# Star Formation Across the Galaxy

**Will Armentrout**

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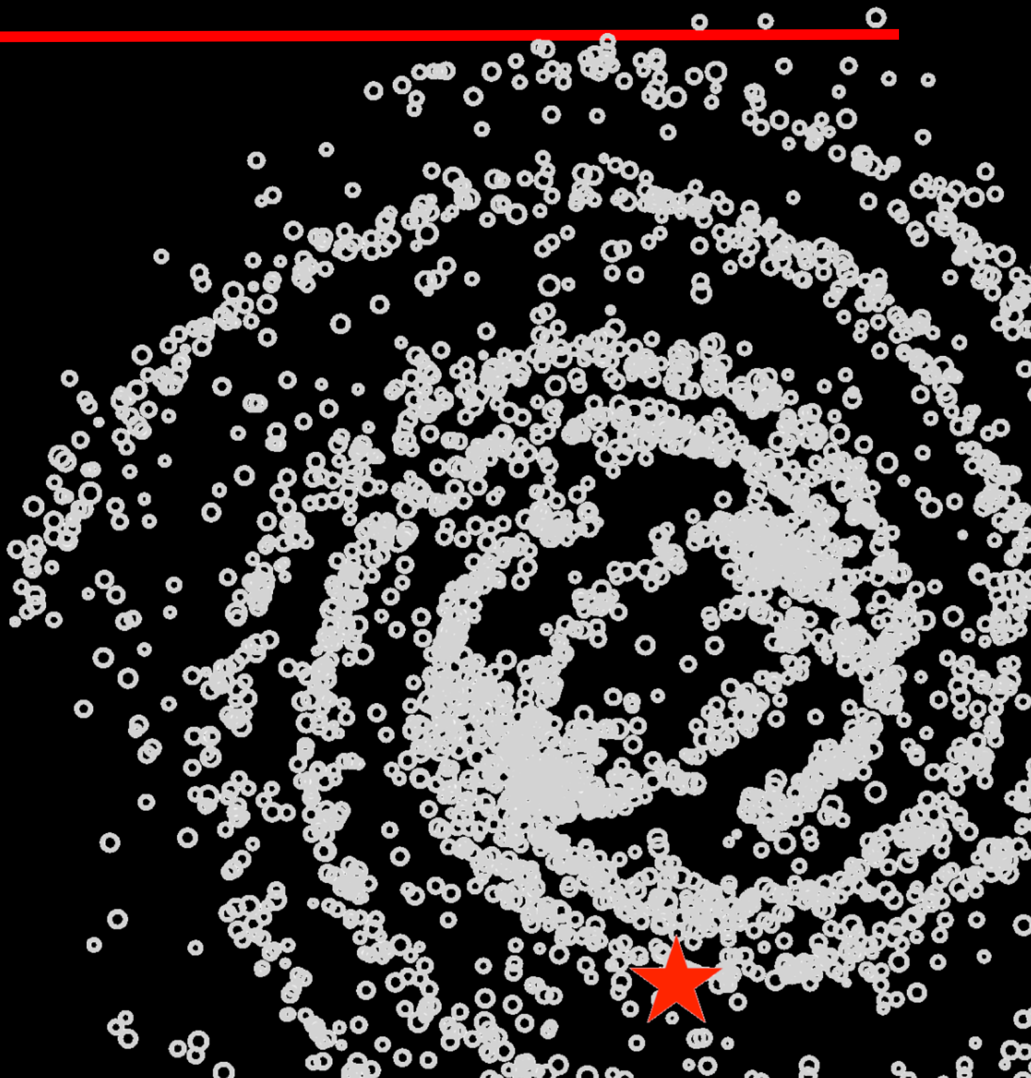
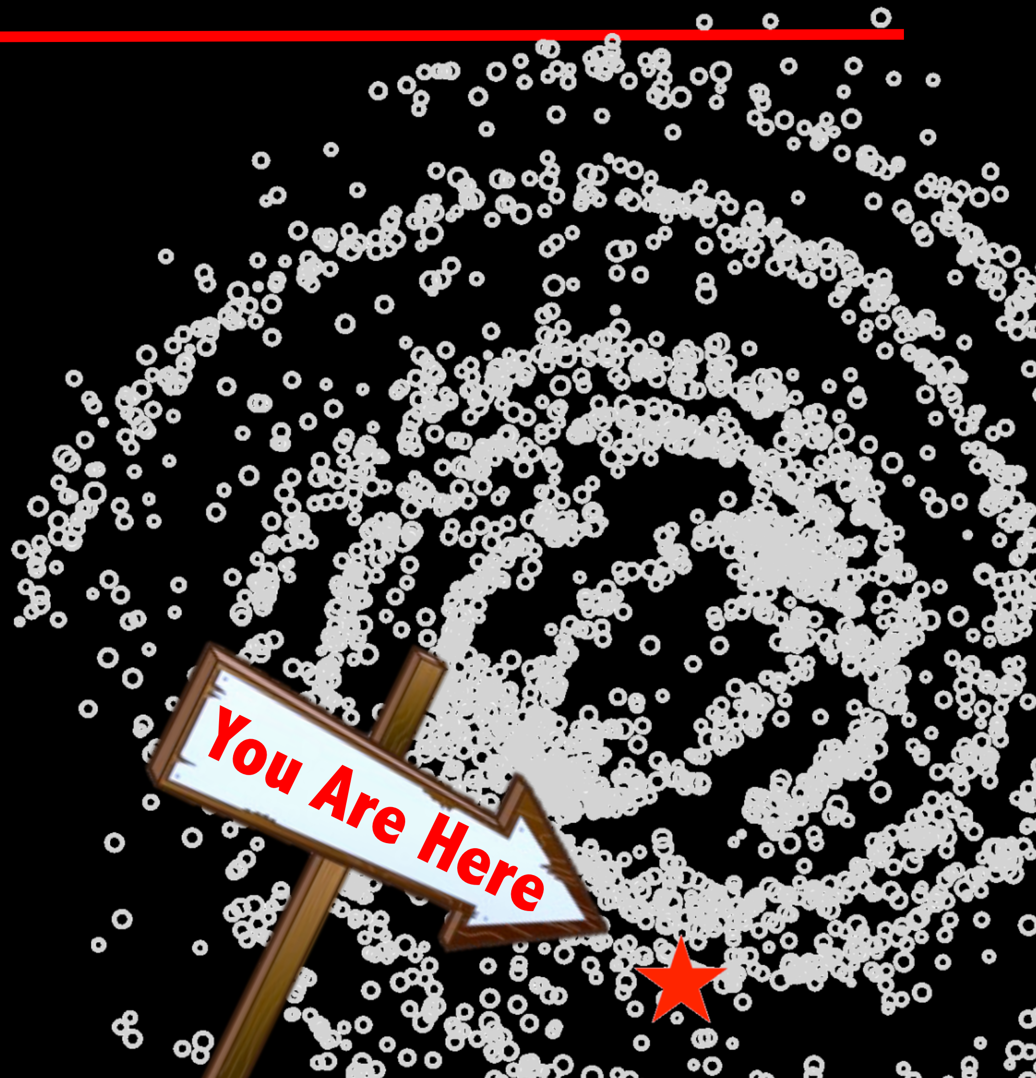
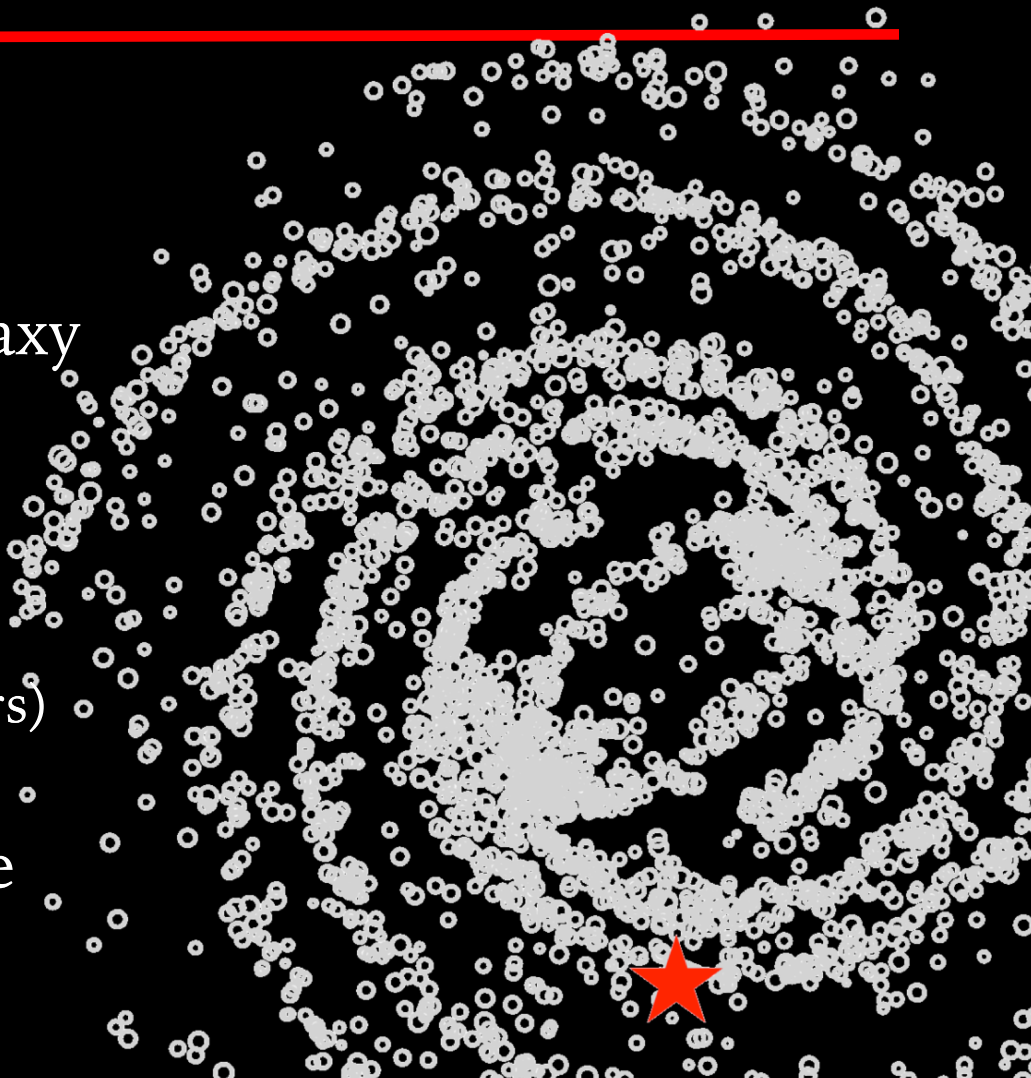


# Star Formation Across the Galaxy



# Talk Outline

- Historical Star Formation Studies
- The Ingredients of our Galaxy
- Stages of Star Formation
  - Molecular Gas
  - Protostars & Protoplanetary Disks
  - H II Regions (High-Mass Stars)
  - Stellar Death
- Star Formation across Time and Space



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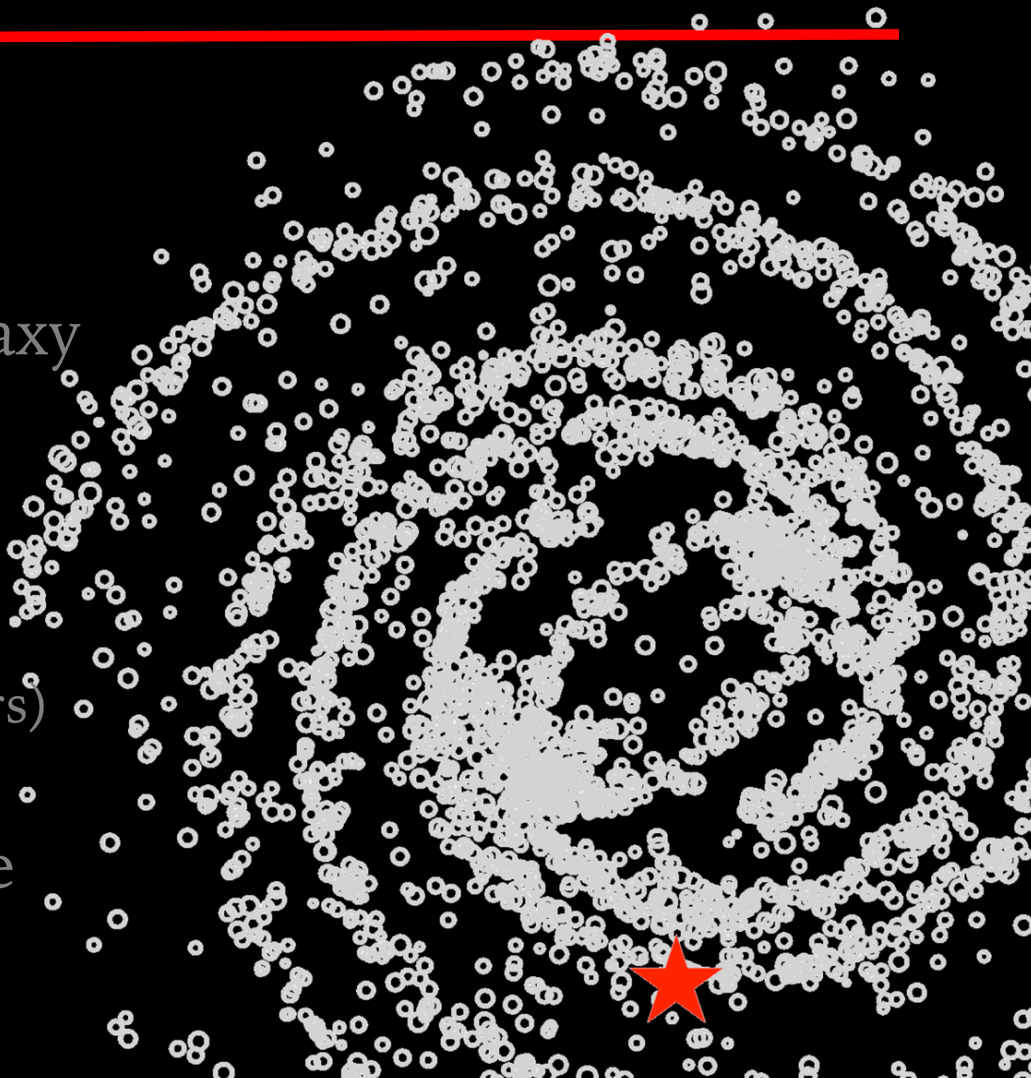
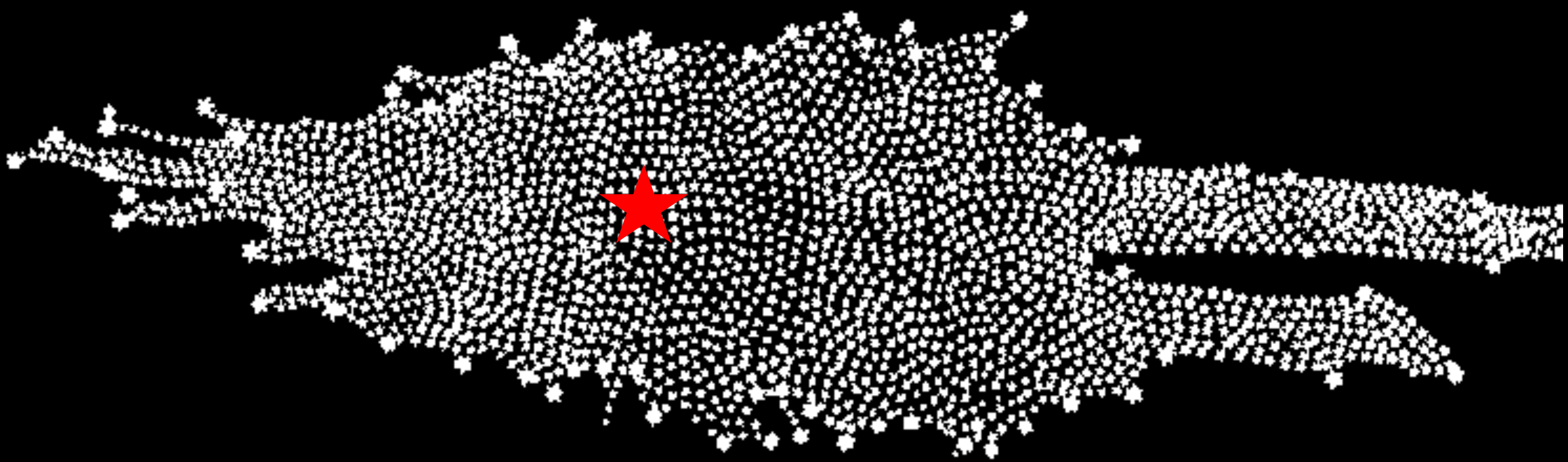
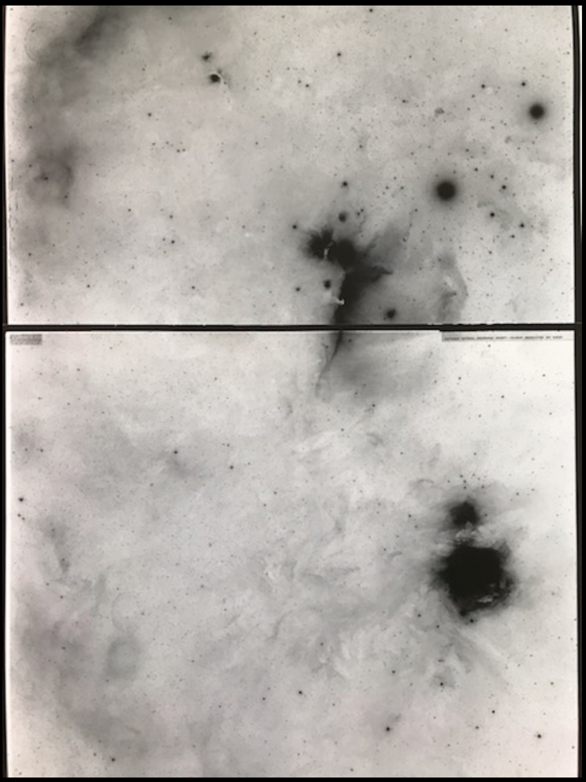


# The First "Map" of the Milky Way



William Herschel, 1785

# First Catalog of Star Formation Regions

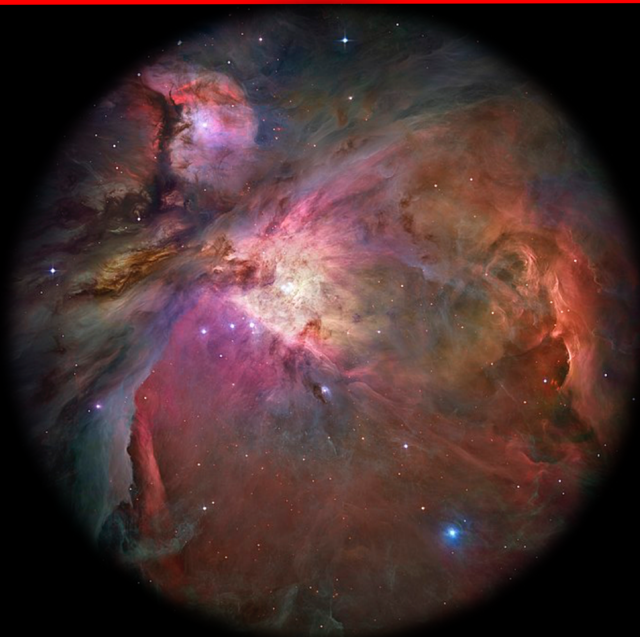



142 "Emission Nebulae"

Stewart Sharpless (1953)

Palomar Plates (Orion)

# First Detection of Radio Recombination Lines

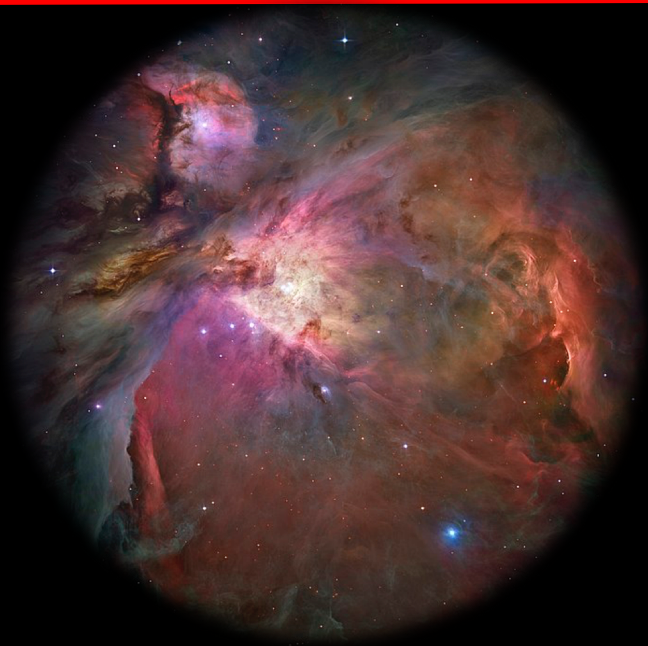


Orion Nebula & 10 Other
Star Forming Regions

Hogland & Mezger (1965)

140-ft Telescope (Green Bank)

# First Detection of Interstellar CO



Orion Nebula & 8 Other Star Forming Regions

Penzias, Wilson, & Jefferts (1970)

36-ft Telescope (Arizona)

# Tracers Across the Electromagnetic Spectrum

| | |
|---|---|
| Radio : | Interstellar gas, HII regions, Supernovae remnants (SNR) |
| Sub-mm : | Dust |
| Infrared and Optical : | Stars, Interstellar gas |
| X-rays : | Stars, SNR |
| Gamma-Rays : | SNR, compact objects, merging neutron stars |

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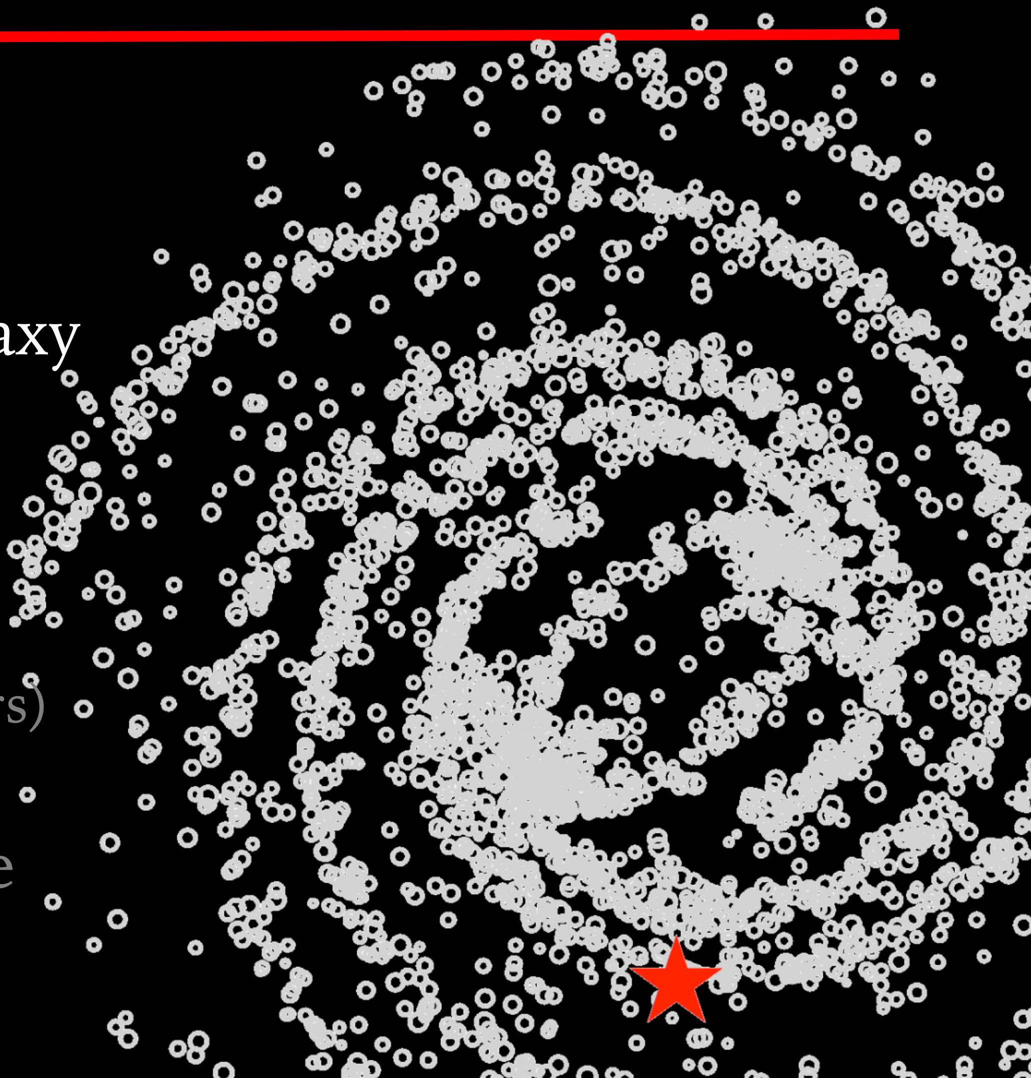

# Composition of the Milky Way

**Stellar Disk**

Thin Disk – 80% of Mass – Stars of all ages 0-12 Gyr

Thick Disk – 5% of Mass – Old stars with low metallicity

**Interstellar Medium (ISM)**

Gas – 15% of Mass – Hot, warm, and cool component

Atomic and molecular

Dust – <1% of Gas Mass – Well mixed with the cool gas

Very important for the formation of molecules

Drives much of the chemistry of the ISM

| Element | Symbol | Atomic # | Abundance |
|---|---|---|---|
| Hydrogen | H | 1 | 1,000,000 |
| Deuterium | | | 16 |
| Helium | He | 2 | 68,000 |
| Carbon | C | 6 | 420 |
| Nitrogen | N | 7 | 90 |
| Oxygen | O | 8 | 700 |
| Neon | Ne | 10 | 100 |
| Sodium | Na | 11 | 2 |
| Magnesium | Mg | 12 | 40 |
| Aluminum | Al | 13 | 3 |
| Silicon | Si | 14 | 38 |
| Sulfur | S | 16 | 20 |
| Calcium | Ca | 20 | 2 |
| Iron | Fe | 26 | 34 |
| Nickel | Ni | 28 | 2 |

Abundances of common elements, scaled to 1,000,000 Hydrogen Atoms.

~99.9% of the Universe is Hydrogen and Helium by number.

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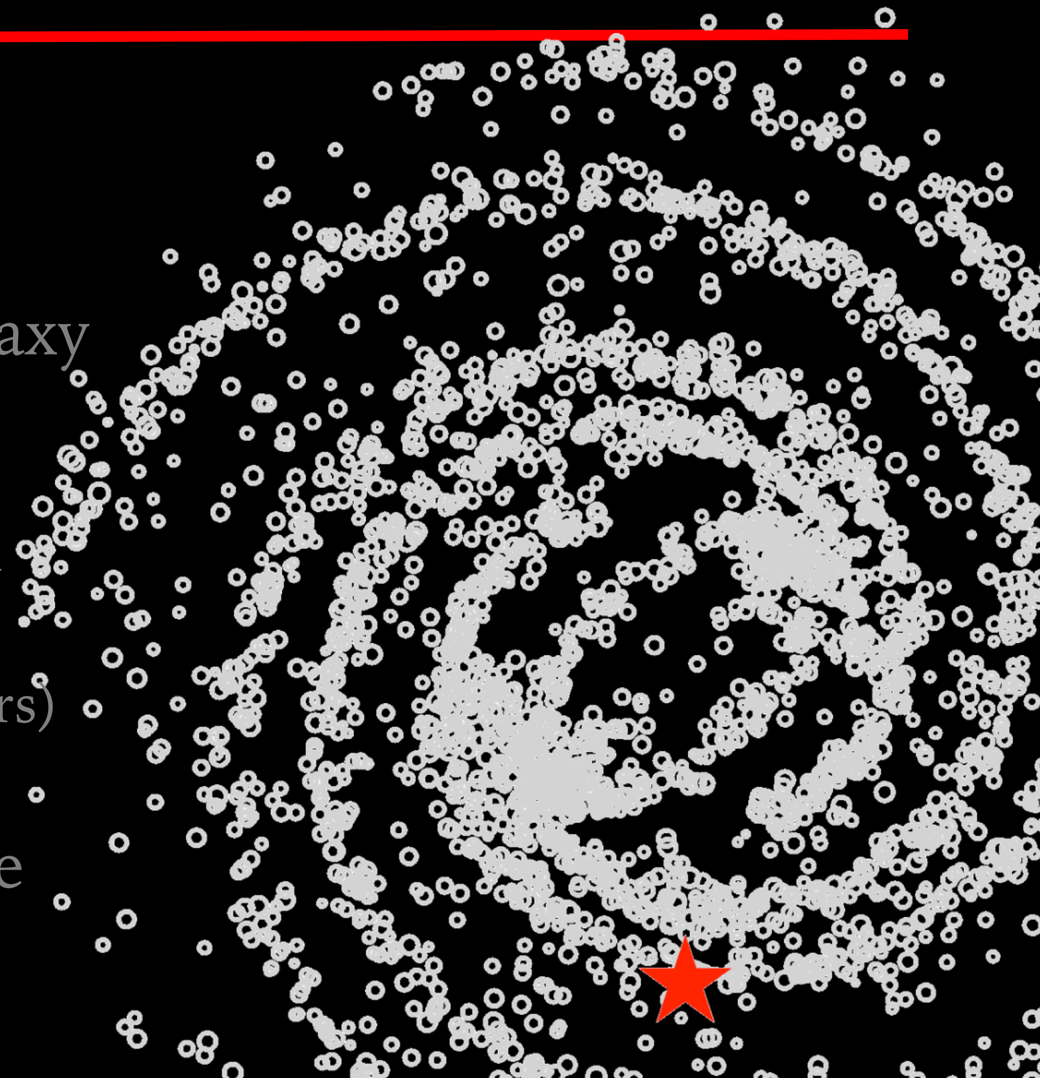


# How Do We Make A Star?

**To first order, you need cool, dense gas.**

**[Why cool?]** Warm / hot gas has a lot of kinetic energy and wants to naturally expand. ~10 K

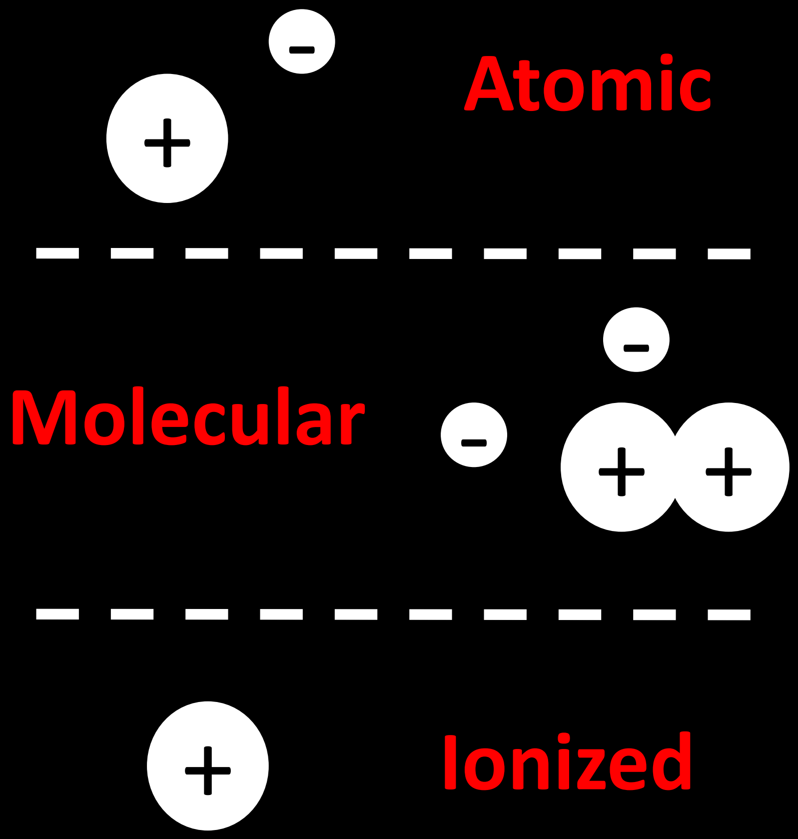
**[Why dense?]** The ignition of star formation is the result of gravitational collapse. The gas must be compact enough that it collapses under its own gravity.**

~1000 particles per $cm^3$

# How Do We Make A Star?

Like ~everything else in the Universe, we need to start with Hydrogen.

However, atomic hydrogen is not the direct fuel for star formation.



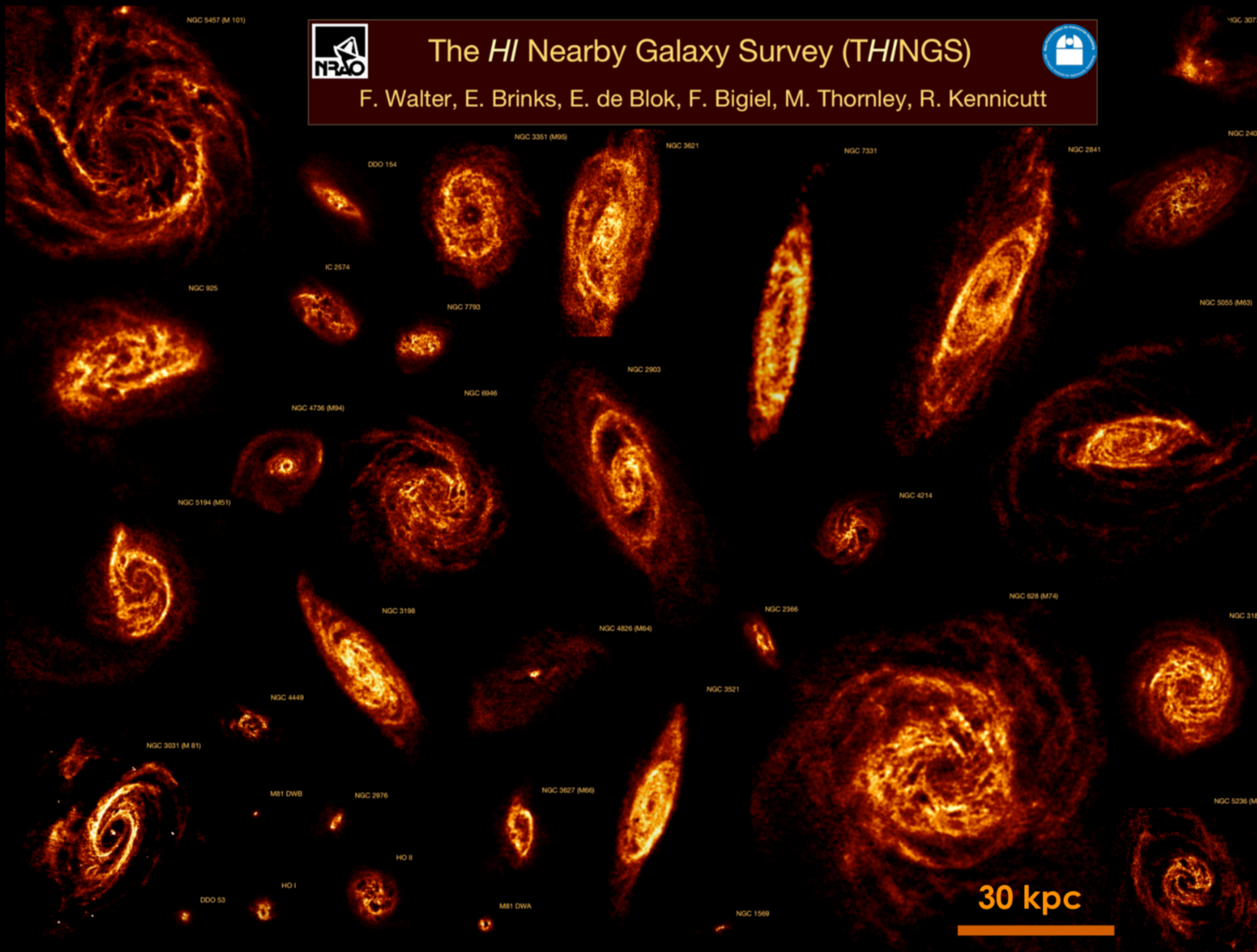
# How Do We Make A Star?

When atomic hydrogen (HI) becomes dense enough, molecular hydrogen forms ($H_2$)

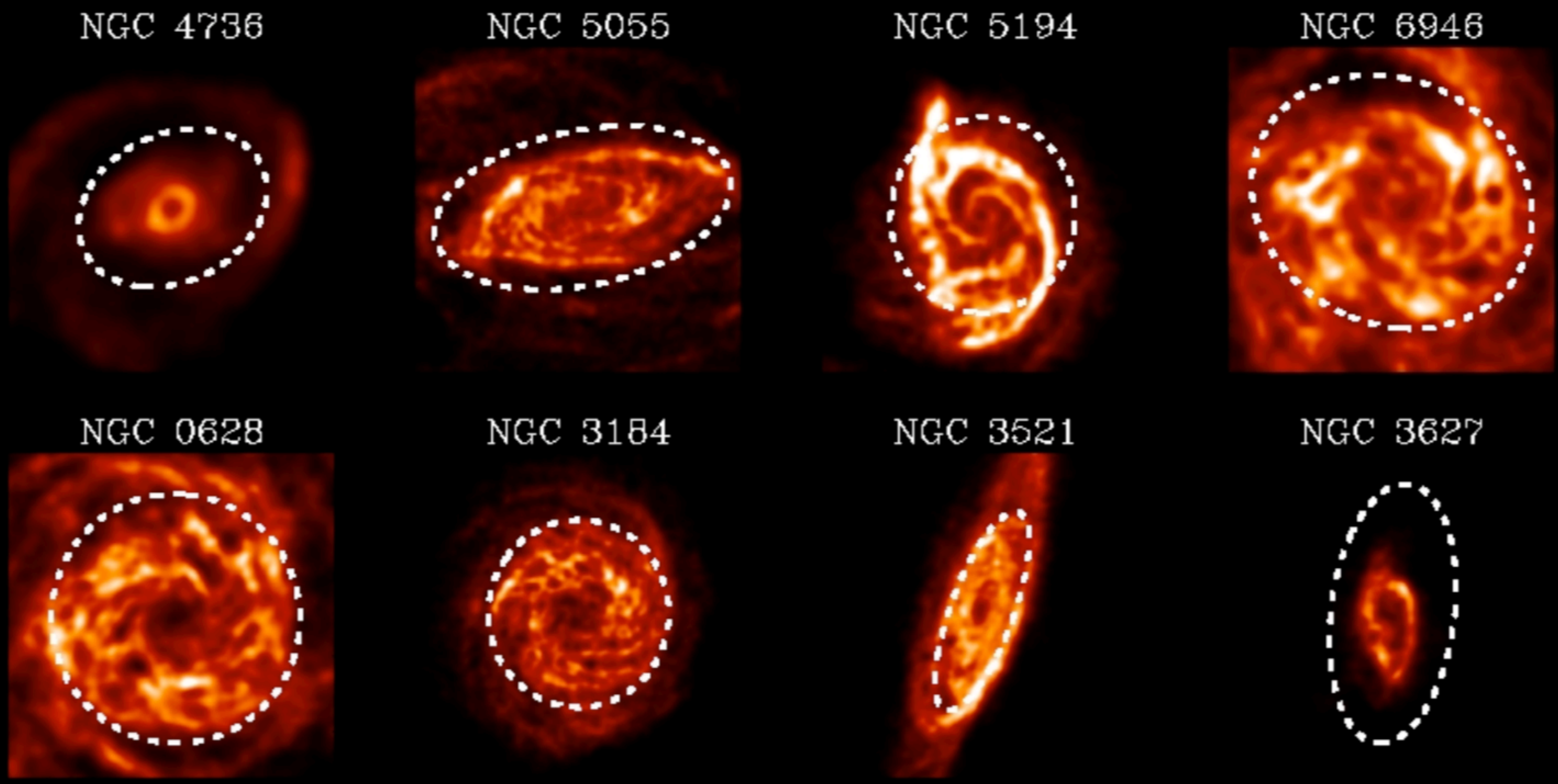
$H_2$ is the fuel for star formation.

**[Why?]** Think about the mean density of a cloud of molecular hydrogen vs atomic hydrogen

EveryTHINGS

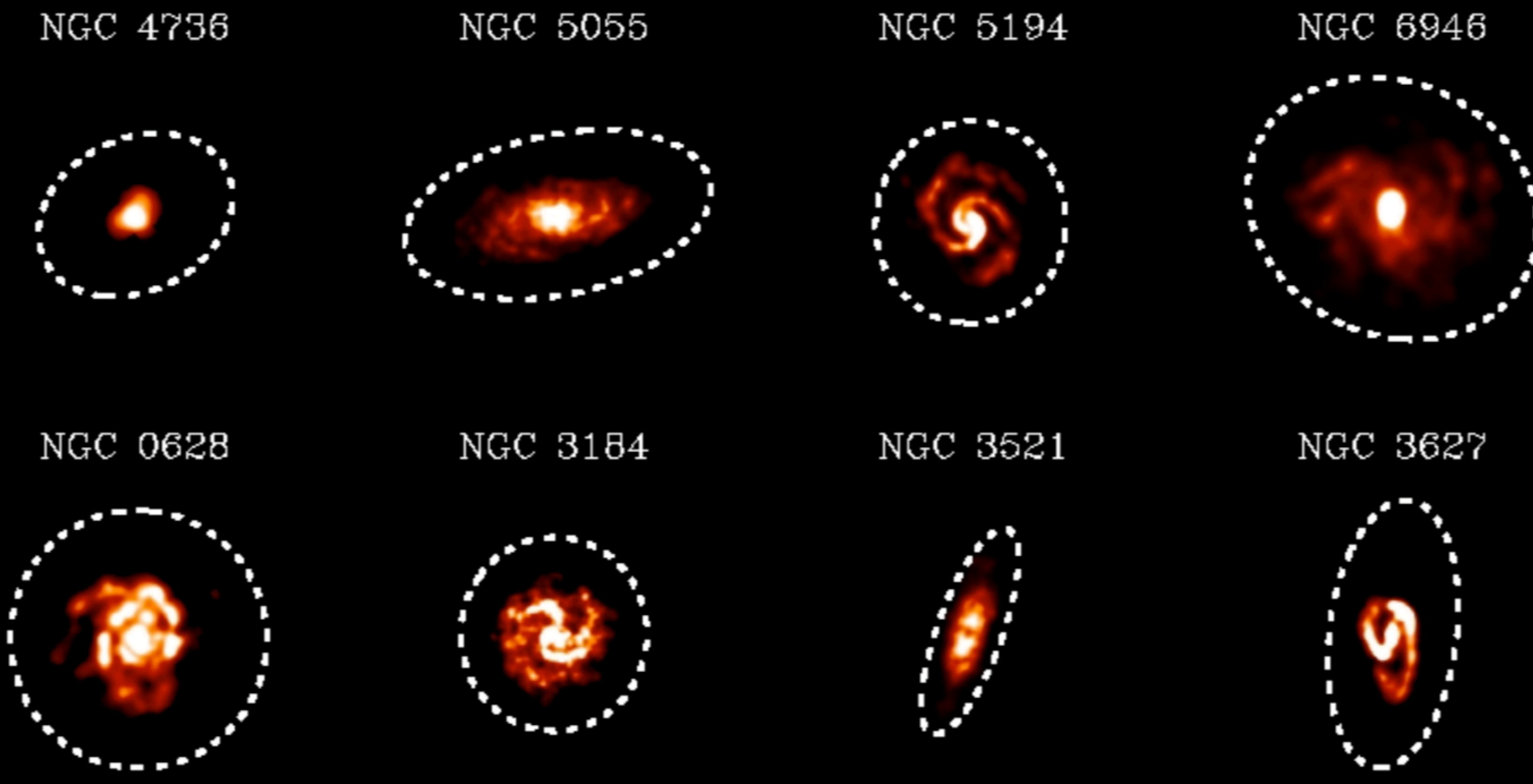


# HI Maps



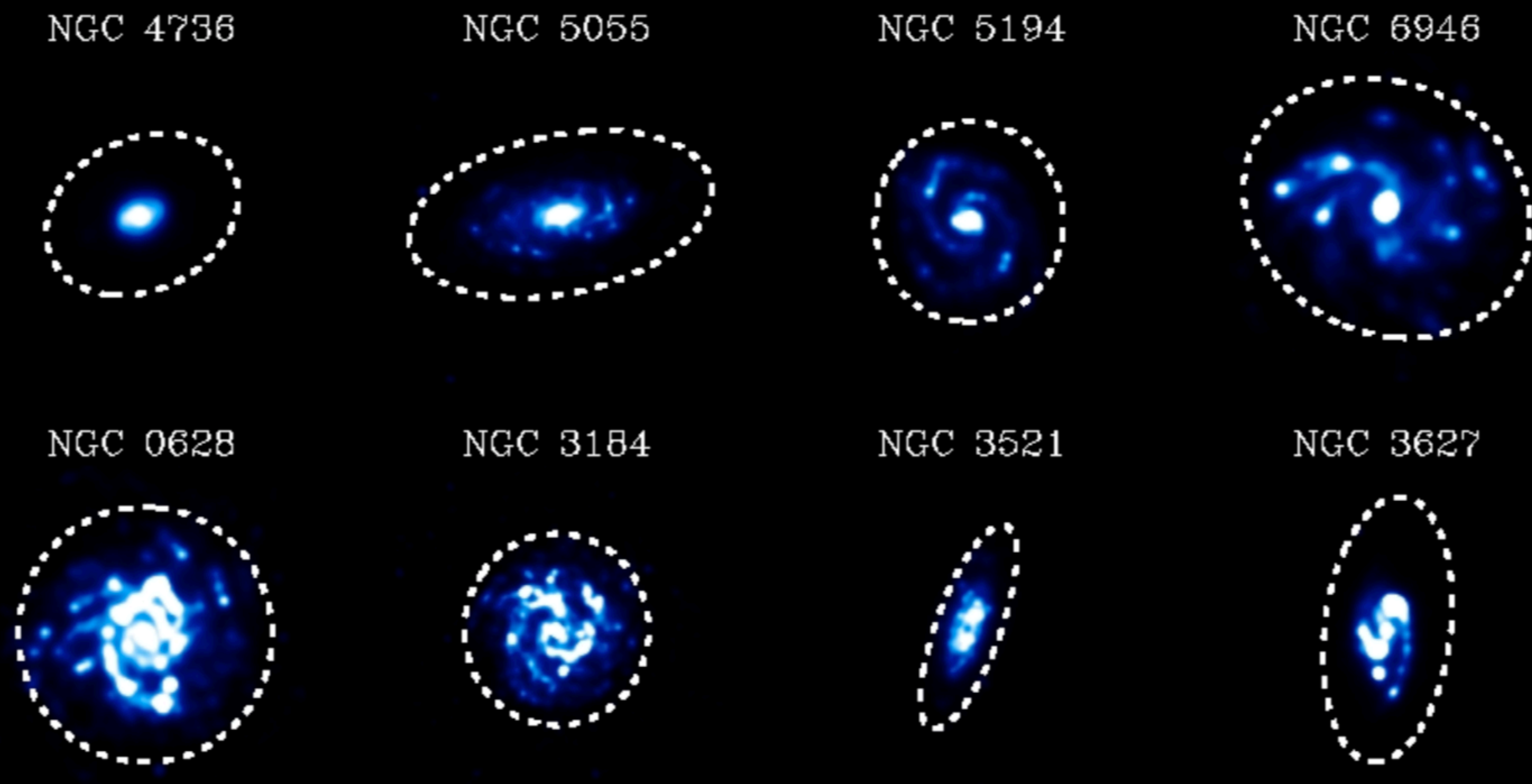

F. Bigiel (Bonn)

# $H_2$ Maps




F. Bigiel (Bonn)

# SFR Maps




F. Bigiel (Bonn)

# How Do We Make A Star?

The problem is that $H_2$ is *very* difficult to observe.

(no permanent magnetic dipole moment, most commonly observed line is in Far IR which is shielded by our atmosphere)

**Common Molecular Gas Tracers**

| | |
|---|---|
| Carbon Monoxide : | Total Molecular Gas Mass |
| Ammonia : | Dense Gas, Temperature Probe |
| HCO+ : | Dense Gas |
| HCN : | Dense Gas, Metallicity Probe |
| OH : | Total Molecular Gas Mass, “Dark” Gas |

Carbon Monoxide (CO) is the ubiquitous tracer for molecular gas clouds (in lieu of $H_2$).

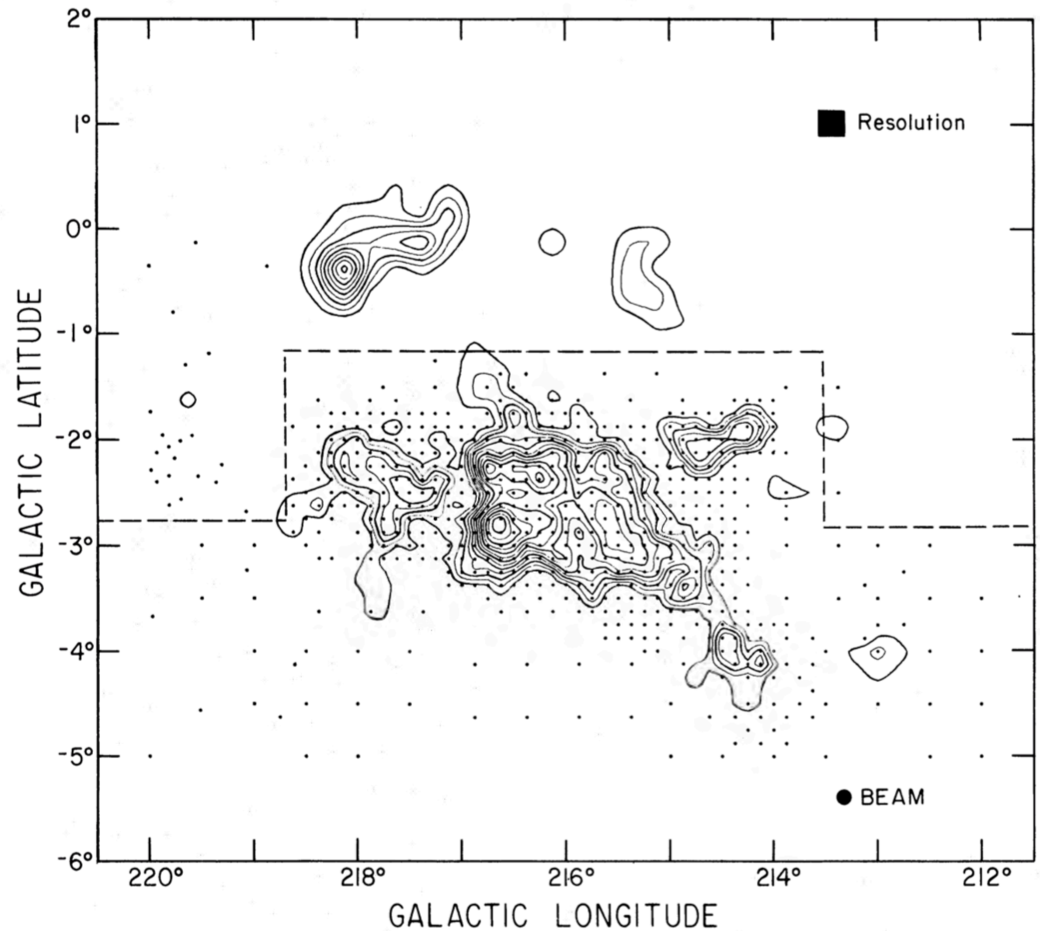



FIG. 2.—A map of the new, quiescent cloud and its vicinity that shows integrated CO emission, $W_{CO}$, in the velocity range of 15 to 40 km s$^{-1}$. The lowest contour level and the increment between levels are 1.3 K km s$^{-1}$. Dots indicate the positions of observations at full angular resolution: 8'.7. To shorten the time needed to sample the region north of the dotted line fully, we reduced the resolution of the telescope to an approximately square beam 0°.25 on a side by stepping the telescope through a two-by-two grid during data acquisition.

CO Observations of the Maddalena Cloud

Maddalena & Thaddeus 1985

A ribbon of ammonia — a tracer of star-forming gas — in the Orion Nebula as seen with the GBT (orange). Background in blue is a WISE telescope infrared image showing the dust in the region.
GBO/AUI/NSF

Friesen+ 2017

# How Do We Make A Star?

**What else impacts how efficiently we form stars out of molecular clouds?**

Turbulence
Fragmentation

Shocks
“Triggering”

Cloud Geometry

Metallicity

Magnetic Fields
Entraining Gas

Cloud Rotation

# How Do We Make A Star?

The dense cores of these molecular clouds are the sites of new star formation.

Things to watch for :

- Filaments
- Clusters of Stars
- Ejection of Stars
- Cloud Rotation

https://www.youtube.com/watch?v=YbdwTwB8jtc

Simulation by Matthew R. Bate, Ian A. Bonnell, and Volker Bromm

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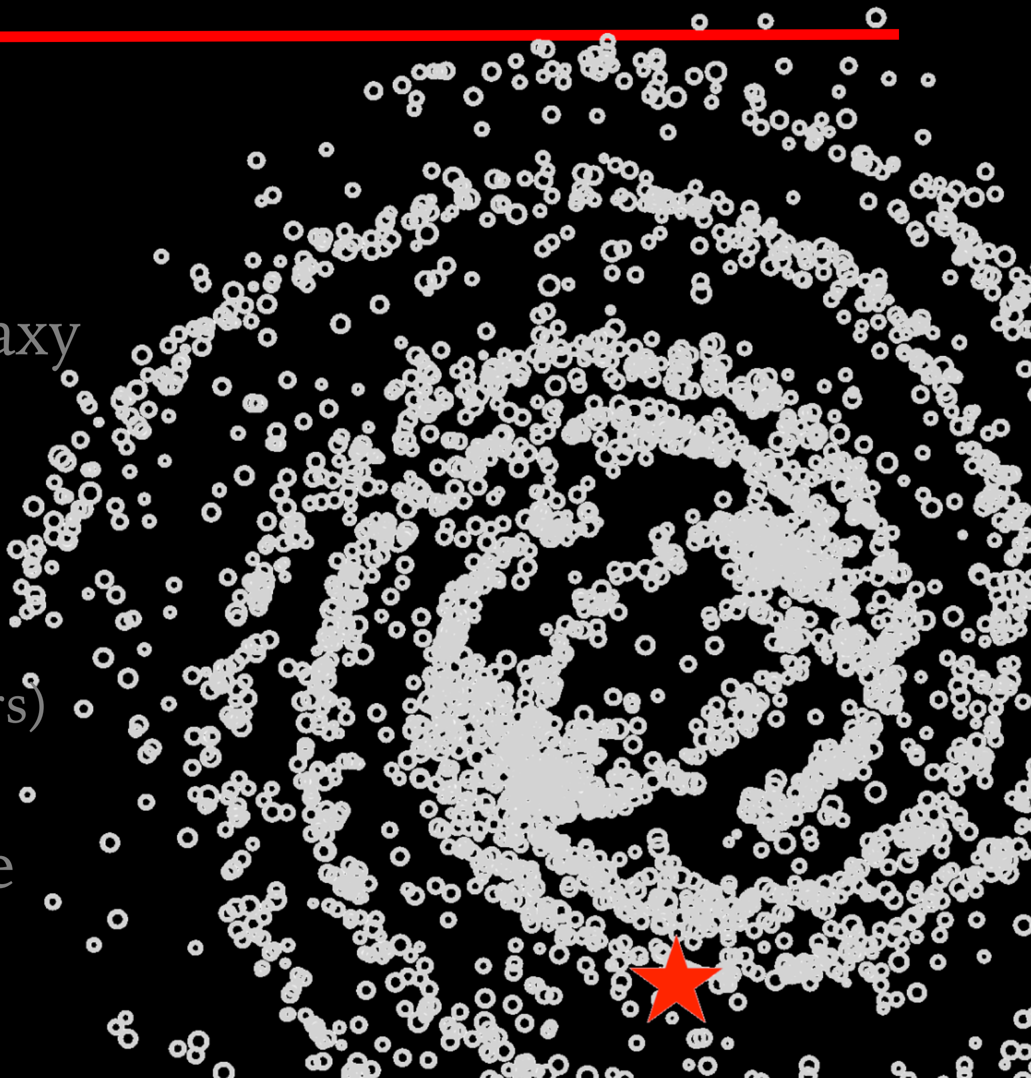


# Protostars & Protoplanetary Disks

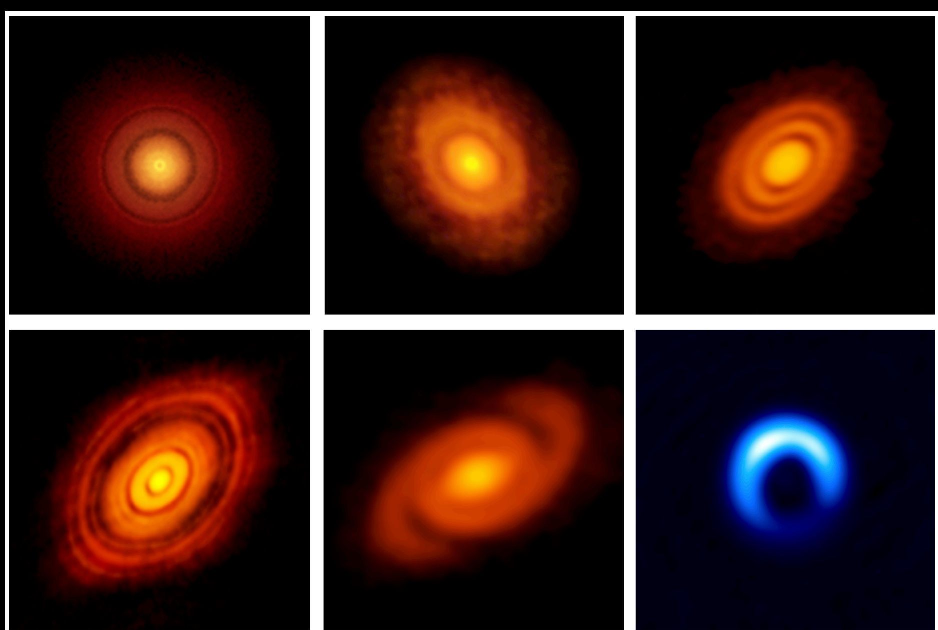
When the molecular cloud is fragmenting and forming the new star, it will have some level of bulk rotation.

This will give the newly formed star some spin.

But! -- The rotating cloud surrounding the star will flatten out into a disk because of random gas interactions.

# What does the region around a baby star look like?

With ALMA in Chile, we are beginning to see these "protoplanetary disks" for the first time.



**From left to right and from top to bottom:** TW Hya (Andrews et al. 2016), V883 Ori (Cieza et al. (2016), HD 163296 (Isella et al. 2016), HL Tau (ALMA Partnership et al. 2015), Elias 2-27 (Pérez et al. 2016), and HD 142527 (Kataoka et al. 2016).

# What does the region around a baby star look like?

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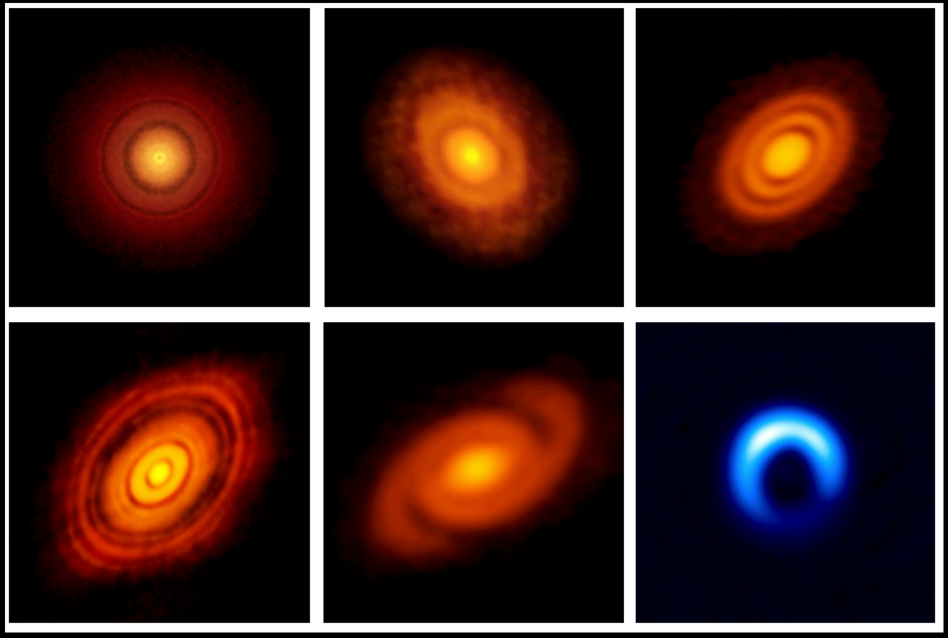

**THOSE DARK LANES ARE LIKELY PLANETARY ORBITS.**

# Protostars & Protoplanetary Disks

At this point, the stars are “Pre-Main Sequence”

Accretion from the disk onto the protostar will continue until Hydrogen fusion begins in the core.

Then, the star clears away excess material in the disk through radiation pressure and the star enters the main sequence (i.e. onto the H-R diagram)

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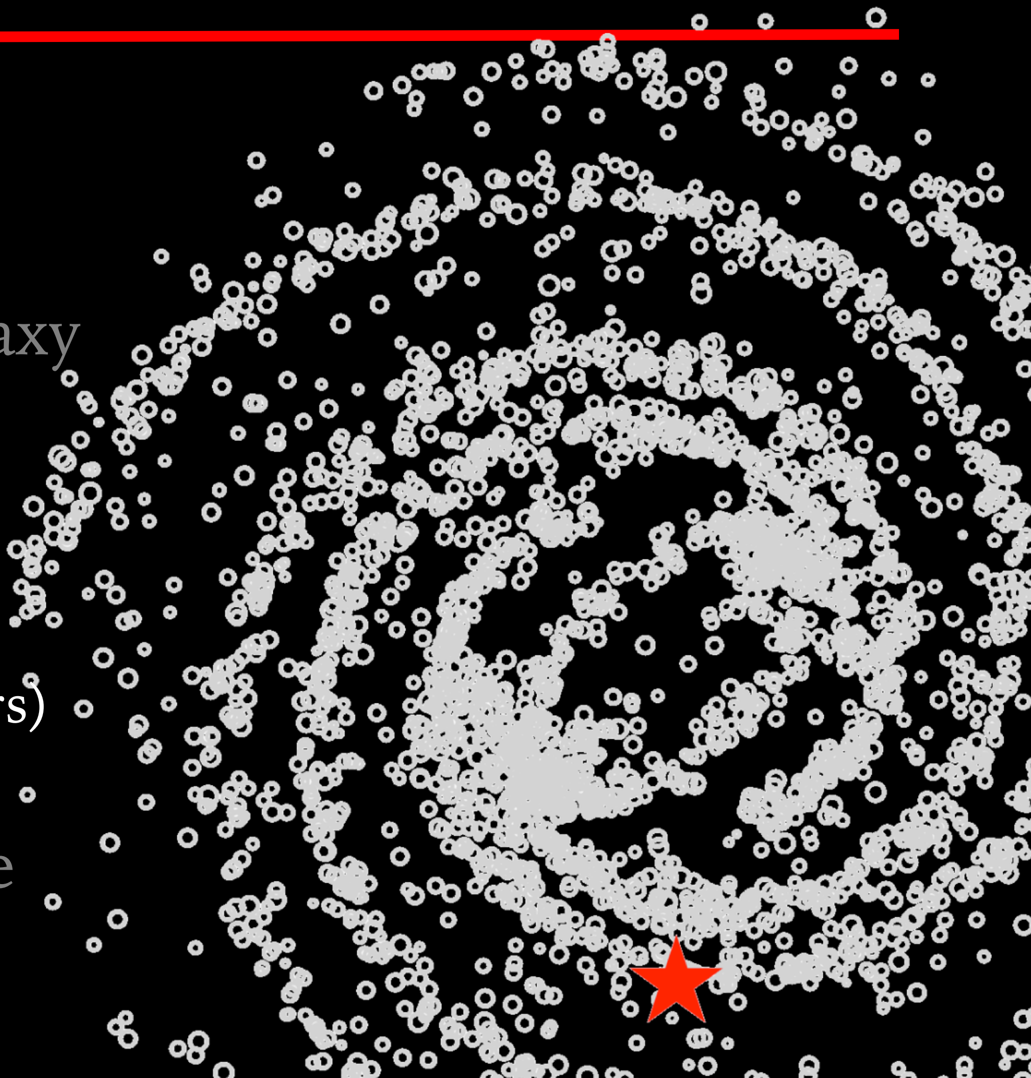
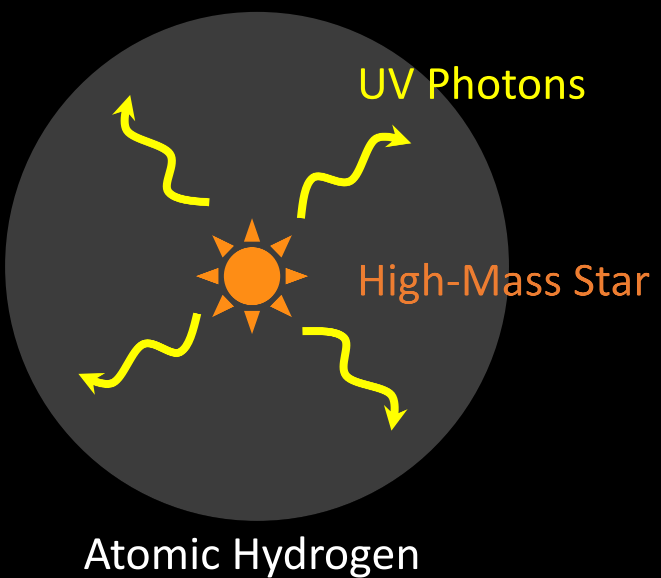


# HII Regions

- Ionized Hydrogen (*HII*) surrounding high-mass stars
- Can be seen across the Galactic disk from the mid-IR to Radio (bright!)
- Zero-age objects compared to the Milky Way



# HII Regions

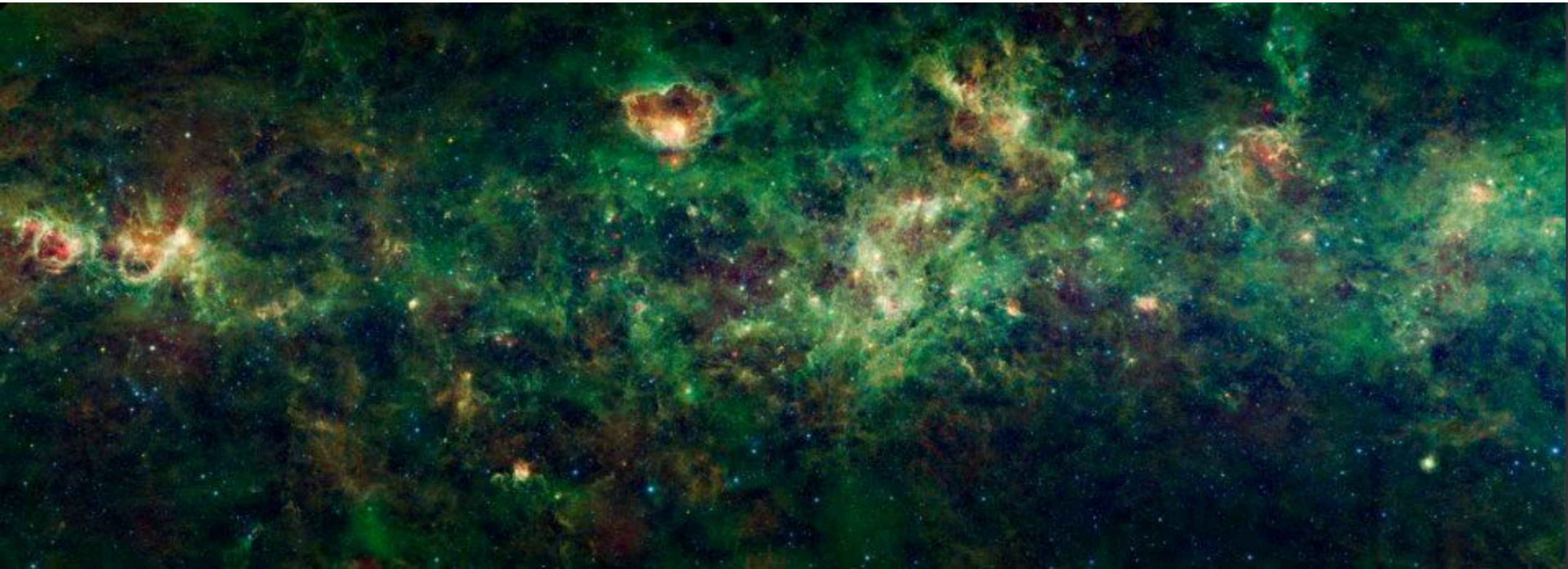
To date, we have catalogued ~2000 Galactic HII regions. Extragalactic observations suggest our surveys are still incomplete.

Where are the missing HII regions?


Image Credit: ESO PESSTO

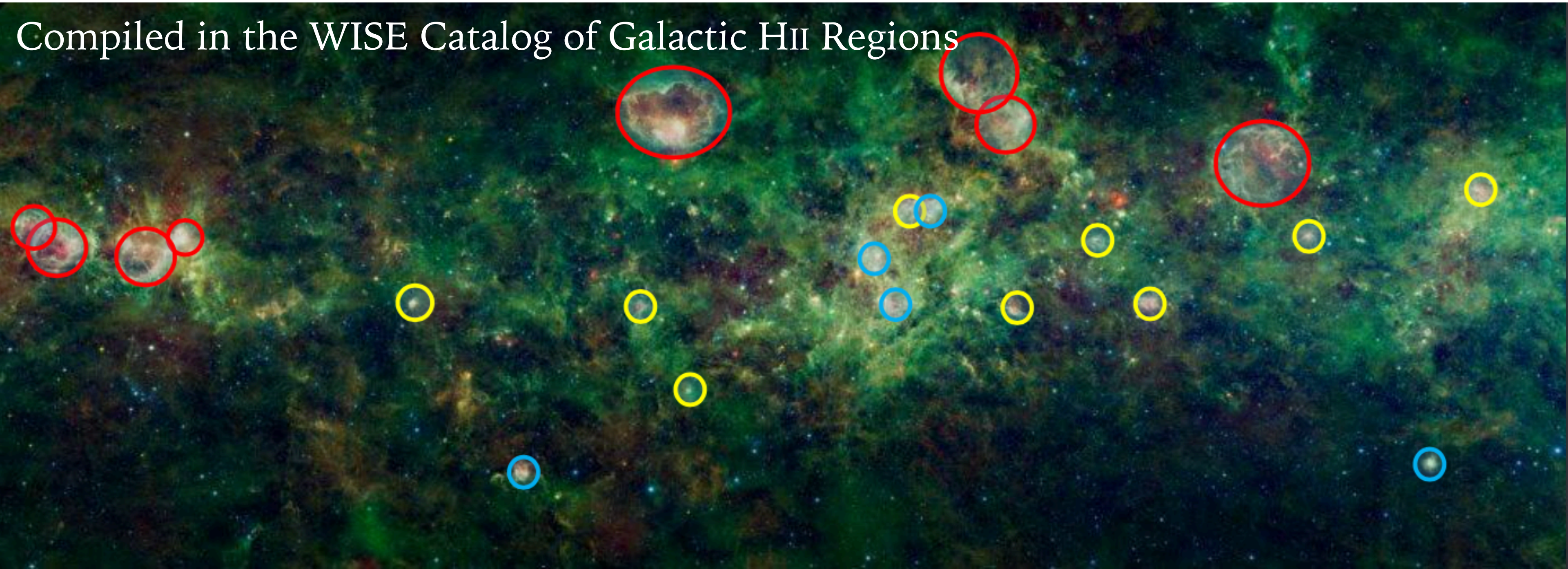
# Early Surveys of Galactic HII Regions

- Sharpless Catalog (1953)
  - 142 "Emission nebulae" with Palomar Observatory
- Lockman (1989)
  - 462 HII regions in the **Northern Sky** with 140-ft telescope
- Caswell & Haynes (1987)
  - 316 HII regions in the **Southern Sky** with Parkes Telescope



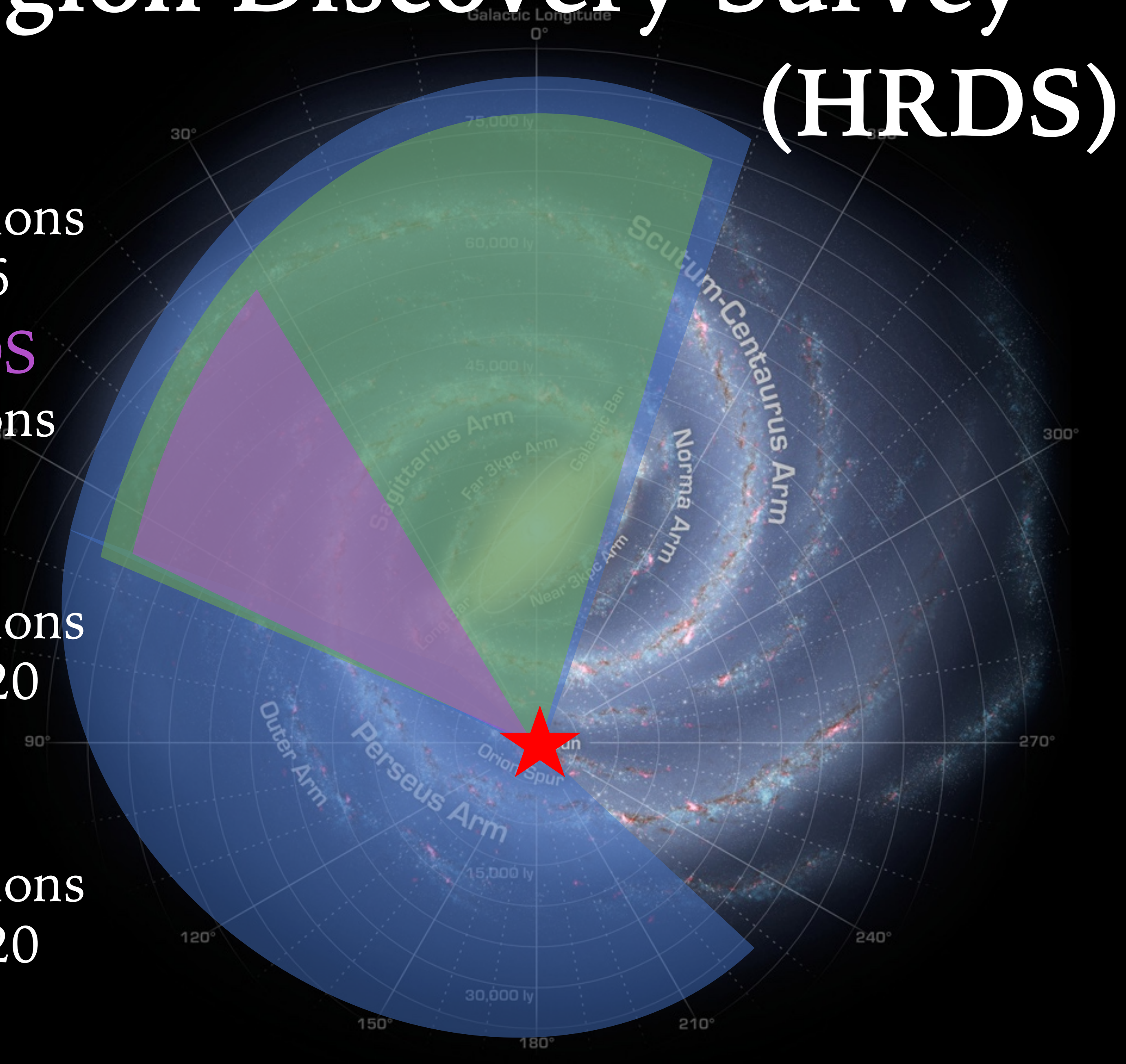
# The WISE Catalog of Galactic HII Regions

- Contains ~2000 known HII regions and ~6000 candidate HII regions
- Characteristic Infrared Morphology
  - 22 μm core – Hot (≈100 K) small grain emission, traces massive stars
  - 12 μm, diffuse – PAH emission, traces photodissociation regions
- After we determine candidates in IR, we confirm with radio



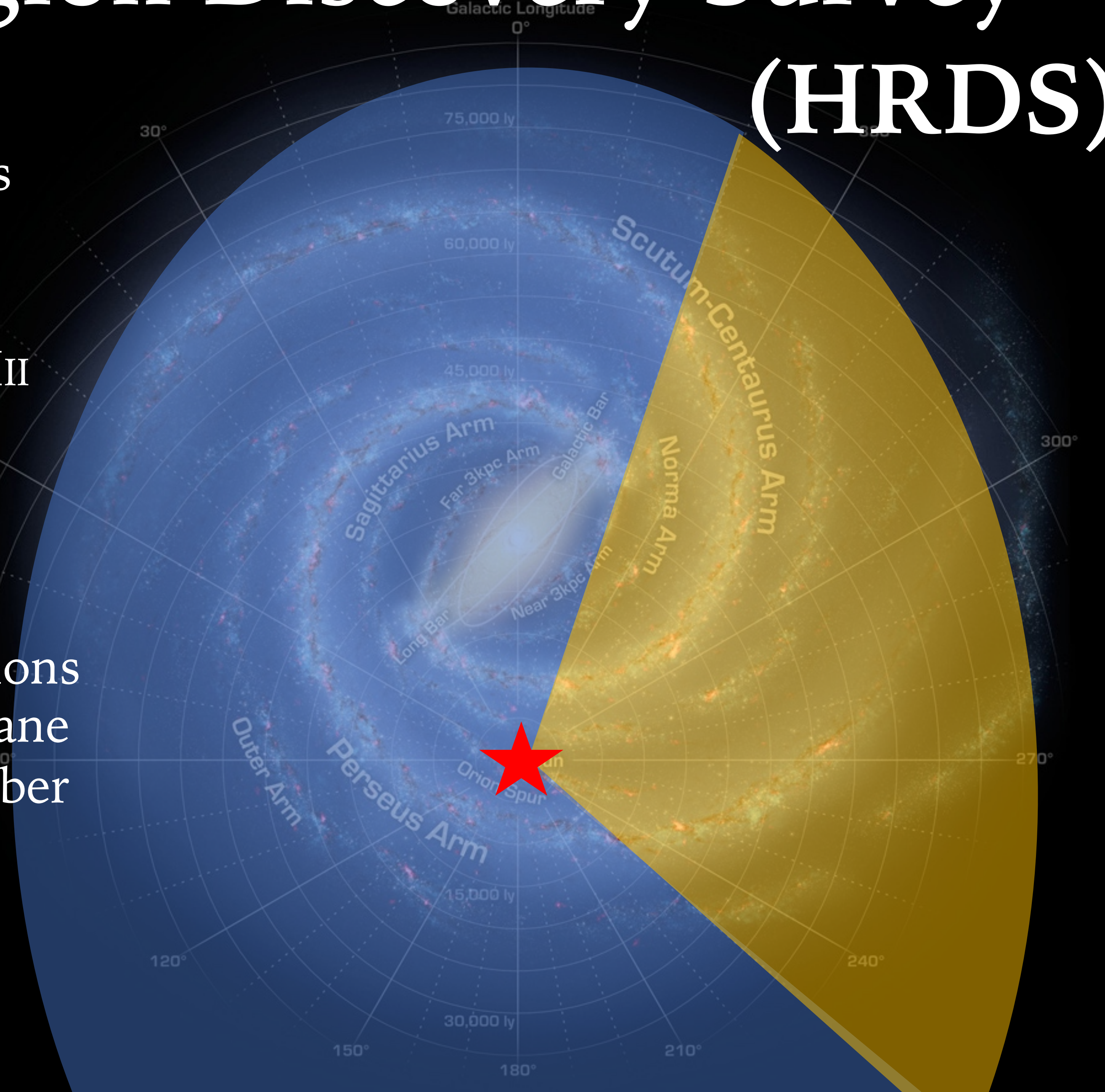
# H II Region Discovery Survey (HRDS)

- GBT HRDS
  - 448 H II Regions
  - 67 < l < -16
- Arecibo HRDS
  - 37 H II Regions
  - 66 < l < 31
- WISE HRDS
  - 302 H II Regions
  - 225 < l < -20
- Total HRDS
  - 787 H II Regions
  - 225 < l < -20



# HII Region Discovery Survey (HRDS)

- Original HRDS
  - 787 HII Regions
  - 225 < l < -20
- Southern HRDS
  - 500 expected HII Regions
- Total HRDS + SHRDS
  - ~1300 HII Regions
  - Full Galactic Plane
  - Will bring number of known HII regions up to ~2500 (from ~1200 before)



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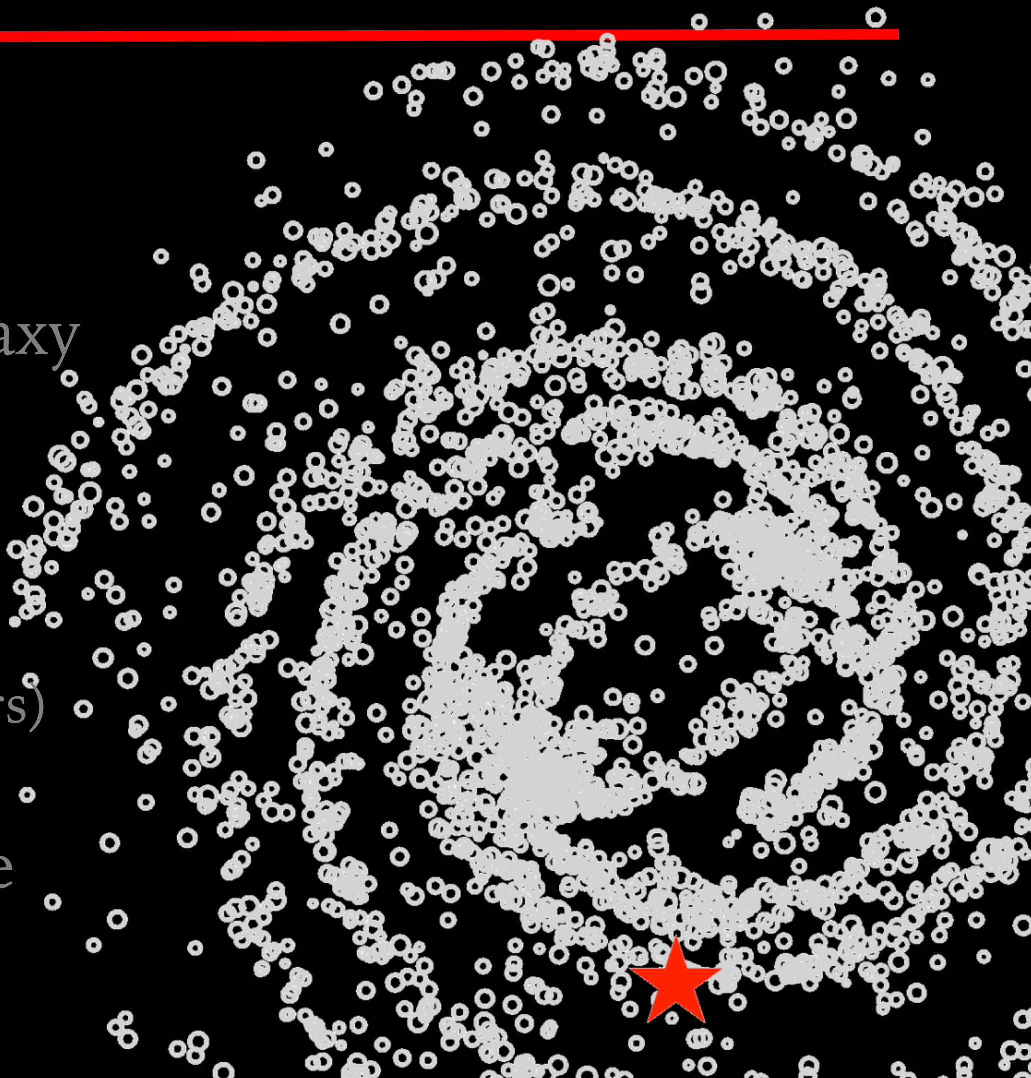


# What happens to a low-mass star?

$M < 0.5\ M_{\odot}$

Well, not a lot.

# What happens to a Solar-mass star?

$M \approx M_{\odot}$

X-Ray / Optical Composite of the Cat's Eye Planetary Nebula

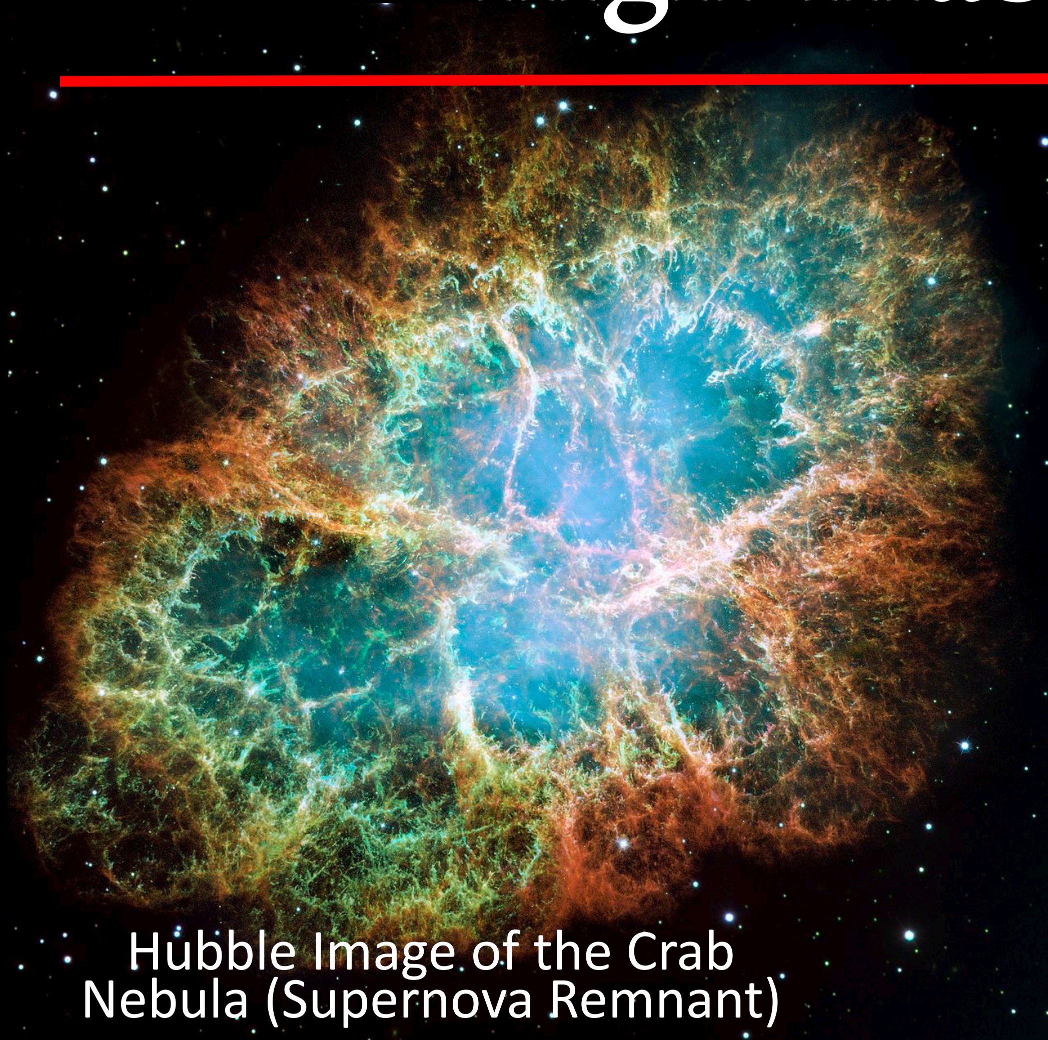
Harrington & Borkowski

**Slightly more!**

Lifetime ~10 billion years

Inject metals back into the Interstellar Medium (slowly)

# What happens to a high-mass star?



Hubble Image of the Crab Nebula (Supernova Remnant)

Hester & Loll

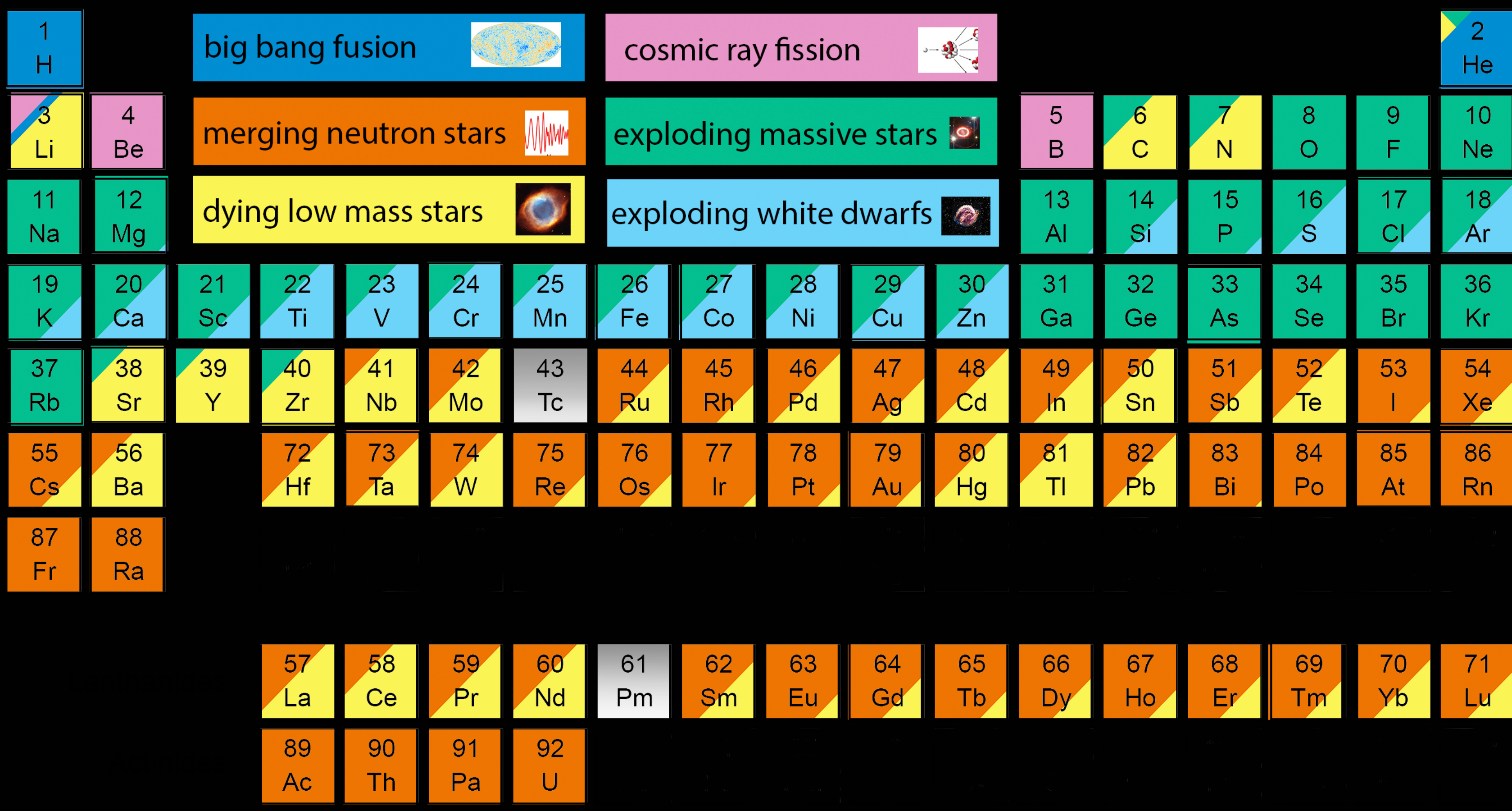
$M > 8 M_{\odot}$

**A Whole Bunch**

Lifetimes of ~10 Million Years

Supernova explosion ejecting LOTS of material back into the Interstellar Medium

# The Origin of the Solar System Elements

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Graphic created by Jennifer Johnson

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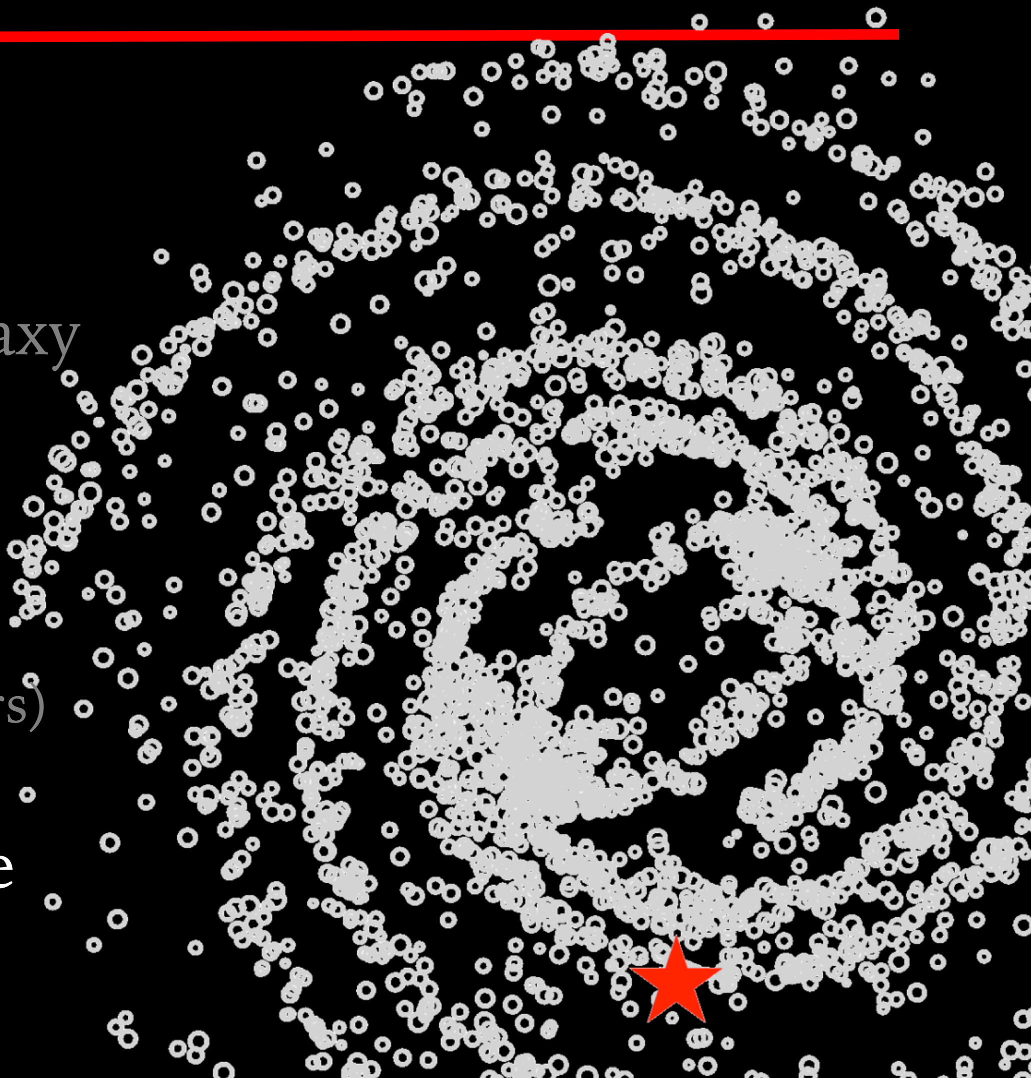
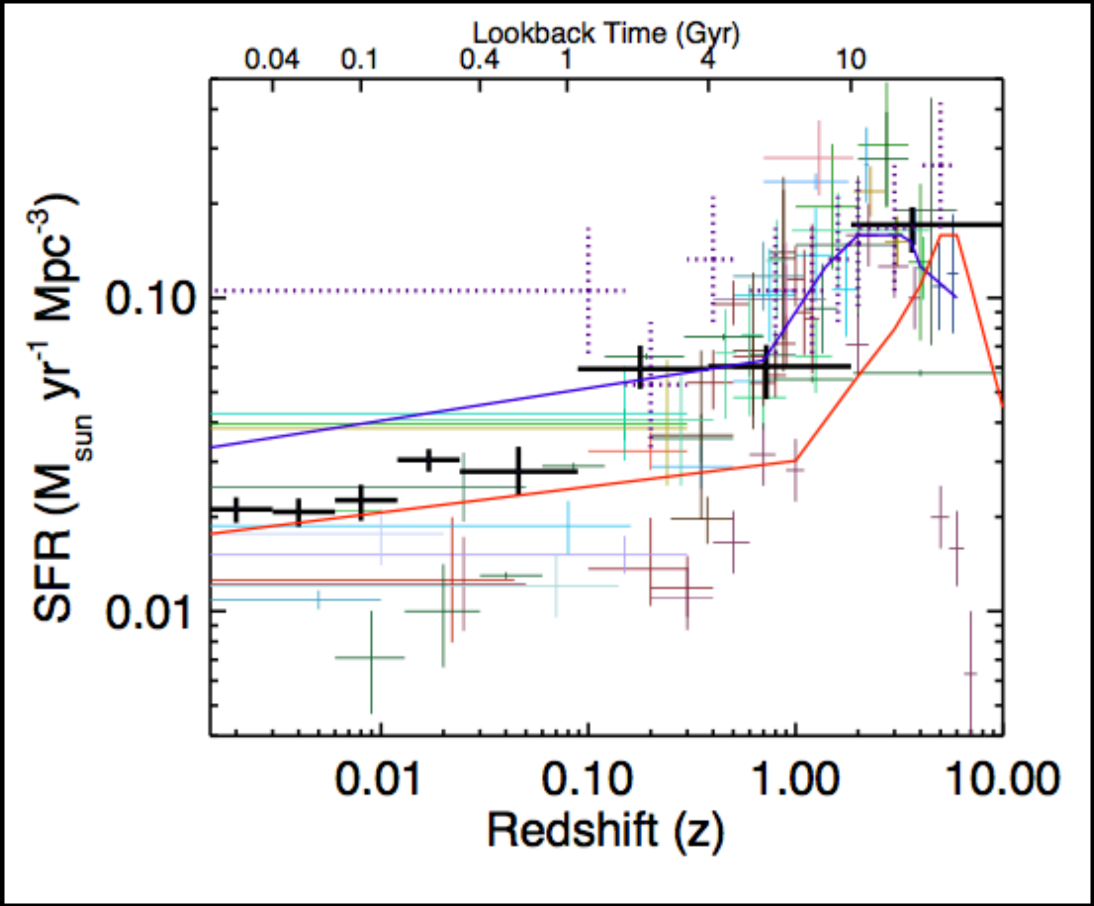


# Star formation variations across time

Star formation in the Universe peaked about 10 billion years ago.

(Redshift z~1)

Why? Lots of excess gas.



# Composition of the Milky Way Right Now

**Stellar Disk**

Thin Disk – 80% of Mass – Stars of all ages 0-12 Gyr

Thick Disk – 5% of Mass – Old stars with low metallicity

**Interstellar Medium (ISM)**

Gas – 15% of Mass – Hot, warm, and cool component

Atomic and molecular

Dust – <1% of Gas Mass – Well Mixed with the cool gas

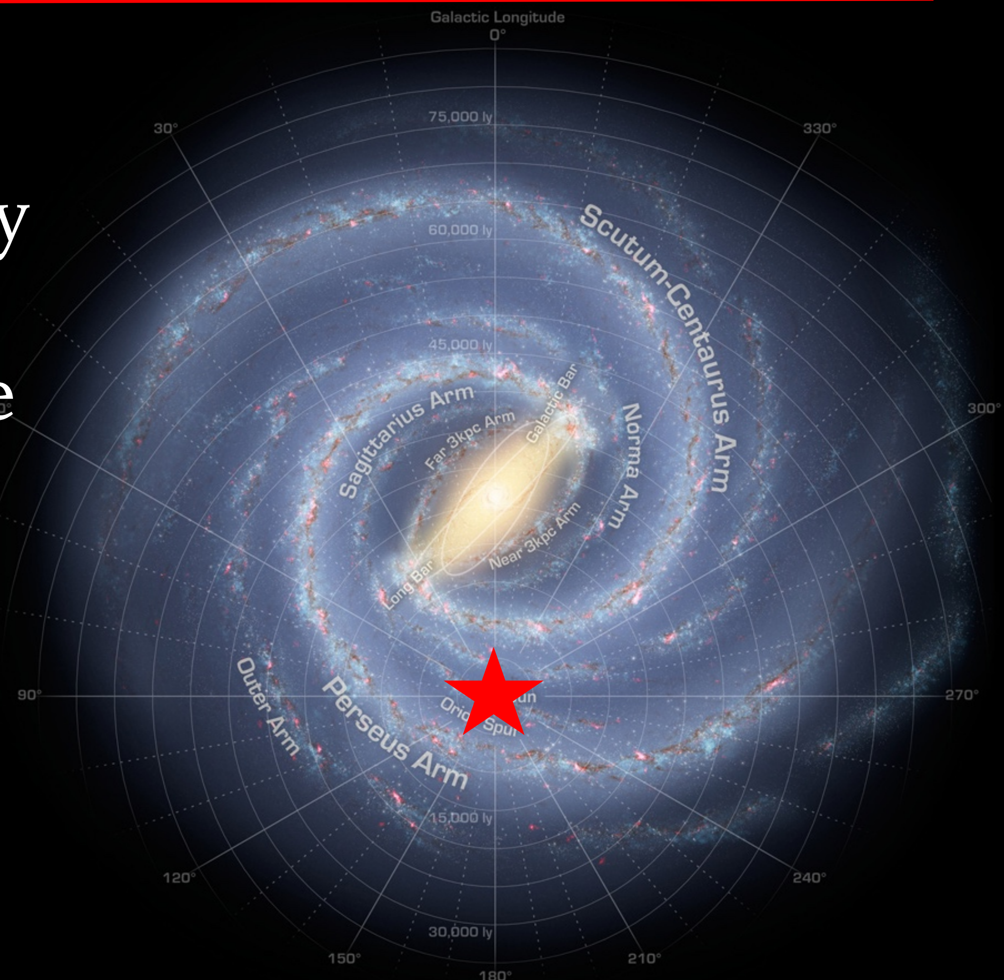
Very important for the formation of molecules

Drives much of the chemistry of the ISM

# Star formation variations across the Milky Way

Density and metallicity both decrease as you move further from the center of the Galaxy.

BUT! – The center of the Galaxy is also hot and turbulent.



# Star formation variations across the Milky Way

Why would metallicity affect star formation?

Metals are efficient coolers for gas (they radiate away energy through lots of infrared lines)

Remember – You need cool, dense gas for star formation.

Without metals, the stars you form are more massive, on average.

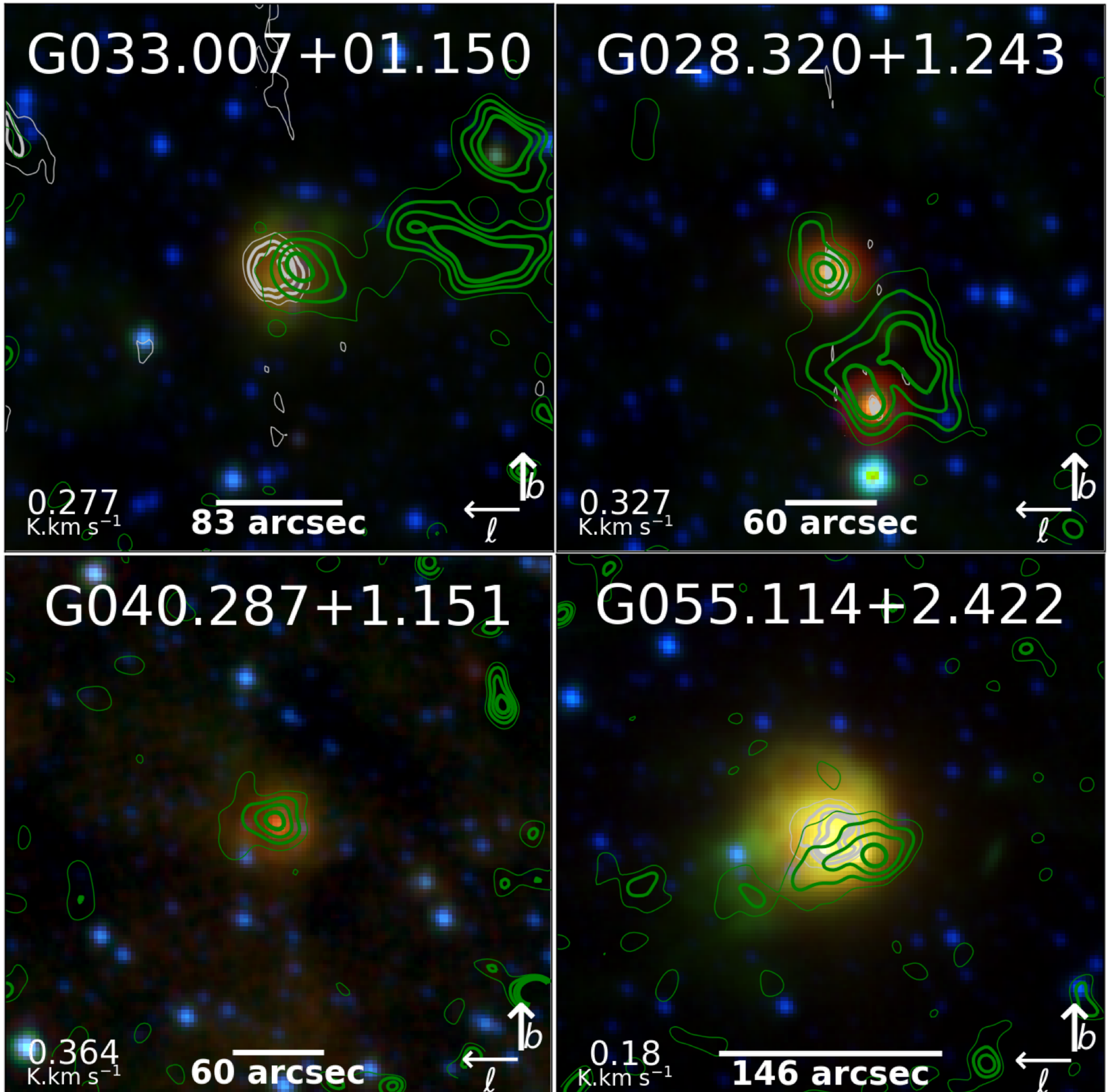
(This would mean the first generation of stars were behemoths!)

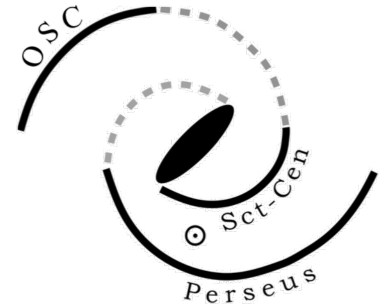
# Star formation variations across the Milky Way

Part of my current research interest is to look at the molecular gas environment surrounding high-mass stars in the outermost parts of the Galaxy.

We're characterizing how "star formation efficiency" changes as you move far away from the center of our Galaxy into low density, low metallicity environments.

# Molecular Gas Maps with Argus (GBT)




Sample of OSC HII regions mapped with Argus

3-color image from WISE (4.6, 12, 22 microns)

VLA Contours in Grey
(10 GHz Continuum)

$^{13}CO$ Contours in Green (Moment 0 Maps)

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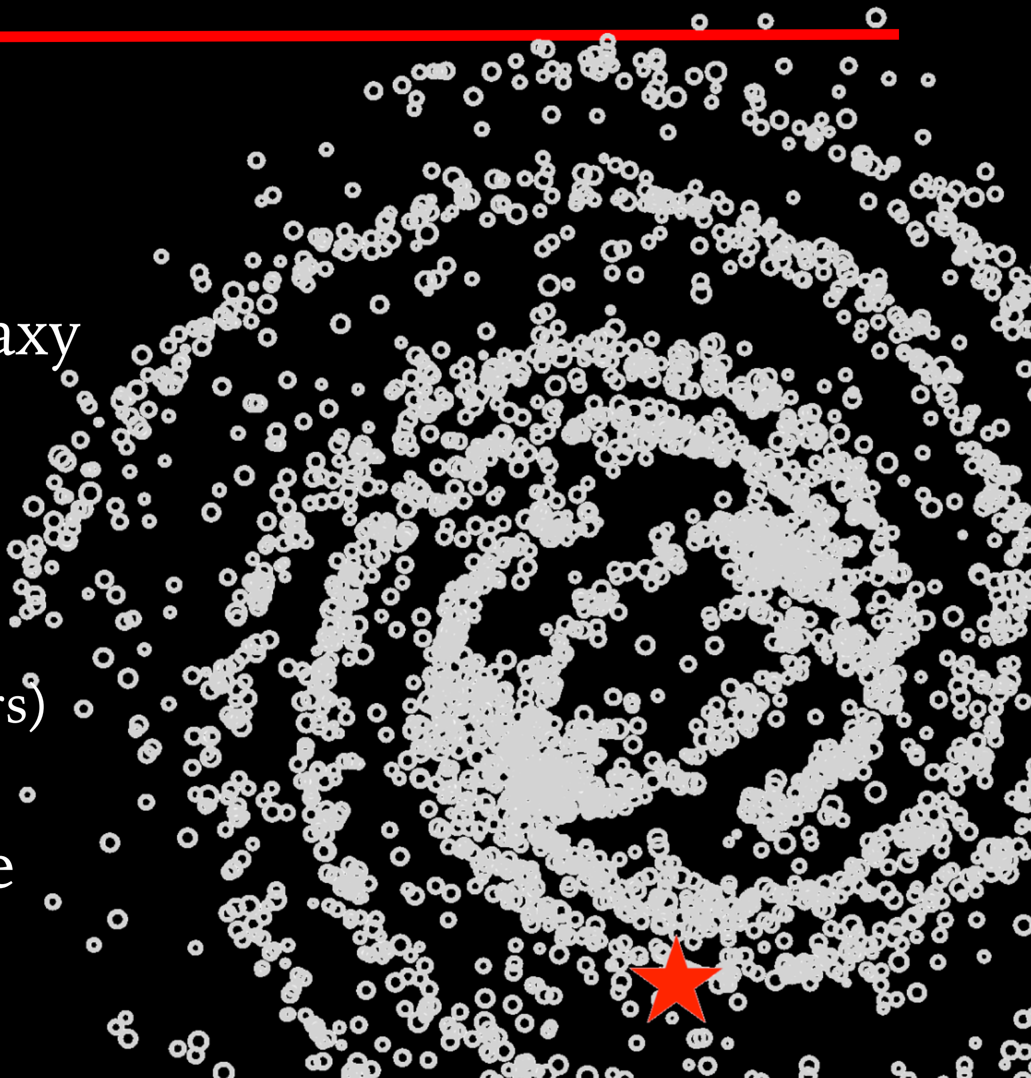

# Thank you! Questions?

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WISE HRDS : http://astro.phys.wvu.edu/wise