Astr 511: Galactic Astronomy

Winter Quarter 2009, University of Washington, Željko Ivezić

Lecture 6:

Basic Properties of the Milky Way

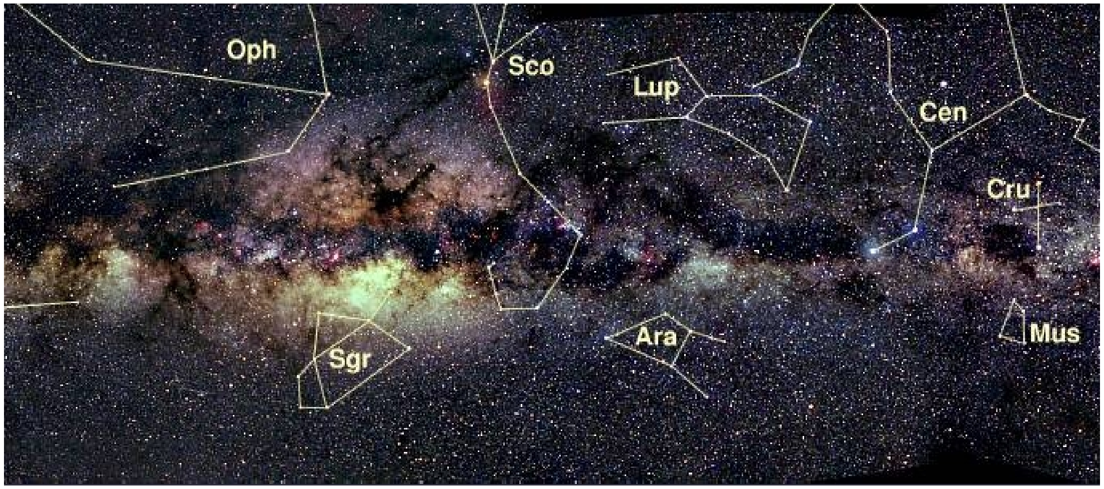
Outline

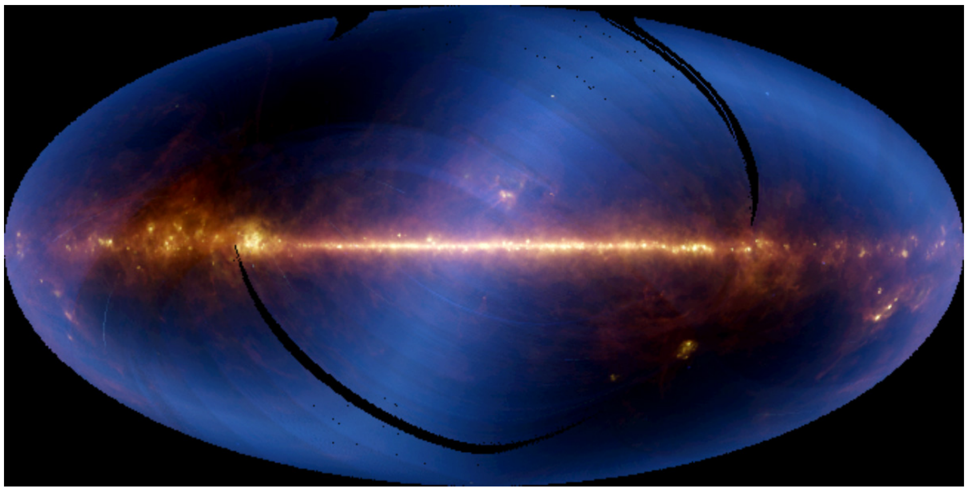
- Spatial distribution of stars: disk, halo, bulge
- Stellar kinematics: rotation vs. random motions
- Interstellar medium: gas and dust
- Stellar counts: simple analysis

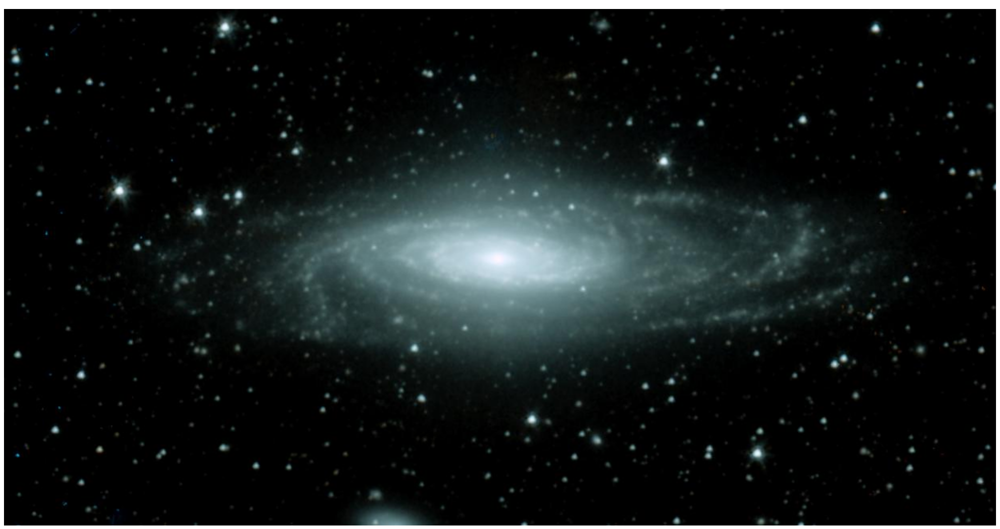
Good sites:

http://seds.lpl.arizona.edu/messier/more/mw.html

http://www.space.com/milkyway

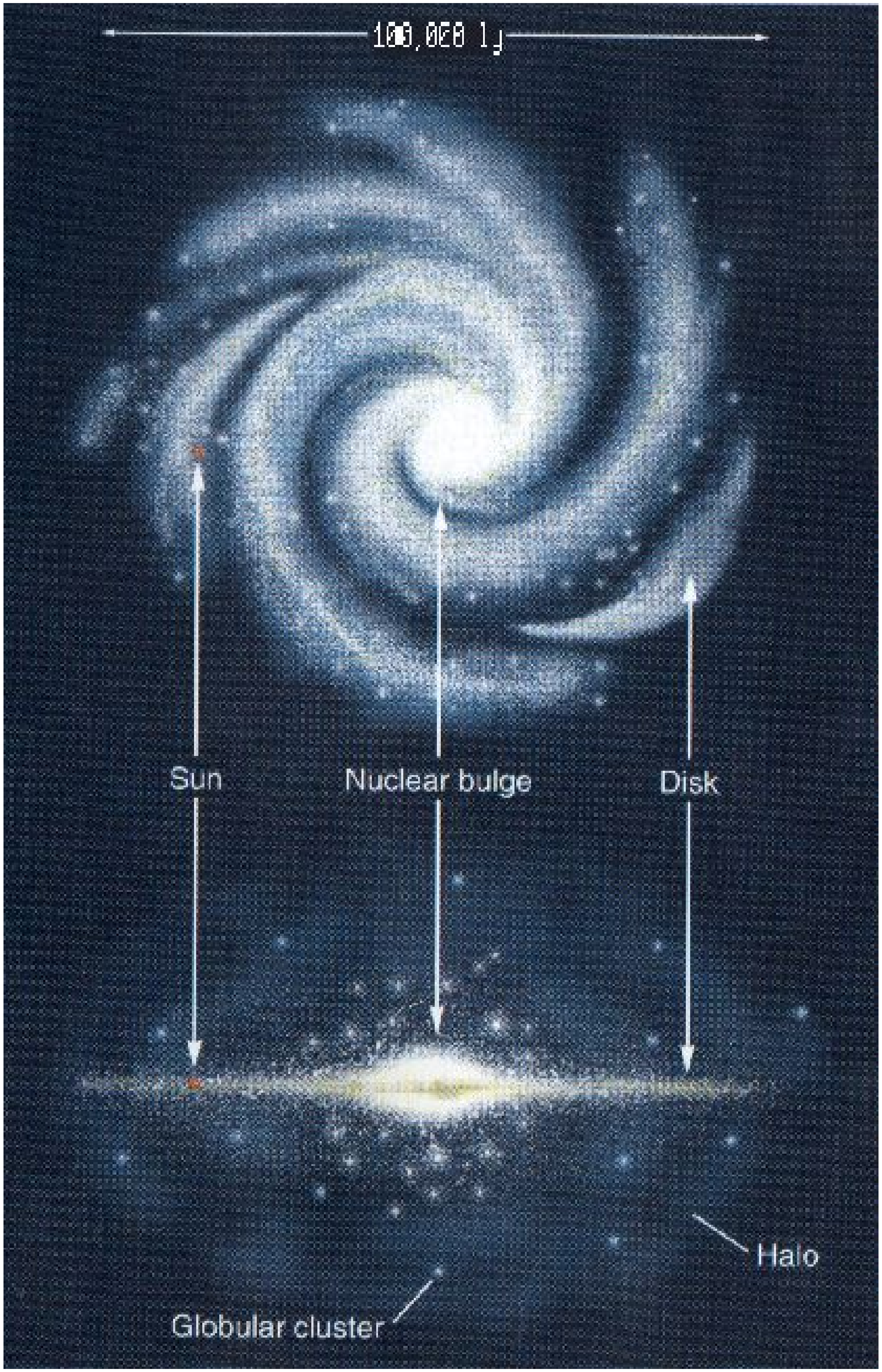




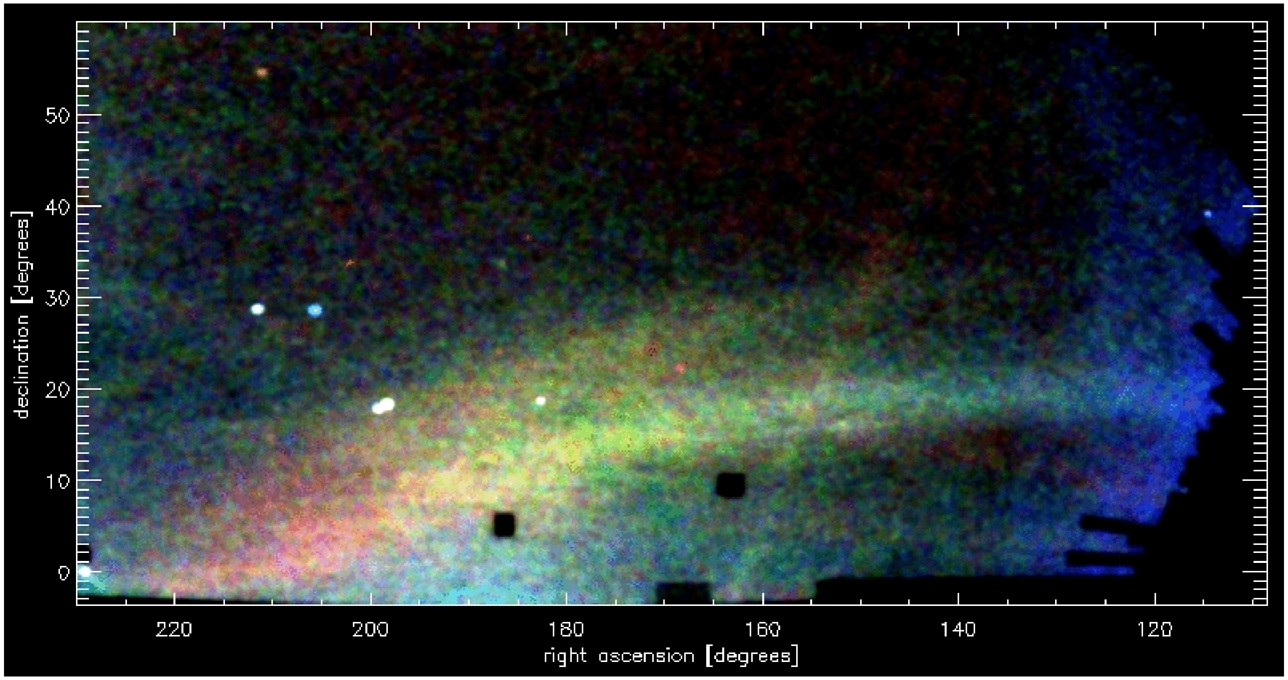


Introduction

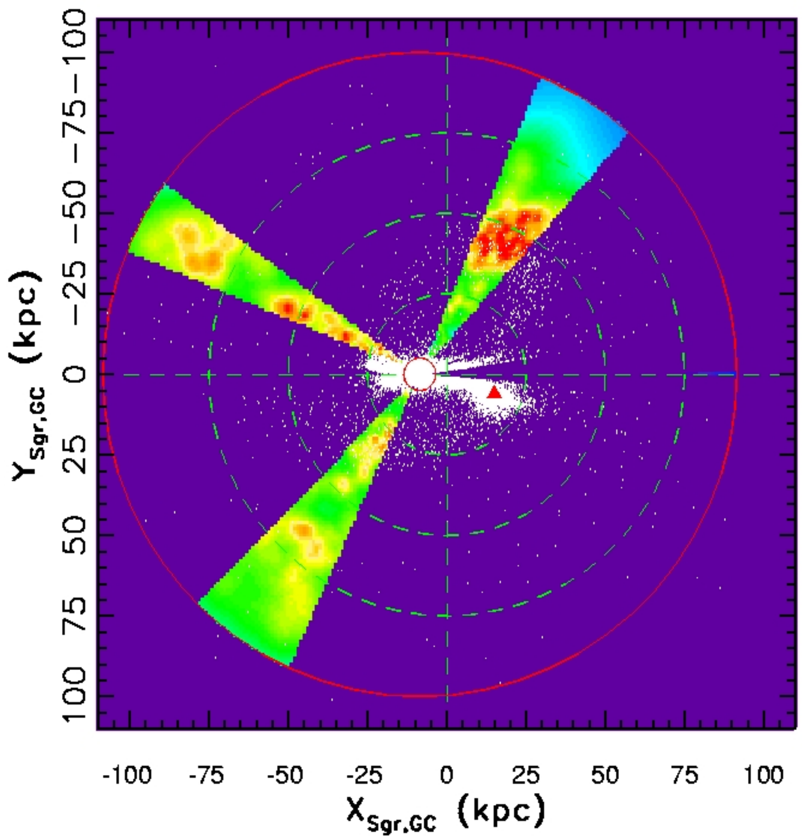
- Top left: 30° by 10° (optical) view towards the Galactic center (from Axel Mellinger)
- Middle left: The all-sky view by the Infrared Astronomical Satellite
- Bottom left: a spiral galaxy (NGC 7331) similar to the Milky Way
- Conclusion: the density of stars on the sky varies greatly because we are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



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

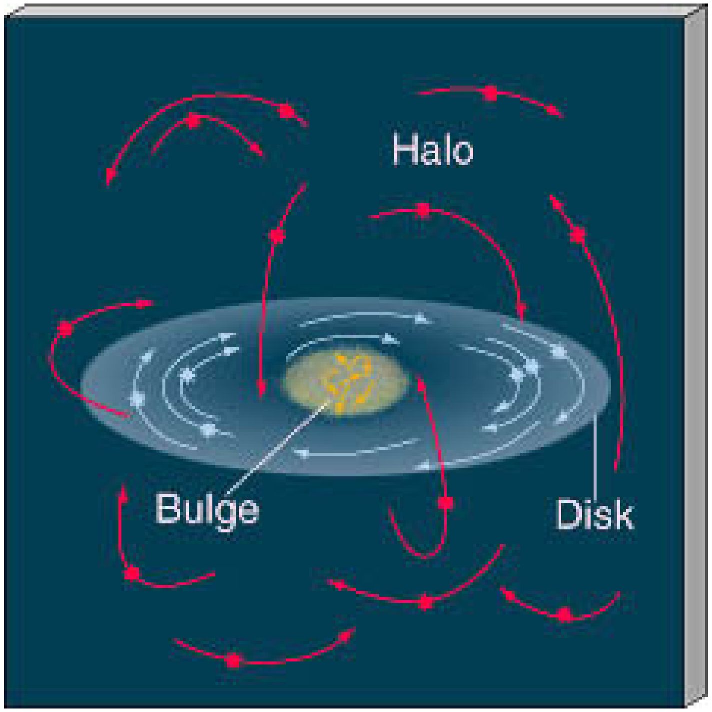


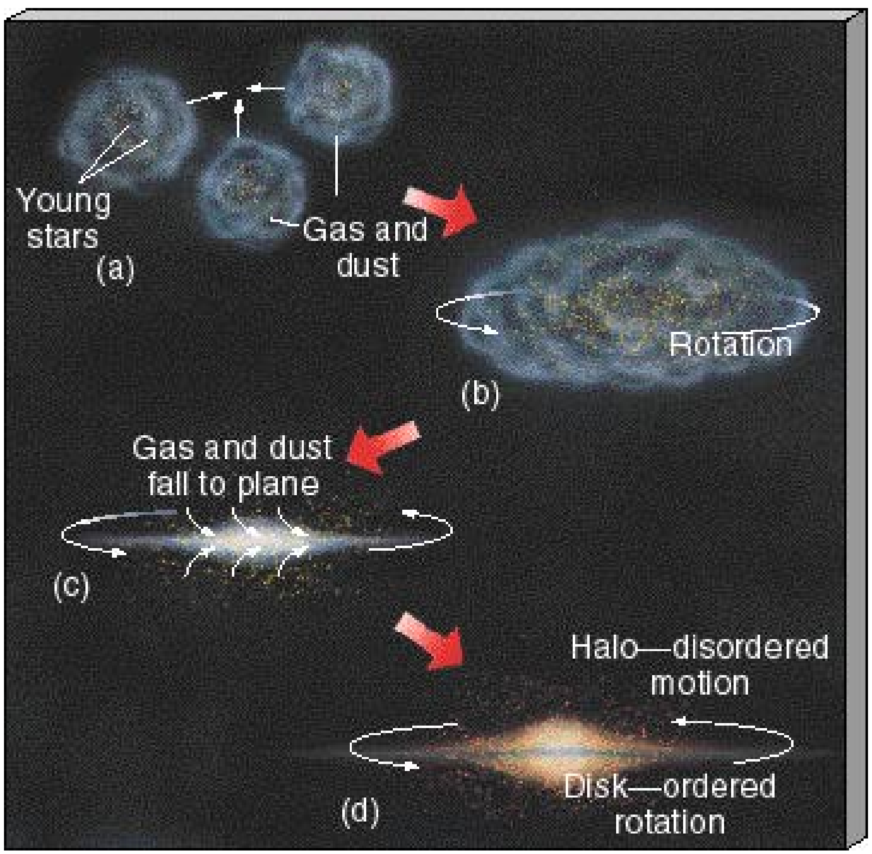
Halo Substructure



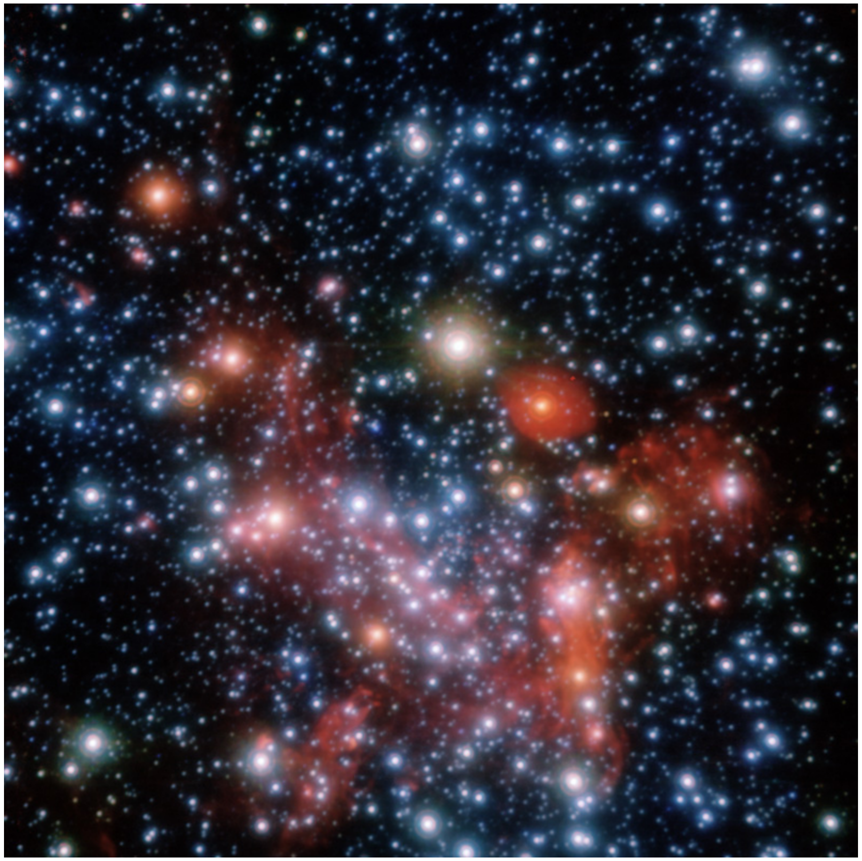
- The table on the previous page is wrong: most recent data clearly show that **halo has rich substructure**
- Top left: the counts of SDSS stars color-coded by distance (red: ∼10 kpc, blue: several kpc) from Belokurov et al. (2007)
- Bottom left: the distribution of SDSS RR Lyrae stars and 2MASS red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

Kinematics



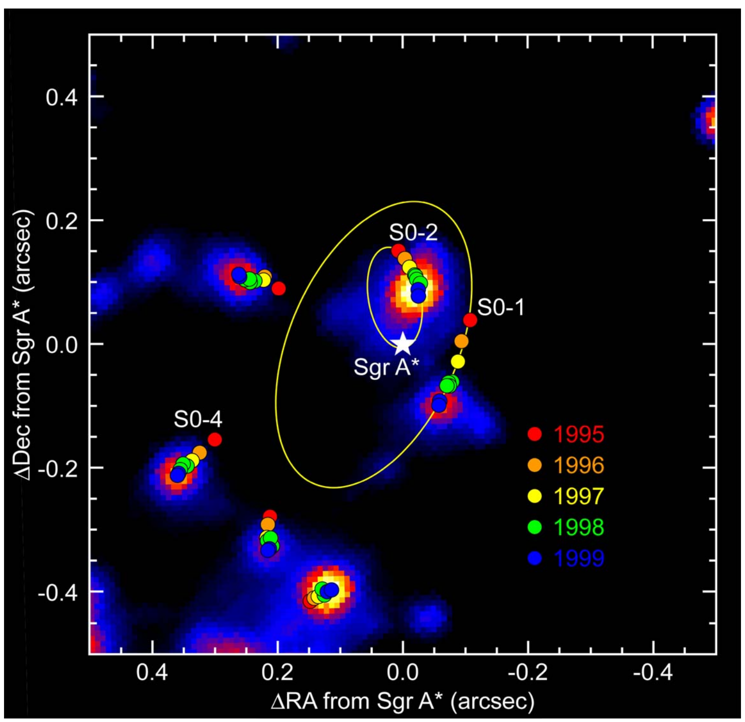


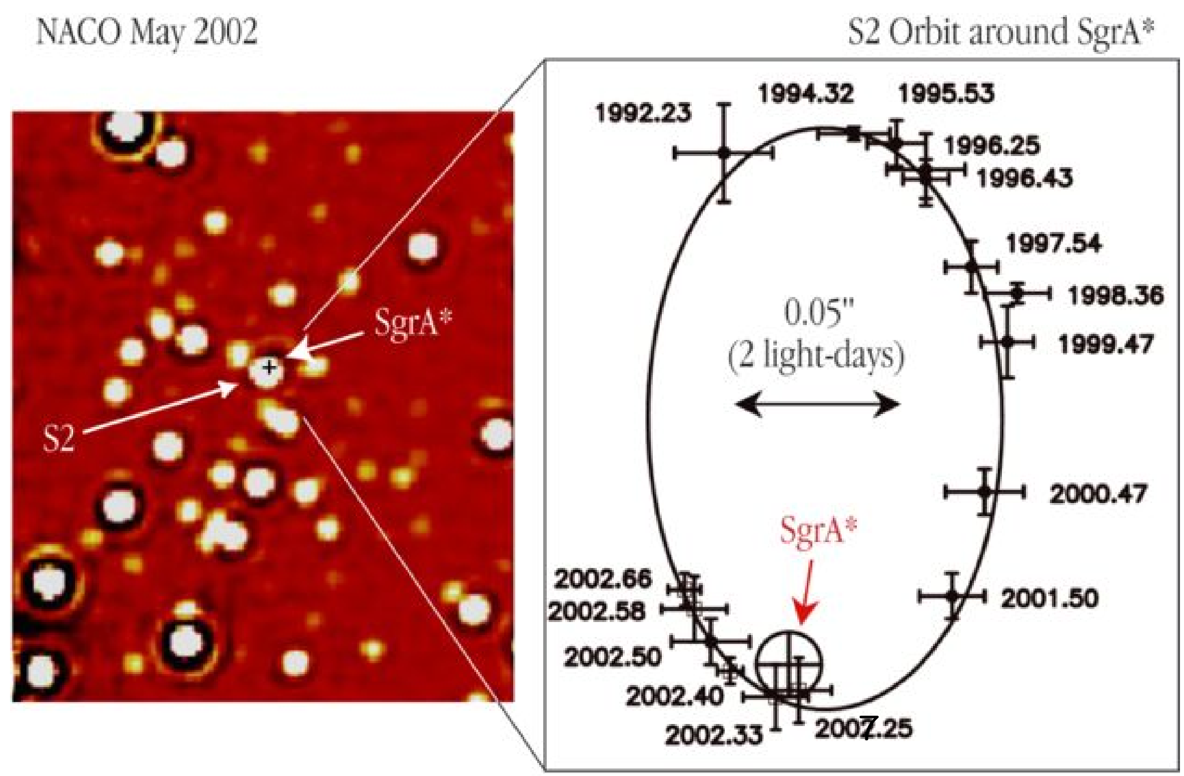
- Stars move in a gravitational potential (more in L13)
- Two types of motion: disk stars **rotate** around the center, while halo stars are on randomly distributed elliptical orbits (more in L11)
- The motion of stars was set during the formation period
- The details are governed by the laws of physics: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

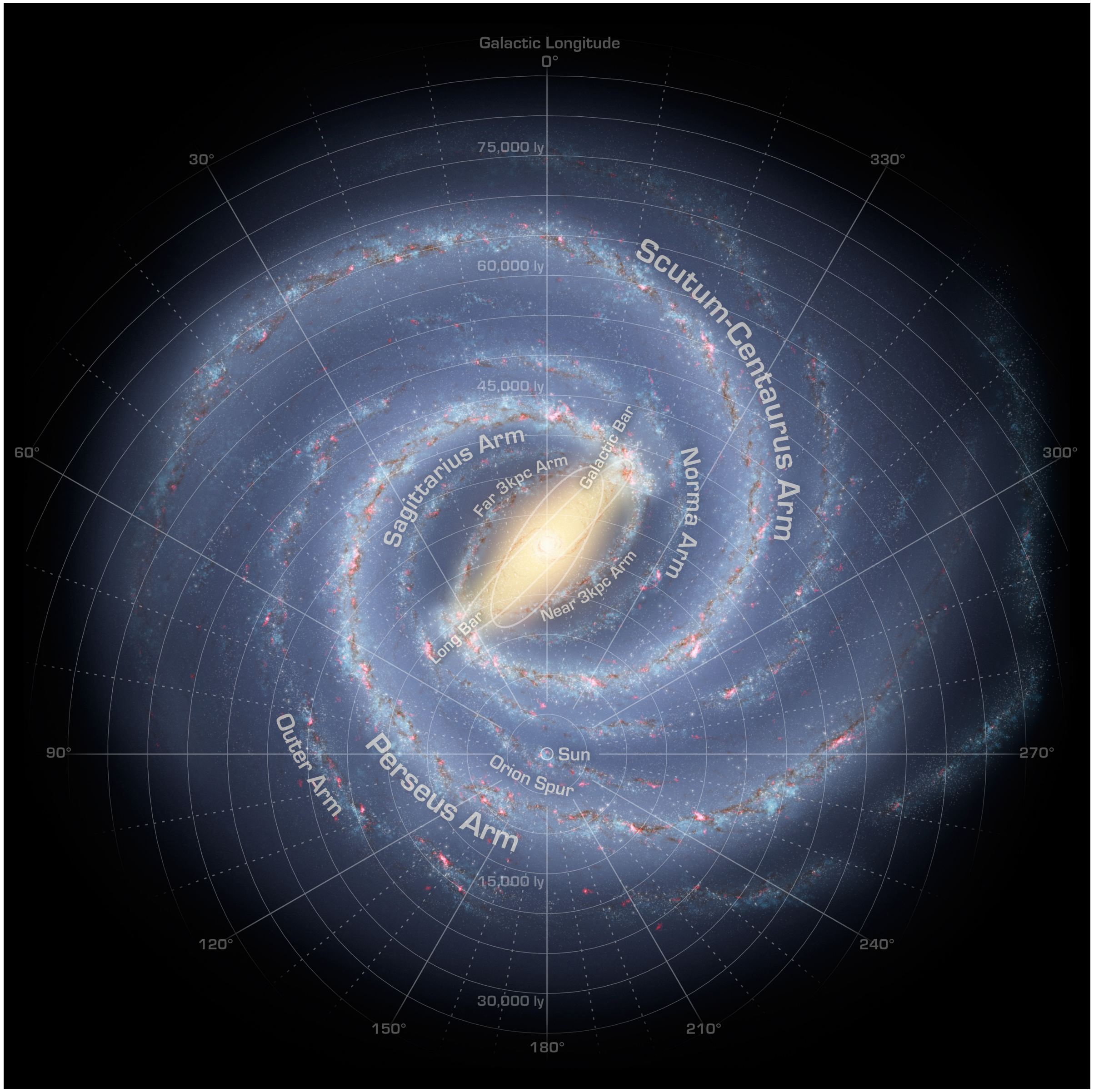


Black Hole in the Galactic Center

- 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 $\sim$30 **observed** orbits
- Two teams: UCLA team led by Andrea Ghez, and European team led by Reinhard Genzel





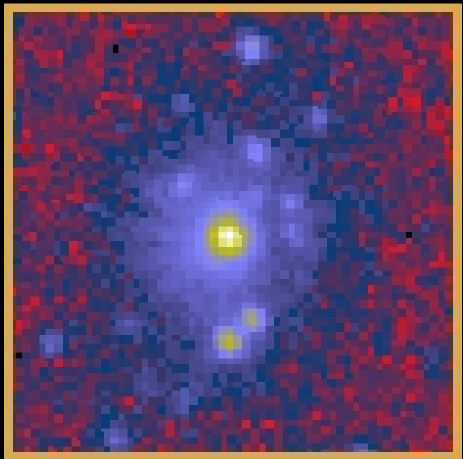


Revised Spiral Arms

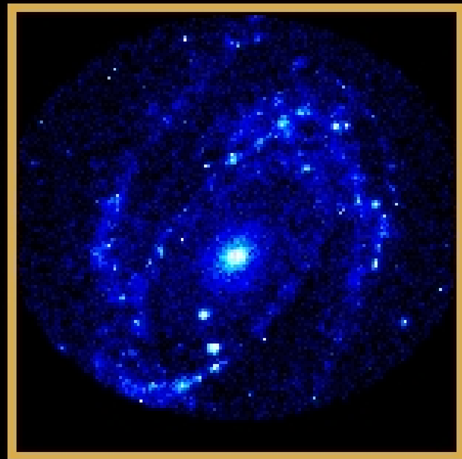
- The stellar bar was discovered in 1990s based on IRAS data
- It was believed that the Galaxy has four spiral arms: the Scutum-Centaurus, Perseus, Sagittarius and Norma
- The stellar counts from Spitzer galactic plane survey (Benjamin et al. 2008) strongly suggest that there are only two major arms,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

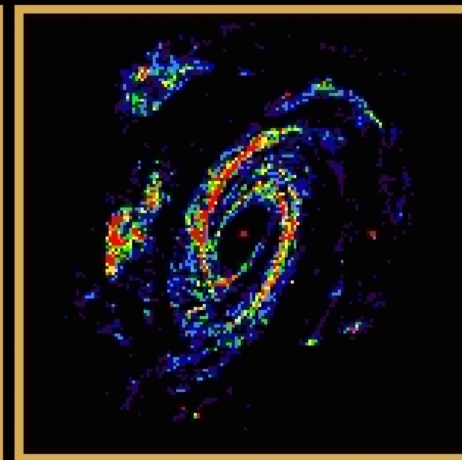
Visible: DSS

Visible: R. Gendler

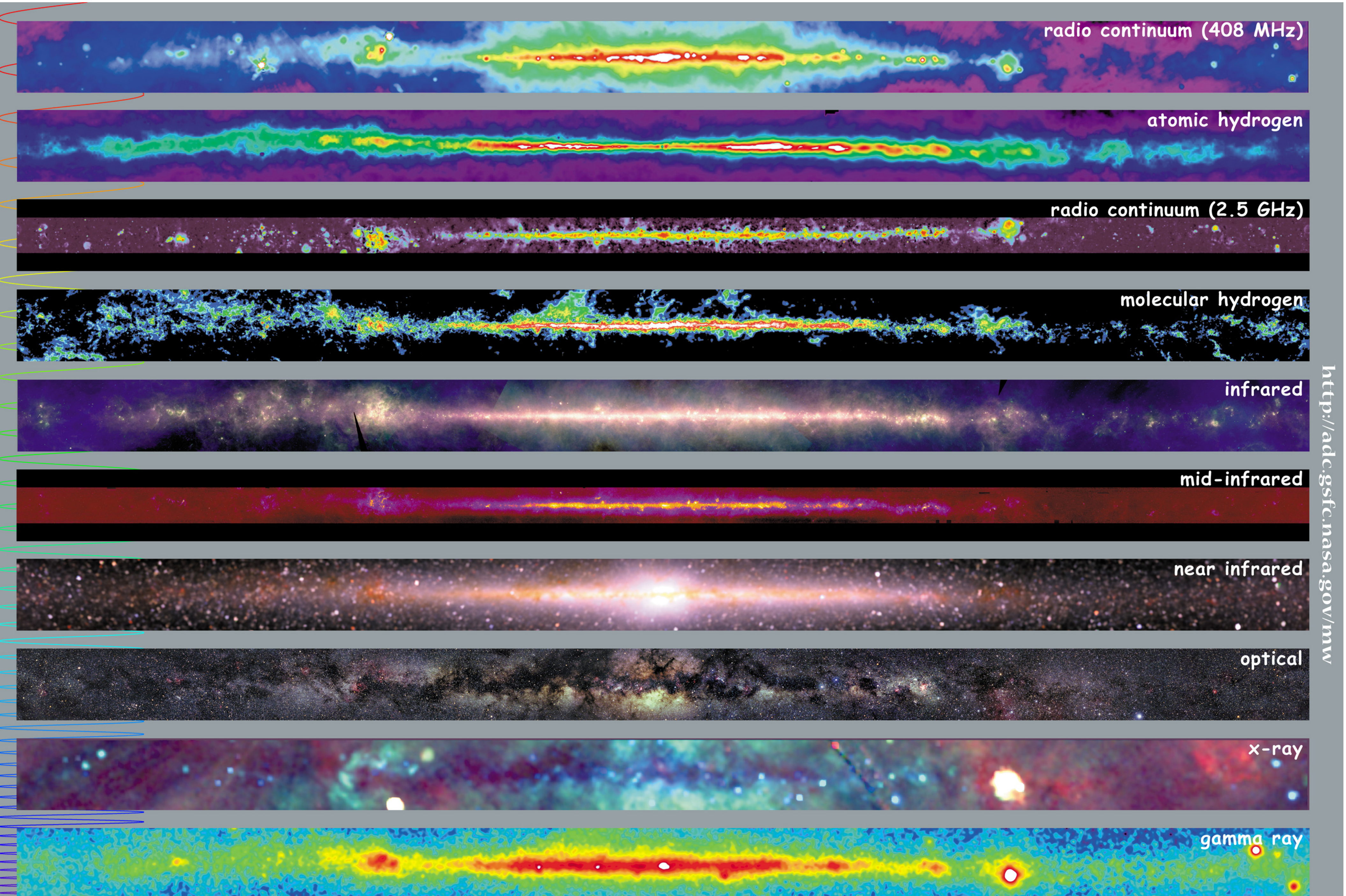
Near-Infrared: Spitzer

Mid-Infrared: Spitzer

Far-Infrared: Spitzer



Radio: VLA



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 ← "HII" = "H two"
- Neutral Atomic Gas ← "HI" = "H one"
- Cold Molecular Gas ← "H_2"
- Dust ← "Dust"

Nomenclature: "ElementI" = unionized Element
"ElementII" = singly ionized Element
"ElementIII" = doubly ionized Element…etc

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What fraction is in each phase?

- Hot ionized Gas — <15%
- Neutral Atomic Gas — ~65%
- Cold Molecular Gas — ~20%
- Dust — <5%

Typical Densities

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

Low (<0.5 atoms/cm^3) → Hot ionized Gas

Medium (1-10 atoms/cm^3) → Neutral Atomic Gas

High (10^2-10^5 atoms/cm^3) → Cold Molecular Gas

Very High (solid) → Dust

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Typical Temperatures

- Hot ionized Gas — Hot ($>10^4$-10^7 K)
- Neutral Atomic Gas — Medium (100 -10^4 K)
- Cold Molecular Gas — Cold (<50K)
- Dust — Medium-cold (<100K)

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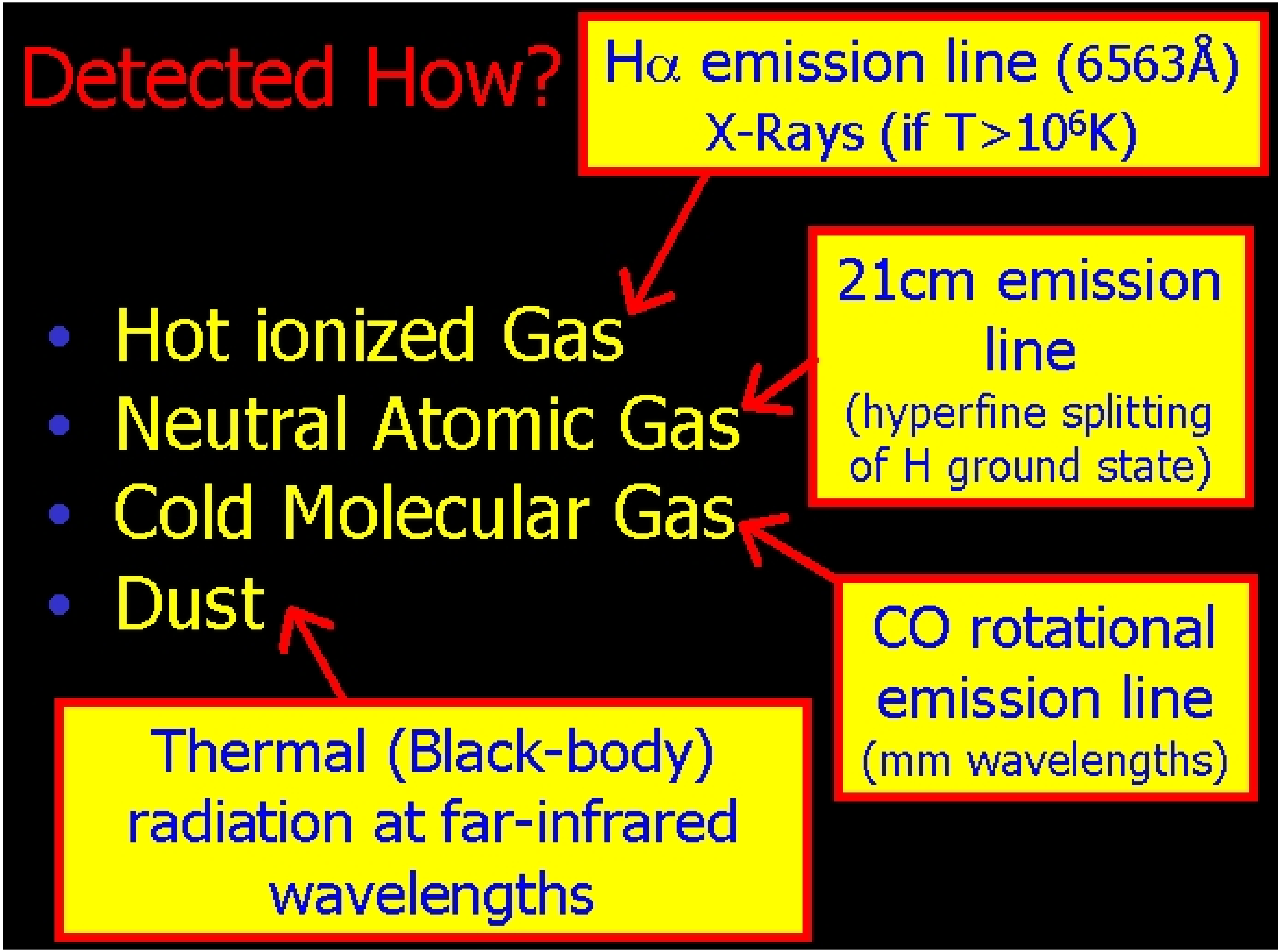

Detected How?
Hα emission line (6563Å)
X-Rays (if T>10⁶K)
• Hot ionized Gas
• Neutral Atomic Gas
• Cold Molecular Gas
• Dust
21cm emission line
(hyperfine splitting of H ground state)
CO rotational emission line
(mm wavelengths)
Thermal (Black-body) radiation at far-infrared wavelengths

Distributed How?

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

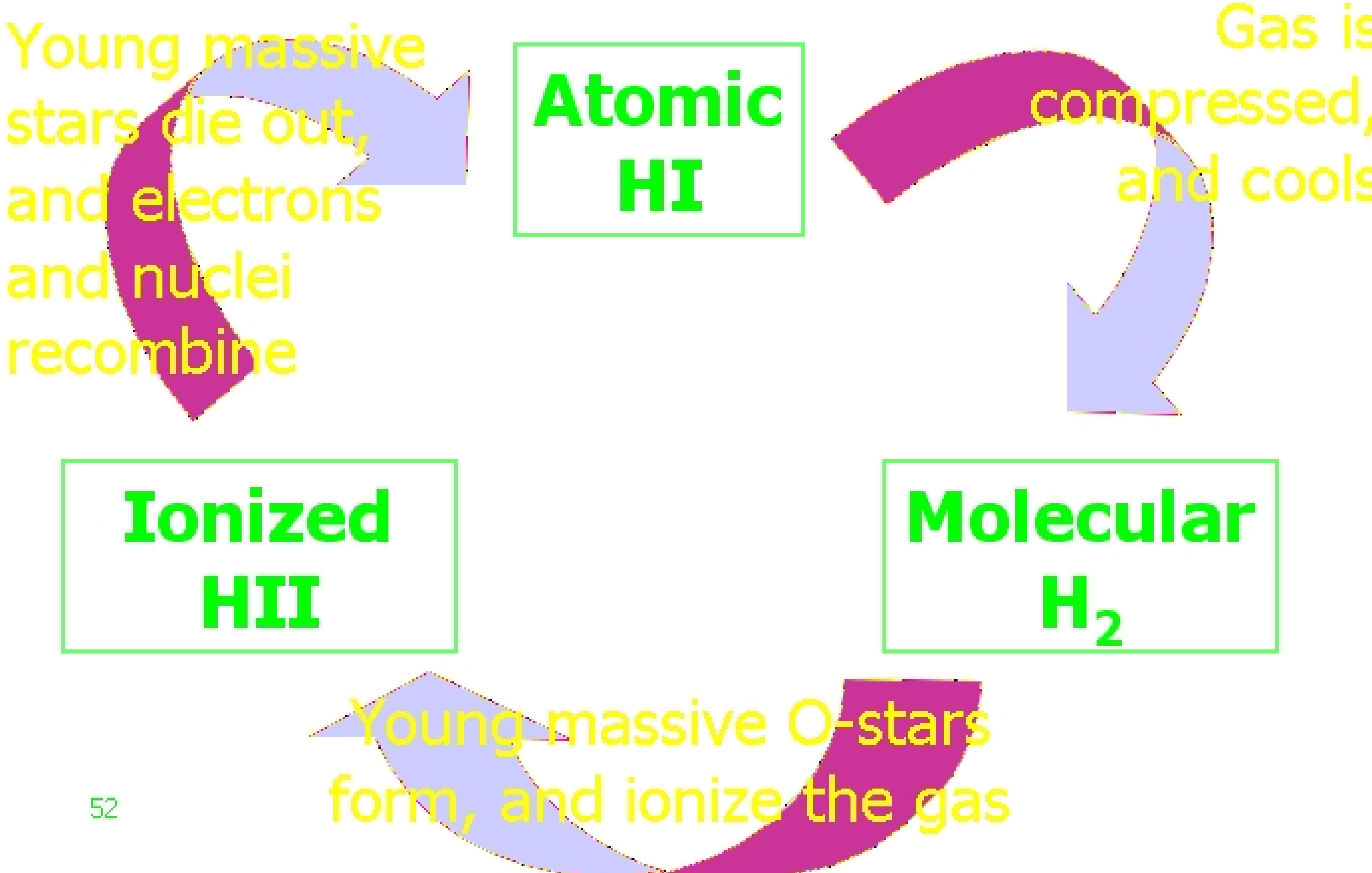
Halos of Galaxies

Galaxy Midplane, out to large radii beyond stars

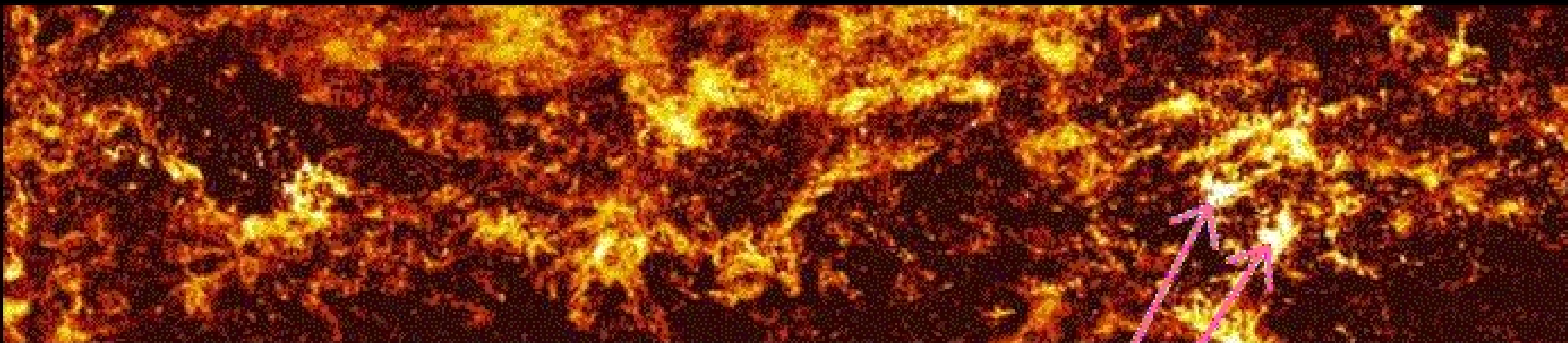
Galaxy Midplane, concentrated in spiral arms

Tracks the distribution of gas

How are the three phases of gas inter-related?



Molecular gas is clumpy on small scales.

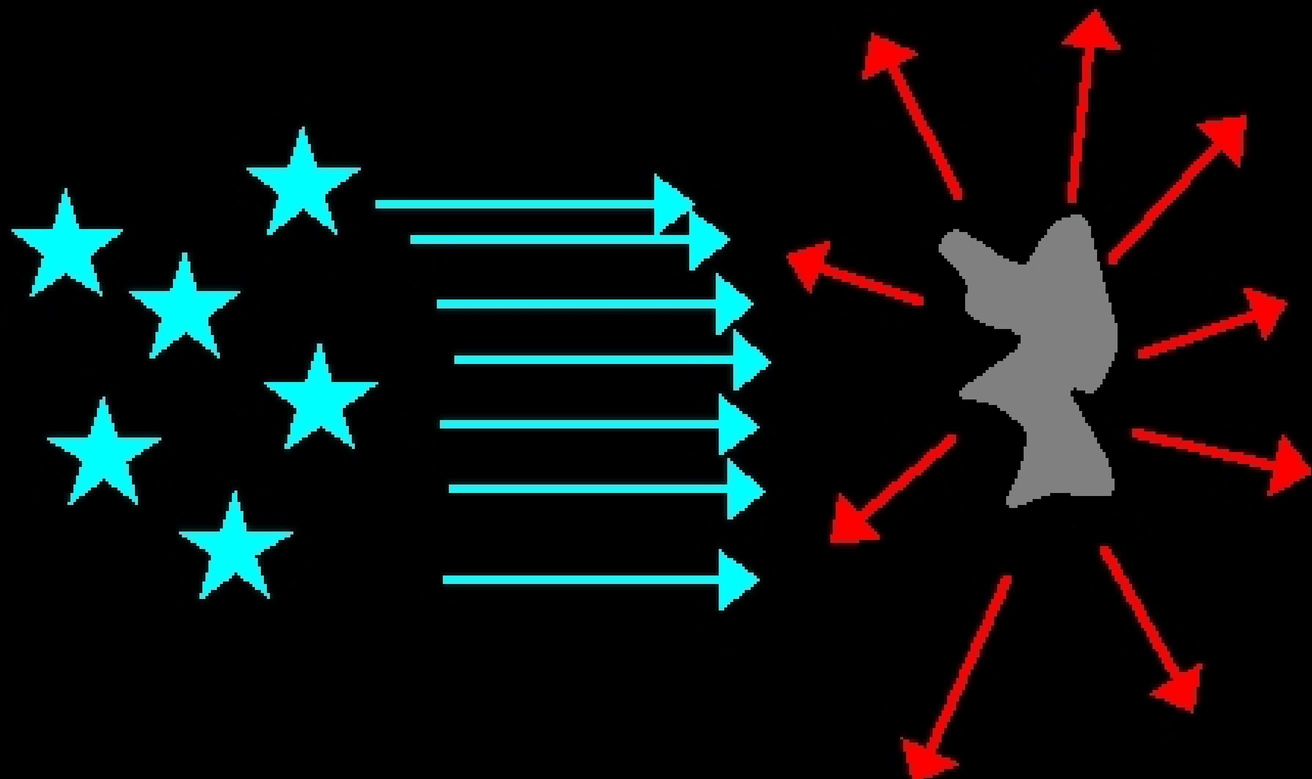


(View of the outskirts, away from the center)

"Molecular Clouds"

This is why stars form in clusters!

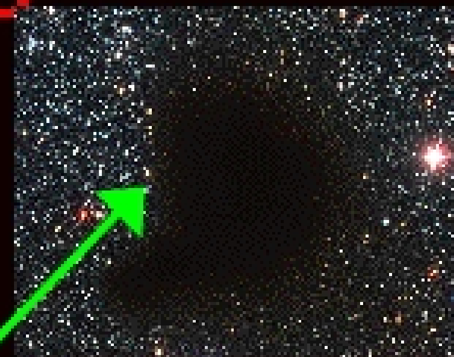
The amount of dust can be measured using light that has been **reprocessed** into the infrared.

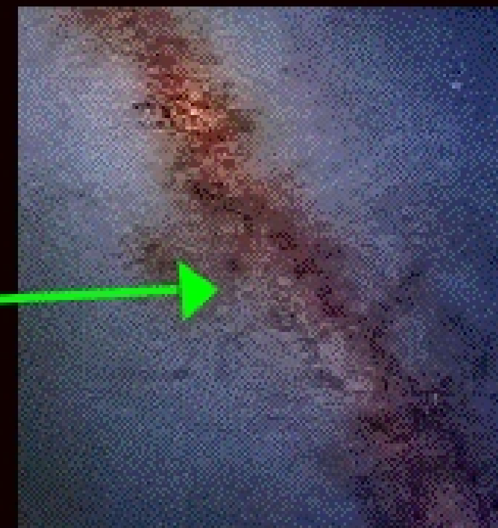


UV & optical light is absorbed by dust...

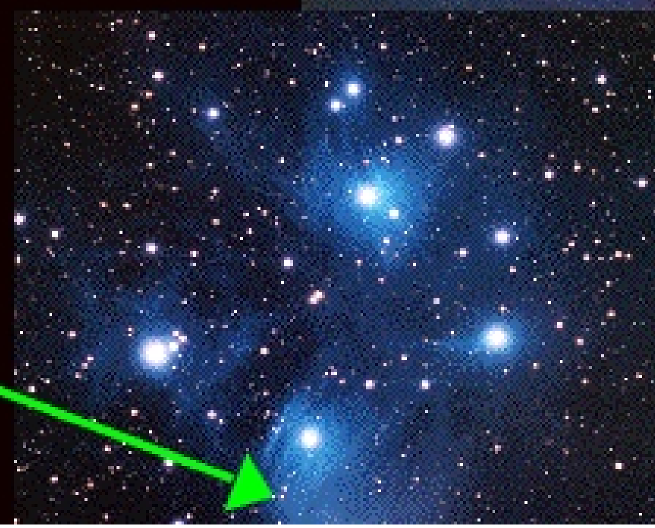
...which heats up to 10-100K and radiates like a greybody at 10-300μm

Dust plays many important roles in galaxies

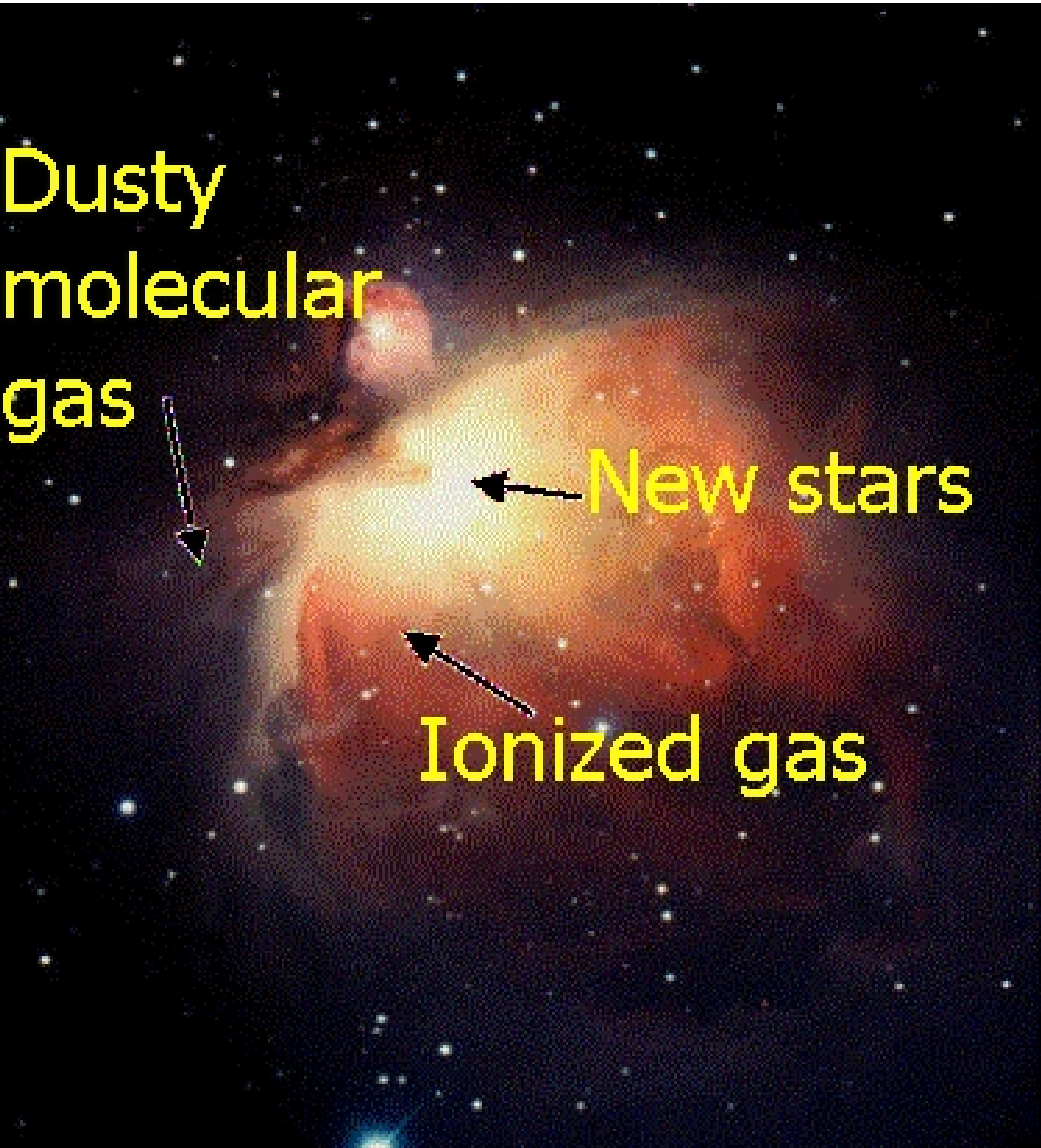




1. Extinction/Attenuation
2. Reddening
3. Reprocessing UV/optical light into the infrared
4. Scatters light.
5. Locks up metals



The Orion Nebula

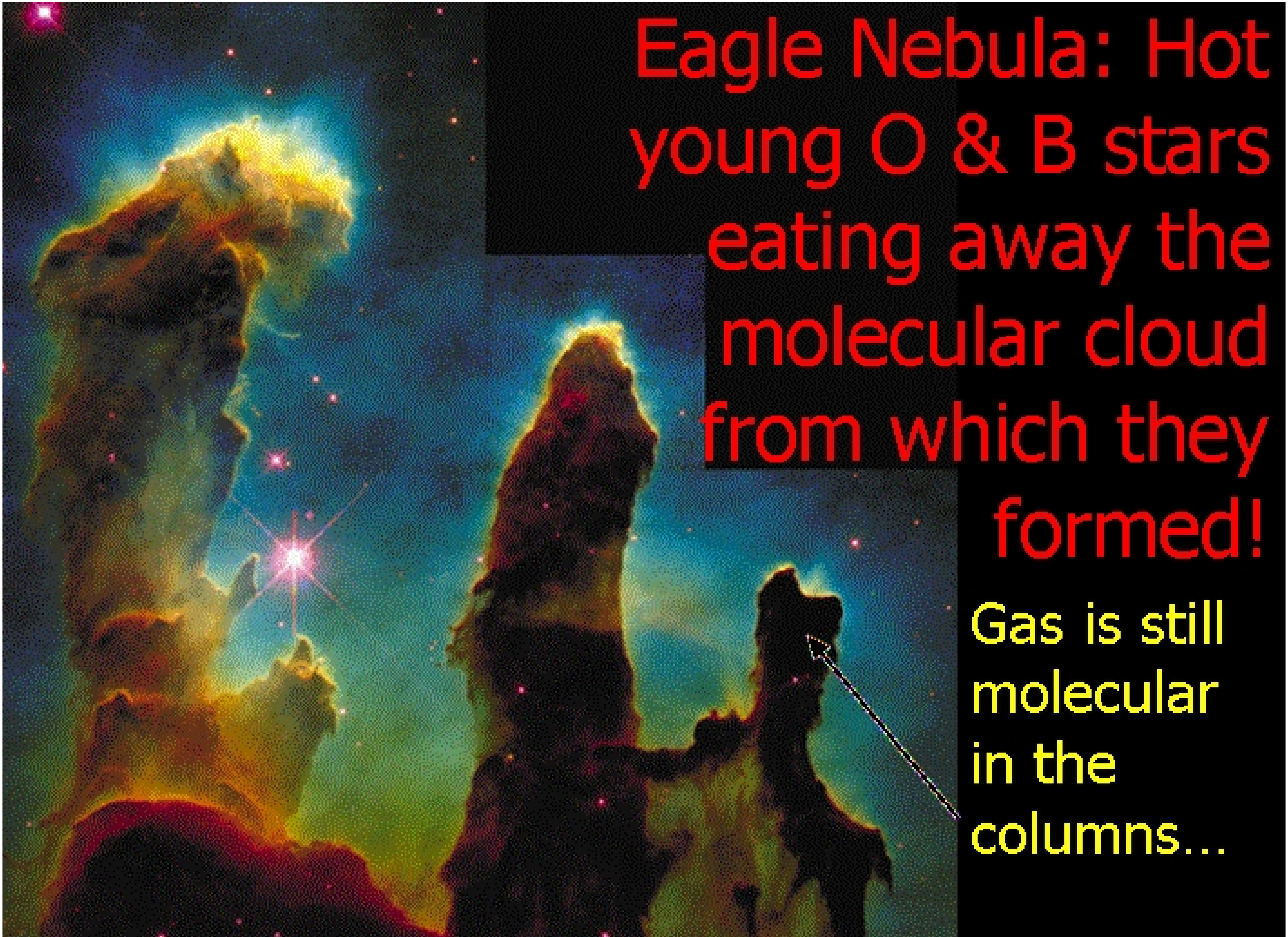


- Hot young O & B stars heat the surrounding gas, ionizing it.

$H_2 \rightarrow HII$

Molecular H — Ionized H

Star formation transforms a molecular cloud into an "HII Region"


Eagle Nebula: Hot young O & B stars eating away the molecular cloud from which they formed!
Gas is still molecular in the columns…

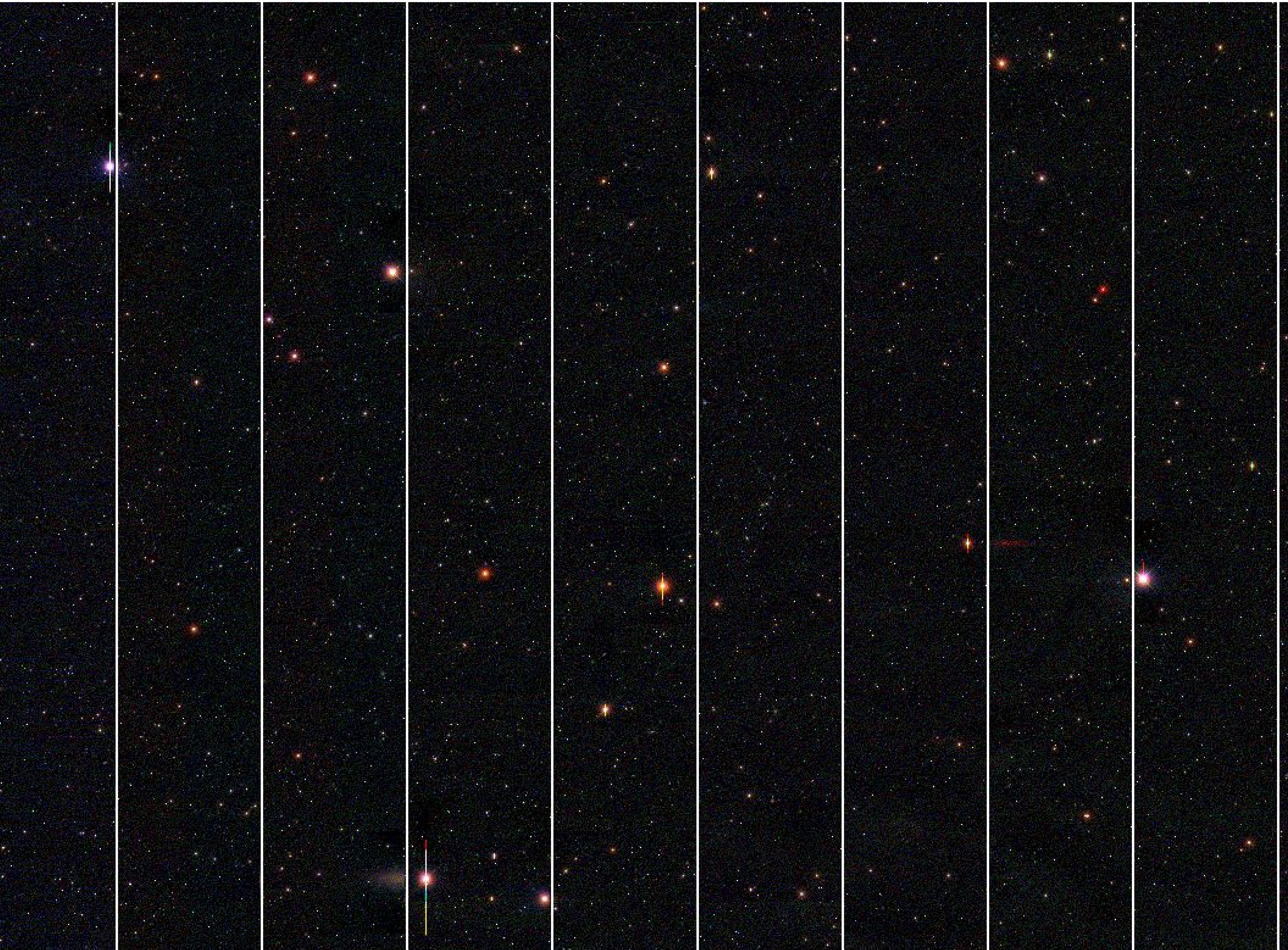
Optical Surveys

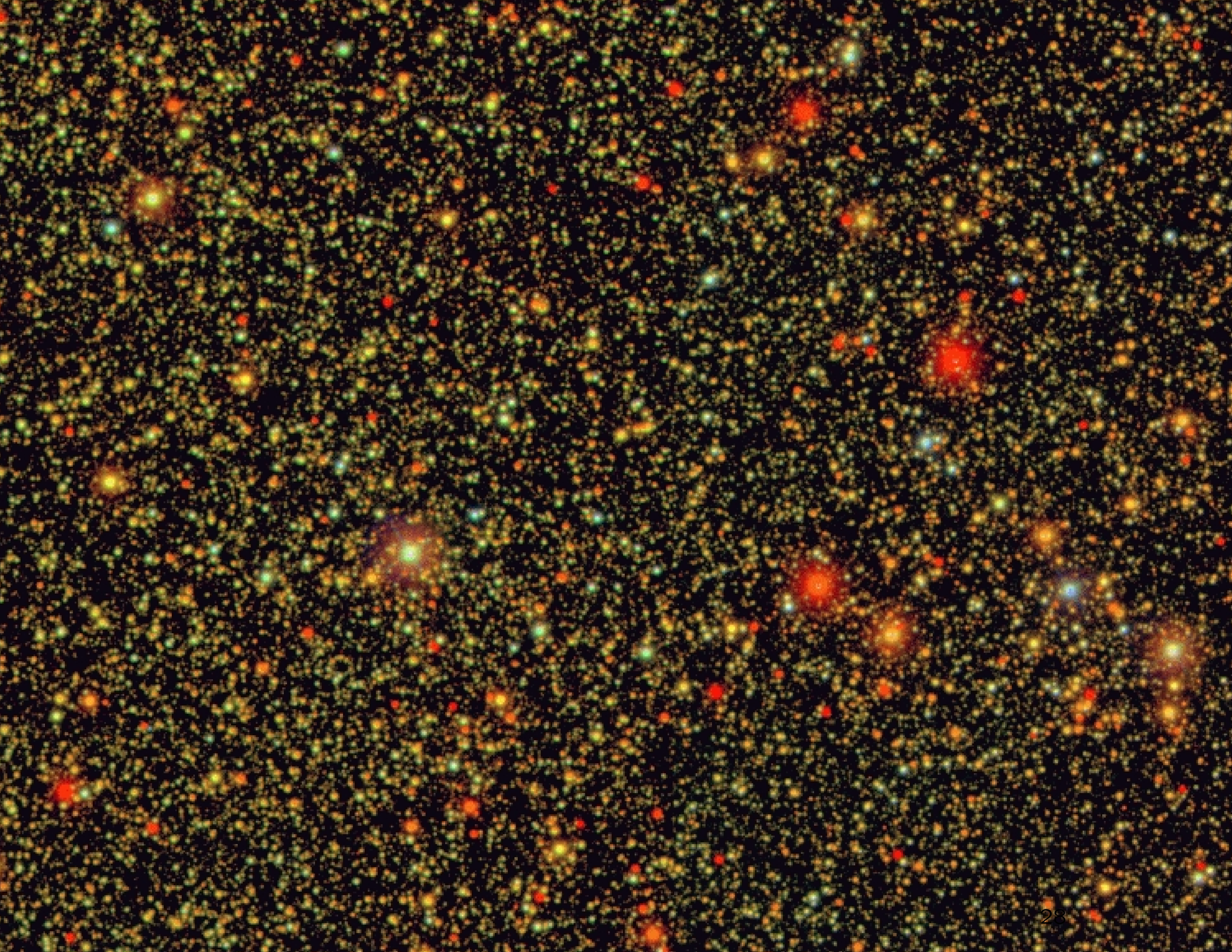
- Hipparcos: 3,000 stars visible by naked eye

- and many others...

- Palomar Observatory Sky Survey: (first 1950-57, second 1985-1999) photographic, nearly all-sky, two bands, $m<20.5$, astrometric accuracy $\sim$0.5 arcsec, photometric accuracy 0.2-0.4 mag (both very non-Gaussian), USNO-B catalog: 10^9 sources

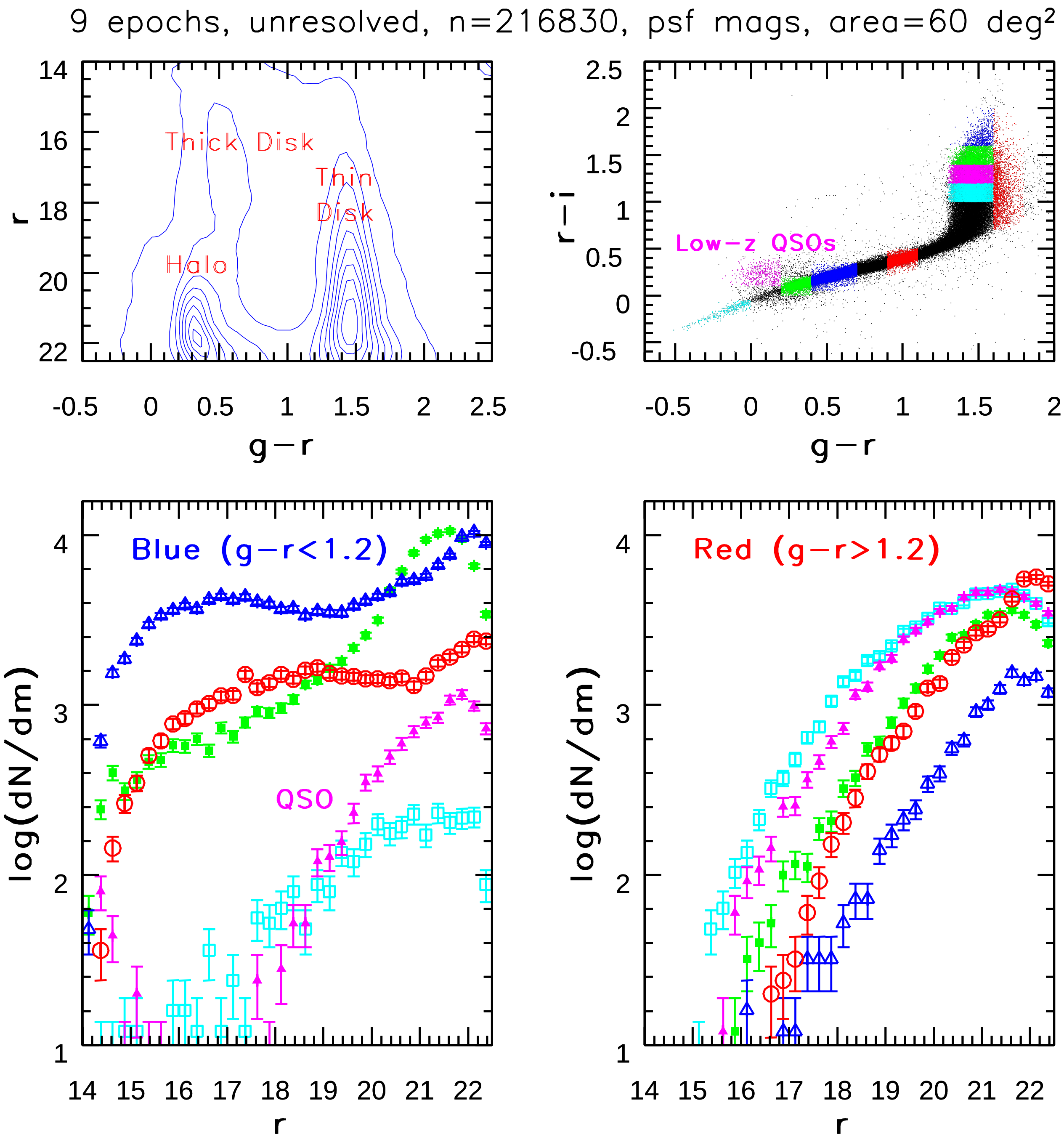
- SDSS: digital, 1/4 sky, 5 bands, $m<22.5$, astrometric accuracy $<$0.1 arcsec absolute, $\sim$0.02 arcsec relative, photometric accuracy 0.02 mag (both nearly Gaussian), several 10^8 sources





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
Thick Disk
Thin Disk
Halo
r
g−r
r−i
Low−z QSOs
Blue (g−r<1.2)
QSO
Red (g−r>1.2)
log(dN/dm)

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. $n(m) = \rho(l, b, m) \, 0.2 \, \Delta\Omega \, ln(10) \, (10 \, pc)^3 \, 10^{-0.6M} \, 10^{0.6m}$

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

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

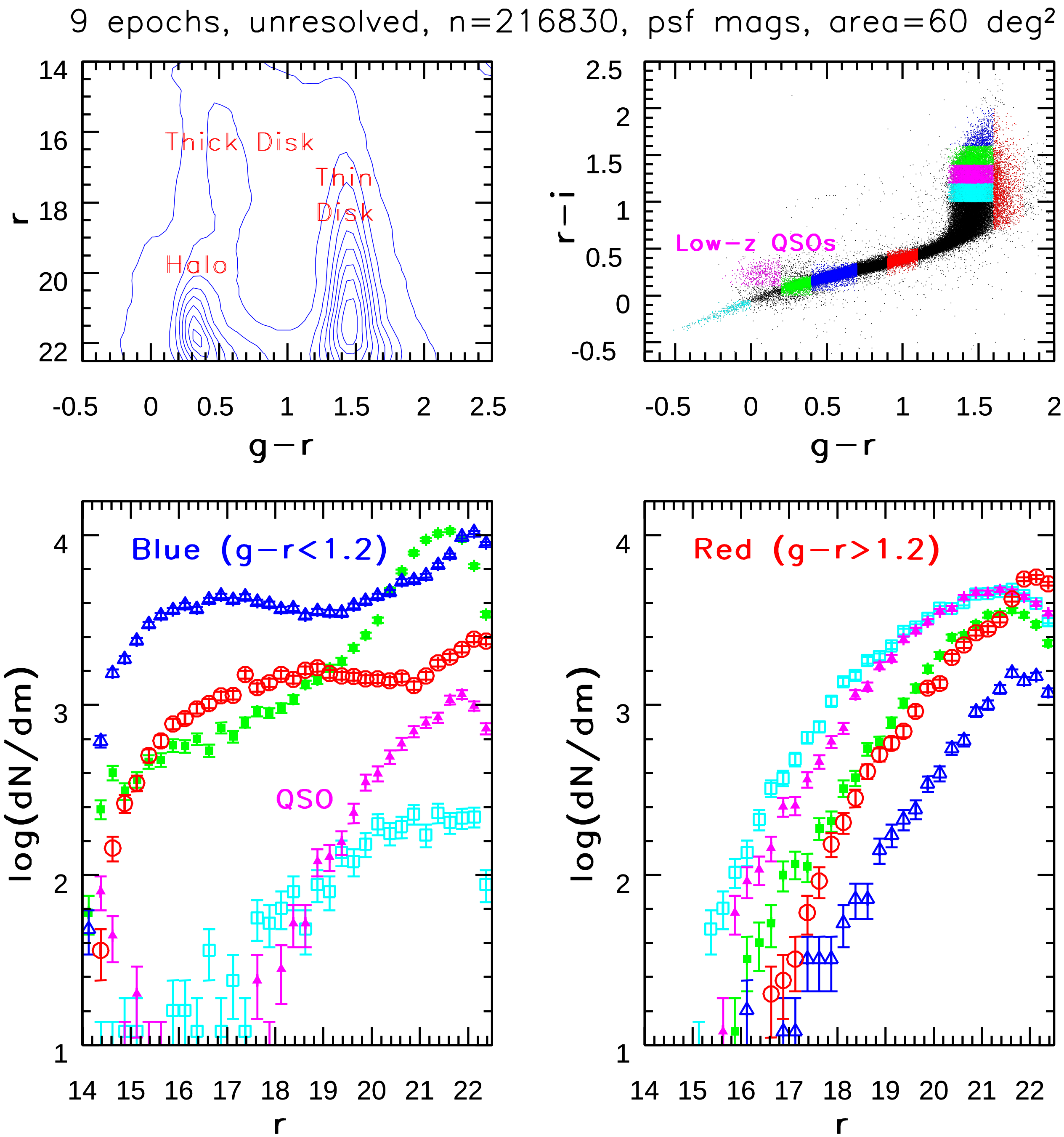
- Power-law: $\rho(l,b,D) \propto D^{-n}$

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

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

  – Halo counts (n=3): $n(m) = const.$

- 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!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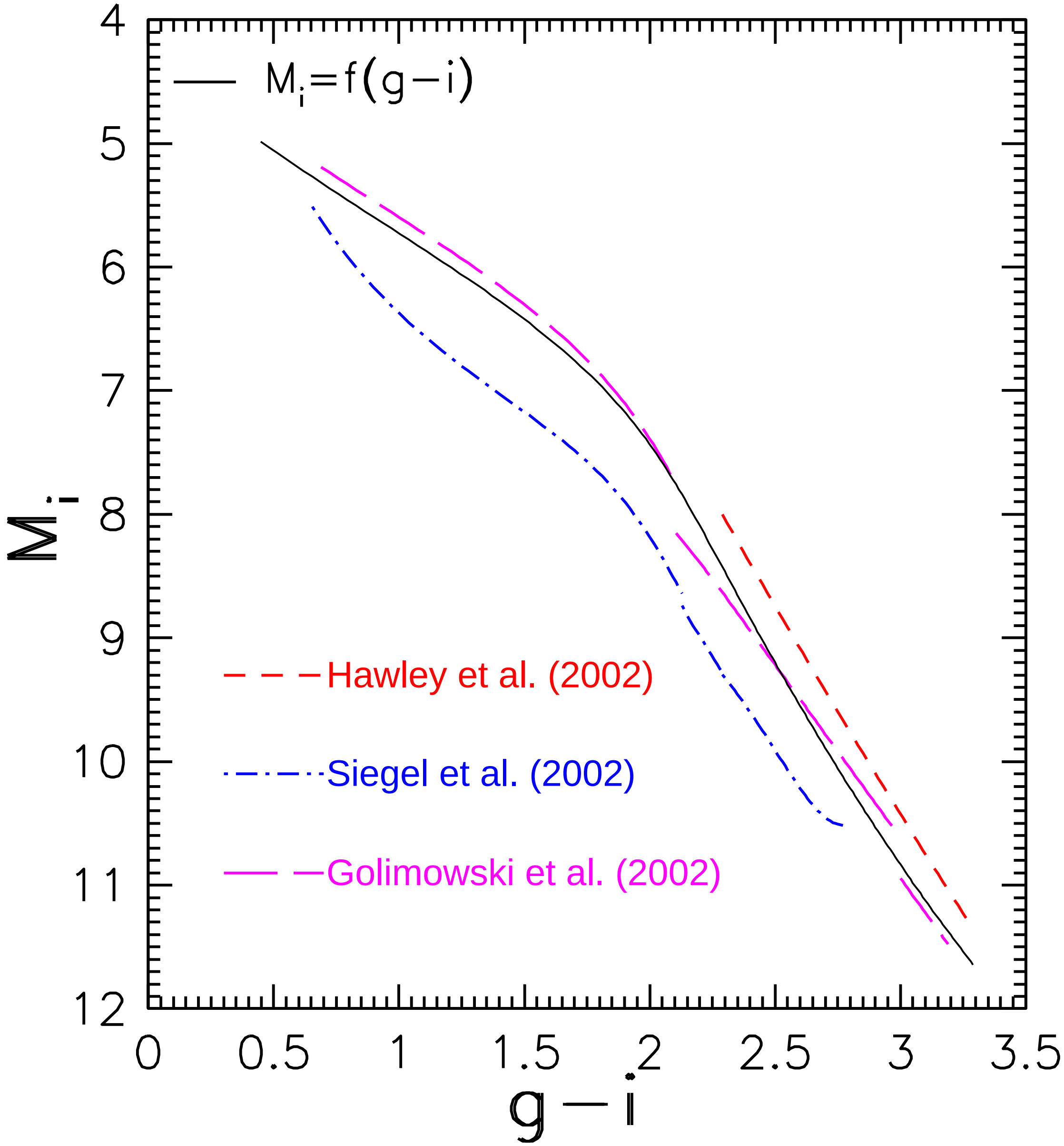

M_i
$g-i$
$M_i=f(g-i)$
Hawley et al. (2002)
Siegel et al. (2002)
Golimowski et al. (2002)
4
5
6
7
8
9
10
11
12
0
0.5
1
1.5
2
2.5
3
3.5

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 $M_r \sim 5.7$: $H' \sim 1800$ pc

- 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 $M_r \sim 12$: $H' \sim 800$ pc

- $H' = H/\sin b \sim 2\,H$, in agreement with expectations for thin ($H \sim 300$ pc) and thick ($H \sim 1.0$ kpc) 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: **next time**