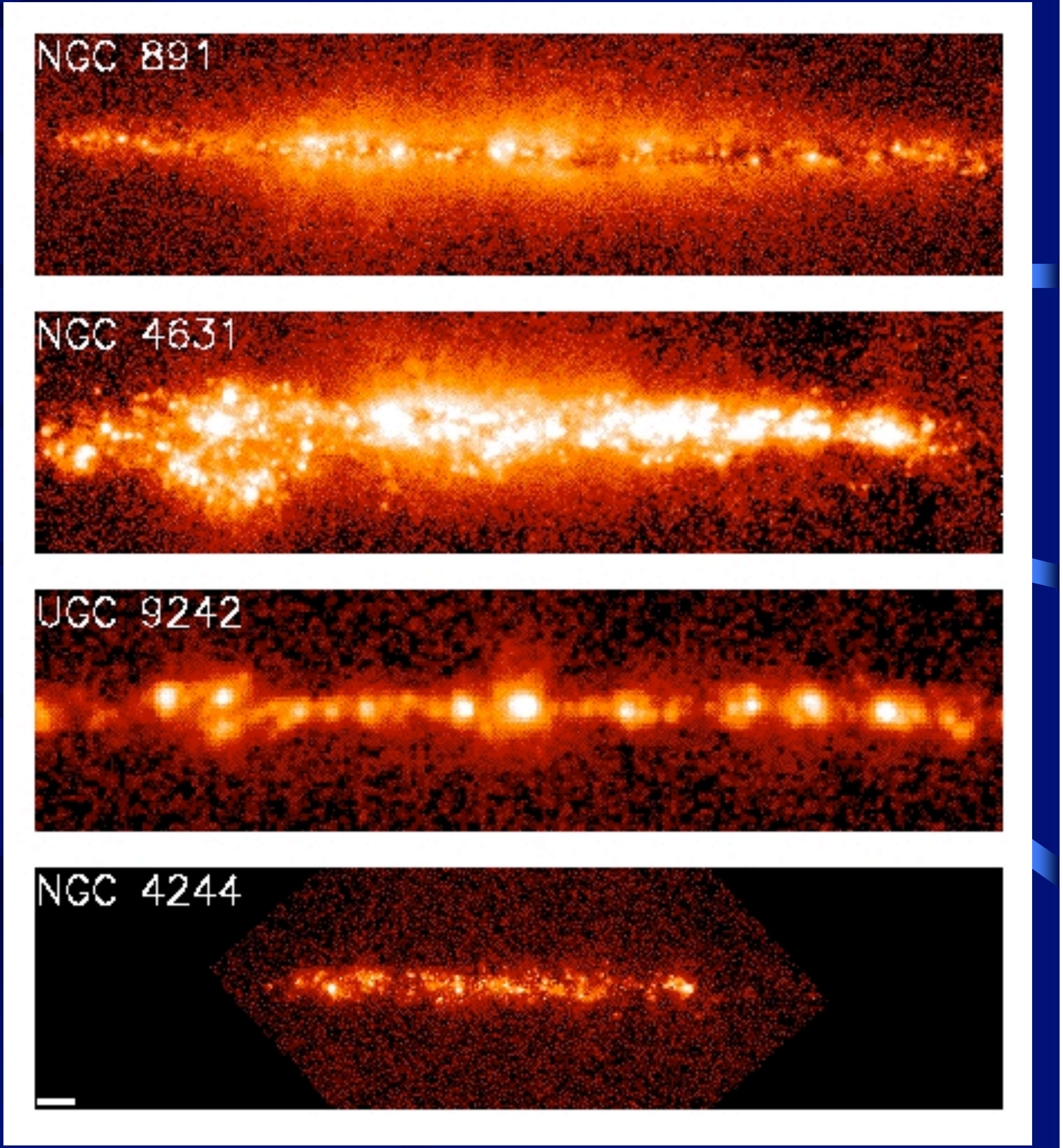
Ionized Hydrogen (HII)

- While ionized hydrogen (protons, electrons) forms the majority of the ionized phase of the ISM, it also contains ionized forms of other elements: e.g., OII, OIII, CIV, MgII.
- Highest temperature and lowest density of the three gaseous phases (hot, tenuous phase of the ISM):
  $T \sim 10^3$ to 10^6 K; $n \sim 10^{-5}$ to 10^{-3} ions/cm^3
- Weak degree of concentration to the plane of the Galactic disk: scale height z is a few kpc. Also seen in dense knots known as "HII regions" marking areas of intense star formation activity. HII regions tend to lie along spiral arms.
- Radiation from hot, young stars causes the gas to be ionized. The cascade of electrons down atomic energy levels results in an emission line spectrum. Examples of emission lines in the ultraviolet and optical part of the electromagnetic spectrum include: Lyα (2→1; 1216 Å), Hα (3→2; 6563 Å), Hβ (4→2; 4861 Å), OII (3727 Å).

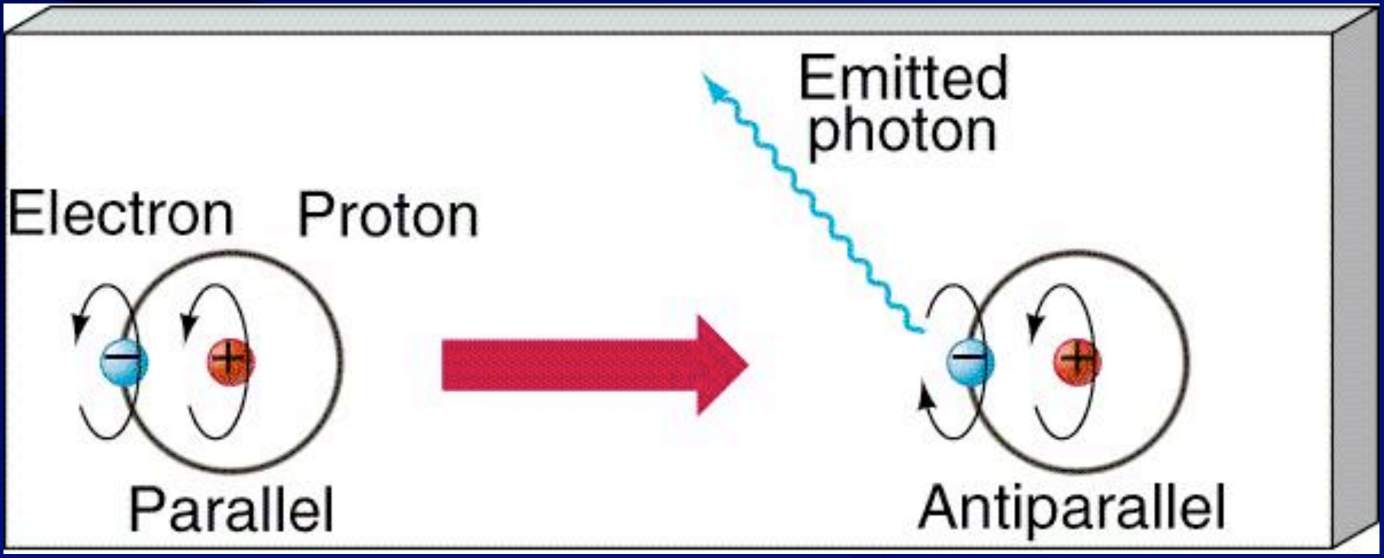
Hα emission line seen in four edge-on galaxies:

The top two galaxies display the largest concentration of HII regions and young stars. The galaxy at the bottom has the sparsest collection of HII regions.



Atomic Hydrogen (HI)

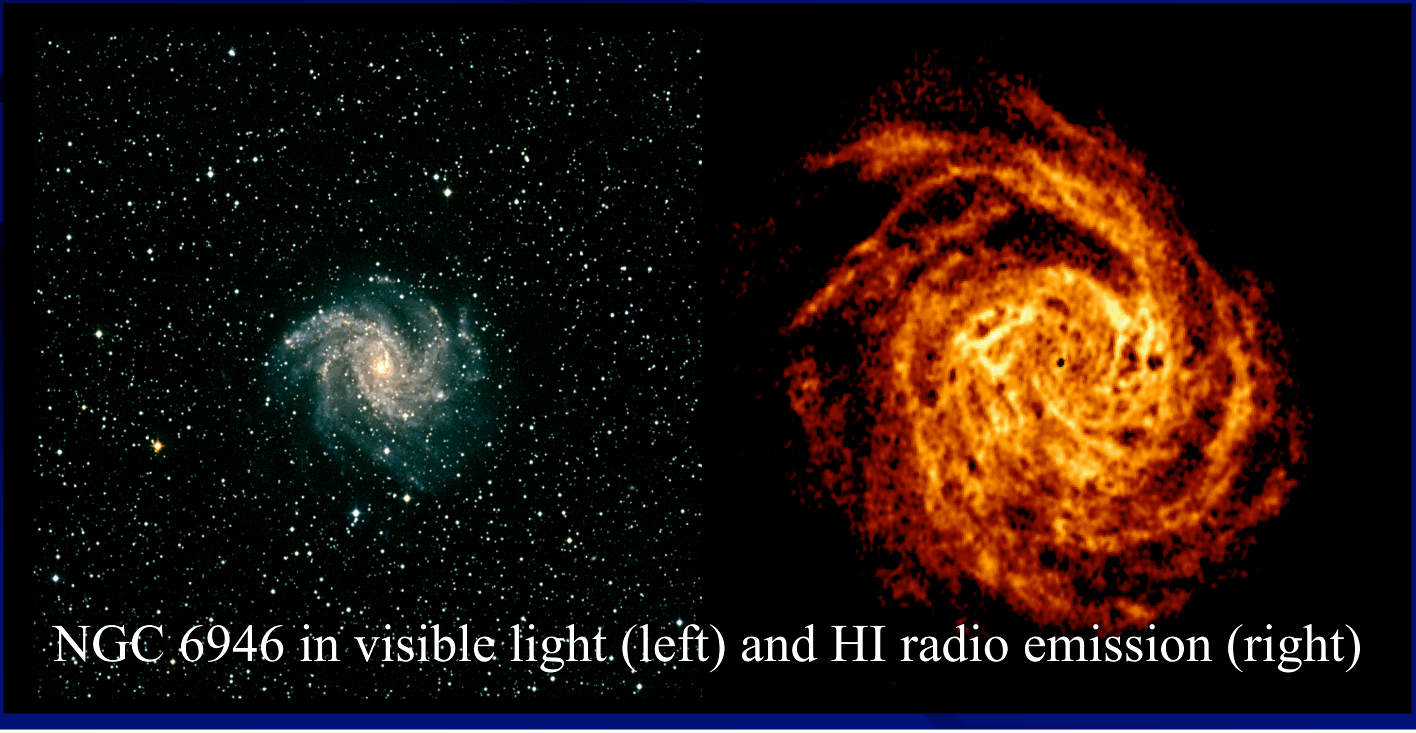
- An atom of neutral hydrogen consists of an electron and a proton. The electron and proton can either spin in the same direction or in opposite directions, and the energy of the atom is slightly different in these two states. A transition between these two states is called a “hyperfine” or “spin-flip” transition and leads to the emission of a photon whose wavelength is 21 cm. This is in the radio part of the electromagnetic spectrum.



Atomic Hydrogen (HI)

- Intermediate in temperature and density between the other two gaseous phases (warm, diffuse phase of the ISM):
  T ~ 10 to 100 K; n ~ 1 to 100 atoms/cm^3

- Moderate degree of concentration to the plane of the Galactic disk: scale height z ~ 100 pc - 1 kpc. Complicated spatial distribution consisting of clouds, filaments, bubbles, dense knots, etc.

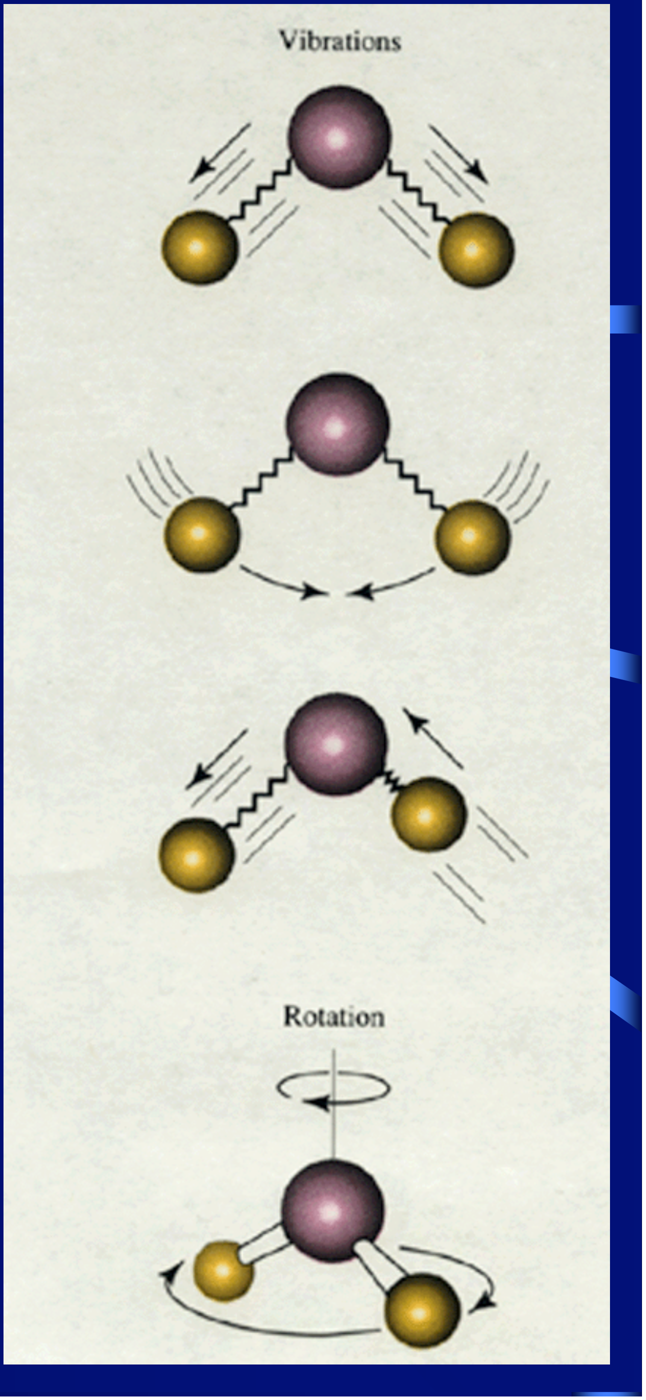


NGC 6946 in visible light (left) and HI radio emission (right)

Molecular Hydrogen (H_2)

- It is difficult (though not impossible) to detect molecular hydrogen directly. There are several other molecules that are usually found in molecular clouds: e.g., CO (carbon monoxide), HCHO (formaldehyde), CH_4 (methane), and even C_2H_5OH (ethyl alcohol).

- These molecules can be in various energy states due to the vibrations of their molecular bonds and due to their rotation. Transitions between vibrational and rotational energy states result in the emission or absorption of photons in the infrared and submillimeter parts of the electromagnetic spectrum, respectively.

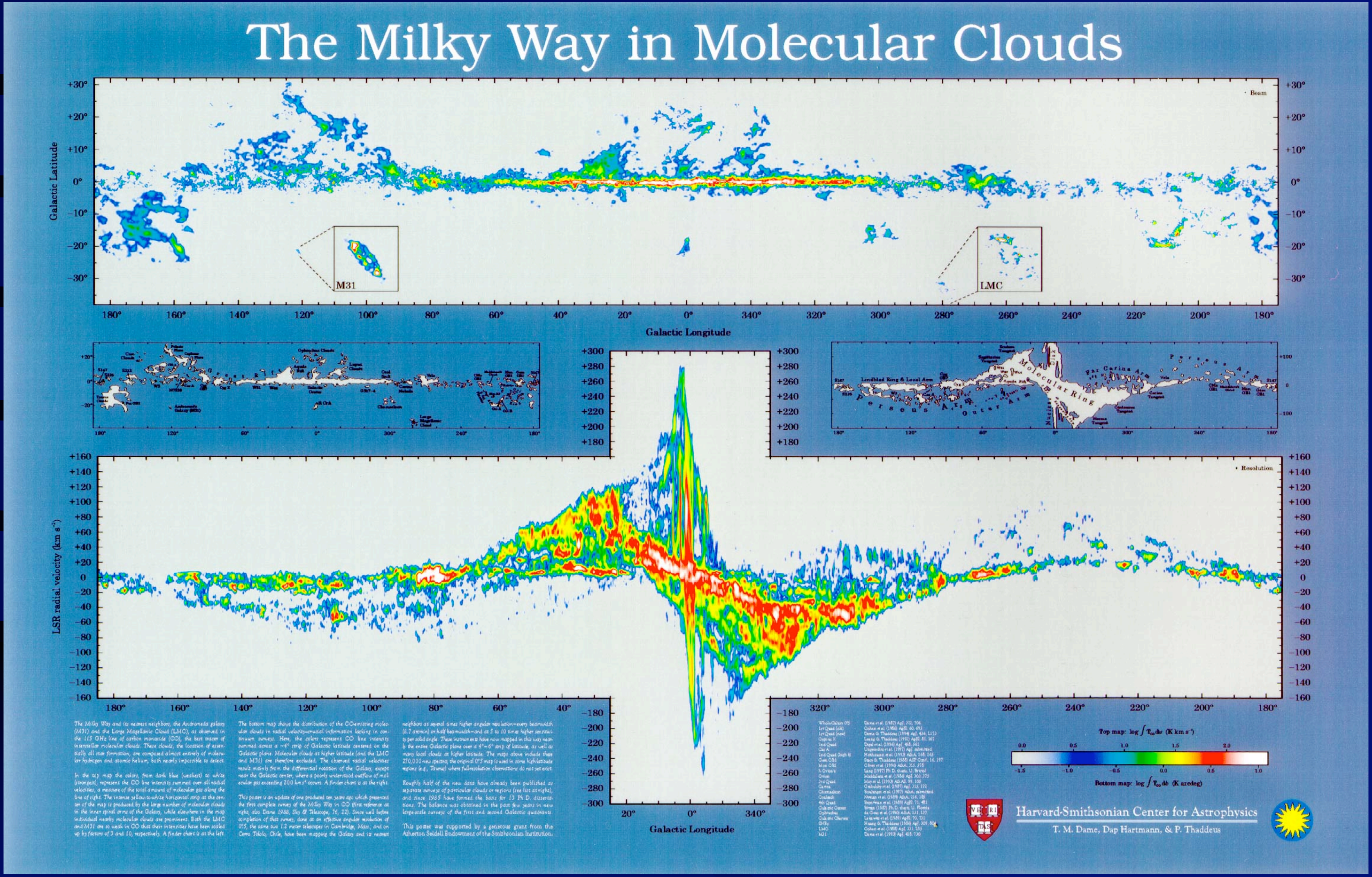


Molecular Hydrogen

- Lowest temperature and highest density of the three gaseous phases (cold, dense phase of the ISM):
  $T \sim 10$ K; $n \sim 10^3$ to 10^6 molecules/cm^3

- High degree of concentration to the plane of the Galactic disk: scale height $z < 100$ pc. Primarily confined to large and dense concentrations known as giant molecular clouds.

- Molecules are easily broken up by energetic photons (a process called photodissociation). They form in dense and dusty environments where they can be shielded from the radiation of nearby stars.



The Milky Way in Molecular Clouds

The Milky Way and its nearest neighbors, the Andromeda galaxy (M31) and the Large Magellanic Cloud (LMC), as observed in the 115 GHz line of carbon monoxide (CO), the best tracer of interstellar molecular clouds. These clouds, the location of essentially all star formation, are composed almost entirely of molecular hydrogen and atomic helium, both nearly impossible to detect.

In the top map the colors, from dark blue (weakest) to white (strongest), represent the CO line intensity summed over all radial velocities, a measure of the total amount of molecular gas along the line of sight. The intense yellow-to-white horizontal strip at the center of the map is produced by the large number of molecular clouds in the inner spiral arms of the Galaxy, while elsewhere in the map individual nearby molecular clouds are prominent. Both the LMC and M31 are so weak in CO that their intensities have been scaled up by factors of 3 and 10, respectively. A finder chart is at the left.

The bottom map shows the distribution of the CO-emitting molecular clouds in radial velocity—crucial information lacking in continuum surveys. Here, the colors represent CO line intensity summed across a ~4° strip of Galactic latitude centered on the Galactic plane. Molecular clouds at higher latitude (and the LMC and M31) are therefore excluded. The observed radial velocities result mainly from the differential rotation of the Galaxy, except near the Galactic center, where a poorly understood outflow of molecular gas exceeding 200 km s⁻¹ occurs. A finder chart is at the right.

This poster is an update of one produced ten years ago which presented the first complete survey of the Milky Way in CO (first reference at right; also Dame 1988, Sky & Telescope, 76, 22). Since well before completion of that survey, done at an effective angular resolution of 0°.5, the same two 1.2 meter telescopes in Cambridge, Mass., and on Cerro Tololo, Chile, have been mapping the Galaxy and its nearest neighbors at several times higher angular resolution—every beamwidth (8.7 arcmin) or half beamwidth—and at 5 to 10 times higher sensitivity per solid angle. These instruments have now mapped in this way nearly the entire Galactic plane over a 4°–6° strip of latitude, as well as many local clouds at higher latitude. The maps above include these 270,000 new spectra; the original 0°.5 map is used in some high-latitude regions (e.g., Taurus) where full-resolution observations do not yet exist.

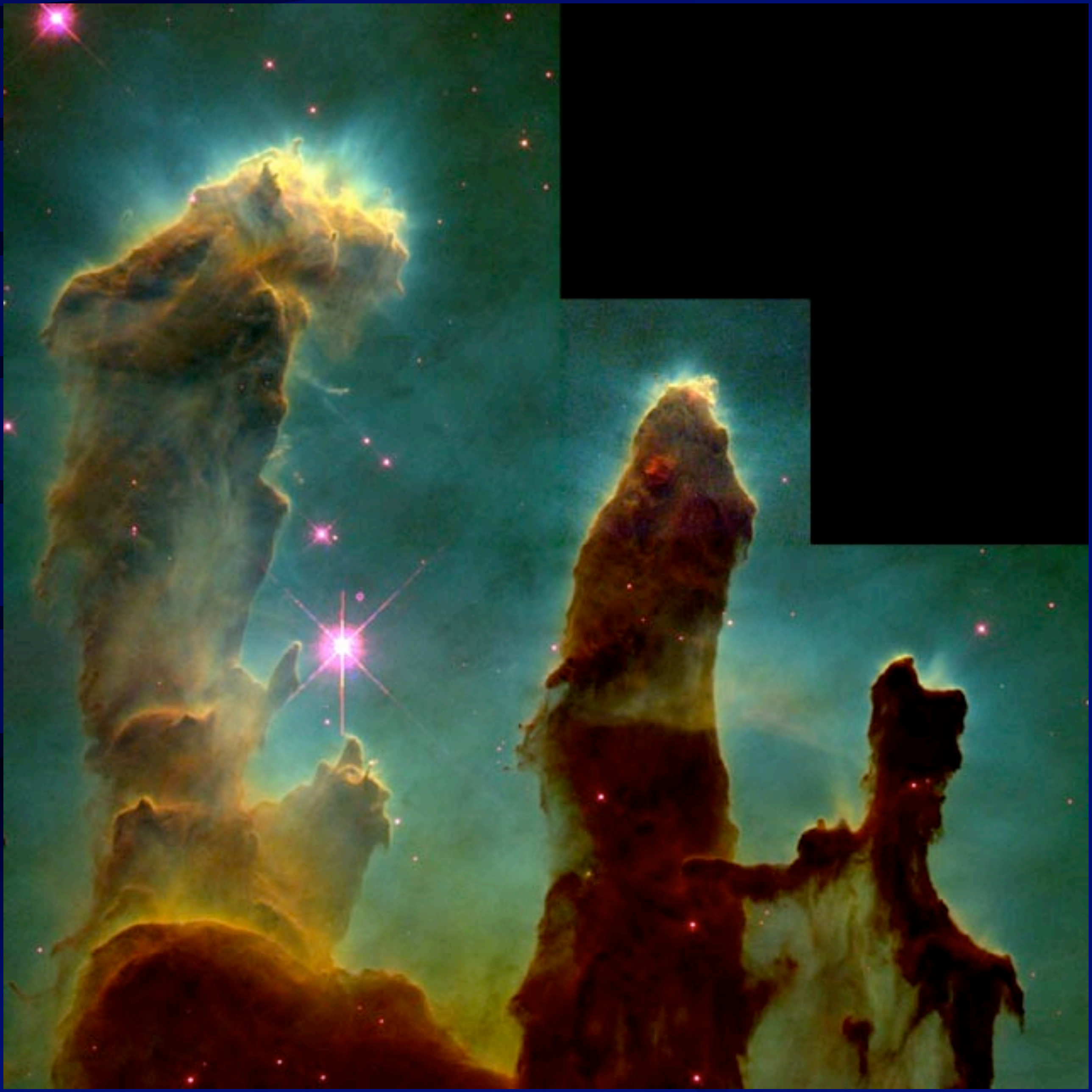
Roughly half of the new data have already been published as separate surveys of particular clouds or regions (see list at right), and since 1985 have formed the basis for 13 Ph.D. dissertations. The balance was obtained in the past few years in new large-scale surveys of the first and second Galactic quadrants.

This poster was supported by a generous grant from the Atherton Seidell Endowment of the Smithsonian Institution.

Whole Galaxy 0°.5	Dame et al. (1987) ApJ, 322, 706
1st Quad (old)	Cohen et al. (1986) ApJS, 60, 695
1st Quad (new)	Dame & Thaddeus (1994) ApJ, 436, L173
Cygnus X	Leung & Thaddeus (1992) ApJS, 81, 267
2nd Quad	Digel et al. (1996) ApJ, 458, 561
Cas A	Ungerechts et al. (1997) ApJ, submitted
2nd Quad (high b)	Heithausen et al. (1993) A&A, 268, 265
Gem OB1	Stacy & Thaddeus (1988) ASP Conf., 16, 197
Mon OB1	Oliver et al. (1996) A&A, 315, 578
λ Orionis	Lang (1997) Ph.D. thesis, U. Bristol
Orion	Maddalena et al. (1986) ApJ, 303, 375
3rd Quad	May et al. (1993) A&AS, 99, 105
Carina	Grabelsky et al. (1987) ApJ, 315, 122
Chamaeleon	Boulanger et al. (1997) A&A, submitted
Coalsack	Nyman et al. (1989) A&A, 216, 185
4th Quad	Bronfman et al. (1989) ApJS, 71, 481
Galactic Center	Bitran (1987) Ph.D. thesis, U. Florida
Ophiuchus	de Geus et al. (1990) A&A, 231, 137
Galactic Clusters	Leisawitz et al. (1989) ApJS, 70, 731
SNRs	Huang & Thaddeus (1986) ApJ, 309, 804
LMC	Cohen et al. (1988) ApJ, 331, L95
M31	Dame et al. (1993) ApJ, 418, 730

Harvard-Smithsonian Center for Astrophysics

T. M. Dame, Dap Hartmann, & P. Thaddeus



Dust Grains

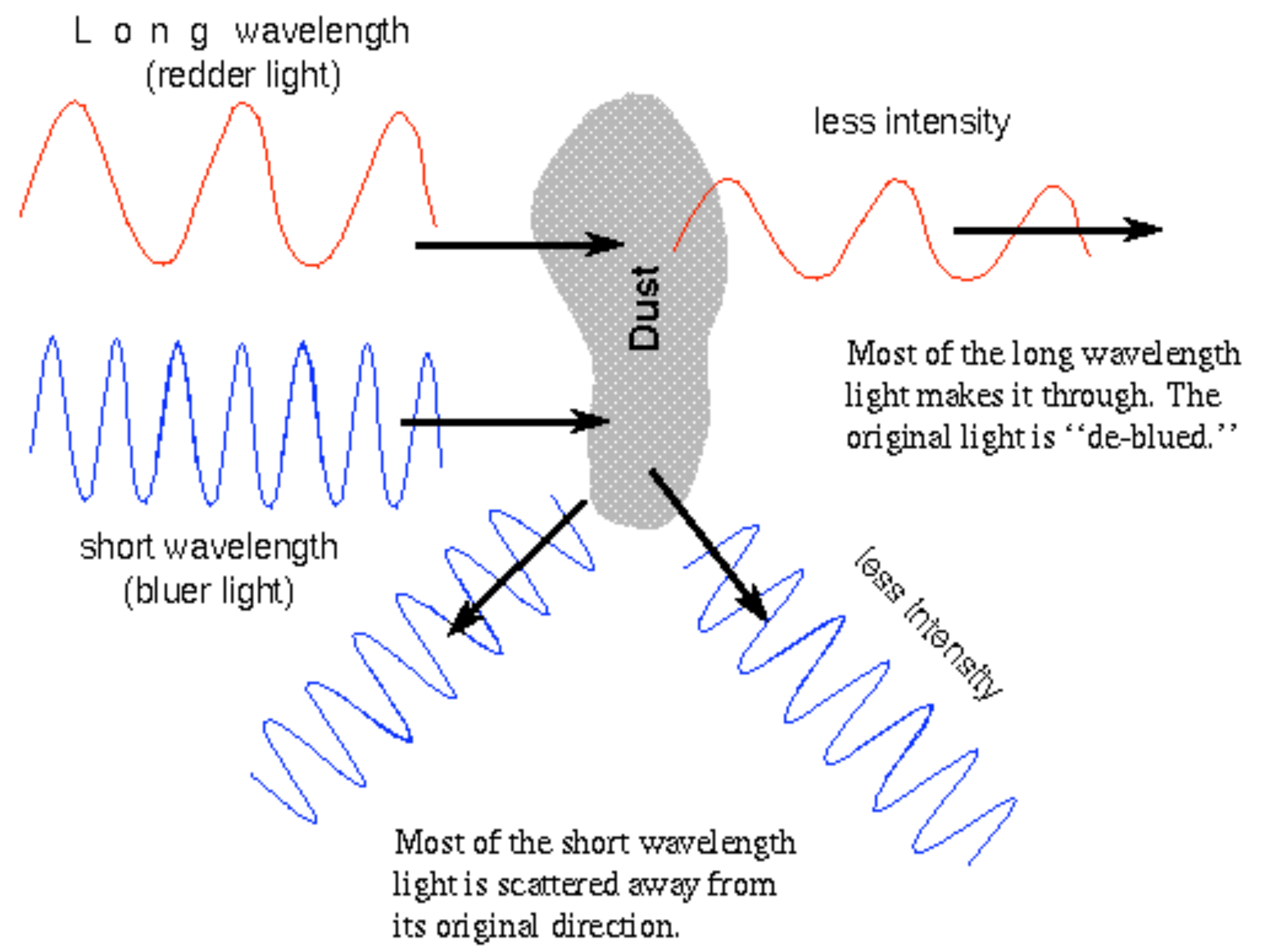
- Solid particles of C (graphite, soot) and Fe & Mg silicates, often with mantles of water or CO_2 ice.

- Grain sizes range from about 1 μ m (10^{-4} cm) down to a few tens of Angstroms (10^{-7} cm).

- Dust particles absorb and scatter some fraction of the incident radiation. The shorter the wavelength of the photon, the higher the efficiency of this process (and vice versa): i.e., ultraviolet photons are easily absorbed and scattered by dust, while infrared photons tend to pass right through. Stars appear to be fainter and redder when viewed through a dust cloud.

- The energy absorbed by dust grains causes them to be heated to T ~ 15 - 50 K. They are then capable of emitting black body radiation. Most of this energy comes out in the far infrared part of the electromagnetic spectrum ($\lambda_{peak} \geq 100$ μm).

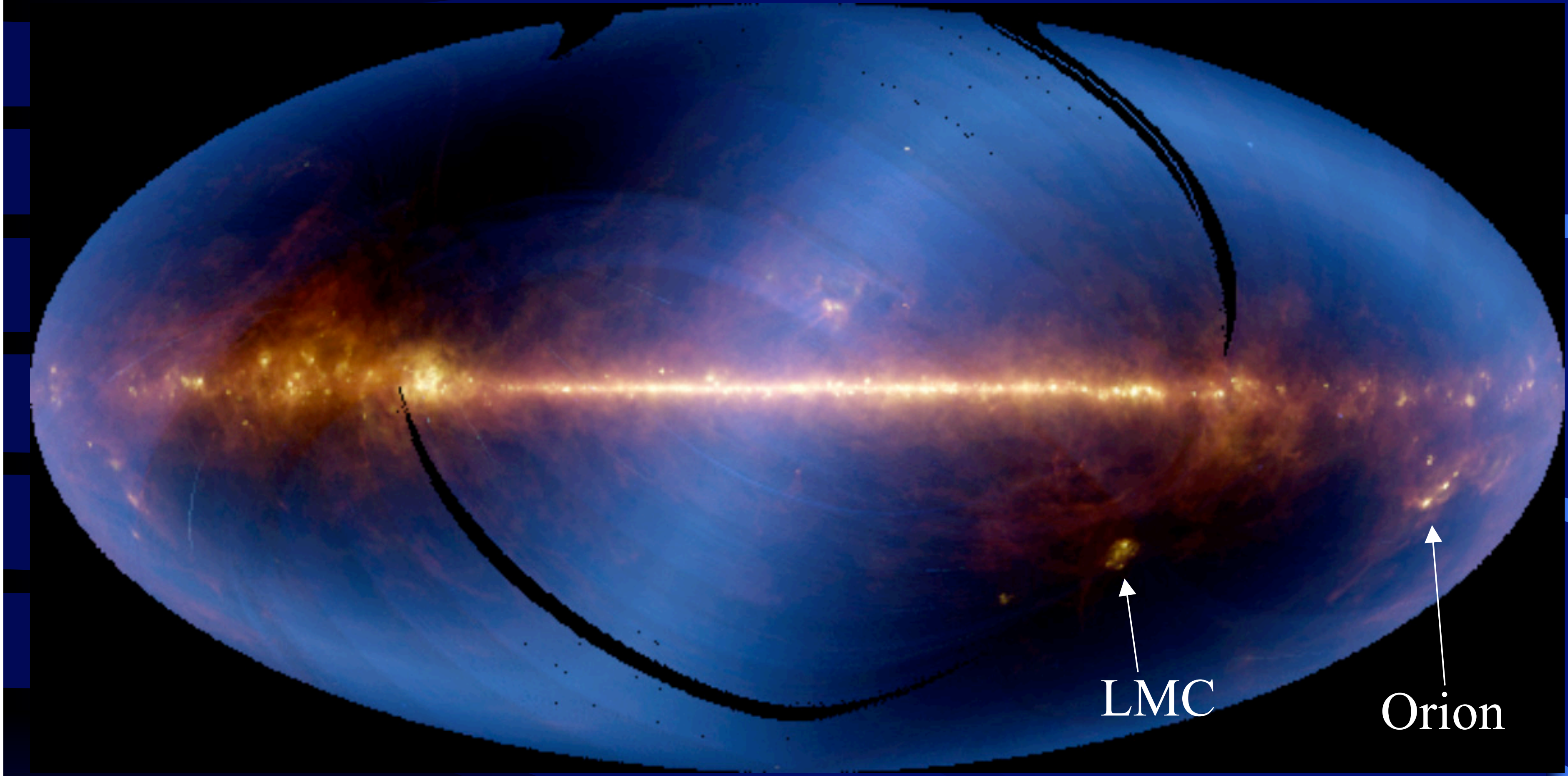
Reddening and Extinction



Most of the long wavelength light makes it through. The original light is "de-blued."

Most of the short wavelength light is scattered away from its original direction.

DIRBE image of old stars in the Milky Way



IRAS composite image of interstellar dust in the Milky Way

What Do We Mean by the Term “Dark Matter”?

- Includes any form of non-luminous or unseen matter —i.e., matter that does not emit any form of electromagnetic radiation.
- Often loosely used to include any matter from which we do not detect electromagnetic radiation.
- A planet reflects light but does not typically emit detectable amounts of radiation; therefore, planets should (and are) included in this category.
- Neutral hydrogen gas in the interstellar medium emits no optical light but does emit radiation at radio frequencies (λ=21 cm) so is not considered dark matter.

Detecting Dark Matter

- Dark matter makes its presence felt through its gravitational field (gravitational force or potential).
- The motion of stars and/or gas in a gravitational field or the effects of light bending in a gravitational field allow us to study the strength of the field, and thereby infer the amount of matter present.
- All forms of matter exert gravitational forces. Thus, the strength of a gravitational field tells us about both luminous and non-luminous forms of matter.
- The luminous form of matter emits radiation, of course, so we can (directly) tell how much of it there is.

Is Dark Matter Really There?

- The term “missing matter” was in fairly common use early on, but it is misleading because the matter really is there—it is not missing!
- There were also attempts by some scientists (Milgrom & collaborators) to see if a MOdified theory of Newtonian Dynamics (MOND) might explain the observed motion of stars without requiring dark matter.
- This theory made specific predictions which were not borne out by observation, and now is (almost) universally believed to be wrong.

Dark Matter in Galaxies

- The observed motion of stars near the Sun, specifically their motion along the direction perpendicular to the plane of the Galactic disk, indicates the presence of a certain amount of matter in the Solar neighborhood (or else the stars would no longer be confined to a thin disk).

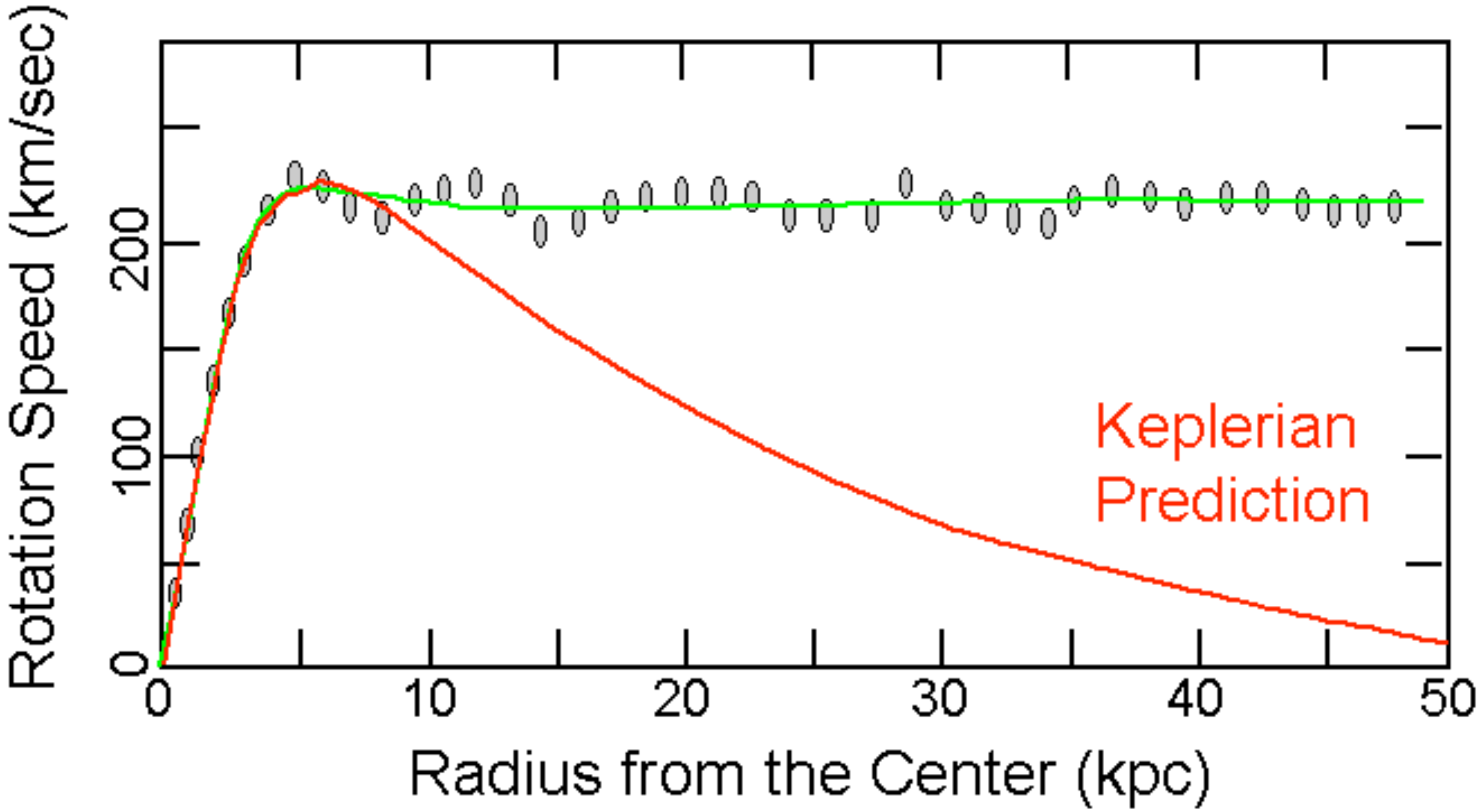
- The stars that are actually seen in this region provide only a fraction of the required gravity. The required mass-to-light ratio is: $M/L \approx 5\text{–}10\ (M/L)_{\odot}$.

- This provides a lower limit to the amount of dark matter present in the Galaxy's disk, and is called the Oort limit after the Dutch astronomer, Jan Oort, who first proposed and carried out this experiment.

Spiral Galaxy Rotation Curves

- The shape of the rotation curve of spiral galaxies (rotation velocity as a function of radius) is a measure of how the density of matter within the galaxy is distributed as a function of radius.
- Most spirals are observed to have `flat' rotation curves ($v \approx$ constant) in their outer parts, which corresponds to an `isothermal' density profile: ρ α $1/R^2$.
- The light distribution in galaxies, however, is observed to fall off more steeply towards increasing radii than this (roughly as $1/R^3$).
- The inferred M/L of spiral galaxies is about $M/L \approx 10$–$30\ (M/L)_{☼}$ and the fraction of dark matter increases outwards (i.e., the dark matter is less centrally concentrated than the luminous matter).

Observed *vs.* Predicted Keplerian



Elliptical Galaxies

- The speed at which stars move (on average) within an elliptical galaxy can be measured by its `velocity dispersion' (or spread in velocity among the different stars relative to us) along the line of sight.
- The indication is that elliptical galaxies too contain dark matter (a somewhat higher proportion than spiral galaxies, in fact), with M/L ratios as high as $100\ (M/L)_{\odot}$
- This massive but mostly dark and relatively low central concentration component of galaxies is referred to as their dark halo.

Dark Matter in Groups and Clusters of Galaxies

- The typical speed of galaxies within a group or cluster, as measured by the velocity dispersion, indicates the strength of the gravitational field.
- The line-of-sight velocity dispersion of groups is in the range 100—500 km/s, while that of clusters is in the range 500—1500 km/s.
- The velocity dispersion and physical size (radius R) of a group or cluster can be used to determine its total matter content: $M \sim v^2R/G$.

Intra-cluster Gas

- Most groups and clusters contain intergalactic (intragroup or intracluster) gas.
- This gas experiences the gravitational potential of the group/cluster, and the atoms comprising the gas are accelerated to very high speeds.
- In fact, the atoms become ionized and the resulting electrons and ions (mostly protons) move at speeds characteristic of a very high temperature gas ($T \sim 10^6$ K).
- This hot plasma emits black body (or thermal) radiation in the X-ray part of the electromagnetic spectrum. The more massive (and compact) the group or cluster, the higher the temperature of the X-ray radiation: $T \propto M/R$.

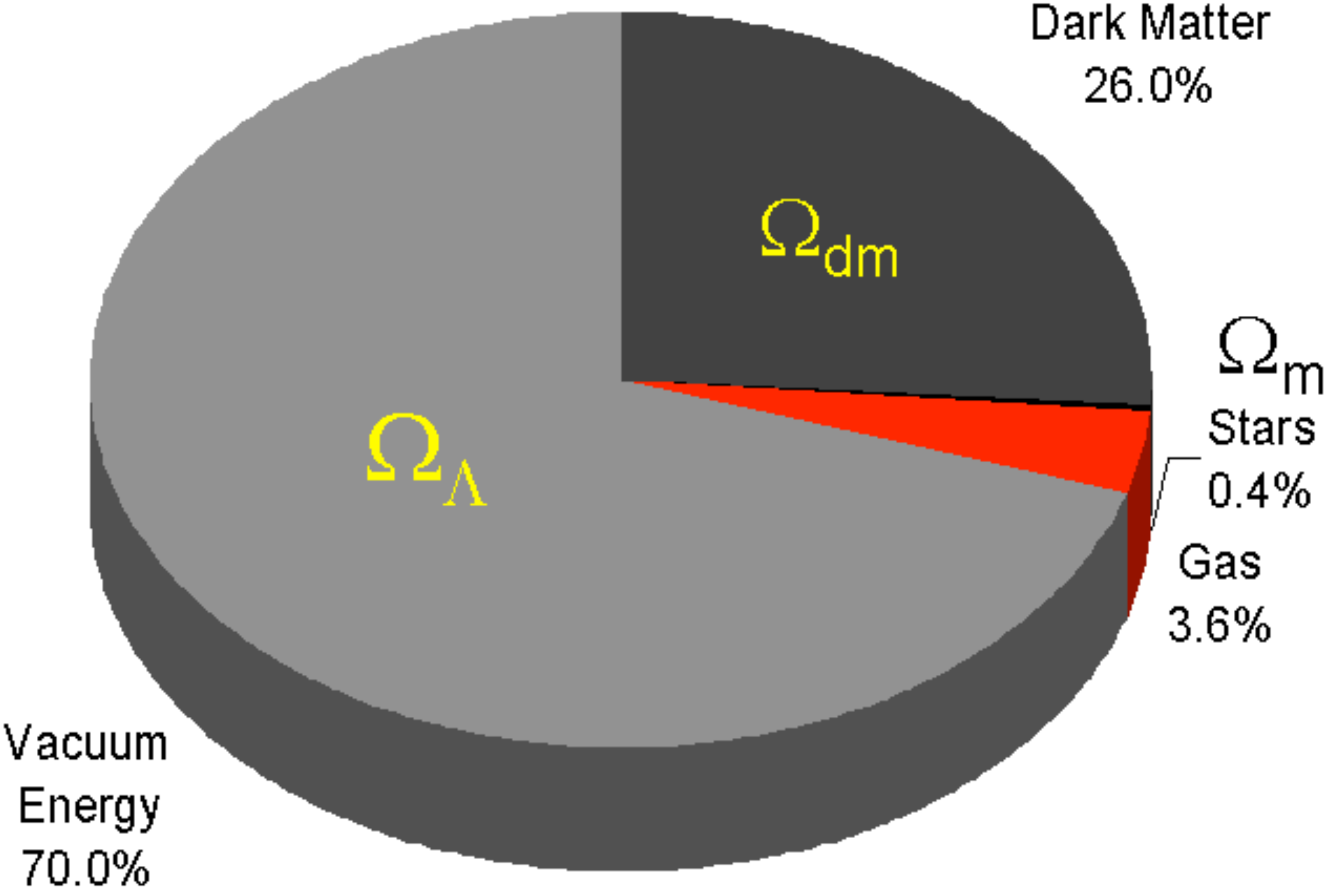
Gravitational Lensing

- The bending of light in the strong gravitational field of massive galaxy clusters causes distortions in the images of the more distant background galaxies (e.g., arcs, arclets, Einstein ring).
- The amount of distortion can be measured and used to determine the amount of mass present in the cluster.
- The above three methods of measuring the masses of groups and clusters are complementary to one another. They all indicate the presence of copious quantities of dark matter in groups/clusters, with $M/L \sim 300(M/L)_{\odot}$.

Dark Matter Candidates and Searches

- Understanding the nature of dark matter is critical since it appears to be the most common type of matter in the Universe.
- Astronomers measure the abundance of various light elements and relate this to the theory of nucleosynthesis in the early Universe in order to infer the amount of baryonic matter (i.e., normal matter consisting of protons, electrons, neutrons) present in the Universe.
- The amount of (baryonic) matter required to explain the products of nucleosynthesis is less than the amount of (total) matter required to explain the gravitational field in clusters of galaxies.
- Some fraction of the dark matter must be non-baryonic.

Matter & Energy Content of the Universe



Forms of Dark Matter

- The exact form in which non-baryonic dark matter exists is not known.

- Its form and nature determines how it responds to gravity and thus determines the exact way in which density perturbations (fluctuations) grow in the early Universe.

- There is a variety of theories suggesting what the nature of non-baryonic dark matter might be: "cold" (massive and relatively slow moving: e.g., axions), "hot" (low mass and fast moving: e.g., neutrinos with finite mass), or a mixture of the two.

MACHOs

- Several extensive searches are underway to look for the dark matter that makes up the halo of our Galaxy.
- If this matter is in the form of dense lumps (dubbed MACHOs for MAssive Compact Halo Objects), these lumps can act as micro gravitational lenses.
- Such lenses should cause the occasional apparent brightening of a background star for a brief period (days or months) as the MACHO happens to line up with the background star.
- While microlensing events have been observed, the number of MACHOs inferred from such observations falls short of the number required to explain the shape of the Galaxy's rotation curve.

WIMPs

- If the dark matter is composed of tiny elementary particles (e.g. massive neutrinos or Weakly Interacting Massive Particles), there should be a number of particles rushing about in any given volume of the Universe.
- There are many ongoing laboratory experiments designed to look for such elementary particles.
- No definite candidates have been found so far.

i>clicker Quiz #28

Which of the following is a founding principle of the General Theory of Relativity?

A. All objects, irrespective of their mass, move in identical fashion within a given gravitational field
B. The speed of light is the same to all observers
C. Mass and energy are equivalent to each other and one can be converted to the other
D. A moving ruler is measured to be shorter than its twin ruler at rest
E. A moving clock is observed to run faster than its twin clock at rest

i>clicker Quiz #29

Which of the following statements about protostars is **FALSE**?

A. Their path on an H-R diagram is called a Hayashi track
B. The luminosity of a 15 M_{sun} does not change by much along its Hayashi track
C. The points on the H-R diagram where proto-stars of different masses start nuclear fusion reactions in their core (and thereby become stars) is called the ZAMS
D. The temperature of a 0.5 M_{sun} does not change by much along its Hayashi track
E. A protostar shines because of nuclear fusion reactions in their core