Astr 511: Galaxies as galaxies

Winter Quarter 2017, University of Washington

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Lecture 2:

Basic properties of the Milky Way and the Local Group

Outline

- Spatial distribution of stars: disk, halo, bulge

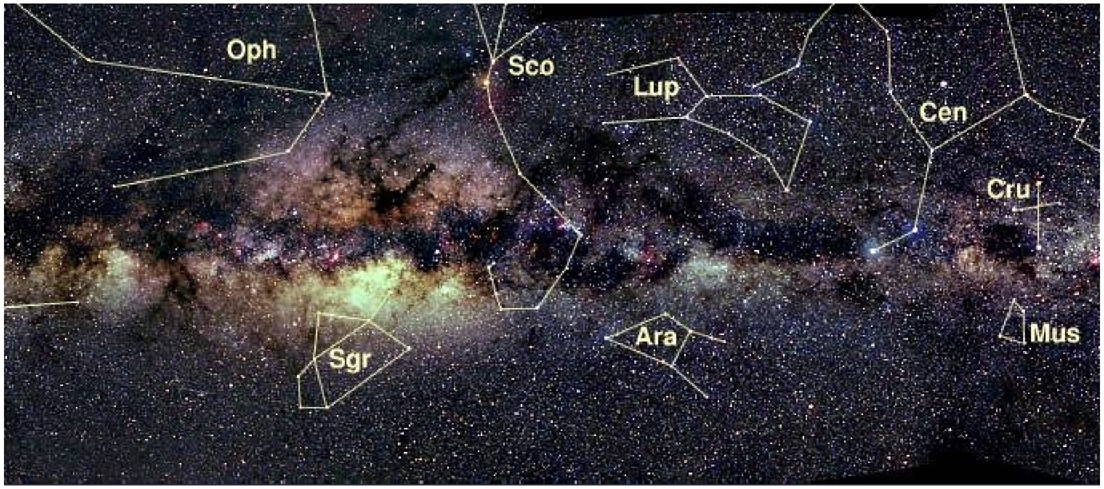
- Stellar kinematics: rotation vs. random motions

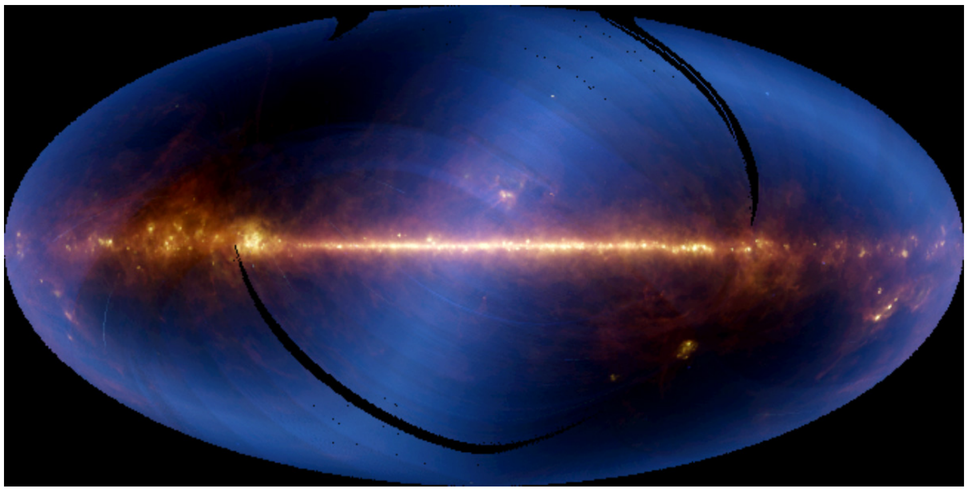
- Galactic center: black hole measurements

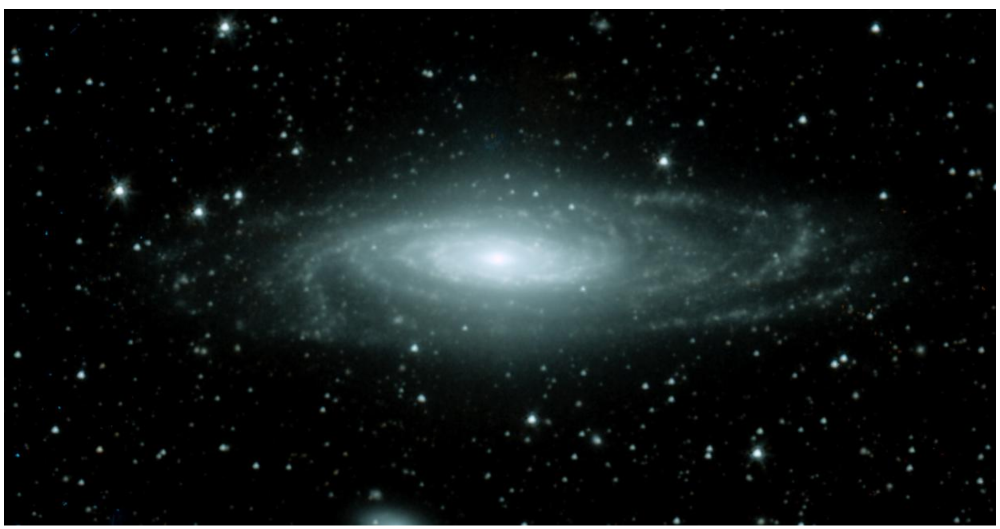
- Interstellar medium: gas and dust

- Stellar counts: simple analysis

- The Local Group: our nearest galaxy neighborhood





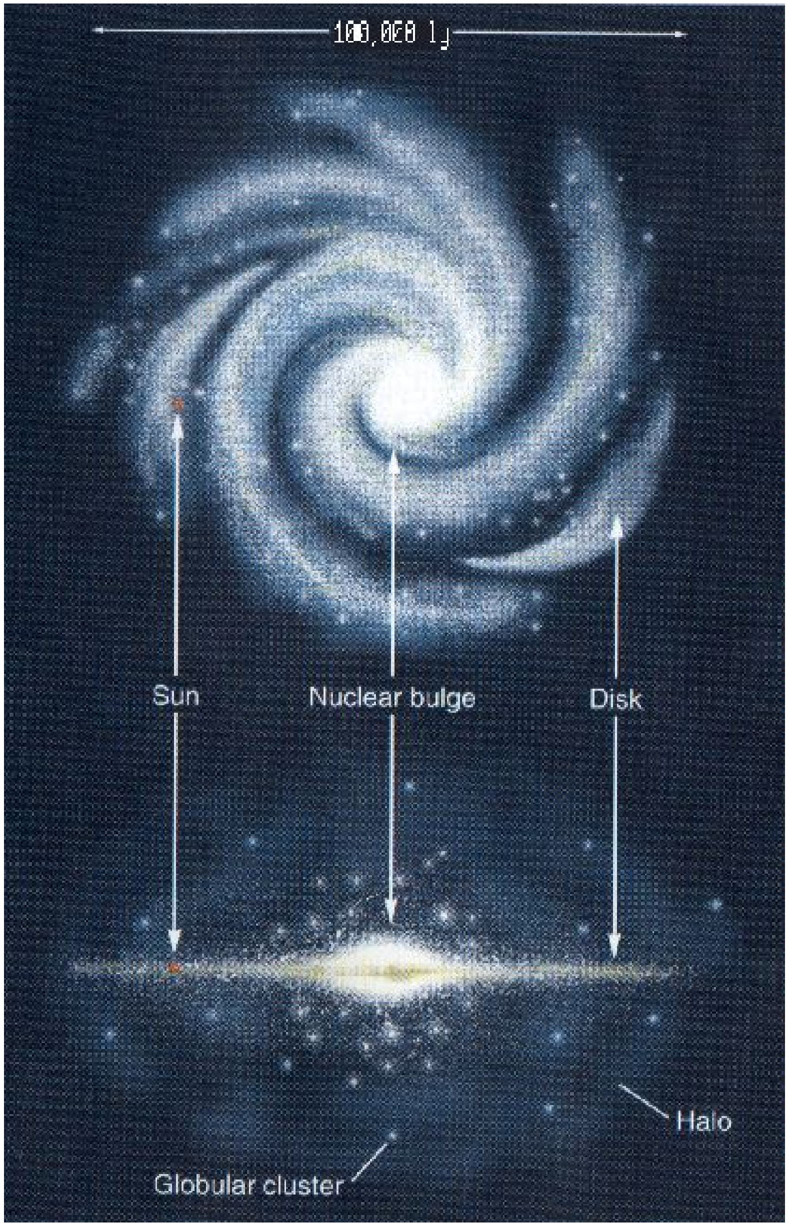


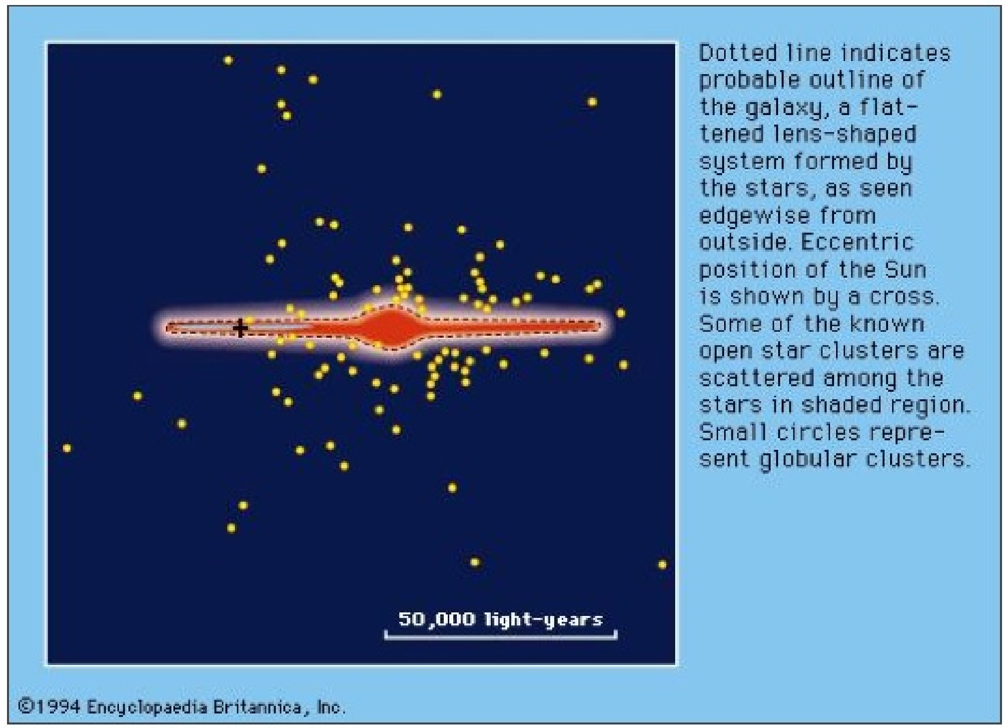
Introduction

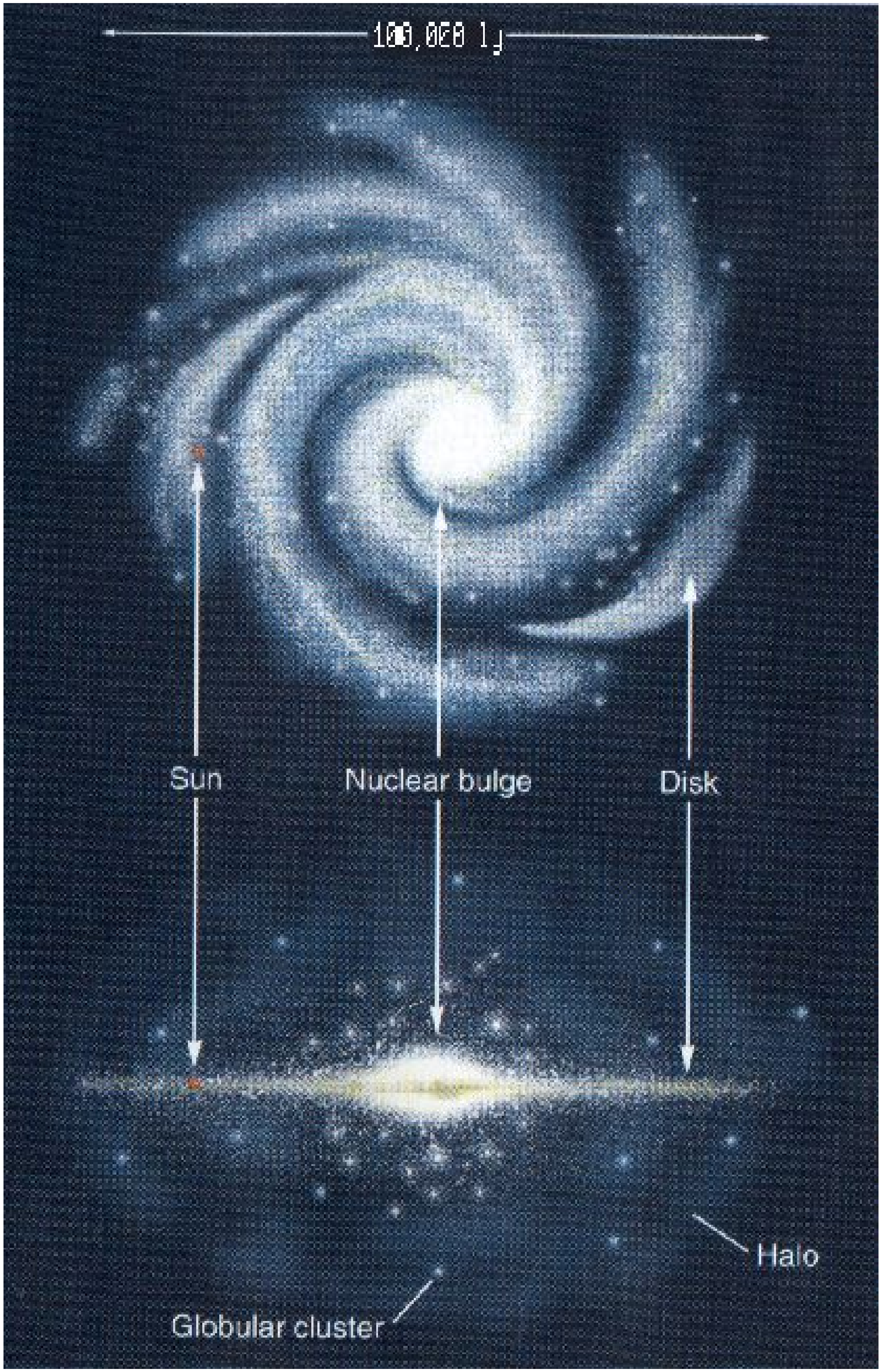
- Top left: 30° by 10° (optical) view towards the Galactic center (from Axel Mellinger)
- Middle left: The all-sky view by the Infrared Astronomical Satellite
- Bottom left: a spiral galaxy (NGC 7331) similar to the Milky Way
- Conclusion: the density of stars on the sky varies greatly because we are 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)

The position of the Galactic center

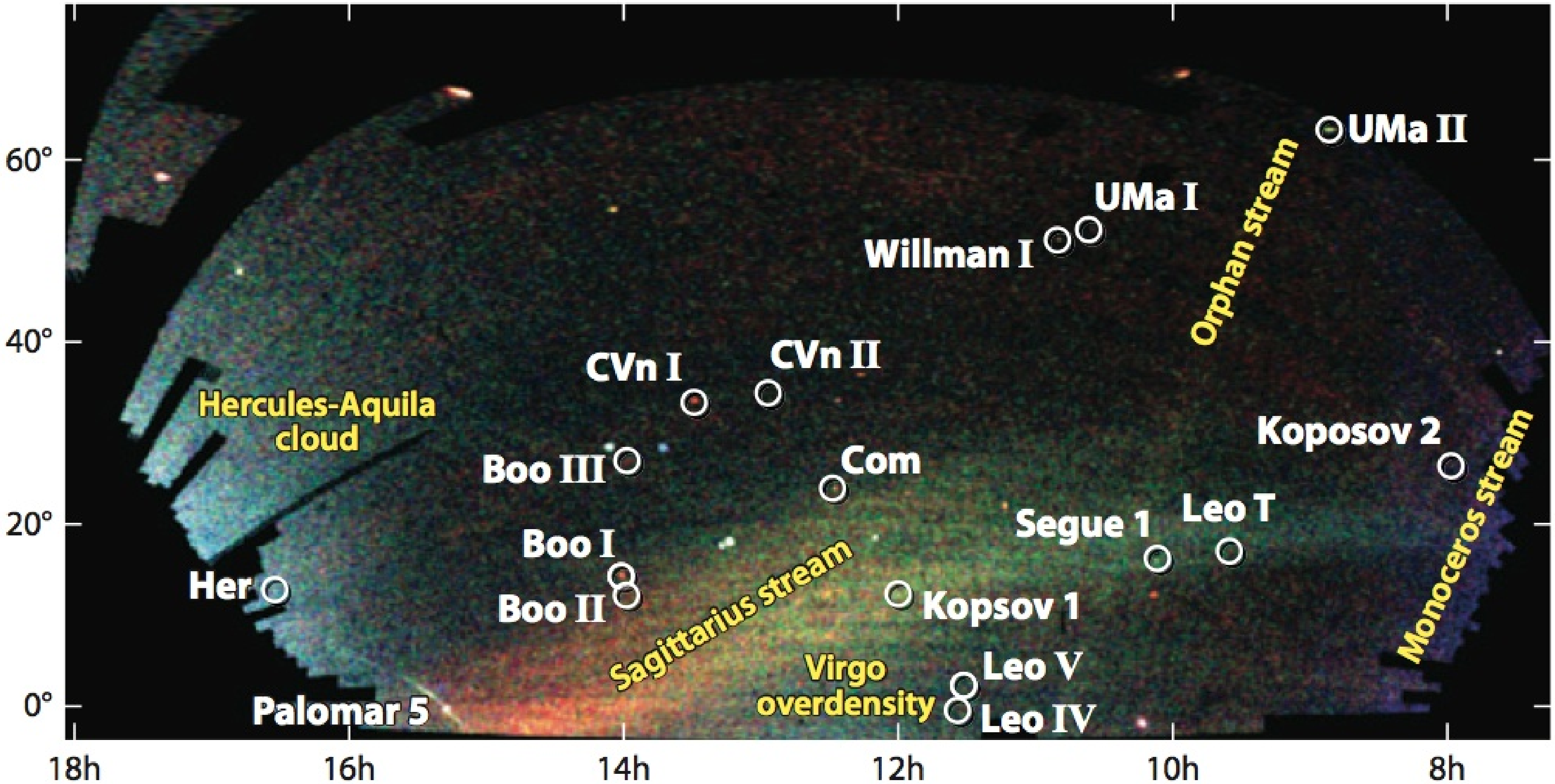
- Shapley used the distribution of globular clusters to demonstrate that the Sun is not in the center of the Milky Way (8 kpc)

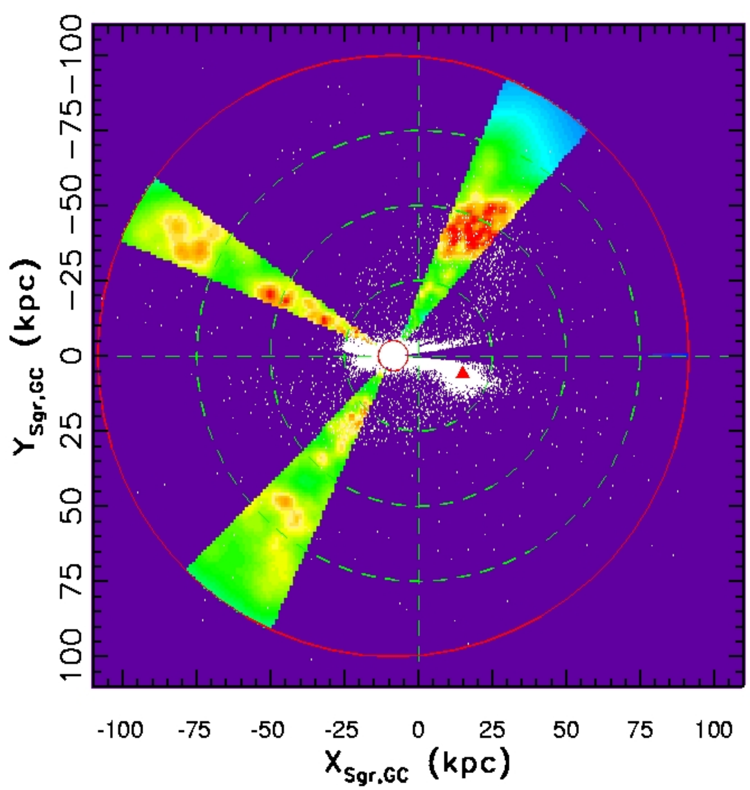






GALACTIC DISK	**GALACTIC HALO**	**GALACTIC BULGE**
Highly flattened	Roughly spherical—mildly flattened	Somewhat flattened and elongated in the plane of the disk ("football shaped")
Contains both young and old stars	Contains old stars only	Contains both young and old stars; more old stars at greater distances 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)

The Virgo Overdensity: the latest news

- "...the Virgo Overdensity ... is best explained by a minor merger." (Bonaca et al. 2012, AJ 143, 105),
- "... a tri-axial dark matter halo is favored and we exclude a prolate shape." (Casey, Keller & Da Costa 2012, AJ 143, 88; figure below is from this paper)

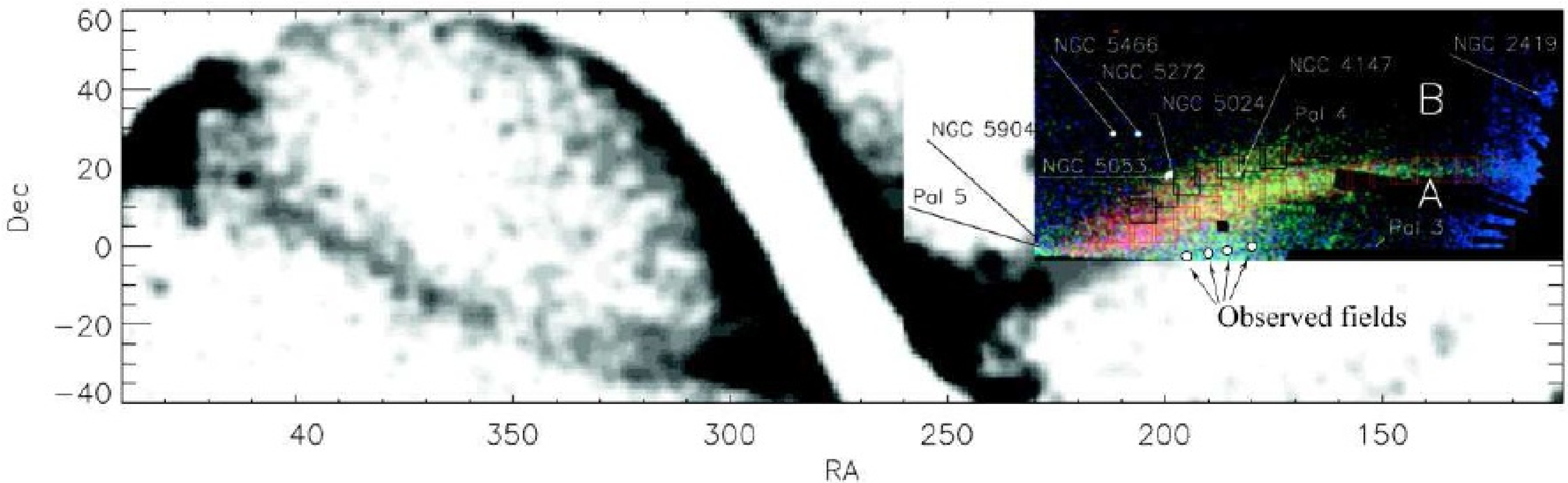
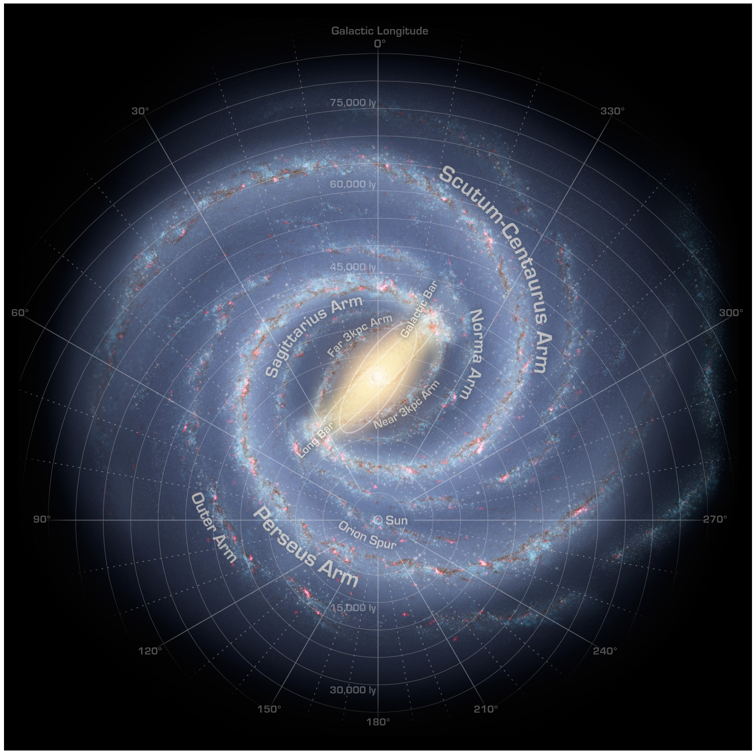
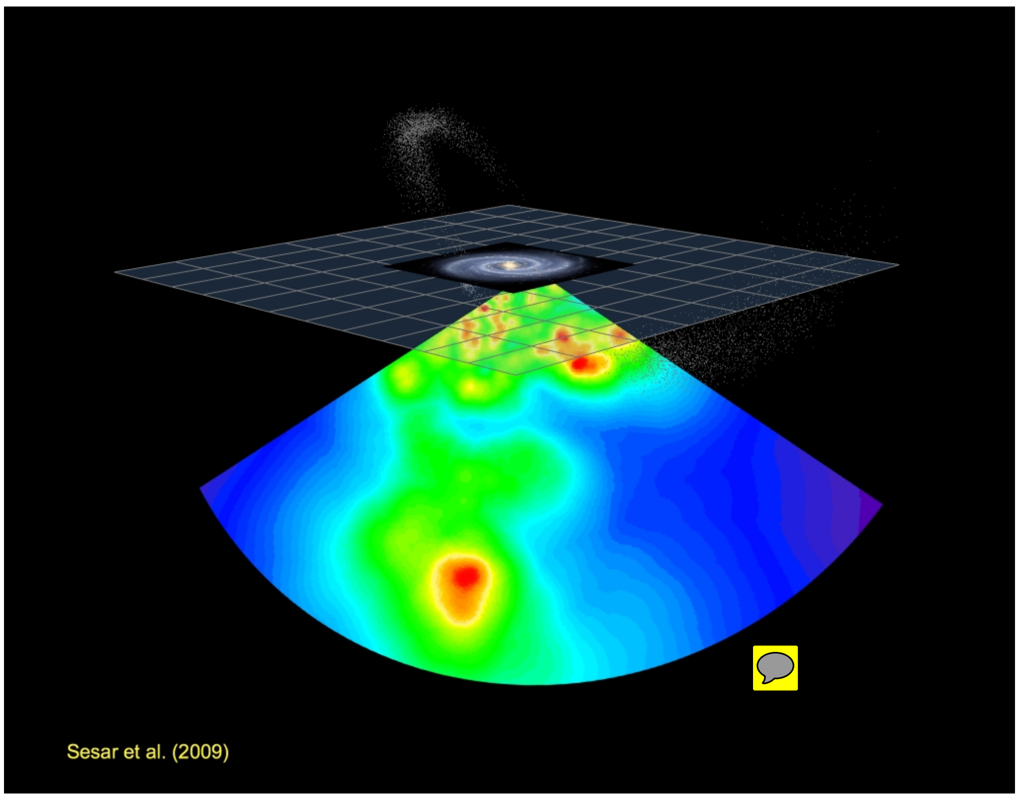


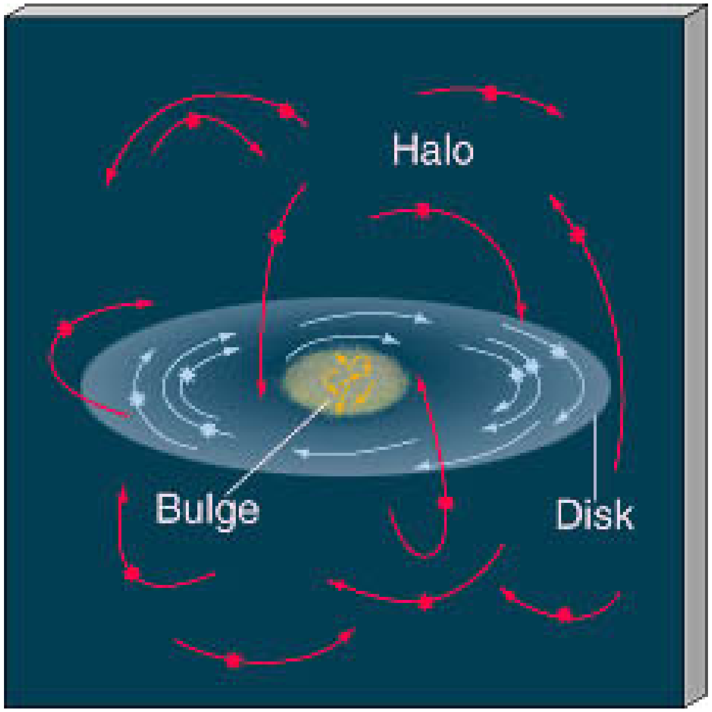
Fig. 5.— Observed fields are outlined upon a panoramic view of the Sgr stream, to demonstrate our field locations in context with the Sgr stream. This plot is an adaptation of Figure 2 in Belokurov et al. (2006), which uses the 2MASS M-giant sample of Majewski et al. (2003).

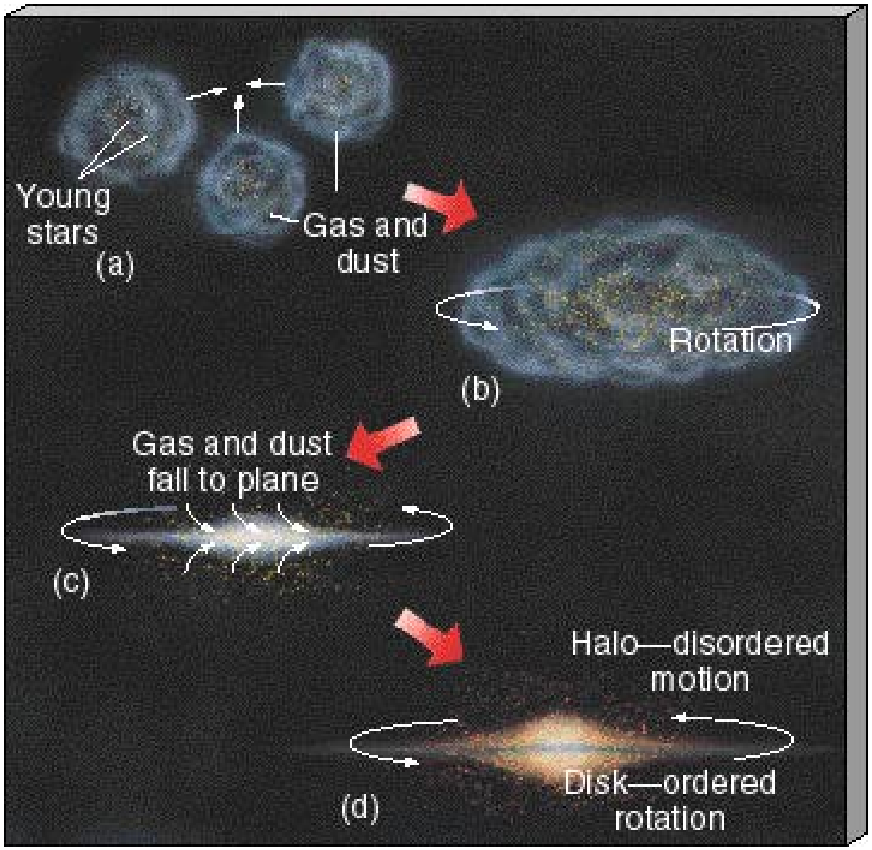




Outer halo studies: RR Lyrae (from SDSS)

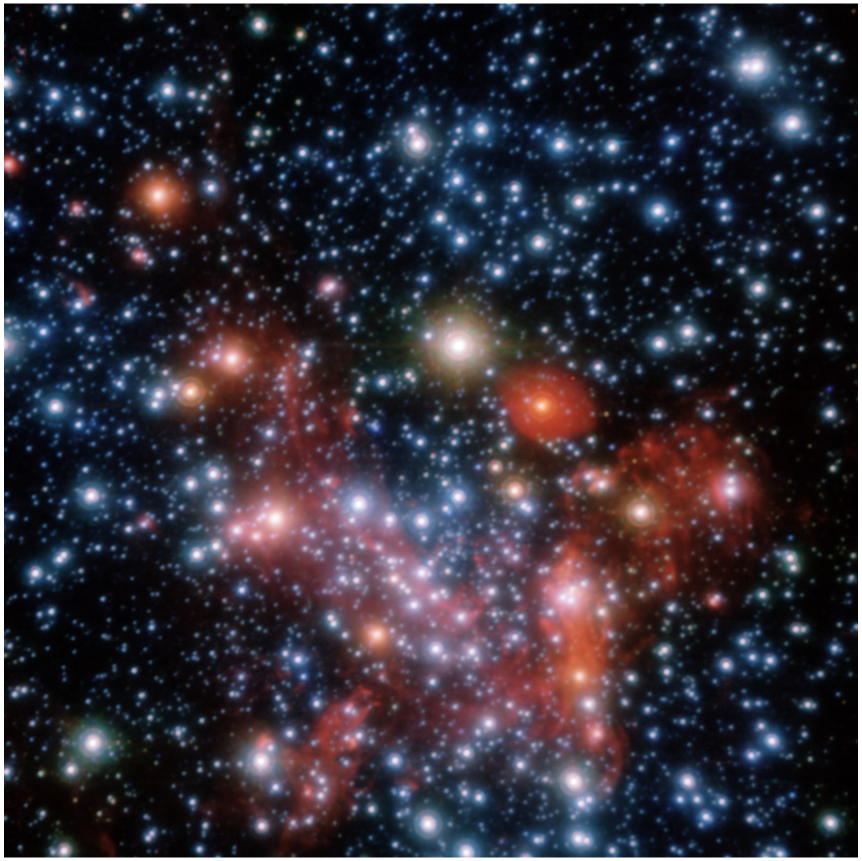
- **Top left:** the disk structure (artist's conception based on the Spitzer and other surveys of the Galactic plane)
- **Bottom left:** the halo density (multiplied by R^3; yellow and red are overdensities relative to mean $\rho(R) \propto R^{-3}$ density) as traced by RR Lyrae from SDSS Stripe 82 (Sesar et al. 2010ab, ApJ 708, 717; ApJ 717, 133), compared in scale to the top panel
- Conclusions: the spatial distribution of halo stars is highly inhomogeneous (clumpy); when averaged, the stellar volume density decreases as $\rho(R) \propto R^{-3}$ out to $\sim$30 kpc, and then becomes steeper.





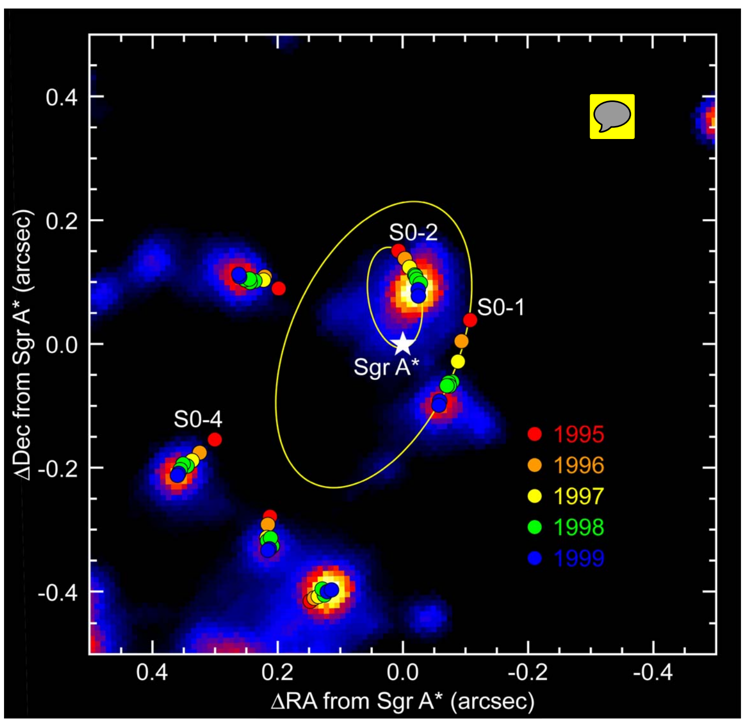
Kinematics

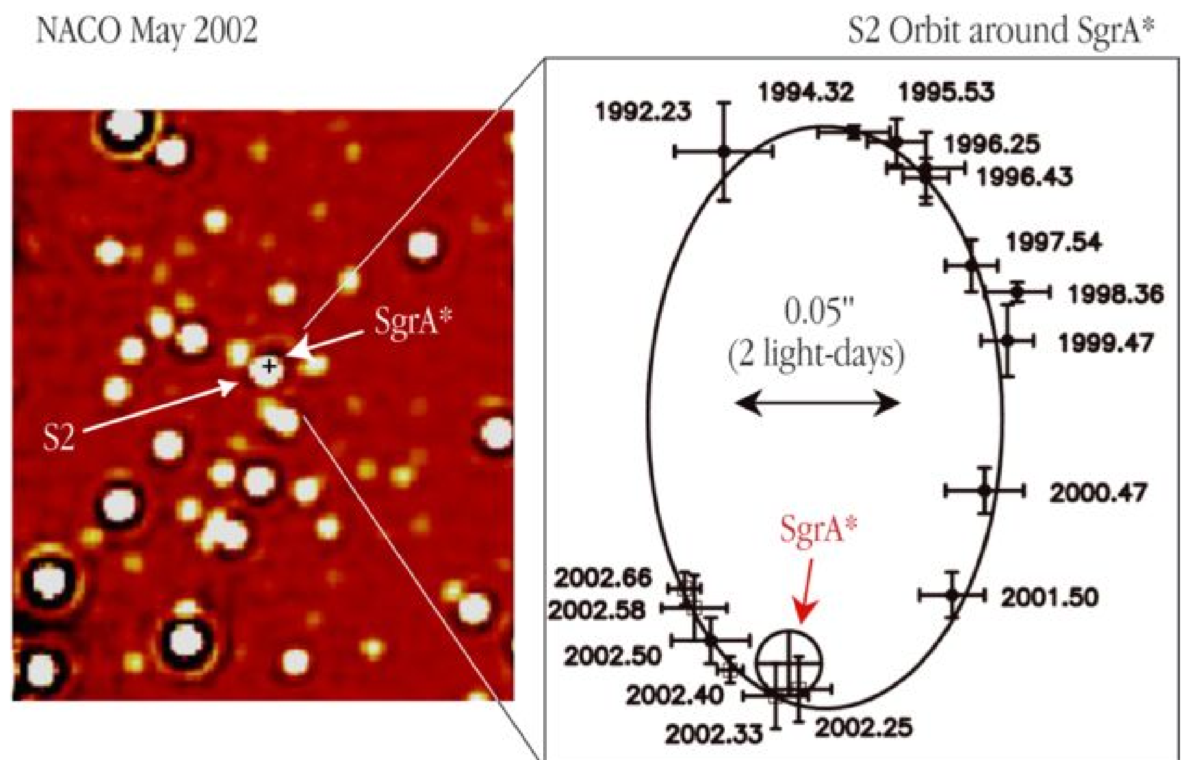
- Stars move in a gravitational potential (more in L13)
- Two types of motion: disk stars **rotate** around the center, while halo stars are on randomly distributed elliptical orbits (more in L11)
- The motion of stars was set during the formation period
- The details are governed by the laws of physics: 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

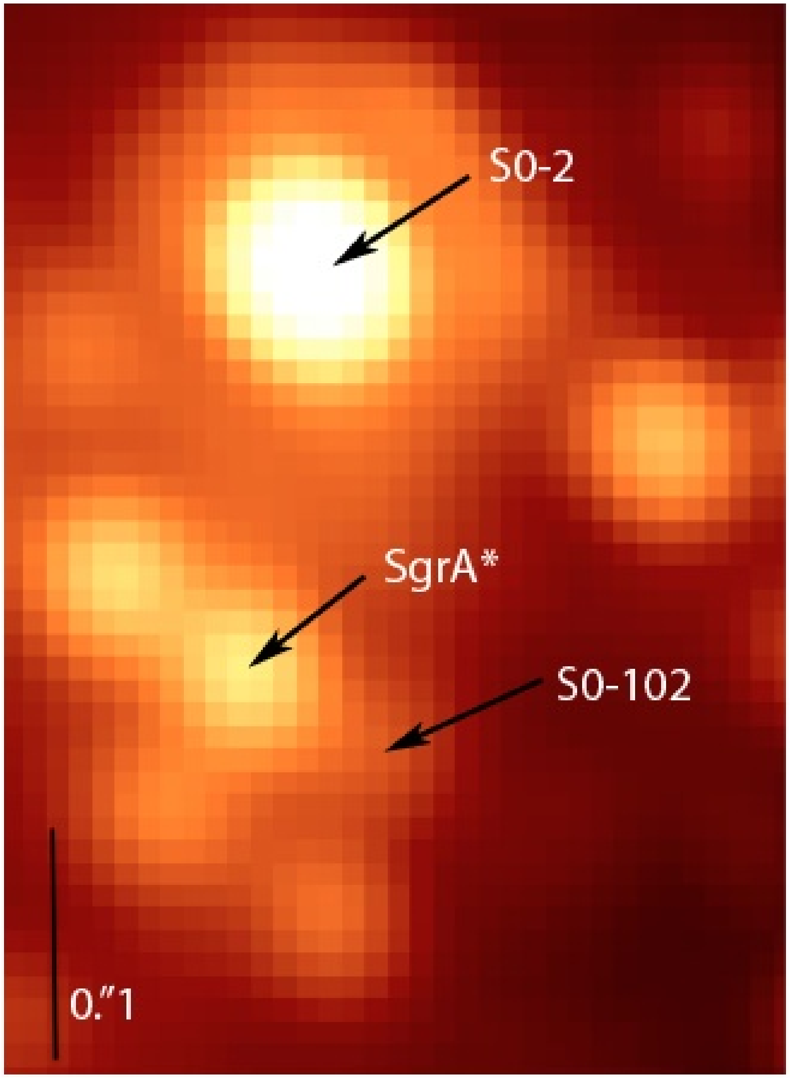
- Stars move in a gravitational potential: a large mass (a few 10^6 $M_{\odot}$) confined to small space (0.1-0.2 AU) is required to explain about ~30 **observed** orbits
- Two teams: UCLA team led by Andrea Ghez, and European team led by Reinhard Genzel





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.



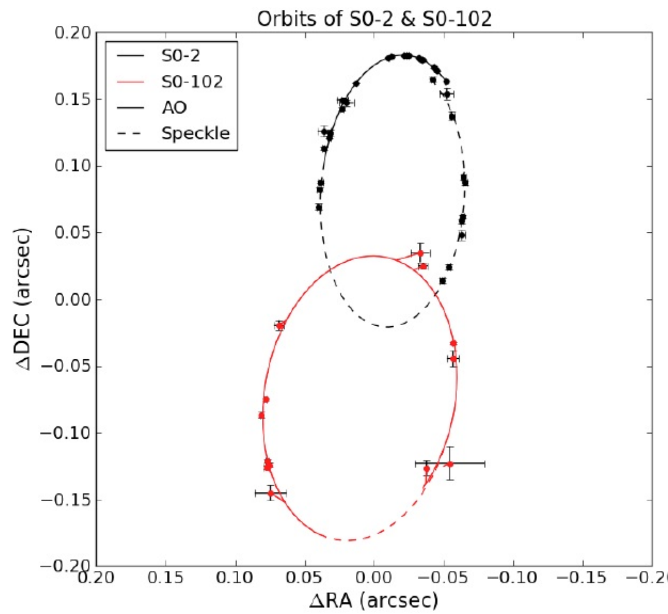
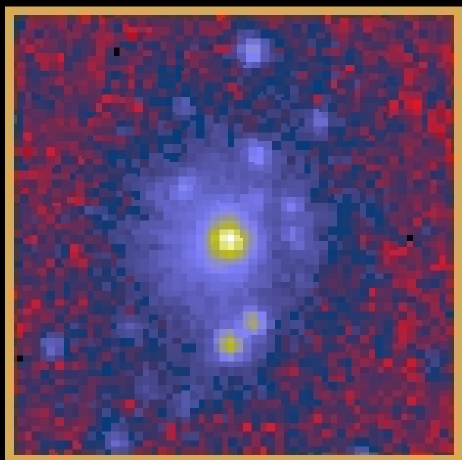


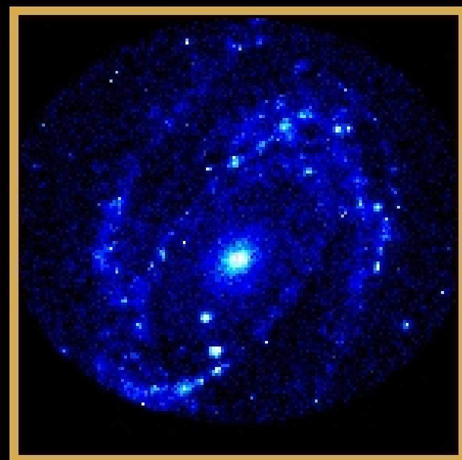
Figure 1 A Keck/NIRC2 adaptive optics image from May 2010 showing the short-period star S0-102, which is besides S0-2 the only star with full orbital phase coverage, and the electromagnetic counterpart of the black hole, Sgr A*. The image was taken at a wavelength of 2.12 μm and shows the challenge of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

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

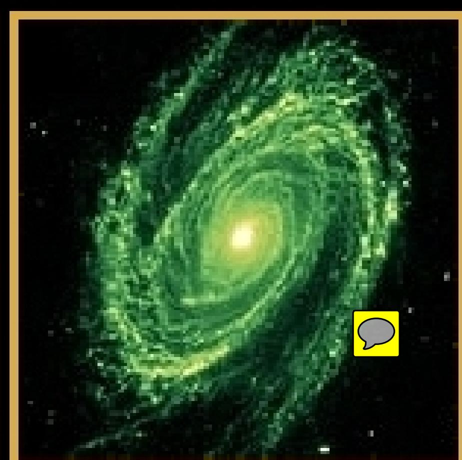


Ultraviolet: ASTRO-1

Visible: DSS

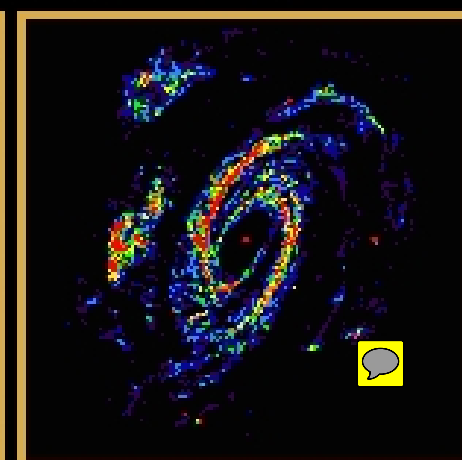
Visible: R. Gendler

Near-Infrared: Spitzer

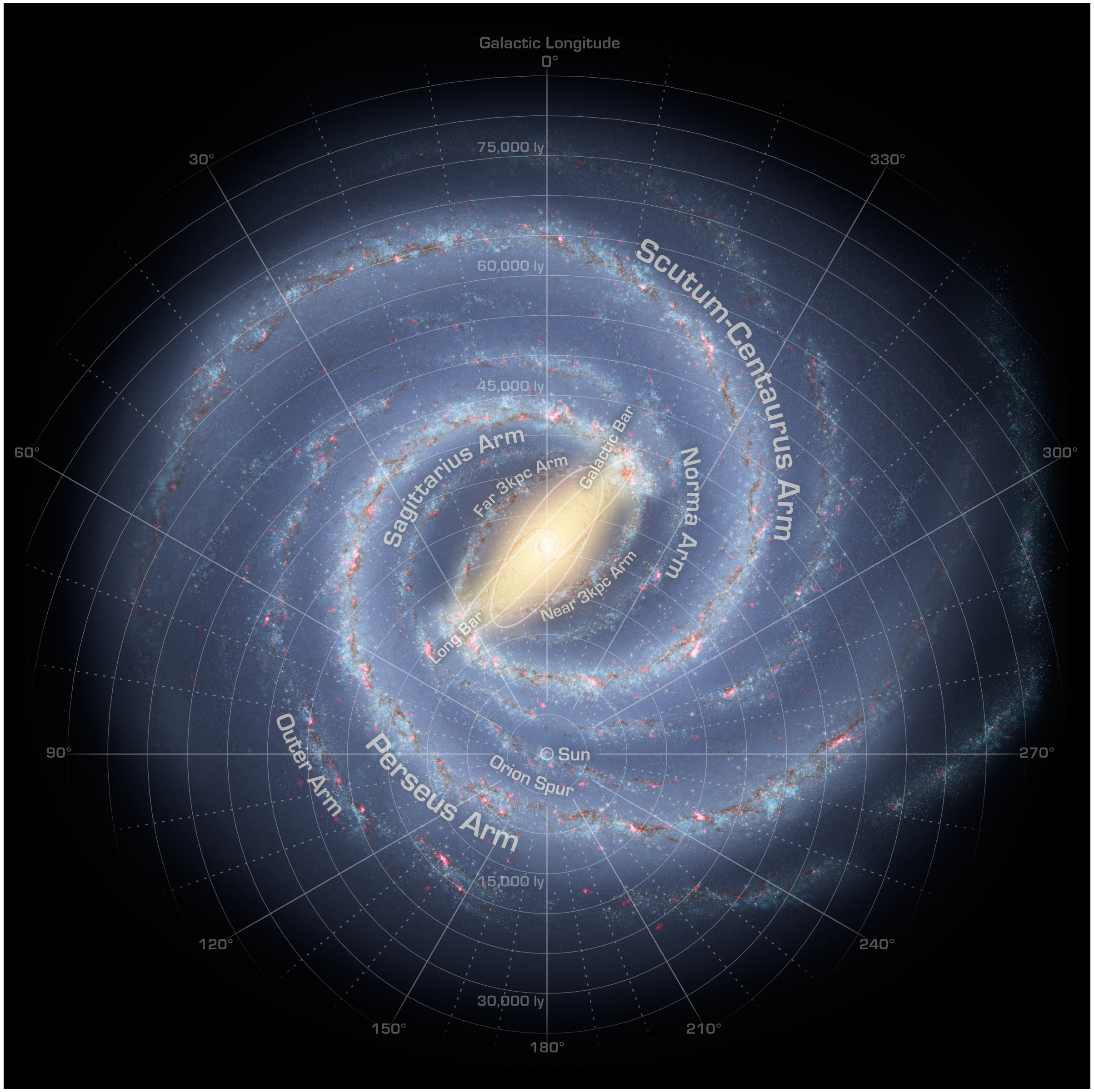


Mid-Infrared: Spitzer

Far-Infrared: Spitzer

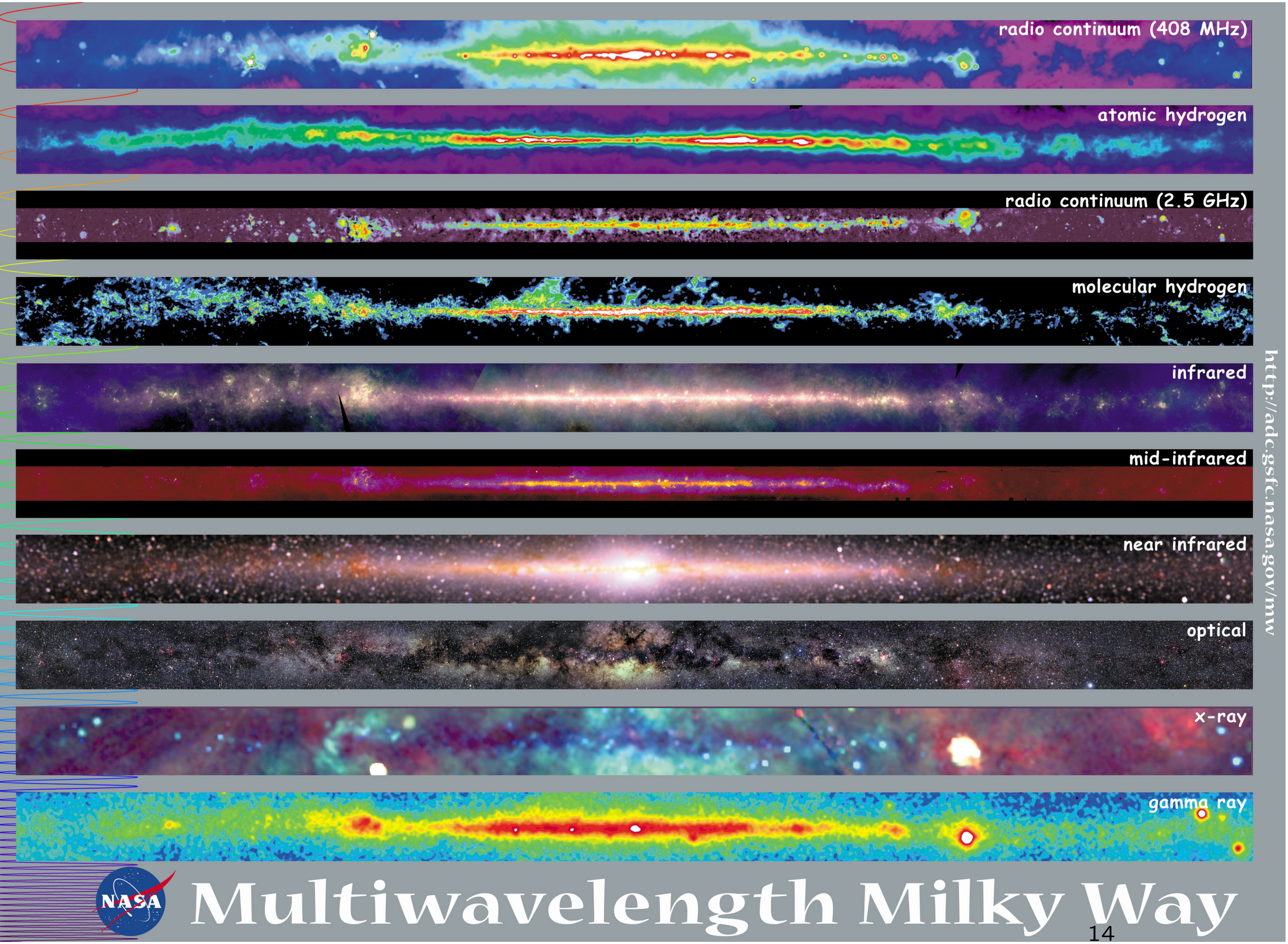


Radio: VLA



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


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
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"

"H_2"

"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)

Medium
(1-10 atoms/cm^3)

High
(10^2-10^5 atoms/cm^3)

Very High
(solid)

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Typical Temperatures

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

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

Medium (100 -10^4 K)

Cold (<50K)

Medium-cold (<100K)

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Detected How?

Hα emission line (6563Å)
X-Rays (if $T > 10^6$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

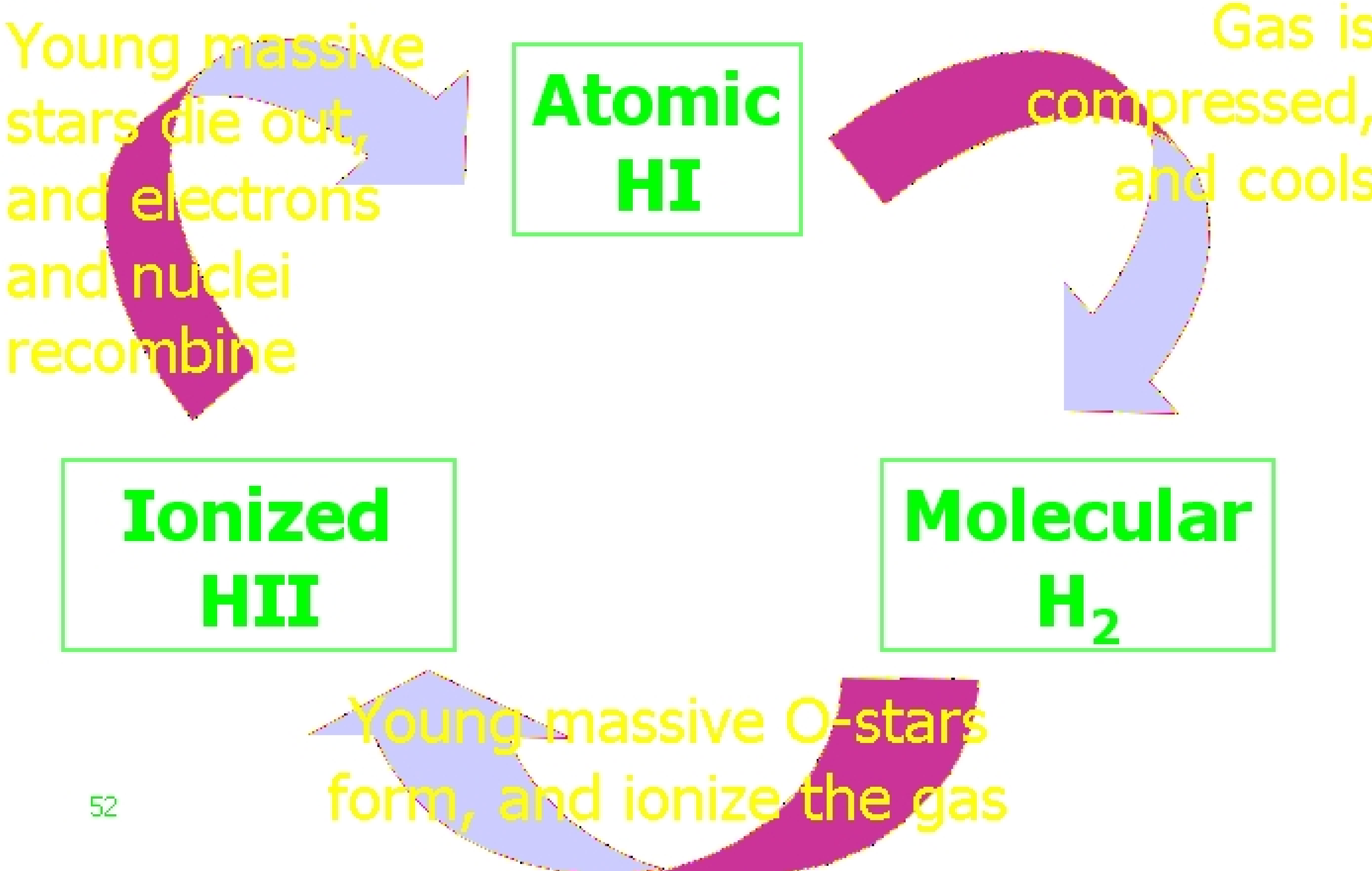
Halos of Galaxies

Galaxy Midplane, out to large radii beyond stars

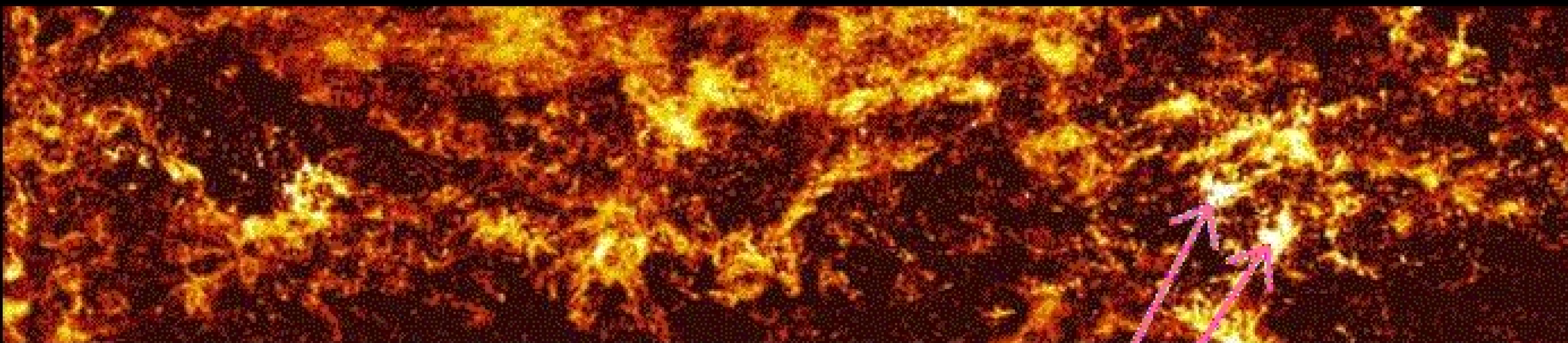
Galaxy Midplane, concentrated in spiral arms

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!

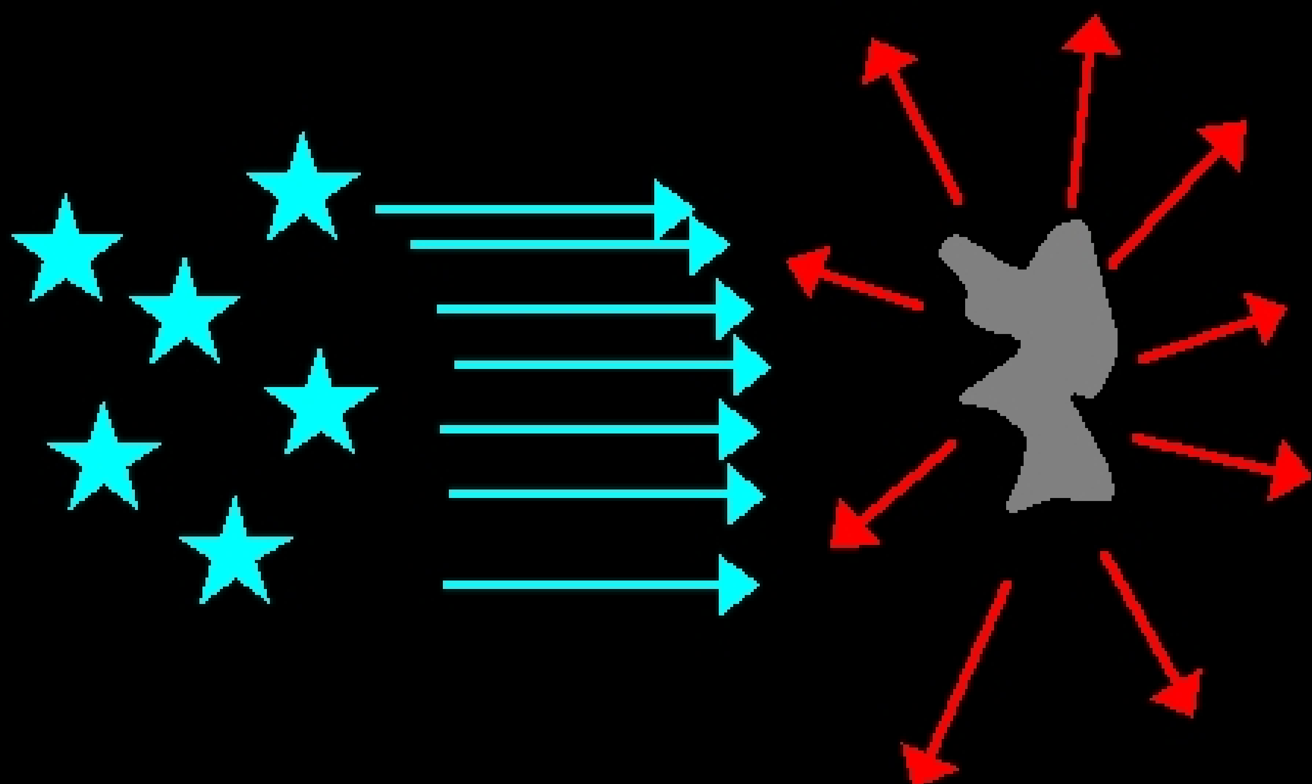
A comment about detection of molecular hydrogen

- 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 H2).

- 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. 2002, ApJ 577, 221).

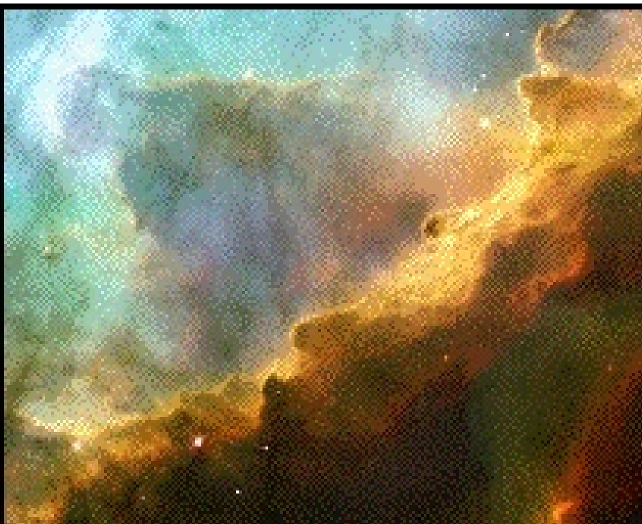
- Nevertheless, H_2 **is** directly detectable: in the UV via absorption (Copernicus and FUSE space missions, e.g. Richter, Sembach & Howk 2003, A&A 405, 1013), and in the mid-IR via emission lines (the Spitzer space mission, e.g. Ingalls et al. 2011, ApJ 743, 174).

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

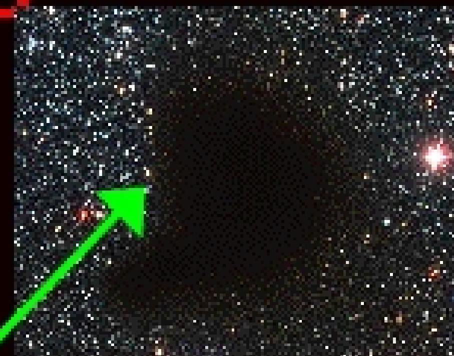


UV & optical light is absorbed by dust…

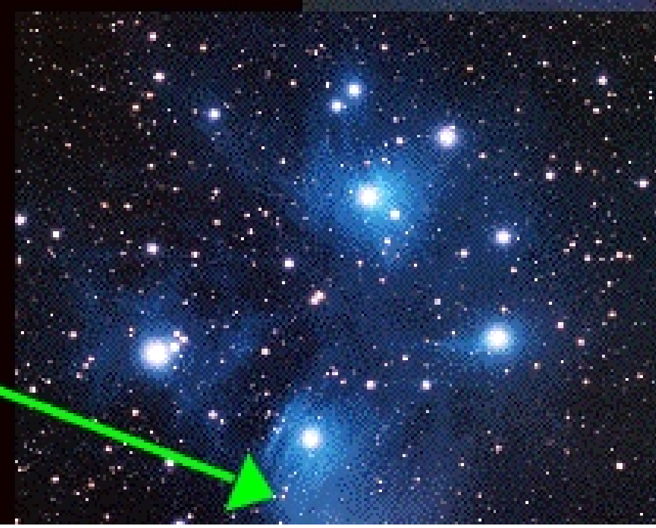
…which heats up to 10-100K and radiates like a greybody at 10-300μm



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



Dust & radiative transfer

- Left: radiative transfer modeling (fig. 3 from Ivezić & Elitzur 1997, MNRAS 287, 799)
- https://github.com/ivezic/dusty

where $\mu = \cos\theta$. In this equation

$$\frac{q_{\rm ap}(T')}{q_{\rm ap}(T_1)}\left(\frac{T'}{T_1}\right)^4 = \frac{\int q_{\rm a\lambda} u_\lambda(y')\,{\rm d}\lambda}{\int q_{\rm a\lambda} u_\lambda(1)\,{\rm d}\lambda}$$

APPENDIX C: NUMERICAL PROCEDURES

The code DUSTY, which solves the spherical radiative transfer problem employing the scaling approach described here, is publicly available for general use (Ivezić et al. 1997). The numerical calculations are conveniently performed with the aid of the dimensionless energy density

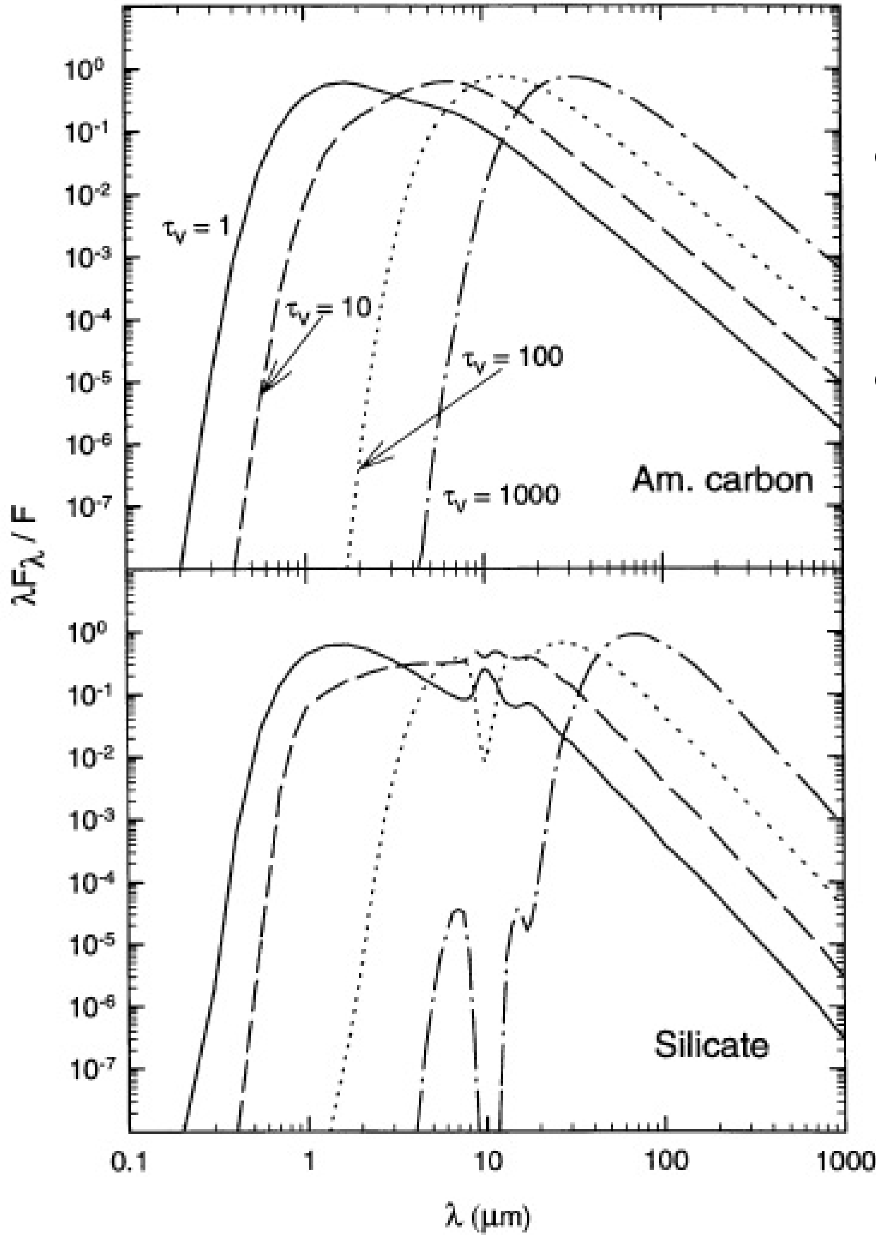
$$u_\lambda = \frac{4\pi y^2}{F_{\rm e1}} J_\lambda. \tag{C1}$$

Extracting the y^2 radial dilution reduces the dynamic range of the density, helping the numerical accuracy. For isotropic scattering, u_λ at radius y obeys the integral equation

$$u_\lambda(y) = f_{\rm e\lambda} {\rm e}^{-\tau_\lambda(y)} + \frac{1}{2}\int\left[\varpi_\lambda u_\lambda(y') + (1-\varpi_\lambda)\Psi\left(\frac{T'}{T_1}\right)^4 b_\lambda(T')\right] \times {\rm e}^{\tau_\lambda(y',\mu)-\tau_\lambda(y,\mu)}\left(\frac{y}{y'}\right)^2 {\rm d}\tau_\lambda(y',\mu)\,{\rm d}\mu\,, \tag{C2}$$

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 ($\rho(r) \propto 1/r^2$).

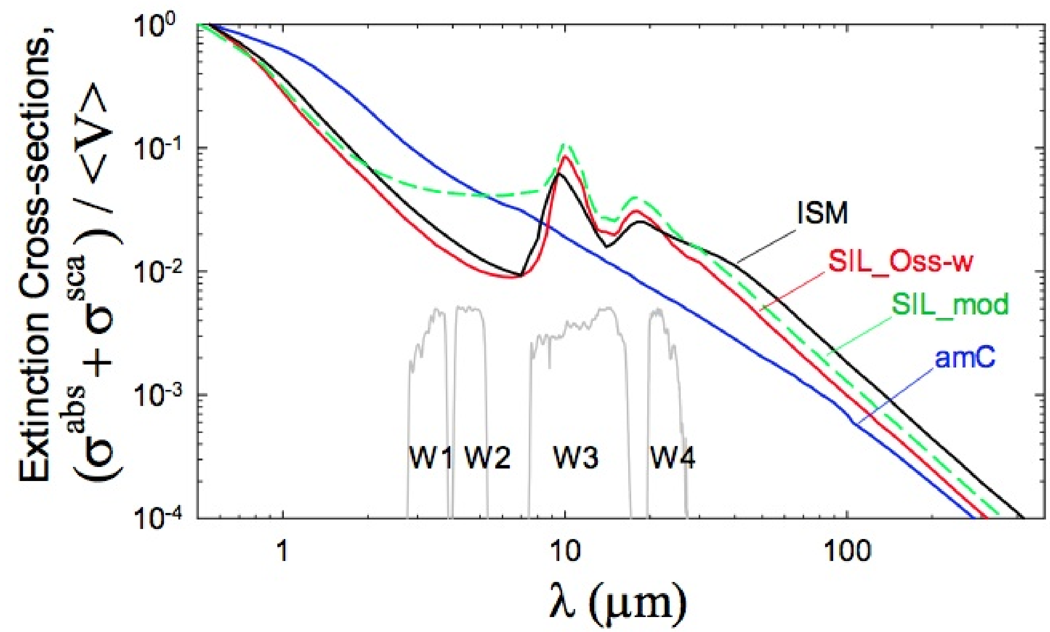
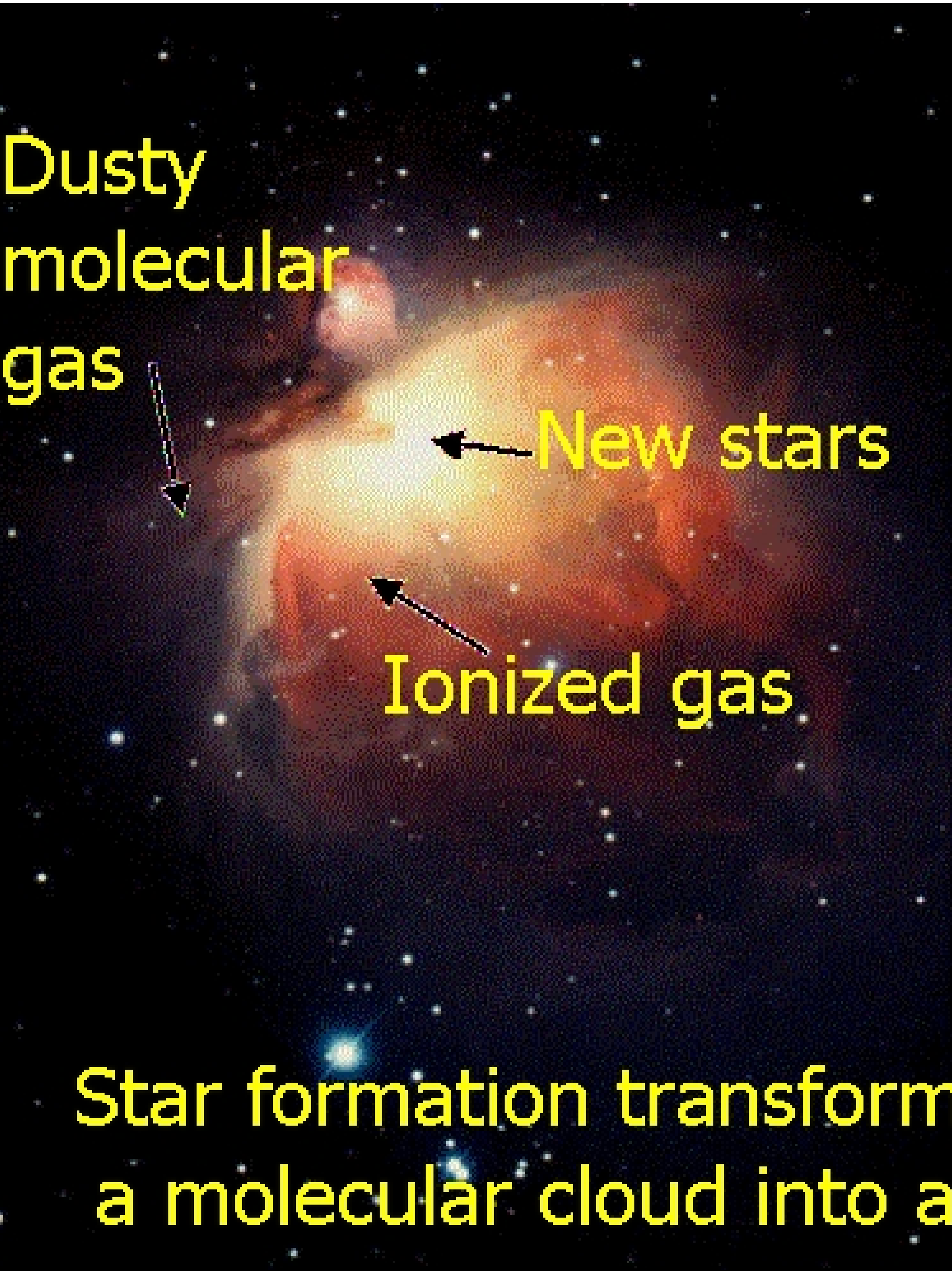


Figure 8. Extinction cross-sections of the model dust compared to the normalized response functions of the WISE filters. Dust types included: standard ISM dust mixture from Draine (2003) (black line), warm silicates from Ossenkopf et al. (1992) (Oss-w, red line) and amorphous carbon from Hanner (1988)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

The Orion Nebula



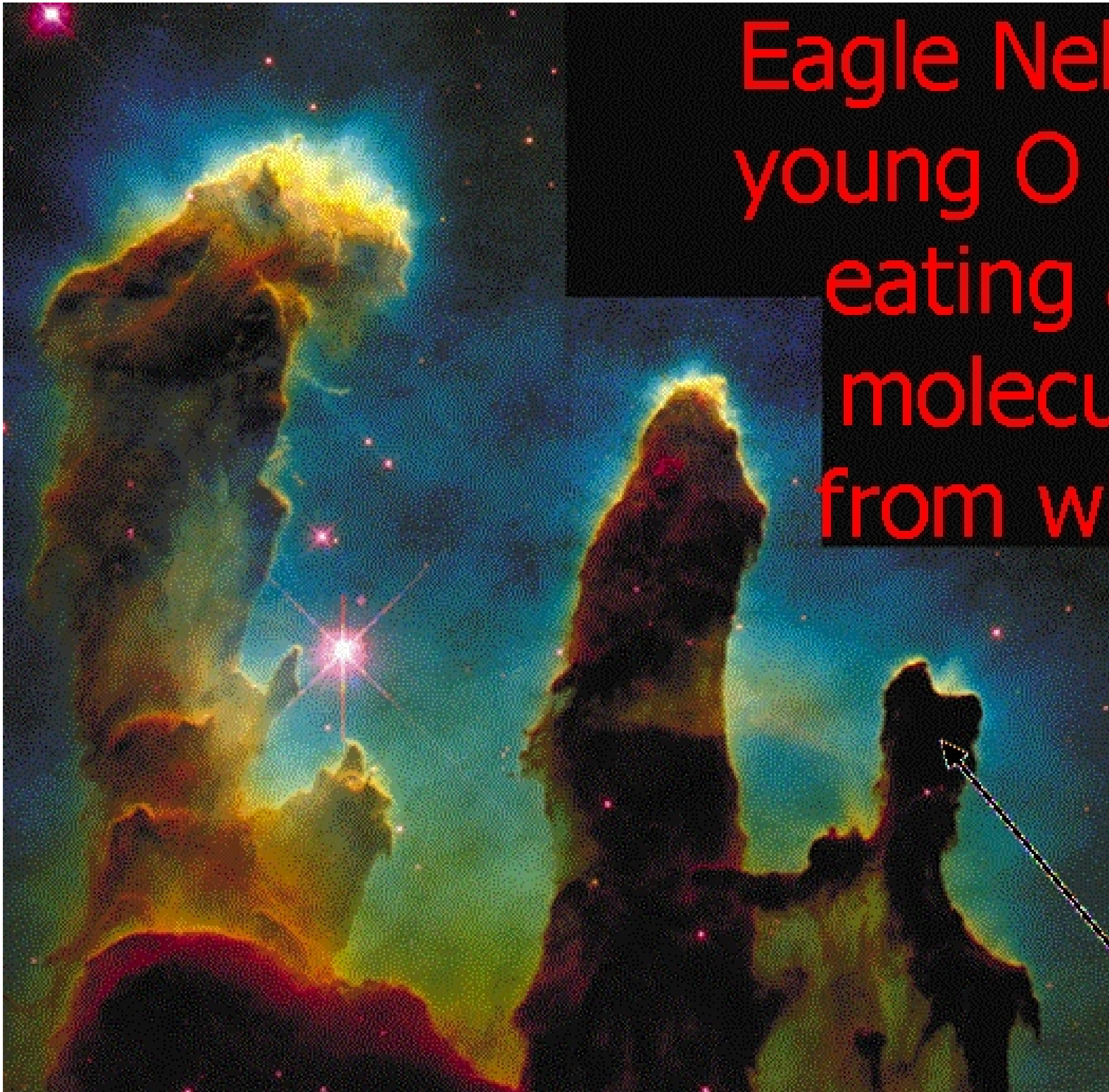
- Hot young O & B stars heat the surrounding gas, ionizing it.

$$H_2 \rightarrow HII$$

Molecular H — Ionized H

Star formation transforms a molecular cloud into an

$\boxed{\text{“HII Region”}}$



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

Gas is still molecular in the columns…

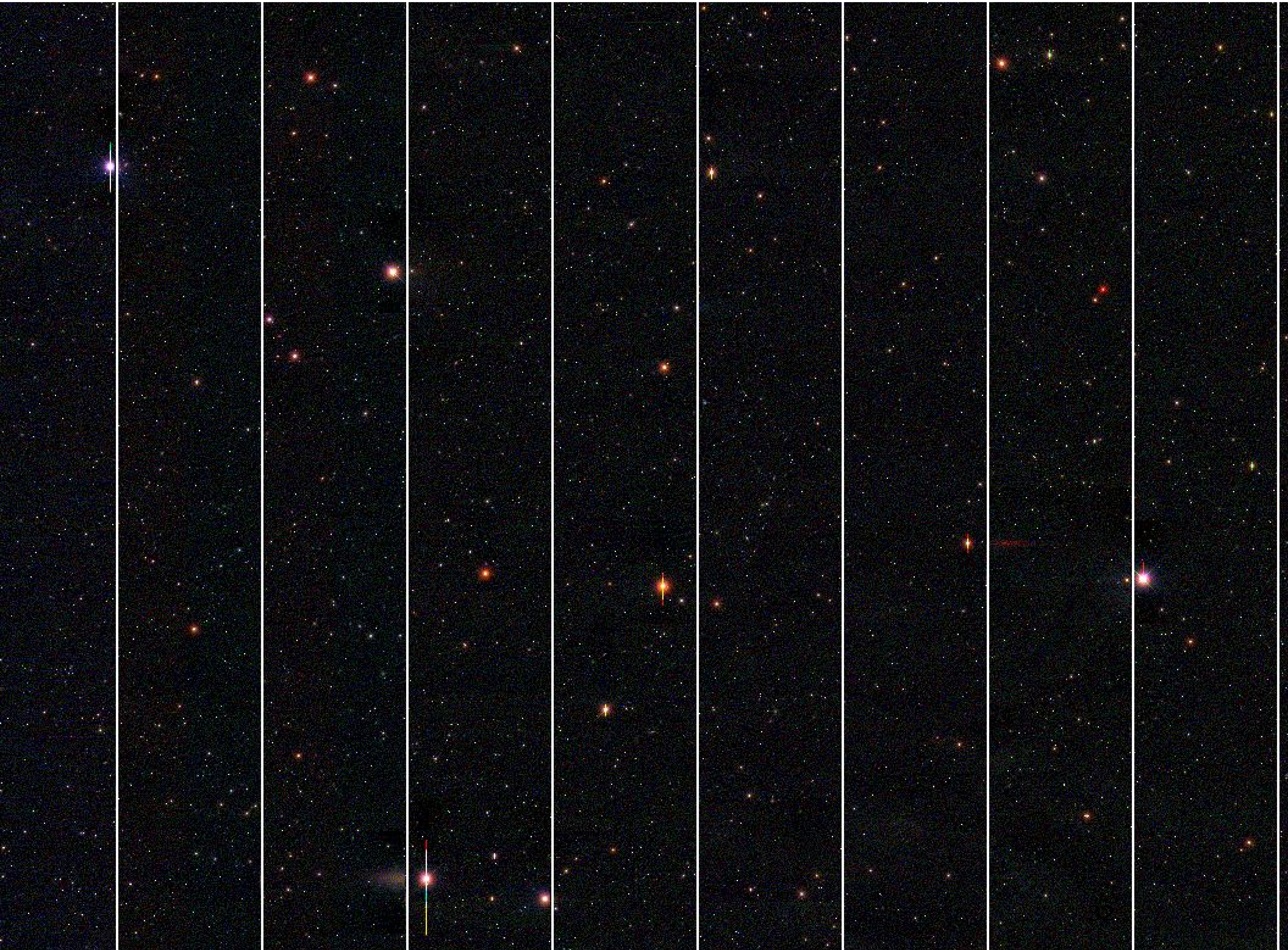
Optical Surveys and Stellar Counts

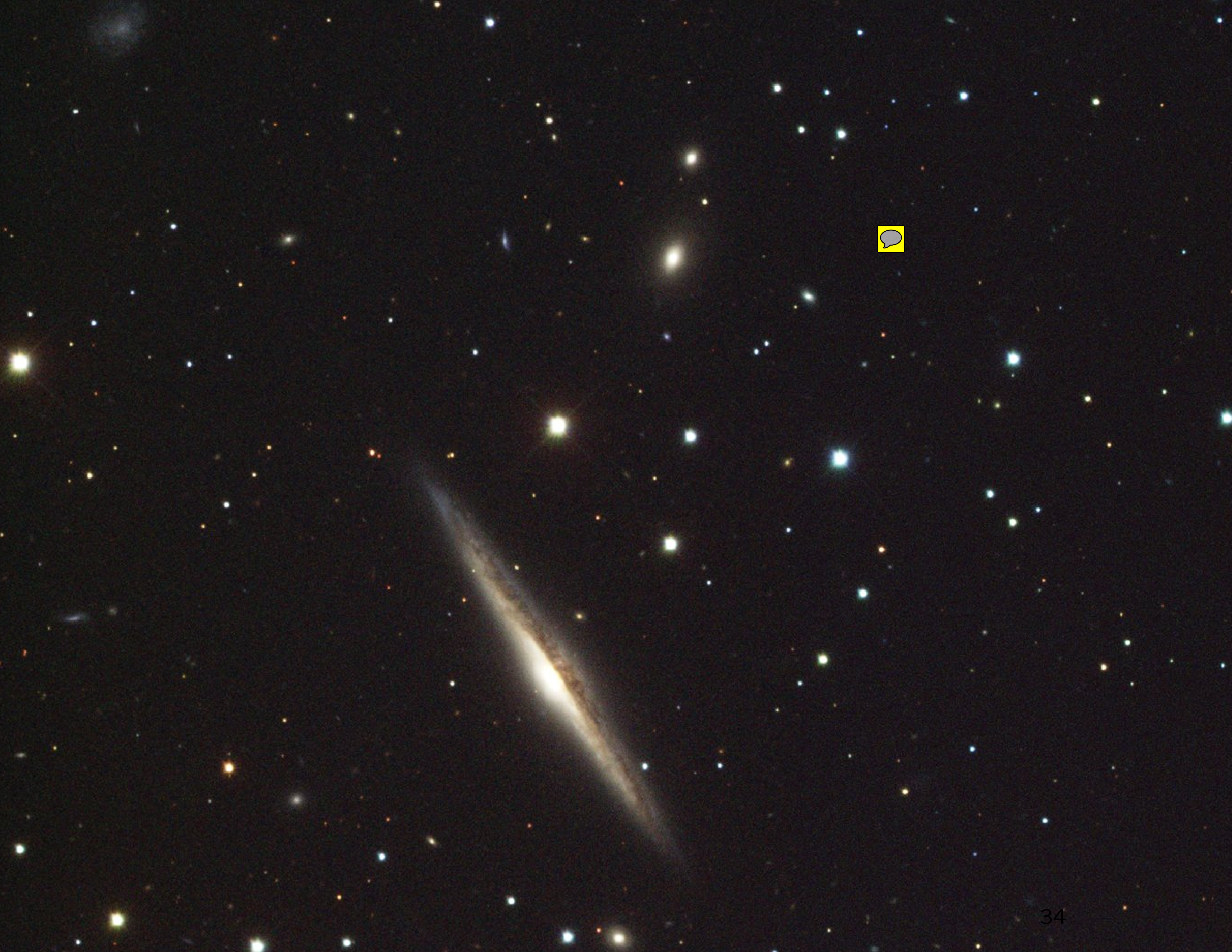
- Hipparcos: 3,000 stars visible by naked eye

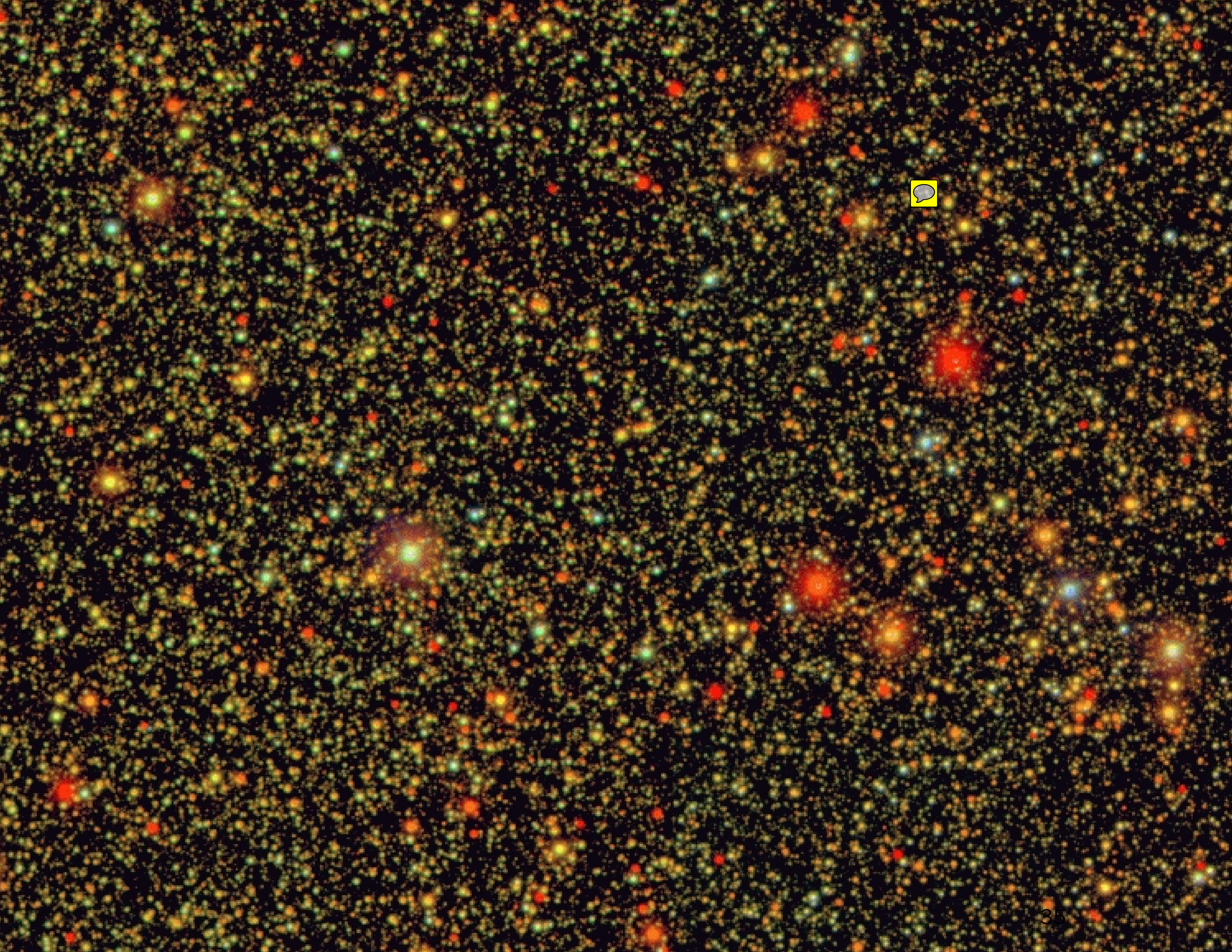
- and many others...

- 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



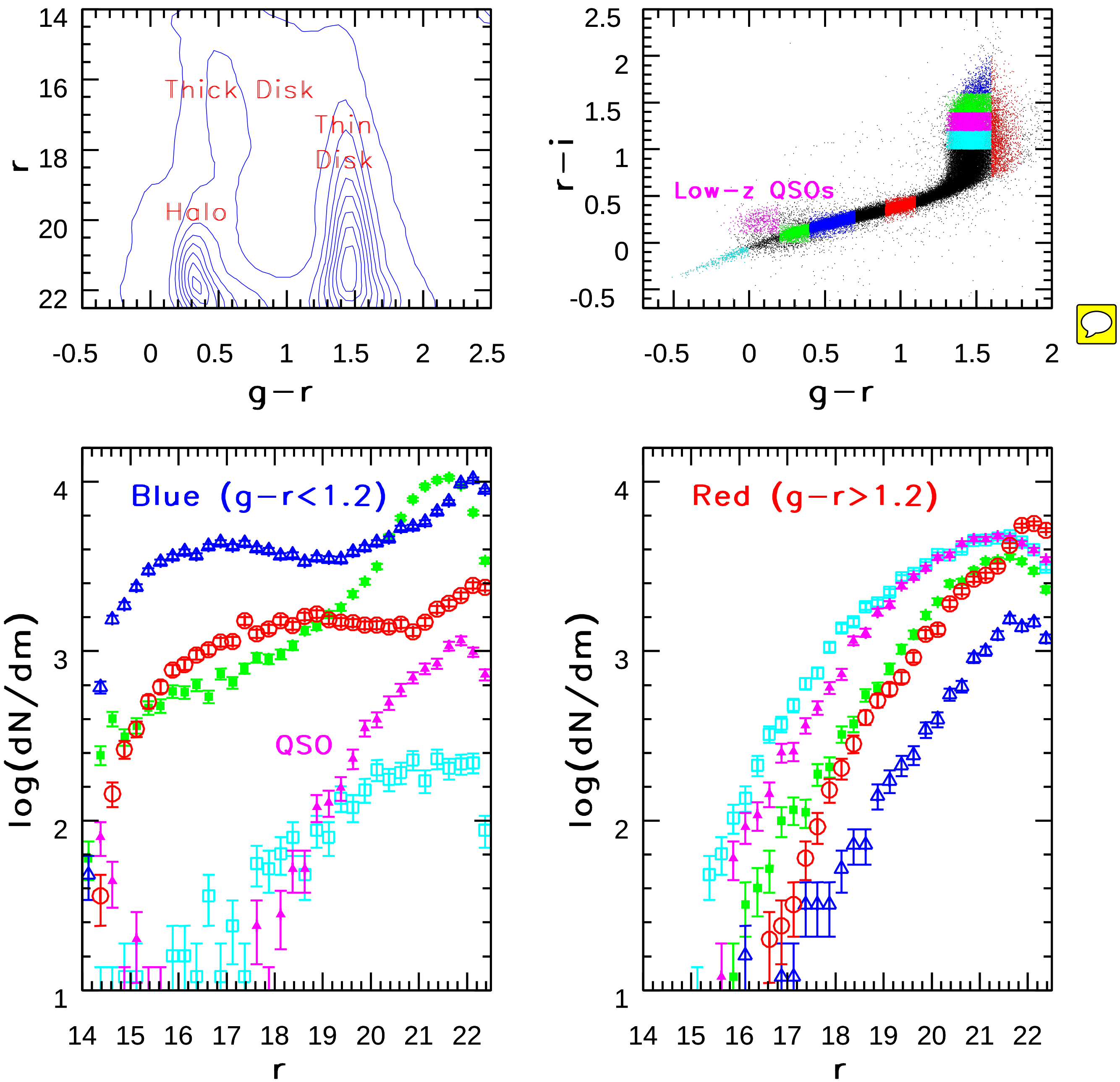




Stellar Counts

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

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

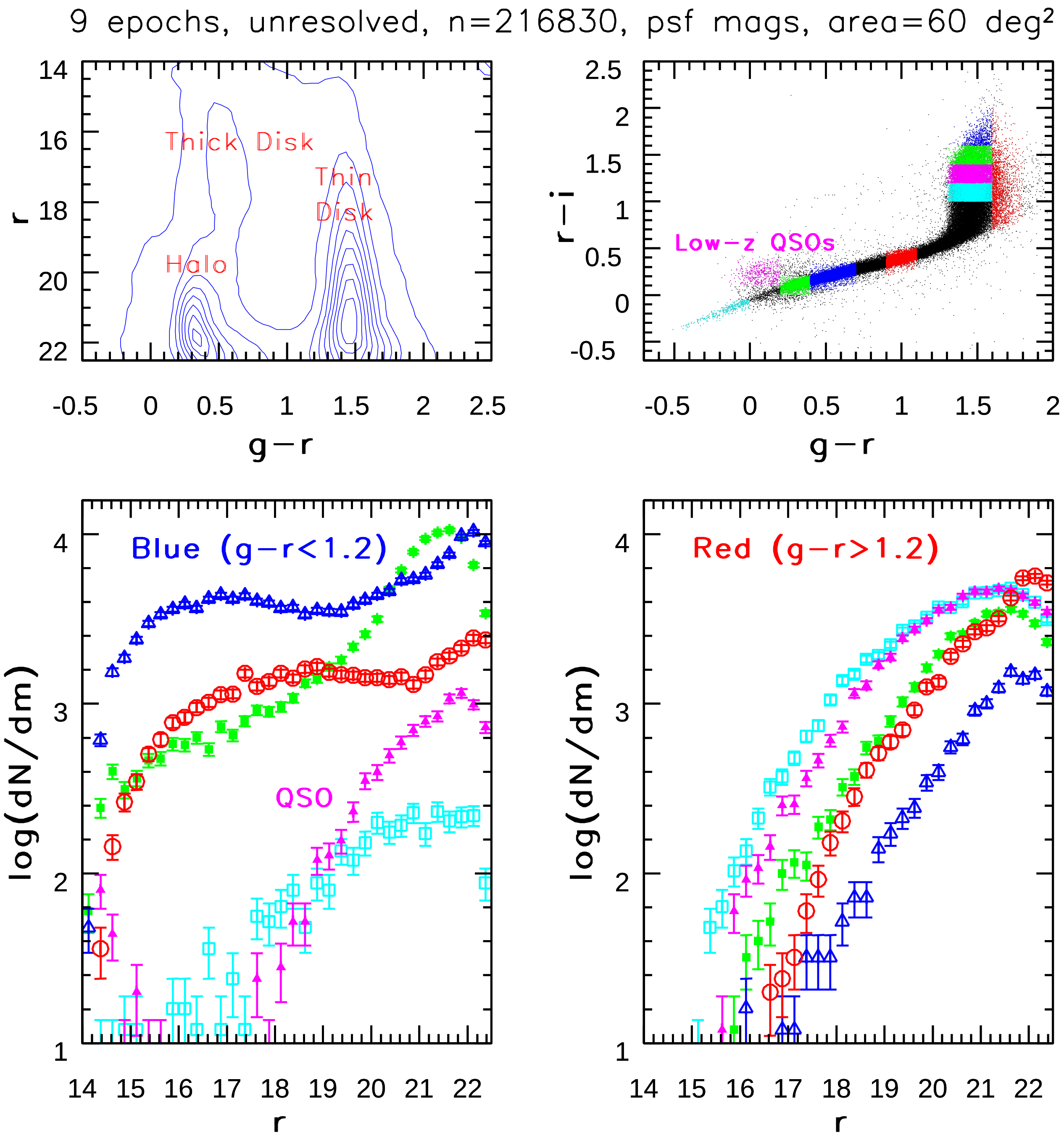
Examples for $n(m) \propto \rho(l,b,m)\, 10^{0.6m}$

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

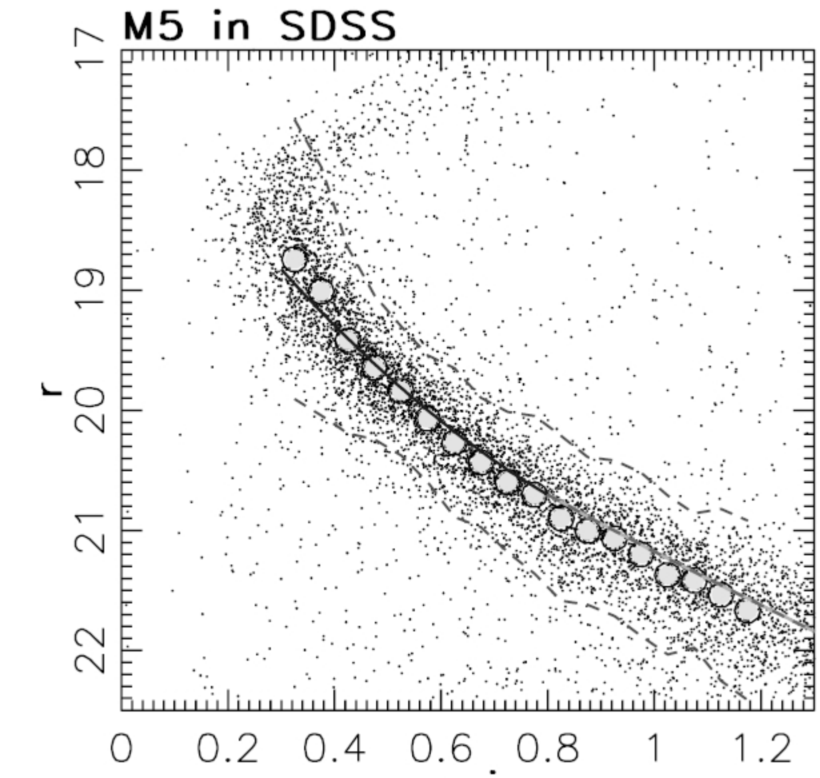
$$n(m) \propto 10^{k\,m},\ k = 0.6 - 0.2\,n$$

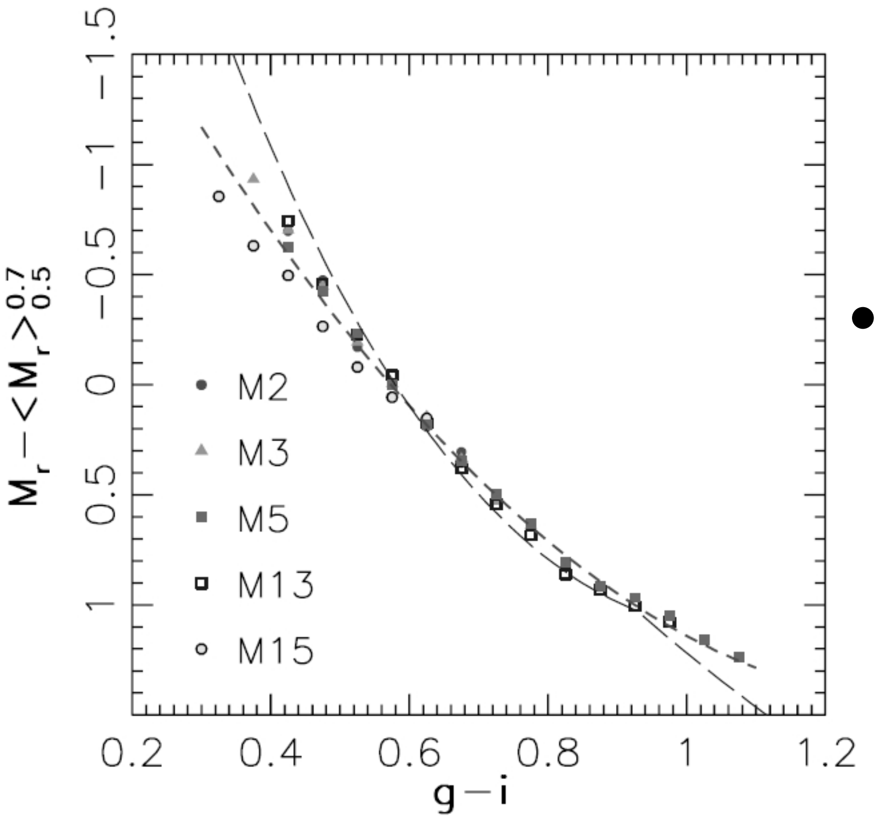
  - Euclidian counts (n=0): $n(m) \propto 10^{0.6\,m}$,
  - Halo counts (n=3): $n(m) = const.$

- 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!



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)



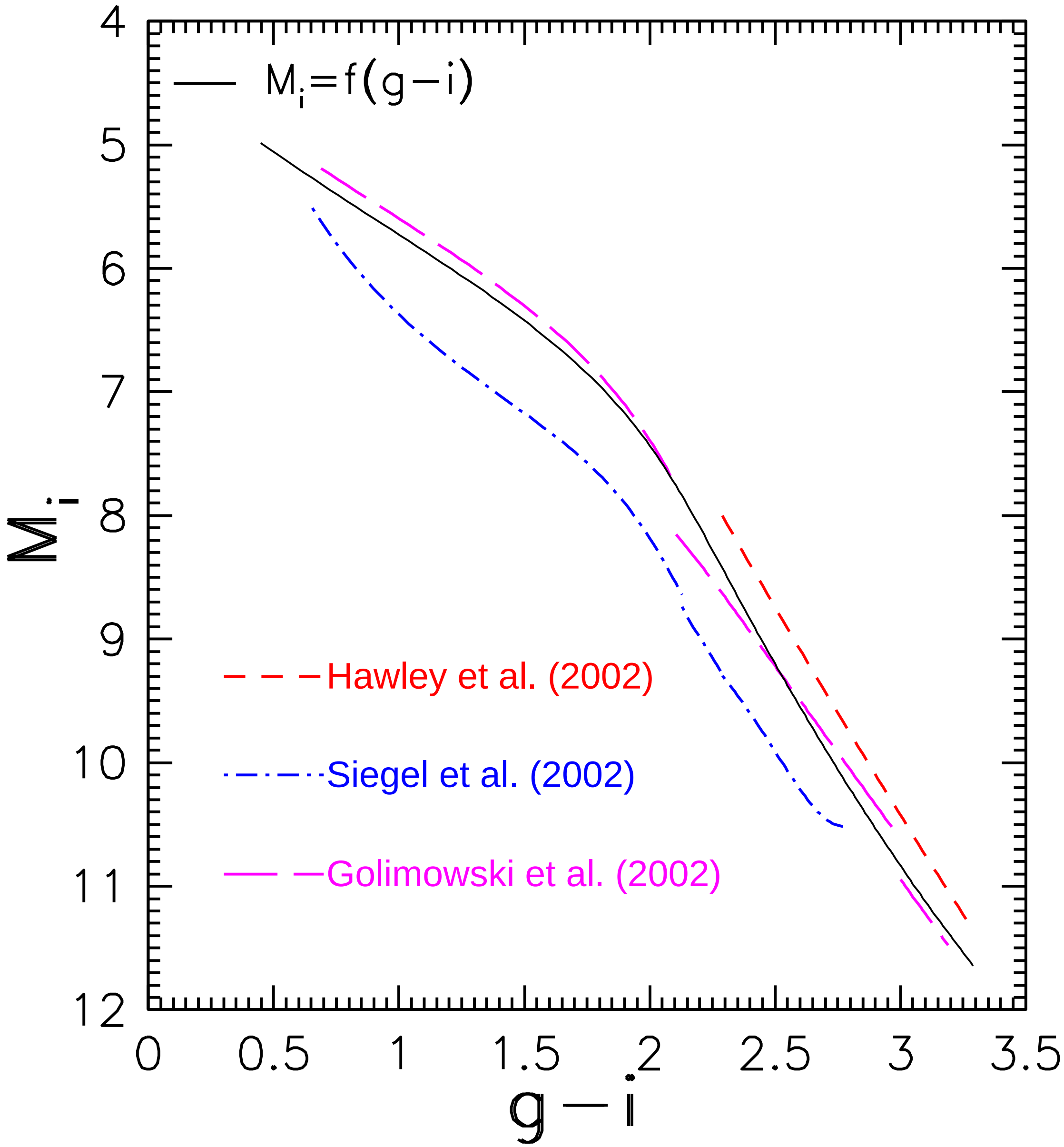


Photometric Parallax Calibration

- 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):

$$M_r = M_r^{0.6} - 2.85 + 6.29\,(g-i) - 2.30\,(g-i)^2 \quad (1)$$

  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*.



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

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

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

- $H' = H/\sin b \sim 2\,H$, 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.

The Local Group

- Edwin Hubble introduced "The Local Group" classification and assigned a dozen galaxies to it: Milky Way, Andromeda (M31), M33, LMC, SMC, ... (today there are over 50 known galaxies in the Local Group - SDSS played a major role in new discoveries). Andromeda is 1 Mpc away (770 kpc), while LMC is 50 kpc away.

- The Local Group is about 3 Mpc across, and itself is a part of the larger Virgo Supercluster.

- The two largest galaxies are Milky Way and Andromeda, and they dominate the total mass. A great astro-trivia question is "What is the third largest galaxy in the Local Group?" (the Triangulum Galaxy).

- Both Milky Way and Andromeda have their own systems of satellite galaxies (that is, they are gravitationally bound). For Milky Way, the most famous ones are LMC/SMC and Sagittarius Dwarf galaxy.