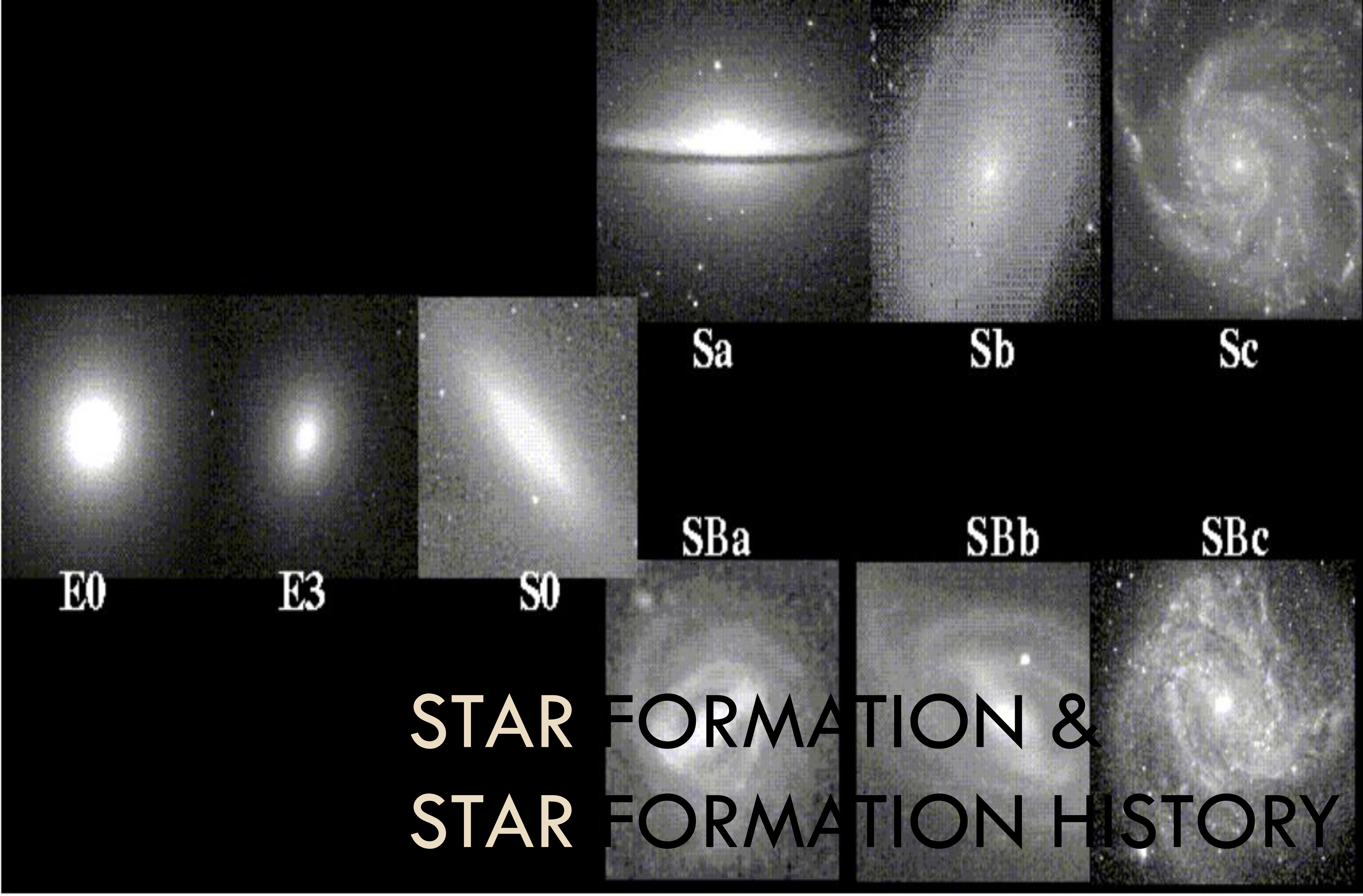


STAR FORMATION & STAR FORMATION HISTORY

Graziano Coppa

PhD Lectures, November 26th, 2009

Summary

- Introduction
- Star Formation indicators
  - Synthesis models
  - UV continuum
  - Recombination & forbidden lines
  - FIR continuum
  - Radio emission (thermal Bremsstrahlung)
- Where is Star Formation?
  - Disk SF
  - Circumnuclear SF
- Evolutionary picture
- Trigger/quenching mechanisms

Star Formation

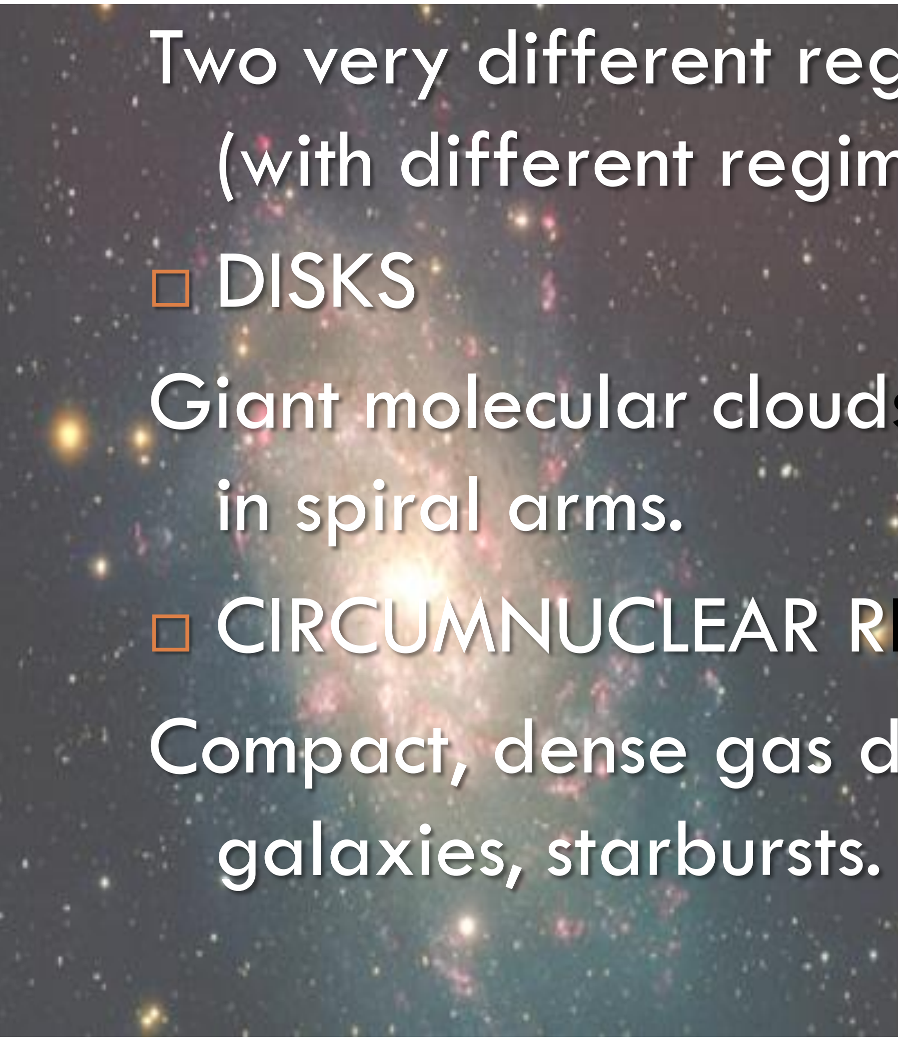
- Studying the STAR FORMATION HISTORY (temporal evolution of the star formation) is key in understanding galaxy evolution in its broader context.
- Two different models of galaxy formation and evolution:
  - MONOLITHIC: simultaneous formation of structures from primordial fluctuations of densities, subsequent fragmentation (e.g. Eggen et al 1962).
  - HIERARCHICAL: smaller galaxies build up larger ones by merger events (e.g. Cole et al. 1994).

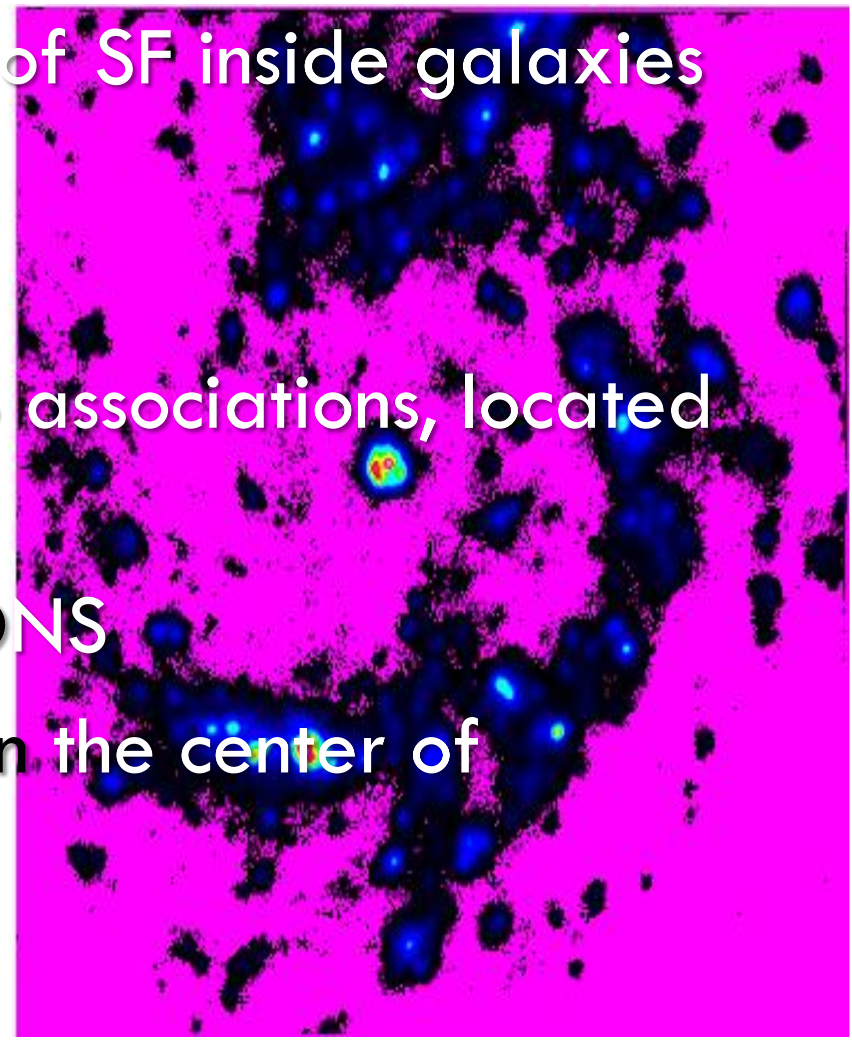
Star Formation (2)

- Different galaxy formation models imply different SFHs:
  - MONOLITHIC: a burst, then a declining rate of SF, based on gas supplied by evolved stars; different SFH slope for different morphological types;
  - HIERARCHICAL: SF is not continuous; burst triggered by tidal interactions. Different morphological types created by the magnitude of the mergers.

- SFH can help discriminate

Where is Star Formation? (prelude)





Two very different regions of SF inside galaxies (with different regimes):

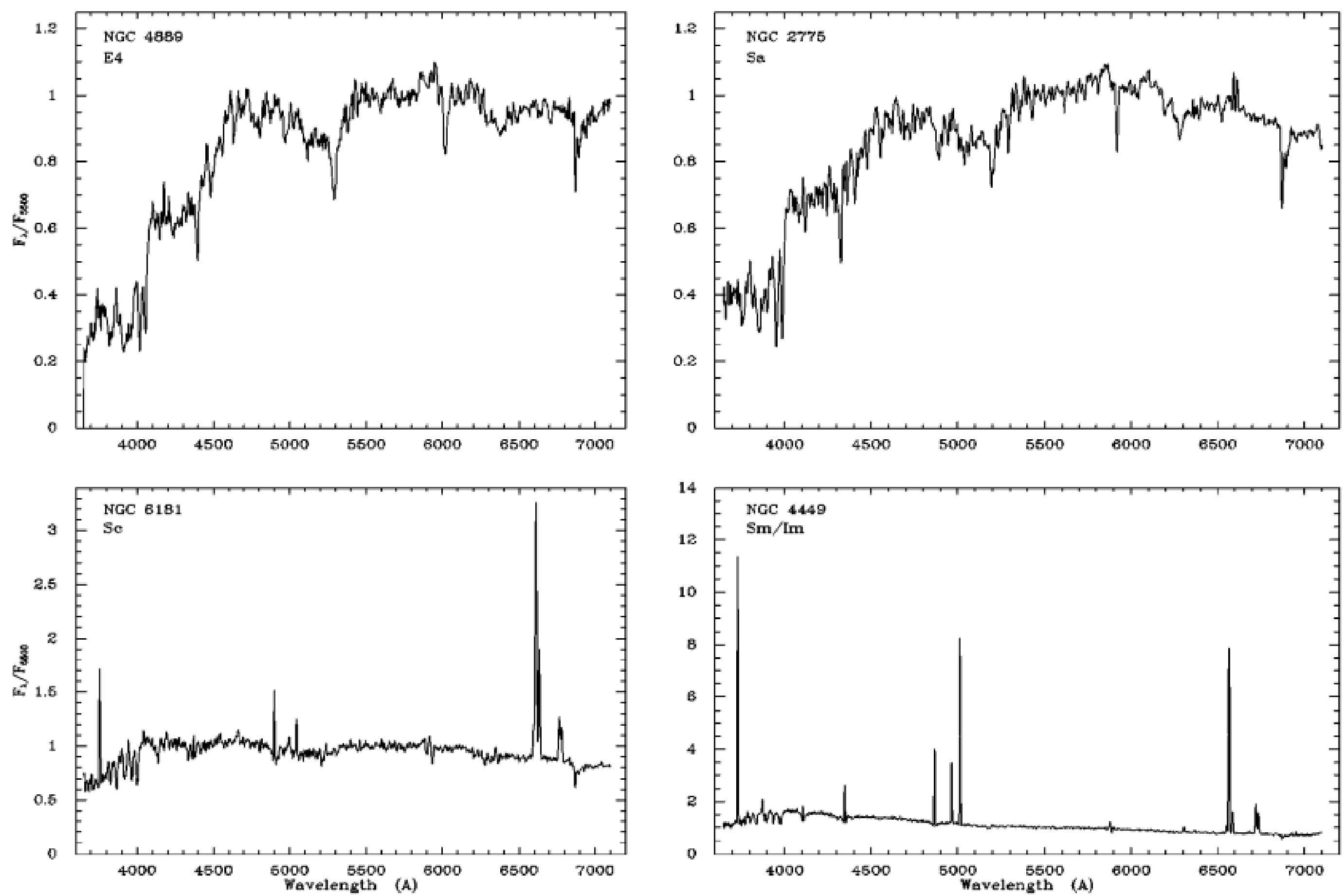
- DISKS

Giant molecular clouds, OB associations, located in spiral arms.

- CIRCUMNUCLEAR REGIONS

Compact, dense gas disks in the center of galaxies, starbursts.

Star Formation indicators



Star Formation indicators (2)

- Several changes along this sequence:
  - rise in the blue continuum,
  - change in the stellar absorption spectrum from K-giant to A-star,
  - dramatic increase in the nebular emission lines, especially Hα
- Dominant contributors at visible wavelengths are intermediate main sequence stars (A to early F) and G-K giants.
- The spectrum of any given object dictated by the ratio of young (< 1 Gyr) to old (> 3 Gyr) stars.
- The contributions to the spectrum by young and old stars need t o be discriminated using evolutionary synthesis models to infer the evolution and SF history of the galaxy

Star Formation indicators (3)

- Integrated colors and spectra, to estimate ratio of young to old stars, compare to synthesis models to derive SFH.
- Synthesis models:
  - Individual stellar evolutionary tracks;
  - Luminosity through atmospheric models;
  - Sum together weighting by an IMF;
  - Derive luminosities, colors, spectra of a population.

Star Formation indicators (4)

- Ultraviolet continuum

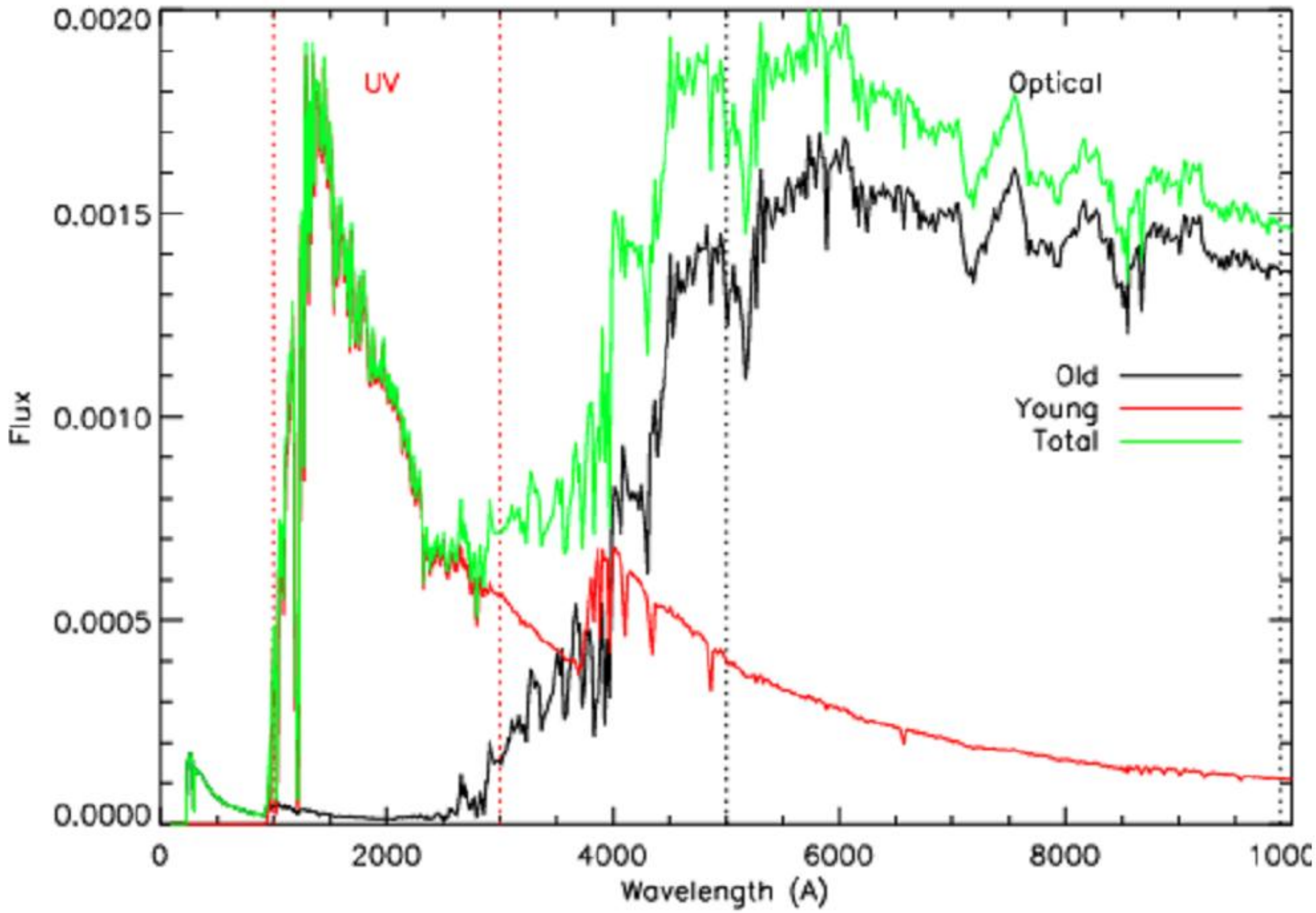
UV spectrum (1250-2500 Å) is dominated by young massive stars, SFR scales linearly with luminosity.

SFR (Msun /yr) = 1.4 x 10^(-28) L (ergs /s /Hz)

- Pros: directly linked to young stellar pop., wide range in redshift explorable.
- Cons: sensitivity to extinction and IMF

Star Formation indicators (5)

- Ultraviolet continuum



Star Formation indicators (5)

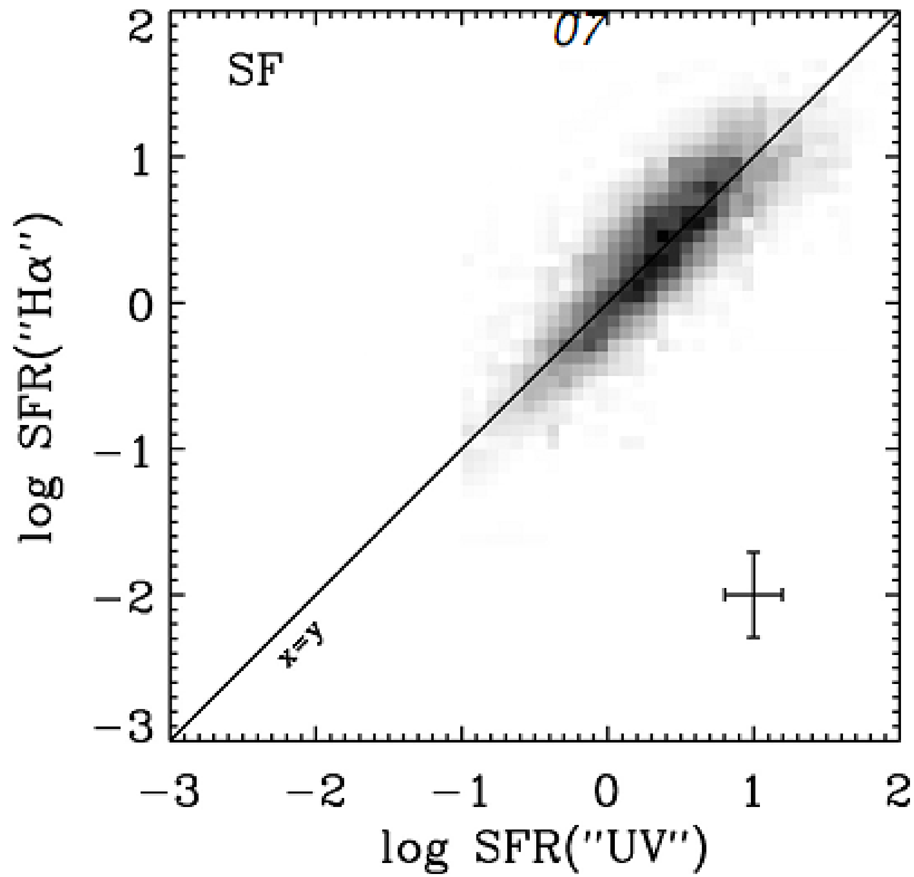
Recombination lines

Young stars emit UV radiation that ionizes atoms (mostly H) in nearby gas clouds. Free electrons in the ionized gas then **recombine** with the atoms. They then jump down the energy level "ladder" to less excited states. Hα is the most important.

SFR (Msun/yr) = 7.9 x 10^(-42) L(Hα) (ergs/s)

- Pros: direct, highly sensitive,
- Cons: extinction, IMF, uncertainty in gas distrib.

Salim et al. 07



Star Formation indicators (6)

- **Forbidden lines** (e.g. [OII]@3727Å)

(not strictly "forbidden" → most unlikely)

Mechanism similar to recombination lines but poorer performance (at 10k K the excitation energy between the two upper D levels and the lower S level is roughly the thermal electron energy kT. [OII] doublet is therefore closely linked to electron temperature and consequently abundance). Calibrated thru Hα

SFR (Msun/year) = 1.4 x 10^(-41) L (ergs/s)

- Pros: very large z range
- Cons: not direct, extinction, uncertainty in gas distrib.

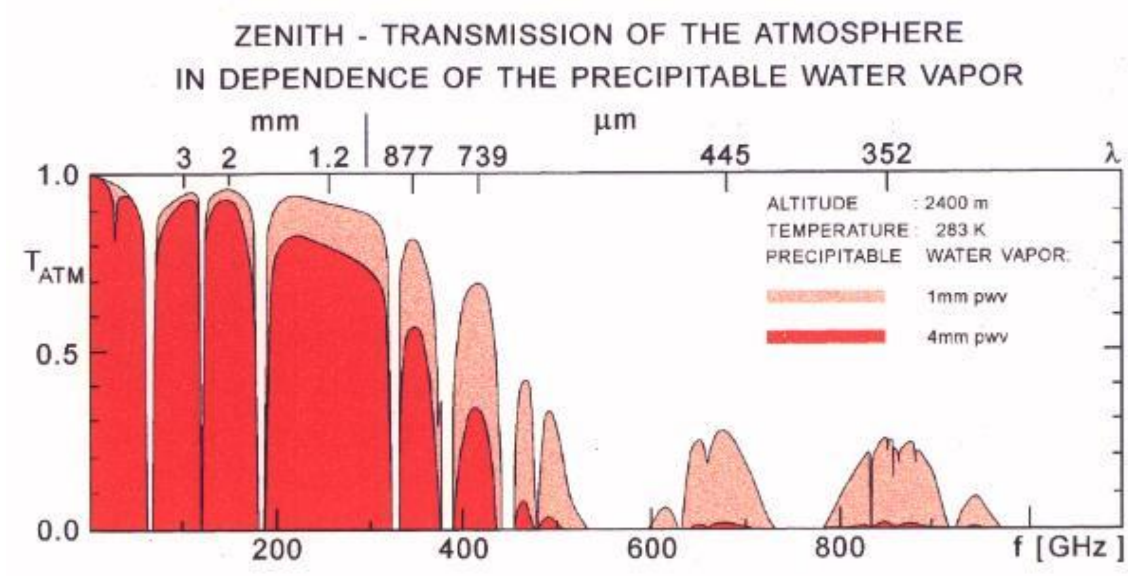
Star Formation indicators (7)

Far Infrared continuum

UV radiation from young stars can be absorbed by IS dust and re-emitted in thermal IR (~10-300 μm).

SFR (Msun/year) = 4.5 x 10^(-44) L (ergs/s) (SBs)

- Pros: sensitivity
- Cons: not direct (opt. depth of dust, contrib. of old stars for early types), atm. abs., distribution of dust



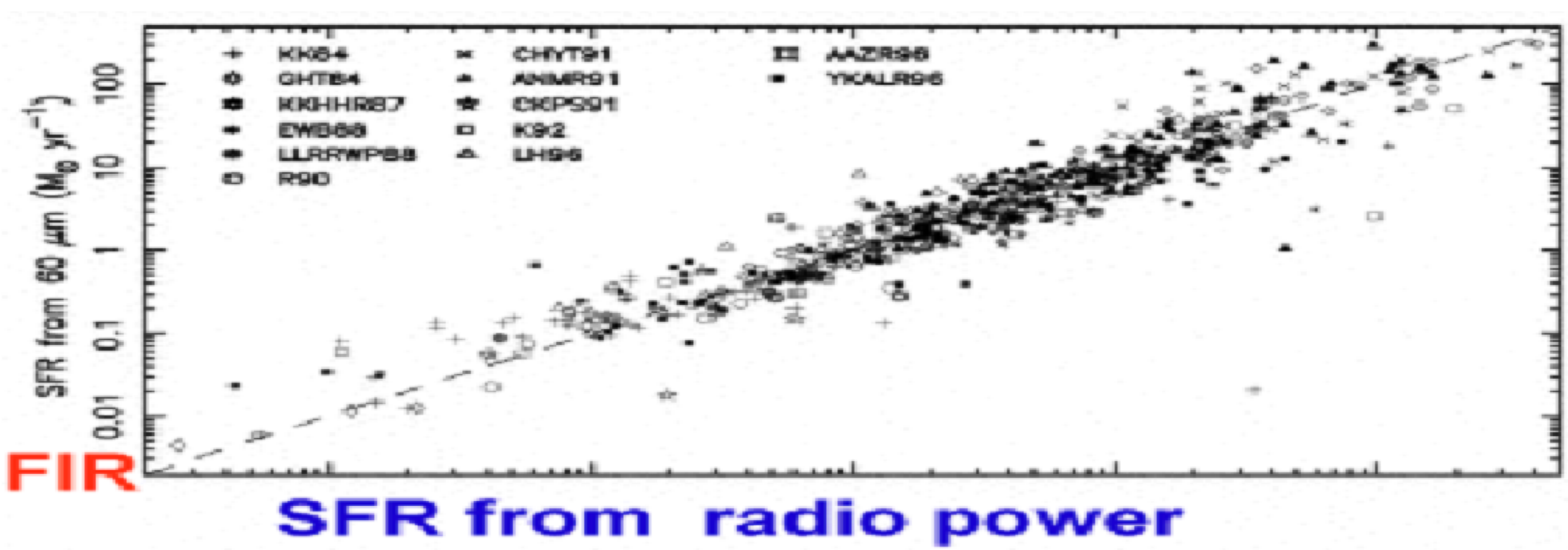
Star Formation indicators (8)

Radio continuum

Very tight correlation between SFRs from FIR and radio. Same massive young stars produce synchrotron emission (SNs) and FIR emission. SFR can also be estimated from the number of O stars required to produce thermal free-free continuum emission.

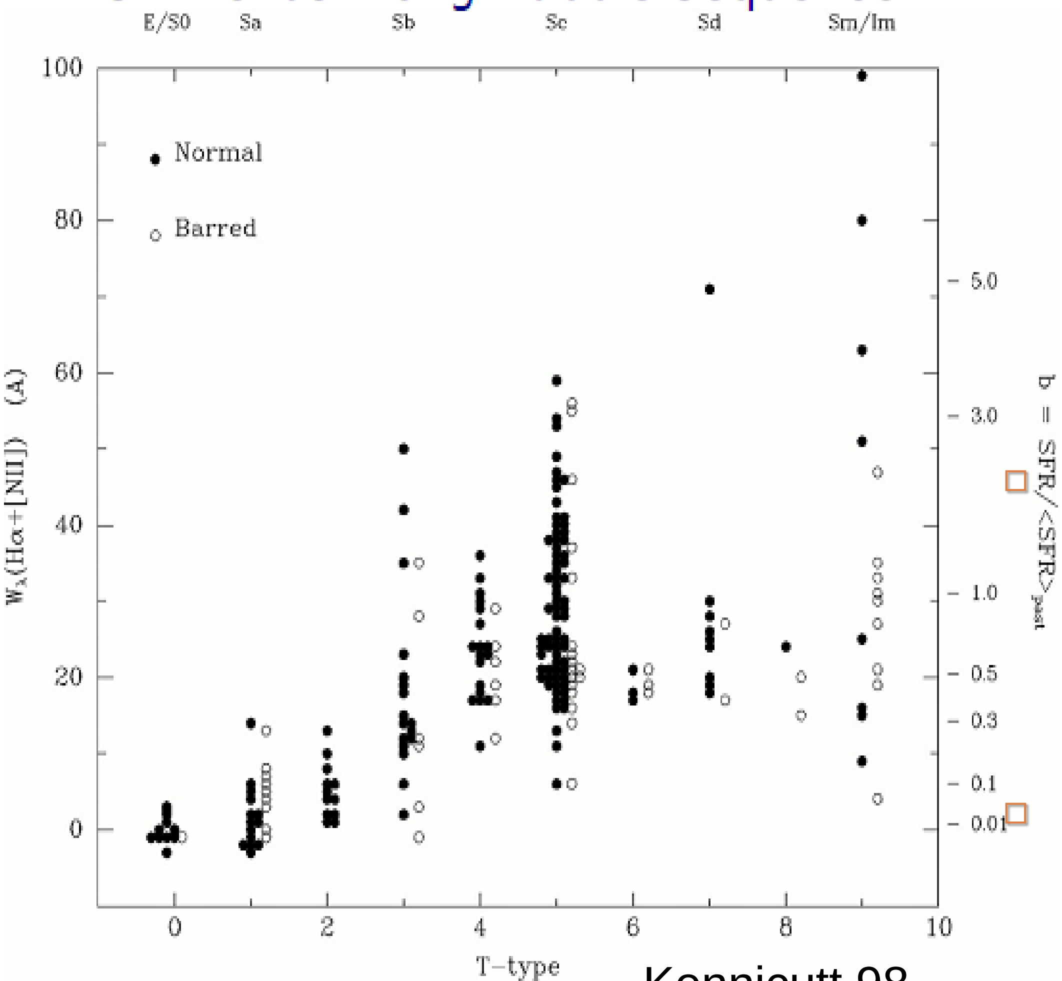
SFR (Msun/year) = 2.5 x 10^(-22) L(1.4) (ergs/s/Hz)

- Pros: no dust extiction.
- Cons: separate thermal and non thermal components



Where is Star Formation? -Disks

SF Trends Along Hubble Sequence

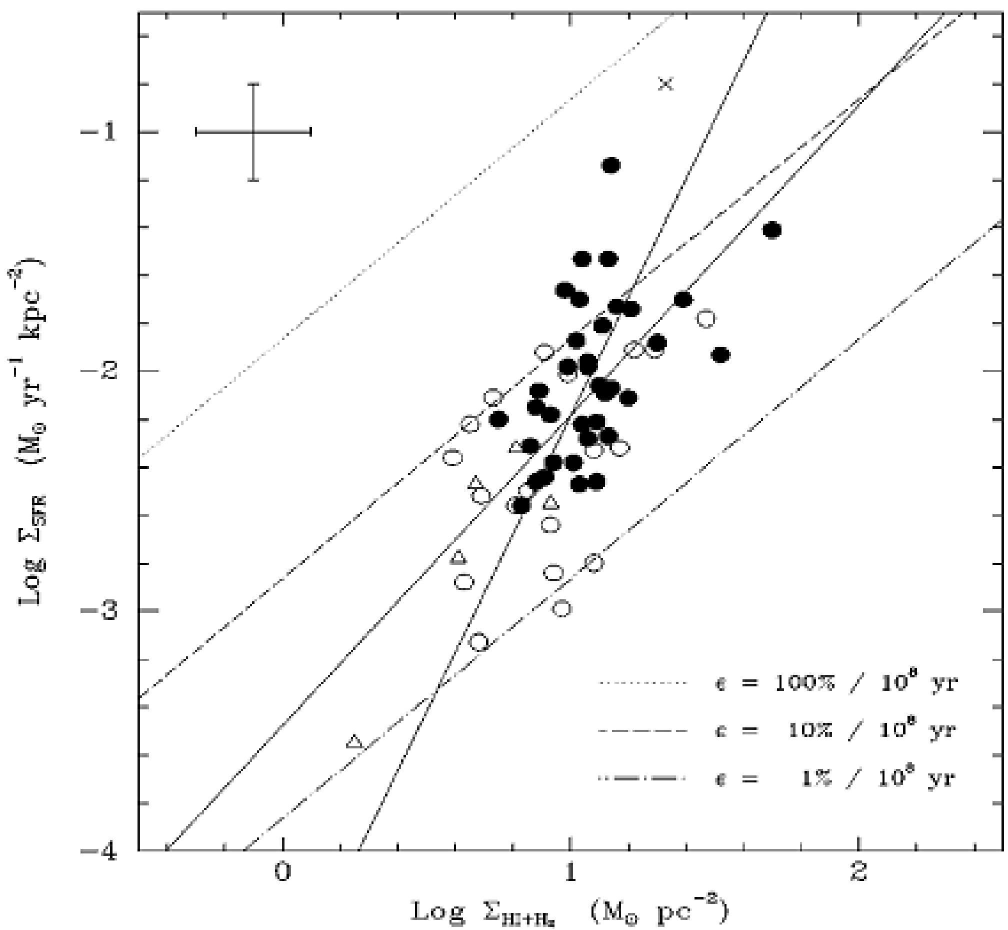


Kennicutt 98

- SFRs range:
  - ~0 in gas-poor ellipticals, S0s, and dwarfs
  - ~20 Msun yr−1 in gas-rich spirals.
  - up to ~100 Msun yr−1, in optical starburst galaxies
  - up to 1000 Msun yr−1 in IR starbursts.
- Changes in disk SFR along Hubble sequence are produced by:
  - increase in the total number of star forming regions, and
  - increase in their characteristic masses.
- Large dispersion in SFR among galaxies of same Hubble type (gas content, nuclear emission, interactions, short-term variation of SF.

Where is Star Formation? -Disks (2)

- For evolutionary purposes, more useful to see SSFR (Specific Star Formation RATE – SFR/Mass)
- For parametrizing the dependence of SFR on gas density, more useful to see ΣSFR (SFR/area)
- Large ranges in gas and surface SFR densities. Scatter in SFR for given type is dispersion in gas content.
- SFEfficiency ε = Mstar/Mgas ~5%
- Bars, spiral arm structures do not affect disks SFRs
- Interactions & environment do affect SFR.

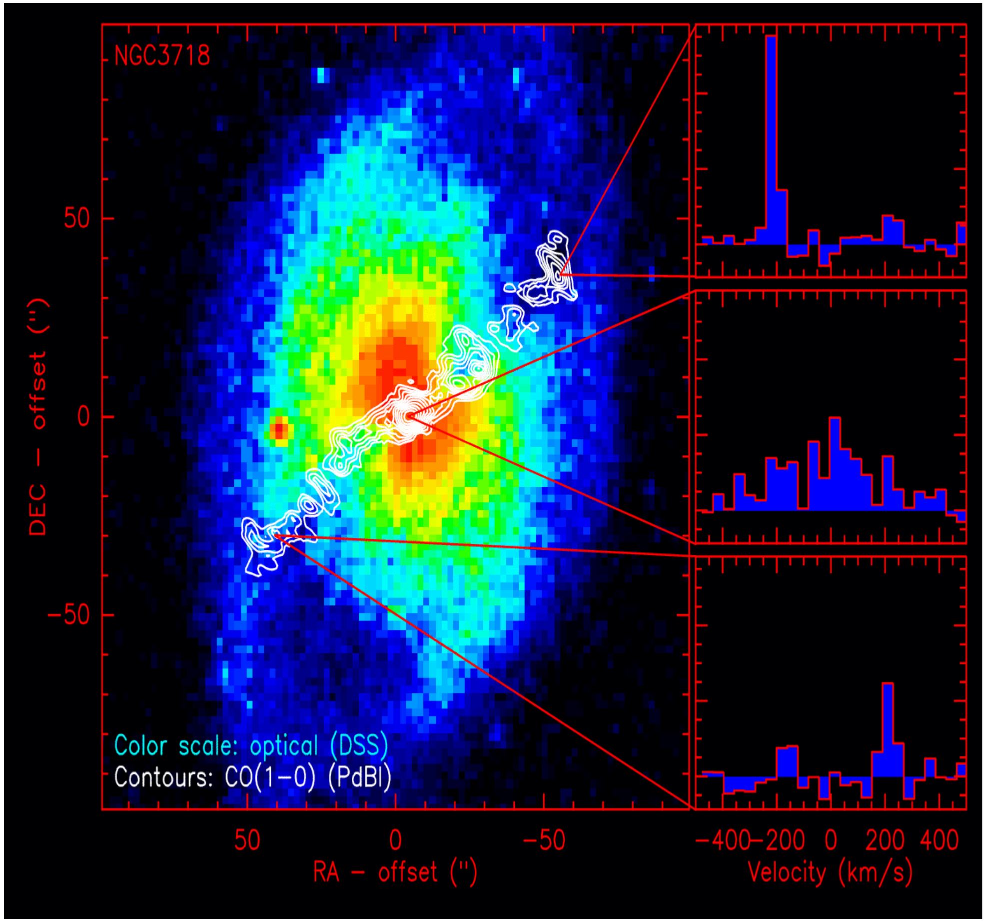


Where is Star Formation? -Nuclei

- Circumnuclear regions of many spiral galaxies harbor SF regions, with properties different from SF disks, in:
  - much higher spatial concentration of gas and stars,
  - burst-like nature
  - lack of variation with morphology
- Dynamical influences, e.g. bars or external gravitational perturbation, stimulate gas flow into nuclear regions.
- Nuclear SFRs in most galaxies are modest, e.g. on average ~0.1 - 0.2 Msun yr−1 ; similar to disk HII regions.
- Luminous IR galaxies (L(FIR) > 10^(10) Lsun) SFRs ~1–1000 Msun yr−1 .

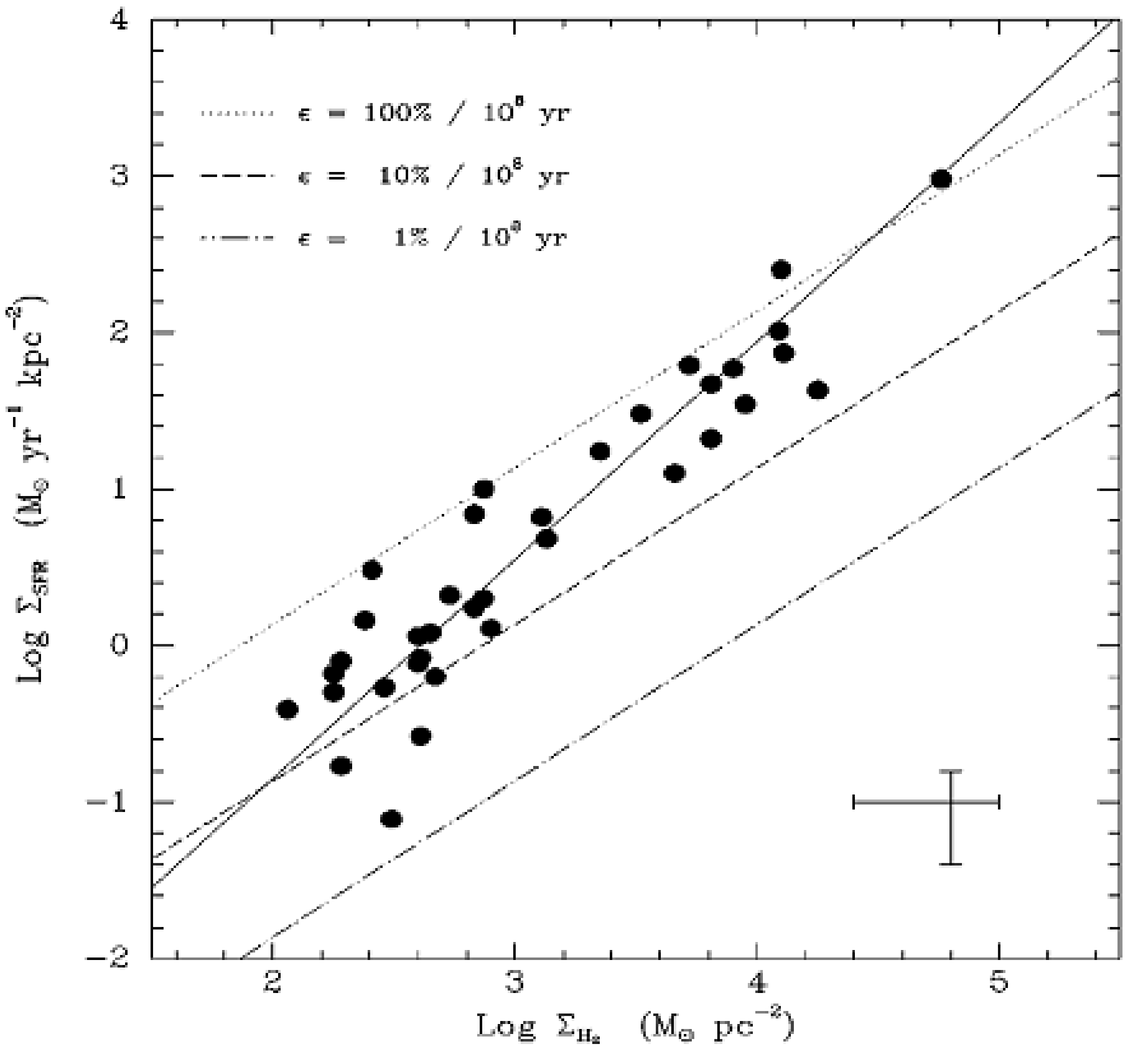
Where is Star Formation? -Nuclei(2)

- Maintaining such huge luminosity in these starbursts leads to exhaustion of galactic gas supply in ~10^8 yr, so their high SFRs can only be sustained for a small fraction of Hubble time. Strong tidal interactions and mergers are thought to trigger such a huge mass transfer and SFR.
- Molecular gas is concentrated in central region (typical radii 0.1–1 kpc), with surface densities 10^2–10^5 Msun/pc^2.



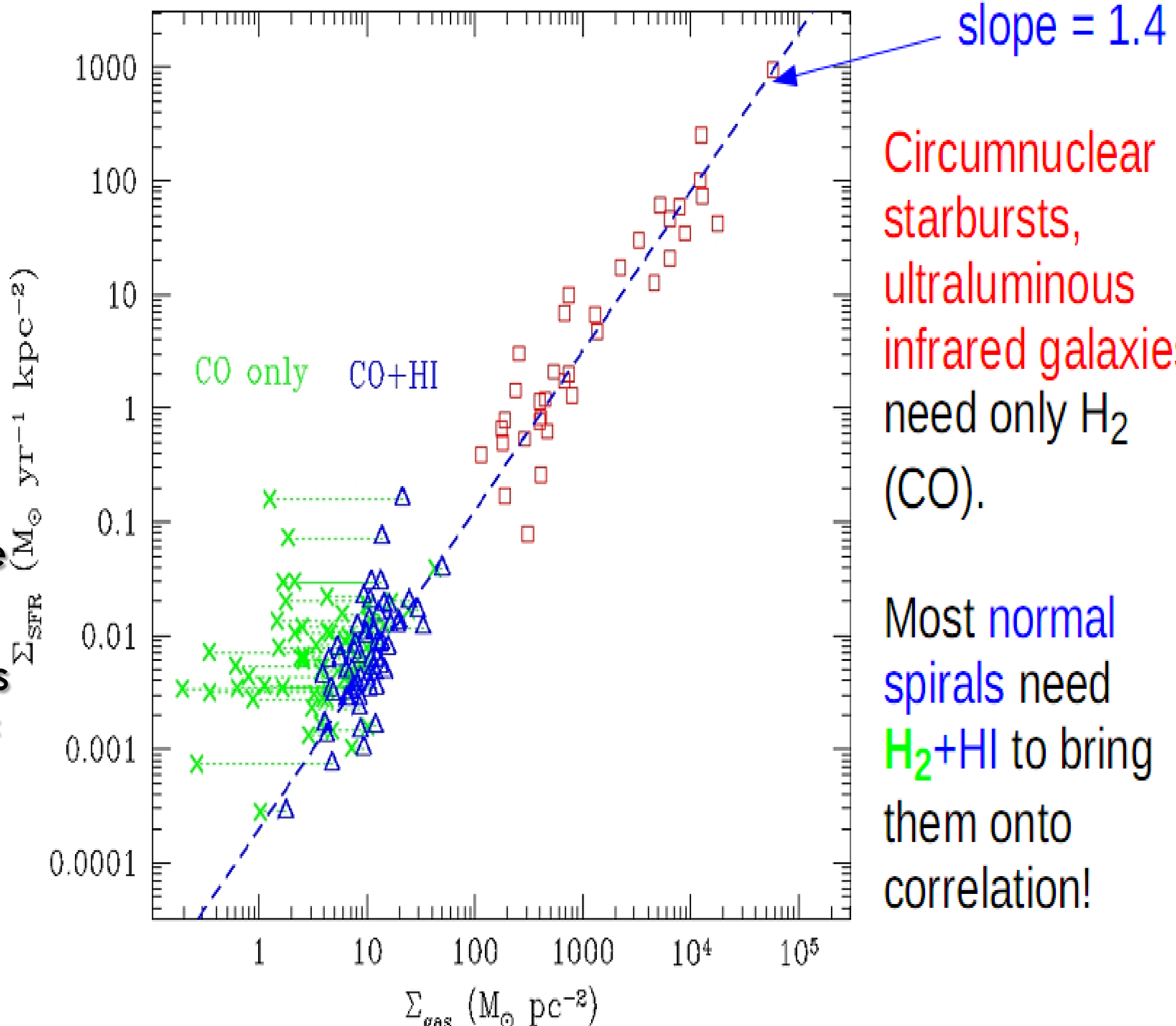
Where is Star Formation? -Nuclei(3)

- Surface gas densities and SF in nuclear starbursts many orders of magnitude higher w/ respect to disk SF
- Efficiency ~30% to 100% in 10^8 yrs
- No dependence on Hubble type
- Bars strongly correlated w/ SBs (gas driven inwards)
- Interactions strongly correlated w/ SBs (all ULIRGS are mergers)



Where is Star Formation? -Both

- **Global Kennicutt-Schmidt Law**
- Global SFRs of disks and nuclear starbursts are correlated with local gas density, over the entire range, on a power-law (Schmidt 1959).
- This tight relation across the whole range of SFR, suggests that **gas density** is the primary determinant of the SFR on all scales.



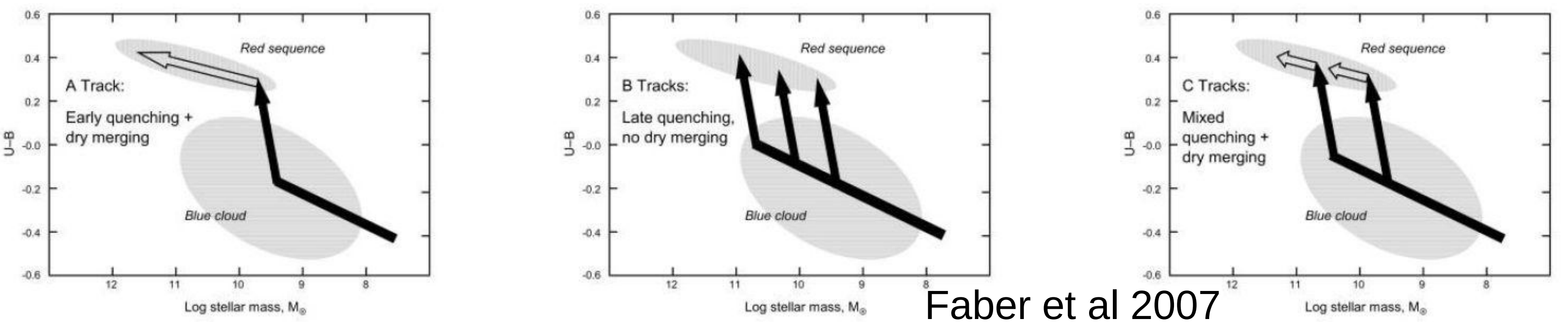
Circumnuclear starbursts, ultraluminous infrared galaxies need only H_2 (CO).

Most normal spirals need H_2+HI to bring them onto correlation!

Where is Star Formation? -Both(2)

Property	Spiral disks	Circumnuclear regions
Radius	1–30 kpc	0.2–2 kpc
Star formation rate (SFR)	0–20 $M_\odot$ year^{-1}	0–1000 $M_\odot$ year^{-1}
Bolometric luminosity	10^6–10^{11} $L_\odot$	10^6–10^{13} $L_\odot$
Gas mass	10^8–10^{11} $M_\odot$	10^6–10^{11} $M_\odot$
Star formation time scale	1–50 Gyr	0.1–1 Gyr
Gas density	1–100 $M_\odot$ pc^{-2}	10^2–10^5 $M_\odot$ pc^{-2}
Optical depth (0.5 μm)	0–2	1–1000
SFR density	0–0.1 $M_\odot$ year^{-1} kpc^{-2}	1–1000 $M_\odot$ year^{-1} kpc^{-2}
Dominant mode	steady state	steady state + burst
Type dependence?	strong	weak/none
Bar dependence?	weak/none	strong
Spiral structure dependence?	weak/none	weak/none
Interactions dependence?	moderate	strong
Cluster dependence?	moderate/weak	?
Redshift dependence?	strong	?

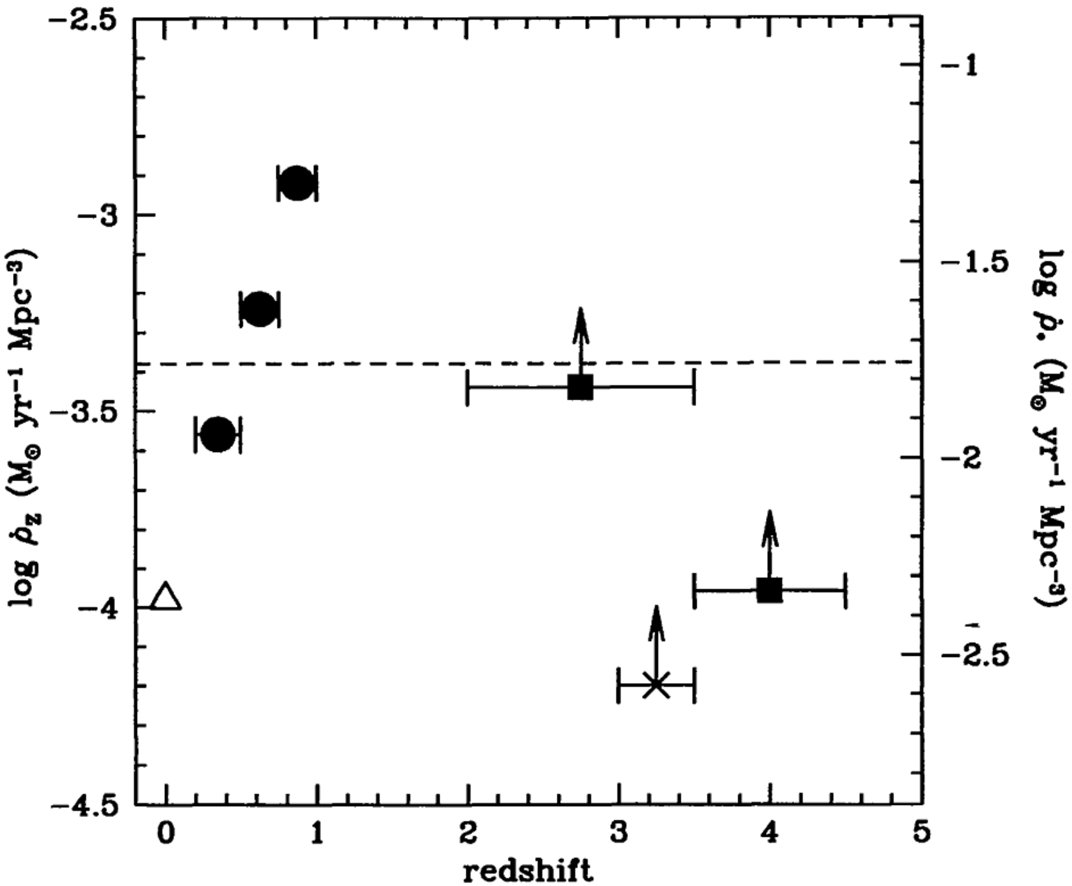
SFH – Evolution of galaxies



Faber et al 2007

- Galaxies evolve from blue star-forming spirals to red passive ellipticals through different possible mechanisms
- As long as the star formation is active, galaxies remain in the "blue cloud"; a quenching mechanism is required to stop star formation, then galaxies drift toward the "red sequence"
- Bimodalities in many properties – fast timescales for the changes in colors, spectral features, morphologies.

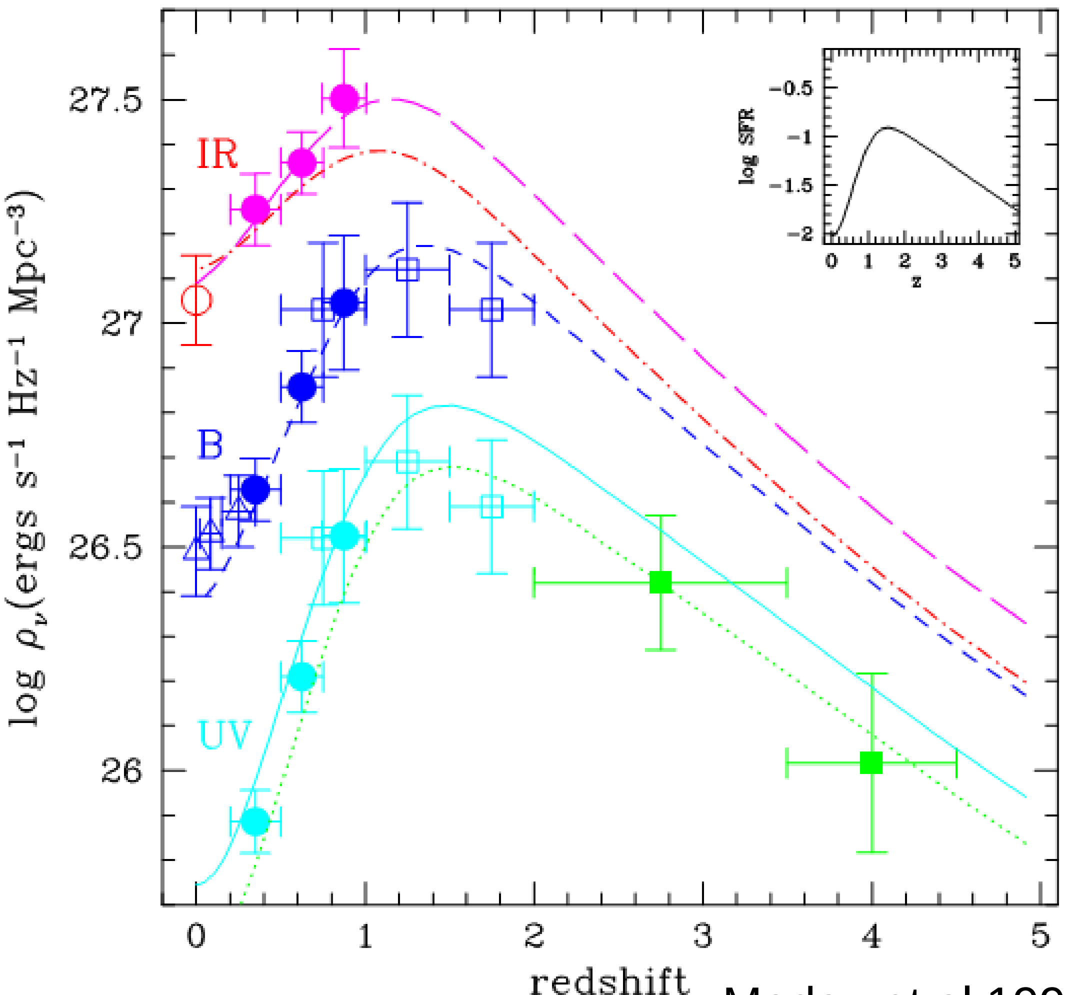
SFH – Evolution of galaxies (2)



Madau 1996

- **Madau** or **Lilly-Madau plot**
- Existence of a peak in cosmic metal production rate (which traces SFR) in redshift range $1<z<2$

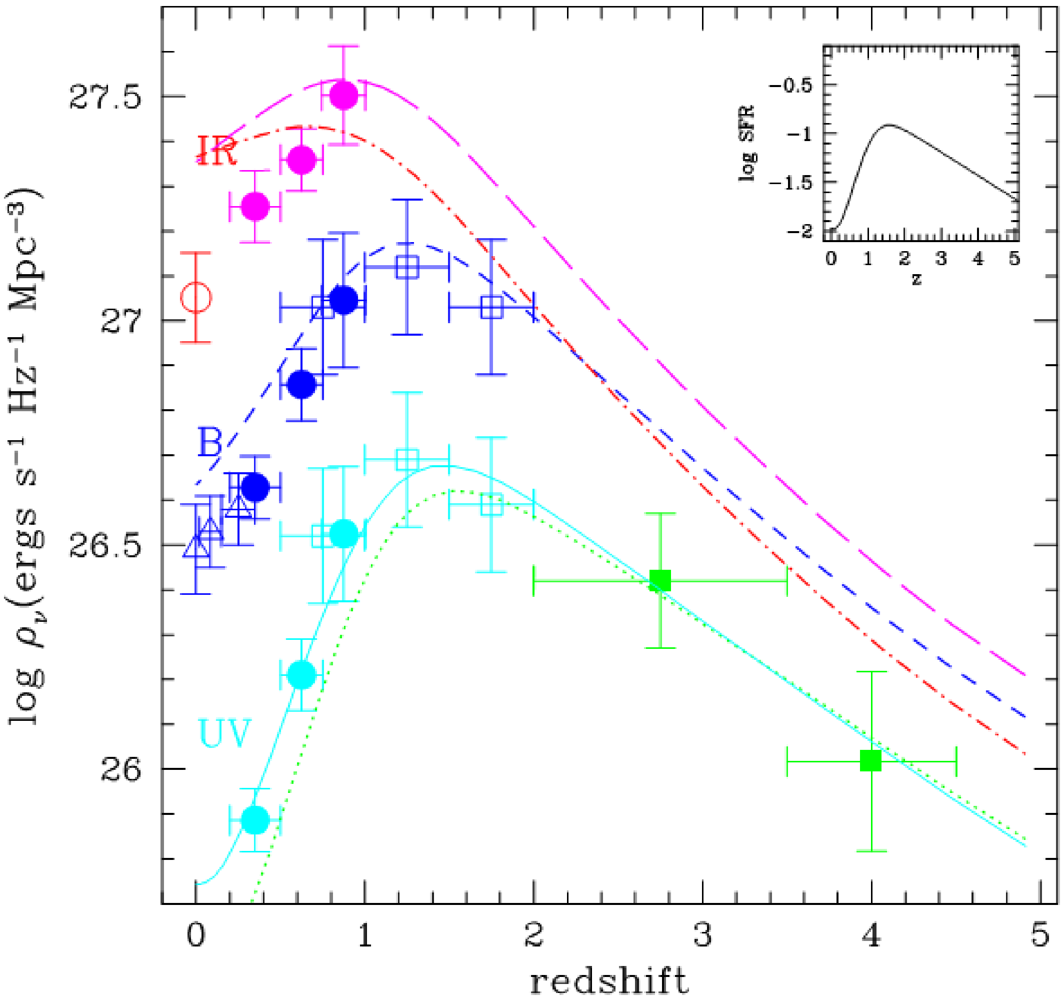
SFH – Evolution of galaxies (3)



Madau et al 1998

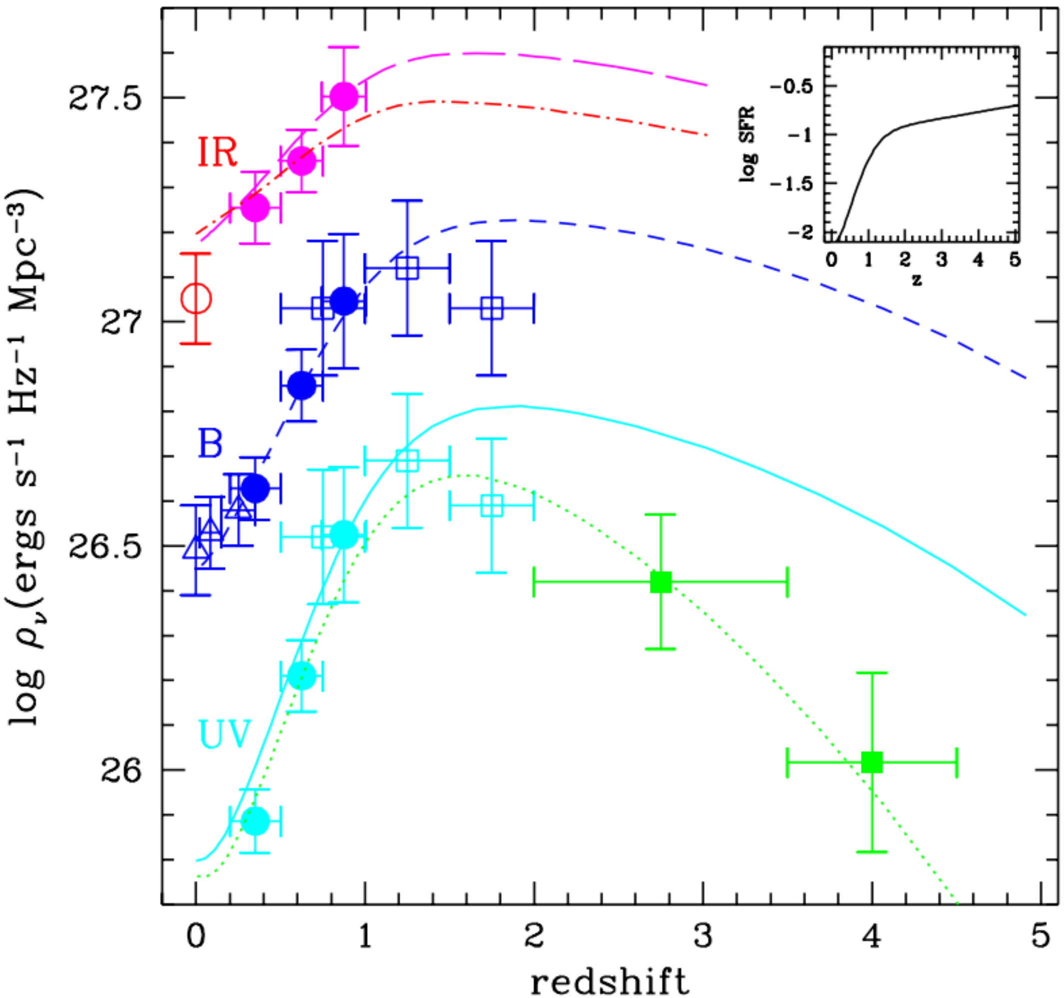
- **Madau** or **Lilly-Madau plot**
- Existence of a peak in cosmic metal production rate (which traces SFR) in redshift range 1<z<2
- Peak in SFR reflects peaks in luminosity density at different wavelengths
- Salpeter IMF, good agreement with data.

SFH – Evolution of galaxies (4)



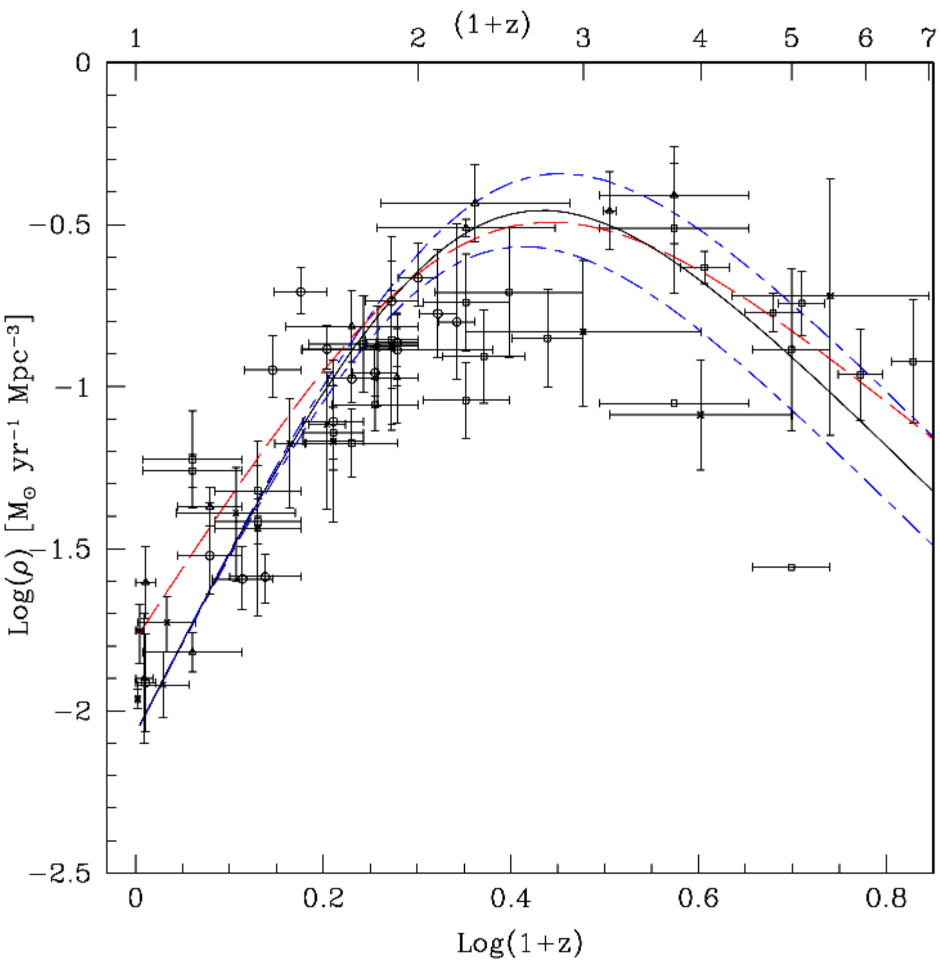
- **Madau** or **Lilly-Madau plot**
- Existence of a peak in cosmic metal production rate (which traces SFR) in redshift range 1<z<2
- Peak in SFR reflects peaks in luminosity density at different wavelengths
- Scalo IMF, overproduction of local K-band emissivity

SFH – Evolution of galaxies (5)



- **Madau** or **Lilly-Madau plot**
- Existence of a peak in cosmic metal production rate (which traces SFR) in redshift range 1<z<2
- Peak in SFR reflects peaks in luminosity density at different wavelengths
- Monolithic models still possible in 1998

SFH – Evolution of galaxies (6)

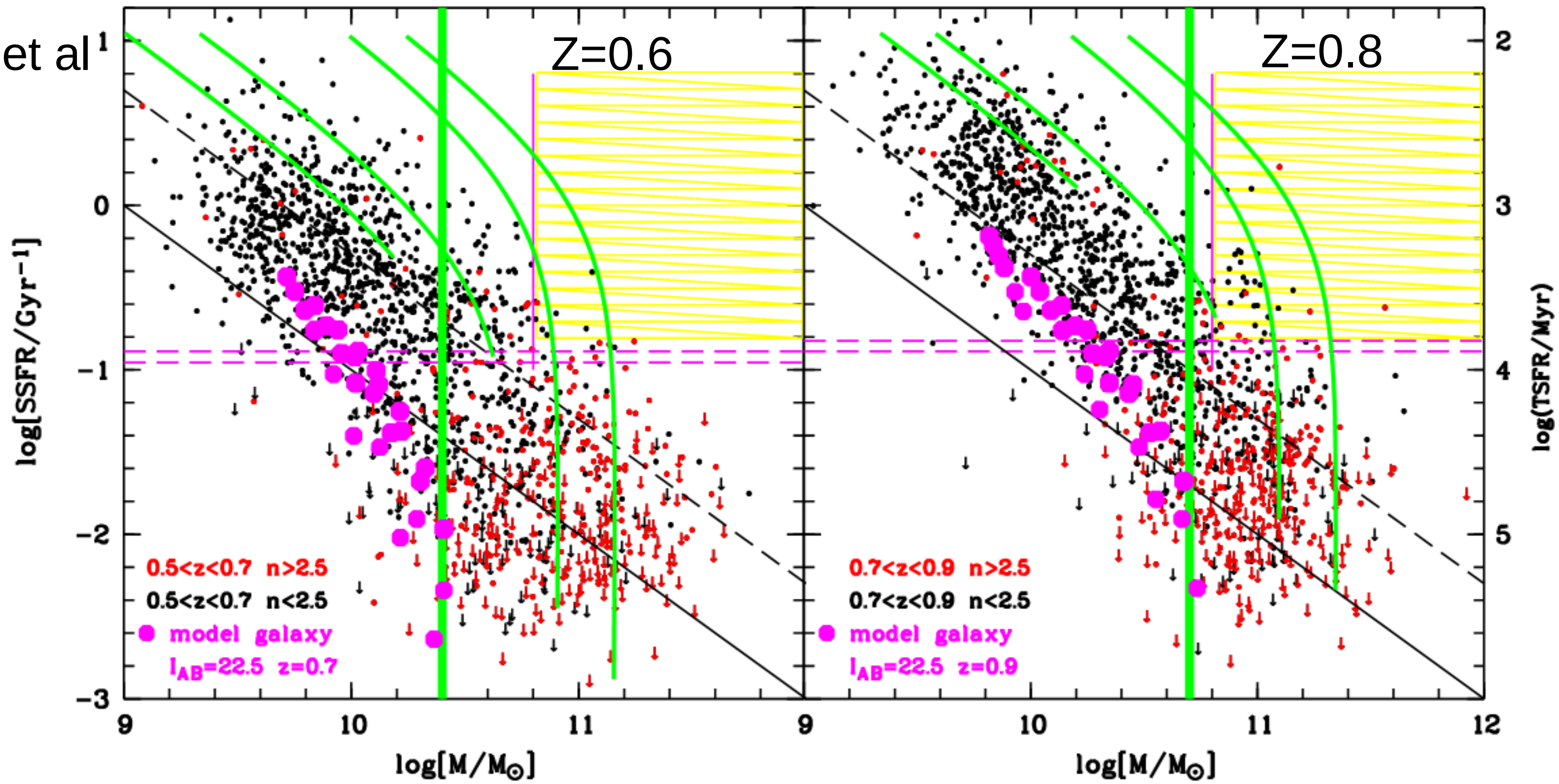


Hopkins 2004

- **Madau** or **Lilly-Madau plot**
- Existence of a peak in cosmic metal production rate (which traces SFR) in redshift range 1<z<2
- Peak in SFR reflects peaks in luminosity density at different wavelengths
- Monolithic models still possible in 1998 … not so much a few years later…

SFH – Evolution of galaxies (7)

Maier et al 2009



SSFR vs Mass as a function of morphological type.

Downsizing (at fixed mass, galaxies at z=.8 had larger SSFR than at z=.6)

Different SFR, at fixed mass, for different morphological types.

SF trigger/quenching mechanisms

- Several possible mechanisms to trigger and quench star formation
- Some mechanisms are twofold – they can promote the formation of new stars in some cases, and make it more difficult in others
- "Local" and "external" ("environmental") mechanisms

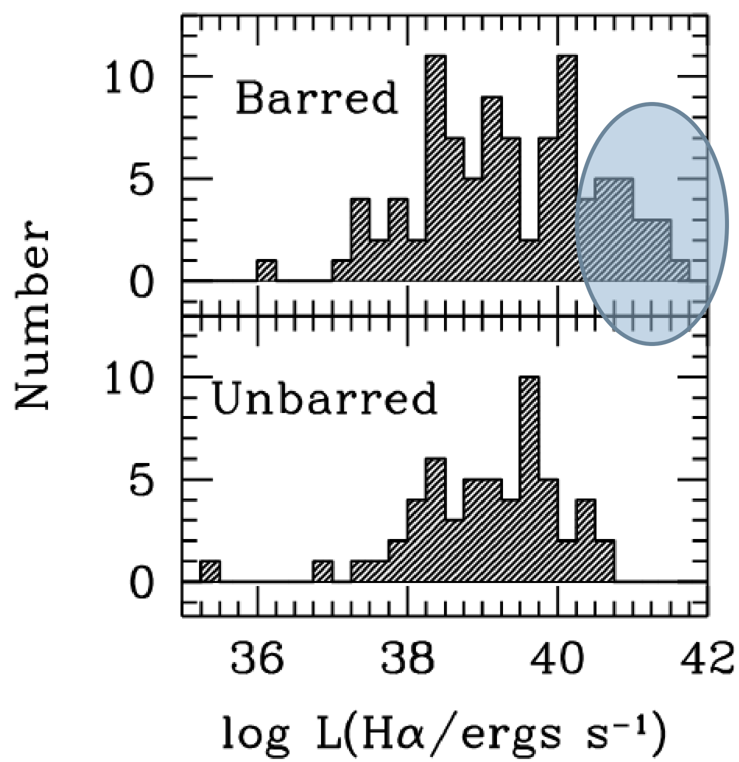
SF "local" mechanisms

Supernova explosions…

- Very massive stars form and explode into supernova. This makes shock waves into the molecular cloud, causing nearby gas to compress and form more stars.

SF "local" mechanisms (2)

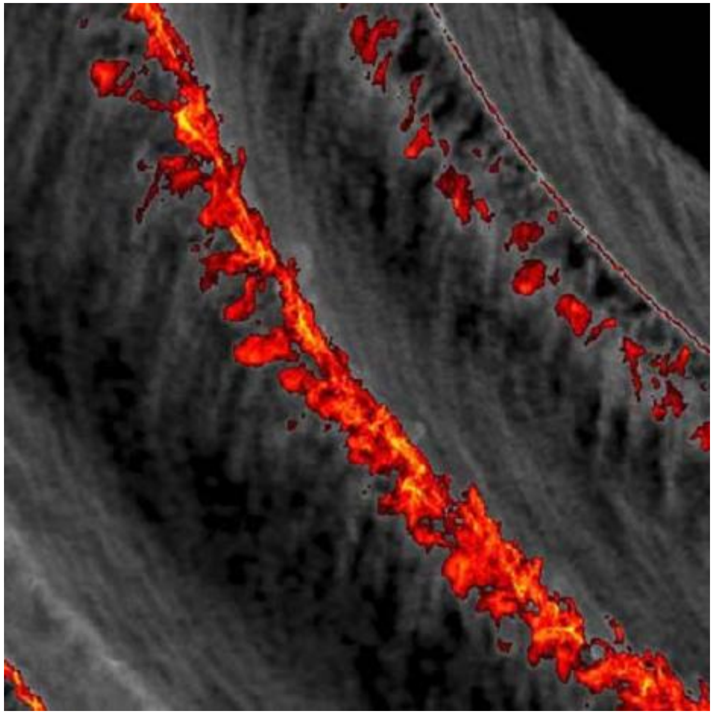
Bar structure…



Ho et al 1997

SF "local" mechanisms (3)

Spiral arm density waves…

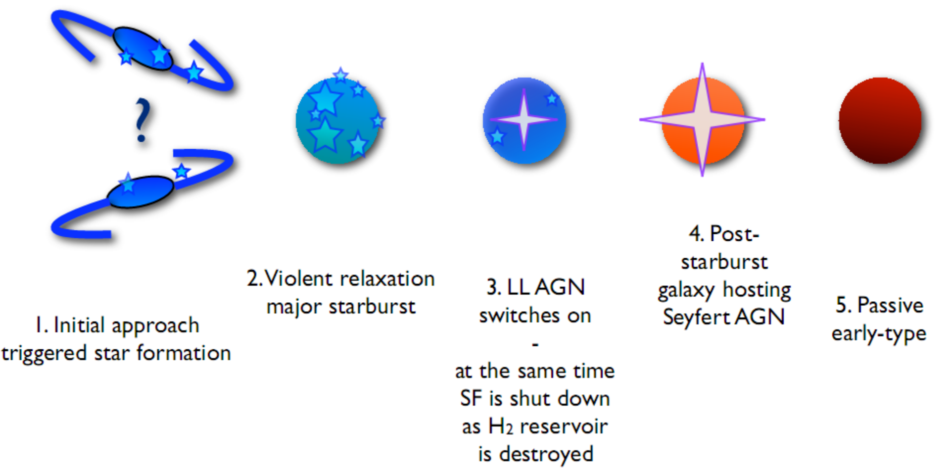


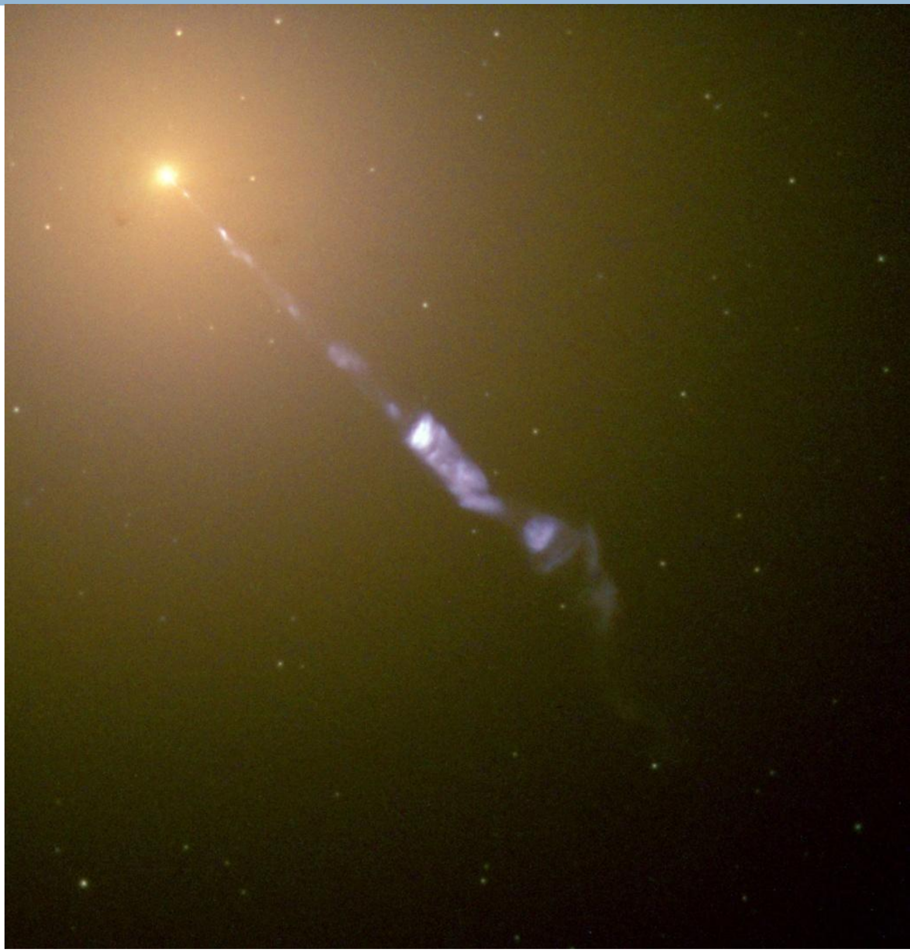
Dobbs et al 2006

SF "local" mechanisms

AGN activity…

A Sequence of Events for AGN Feedback in the formation of early-type galaxies



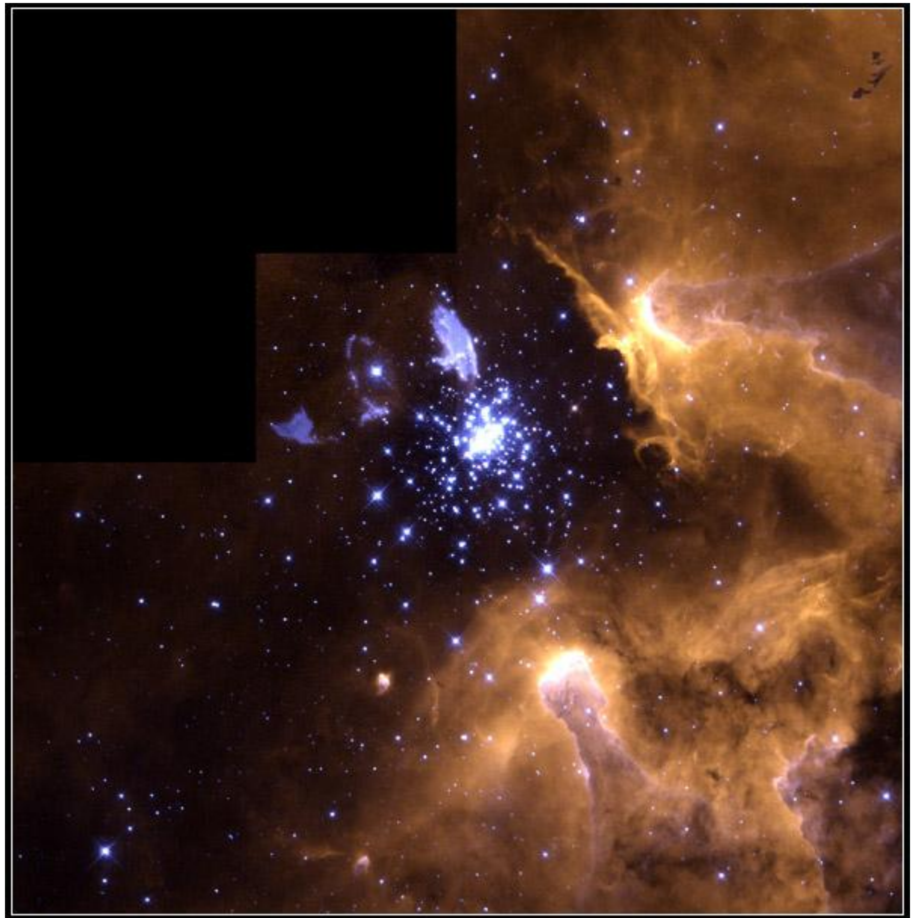


Schawinski 2009

SF "local" mechanisms

Massive stars' winds…

- Intense stellar winds and radiation pressure (because of the high luminosity) from massive young stars may compress ISM clouds and trigger star formation.



NGC 3603 **HST** • WFPC2
PRC99-20 • STScI OPO • June 1, 1999
Wolfgang Brandner (JPL/IPAC), Eva K. Grebel (Univ. Washington), You-Hua Chu (Univ. Illinois, Urbana-Champaign) and NASA

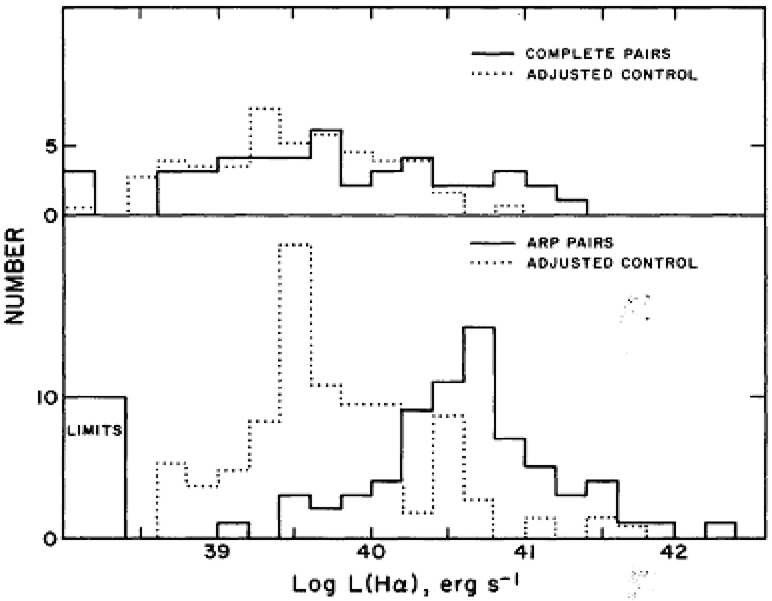
SF trigger/quenching mechanisms

- Galaxies live in a complex environment, made up of other galaxies and an Intra-Cluster Medium (ICM), so a galaxy is not sufficient to explain itself: interactions.
- Different interactions can influence the SFR of a galaxy
- "Same normal interactions regulating human relationships (harassment, stripping, starvation, suffocation, strangulation)"

SF "external" mechanisms

Mergers…

- Promote an increase in SFR and a more rapid depletion of gas → forming ellipticals?



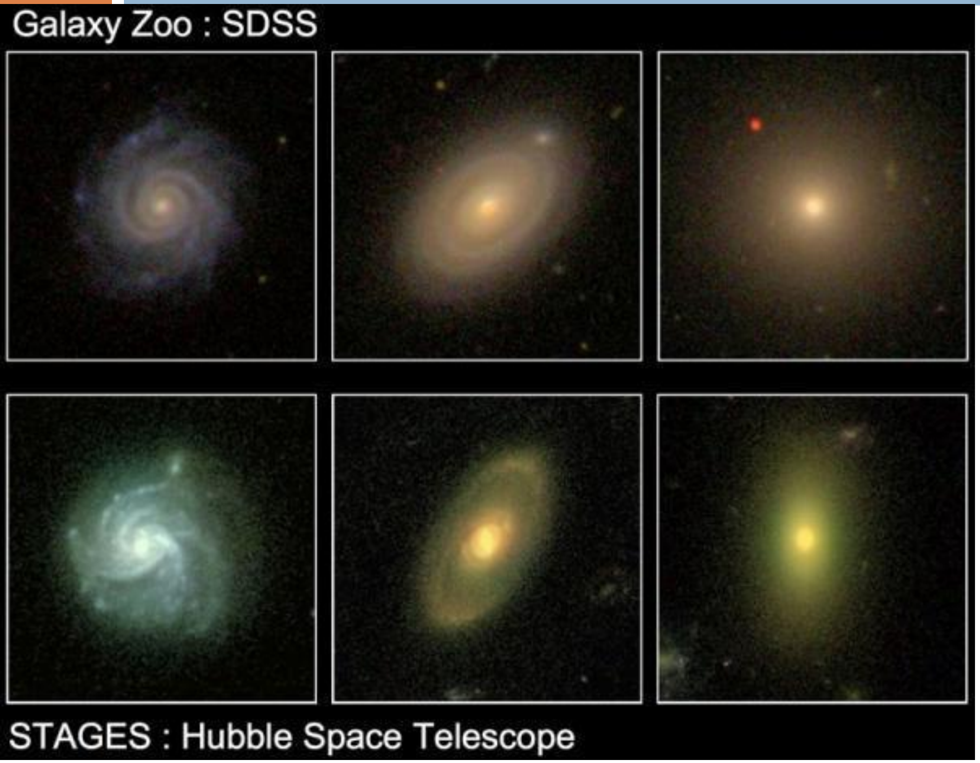
Keel et al 1985

SF “external” mechanisms (2)

Harassment

- Interactions involving high-speed fly-bys are often referred to as galaxy 'harassment'.
- Harassment can disturb, or even radically change, the morphologies of the galaxies involved, often inducing new bursts of star formation. Asymmetrical galaxies, disturbed galaxies, warps, bars and tidal tails can all be produced through galaxy harassment.

SF "external" mechanisms



Strangulation

- As galaxies fall into the cluster environment for the first time, the gravitational potential of the cluster (and its dark matter halo) create tidal effects that enable the gas contained within the galaxies to escape. As the gas is lost to the ICM, the amount available to produce stars inside the galaxy gradually falls, and eventually, SF within the galaxy will cease. In other words, SF in the galaxy has died for want of gas - the galaxy has been strangled.

SF “external” mechanisms (3)

Ram pressure stripping

- As galaxies move within ICM, they experience this gas as a 'wind‘. ‘Ram pressure stripping' occurs if this wind is strong enough to overcome the gravitational potential of the galaxy to remove the gas contained within it. Evidences:
  - The disk of dust and gas appears bowed. This indicates that the galaxy is having trouble holding onto the loosely bound dust and gas in the outer regions of the disk against the pressure of the 'wind'.
  - The stellar disk (blue) appears to extend well beyond the star forming disk of dust and gas. Loosely bound dust and gas in the outer regions of the disk has been stripped from the galaxy after the formation of these stars.

- Streamers of dust and gas can be seen trailing behind the motion of the galaxy, obscuring and reddening the stars behind (top of the galaxy in the image). At the same time, the 'wind' has pushed the dust and gas that would normally be found ahead of the motion of the galaxy up into the galaxy itself. This has revealed bright blue stars along the leading edge of the galaxy (bottom of the galaxy in the image).

Final words

- Many SF indicators available (*choose wisely*!)
- Hierarchical models are favoured
- Galaxies ARE NOT island-universes!!

Final words (2)

Thanks!