GAS AND DUST IN THE MW

Lezione XI- Fisica delle Galassie

Carrol & Ostlie (2014): Cap 12.1, 25.[1,2,3]
Binney & Merrifield (1998): 8.1.[1,4,6], 9.[1,2,3.1]
Draine's *Rossi Lectures* https://www.arcetri.inaf.it/seminari/rossi-lectures

Simone Bianchi

Outline

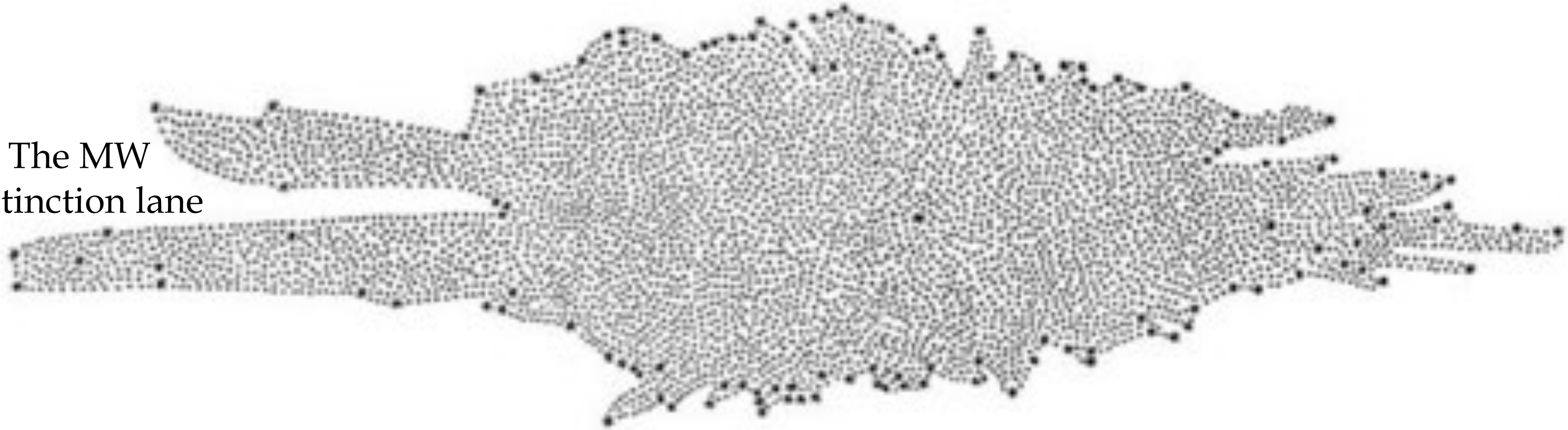
- Early evidences for an interstellar medium
- The atomic gas: HI
- The molecular gas: CO
- Dust: extinction, emission and models

First Evidences

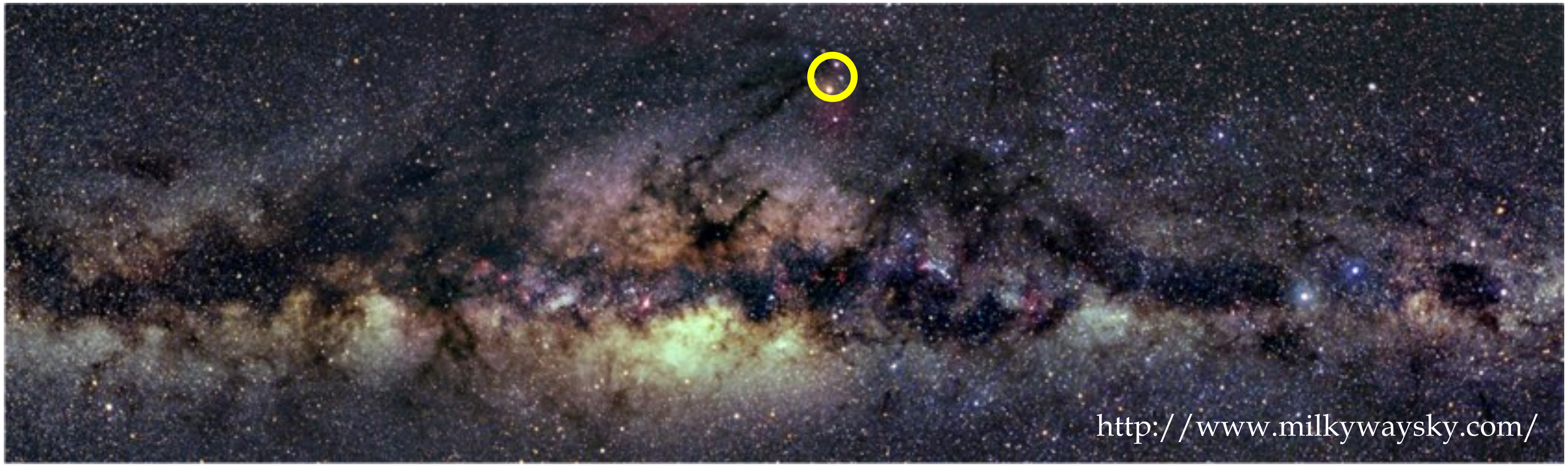
In the body of the Scorpion is an opening, or hole... (Herschel 1785)

First Evidences

Herschel’s map of the Milky Way



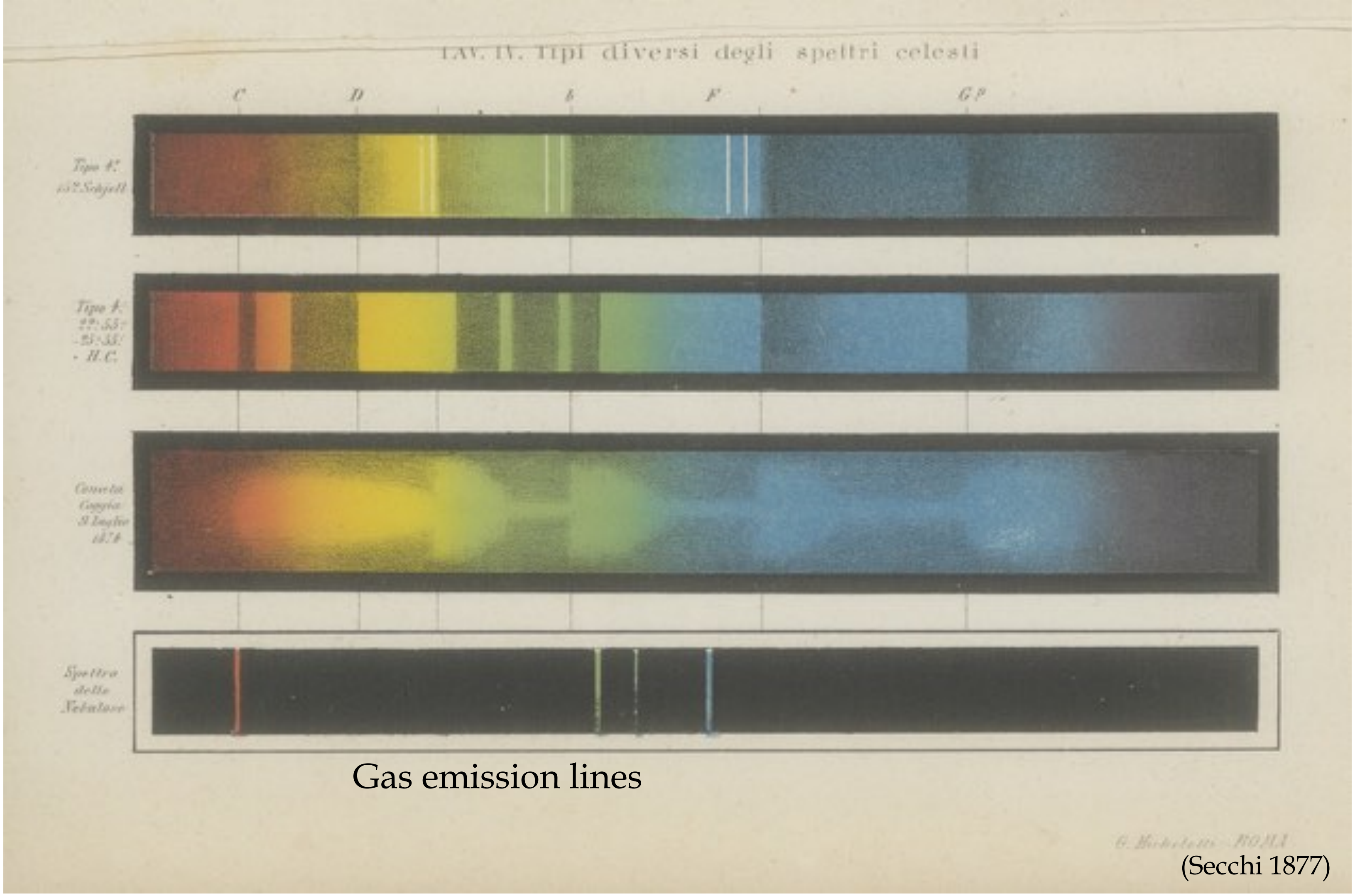
The MW extinction lane



http://www.milkywaysky.com/

First Evidences

Gas in MW Nebulae (Huggins 1864)



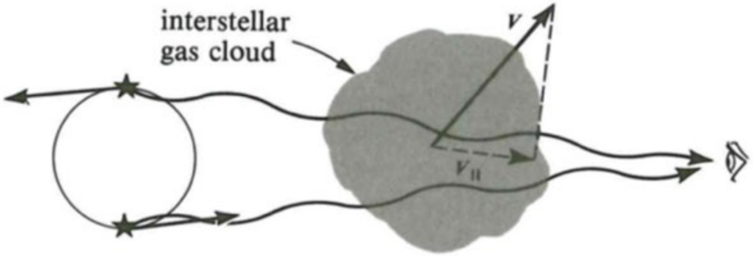
Gas emission lines

(Secchi 1877)

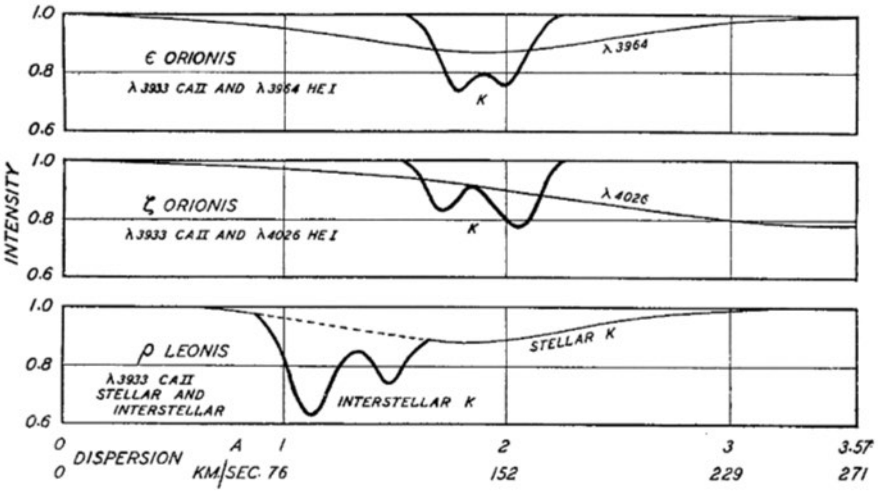
First Evidences

Interstellar absorption lines

Hartmann (1904) finds a «stationary lines» of Calcium in the spectrum of the double star δ Orionis



Shu (1982)



Beals (1936)

- Stationary
- Different redshift
- Narrow
- Ubiquitous

First Evidences

Interstellar continuum absorption (Trumpler 1930)

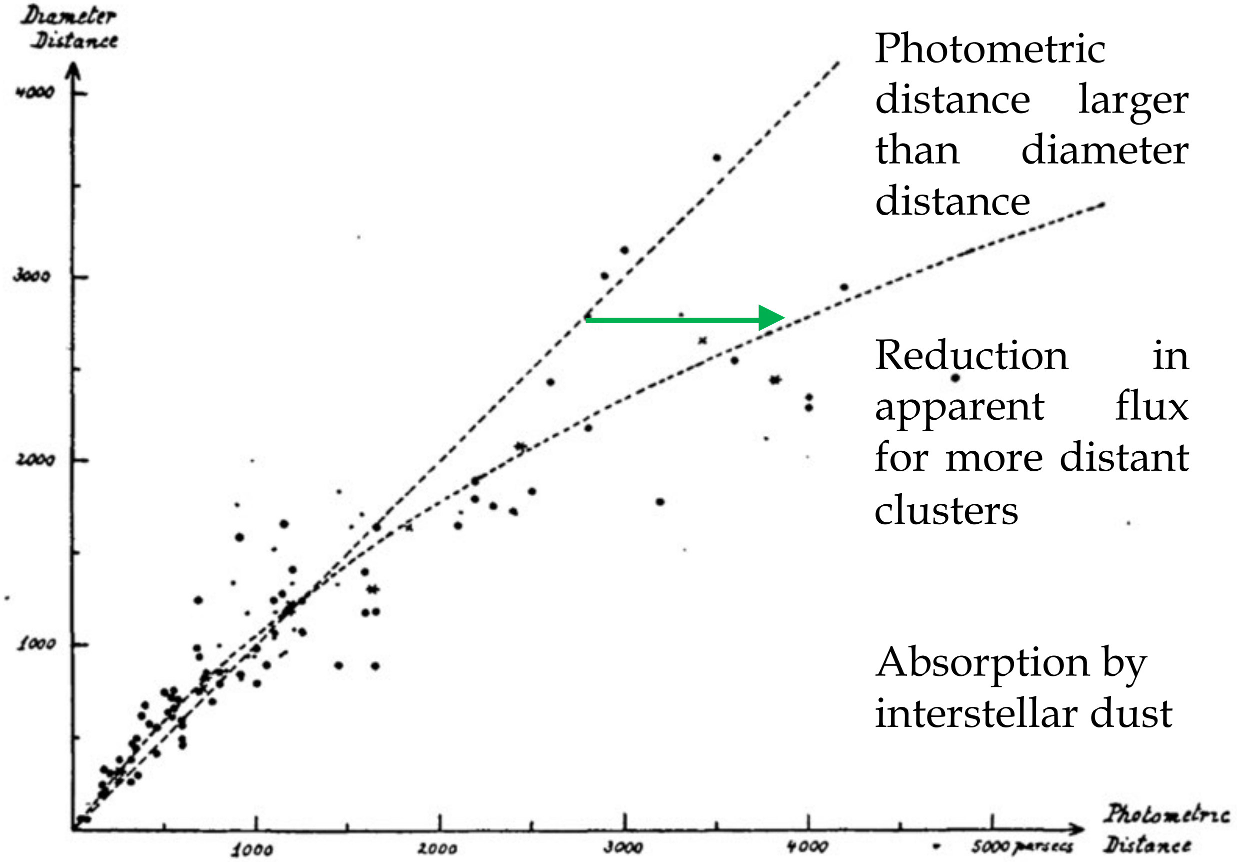
Assumption: all open clusters have the same true diameter D and Luminosity L

$$\theta = \frac{D}{d}$$

Diameter distance

$$f = \frac{L}{4\pi d^2}$$

Photometric distance



Photometric distance larger than diameter distance

Reduction in apparent flux for more distant clusters

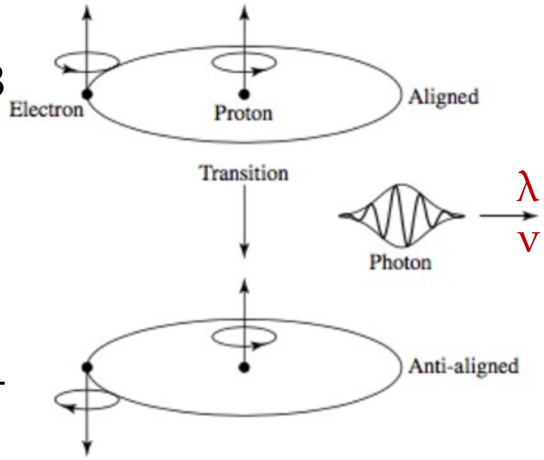
Absorption by interstellar dust

The HI 21 cm line

Predicted by Van der Hults in 1944, observed with radiotelescopes in 1951

Hyperfine structure of the ground level of HI due to the coupling of the spin of electron and proton.

F=1 g=3



λ = 21.1 cm
v = 1420.4 MHz

F=0 g=1

Spontaneous emission
A_{10}=2.85 x 10^{-15} s^{-1}
Mean lifetime
t = 1/ A_{10} = 1.1 x 10^{7} years

Extremely unprobable, but many HI atom…

In most cases of interest here, optically thin and collisionally excited:

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-\frac{h\nu}{KT}} = 3 \times e^{-\frac{0.068K}{T}} \approx 3$$

$$n_0 = \frac{1}{4} n_{\mathrm{H}}$$

Basic radiative transfer

Specific intensity

Absorption and emission coefficients

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

path along propagation dir.

The RT equation (Magrini, lecture 6)

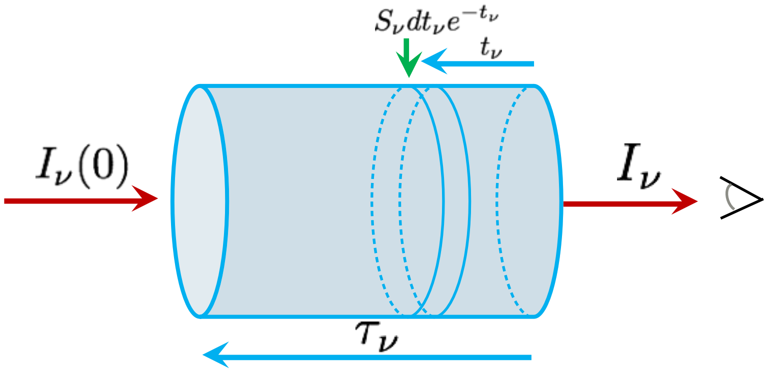
Optical depth

$$\tau_\nu = \int \kappa_\nu ds$$

$$\frac{dI_\nu}{d\tau_\nu} + I_\nu = S_\nu$$

Source Function

$$S_\nu = \frac{\epsilon_\nu}{\kappa_\nu}$$



Assumed constant

$$I_\nu = I_\nu(0)e^{-\tau_\nu} + S_\nu(1 - e^{-\tau_\nu})$$

$$I_\nu = S_\nu \tau_\nu$$

Optically thin limit, no background

The hydrogen column density N_{HI}

At radio frequencies, Rayleigh-Jeans approximation

$$S_\nu = B_\nu(T) \approx \frac{2kT\nu^2}{c^2} \quad \text{for} \quad \frac{h\nu}{kT} \ll 1$$

A radio-astronomy convention

$$I_\nu = \frac{2kT_B\nu^2}{c^2}$$

T_B brightness temperature

RT equation for the optically thin limit $I_\nu = S_\nu \tau_\nu \longleftrightarrow T_B = T\tau_\nu$

$$\tau_\nu = \frac{1}{C}\frac{N_H \boxed{f(v)}}{T}$$

Line profile

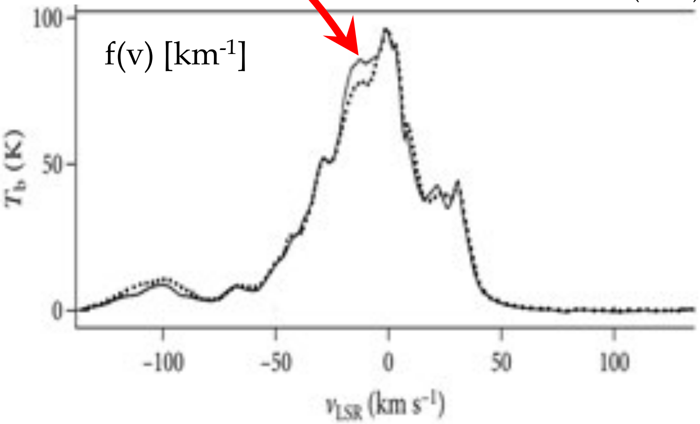
$$v = \frac{c(\nu_0 - \nu)}{\nu_0}$$

$$N_H = C\int T\tau(v)dv$$

$$= C\int T_B(v)dv$$

$$C = 1.82 \times 10^{18}\ \frac{\text{atoms}}{\text{K km/s cm}^2}$$

Condon & Ransom (2015)



See Binney & Merrifield (1998) for full derivation

N_{HI} map of the whole sky

HI4PI Collaboration: HI4PI: A full-sky H I survey based on EBHIS and GASS (2016)

fwhm=16′
64-m dish

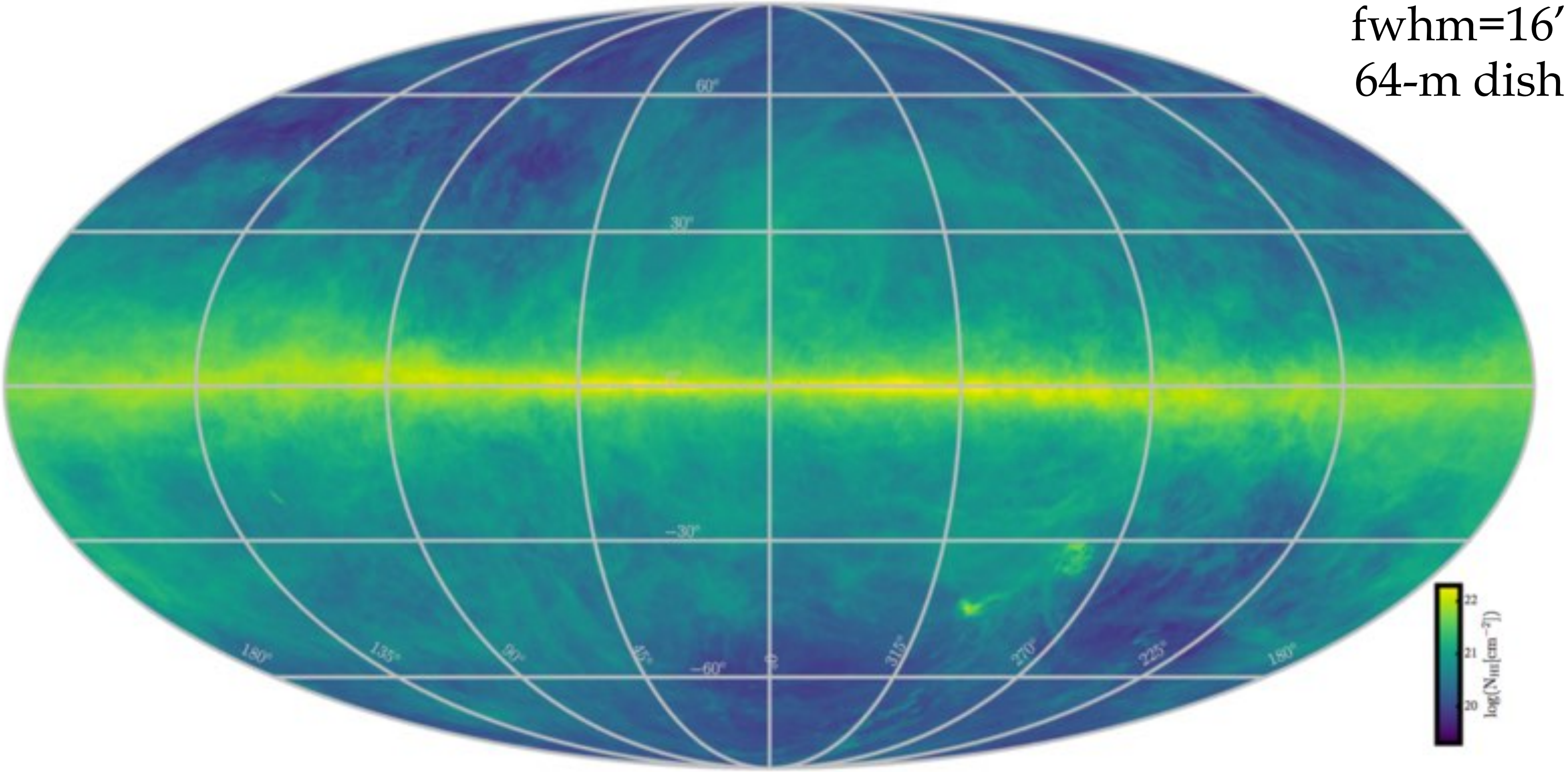
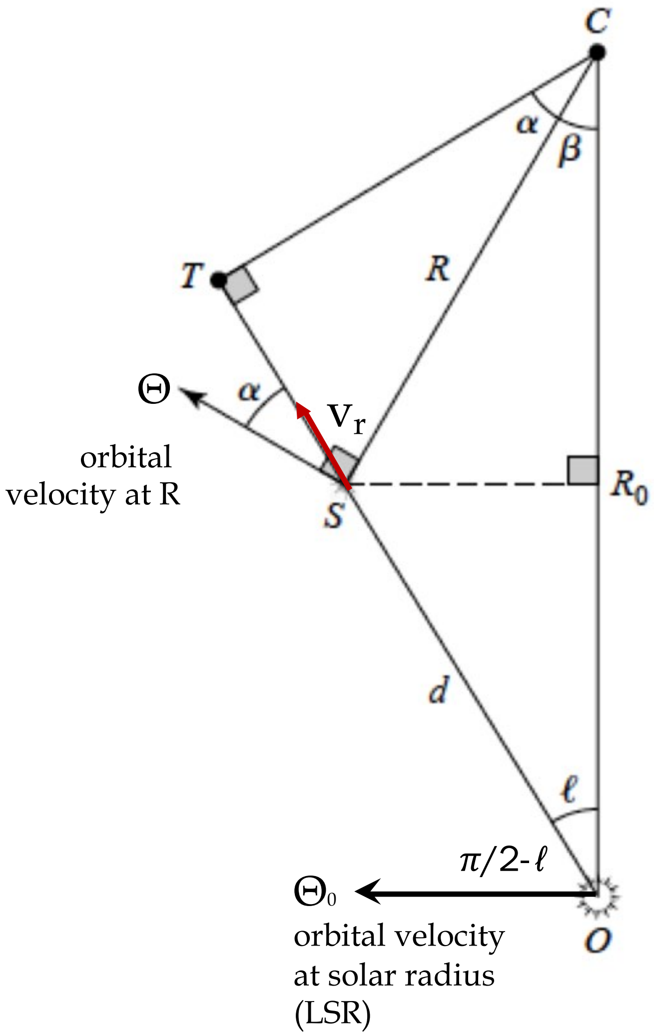


Fig. 2. HI4PI: all-sky column density map of H I gas from EBHIS and GASS data as integrated over the full velocity range $-600 \leq v_{\rm lsr} \leq 600$ km s^{-1}. The map is in Galactic coordinates using Mollweide projection.

M_{HI}=8 x 10^9 M_{sun} M_{stars}=8 x 10^9 $M_{sun.}$ (Kalberla & Kerp 2009)

Galactic Rotation from HI

(Magrini, lecture 4)



- C position of the Galactic Centre
- O position of the Sun
- S position of an HI cloud seen at Galactic longitude ℓ

The **observed** radial velocity of S is:

$$v_r = \Theta \cos \alpha - \Theta_0 \sin \ell$$

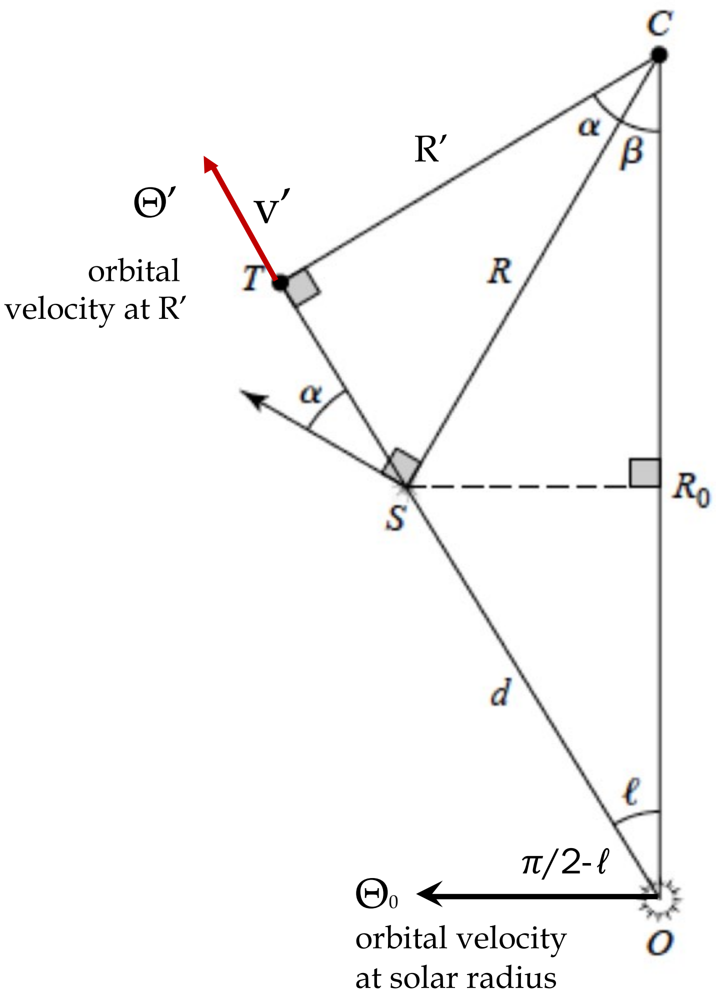
$$v_r = \Omega R \cos \alpha - \Omega_0 R_0 \sin \ell$$

$\Omega(R)$ Angular velocity

$$R \cos \alpha = R_0 \sin \ell$$

$$v_r = (\Omega - \Omega_0)\, R_0 \sin \ell$$

Galactic Rotation from HI



$$v_r = (\Omega - \Omega_0)\, R_0 \sin \ell$$

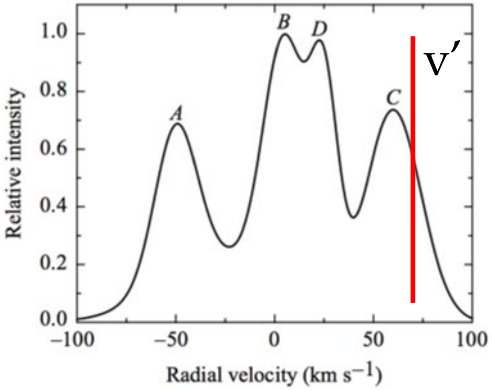
- Ω(R) monotonically decreasing with R
- Maximum of v_r at tangential point T

$R' = R_0 \sin \ell$ (TC, α=0)

$v' = (\Omega(R') - \Omega_0)\, R_0 \sin \ell$

$= \Theta(R') - \Theta_0 \sin \ell$

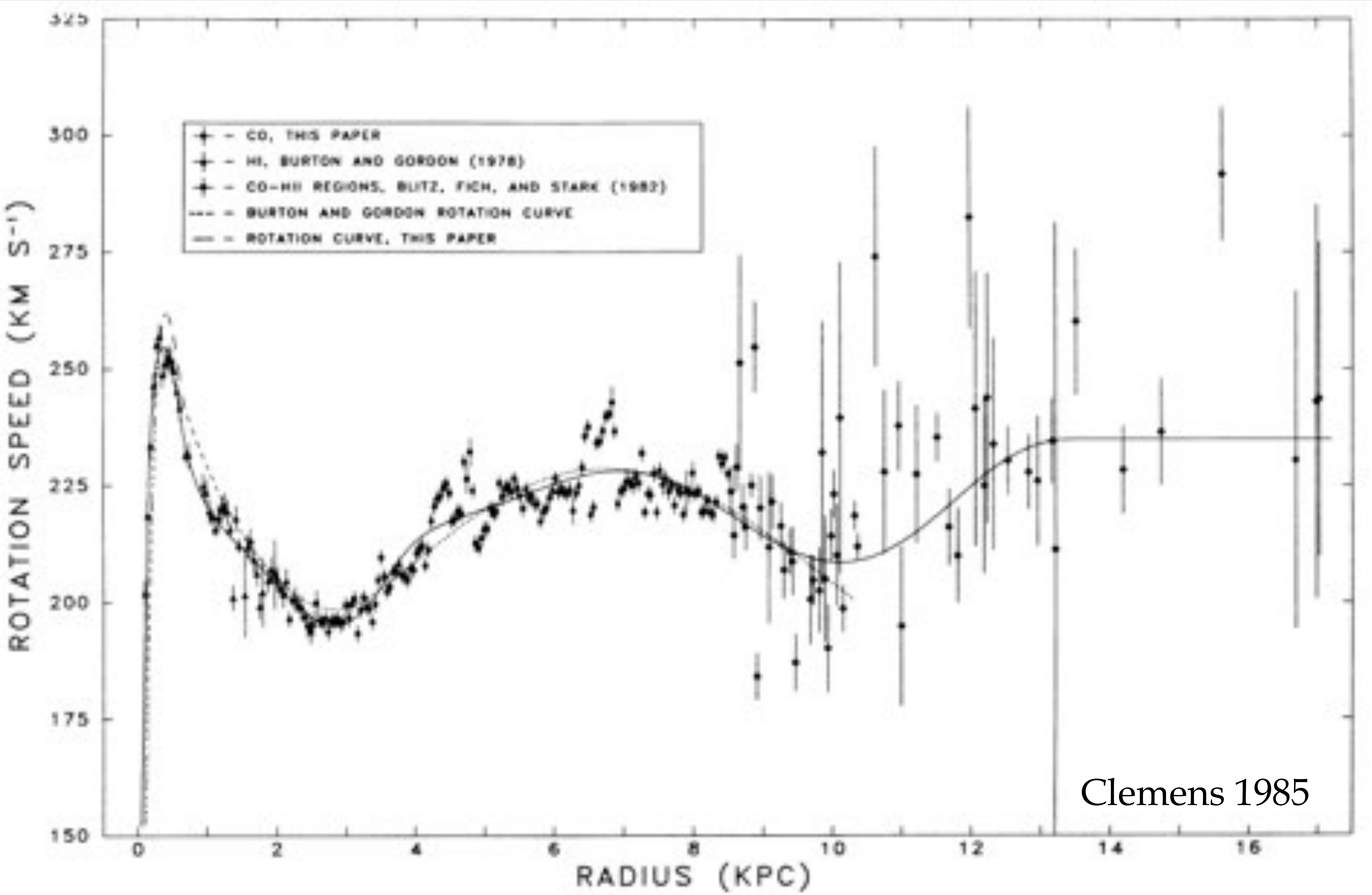
Typical profile of the 21 cm line in the MW



$\Theta(R') = v' + \Theta_0 \sin \ell$

$\Theta_0 = 220$ km/s
$R_0 = 8.5$ kpc

Galactic Rotation from HI



Clemens 1985

(Magrini, lecture 4; Zibetti lecture 8)

Spiral structure from HI

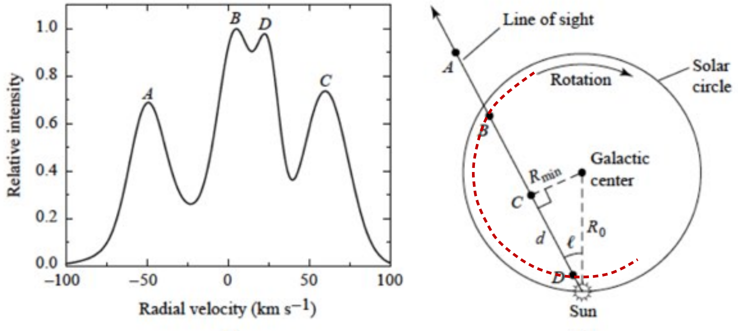
Kinematic distances

$$v_r = (\Omega - \Omega_0)\, R_0 \sin \ell$$

find R knowing Ω and v_r

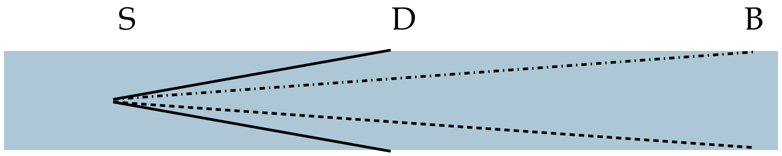
find d

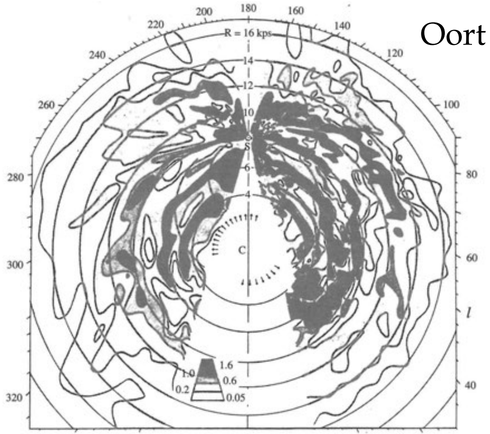
Distance ambiguity (for $R < R_0$)



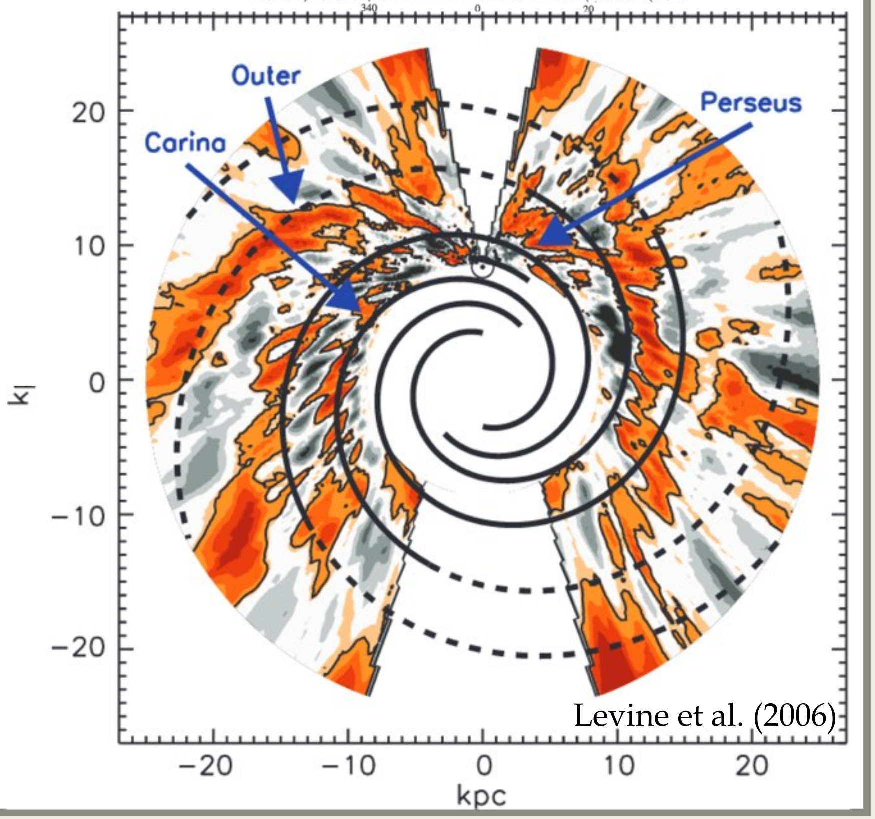
(a) (b)

Use the disk thickness to solve the problem





Oort 1962



Levine et al. (2006)

The velocity-longitude diagram

$$v_r = (\Omega - \Omega_0)\, R_0 \sin \ell$$

Slope proportional to Ω–Ω_0

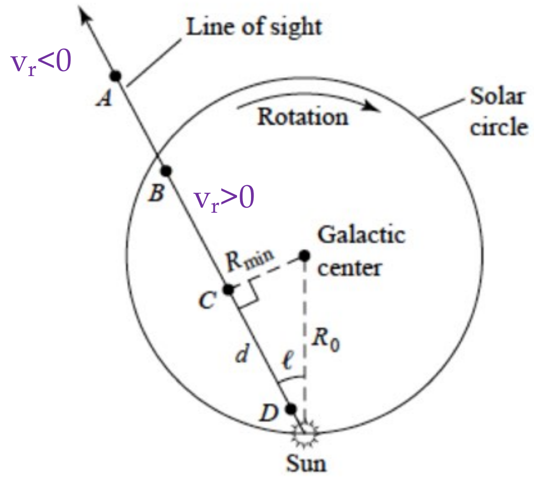
┈┈┈┈┈┈ R=0.1 R_0

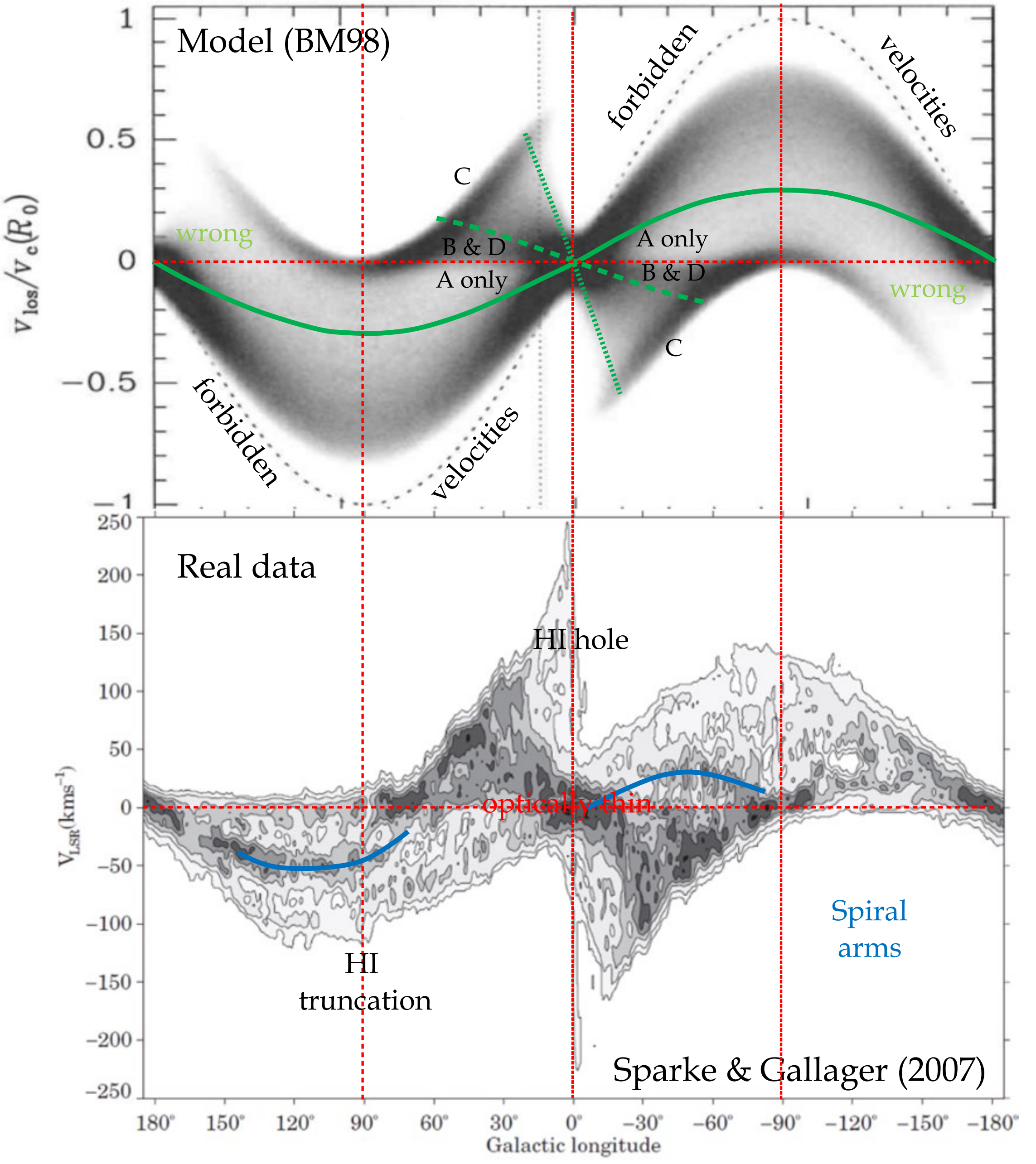
- - - - - - R=0.9 R_0

ℓ_{max} = arcsin(R/R_0)

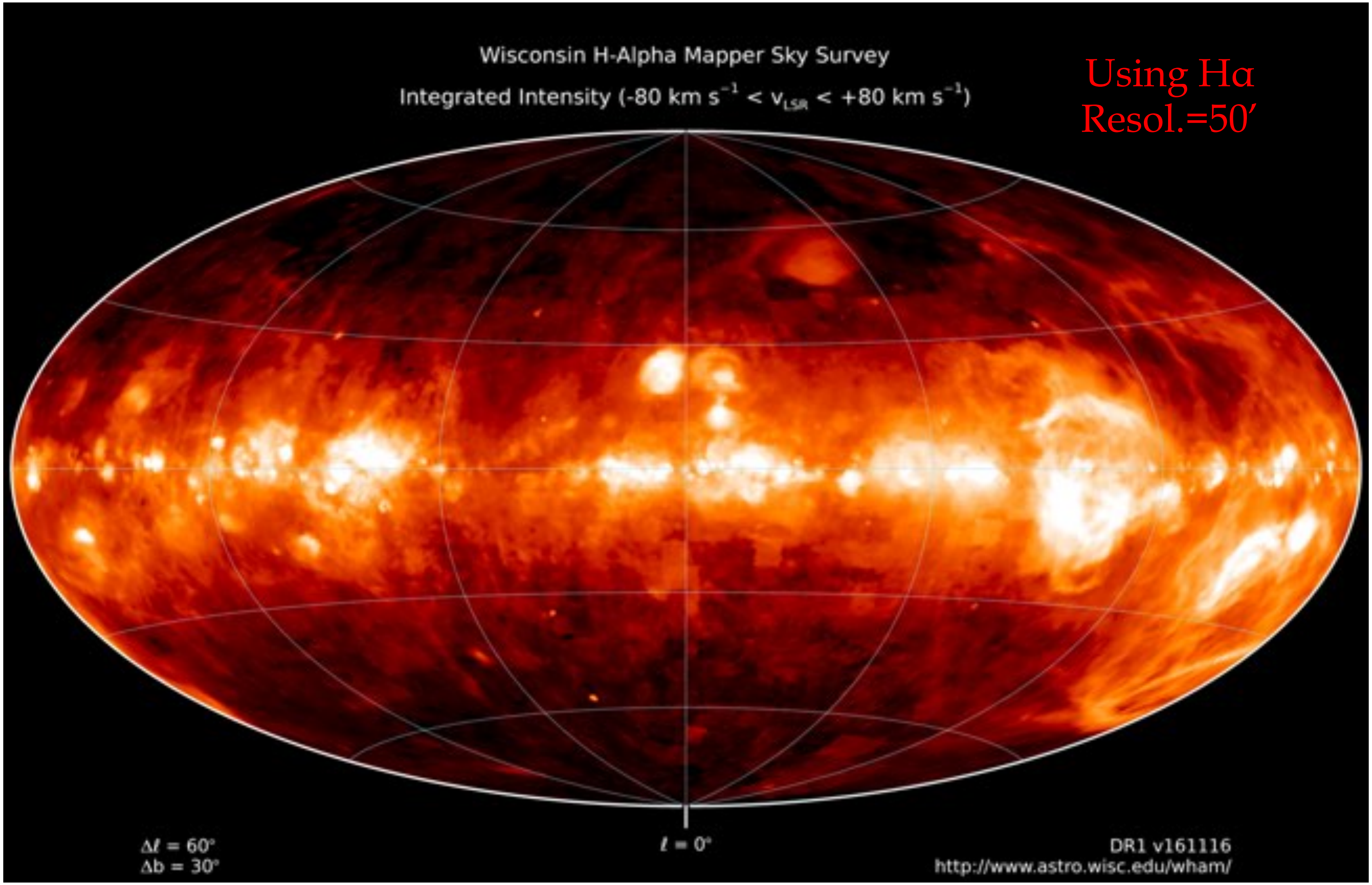
———— R=1.5 R_0

-------- R=∞, v_r=- Ω_0 R_0 sin ℓ





N_{HII} map of the whole sky



Wisconsin H-Alpha Mapper Sky Survey

Integrated Intensity (-80 km s^{-1} < v_{LSR} < $+80$ km s^{-1})

Using Hα
Resol.=50′

M_{HII}=2 x 10^9 M_{sun} (20% of HI) M_{stars}=8 x 10^9 $M_{sun.}$ (Kalberla & Kerp 2009)

What about molecular gas?

Energy levels of electrons in a molecule are the combination of the electronic, vibrational and rotational quantum numbers.

Lowest energies are for pure rotational levels of the ground state. Lines for transitions between these states can be observed in the radio domain with no dust extinction.

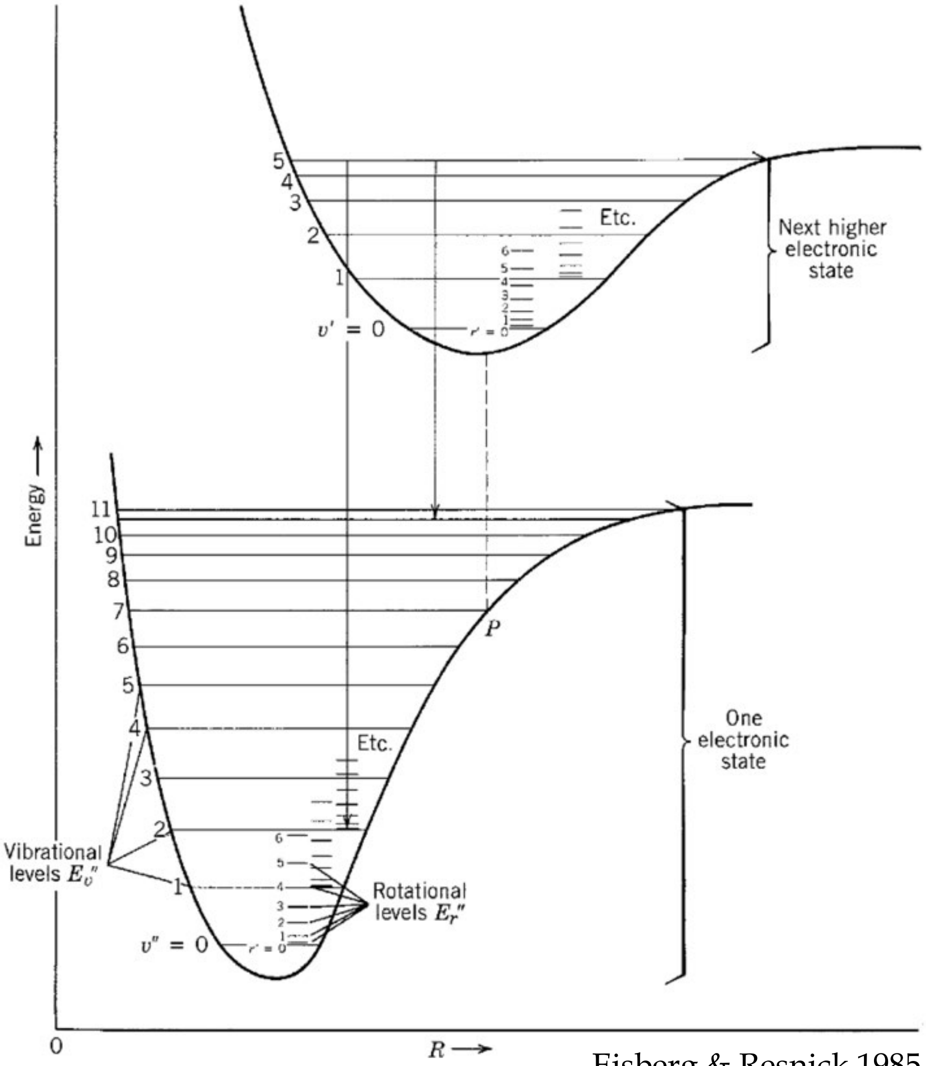
But H_2 has no permant electric dipole.

allowed transitions in the UV;
forbidden ro-vibrational transitions
in the MIR

Use other molecules as tracers of H_2

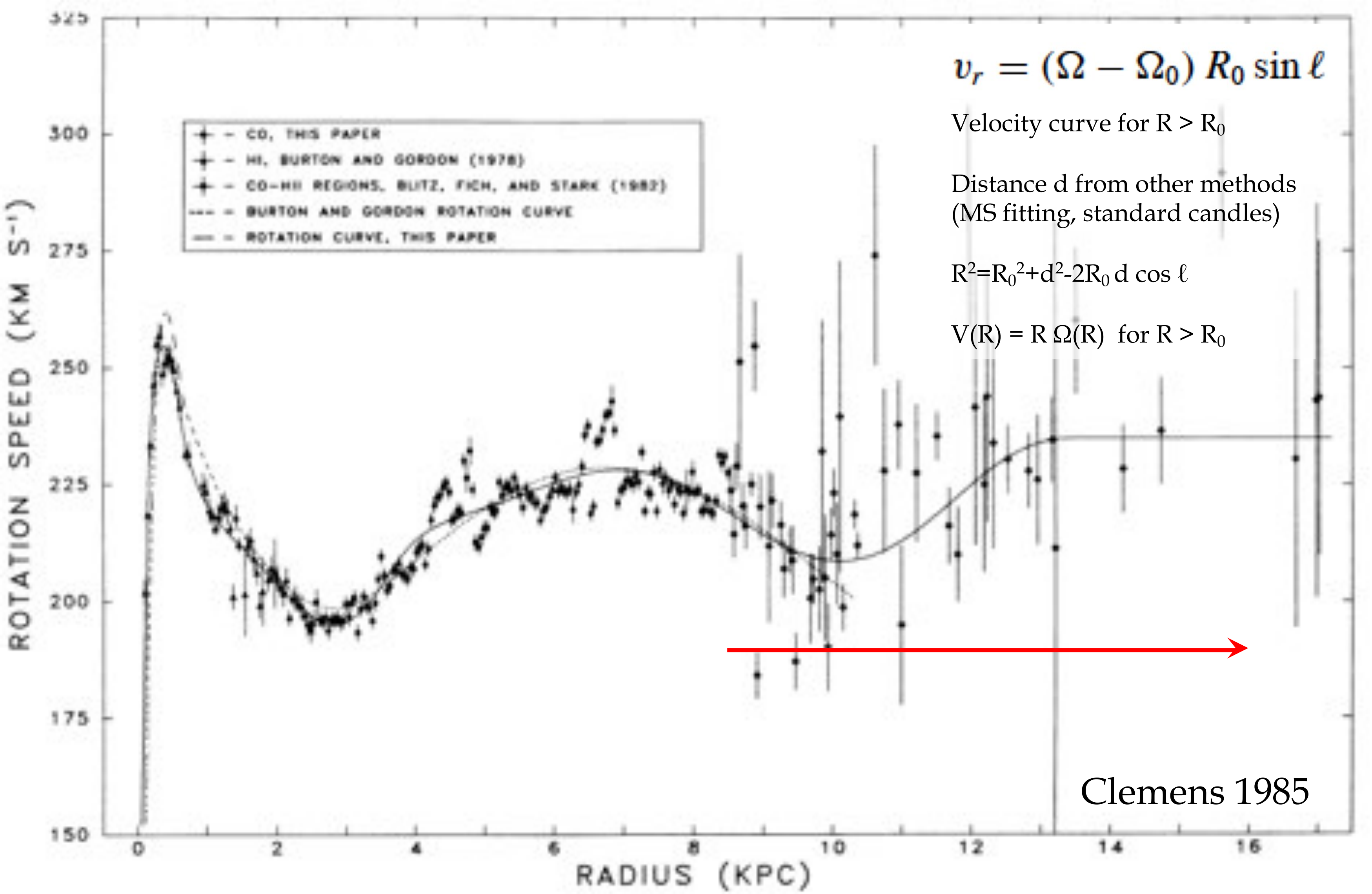
Rotational lines of CO:
CO(1-0) 2.6 mm (first detected in 1970)
CO(2-1) 1.3 mm
CO(3-2) 0.87 mm

(See also Zibetti lecture 6)



Eisberg & Resnick 1985

Galactic Rotation from CO



$$v_r = (\Omega - \Omega_0)\, R_0 \sin \ell$$

Velocity curve for $R > R_0$

Distance d from other methods (MS fitting, standard candles)

$R^2 = R_0^2 + d^2 - 2R_0\, d \cos \ell$

$V(R) = R\, \Omega(R)$ for $R > R_0$

Clemens 1985

The CO(1-0) 2.6 mm line

$$I_{\rm CO} = \int T_B(v)dv$$ [K km s^{-1}] at 2.6 mm (J=1-0 transition)

The line is optically thick for
N_H > a few 10^{20} H cm^{-2}

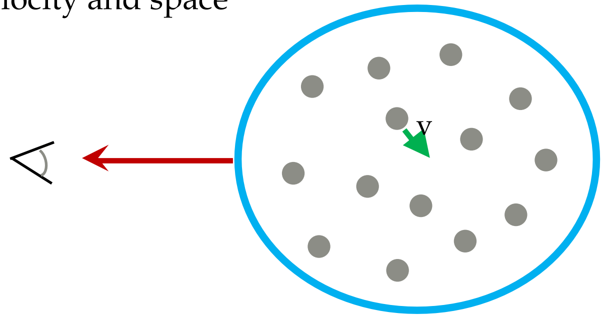
One can use optically thin isotopologues lines: $^{13}C^{16}O$ (1-0) or $^{12}C^{18}O$ (1-0)

Nevertheless, molecular cloud masses

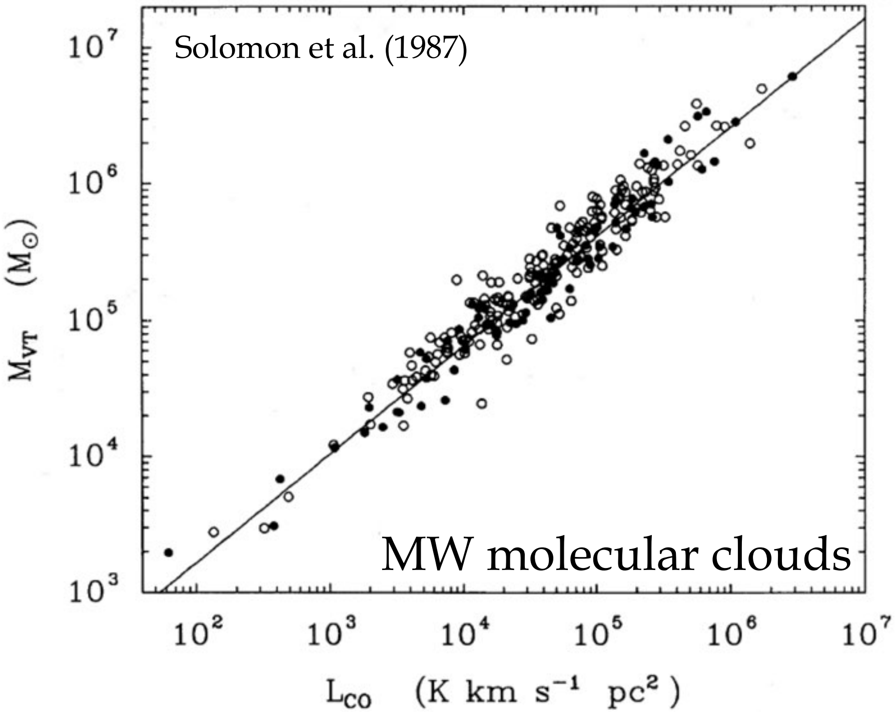
$$M_{VT} \propto \frac{R\sigma_v^2}{G}$$

are proportional to L_{CO}=I_{CO}*Area

A MC made of small opaque cloudlets with a small filling factor, without a significant overlap in velocity and space



L_{CO} counts the number of cloudlets in the area

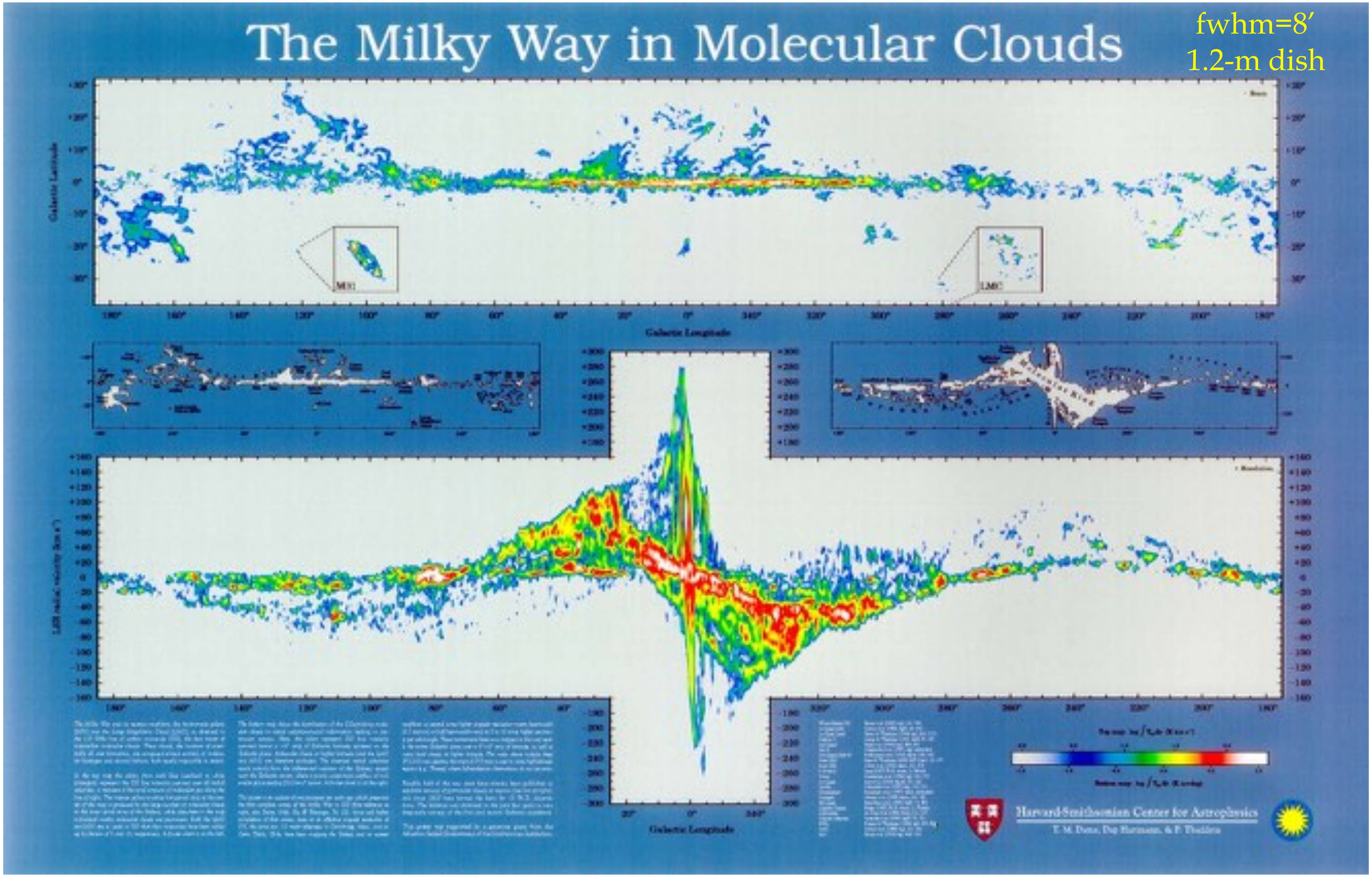

Solomon et al. (1987)

$$N(H_2) = X_{\rm CO} I_{\rm CO}$$

X_{CO}=2 x 10^{20} cm^{-2}/(K km/s)$^{-1}$ (Bolatto et al. 2013)

CO-to-H_2 conversion factor

CO(1-0) survey of the MW

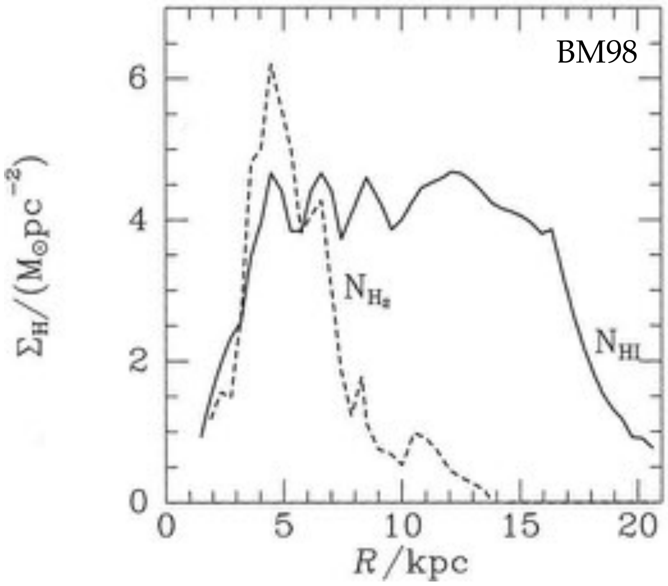


fwhm=8′
1.2-m dish

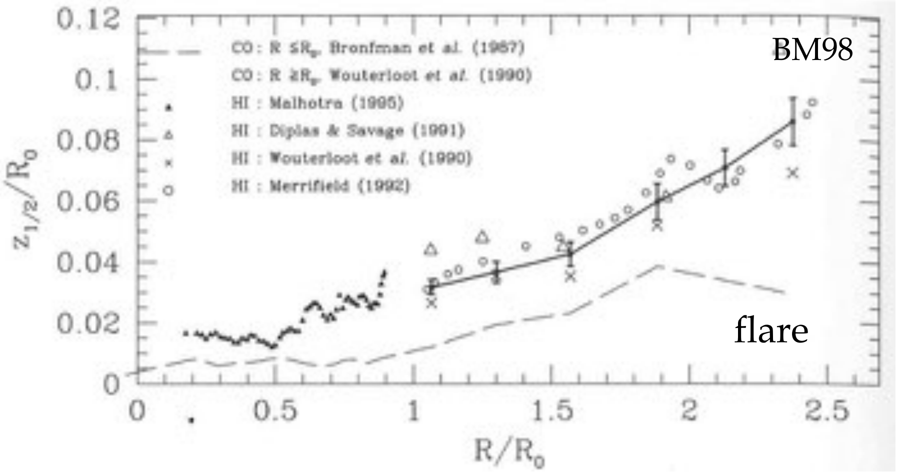
M_{H2}=2.5 x 10^9 M_{sun} (20% of H) M_{stars}=8 x 10^9 $M_{sun.}$ (Kalberla & Kerp 2009)

Radial and vertical gas distributions

Radial profile

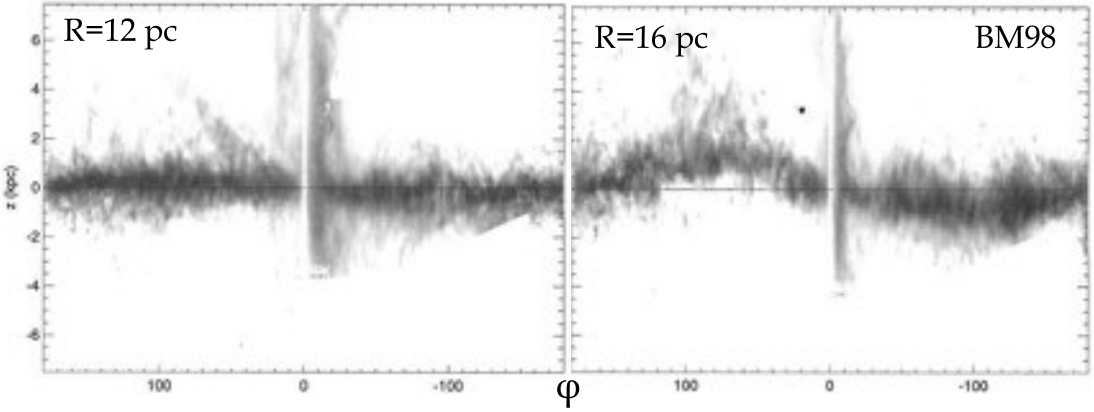


Disk thickness



$Z_{1/2}$ = 70 pc (H_2), 210 pc (HI)
half thickness at half intensity

Disk warp in HI

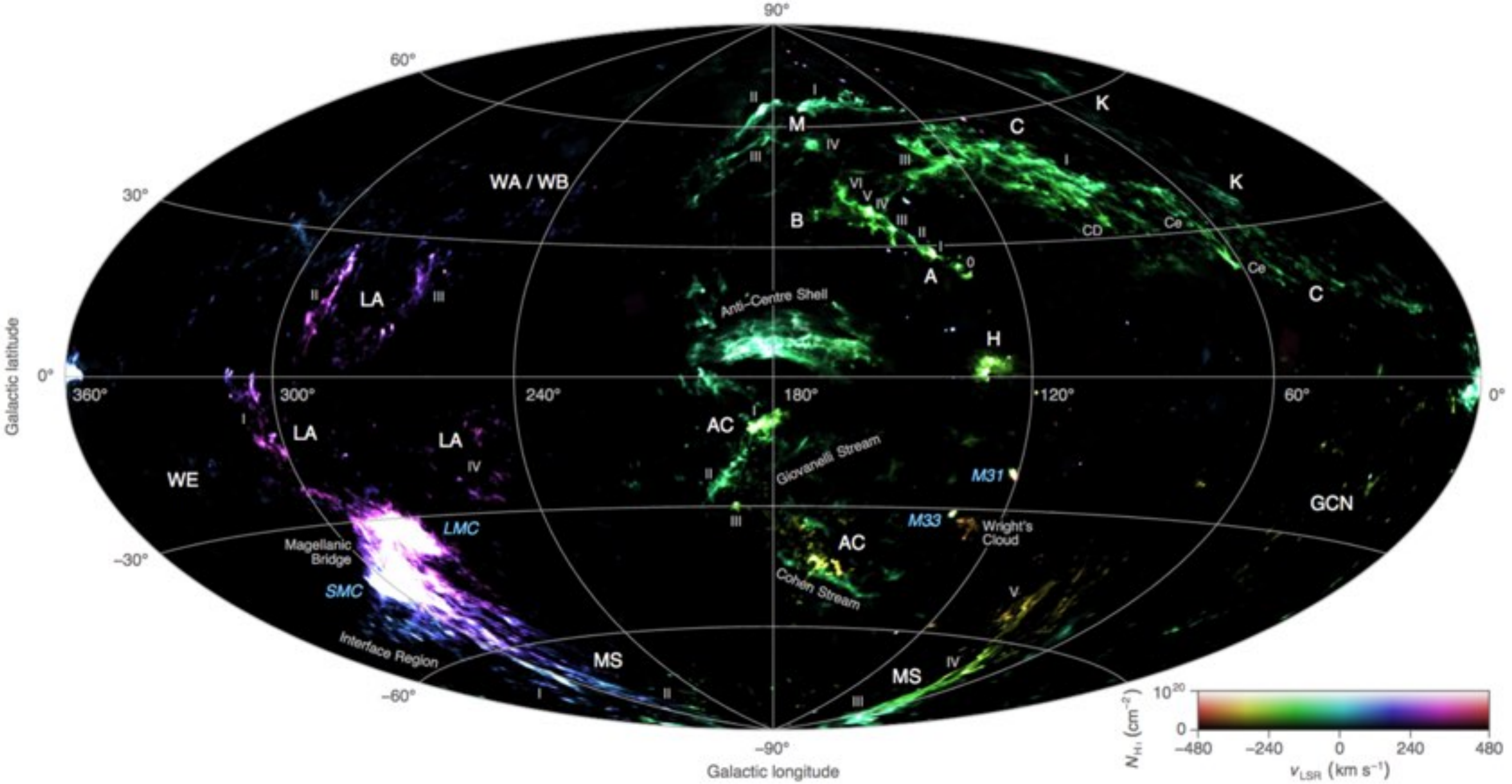


Shu 1982

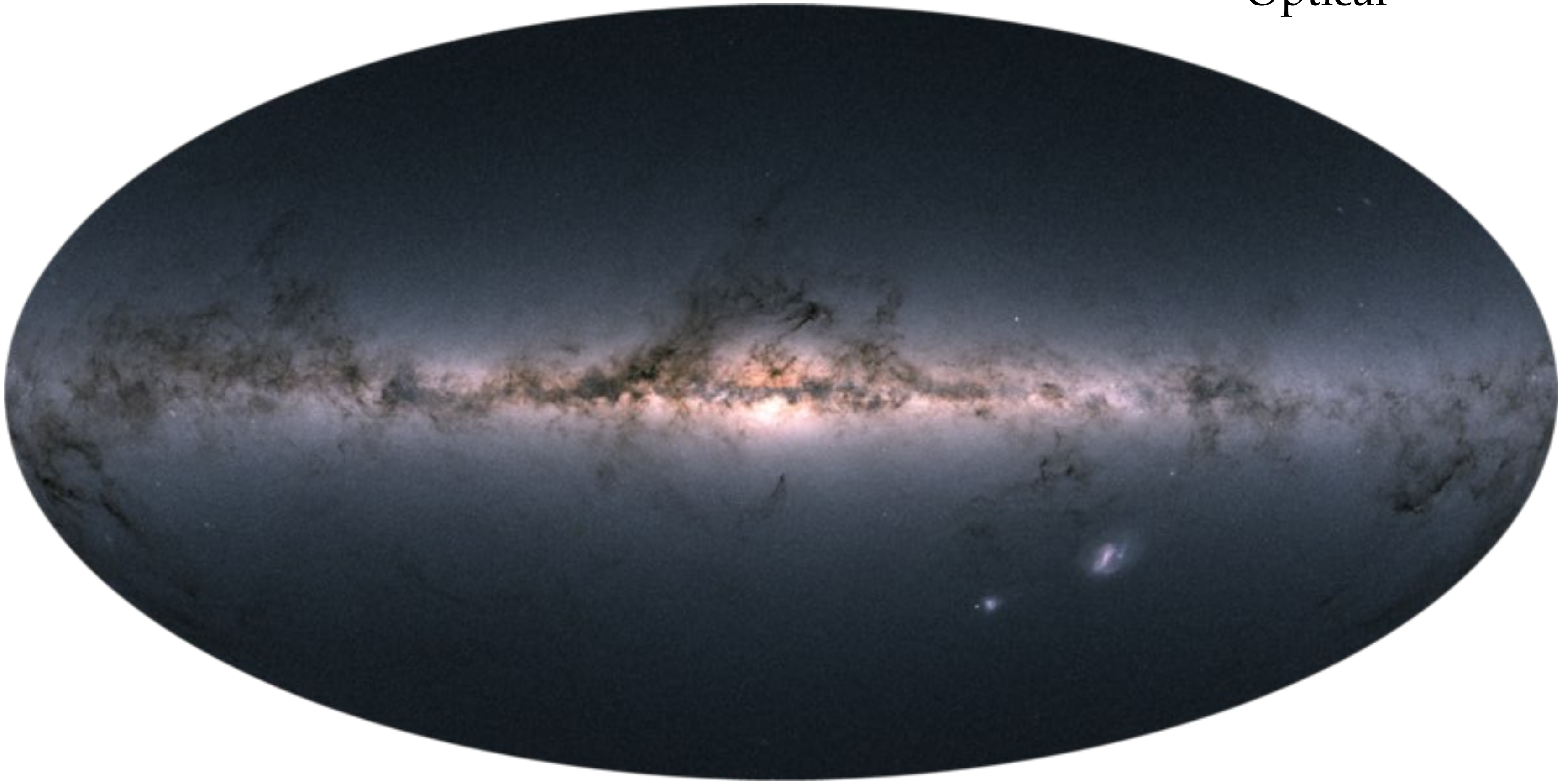
Figure 12.18. A schematic edge-on view of the gaseous disk of our Galaxy illustrating both the flare of the disk thickness beyond the solar circle and the warp of the plane.

High velocity clouds in the MW halo

Westmeyer 2017

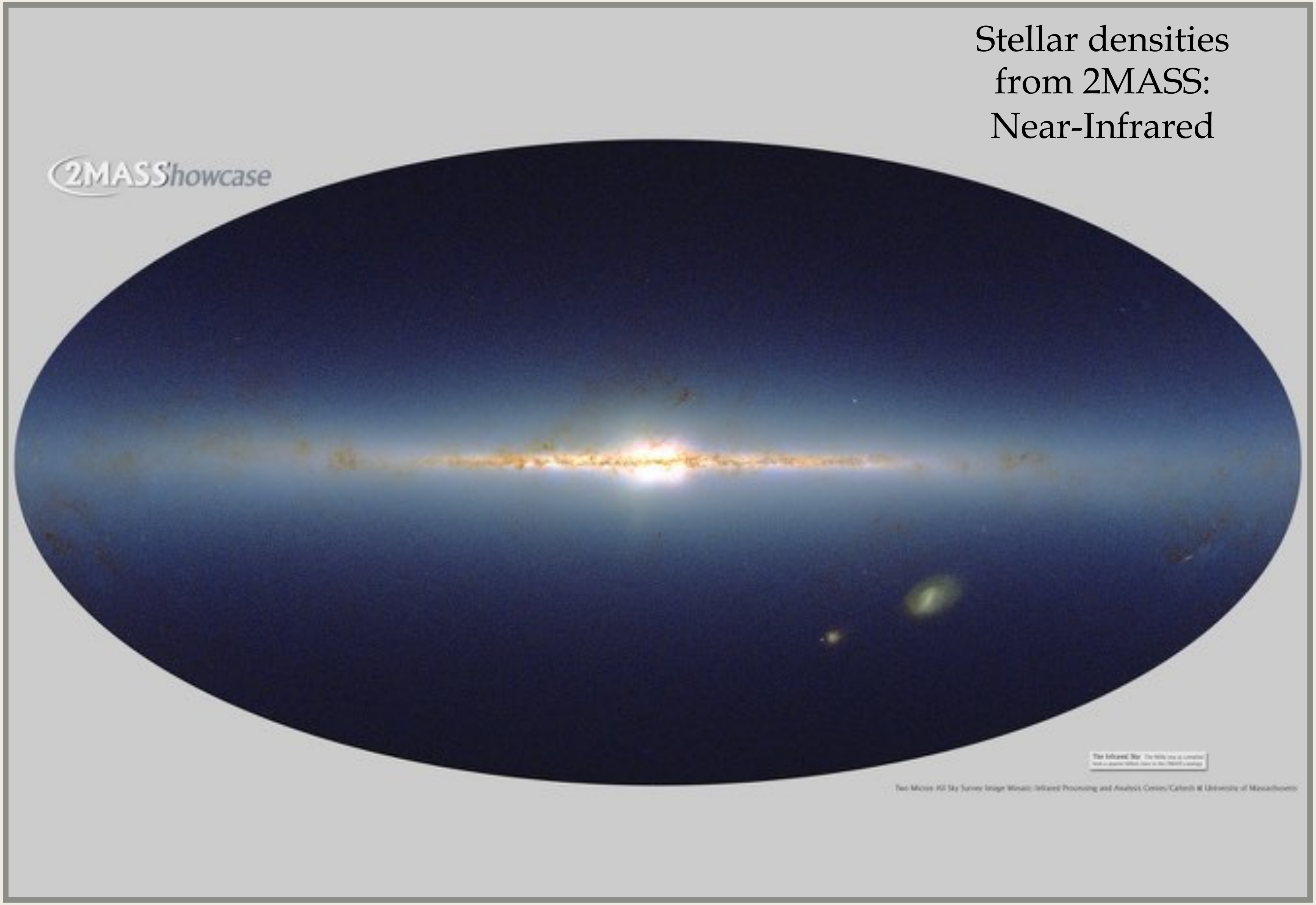


Dust in the Milky Way



Stellar densities
from the Gaia satellite:
Optical

Dust in the Milky Way

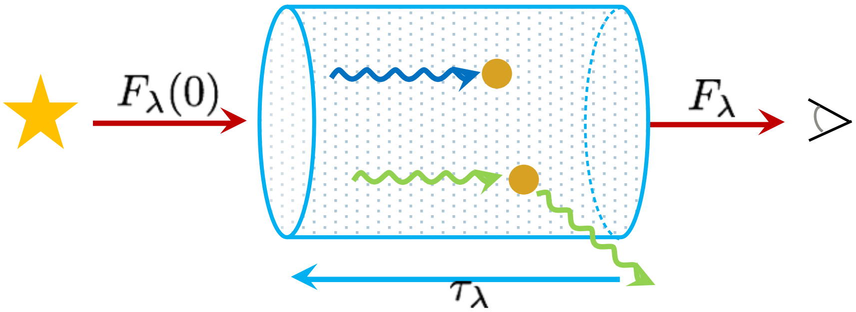


Stellar densities
from 2MASS:
Near-Infrared

Two Micron All Sky Survey Image Mosaic: Infrared Processing and Analysis Center/Caltech & University of Massachusetts

Interstellar extinction

Extinction = absorption + scattering



$$F_\lambda = F_\lambda(0)e^{-\tau_\lambda}$$

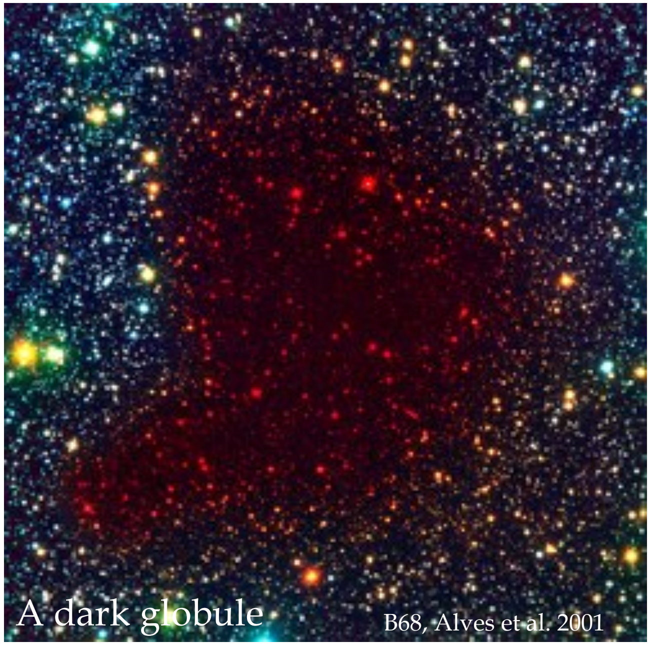
$$\tau_\lambda = \int \kappa_\lambda \, ds = \int \boxed{n_{\rm d}}\boxed{C_{\rm ext}(\lambda)} \, ds$$

grain number density

cross section, depending on radius and material

$$A_\lambda = m_\lambda - m_\lambda(0) = -2.5 \ \log_{10} \frac{F_\lambda}{F_\lambda(0)} = -2.5 \ \log_{10}(e^{-\tau_\lambda}) = 1.086 \ \tau_\lambda$$

Extinction


A dark globule

B68, Alves et al. 2001

blue is more extinguished than red: *Reddening*

$$C_{\rm ext} = C_{\rm abs} + C_{\rm sca}$$

Albedo $\omega = \frac{C_{\rm sca}}{C_{\rm ext}}$

Asimmetry factor

$$g =< cos\theta >$$


A reflection nebula

IC2118 APoD

Extinction measurements

$$F_\lambda = \frac{L_\lambda}{4\pi D^2} e^{-\tau_\lambda}$$

Pair method: observe two stars of the same spectral type, X and Y, at two wavelengths λ_1 and λ_2

$$\frac{(F_{\lambda_1}/F_{\lambda_2})_X}{(F_{\lambda_1}/F_{\lambda_2})_Y} = \boxed{\frac{(L_{\lambda_1}/L_{\lambda_2})_X}{(L_{\lambda_1}/L_{\lambda_2})_Y}} \times \frac{e^{-\tau_X(\lambda_1)+\tau_X(\lambda_2)}}{\boxed{e^{-\tau_Y(\lambda_1)+\tau_Y(\lambda_2)}}}$$

= 1 if star B unextinguished

= 1 if same spectral type (same color)

$$-2.5\ \log\left[\frac{(F_{\lambda_1}/F_{\lambda_2})_X}{(F_{\lambda_1}/F_{\lambda_2})_Y}\right] = 1.086\,[\tau_X(\lambda_1) - \tau_X(\lambda_2)] = A_{\lambda_1} - A_{\lambda_2} = E(\lambda_1 - \lambda_2)$$

colour excess

$$= A_{\lambda_1}$$

extinction

$$\lim_{\lambda_2 \to \infty} A_{\lambda_2} = 0$$

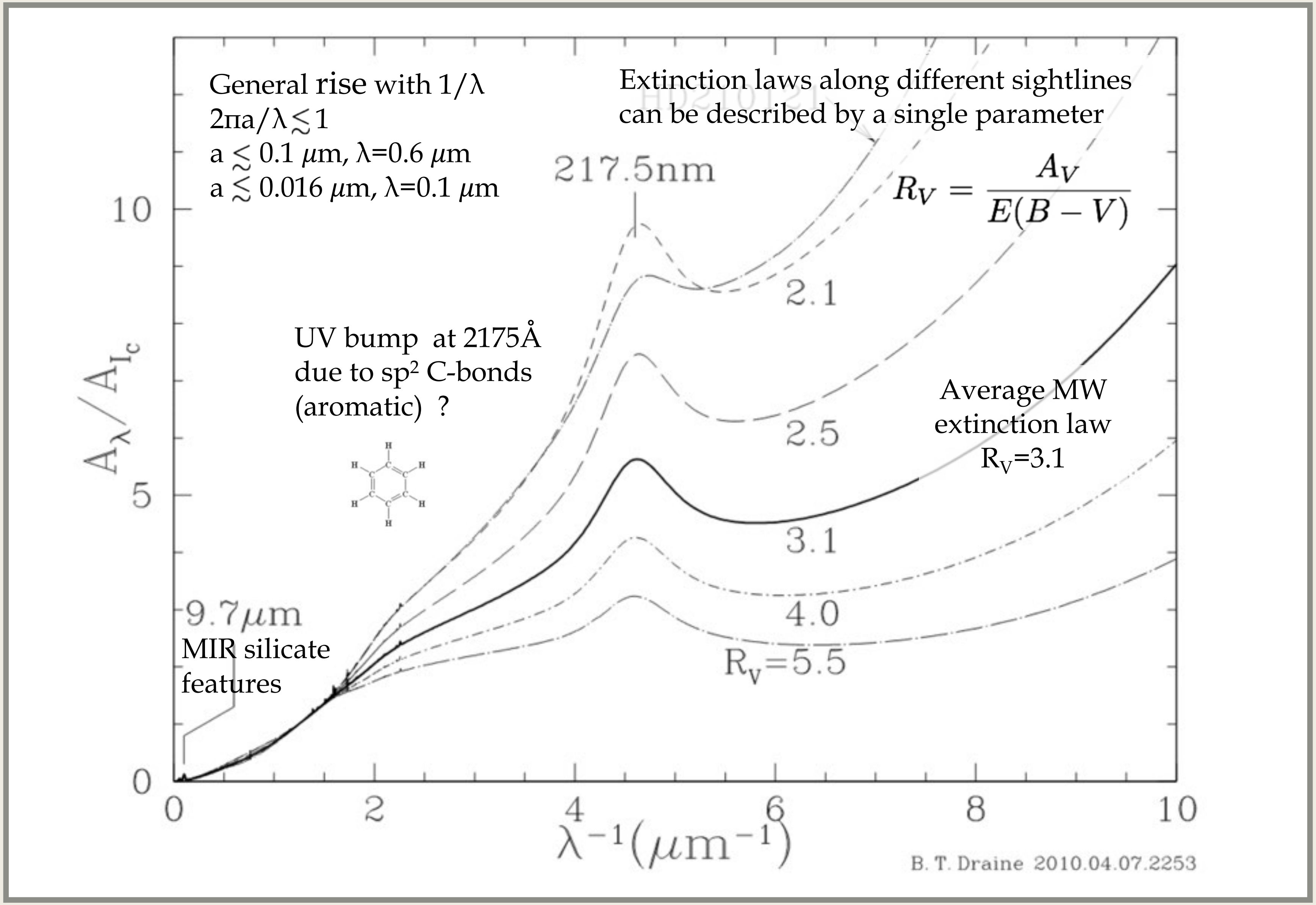
Normalised to remove dependence on the column density

$$\frac{A_\lambda}{A_V} \qquad \frac{E(\lambda - V)}{E(B - V)}$$

as a function of λ

Extinction law

The extinction law



General rise with $1/\lambda$
$2\pi a/\lambda \lesssim 1$
$a \lesssim 0.1\ \mu m$, $\lambda=0.6\ \mu m$
$a \lesssim 0.016\ \mu m$, $\lambda=0.1\ \mu m$

Extinction laws along different sightlines can be described by a single parameter

$$R_V = \frac{A_V}{E(B-V)}$$

UV bump at 2175Å due to sp^2 C-bonds (aromatic) ?

Average MW extinction law R_V=3.1

MIR silicate features

Extinction and gas column density

UV interstellar absorption lines from HI (Lyα) and H2 (Lyman/Werner bands) seen with satellites in the 1970's

$$N(H) = N(HI) + 2N(H_2)$$

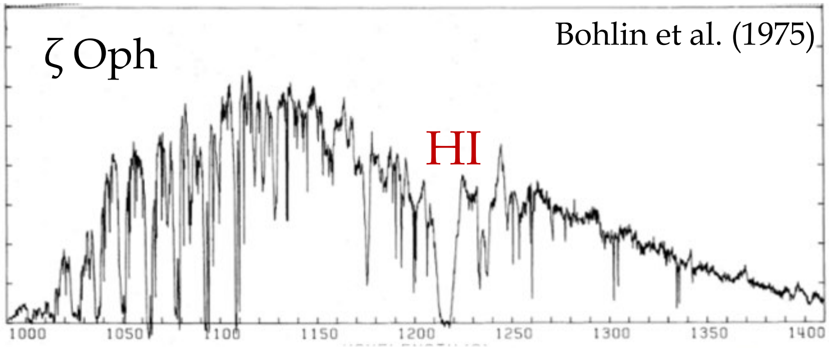
$$\frac{N(H)}{E(B-V)} = 5.8 \times 10^{21}\ \mathrm{H\ cm^{-2}\ mag^{-1}}$$

Bohlin et al. (1978)

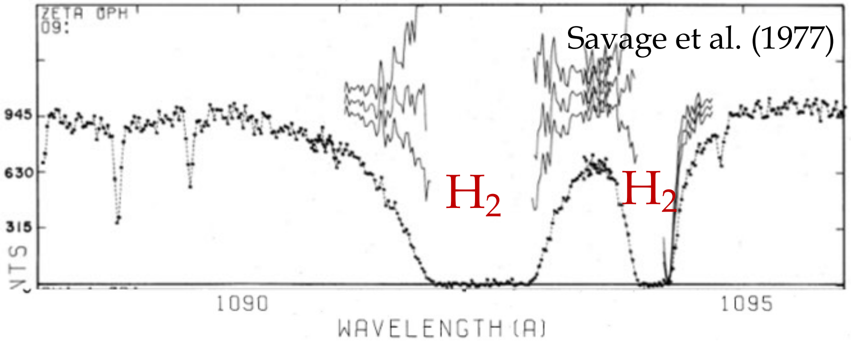
$$\frac{A_V}{N(H)} = 5.3 \times 10^{-22}\ \mathrm{mag\ cm^2\ H^{-1}}$$

$$A_V = 1.086\,\tau_V = 1.086\,N_d \overset{C_{\mathrm{ext}}}{\boxed{\pi a^2 Q_{\mathrm{ext}}}}$$

$$N_d\,L = \frac{M_d}{\frac{4}{3}\pi a^3 \rho} \qquad N(H)\,L = \frac{M_{\mathrm{H}}}{m_{\mathrm{H}}}$$



Bohlin et al. (1975)



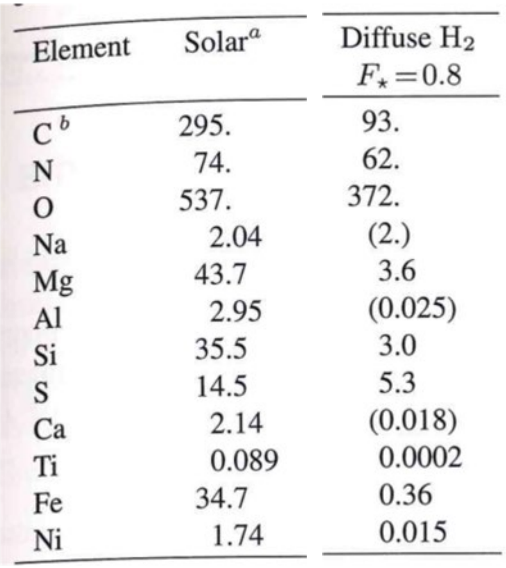
Savage et al. (1977)

$$Q_{\mathrm{ext}}(V) = 1.5$$
$$a = 0.1\ \mu\mathrm{m}$$
$$\rho = 3\ \mathrm{g\ cm^{-3}}$$

$$\frac{M_d}{M_{\mathrm{H}}} \approx \frac{1}{130}$$

dust-to-gas ratio ~1/100

Interstellar depletion



Element	Solar[a]	Diffuse H_2 $F_\star=0.8$
C[b]	295.	93.
N	74.	62.
O	537.	372.
Na	2.04	(2.)
Mg	43.7	3.6
Al	2.95	(0.025)
Si	35.5	3.0
S	14.5	5.3
Ca	2.14	(0.018)
Ti	0.089	0.0002
Fe	34.7	0.36
Ni	1.74	0.015

Table 9.5 Gas-Phase Abundances Relative to H of Selected Elements (ppm) in HI regions (Draine 2011).

$F_\star$=1 for ζ Ophi (Jenkins 2009)

ISM absorption lines in the UV allow to derive the ISM abundance

some metals are depleted in the ISM,
i.e. they are underabundant w.r.t. the Sun

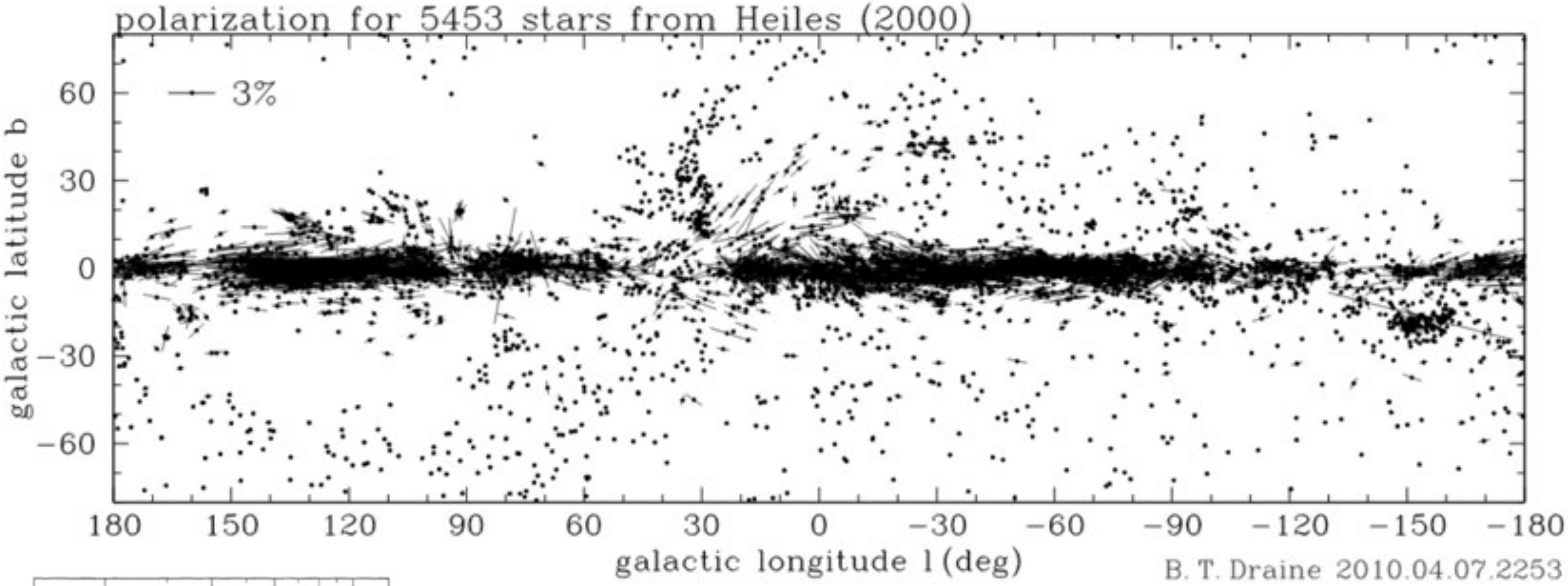
Dust grains are made of these *missing* metals

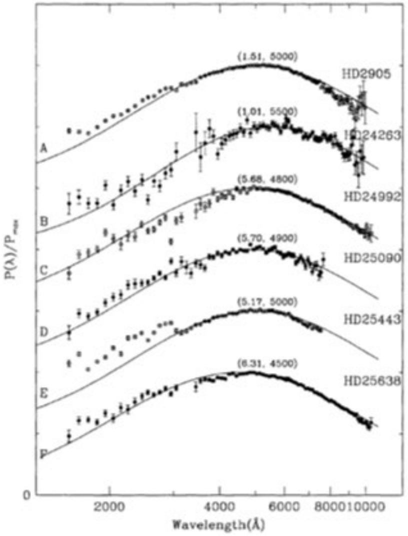
$$\frac{M_d}{M_{\rm H}} \approx \frac{1}{110}$$

40-50% of all the metals in the ISM are in dust, the rest in gas

In the MW, $M_d \sim 10^8 M_{sun}$

Interstellar polarization





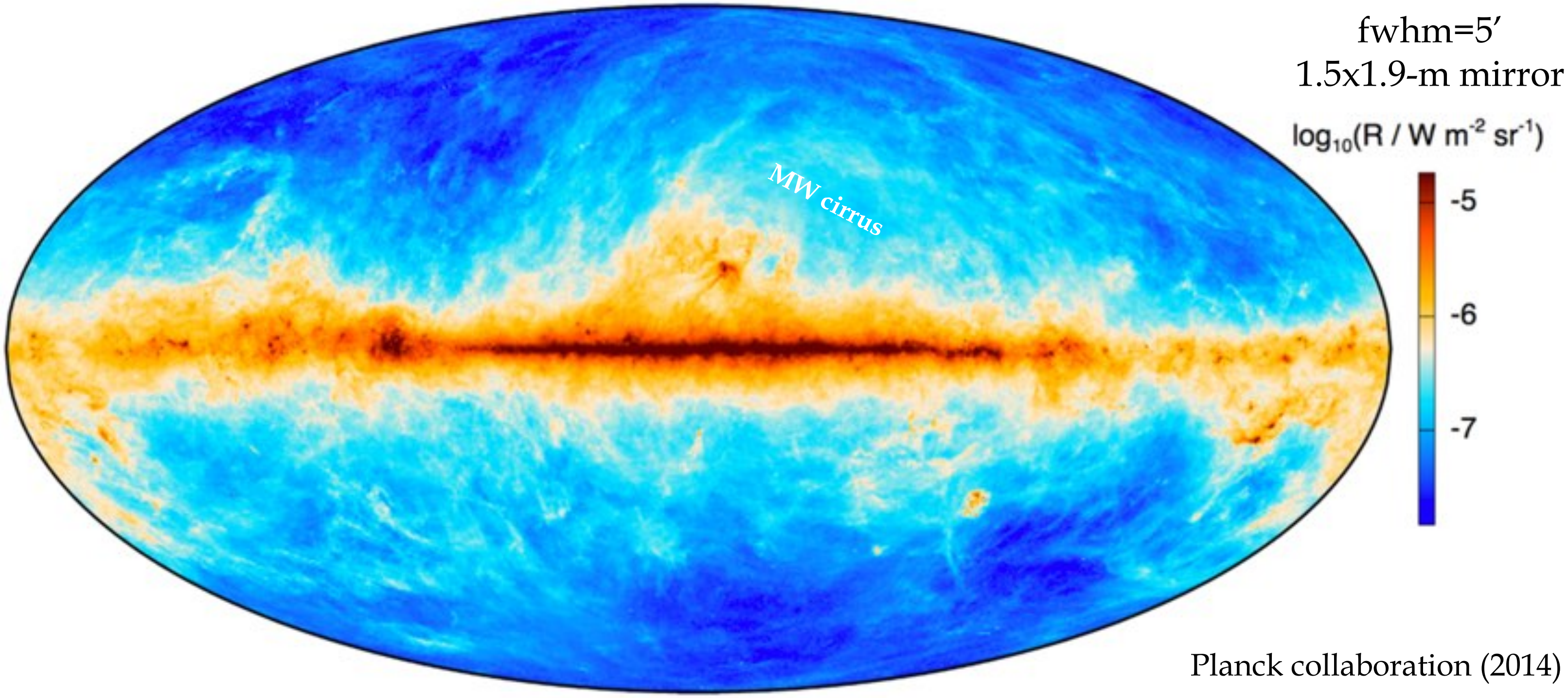
Starlight is polarized parallel to the Galactic plane

Some dust grains must be elongated and aligned perpendicular to the plane (due to grain charge and magnetic field).

Polarization follows the empyrical ‘Serkovski (1973) law’

Peak at V, so preferentially large grains (a=0.1 μm) are elongated and/or aligned

Dust emission in the Far-Infrared



fwhm=5′
1.5x1.9-m mirror

Planck collaboration (2014)

Energy absorbed by grains in UV/optical is emitted in the Mid and Far-IR

All sky surveys of dust at thermal equilibrium:
IRAS - Infrared Astronomical Satellite (1983): 100 μm
Planck (2009-2013): 350, 550, 850 μm

Optically thin emission
Thin disk as that of molecular gas

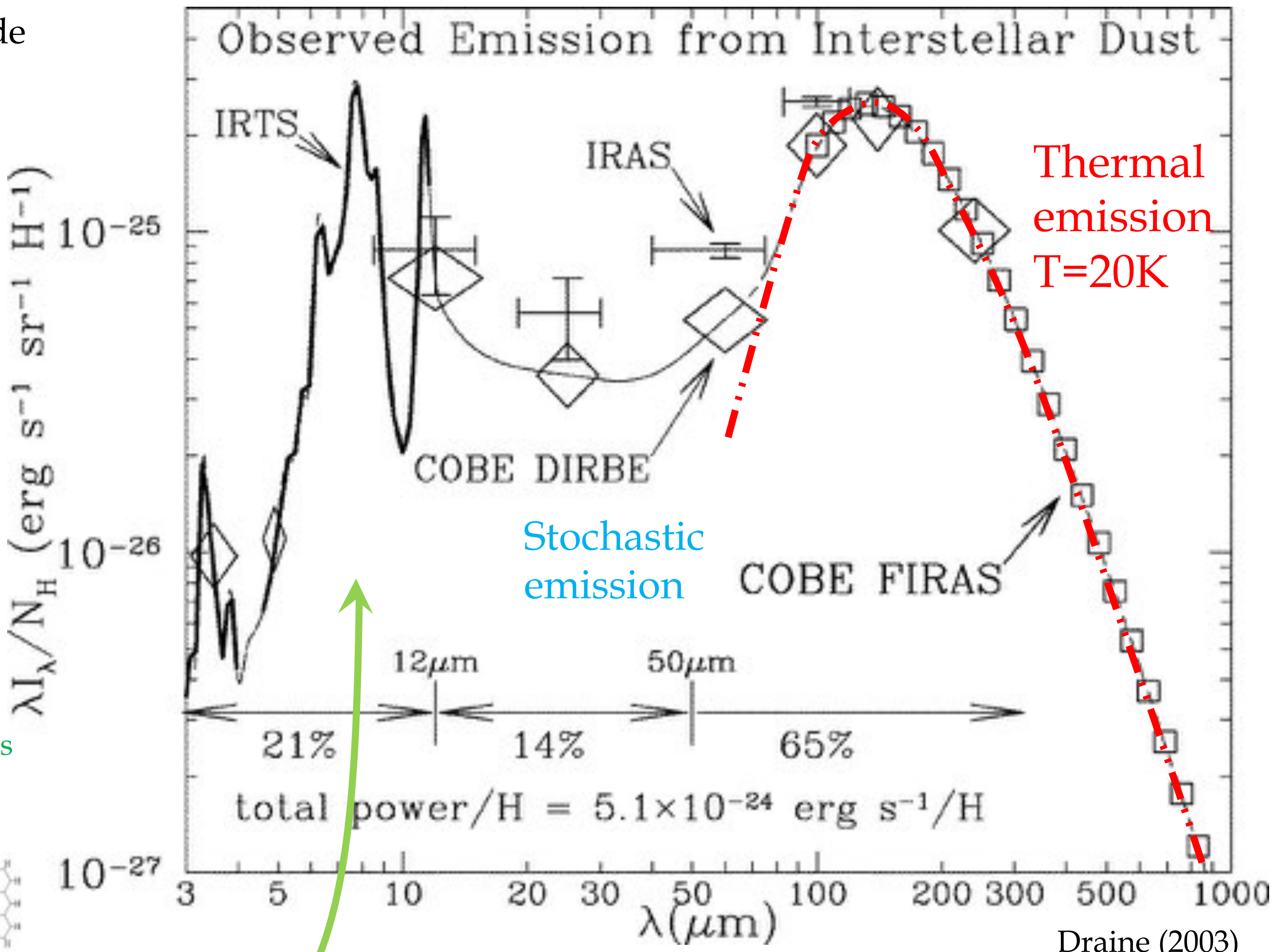
Other FIR missions: COBE, WISE, AKARI (whole sky surveys) ISO, Spitzer, Herschel

The MW *cirrus* spectrum

High Galactic latitude spectrum |b| > 20˚

normalised to
H column density

In the MW, 30% of the luminosity emitted by dust (the same for other galaxies; Bianchi et al. 2018)

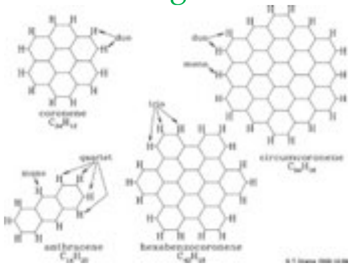


Thermal emission T=20K

Stochastic emission

Draine (2003)

PAHs – macro molecules or aromatic-rich small carbon grains



Herschel and Planck estimates agree with COBE/IRAS (Bianchi et al. 2019)

Dust models

Observations require grains of different sizes and materials

Observational constraints:

- ☐ Extinction law
- ☐ Albedo
- ☐ Asymmetry parameter
- ☐ Emission
- ☐ Abundance
- ☐ Polarization

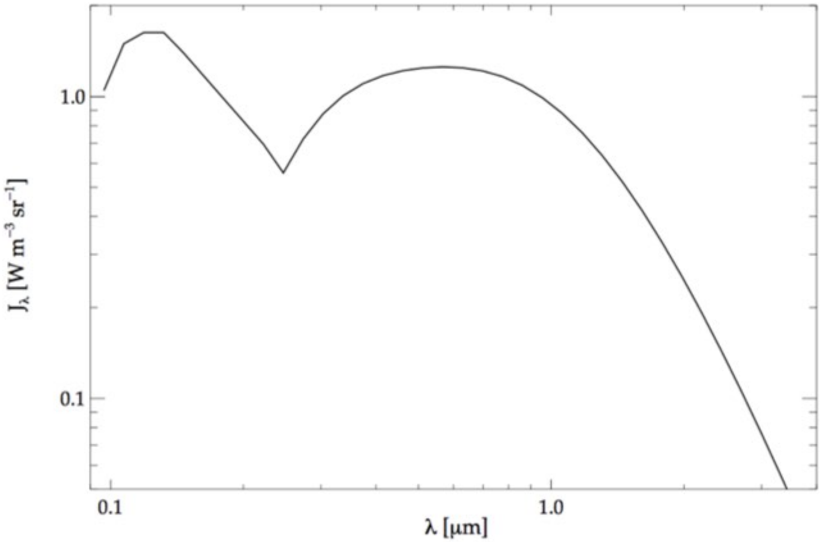
Ingredients:

- ☐ Shape:
  - Sphere
  - Spheroidal
  - Other
- ☐ Material
  - Silicates
  - Carbonaceous
  - PAHs?
- ☐ Size distribution
- ☐ ISRF field (for emission)

Mie theory (1908) for spherical grains. For a given refractive index and radius *a*, derive C_{ext}, C_{sca}, C_{abs} vs λ

Optical properties (refractive index) measured in a laboratory, sometimes tuned to better match observations: *astronomical silicates.*

Dust heating



The Local Interstellar Radiation Field (LISFR), from stellar emission and diffuse starlight (Mathis et al. 1983)

$$I_\nu = \tau_\nu S_\nu = \tau_\nu B_\nu$$

RT solution, optically thin limit, no background, thermal equ.

$$Q_{\rm abs} = Q_{\rm emi}$$

Kirchhoff's law

$$\int \overbrace{\boxed{4\pi\, a^2\, Q_{\rm abs}}}^{C_{\rm abs}} J_\nu\, d\nu = \int \boxed{4\pi\, a^2\, Q_{\rm abs}} B_\nu(T_d)\, d\nu$$

absorption = emission

UV, optical = MIR, FIR submm

equilibrium temperature

Dust Mass for a cloud (or galaxy) at distance D

Observed flux

$$F_\nu = I_\nu \Omega \qquad \Omega = \frac{S}{D^2}$$

Cloud solid angle

$$\tau_\nu = N_d\, \pi a^2\, Q_{\rm abs}$$

S area

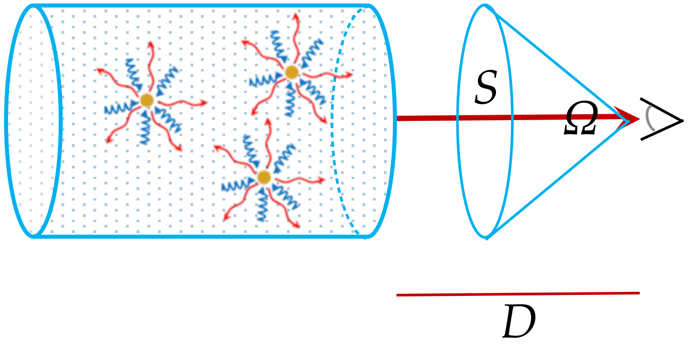
$$M_d = N_d S\, \frac{4}{3}\pi a^3\, \rho$$

$N_d S$ total number of grains in the cloud

$$F_\nu = \frac{M_d}{D^2} \boxed{\frac{3Q_{\rm abs}}{4a\rho}} B_\nu(T_d)$$

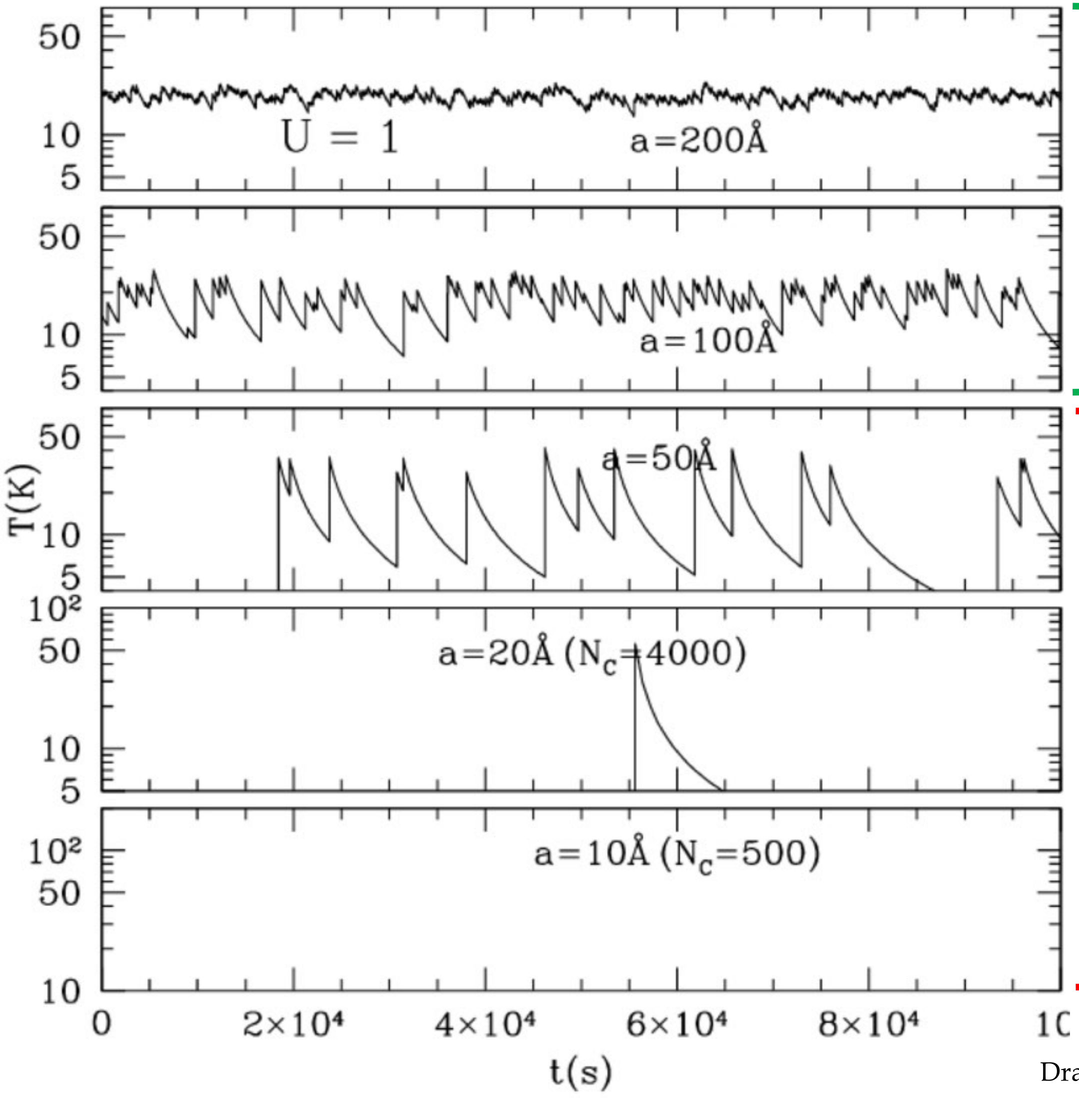
Absorption cross section per dust mass

If you have a dust model, you can fit the SED to obtain T_d and M_d



Dust heating

A day in the life of an interstellar grain heated by the LISRF



H(a,T) internal energy of the grain

hν absorbed photon energy

Thermal equilibrium heating

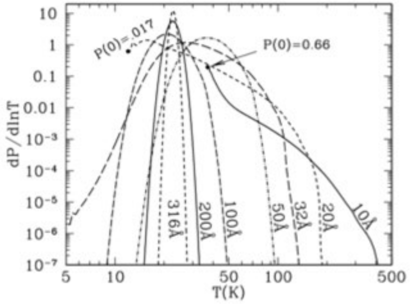
H(a,T) > hν

steady-stade equilibrium between absorption and emission, an equilibrium temperature can be defined

Stochastic heating

H(a,T) < hν

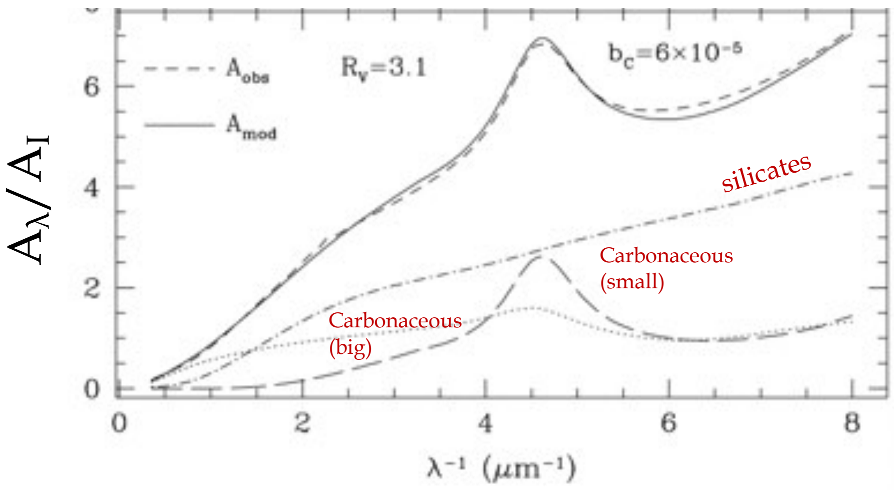
A small grain absorbing photons at short λ undergoes temperature fluctuations; it has a temperature distribution



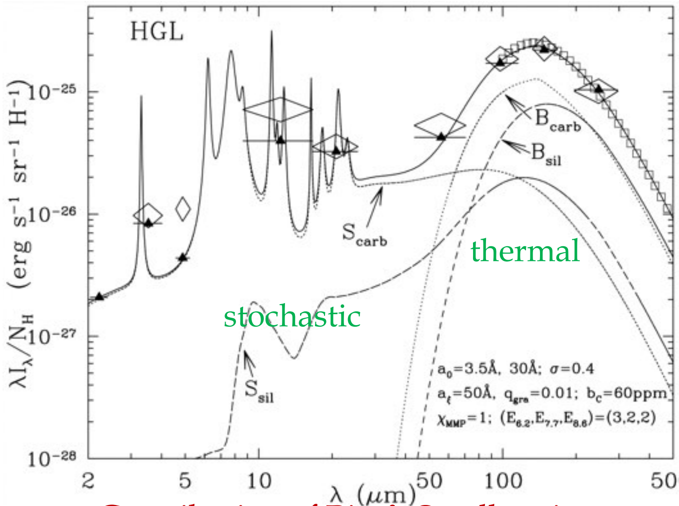
Draine (2011)

Dust models: results

Extinction law (Weingartner & Draine 2001)

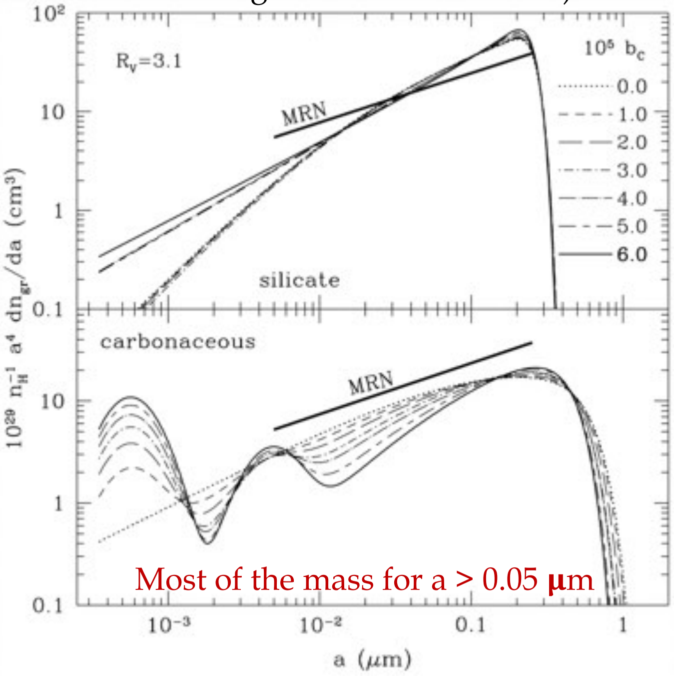


Cirrus emission (Li & Draine 2001)



Contribution of **B**ig & **S**mall grains

Grain size dV/dln(a)
Weingartner & Draine 2001)



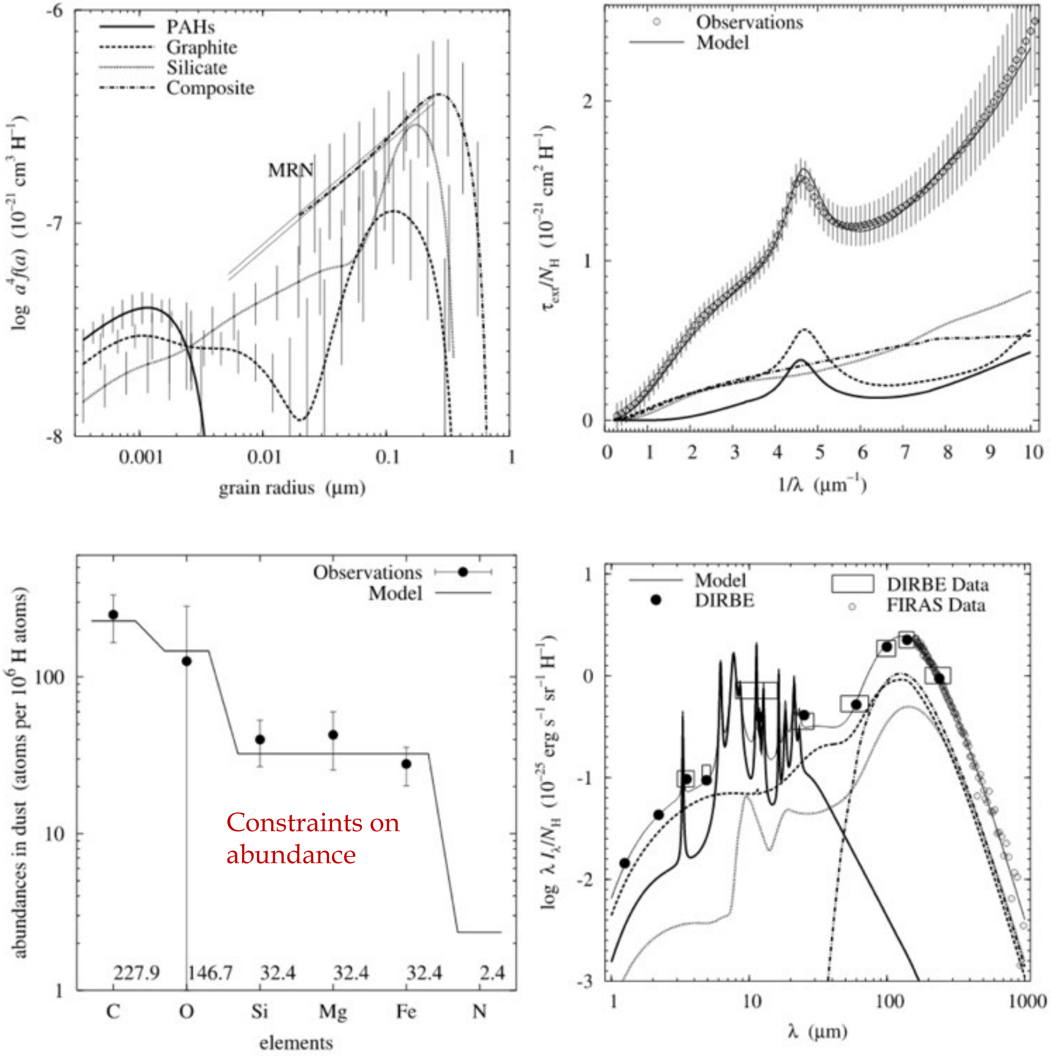
Most of the mass for a > 0.05 **μ**m

MRN: $dn/da \propto a^{-3.5}$
(Mathis et al. 1977)

Dust models: other results

Zubko et al. (2003)

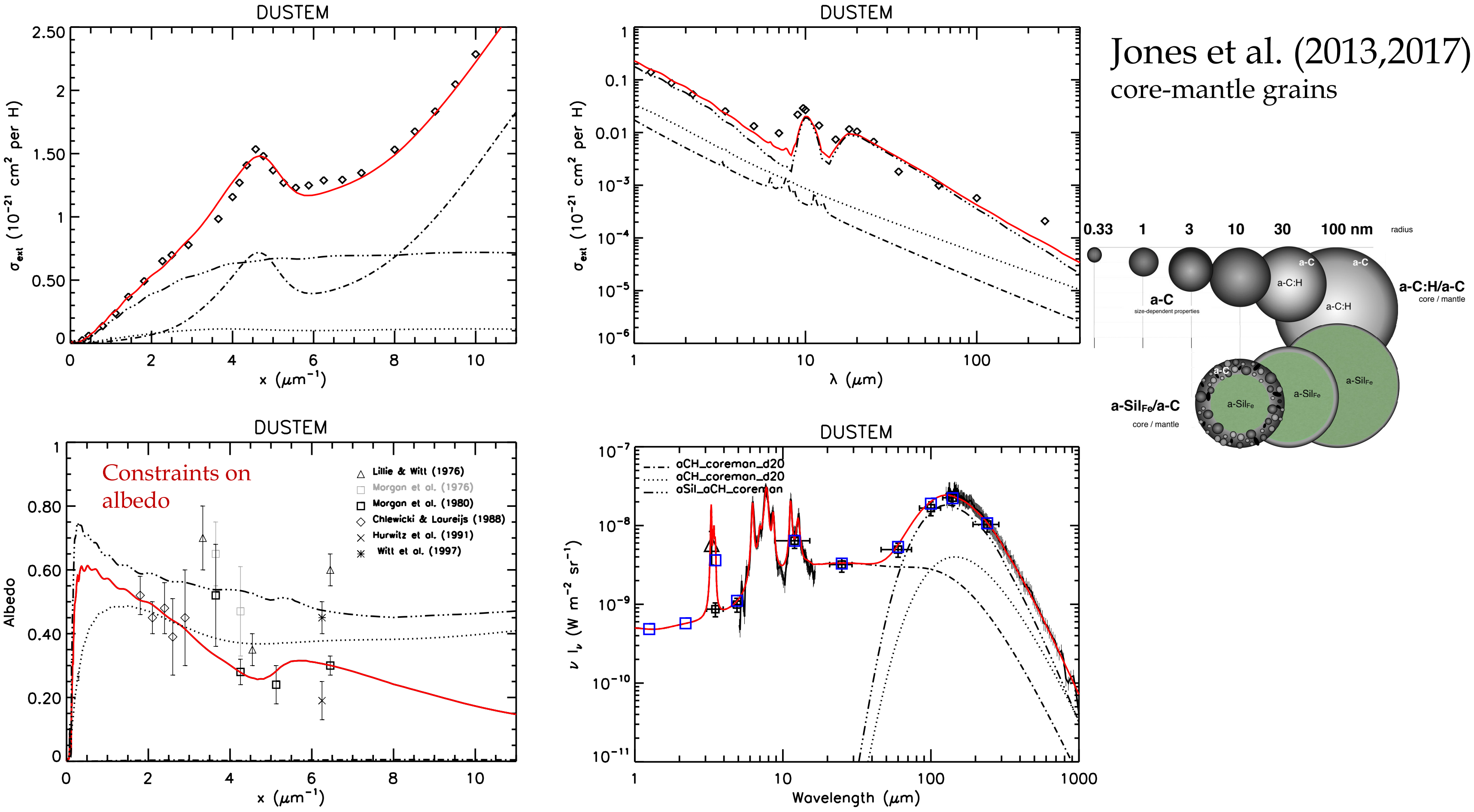
Explored 15 different material combinations



Constraints on abundance

FIG. 11.—COMP-GR-FG dust model: the size distributions (*top left*), extinction curve (*top right*), elemental requirements (*bottom left*), and emission spectrum (*bottom right*). Two straight lines are the MRN size distributions for silicate (*upper line*) and graphite (*lower line*).

Dust models: other results



Jones et al. (2013,2017)

core-mantle grains

Marginal agreement between the various models.
Dust mass estimates varies by a factor 3 (Nersesian et a. 2019)

Stardust vs Interstellar dust

Stardust: dust grains condense in the later stages of stellar evolution
(AGB stars, Planetary nebulae, SN, etc.)

$$dM_{d,inj}/dt \sim 4 \times 10^{-2}\ M_{sun}\ yr^{-1}$$

But dust can be destroyed by SN shocks and star formation in the ISM. The lifetime against destruction by SN and ISM processing are estimated to be

$$\tau_{dest} = 4 \times 10^{8}\ yr \qquad \tau_{ISM} = 4 \times 10^{9}\ yr$$

Steady state equilibrium requires:

$$dM_{d,inj}/dt = M_d \times (1/\tau_{dest} + 1/\tau_{ISM}) \cong M_d/\tau_{dest}$$

$$M_d = 1.6 \times 10^{6}\ M_{sun}$$

but

$M_d \sim 10^{8}\ M_{sun}$ in the MW

Thus, the bulk of the dust mass must form in the ISM, by accretion on initial seeds produced by stars (see: Draine 2003, Rossi Lectures).

Summary

The MW mass

- Total (with DM) $4.6 \times 10^{11}\,M_{sun}$
- Baryons $9.5 \times 10^{10}\,M_{sun}$
- Stars $8.2 \times 10^{10}\,M_{sun}$ M_{stars} = 87% $M_{baryons}$
- Atomic gas HI $8 \times 10^{9}\,M_{sun}$
  HII $2 \times 10^{9}\,M_{sun}$
  M_{gas} = 13% $M_{baryons}$
- Molecular gas $2.5 \times 10^{9}\,M_{sun}$

Kalberla & Kerp (2009)
From a dynamical model
(including He? $M_{He}/M_{H} \cong 25\%$)

- Dust $\sim 10^{8}\,M_{sun}$ $M_{dust} \cong 1/100\,M_{H}$
- Metals *in the gas phase* $\sim 10^{8}\,M_{sun}$ $M_{dust} \cong M_{metals}$