What Do Gamma-Ray Astronomers Need to Know about Molecular Clouds?

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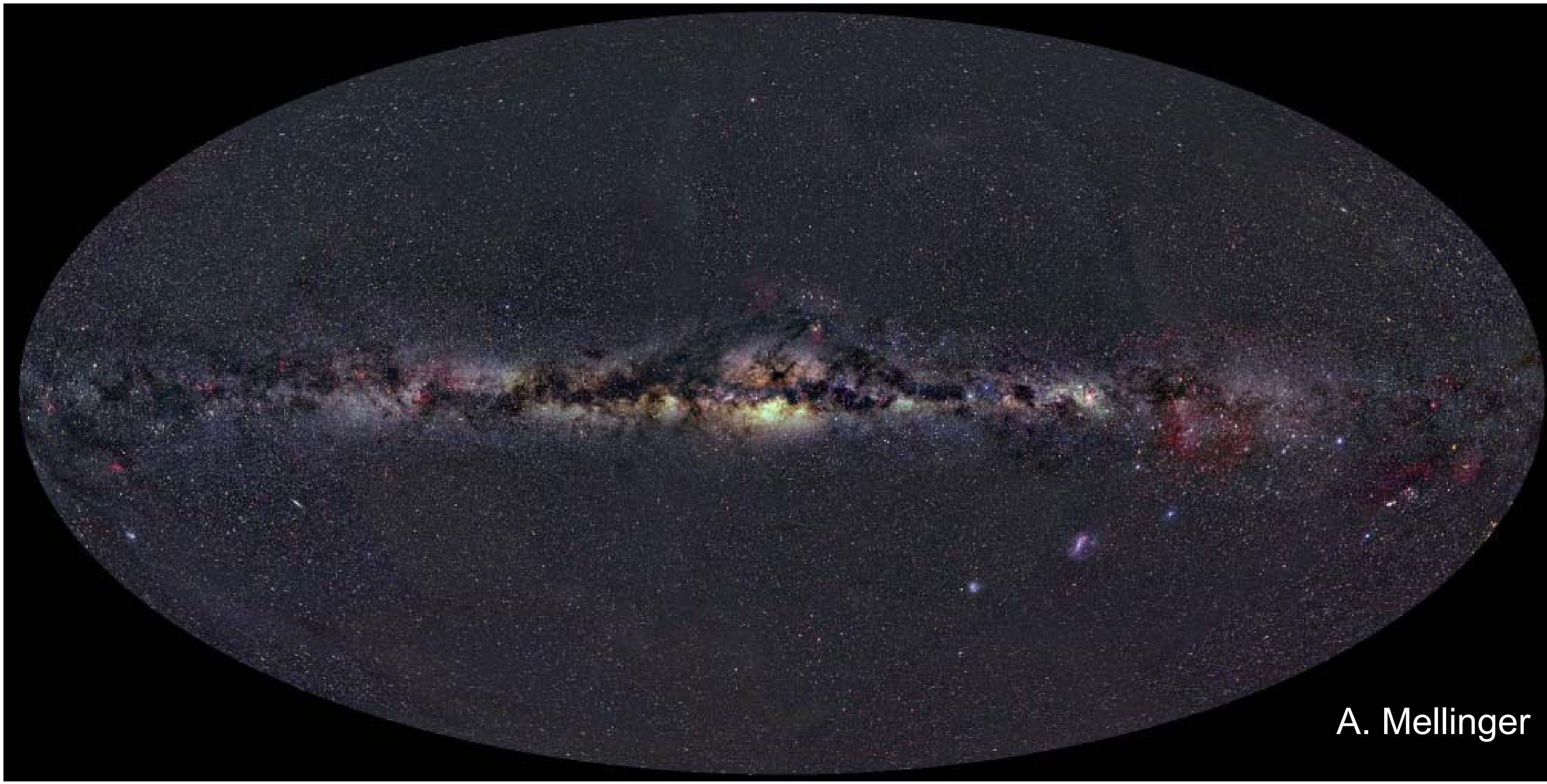
Outline

- A biased and incomplete summary of some important aspects of the interstellar medium
- Followed by what we know and can anticipate learning about molecular clouds from gamma-ray observations

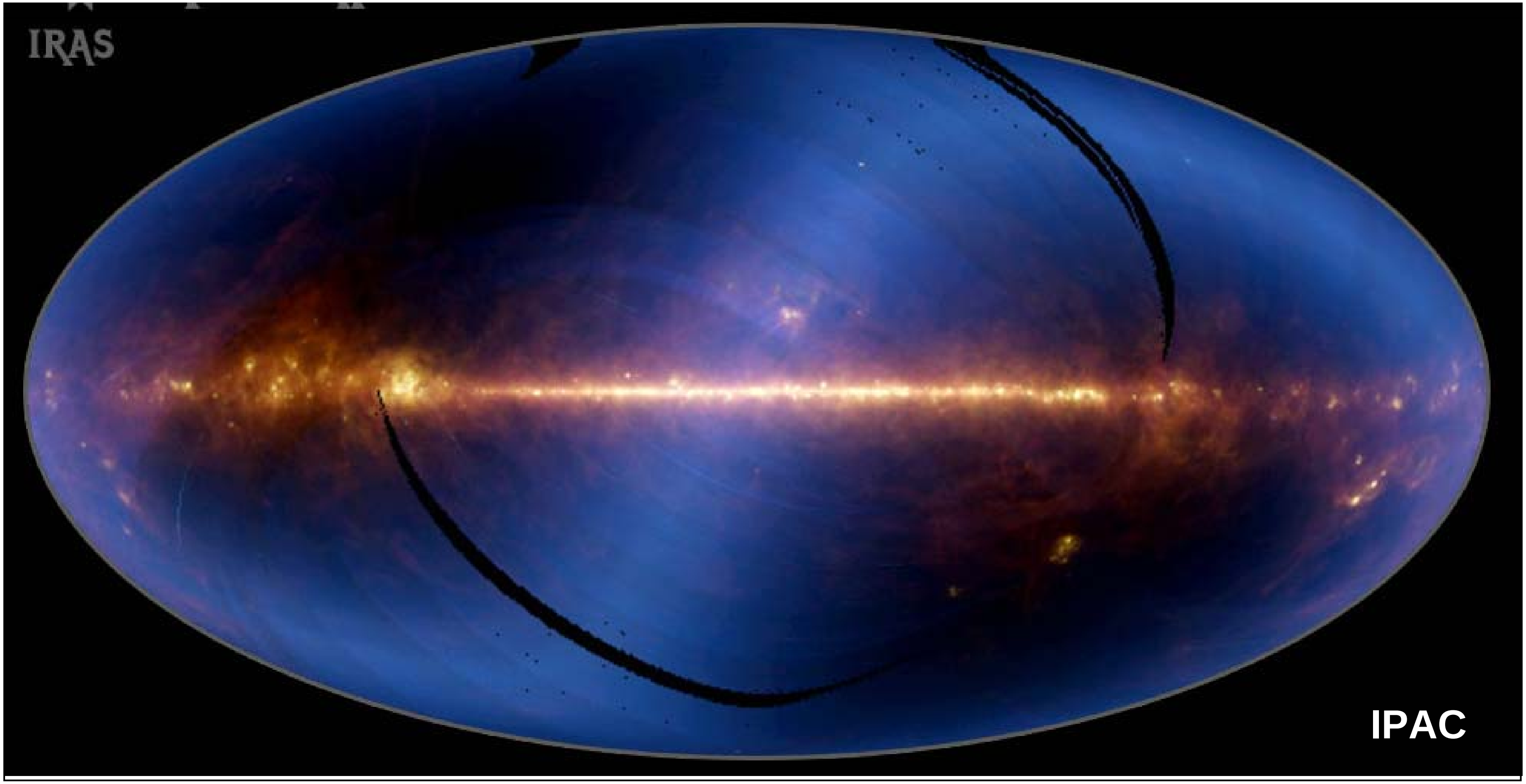
Are they clouds?

- Interstellar clouds are not literally clouds but appear as dark nebulae or 'clouds' against the Milky Way



Why are the clouds dark?

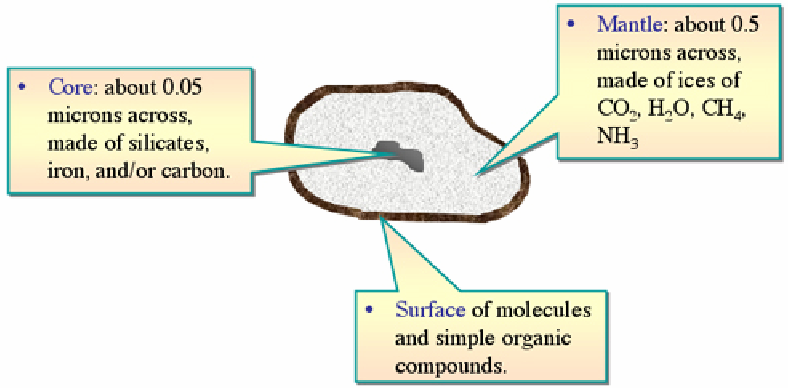
- What we see (in absorption) is the interstellar *dust*



25-60-100 μm

Dust

- Grains of ‘metals’ – carbon-ish and silicon-ish – with a size spectrum ranging from very small to small and
  - About 1% by mass of the interstellar medium



Swinburne Univ. Astronomy Online Encyc

- Dust is fantastically important to the interstellar medium – reprocesses star light (incidentally absorbs UV to shield clouds), and catalyzes the formation of molecular hydrogen
  - Otherwise, even if they wanted to, two H atoms would have no phase space for combining to form H_2
- Realization of the catalytic aspect of dust (Hollenbach & Salpeter 1971) was a great advance and (I imagine) spurred the search for tracers of molecular hydrogen

Neutral interstellar medium

- The neutral interstellar medium is gas mixed with dust; associations of gas, especially dense ones, are referred to as clouds – which doesn't meaningfully help for understanding them
- The gas very, very cold (few K to 10s of Kelvin) and very, very tenuous (10^3 cm^{-3} is a *high* density)
  - 10^3 H_2 molecules cm^{-3} at 5 K corresponds to a pressure of 10^{-13} torr, much lower than can be achieved in the laboratory
- They are quite unlike atmospheric clouds in other ways
  - To the extent that they are stable, they are (sort of) self gravitating, with important magnetic support
  - They are huge and massive – largest ~100 pc and ~10^6 Msun.
- Overall, most of the mass of the interstellar medium is atomic hydrogen* (*which I won't say anything about here*)
  - The densest component of the neutral medium is primarily H_2
  - This is where stars (OB assoc., SNR, pulsars, XRB, …) form

* He makes up 21% by mass of the ISM and is assumed to be in proportion to the H

Studying the dense ISM

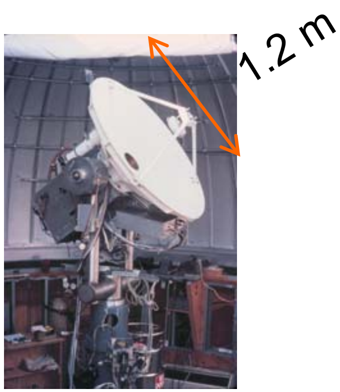
- H_2 has no dipole moment, and so no rotational spectrum. The lowest vibrational bands are a few 1000 K above ground. It can be detected directly when shock heated or in absorption in the UV, but is not directly detectable under ordinary interstellar conditions
- CO is the 2nd most abundant molecule, down by a factor of ~10^5 from H_2, but it does have a permanent dipole moment (0.1 Debye or so) and the lowest excited rotational level (J = 1) is only a ~5 K above ground

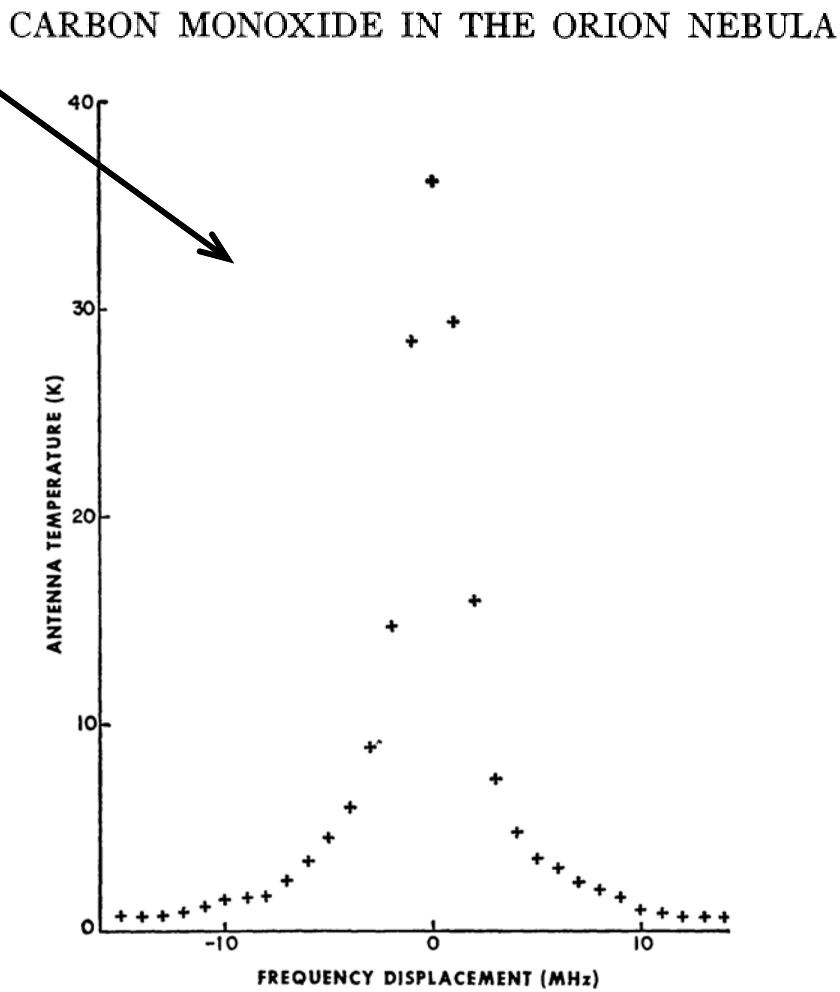
More on interstellar CO

- Interstellar CO (which also forms on grains) is collisionally excited by H_2, and then emits a microwave (115.271 GHz) photon from the *J* = 1-0 transition
- This transition is forbidden; the spontaneous rate is about 1 yr^{-1}, but conditions in molecular clouds are such that collisional de-excitation is not a serious problem even for such a long-lived state
- Note that this is a spectral line and that millimeter wave spectroscopy can be extremely high resolution – one part in 10^6 is absolutely no problem
  - This is one reason that CO observations are extremely useful for studies of Galactic structure, which I will not say anything about

More on interstellar CO

- Interstellar CO was detected in 1970 (Wilson, Jefferts, & Penzias)
- Surveys of CO in the Milky Way were published by the mid 1970s, and small survey telescopes were operational in the early 1980s, built by the Columbia Univ./GISS group led by P. Thaddeus





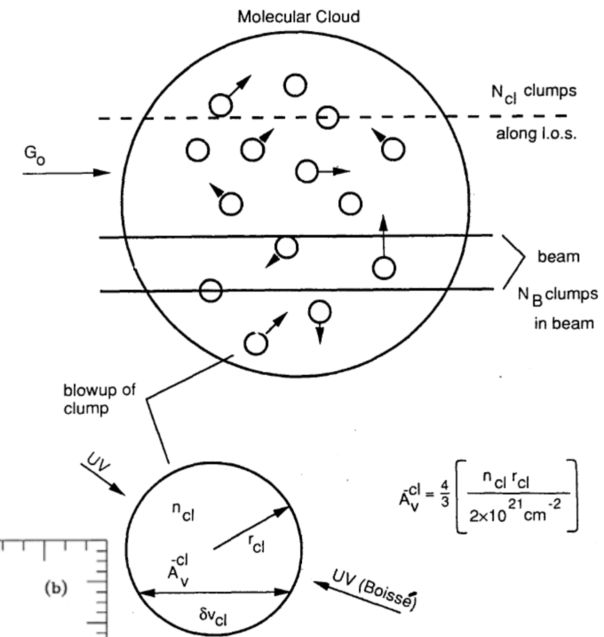
CO as a tracer of molecular clouds

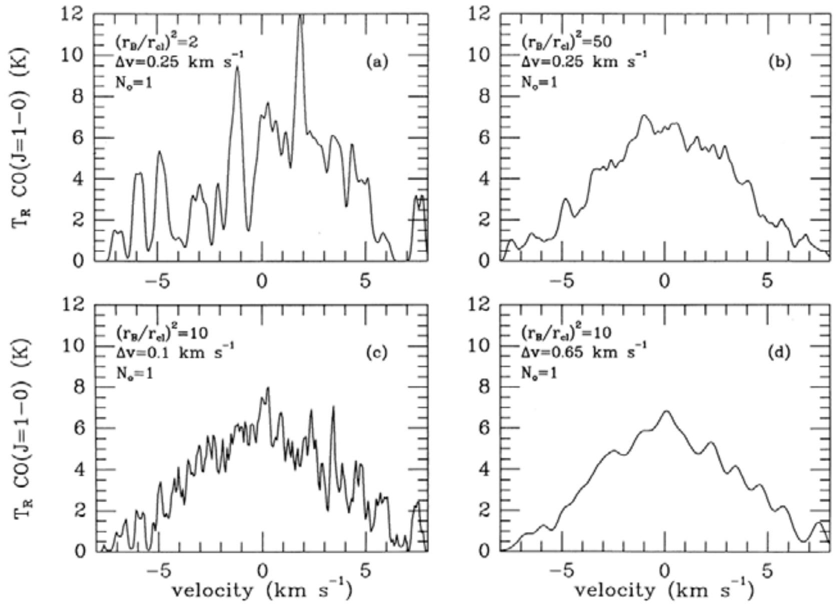
Dame/Mellinger

- **For various reasons, CO ought to be at least an ok tracer of molecular hydrogen**
  - **Conditions for their formation and destruction are similar, and as mentioned collisional excitation is well matched to conditions of molecular clouds**
- **However, CO is abundant enough that it is certainly optically thick (=*bad news for a mass tracer*; in principle you measure its temperature rather than its column density)**

No, really

- However², molecular clouds are extremely clumpy, and the semi-quantitative reasoning is that clumps exist down to the scale where CO is just optically thick, and observations of the CO line are in effect counting 'clumps', and the integrated intensity of the CO lir is an ok surrogate tracer of molecular mass.





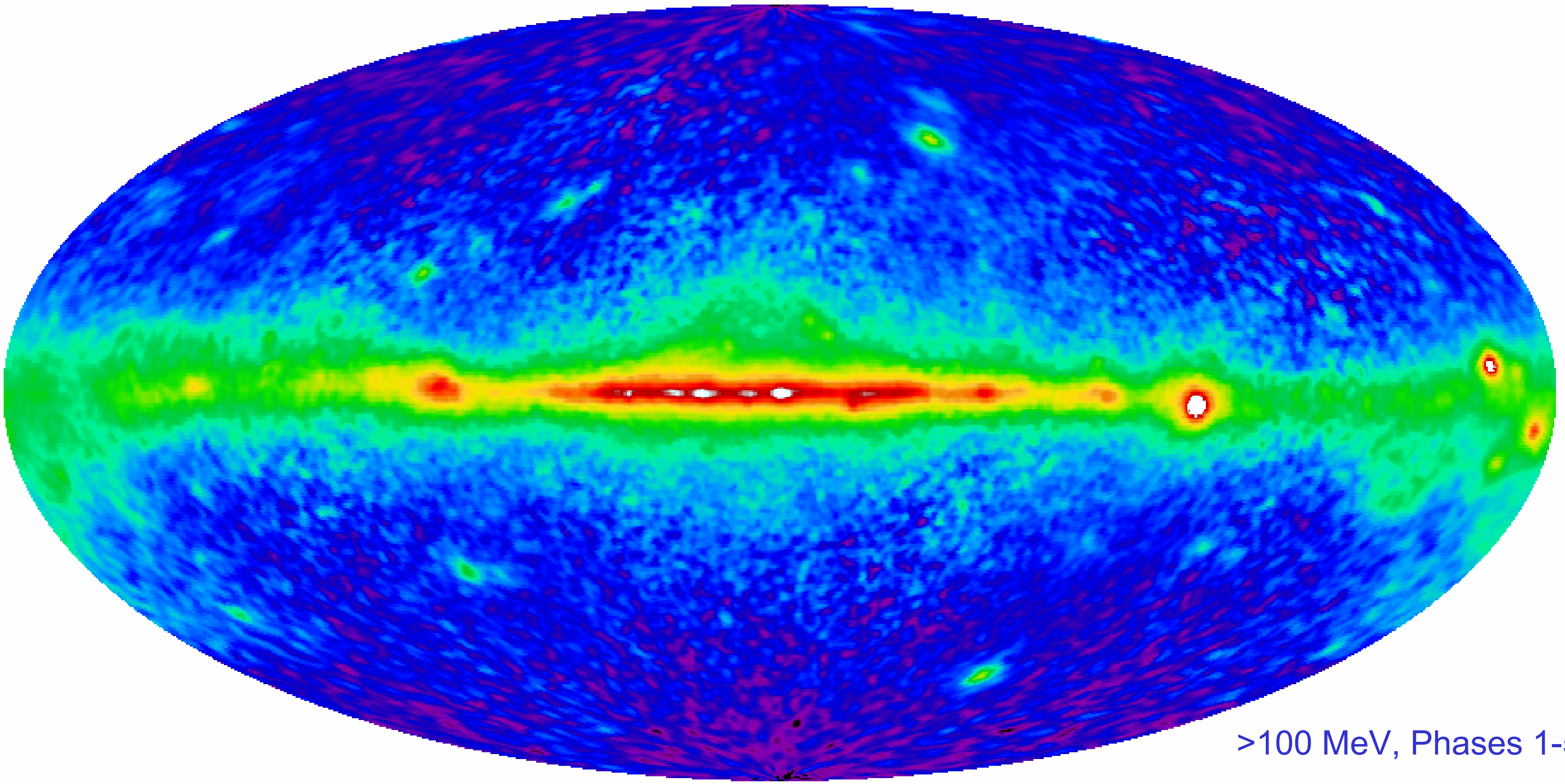
Wolfire, Hollenbach, & Tielens (1993)

CO as a tracer of molecular mass

- The relationship between *W*(CO) and N(H_2) obviously needs to be calibrated indirectly
- Many approaches have been taken
- Some related to dust, like obscuration optically or (better) in the near infrared
- Also 'virial equilibrium' arguments
- High energy gamma rays were recognized early (like in the COS-B era) as potentially a very good calibrator
  - The availability of large-area CO surveys was fortuitously coincident with COS-B's analysis needs
  - More later
- The 'standard' value of N(H_2)/*W*(CO) is ~2 x 10^{20} cm^{-2} s^{-1} (K km s^{-1})$^{-1}$, and of course it is not a physical constant of Nature

EGRET all-sky map

- EGRET (1991-2000)



- Individual molecular cloud complexes – a few of them – can be studied by themselves with EGRET data

Modeling the diffuse gamma-ray emission

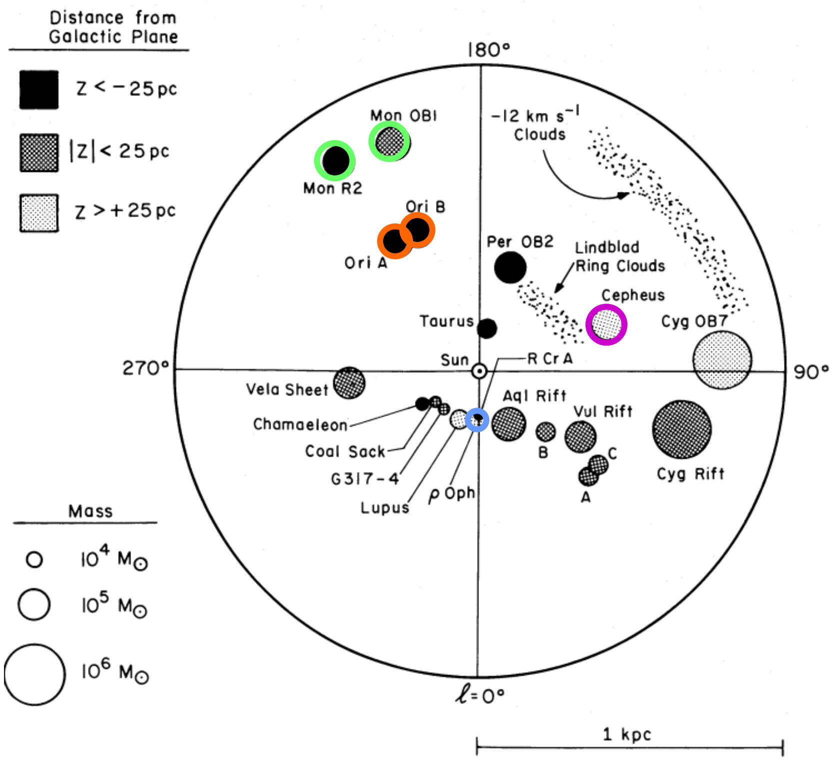
- Briefly, the diffuse emission is modeled as a linear combination of N(H I), W(CO), IC (model), and isotropic maps, plus point sources

$$I(l,b,E) = \iint \rho_{CR,p}(E',s) q_{\pi^0}(E,E') \rho_{ISM}(s) dE' ds +$$
$$\iint \rho_{CR,e}(E',s) [q_B(E,E') \rho_{ISM}(s) + q_{IC}(E,E') \rho_{ISRF}(s,E')] dE' ds$$

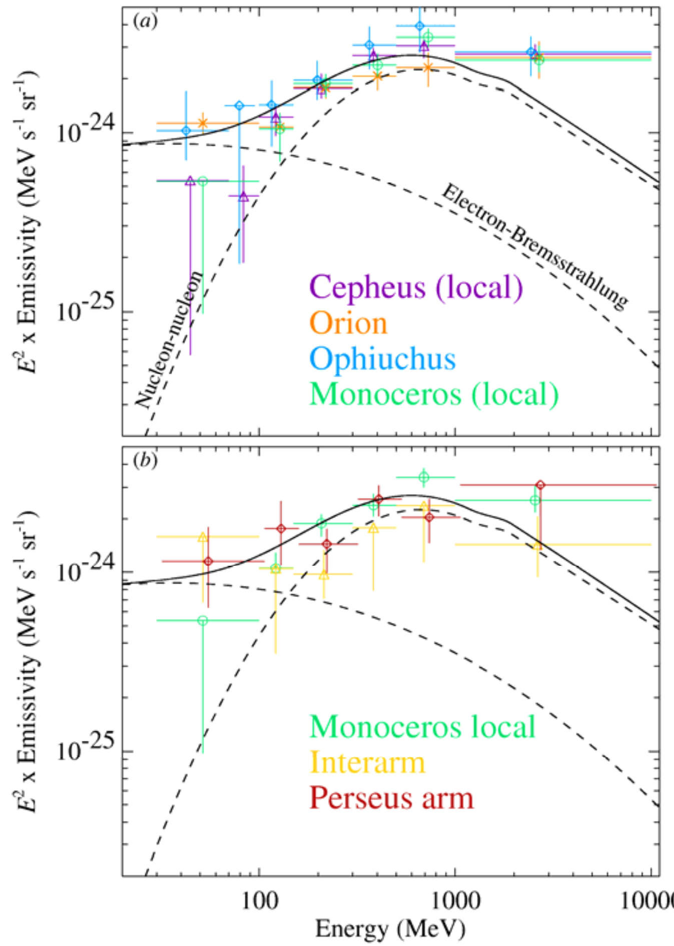
- As long as the maps are not linearly dependent, a likelihood analysis can tell you the contribution from each one
  - Note important assumption: CR densities & spectra are uniform across the region being studied
  - Interpretations are emissivity (effective rate of gamma-ray emission per H atom), N(H2)/W(CO),

Wolfire, Hollenbach, & Tielens (1993)

Some targets and results



Dame et al. (1987)

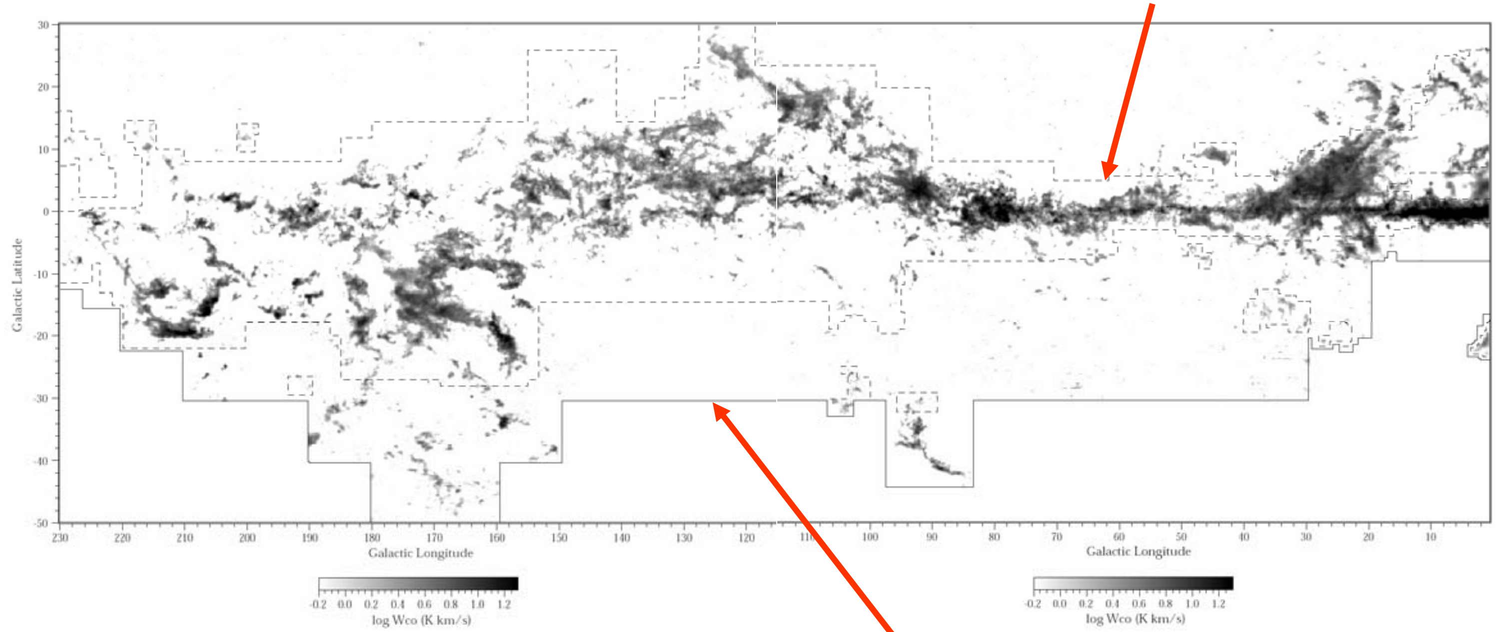


Digel et al. (1996 & 2001)

An aside on high-latitude clouds

- **High-latitude translucent clouds are small (typically < 1°) and faint (~1 K km s^{-1} deg^2) in CO and being revealed by an unbiased 0.25° sampling CO survey (Dame & Thaddeus)**

Dame, Hartmann & Thaddeus (2001)

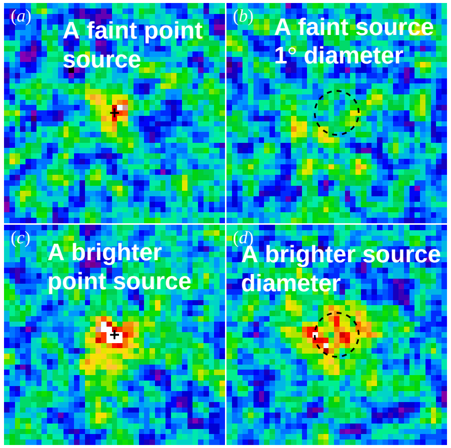


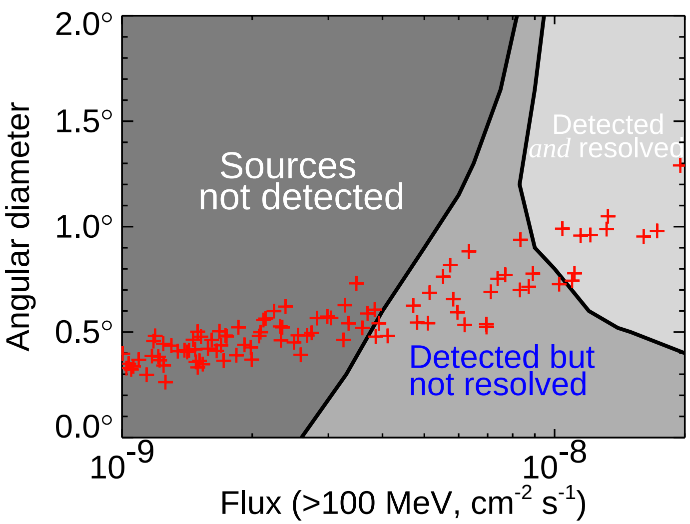
Dame & Thaddeus (2004)

(Not centered on l = 0)

Translucent clouds, cont.

- *Once you guess a value for $X = N(H_2)/W_{CO}$*, simulation of LAT observations and analysis can be used to figure out which clouds will be detected and/or resolved
- The interest for LAT is in not misidentifying sources in the source catalog
  - Otherwise, many of these clouds would appear to be point sources that are faint enough so that nothing much could be inferred from their lack of variability or their spectra





Torres et al. (2005)

Looking forward to LAT data

- (Old) simulations of LAT observations compared with CO and EGRET gamma-ray observations of the Orion molecular clouds
- The sensitivity of the LAT will permit studying molecular clouds in detail – at low and high latitudes
- We should be able to go well beyond calibrating masses to studying variations of CR density (sources) and resolving point-source contributions

Orion example