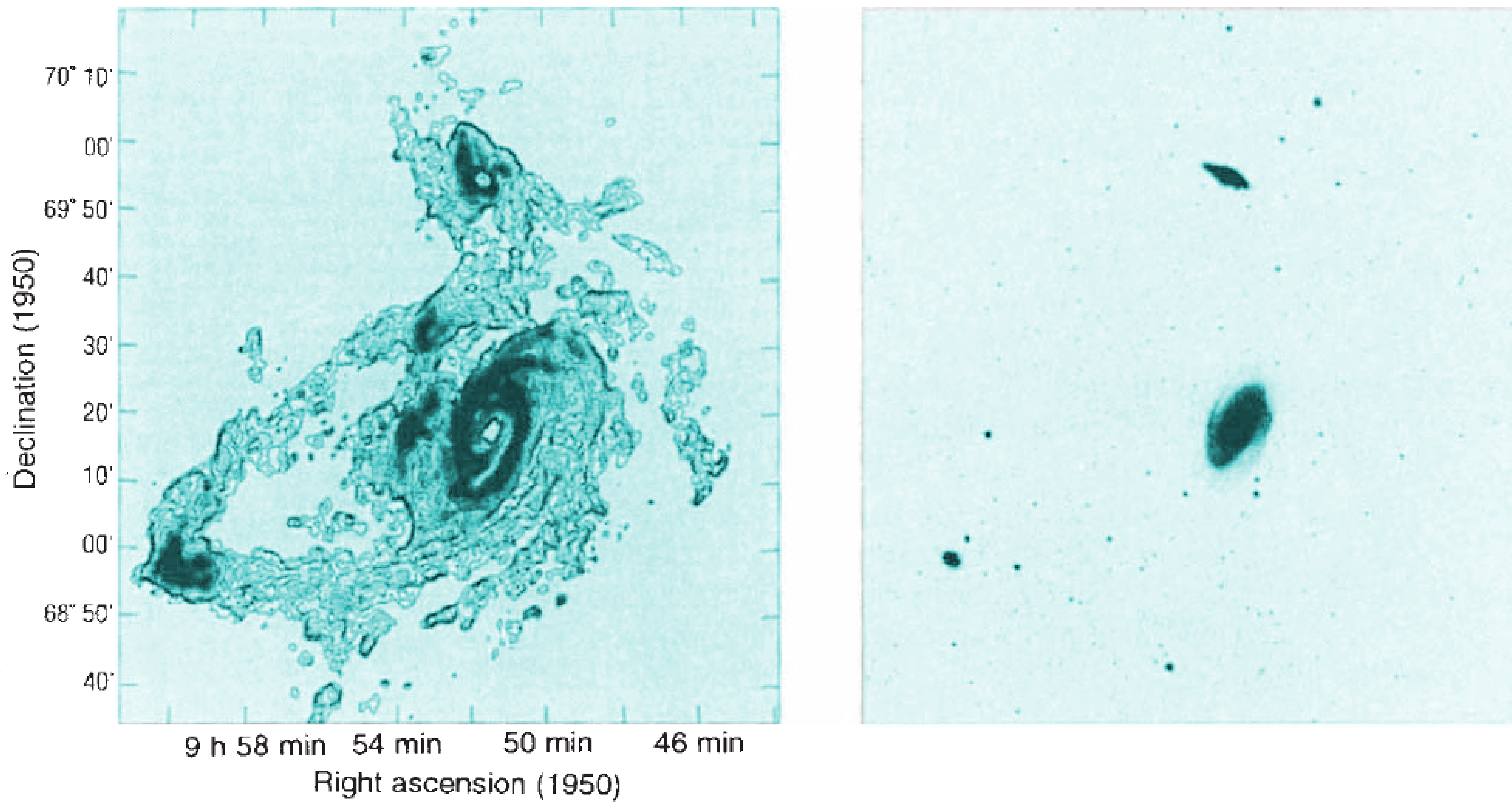
$$t_{1/2} = 1.11 \cdot 10^{7} yr$$



$$\frac{N_{\mathrm{H\,I}}}{\mathrm{atoms\,cm^{-2}}} \underset{LTE}{=} 1.823 \cdot 10^{18} \cdot \frac{T_{\mathrm{spin}}}{\mathrm{K}} \int \tau_{\nu}(V_{\mathrm{radio}}) \frac{dV_{\mathrm{radio}}}{\mathrm{km\,s^{-1}}}$$

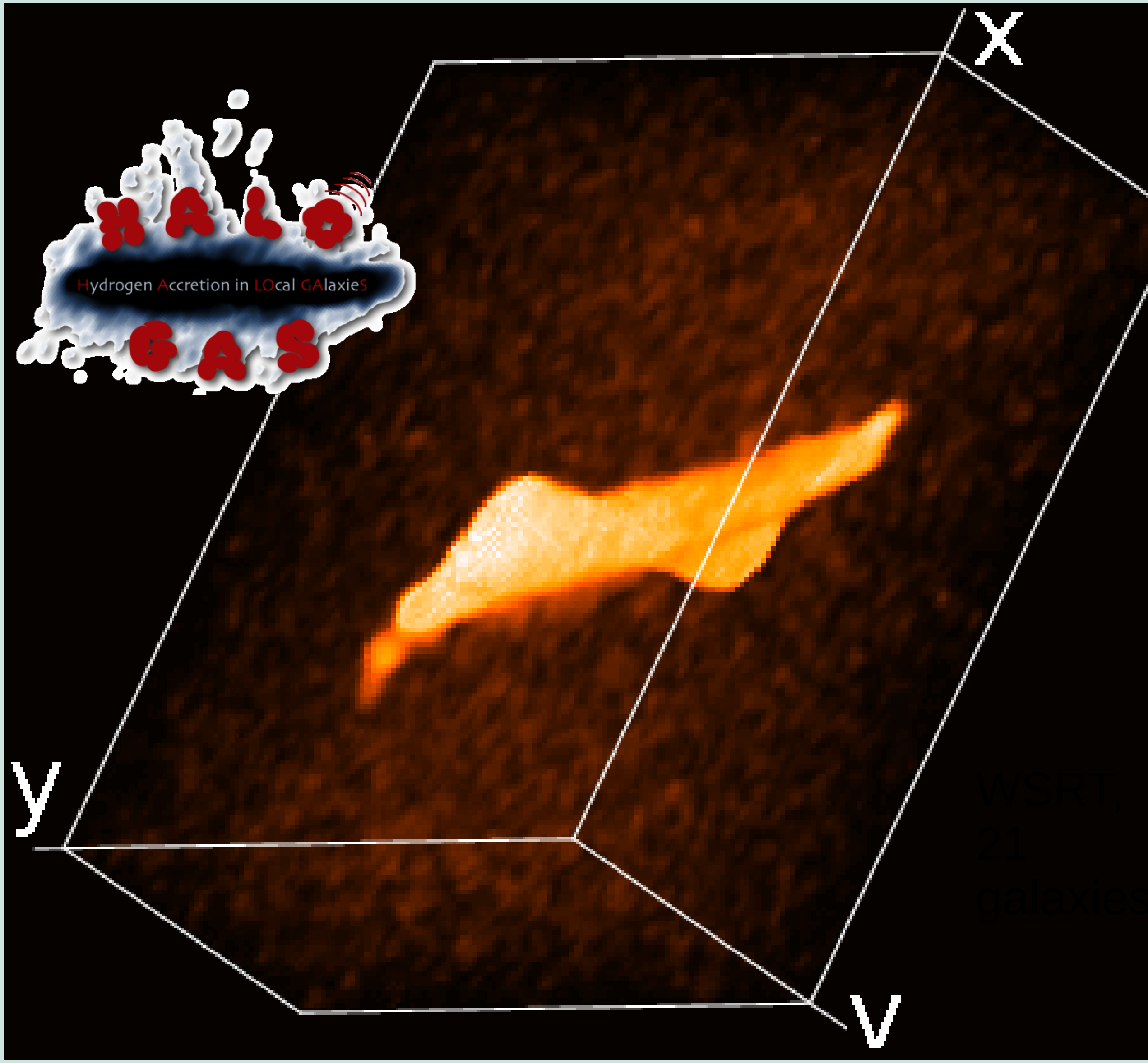
$$\frac{V_{\mathrm{radio}}(\nu)}{c} = \frac{\nu_0 - \nu}{\nu_0} \qquad \frac{N_{\mathrm{H\,I}}}{\mathrm{atoms\,cm^{-2}}} \underset{opt.thin}{=} 1.823 \cdot 10^{18} \int \frac{T_{\mathrm{b}}}{\mathrm{K}} \frac{dV_{\mathrm{radio}}}{\mathrm{km\,s^{-1}}}$$

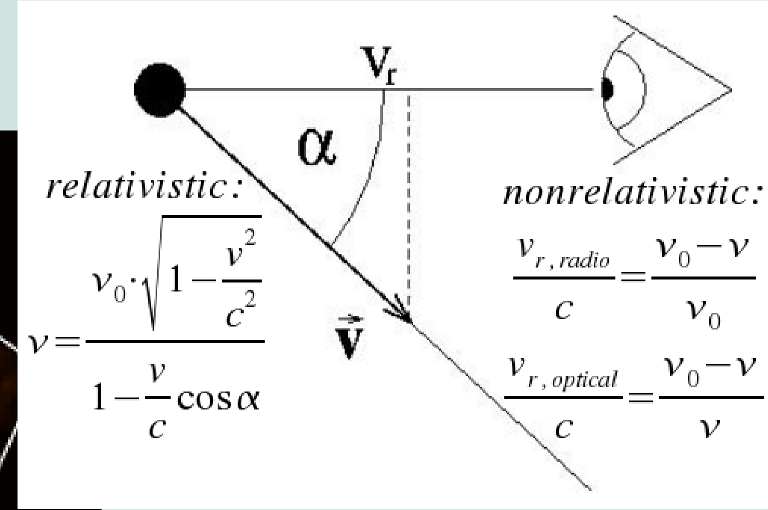
Neutral hydrogen (H I)

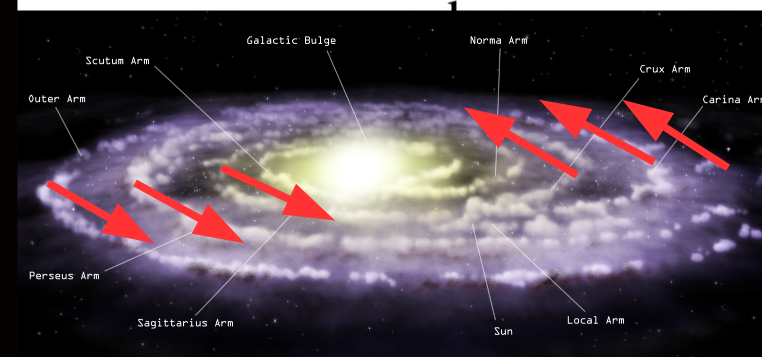


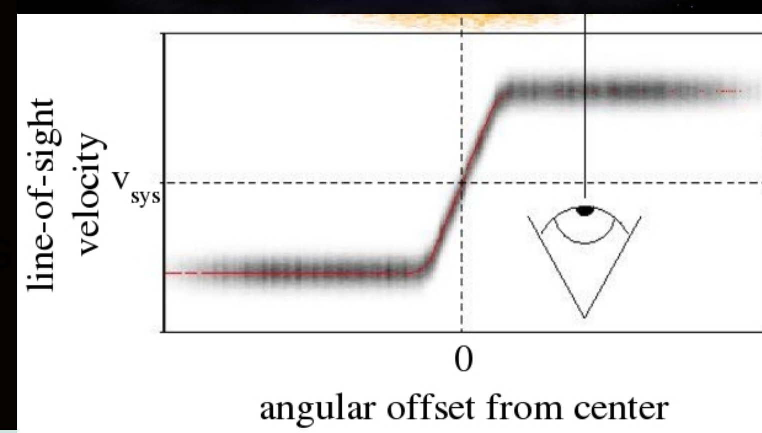
M81 system: Dr. Jekyll & Mr. Hyde

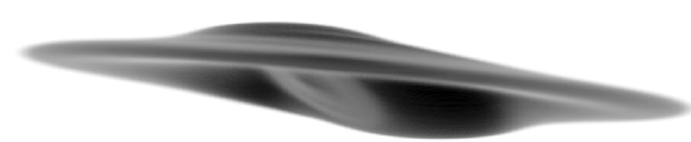
Neutral hydrogen: kinematics



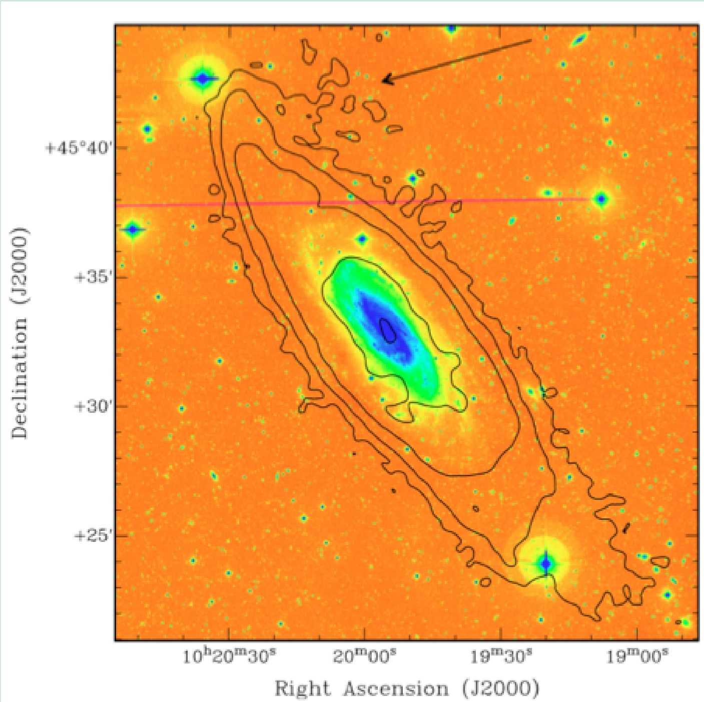




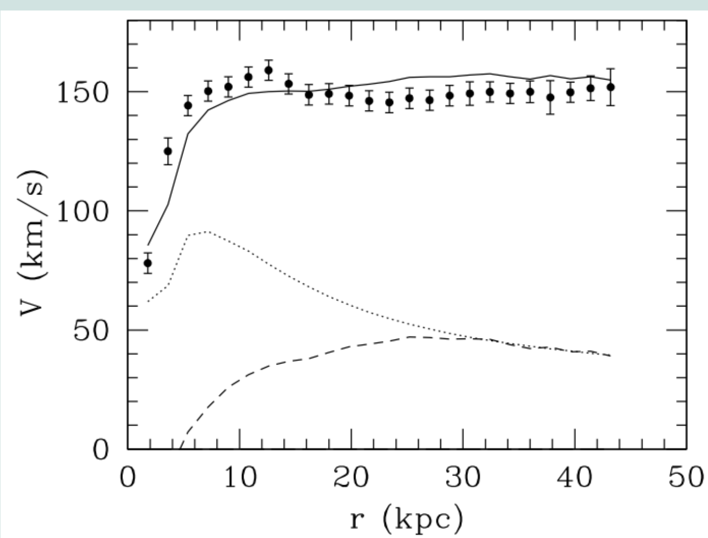




Neutral hydrogen: kinematics

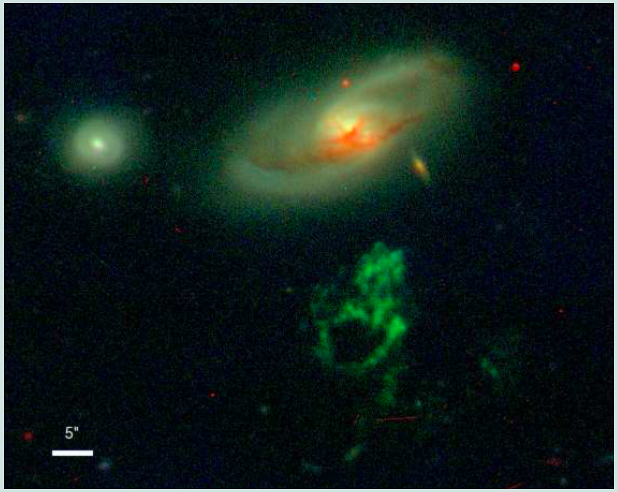


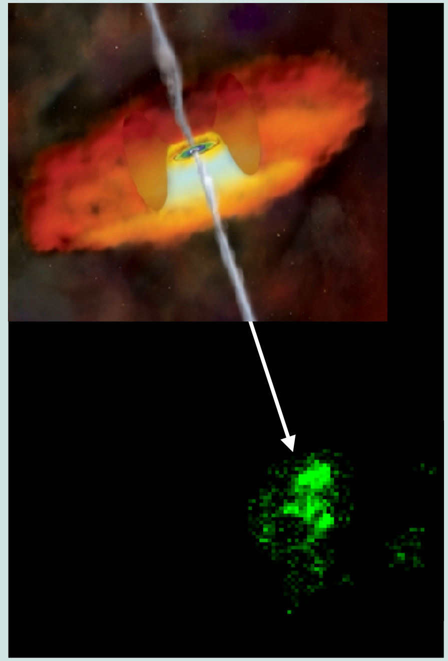
NGC 3198, Gentile et al. 2013

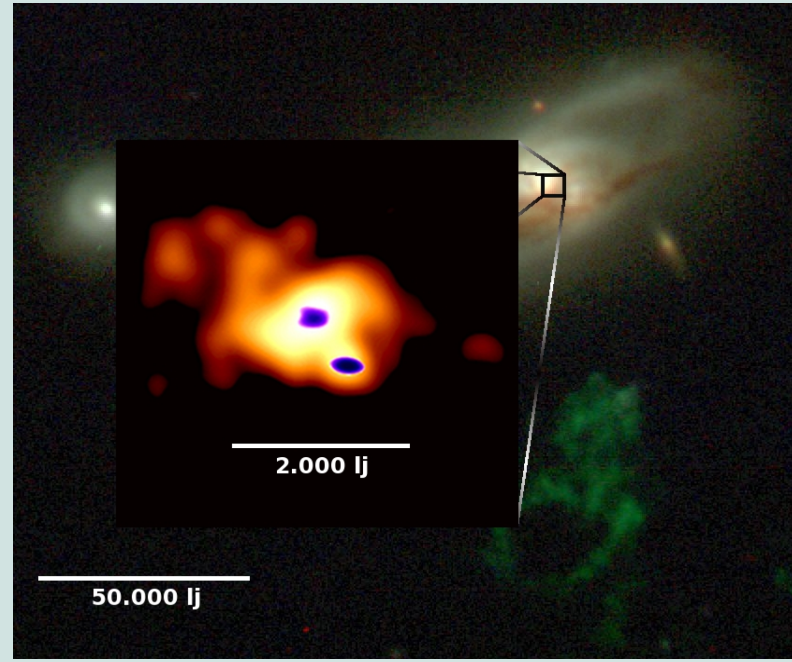


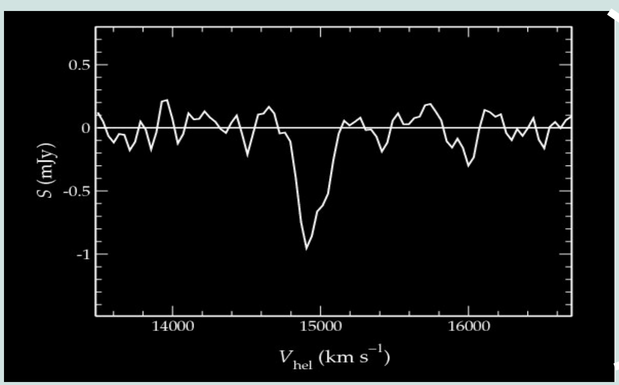
Tomography of NGC 5023
Kamphuis et al. 2013

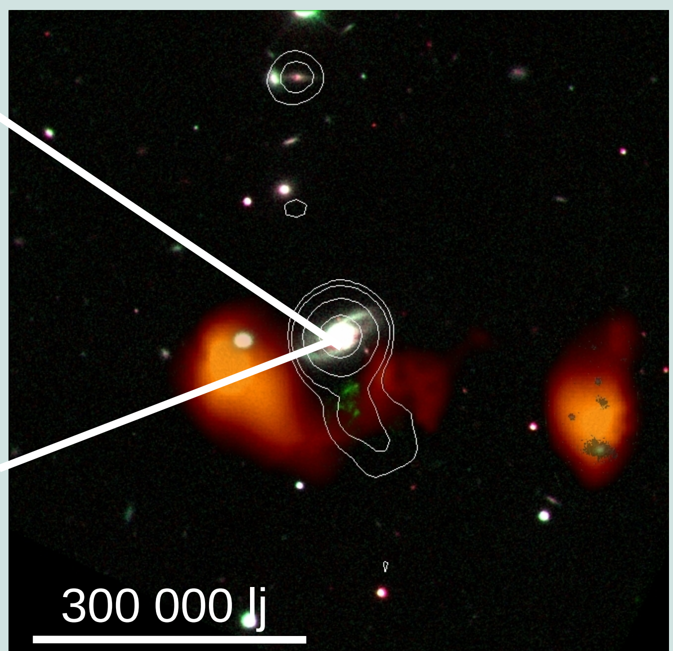
Combining observations

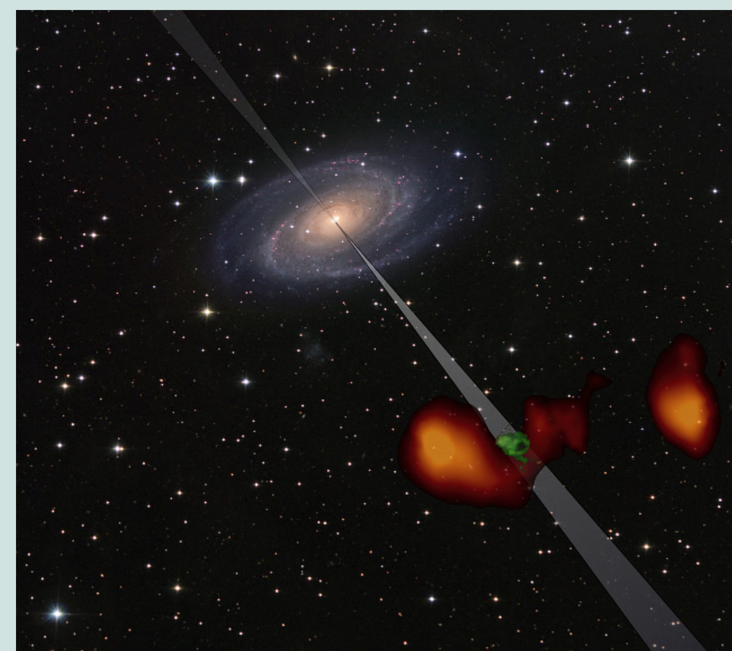












Take away message and literature

- Learn what intensity, flux density, brightness temperature are
- Contemplate how important radio astronomy (at high resolution) is for astronomy

Online course: Essential radioastronomy, James J. Condon and Scott M. Ransom, http://www.cv.nrao.edu/~sransom/web/xxx.html

Book: Tools of Radio Astronomy, 5th edition, by Thomas L. Wilson; Kristen Rohlfs and Susanne Hüttemeister. Moscow: Fizmatlit