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# Complementary Astrophysics

## L6 - Star Formation

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# What did we learn?

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# What did we learn?

1. Scaling relations
2. Main sequence
3. Mass-Metallicity Relation
4. Fundamental MMR
5. Luminosity function
6. Mass function
7. Halo mass function

# Highlights

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# SMF

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## The evolution of the galaxy stellar mass function over the last twelve billion years from a combination of ground-based and *HST* surveys

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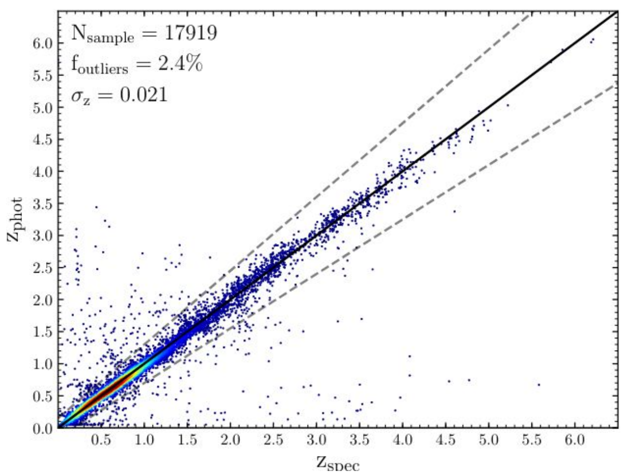
Accepted XXX. Received YYY; in original form ZZZ

**ABSTRACT**

We present a new determination of the galaxy stellar mass function (GSMF) over the redshift interval $0.25 \leq z \leq 3.75$, derived from a combination of ground-based and *Hubble Space Telescope* (*HST*) imaging surveys. Based on a near-IR selected galaxy sample selected over a raw survey area of 3 deg$^2$ and spanning $\geq 4$ dex in stellar mass, we fit the GSMF with both single and double Schechter functions, carefully accounting for Eddington bias to derive both observed and intrinsic parameter values. We find that a double Schechter function is a better fit to the GSMF at all redshifts, although the single and double Schechter function fits are statistically indistinguishable by $z = 3.25$. We find no evidence for significant evolution in $M^{\star}$, with the intrinsic value consistent with $\log_{10}(M^{\star}/\mathrm{M}_{\odot}) = 10.55 \pm 0.1$ over the full redshift range. Overall, our determination of the GSMF is in good agreement with recent simulation results, although differences persist at the highest stellar masses. Splitting our sample according to location on the UVJ plane, we find that the star-forming GSMF can be adequately described by a single Schechter function over the full redshift range, and has not evolved significantly since $z \simeq 2.5$. In contrast, both the normalization and functional form of the passive GSMF evolves dramatically with redshift, switching from a single to a double Schechter function at $z \leq 1.5$. As a result, we find that while passive galaxies dominate the integrated stellar-mass density at $z \leq 0.75$, they only contribute $\lesssim 10\%$ by $z \simeq 3$. Finally, we provide a simple parameterization that provides an accurate estimate of the GSMF, both observed and intrinsic, at any redshift within the range $0 \leq z \leq 4$.

# SMF

| Field | Area/arcmin$^2$ | $H_{160}$ depth/mag | Referenc |
|---|---|---|---|
| UDS | 202 | 27.5 | 1,3 |
| GOODS-South | 170 | 27.4–29.7 | 2,3 |
| COSMOS | 216 | 27.6 | 4 |
| EGS | 206 | 27.6 | 5 |
| GOODS-North | 171 | 27.8–28.7 | 6 |



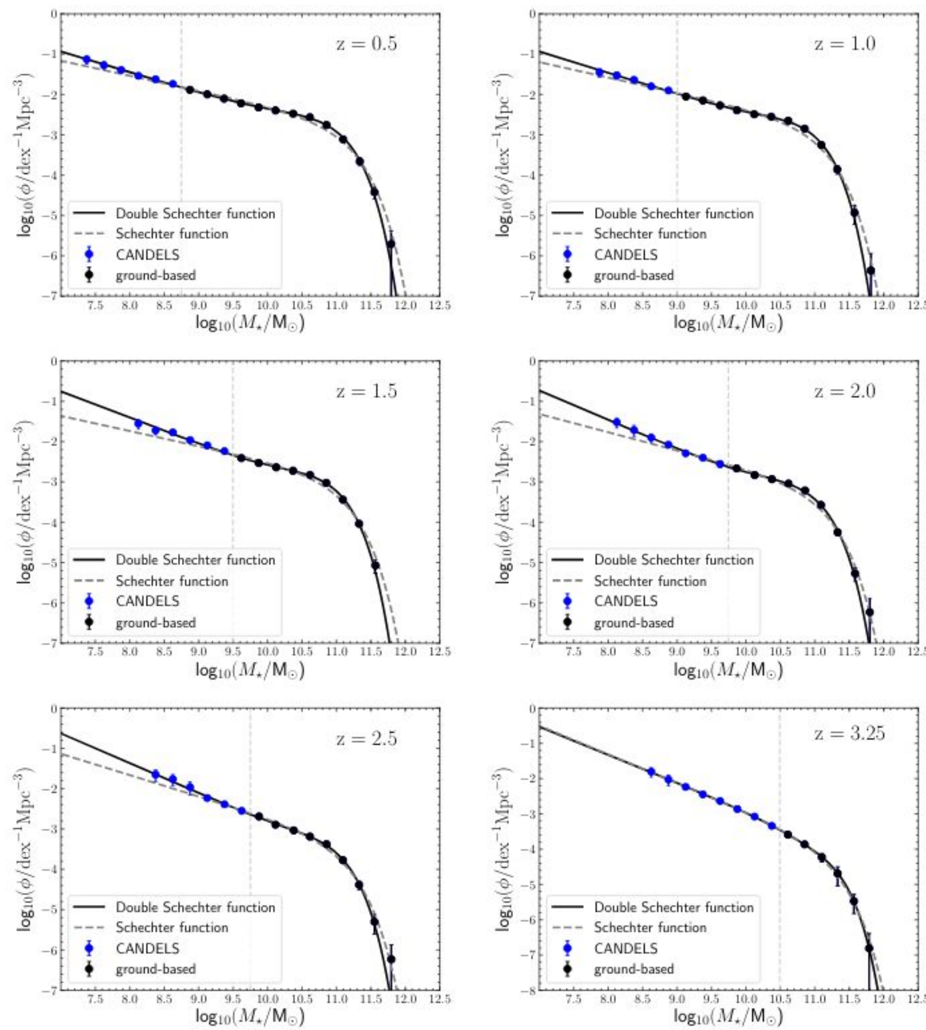




**Figure 4.** The observed GSMF as a function of redshift, based on the combined ground-based and *HST* data set. Also plotted are the best-fitting single (dashed grey) and double (solid black) Schechter function fits. The black data points are derived from the ground-based data set alone, while the blue data points are derived from the *HST* data set alone. The split between the ground-based and *HST* data is highlighted by the dashed grey vertical line. Over the redshift range $0.25 \leq z \leq 2.75$, the double Schechter fit is seen to be a better representation of the observed GSMF than the single Schechter fit. However, in the final redshift bin centred on $z = 3.25$, the single and double Schechter function fits are basically indistinguishable.

# SMF

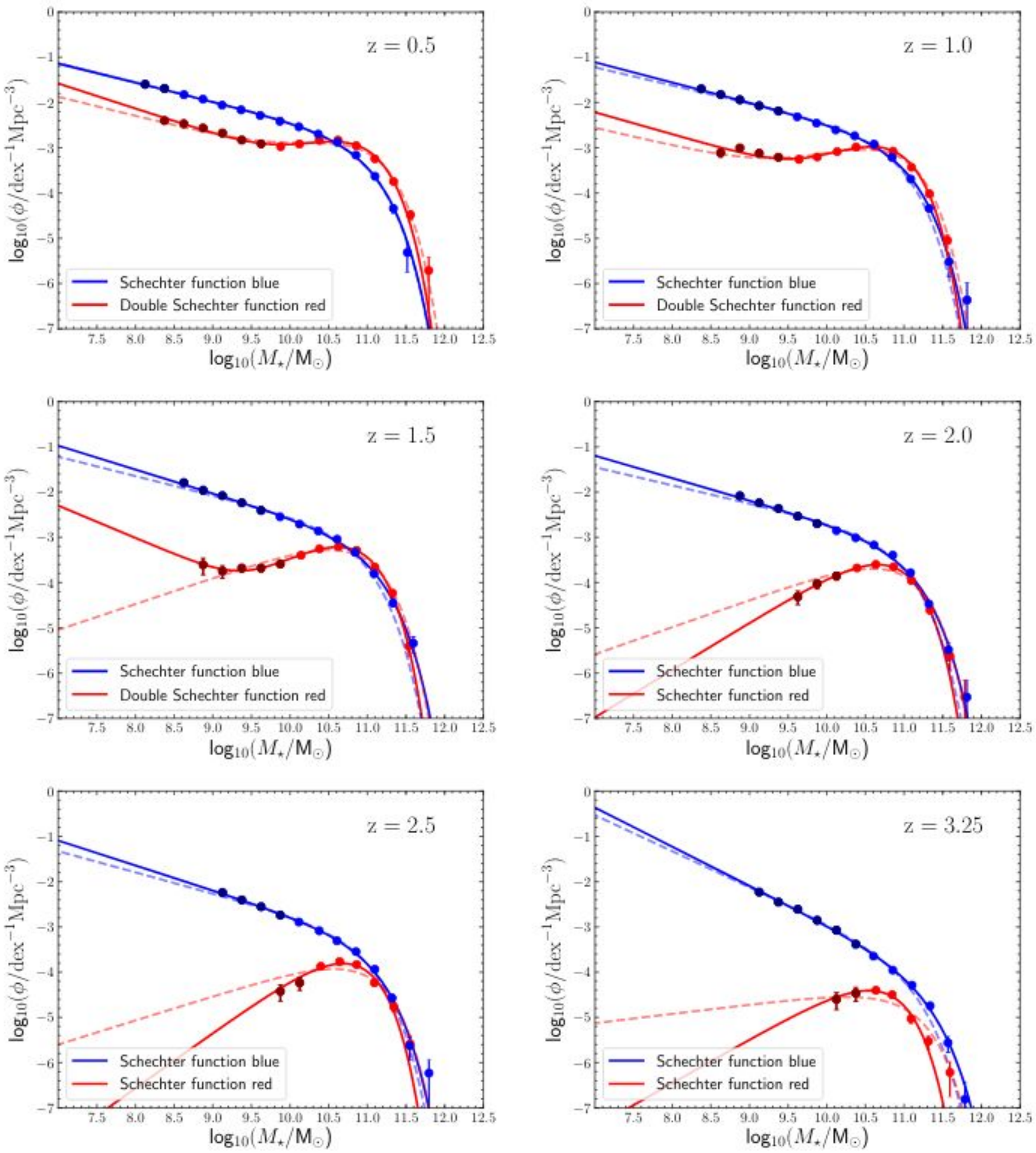



**Figure 12.** The redshift evolution of the observed GSMF for star-forming (blue data points) and passive galaxies (red data points). A darker shade of blue/red is used for the datapoints that are determined using CANDELS

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# Outline of the course

1. History
2. Review of the general concepts
3. Galaxies in our local Universe
4. Galaxies kinematics
5. Scaling relations
6. **Star formation**

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# Galaxy constituents

- Dark Matter – 90% of total mass from rot. Curves.
- Stars – 5-10% from optical/near-IR surveys
- Neutral Gas (HI) – 0-5% from 21cm observations
- Molecular Gas (HII, CO) – 0-1% from line observations
- Ionised Gas ($H^+$)
  - Hot interstellar medium
  - Warm interstellar medium
- Dust - <0.1% - From FAR BB Peak
- SMBHs < 1% - From core velocity dispersion studies
- WDs and BHs < 1% - stellar population synthesis
- Planets < 0.001% - Solar system

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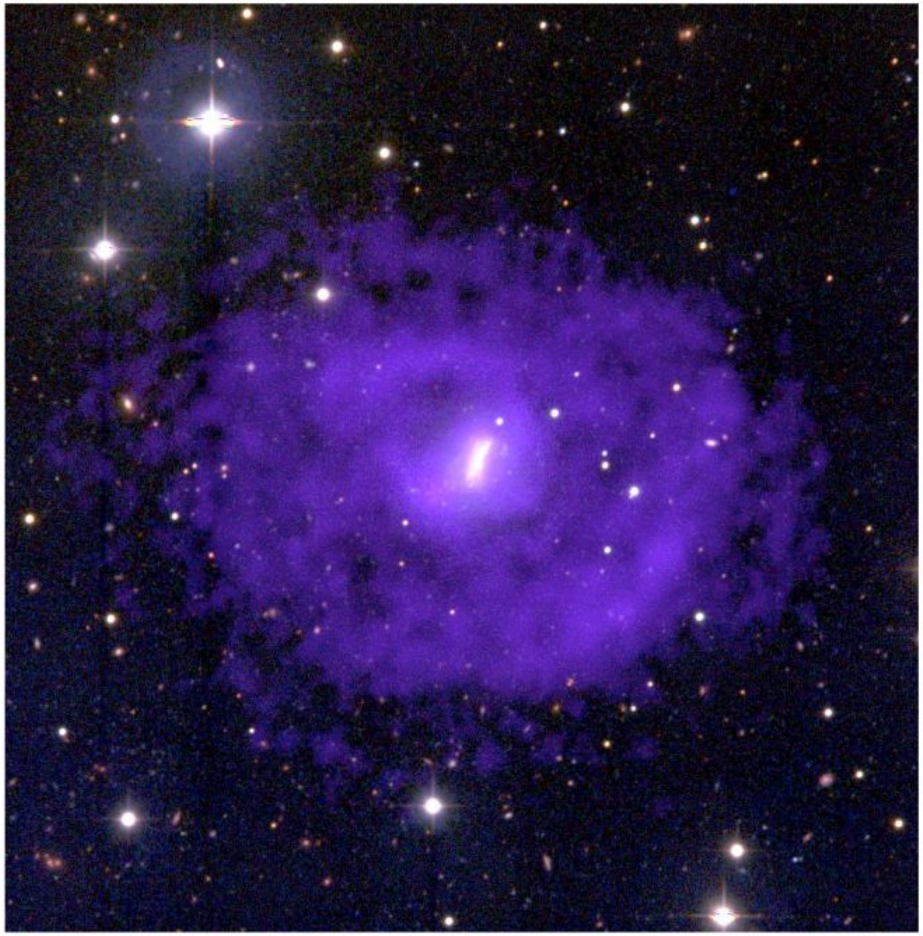
# Giant Gas discs (UGC5288, NRA, USA)

Purple = HI
White = stars



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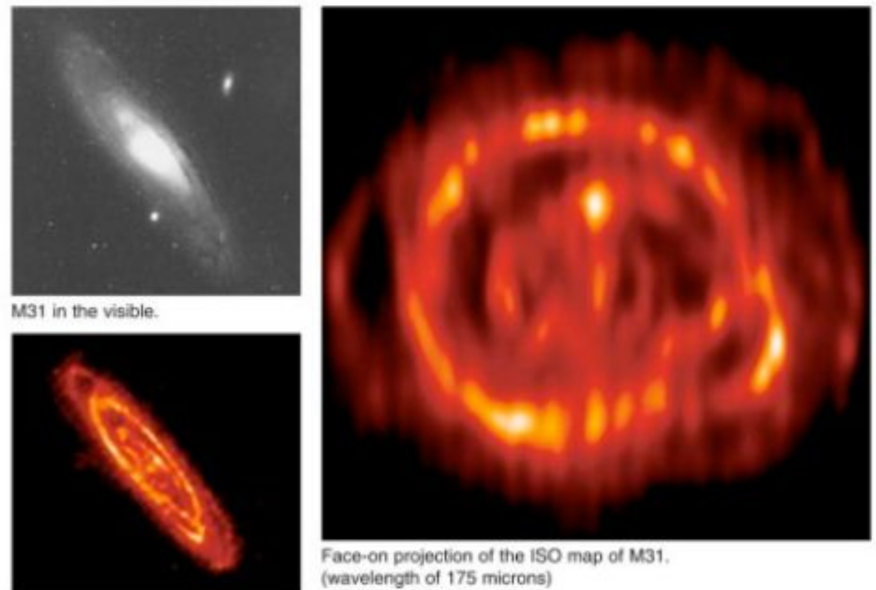
# Other gas phases

- gas distribution can be very complex, as a diffuse gas phase may fill ‘holes’ in a denser one (e.g. HI in $H_2$)
- gas ranges from cold molecular clouds through cold neutral medium, warm neutral medium, warm ionized medium up to hot ionized gas phase
  - powered by massive stars and supernovae
  - from ~ 10 K in molecular gas up to ~$10^6$ degrees in plasma
  - hotter phases form thick layers, because thermal velocities of particles are higher,

# Galaxy constituents

- much easier to map in other galaxies, e.g. M31, the nearest spiral
  - differs from MW in the location of the molecular gas clouds that will form the next generation of stars
    - in the Galaxy, these form a ring at 5 kpc, whereas in M31 the equivalent is the ‘ring of fire’ at 10 kpc



M31 in the visible.

ISO map of M31.
(wavelength of 175 microns)
North is up, east is left.

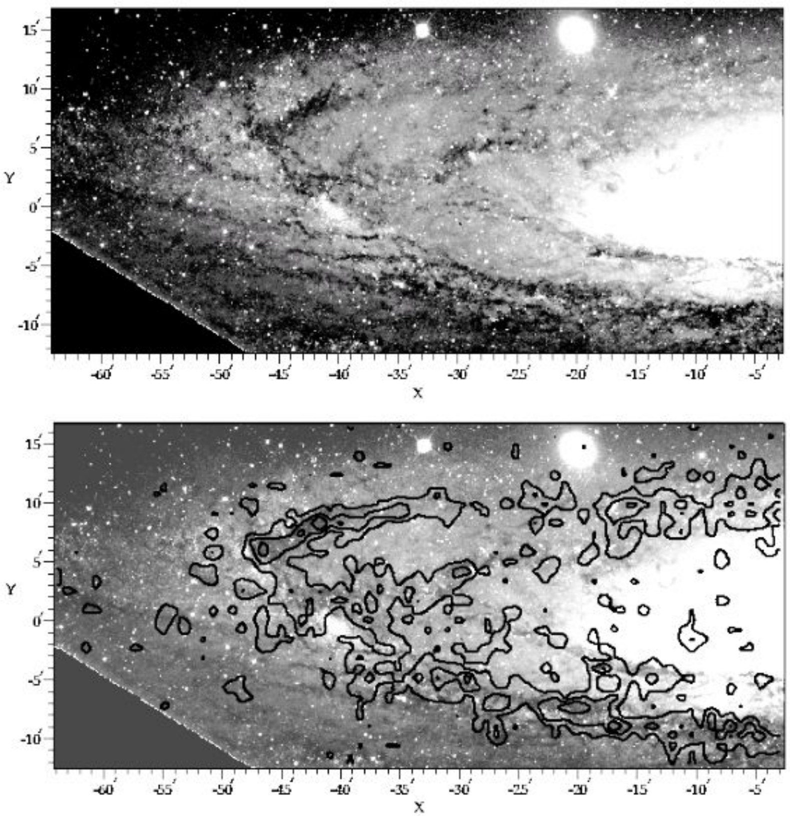
Face-on projection of the ISO map of M31.
(wavelength of 175 microns)
North-east is on the left.

*Credit:*
*For the infrared: ESA/ISO/ISOPHOT and M. Haas et al.*

images from ESO

# Clouds in Andromeda

- star formation only happens in the dense parts of the clouds as stars can only form from HII which MUST be shielded:
  - contours show CO emission while image is star light
  - the stars travel between arms but the clouds disperse




Plateau de Bure and IRAM 30m

# Cold material in galaxies

- some galaxies may have a reservoir of very cold gas and dust (much more non-stellar material than suspected)
  - e.g. the IRAS satellite observed cold dust emission out to 100 microns wavelength
- Wien's law tells us

$$T(\text{dust}) \times \lambda_{peak}\,(\text{mm}) = 3$$

for blackbody emission, so IRAS was not sensitive to material at less than ~ 30 K

  - measurements of the flux at 1 mm are needed to detect any very cold dust that was missed by IRAS

# Cloud masses

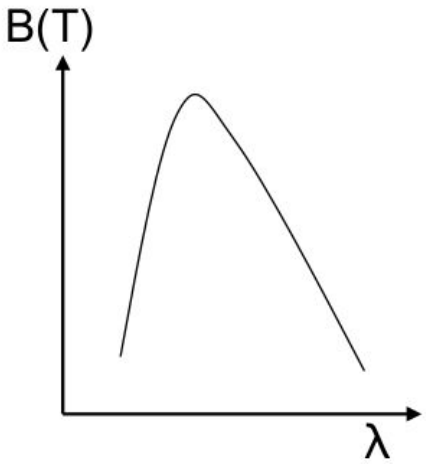
- for blackbody emission from dust particles:

  $M = F_\nu d^2 / B_\nu(T)\kappa_\nu$ (standard thermodynamics)

  where $F_\nu$ is the flux, d the distance, $B_\nu(T)$ is the Planck function and $\kappa_\nu$ is the opacity

  - $B_\nu(T) = (2h\nu^3/c^2)\,(\exp(h\nu/kT)-1)^{-1}$ and $\kappa_\nu$ is in $m^2$ per kg

- at long wavelengths, $B_\nu(T)$ simplifies to: $2kT\,(\nu^2/c^2)$ because $h\nu \ll kT$
- hence in the Rayleigh-Jeans (long-wavelength) tail, a 10x colder temperature implies 10x more mass for the same incident flux.
- however typically M[stars] >> M[clouds]



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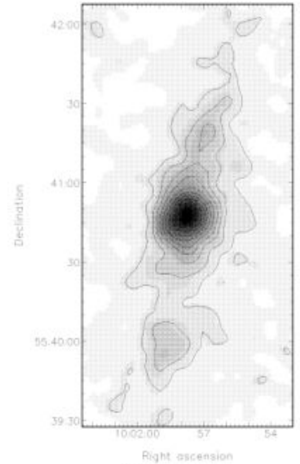
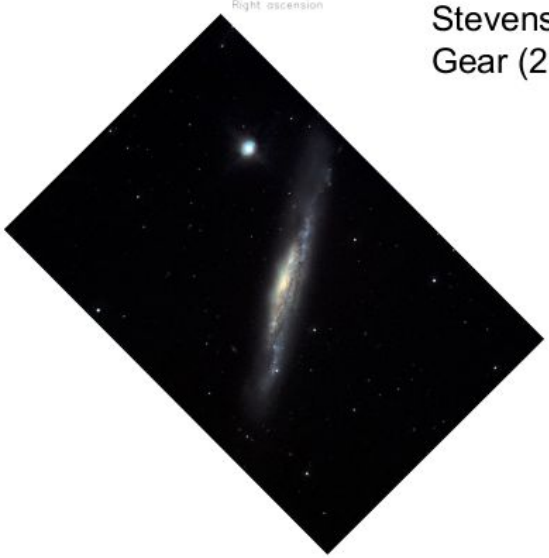
# Cold dust mass

- NGC 3079, nearby spiral
  - 90% of dust is at a temperature of only about 12 K
  - mass goes up ~10×
  - but not enough for dark matter
    - 99% in some galaxies
    - M(stars) is usually >> M(clouds)



Stevens & Gear (2000)

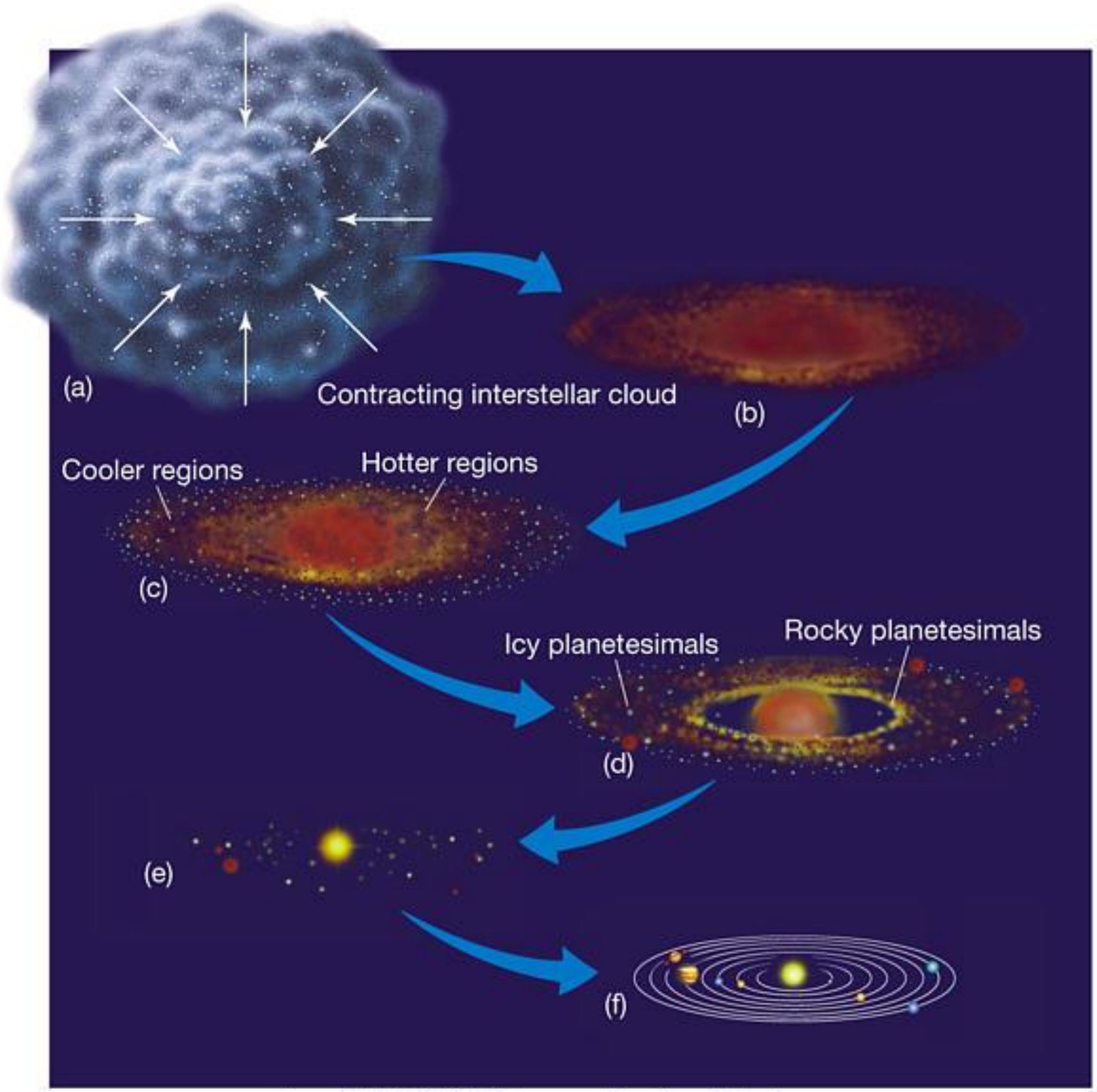
# Star formation

Star-formation is fundamental, but complicated

Involve:

***Interstellar medium =>***
***clouds =>***
***turbulence =>***
***Dense regions =>***
***Collapse =>***
***Star(s)!***

Dusty and obscured environments



# Star formation cycle

Cycle of matter from the ISM to stars and back to the ISM:

1) **Gas cooling process**: new stars form within the ISM. The gas displays dramatic density and temperature contrasts. The densest, coldest molecular regions offer an environment favorable to star formation.

2) **Collapse**: Interstellar gas becomes gravitationally unstable and collapse into new stars.

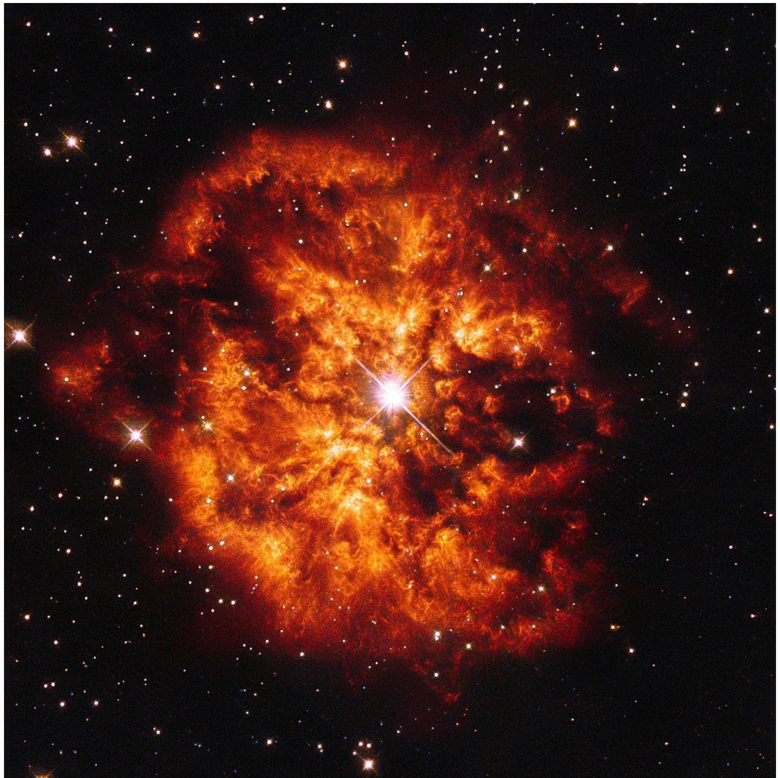
3) **Feedback**: Locked in the stars' interior, gas goes through a succession of thermonuclear reactions, which enrich it in heavy elements. A fraction of this matter returns to the ISM via powerful stellar winds or supernova explosions.

4) **Recycle**: The injection of stellar mass and energy into the ISM generates turbulent motions in the ISM and may give birth to new molecular regions prone to star formation.

This last step closes the loop of the partly self-induced ISM-star cycle.

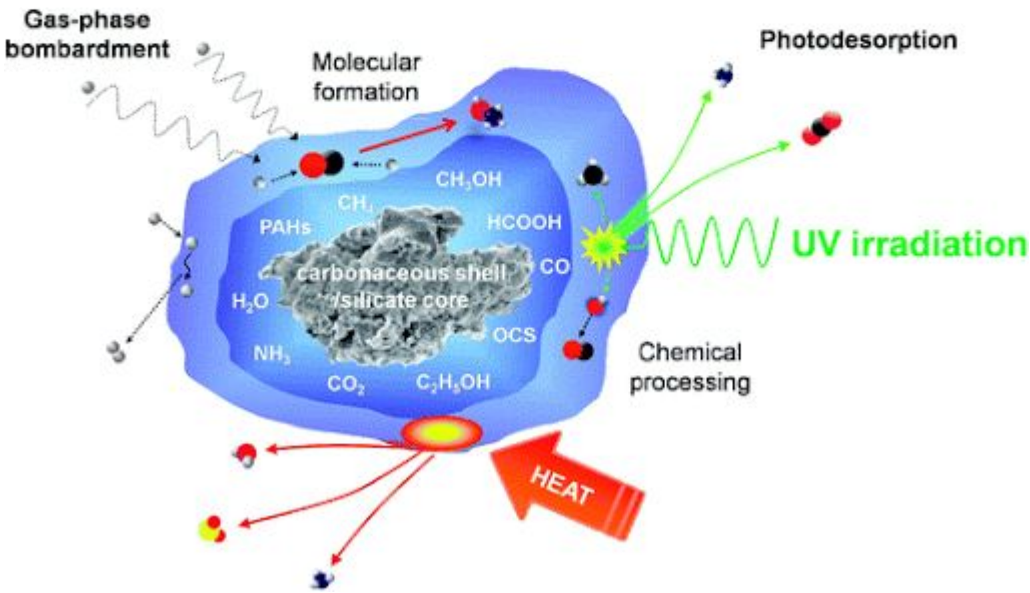
# Star Formation

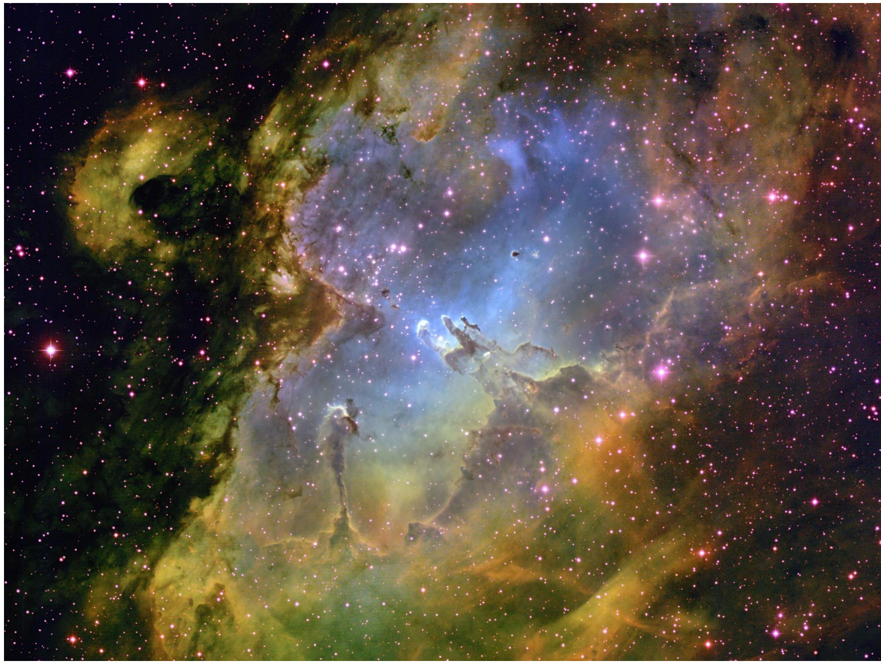
- Galaxies contain neutral (HI) gas
  - detectable at 21cm due to spin-flip transition
- If shielded from UV radiation molecular $H_2$ will form
  - Molecular cloud (typically $10^4 M_o$)
- Collapsing cloud fragments and stars form where $H_2$ gas is densest
  - Supernovae from massive stars with short lifetimes expel remaining gas
  - Young star cluster remains



# Molecular cloud

Star formation occurs in molecular gas clouds.
The process is triggered through the formation of hydrogen molecules ($H_2$) on the surface of dust grains, where two H atoms decay radiatively to a bound state.
The molecule has no permanent dipole moment and a small moment of inertia. The first rotational transition occurs at 28.2 μm, requiring a minimum gas temperature of T~150 K for appreciable collisional excitation.



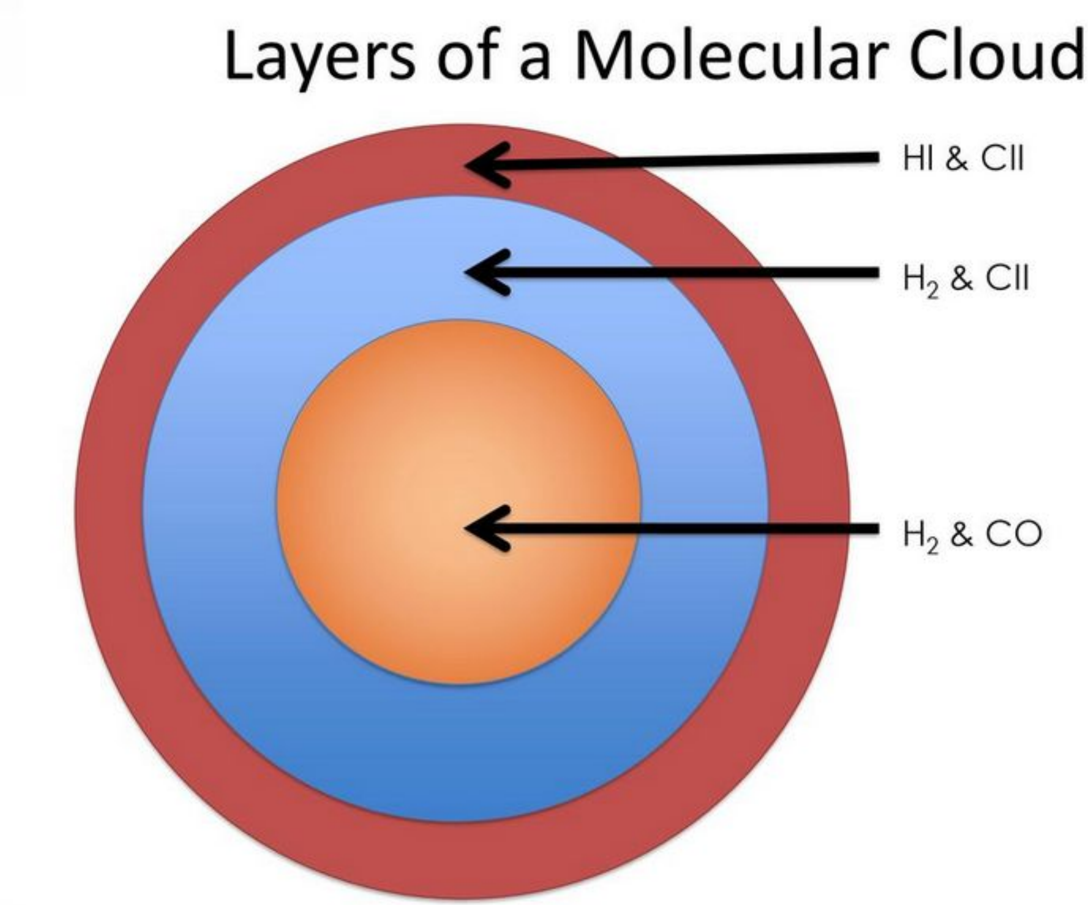



# Giant Molecular Cloud

Many examples exist of opague regions of molecular gas which become visible when viewed in far-IR wavelengths

# Molecular cloud

To overcome this problem other molecules are used as tracers: e.g. CO and HCN. The moment of inertia is higher because of the heavier atoms, and the lowest rotational transitions are at 115.2 and 88.6 GHz (2.6 and 3 mm wavelength), corresponding to 5.5 and 4.2 K.



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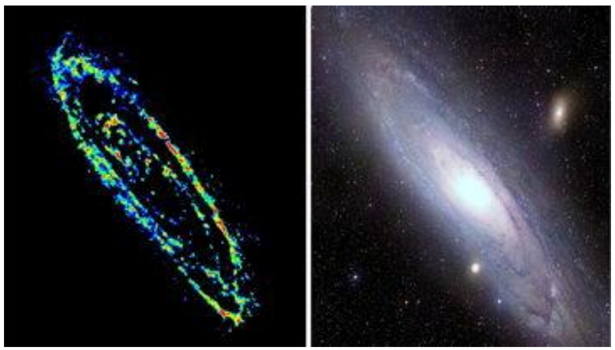
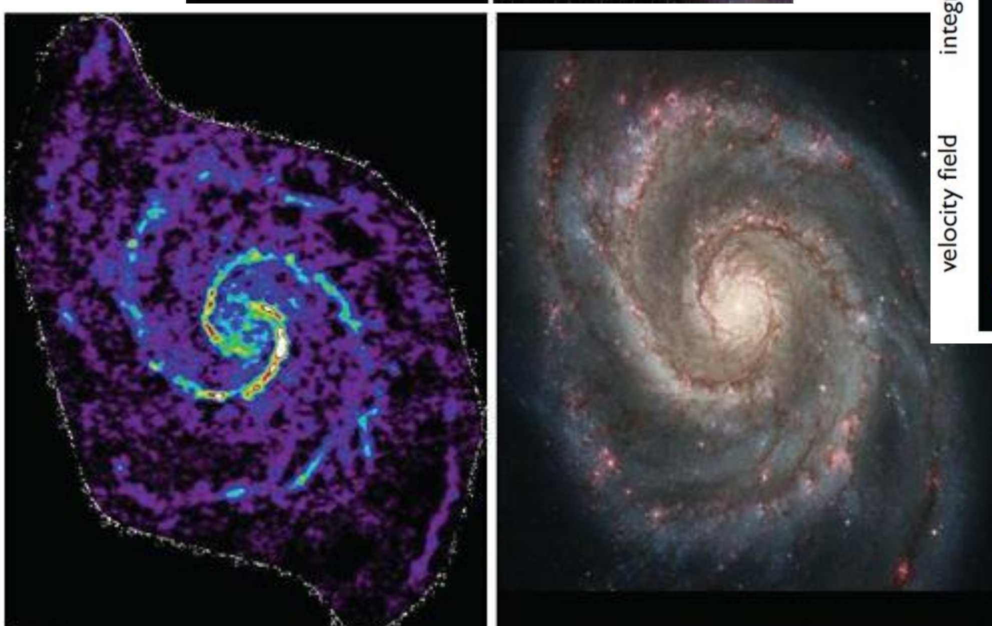
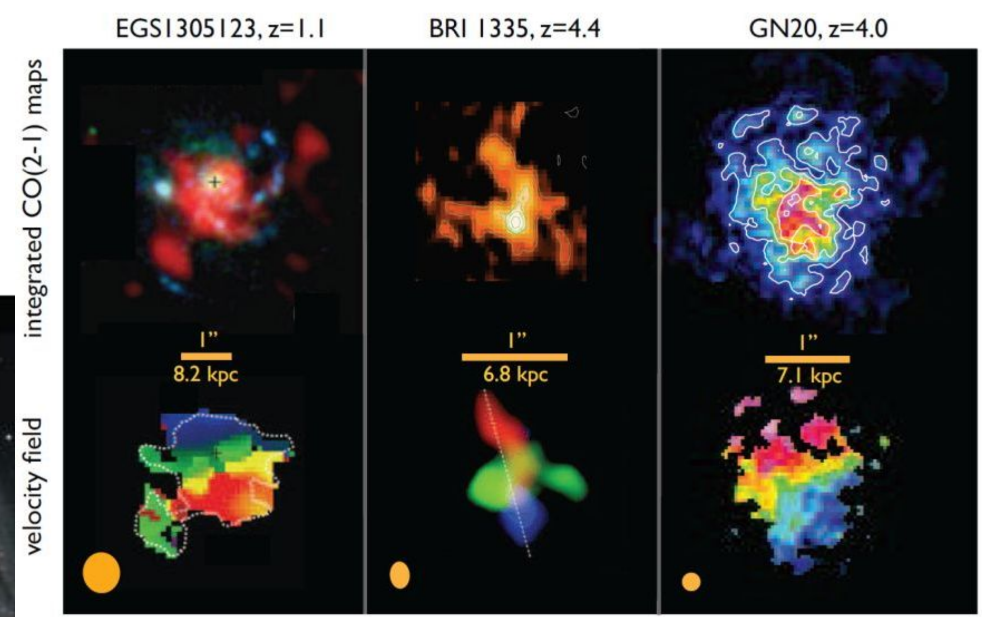


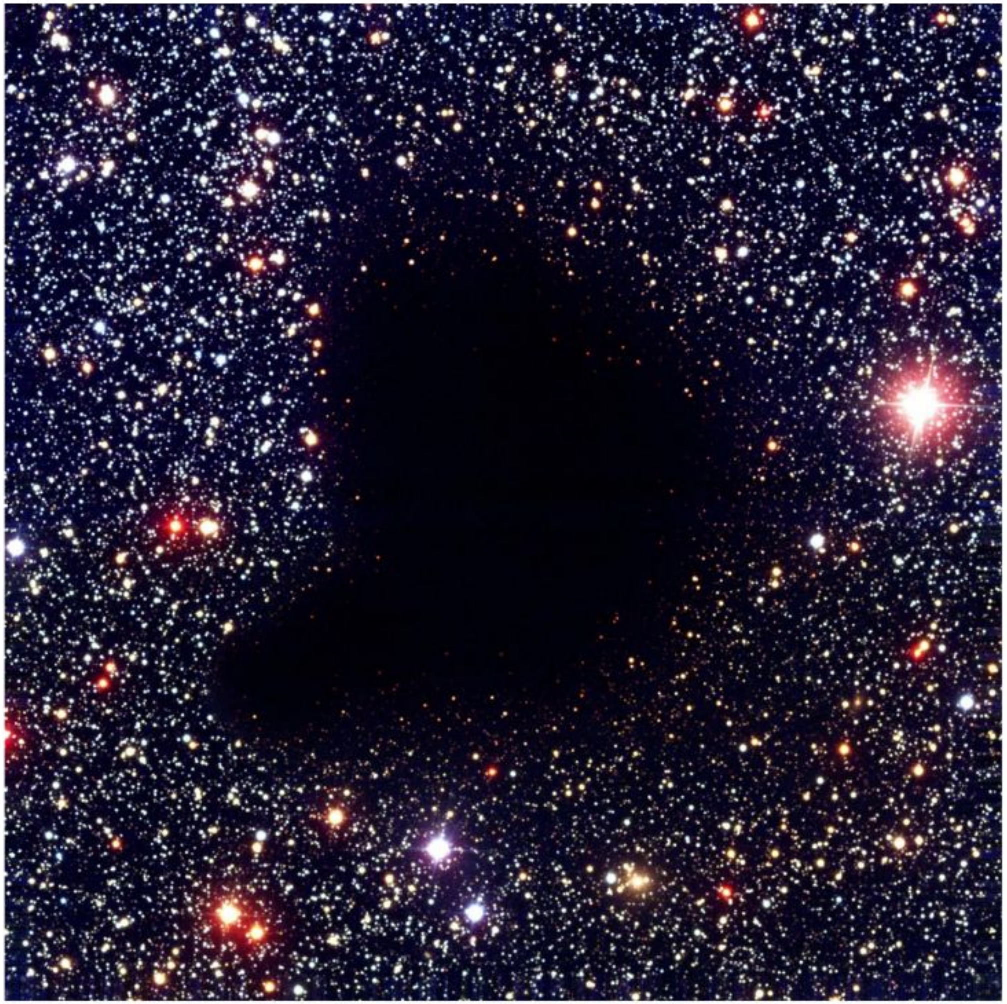




# Giant Molecular Cloud

$H_2$ is not directly detectable but one can take images of other molecules such as CO or see the impact of dust grain attenuation on background light

Here we see a dense clump of foreground dust blocking the background light

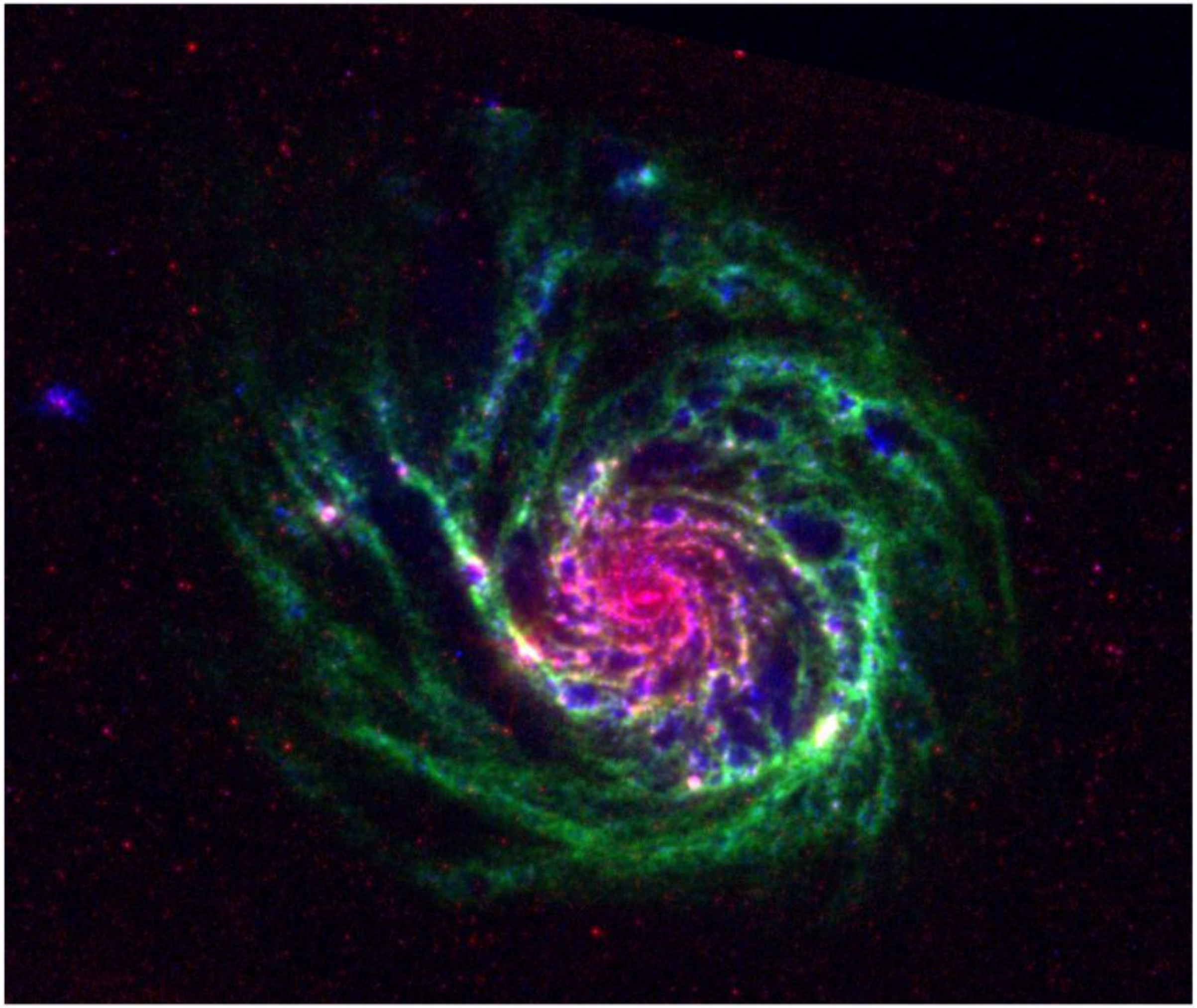


# Nearby galaxy with HI gas disc

Green = HI Gas
Blue = star-formation
Red = warm dust

Ionised gas is constantly accreting onto galaxies from the IGM, as it does so it cools and recombines to create neutral gas (HI) shown here in green.

Star-formation shown in blue occurs in regions where the HI is densest



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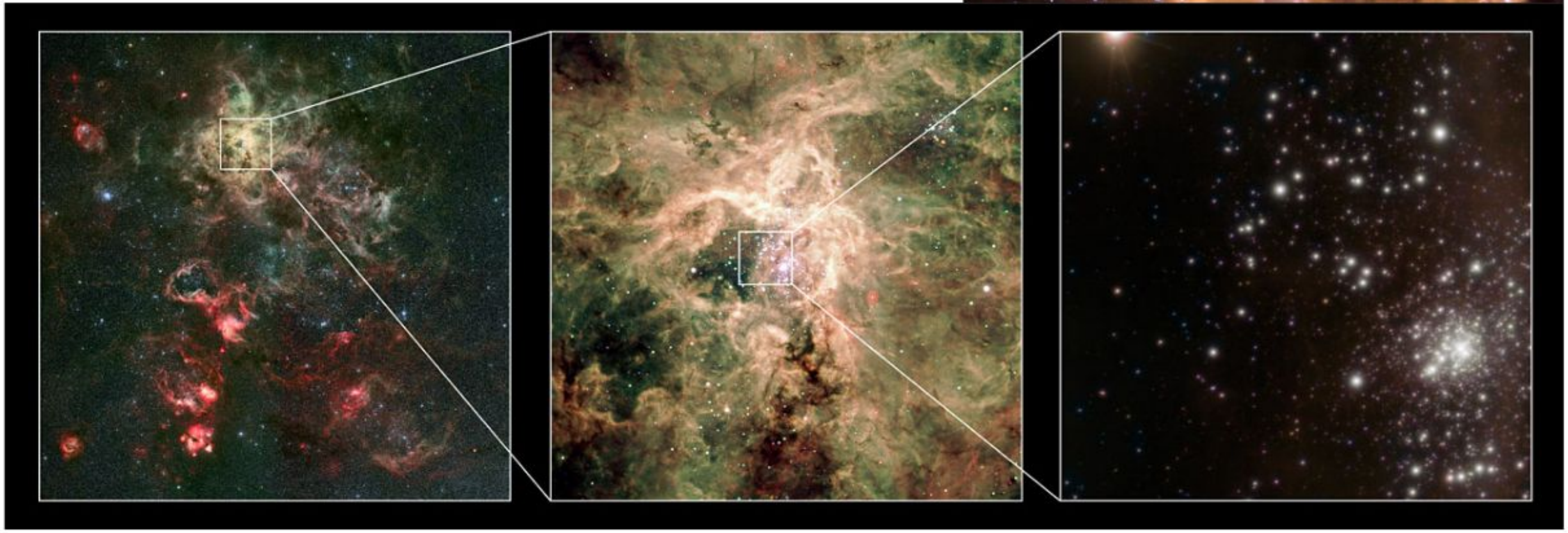
# Emerging star cluster

As stars form they first generate UV radiation ionising the surrounding gas and then SN shocks which push the material away revealing the young star cluster.

# Early Supernovae

Process continues until star cluster is entirely Distinct from the originally cloud.

Typically only a small fraction of the original gas cloud has been converted into stars, the rest survives for now…



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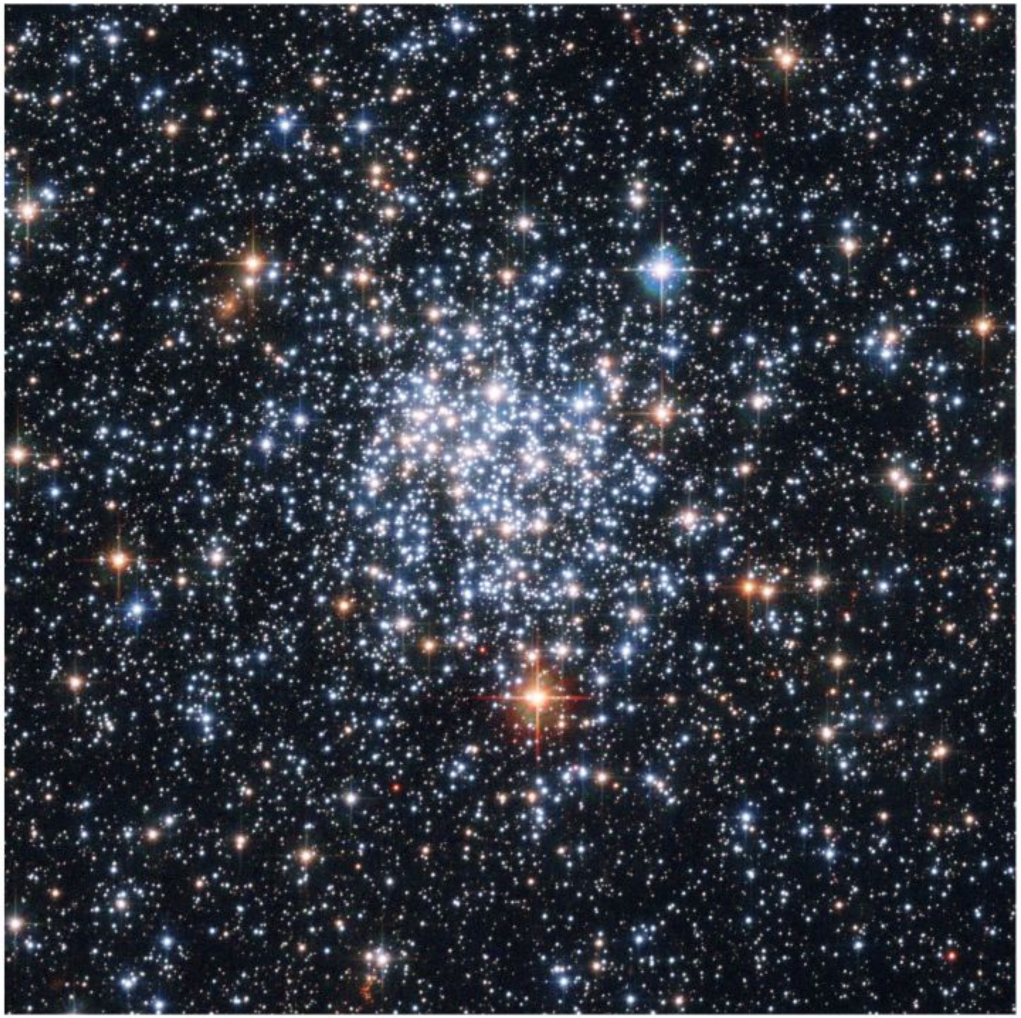
# Young star cluster

In a young star cluster the stars appear to be quite concentrated but are not gravitational bound

As time goes by the stars will dissipate and moving apart to form an Open Cluster



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# Open cluster

After a ~billion years the cluster has integrated into the galaxy as a whole.

Only the dynamical and chemical information provide relic signatures of its point of origin.

All stars formed from a cloud will carry a distinctive chemical tag reflecting the composition of the parent cloud

Projects are underway to tag all stars in the Galaxy to determine their origins.

# Measure Star formation

Measure star formation: obtain the number of stars a galaxy produces from the observed **integrated light** (Star Formation Rate, a.k.a. **SFR**). Problems:

a) “light” = we observe the light, so the estimation is biased towards most luminous stars (OB, 2-90 $M_o$). What we measure is the massive star formation.

b) “integrated” = the light comes from different stellar populations, with different ages and metallicity → needs of the timescale for the physical processes measured.

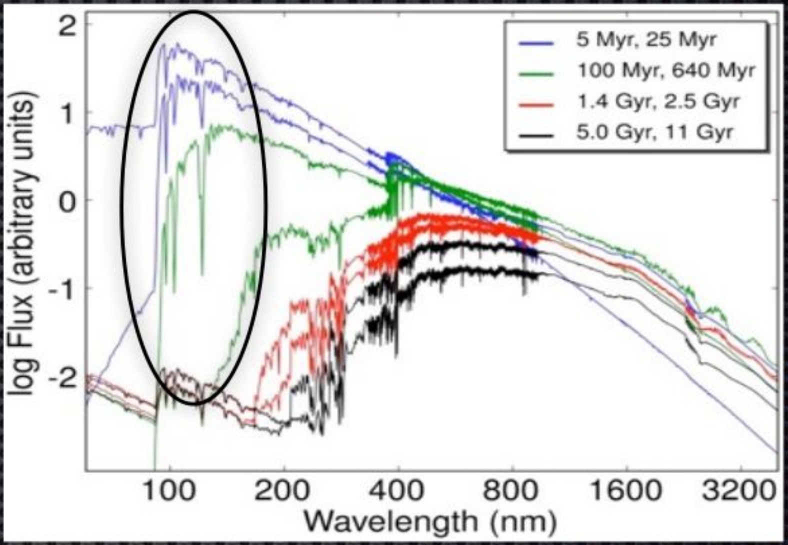
The empirical procedure is:

- Identify a star formation tracer
- Identify the physical mechanism producing emission
- Identify the associated time scale
- Identify the expected correlation with the SFR (linear, quadratic, best-fit procedure, log, etc.)
- Identify the conversion factor through observations

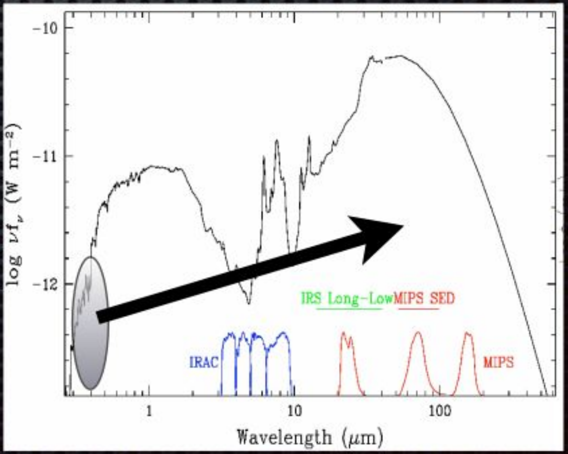
With this workflow different star formation tracers have been identified, described in the next slides.

# Star formation tracer

- Massive newly born stars => strong **UV** and only for a short time
- But... UV highly affected by extinction (up to 3 mag!). Can (and does) miss a huge part of the population




- **Absorbed UV light is re-emitted**
- 1) Ionizing photons... thus **emission-lines** can be used!
- 2) Dust re-emits in the ***Far-infrared*** thermally
- 3) Radio/Far-infrared correlation + Supernova events => Use **radio** as well
- but... different extinctions, biases, timescales

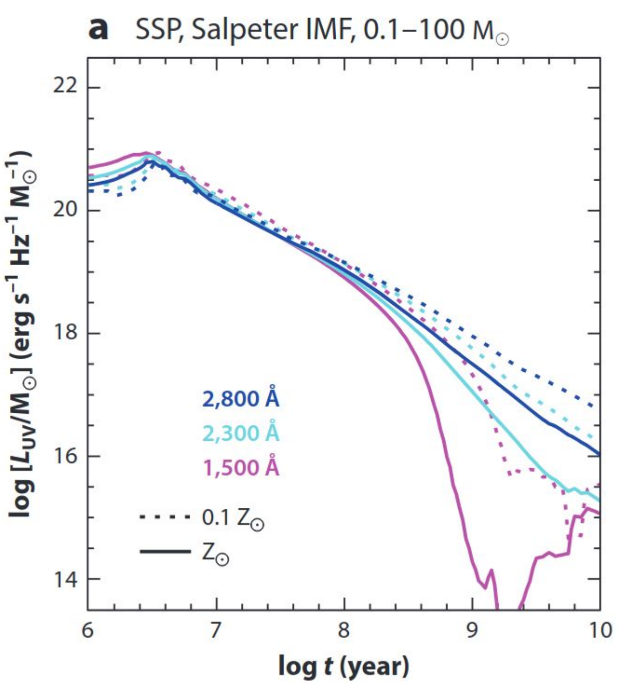


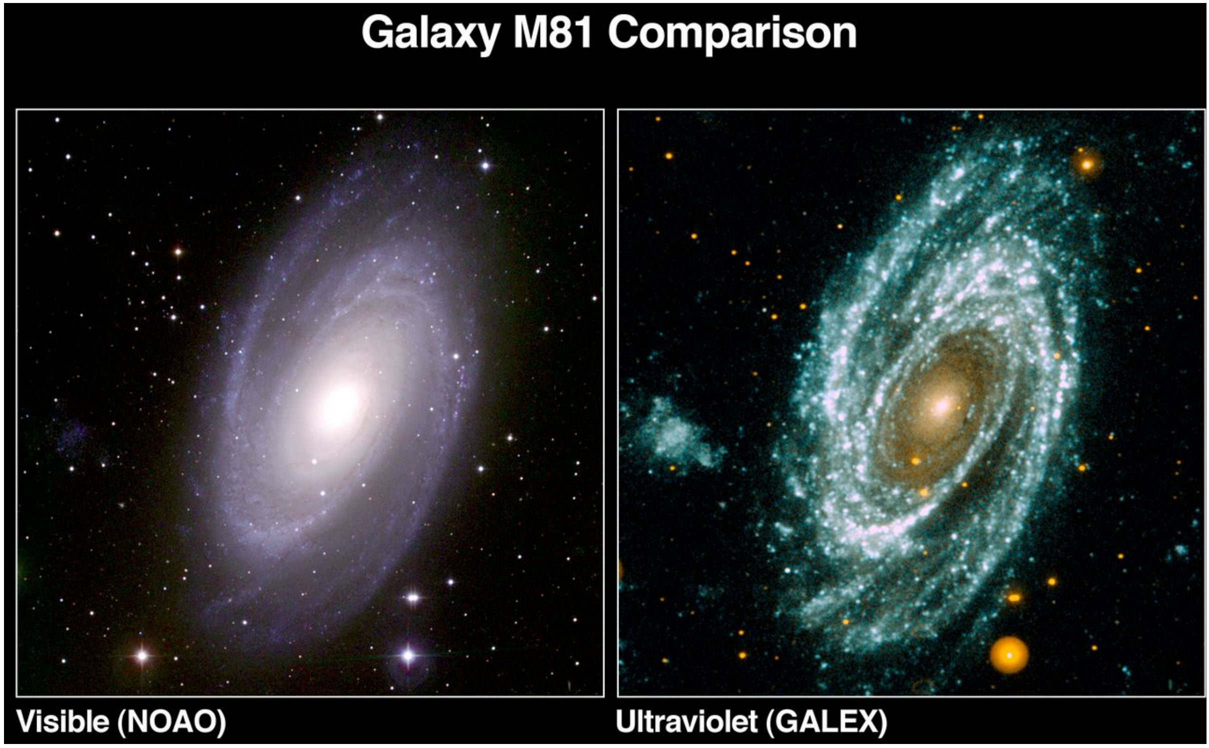
# 1. UV continuum

**PHYSICAL MECHANISM:** Stellar populations emits radiation over a broad range. Massive stars (OB) at young ages produce an intense UV radiation field, at λ <2000 ̊A, (responsible for the ionization of the HII region where the stars formed). Half of the luminosity produced by a stellar population in 10 Gyr is emitted in the first 100 Myr at UV wavelengths: natural SFR tracer.

**TIMESCALE:** This emission fade by a factor 100 after 100 Myr, a factor $10^3$-$10^6$ after 1 Gyr.

**LIMITS:** Space observatories are needed (strong absorption in the atmosphere). This radiation is strongly attenuated by dust extinction in star-forming regions.  Even for the galaxies with detected UV continuum, the extinction corrections can be factors of 5–10.



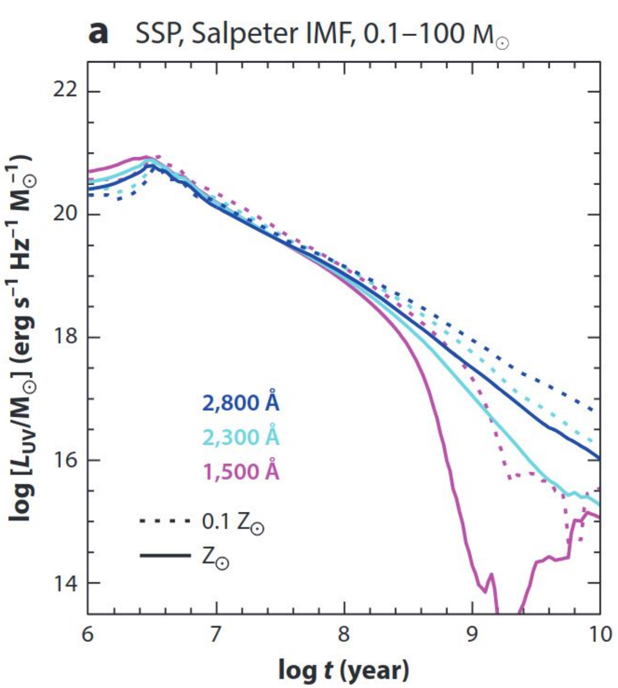



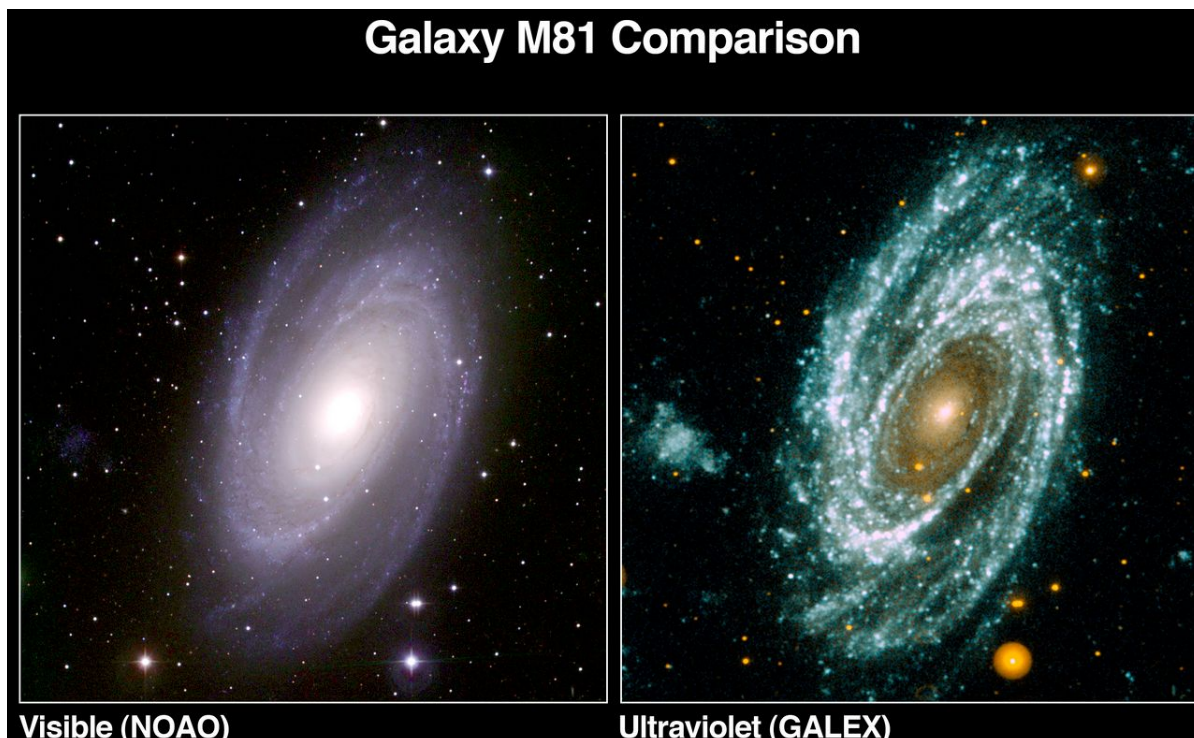
# 1. UV continuum

**RELATION:**

$$SFR = K_{UV} * L(FUV)$$

with $K_{UV}$ varying according to the metallicity. For a Salpeter IMF Conroy et al. 2009 report values between $K_{UV} = 1\text{-}1.55*10^{-28}$ $(M_o/yr)/(erg/s/Hz)$.
L(FUV) is measured in erg/s/Hz and SFR in $M_o$/yr.



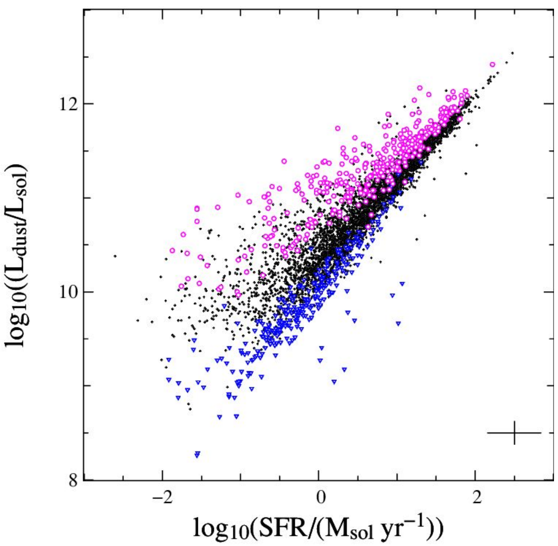



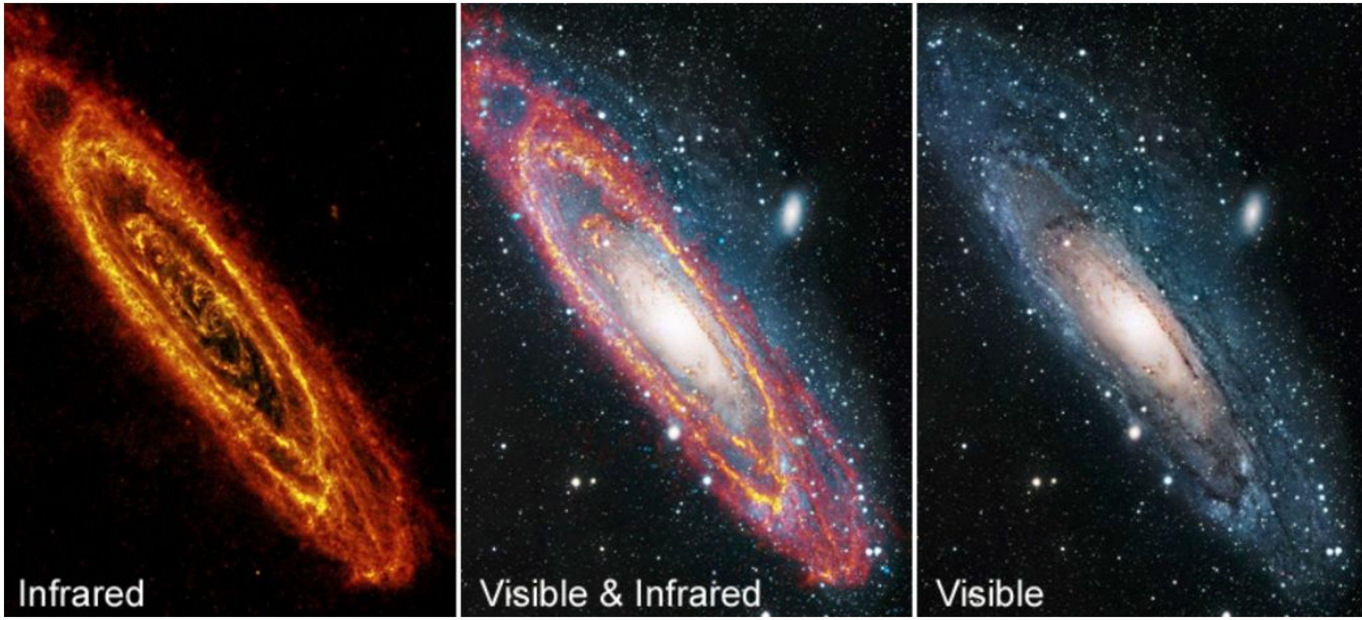
# 2. Infrared Emission

**PHYSICAL MECHANISM:** UV radiation produced by young stellar populations is absorbed by dust grains and reradiated at MIR and FIR wavelengths. The total IR luminosity ($\lambda_{rest}$= 8−1000μm) is a measurement of the energy absorbed by dust, mainly at UV wavebands. For this reason, the total IR luminosity is considered as a tracer of star formation.

**TIMESCALE:** This emission is related to both the young component (<100 Myr) and the old population (>1 Gyr).

**LIMITS:** AGN can produce also a huge UV radiation field, mimicking star formation. The older stellar populations also heat the dust, enhancing the IR emission, and then contaminating the IR as a star formation tracer.



# 2. Infrared Emission

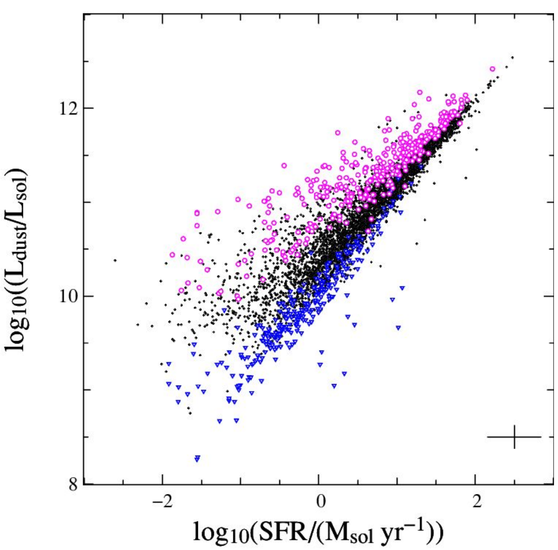
**RELATION:**

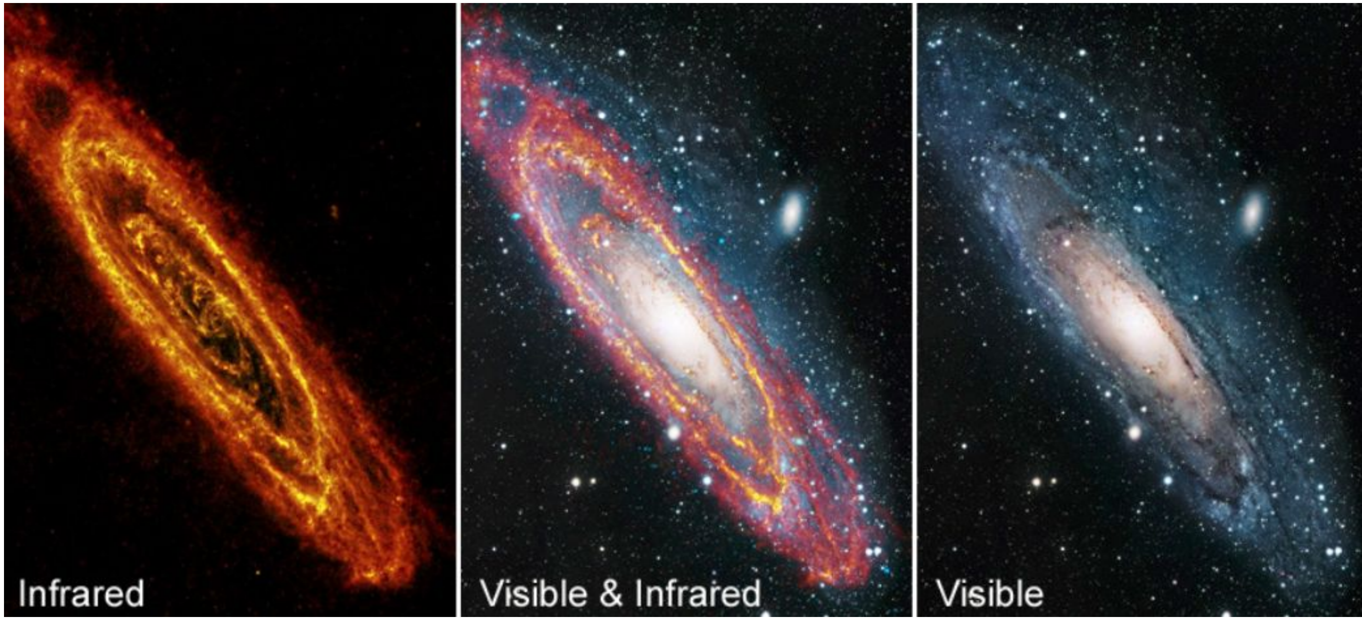
$$SFR = K_{IR} * L_{IR}$$

assuming that all the emission in IR is due to star formation. Since it has already been mentioned that dust can be heated also by AGN and the old stellar population it is more appropriate to write this relation in terms of absorbed and unabsorbed emission:

$$SFR = K_{IR} * L_{IR} + K_{UV} * L_{FUV}$$

with $K_{FUV} = 2.5*10^{-10}$ $(M_o/yr/L_o)$ and $K_{IR} = 1.73*10^{-10}$ $(M_o/yr/L_o)$.



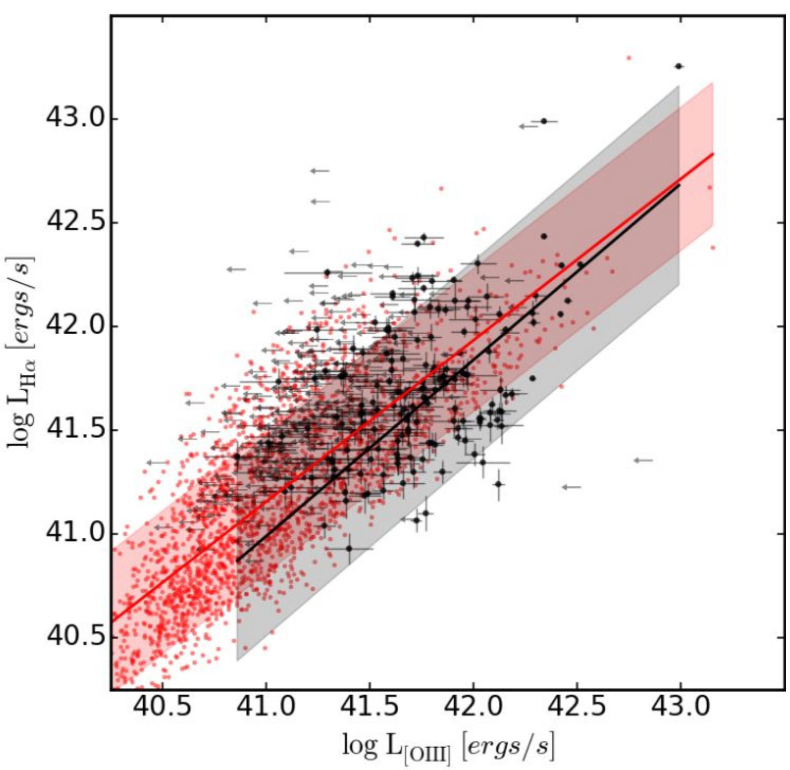



# 3. Nebular emission line

Star formation excites and ionizes gas in HII regions, producing nebular emission lines. This implies that the fluxes of specific nebular emission lines can be used as a star formation tracer. Recombination lines, such as Hα and Lyα, have a linear relation to photoionization rates that are due to the UV radiation field produced by OB stars.

Other lines such as [OII] 3,727 A or [OIII] 5,007 A can be used, but they strongly depend on metallicity. Emission lines are also subject to absorption by dust in the star-forming regions.

Weaker but less extinguished hydrogen lines in the NIR, such as Paschenα, can be used.



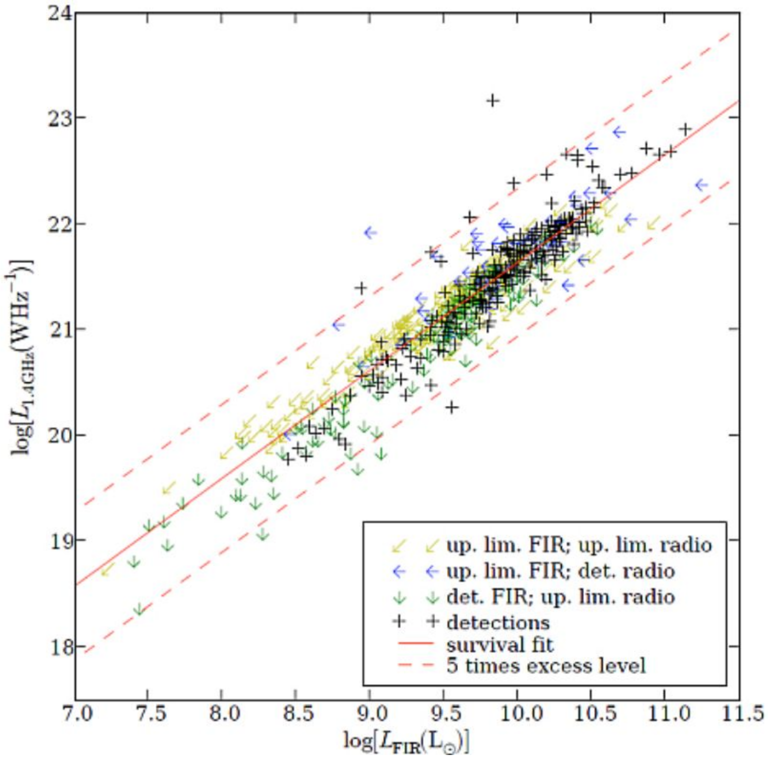

# 4. Radio emission

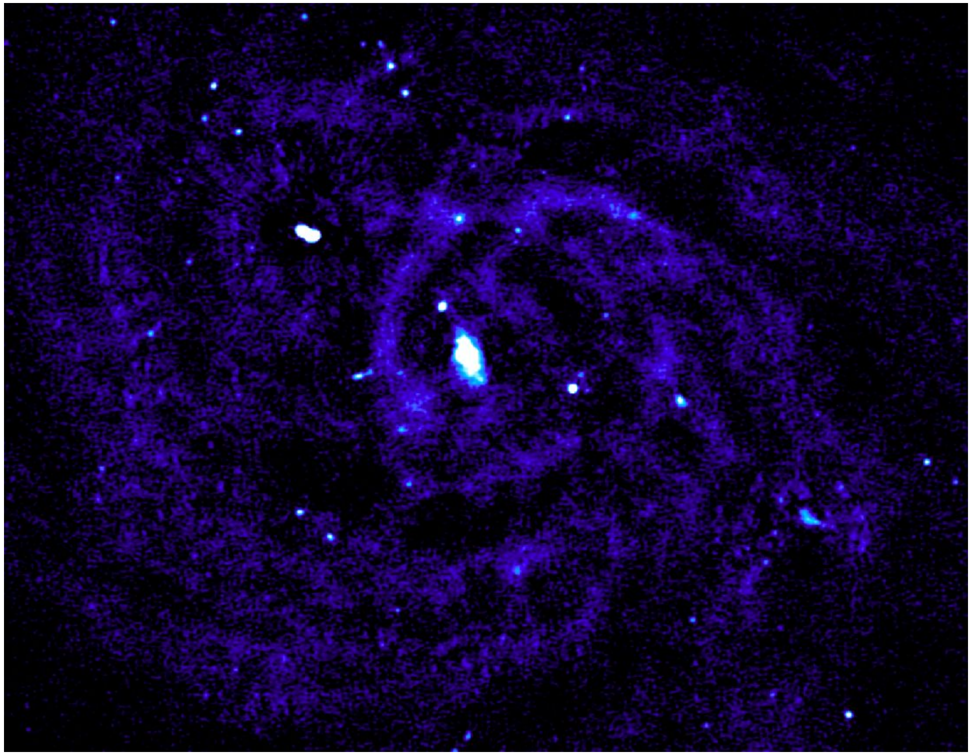
The radio emission is correlated with star formation because electron accelerated by SuperNovae emit non-thermal radiation at centimetre wavelengths.

Thermal (free-free) emission from electrons in HII regions can also contribute, at frequencies >5 GHz.

The physics is complex and a remarkably tight correlation is observed between radio emission and FIR emission in local galaxies spanning many orders of magnitude in luminosity.

The radio emission is free from dust extinction, an unbiased tracer of star formation.

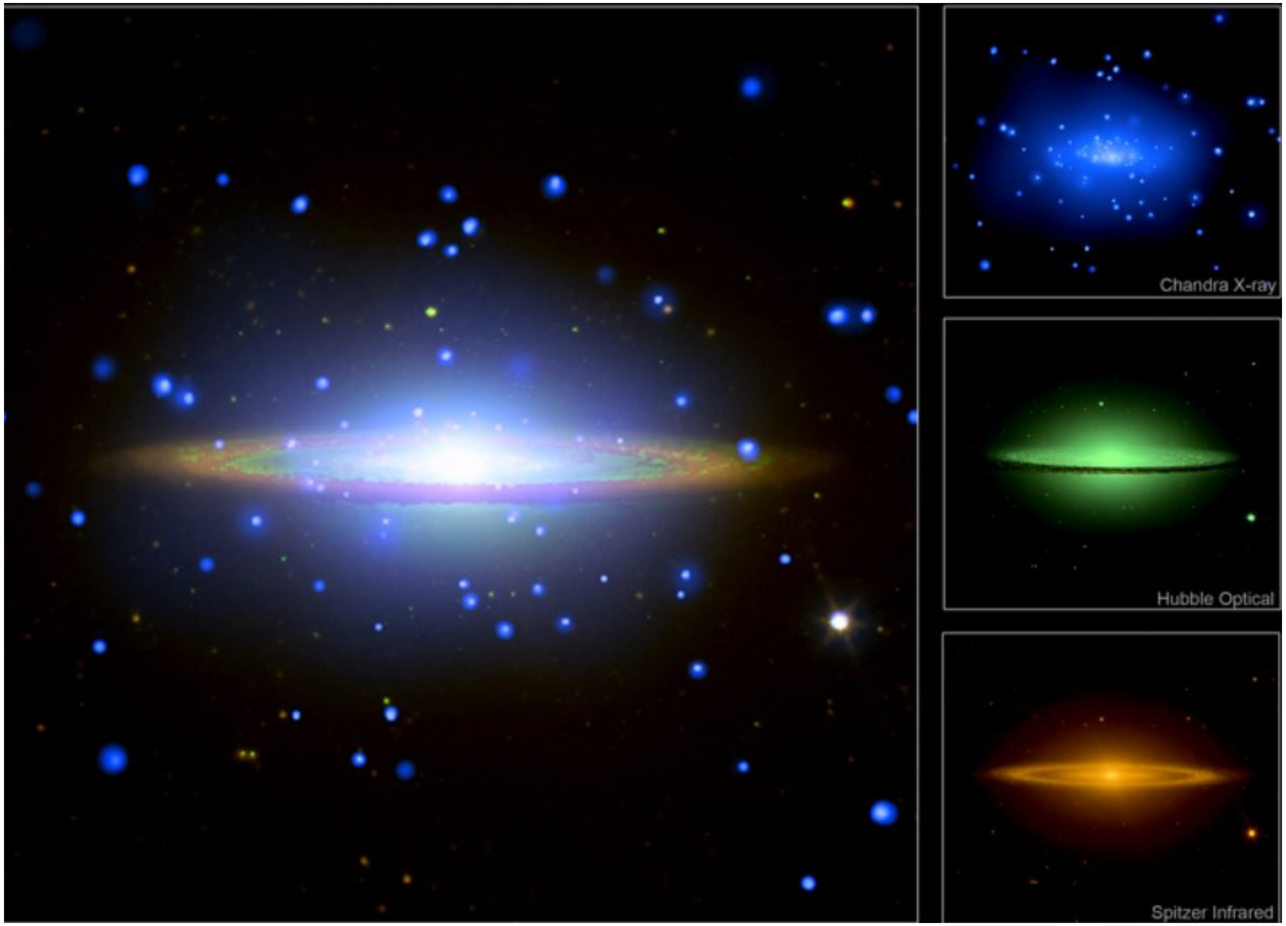


# 5. X-ray

X-rays are usually used to trace AGN, but this emission can be produced by the hot gas heated in young stellar populations, specifically in X-ray binaries. This implies that if there is no AGN activity, X-ray emission may be used as a tracer.

However, these tracer suffers many limitations: the proportionality between X-ray luminosity and SFR may vary with stellar population age, and most of the cosmic X-ray background comes from AGN.



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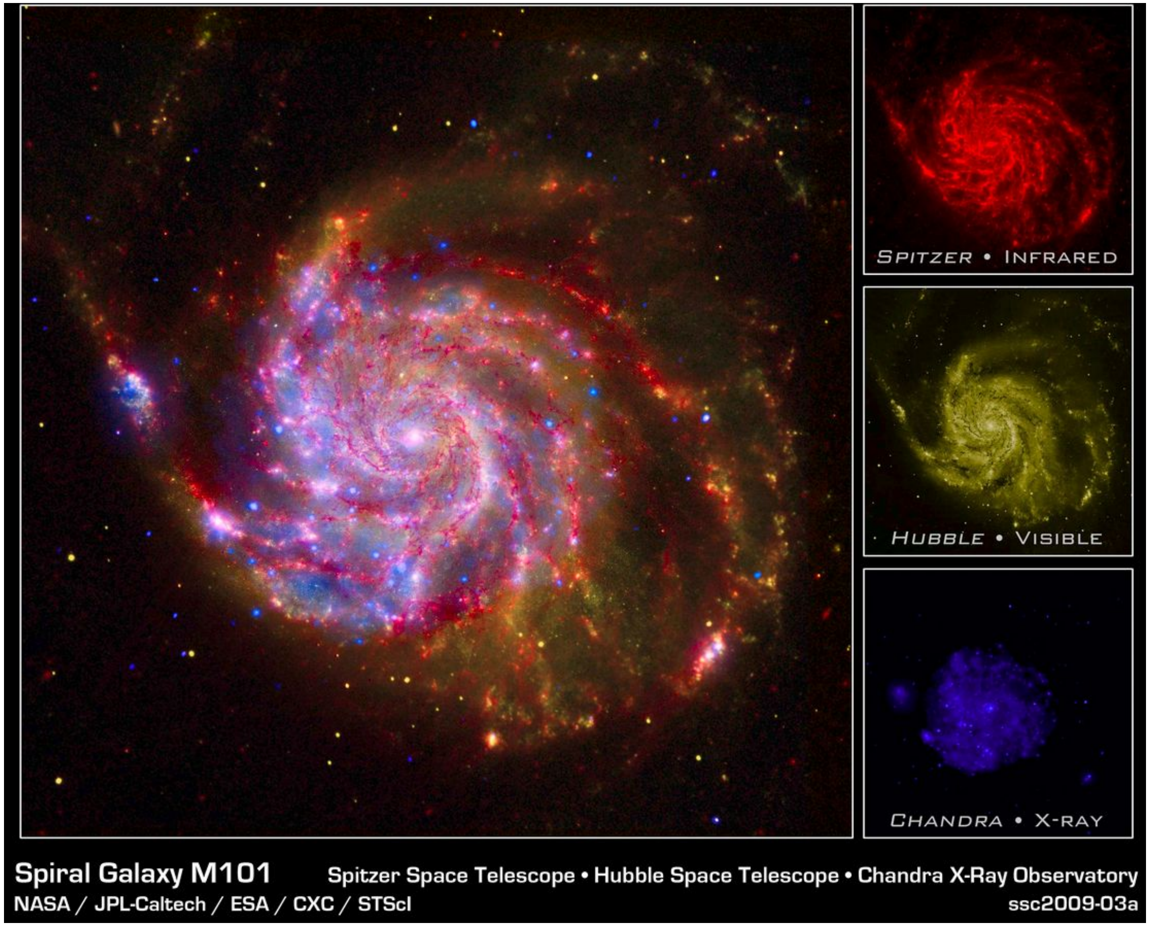

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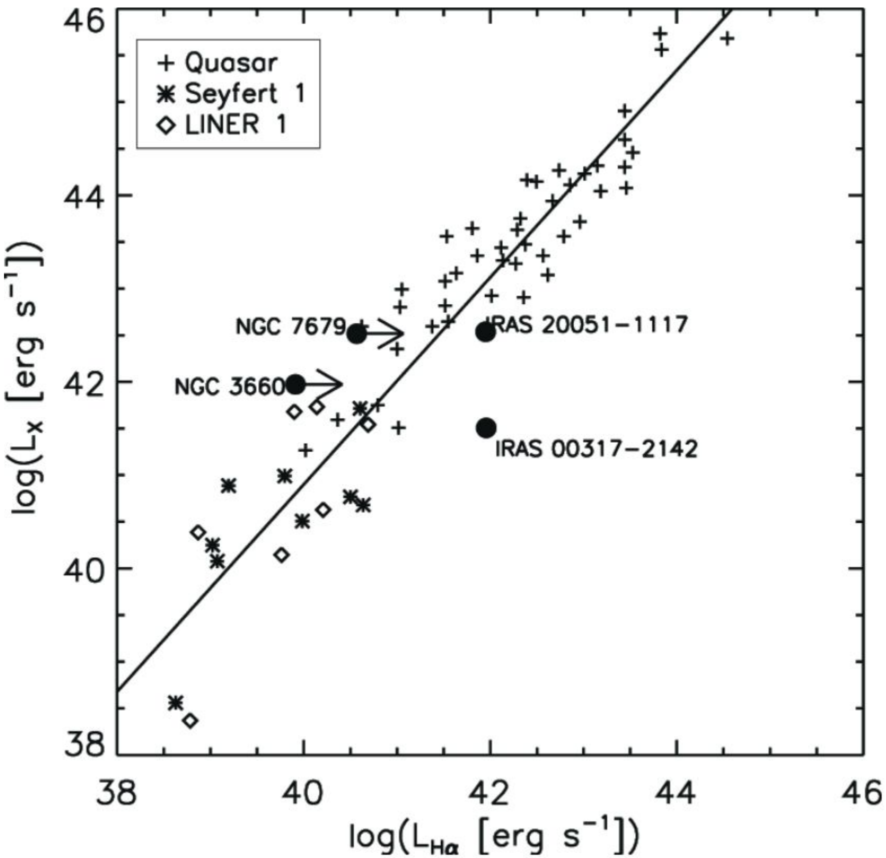
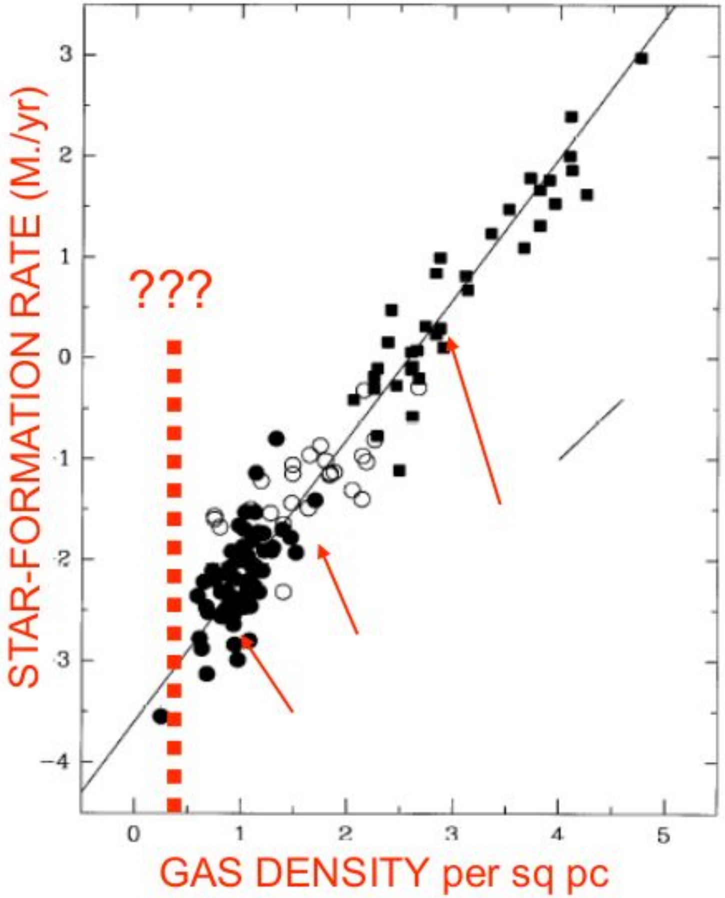


# Kennicutt Star-formation Law




Kennicutt (1998) determined that the surface density of star formation was very tightly correlated with the surface density of gas over a remarkably wide range of gas densities and in a wide variety of galactic states.

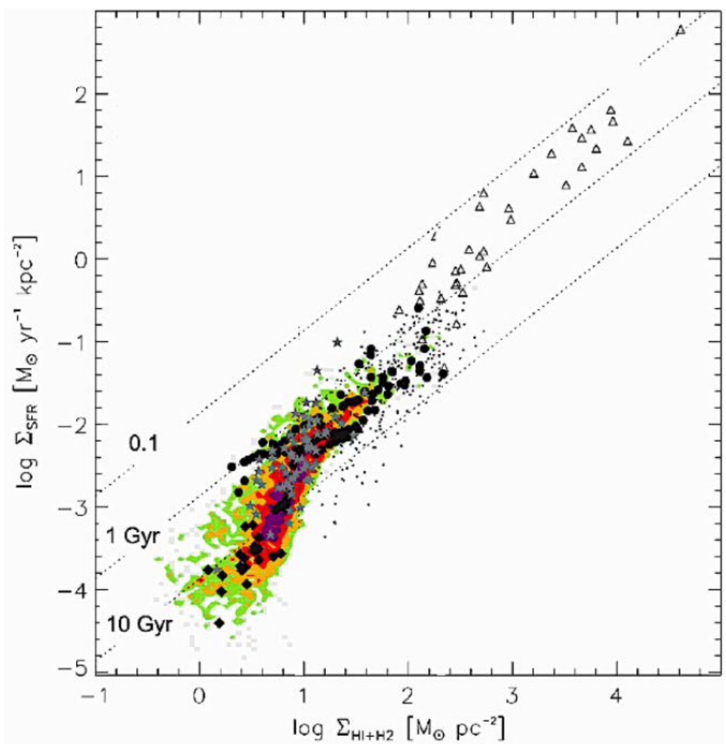
But is there a cutoff below which star-formation cannot occur ?

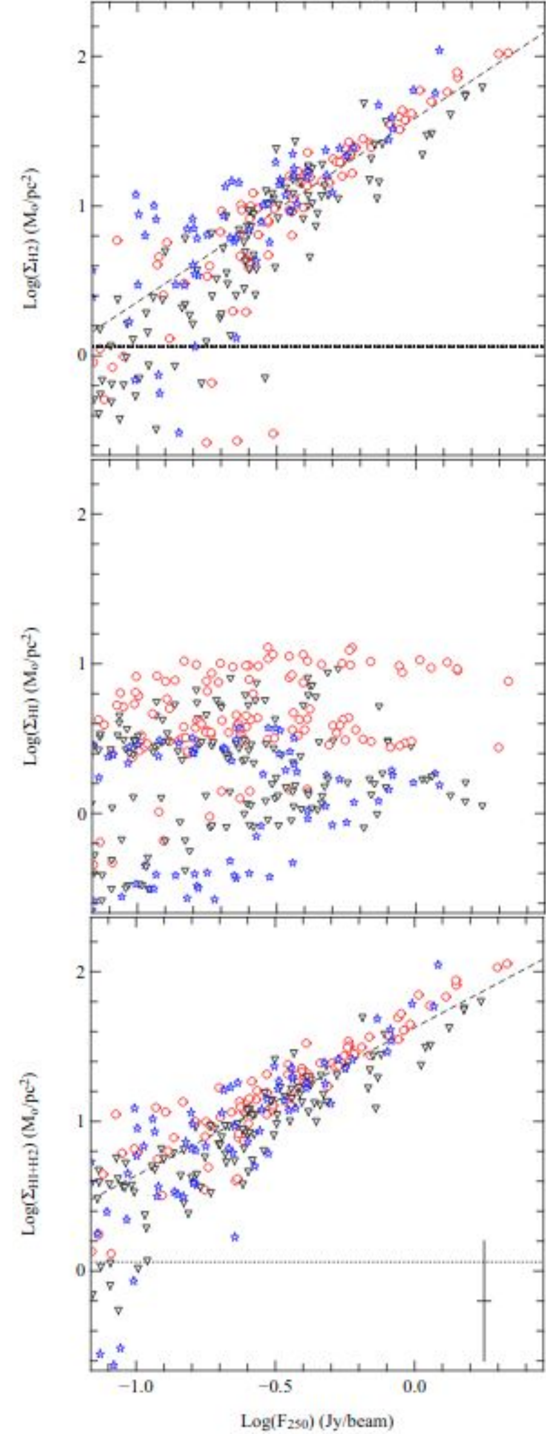
# Star formation law

Extensive studies of Kennicutt in 1998 ended with the Kennicutt-Schmidt SFR law:

$$SFR \propto \Sigma^{1.4}(HI+H2)$$

and a threshold cutoff surface density below which the SFR decreased more steeply.

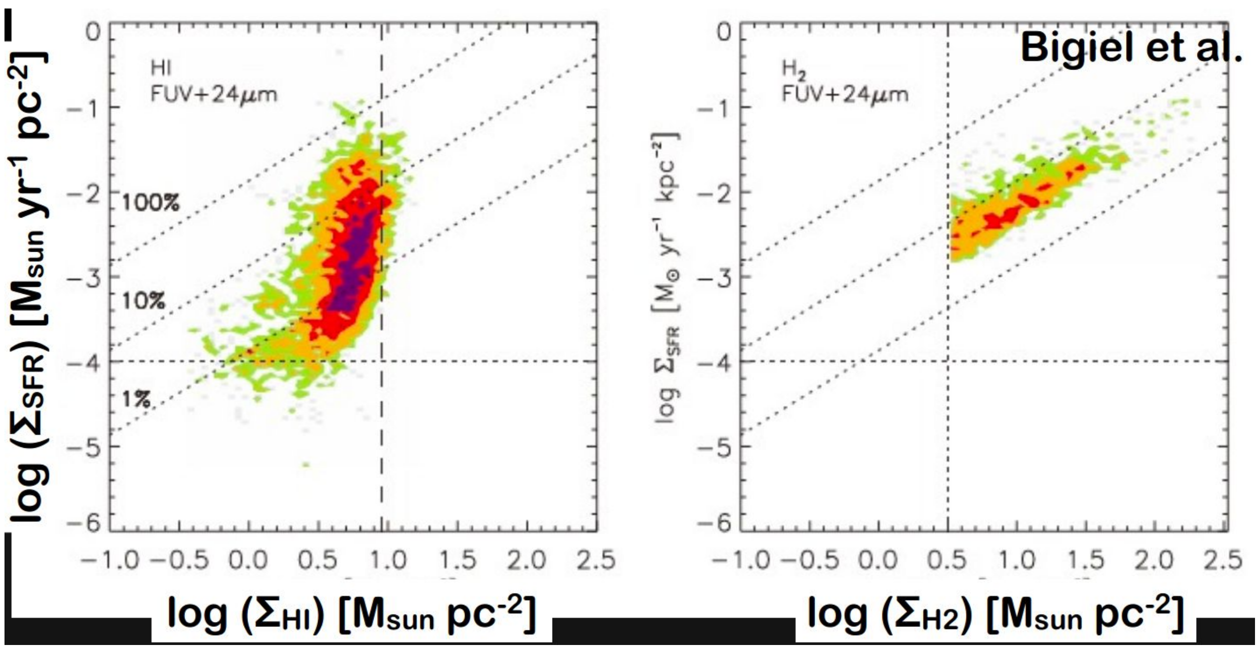


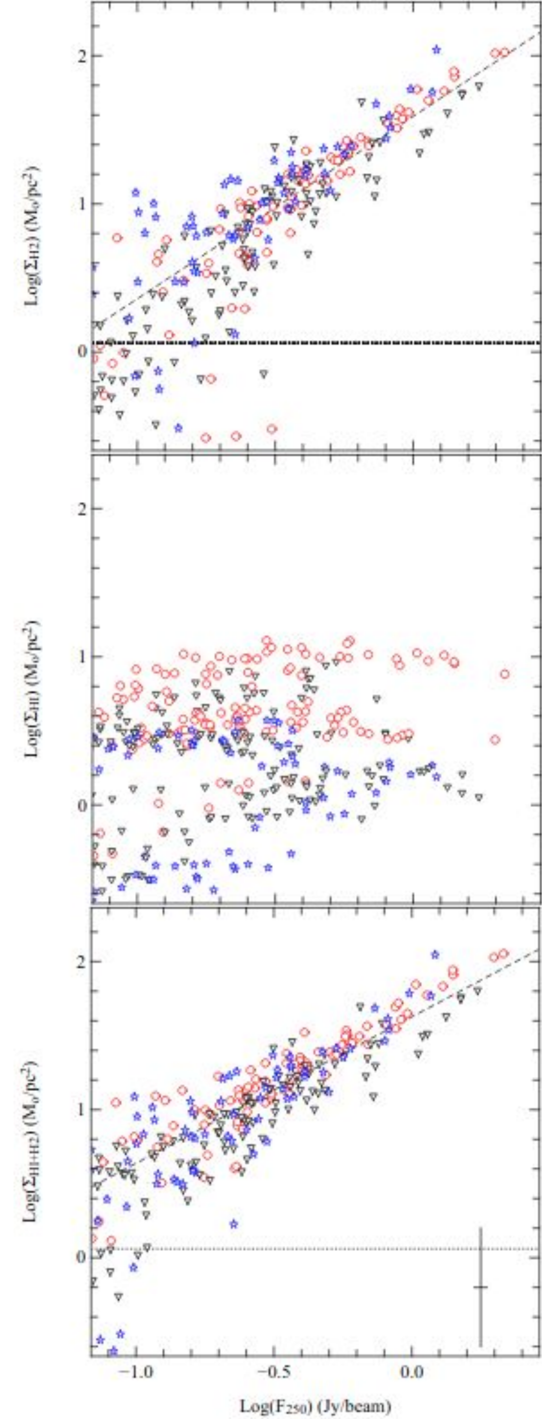



# Star formation law

The atomic gas (HI) has no tight correlation with the SFR tracers and is not relevant to the star formation process in the inner parts of spiral galaxies.

The dependence is due to HII regions and the physical link is via molecular clouds formation.

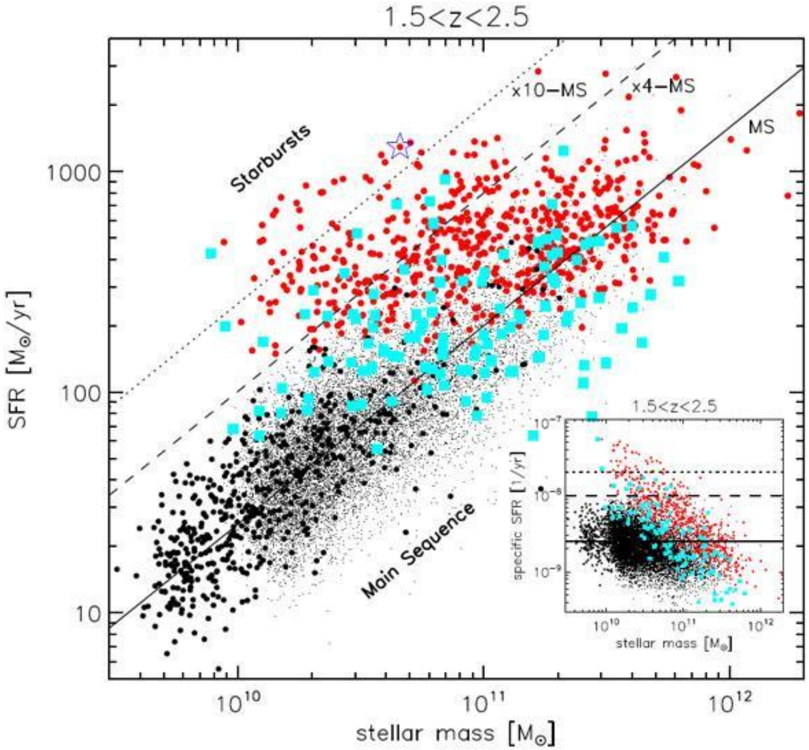


# Starburst systems

A starburst galaxy is a galaxy where the timescale to convert gas into stars is lower than the typical $M_{ISM}$/SFR~1 Gyr for local galaxies like the Milky Way.

This Star Formation Efficiency (SFE) can be characterized by the specific SFR per unit stellar mass (SSFR= SFR/M∗) to identify galaxies where the characteristic timescale (1/SSFR) is much shorter than the 'likely' age of the galaxy.




# What did we learn?

1. Galaxy constituents
2. Star formation cycle
3. Molecular Clouds
4. Star formation Tracer
5. Star Formation Laws
6. Starburst Systems