ASTR 400B

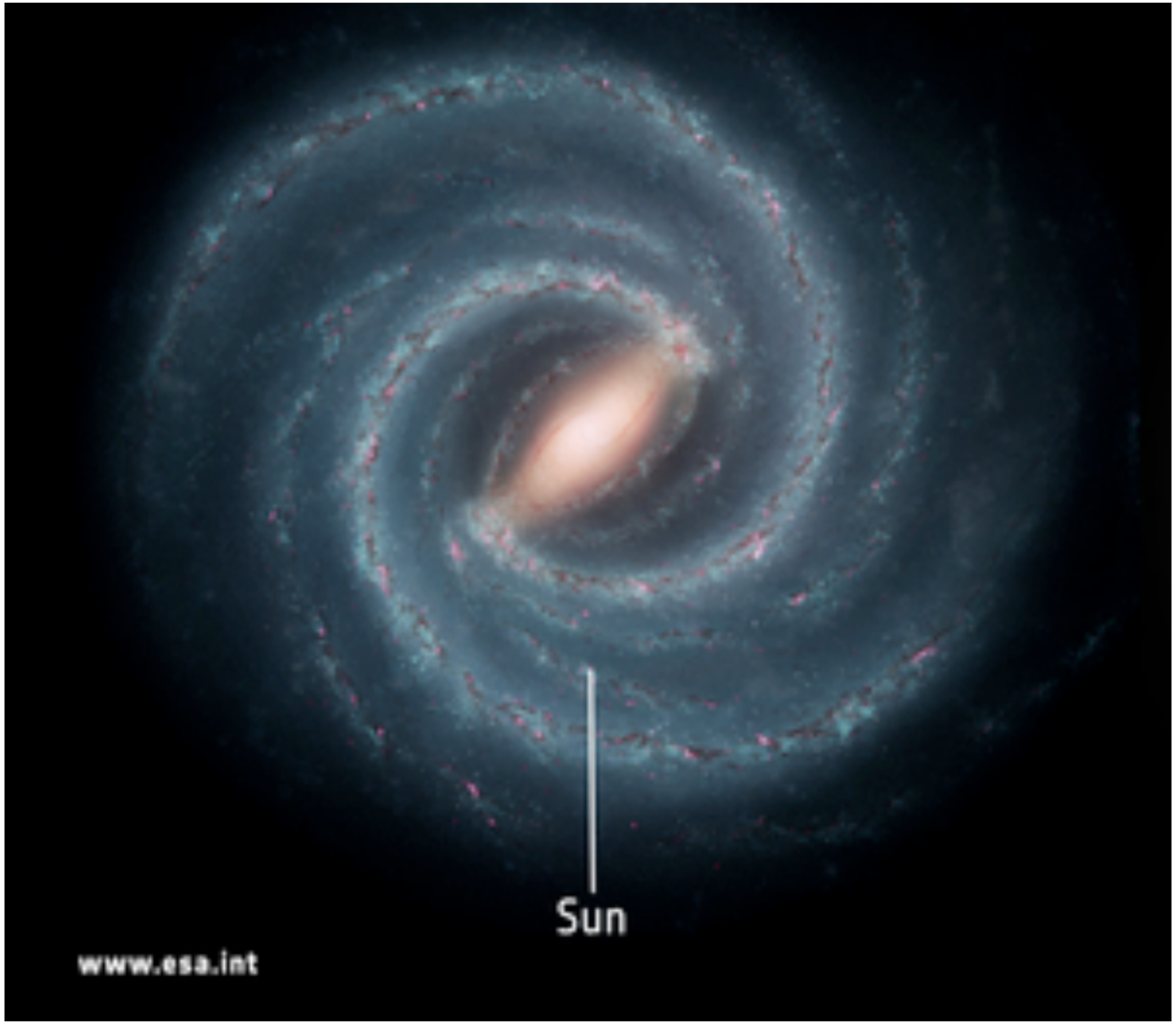
Theoretical Astrophysics II: Galaxies and Cosmology

- Reading: S & G Chapter 2.2, 2.4
- HW 5 due next Tuesday, April 9
- Mapping the Milky Way: bulge, nuclear star cluster
- ISM in the Milky Way
- Chemical Evolution of Galaxies, the Mass Metallicity Relation
- Galaxy Formation Efficiency and Feedback

Lecture 23: April 9, 2024

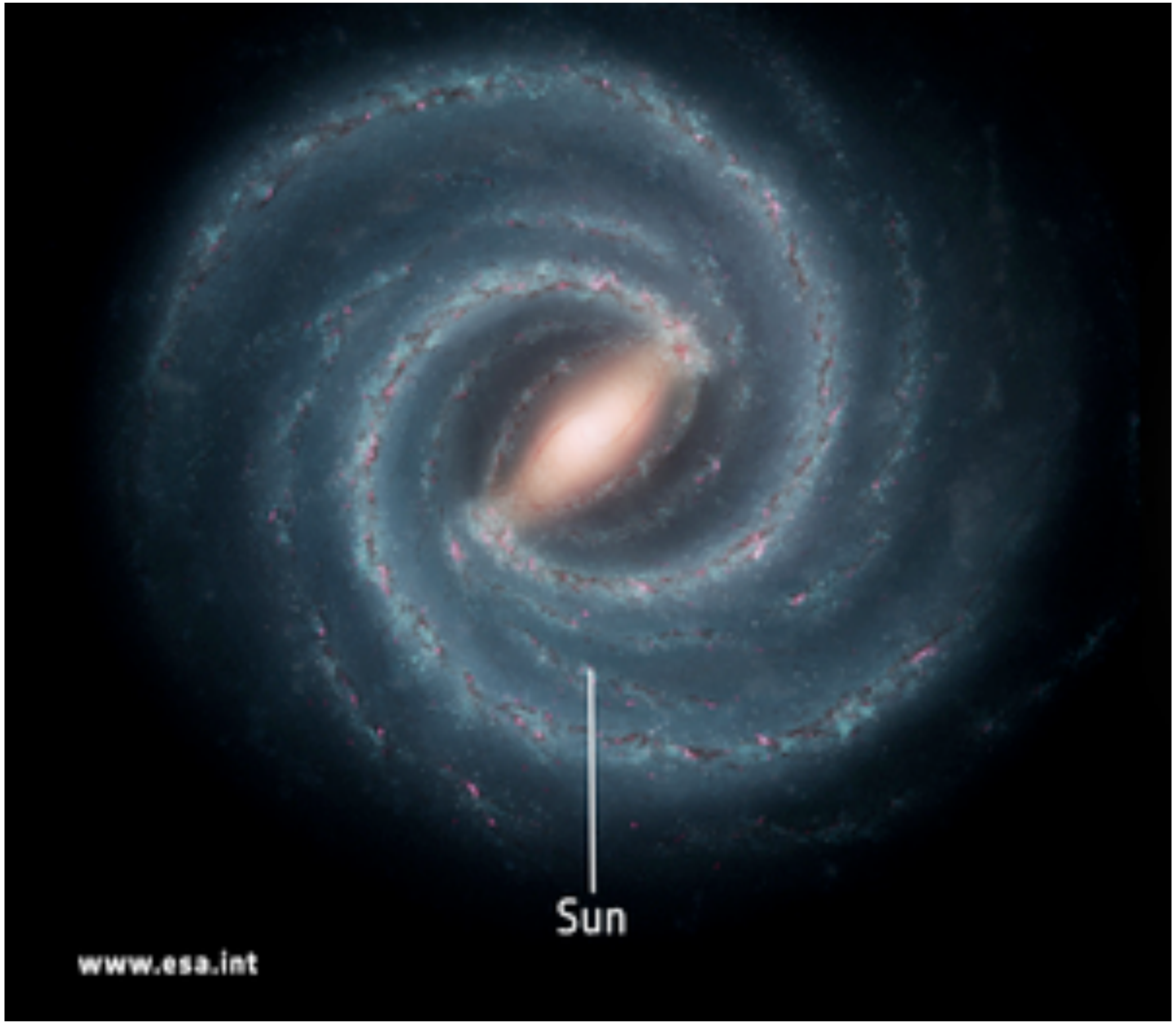
Prof. Kate D. Alexander

The Bulge and Nucleus



- Stellar mass of $20 \times 10^9\ M_\odot$, roughly ~30% of that in the Milky Way.
- Typical rotation speeds of ~100 km/s, more but orbits contain more random motion than the disk.
- Stars in the bulge span a wide range in metallicities
  - Metallicity peaks near solar value (~80% $Z_\odot$), with tail toward lower metallicities.

The Bulge and Nucleus



- Stellar mass of $20 \times 10^9\ M_\odot$, roughly ~30% of that in the Milky Way.
- Typical rotation speeds of ~100 km/s, more but orbits contain more random motion than the disk.
- Our location within Milky Way gives unique perspective on bulge formation
    - Stellar properties (i.e., metallicities)
    - Kinematics
- One major complication: dust
    - look along sightlines without much obscuration.
    - use near-infrared since light travels more freely through dusty mid plane in NIR (i.e., APOGEE survey with SDSS).

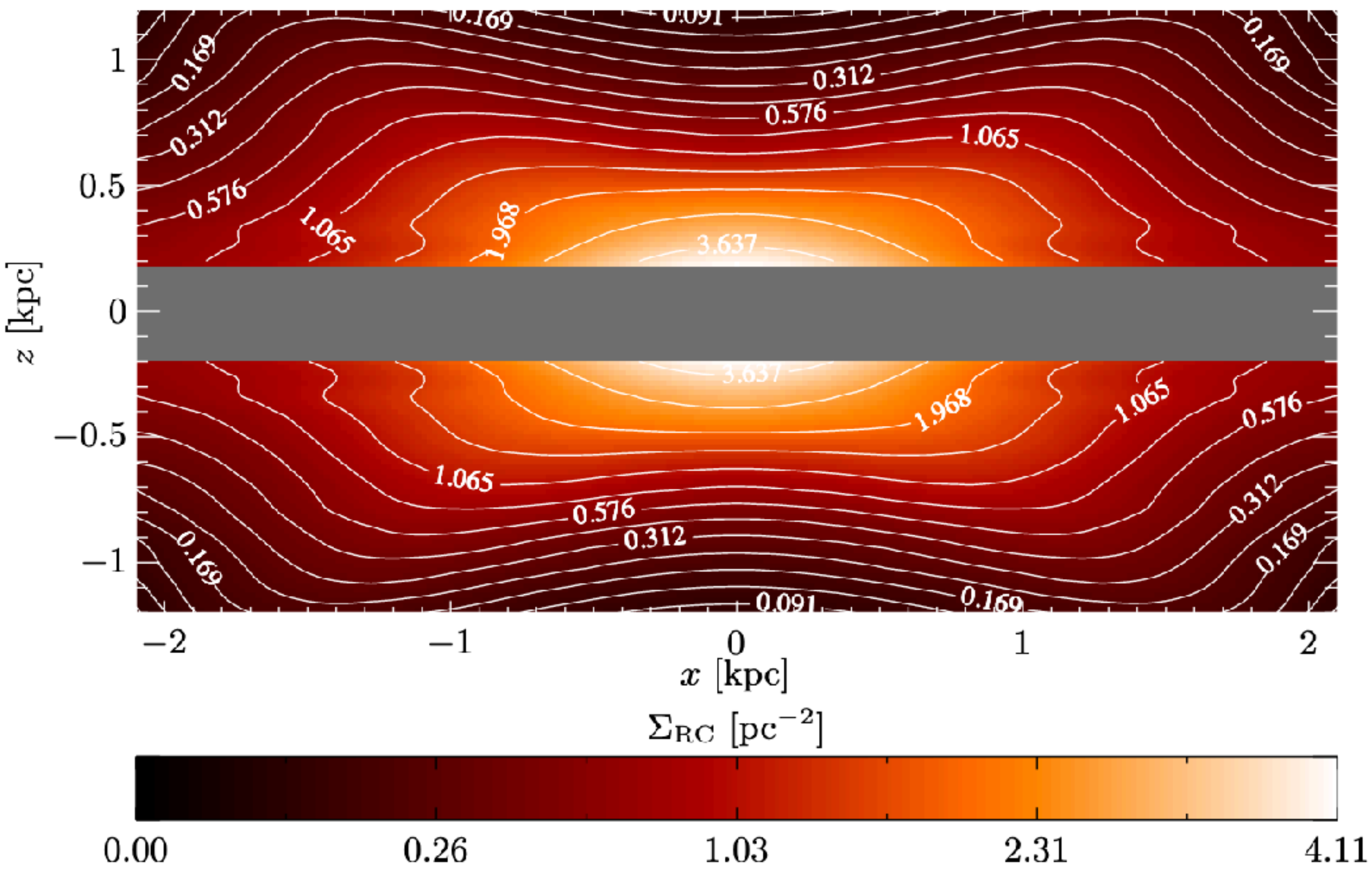
Bulge Formation Scenarios

- The **classical bulge** formation picture:
    - motivated by fact that massive bulges share many properties with elliptical galaxies
        - i.e., spheroid with more random motions than in disk stars
    - maybe form in a similar way?
    - merging of gas-rich galaxies (creates bulge) followed by additional accretion of cold gas (forms disk)

- **Pseudo bulge** from secular evolution
    - less massive bulges show properties closer to disks
    - exponential surface brightness profiles, flattened by rotation
    - predicted to form via secular evolution from disk component
    - stars in inner disk must lose angular momentum to join central bulge
    - bars and spiral arms can re-arrange angular momentum!
    - stars in bars experience a bending mode instability, leading to peanut-shaped or boxy bulges.

Map of Stellar Density in the Bulge

- Use stars bright in the near-IR as tracer via photometric parallax (i.e., red clump stars).
- Apparent magnitude can then be used to get distance if absolute magnitude known.
- Build 3D map of star density in the bulge of the Milky Way.

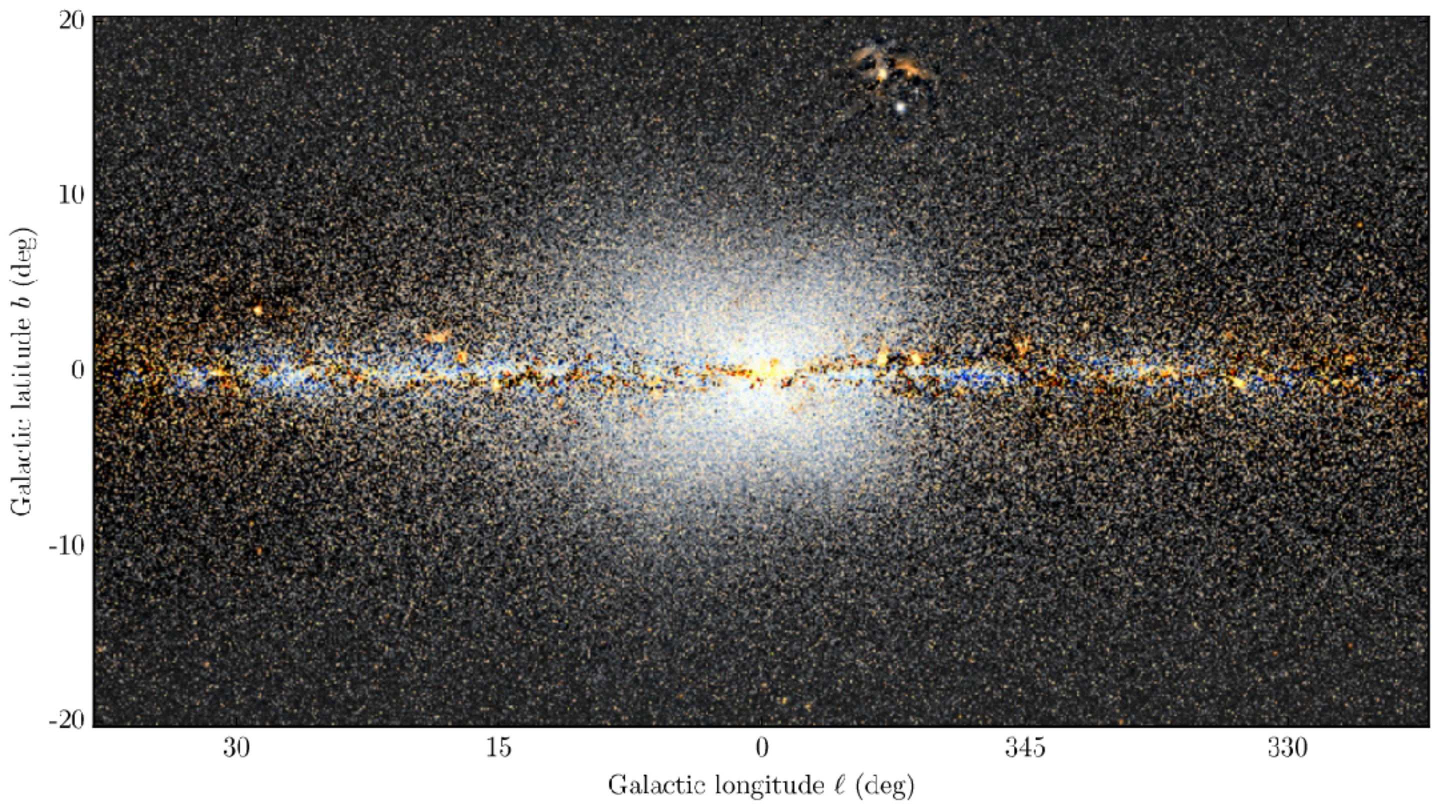


- When viewed from the side, the stars appear elongated or peanut-shaped.

Wegg+2013

Map of Stellar Density in the Bulge

- Use stars bright in the near-IR as tracer via photometric parallax (i.e., red clump stars).
  - Apparent magnitude can then be used to get distance if absolute magnitude known.
  - Build 3D map of star density in the bulge of the Milky Way.



- When viewed from the side, the stars appear elongated or peanut-shaped.

- Same seen in WISE infrared images.

Ness and Lang 2016

Map of Stellar Density in the Bulge

- Use stars bright in the near-IR as tracer via photometric parallax (i.e., red clump stars).
  - Apparent magnitude can then be used to get distance if absolute magnitude known.
  - Build 3D map of star density in the bulge of the Milky Way.

Shen & Zheng 2020

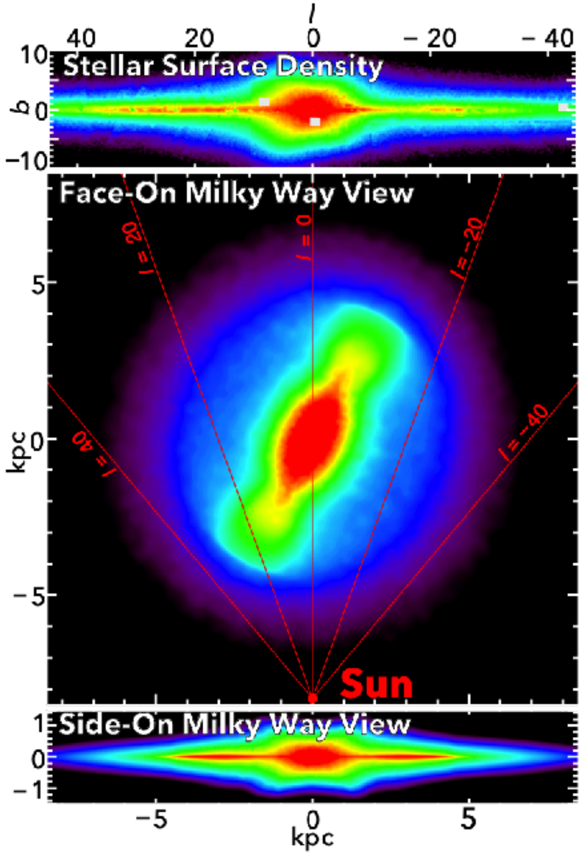


Fig. 2 The Galactic boxy bulge and long bar reconstructed by combining various NIR surveys. *Top*: the inner Galaxy in solar perspective. *Middle*: Face-on projection of best-fitting RCG star count model. *Bottom*: side-on view of the bar/bulge along the intermediate axis. Adapted from Wegg et al. (2015).

- When viewed from the side, the stars appear elongated or peanut-shaped.
- Same seen in WISE infrared images.
- Consistent **with picture of bulge formation via secular evolution** — likely suggests Milky Way is a barred spiral with bulge formed largely form inner disk.

Did the Milky Way Bulge Form Entirely from Secular Evolution?

Shen & Zheng 2020

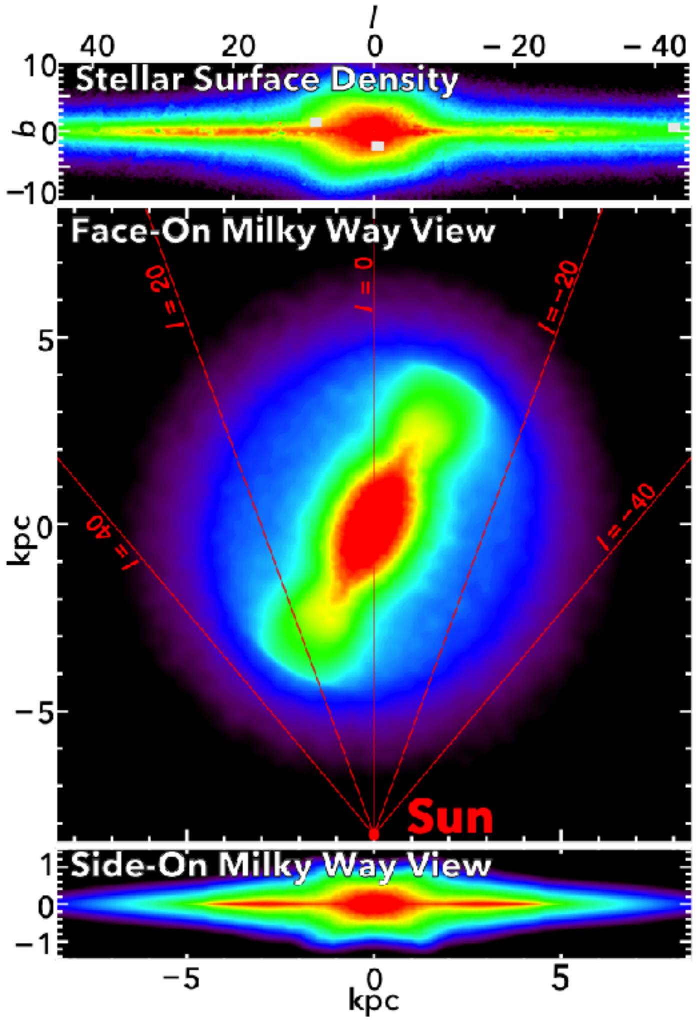
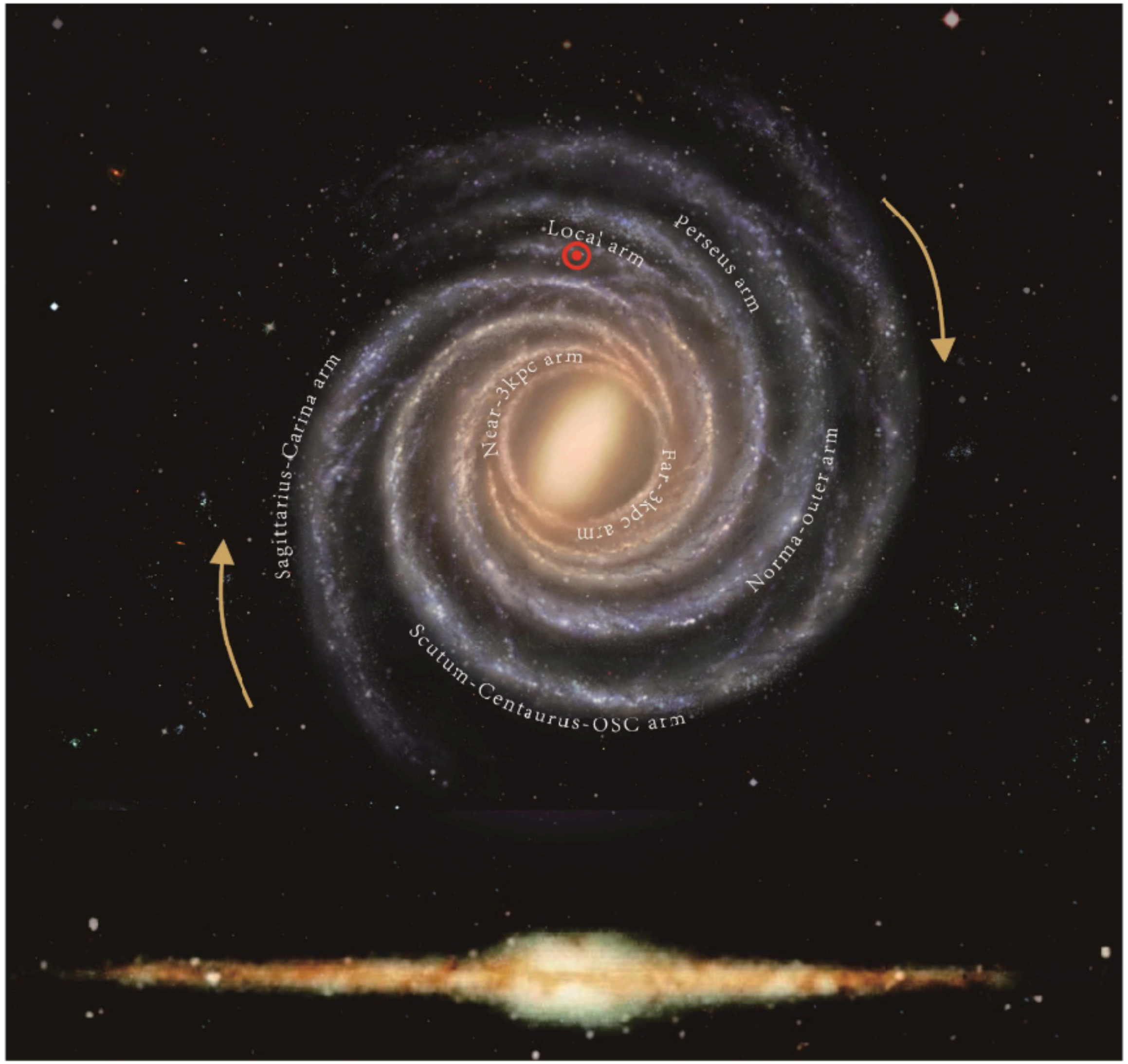


Fig. 2 The Galactic boxy bulge and long bar reconstructed by combining various NIR surveys. *Top*: the inner Galaxy in solar perspective. *Middle*: Face-on projection of best-fitting RCG star count model. *Bottom*: side-on view of the bar/bulge along the intermediate axis. Adapted from Wegg et al. (2015).

- Data support large fraction of bulge forming via secular evolution processes.
- However it is conceivable that some subset of stars in the bulge could have formed in the classical bulge mode.

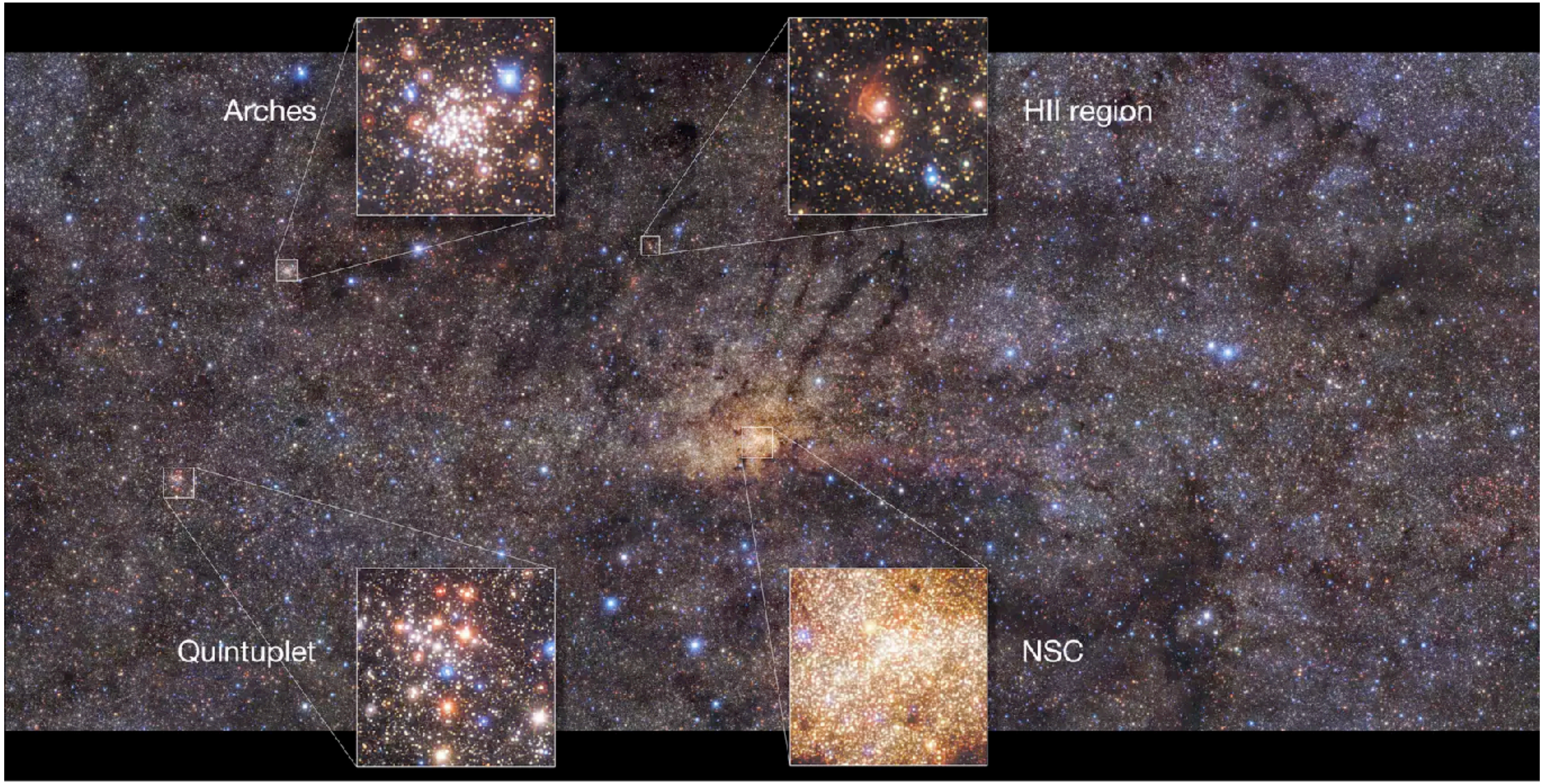
Our View of the Milky Way Bulge



Shen & Zheng 2020

Fig. 1 *Top*: the conceptual picture of the Milky Way with its bar, four major spiral arms, a subsidiary Local arm, and 3-kpc arms. This artistic visualization also contains various important components such as gas, dust, molecular clouds and filaments, HII regions, young OB stars, and young star clusters. The Sun is marked with a circled red dot in the Local arm. The bar angle between the bar major axis and the Sun-Galactic center line is around $25 - 30°$. The Galactic rotation is in the clock-wise direction. (Credit: Xing-Wu Zheng & Mark Reid BeSSeL/NJU/CFA). *Bottom*: the Milky Way seen in the infrared band by Diffuse InfraRed Background Experiment (DIRBE) on board NASA's COBE satellite (left-right flipped from the original image to be more consistent with the face-on picture).

The Milky Way Nucleus



- The central region of the bulge shows recent star formation (note HII regions) and dense star clusters
- At the center, we see the **nuclear star cluster** (NSC) of the Milky Way.

The Milky Way Nucleus

- blue stars in foreground

- The central region of the bulge shows recent star formation (note HII regions) and dense star clusters

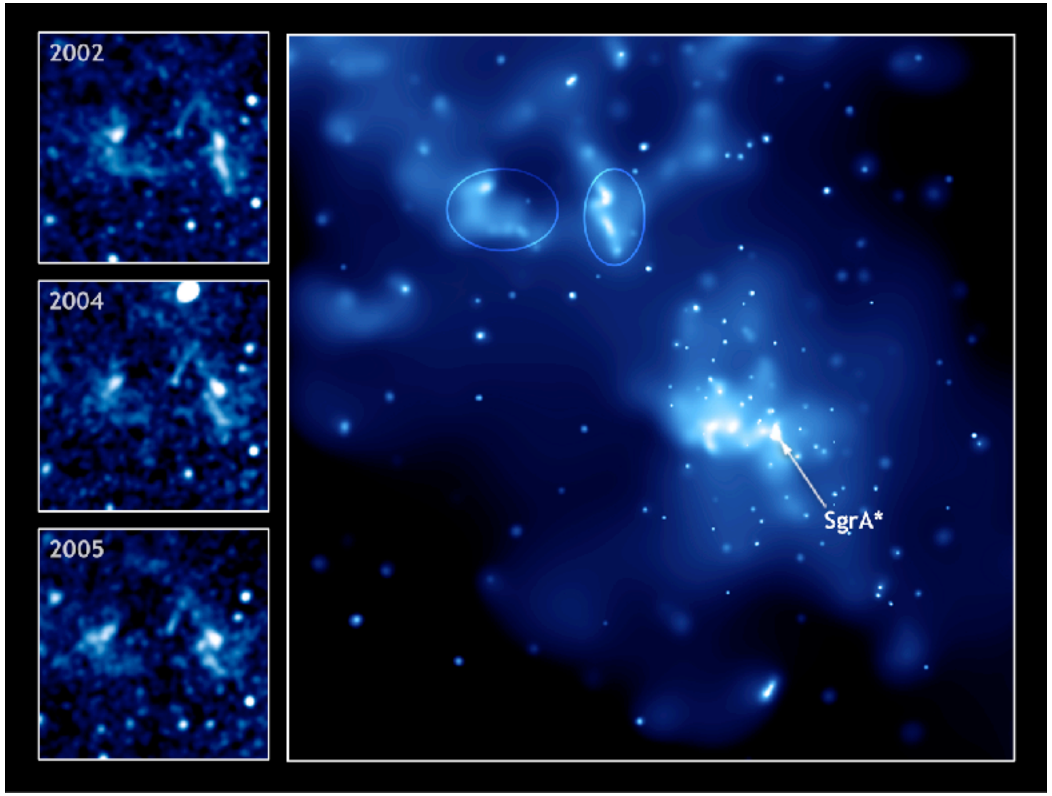
- At the center, we see the **nuclear star cluster** (NSC) of the Milky Way.

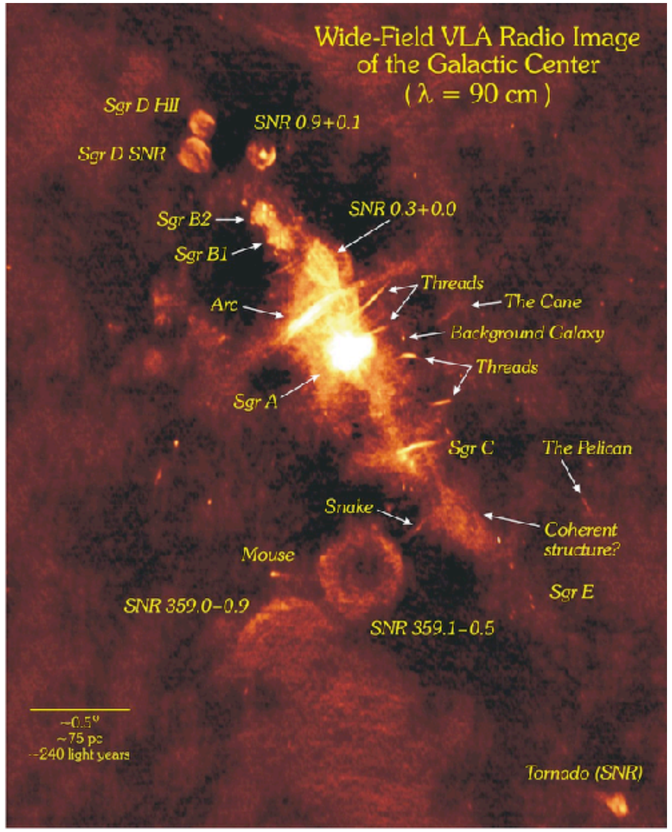
- Lots of gas and dust toward nucleus — 31 mags of extinction in V-band — so must observe in near-IR.

- NSC comparable in density to globular clusters — 3×10^7 $M_\odot$ in 0.2 pc (=10 arcsec) radius.

- Unlike globulars, this is an active site of star formation — still massive stars!

Multi-wavelength view of the Milky Way Nucleus





- Radio maps (right) show lots of filamentary structure in the central few 100 pc of the Milky way — powered by synchrotron emission, with electrons accelerated along magnetic field lines.
- Central point source in radio maps (Sag A*) thought to be just ~1.3 AU in size — scaled down version of AGNs seen in other galaxies.
- X-ray maps (left) show variability in extremely hot gas in nucleus — light echos from accretion events on to central source.

Stellar Orbits in MilKy Way nucleus

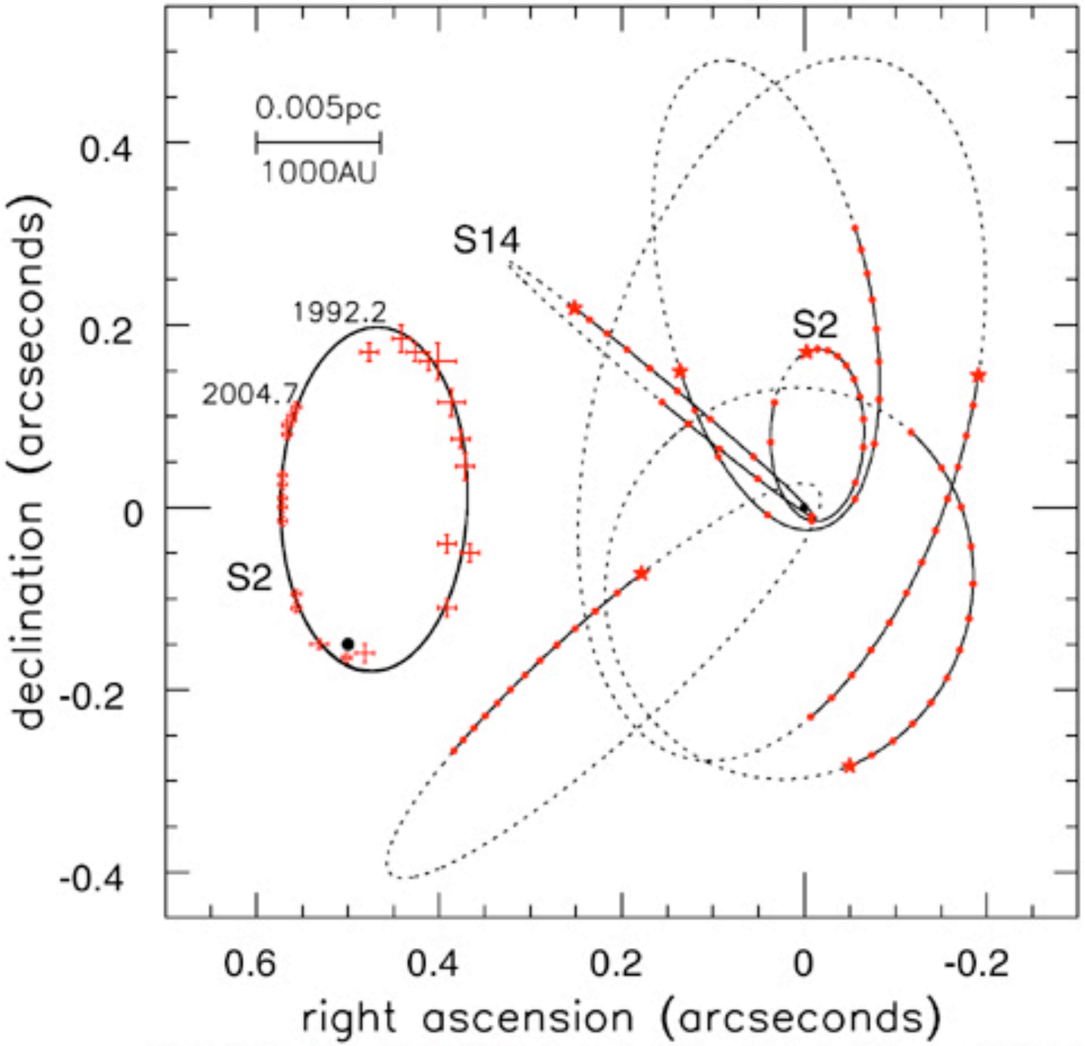
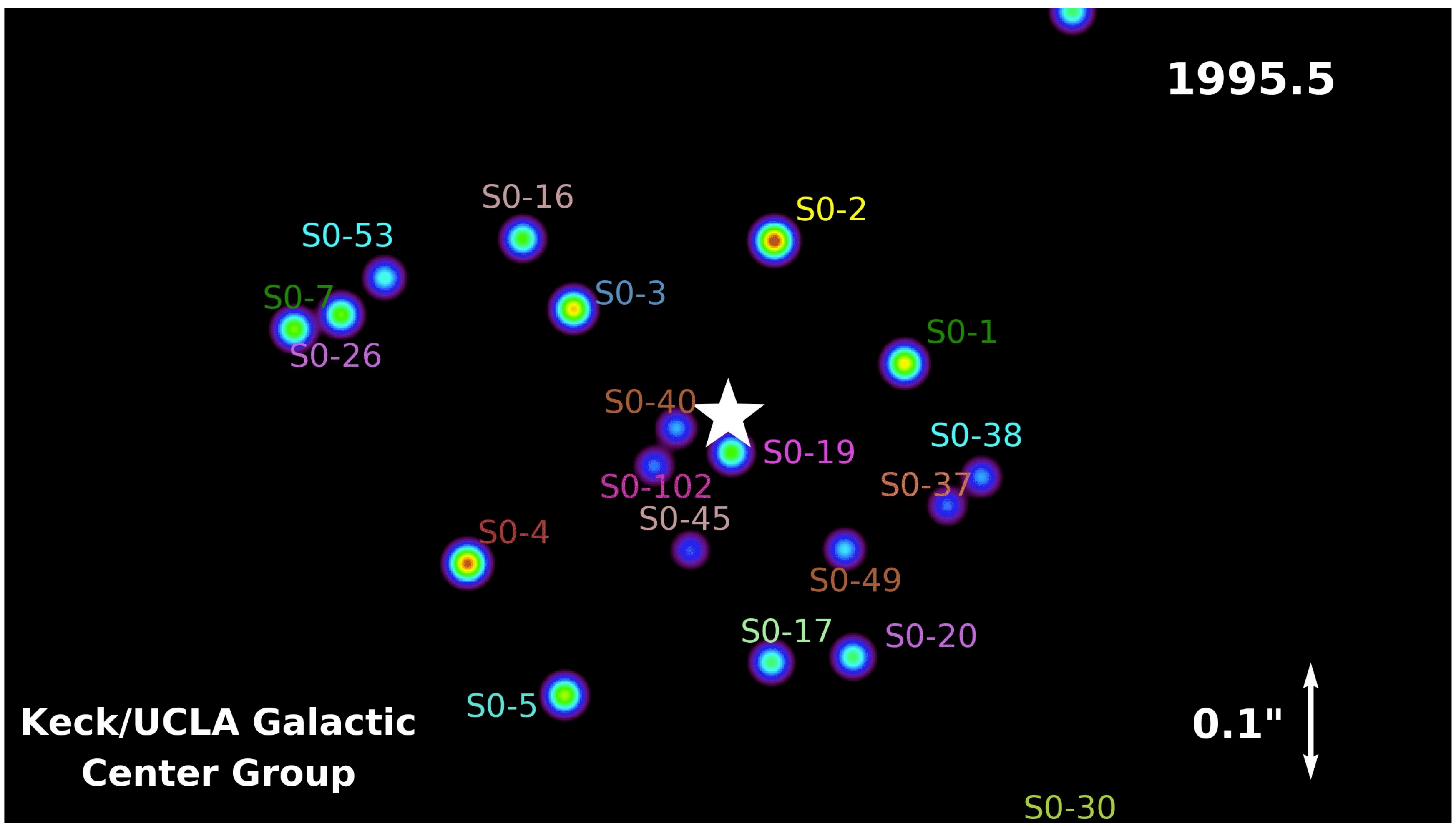


Fig 2.17 (Eisenhauer/MPE) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

- Innermost young stars have orbits of several tenths of an arcsecond about Sag A* (~0.05 pc).
- Requires near-IR imaging + adaptive optics to resolve stars on these scales.
- Orbits have been mapped out over the past several decades from observed proper motions and radial velocities.
- We can use this information to measure the mass contained within the orbits. Recall:

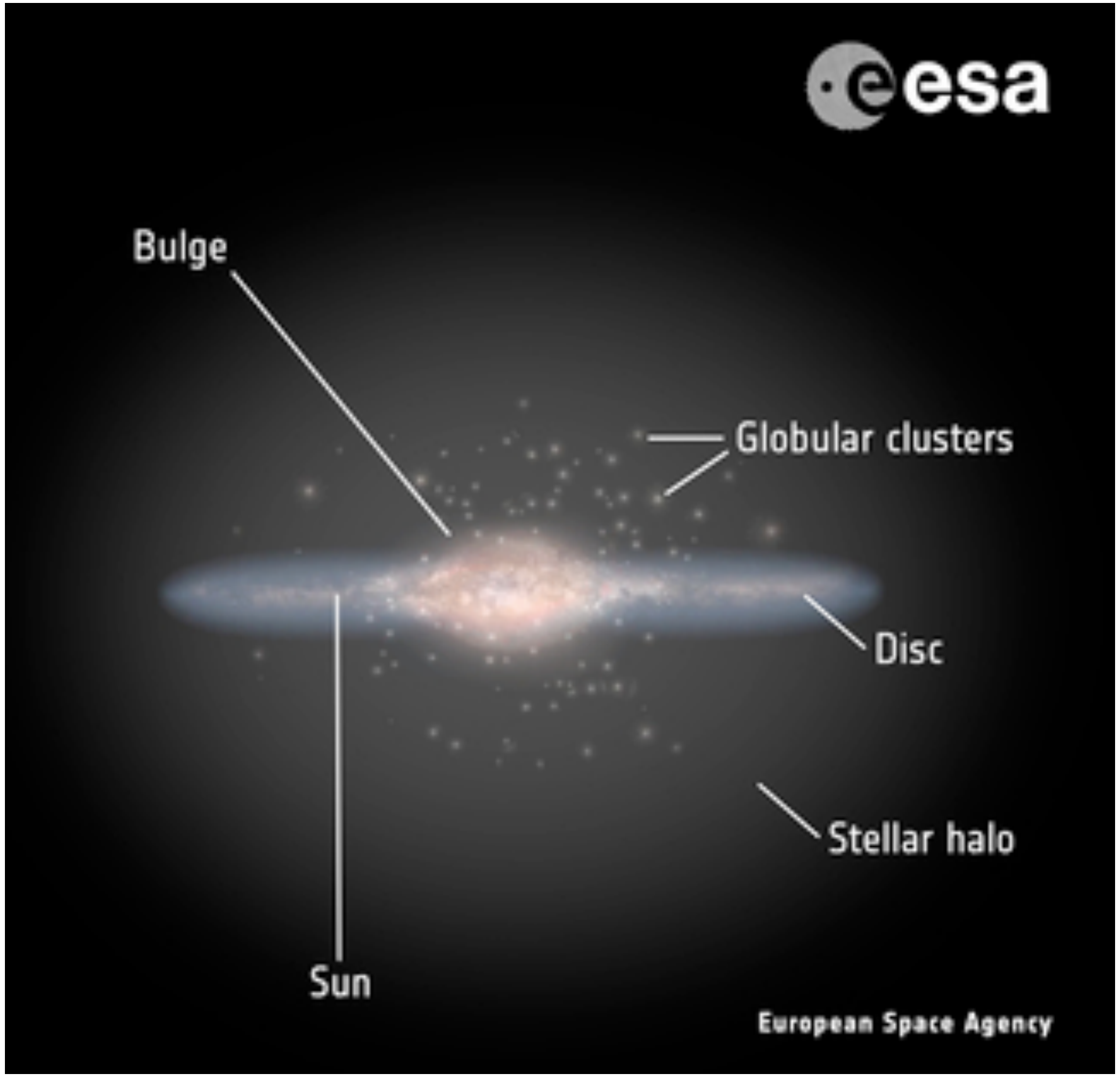
$$V^2(r) \approx \frac{G\mathcal{M}_{\rm BH}}{r}$$

Stellar Orbits in MilKy Way nucleus



- Requires $4 \times 10^6\ M_\odot$ to explain motion of stars.
- Points to supermassive black hole at the center of the Milky Way.

What about Gas?



Thus far our picture of the Galaxy has focused only on stars, ignoring the interstellar gas in the disk and the gas in the circumgalactic medium (CGM).

In the next few slides, we give a brief overview of the gas content of the galaxy.

Why Study the ISM?

- ISM contains the dense molecular gas where stars and planets are formed.

Why Study the ISM?

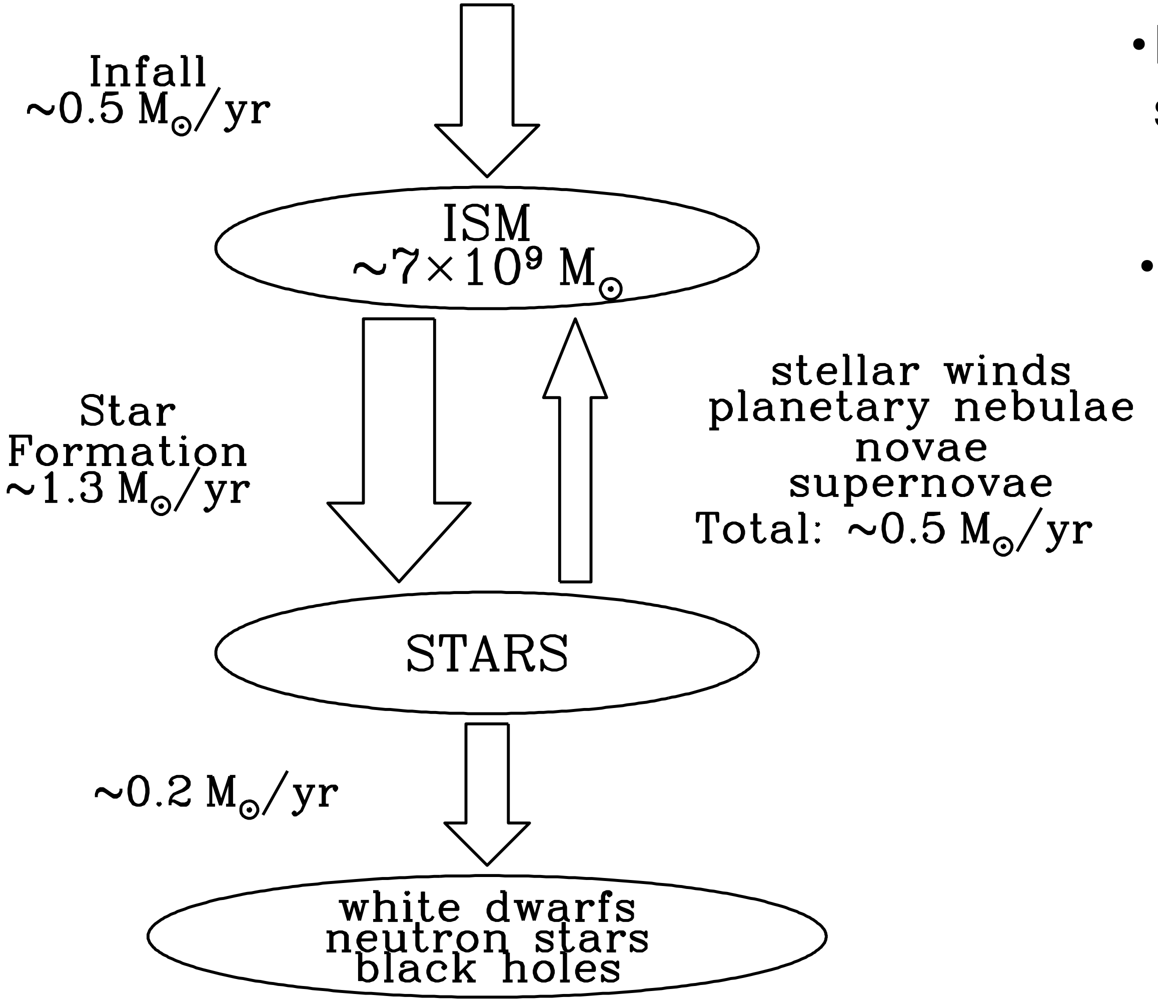
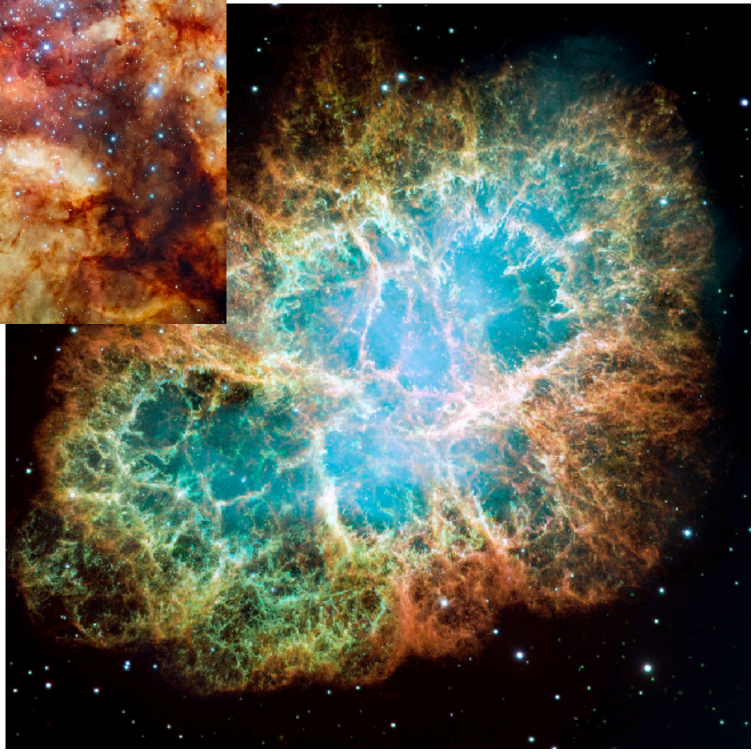


Fig 1.1, Draine, Physics of ISM and IGM

- ISM contains the dense molecular gas where stars and planets are formed.

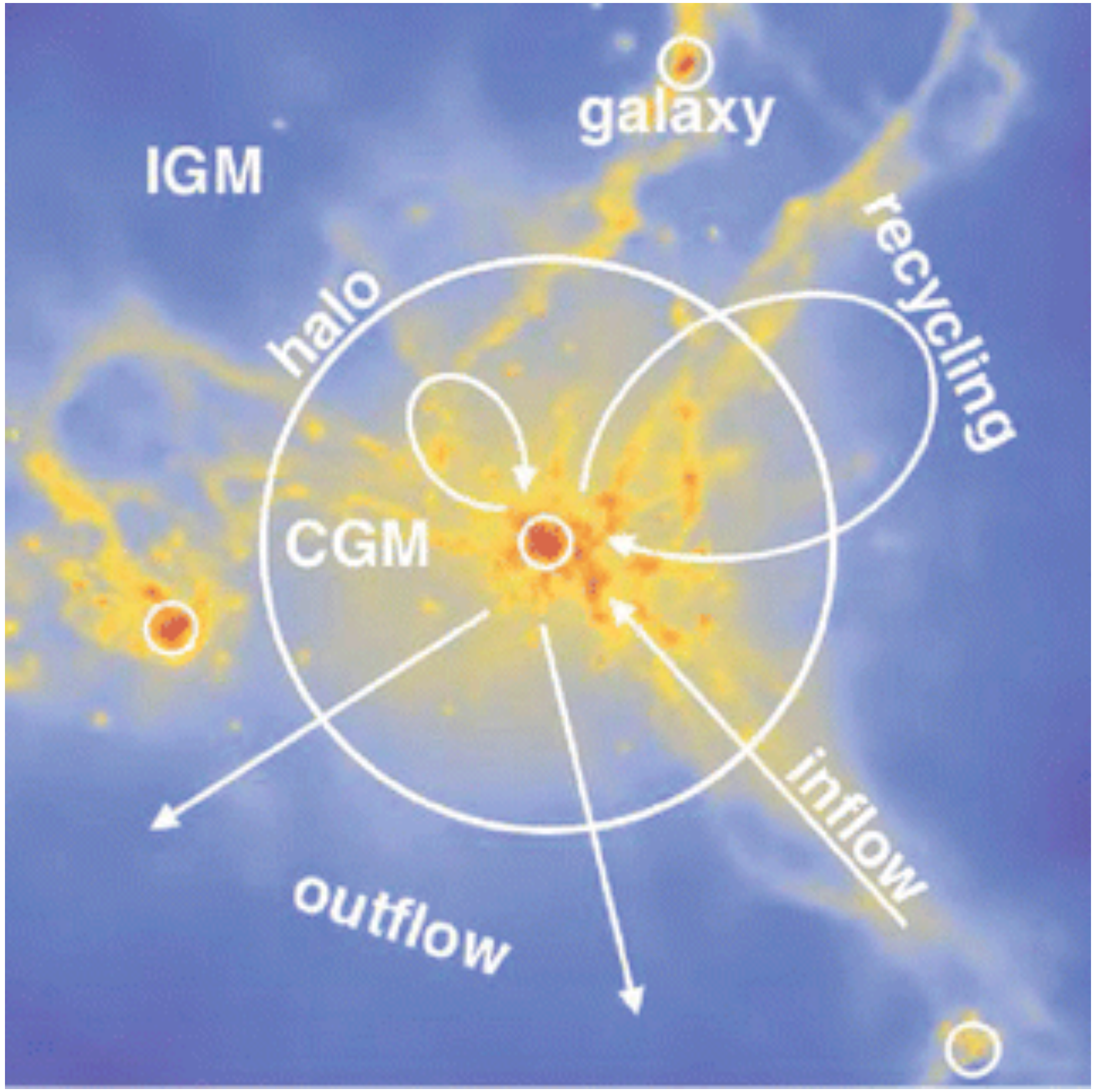
- Following star formation, massive stars deliver energy and mass back into the ISM via stellar winds and supernovae explosions.

Why Study the ISM?



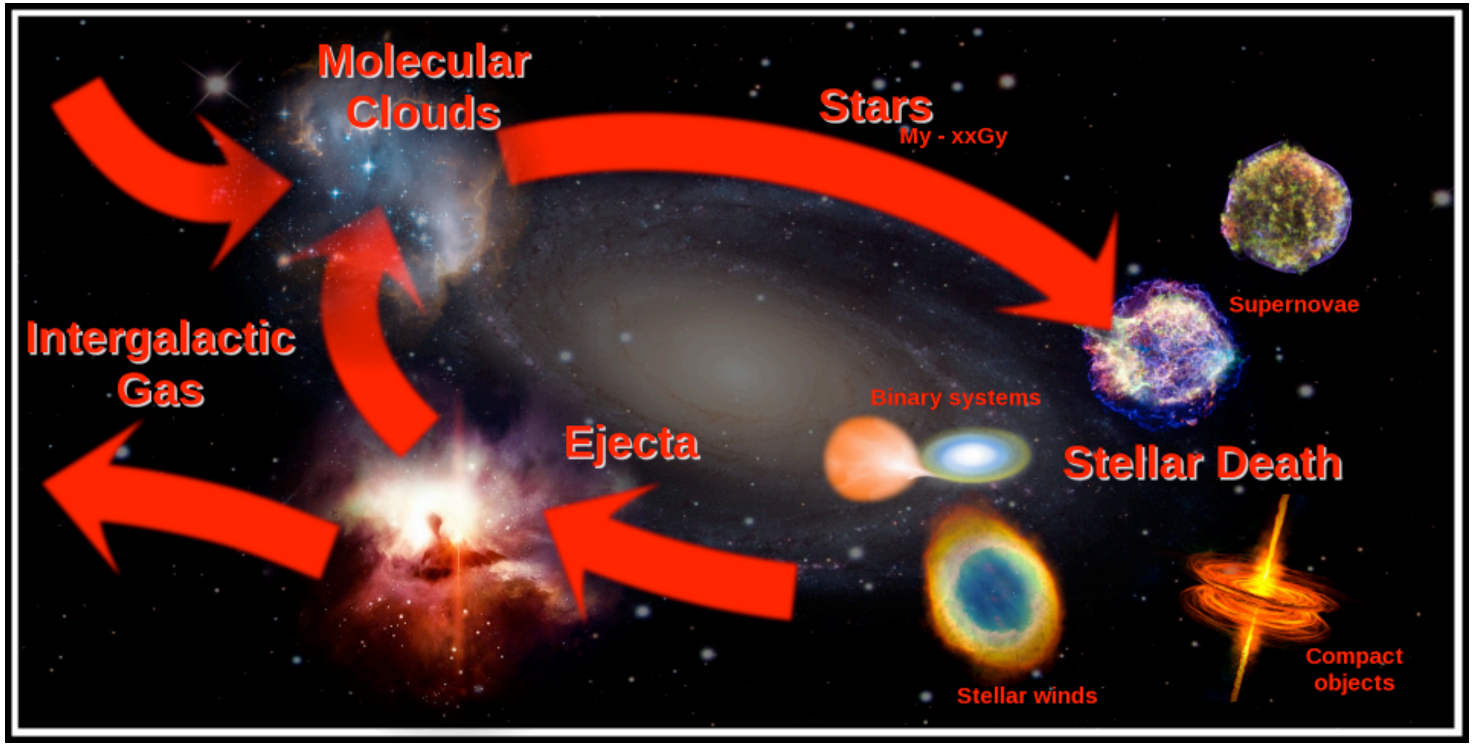
- ISM contains the dense molecular gas where stars and planets are formed.
- Following star formation, massive stars deliver energy and mass back into the ISM via stellar winds and supernovae explosions.
- These events power nebula that offer insight into evolution and endpoints of massive stars.

Why Study the ISM?



- ISM contains the dense molecular gas where stars and planets are formed.
- Following star formation, massive stars deliver energy and mass back into the ISM via stellar winds and supernovae explosions.
- These events power nebula that offer insight into evolution and endpoints of massive stars.
- Massive stars (and AGN activity) drive outflows of matter out of galaxies into the circumgalactic medium (CGM) and/or IGM.
- The balance between these outflows and inflows from the IGM/CGM (the so-called baryon cycle) regulates galaxy evolution.

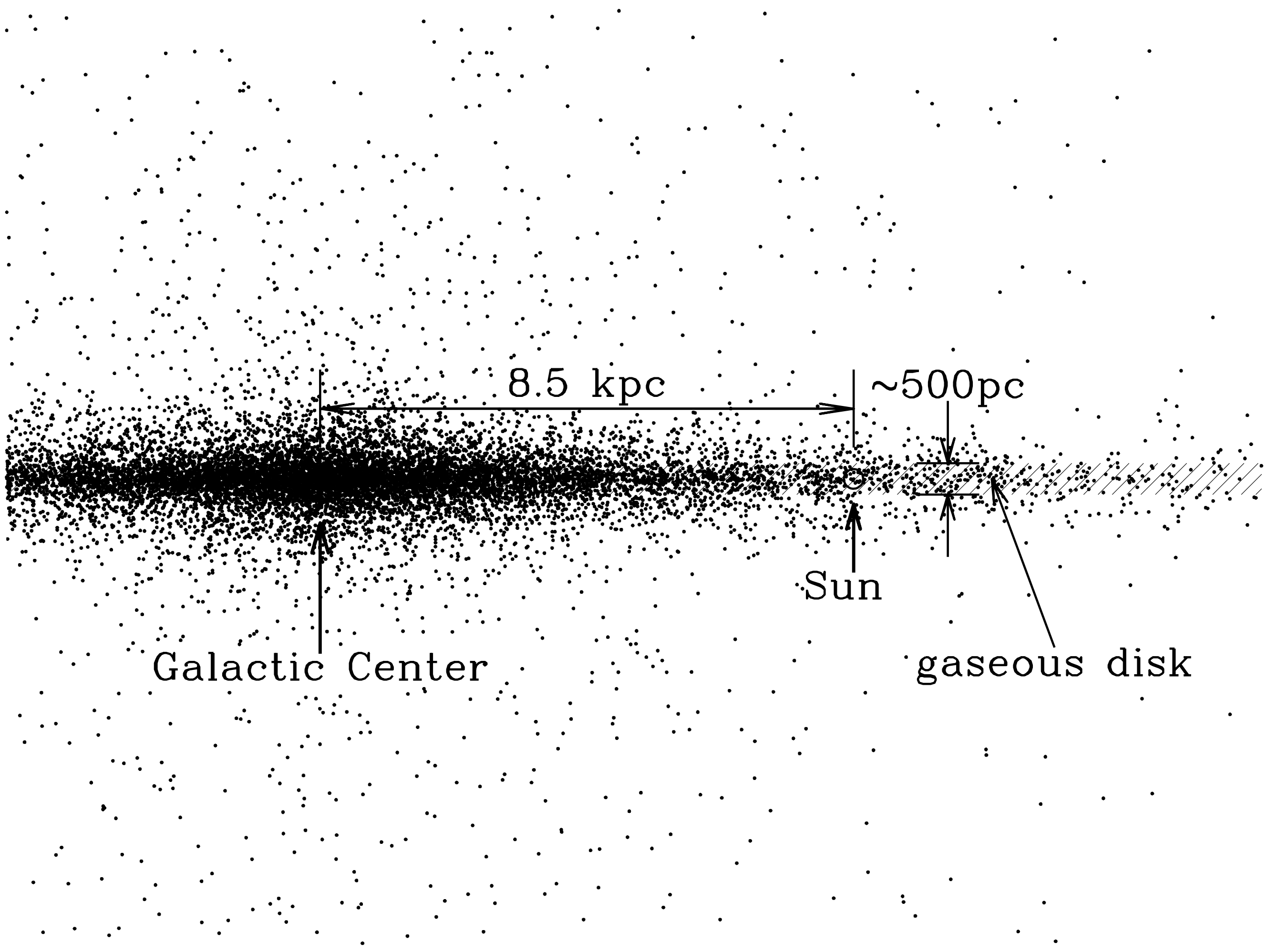
The Baryon Cycle



- Assuming a steady star formation history, the metal content of the ISM builds up over time, as generations of stars form, fuse metals in their interior, and deliver them back to the surrounding gaseous medium.
  - Future generations of stars form with higher metallicity.

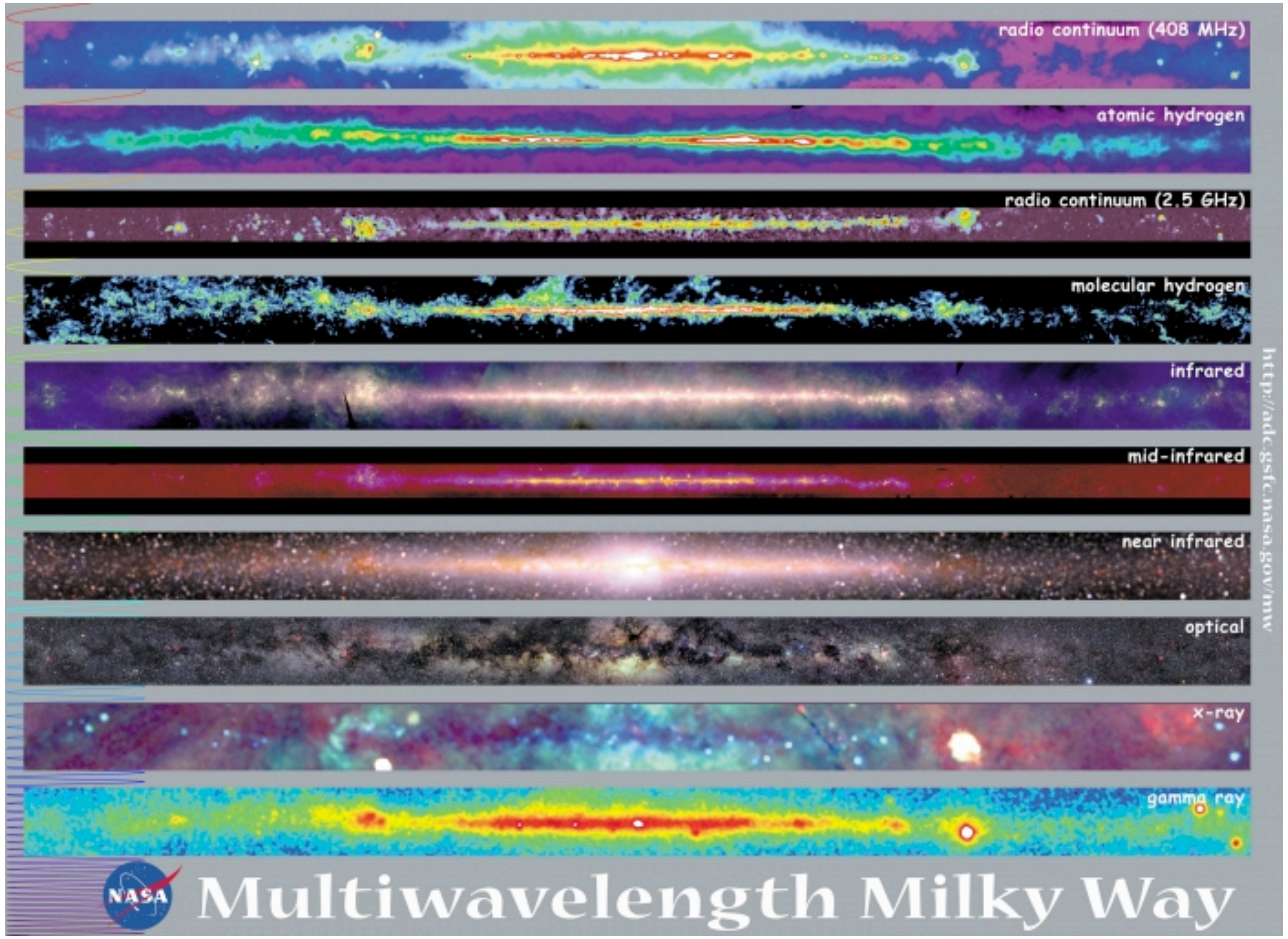
Explains why stars in the Milky Way are observed to have a variety of metallicities, as we discussed last week.

The ISM of the Milky Way



- Most interstellar gas found within a few hundred parsecs of the mid plane of the Milky way (here we are ignoring the CGM).
- Total mass of ISM is ~7x10^9 M$_\odot$, 12% of the mass in stars. Roughly 1% of the mass of the ISM is in the form of dust.
- Baryons in the disk can be found spanning a wide range of temperatures and densities, typically divided into various characteristic “ISM phases.”

The Phases of the ISM

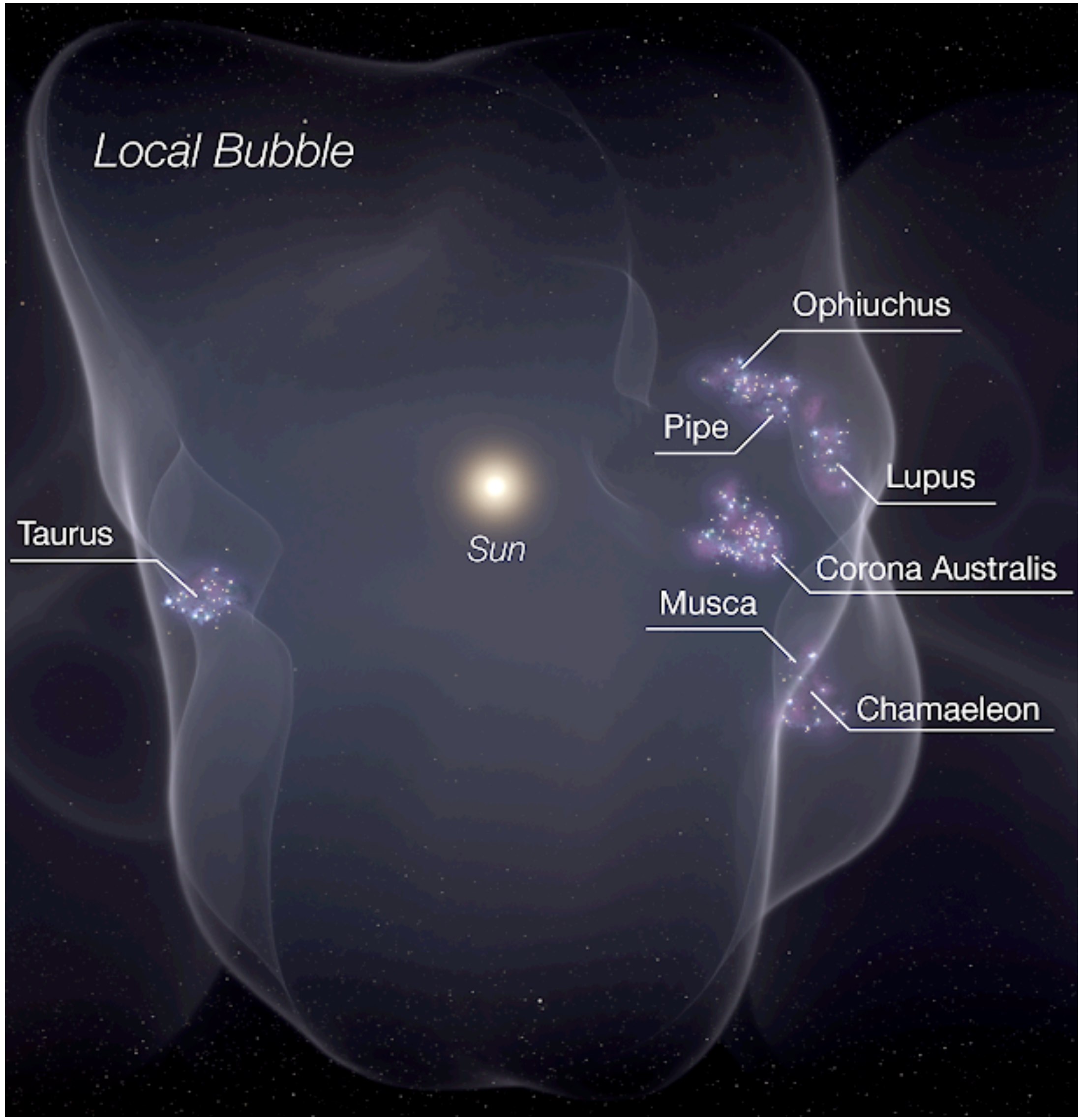


- **Molecular gas:** where star formation takes place. Temperatures of 10-50 K, densities reaching as high as 10^3-10^6 cm^{-3}.
- **Cold neutral medium (CNM):** mostly atomic gas with T~100 K and n_H~30 cm^{-3}.
- **Warm neutral medium (WNM):** mostly atomic gas with T~5000K and n_H~0.6 cm^{-3}.
- **Warm ionized medium:** gas that is photoionized by hot stars with T~10^4 K and a wide range of densities.
- **Hot ionized medium:** gas that is shock heated by supernovae, with T>$10^{5.5}$ K and very low density (n_H~0.004 cm^{-3}).

Observing the Multiphase ISM

- How to study the hot ionized medium?
  - absorption lines of ions such as OVI in spectra of background stars
  - diffuse X-ray emission
- How to study cold and warm neutral medium?
  - emission from HI 21 cm emission (or absorption toward background QSOs)
  - emission from fine structure metals, i.e. [CII], [OI]
- How to study warm ionized medium?
  - emission from hydrogen recombination lines (i.e., H-alpha)

Gas in the Solar Neighborhood



- The Sun sits inside a bubble of hot ionized gas called the Local bubble, thought to be roughly 100 pc across.

- Generated by supernovae explosion within the last 20 Myr.

Radial Distribution of Cool Gas in the Galaxy

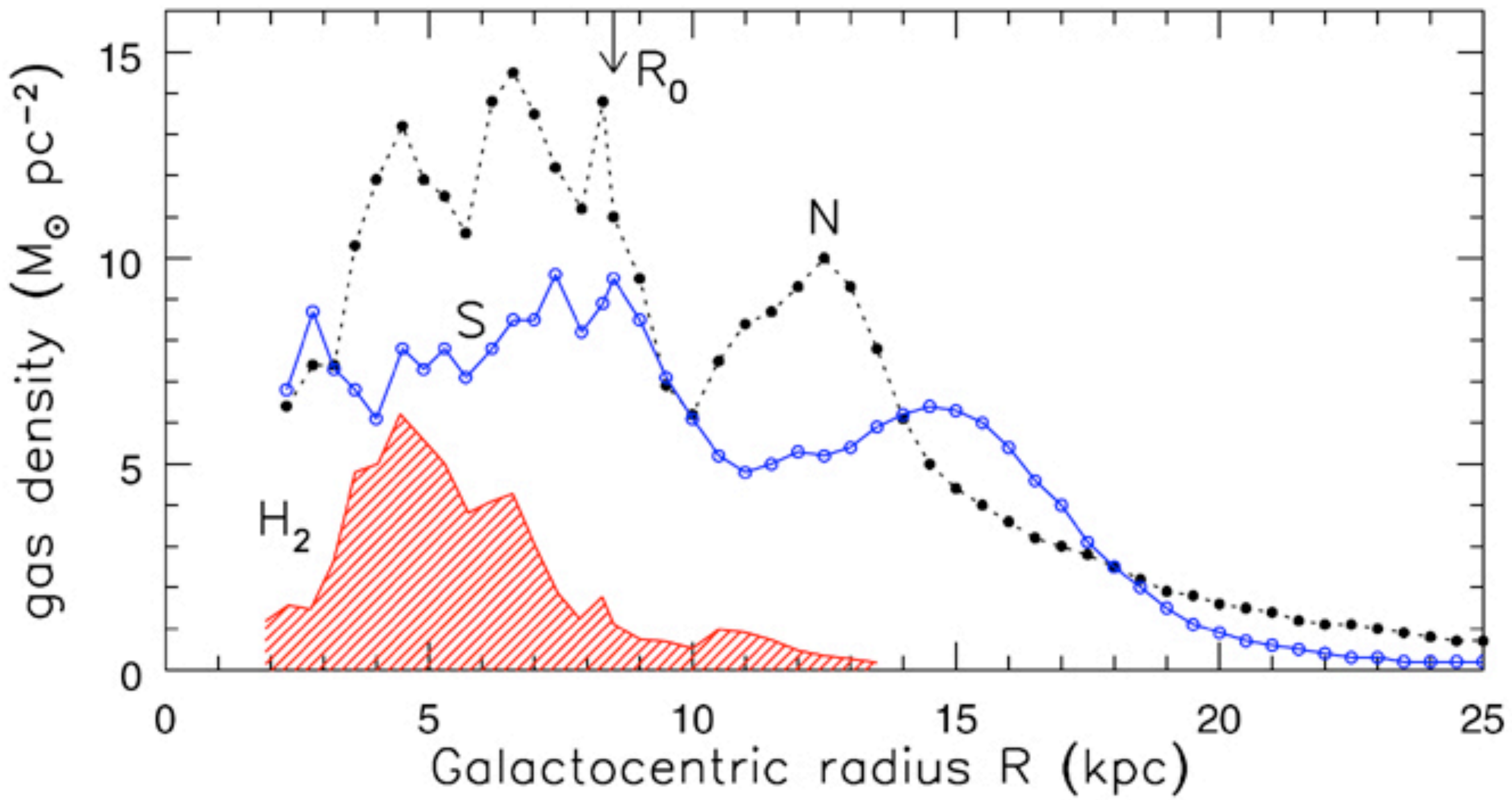
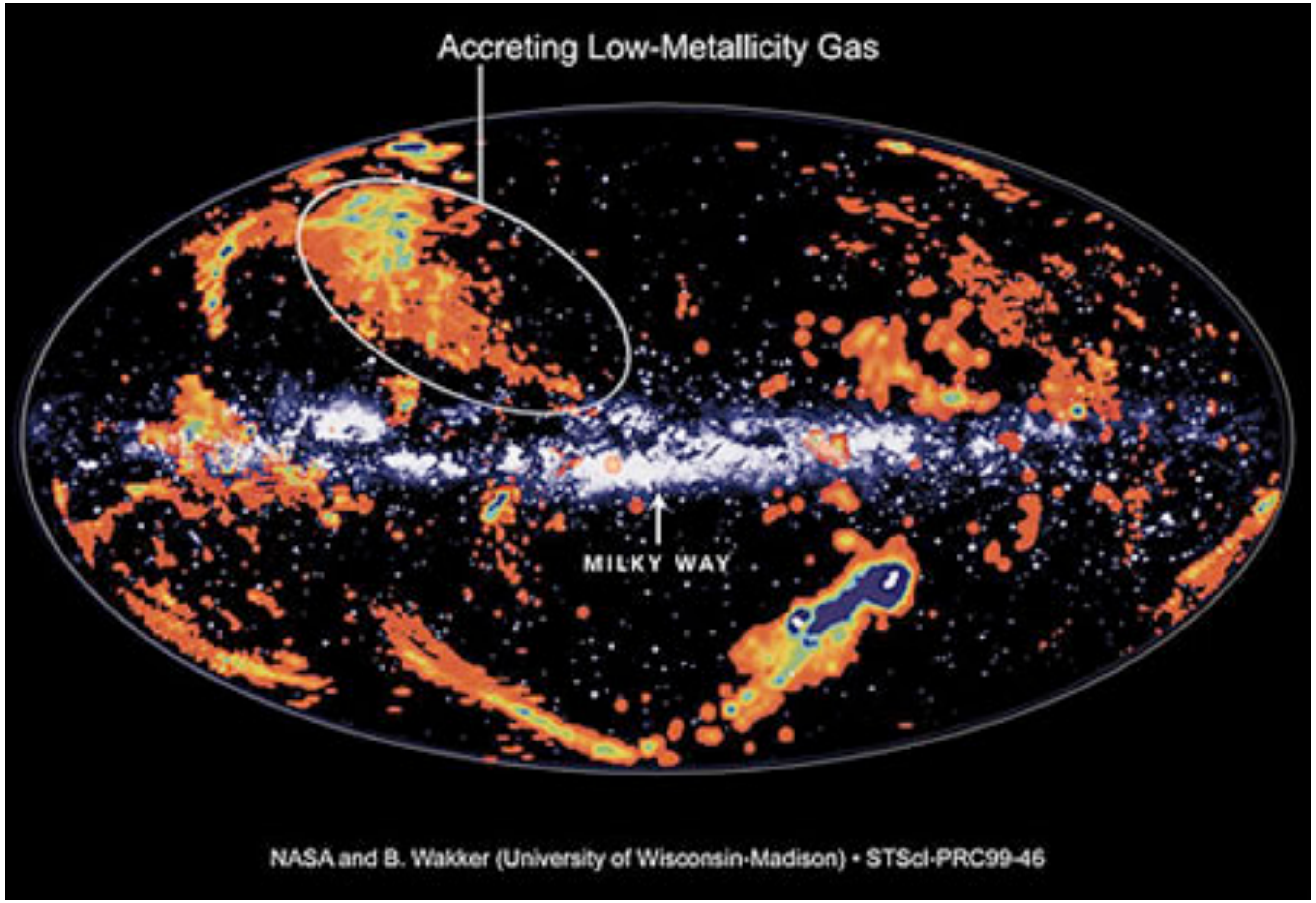


Fig 2.22 (Burton, Dame) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

- HI gas density begins to fall off beyond R_0 but extends to large radii.
- HI is thicker than molecular gas and puffs up at larger radii.
- Molecular gas concentrated in spiral arms. Most within the Solar circle (i.e., <R_0), concentrated in ring at R~4 kpc.
  - Inside this ring, little molecular gas (except in and around nucleus).

Gas above the Midplane



- As we look above mid plane, we see high-velocity clouds of HI gas.
- Origin?
- Disk material thrown up via supernovae? Gas accreting from IGM?
- Beyond 1-2 kpc from mid plane most gas in Milky Way is hot or warm. Seen in absorption toward background stars/quasars).

The Phases of the ISM

Table 1.1 Ryden & Pogge, ISM and IGM

Name	T [K]	n_H [cm^{-3}]	Mass fraction	h_z [pc]
Molecular Clouds	15	>100	20%	75
Cold Neutral Medium	80	40	30%	100
Warm Neutral Medium	6000	0.4	35%	300
Warm Ionized Medium	8000	0.2	12%	900
Hot Ionized Medium	10^6	0.004	3%	3000

[a] *Data from Ferrière 2001 and Tielens 2005*

- Densities and temperatures suggest all phases have similar pressures (P~nkT~4x10^{-13} dyn cm^{-2}).
- Note these pressures are much lower than those we find on earth. Even our best vacuums only get to $\lesssim 10^{-9}$ dyn cm^{-2}. For room temperature (T~300K), this implies much larger densities (20,000 cm^{-3}) than are typically found in ISM.
- Tempting to think different phases are entirely described by thermal pressure equilibrium, but this picture is too simplistic.
    - Free electrons couple ISM to magnetic field, so magnetic pressure is important.
    - Shock waves from supernovae and stellar winds produce turbulent kinetic energy which also must be taken into account.
    - Lots more to consider than just thermal pressure equilibrium!

Stability of Phases of the ISM

- Starting in a classic paper by Field et al. 1969, astronomers have sought to generalized ISM models that explain how the phases arise and why they have the properties they do.

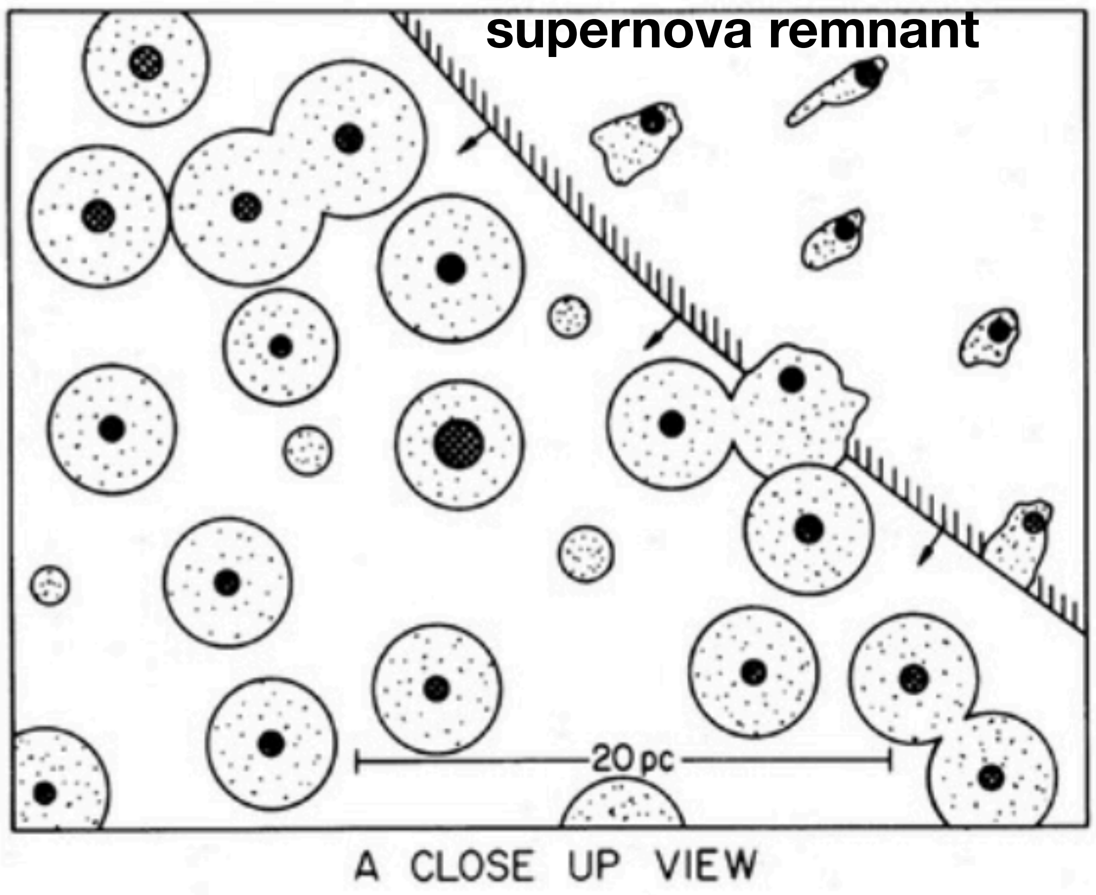


FIG. 2

From McKee & Ostriker, 1977

- Three-phase models by McKee, Ostriker developed in 1970s, linking production of hot ISM phase to expanding supernova blastwaves.

- As supernova remnants (SNRs) expand, they envelope cooler phases of the ISM. Large fraction of ISM volume filled with very hot gas (~10^6 K) at low density (~0.002 cm^{-3}).

- In these models, the filling fraction of the ISM in the hot phase depends on the supernova rate per volume.

- Can make predictions on ISM multiphase nature if you know something about star formation history of your galaxy.

Next Steps in Multiphase ISM Model Development

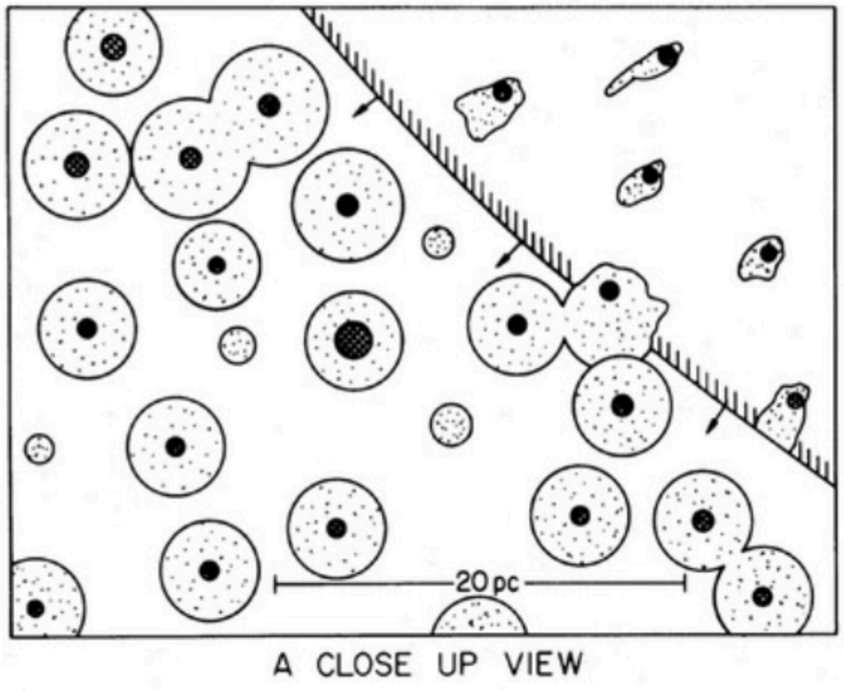


FIG. 2

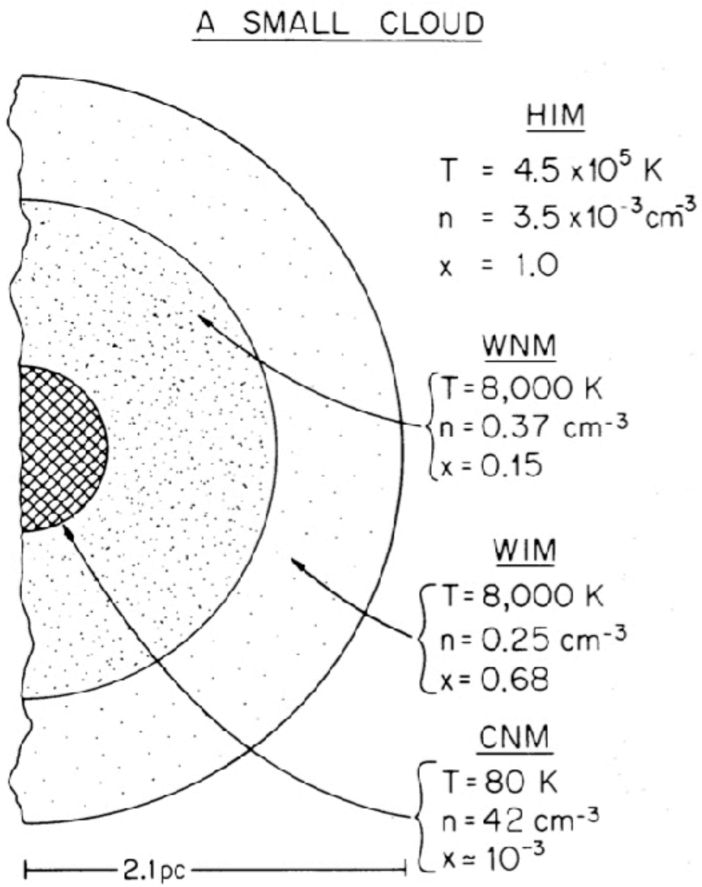
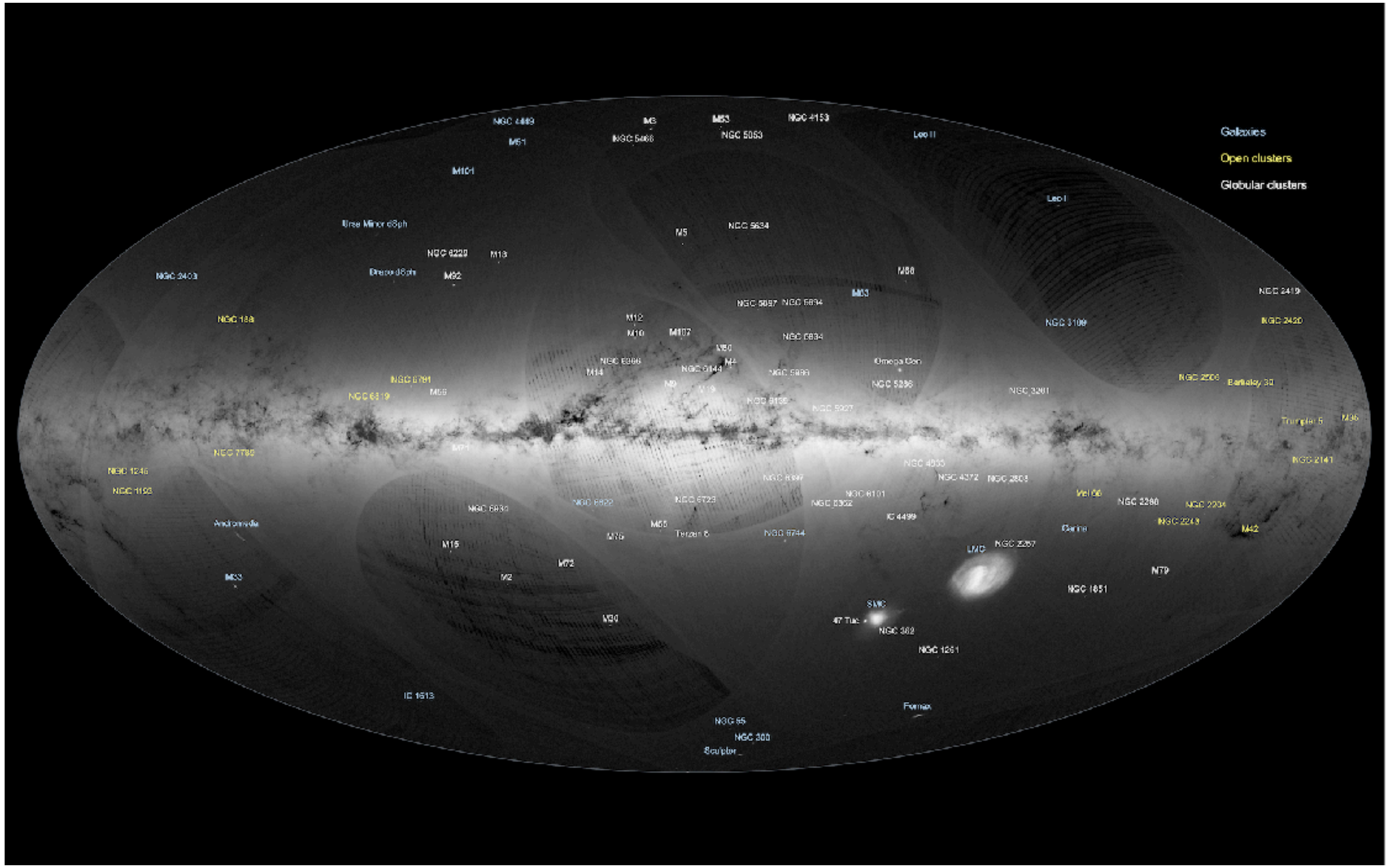


FIG. 1

- Cool clouds within the hot ISM have several phases, with the CNM in the center and WNM around it.
- These models are able to reproduce many of the basic properties of the ISM phases.
- Although clearly some simplifications (not everything is a sphere, need magnetic fields and turbulence!).
- Treatment of the various ISM phases is central to galaxy simulations!

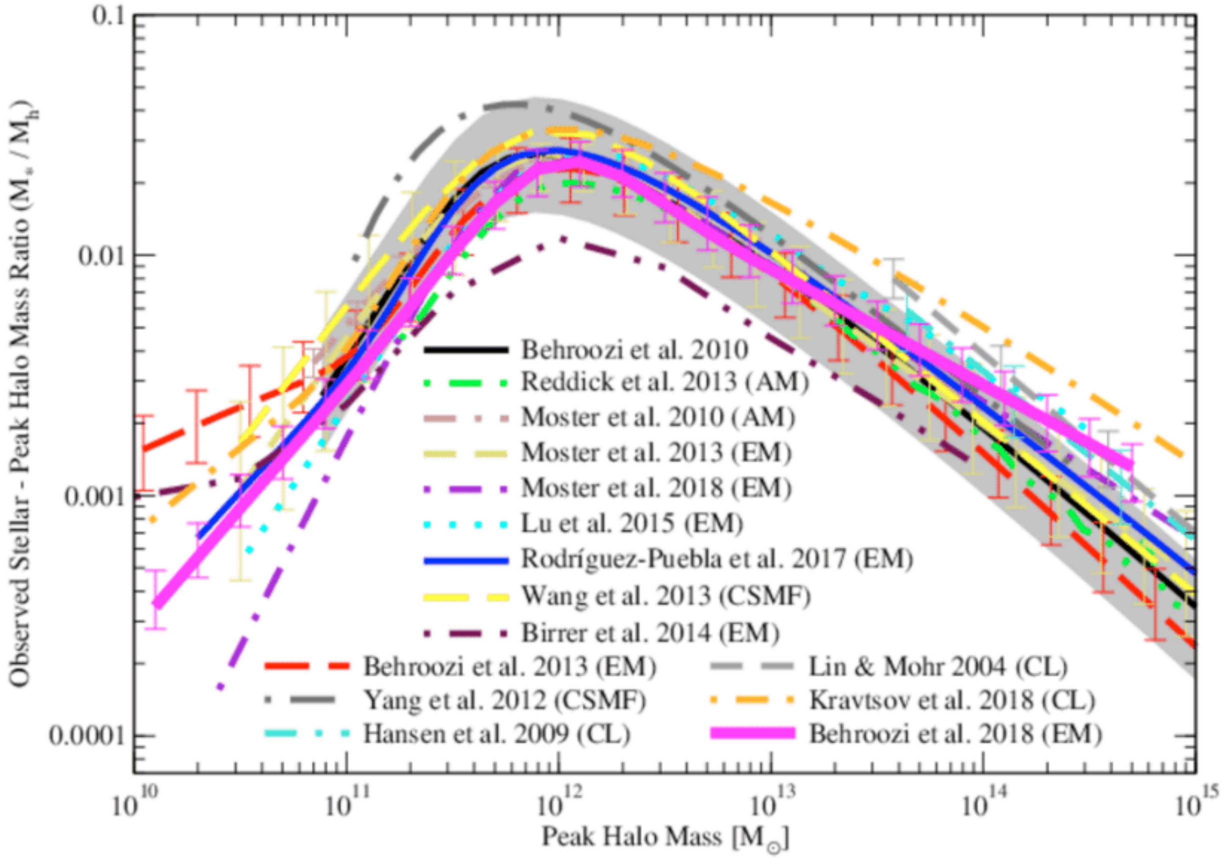
Galaxy Formation Efficiency and Metallicity



- We can characterize the efficiency with which galaxies convert their gas mass to stars using the ratio M(HI) / L_B
- We just learned that the total mass of the Milky Way's ISM is ~12% of its mass in stars. Is this true for all galaxies?
  - No – less massive galaxies tend to have higher gas fractions!
- For the Milky Way, LMC, and SMC:
  - SMC: M(HI) / L_B ~10
  - LMC: M(HI) / L_B ~0.2
  - Milky Way: M(HI) / L_B ~ 0.1

Galaxy Formation Efficiency and Metallicity

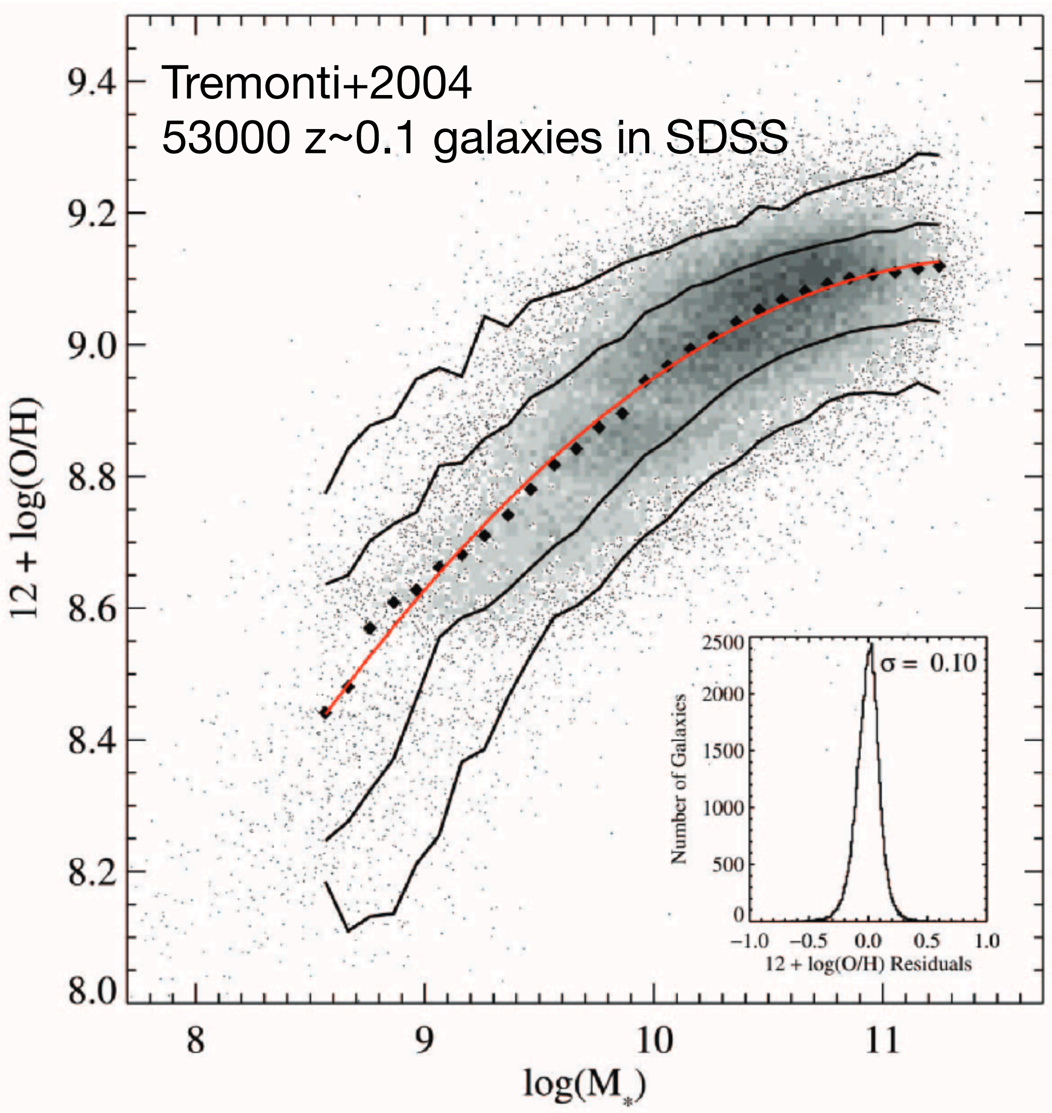
Formation efficiency of a galaxy



- We can characterize the efficiency with which galaxies convert their gas mass to stars using the ratio M(HI) / L_B
- We just learned that the total mass of the Milky Way's ISM is ~12% of its mass in stars. Is this true for all galaxies?
  - No – less massive galaxies tend to have higher gas fractions!
- For the Milky Way, LMC, and SMC:
  - SMC: M(HI) / L_B ~10
  - LMC: M(HI) / L_B ~0.2
  - Milky Way: M(HI) / L_B ~ 0.1

- More generally, we see a relationship between **galaxy mass** and the **formation efficiency of a galaxy,**
  - where ratio of galaxy stellar mass to halo mass = formation efficiency.

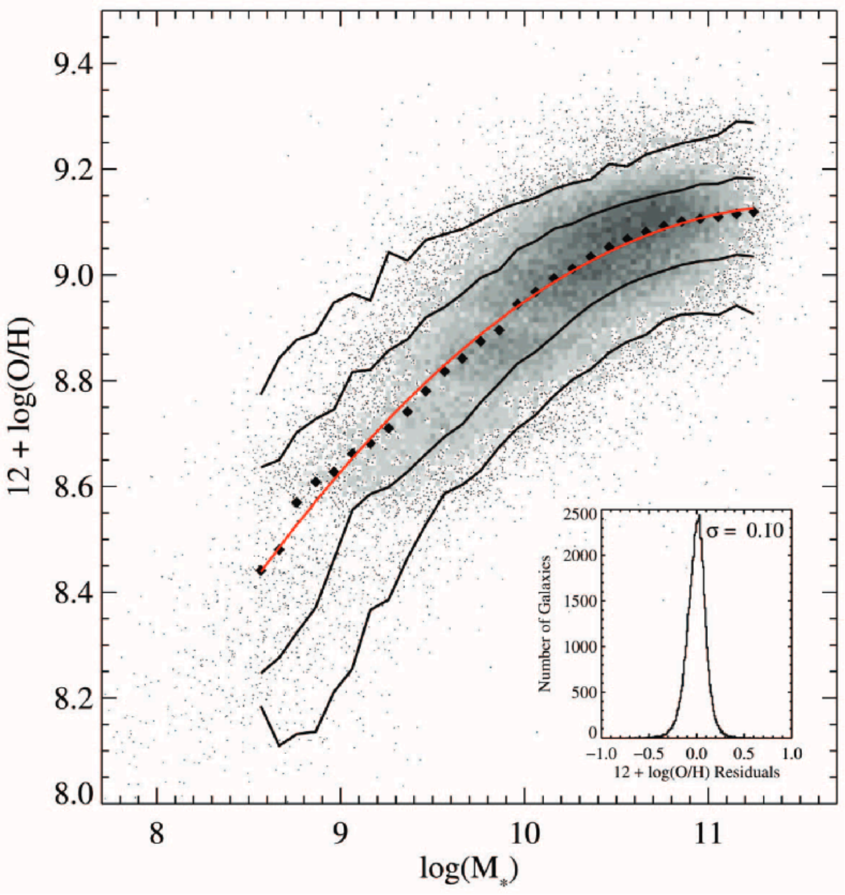
The Metal Content of Gas in Galaxies

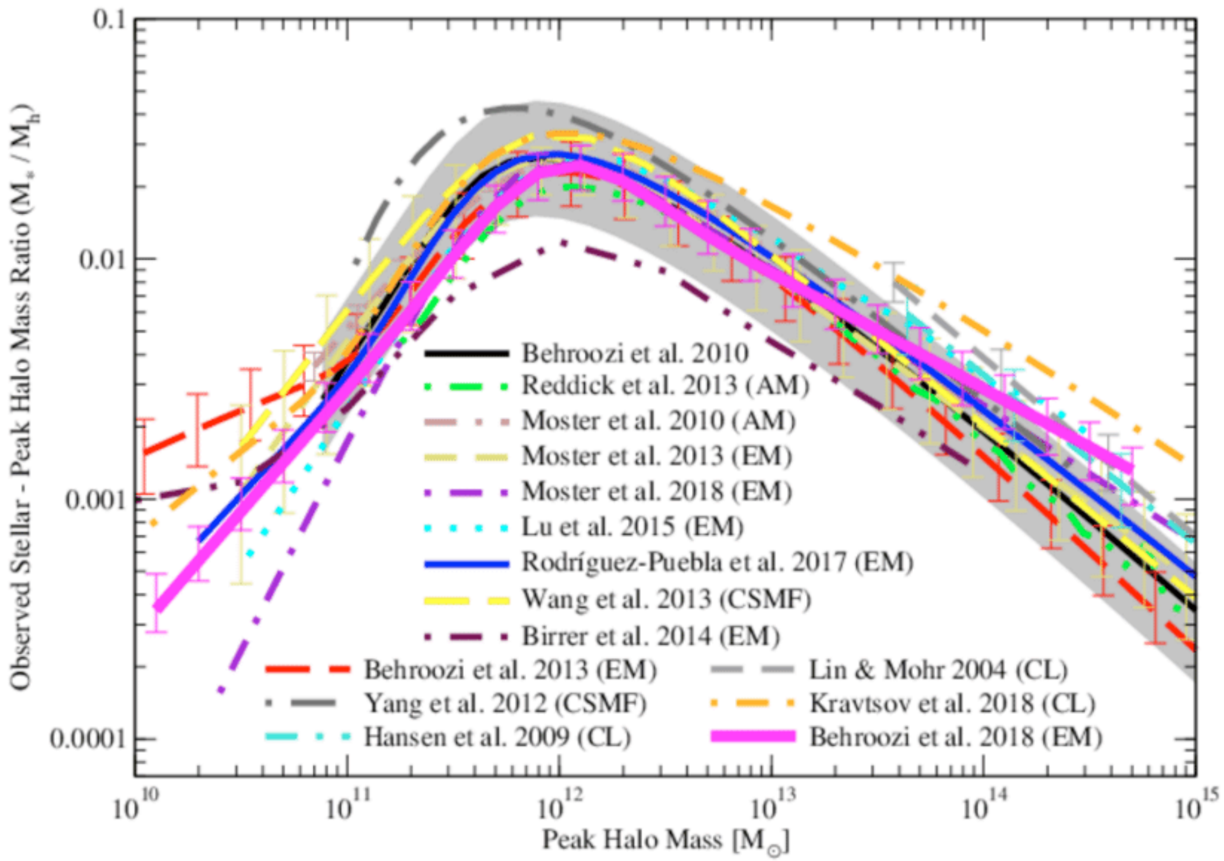


- We also observe a relationship between the metallicity of a galaxy and its stellar mass (i.e. the total mass of stars in the galaxy)
  - At left, we see such a **mass metallicity relationship** where the metallicity = the abundance of oxygen (O/H) in the gas content of the galaxies.
  - It is common to refer to the gas-phase oxygen abundance in units of 12+log O/H, where the solar value is 12+log O/H = 8.8.

    i.e. O/H = $10^{-3.2}$ = 0.00063
  - Note: this is for disk galaxies that have ample supplies of gas!

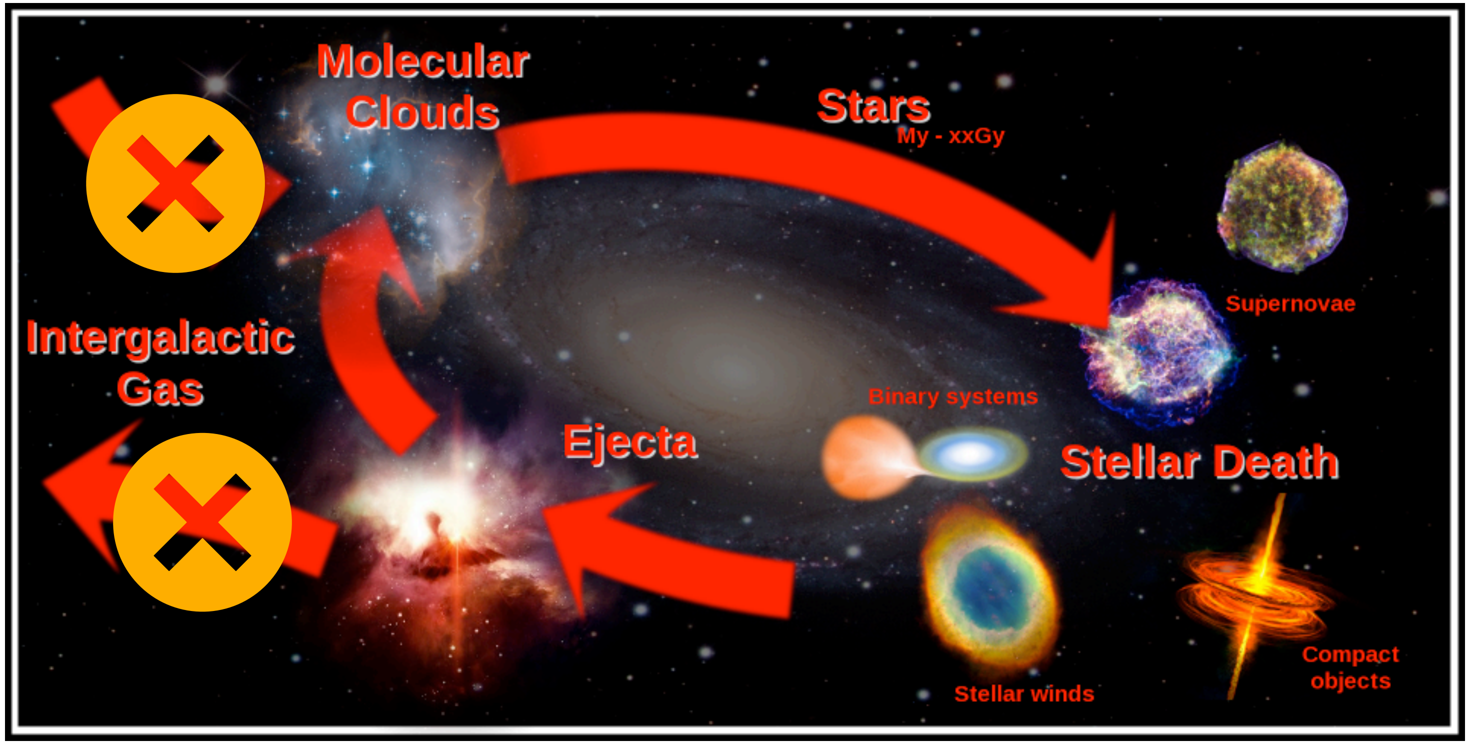
These Relations Tell us Galaxy Formation Depends on Mass!





- Both carry tremendous amount of insight into the process of galaxy formation.
- We must understand what makes low mass galaxies (i) form fewer metals and (ii) form less stellar mess.

To explore this, we can return to the baryon cycle

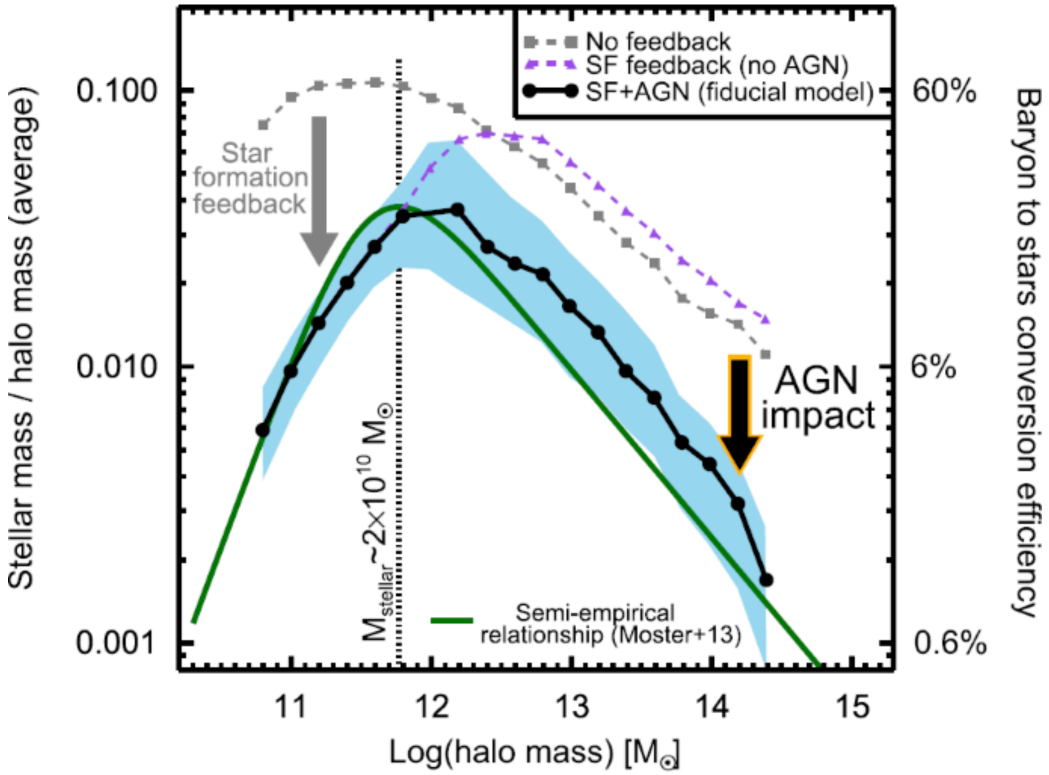


- Mass dependence of galaxy formation efficiency tells us baryon cycle different for galaxies of low/high mass.
- This in turn will contribute to mass-dependence of metal content.
- As we will see in today's breakout activity, a simple "closed box" model where we ignore gas exchange with the intergalactic medium can explain observations of the gas content of the Milky Way, LMC, and SMC.

Understanding Galaxy Formation Efficiency

- Some objects (e.g. globular clusters, dwarf spheroidal galaxies) are metal poor but do NOT have high gas fractions. In these systems, exchange with the IGM matters:
    - (1) Galactic winds common in star forming galaxies, carrying gas + metals away.
        - Winds likely driven by supernovae.
        - Low mass galaxies hold onto smaller fraction of gas + metals (weaker gravitational potential).
        - Less fuel for future star formation.
        - This is referred to as **supernovae feedback,** and it is thought to play a central role in limiting the build-up of stars in low mass galaxies.

Understanding Galaxy Formation Efficiency



- Some objects (e.g. globular clusters, dwarf spheroidal galaxies) are metal poor but do NOT have high gas fractions. In these systems, exchange with the IGM matters:
  - (1) Galactic winds common in star forming galaxies, carrying gas + metals away.
    - Winds likely driven by supernovae.
    - Low mass galaxies hold onto smaller fraction of gas + metals (weaker gravitational potential).
    - Less fuel for future star formation.
    - This is referred to as **supernovae feedback,** and it is thought to play a central role in limiting the build-up of stars in low mass galaxies.
- In massive galaxies, AGN feedback may play a similar role in limiting star formation by heating and accelerating the gas, possibly removing the cold gas supply required for star formation entirely