A radio astronomy primer

Maurilio Pannella – mpannella@units.it - May 2021

Agenda and Outline of this primer

6 May

- What is radio astronomy
- Historical background
- Physical processes

25 May

- Collecting radio signals
- A brief introduction to interferometry

27 May

- Radio astronomy and galaxy evolution
- The present and future of radio astronomy

Galaxy evolution from radio observations

galaxy spectral properties

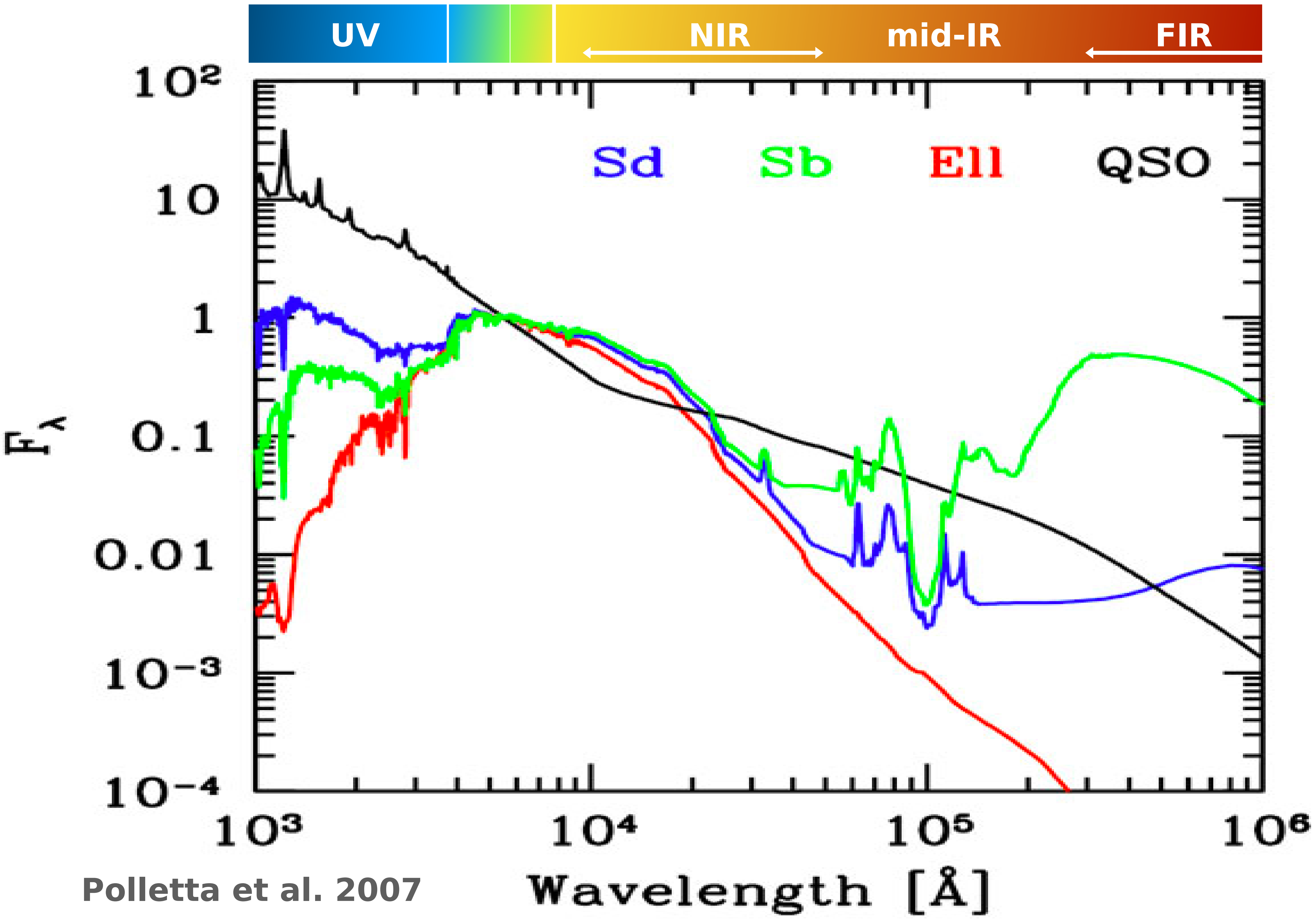
star formation rates

gas content (molecular and atomic)

nuclear activity and its impact on galaxies

Galaxy evolution from radio observations

The SED measures the galaxy flux (luminosity/cm²/s) in wavelength range dλ (F_λ, units of erg/s/cm²/Å) or in frequency range dν (F_ν, units of erg/s/cm²/Hz)



Polletta et al. 2007

Galaxy evolution from radio observations

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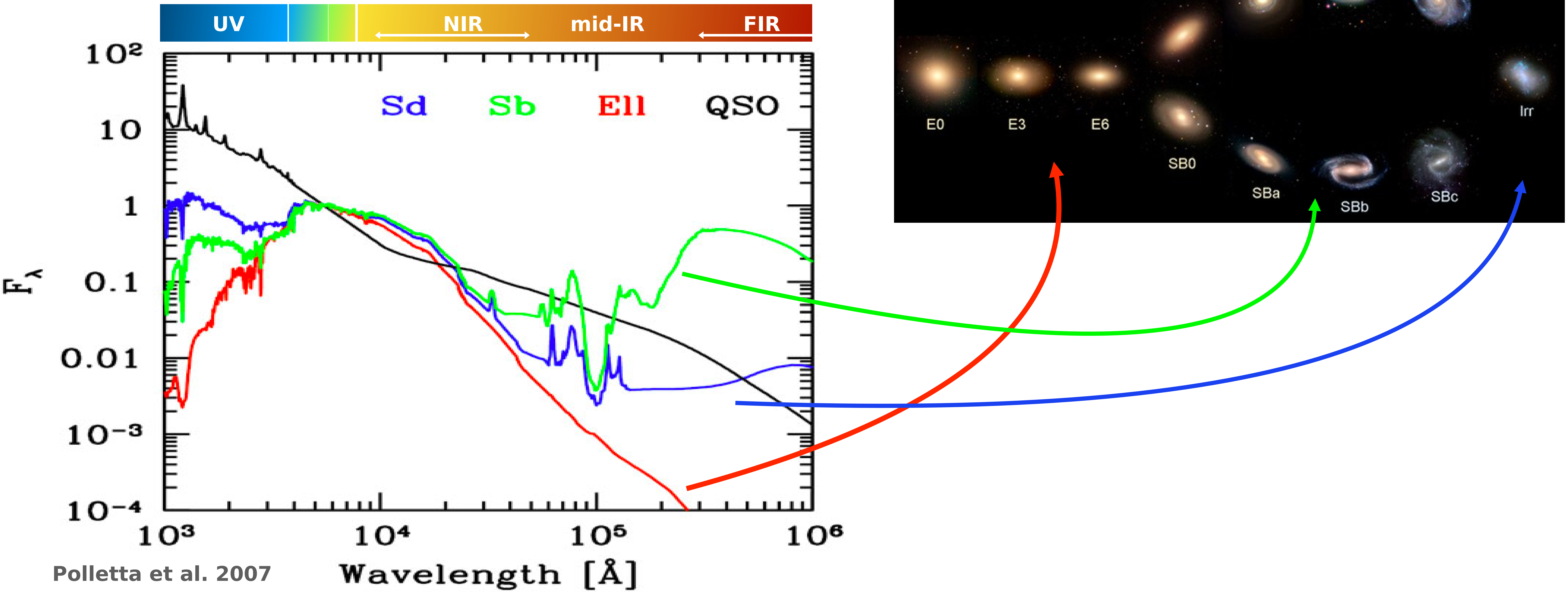
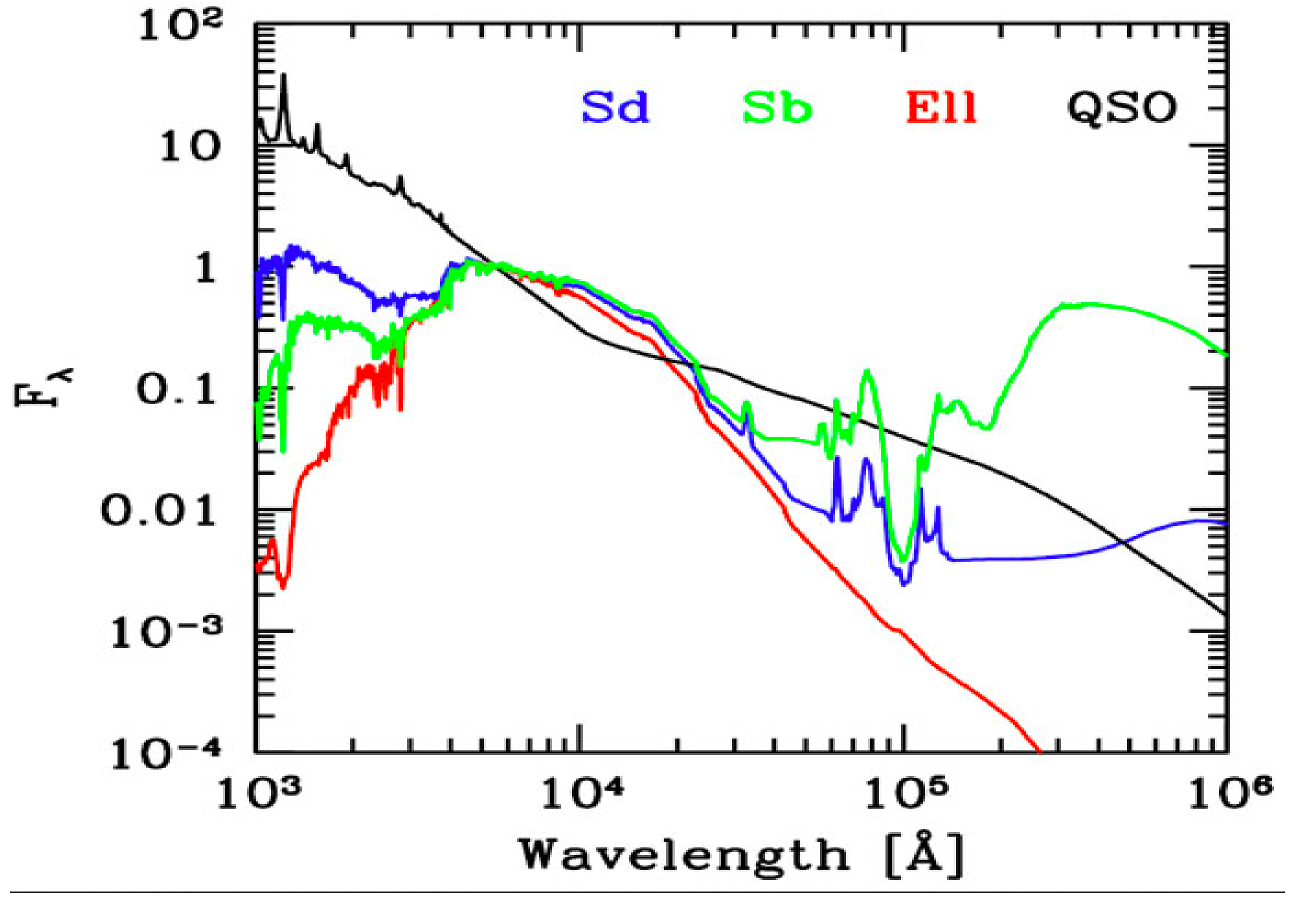


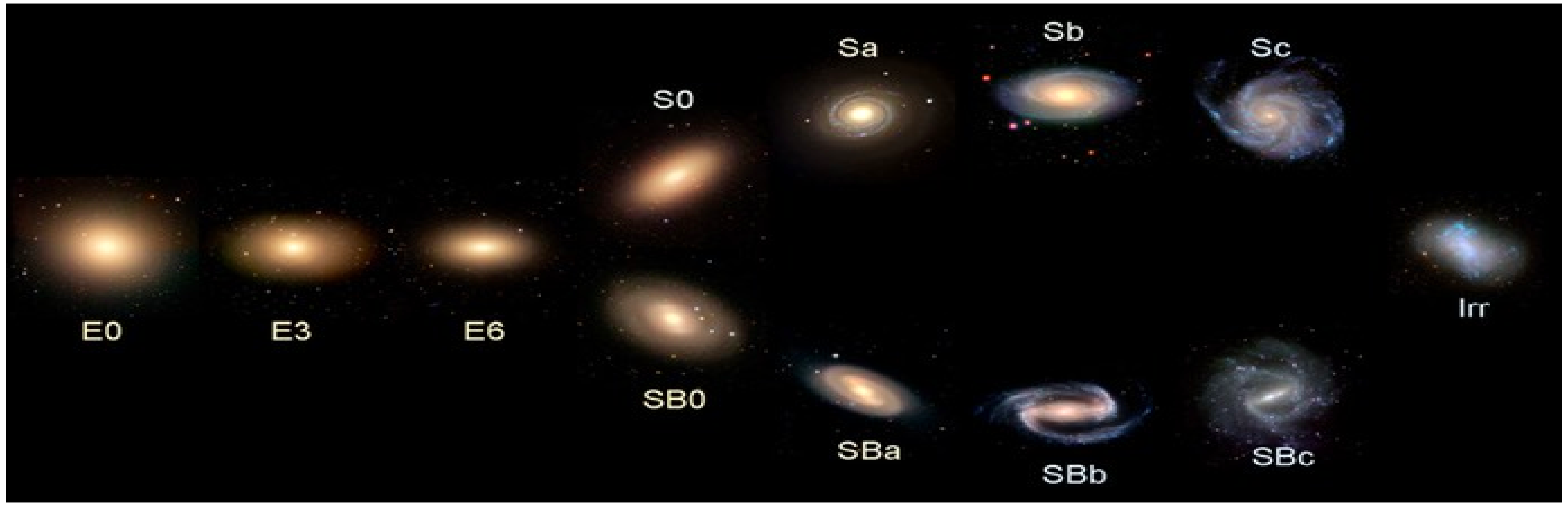
Polletta et al. 2007

Galaxy evolution from radio observations

Galaxy spectral energy distributions are the result of the combination of light emission and absorption from the (baryonic) galaxy consituents:

- **stars**
- **gas**
- **dust**



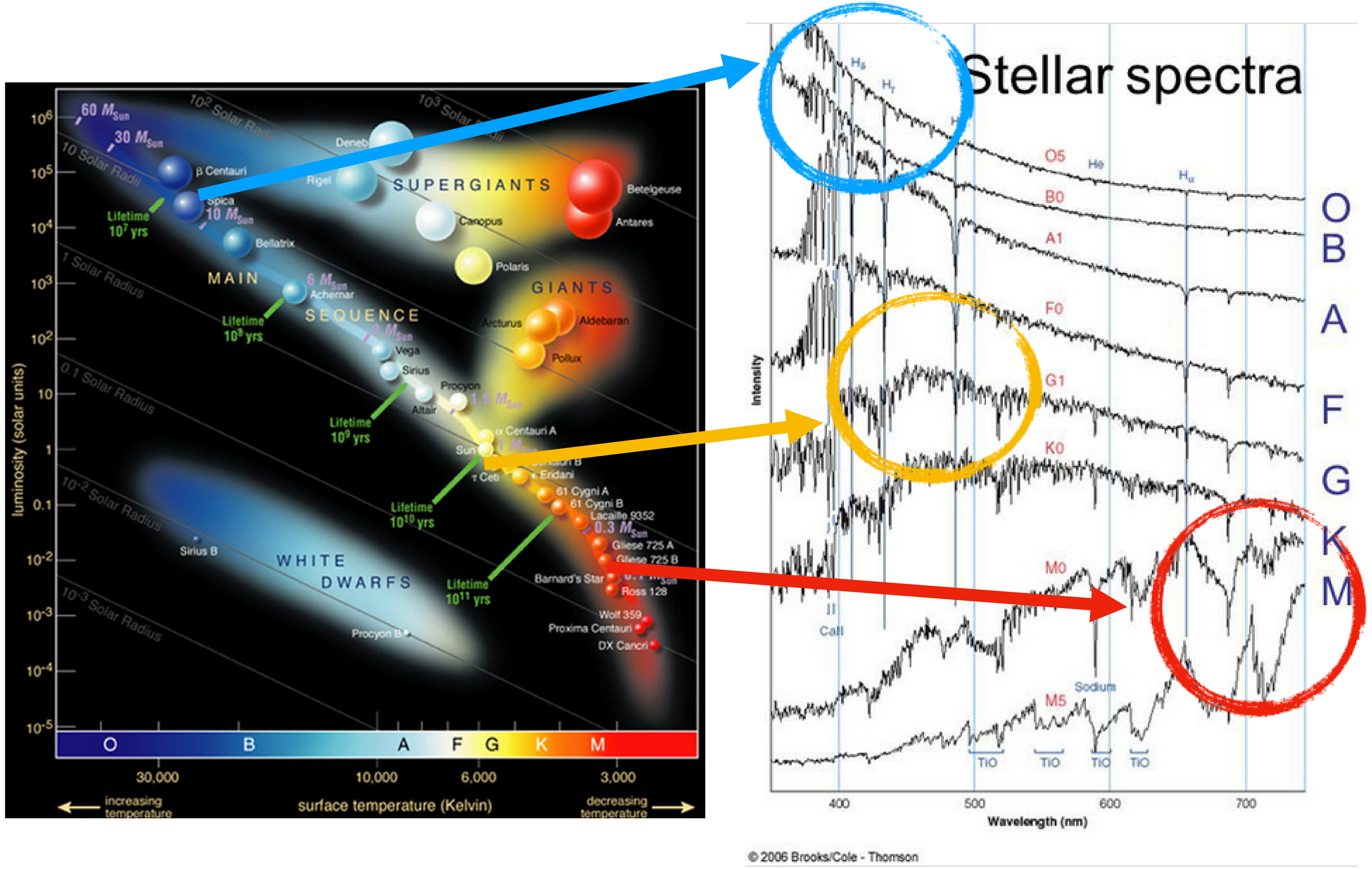


Galaxy evolution from radio observations

Stars - the primary source of light in (most) galaxies

The light of a galaxy is to first order “the sum of the light from all its stars” (see later) -> to build a galaxy SED start by summing up the spectra of all its stars:

- **how many stars ?**
- **what type of stars (which spectra) ?**



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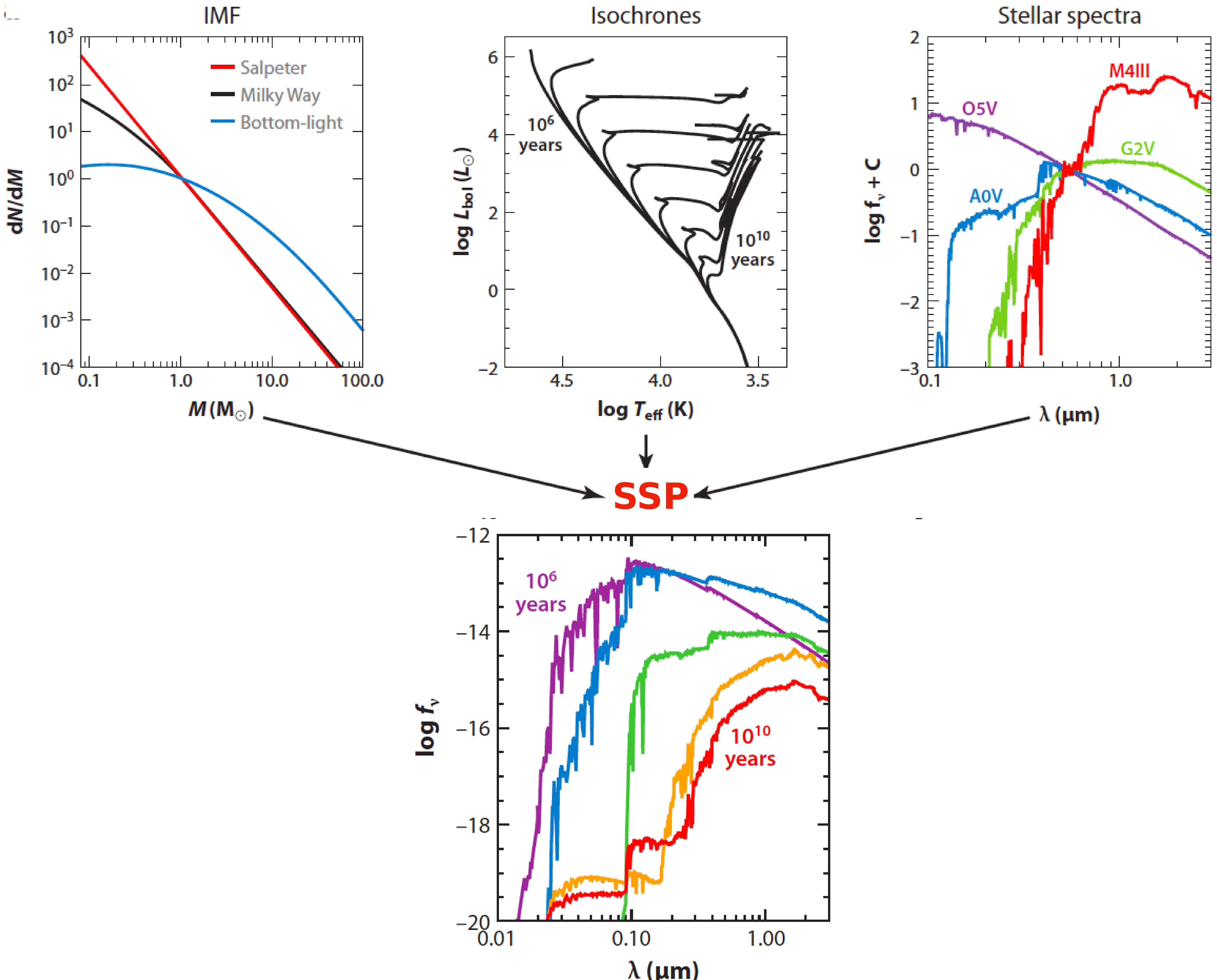
Galaxy evolution from radio observations

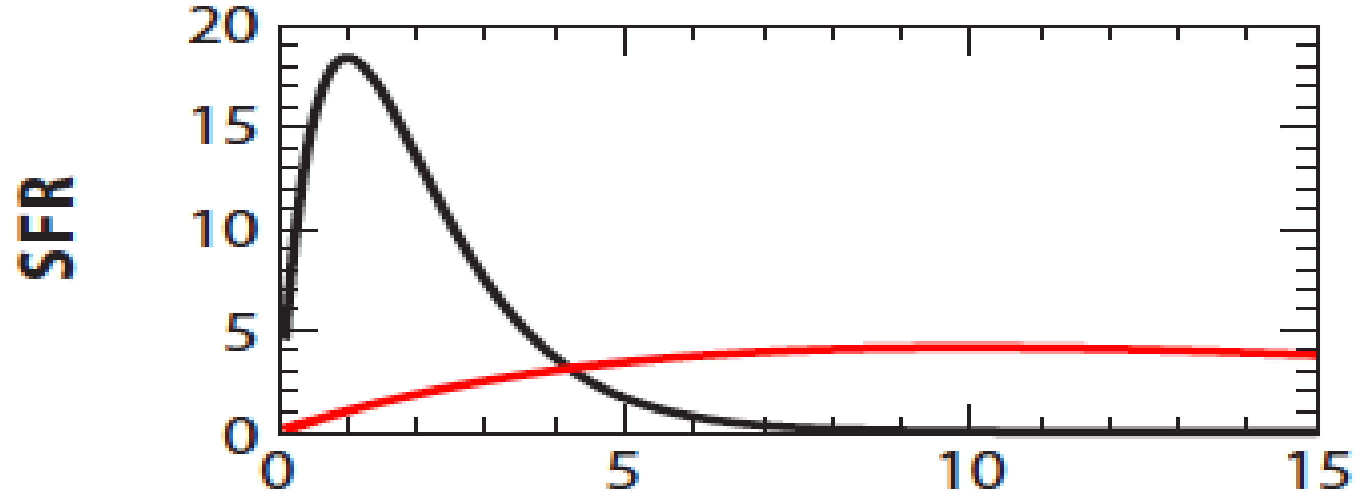
Stars - the primary source of light in (most) galaxies



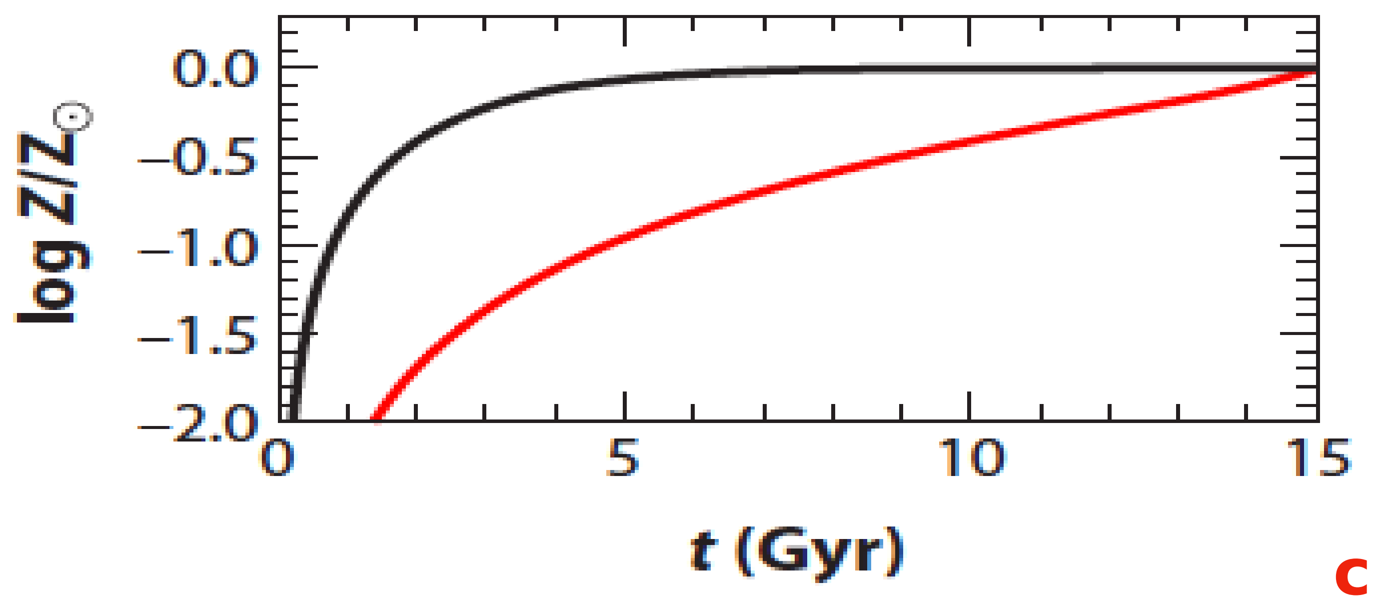
Galaxy evolution from radio observations

<u>Stars</u> - the primary source of light in (most) galaxies

star formation history (SFH)

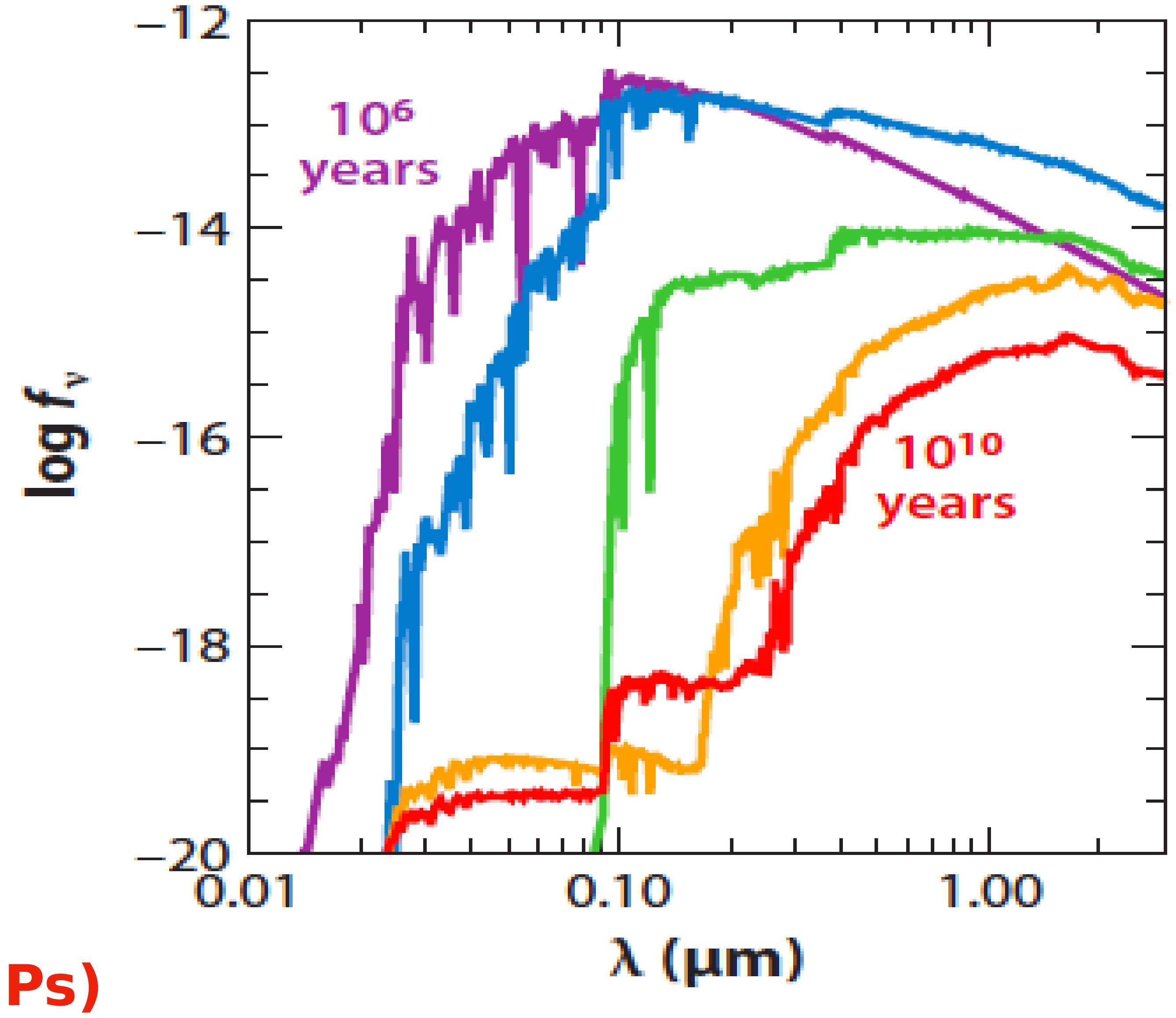


(chemical evolution)

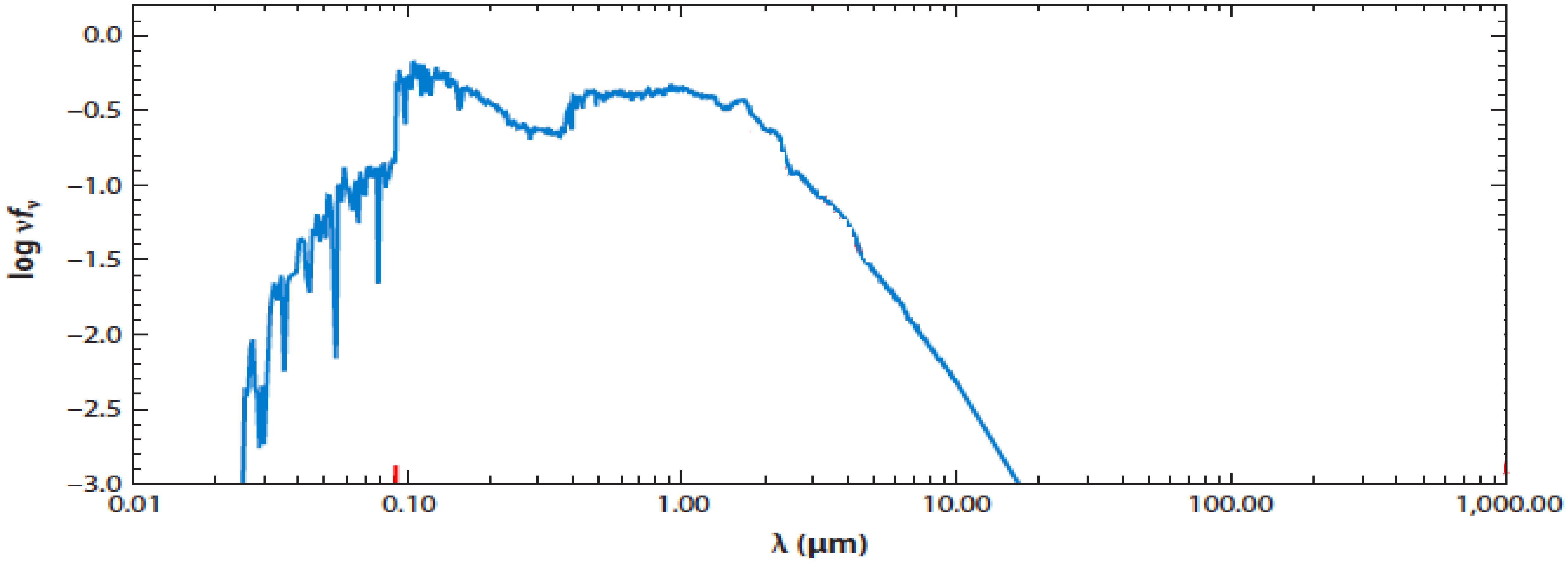


Conroy 2013

SSP (time evolution)



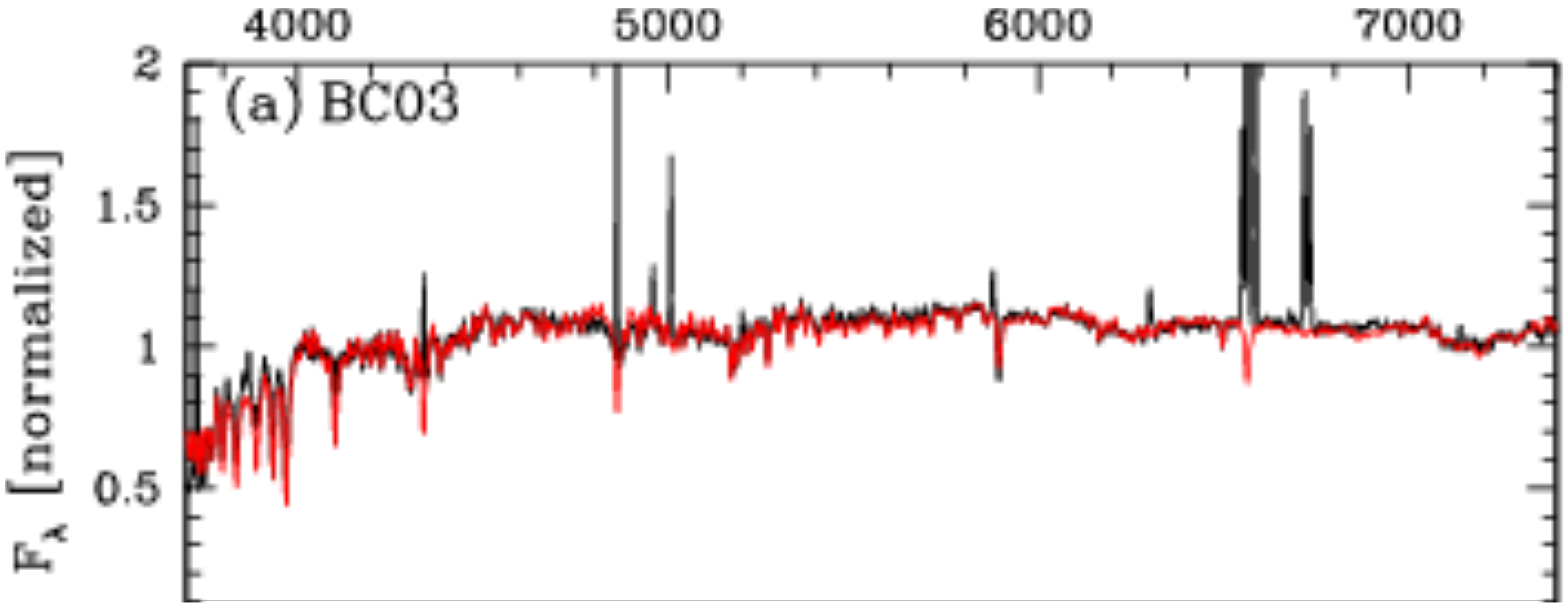
composite stellar populations (CSPs)



Galaxy evolution from radio observations

Gas – line emission from the ionized ISM

Nebular emission from ionised (HII) regions of the ISM (continuum and emission lines). Associated with star-forming galaxies, because only massive O and early B stars emit UV photons that efficiently ionize HI gas to HII. Emission lines from heavier elements are also observed - depending on ionization level and metallicity of the gas.



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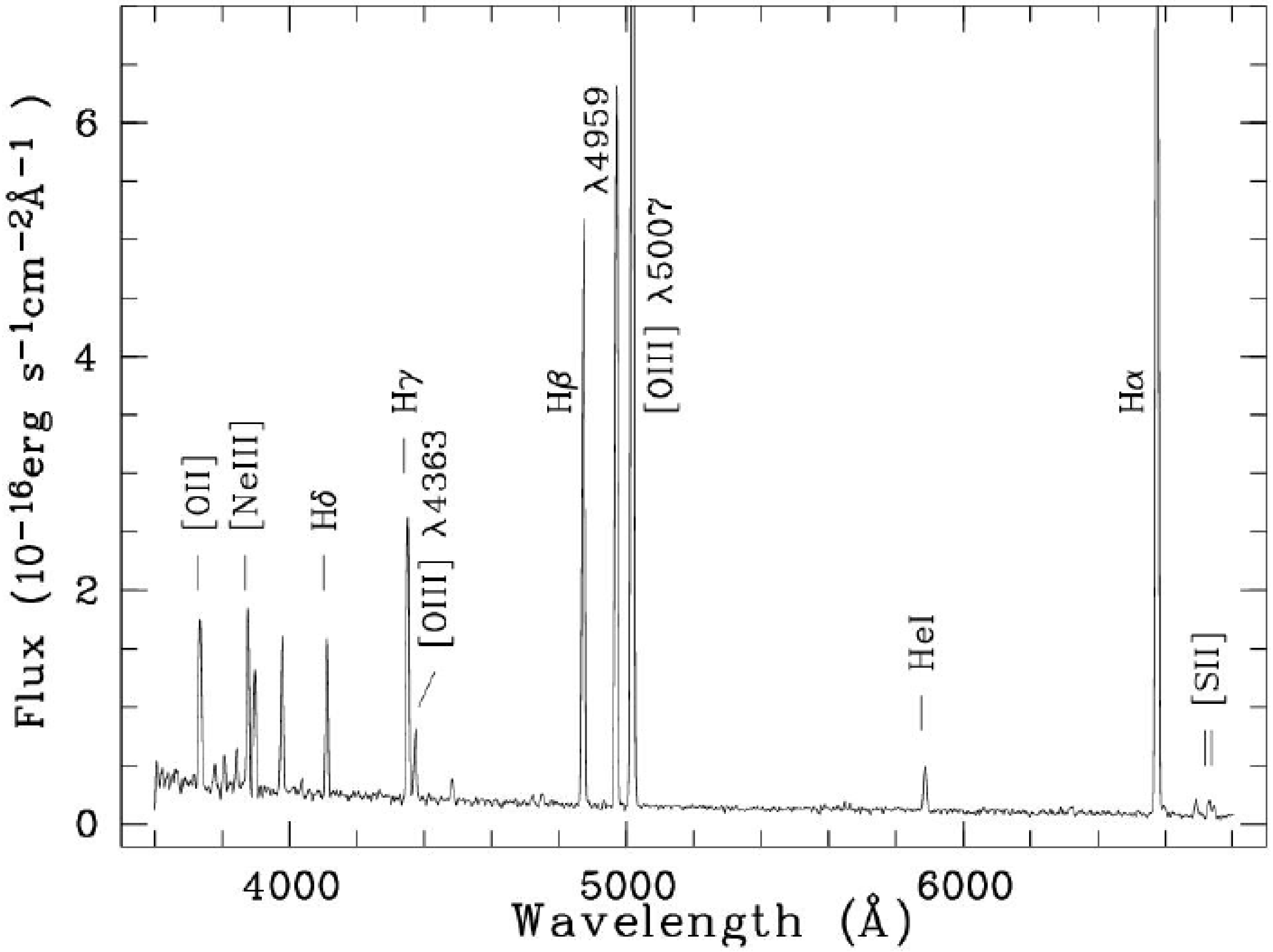
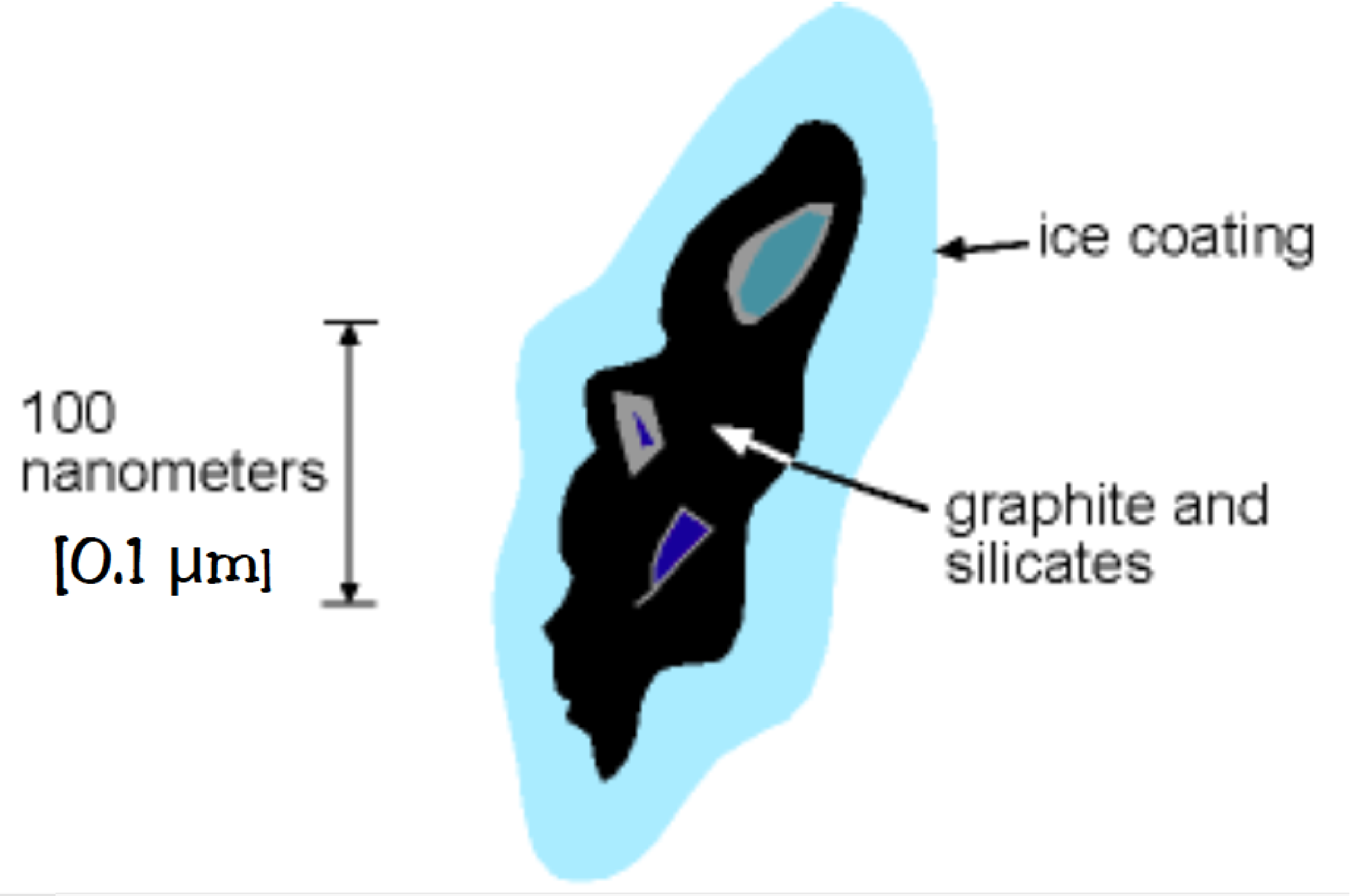
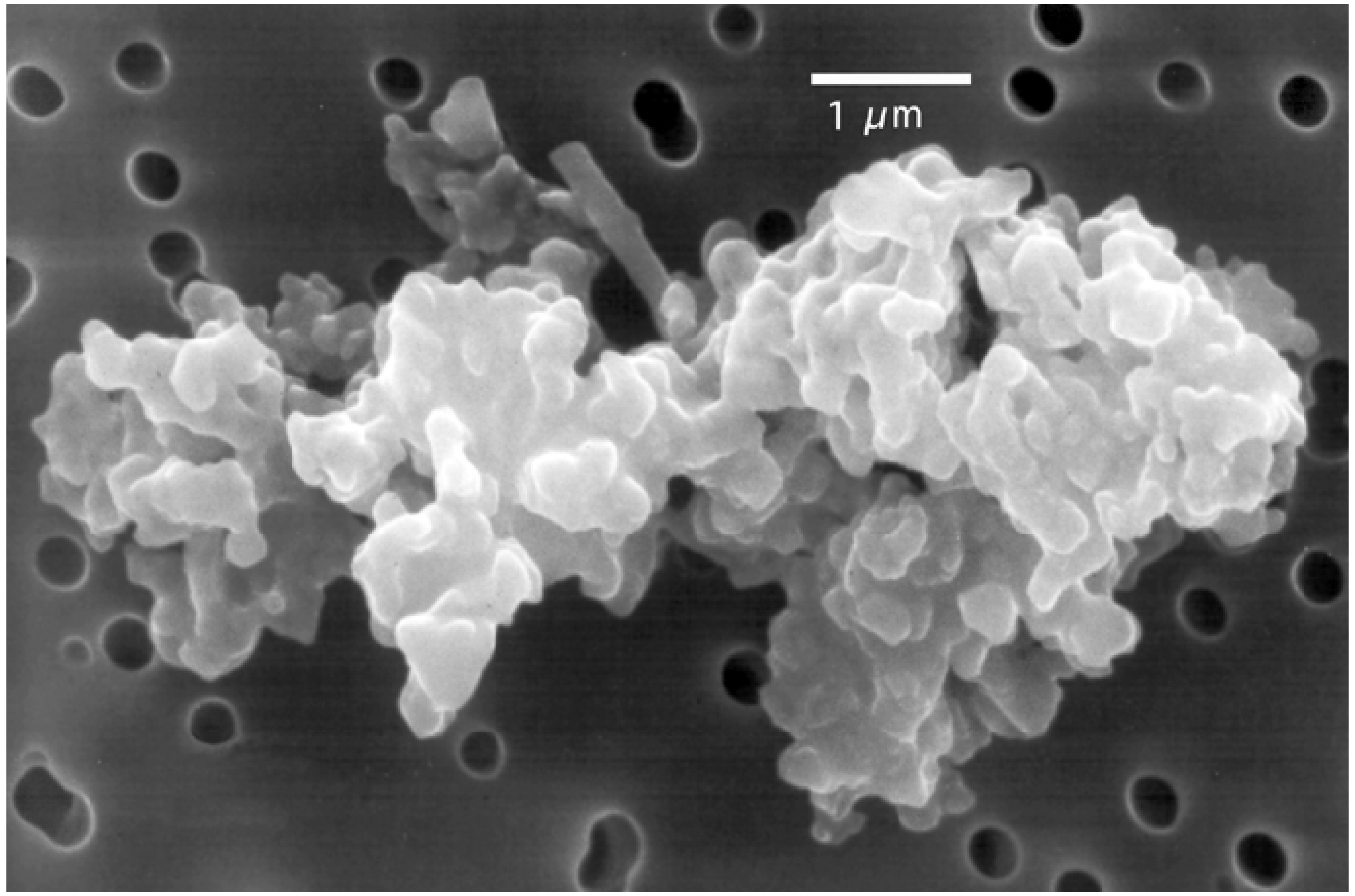


Galaxy evolution from radio observations

Dust – the dark side of galaxies

Cosmic dust is made of aggregates of sub-μm grains - silicates and carbonaceous grains (graphite, polycyclic aromatic hydrocarbons). It may scatter starlight, absorb it, and re-radiate it a different wavelengths.





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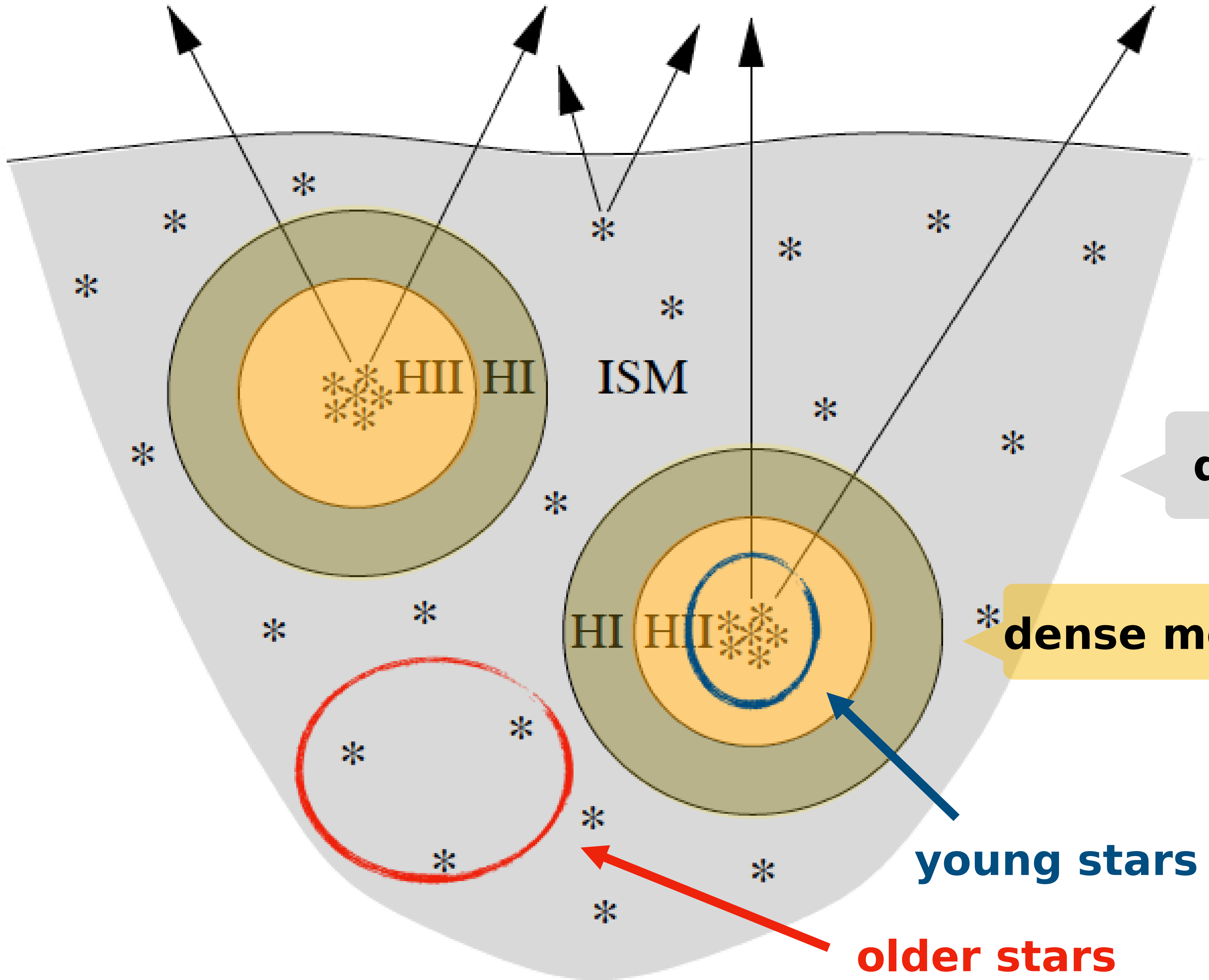

diffuse interstellar medium (ISM)

dense molecular clouds

young stars forming in the clouds

older stars

Charlot & Fall 2000

Galaxy evolution from radio observations

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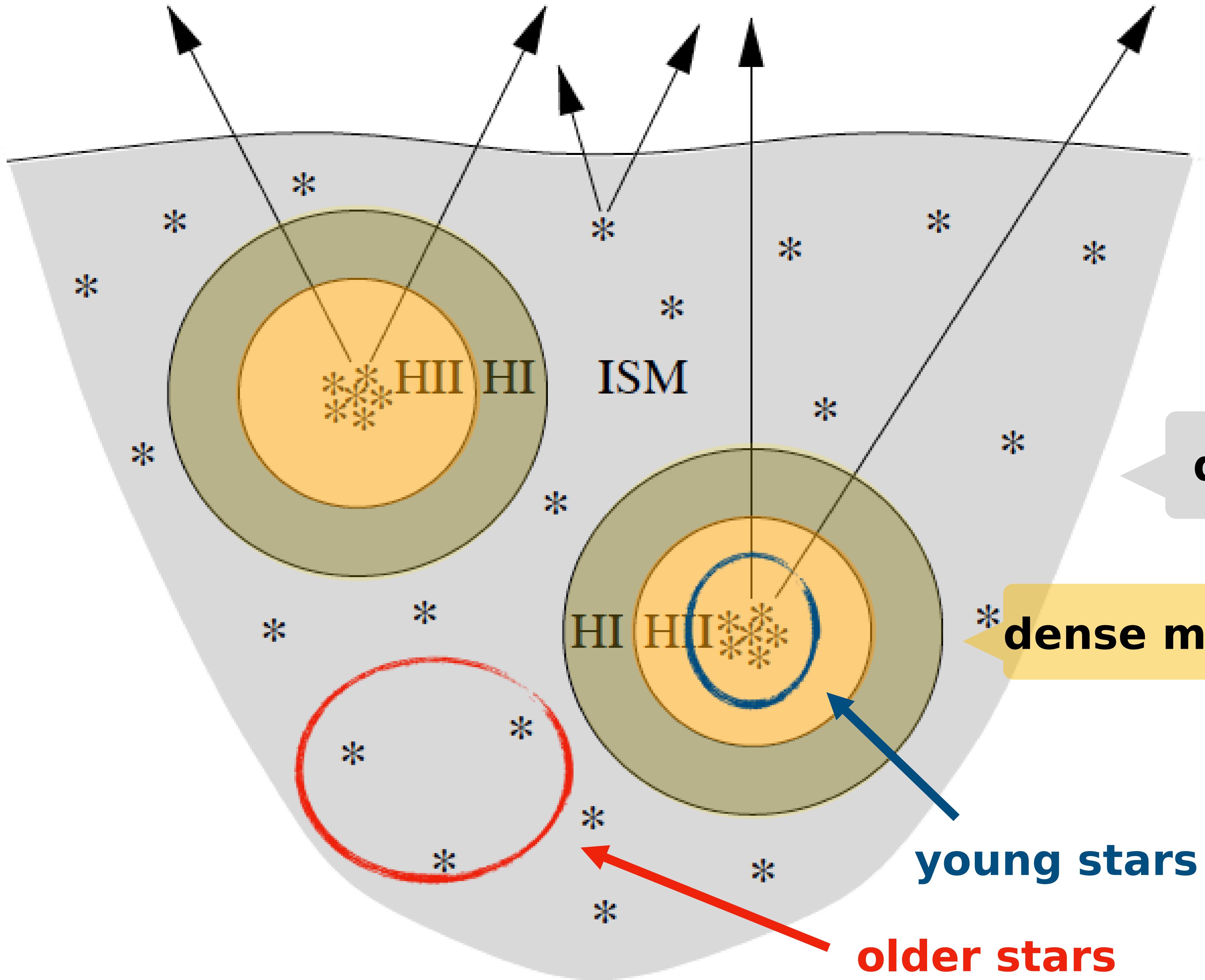
The emerging starlight is affetcted by <u>extinction</u>
(due to <u>absorption</u> and <u>scattering</u> in/out of the line of sight)
- to different extent depending on wavelength



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Galaxy evolution from radio observations

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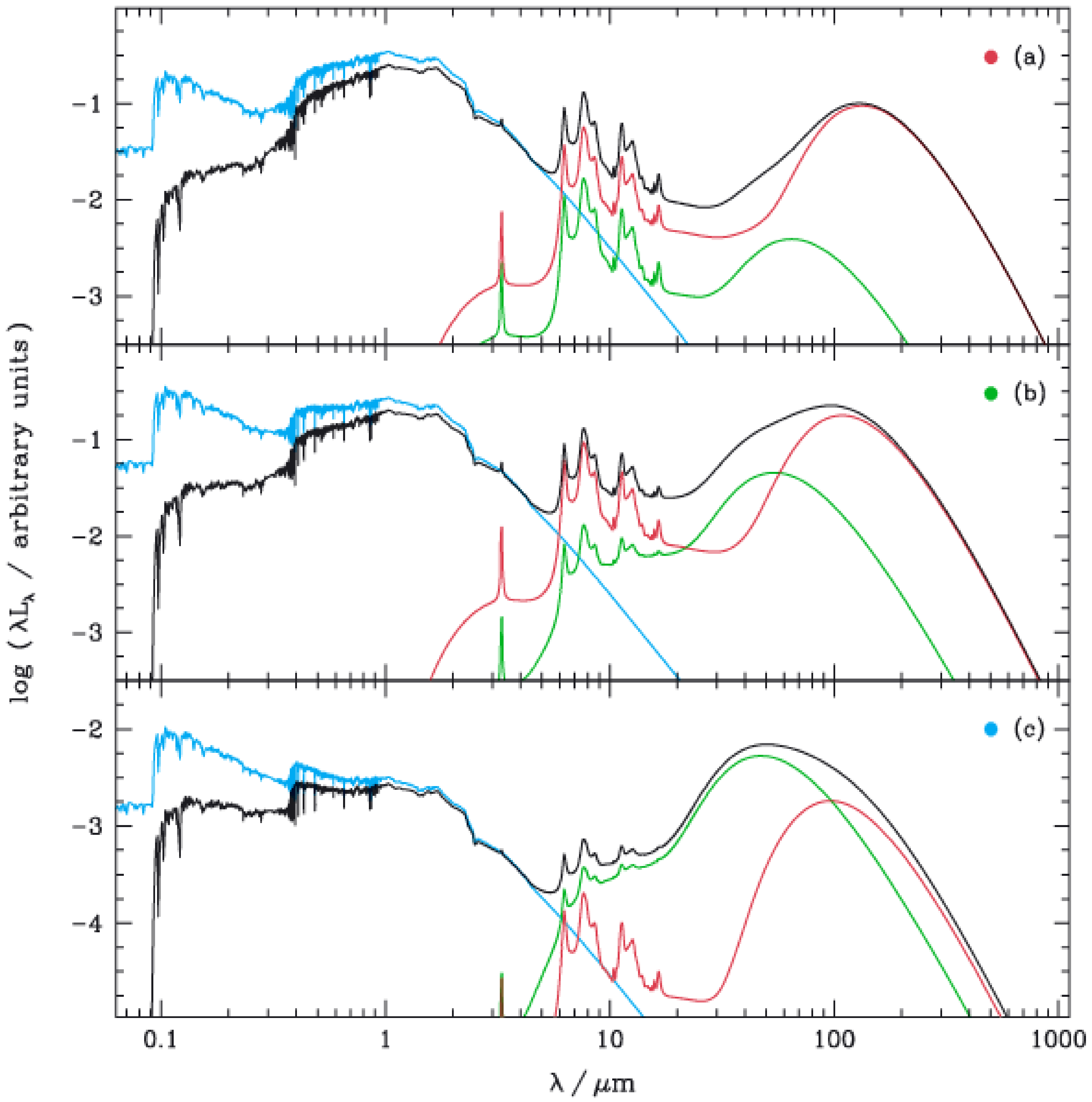
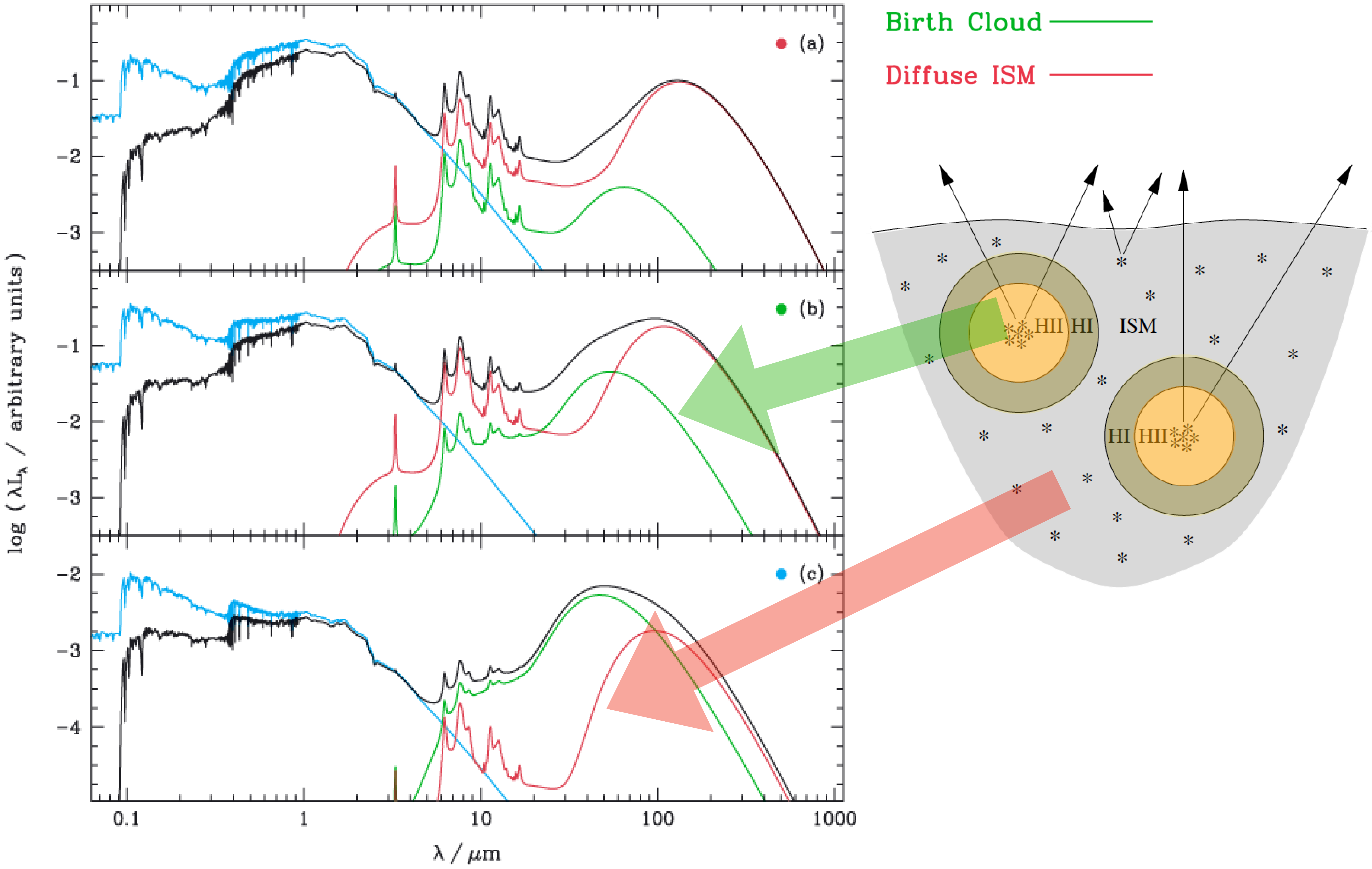


the absorbed starlight heats the dust, which re-radiates this energy in the IR

emission in the mid-/far-IR range reflects the heating of dust in different ISM components from stars of all ages

Galaxy evolution from radio observations

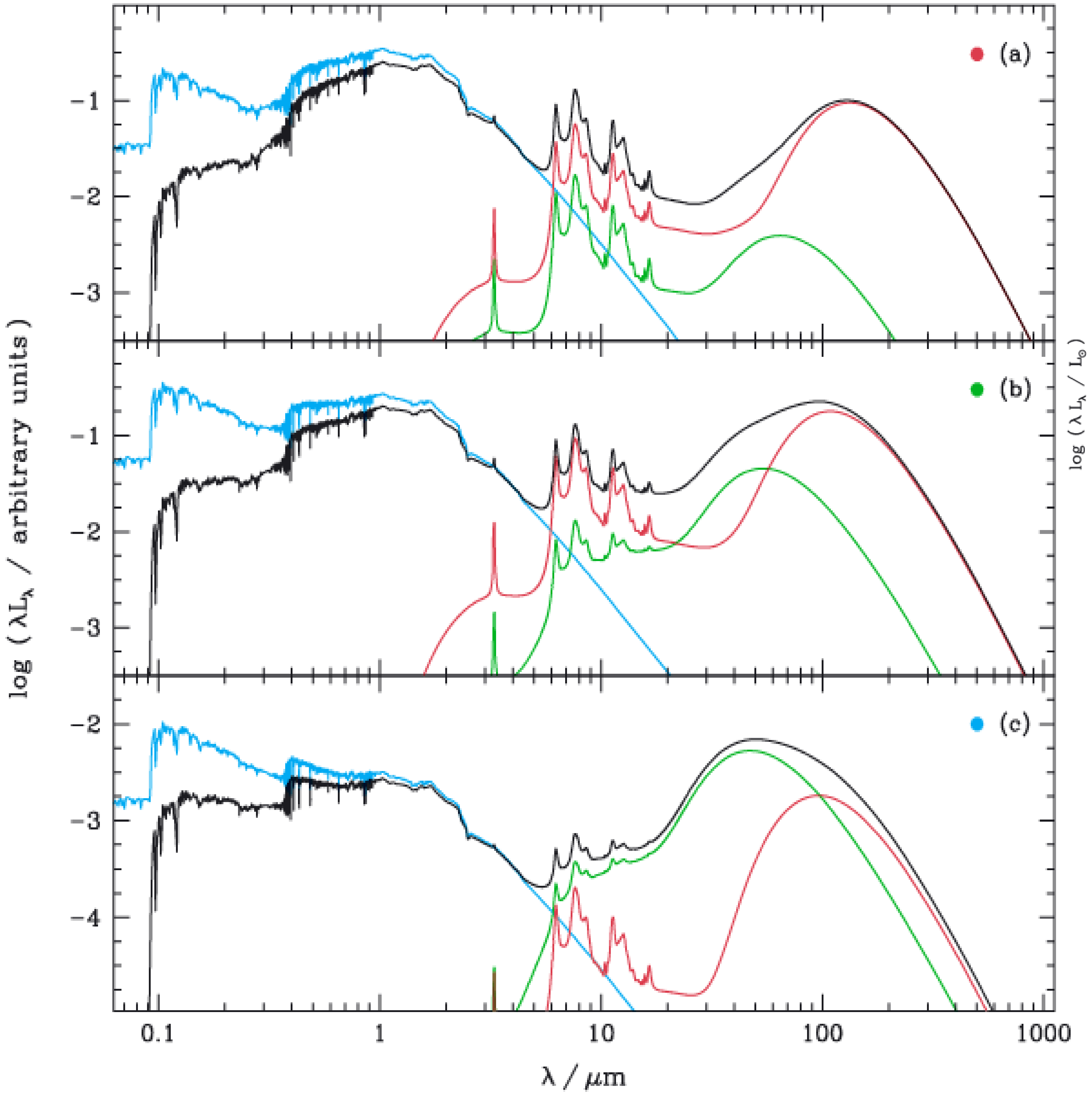
Dust – the dark side of galaxies



da Cunha et al. 2008

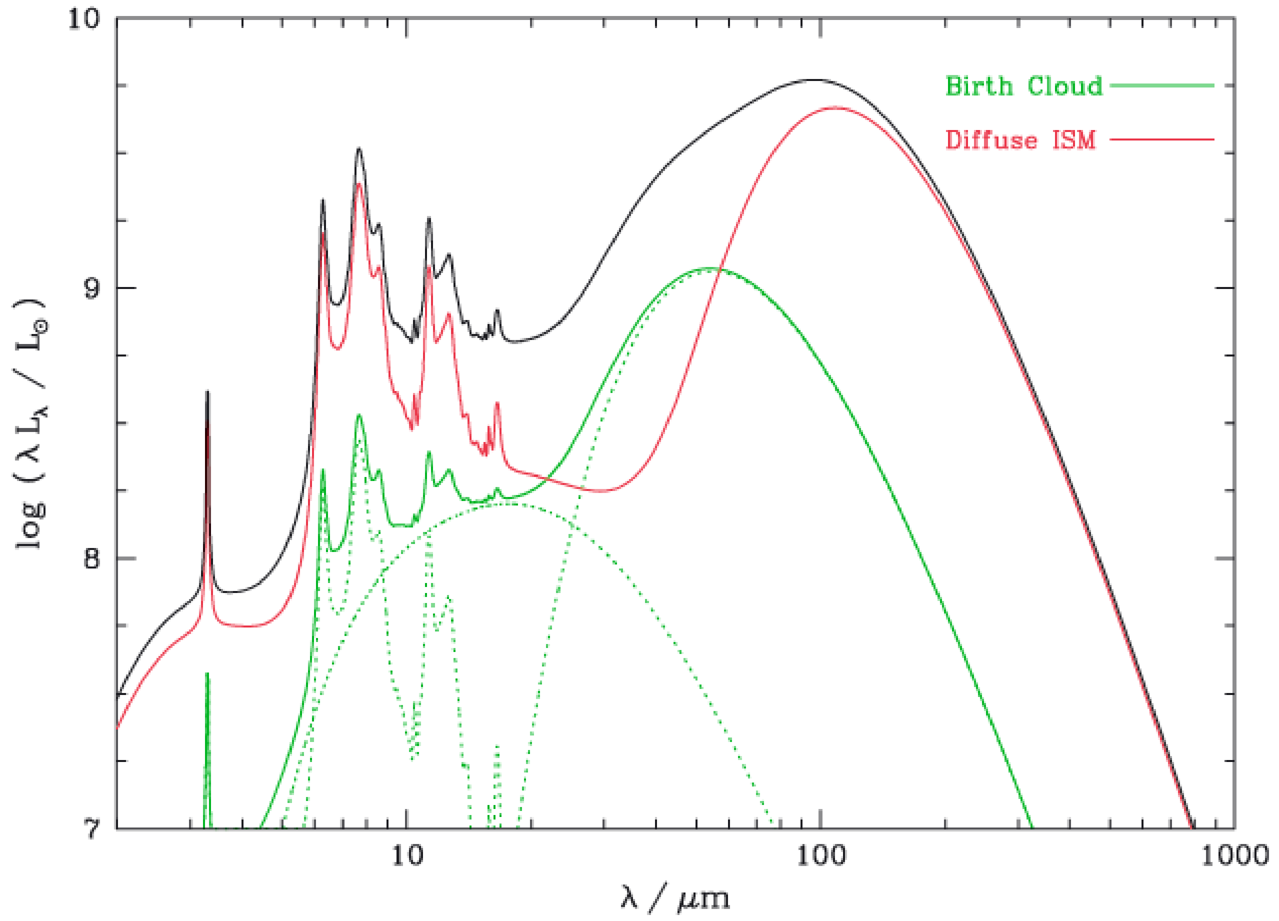
Galaxy evolution from radio observations

Dust – the dark side of galaxies



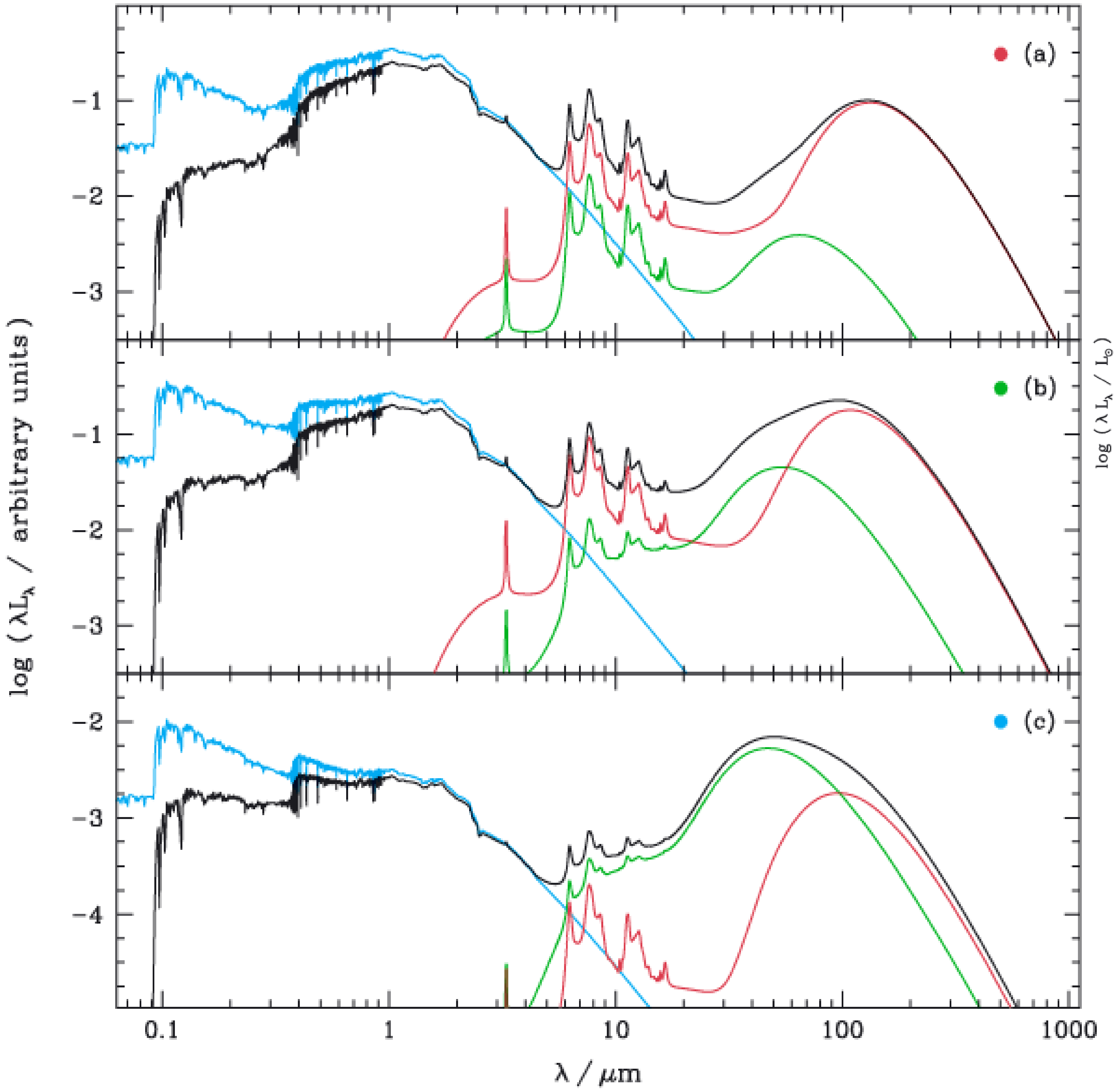
Birth Cloud

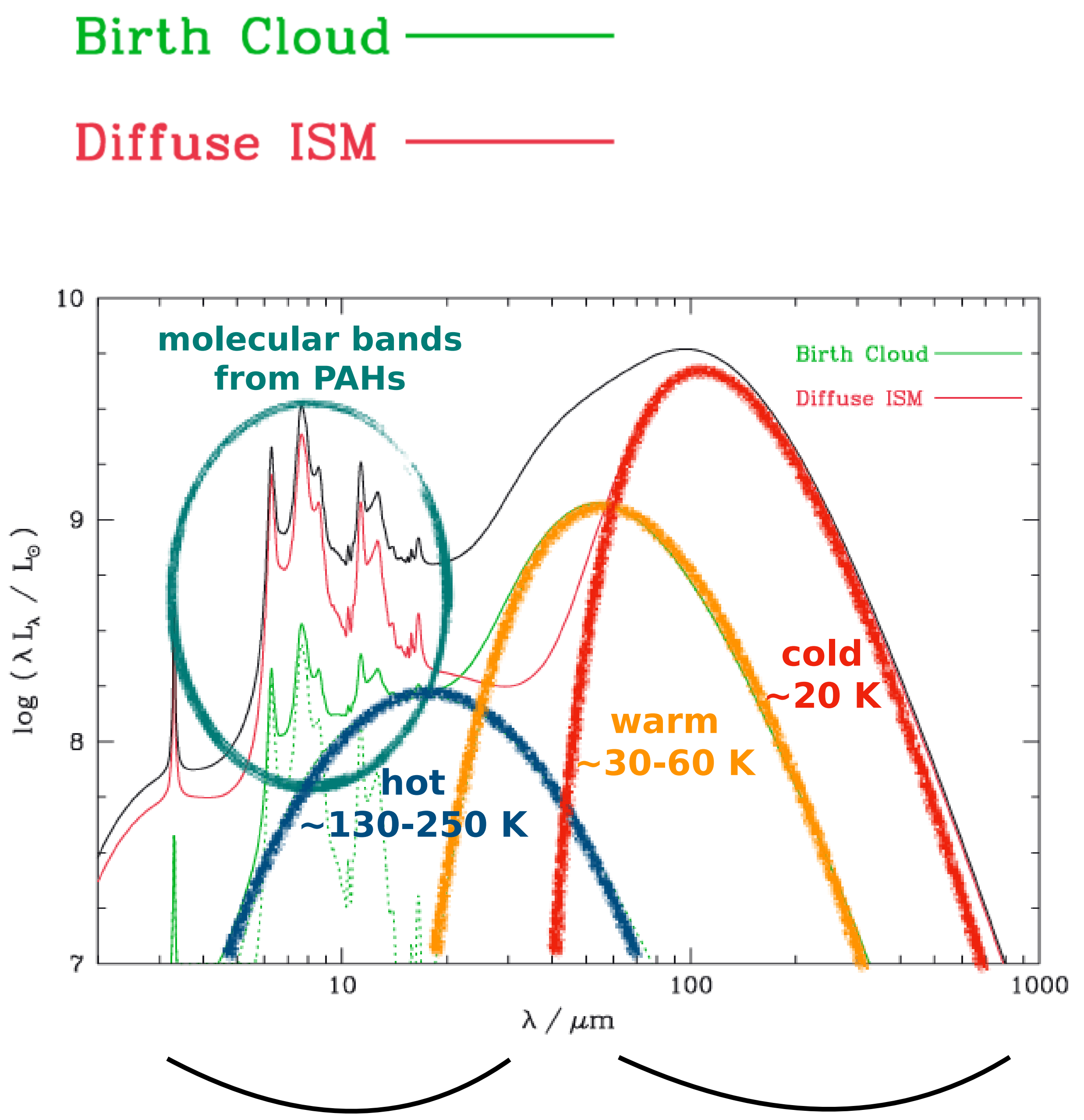
Diffuse ISM



Galaxy evolution from radio observations

Dust – the dark side of galaxies





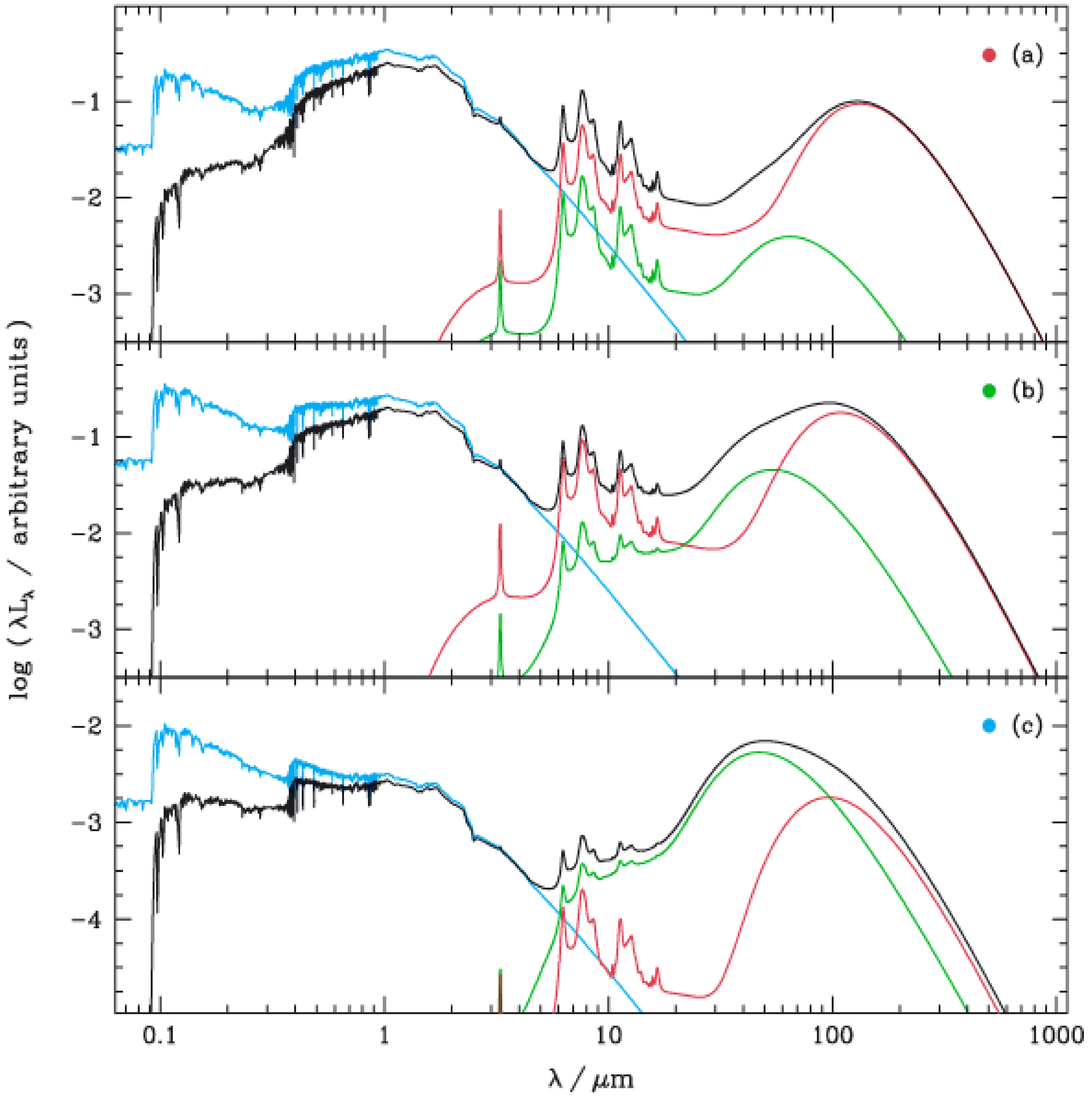
< 30μm continuum:
emission from
small grains (5-50 Å)
T~10^2-10^3 K

FIR continuum:
emission from
larger grains (>100 Å)
in thermal equilibrium
with ambient radiation
field
T≲40 K

da Cunha et al. 2008

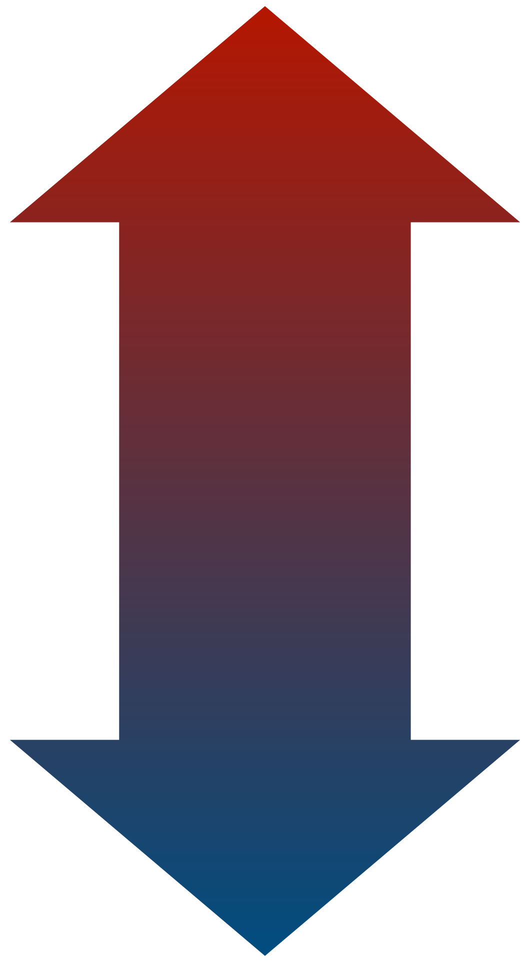
Galaxy evolution from radio observations

Dust – the dark side of galaxies



da Cunha et al. 2008

more “quiescent” star-forming galaxy with colder IR emission

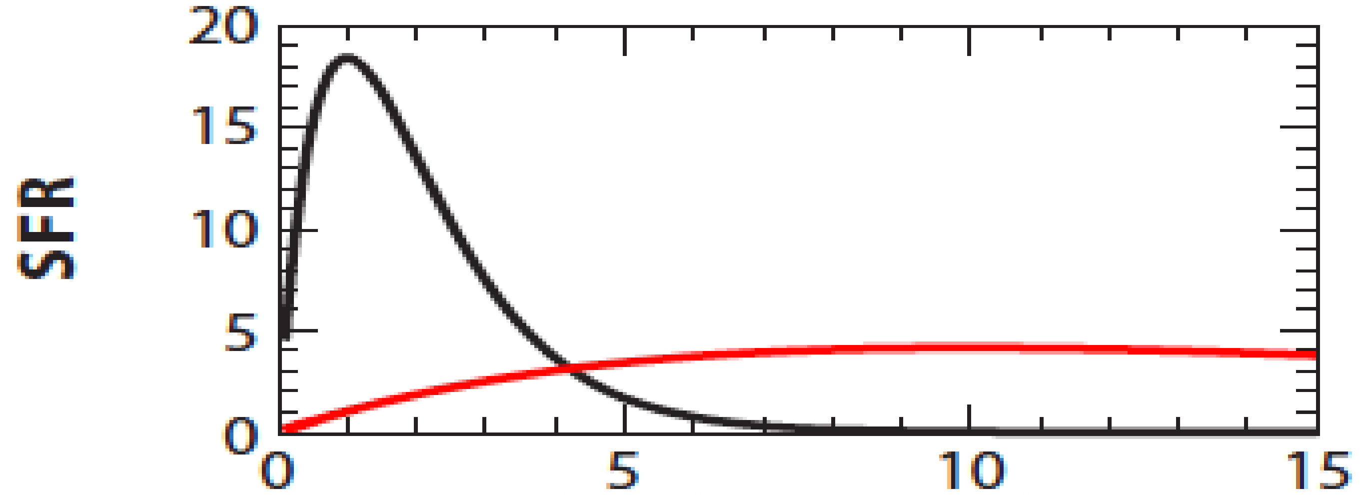


more “starburst" star-forming galaxy with hotter IR emission

Galaxy evolution from radio observations

Stars - the primary source of light in (most) galaxies

star formation history (SFH)



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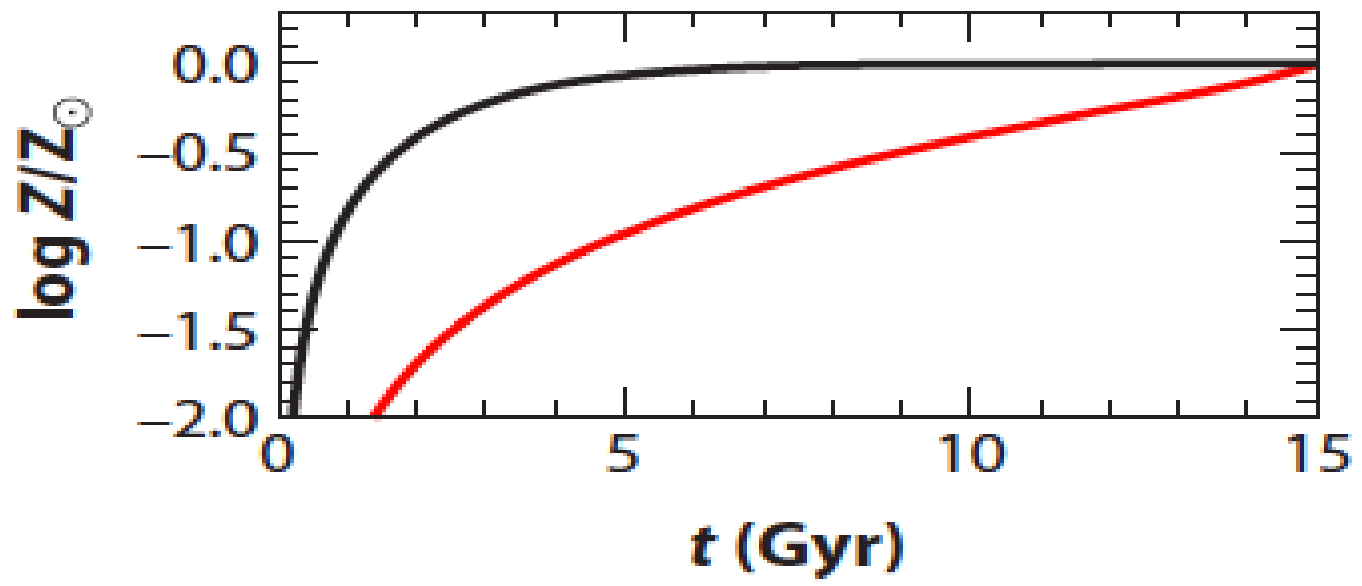

Conroy 2013

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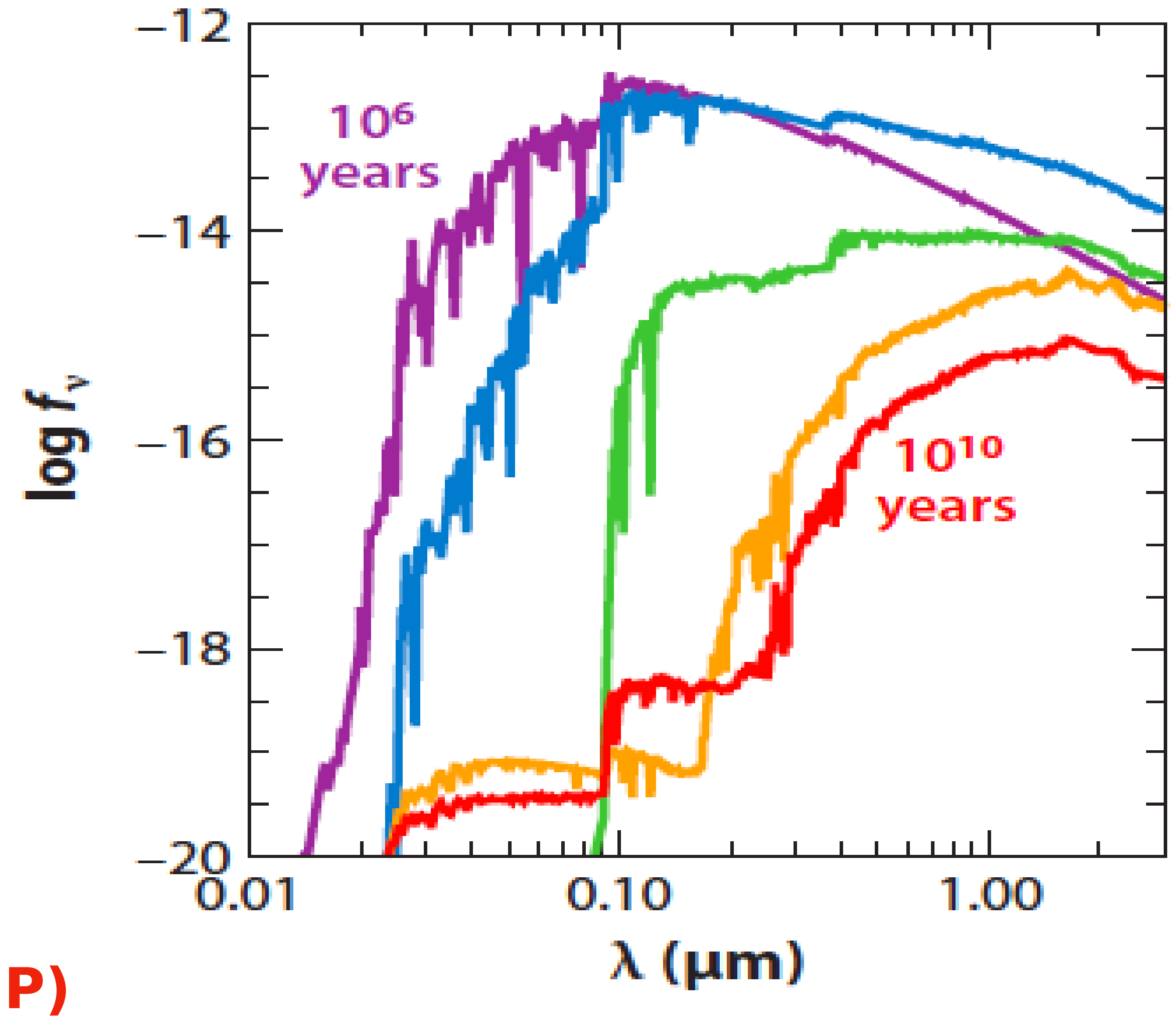

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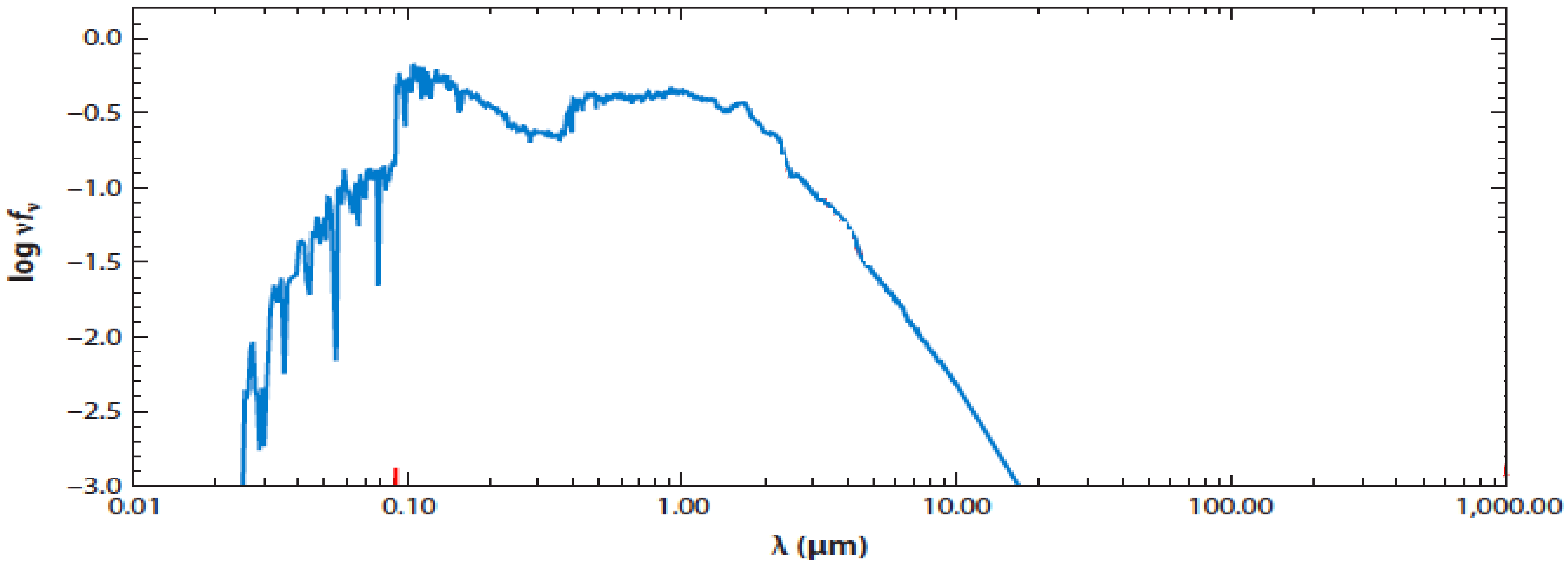
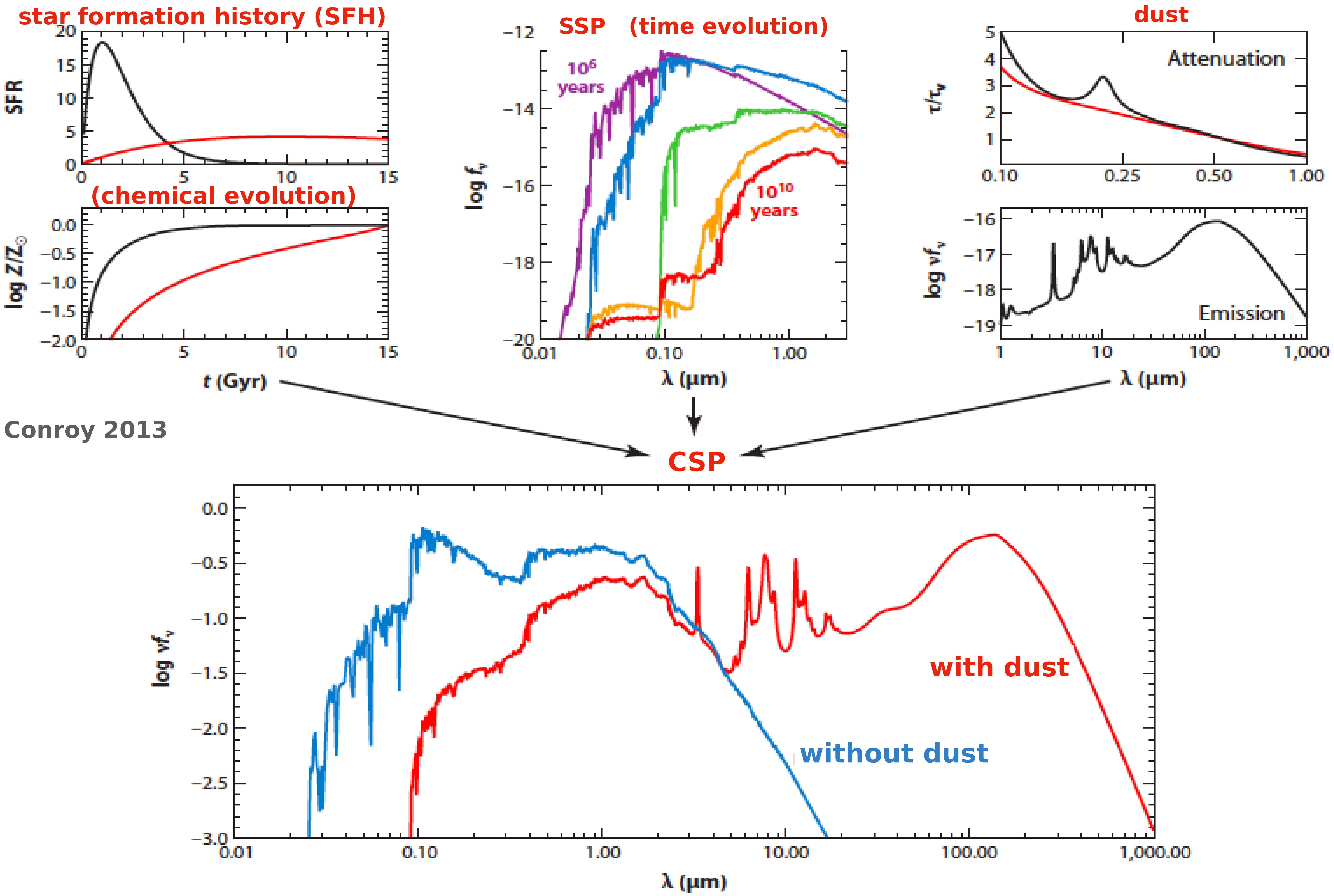


Galaxy evolution from radio observations

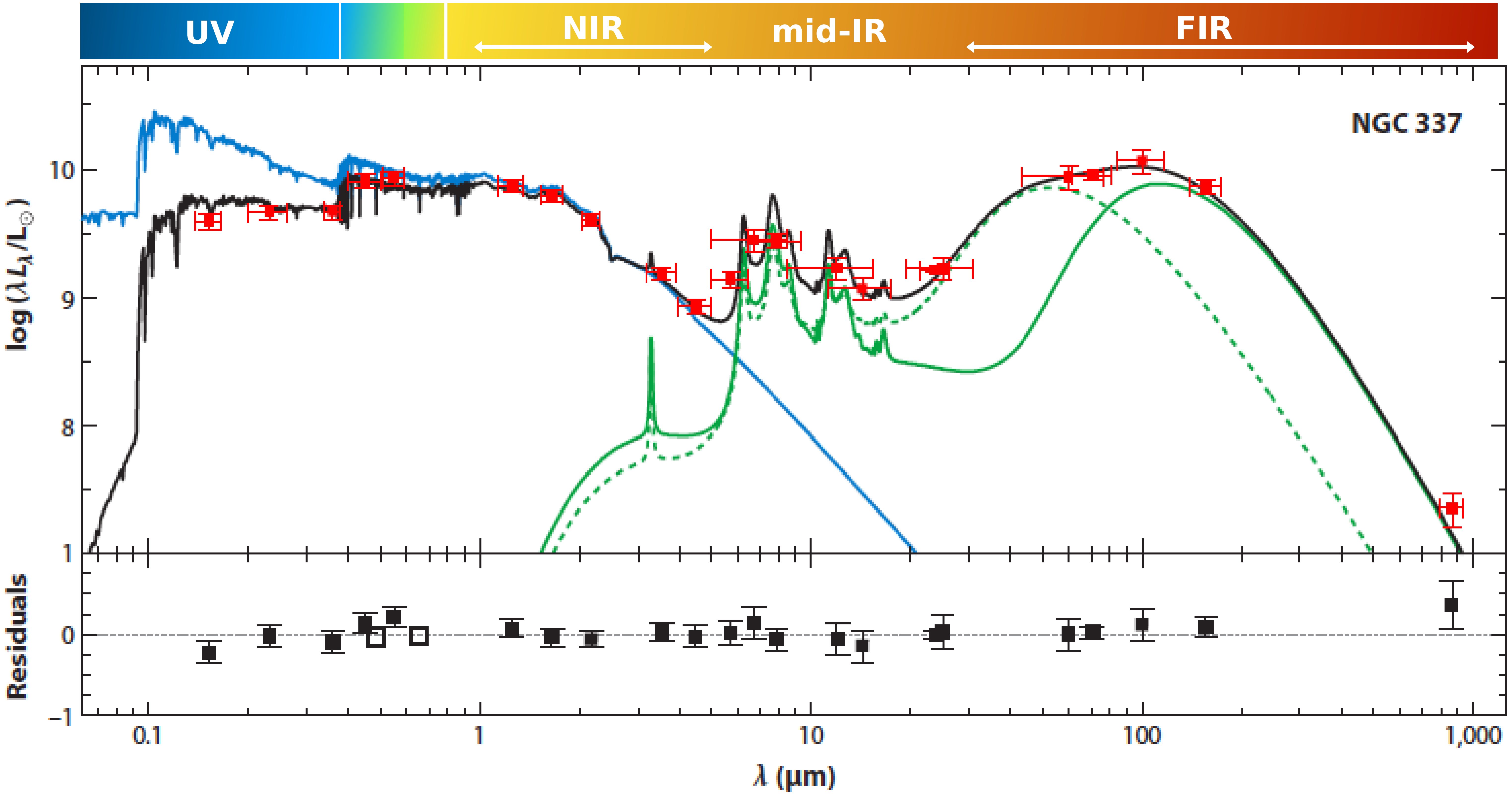
Stars + Dust + Gas: toward a realistic galaxy modeling



Conroy 2013

Galaxy evolution from radio observations

Turning it the other way around:
estimate galaxy properties from observed SEDs



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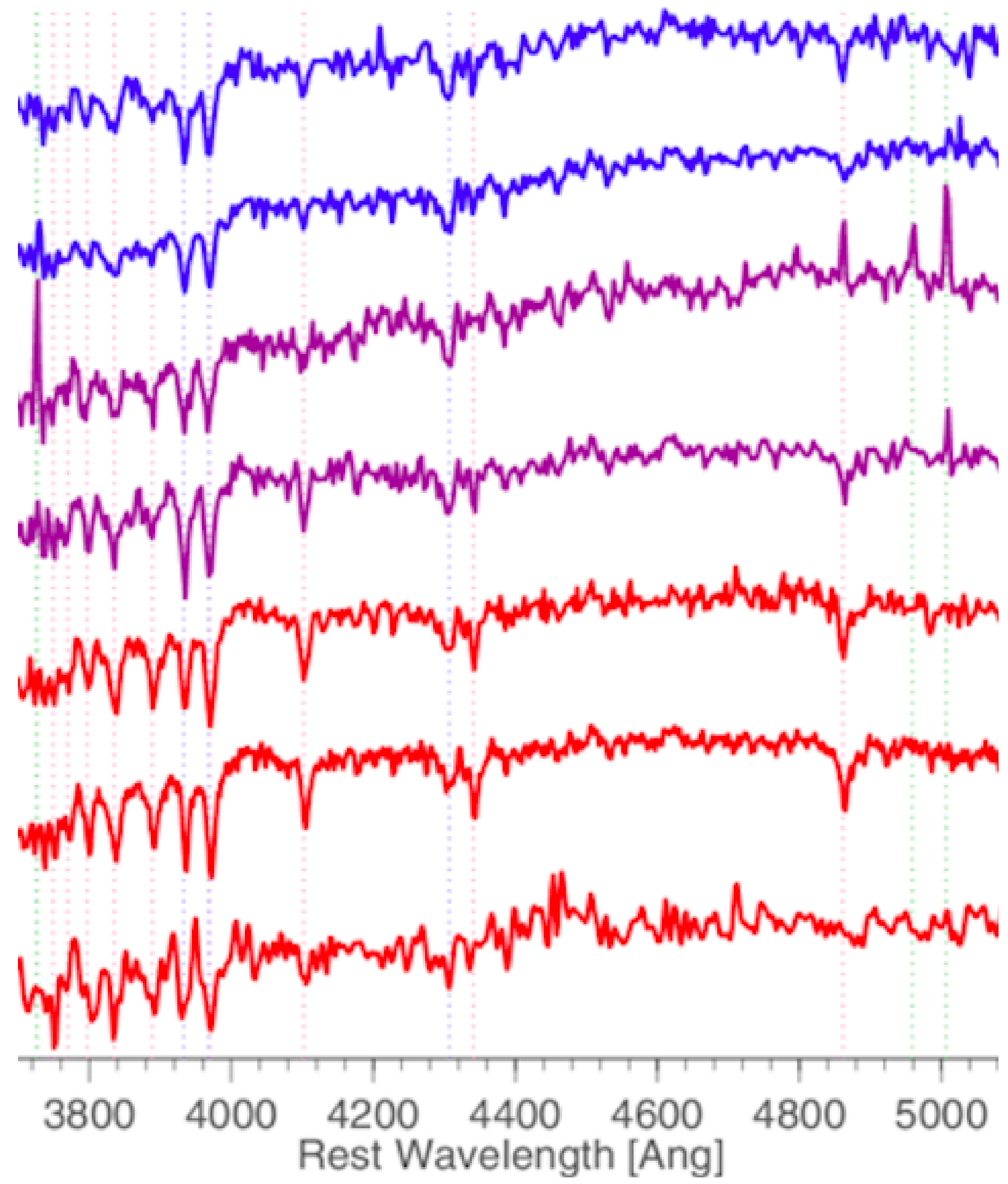
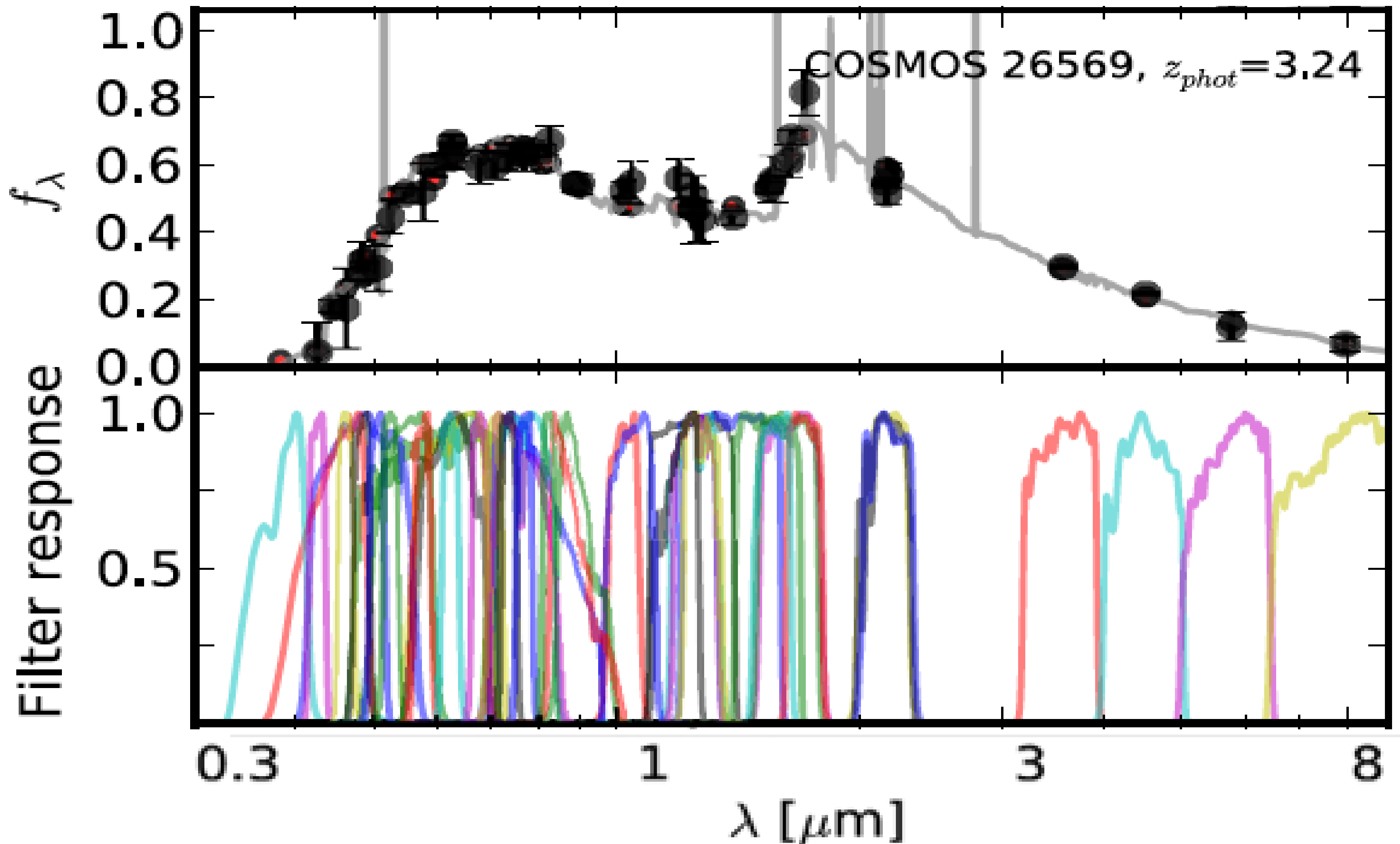


What do we have:

- **spectra (or spectral features / indices)**
- **color (broad/medium/narrow-band SEDs)**



Galaxy evolution from radio observations

Turning it the other way around:
estimate galaxy properties from observed SEDs

What do we have:

- spectra (or spectral features / indices)
- color (broad/medium/narrow-band SEDs)

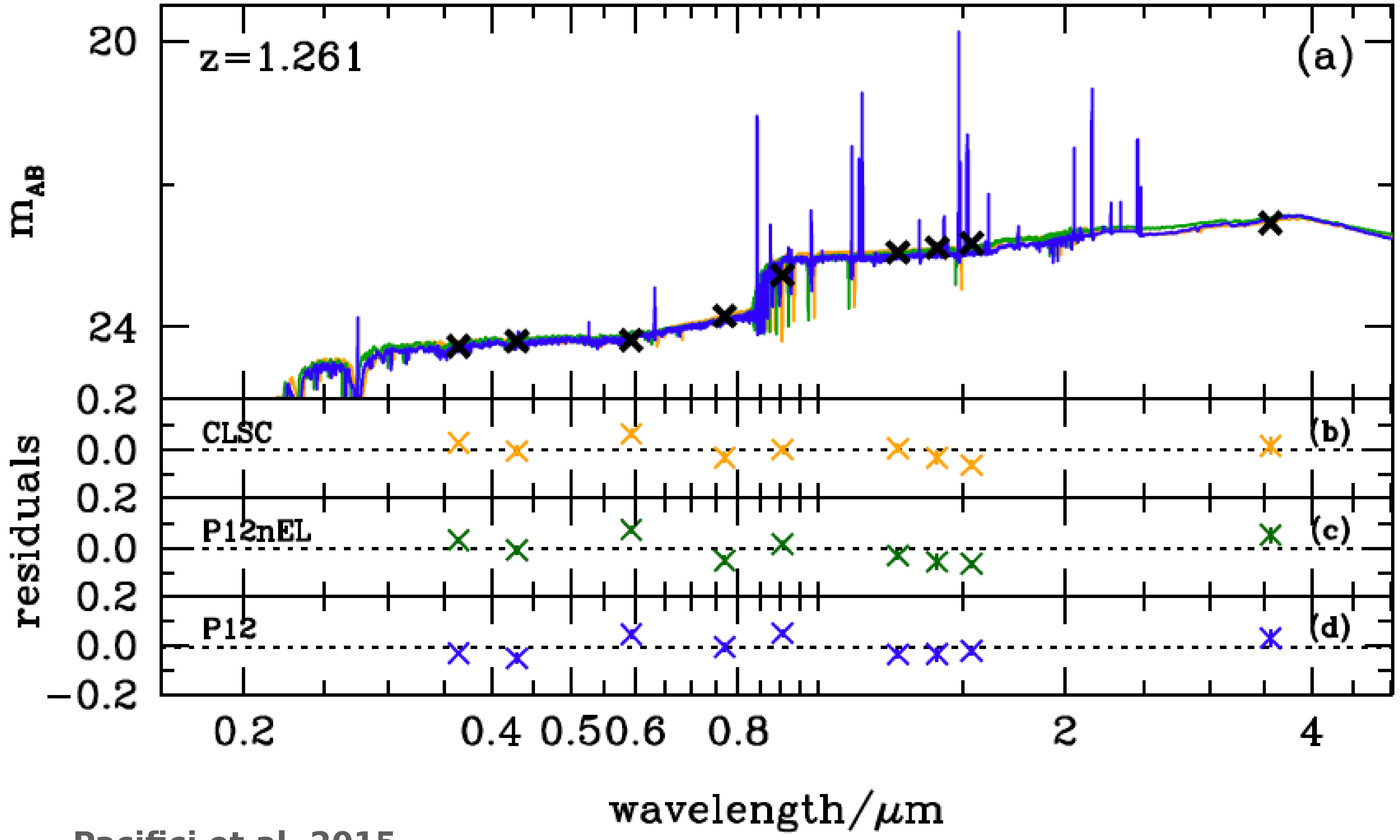
What do we want:

- stellar mass
- stellar age / SFH / SFR
- metallicity (stellar / gas)
- dust mass / temperature
- AGN ?
- galaxy redshift
- …

Galaxy evolution from radio observations

Turning it the other way around:
estimate galaxy properties from observed SEDs

Broad-band SED fitting for stellar population properties



Pacifici et al. 2015

standard modeling with parametric SFHs, single metallicity, no emission lines
more realistic SFH, chemical evolution, dust attenuation modeling
more realistic SFH, chemical evolution, dust attenuation modeling , plus emission lines

Galaxy evolution from radio observations

Turning it the other way around:
estimate galaxy properties from observed SEDs

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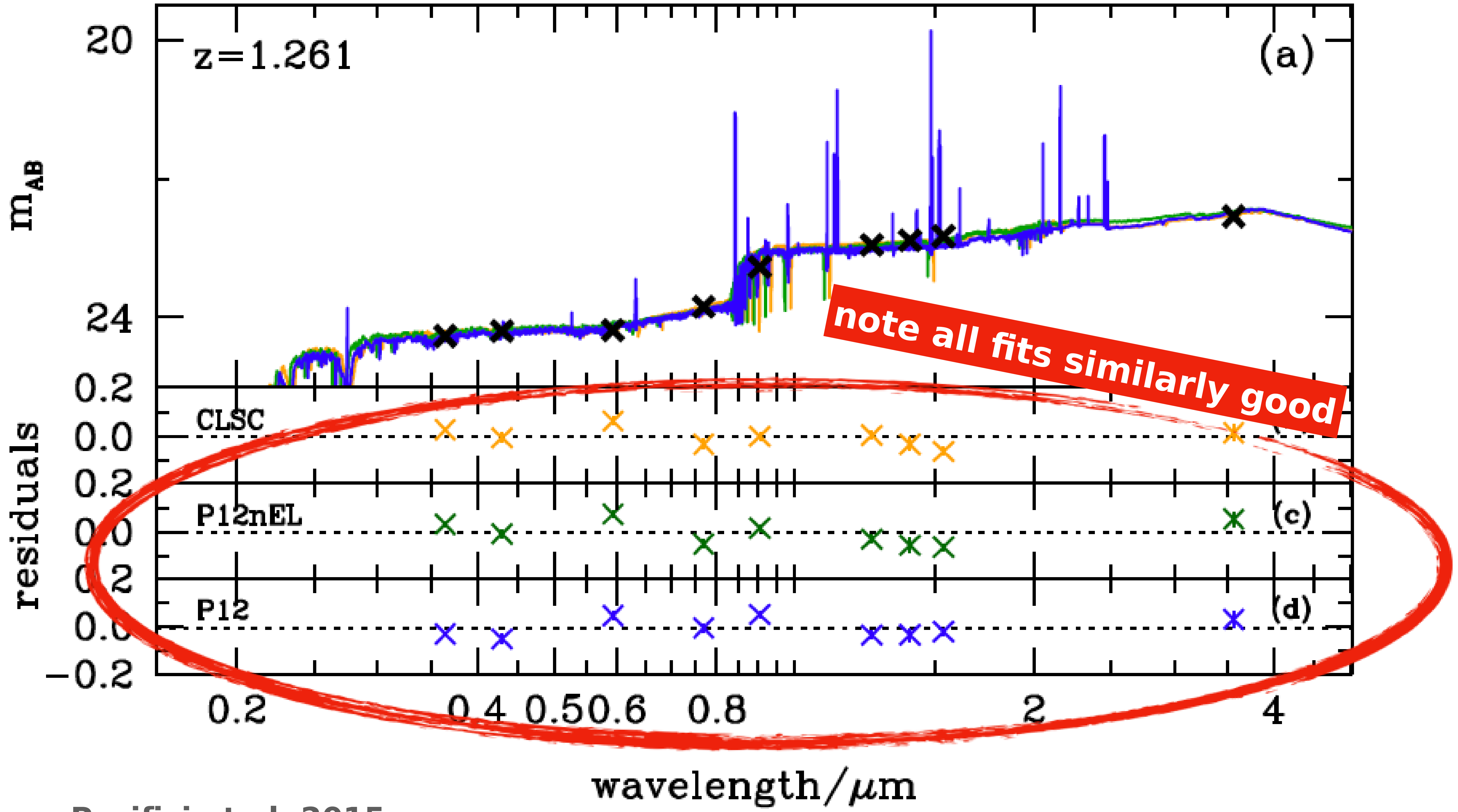

note all fits similarly good

Pacifici et al. 2015

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more realistic SFH, chemical evolution, dust attenuation modeling

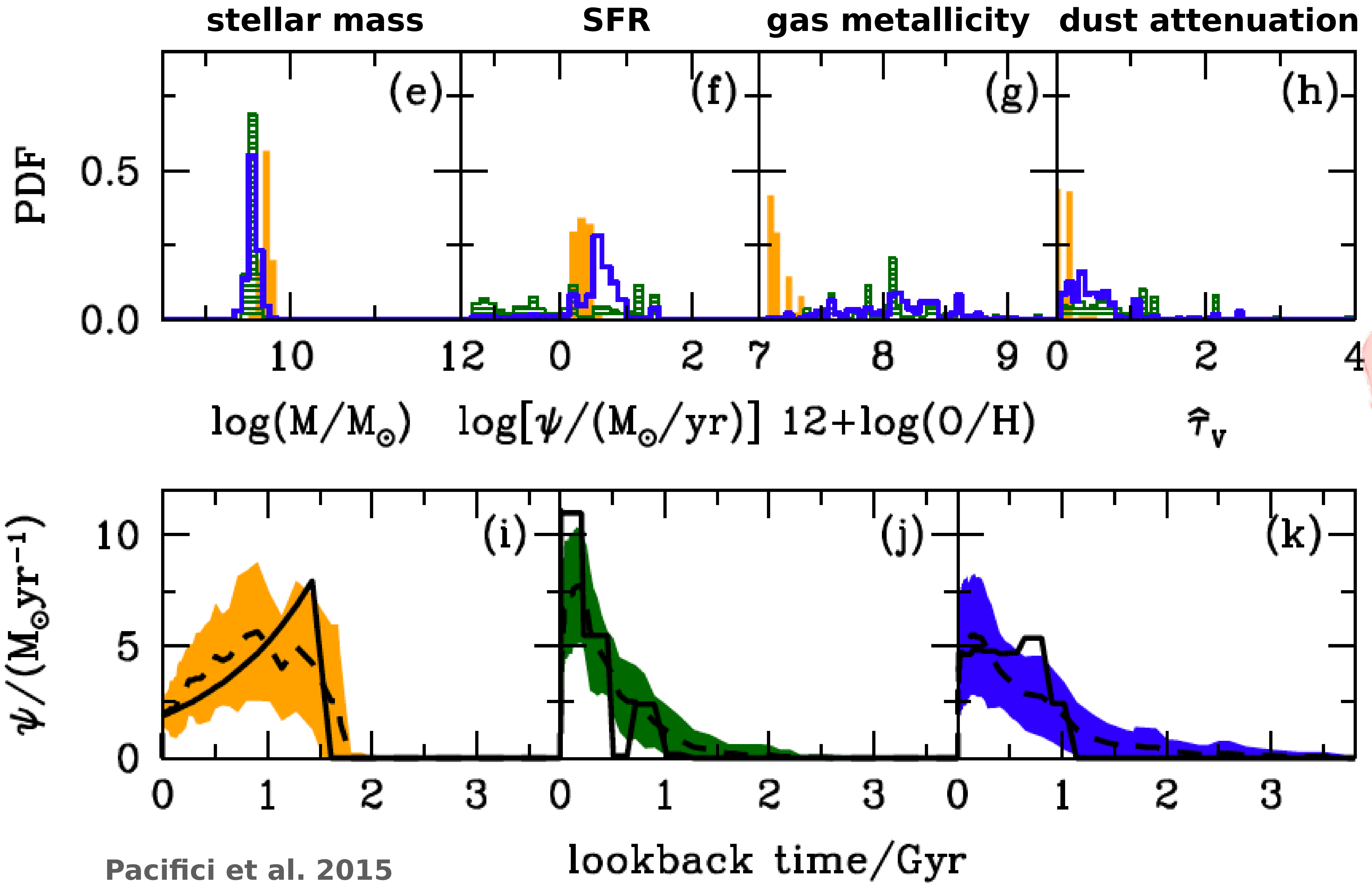
more realistic SFH, chemical evolution, dust attenuation modeling , plus emission lines

Galaxy evolution from radio observations

Turning it the other way around:
estimate galaxy properties from observed SEDs

Broad-band SED fitting for stellar population properties

... but quite different retrived parameters

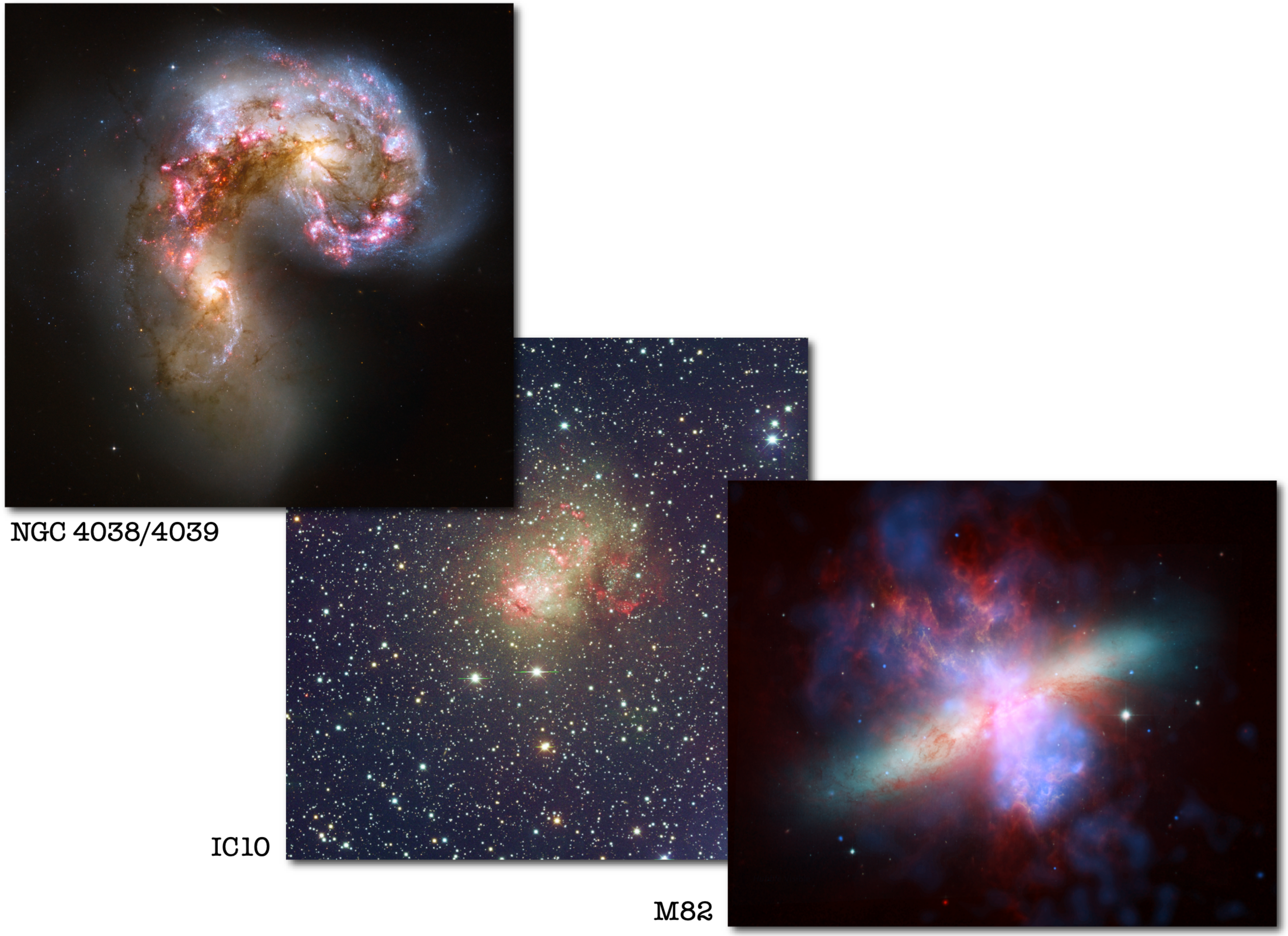


stellar mass **SFR** **gas metallicity** **dust attenuation**

Pacifici et al. 2015

degeneracies between age/SFH, metallicity, dust

Galaxy evolution : hunting for star formation rates



NGC 4038/4039

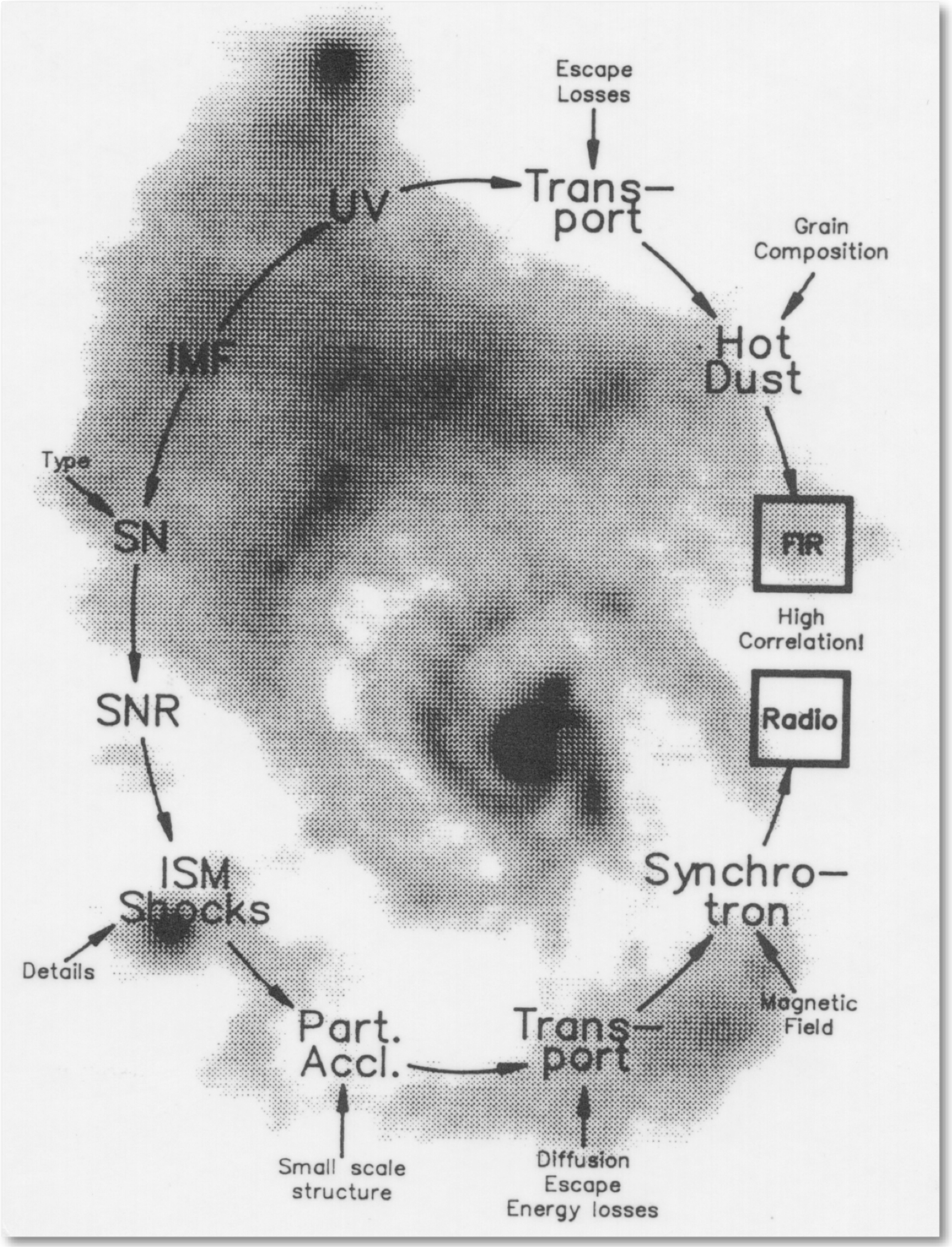
IC10

M82

A star formation tracer that, ideally, should be:

- **unobscured**
- **independent of viewing angle**
- **not a function of environment**
- **time/redshift-invariant**

Galaxy evolution



IR emission is affected by:

- IMF
- UV photon transport
- optical depth
- dust grain distribution/composition

Radio emission is affected by:

- IMF
- acceleration Mechanisms
- primary/secondary e^-
- magnetic fields
- transport (diffusion & confinement)

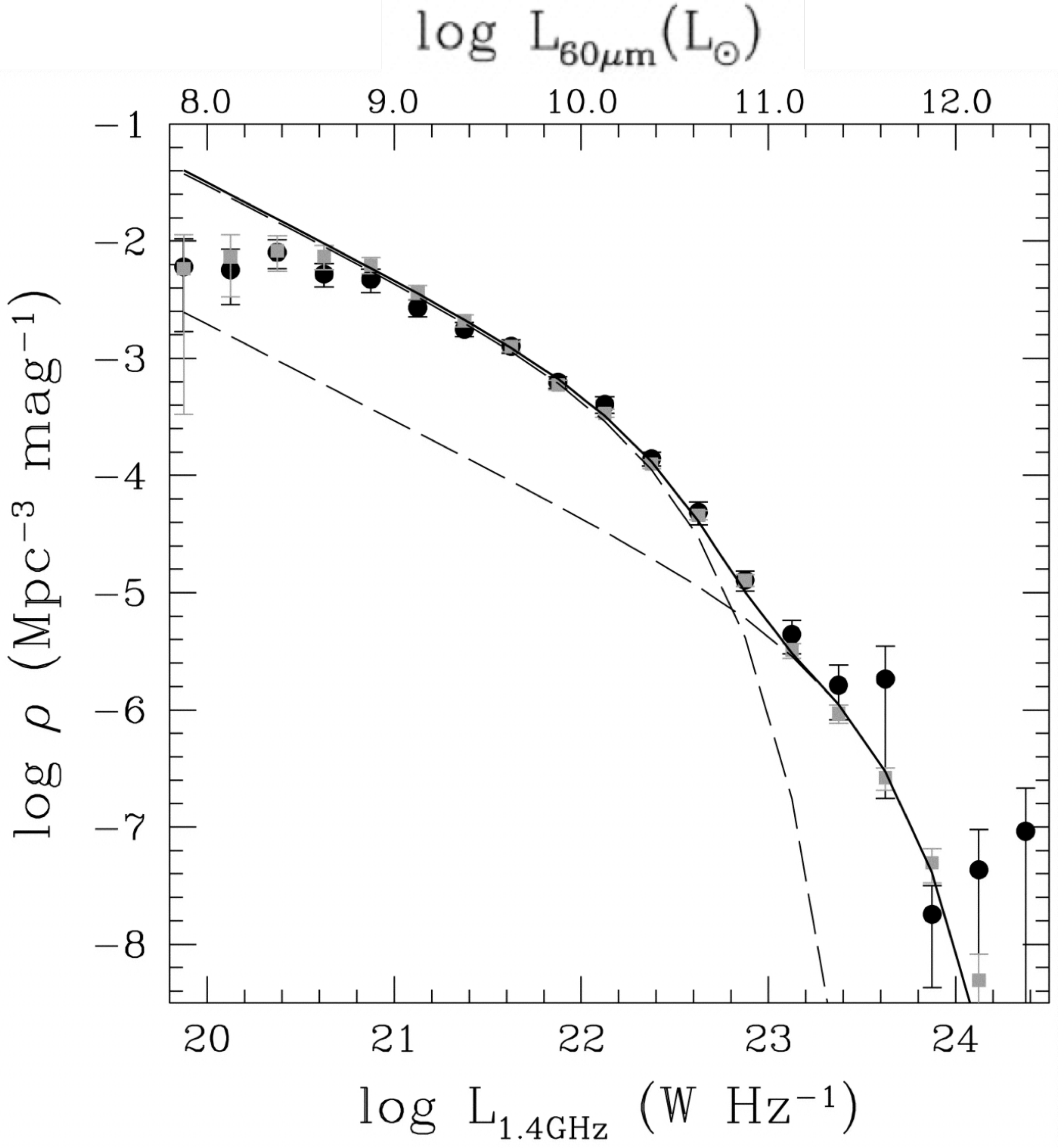
Galaxy evolution

Radio & 60 micron luminosity functions of galaxies (Yun+ '01):

Common link to life cycle of massive stars:

Non-thermal radio (synchrotron)

re-radiated UV light (IR thermal).



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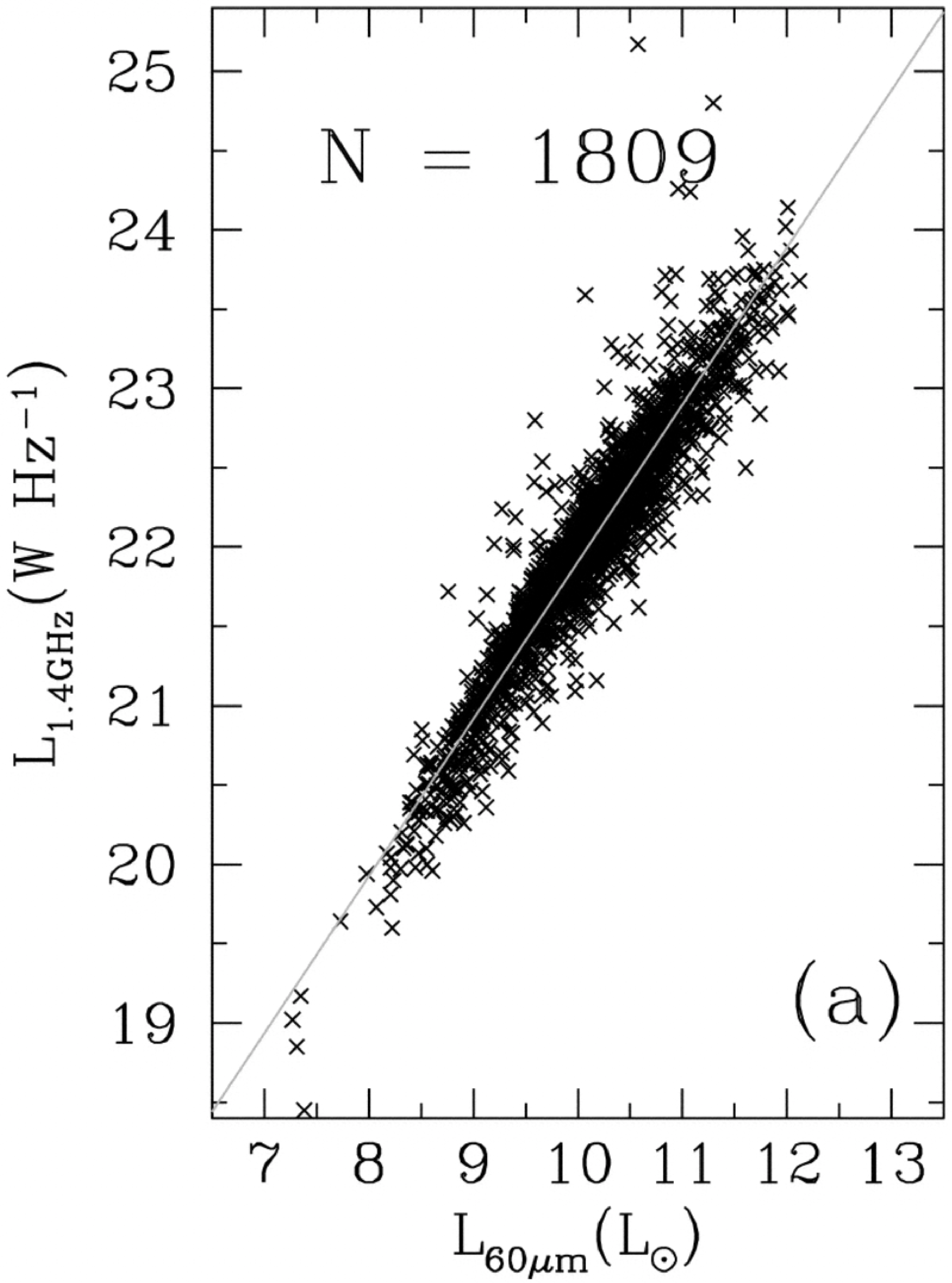
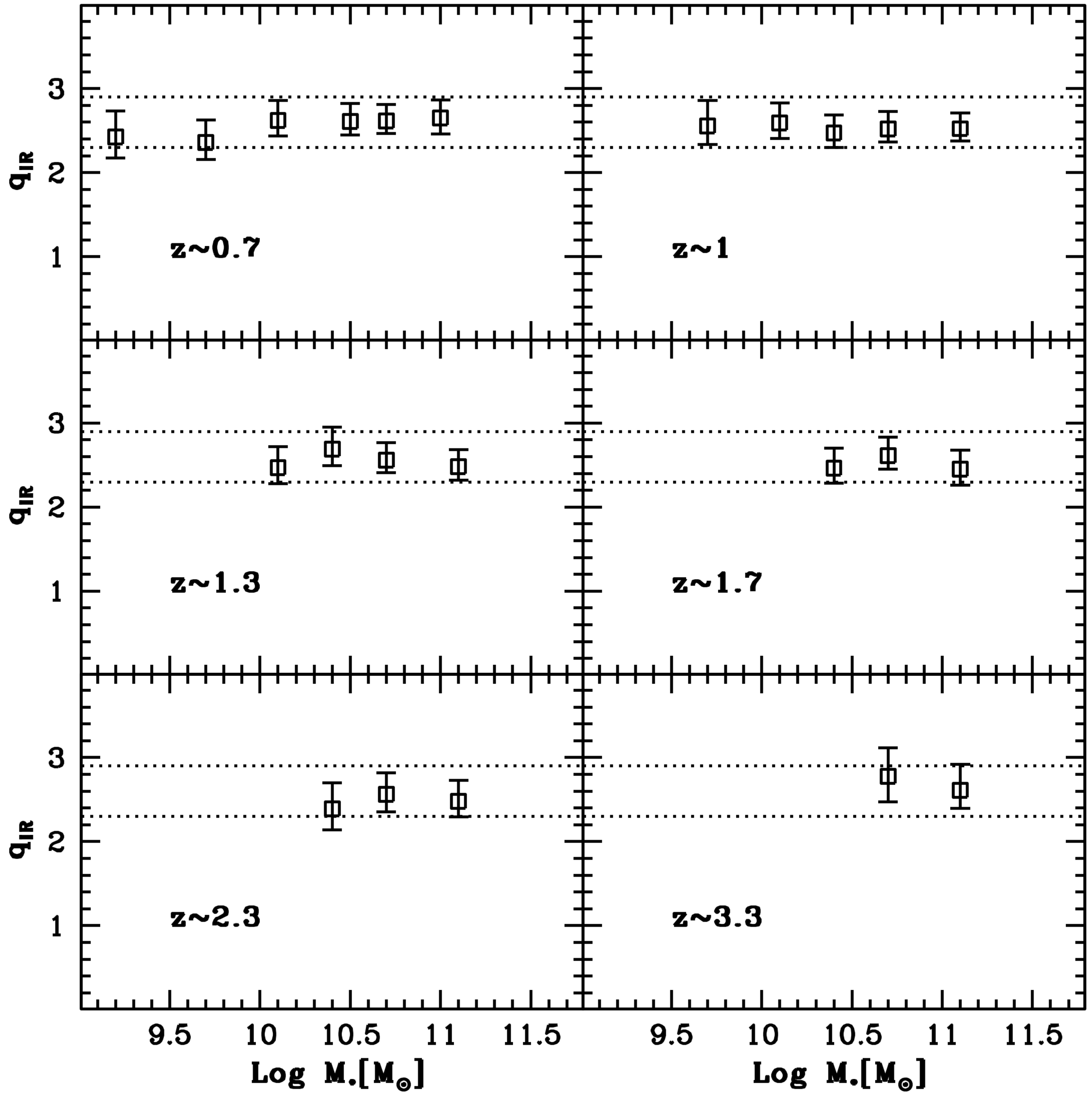


Galaxy evolution



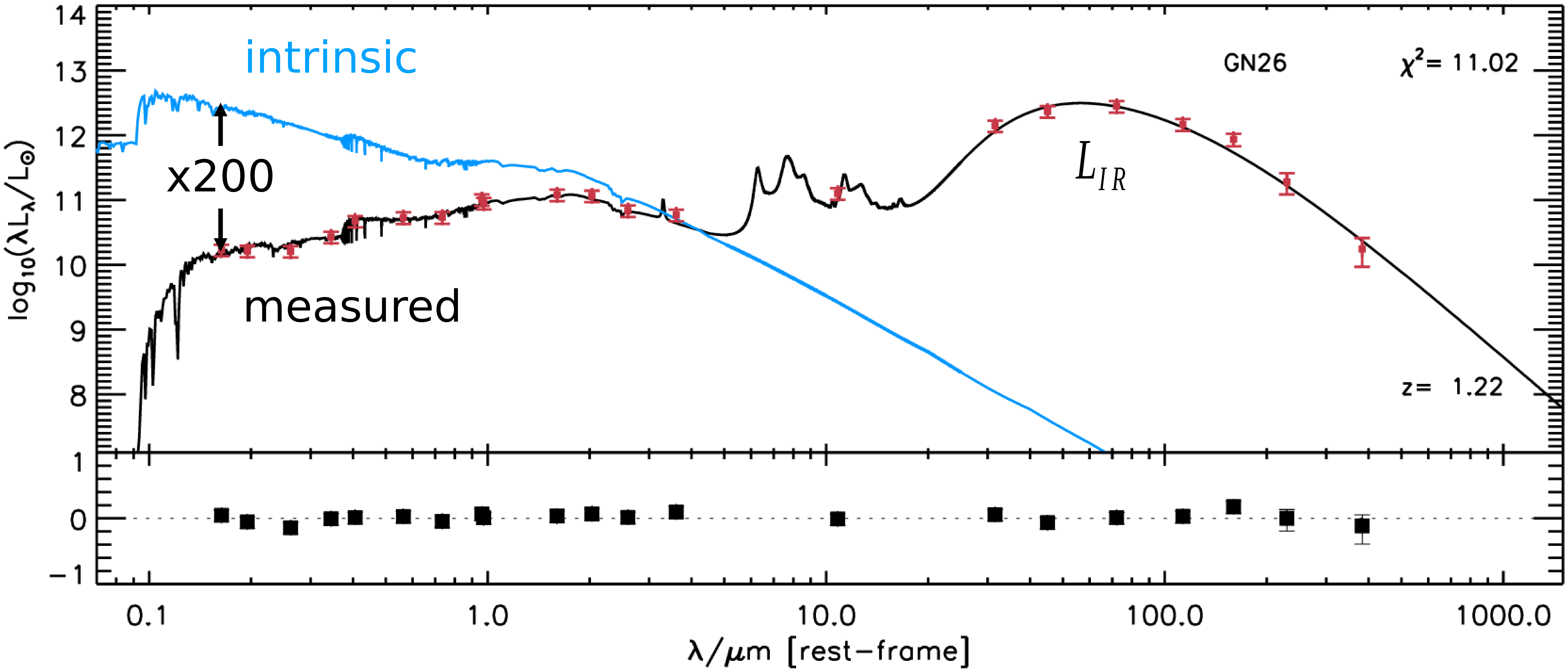
The radio-FIR correlation

$$q_{IR} = \log \frac{L_{IR}/(3.75 \times 10^{12} W)}{L_{1.4}/WHz^{-1}}$$

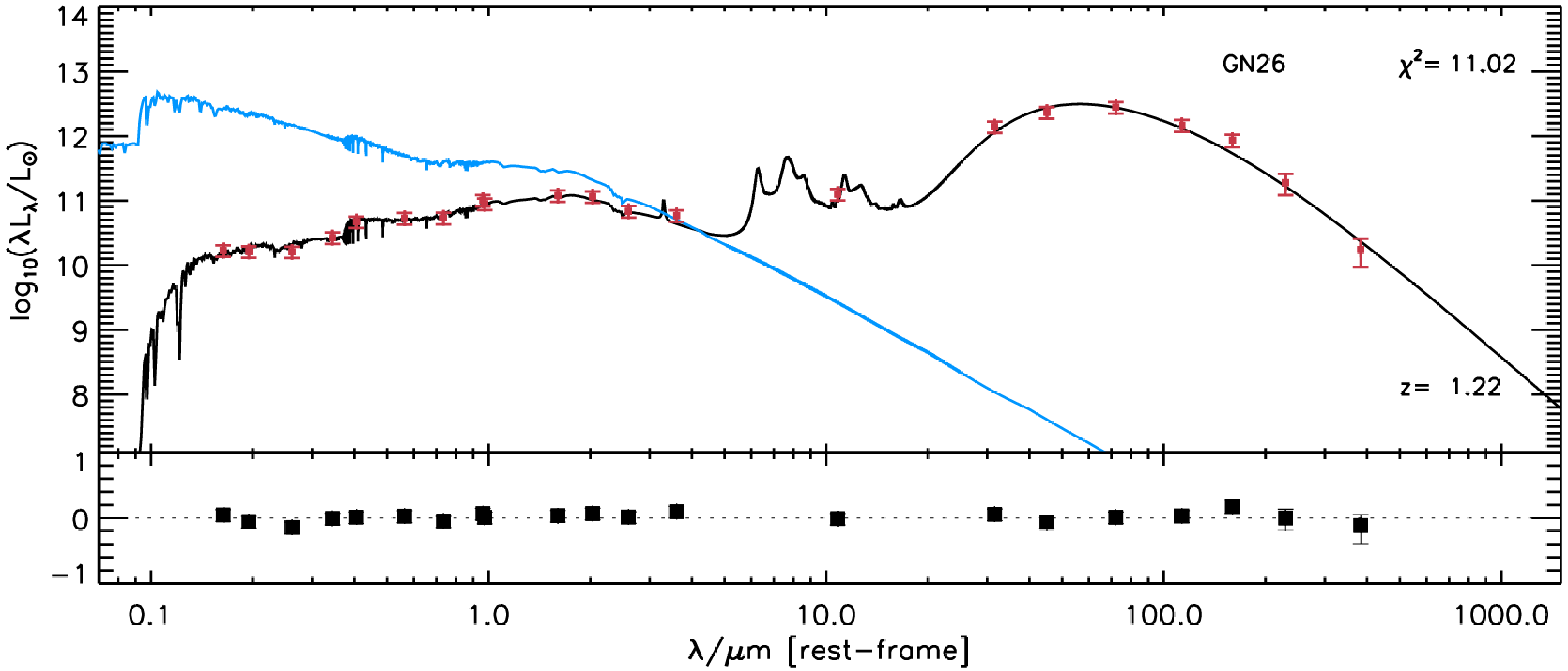
Long story short …

- **the correlation holds up to high z**
- **stays (fairly) constant with redshift**

Galaxy evolution



Galaxy evolution



What we are after:

$$SFR = \kappa_{UV} \cdot L_{UV}[intrinsic]$$

What we hope to measure is (assuming that energy conservation holds):

$$SFR = \kappa_{UV} \cdot L_{UV}[measured] + \kappa_{IR} \cdot L_{IR}$$

$$SFR = \kappa_{UV} \cdot L_{UV}[measured] + \kappa_{radio} \cdot L_{radio}$$

What we usually have is:

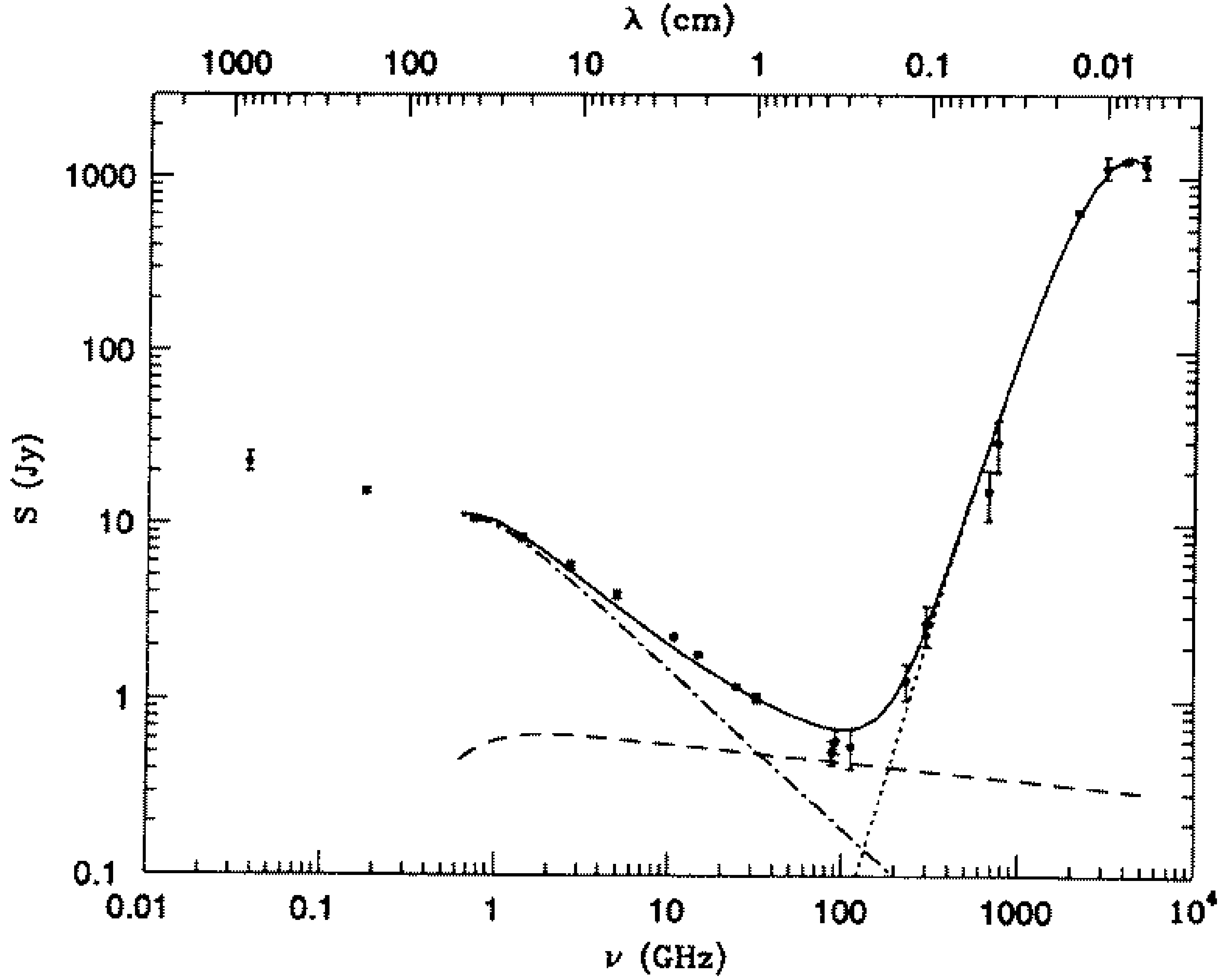
$$SFR = \kappa_{UV} \cdot L_{UV}[measured] \cdot 10^{A_{UV}/2.5}$$ from SED fitting!

Galaxy evolution

	UV	**IR**	**Radio**
PROS	• easy to collect • high resolution • high sensitivity	• 20% accuracy	• ~x2 accuracy • good resolution • “easy” K-corr • ground based • wide FOV
CONS	• SFH dependent • ~x5 accuracy	• poor resolution • poor sensitivity • space based • PAH/dust comp • IR SED evolution • small FOV	• poor sensitivity • radio-IR correlation • pre-selection

Galaxy evolution

Radio data are an important ingredient of an holistic approach to study galaxy evolution



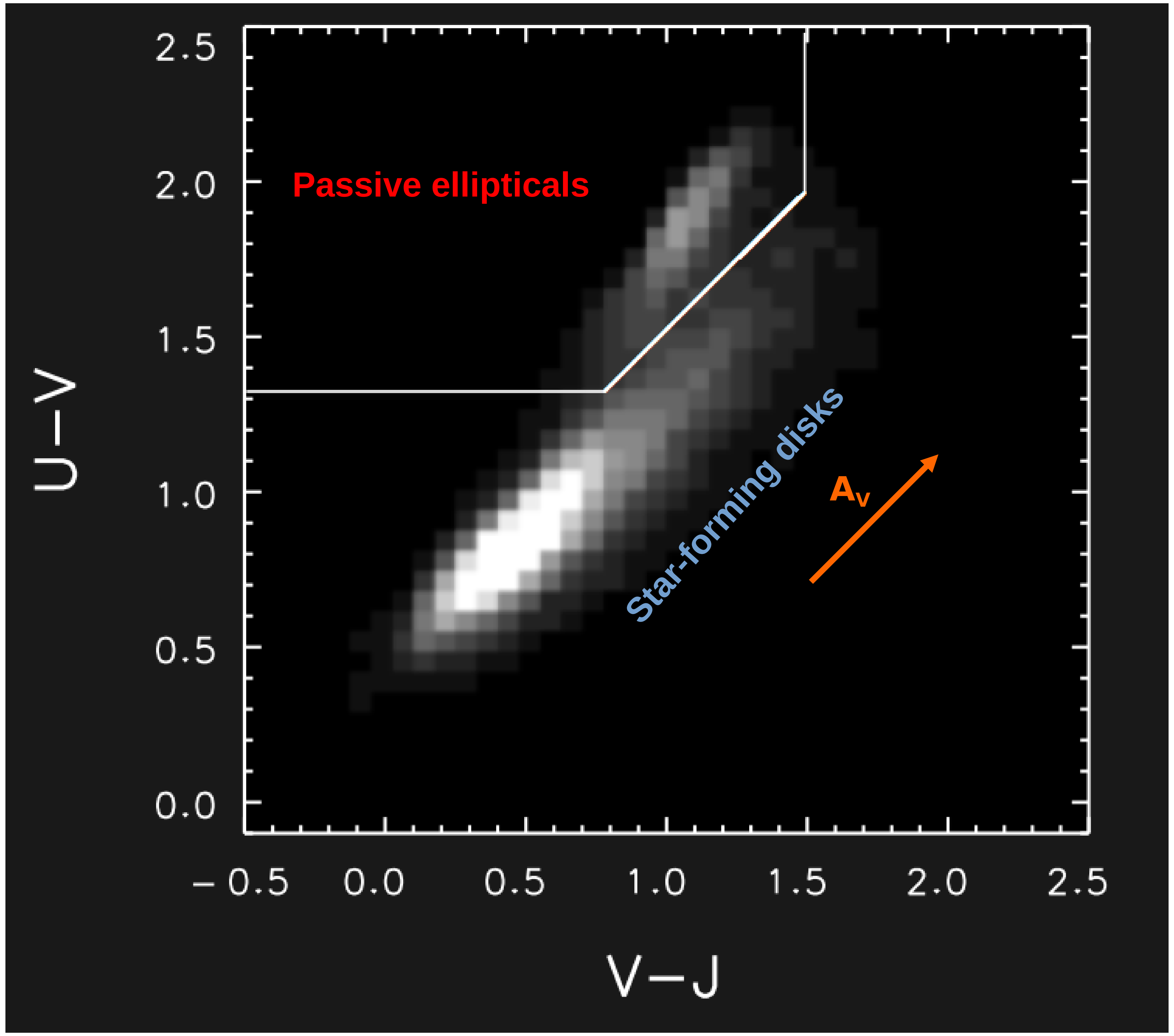
– radio spectra is featureless

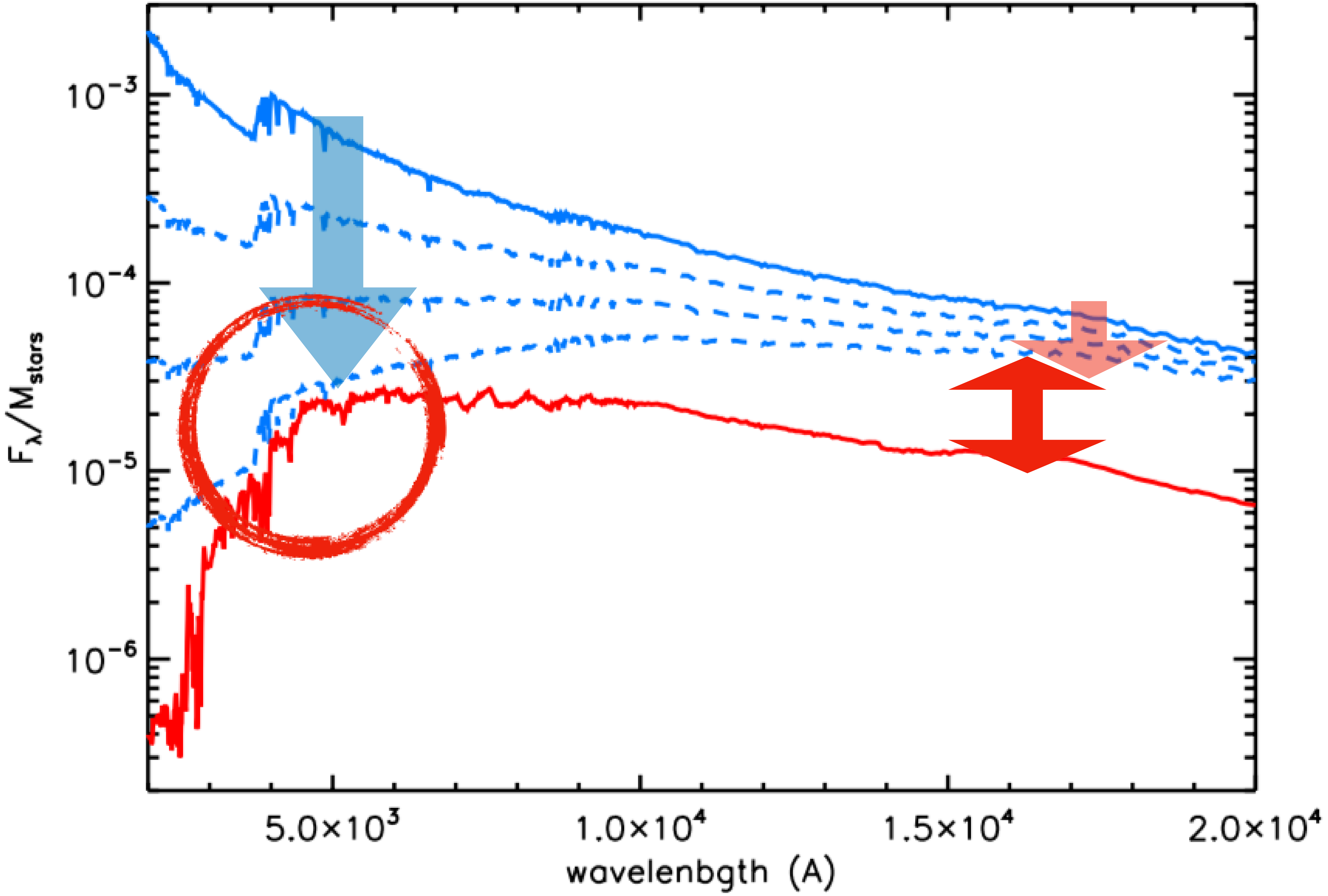
– we need distance (redshift)

– we need a broad classification
of galaxies (passive/star-forming)

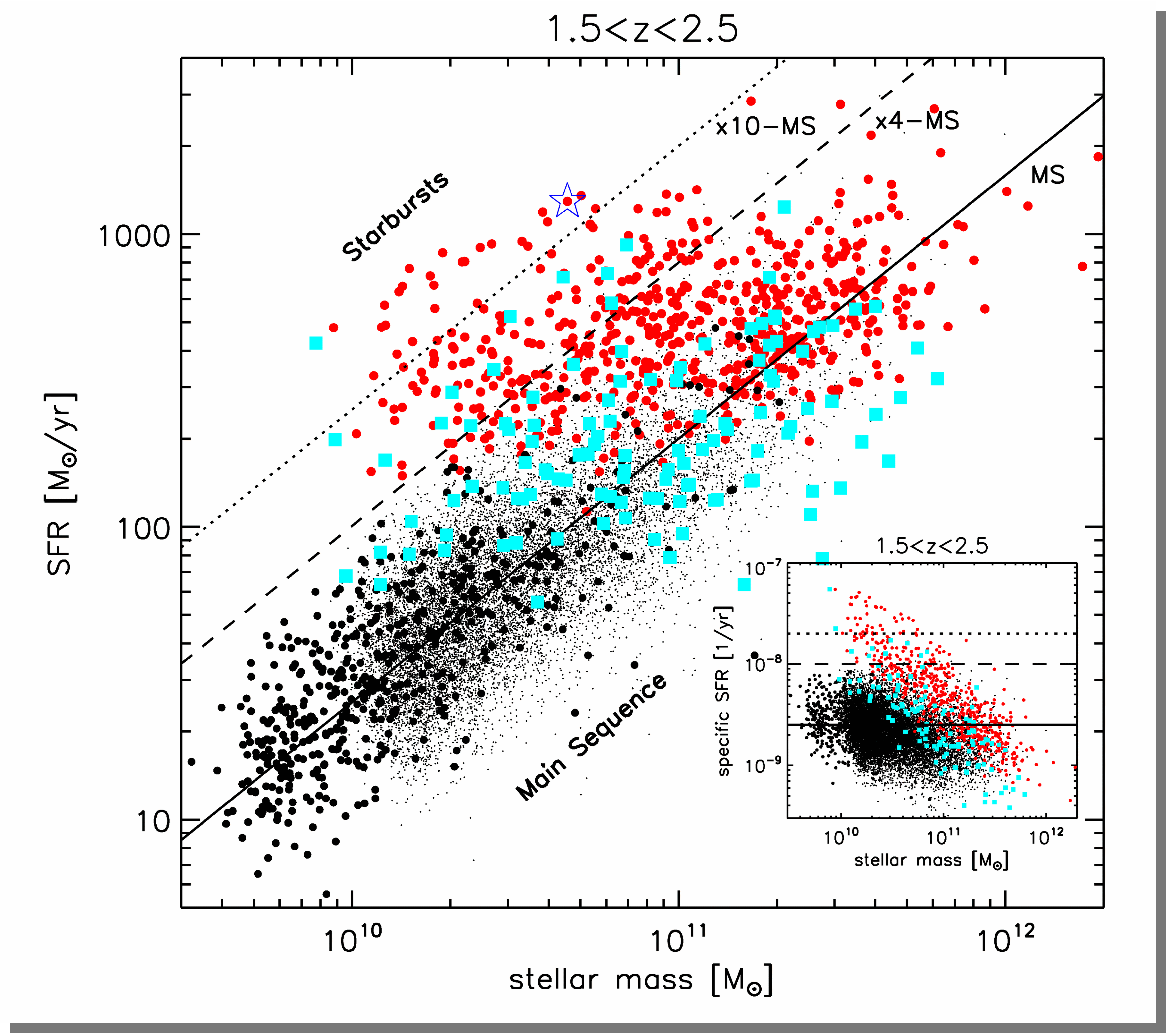
Galaxy evolution

The UVJ classification of passive and star-forming galaxies



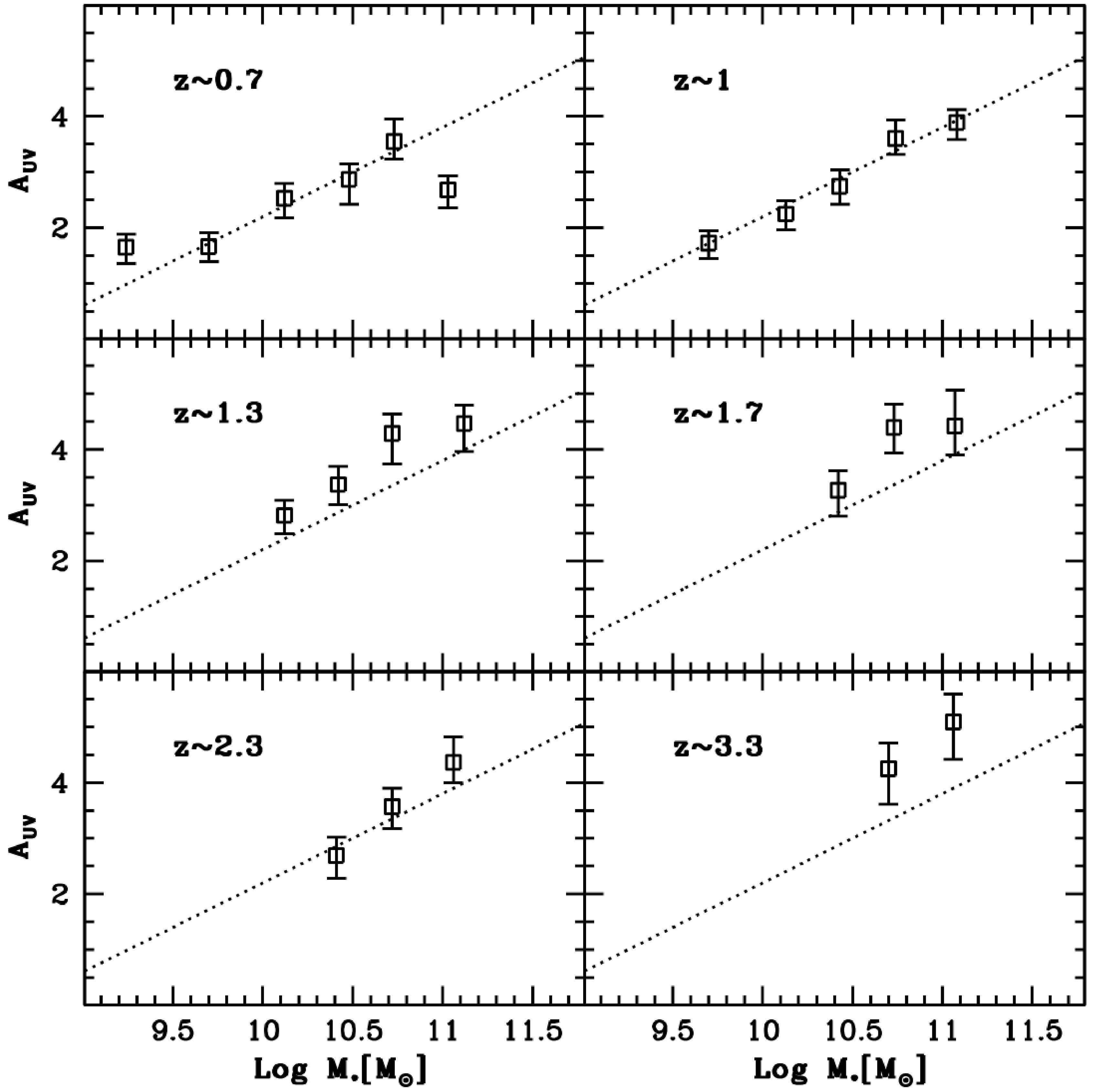


Galaxy evolution : the star formation histories of galaxies



- log M_* ~ log SFR
- Inefficient and long lasting conversion of gas in stars (~ 1Gyr)
- 0.3 dex scatter is incompatible with SFR/mass growth driven by stocastic events, e.g. mergers
- Outliers ("Starburst") are a minority (~2%) and almost irrelevant (~10%) in terms of SFRD and stellar mass growth budget at all z

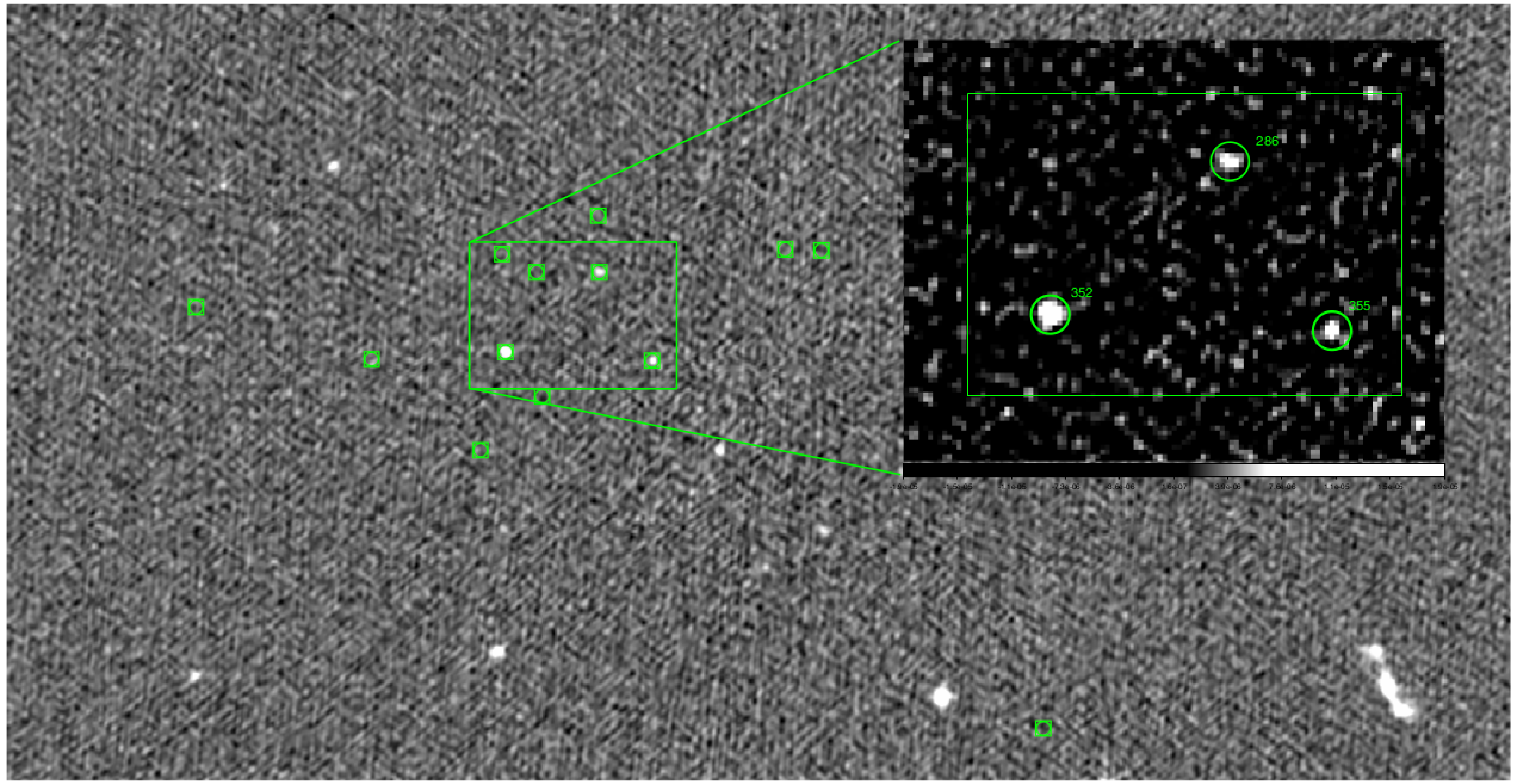
Galaxy evolution : the UV dust attenuation in galaxies

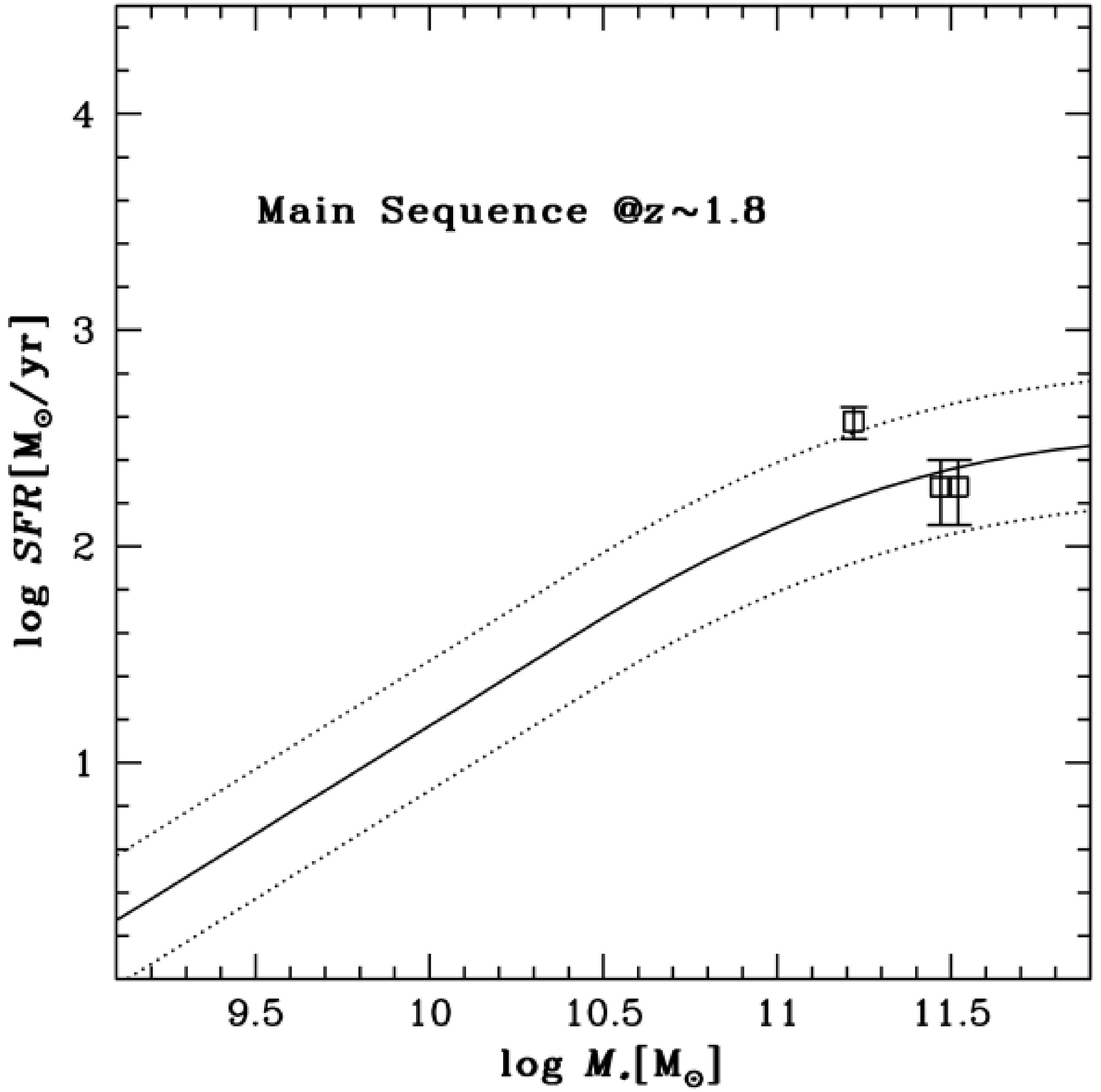


- The correlation between M_* and A_{UV} does not evolve much up to z~4
- The same amount of SFR is less attenuated at higher redshift

Galaxy evolution : hidden star formation in galaxy clusters

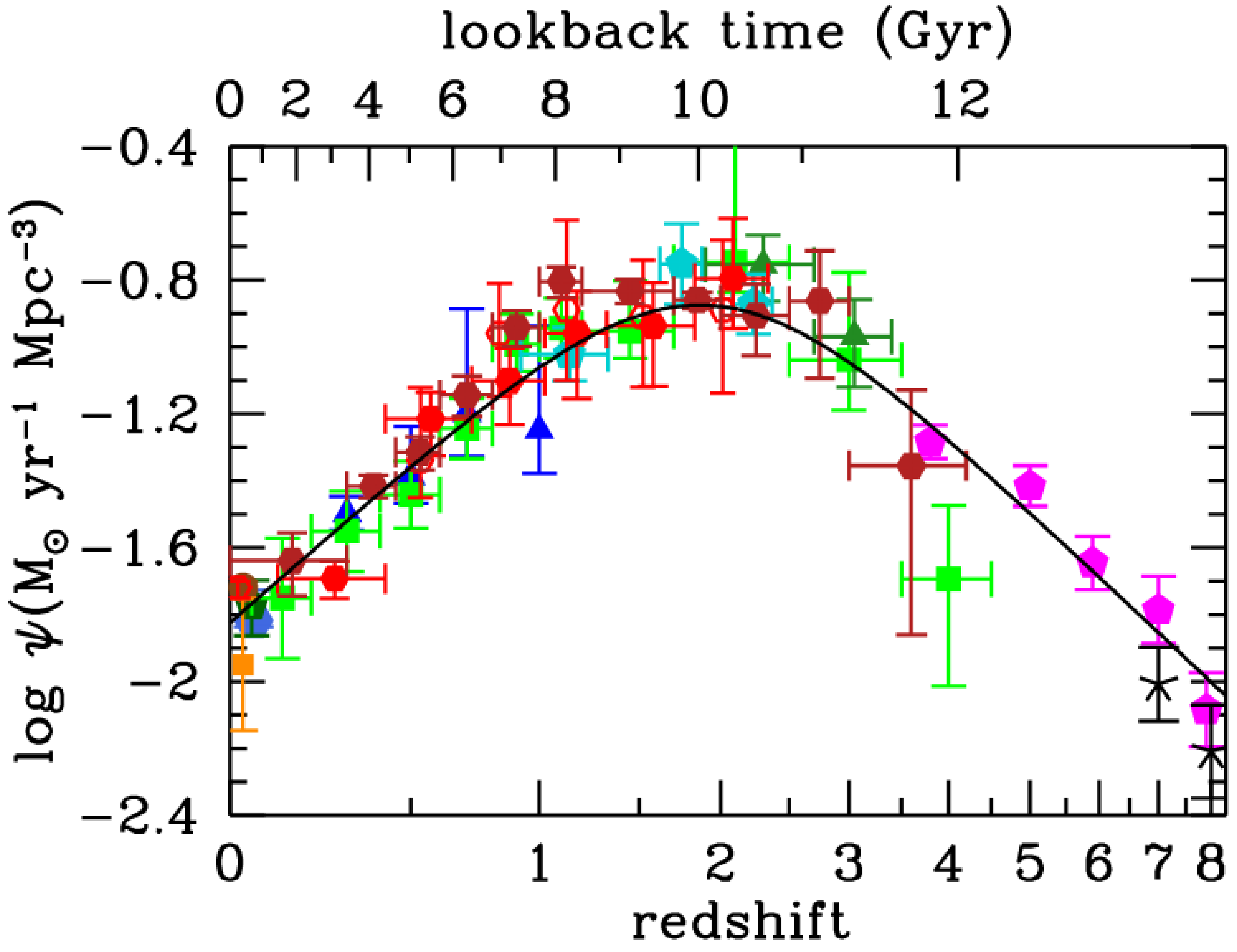
The strange case of JKCS041 a galaxy cluster at z = 1.81

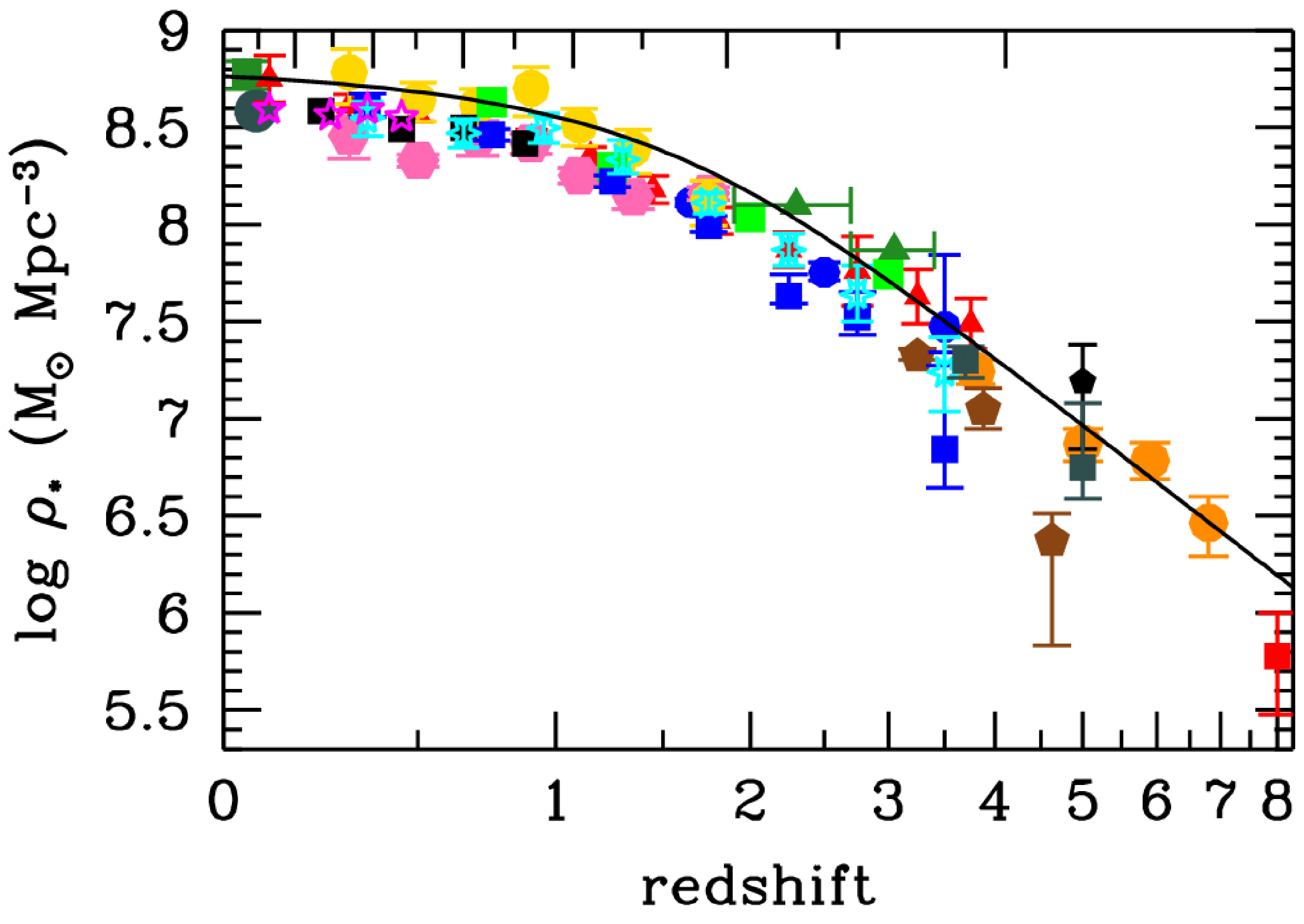




The combination of high angular resolution and dust unbiased nature makes of the radio continuum data a unique tool to explore galaxy evolution in overdense environments and in particular at cosmic times when lots of activity (star-formation and nuclear activity) is expected!

Galaxy evolution



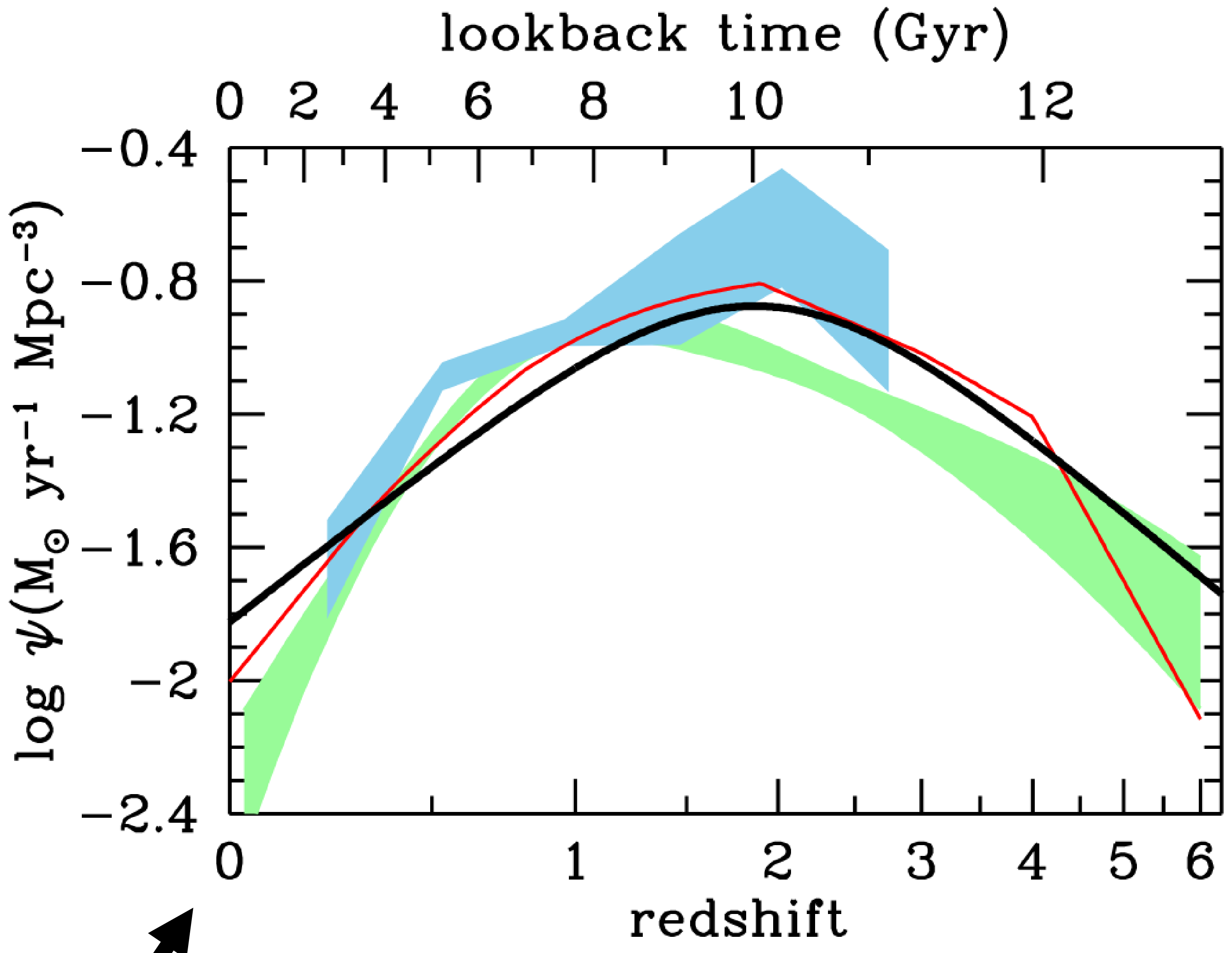


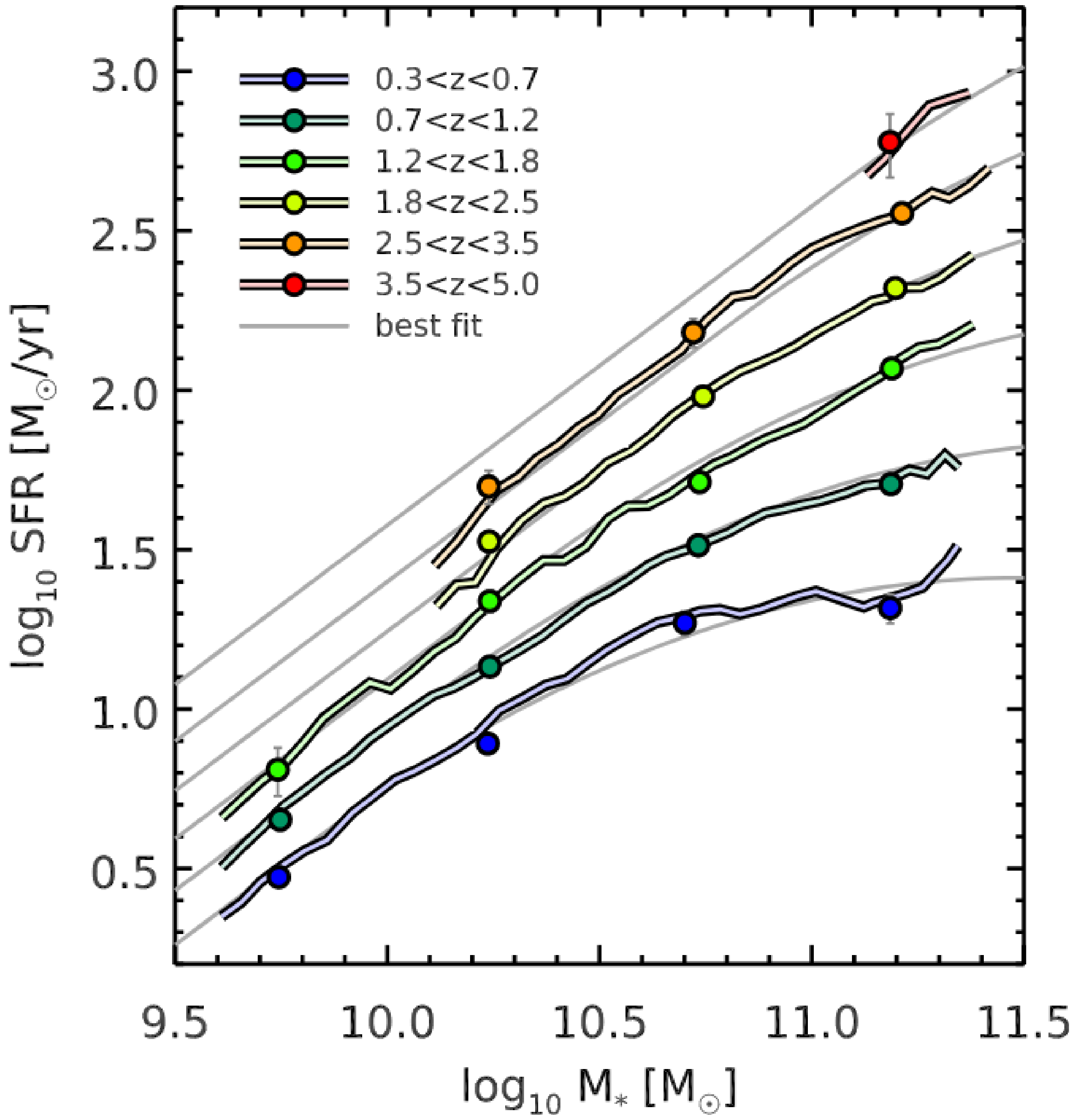
Cosmic SF history

Stellar Mass growth

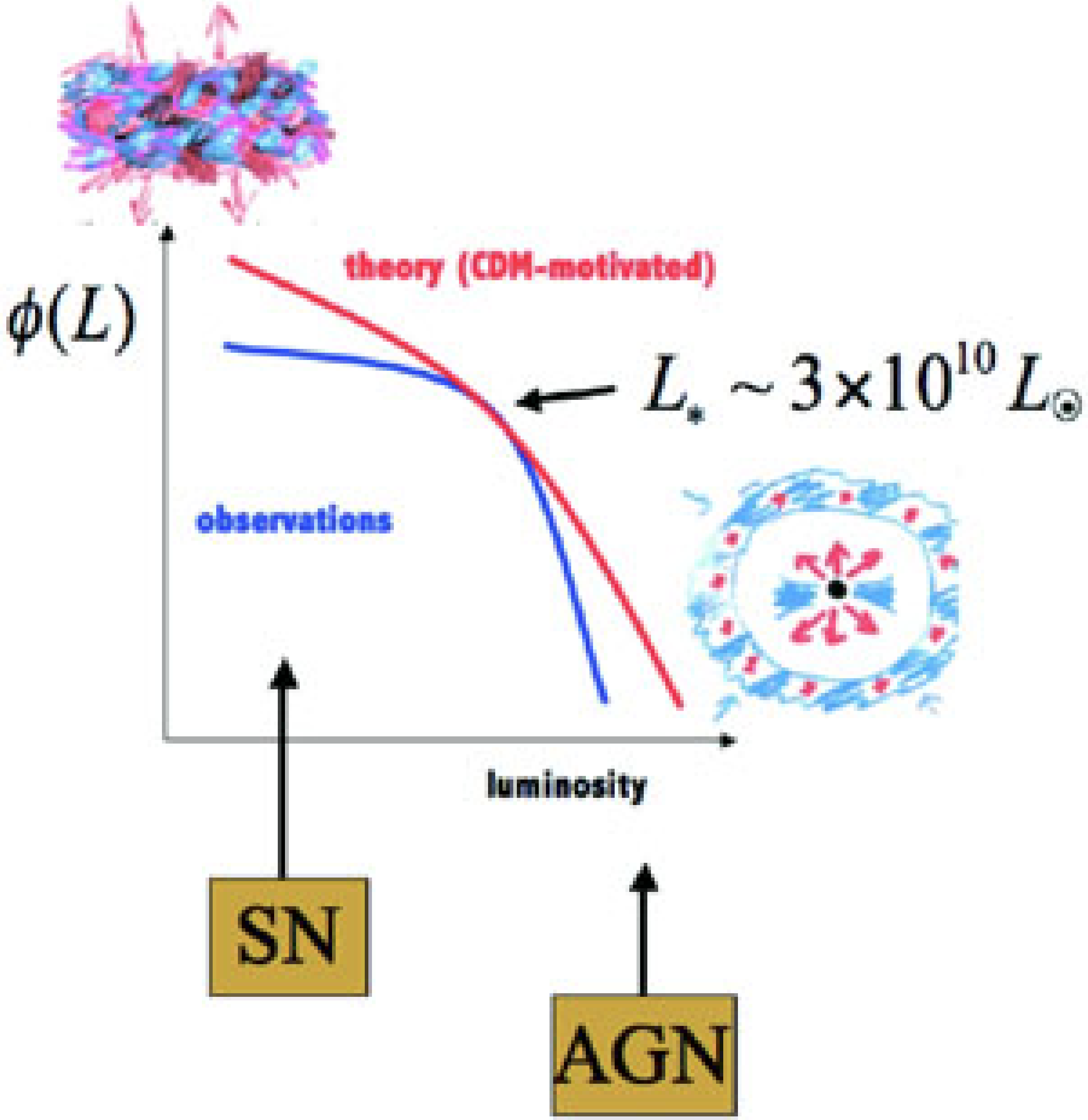
Massive BH growth

Galaxy SF histories





Galaxy evolution



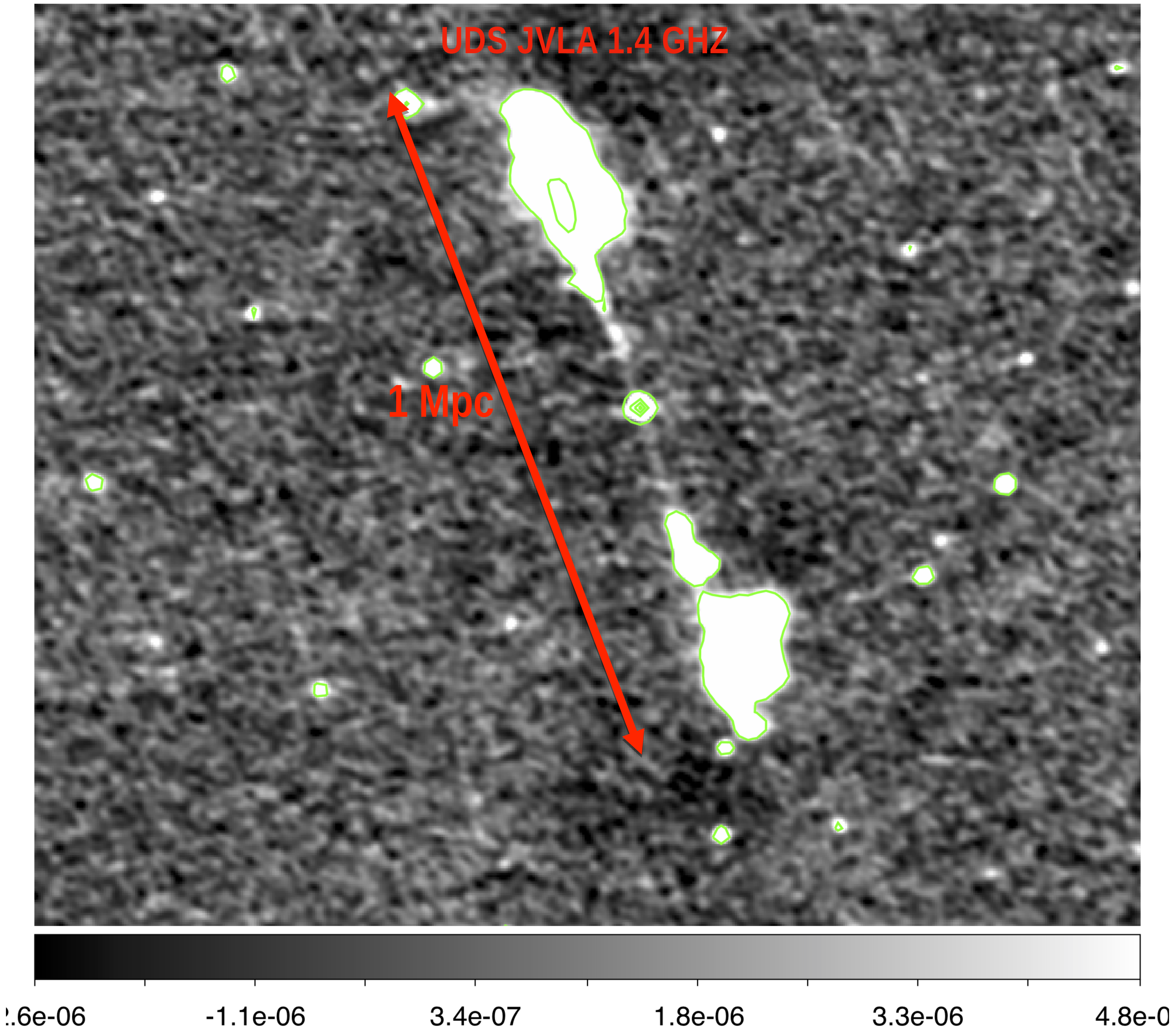
Mechanical feedback by injection of kinetic energy that shock heats the ISM/IGM gas

Needed by galaxy formation models to prevent gas cooling:

- **Stellar mass overgrowth**
- **Massive star-forming galaxies**

Different models use different feedback implementations in order to reproduce observed galaxy properties

Galaxy evolution



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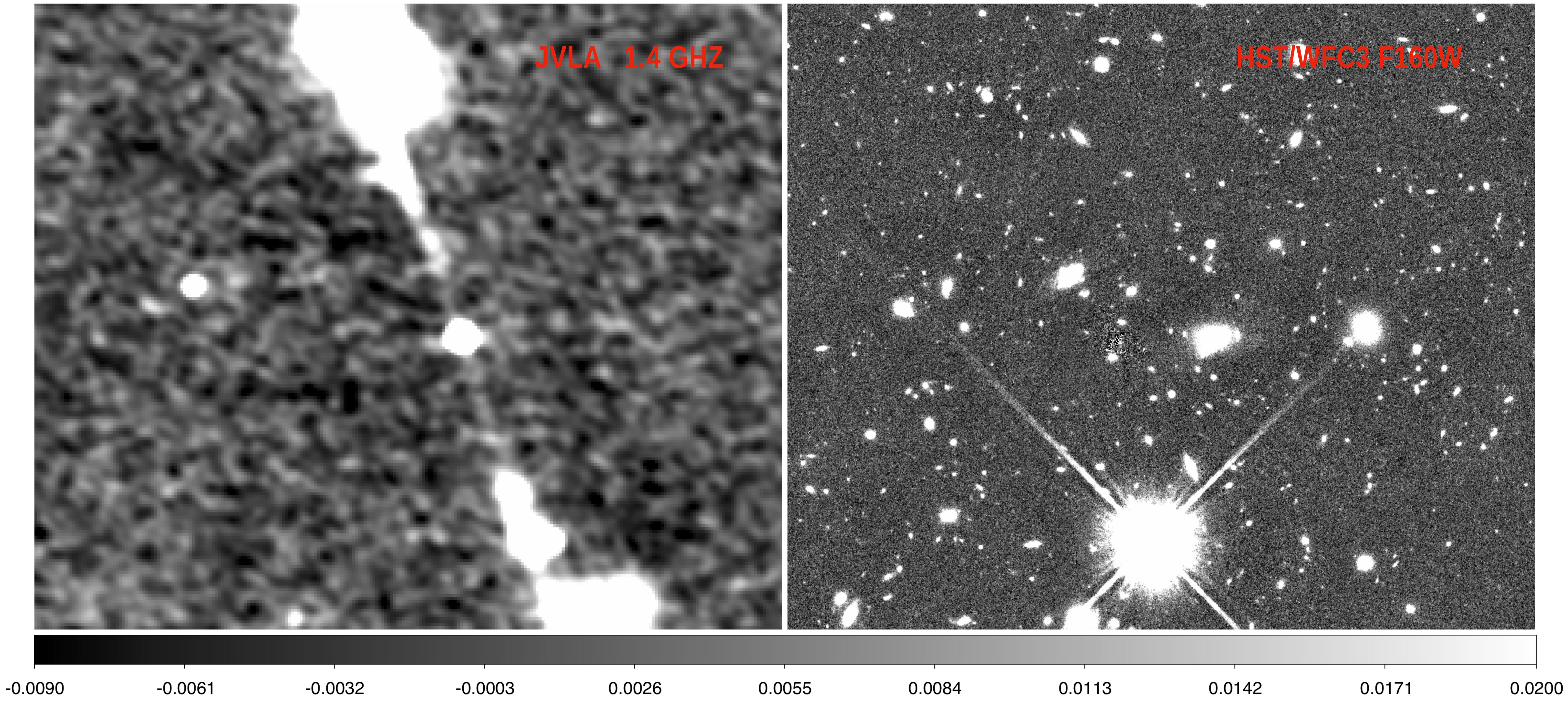
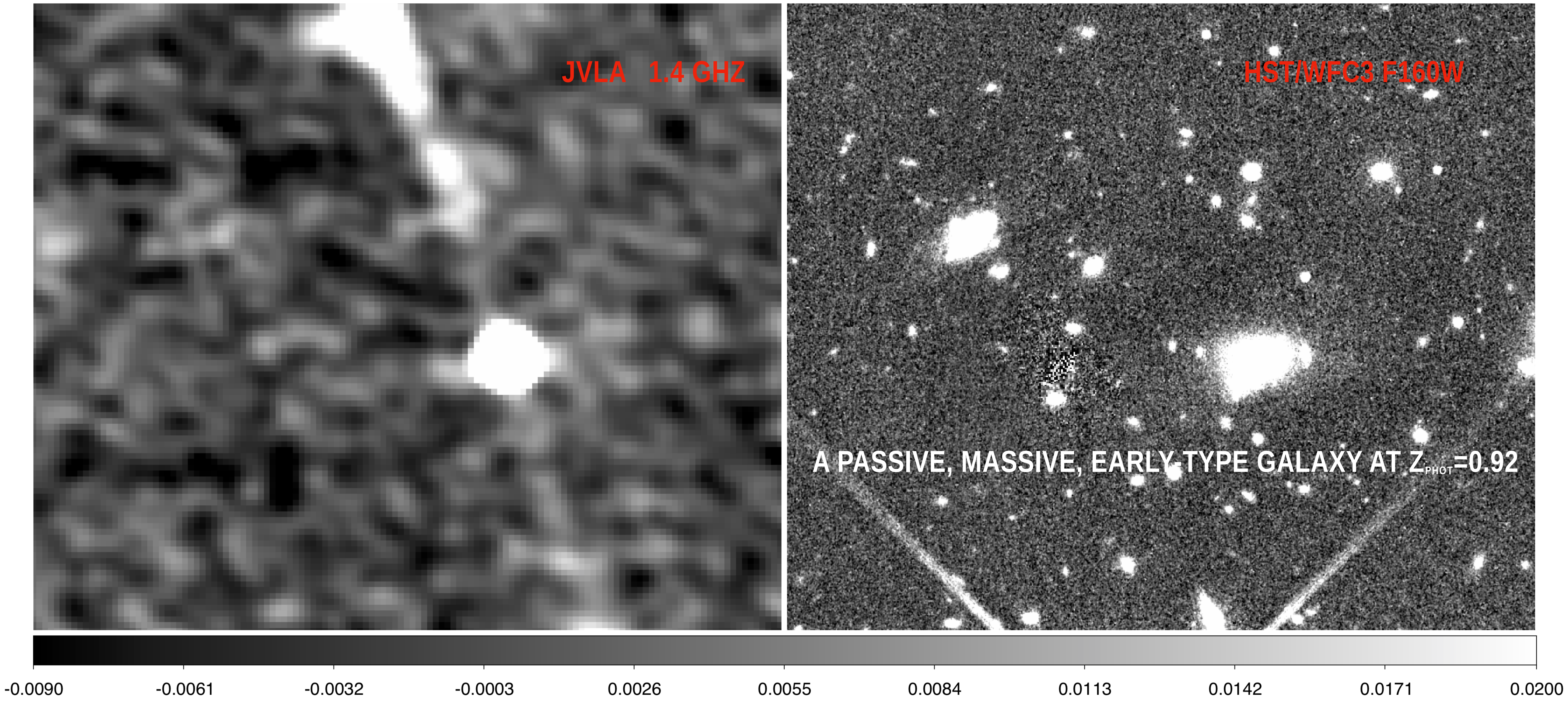
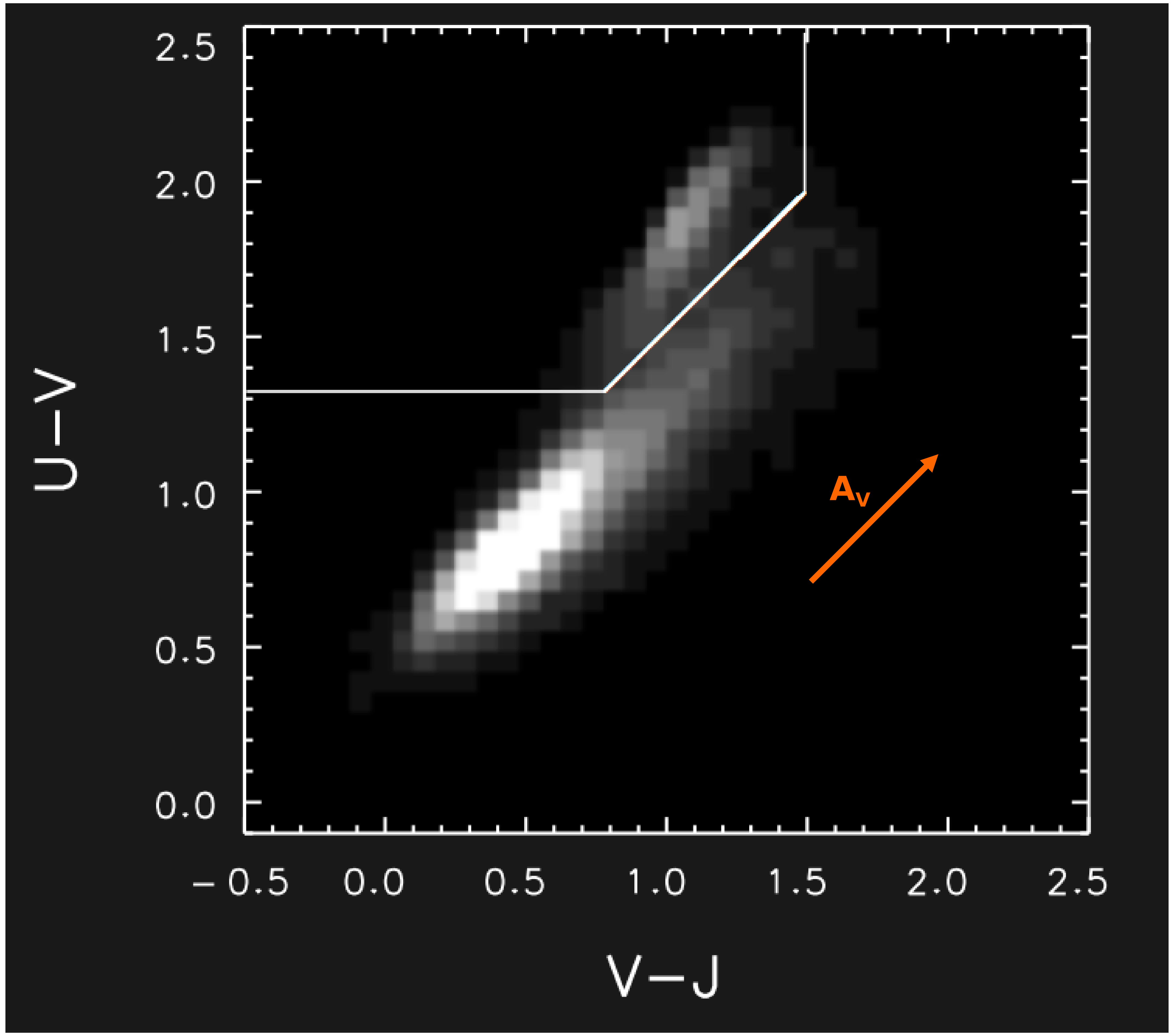


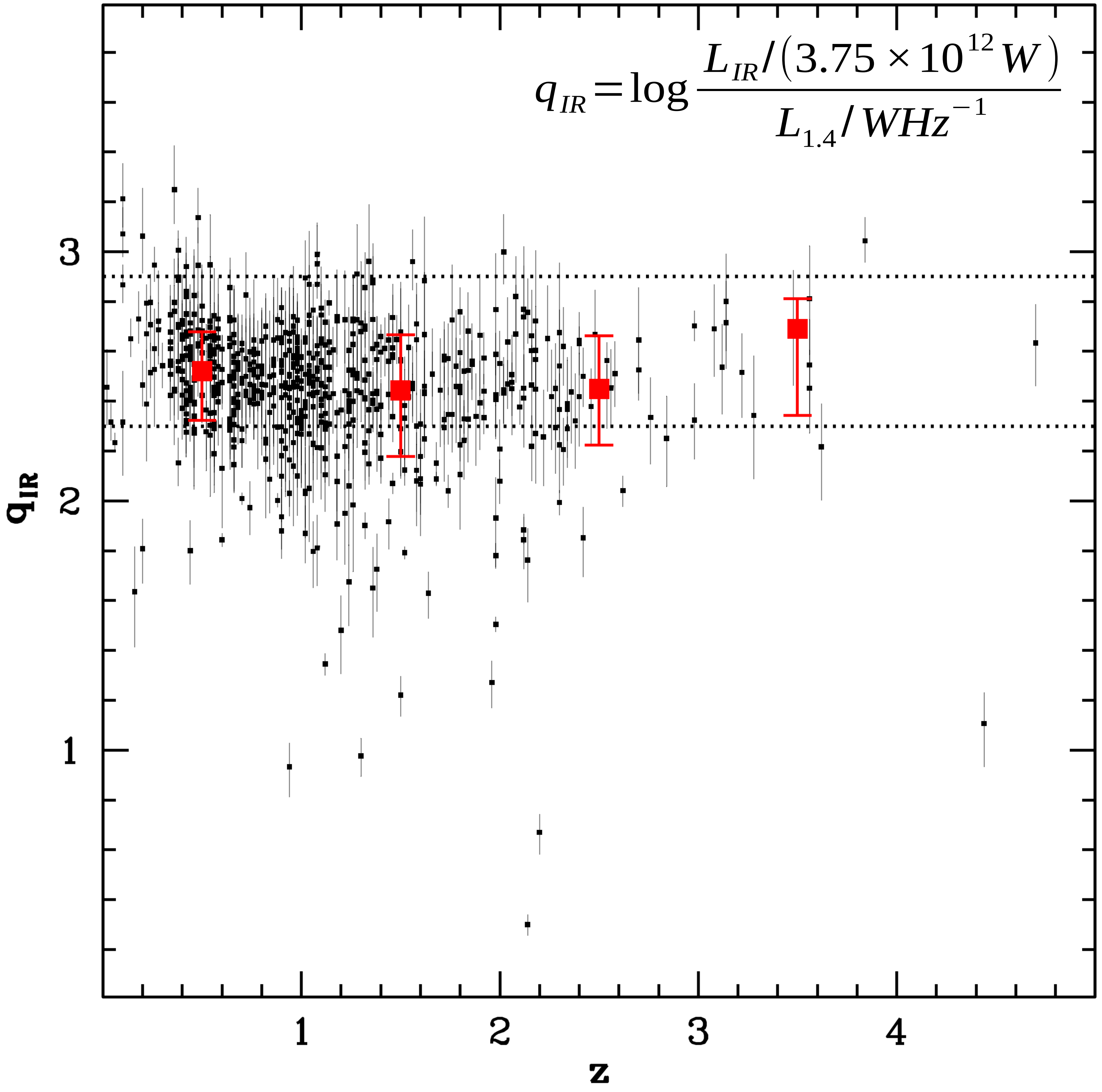
Galaxy evolution



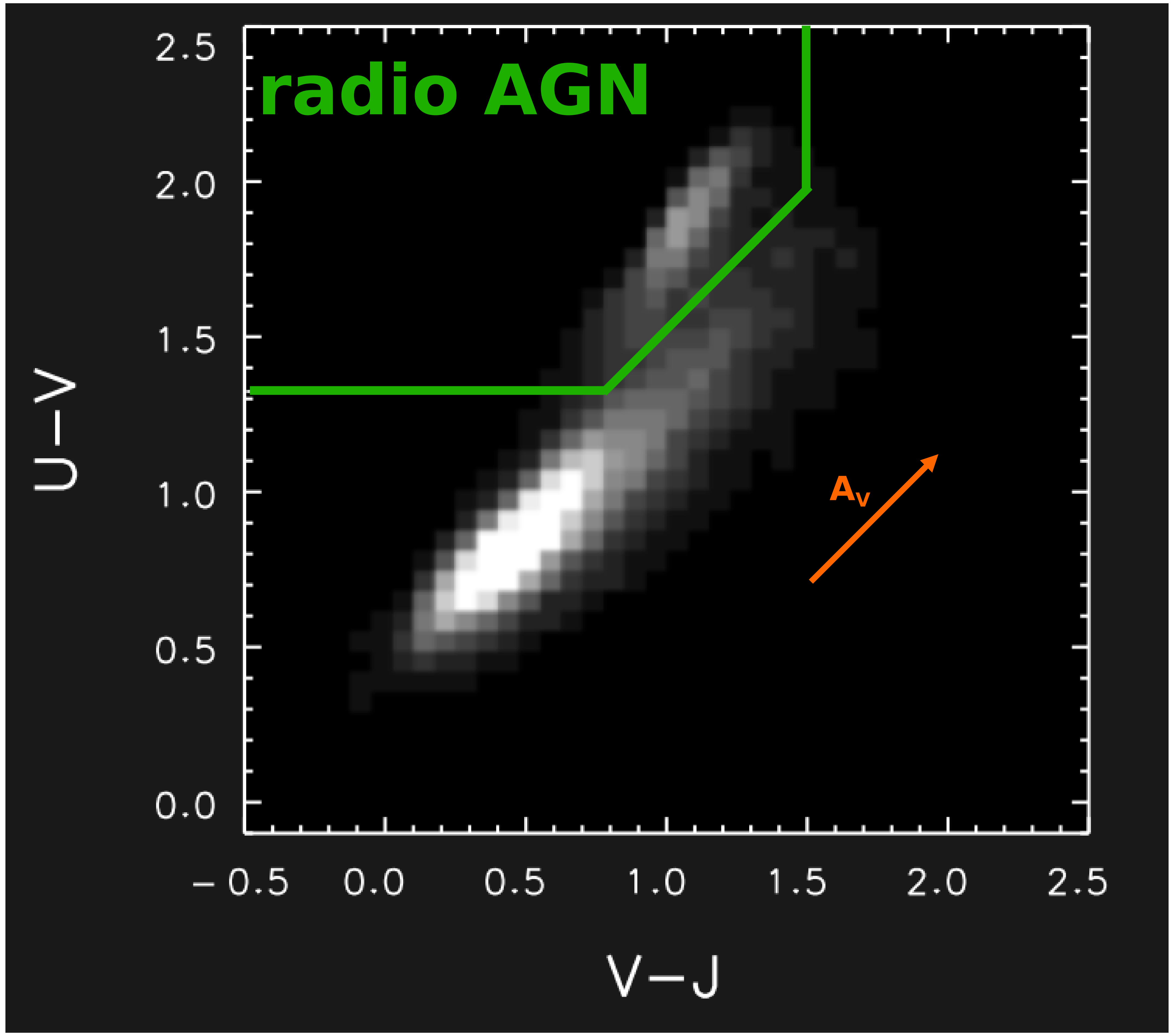
A PASSIVE, MASSIVE, EARLY-TYPE GALAXY AT $Z_{PHOT}=0.92$

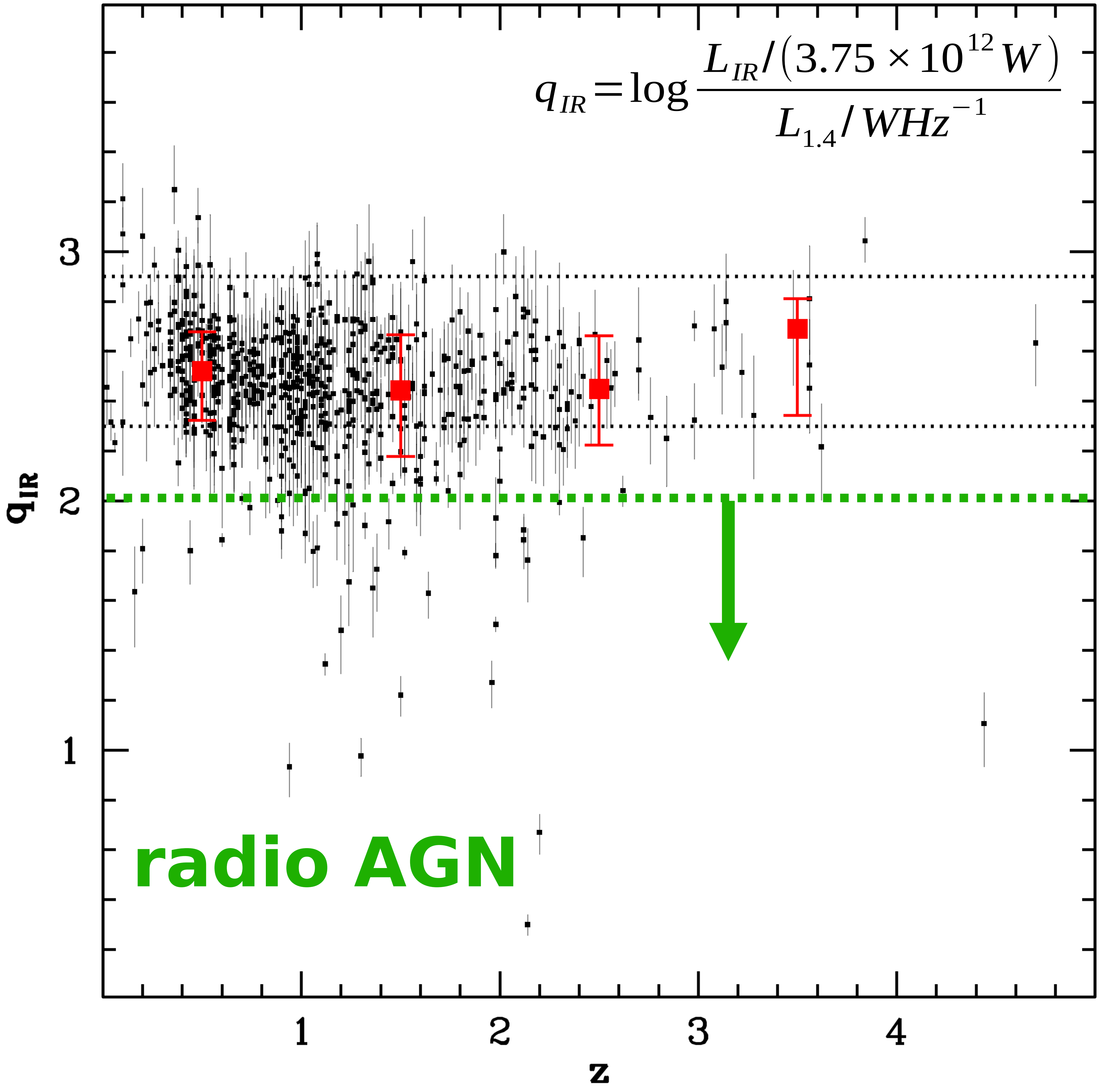
Galaxy evolution





Galaxy evolution





Galaxy evolution: molecular gas, the fuel for star formation

CO emission is by far the brightest and most reliable tracer of molecular gas in galaxies:

$$M_{mol} = \alpha_{CO} L_{CO}$$

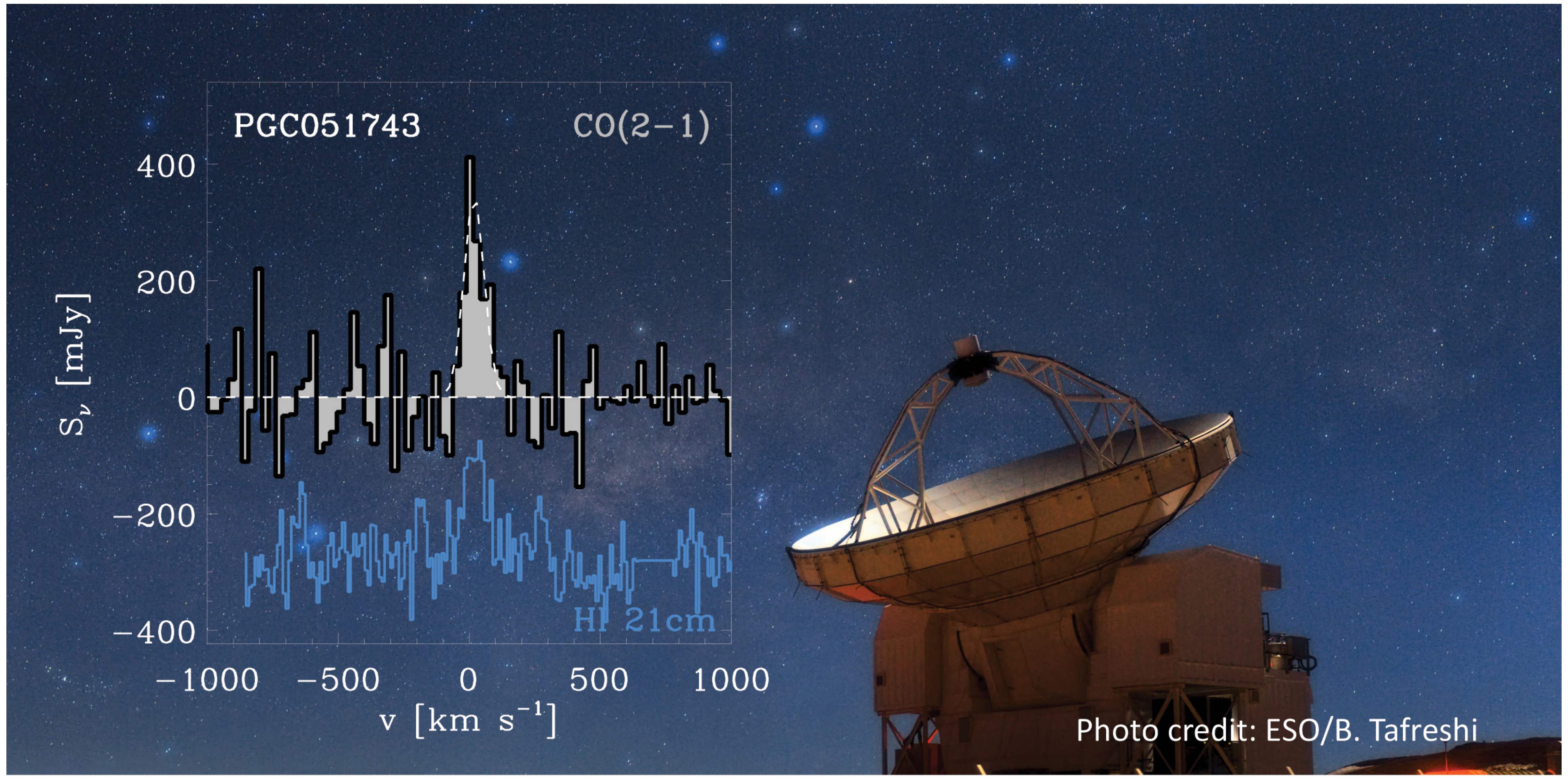
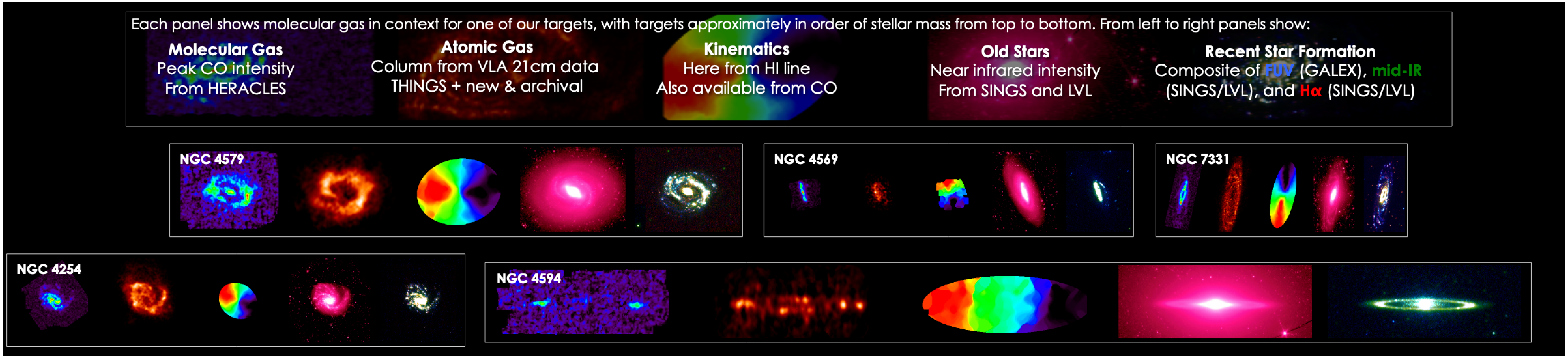


Photo credit: ESO/B. Tafreshi



Each panel shows molecular gas in context for one of our targets, with targets approximately in order of stellar mass from top to bottom. From left to right panels show:

Molecular Gas
Peak CO intensity
From HERACLES

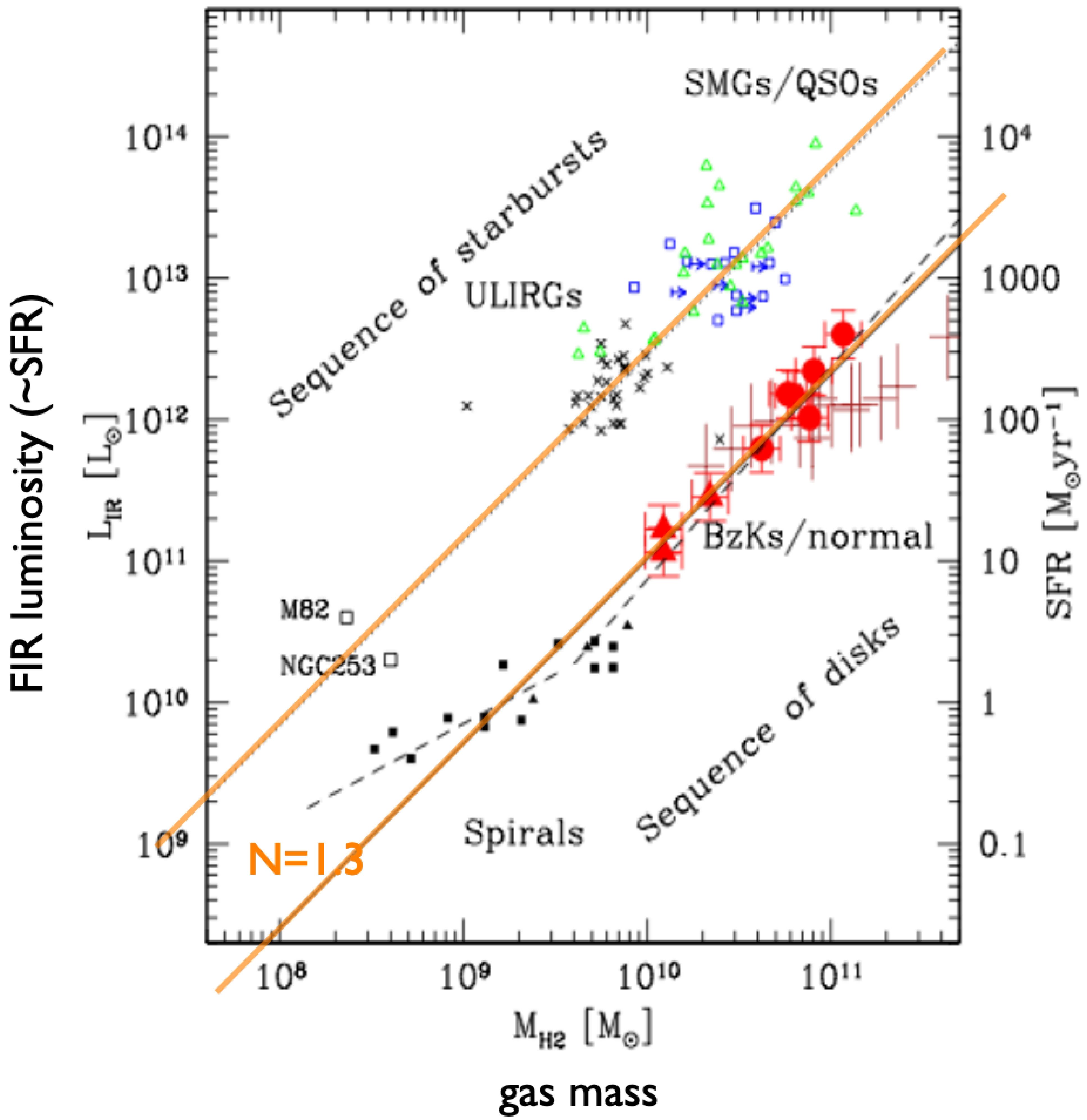
Atomic Gas
Column from VLA 21cm data
THINGS + new & archival

Kinematics
Here from HI line
Also available from CO

Old Stars
Near infrared intensity
From SINGS and LVL

Recent Star Formation
Composite of FUV (GALEX), mid-IR
(SINGS/LVL), and Hα (SINGS/LVL)

Galaxy evolution: molecular gas, the fuel for star formation



Two mode of star formation in the Universe

If we define the gas depletion time scale as:

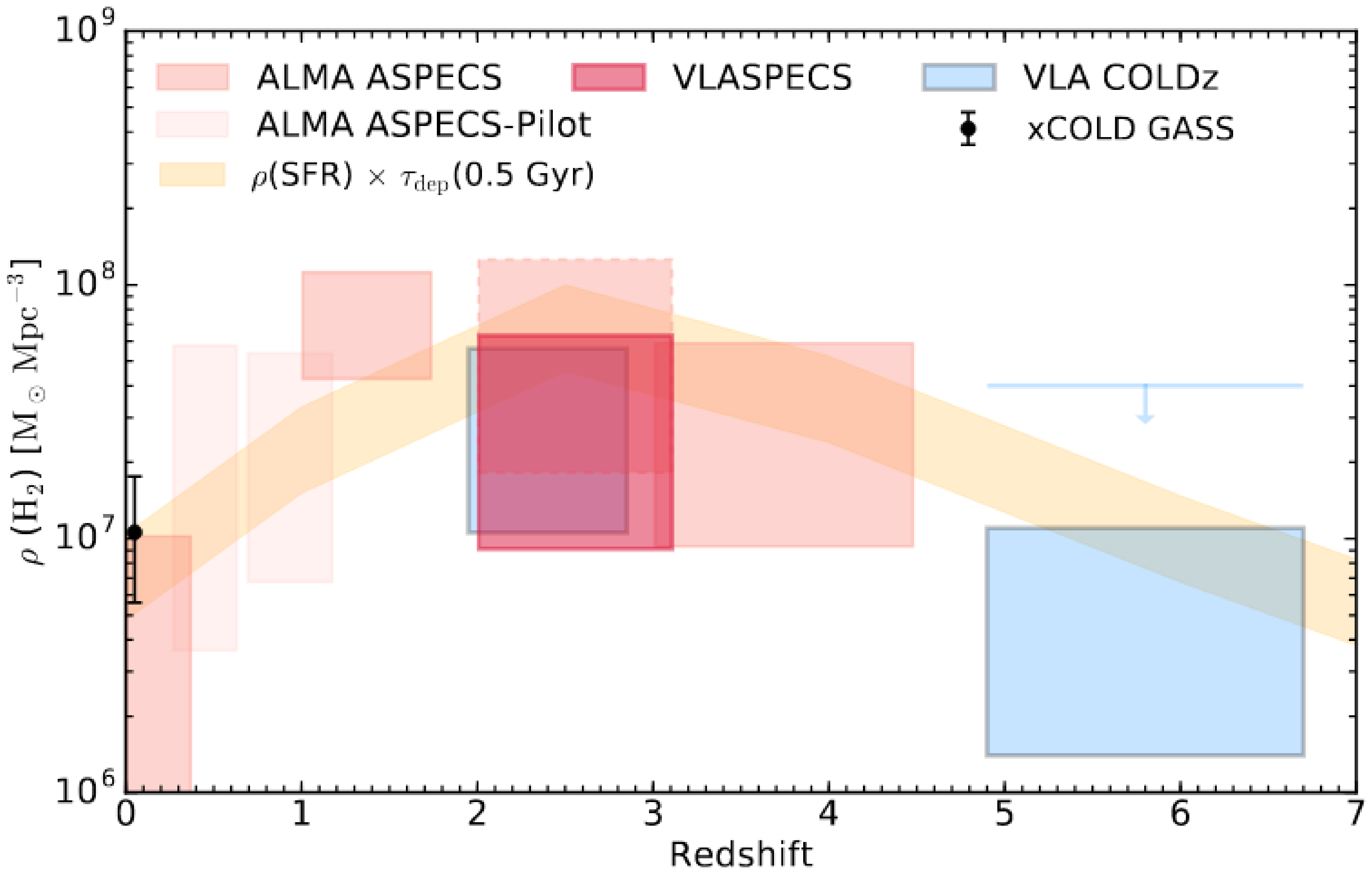
$$t_{dep} = M_{gas}/SFR$$

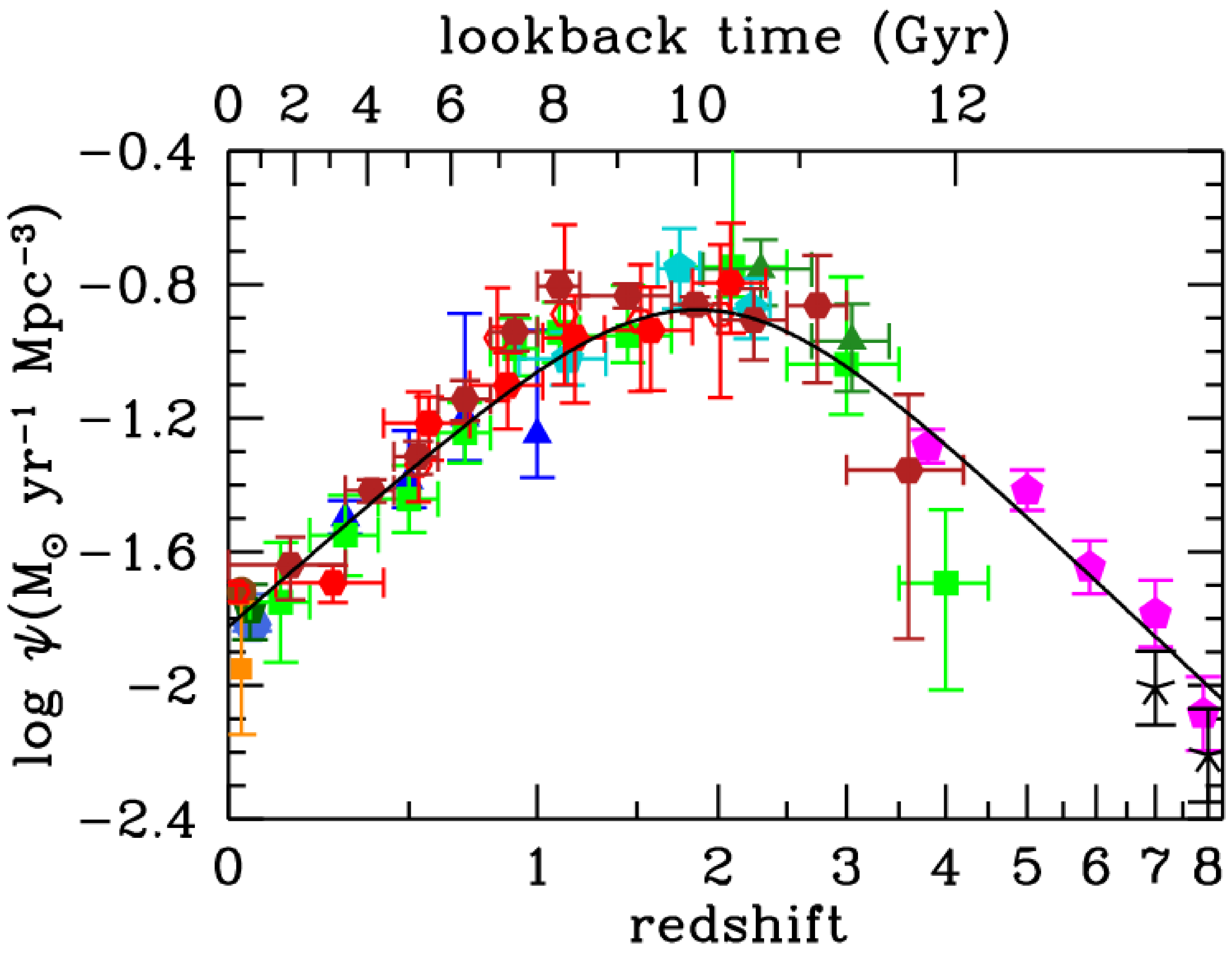
galaxies split in two diverse mode of converting gas into stars:

— Normal star-forming (Main Sequence) galaxies have depletion times of ~ 1Gyr. Stars are formed in an inefficient and quiescent mode over the whole galaxy.

— Extreme (Starbursts) galaxies have depletion times of ~ 100 Myr. Stars are formed very efficiently in compact regions where gas has been compressed by galaxy encounters or merger events.

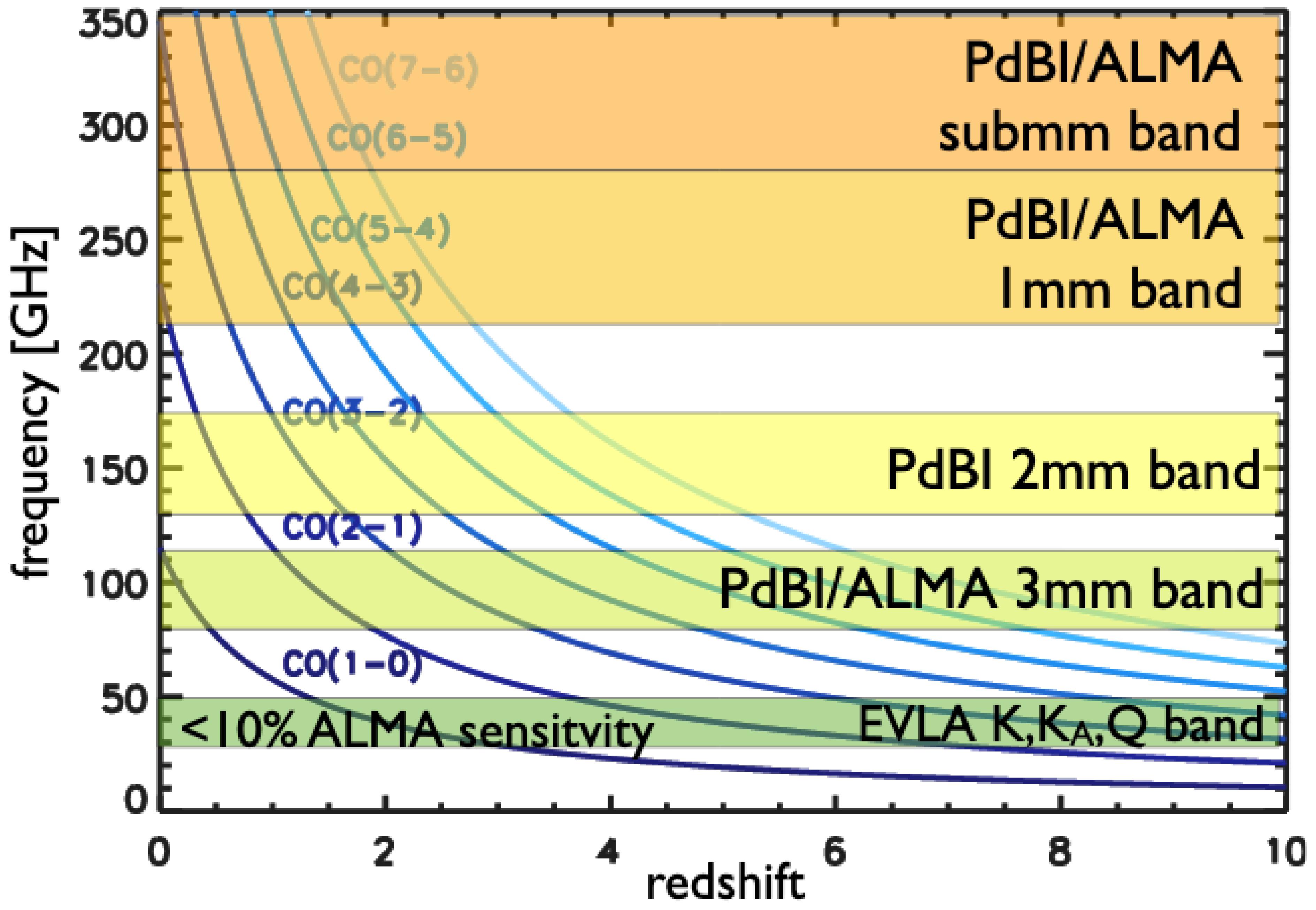
Galaxy evolution: molecular gas, the fuel for star formation

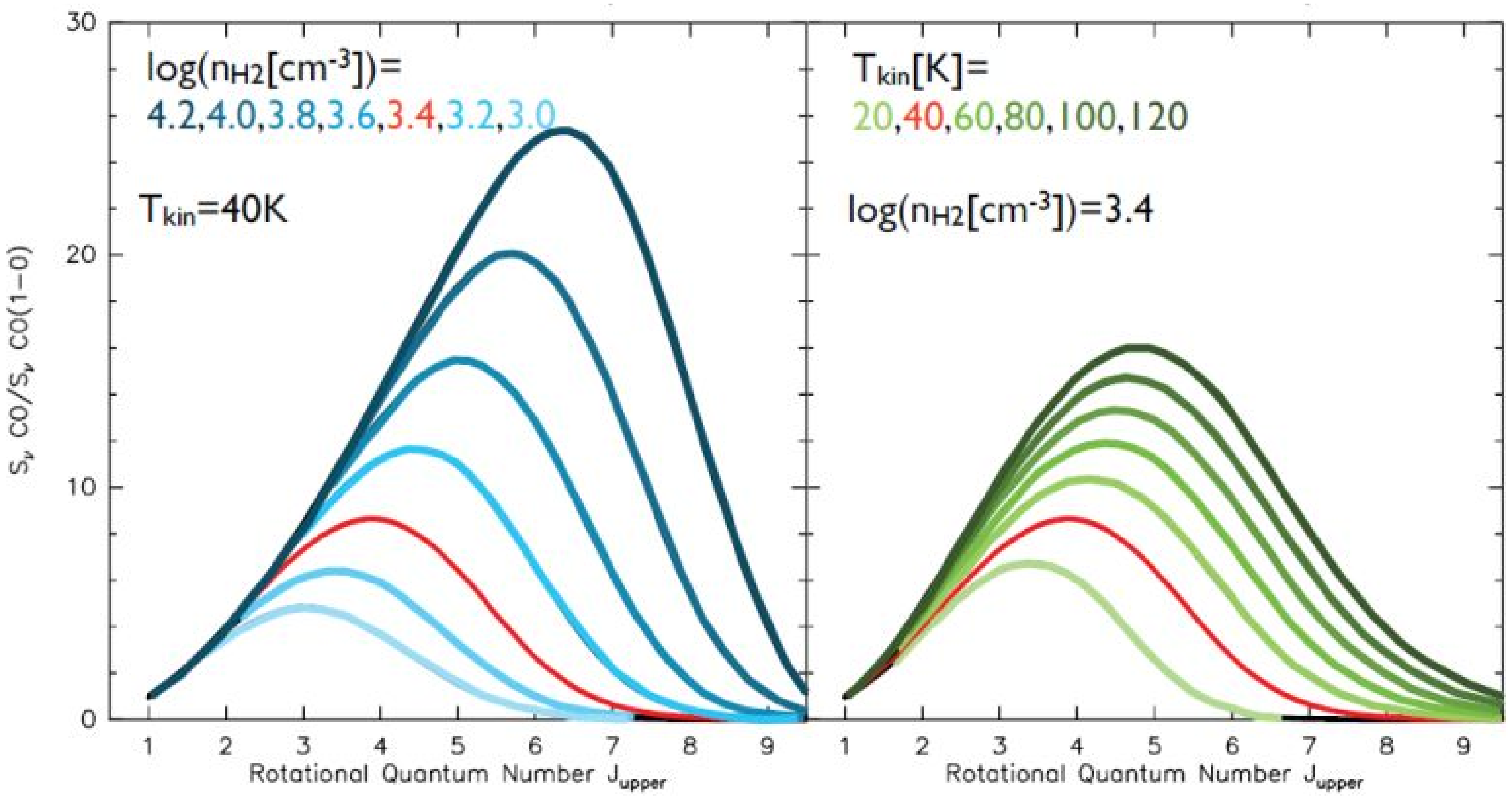




Galaxy evolution: molecular gas, the fuel for star formation

CO transitions as function of redshift, f(T, ρ)

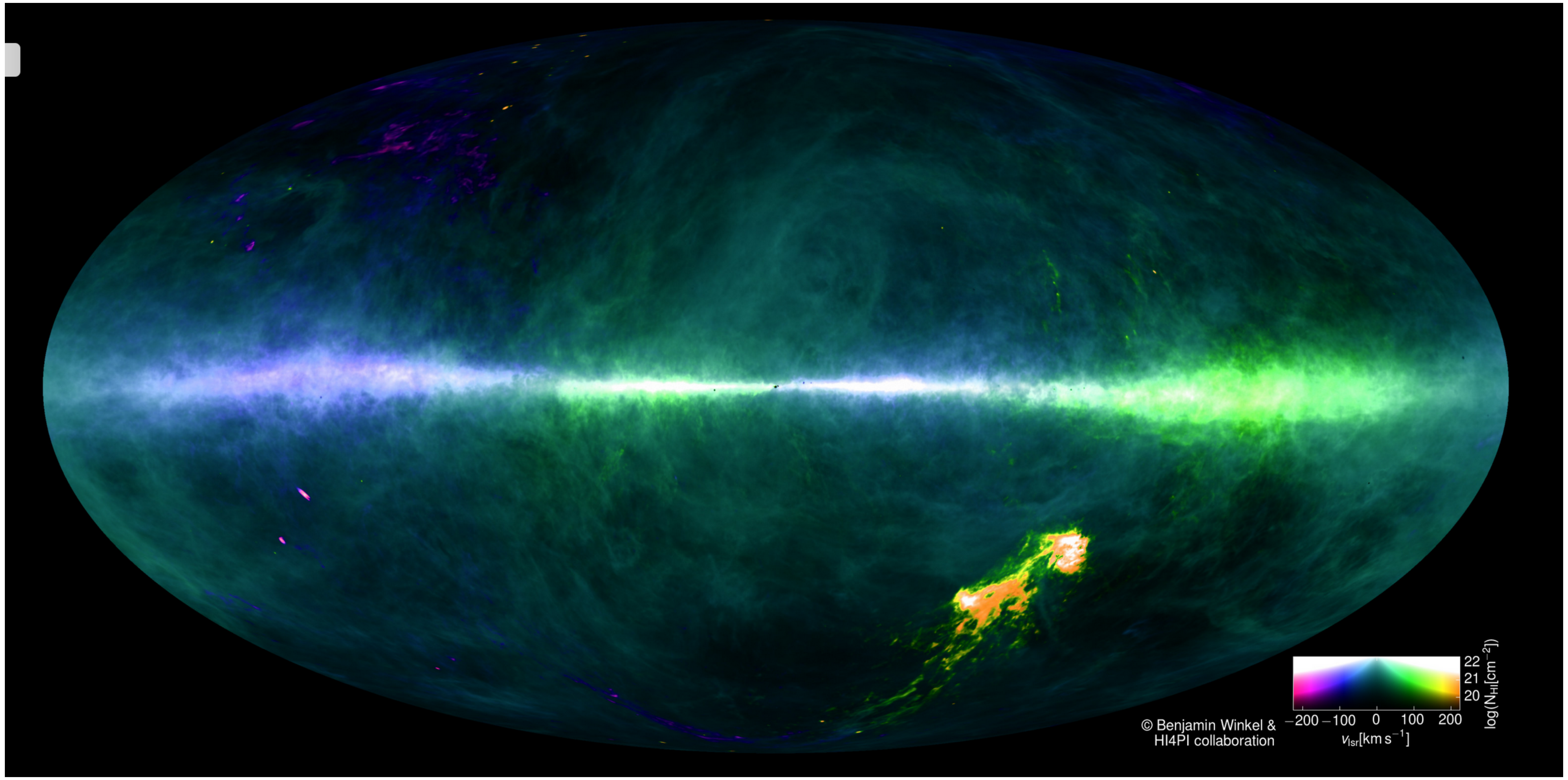




Different transitions are usually accessible at different redshifts. Different J-level transitions depend on both temperature and density of the gas. To put them together we need to know, or assume, a CO SLED (Spectral Line Energy Distribution). In order to break the degeneracy we have to use some prior information or independent tracers of Temperature/density.

Galaxy evolution: molecular gas, the fuel for star formation

HI atoms are abundant and ubiquitous in low-density regions of the ISM



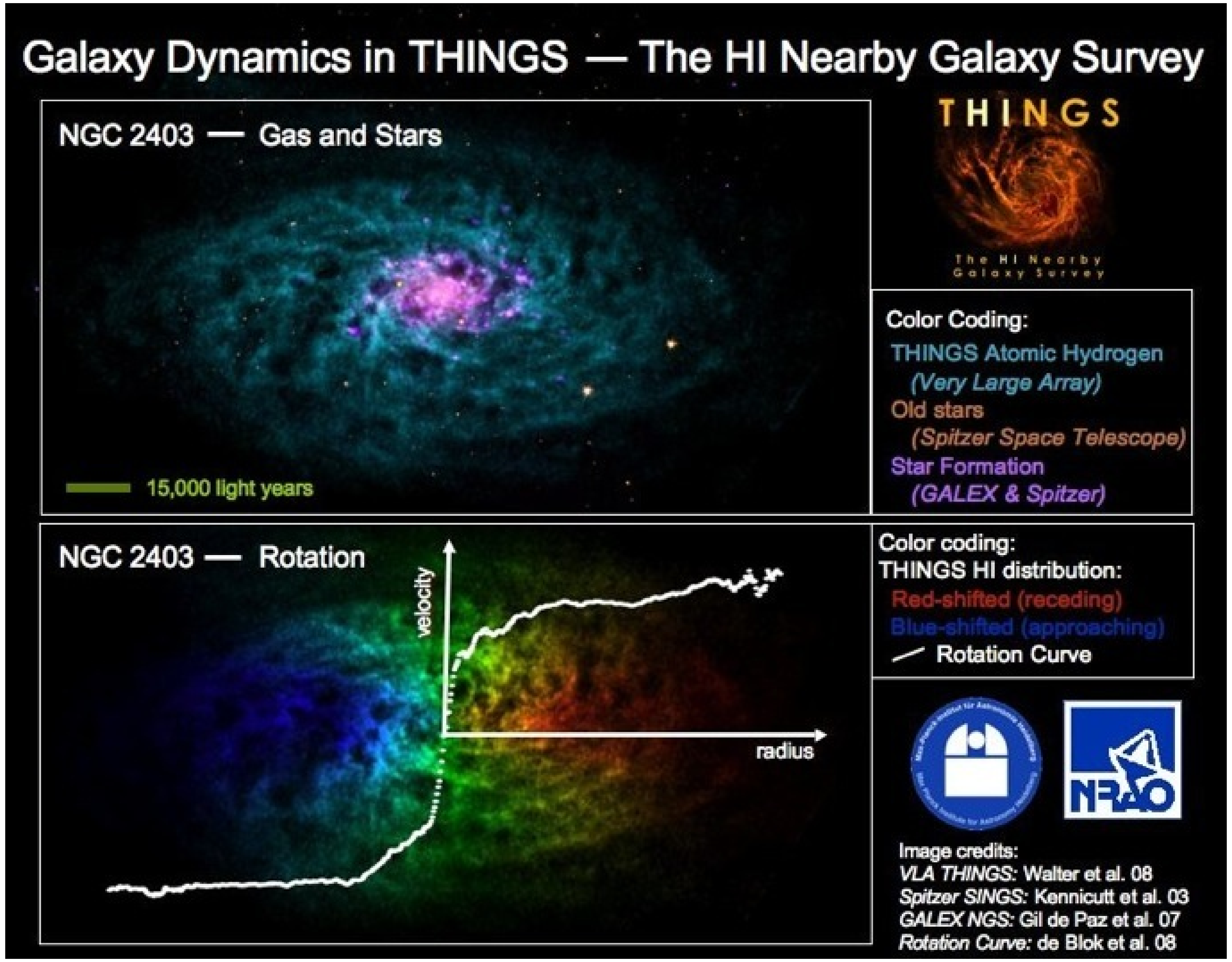
© Benjamin Winkel &
HI4PI collaboration

mapping accurate velocity fields

infall and outflow structures

Galaxy evolution: molecular gas, the fuel for star formation

HI atoms are abundant and ubiquitous in low-density regions of the ISM



Galaxy Dynamics in THINGS — The HI Nearby Galaxy Survey

Color Coding:
THINGS Atomic Hydrogen (Very Large Array)
Old stars (Spitzer Space Telescope)
Star Formation (GALEX & Spitzer)

Color coding:
THINGS HI distribution:
Red-shifted (receding)
Blue-shifted (approaching)
Rotation Curve

Image credits:
VLA THINGS: Walter et al. 08
Spitzer SINGS: Kennicutt et al. 03
GALEX NGS: Gil de Paz et al. 07
Rotation Curve: de Blok et al. 08

mapping accurate velocity fields

infall and outflow structures

dynamical mass estimate
(dark matter)

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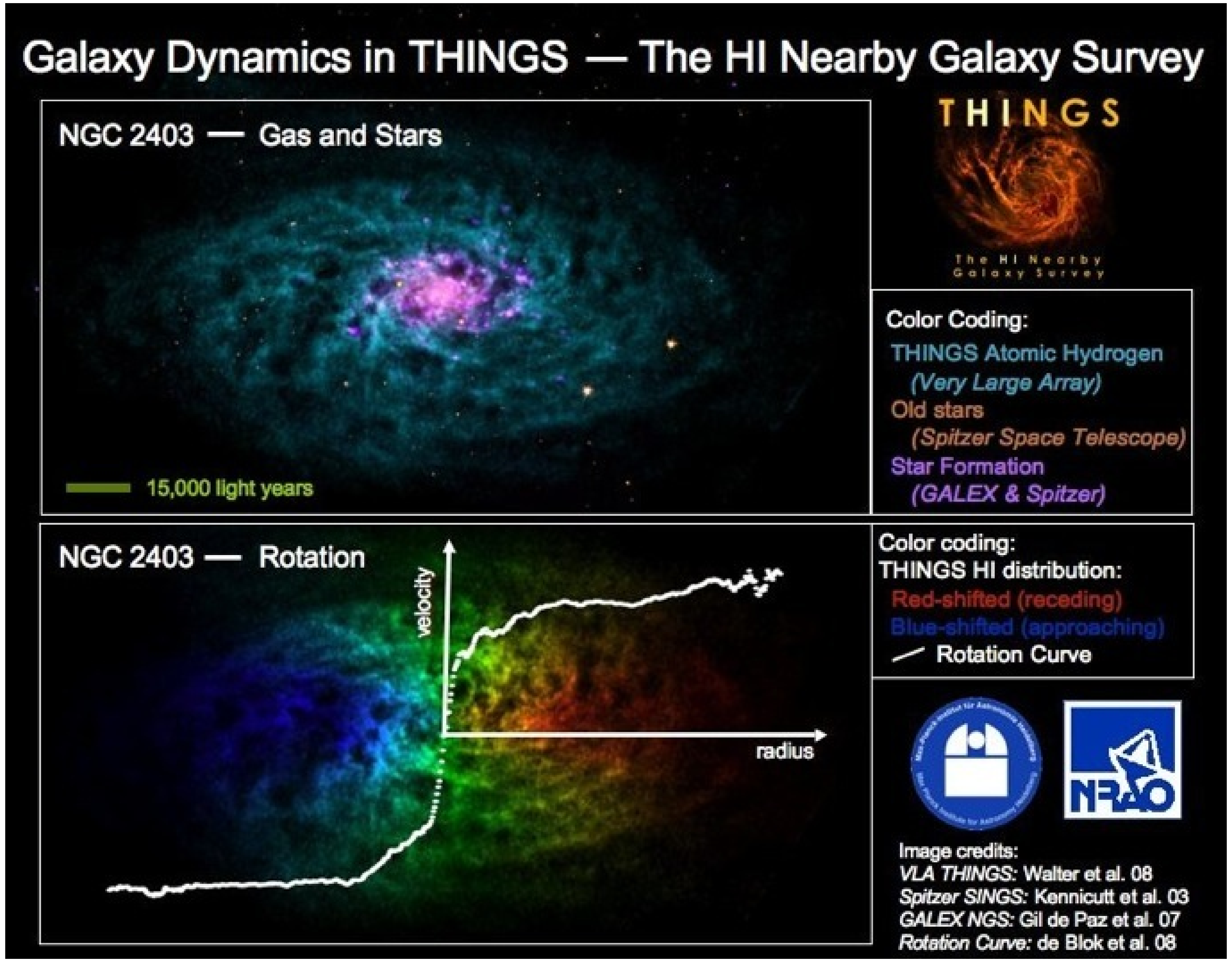

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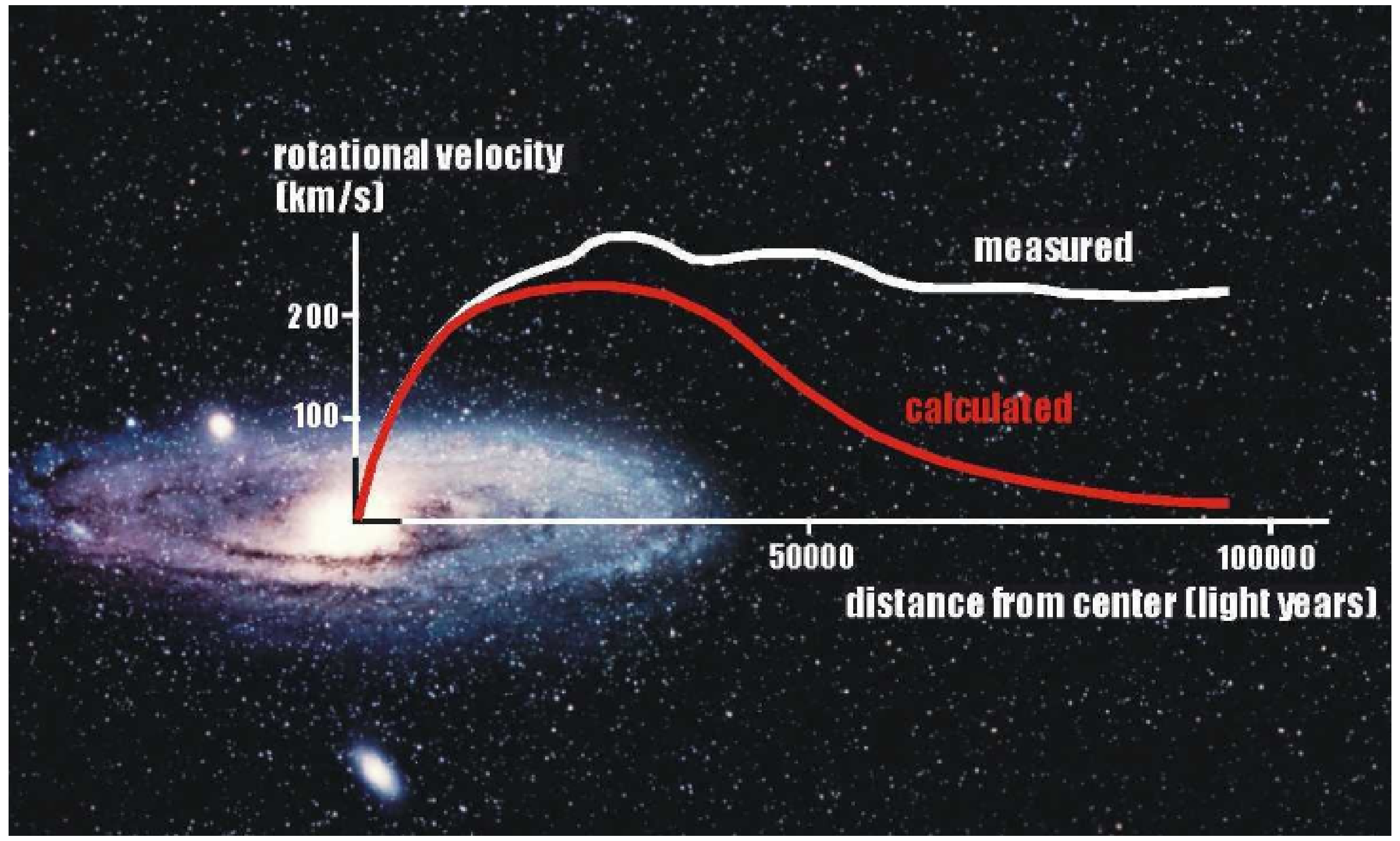

Galaxy evolution: molecular gas, the fuel for star formation

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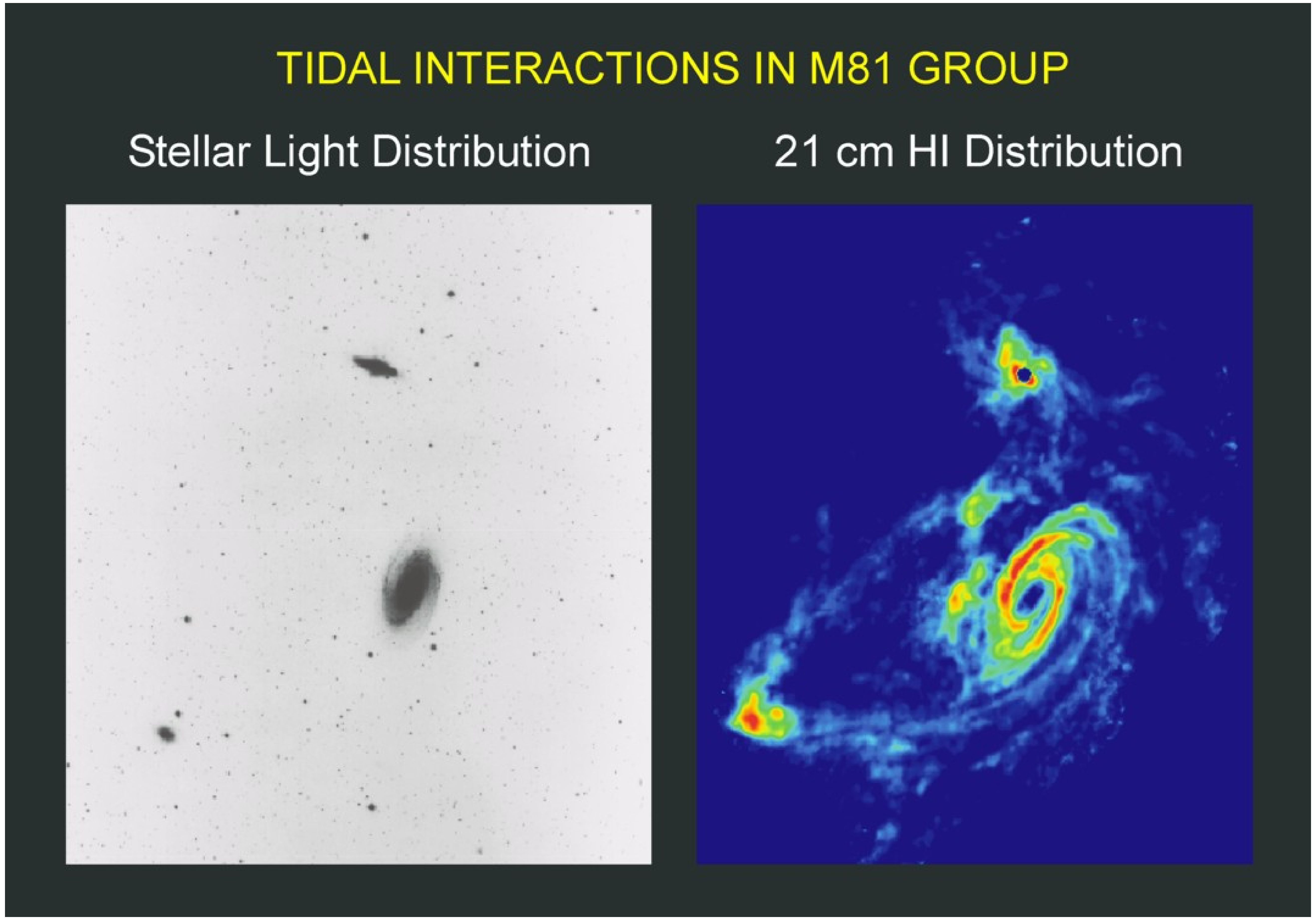

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tidal streams

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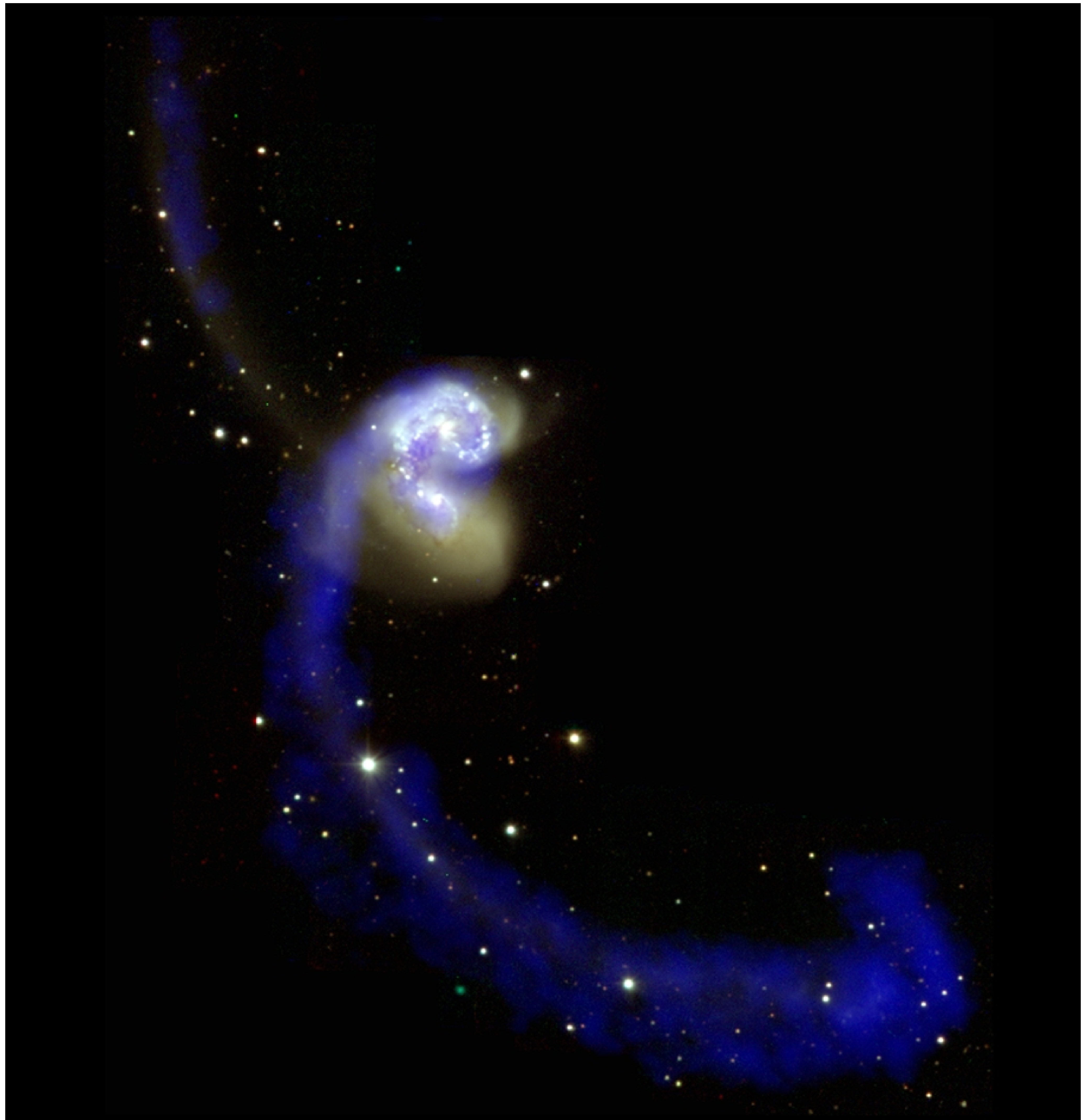

mapping accurate velocity fields

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Present and future of radio astronomy

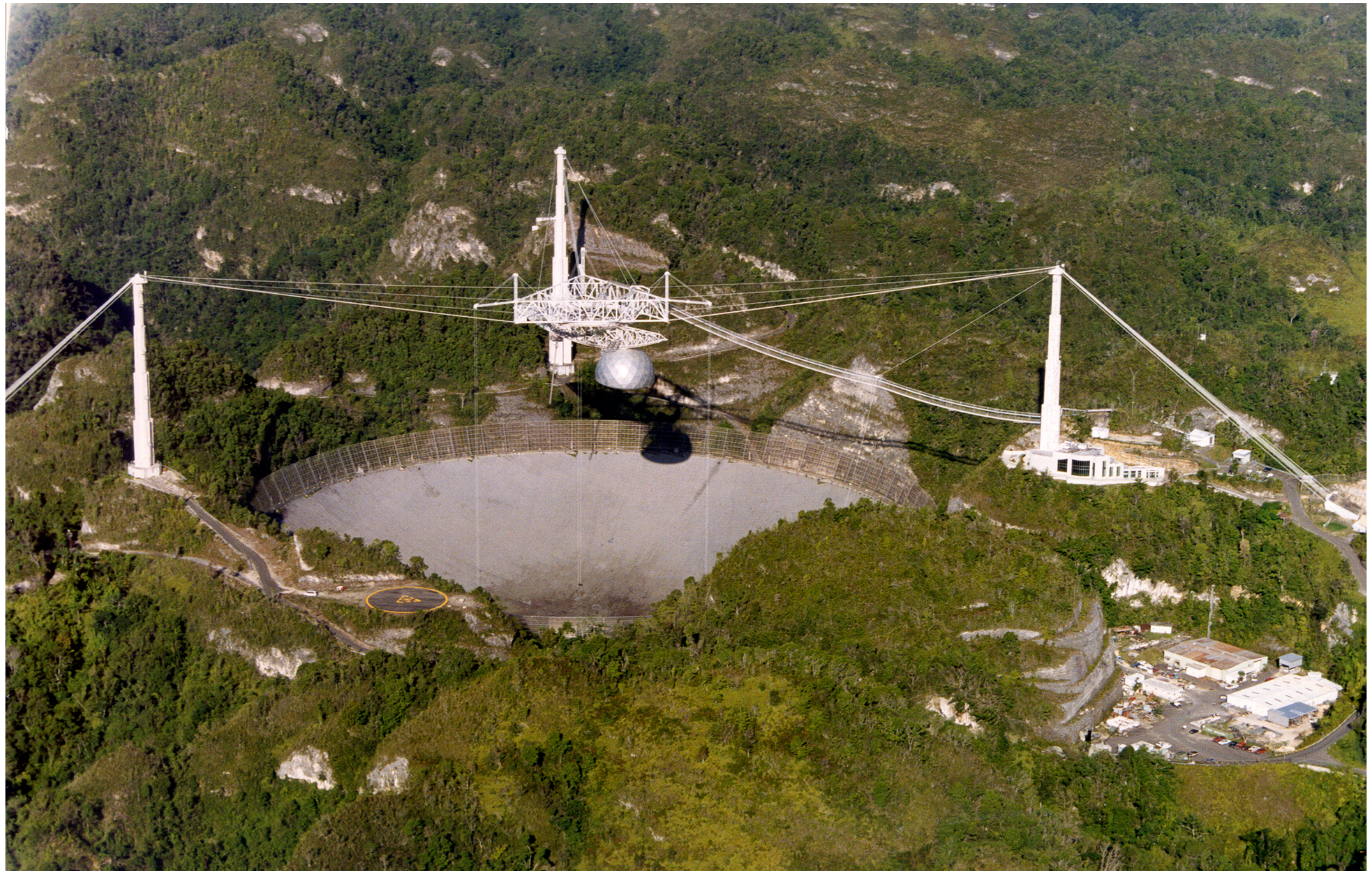
Green Bank Telescope - West Virginia

100 mt diameter

Receivers: 0.3 / 100 GHz

FWHM ~ 13/f_{GHz} arcmin

Present and future of radio astronomy



Arecibo Observatory - Puerto Rico

220mt diameter

Receivers: 0.3 / 10 GHz

FWHM ~ 3.5 arcmin@21cm (HI)

Present and future of radio astronomy

Arecibo Observatory - Puerto Rico

220mt diameter

Receivers: 0.3 / 10 GHz

FWHM ~ 3.5 arcmin@21cm (HI)

Present and future of radio astronomy

FAST Observatory - China

500mt diameter

Receivers: 1050 / 1450 GHz
Multi-beam (19 beams)

FWHM ~ 3 arcmin@21cm (HI)

Present and future of radio astronomy

Very Large Array - New Mexico

27 Antennae x 25mt diameter

A-to-D configurations (0.6/21km)

Receivers: 73 MHz / 50 GHz

Field of view ~ $45/f_{\mathrm{GHz}}$ arcmin

Resolution ~ $\theta_{\mathrm{arcsec}} \approx 2\lambda_{\mathrm{cm}}/D_{\mathrm{km}}$

Present and future of radio astronomy

ALMA – Chile
NRAO/ESO/NAOJ/TAIWAN/CHILE

50 Antennas x 12mt diameter

Many configurations (0.15/16km)

Receivers: 31 / 1000 GHz

Atacama Compact Array (ACA)

4/12 antennae x 12/7mt

Present and future of radio astronomy


LOFAR radio telescope – ASTRON

LOFAR - Low Frequency Array

European Cosortium (ASTRON)

36+ (aperture array) Stations

Covering many baselines: (18) 2/3 km
(10+) 50 km
(++) 1500 km

Receivers: LBA (10-90MHz)
HBA (110-250 MHz)

Present and future of radio astronomy

Australian SKA Pathfinder – ASKAP

36 Antennas x 12mt diameter

Phased array feeds 36 beams

30 square degrees field-of-view

Max Baseline 6.5 km

Receivers: 0.7/1.8 GHz

Present and future of radio astronomy

Australian SKA Pathfinder

36 Antennas x 12mt diameter

Phased array feeds 36 beams

Atomic Hydrogen (HI) in the SMC

Present and future of radio astronomy

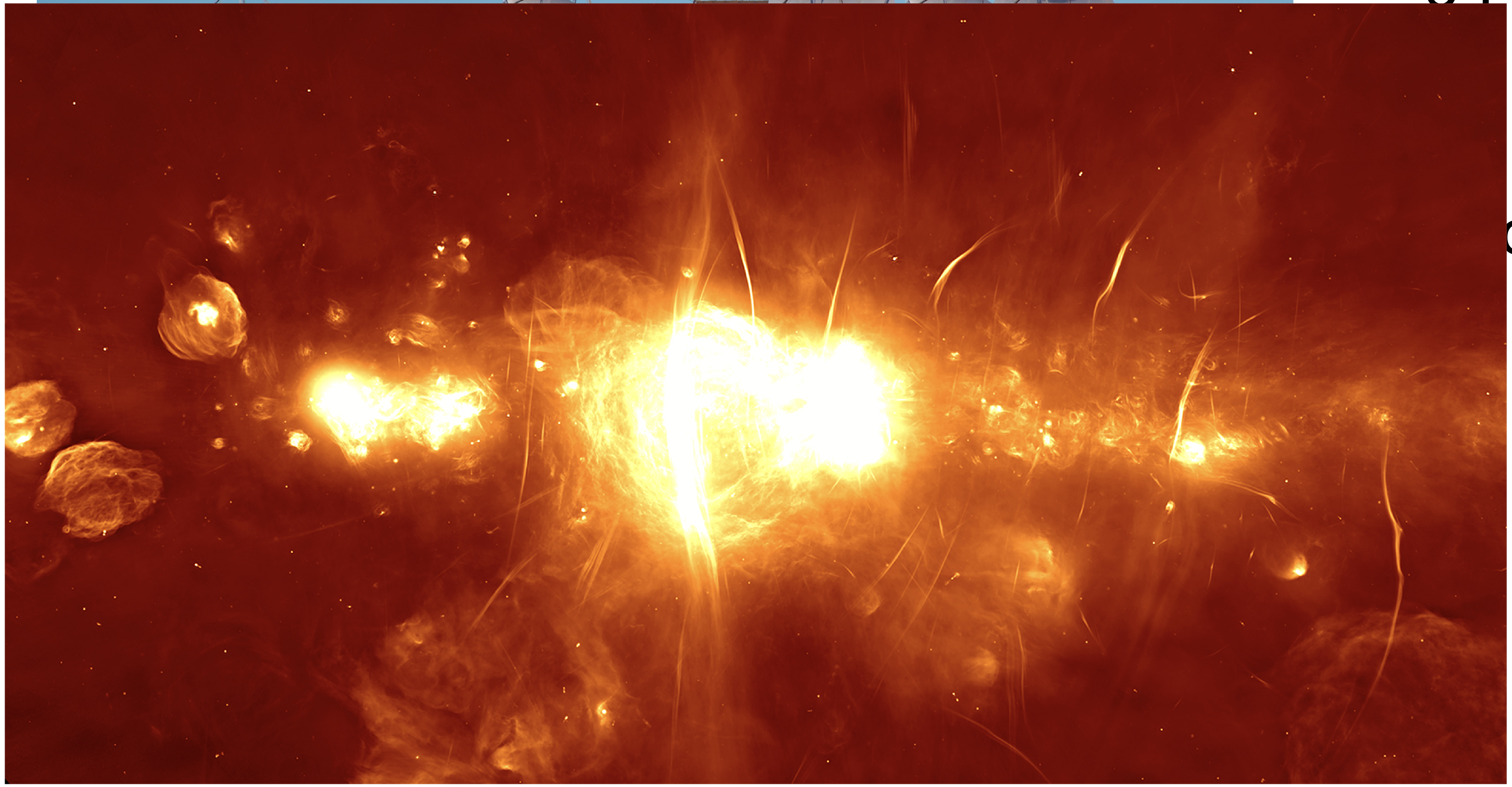
MeerKAT – SKA South Africa

64 Antennas x 13.5mt diameter

Max Baseline 8 km

Receivers: 0.6/14.5 GHz

Present and future of radio astronomy



MeerKAT - South Africa

64 Antennas x 13.5mt diameter

x Baseline 8 km

ceivers: 0.6/14.5 GHz

MW 1.4 GHz continuum

How does SKA1 compare with the world's biggest radio telescopes?

SKA1 LOW
Australia
419,000m²
~130,000 antennas

SKA1 MID
South Africa
33,000m²
~200 dishes

MWA
Murchison Widefield Array, Australia
2,500m²
2048 antennas

LOFAR
Low Frequency Array for Radio astronomy, Netherlands
52,000m²
34,000 antennas

GMRT
Giant Metrewave Radio Telescope, India
48,000m²
30 dishes

ASKAP
Australian SKA Pathfinder, Australia
4,000m²
36 dishes

MeerKAT
South Africa
9,000m²
64 dishes

JVLA
Karl G. Jansky Very Large Array, USA
13,200m²
27 dishes

NRT
Nancay Radio Telescope, France
7,000m²
300m x 35m antenna

Lovell
UK
4,500m²
76m dish

Effelsberg
Germany
7,800m²
100m dish

Parkes
Australia
3,200m²
64m dish

GBT
Green Bank Telescope, USA
7,800m²
100m dish

FAST
Five Hundred Meter Aperture Spherical Telescope, China
71,000m²
500m dish

Arecibo
Puerto Rico
42,000m²
305m dish

ALMA
Atacama Large Millimeter/submillimeter Array, Chile
6,500m²
66 dishes

The Square Kilometre Array (SKA) will be the world's largest radio telescope, revolutionising our understanding of the Universe. The SKA will be built in two phases - SKA1 and SKA2 - starting in 2018, with SKA1 representing a fraction of the full SKA. SKA1 will include two instruments - SKA1 MID and SKA1 LOW - observing the Universe at different frequencies.

A telescope's capacity to receive faint signals - called sensitivity - depends on its collecting area, the bigger the better. But just like you can't compare radio telescopes and optical telescopes, comparison only works between telescopes working in similar frequencies, hence the different categories above.

The collecting area is just one aspect of a telescope's capability though. Arrays like the SKA have an advantage over single dish telescopes: by being spread over long distances, they simulate a virtual dish the size of that distance and so can see smaller details in the sky, this is called resolution.

www.skatelescope.org Square Kilometre Array @SKA_telescope YouTube The Square Kilometre Array