

Astr 511: Galactic Astronomy

Winter Quarter 2015, University of Washington, Željko Ivezić

Lecture 5:

Basic Properties of the Milky Way

First, a few words about homework # 1

Problem 1.1)

- Absolute magnitude at $g - r = 0.4$ and $[Fe/H] = -1.5$ (the median halo metallicity) is about $M_r = 5.5$.
- The sample is limited to $r < 21$, therefore, we have $DM = r - M_r = 15.5 \sim 15$ mag.
- We can assume that the sample is complete to about 10 kpc (i.e. DM=15 mag; 12.6 kpc for DM=15.5 mag).
- Halo stars can have $[Fe/H] < -1.5$, assuming $[Fe/H] = -2.0$ for the lower limit results in another 0.3 mag loss of limiting DM, and the limiting distance is about 8-9 kpc!

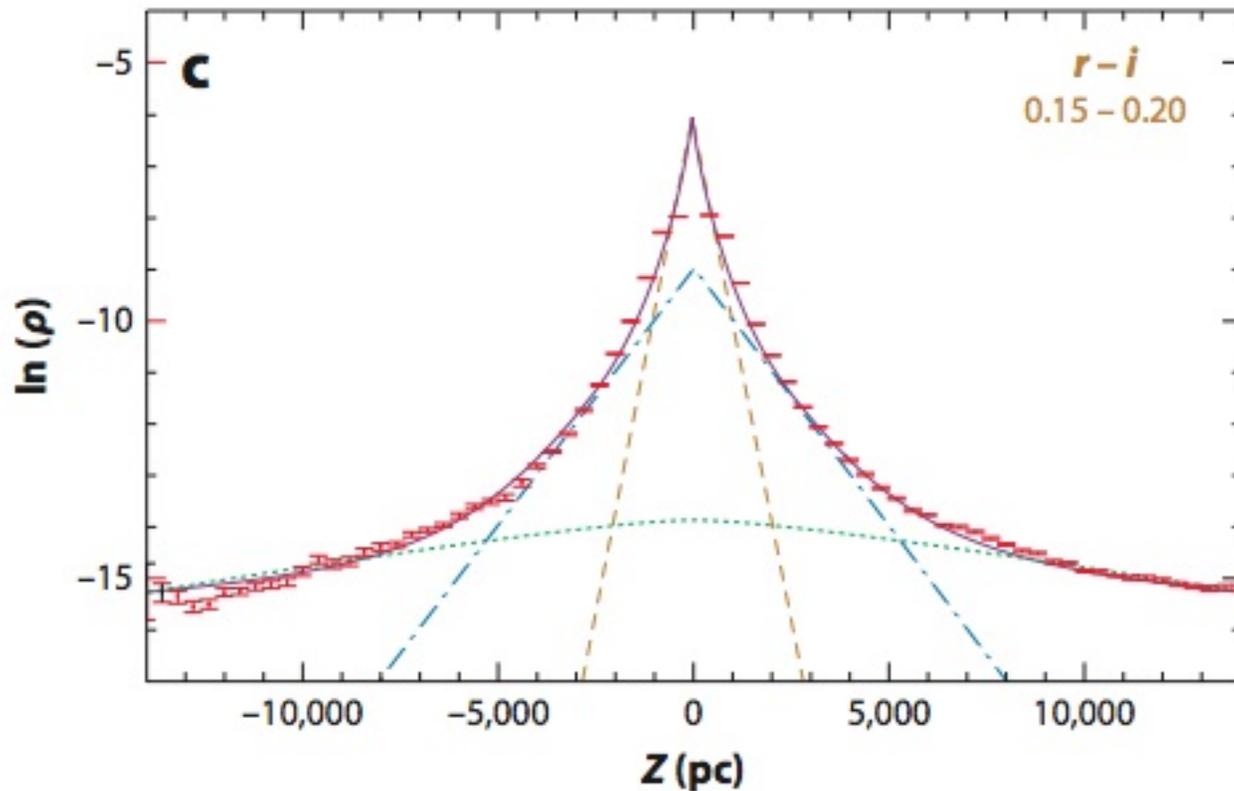


Figure 4

Cross sections through maps, similar to those shown in **Figure 3**, showing the vertical ($|Z|$) distribution at $R = 8$ kpc and for different $r - i$ color bins. The orange dashed lines are exponential models fitted to the red points (the sech^2 function is not a good fit; see footnote 28 of Jurić et al. 2008). The orange dashed lines in panel *a* correspond to a fit with a single, exponential disk. The vertical dashed line shows the best-fit position of the maximum density (not at 0 due to the Sun’s offset from the disk midplane). The blue dot-dashed line in panel *b* corresponds to an additional disk component, and the data are fit with a sum of two disks with scale heights of 270 pc and 1,200 pc, respectively, and a relative normalization of 0.04 (the “thin” and the “thick” disks). The purple line in the bottom panel (closely following the data points) corresponds to a sum of two disks and a power-law spherical halo. The orange dashed line and the blue dot-dashed line are the disk contributions, and the halo contribution is shown by the green dotted line. For the best-fit parameters, see **Table 1**. Reprinted from Jurić et al. (2008).

Problem 1.5)

- First, we get volume for 1 deg² of sky and distances between 90 kpc and 100 kpc

$$\Delta V = \left(\frac{\Delta\Omega}{41,253 \text{ deg}^2} \right) \frac{4\pi}{3} (D_2^3 - D_1^3) = 27.5 \text{ kpc}^3 \quad (1)$$

- Then we get the number of stars with $0.2 < g - r < 0.4$ and (say) $4.8 < Z/\text{kpc} < 5.2$: 2,624 for our area of 314 deg² towards NGP (the volume is 0.957 kpc³)
- $Z = 5$ kpc is $R = 9.4$ kpc, and we assume $\rho(R) \propto R^{-3}$, which gives a number density ratio of 9.7×10^{-4} .
- So I get $N = 2,624 \times 9.7 \times 10^{-4} \times (27.5/0.957) = 73$ stars (per deg²) (same result for $Z = 4 - 6$ kpc); if $\rho \propto R^{-2.8}$, about 100 stars.

Problem 1.5)

- How do we choose optimal bin width?
- Look at Book Figure 5.20 in astroML; a good summary of the so-called Knuth's rule is

$$\Delta_b = \frac{2.7\sigma_G}{N^{1/4}}, \quad (2)$$

where Δ_b is the optimal bin width, N is the sample size, and σ_G is a robust estimate of the distribution width (equal to the standard deviation for a Gaussian distribution),

$$\sigma_G = 0.7413 (q_{75} - q_{25}), \quad (3)$$

where q_{25} and q_{75} are the 25% and 75% distribution quartiles.

Problem 1.5)

Never access individual elements - use numpy arrays instead!

```
def FeH(ug, gr):
    FeH = FeHpoly(ug, gr)
    FeH[gr>0.6] = -0.6
    FeH[FeH < -2.5] = -2.5 # sanity limit
    FeH[FeH > 0.5] = 0.5   # sanity limit
    return FeH

# alternatively,
def FeH(ug, gr):
    FeH = FeHpoly(ug, gr)
    return numpy.where(gr > 0.6, -0.6, FeH)
```

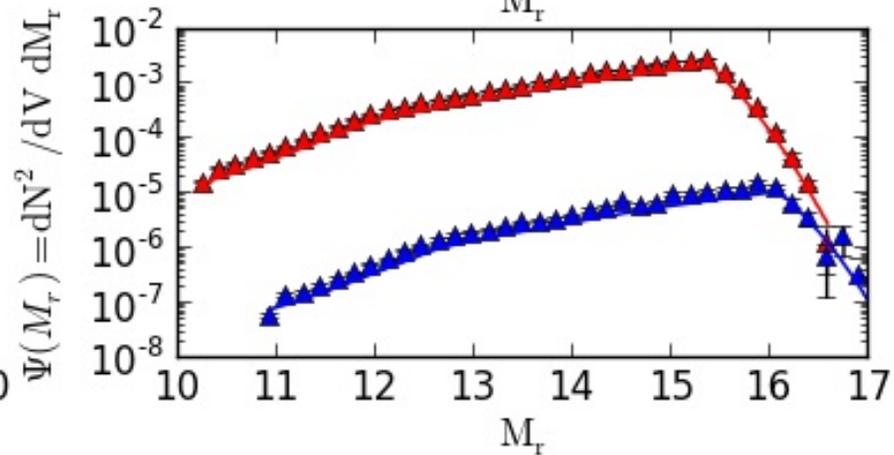
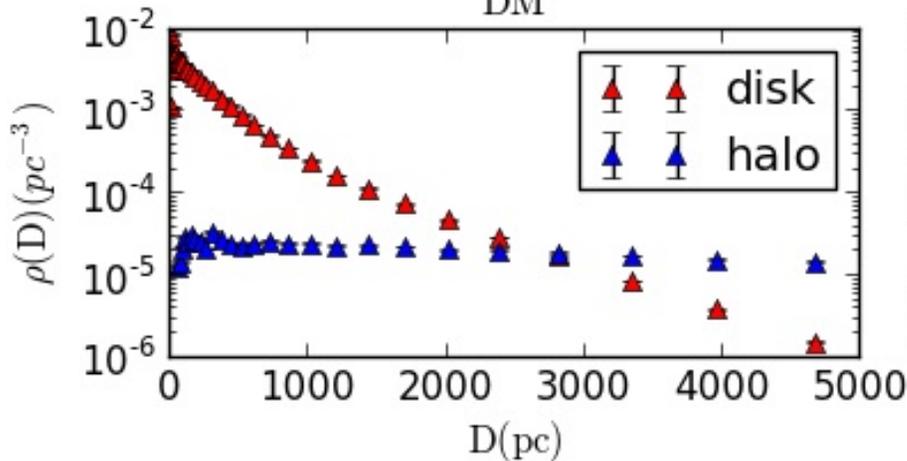
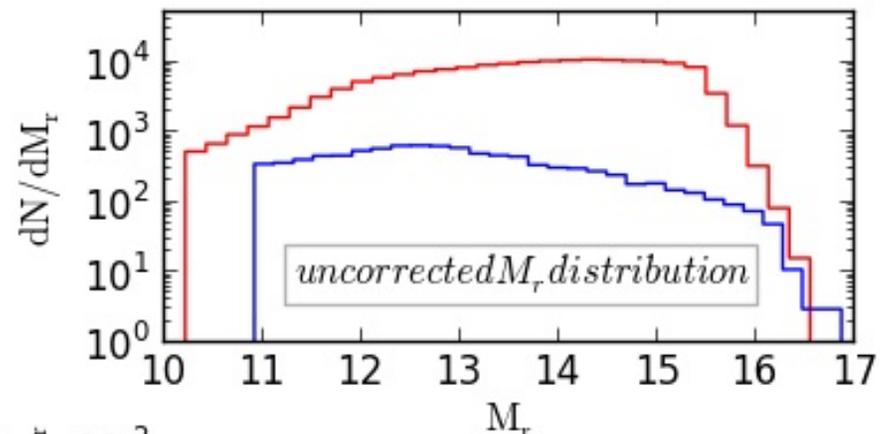
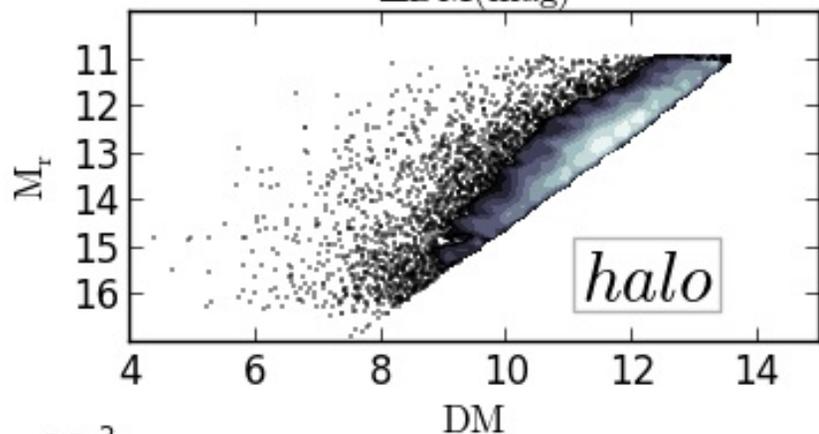
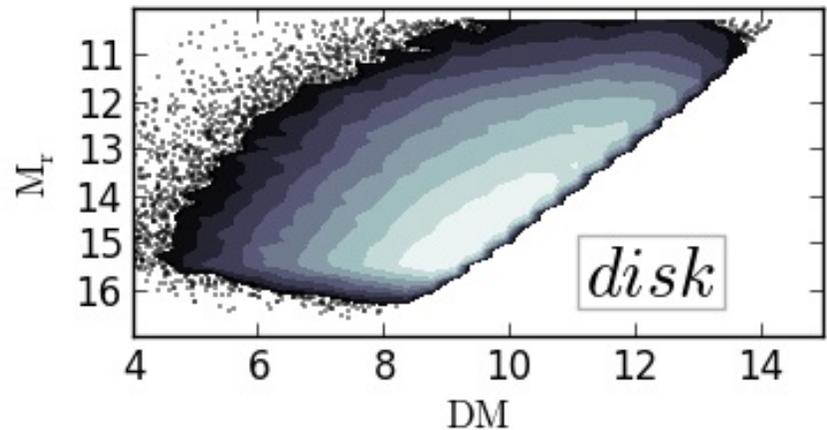
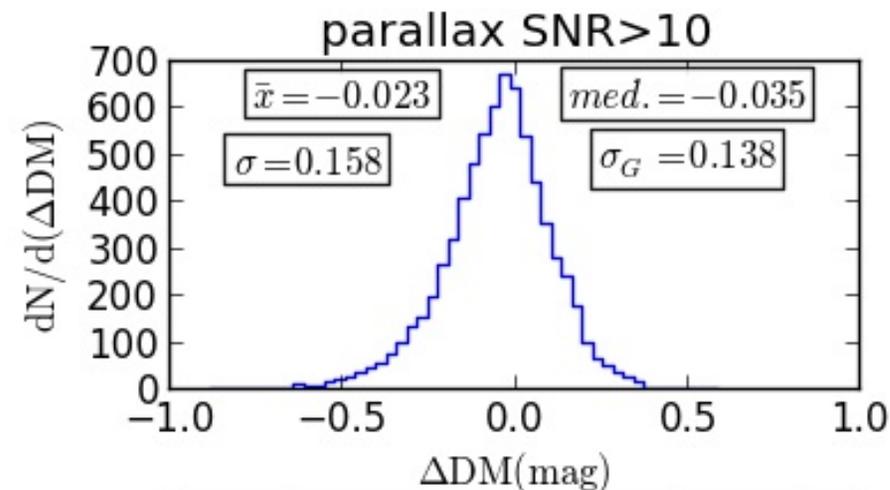
Heads-up for Project 3

- Collaborative work: two teams working on two problems based on APOGEE-ASPCAP data, see <http://www.sdss.org/dr12/irspec/>
- Using abundances for 15 elements (allStar file), we will study the variation of their 15-D distribution in the 3D XYZ space, as a function of stellar population (halo, thin disk, thick disk); we will use Extreme Deconvolution method to quantify the 15-D distributions, see astroML Book Figures 6.11 and 6.12
- Using spectra (apStar files), we will run PCA, ICA and NMF methods on them, see astroML Book Figures 7.4, 7.6 and 7.7

Heads-up for Project 3

- The first step: define the teams, and within each team assign responsibilities for
 1. learning about the data properties and starting a “paper” with a brief Introduction about APOGEE and data properties;
 2. learning about how to download and access data (including writing python code);
 3. learning about how to (modify and) run appropriate astroML tools;
 4. writing analysis summary (including plots) for the “paper”

E.g., Covey et al. (2007, *Astronomical Journal* 134, 2398): 186 citations!

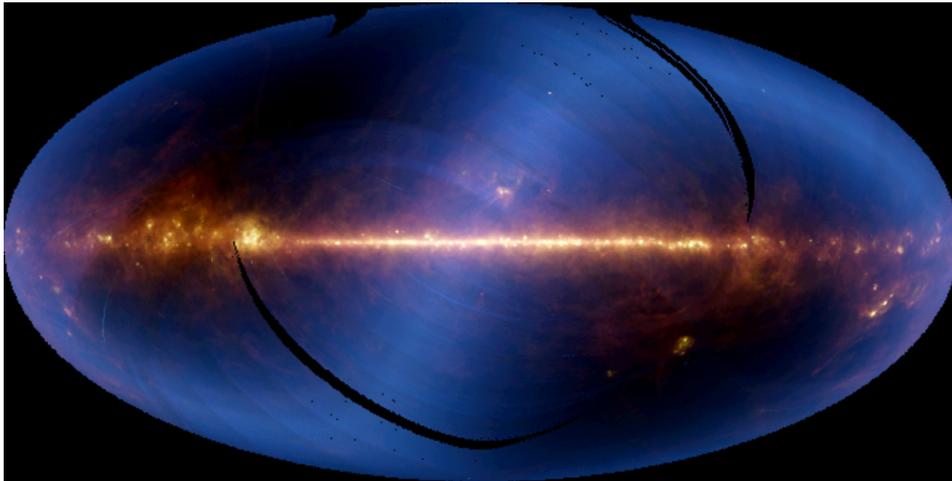
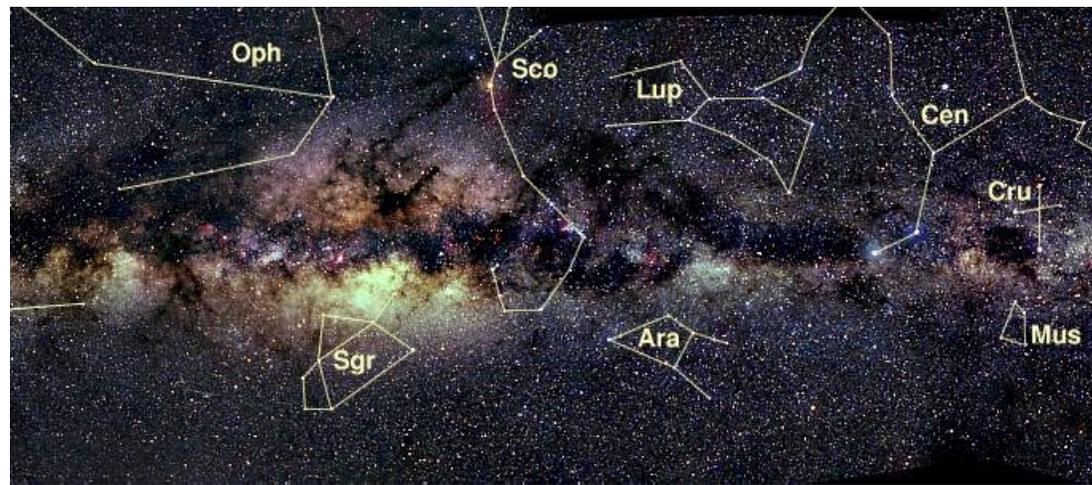


Outline

- Spatial distribution of stars: disk, halo, bulge
- Stellar kinematics: rotation vs. random motions
- Galactic center: black hole measurements
- Interstellar medium: gas and dust
- Stellar counts: simple analysis

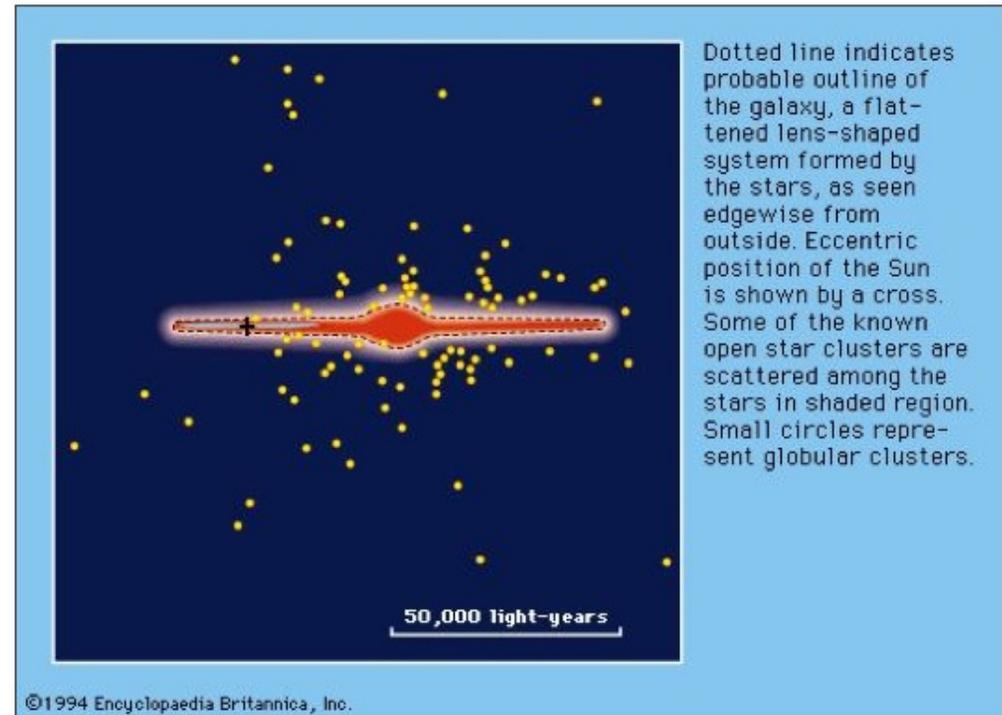
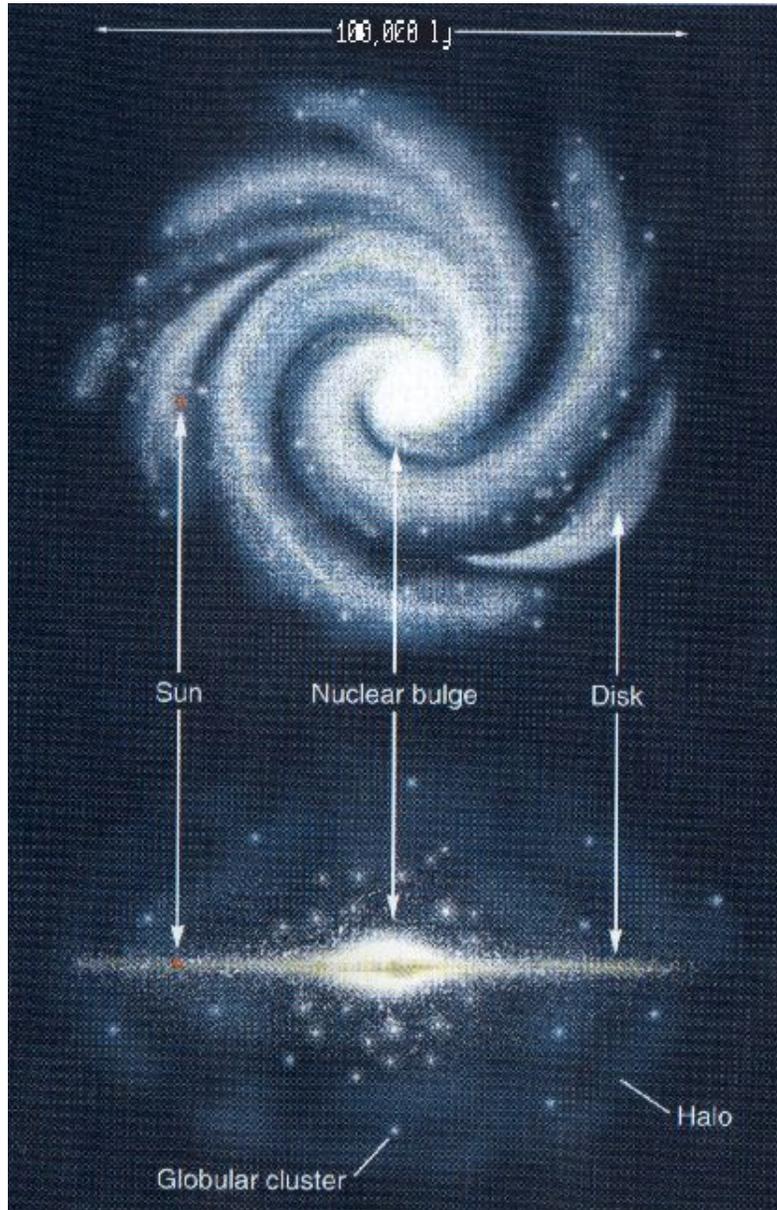
Introduction

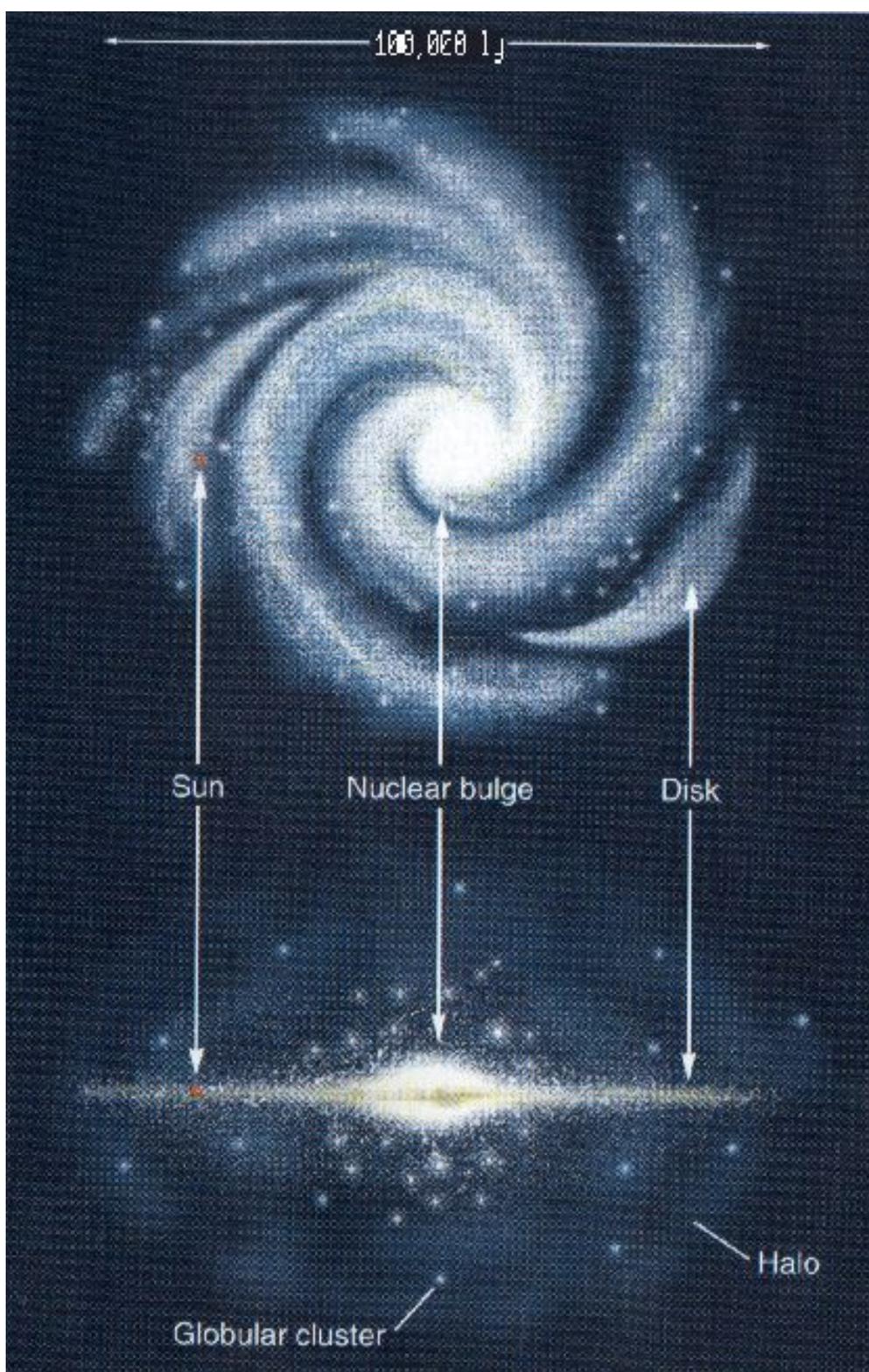
- **Top left:** 30° by 10° (optical) view towards the Galactic center (from Axel Mellinger)
- **Middle left:** The all-sky view by the Infrared Astronomical Satellite
- **Bottom left:** a spiral galaxy (NGC 7331) similar to the Milky Way
- **Conclusion:** the density of stars on the sky varies greatly because we are observing from inside a disk of stars
- **We live in a spiral galaxy** the same conclusion supported by the motions of stars and the presence of abundant interstellar medium (more later)



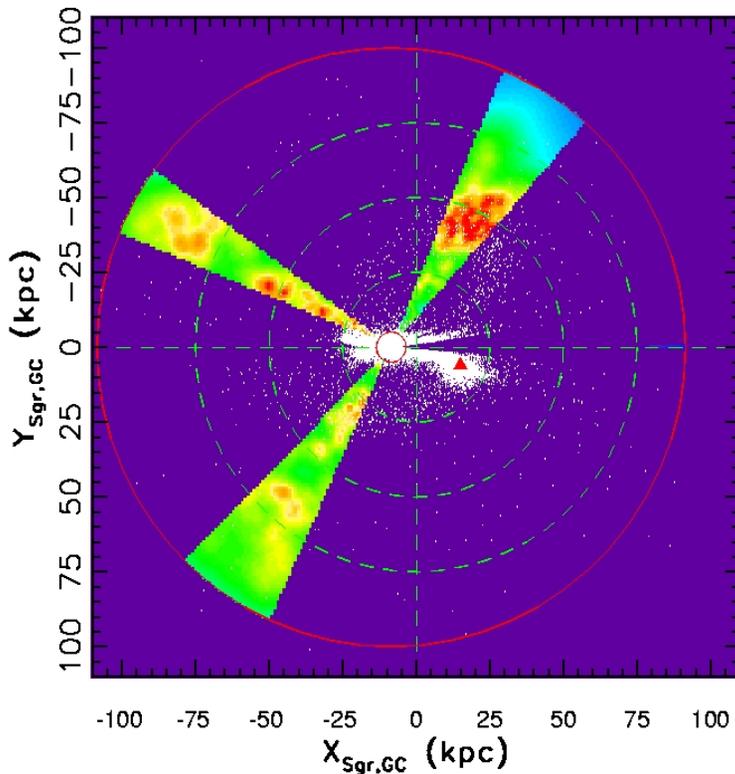
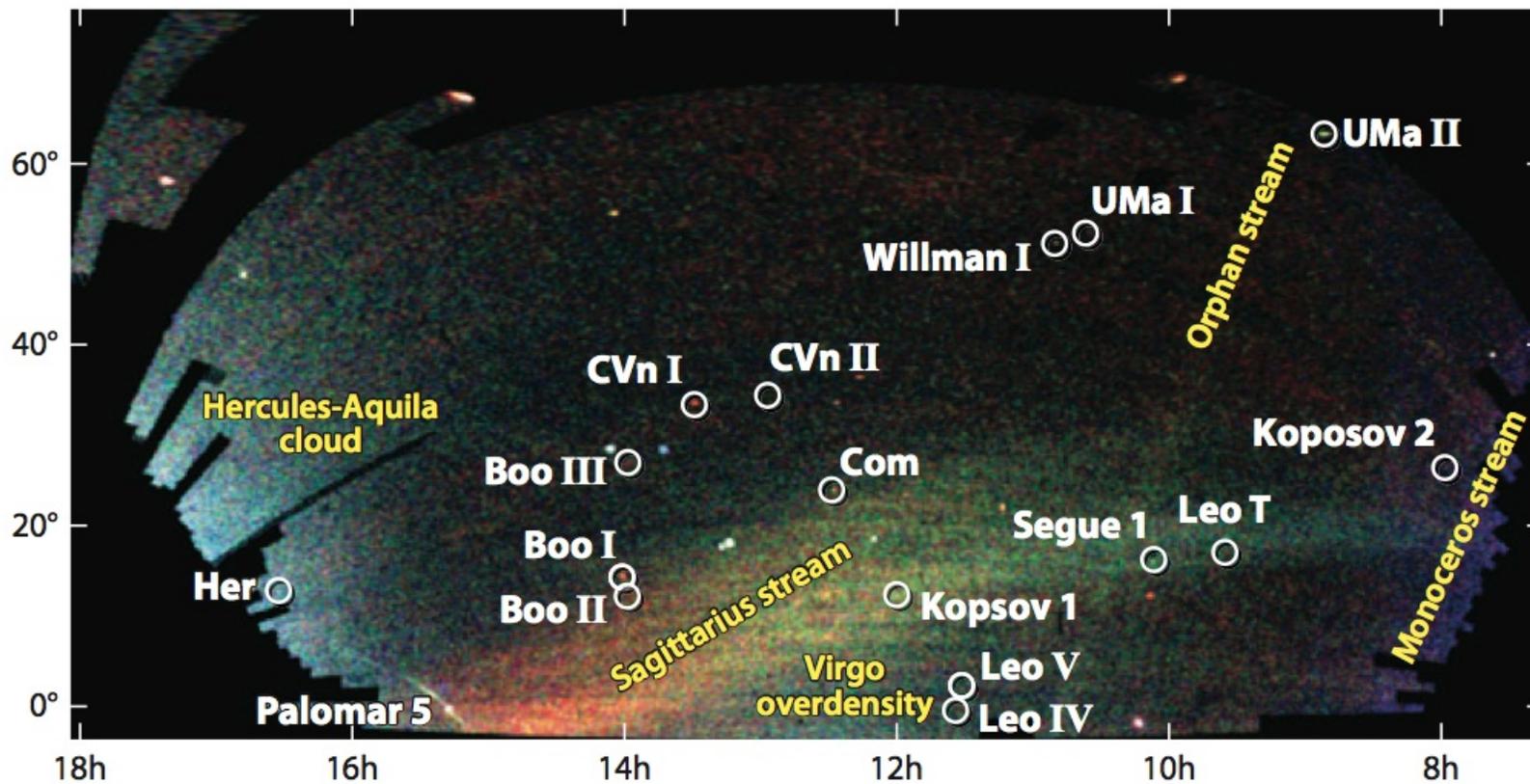
The position of the Galactic center

- Shapley used the distribution of globular clusters to demonstrate that the Sun is not in the center of the Milky Way (8 kpc)



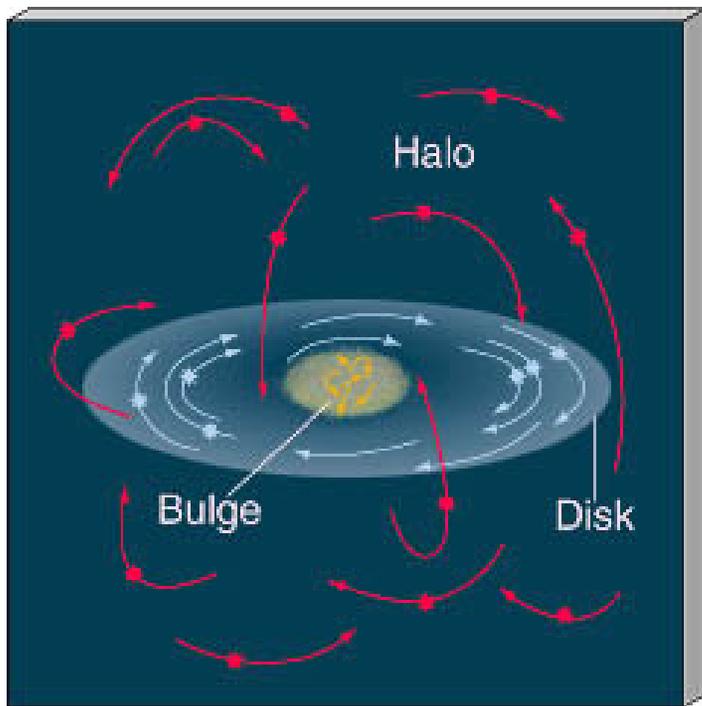


GALACTIC DISK	GALACTIC HALO	GALACTIC BULGE
Highly flattened	Roughly spherical—mildly flattened	Somewhat flattened and elongated in the plane of the disk ("football shaped")
Contains both young and old stars	Contains old stars only	Contains both young and old stars; more old stars at greater distances from the center
Contains gas and dust	Contains no gas and dust	Contains gas and dust, especially in the inner regions
Site of ongoing star formation	No star formation during the last 10 billion years	Ongoing star formation in the inner regions
Gas and stars move in circular orbits in the Galactic plane	Stars have random orbits in three dimensions	Stars have largely random orbits but with some net rotation about the Galactic center
Spiral arms	No obvious substructure	Ring of gas and dust near center; Galactic



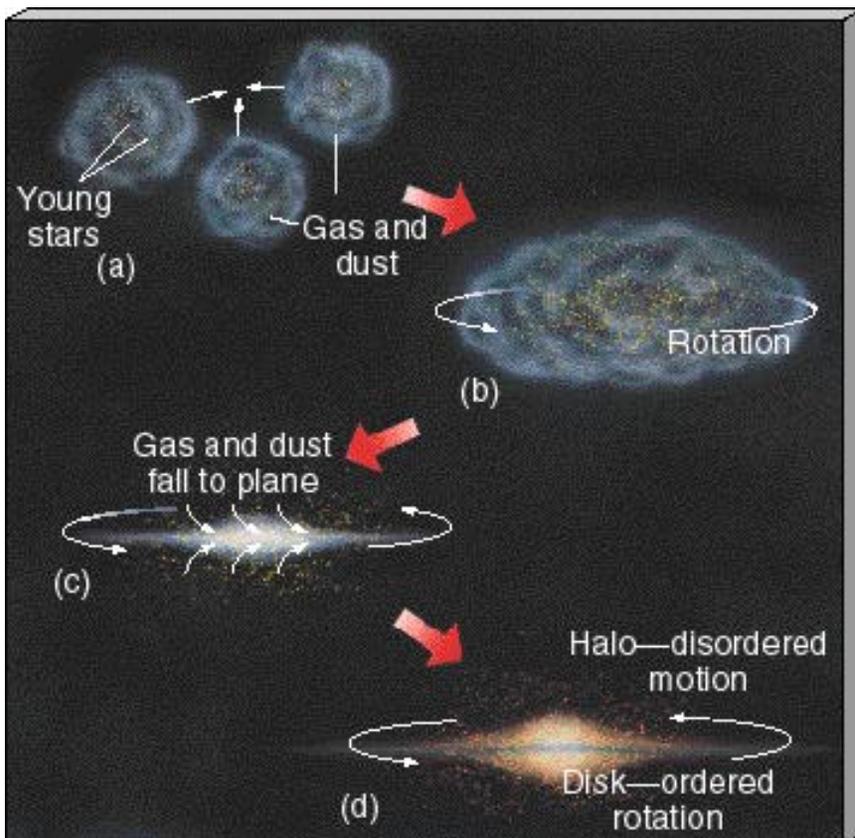
Halo Substructure

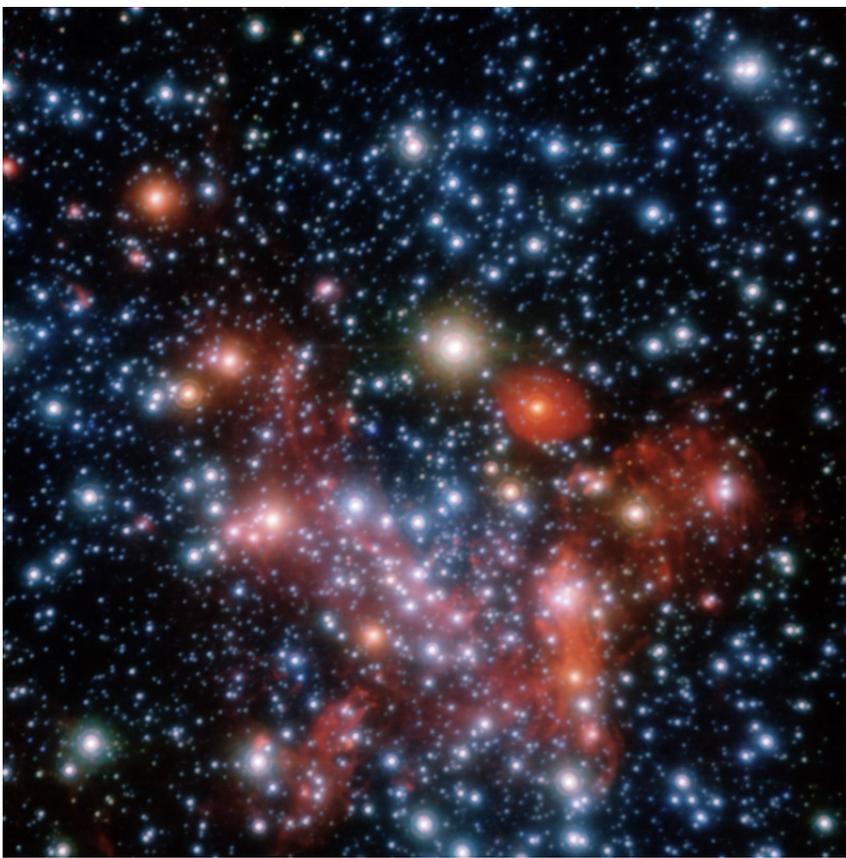
- The table on the previous page is wrong: most recent data clearly show that **halo has rich substructure**
- **Top left:** the counts of SDSS stars color-coded by distance (red: ~ 10 kpc, blue: several kpc) from Belokurov et al. (2007)
- **Bottom left:** the distribution of SDSS RR Lyrae stars and 2MASS red giants (Ivezić et al. 2003)



Kinematics

- Stars move in a gravitational potential (more in L13)
- Two types of motion: disk stars **rotate** around the center, while halo stars are on randomly distributed elliptical orbits (more in L11)
- The motion of stars was set during the formation period
- The details are governed by the laws of physics: conservation of energy and conservation of angular momentum!
- As the cloud collapses, its rotation speed must increase. As it spins faster, it must flatten.

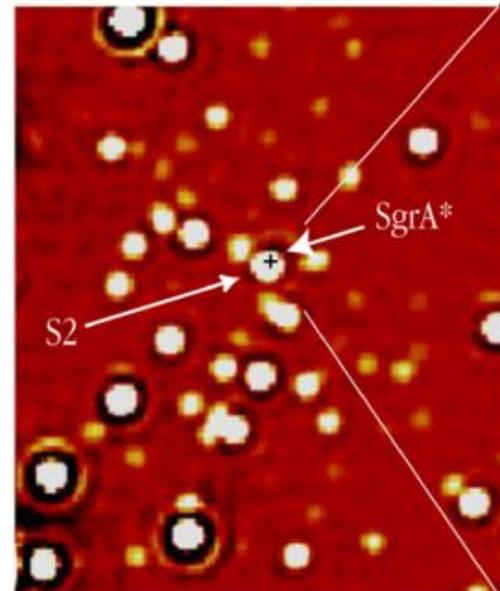




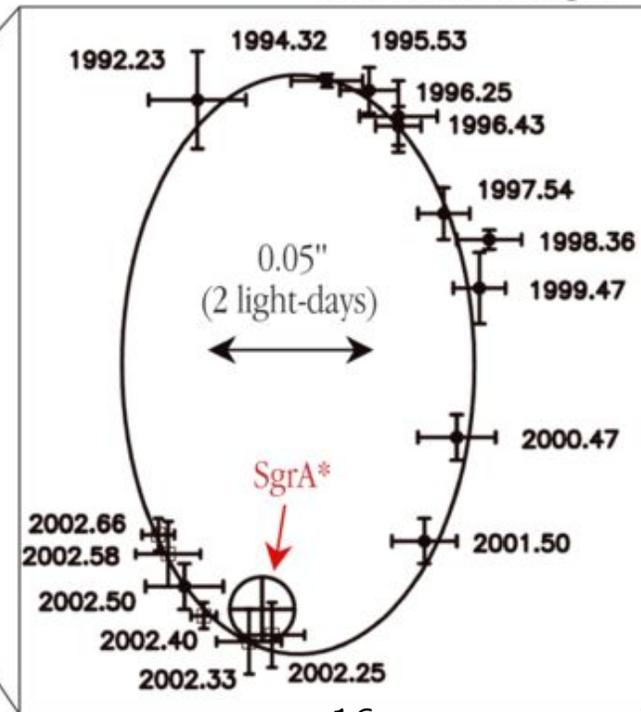
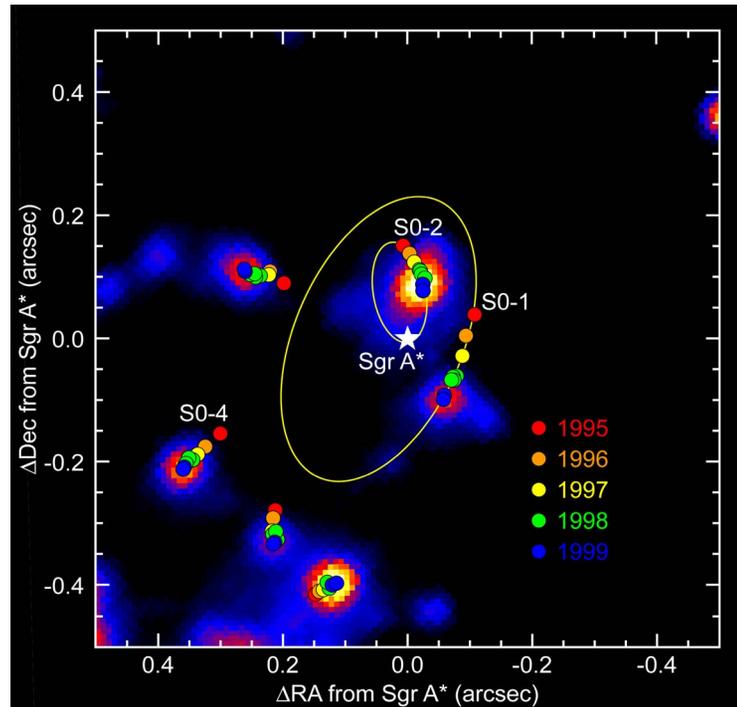
Black Hole in the Galactic Center

- Stars move in a gravitational potential: a large mass (a few $10^6 M_{\odot}$) confined to small space (0.1-0.2 AU) is required to explain about ~ 30 **observed** orbits
- Two teams: UCLA team led by Andrea Ghez, and European team led by Reinhard Genzel

NACO May 2002



S2 Orbit around SgrA*



Black Hole in the Galactic Center

- Meyer et al. (2012, Science 338, 84): after 17 years of imaging the galactic center at the highest angular resolution possible today: two stars with full phase coverage and periods of less than 20 years.

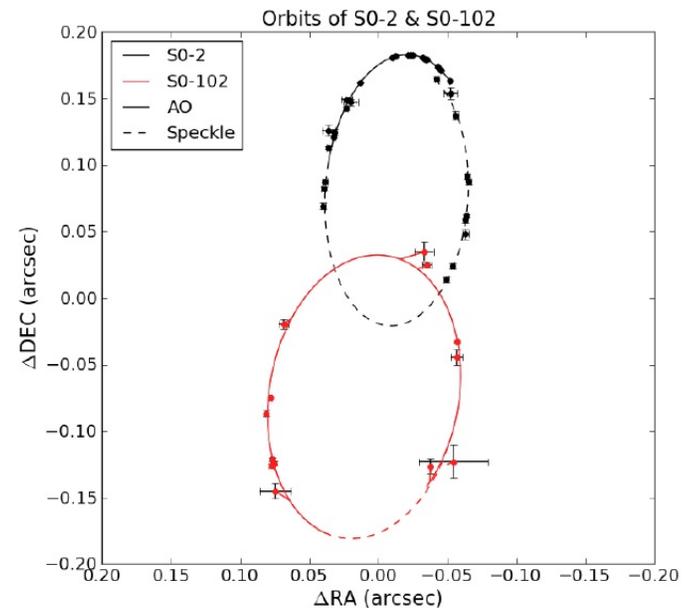
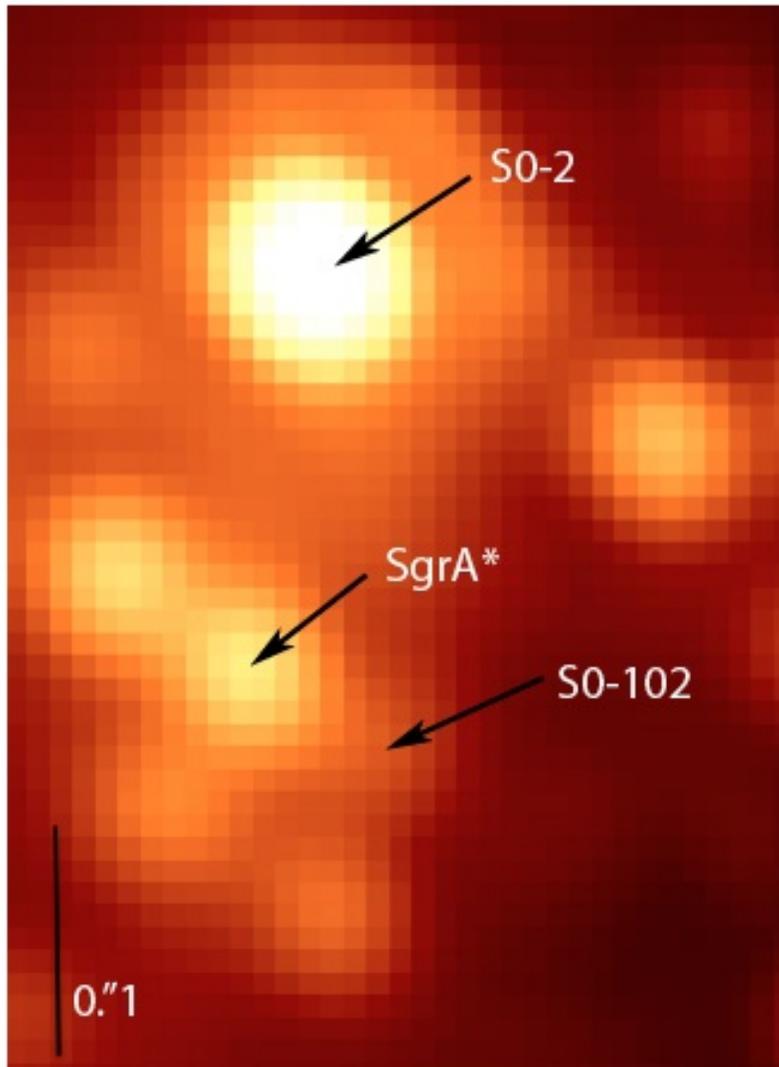
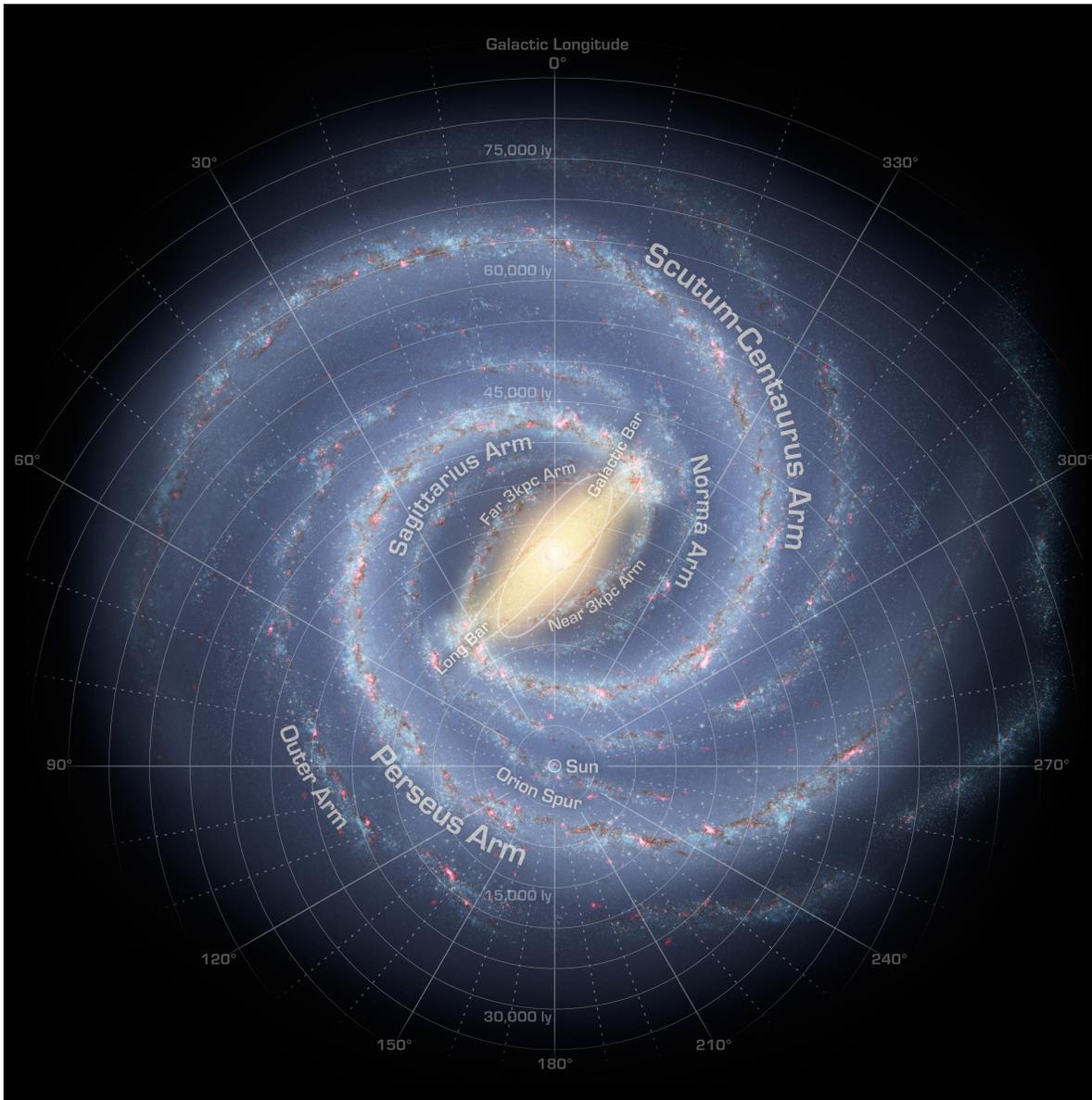


Figure 1 A Keck/NIRC2 adaptive optics image from May 2010 showing the short-period star S0-102, which is besides S0-2 the only star with full orbital phase coverage, and the electromagnetic counterpart of the black hole, Sgr A*. The image was taken at a wavelength of 2.12 μm and shows the challenge of detecting S0-102, which is 16 times fainter than S0-2 and lies in this crowded region.



Revised Spiral Arms

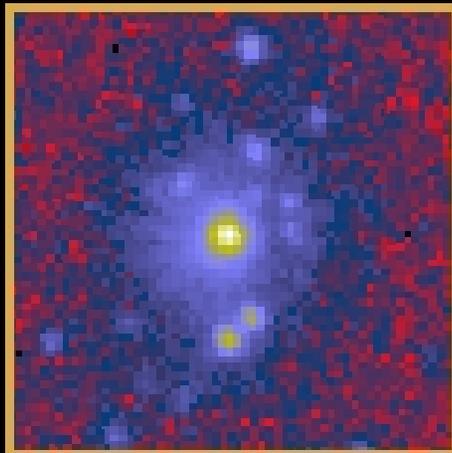
- The stellar bar was discovered in 1990s based on IRAS data
- It was believed that the Galaxy has four spiral arms: the Scutum-Centaurus, Perseus, Sagittarius and Norma
- The stellar counts from Spitzer galactic plane survey (Benjamin et al. 2008) strongly suggest that there are only two major arms, the Scutum-Centaurus and Perseus arms, as is common for barred galaxies

M81 – Spiral Galaxy (Type Sb)

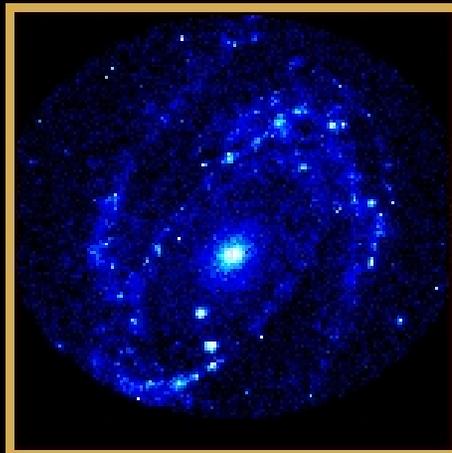
Distance: 12,000,000 light-years (3.7 Mpc)

Image Size = 14 x 14 arcmin

Visual Magnitude = 6



X-Ray: ROSAT



Ultraviolet: ASTRO-1



Visible: DSS



Visible: R. Gendler



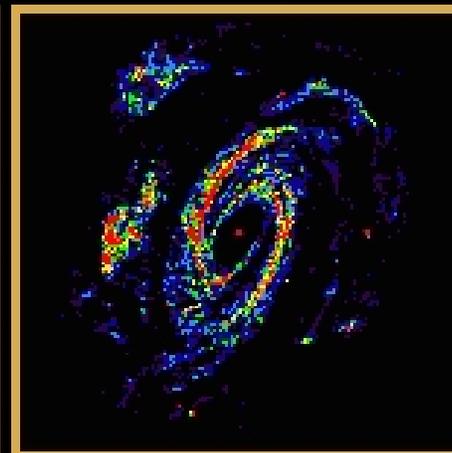
Near-Infrared: Spitzer



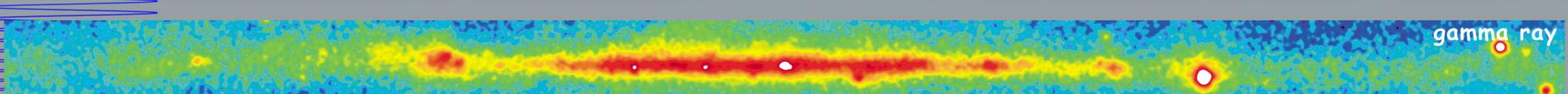
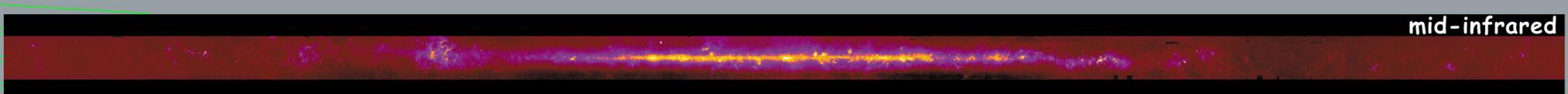
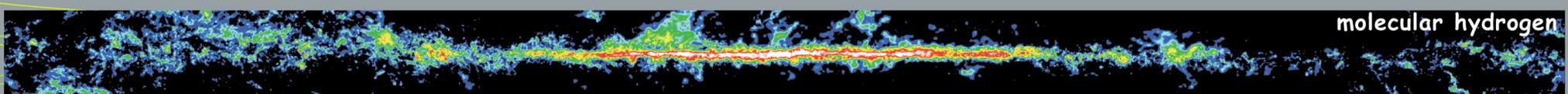
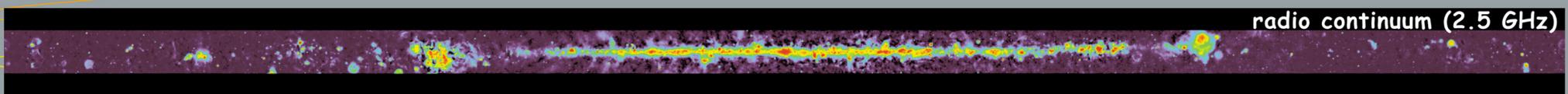
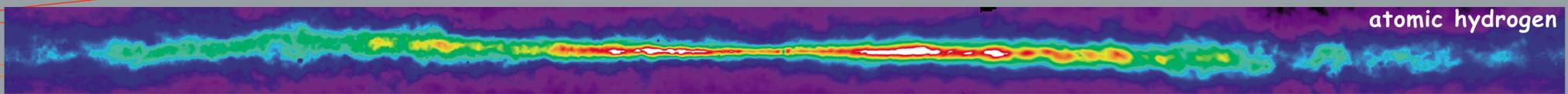
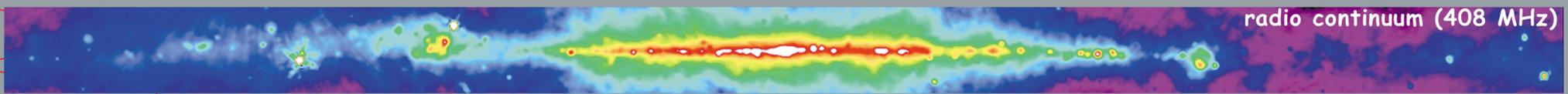
Mid-Infrared: Spitzer



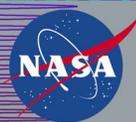
Far-Infrared: Spitzer



Radio: VLA



<http://adc.gsfc.nasa.gov/mw>



Multiwavelength Milky Way

Stars form from gas in galaxies

“Interstellar Medium” = “ISM”

- Hot ionized Gas
- Neutral Atomic Gas
- Cold Molecular Gas
- Dust

What these phases are called:

- Hot ionized Gas
- Neutral Atomic Gas
- Cold Molecular Gas
- Dust

"HII" = "H two"

"HI" = "H one"

"H₂"

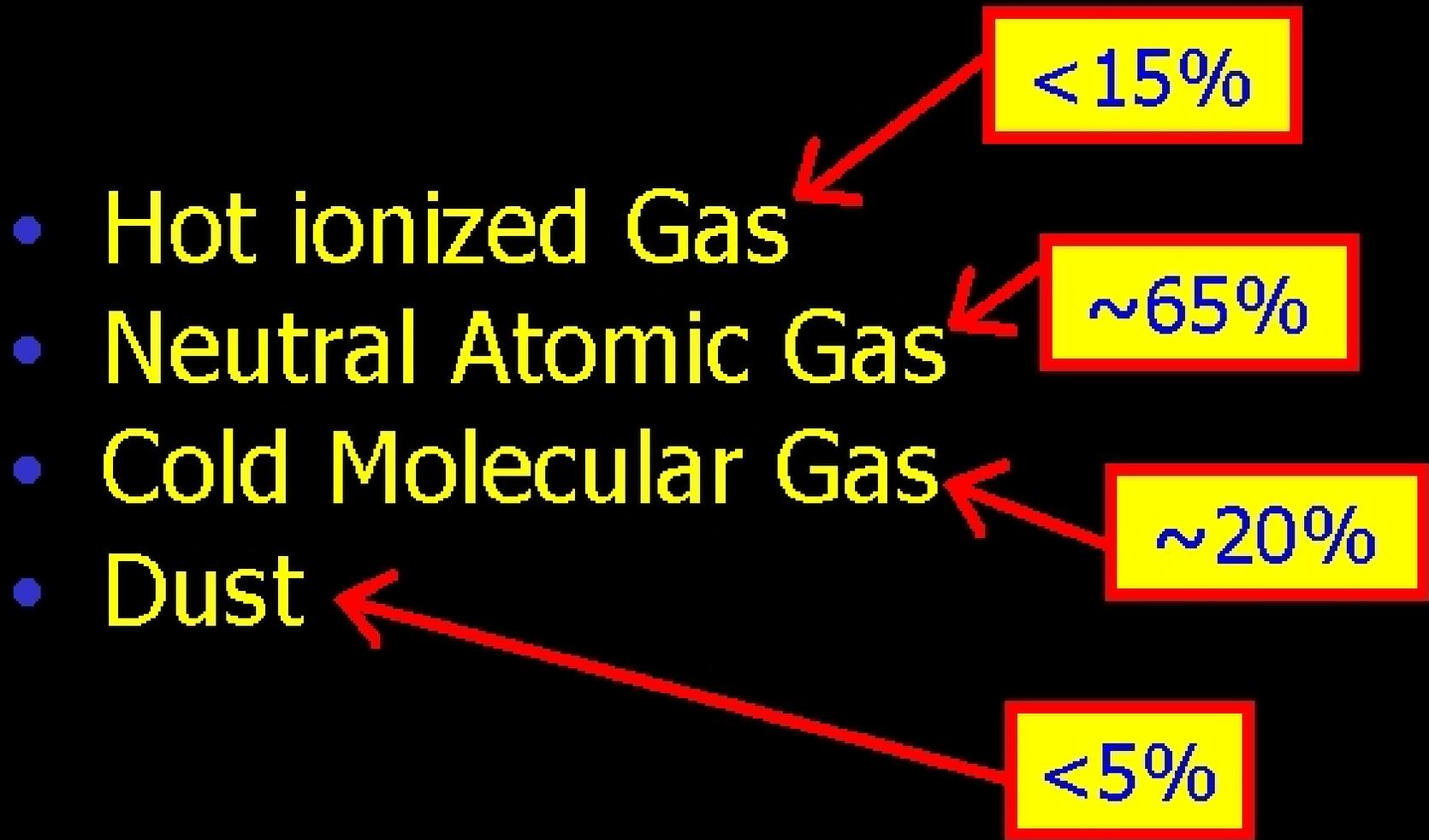
"Dust"

Nomenclature: "ElementI" = unionized Element

"ElementII" = singly ionized Element

"ElementIII" = doubly ionized Element...etc

What fraction is in each phase?



Typical Densities

- Hot ionized Gas
- Neutral Atomic Gas
- Cold Molecular Gas
- Dust

Low
(<0.5 atoms/cm³)

Medium
(1-10 atoms/cm³)

High
(10^2 - 10^5 atoms/cm³)

Very High
(solid)

Typical Temperatures

Hot
($>10^4$ - 10^7 K)

Medium
(100 - 10^4 K)

Cold
(<50 K)

Medium-cold
(<100 K)

- Hot ionized Gas
- Neutral Atomic Gas
- Cold Molecular Gas
- Dust

Detected How?

H α emission line (6563Å)
X-Rays (if $T > 10^6\text{K}$)

- Hot ionized Gas
- Neutral Atomic Gas
- Cold Molecular Gas
- Dust

21cm emission line

(hyperfine splitting of H ground state)

CO rotational emission line
(mm wavelengths)

Thermal (Black-body) radiation at far-infrared wavelengths

Distributed How?

- Hot ionized Gas
- Neutral Atomic Gas
- Cold Molecular Gas
- Dust

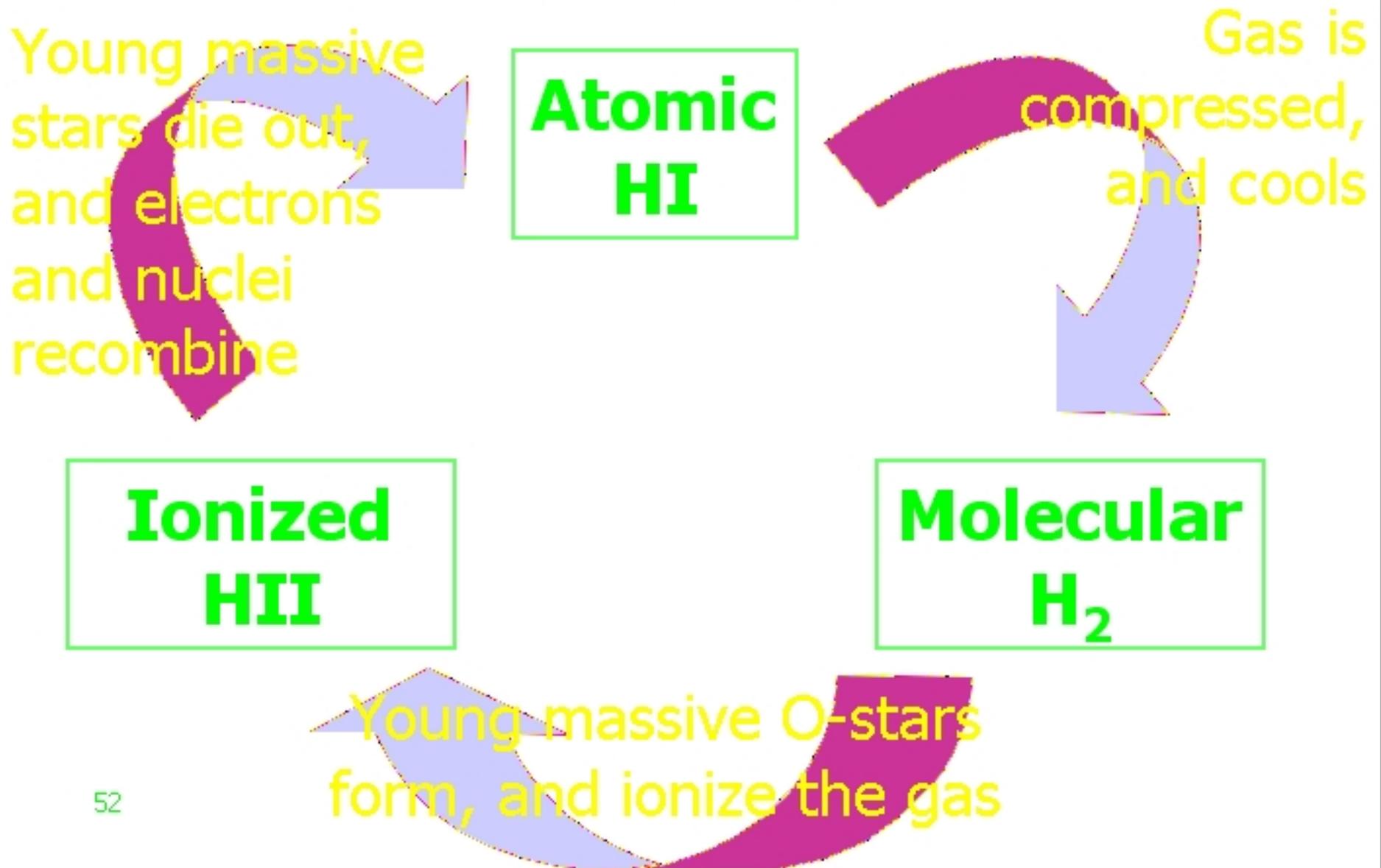
Halos of
Galaxies

Galaxy
Midplane, out to
large radii
beyond stars

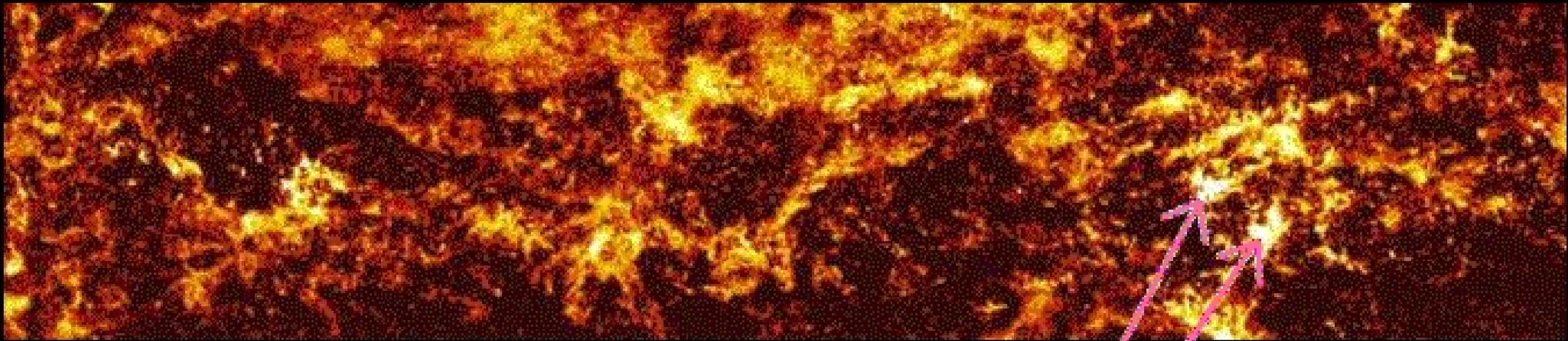
Galaxy Midplane,
concentrated in
spiral arms

Tracks the
distribution of gas

How are the three phases of gas inter-related?



Molecular gas is clumpy on small scales.



(View of the outskirts, away from the center)

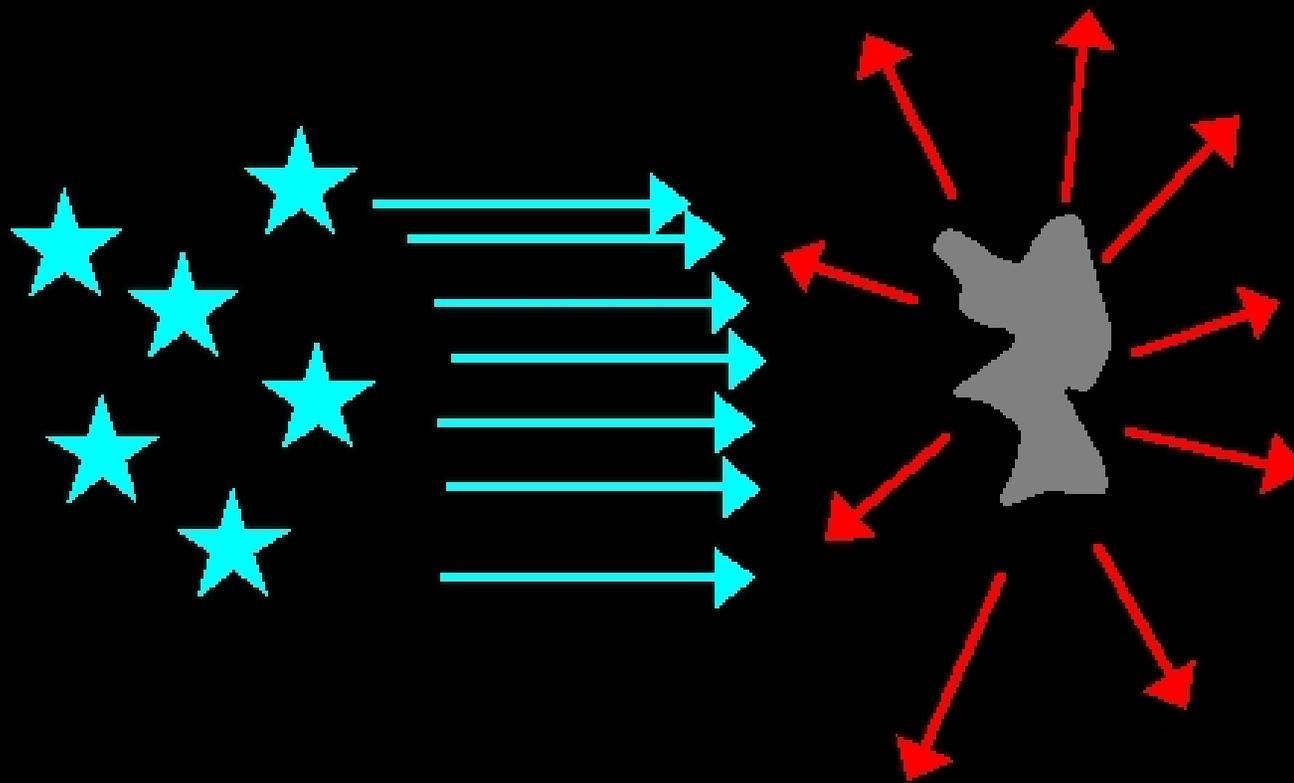
“Molecular Clouds”

This is why stars form in clusters!

A comment about detection of molecular hydrogen

- Molecular hydrogen (H_2) is hard to detect in ground-based observations (optical, near-IR, radio). The reason is that its rotational energy levels are difficult to excite in the cold ISM (due to small moment of inertia of H_2).
- Various tracer molecules, such as carbon monoxide, hydrogen cyanide, ammonia, water, and formaldehyde, are used instead to infer the amount of H_2 (how do we know that e.g. CO is correlated with H_2 ? See, for example, Rachford et al. 2012, ApJ 577, 221).
- Nevertheless, H_2 is directly detectable: in the UV via absorption (Copernicus and FUSE space missions, e.g. Richter, Sembach & Howk 2003, A&A 405, 1013), and in the mid-IR via emission lines (the Spitzer space mission, e.g. Ingalls et al. 2011, ApJ 743, 174).

The amount of dust can be measured using light that has been **reprocessed** into the **infrared**.

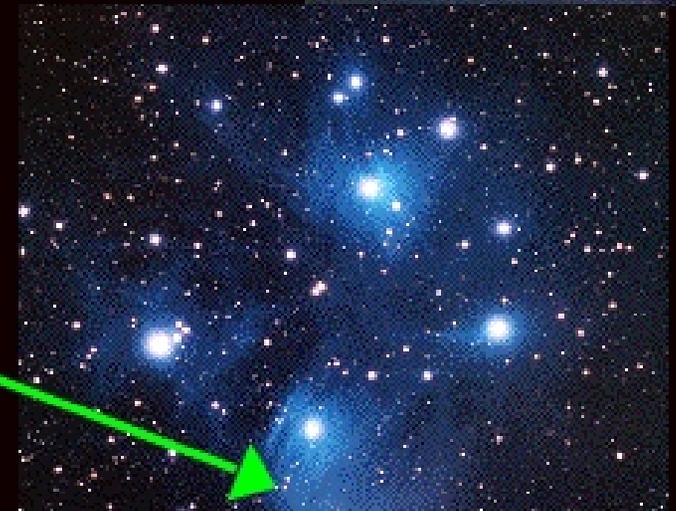
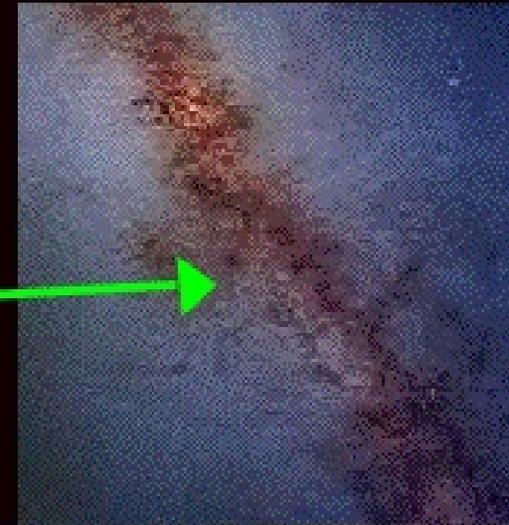
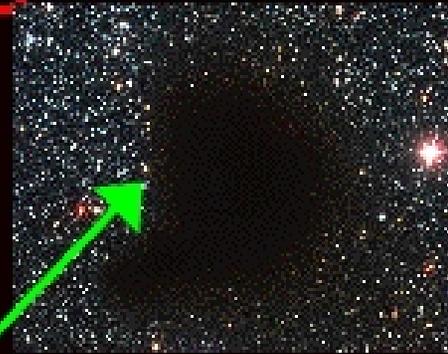


UV & optical light is absorbed by dust...

44

...which heats up to 10-100K and radiates like a greybody at 10-300 μ m

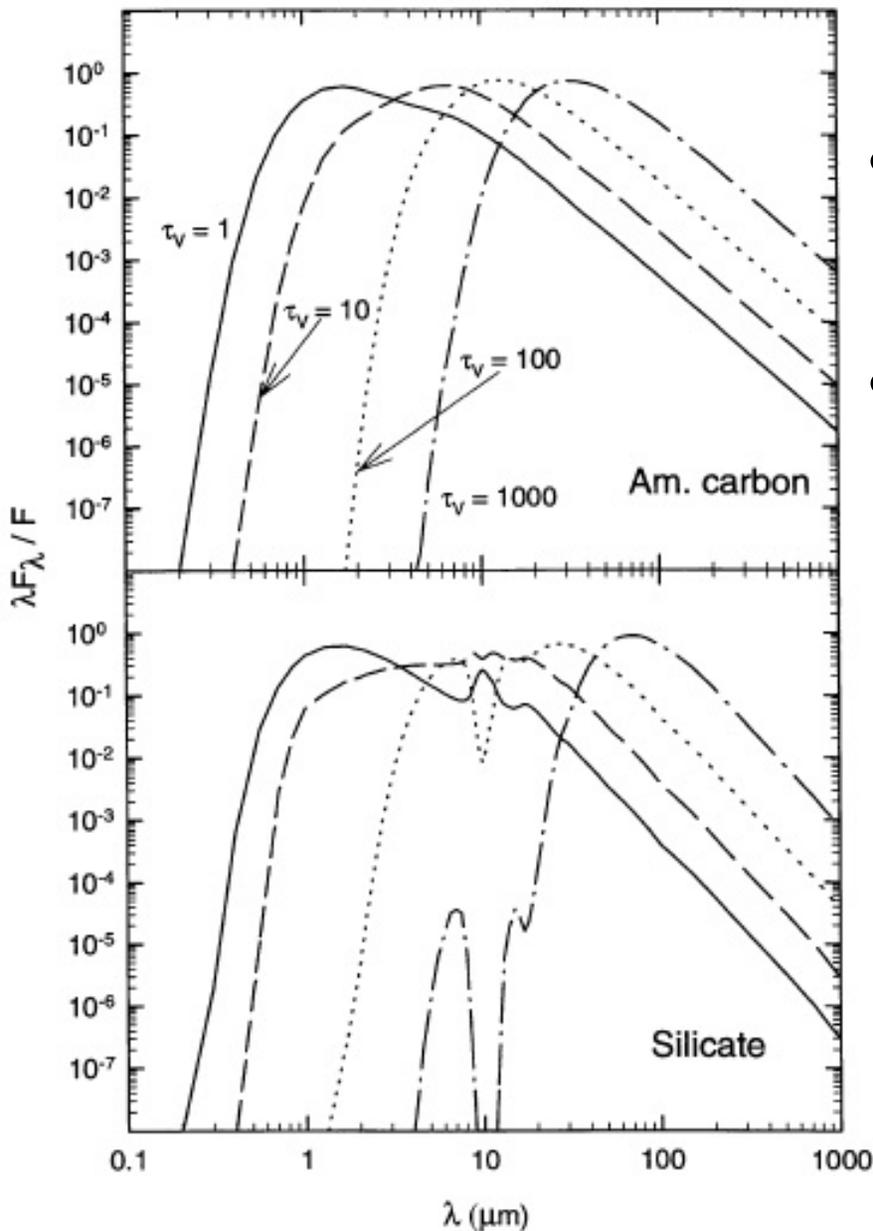
Dust plays many important roles in galaxies



1. Extinction/Attenuation
2. Reddening
3. Reprocessing UV/optical light into the infrared
4. Scatters light.
5. Locks up metals

Dust & radiative transfer

- **Left:** radiative transfer modeling (fig. 3 from Ivezić & Elitzur 1997, MNRAS 287, 799)
- **Below:** modeling of dust optical properties.



Spectral energy distributions for a star embedded in a spherical dusty shell ($\rho(r) \propto 1/r^2$).

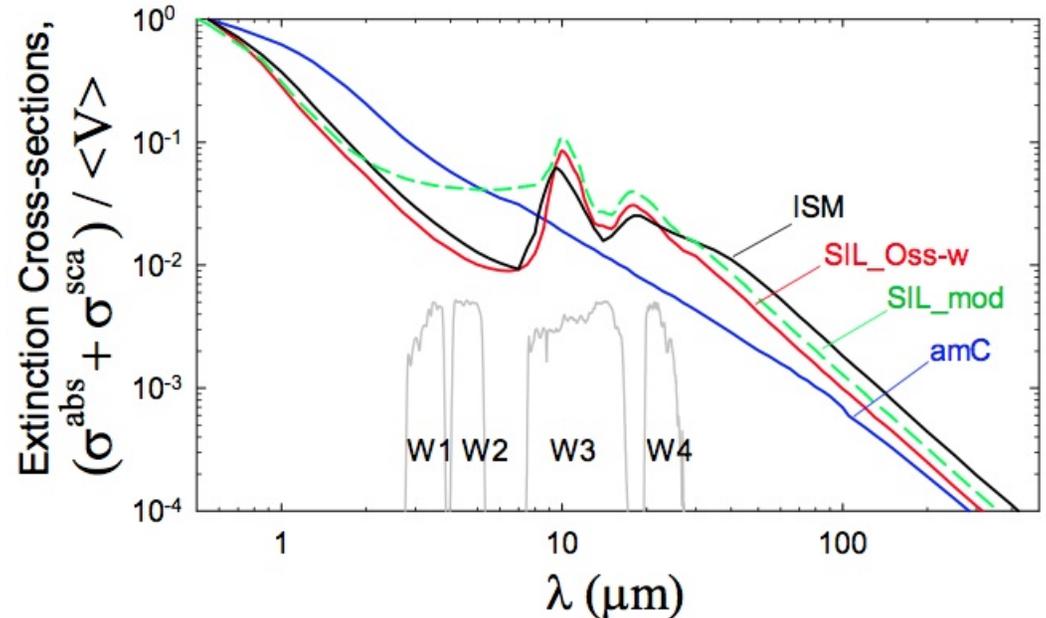


Figure 8. Extinction cross-sections of the model dust compared to the normalized response functions of the WISE filters. Dust types included: standard ISM dust mixture from [Draine \(2003\)](#) (black line), warm silicates from [Ossenkopf et al. \(1992\)](#) (Oss-w, red line) and amorphous carbon from [Hanner \(1988\)](#) (amC, blue line). All grains are considered spherical with an MRN size distribution.

Dusty
molecular
gas

New stars

Ionized gas

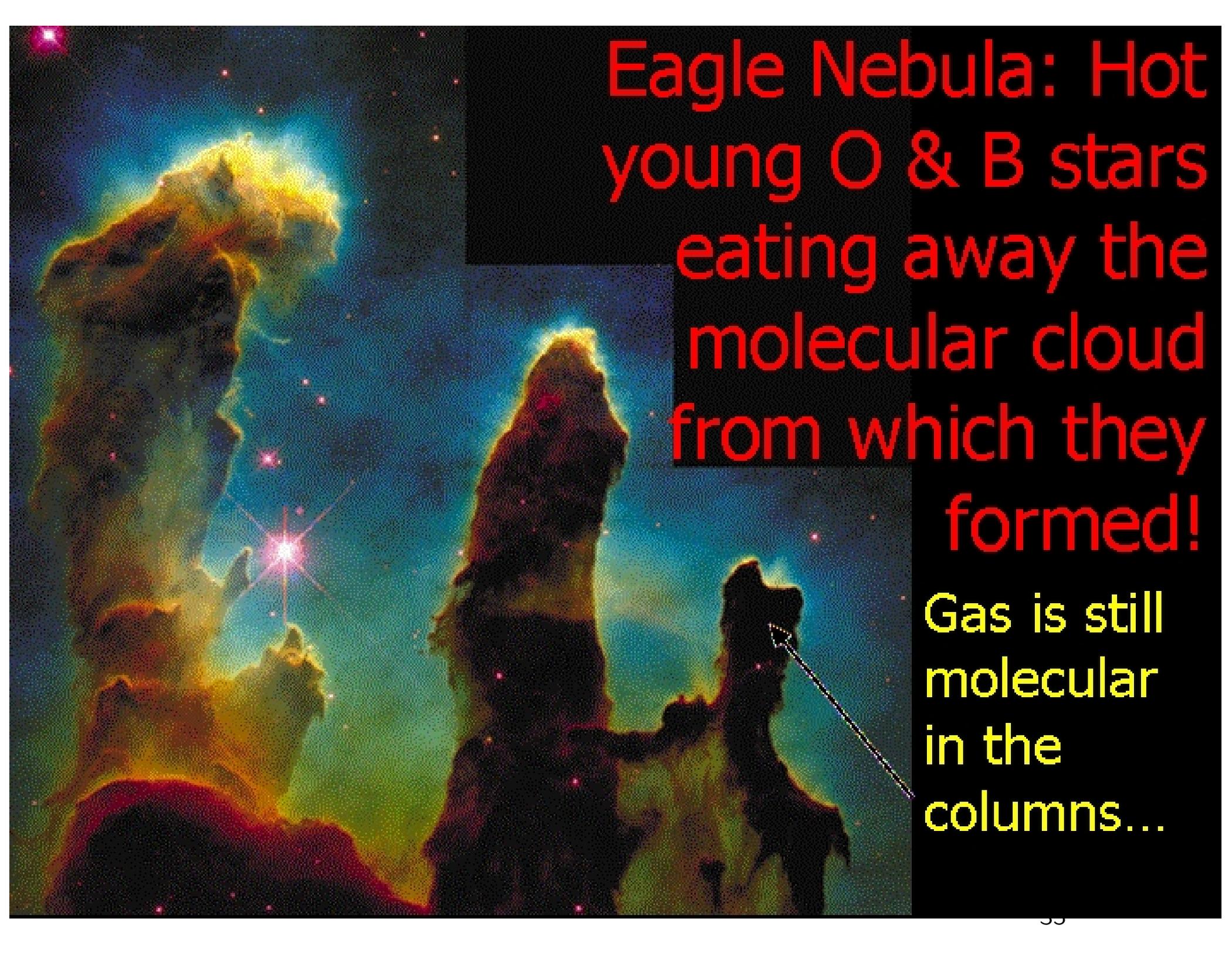
The Orion Nebula

- Hot young O & B stars heat the surrounding gas, ionizing it.



Star formation transforms
a molecular cloud into an

“HII Region”

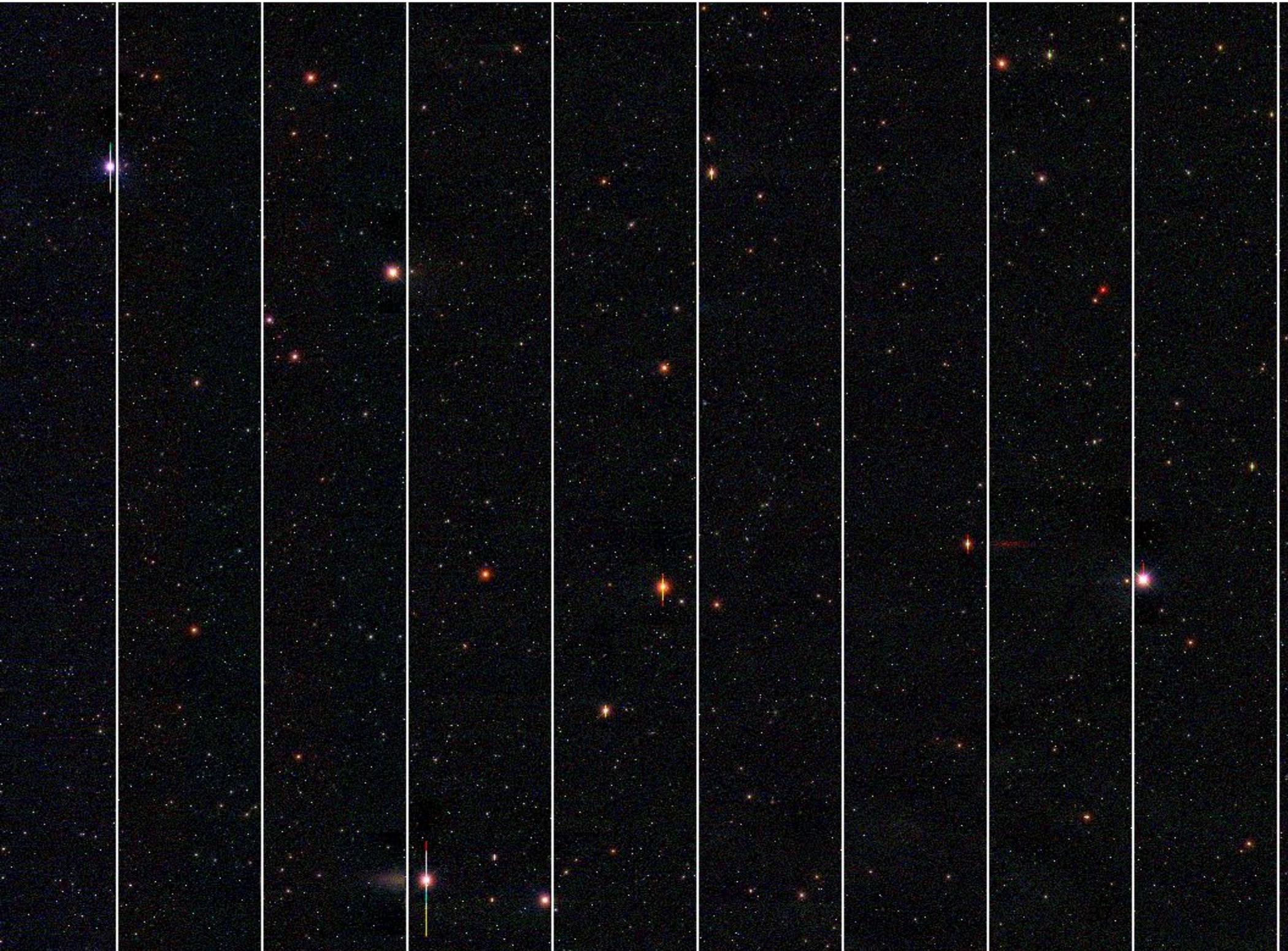
The image shows the Eagle Nebula, a stellar nursery. It features several prominent, dark, columnar structures of interstellar dust and gas, known as the 'Pillars of Creation'. The background is a vibrant blue and green, with numerous bright stars scattered throughout. A large, bright star with a prominent diffraction pattern is visible in the lower-left quadrant. The text 'Eagle Nebula: Hot young O & B stars eating away the molecular cloud from which they formed!' is overlaid in red on the right side of the image. A yellow arrow points from the text 'Gas is still molecular in the columns...' to one of the dark columns.

Eagle Nebula: Hot
young O & B stars
eating away the
molecular cloud
from which they
formed!

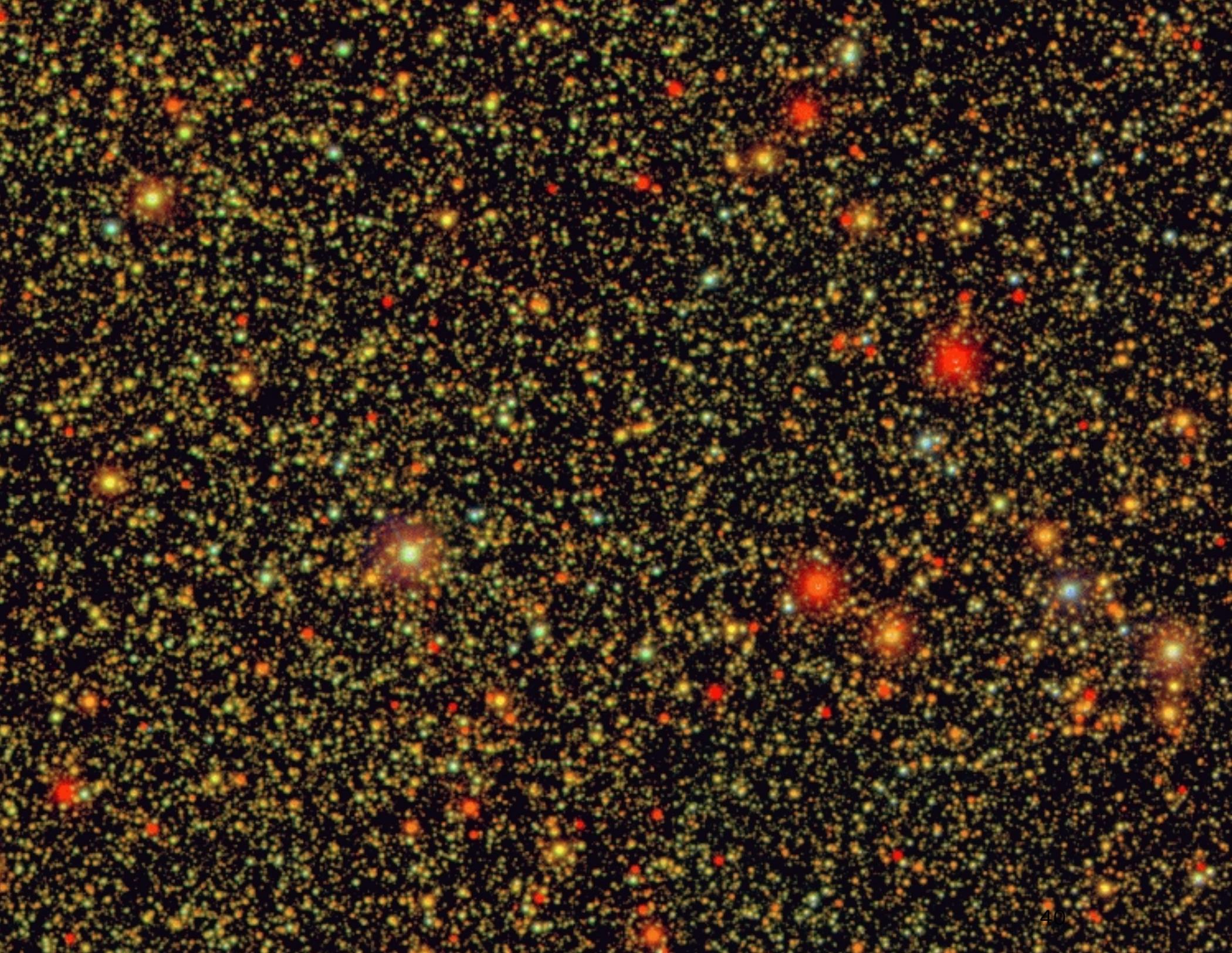
Gas is still
molecular
in the
columns...

Optical Surveys and Stellar Counts

- **Hipparcos:** 3,000 stars visible by naked eye
- and many others...
- **Palomar Observatory Sky Survey:** (first 1950-57, second 1985-1999) photographic, nearly all-sky, two bands, $m < 20.5$, astrometric accuracy ~ 0.5 arcsec, photometric accuracy 0.2-0.4 mag (both very non-Gaussian), USNO-B catalog: 10^9 sources
- **SDSS:** digital, 1/4 sky, 5 bands, $m < 22.5$, astrometric accuracy < 0.1 arcsec absolute, ~ 0.02 arcsec relative, photometric accuracy 0.02 mag (both nearly Gaussian), several 10^8 sources



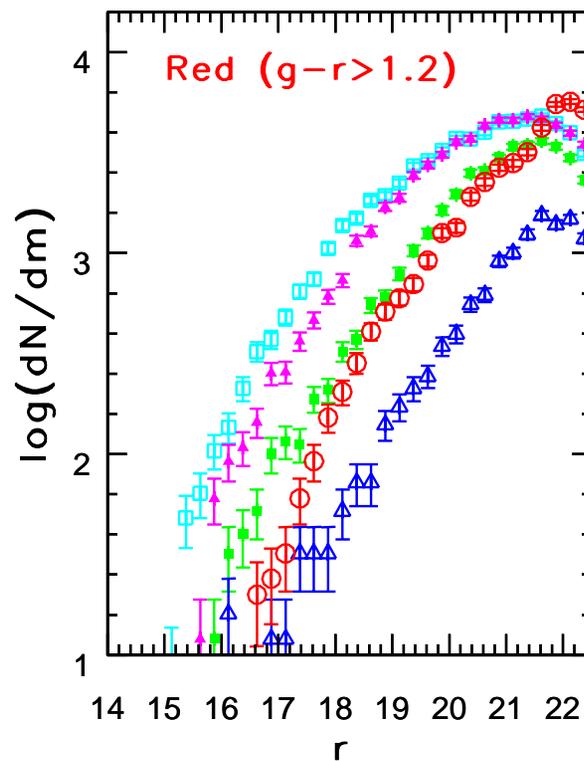
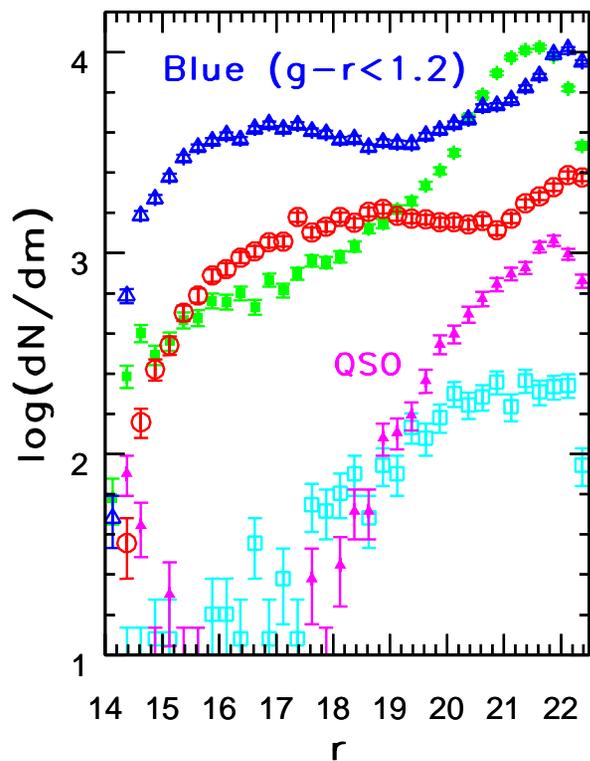
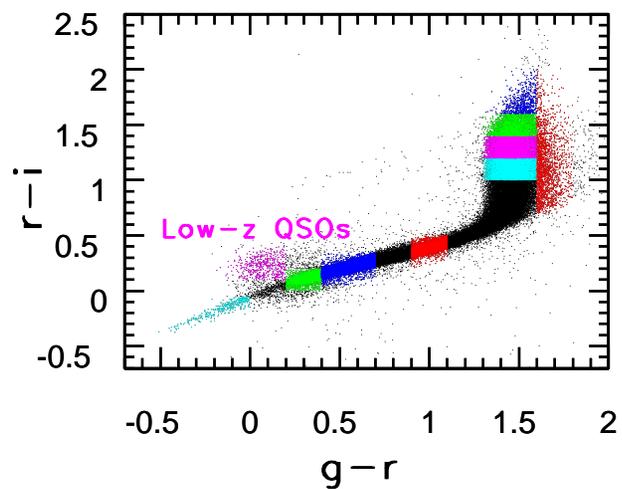
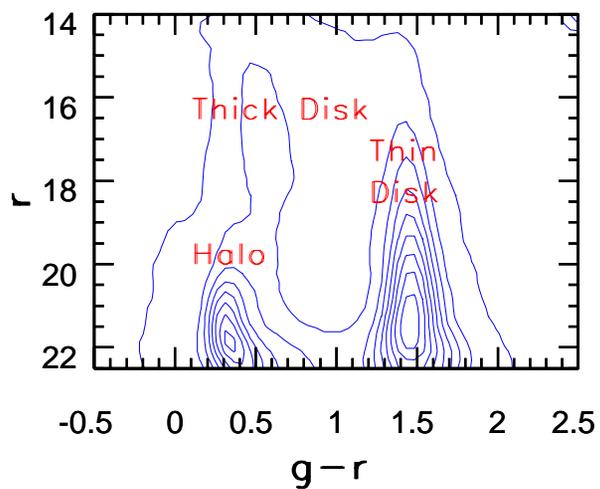




Stellar Counts

There is a lot of information about the Milky Way structure (and stellar initial mass function, and stellar evolution) in SDSS imaging data.

9 epochs, unresolved, $n=216830$, psf mags, area=60 deg²



Stellar Counts

There is a lot of information about the Milky Way structure (and stellar initial mass function, and stellar evolution) in SDSS imaging data.

How can we extract and interpret this information? What is the meaning of local maxima in the differential counts for some (but not all) color cuts?

Computing Differential Stellar Counts $n(m)$

1. $n(m) = dN/dm = dN/dV dV/dm$,
 $dN/dV = \rho(l, b, D)$ (ρ constrains Galactic Model)
2. For a pencil beam: $dV = \Delta\Omega D^2 dD$
3. $D = 10\text{pc} 10^{0.2(m-M)}$, $dD/dm = 0.2 \ln(10) D(m)$
4. $n(m) = \rho(l, b, m) 0.2 \Delta\Omega \ln(10) (10\text{pc})^3 10^{-0.6M} 10^{0.6m}$

$$n(m) \propto \rho(l, b, m) 10^{0.6m}$$

Examples for $n(m) \propto \rho(l, b, m) 10^{0.6m}$

- Power-law: $\rho(l, b, D) \propto D^{-n}$

$$n(m) \propto 10^{k m}, \quad k = 0.6 - 0.2 n$$

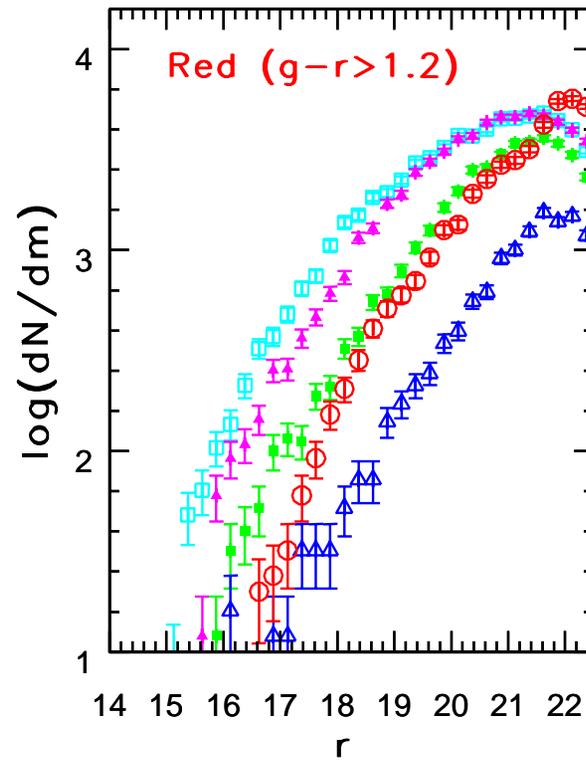
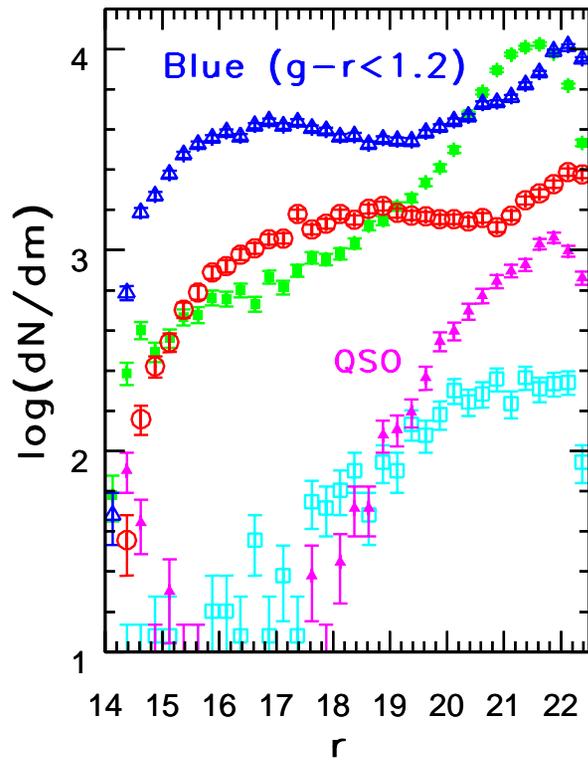
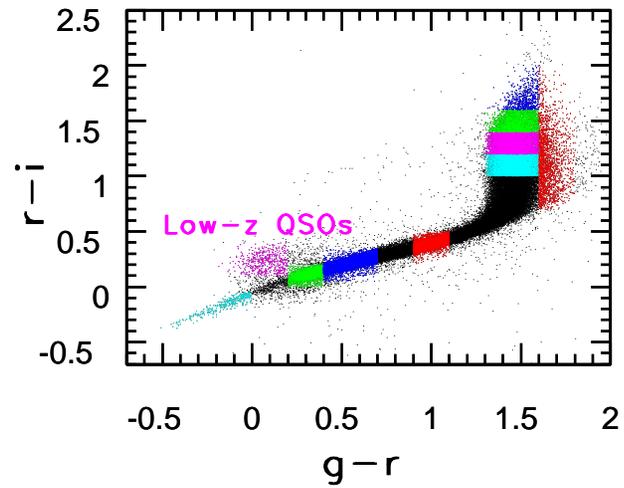
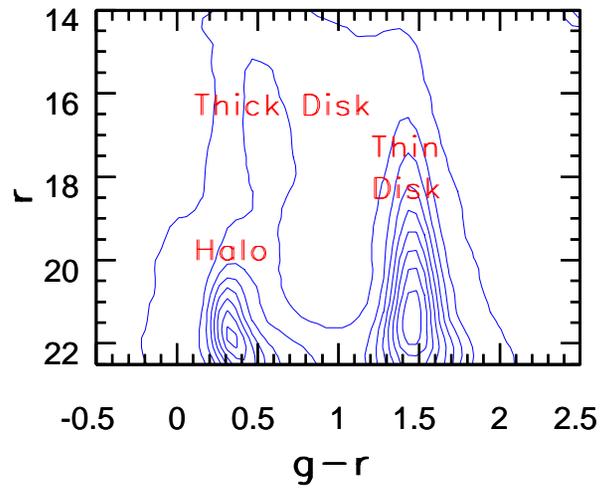
– Euclidian counts ($n=0$): $n(m) \propto 10^{0.6 m}$,

– Halo counts ($n=3$): $n(m) = \text{const.}$

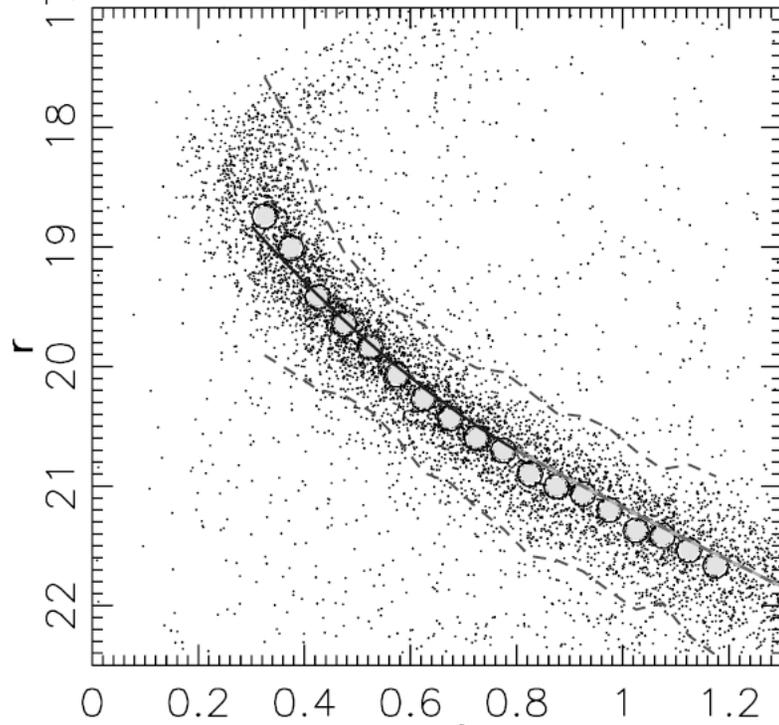
- Exponential disk: $\rho(l, b, D) \propto e^{-D/H}$

at a distance $D = k H$, $n(m)$ has a local slope corresponding to a power-law with $n = k$. Hence, for $D = 3 H$, the differential counts for exponential density distribution have a local maximum!

9 epochs, unresolved, $n=216830$, psf mags, area=60 deg²



M5 in SDSS



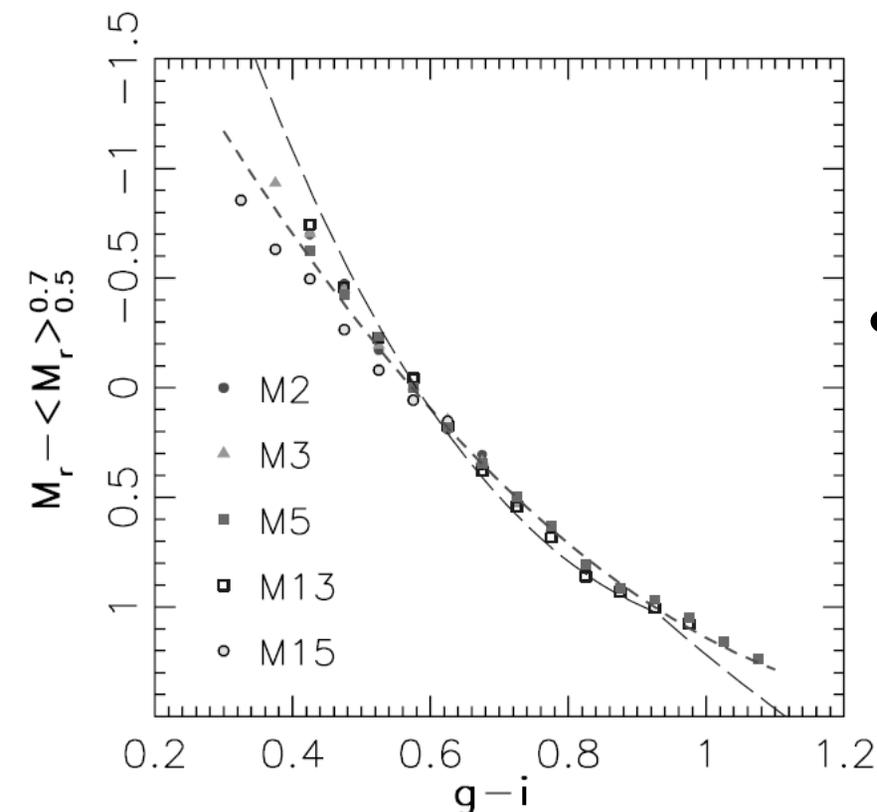
Photometric Parallax Calibration

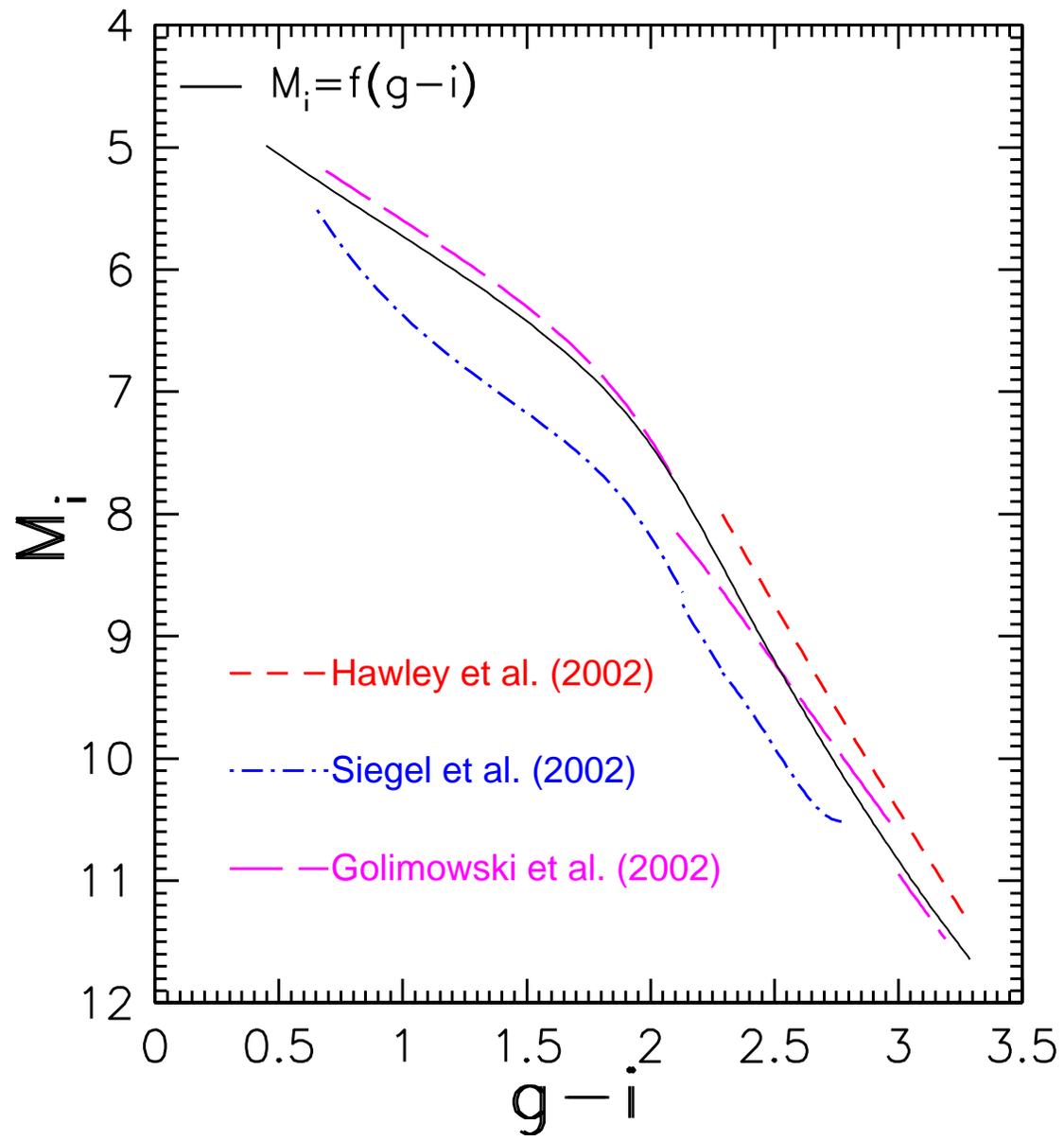
- Using a large sample of globular clusters, we can calibrate $M_r(g-i, [Fe/H])$, and then apply it to field stars to get their distances.
- Top Left:** an example of a globular cluster (M5) as observed by SDSS; the line is a polynomial fit to the median main sequence (large circles):

$$M_r = M_r^{0.6} - 2.85 + 6.29(g-i) - 2.30(g-i)^2 \quad (4)$$

where $M_r^{0.6}$ is the median absolute magnitude for stars with $0.5 < g-i < 0.7$.

- Bottom Left:** this is a good fit to a number of globular clusters observed by SDSS, showing that the main effect of metallicity is to slide the main sequence vertically (i.e. along luminosity axis, changing $M_r^{0.6}$), without much effect on its *shape*.





What are SDSS counts telling us?

- For $g - r \sim 0.5$, maximum for $n(m)$ at $r = 17$
 $g - r \sim 0.5$ implies $g - i \sim 0.8$ and $M_r \sim 5.7$: $H' \sim 1800kpc$
- For $r - i \sim 1.5$, maximum for $n(m)$ at $r = 21.5$
 $r - i \sim 1.5$ implies $g - i \sim 2.9$ and $M_r \sim 12$: $H' \sim 800kpc$
- $H' = H / \sin b \sim 2H$, in agreement with expectations for thin ($H \sim 300pc$) and thick ($H \sim 1.0kpc$) disks.
- With SDSS we can do better than with this standard approach because the vast majority ($\sim 98 - 99\%$) of detected stars are on the main sequence.