Star formation

Tracers of molecular clouds and star formation

Diagnostics of molecular clouds and embedded star-formation

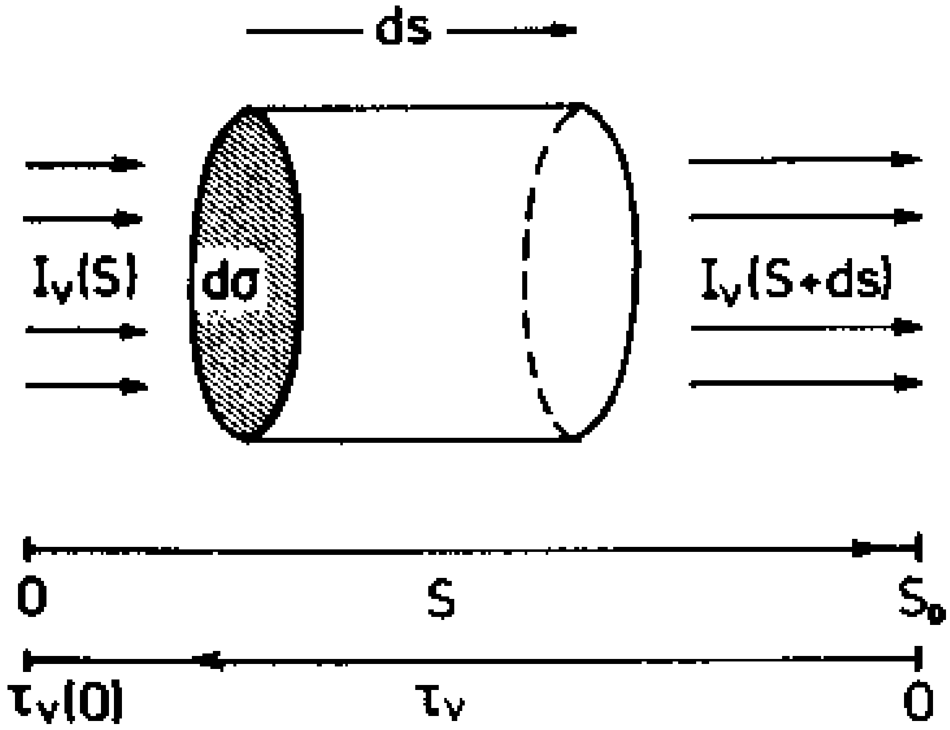
Radiation is the only way to get information about the universe

- Temperature
- Density
- Molecular abundances
- Spatial (3-D) structures
- Velocity fields
- Magnetic fields

Diagnostics of molecular clouds and embedded star-formation

- Continuum
  - Dust
  - Free-free
  - Synchrotron
- Line radiation
  - Molecular lines
  - Atomic (HI fine structure) or recombination lines
  - Masers
  - Zeeman effect

Radiative transfer

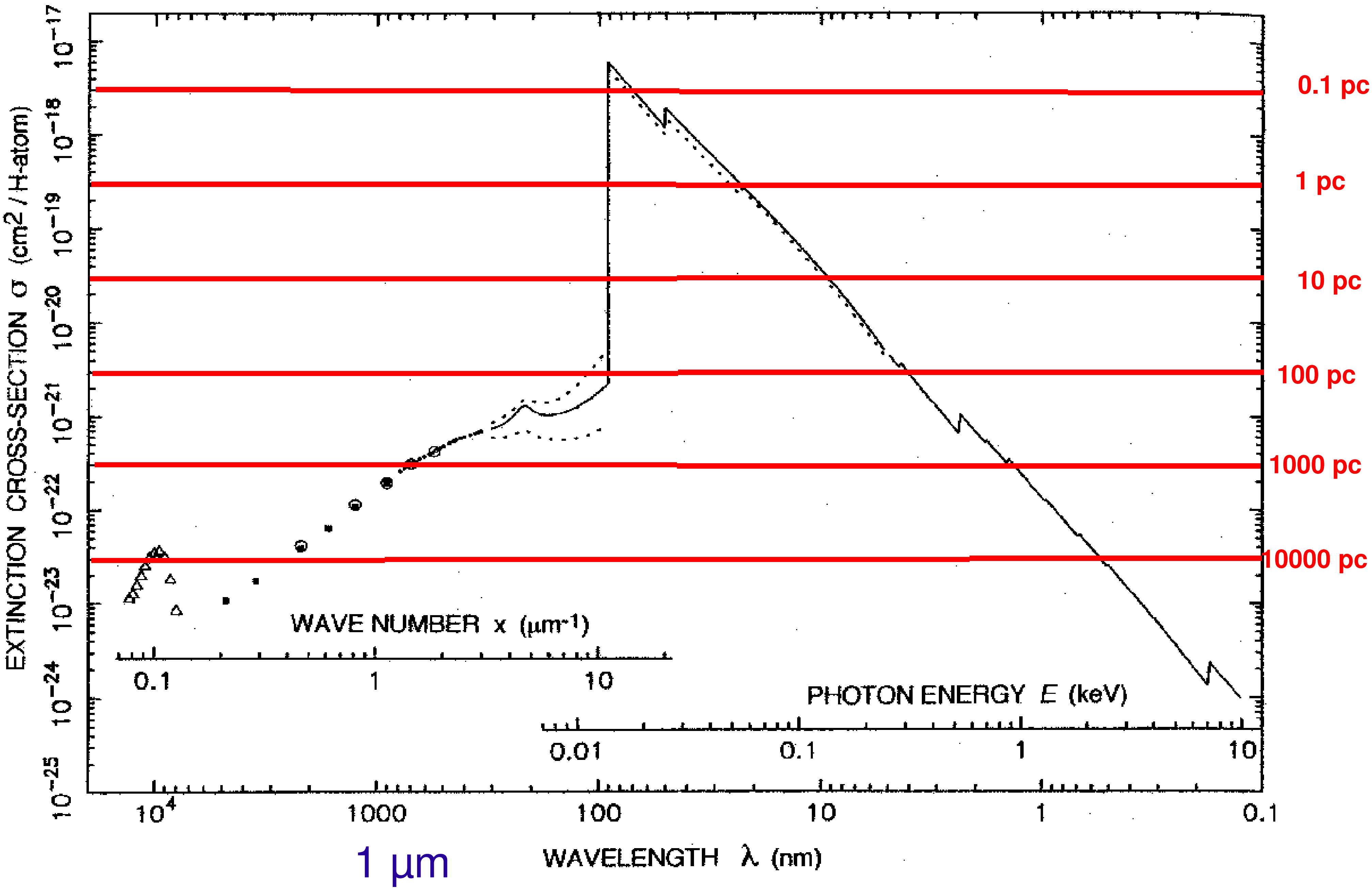


$$\frac{dI_\nu}{ds} = -\kappa_\nu I_\nu + \varepsilon_\nu$$

κ_ν: absorption coefficent

ε_ν: emission coefficent

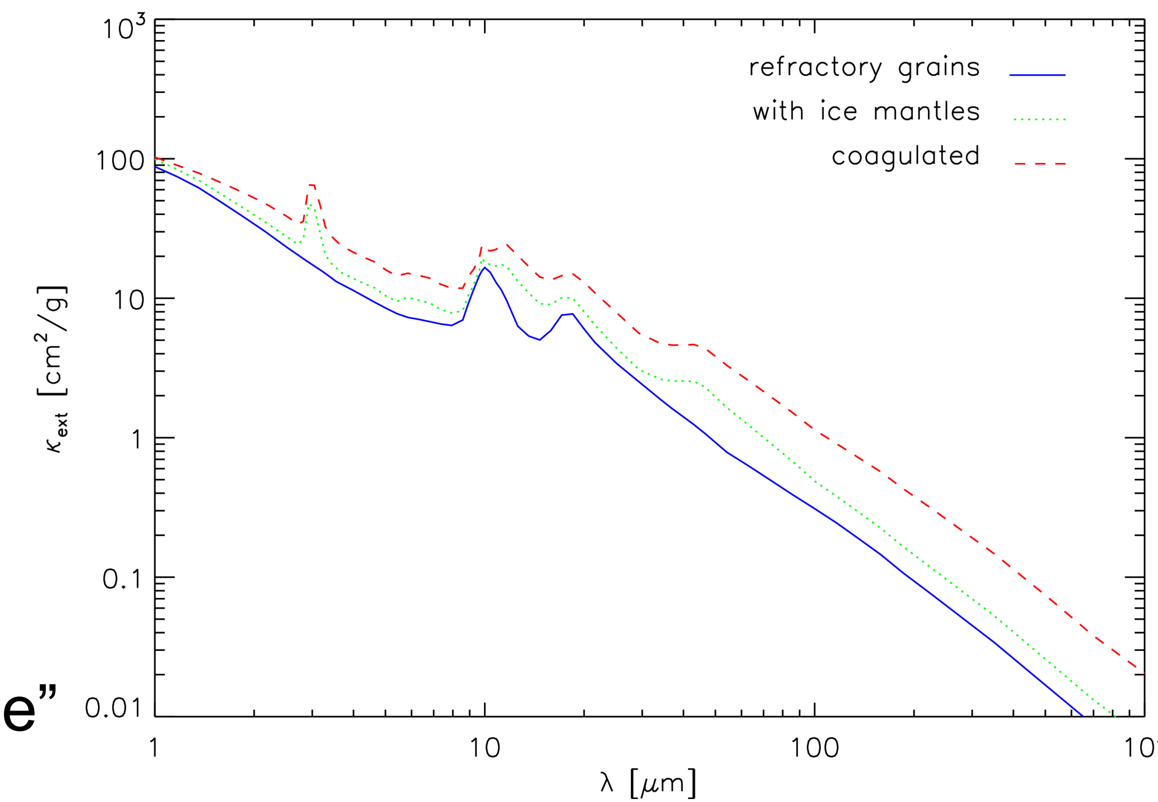
Galactic extinction



Dust extinction

- Dust mass absorption coefficient approximately:

$$\kappa = \kappa_0 \left(\frac{\nu}{230\,\mathrm{GHz}} \right)^{\beta} \mathrm{cm}^2\,\mathrm{g}^{-1} \qquad \beta \approx 2$$

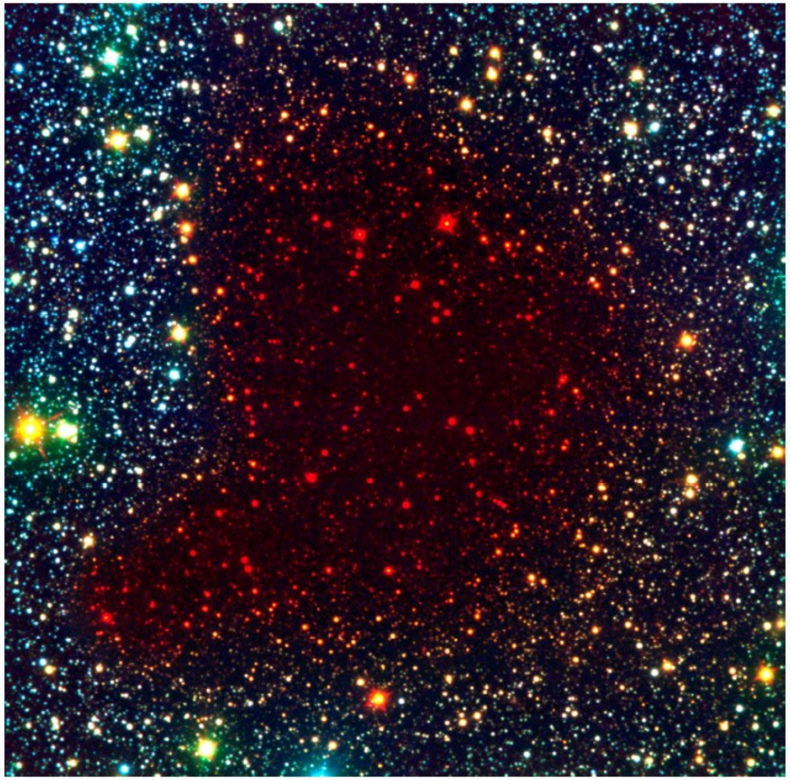


Ossenkopf & Henning (1994)

- Extinction decreasing towards IR and (sub)mm
- Cloud centers only “visible” at long wavelengths

Dust extinction

Optical



Infrared

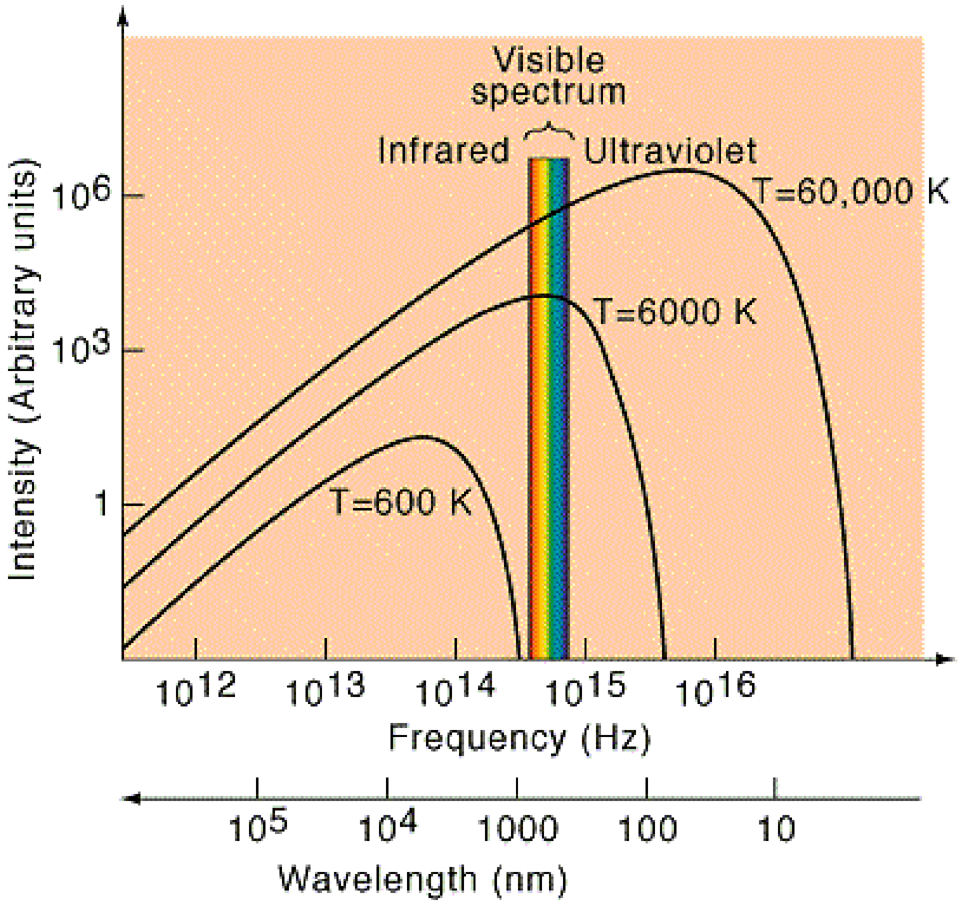
Alves et al. 2001

- Extinction measured through “reddening” assuming spectrum of background stars
- Quantified in terms of visual extinction A_V

Emission - black body radiation

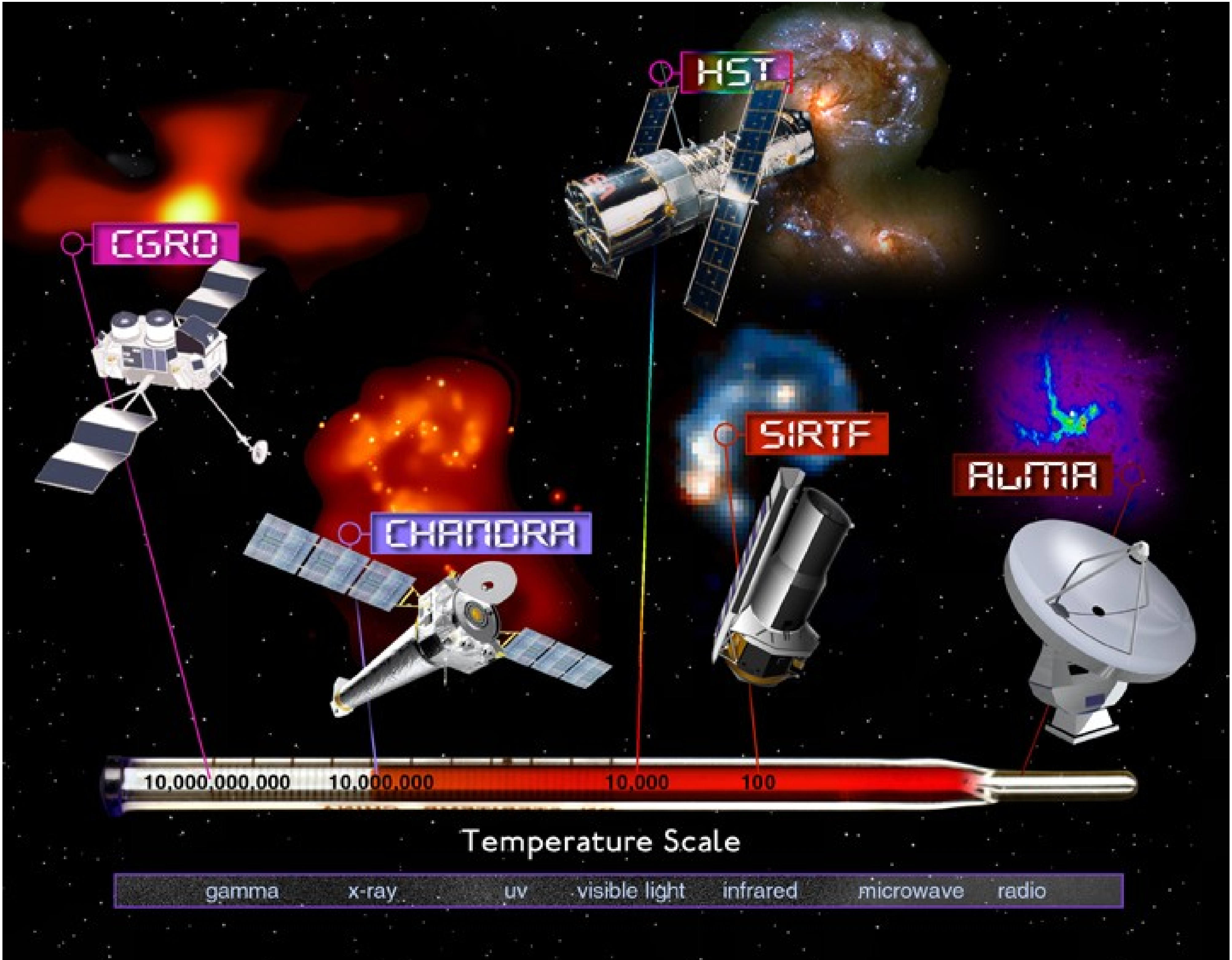
- Planck radiation law:

$$B_\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$$



Temperature-wavelength-relation (Wien's law):

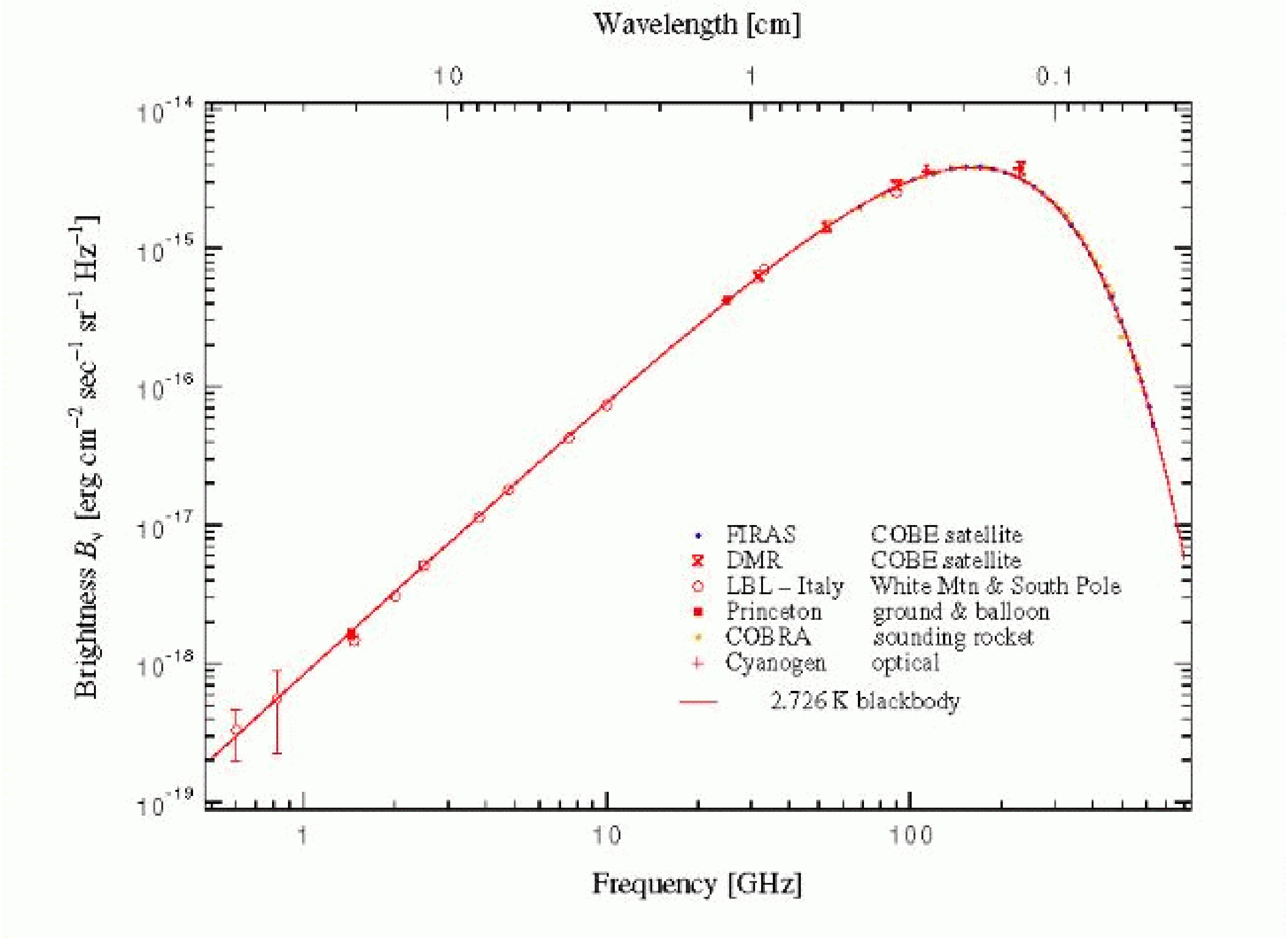
$$\lambda_{\mathrm{max}} T = 3\mathrm{mm\ K}$$


HST
CGRO
SIRTF
ALMA
CHANDRA
10,000,000,000
10,000,000
10,000
100
Temperature Scale
gamma
x-ray
uv
visible light
infrared
microwave
radio

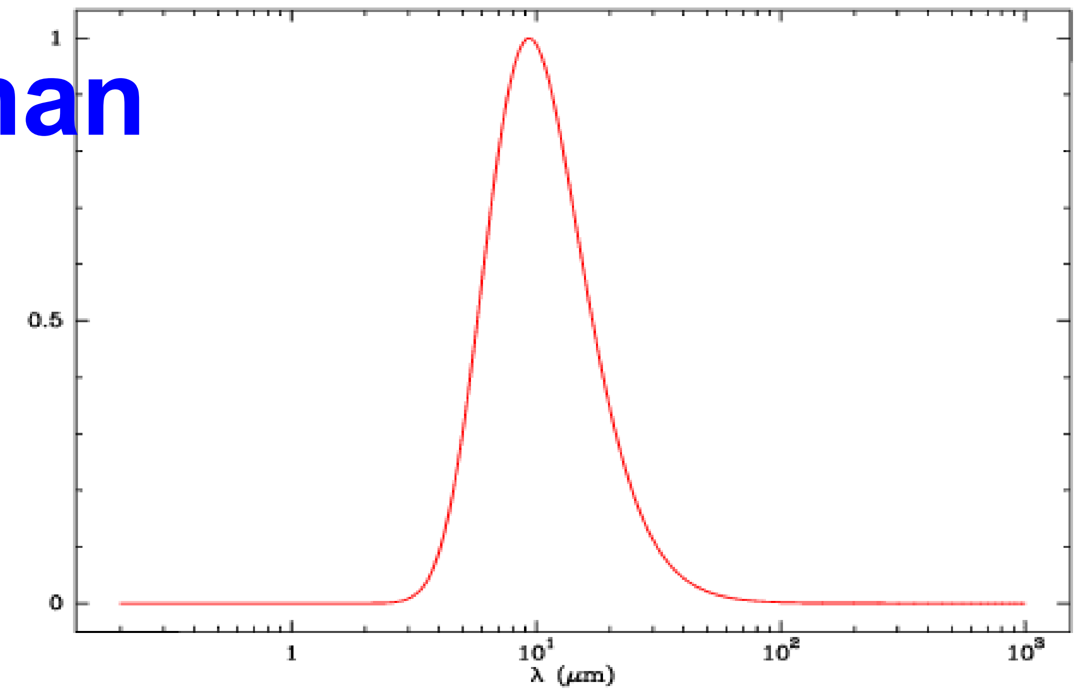
Example: Comsic microwave back-ground

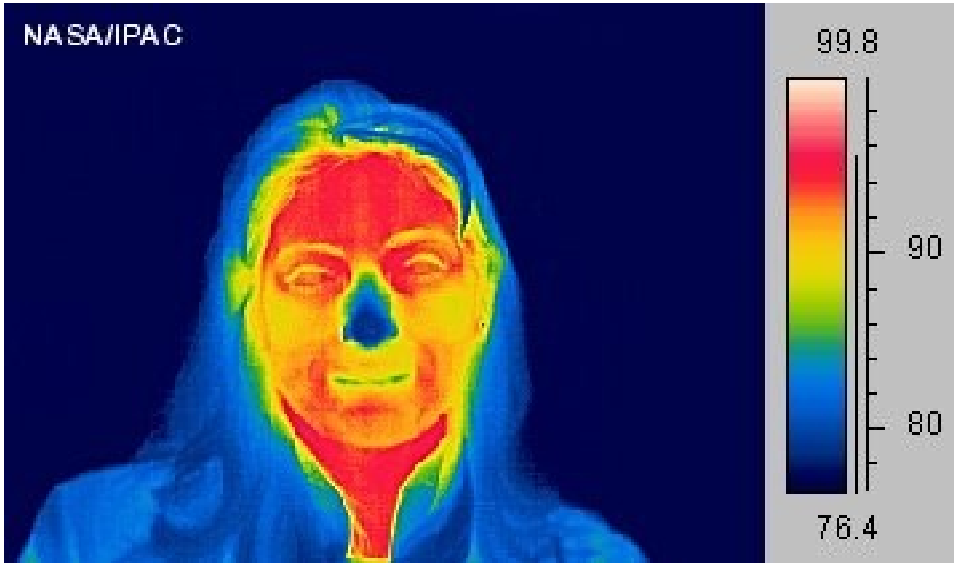
- Best known blackbody

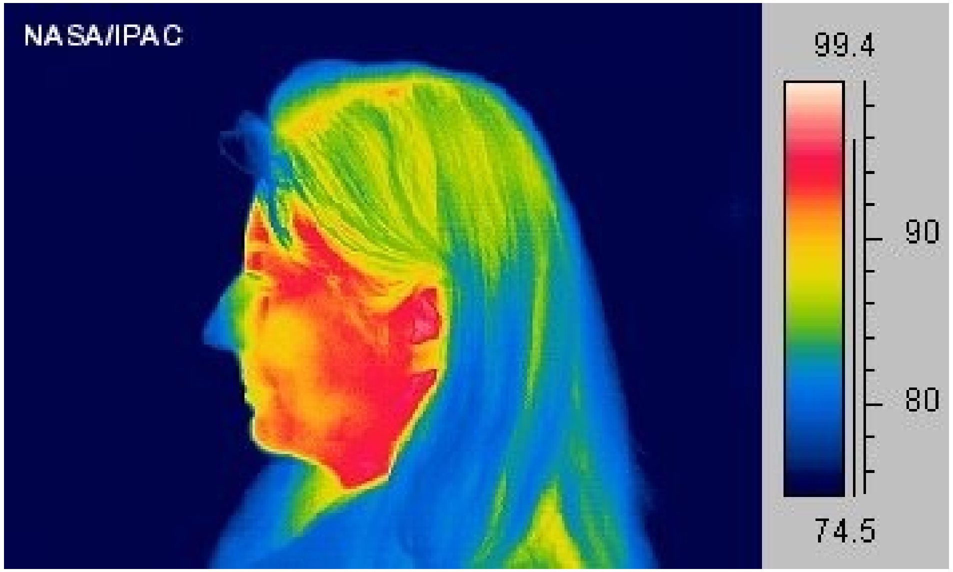
$$T = 2.73\,K \quad \Longrightarrow \lambda_{\rm max} = 1{\rm mm} \Longrightarrow \nu = 200{\rm GHz}$$



Spectrum of human







Rayleigh-Jeans approximation

For $h\nu \ll kT$ $\left(\frac{\nu}{\mathrm{GHz}} \ll 21\frac{T}{\mathrm{K}}\right)$

$\rightarrow$ $B_{\mathrm{RJ}} = \frac{2\nu^2}{c^2}kT$

Inverse relation: Definition of radio-astronomical brightness temperature

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

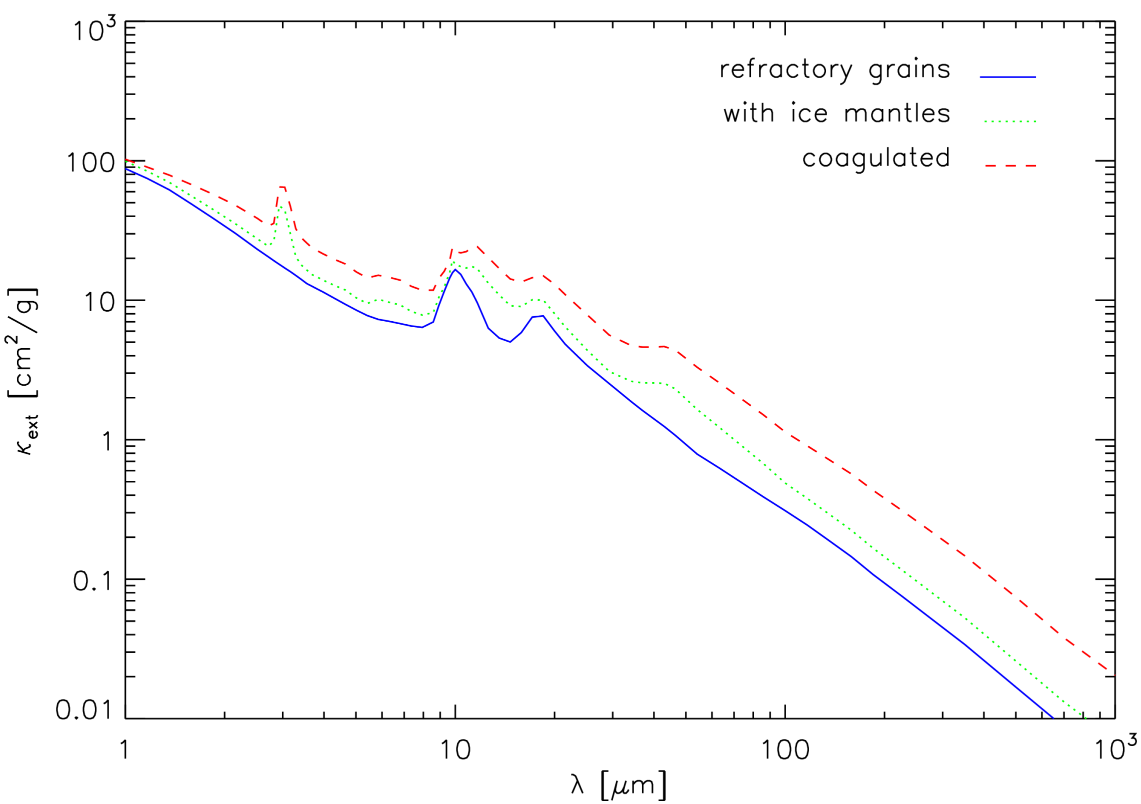
- Line intensities are expressed in Kelvin
- Tr = Tkin for optically thick media and $h\nu \ll kT$

Dust radiation

- Not blackbody but
  - Dust mass absorption coefficient approximately:

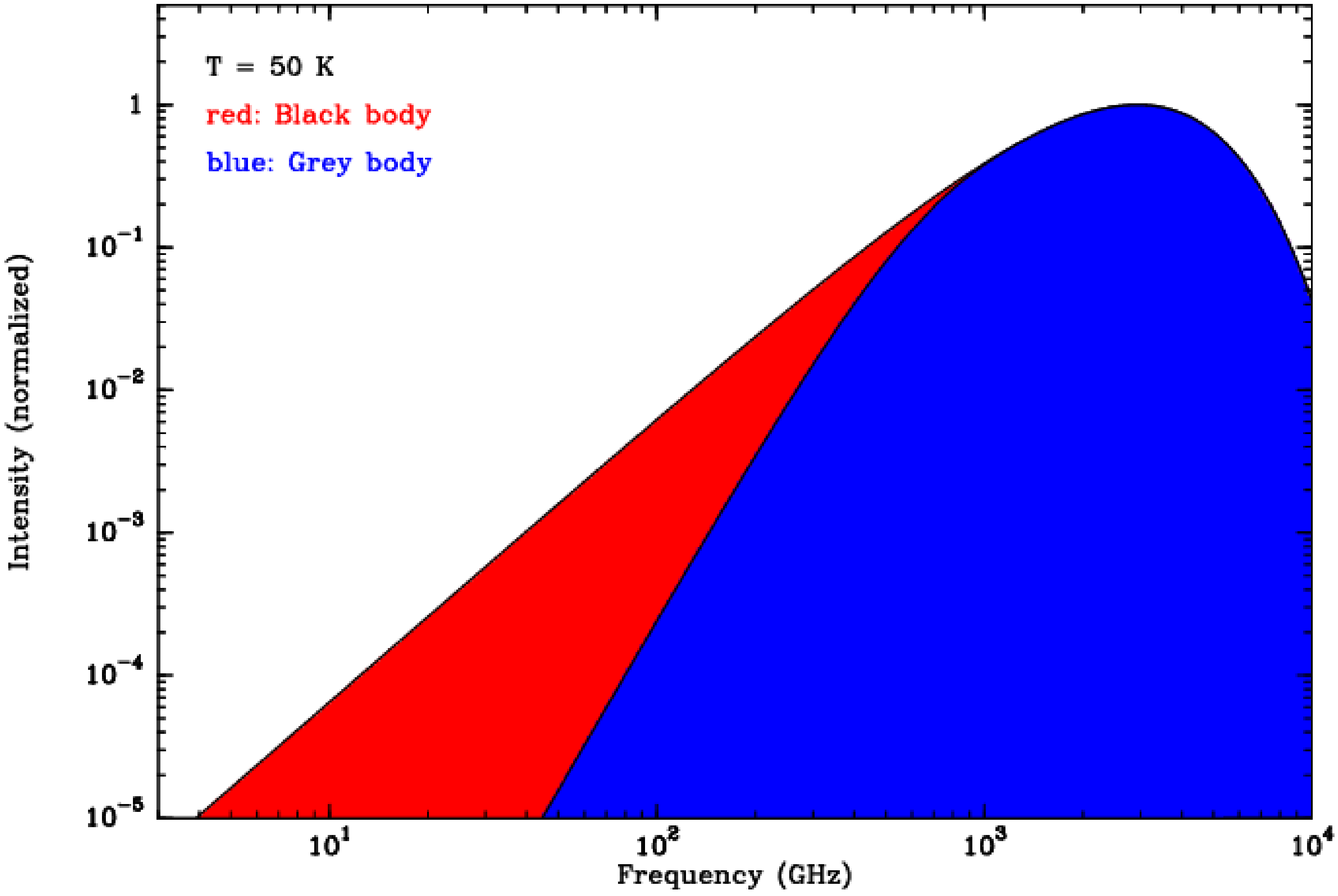
$$\kappa = \kappa_0 \left(\frac{\nu}{230\,\mathrm{GHz}} \right)^{\beta} \mathrm{cm}^2\,\mathrm{g}^{-1}$$

    - κ_0 is typically 0.4 $cm^2\ g^{-1}$, varies
      - Grain size
      - Grain properties (fluffy, ice mantle)
    - β around 2 in the ISM, lower (1-2) in disks
  - Additional spectral features
  - Low emission/extinction in FIR/mm



Ossenkopf & Henning (1994)

Dust radiation



Dust radiation

- Dust opacity

$$\tau_{\text{dust}} = \kappa_{\text{dust}} \frac{M_{\text{dust}}}{M_{\text{gas}}} M(\text{H}_2) N(\text{H}_2)$$
$$= 3.3 \times 10^{-26} \kappa_{\text{dust}} N(\text{H}_2)$$

- Used for determination of
  - Gas column densities
  - Gas masses

- Radiation determined by thermal equilibrium:

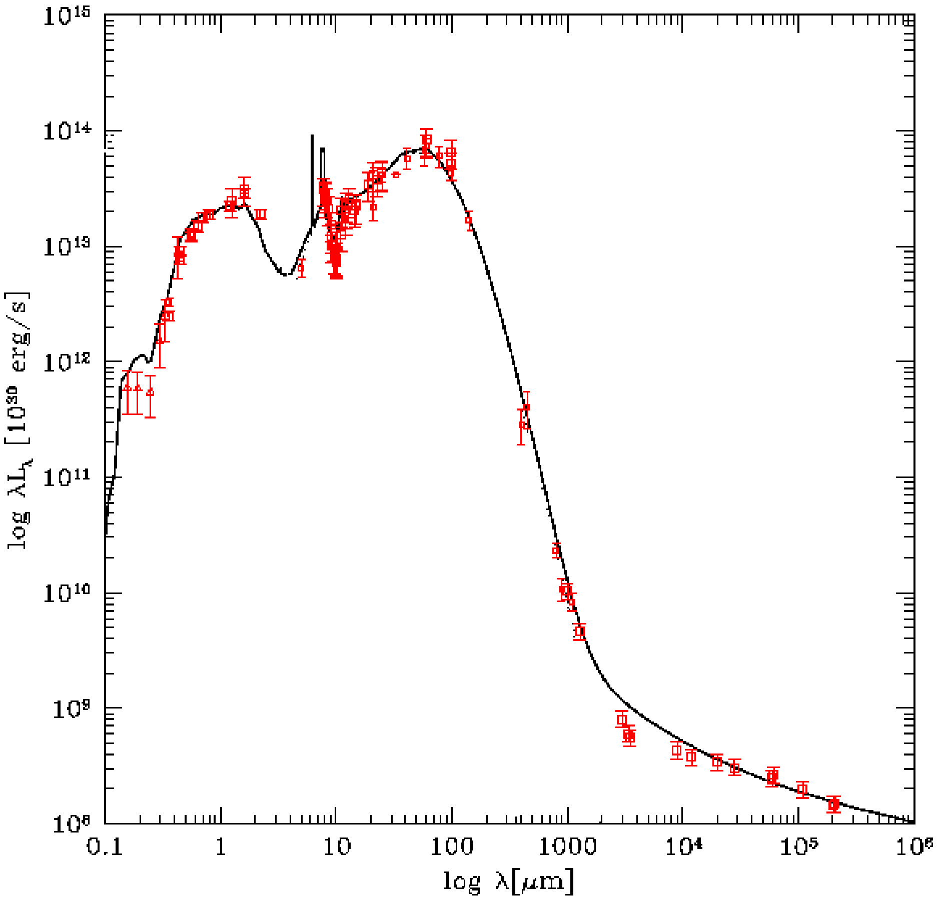
$$\int_0^\infty \kappa_{\text{ext}}(\nu) J_\star(\nu) d\nu = \int_0^\infty \kappa_{\text{ext}}(\nu) B_\nu(T_{\text{dust}}) d\nu$$

- Solution: $T_{\text{dust}} \sim 10 \ldots 30$ K (Radiation maximum around 100µm)

Dust radiation

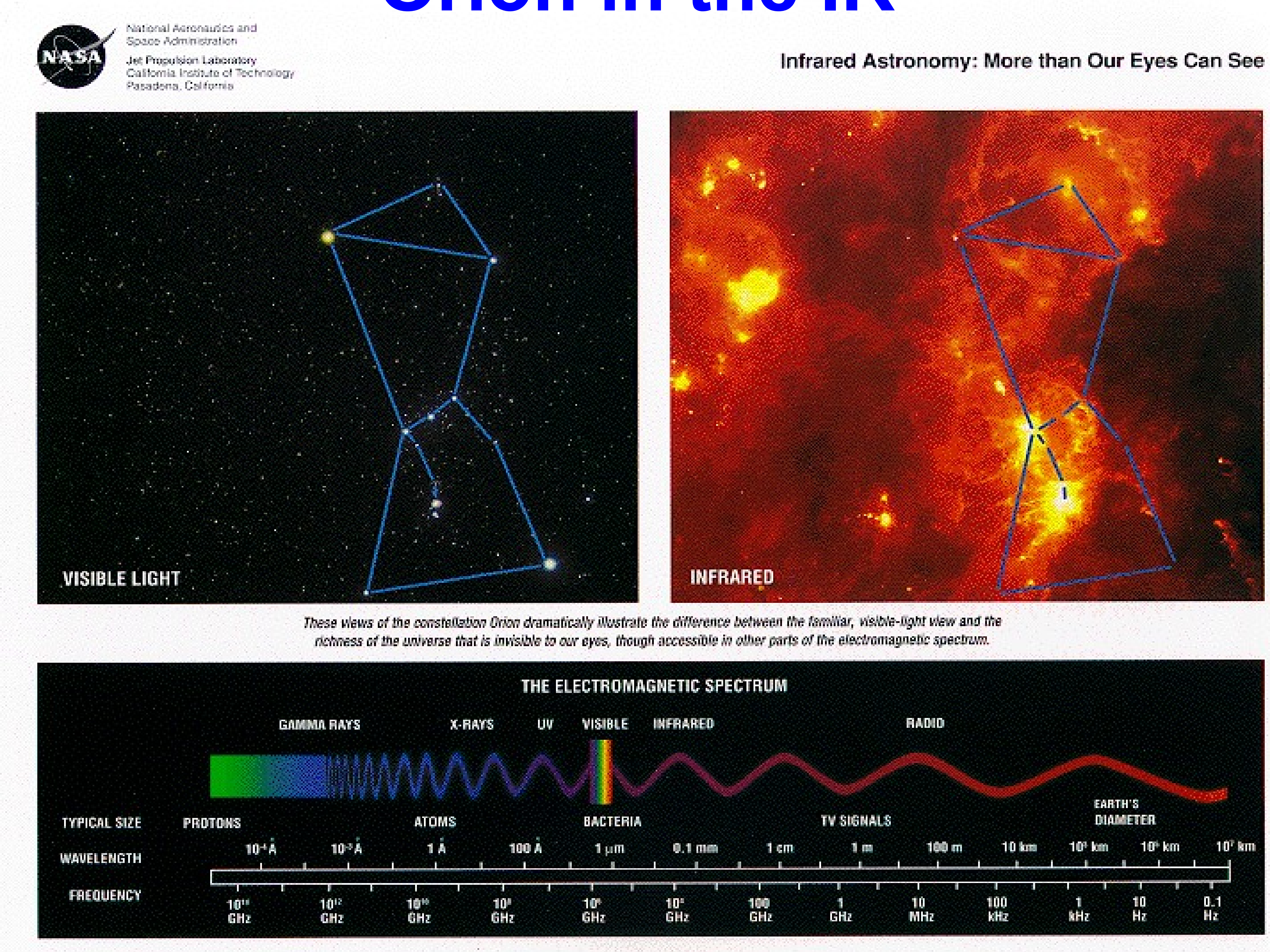
- Dust radiation measures SF activity
  - Young stars still embedded in parental clouds
  - Radiation from young stars absorbed in surrounding dust
  - Heated dust re-radiates in FIR/sub-mm

- **More than 50% of all electro-magnetic radiation that we observe is emitted in the infrared**



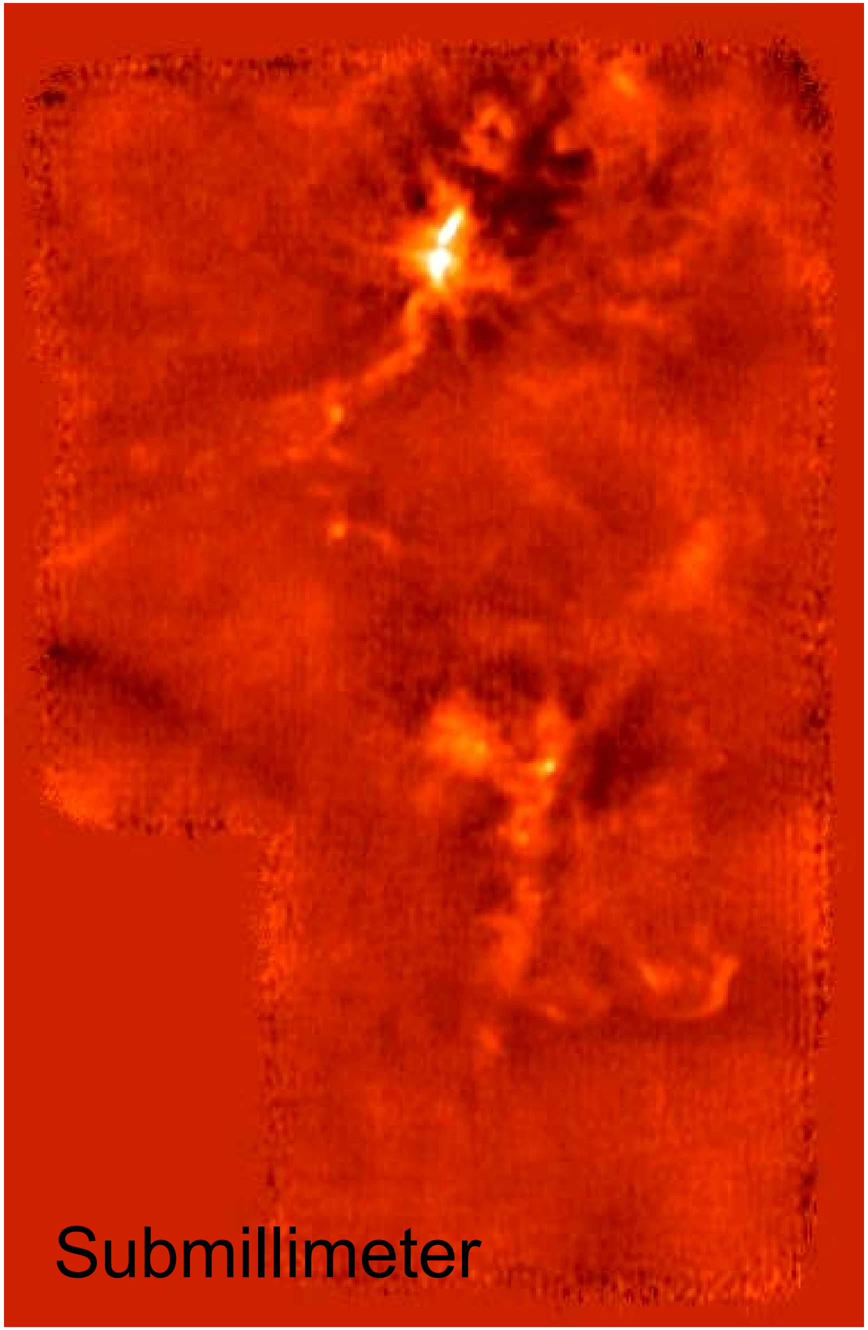
M82 spectrum (Grantano et al. 1997)

Orion in the IR



These views of the constellation Orion dramatically illustrate the difference between the familiar, visible-light view and the richness of the universe that is invisible to our eyes, though accessible in other parts of the electromagnetic spectrum.

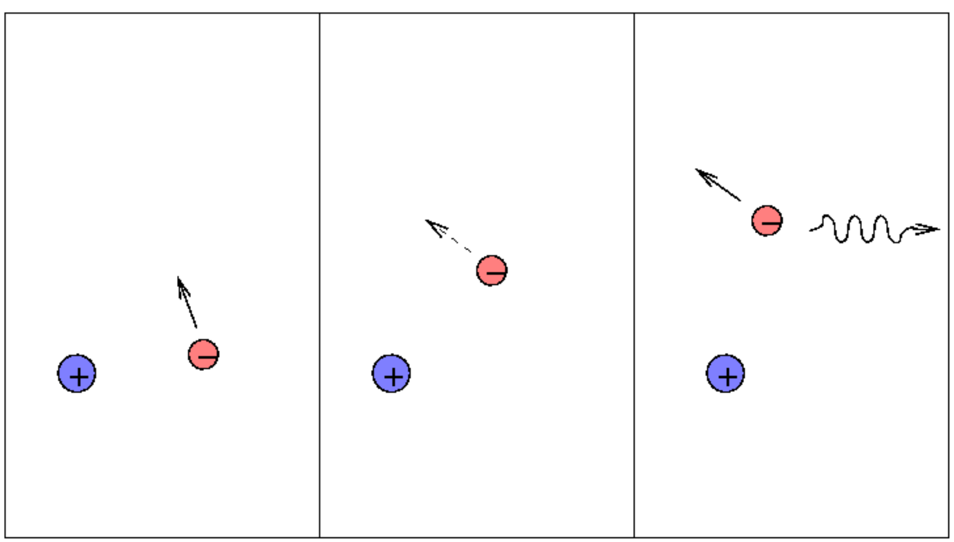
Dust Emission vs. Starlight

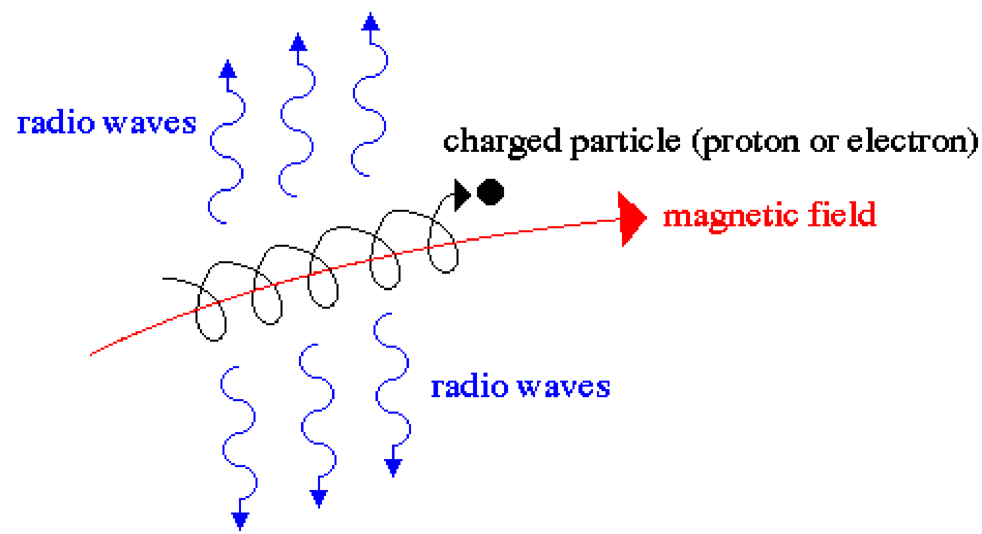


Continuum from ionized gas

Ionized gas: no discrete transitions, but radio continuum of bremsstrahlung

Radiation of accelerated charges



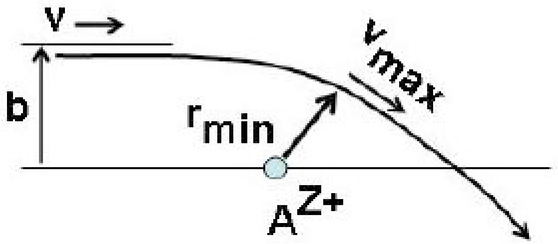


free-free emission

synchrotron radiation

Free-free emission

- Simple model for electron-ion collisions, dominated by Coulomb interaction
  - De-excitation occurs when distance of closest approach is of order of the Bohr radius a_0=5.29x10^{-9} cm



$$r_{\rm min} \leq W\, a_0 = W \frac{\hbar^2}{me^2} \quad \text{with}\, W \approx 1$$

  - Use conservation of energy and angular momentum to relate $r_{\rm min}$ to impact parameter b

$$\frac{1}{2} m v_{\rm max}^2 = \frac{1}{2} m v^2 + \frac{Ze^2}{r_{\rm min}}$$

$$r_{\rm min} v_{\rm max} = bv$$

Free-free emission

- This gives:

$$\sigma_{ul}(v) = \pi\, b_{\rm crit}^2 = \pi W^2 a_0^2 \left(1 + \underbrace{\frac{Ze^2/r_{\rm min}}{\frac{1}{2}mv^2}}_{\text{Coulomb focussing}}\right)$$

Coulomb focussing

- Average of cross section over Maxwellian distribution gives rate coefficient

$$q = \int_0^\infty v\,\sigma(v)\,f(v)\,dv$$

with

$$f(v) = \frac{4}{\sqrt{\pi}}\left(\frac{m}{2kT}\right)^{3/2} u^2 e^{\frac{-mv^2}{2kT}}$$

Free-free emission

- Radiation from individual collision:

$$\vec{E}(\theta) = \frac{1}{4\pi\epsilon_0} \frac{e\dot{\vec{v}}(t)}{c^2} \frac{\sin\theta}{r} \exp\left(-i\left[\omega t - 2\pi r/\lambda\right]\right)$$

- Integrate over
  - Maxwellian distribution of velocities
  - 4π emission angles Θ
  - Impact parameters from 0 → ∞
- Express emission by optical depth and BB radiation:
  - $\varepsilon_\nu = \kappa_\nu B(T_e)$, $\tau_\nu = \kappa_\nu \times s$

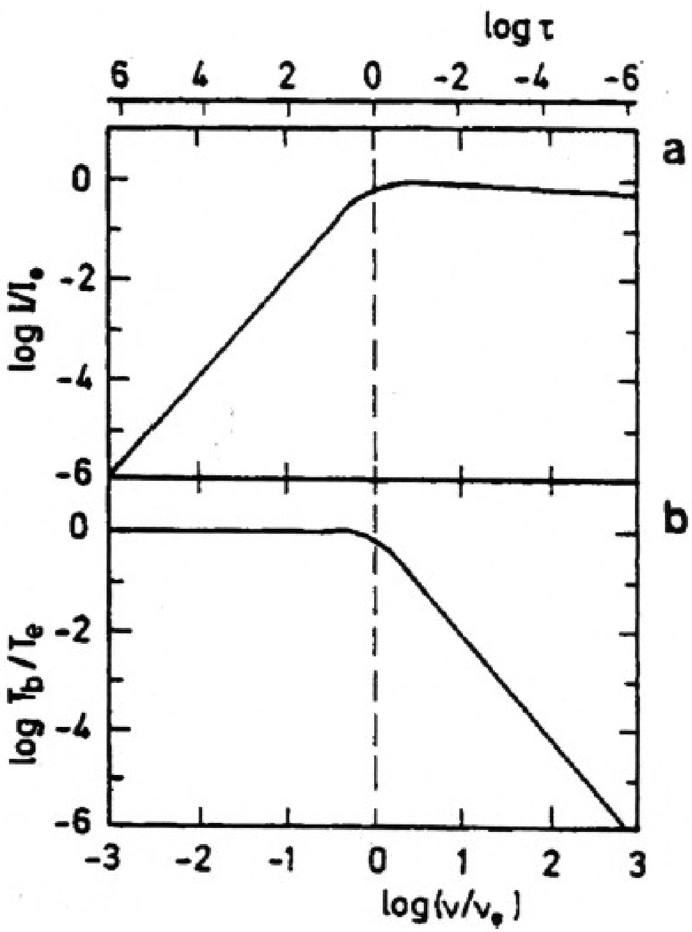
$$\tau_\nu \approx 8.235\,10^{-2} \left(\frac{T_e}{\mathrm{K}}\right)^{-1.35} \left(\frac{\nu}{\mathrm{GHz}}\right)^{-2.1} \left(\frac{EM}{\mathrm{pc\,cm^{-6}}}\right)$$

$$EM = \int n_e^2 ds$$

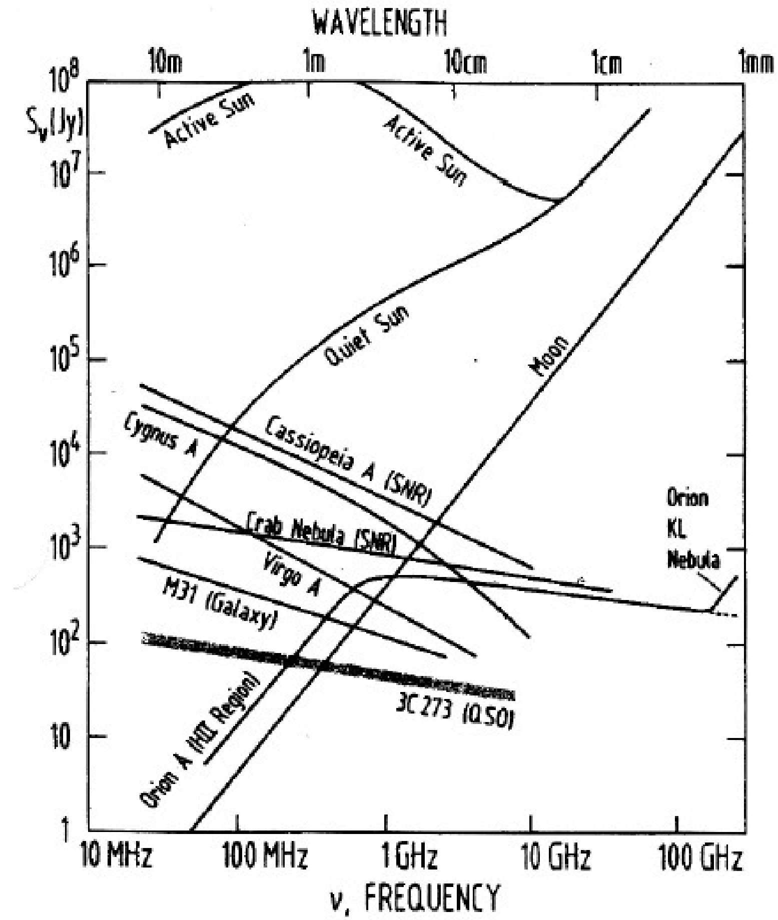
Emission measure

Free-free emission

$$I_\nu = \begin{cases} \tau_\nu B_\nu(T_e) & \propto \nu^{-0.1} T_e^{-0.35} \quad \text{für } \tau_\nu \ll 1 \\ B_\nu(T_e) & \propto \nu^2 T_e \quad \text{für } \tau_\nu \gg 1 \end{cases}$$



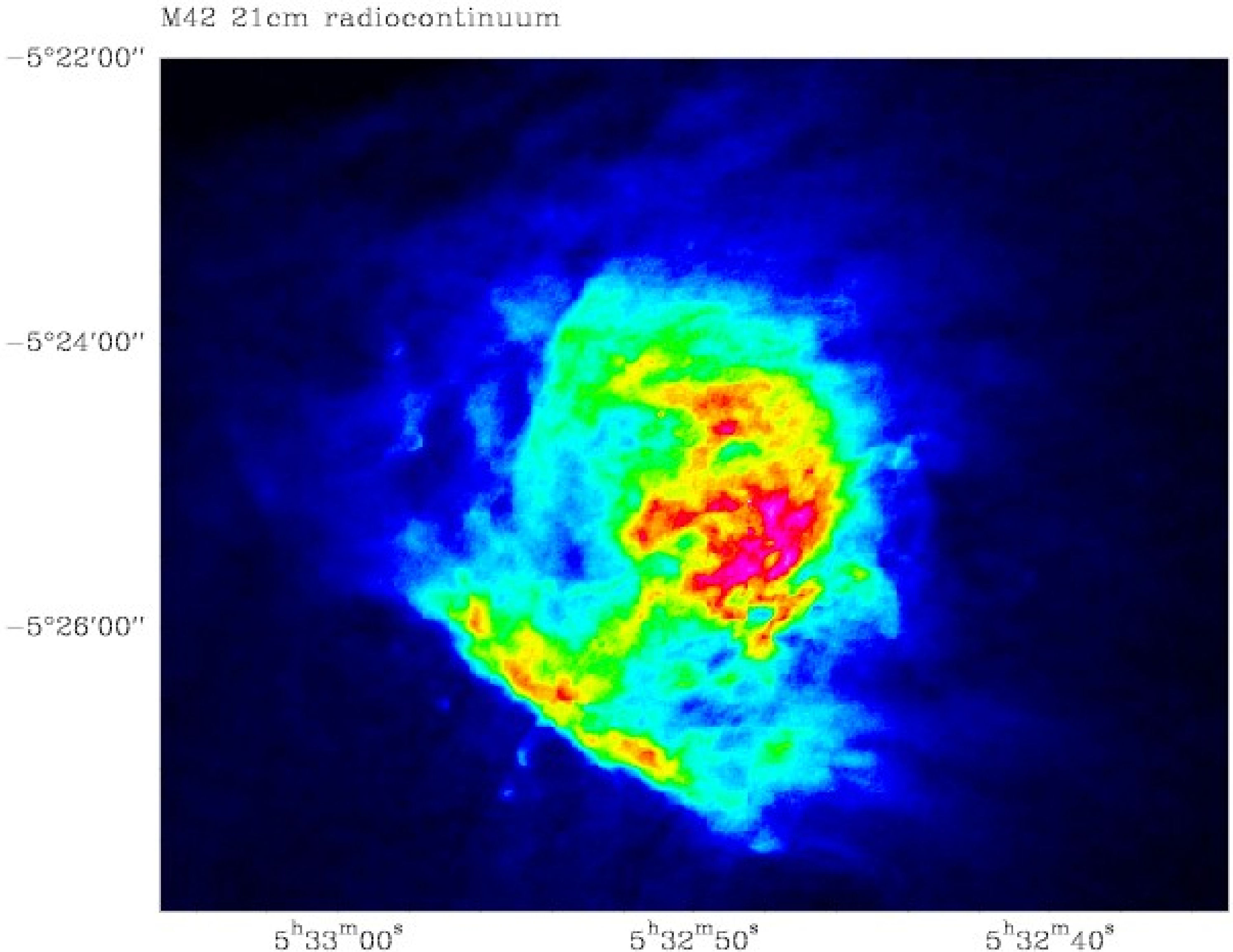
Thermisches frei-frei-Spektrum



Erklärt Radioemission von Orion-KL

Gasparameter aus dem Abknickpunkt: $\frac{\nu_0}{\text{GHz}} = 0.3 \left(\frac{T_e}{\text{K}}\right)^{0.64} \left(\frac{EM}{\text{pc cm}^{-6}}\right)^{0.48}$

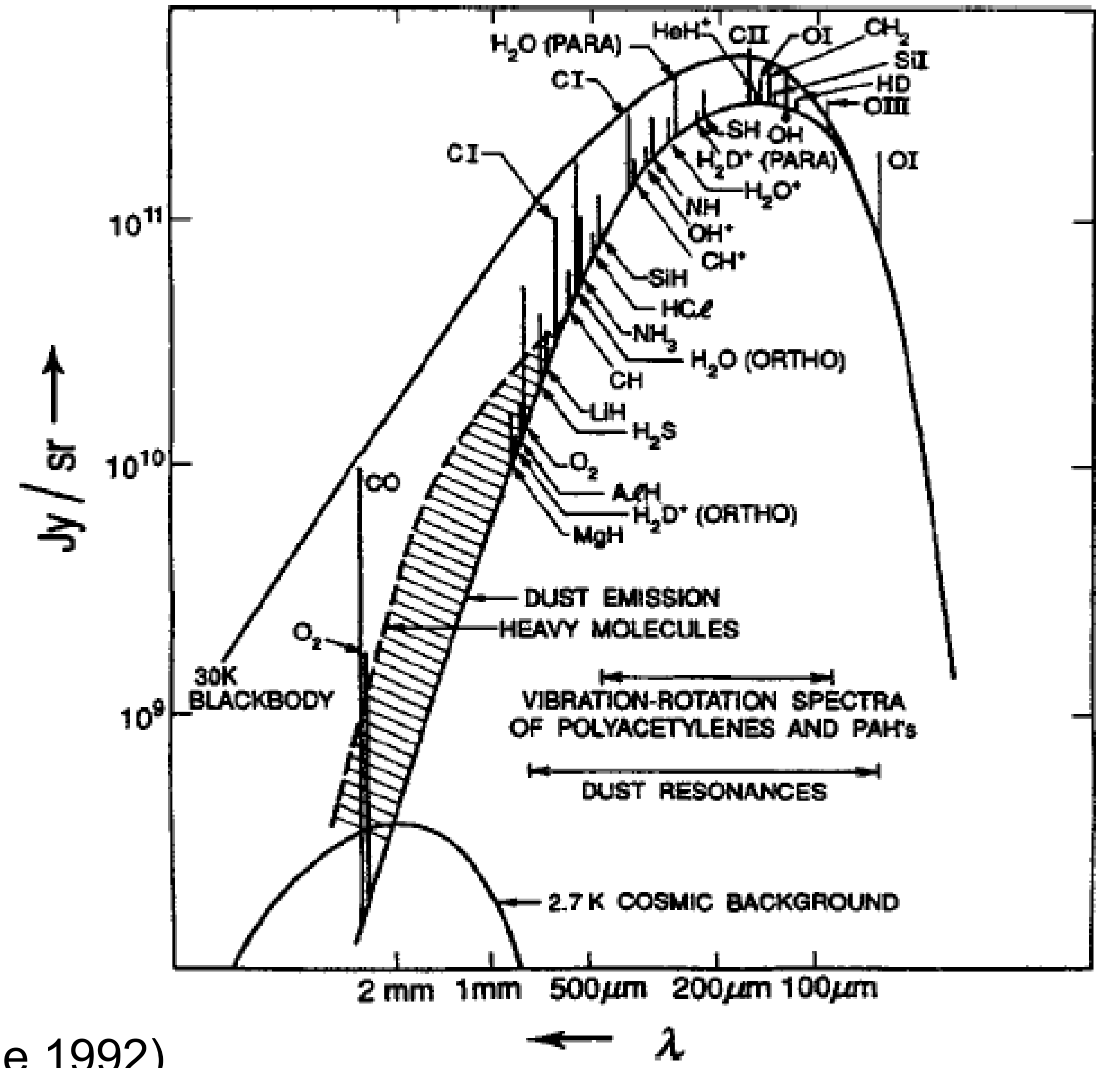
Orion Nebula at 21 cm



Line radiation

- Molecular lines
  - Rotational
  - Rot-vib.

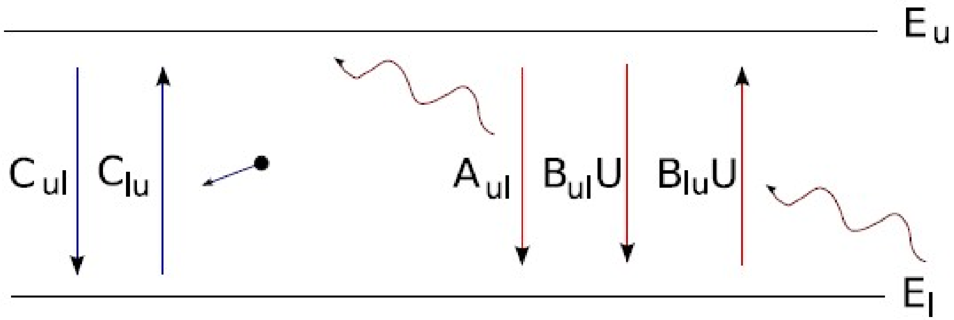
- Atomic fine structure lines



Spectrum of M82 (Phillips & Keene 1992)

Line radiation

- Consider transitions between 2 levels:



  - Spontaneous emission: A_{ul}
  - Stimulated emission: $B_{ul}U$
  - Absorption: $B_{lu}U$
  - Collisional transitions: C_{ul}, C_{lu}

$$U = \iint \frac{I_\nu \phi(\nu)}{c} d\nu d\Omega = \frac{4\pi}{c} \langle I_{\rm line} \rangle$$

- Rate coefficients mutually dependent:

  - Number conservation:

$$C_{lu} = C_{ul} \frac{g_u}{g_l} \exp\left(-\frac{h\nu}{kT_{\rm kin}}\right)$$

$$B_{lu} = B_{ul} \frac{g_u}{g_l}$$

  - Quantum mechanics:

$$B_{ul} = A_{ul} \frac{c^3}{8\pi h \nu^3}$$

Line radiation

- Level populations determined by rate equation:

$$n_u \left(A_{ul} + B_{ul} U + C_{ul} \right) = n_l \left(C_{lu} + B_{lu} U \right)$$

- Description of level populations by excitation temperature:

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} \exp\left(-\frac{h\nu}{kT_{\mathrm{ex}}} \right), \qquad T_{\mathrm{ex}} = T_{\mathrm{kin}} \quad \text{für} \quad C \gg A, BU$$

- General case: transitions between many energy levels

Energy spectrum of a molecule

$$H|\psi\rangle = E|\psi\rangle$$

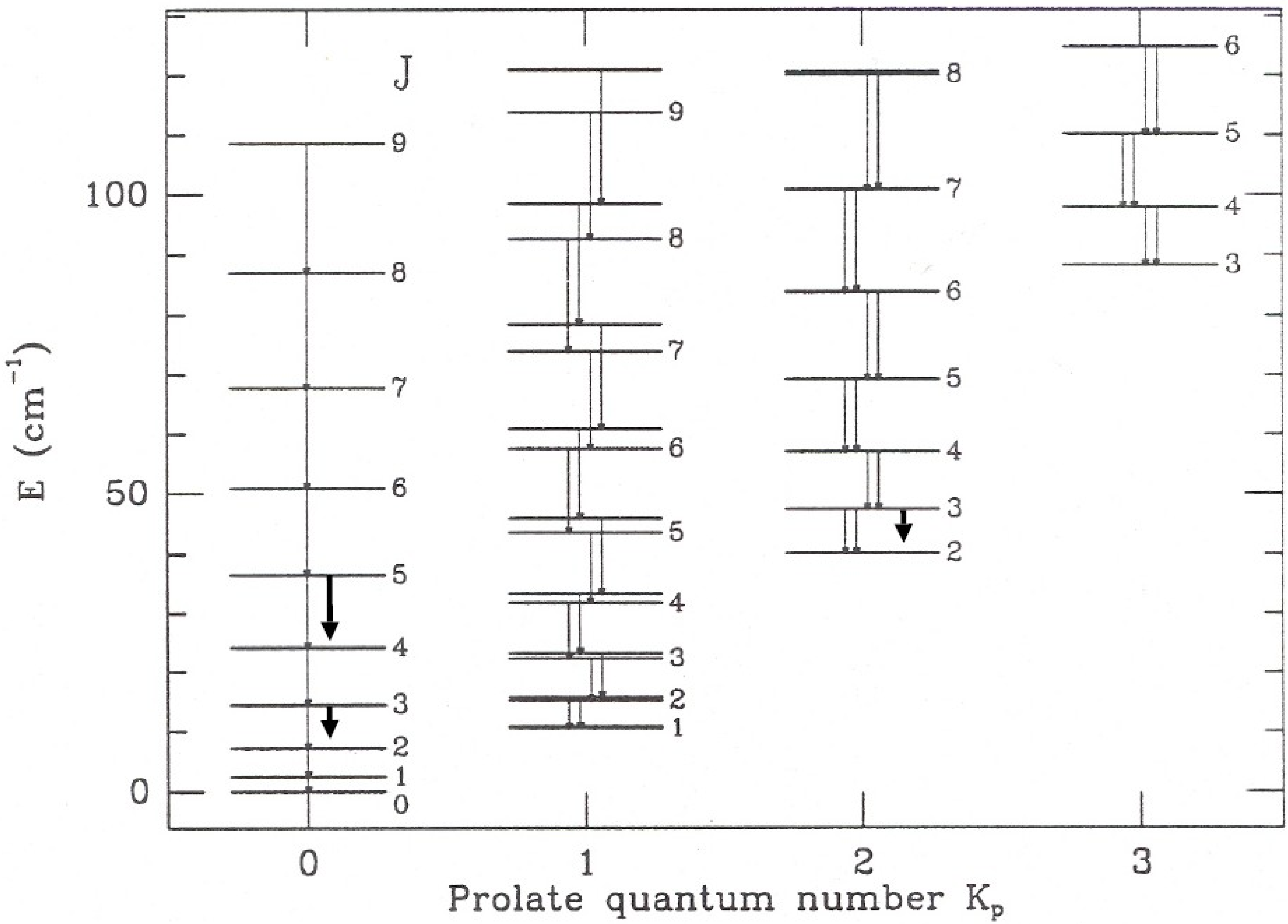
$$H = \underbrace{\frac{\sum \vec{p}_n^{\,2}}{2\mathrm{m}_n}}_{H_{\mathrm{kin}}^{\mathrm{nuclei}}} + \underbrace{\frac{\sum \vec{p}_e^{\,2}}{2\mathrm{m}_e}}_{H_{\mathrm{kin}}^{\mathrm{electrons}}}$$

$$+ \underbrace{\sum_i \sum_{i<j} \frac{Z_i Z_j e^2}{|\vec{r}_{n_i} - \vec{r}_{n_j}|}}_{H_{\mathrm{pot}}^{\mathrm{n\text{-}n}}} + \underbrace{\sum_i \sum_{i<j} \frac{e^2}{|\vec{r}_{e_i} - \vec{r}_{e_j}|}}_{H_{\mathrm{pot}}^{\mathrm{e\text{-}e}}}$$

$$- \underbrace{\sum_i \sum_j \frac{Z_i e^2}{|\vec{r}_{n_i} - \vec{r}_{e_j}|}}_{H_{\mathrm{pot}}^{\mathrm{n\text{-}e}}}$$

Energy spectrum of a molecule

H_2CO
(formaldehyde)

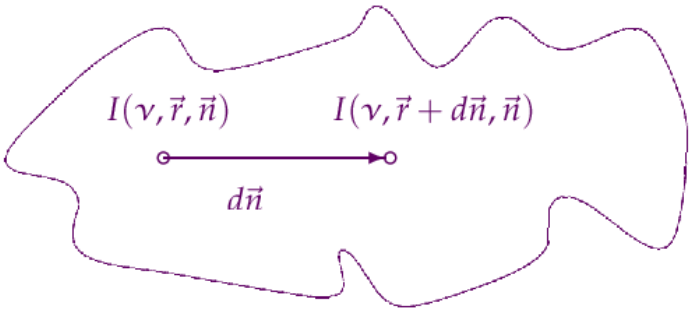


Derivation of physical parameters

- Cannot obtain 3-dimensional information, only quantities integrated along the line-of-sight
- Limited angular resolution (≈ 0.1"… a few arcsec in visible, ≈10"…1 arcmin in mid-IR, several arcmin at longer radio wavelengths)
- Resolution mismatch between different wavelength regimes

Derivation of physical parameters

- To derive physical parameters, the full radiative transfer problem needs to be solved



$$\vec{n} \cdot \mathrm{grad} I_{ul} = -\kappa_{ul} I_{ul} + \epsilon_{ul}$$

$$\kappa_{ul} = \frac{h\nu_{ul}}{c} \left[n_l B_{lu} - n_u B_{ul} \right] \; \Phi(\nu)$$

$$\epsilon_{ul} = \frac{h\nu_{ul}}{c} \, n_u A_{ul} \; \Phi(\nu)$$

$$n_i \left(\sum_{j<i} A_{ij} + \sum_{j \neq i} B_{ij} u_{ij} + \sum_{j \neq i} C_{ij} \right) = \sum_{j>i} A_{ji} n_j + \sum_{j \neq i} B_{ji} u_{ij} n_j + \sum_{j \neq i} C_{ji} n_j$$

$$u_{ul} = \frac{1}{c} \int_{4\pi} d\vec{n} \int_0^{\infty} d\nu \; \Phi(\nu) I_{ul}$$

- Practical way out: **Approximations to derive main parameters**

First approach – abundant and simple molecule: CO and CO isotopes

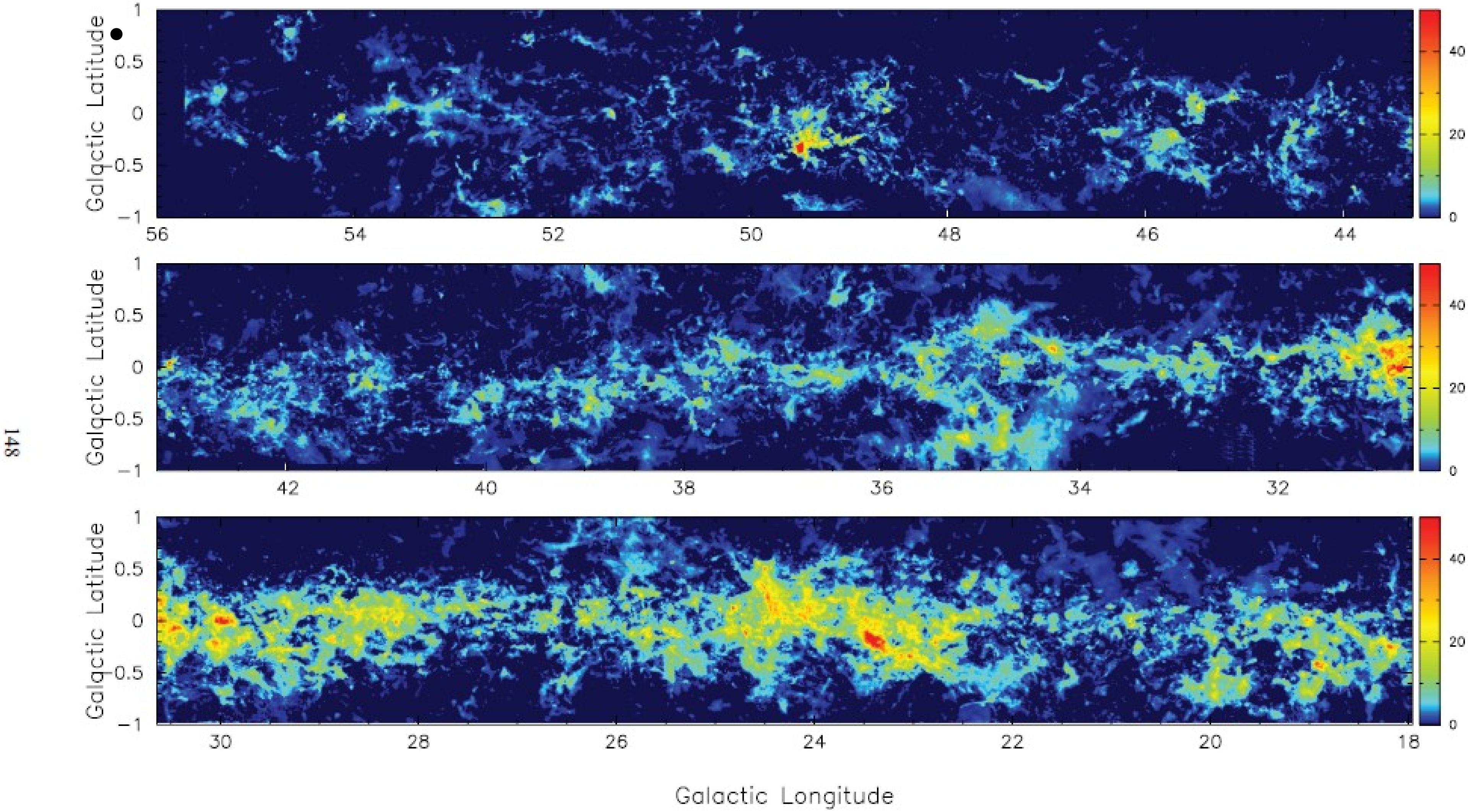


FIG. 1.—Integrated intensity image (zeroth-moment map) of GRS ^{13}CO emission integrated over all velocities ($V_{LSR} = -5$ to 135 km s^{-1} for Galactic longitudes $l \leq 40°$ and $V_{LSR} = -5$ to 85 km s^{-1} for Galactic longitudes $l > 40°$). The image shows that most of the emission is confined to $b \sim 0°$, with concentrations at $l \sim 23°$ and $\sim 31°$. A striking aspect of the image is the abundance of filamentary and linear structures and the complex morphology of individual clouds. The image is in units of K km s^{-1}.

Large-scale distribution of molecular gas

Column density derivation

- Determine A_V
- Measure ^{13}CO line intensity
- Assume ^{13}CO optically thin, ^{12}CO optically thick
- Assume $T_{ex}(^{13}CO) = T_{ex}(^{12}CO)$
- Assume $^{12}CO/^{13}CO \approx$ 40-60 $\Rightarrow \tau(^{13}CO) \Rightarrow N(^{13}CO)$ from LTE analysis

$$N(\mathrm{H_2}) = (5.0 \pm 2.5) \times 10^5 \, N_{\mathrm{LTE}}(^{13}\mathrm{CO})\,\mathrm{cm}^{-2}$$

$$N(\mathrm{H_2})/I_{\mathrm{CO}} = (3-5) \times 10^{20}\,\mathrm{cm}^{-2}\,\mathrm{K}^{-1}\,\mathrm{km}^{-1}\,\mathrm{s}$$

- Problems:
  - Determination of A_V inaccurate
  - Often $T_{ex}(^{13}CO) < T_{ex}(^{12}CO)$
  - Not valid for translucent clouds

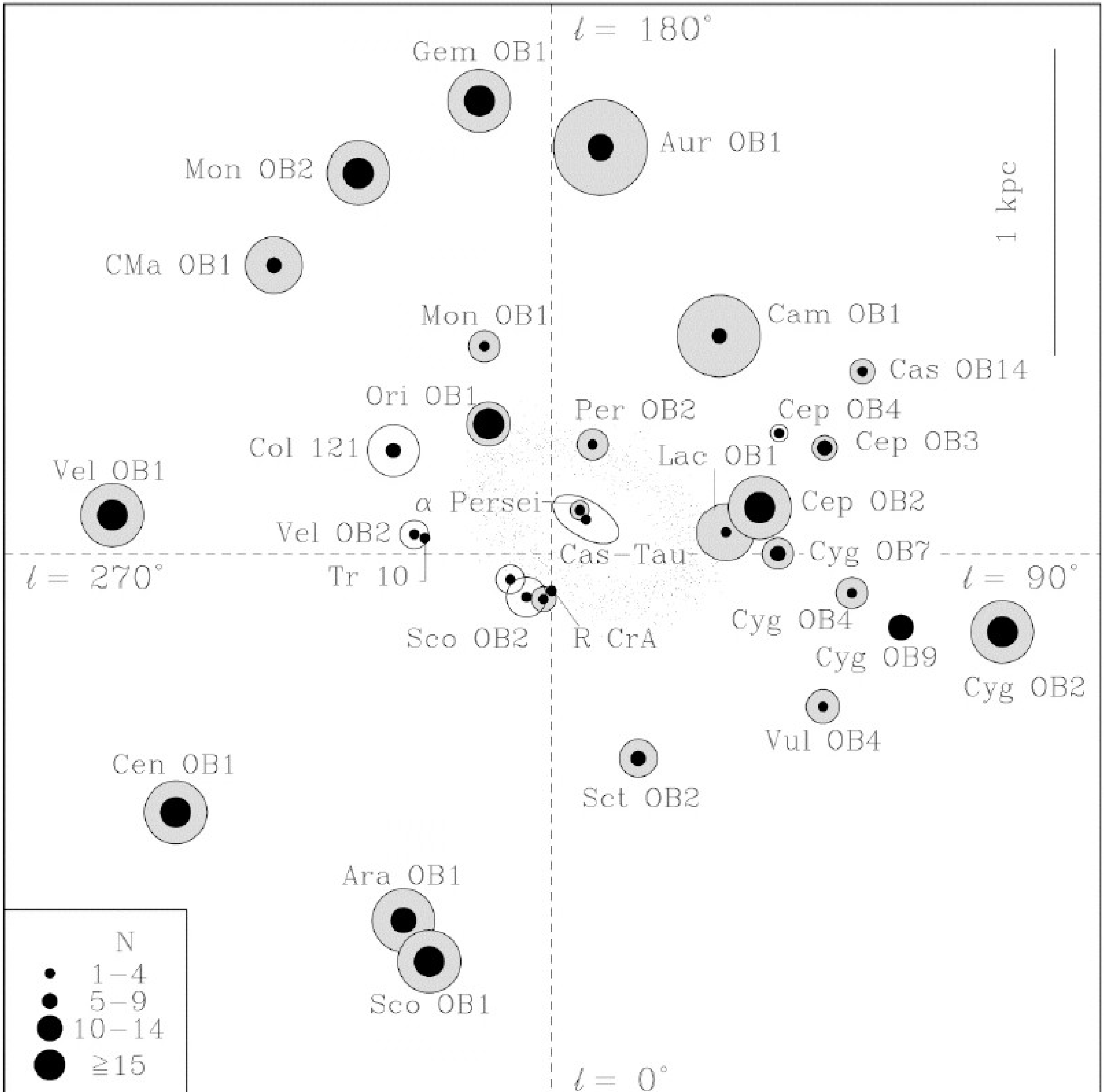
CO results

- About 90% of H_2 mass in 5000 complexes with size > 20 pc; $M > 10^5\ M_{sun}$
- About 50% of H_2 mass in 1000 complexes with size > 50 pc, $M > 10^6\ M_{sun}$
- About 90% of H_2 mass inside solar circle (vs. 33% H I mass)
- Mass spectrum clouds

$$\frac{dN_{\rm cloud}}{dM_{\rm cloud}} \propto \left(\frac{M_{\rm cloud}}{M_\odot}\right)^{-1.7}$$

$M = 10\text{-}10^5\ M_{Sun}$

CO results



- N = # stars with $M_V > -5$

De Zeeuw et al. 1999

Density derivation

Definition of a critical density:

- Time-independent rate equation, neglecting stimulated absorption and emission:

$$\frac{dn_u}{dt} = \left[n_e n_l q_{lu} \right] - \left[n_e n_u q_{ul} + n_u A_{ul} \right] = 0$$

$n_e n_l q_{lu}$: collisional excitation — **Transitions to level u**

$n_e n_u q_{ul}$: collisional deexcitation; $n_u A_{ul}$: spontaneous emission — **Transitions out of level u**

$$\Rightarrow \quad \frac{n_u}{n_l} = \frac{n_e q_{ul}}{A_{ul}} \left(1 + \frac{n_e q_{ul}}{A_{ul}} \right)^{-1}$$

Critical density

- ***Low*** density

$$n_e q_{ul} \ll A_{ul} \Rightarrow \frac{n_u}{n_l} = \frac{n_e q_{lu}}{A_{ul}}$$

- ***High*** density

$$n_e q_{ul} \gg A_{ul} \Rightarrow \frac{n_u}{n_l} = \frac{q_{lu}}{q_{ul}} = \frac{g_u}{g_l} e^{\frac{-\Delta E_{ul}}{kT}}$$

Thermal distribution

- Critical density $n_{\rm crit} = \frac{A_{ul}}{q_{ul}}$

Density derivation

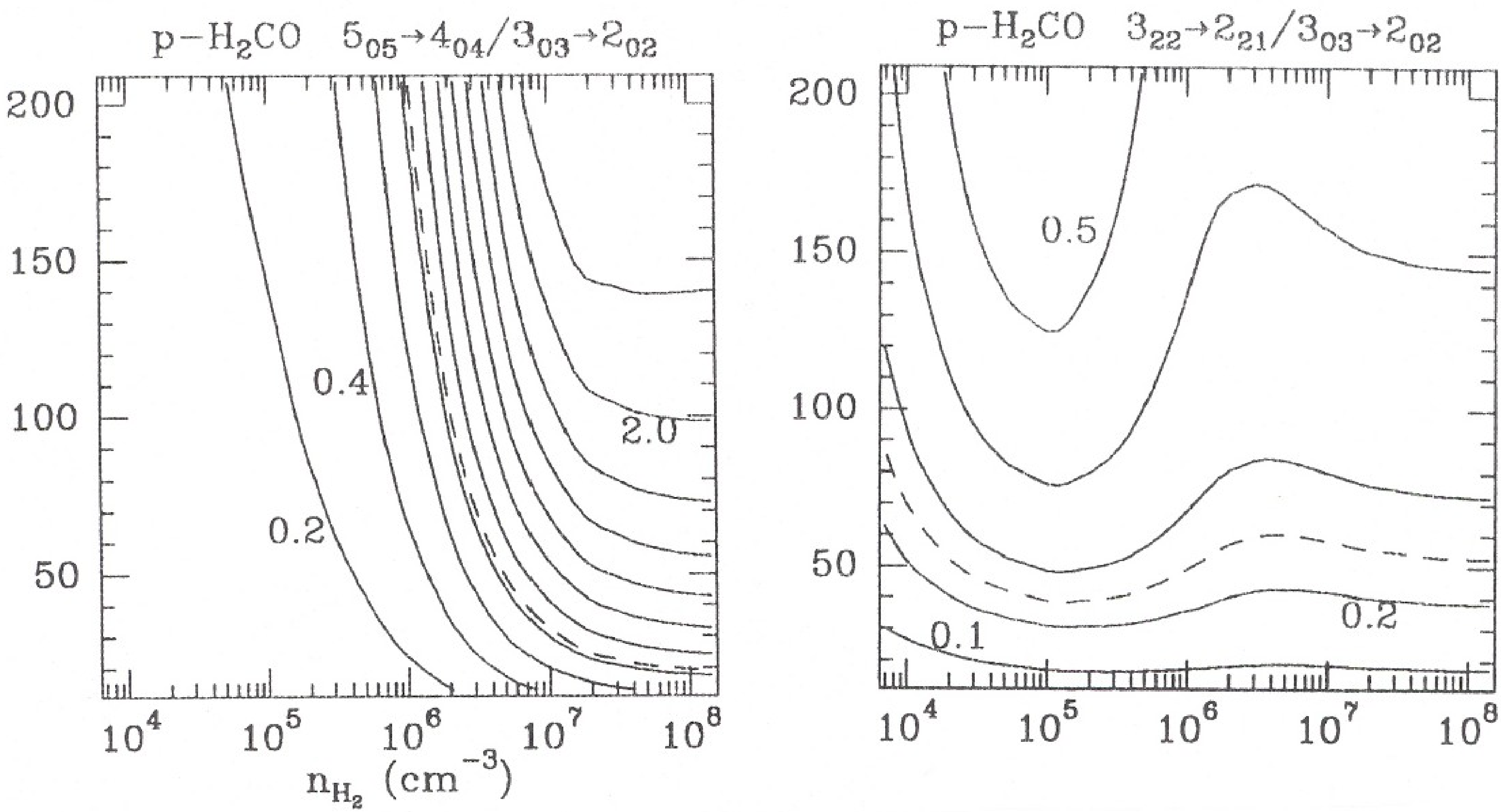
- Critical density defines as for atoms n_{cr}=A_{ul}/q_{ul}
- n_{cr} depends on dipole moment μ: $A \propto \mu^2$
- n_{cr} depends on rotational quantum number J: $A \propto J^3$
- Examples:
  - ^{12}CO 1 – 0: n_{cr} = 4×10^3 cm^{-3} μ (^{12}CO) ≈ 0.1 D
  - ^{12}CO 7 – 6: n_{cr} = 1.6×10^5 cm^{-3}
  - CS 2 – 1: n_{cr} = 5×10^5 cm^{-3} μ (CS) ≈ 2 D
- Molecules with larger μ sample denser regions
- Transitions with different J ⇒ info on n

Density derivation

Molecule	Transition	ν (GHz)	E_{up} (K)	n_c(10 K) (cm^{-3})	n_{eff}(10 K) (cm^{-3})	n_c(100 K) (cm^{-3})	n_{eff}(100 K) (cm^{-3})
CS	$J = 1 \rightarrow 0$	49.0	2.4	4.6×10^4	7.0×10^3	6.2×10^4	2.2×10^3
CS	$J = 2 \rightarrow 1$	98.0	7.1	3.0×10^5	1.8×10^4	3.9×10^5	4.1×10^3
CS	$J = 3 \rightarrow 2$	147.0	14	1.3×10^6	7.0×10^4	1.4×10^6	1.0×10^4
CS	$J = 5 \rightarrow 4$	244.9	35	8.8×10^6	2.2×10^6	6.9×10^6	6.0×10^4
CS	$J = 7 \rightarrow 6$	342.9	66	2.8×10^7	...	2.0×10^7	2.6×10^5
CS	$J = 10 \rightarrow 9$	489.8	129	1.2×10^8	...	6.2×10^7	1.7×10^6
HCO^+	$J = 1 \rightarrow 0$	89.2	4.3	1.7×10^5	2.4×10^3	1.9×10^5	5.6×10^2
HCO^+	$J = 3 \rightarrow 2$	267.6	26	4.2×10^6	6.3×10^4	3.3×10^6	3.6×10^3
HCO^+	$J = 4 \rightarrow 3$	356.7	43	9.7×10^6	5.0×10^5	7.8×10^6	1.0×10^4
HCN	$J = 1 \rightarrow 0$	88.6	4.3	2.6×10^6	2.9×10^4	4.5×10^6	5.1×10^3
HCN	$J = 3 \rightarrow 2$	265.9	26	7.8×10^7	7.0×10^5	6.8×10^7	3.6×10^4
HCN	$J = 4 \rightarrow 3$	354.5	43	1.5×10^8	6.0×10^6	1.6×10^8	1.0×10^5
H_2CO	$2_{12} \rightarrow 1_{11}$	140.8	6.8	1.1×10^6	6.0×10^4	1.6×10^6	1.5×10^4
H_2CO	$3_{13} \rightarrow 2_{12}$	211.2	17	5.6×10^6	3.2×10^5	6.0×10^6	4.0×10^4
H_2CO	$4_{14} \rightarrow 3_{13}$	281.5	30	9.7×10^6	2.2×10^6	1.2×10^7	1.0×10^5
H_2CO	$5_{15} \rightarrow 4_{14}$	351.8	47	2.6×10^7	...	2.5×10^7	2.0×10^5
NH_3	(1,1)inv	23.7	1.1	1.8×10^3	1.2×10^3	2.1×10^3	7.0×10^2
NH_3	(2,2)inv	23.7	42	2.1×10^3	3.6×10^4	2.1×10^3	4.3×10^2

- n_c = critical density
- n_{eff} = density needed to produce a 1 K line at typical column density

Density derivation



Van Dishoeck et al. 1993, 1995
Jansen et al. 1993

Density derivation

METHOD	STRENGTH	WEAKNESS
Average volume density from column density and cloud size (e.g., ^{13}CO or $C^{18}O$)	Easy to measure	Underestimates local densities as volume filling factors $\ll 1$ (clumpiness), strongly depends on abundances and T_{ex}
Detection of "density tracers", such as mm-lines of CS, HCN, and infer $n \approx n_{crit}$	Easy to measure	Rough first order indication, depends strongly on optical depth
Measurement of non-metastable NH_3 inversion lines at 1.2 cm	Many energy levels available at about the same wavelength	Optical depth effects and FIR radiative pumping need to be taken into account
Level population as a function of energy from rotational lines above n_{crit} (subthermal regime), especially for optically thin species ($C^{18}O$, $H^{13}CN$, $C^{34}S$, etc.)	Very sensitive to $n(H_2)$, gives also temperature information	Measurements need to be made at different wavelengths, cross sections for all molecules but CO uncertain, must solve the entire excitation problem, density/temperature information is coupled

Temperature derivation

- For molecule in LTE => $T_{ex}=T_{kin}$ => in RJ limit with $\tau >> 1$
  $T_A = T_{kin} - T_{bg}$

=> antenna temperature is direct measure of T_{kin}

- Examples of thermometers
  - ^{12}CO J=1-0, 2-1, ….
  - Symmetric top molecules such as NH_3 or CH_3CN
    - Radiative transitions with $\Delta K \neq 0$ are forbidden => relative populations only governed by collisions
  - Asymmetric top molecules such as H_2CO

Temperature derivation

METHOD	STRENGTH	WEAKNESS
Brightness of optically thick mm-lines (e.g., ^{12}CO 1→0: $T_R = T_{ex} \approx T_{kin}$)	Easy to measure	Filling factor of emission often less than unity, method may underestimate T_{kin}
Level population as a function of energy from metastable NH_3 inversion lines at $\approx$ 1.2 cm (also other symmetric tops, such as CH_3CN, CH_3C_2H)	Many energy levels available at about the same wavelength	Optical depth and density correction required, only applicable to fairly dense regions where NH_3, CH_3CN, etc. are abundant
Level population as a function of energy from rotational lines of molecules in submm and infrared (emission, e.g., CO, H_2)	Very sensitive for $E_{ul} > kT_{kin}$, also density information	Measurements need to be made at different wavelengths, must solve the entire excitation problem and take into account optical depth effects, density/ temperature information is coupled
...from ro-vibrational lines in near-IR (absorption)	Same as above, many energy levels at about the same wavelength	Only line of sight toward bright continuum sources

Molecular tracers