Galaxy Block Course

Mar 10-18, 2011

Hans-Walter Rix & Fabian Walter

logistics:

2 two-hour lectures each day:

either: 9:00 - 10:50, 11:10 - 13:00
or : 10:00 - 11:50, 13:10 - 15:00

in addition: 'project' description on Friday

the idea is that small sub-groups (3-4 people) each work on the project and submit a report up to one week after the lecture ends (coordinator: Arjen van der Wel).

What is a galaxy?

What is a galaxy?

compact condensation of baryons near the center of dark matter halos.

these halos are at least ~10× more massive ~10× more extended than the luminous baryons at the center

most stars / cold gas lives in galaxies

Galaxies cover a large range in (stellar) mass:

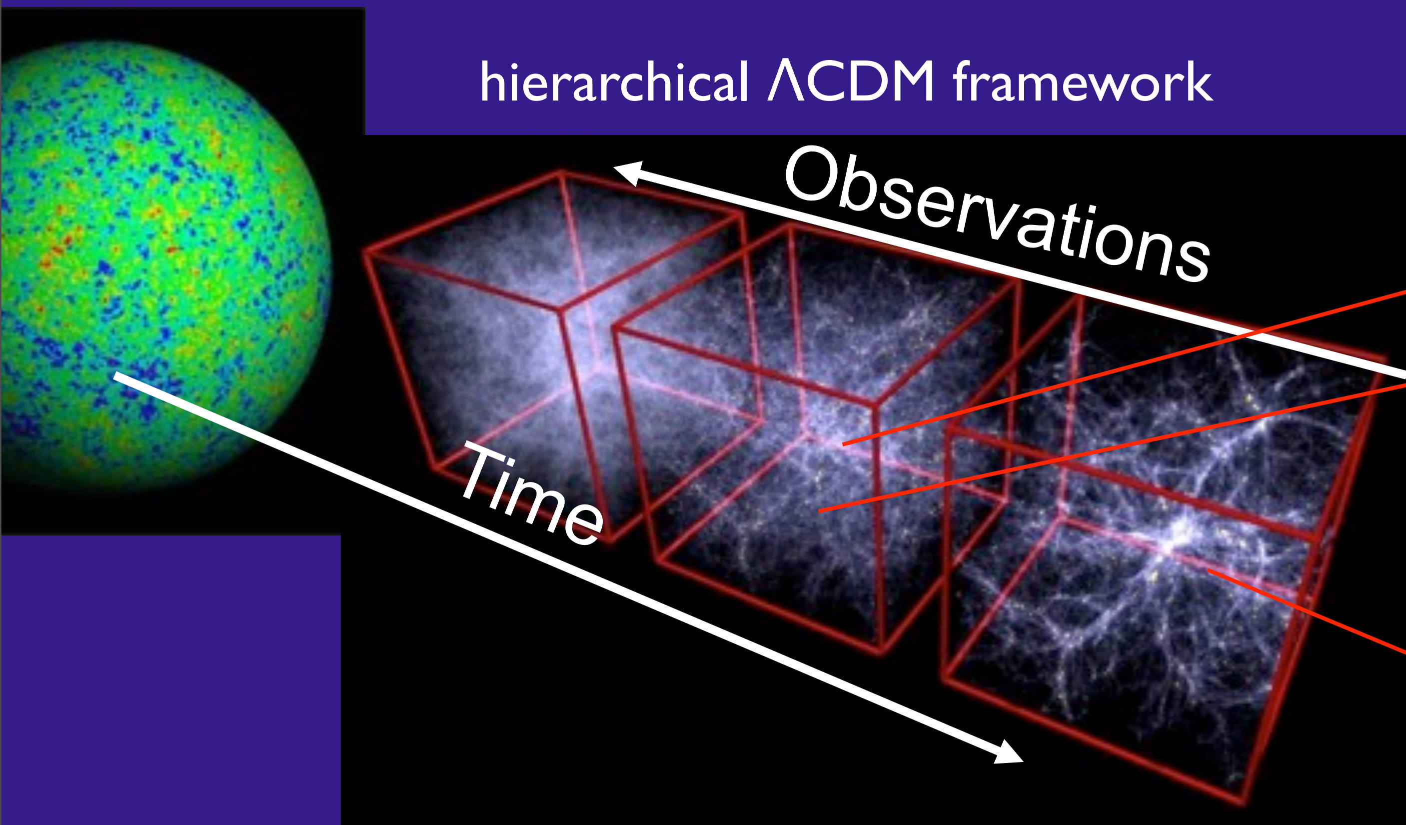
cD galaxies	$L_*=10^{13}$
Milky Way	$L_*=10^{10}$
Dwarf galaxies	$L_*=10^{7}$
Ultra-faint gal's	$L_*=10^{3}$

-- they come in many shapes

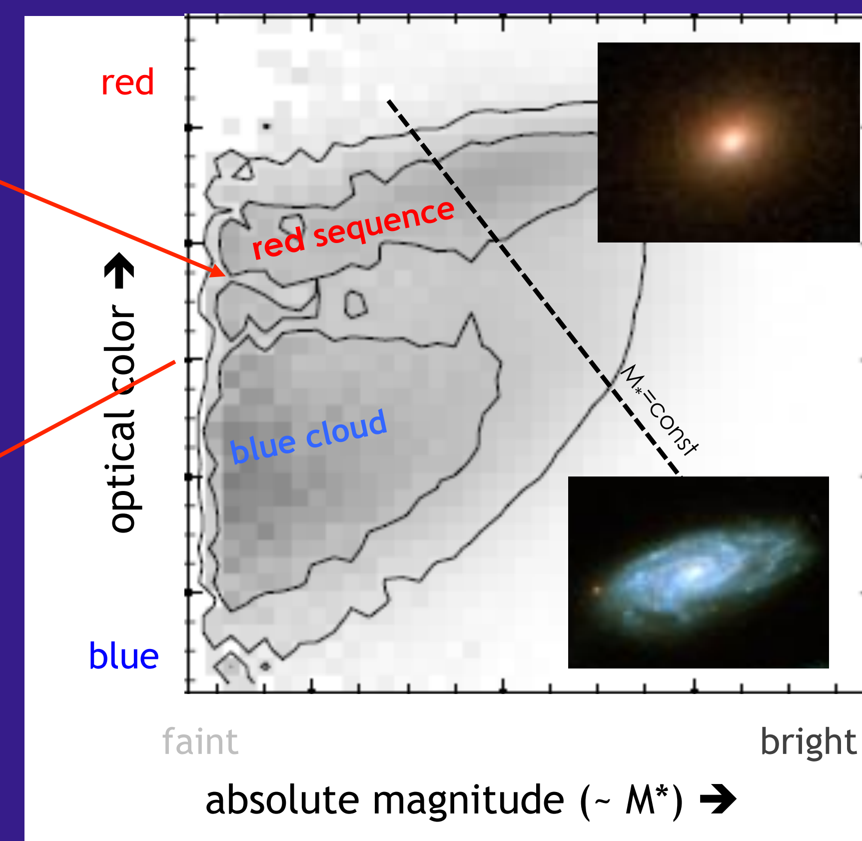
Galaxies in a Cosmological Context

emergence of galaxies

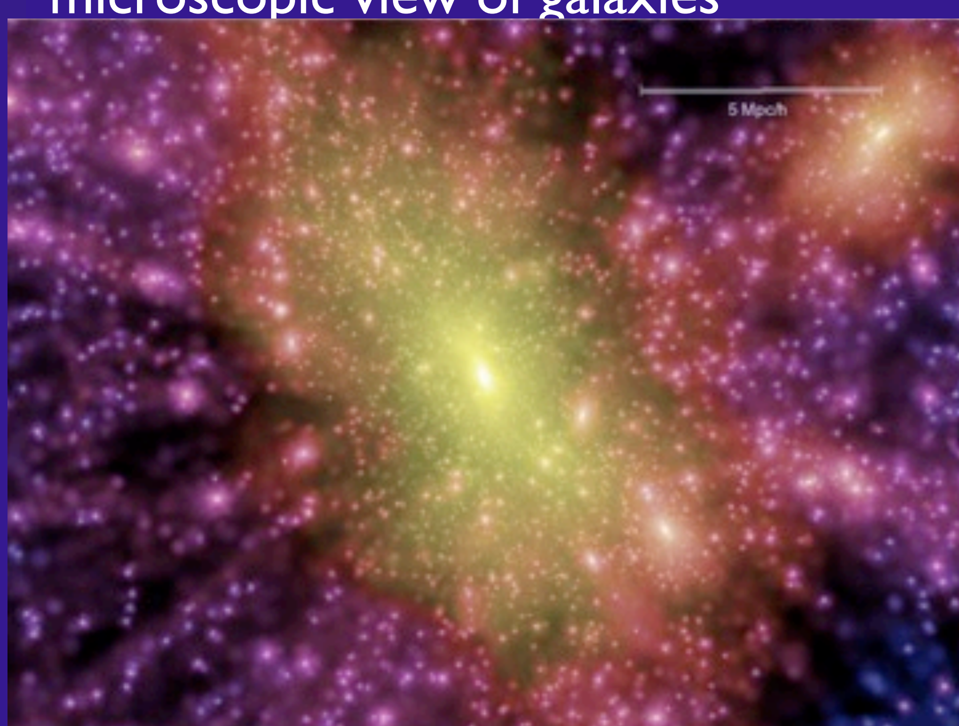
hierarchical ΛCDM framework



ordered population properties



microscopic view of galaxies

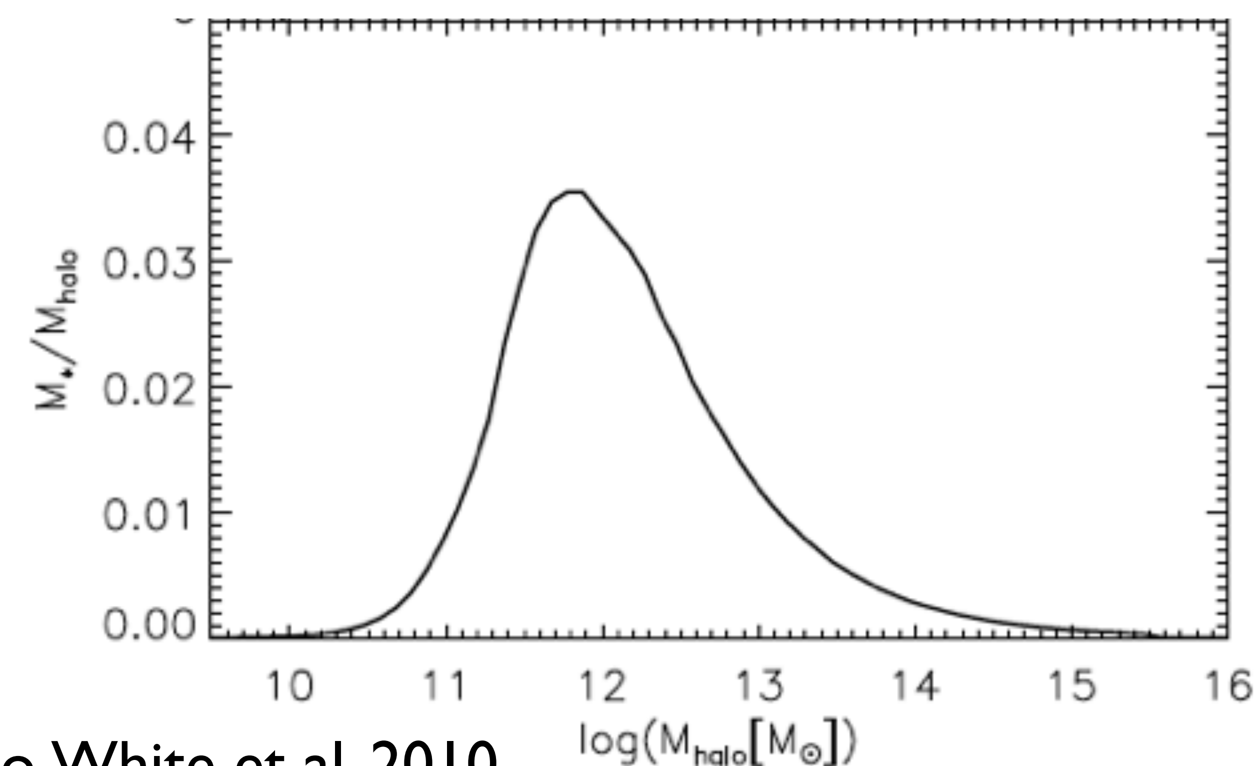


How do galaxies 'work'?

Questions that we want to address in this lecture are:

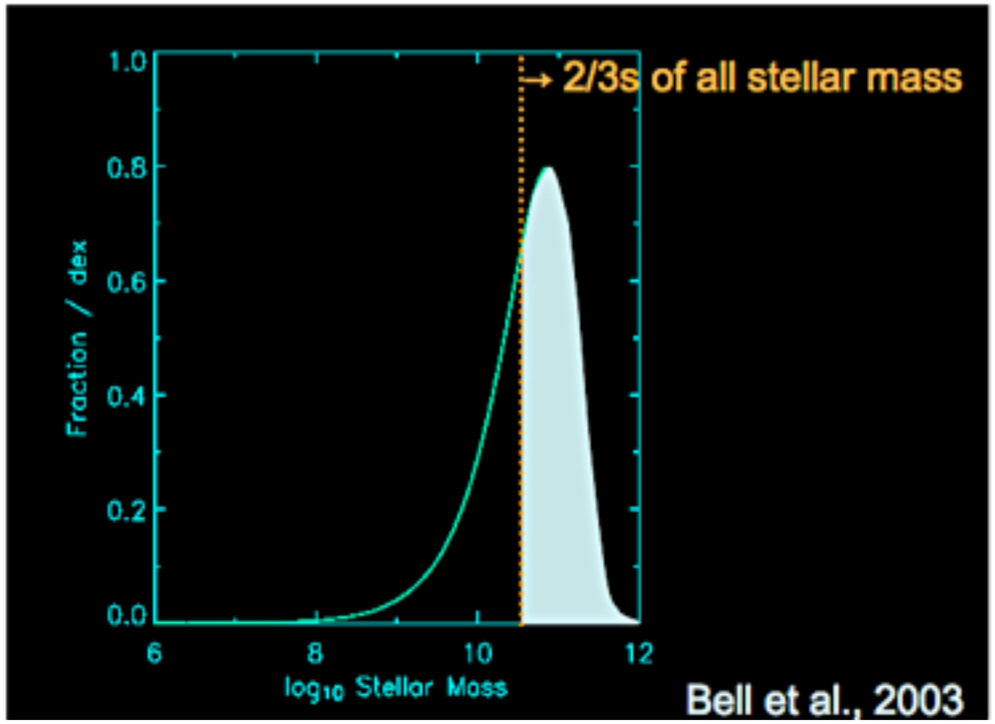
- **why is the galaxy population so regular**

Regular galaxy properties



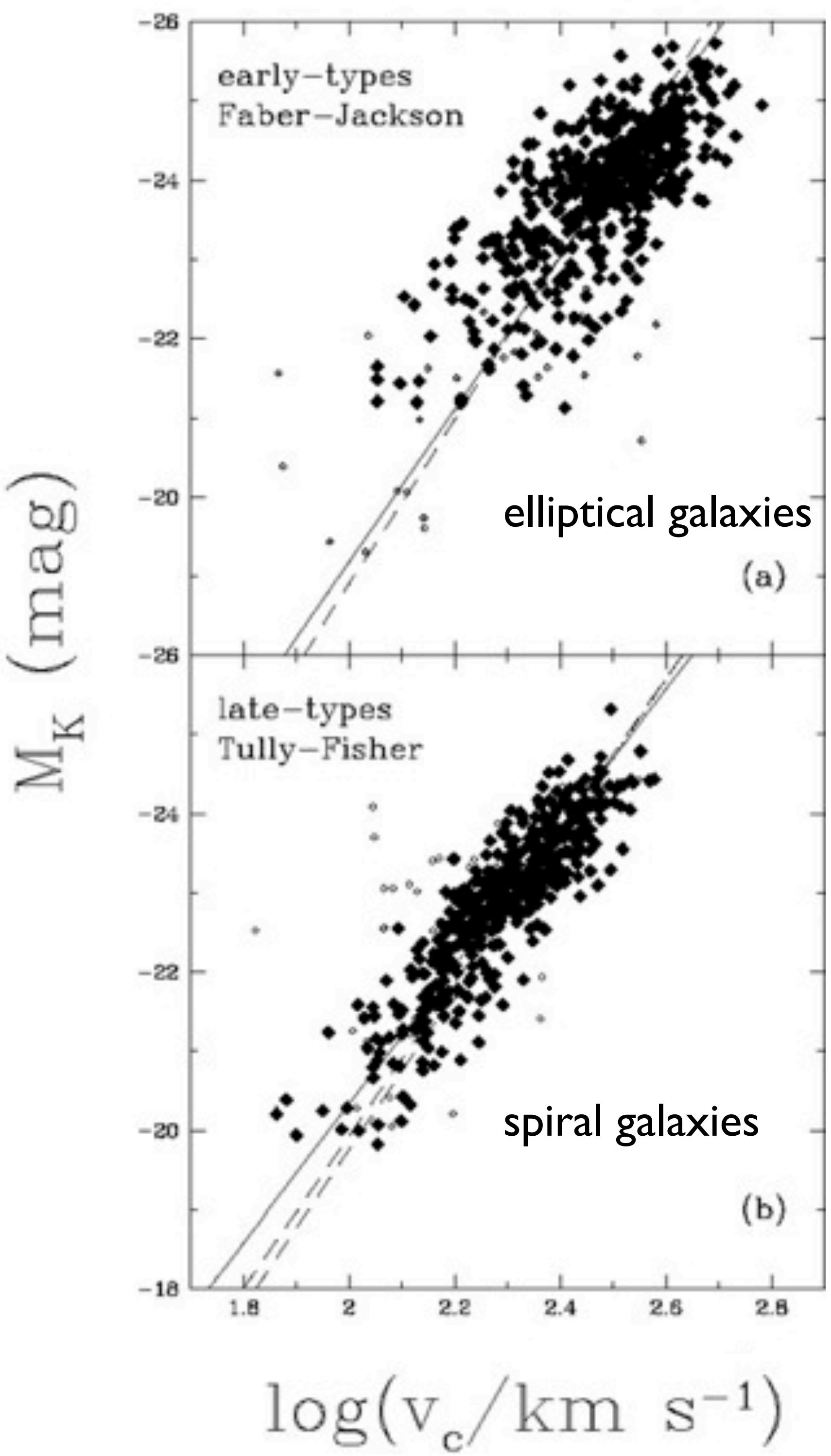
Guo, White et al. 2010

galaxy (star) formation most efficient in MW type halos (M_{halo}~10^{12} M_{sun})



3/4 of all stars live in galaxies w/ masses of $5x10^{10}$ (within factor 5)

Regular galaxy properties

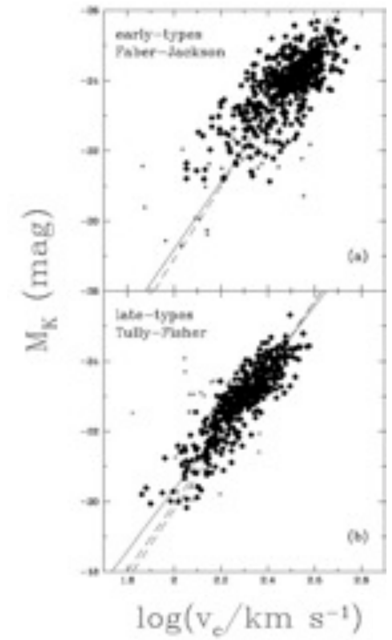


... a lot of parameter space allowed by the laws of physics is not occupied

From the stellar mass of a galaxy one can estimate:

-- potential depth (rotation velocity, velocity dispersion) to 30%
-- the size to a factor of 2
-- the distribution of light to 40%
-- the black hole mass to a factor of 3

Questions that we want to address in this lecture are:



- why is the current population so regular

- **when were the galaxies' masses assembled**

Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys

... multi-wavelength deep fields

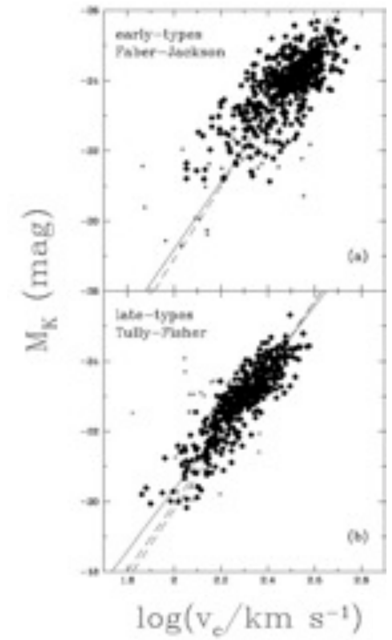
(e.g. UDF: 1000s of galaxies in few square arcmin)

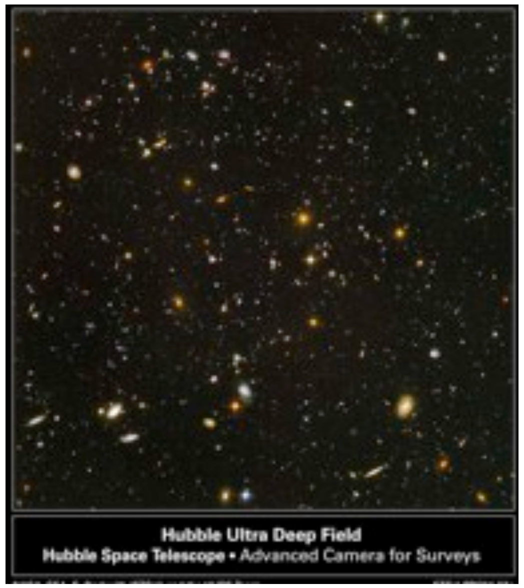
Questions that we want to address in this lecture are:

- why is the current population so regular

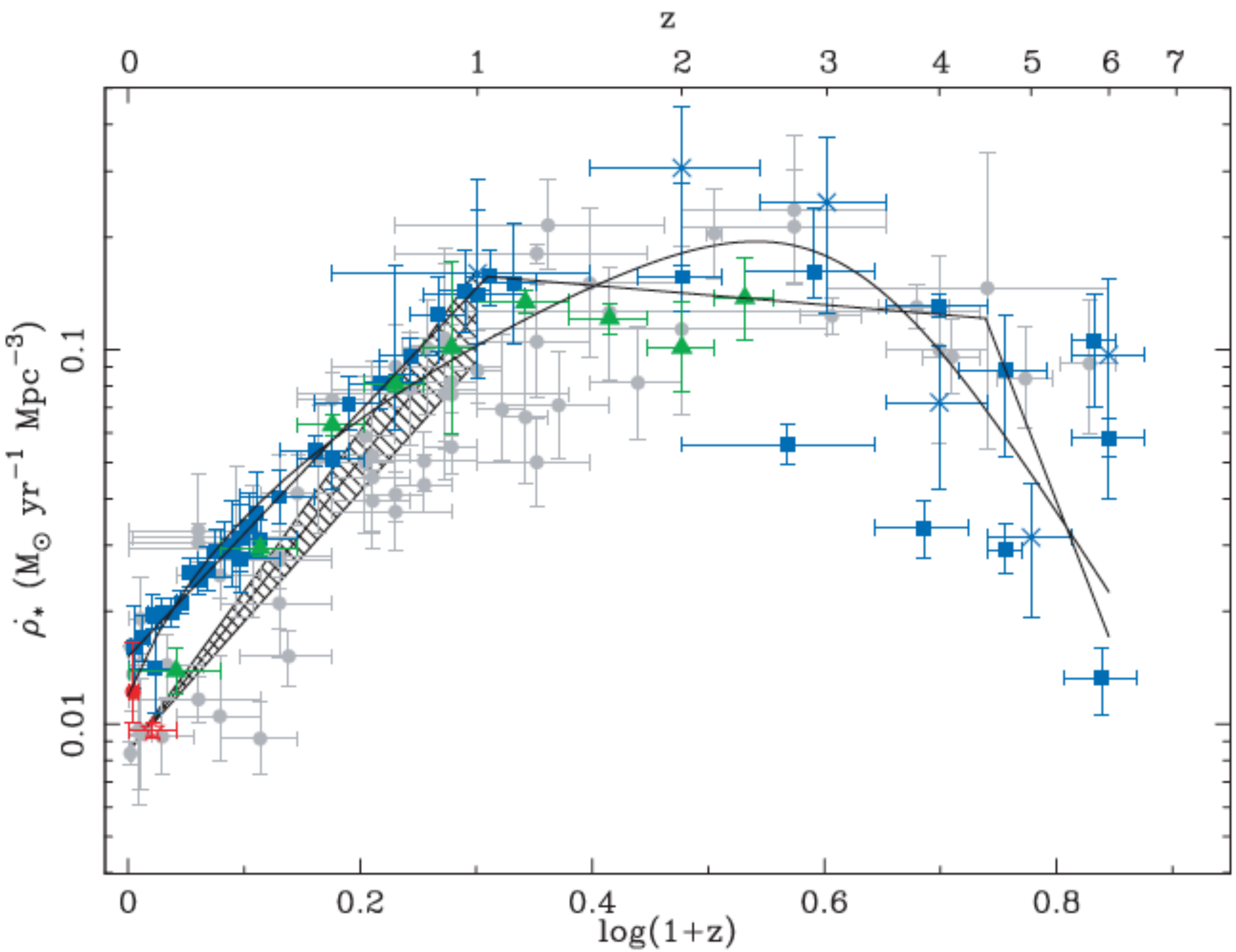
- when were the galaxies' masses assembled

- **when/how did the stars form**





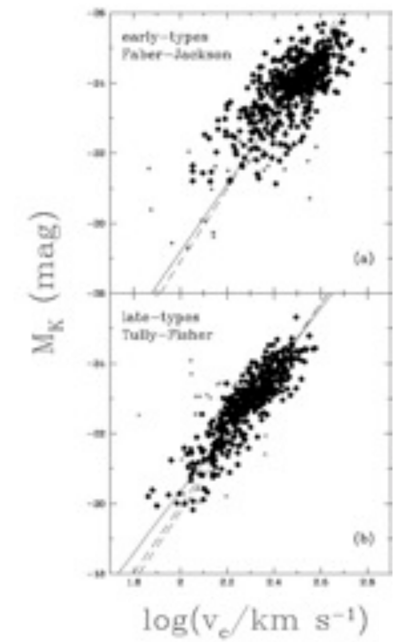
Evolution of cosmic star formation rate density



...by characterizing stellar population and dust through multi-wavelength observations

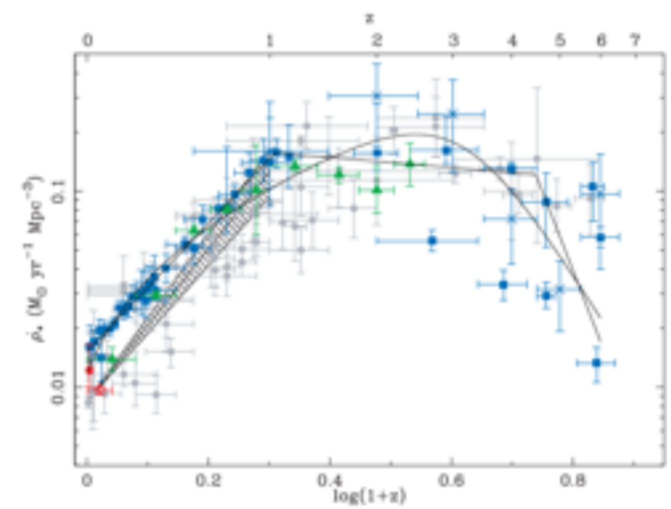
Hopkins & Beacom 2006

Questions that we want to address in this lecture are:



- why is the current population so regular

- when were the galaxies' masses assembled



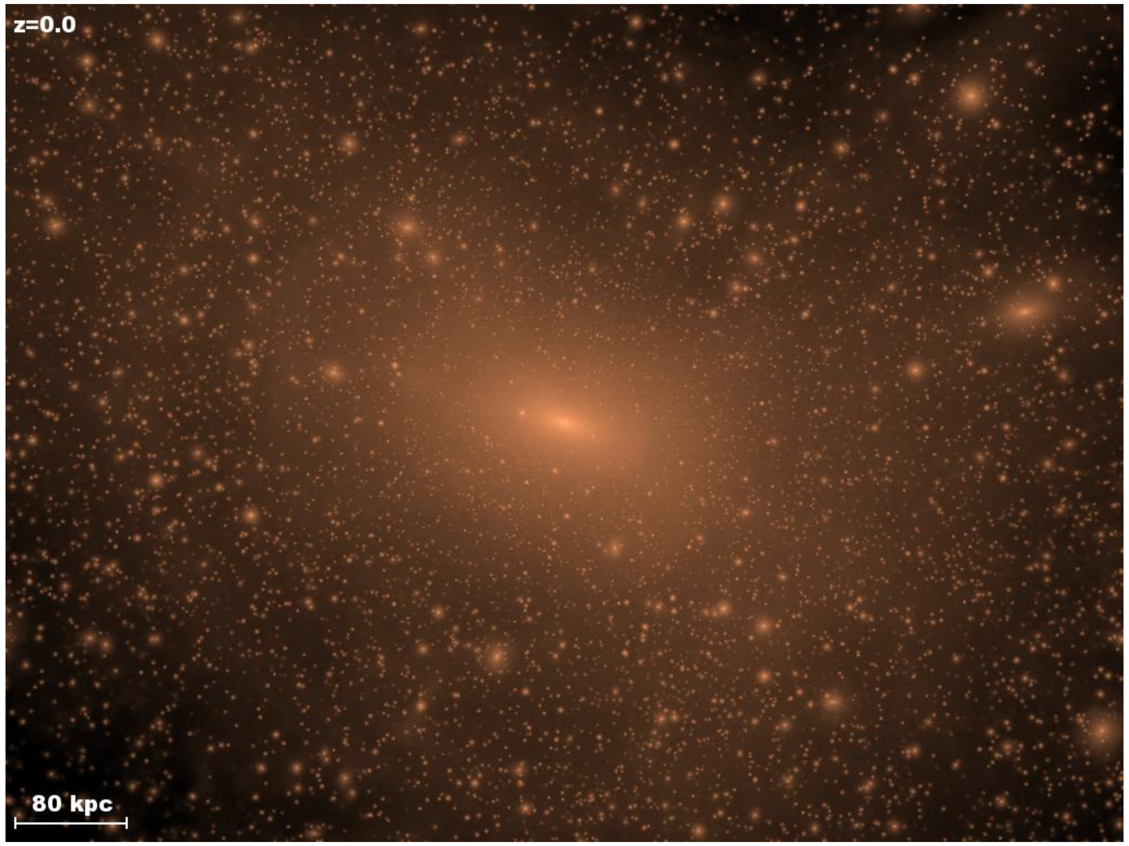
- when/how did the stars form

- why do galaxies emit radiation over ~10 decades in frequency

- what do they do to the rest of the universe

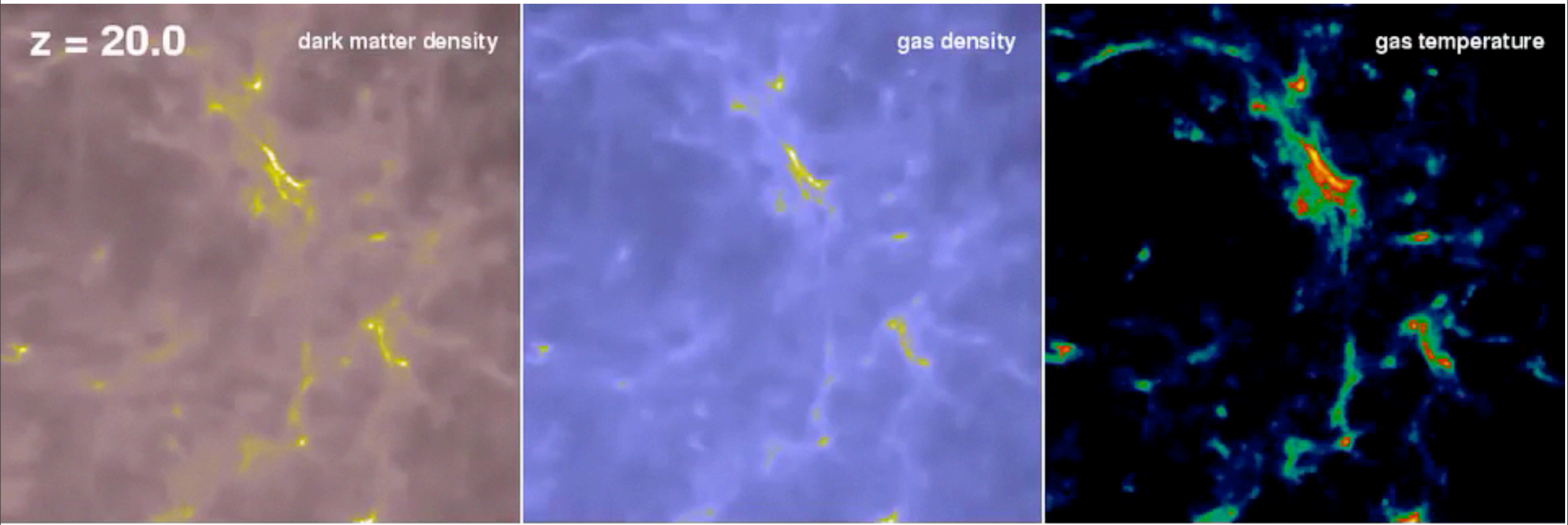
Galaxy Formation and Evolution in a Cosmological Framework

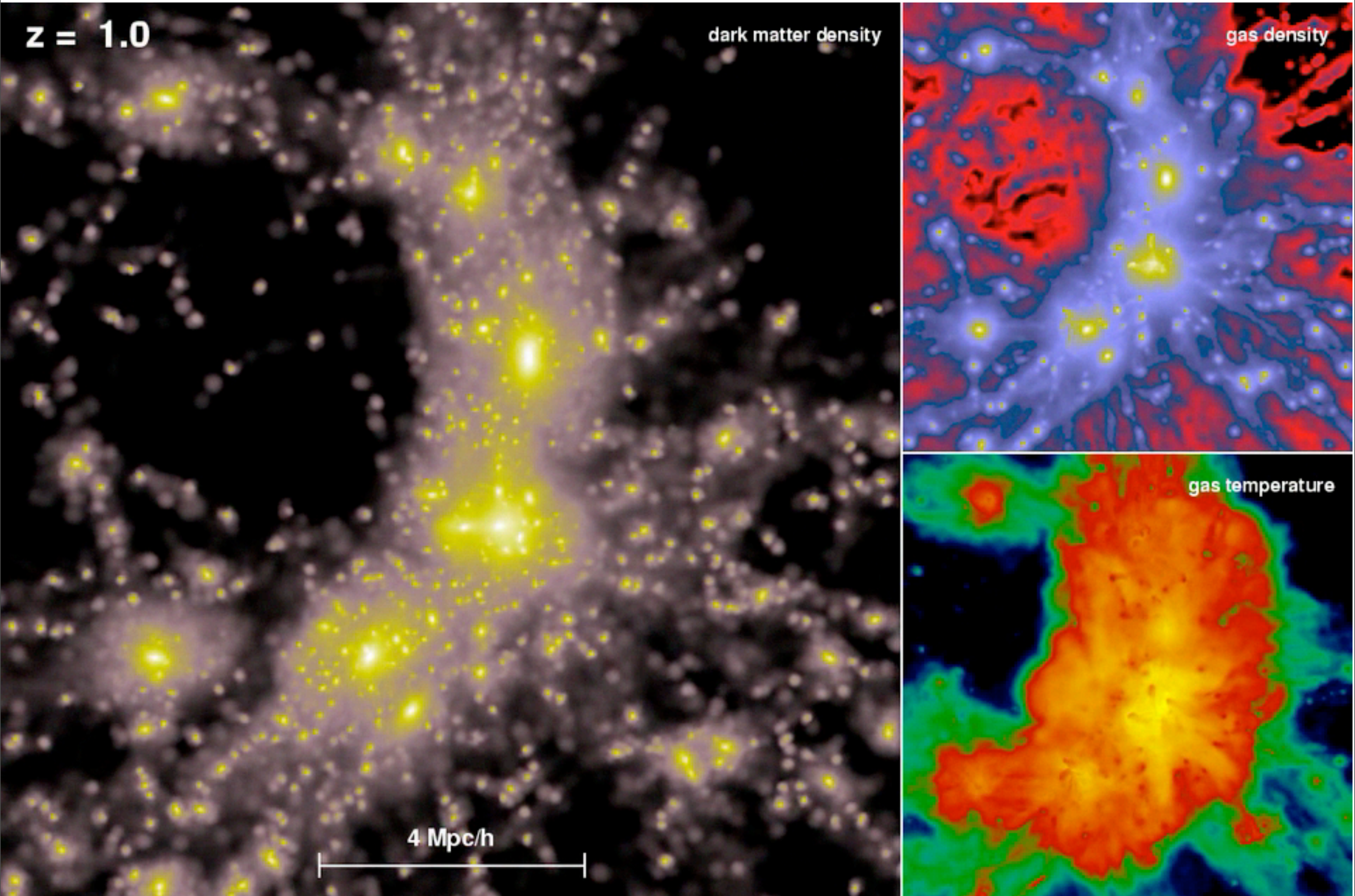
CDM-driven framework for structure formation

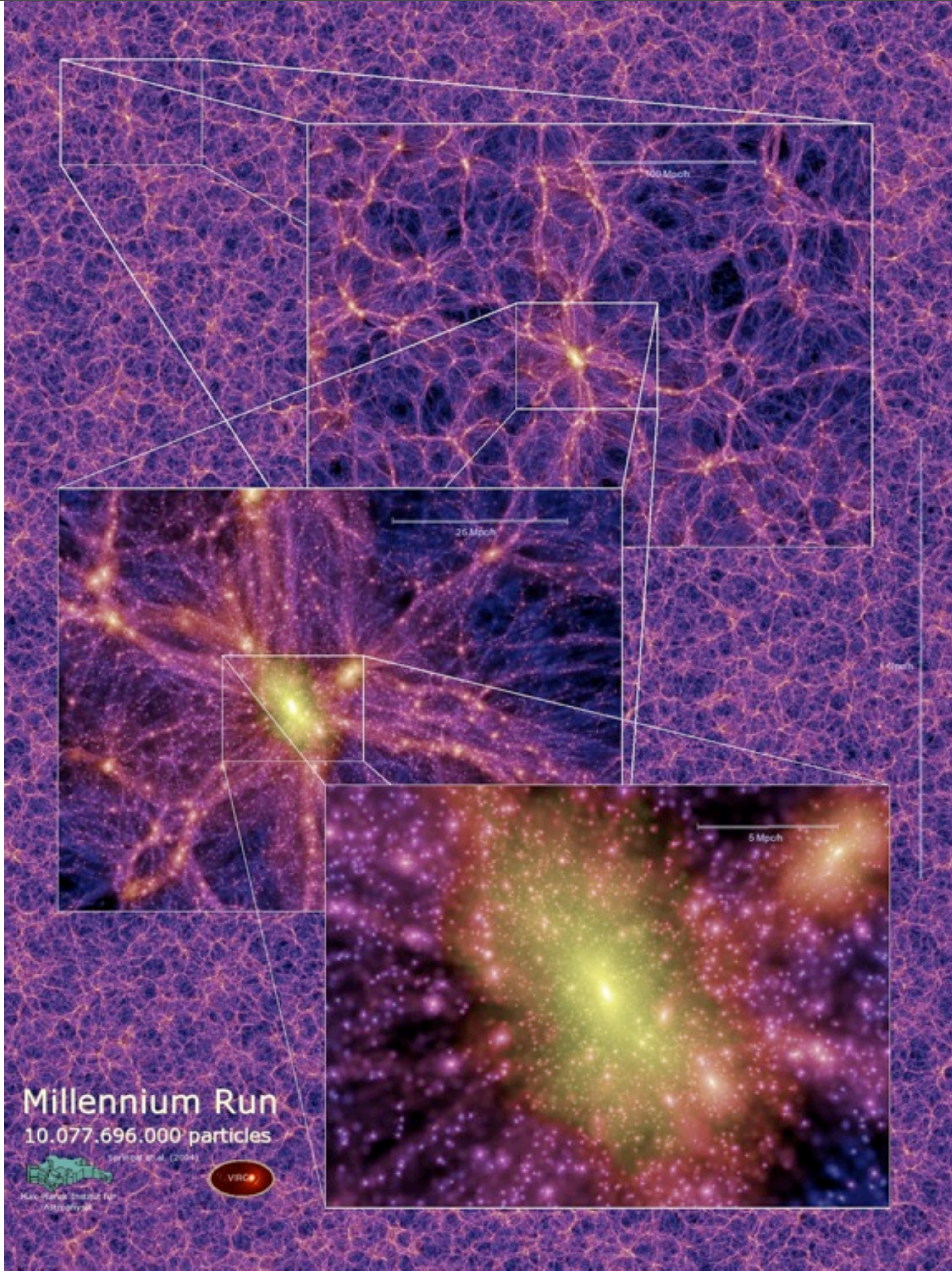


Note: Galaxy Evolution is unobservable
only redshift change of galaxy population properties is observable

Need theoretical framework to interpret observations.


z = 20.0
dark matter density
gas density
gas temperature


z = 1.0
dark matter density
4 Mpc/h
gas density
gas temperature



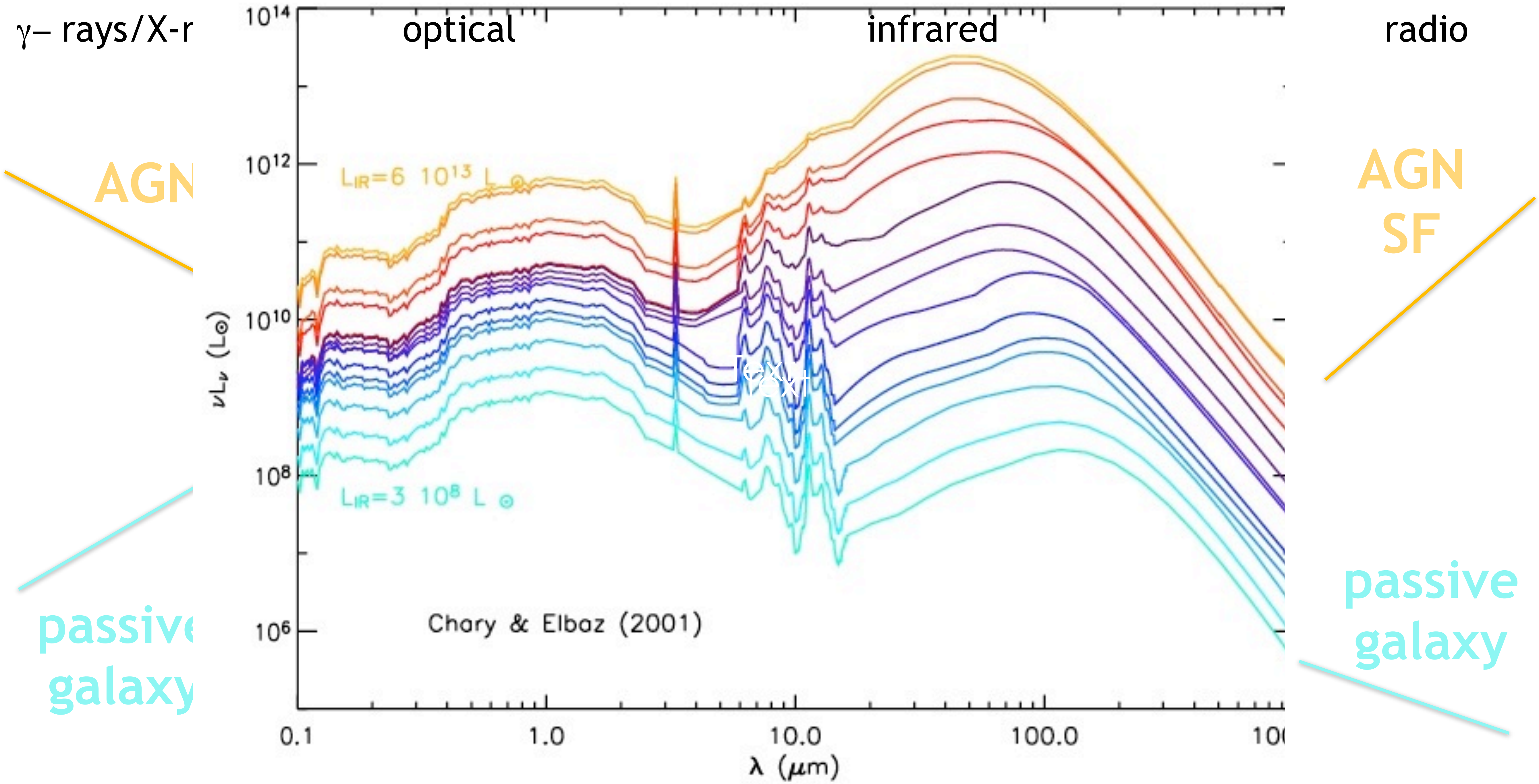
Need theoretical framework to interpret observations.

want: $N(z, M_{star}, t_{age}, M_{gas}, M_{dyn}, size, ...)$

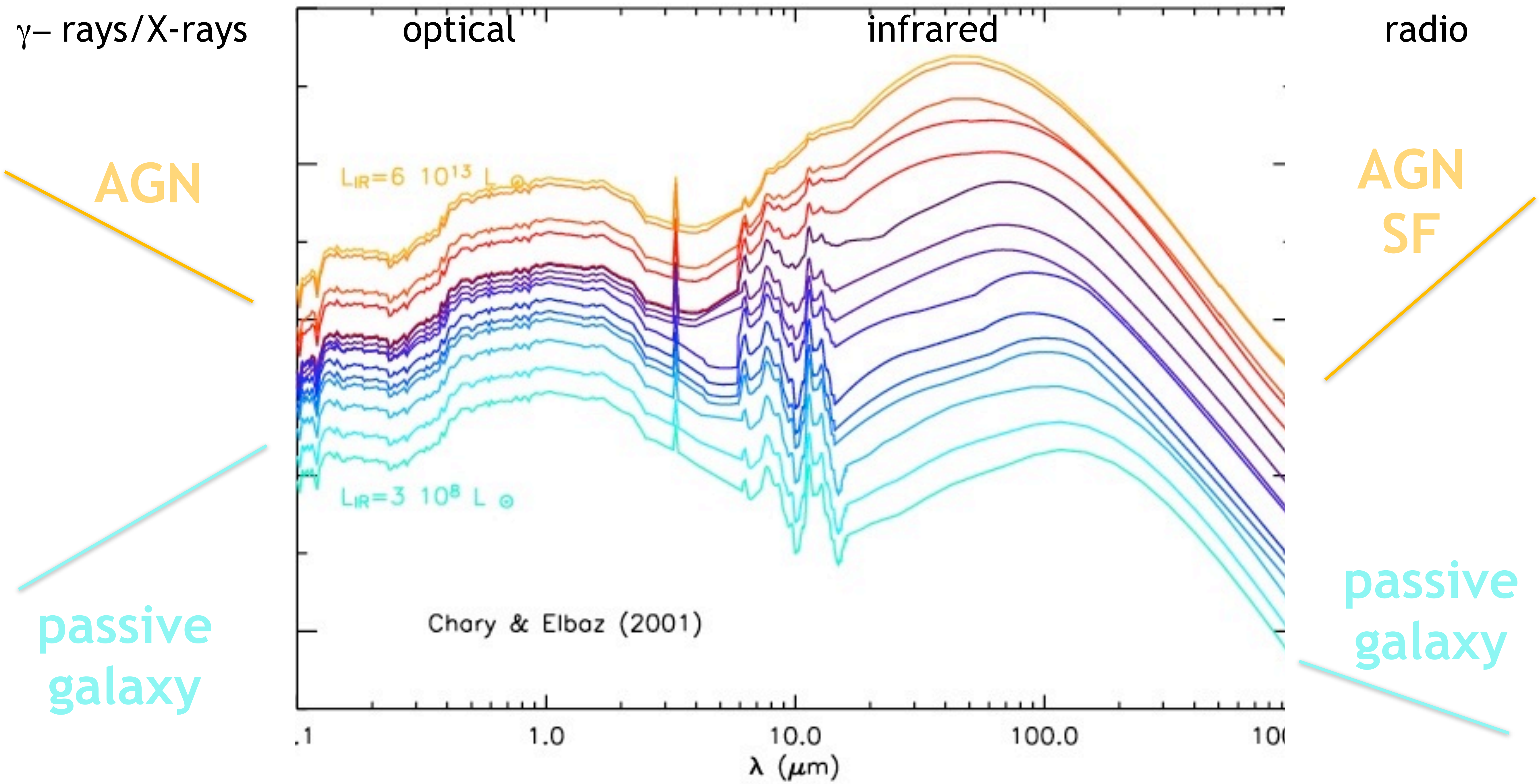
Need multi-wavelength approach

In the following we will discuss some diagnostic tools

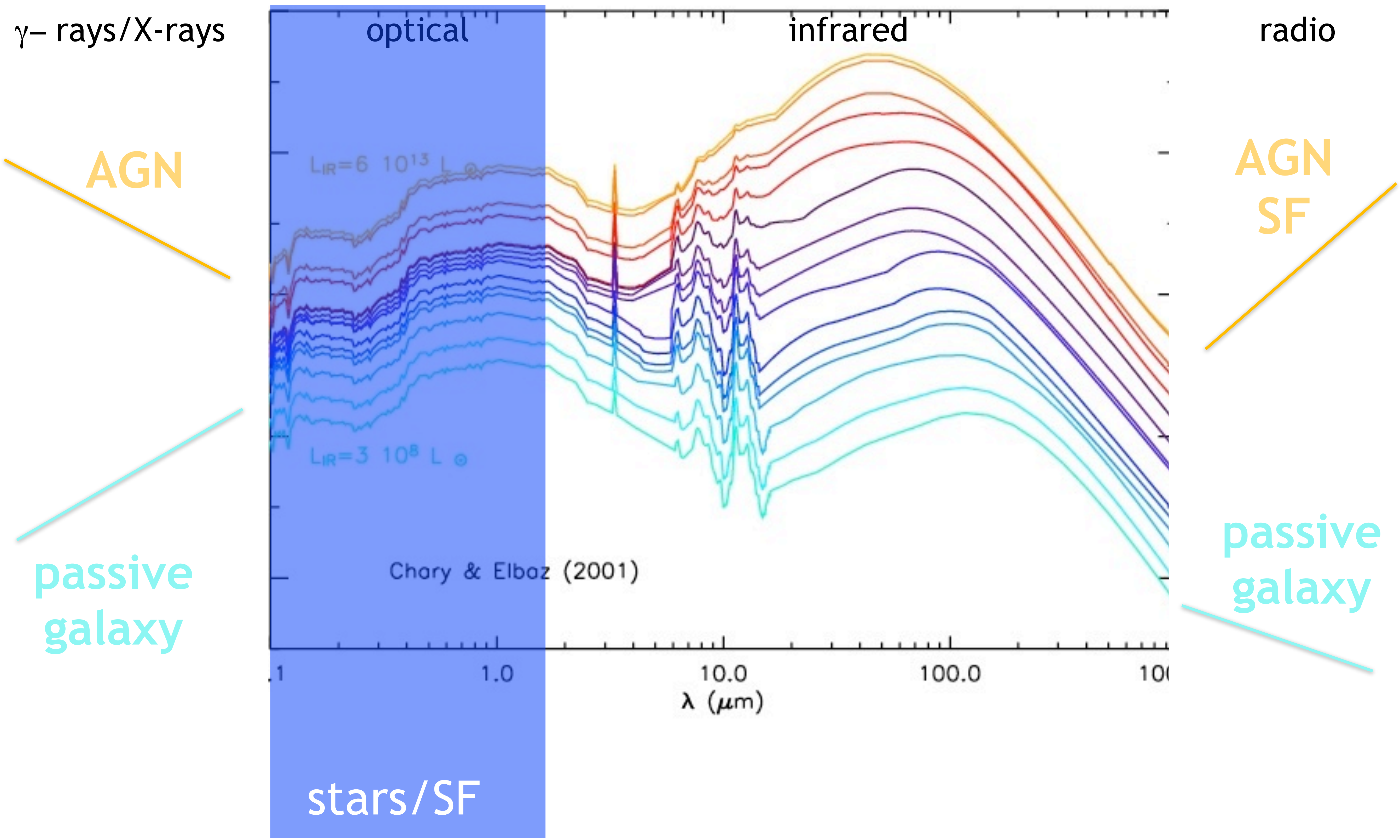
Different galaxy components (stars, gas, dust, AGN,...) emit in different wavelength regimes.



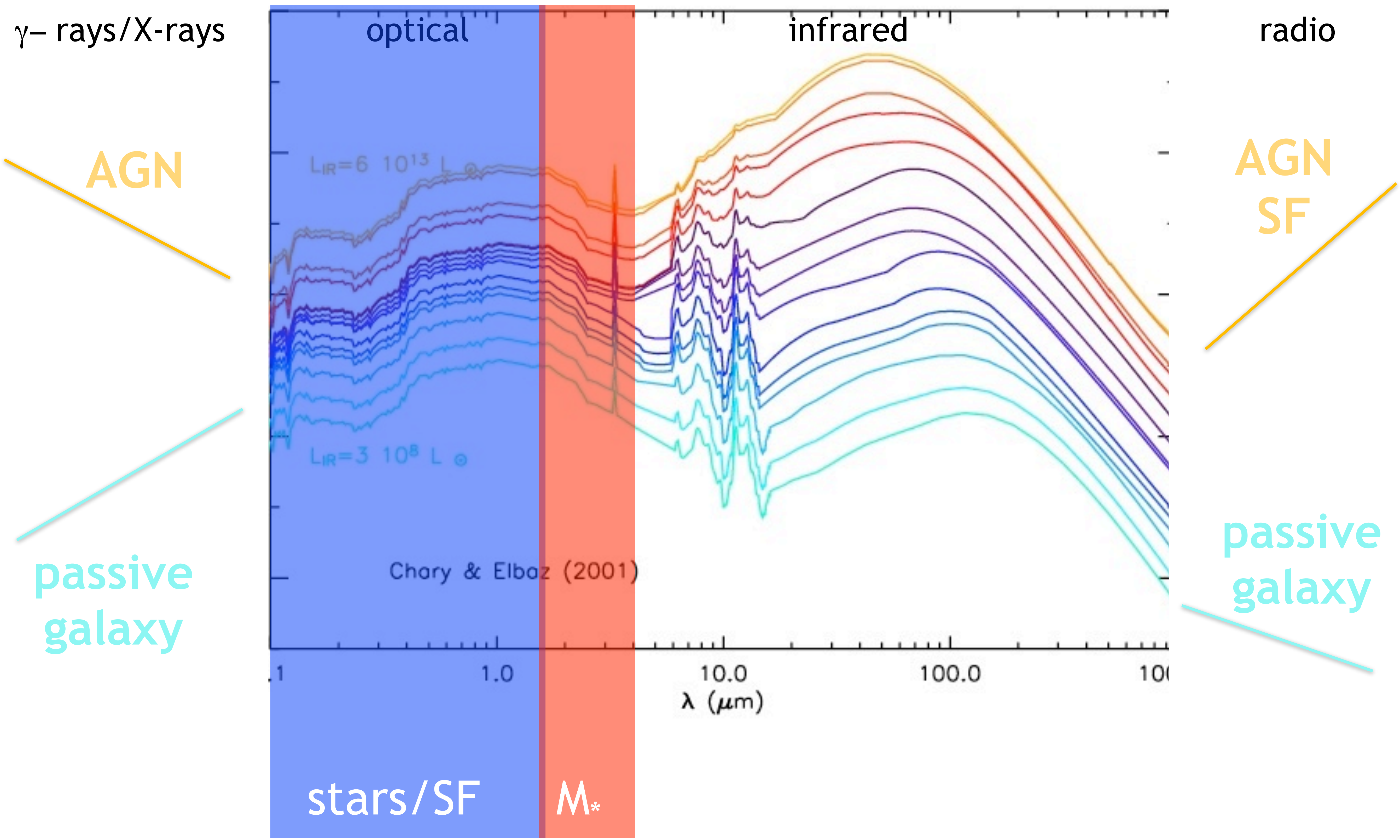
Different galaxy components (stars, gas, dust, AGN,...) emit in different wavelength regimes.



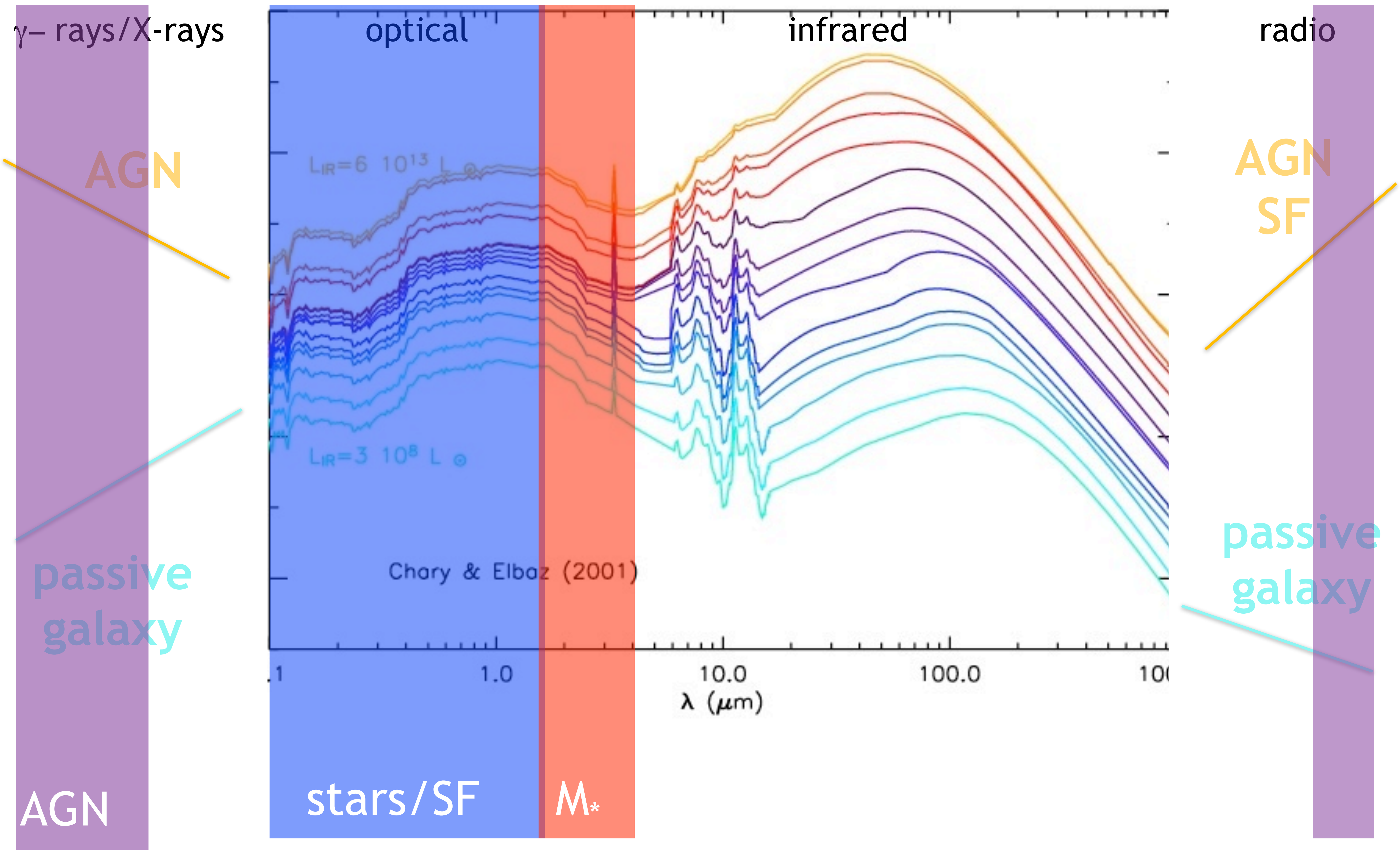
Different galaxy components (stars, gas, dust, AGN,...) emit in different wavelength regimes.



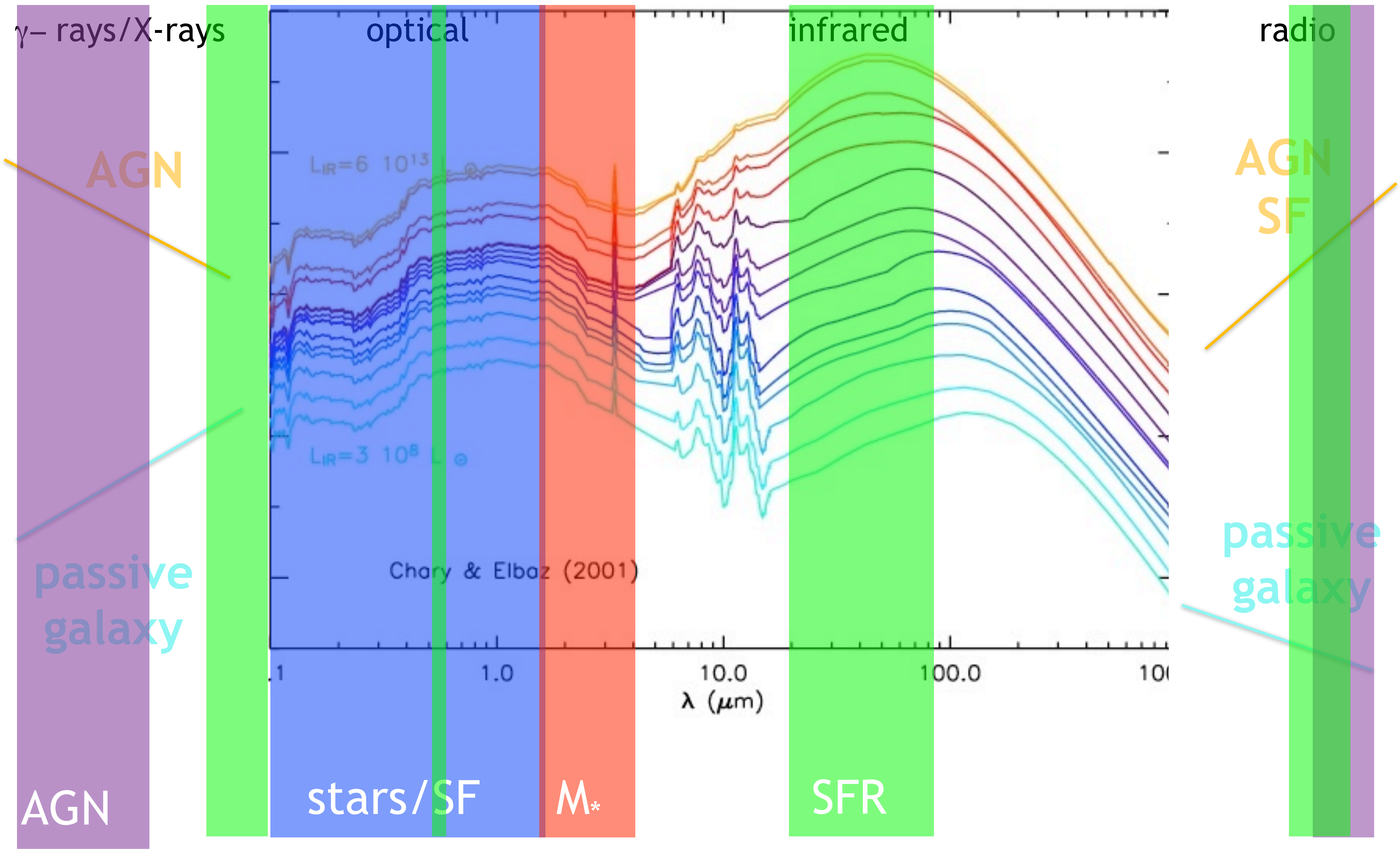
Different galaxy components (stars, gas, dust, AGN,...) emit in different wavelength regimes.



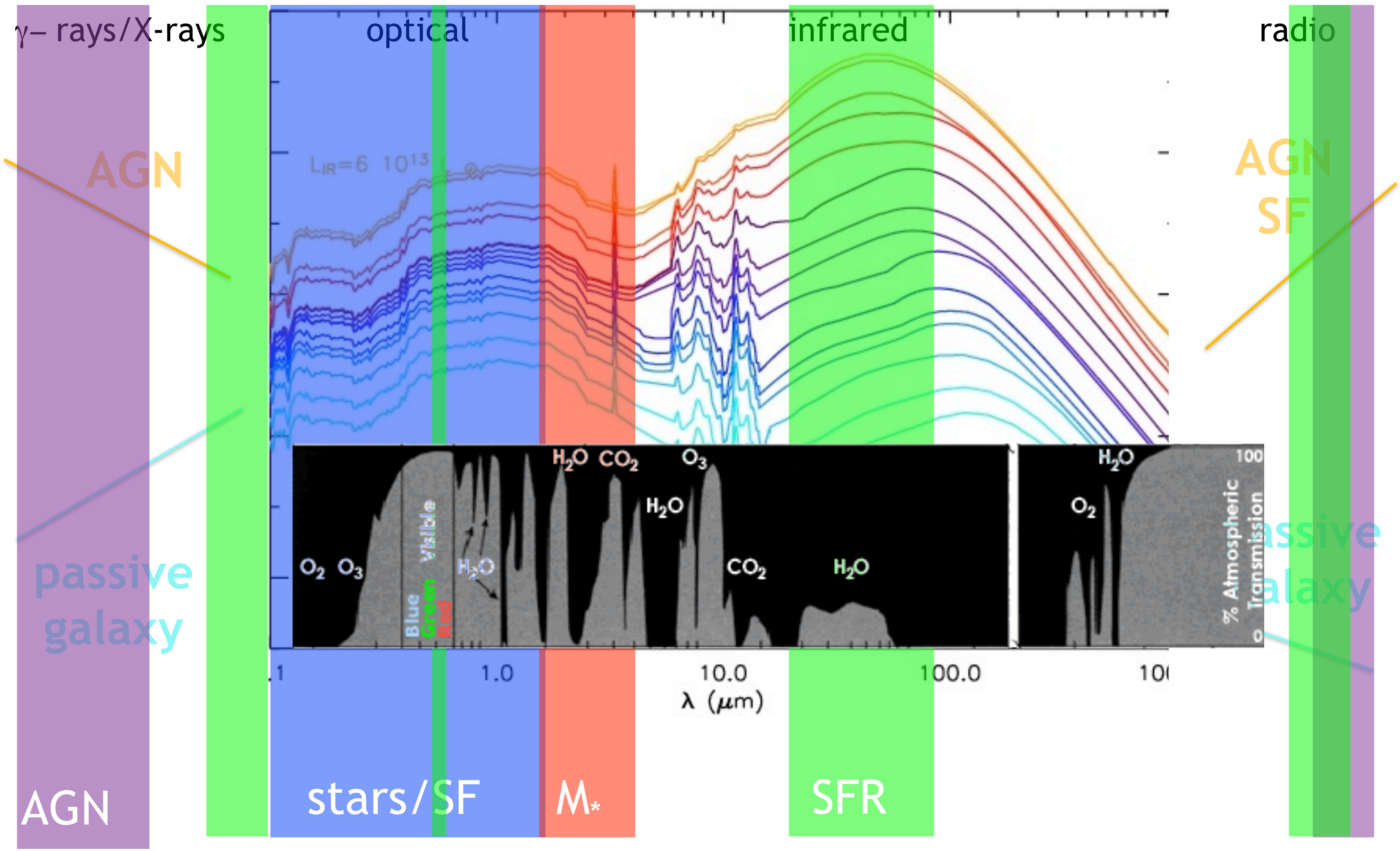
Different galaxy components (stars, gas, dust, AGN,...) emit in different wavelength regimes.



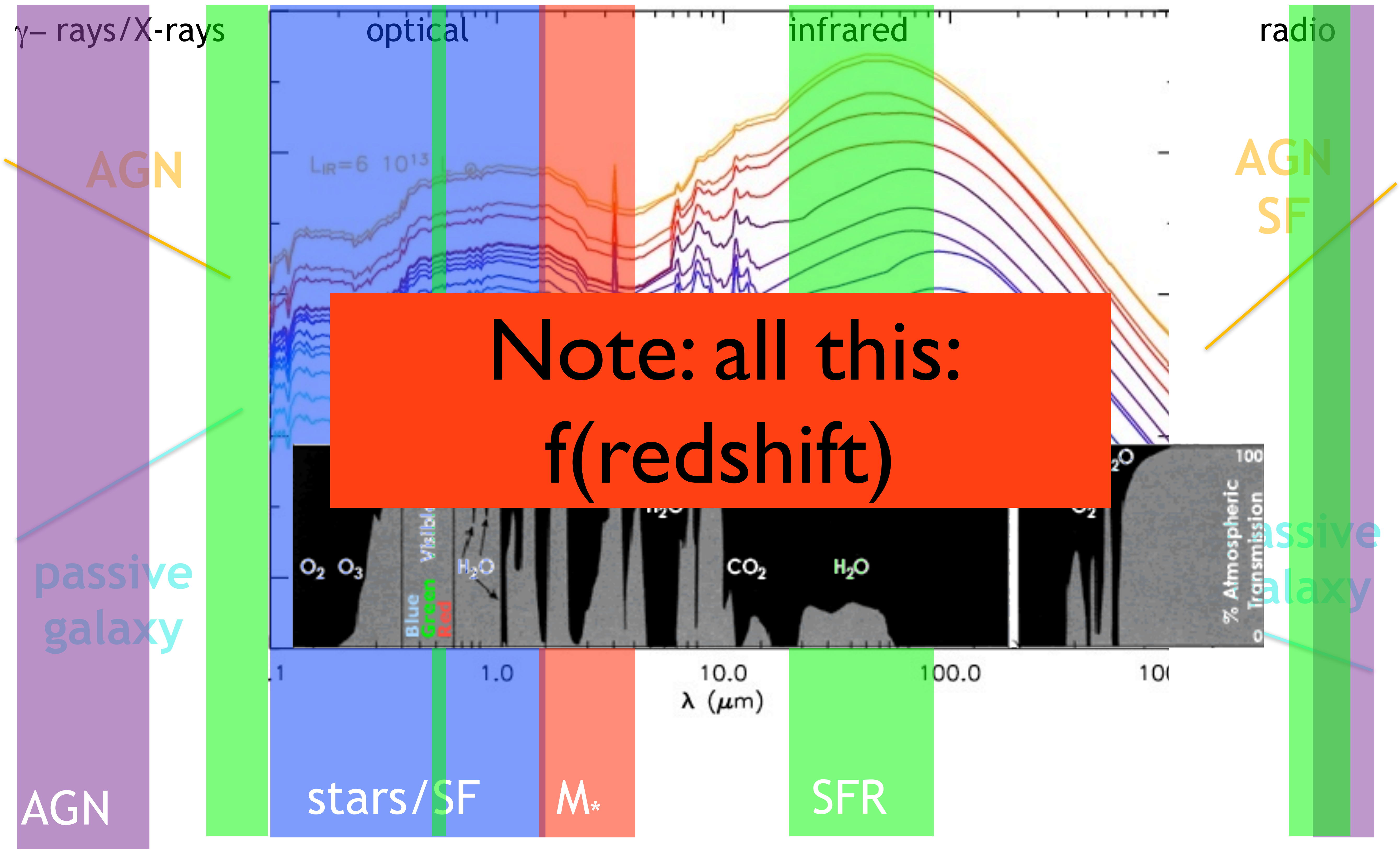
Different galaxy components (stars, gas, dust, AGN,...) emit in different wavelength regimes.



Different galaxy components (stars, gas, dust, AGN,...) emit in different wavelength regimes.

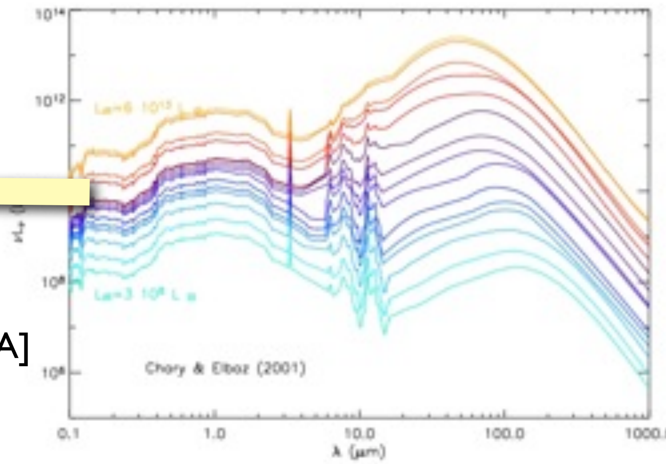


Different galaxy components (stars, gas, dust, AGN,...) emit in different wavelength regimes.



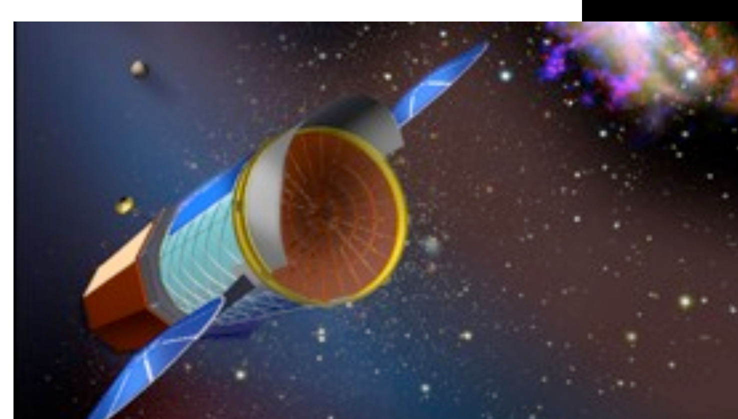
Quick run through diagnostic tools as $f(\lambda)$

X-ray observatories: only from space



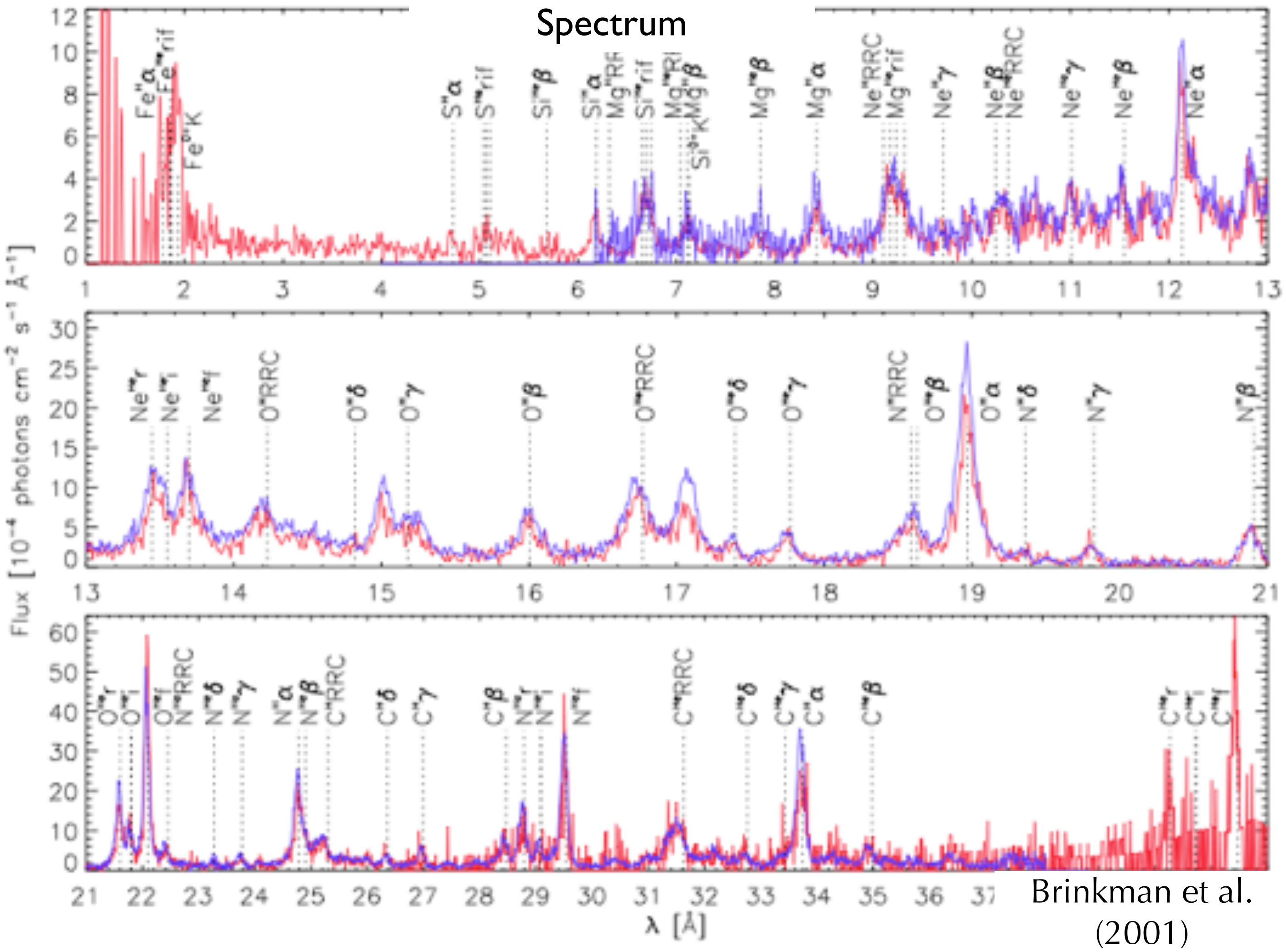
few A
[1 um=10.000 A]

future(?): IXO

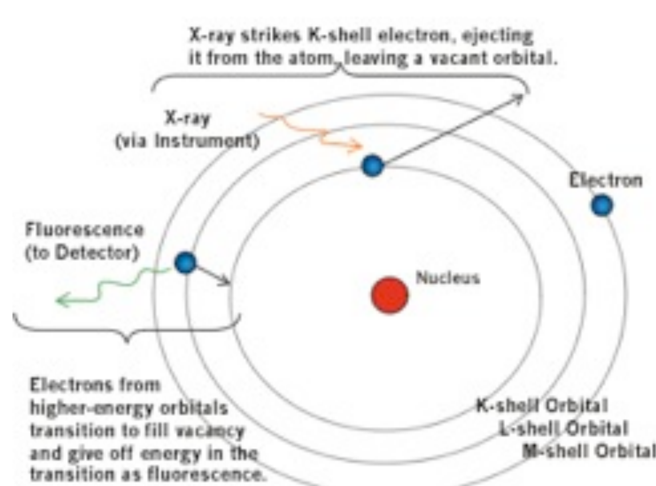


X-ray spectra rich in very energetic processes

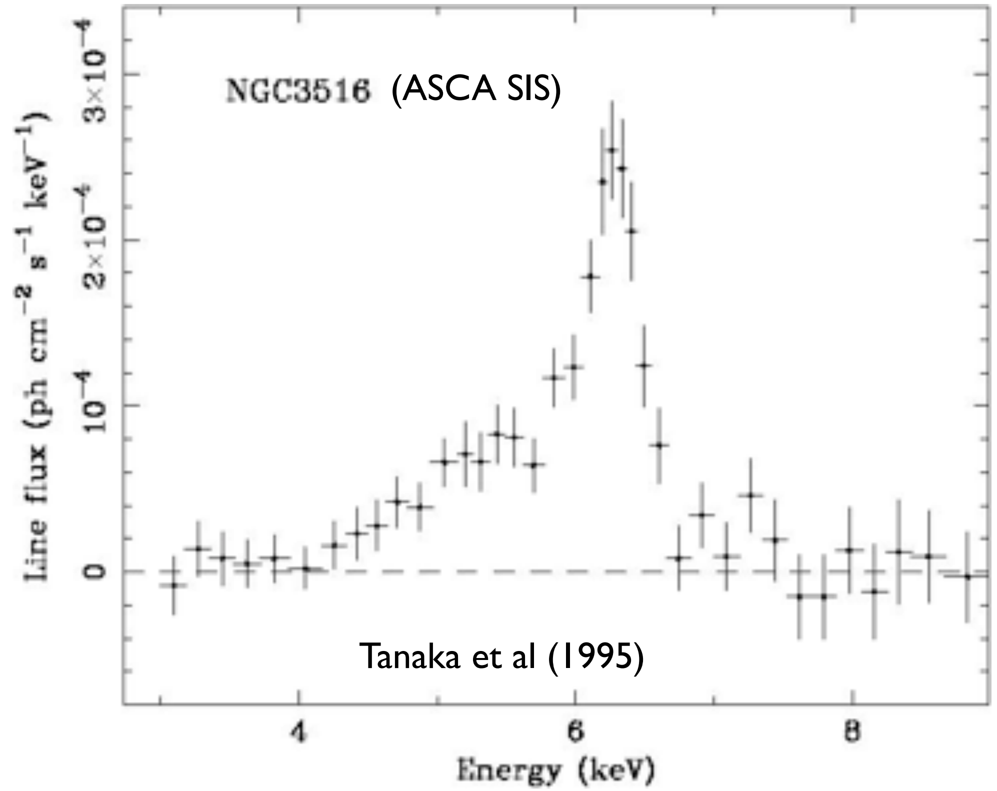
NGC 1068 X-ray Spectrum



Brinkman et al. (2001)

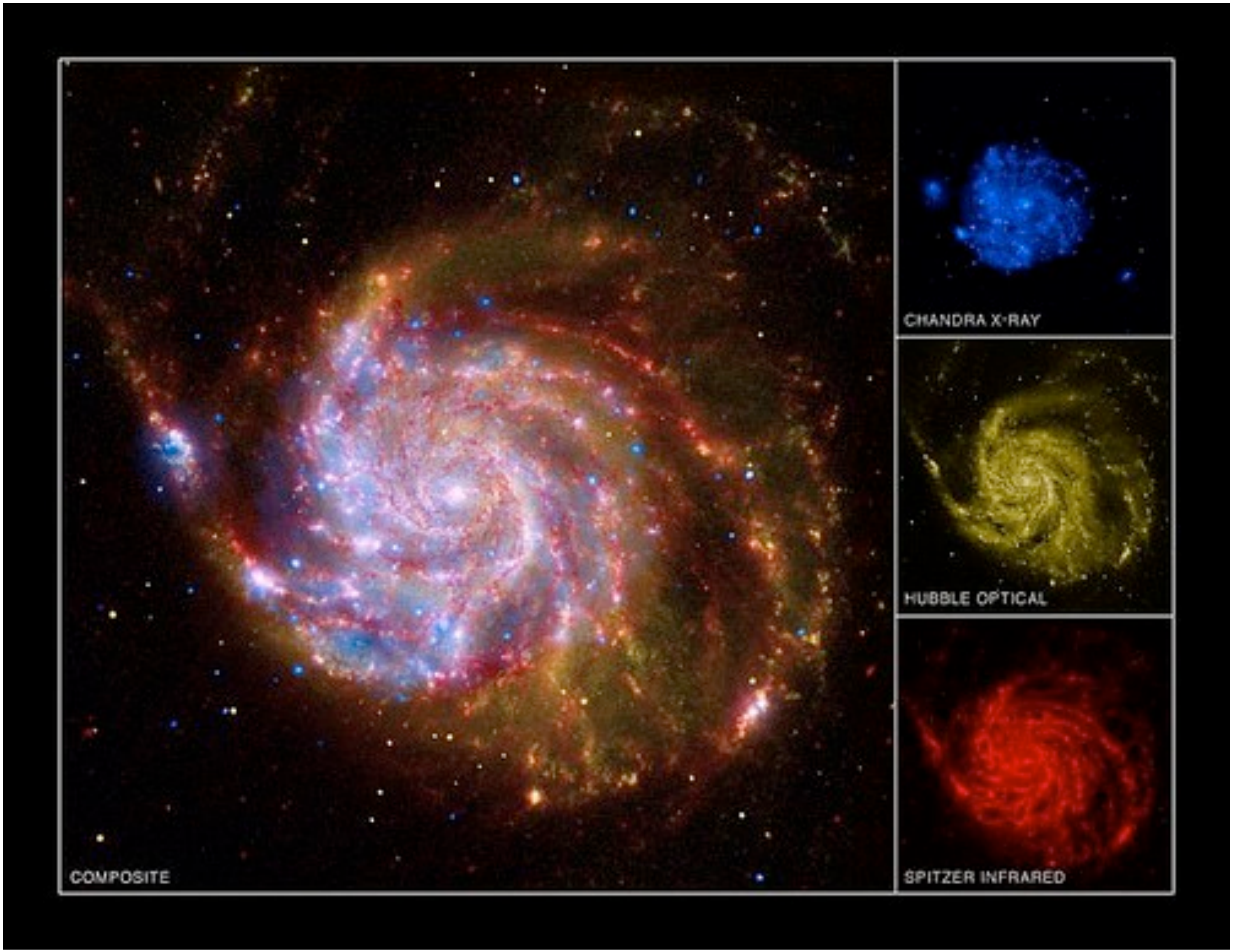


relativistically distorted Fe α line

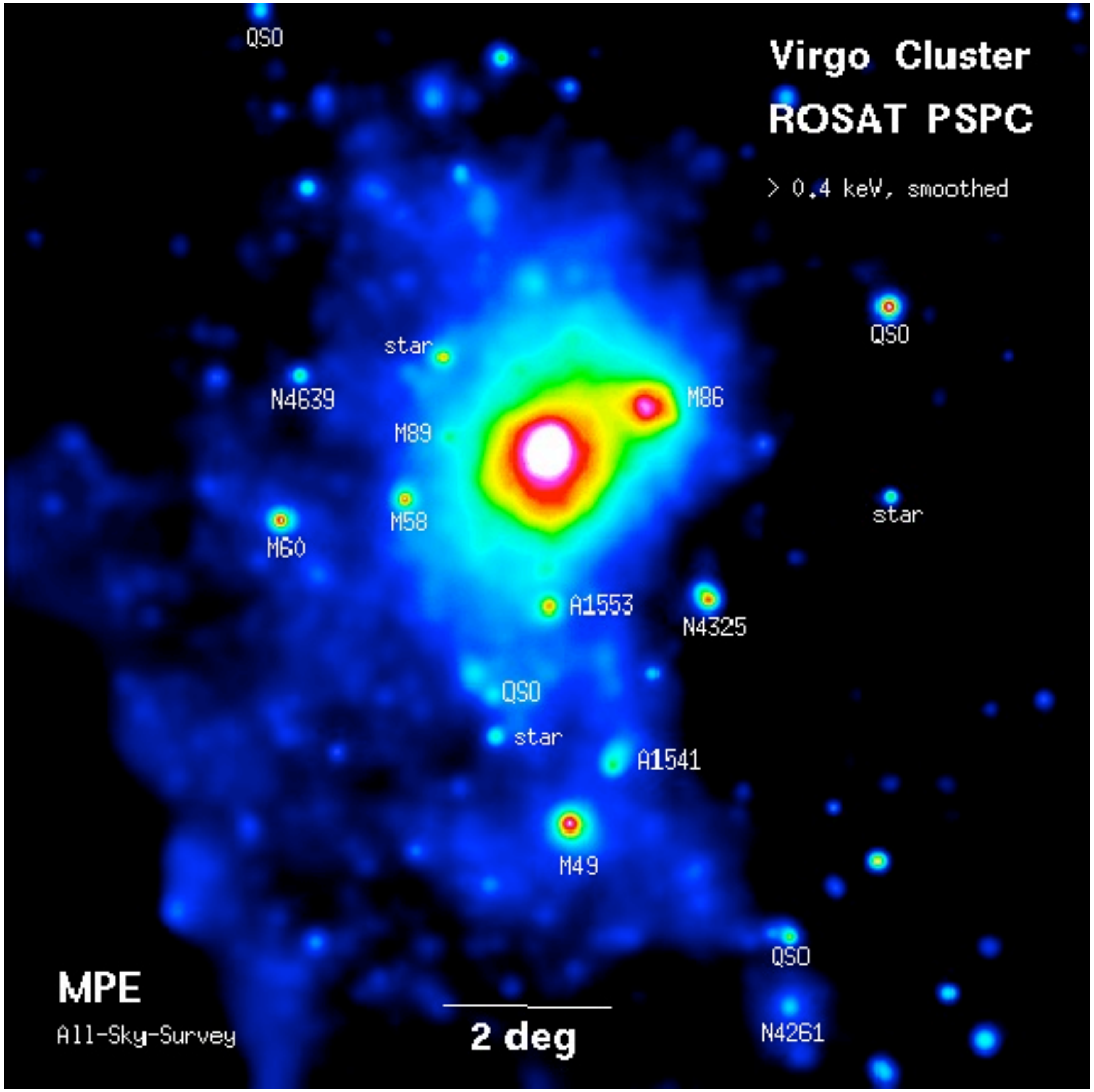


- X-ray emission lines require high energy
- strongest line: Fluorescent Fe K_α at 6.4 keV
- large number of Inner shell transitions
- also found in stellar coronae, shocks
- hot gas (10^6 K ~ 1keV)

X-ray continuum:
combination of point sources (mostly X-ray binaries) and hot (~10^6 K) plasma



X-ray observations demonstrated vast amounts of hot gas in galaxy clusters

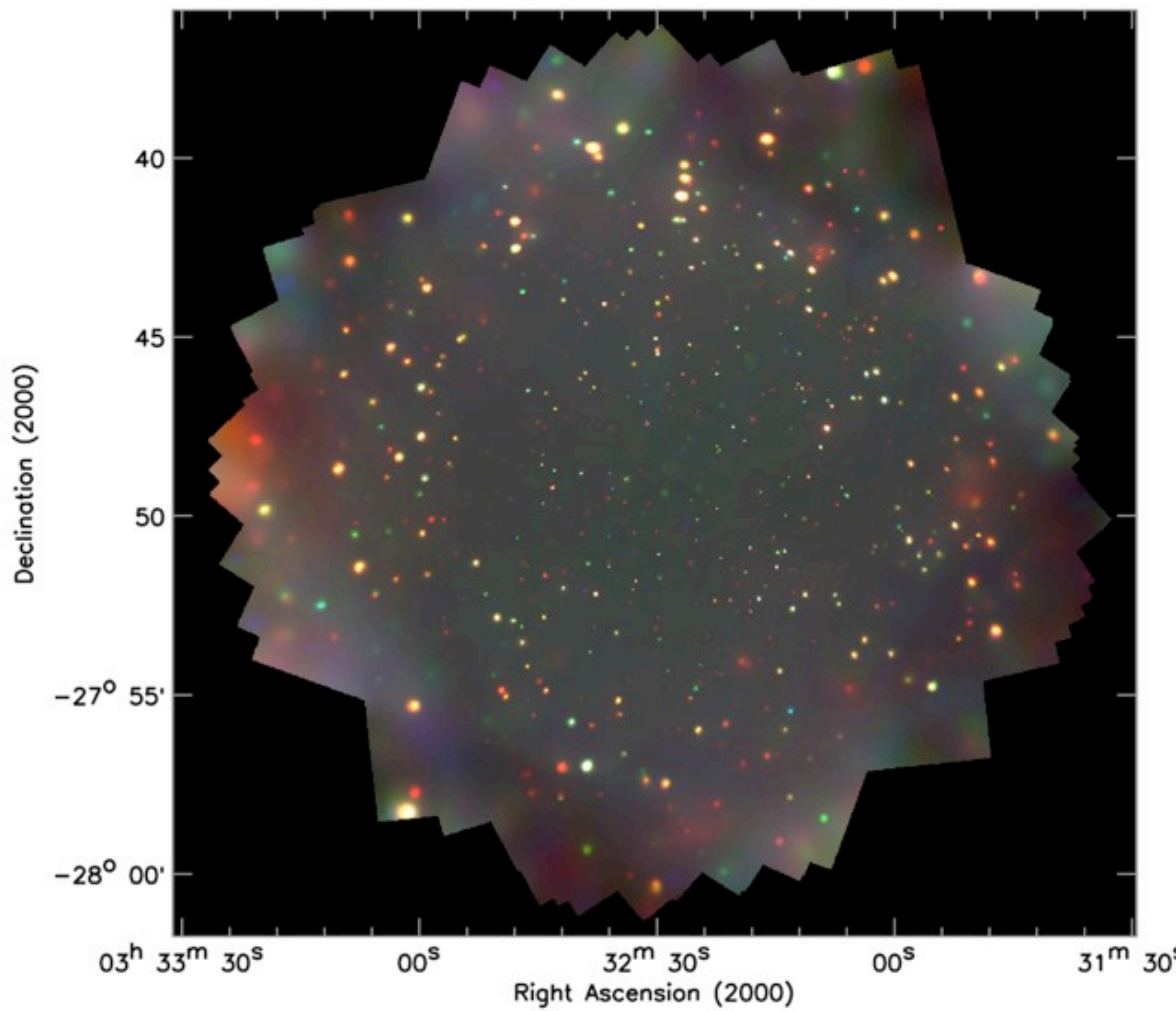


e.g., Virgo Cluster

$T=10^6$ K, ~keV

this gas dominates the visible cluster mass (90%)

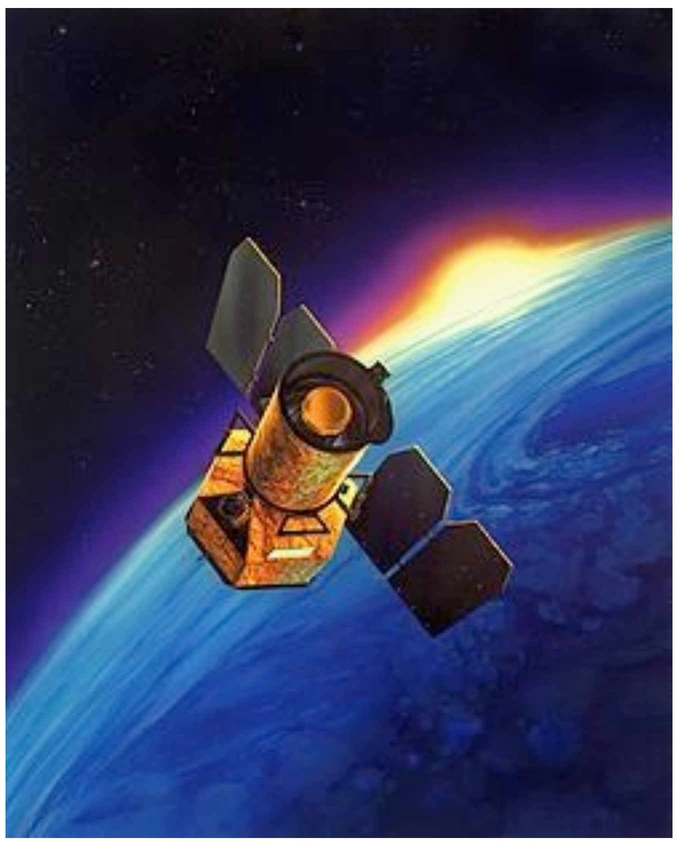
X-ray deep fields reveal mostly high redshift AGN

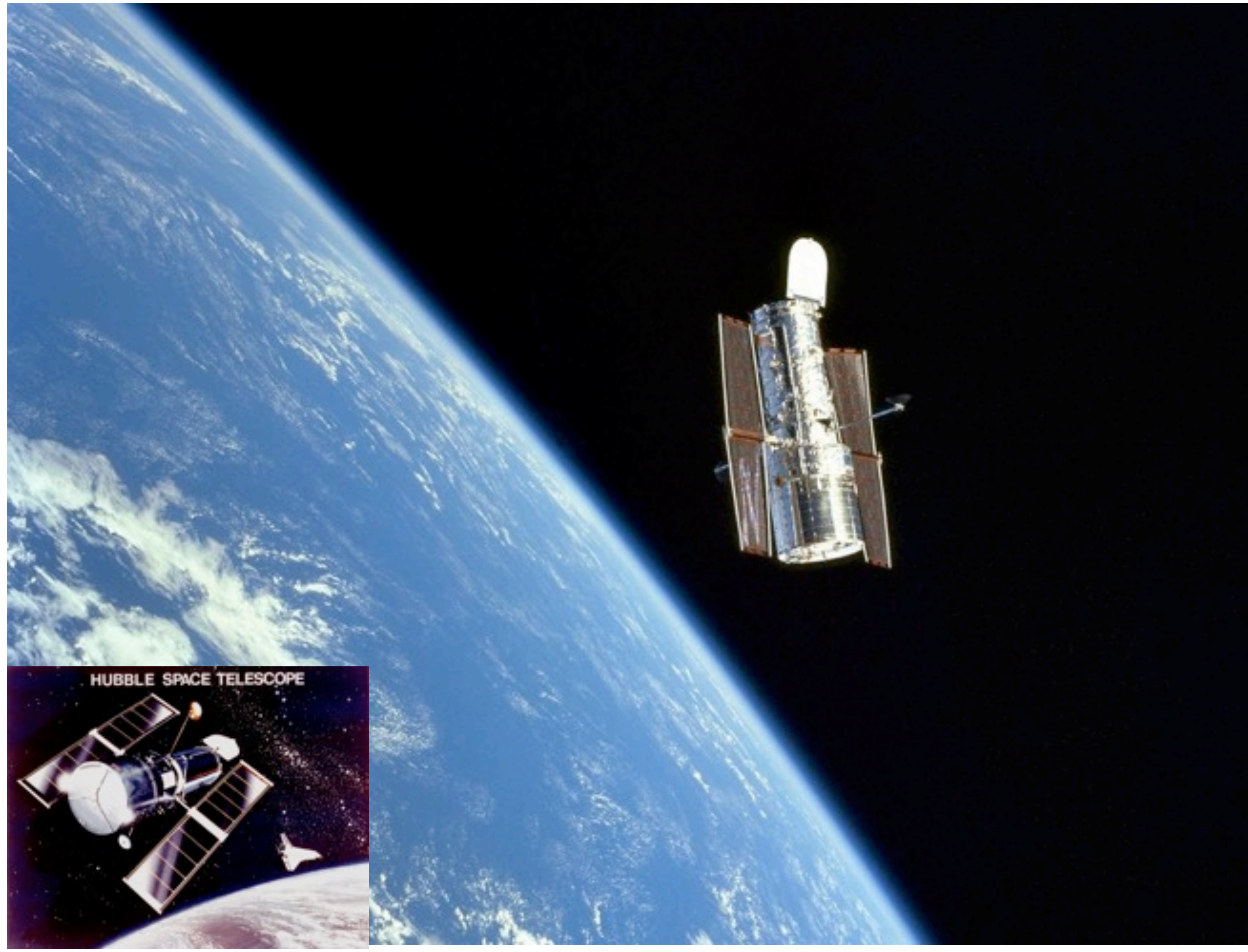


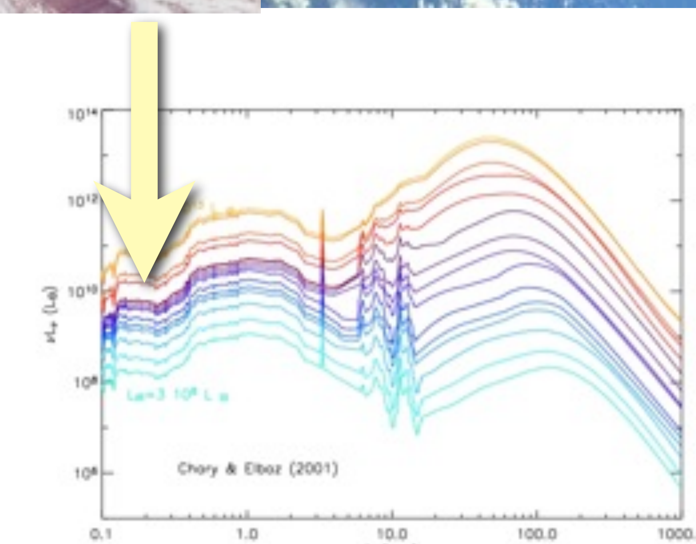
Chandra
2 Ms (555h)
exposure of
ECDFS

UV facilities

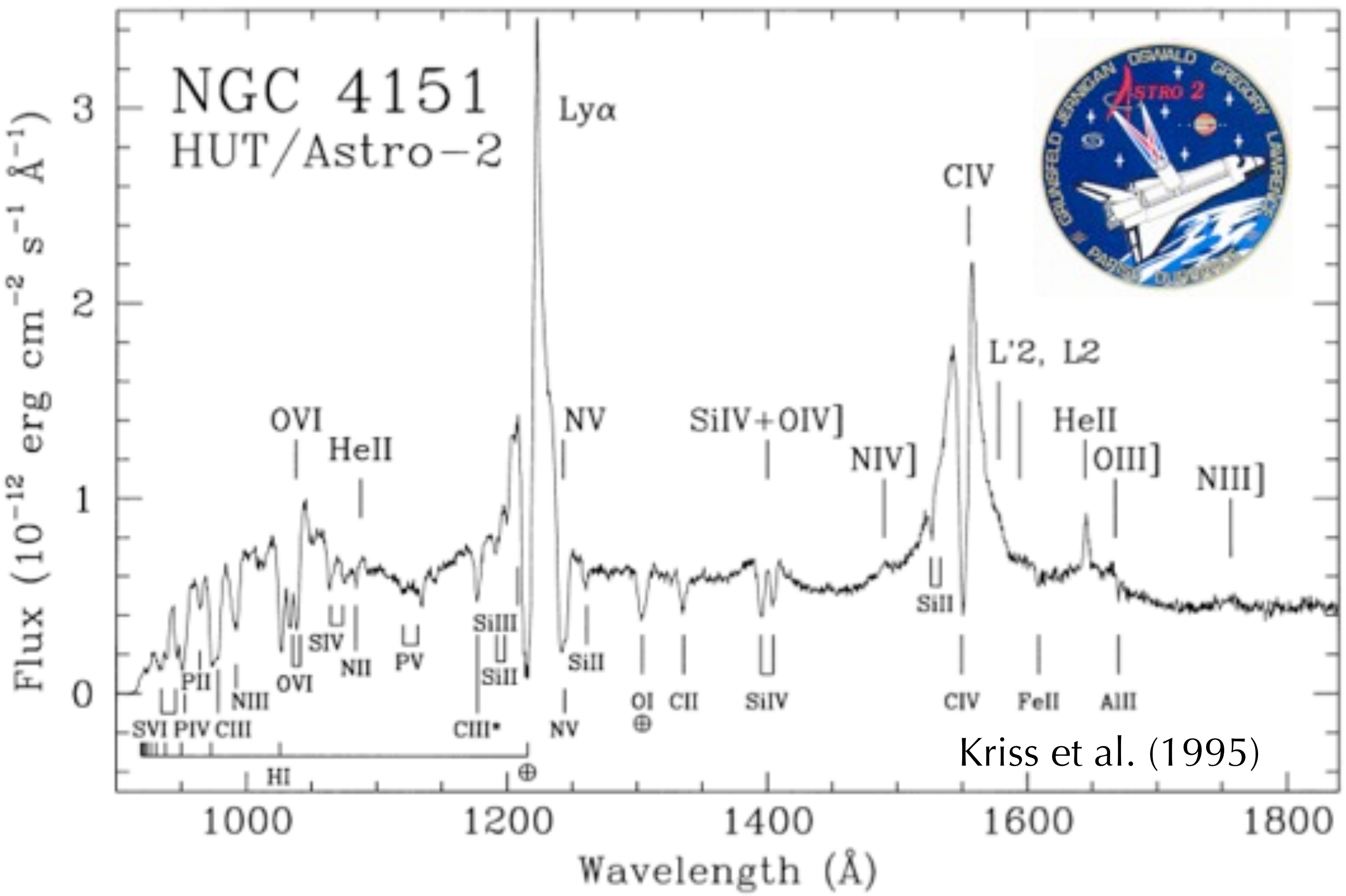
(only from sapce)



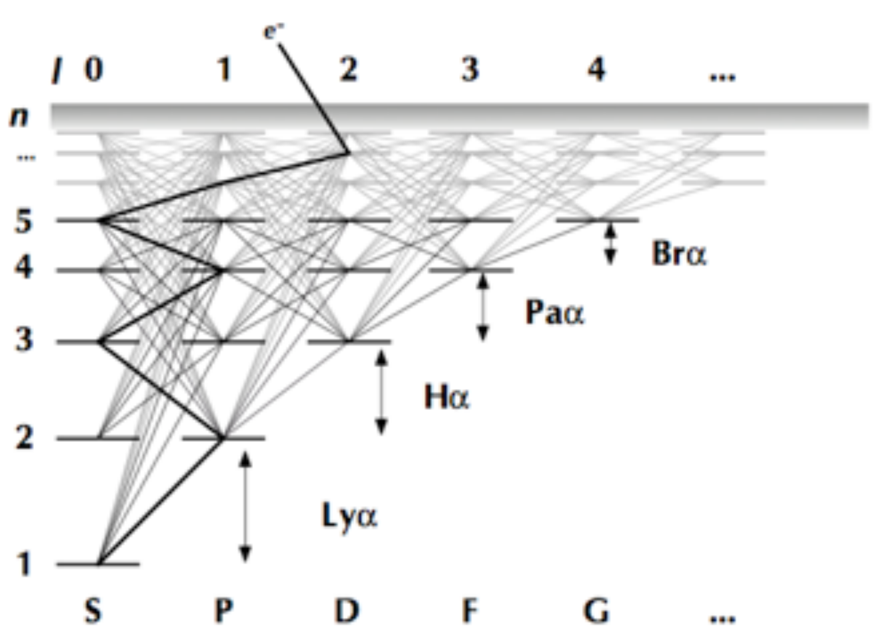




UV spectrum



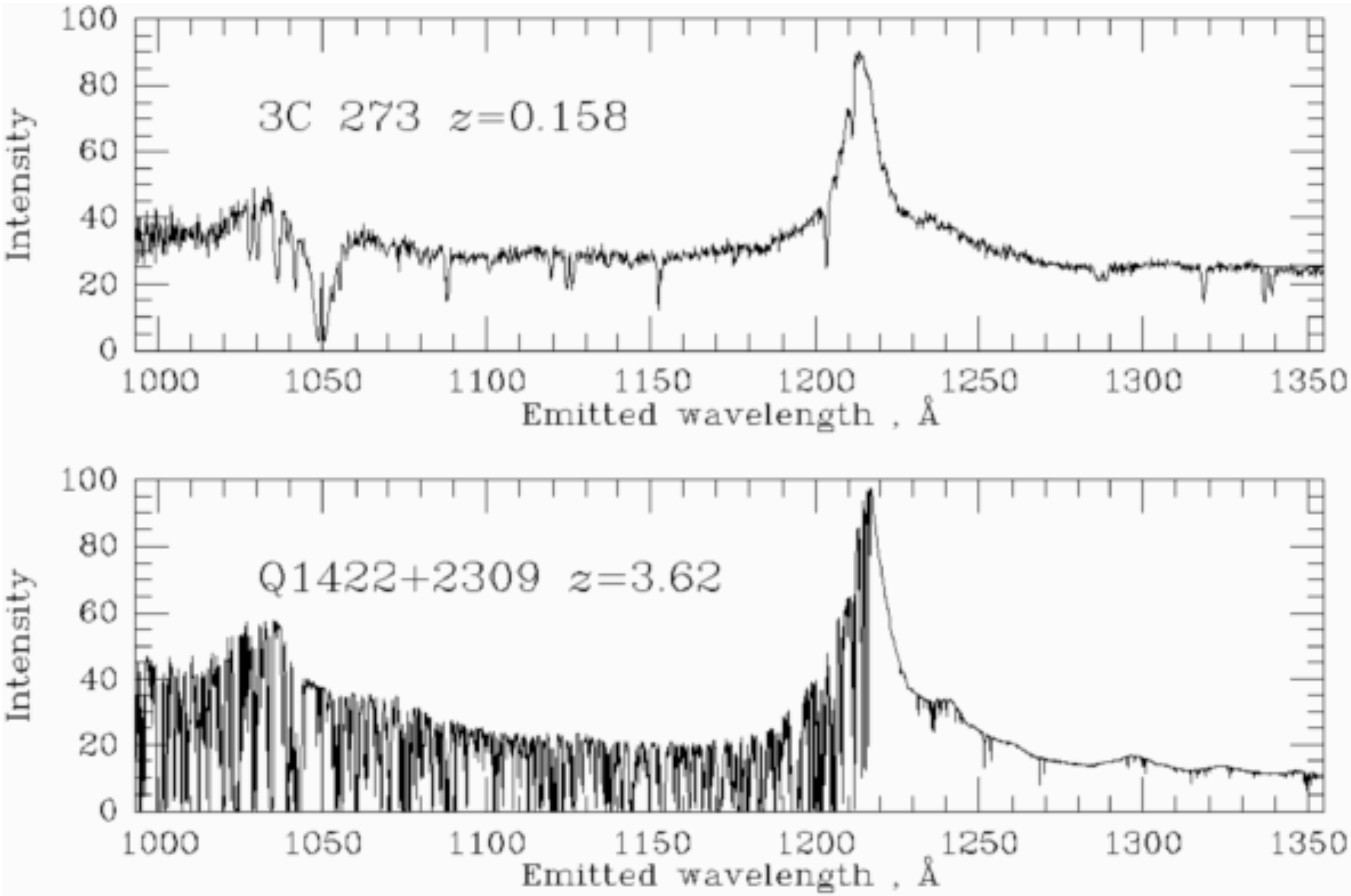
- hot stars are bright in UV continuum
- (Almost) Every recombination of Hydrogen leads to Lyα (2p->1s, 1206Å) - Strongest line



the enemy of UV radiation: dust
(see dust lecture: extinction curves/reddening)

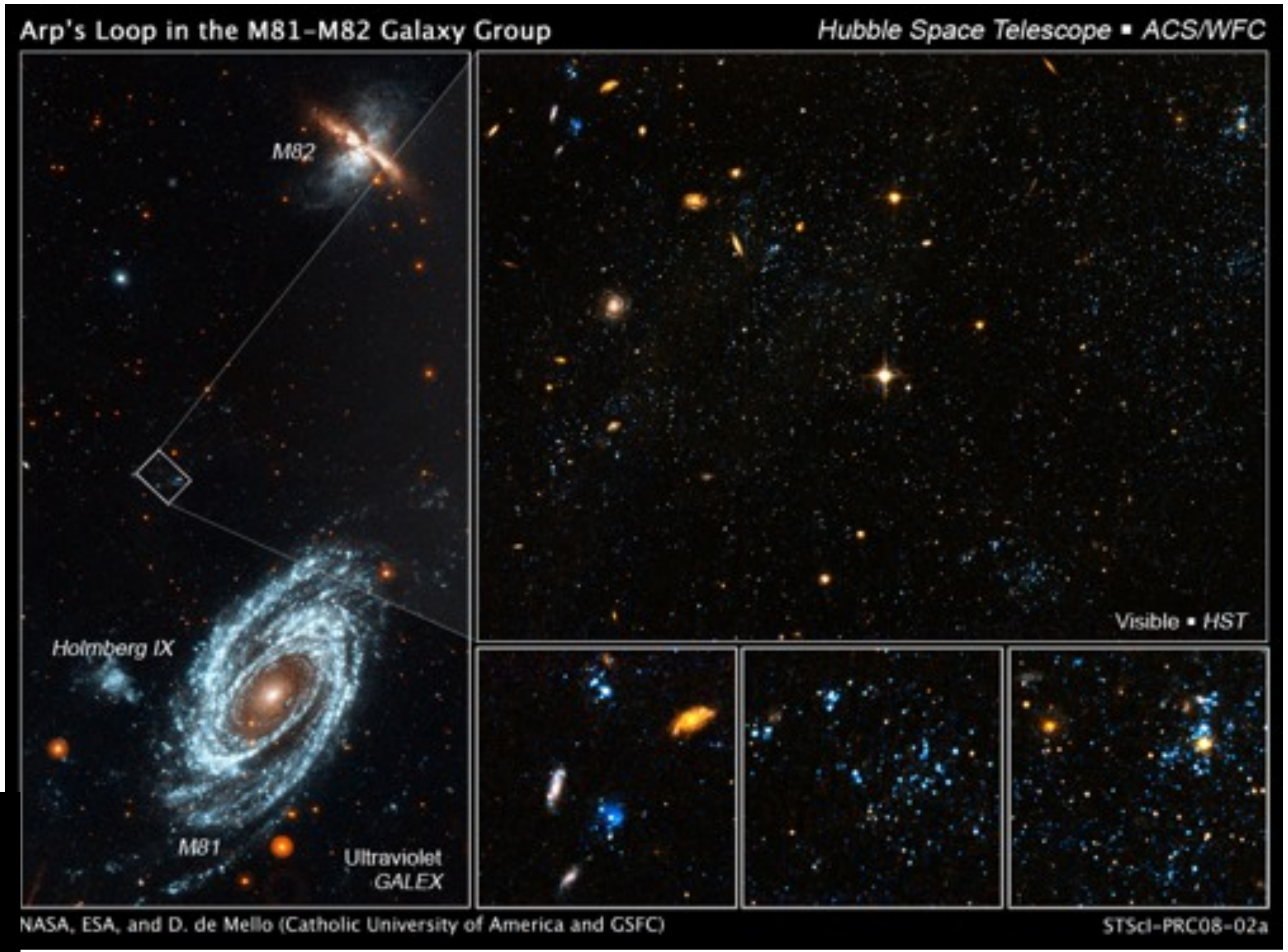
UV absorption spectra

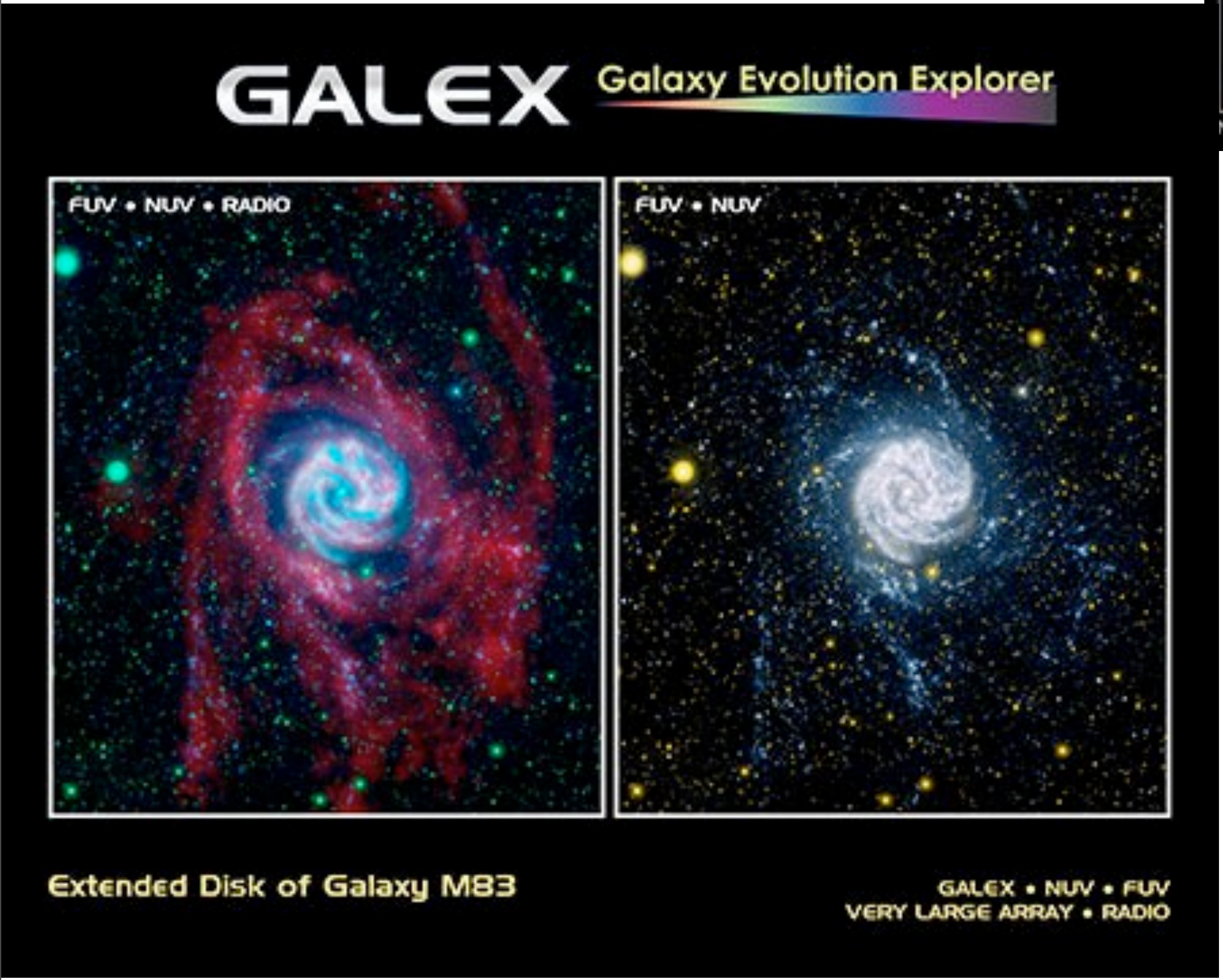
(restframe) UV spectra absorption spectra tell us about the properties of the intergalactic medium



Note: high-redshift optical spectra/images correspond to **UV restframe**

UV: sensitive tracer of star formation

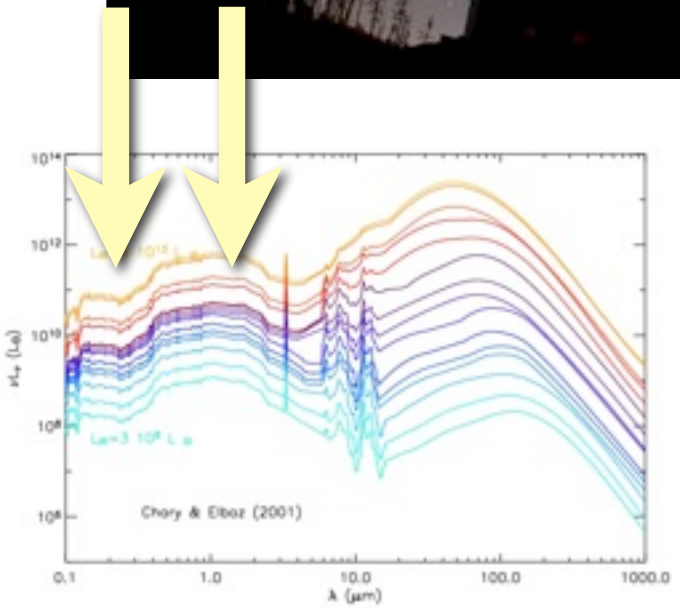




Galex revealed very extended star forming disk in nearby galaxies

all luminous hot stars are short-lived -- must have formed recently

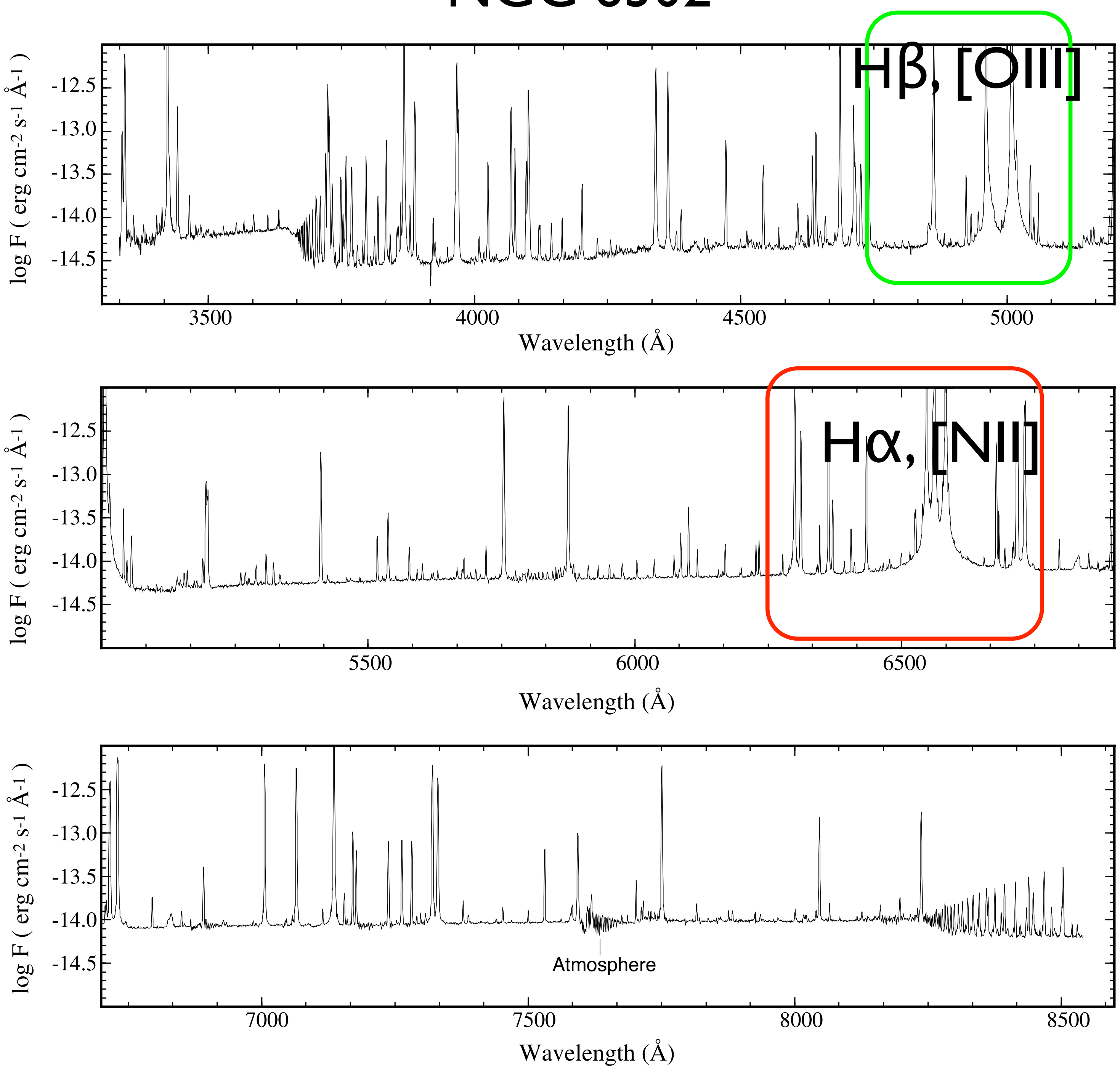
Optical facilities



ground-based high-lighted here: MPIA access

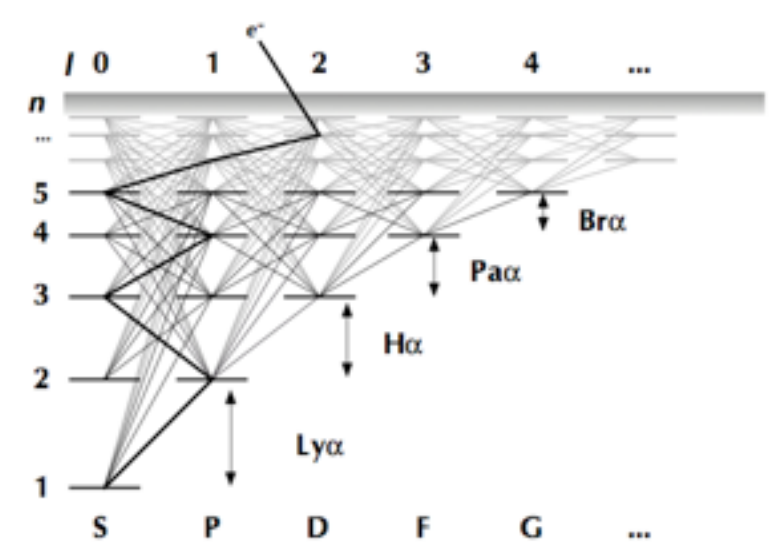
Optical spectra are rich in atomic lines

NGC 6302



Groves et al. (2002)

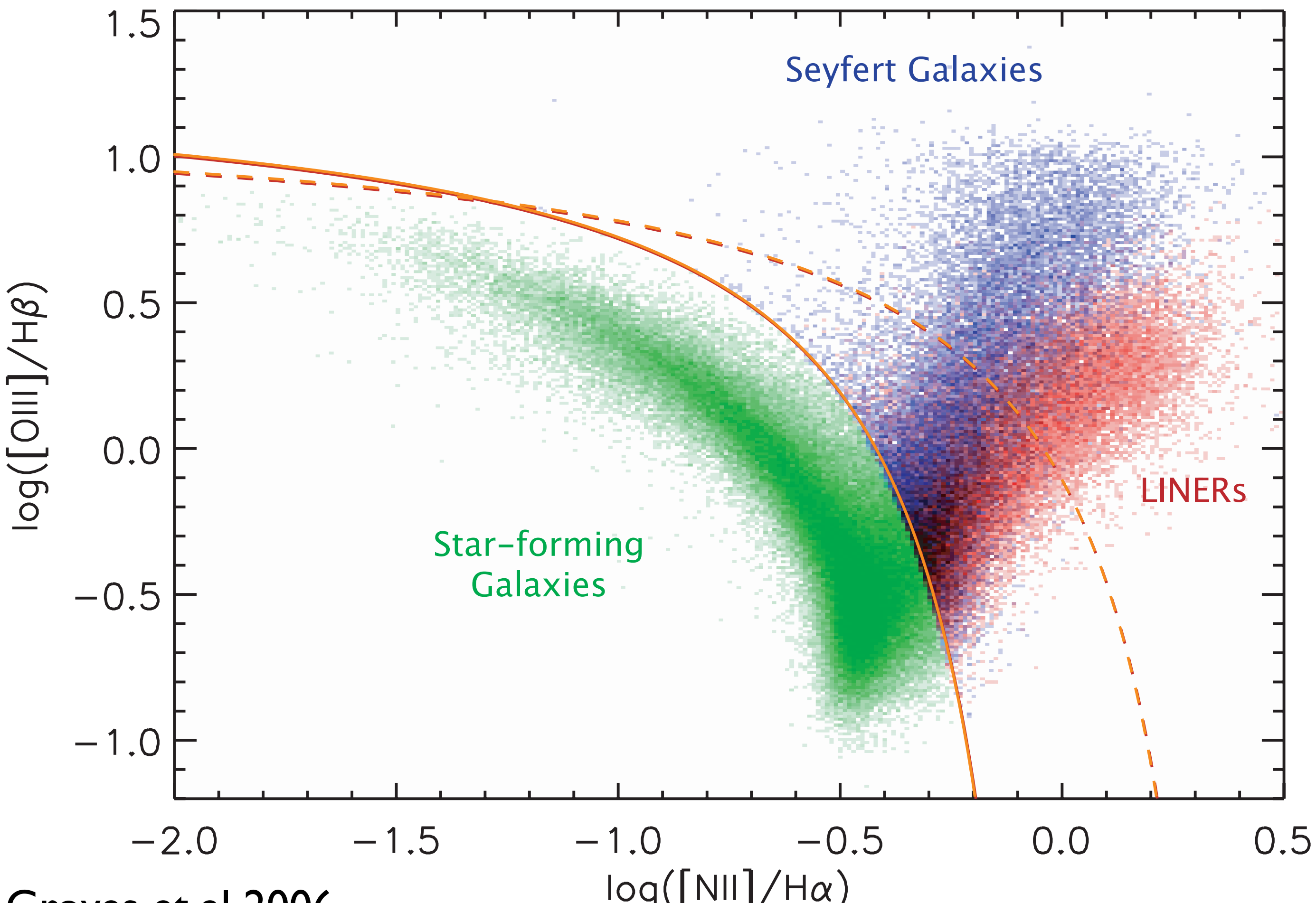
- diffuse gas gets ionized/excited by stellar light
- use strong (easily observable) lines to come up with diagnostic tools.
- H-α line a commonly used tracer for star formation.



‘BPT’ diagrams

- Original Baldwin, Philips & Terlevich (1981) Diagnostic Diagram
- ionized radiation produced by hot stars/BB <-> AGN power law.
- Allows one to classify galaxies

> 100.000 galaxies from SDSS

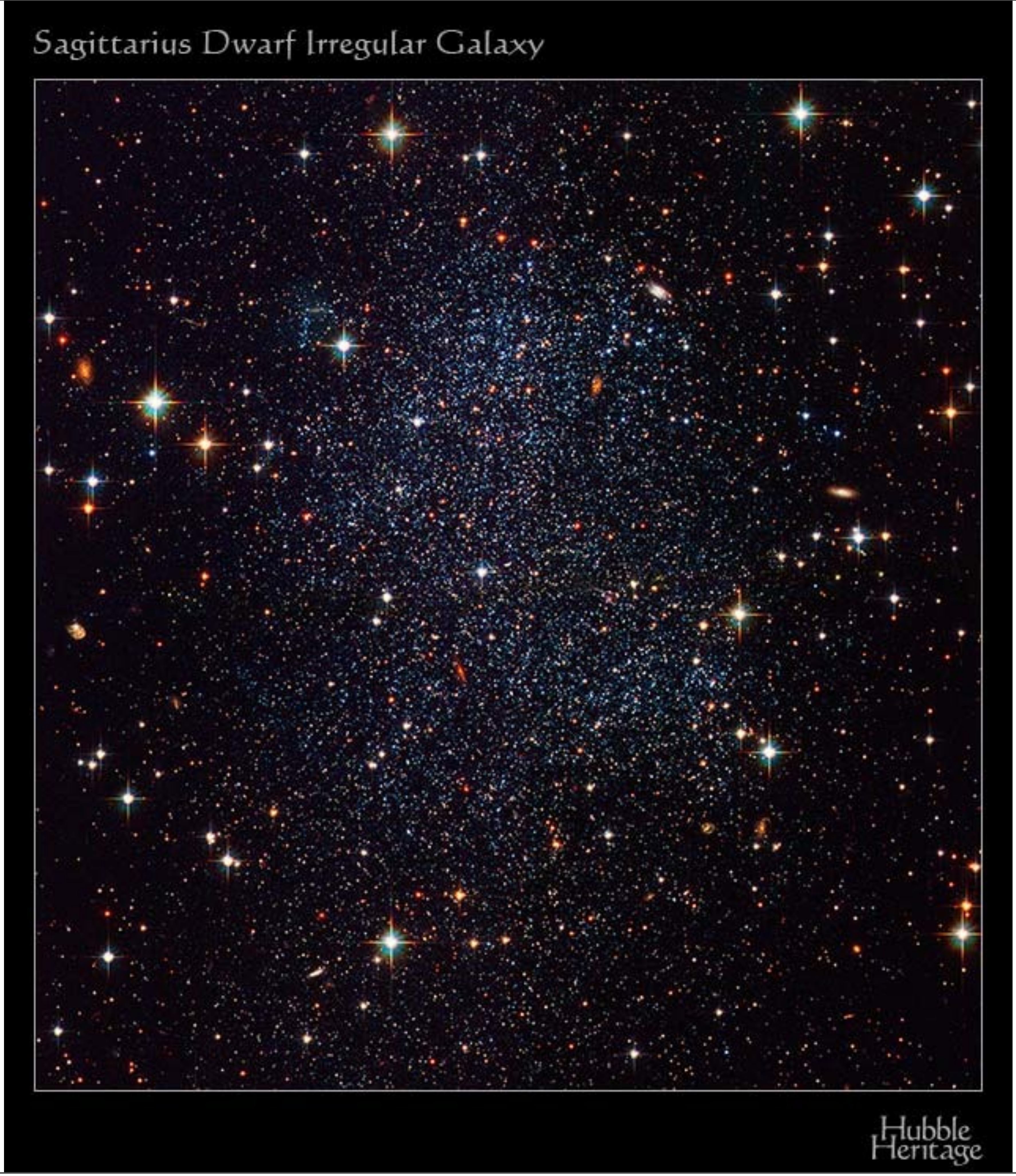


Groves et al 2006

starburst/AGN separator

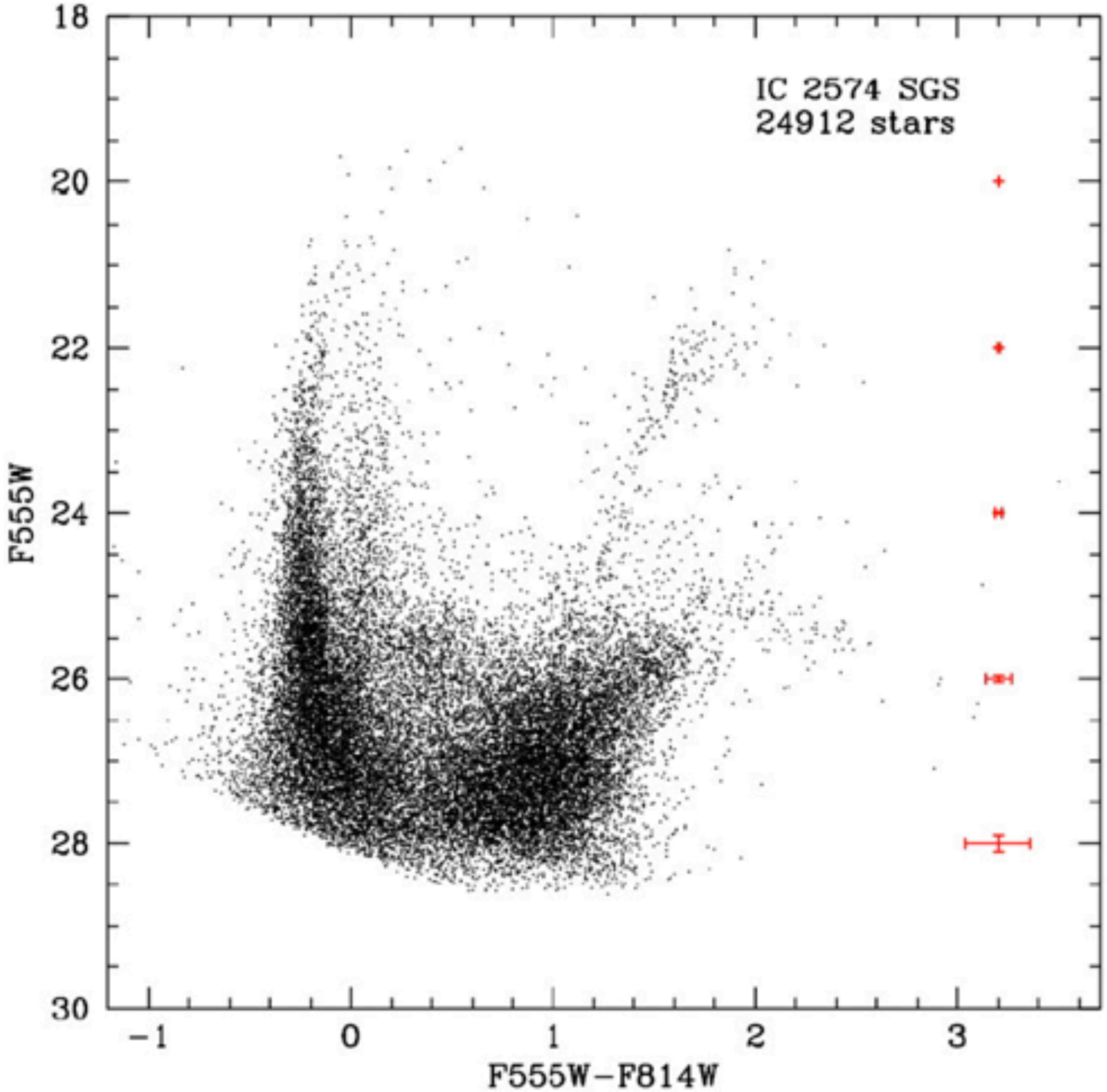
Optical multi-color imaging: dust, star formation and distribution of stars

example:
Antennae HST
composite

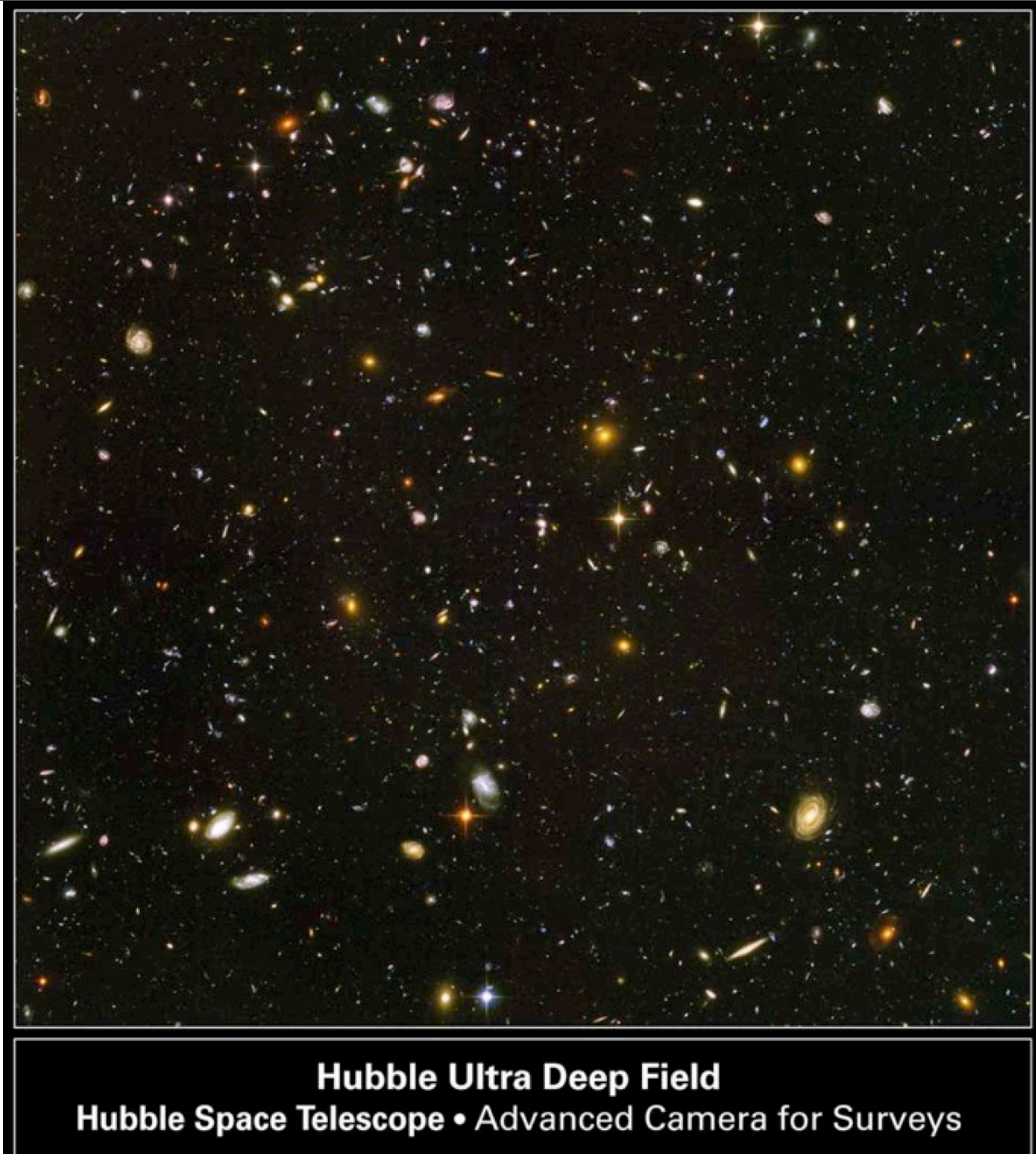


HST resolution allows one to resolve stellar distribution in nearby (dwarf) galaxies

("‘look through galaxies")



- HST resolution enables detailed stellar population studies in nearby (dwarf) galaxies

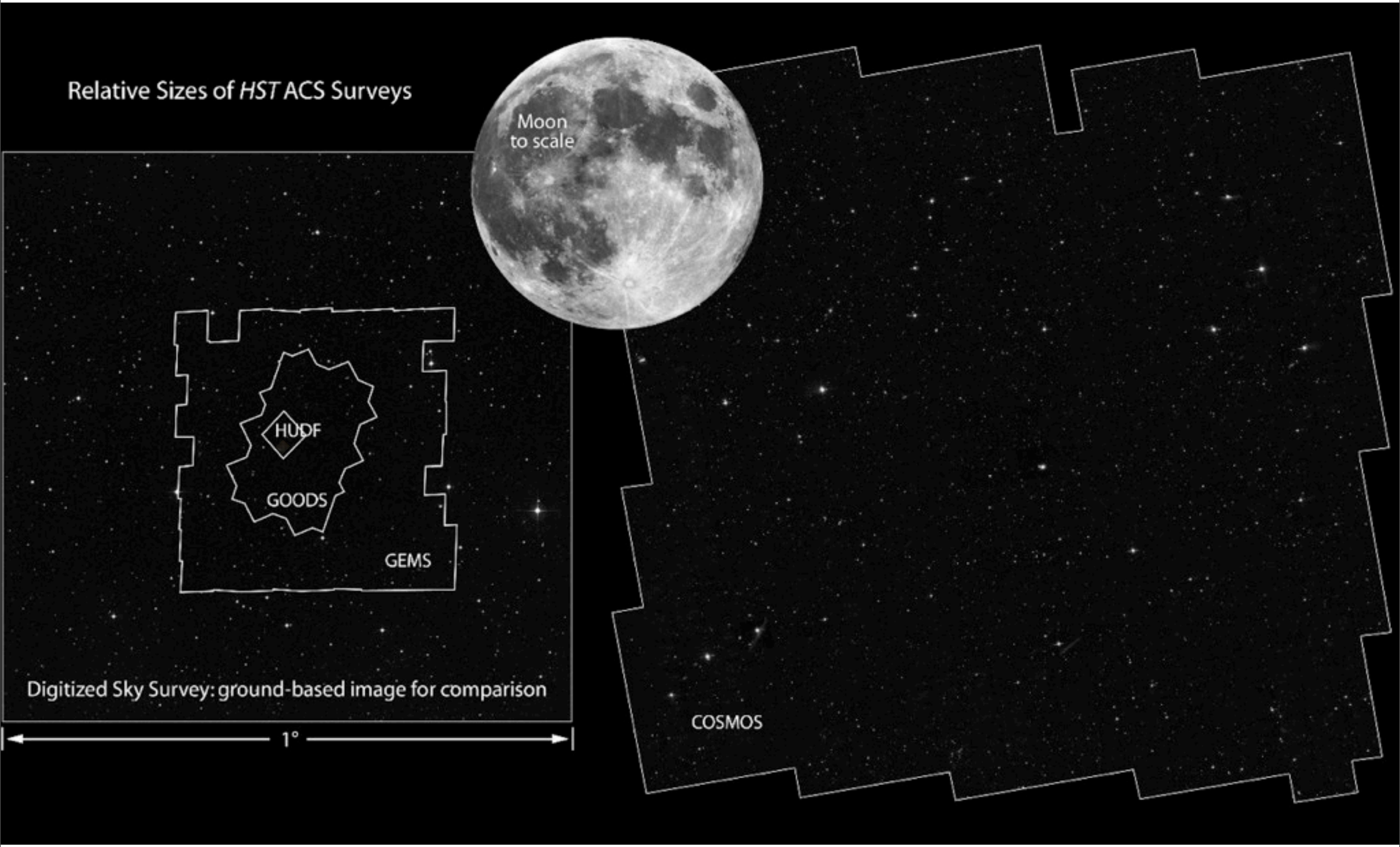


Deep Fields:

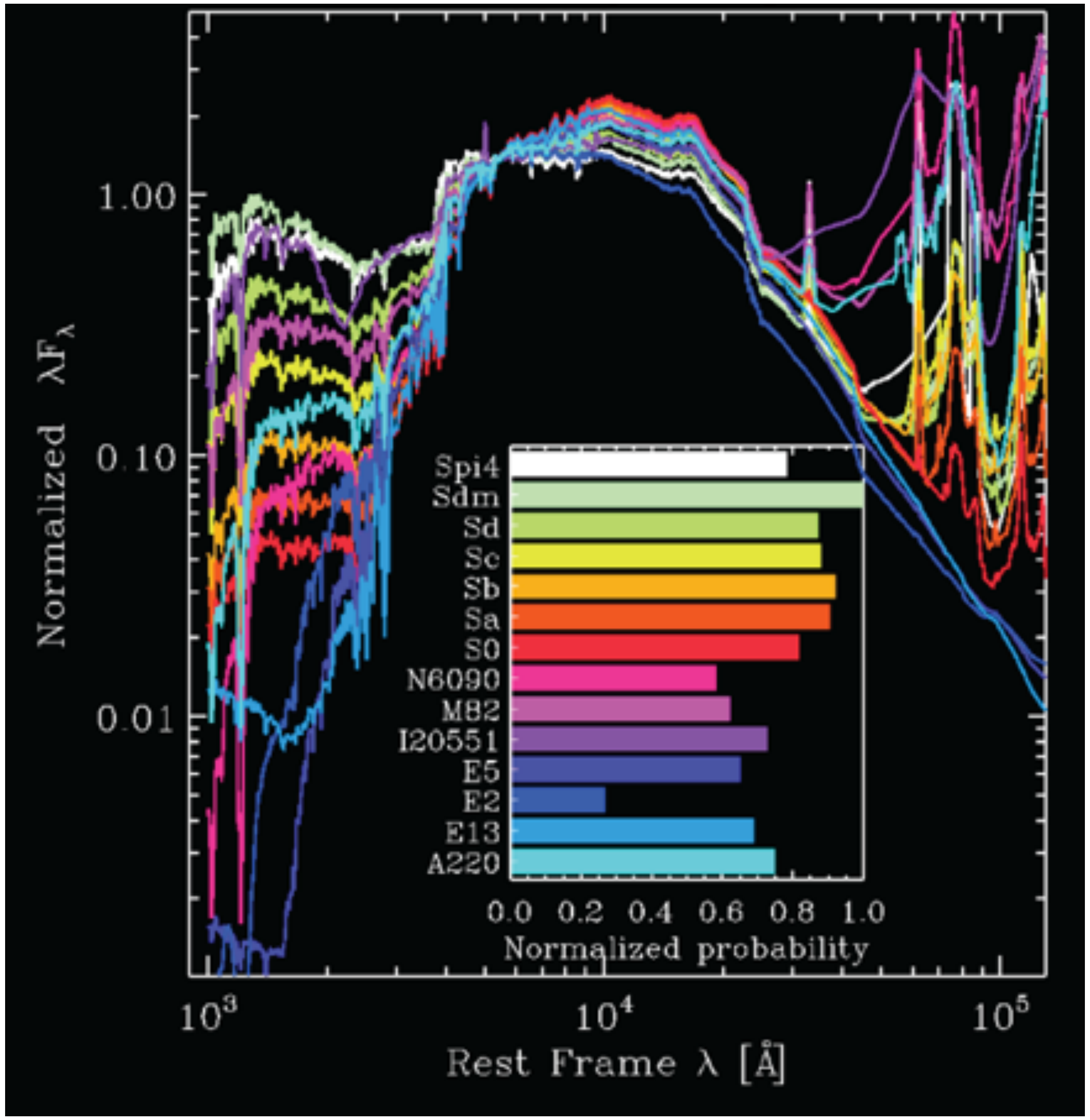
key to understand galaxy evolution

examples: HDF/UDF/
COMBO17/GEMS/COSMOS

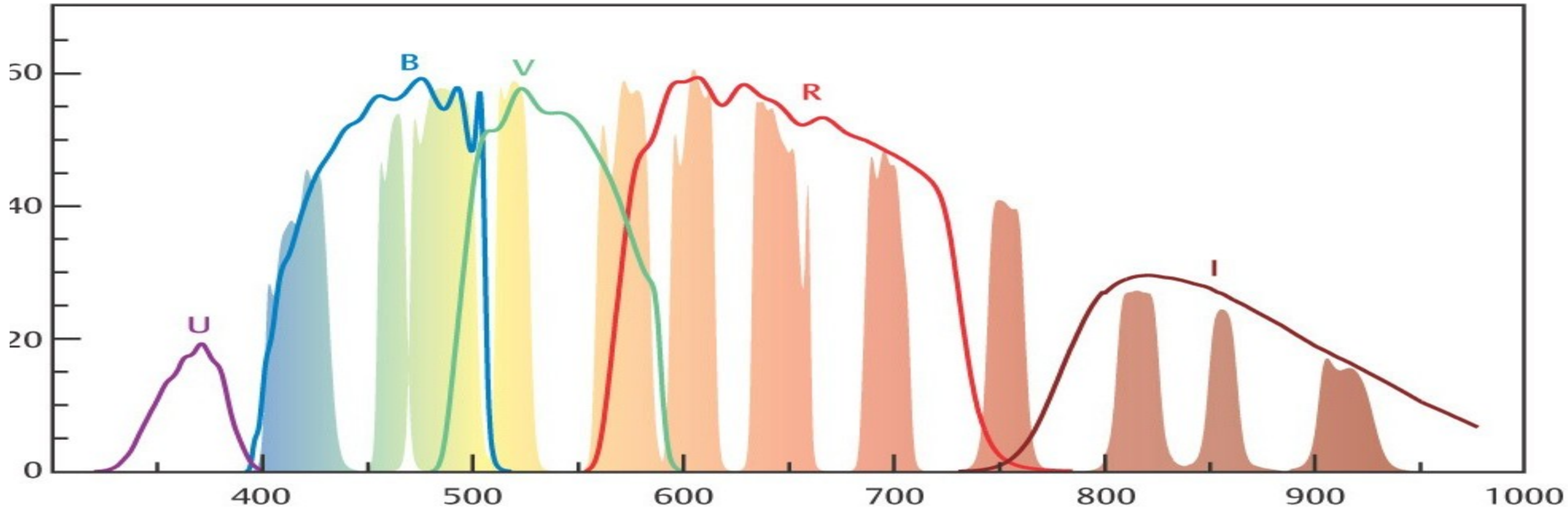
Relative sizes of ACS Surveys



Galaxy Templates



Fit individual galaxies with various galaxy templates to find most probable
- redshift
- star formation
- stellar mass

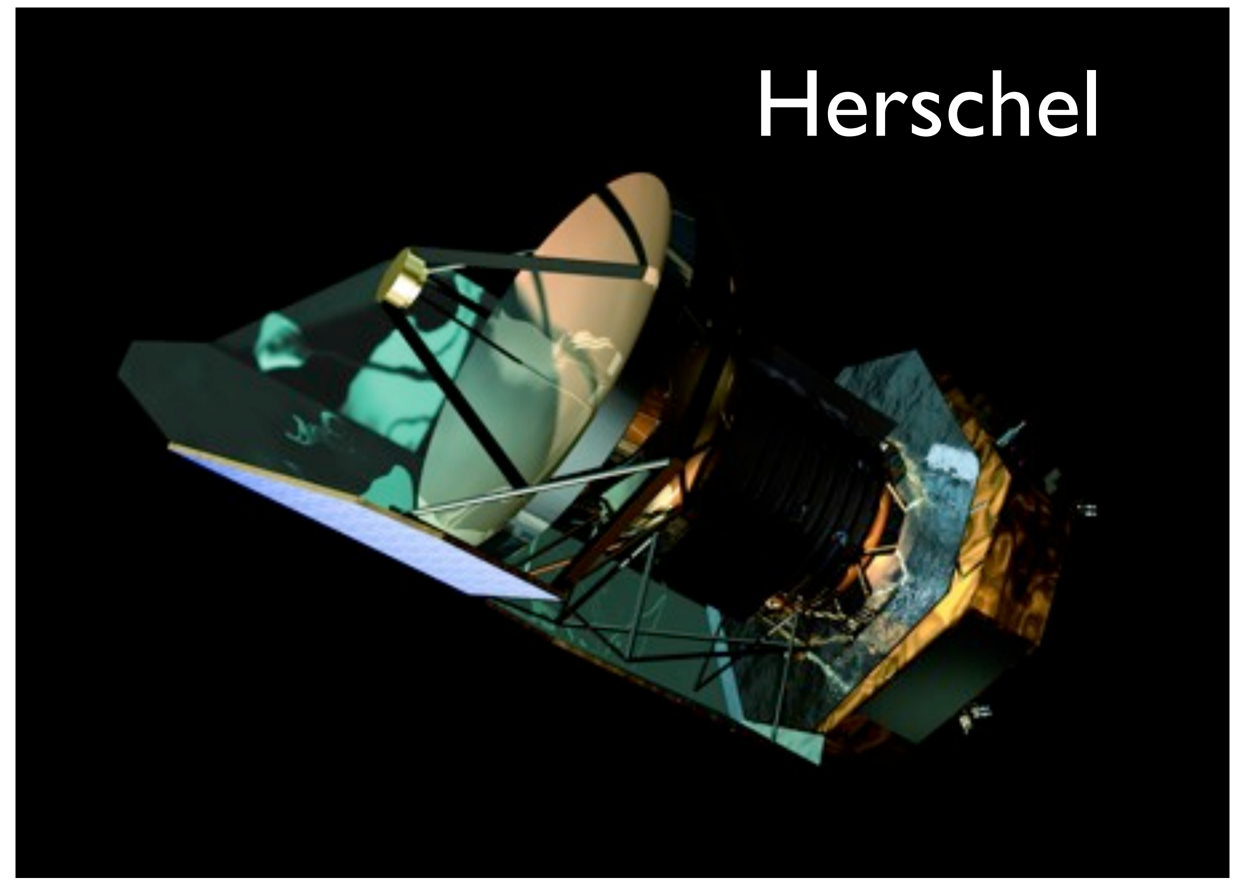


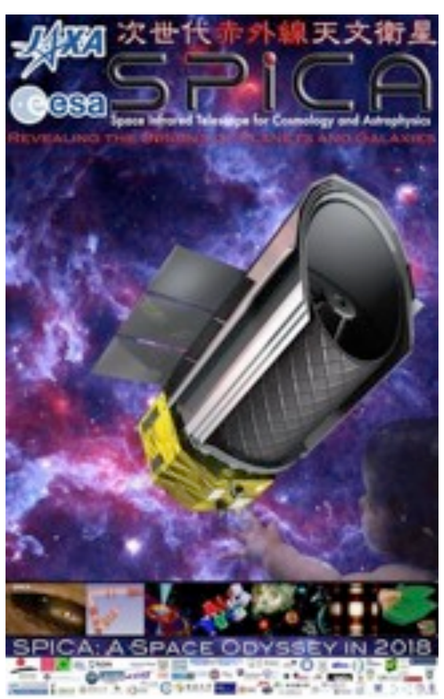
the more filters the better...

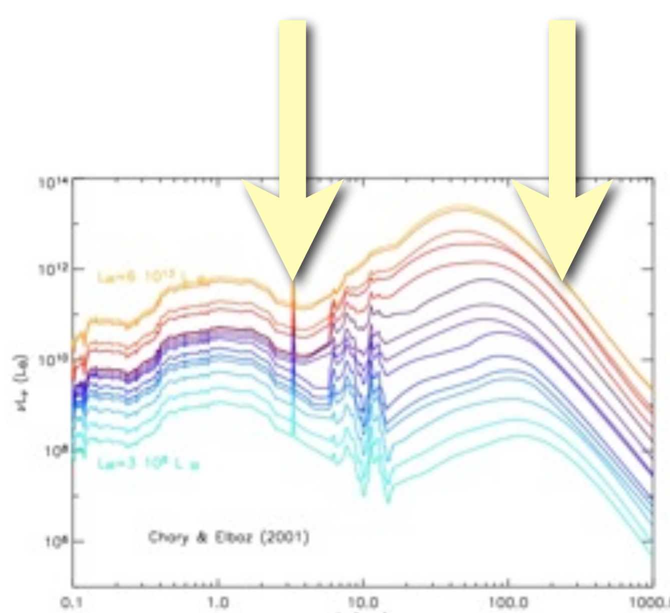
the future

e.g., E-ELT

IR observatories

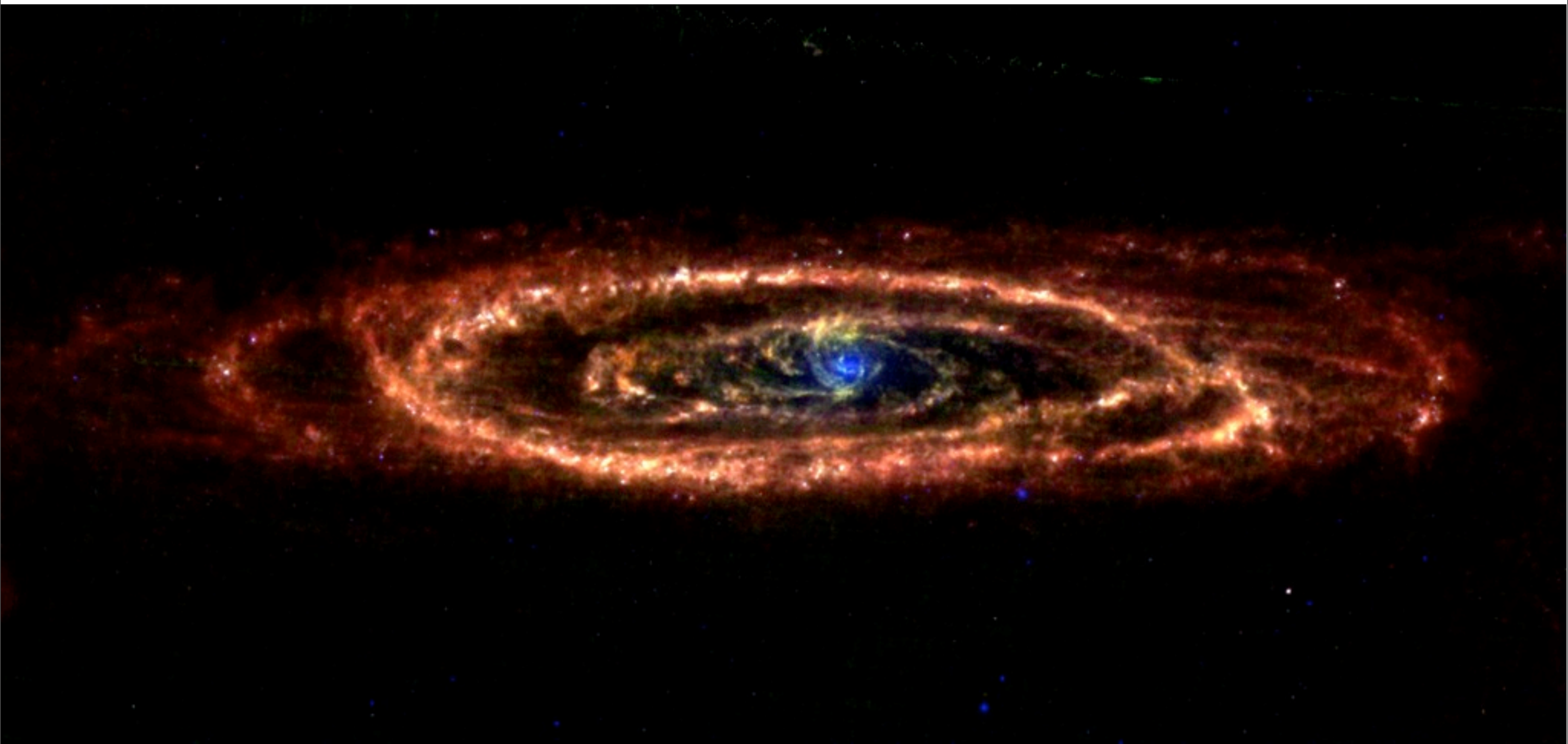






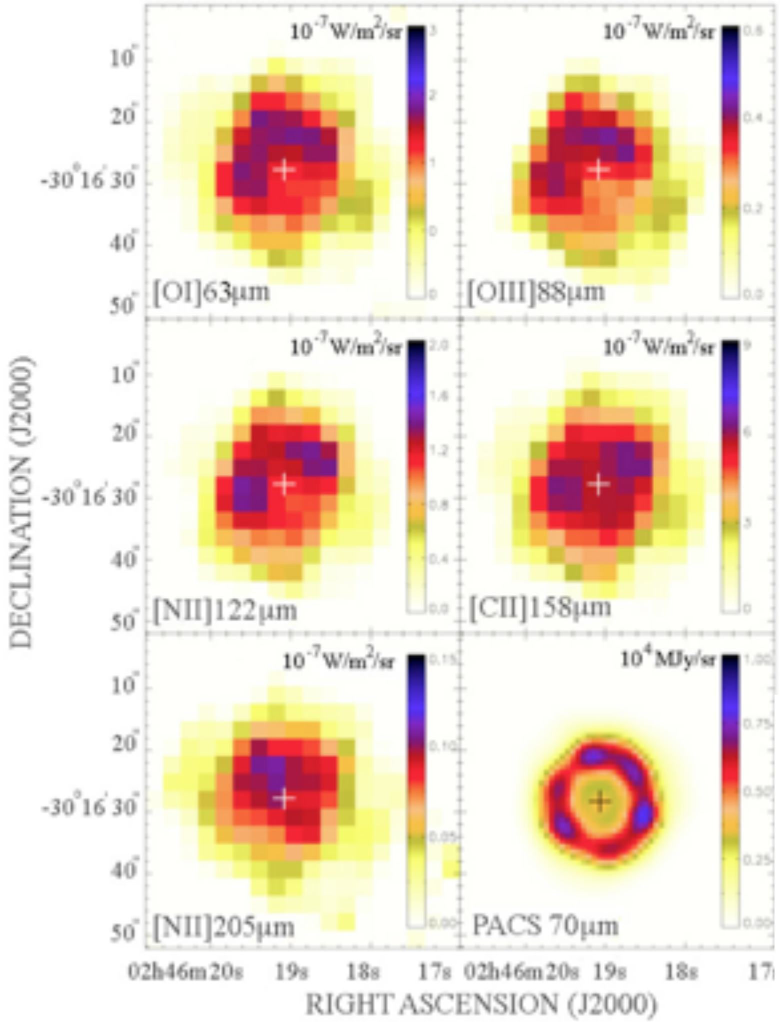
dust re-radiates 50% of all photons emitted by star formation

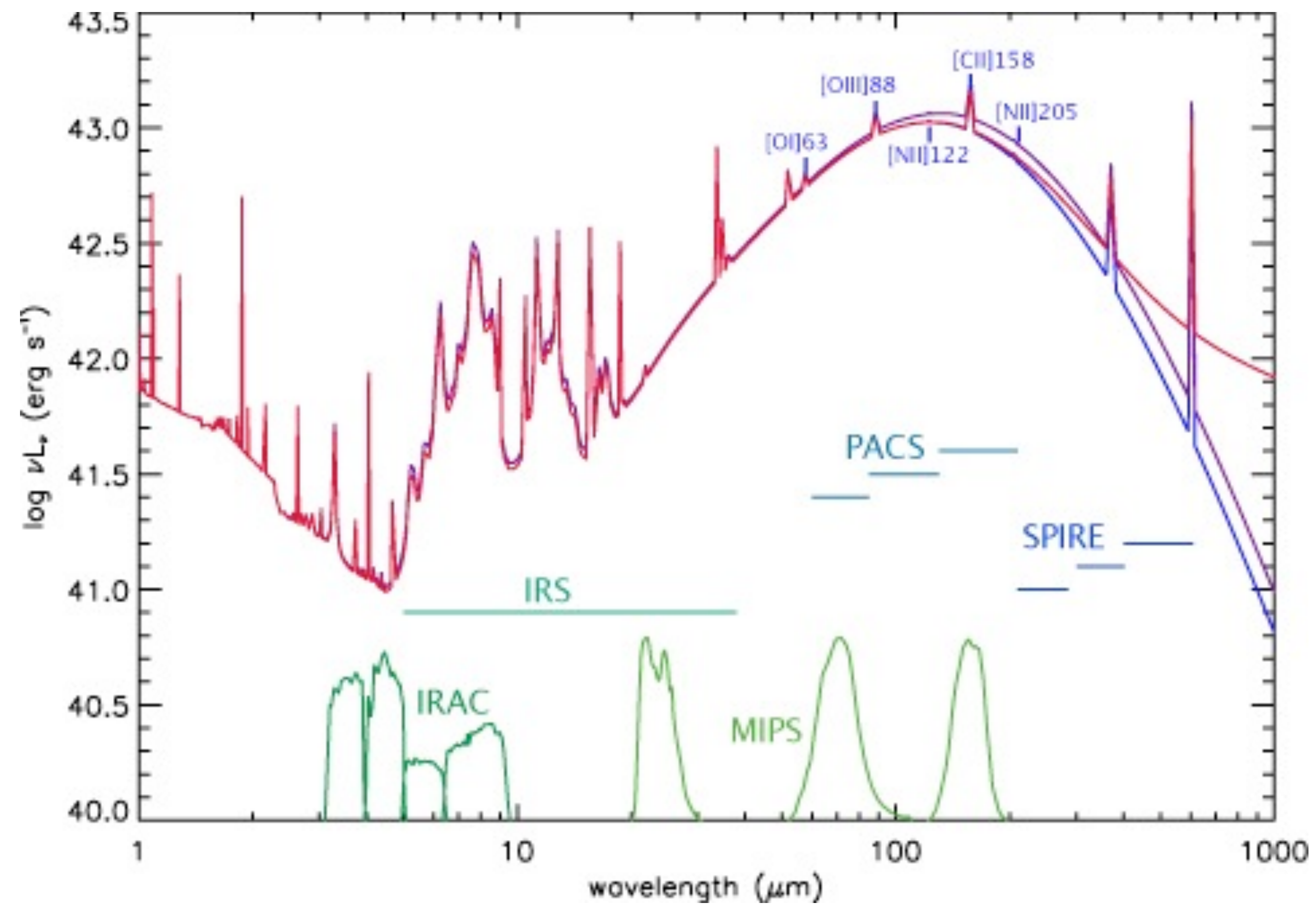
can be used as proxy for SF -- also: dust mass, temperature, composition

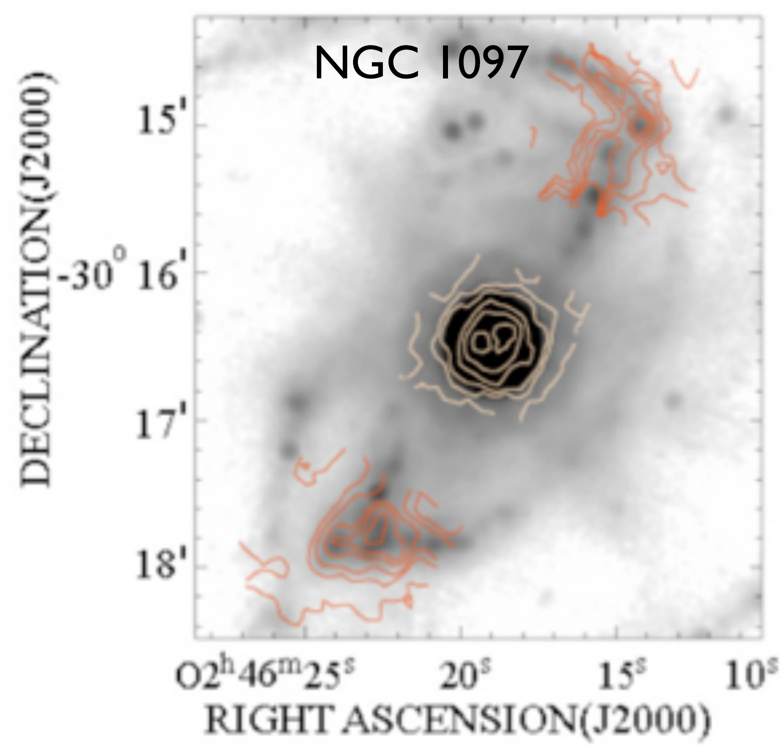


M31 -- 24 (MIPS),160 (PACS),350 (SPIRE) um atomic ('forbidden') spectral lines:

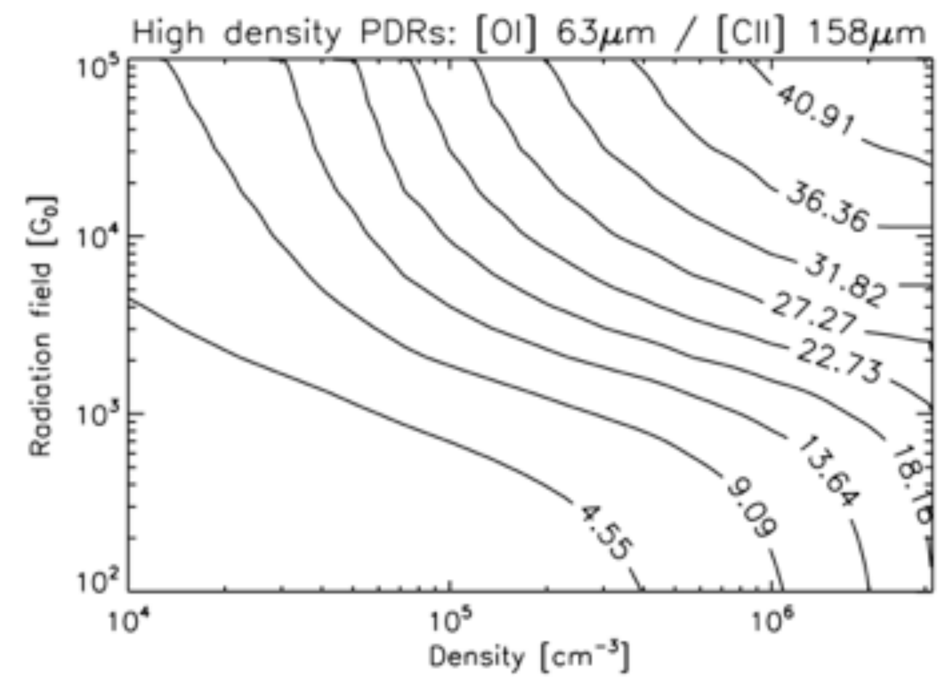
- important cooling lines
- characterize ISM





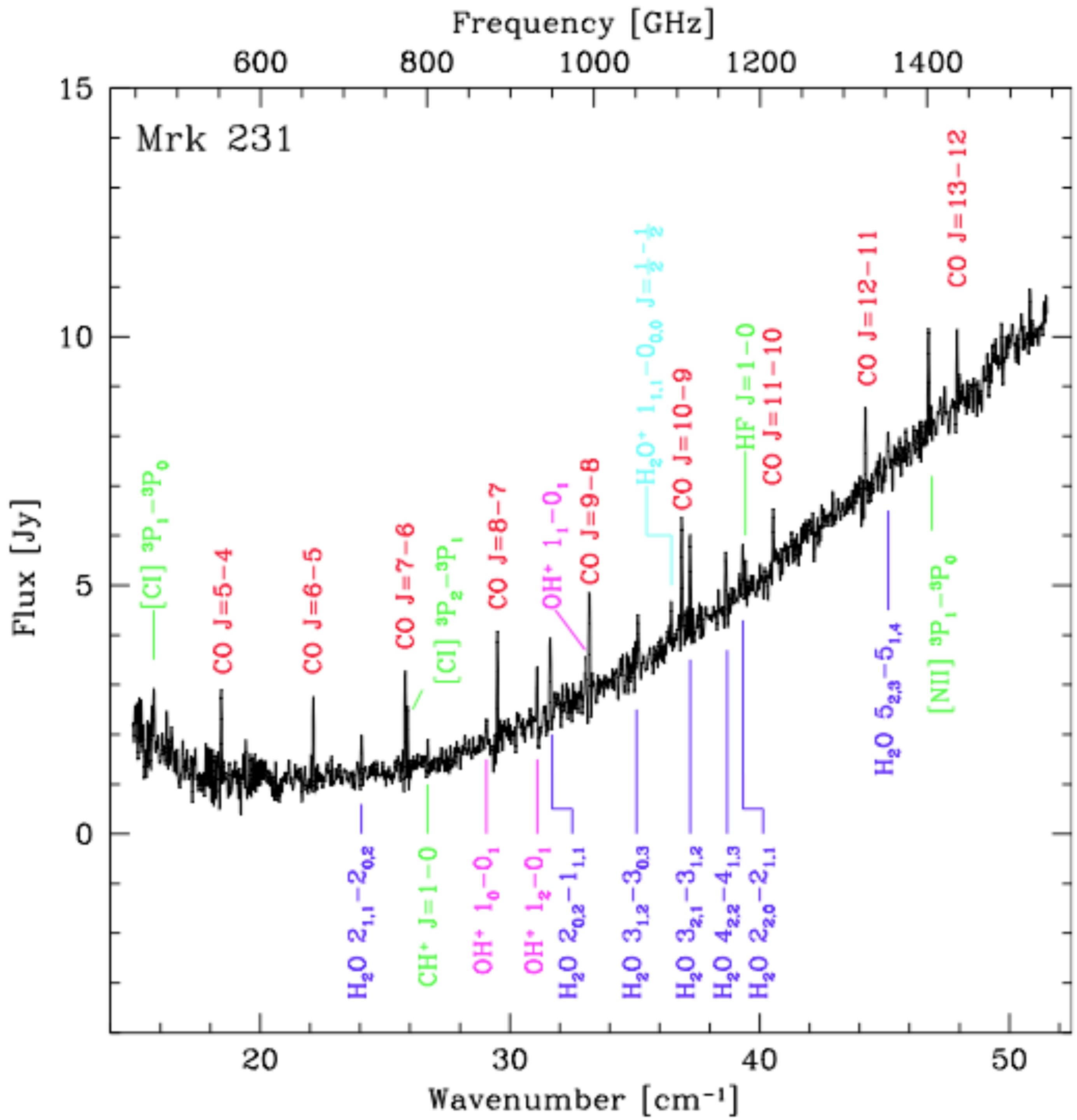


Beirão et al. (2010)



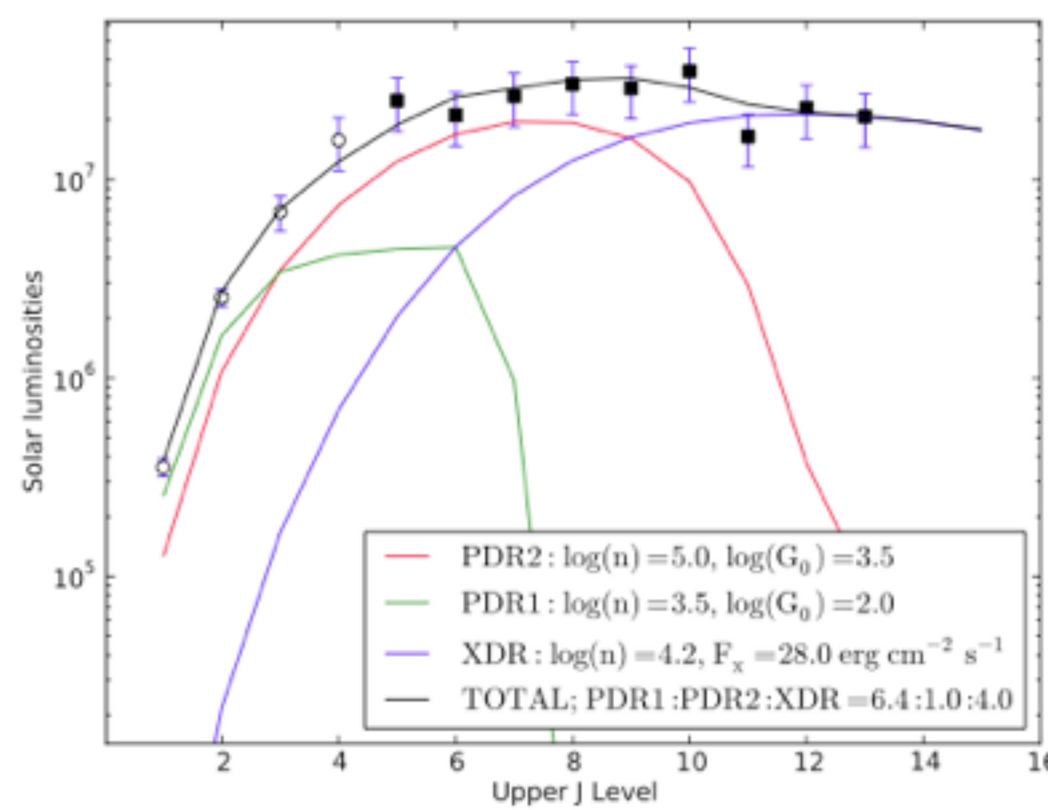
characterize ISM through models

SPIRE FTS -- many transitions ‘in one shot’

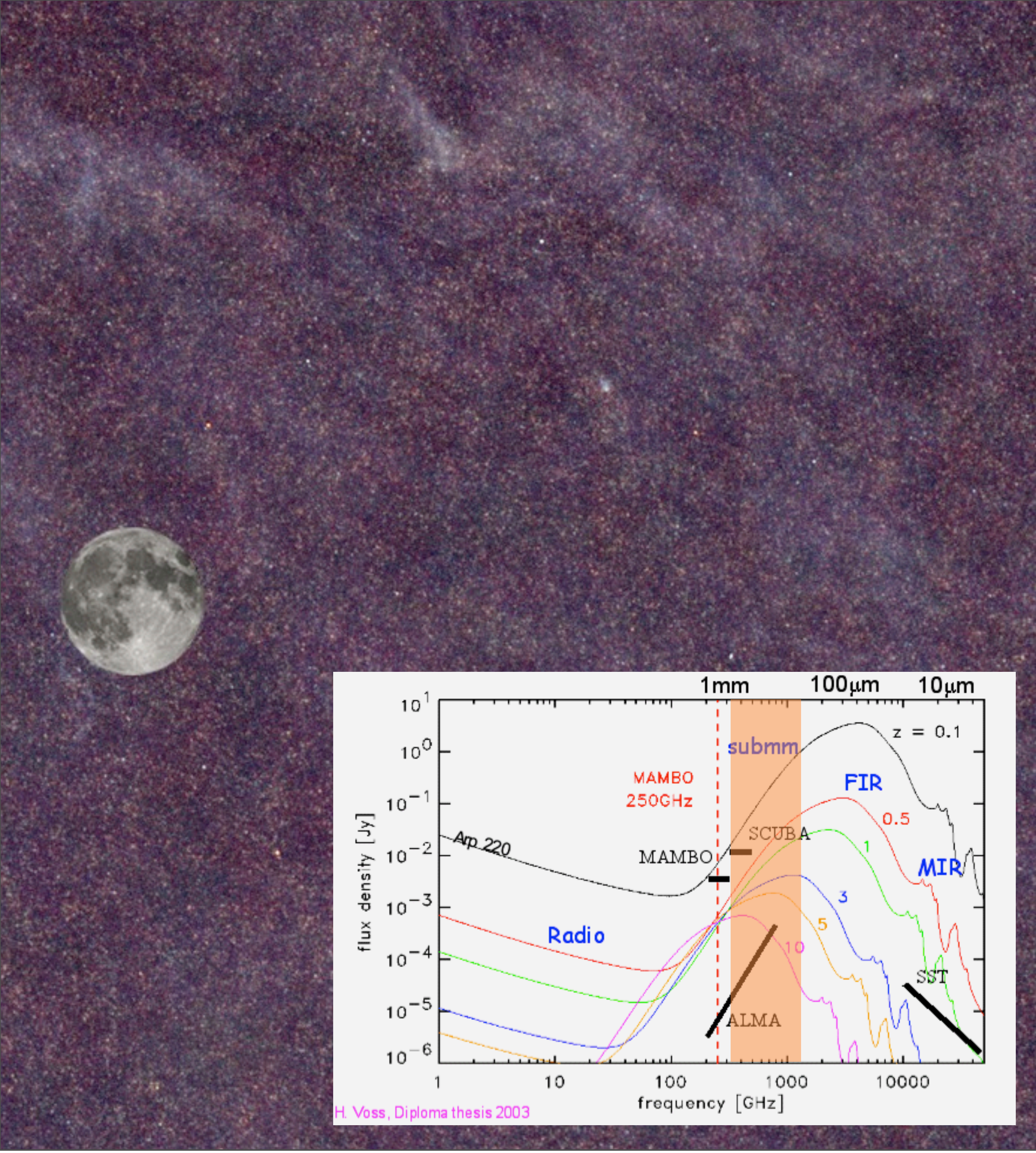


CO: brightest molecule that traces molecular gas

van der Werf et al. (2010)



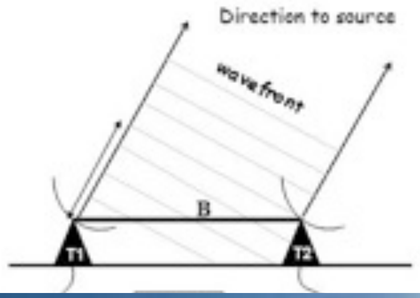
H-ATLAS
(Herschel Deep Field)



H-ATLAS (Herschel Deep Field)

many high-z sources. fluxes in (sub)mm ~const.

(sub)millimeter



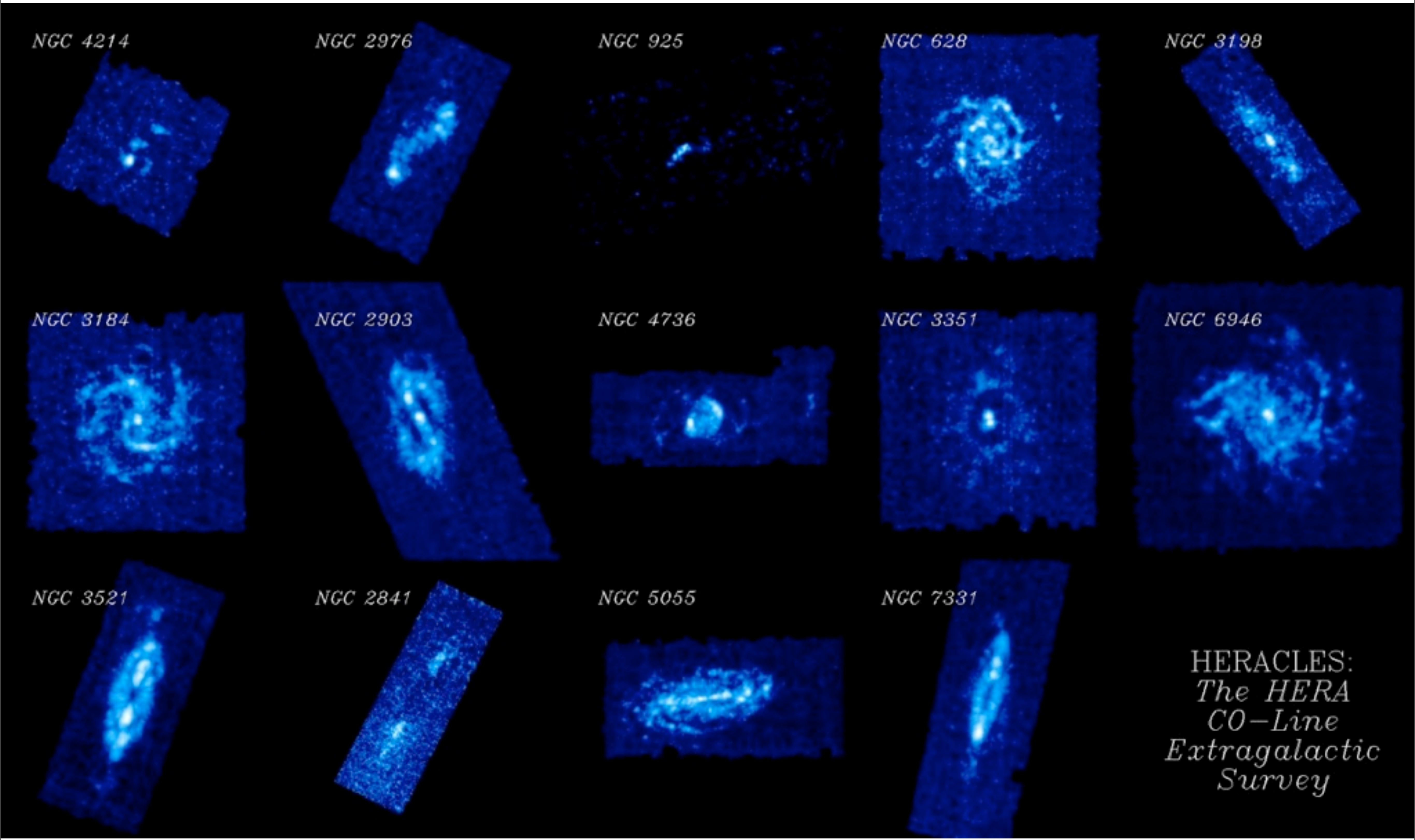
need interferometers (l/D)

Conditions in cold molecular gas phase (where stars form) give rise to rotational transitions.

These are observable in the millimeter regime.

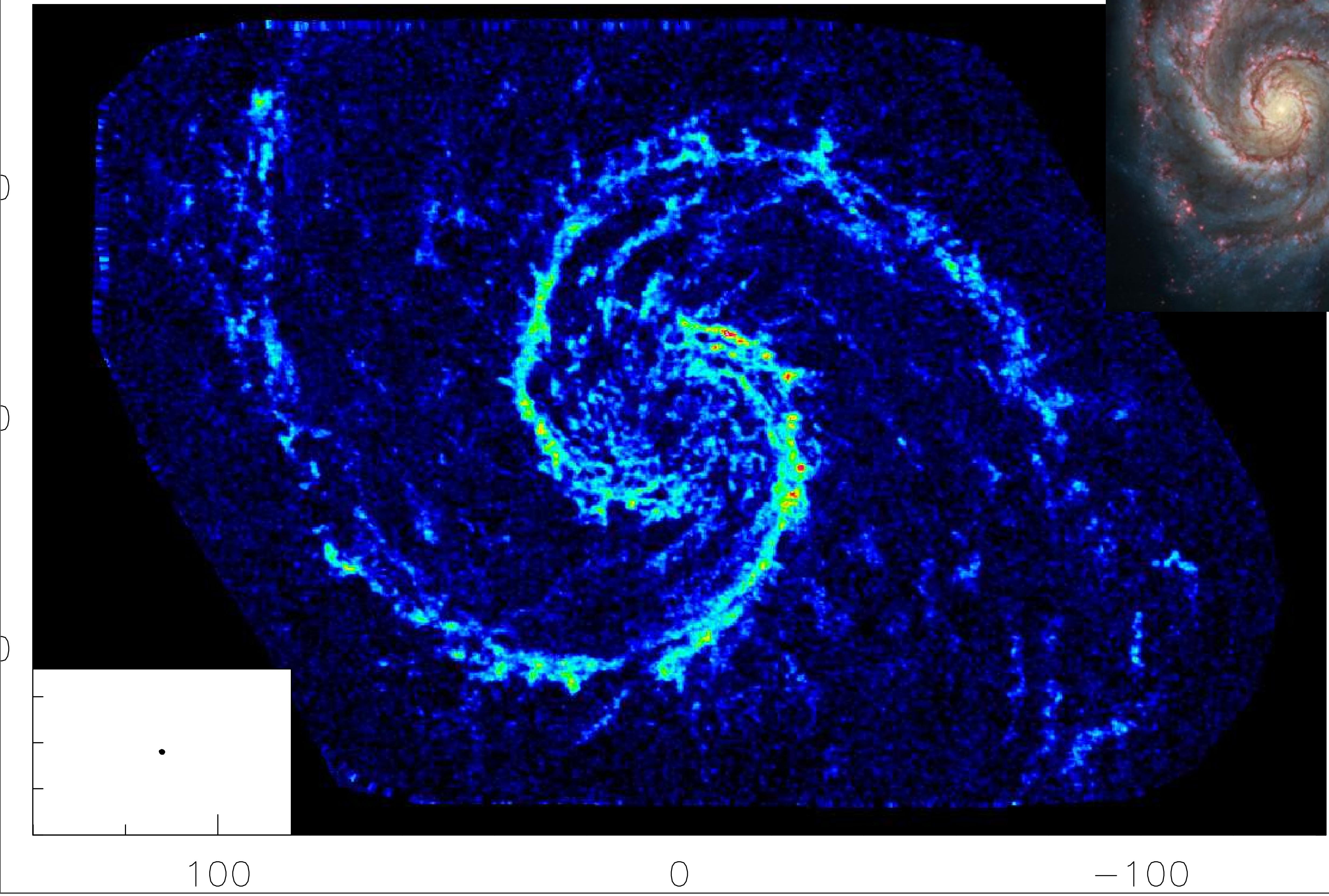
- Emission Lines provide a wealth of information about the interstellar medium:
  - Velocity
  - Excitation Mechanism
  - Phases
  - Density
  - Temperature
  - Abundances/Metallicity
- Models help in the interpretation of these data

CO: brightest molecule that traces molecular gas



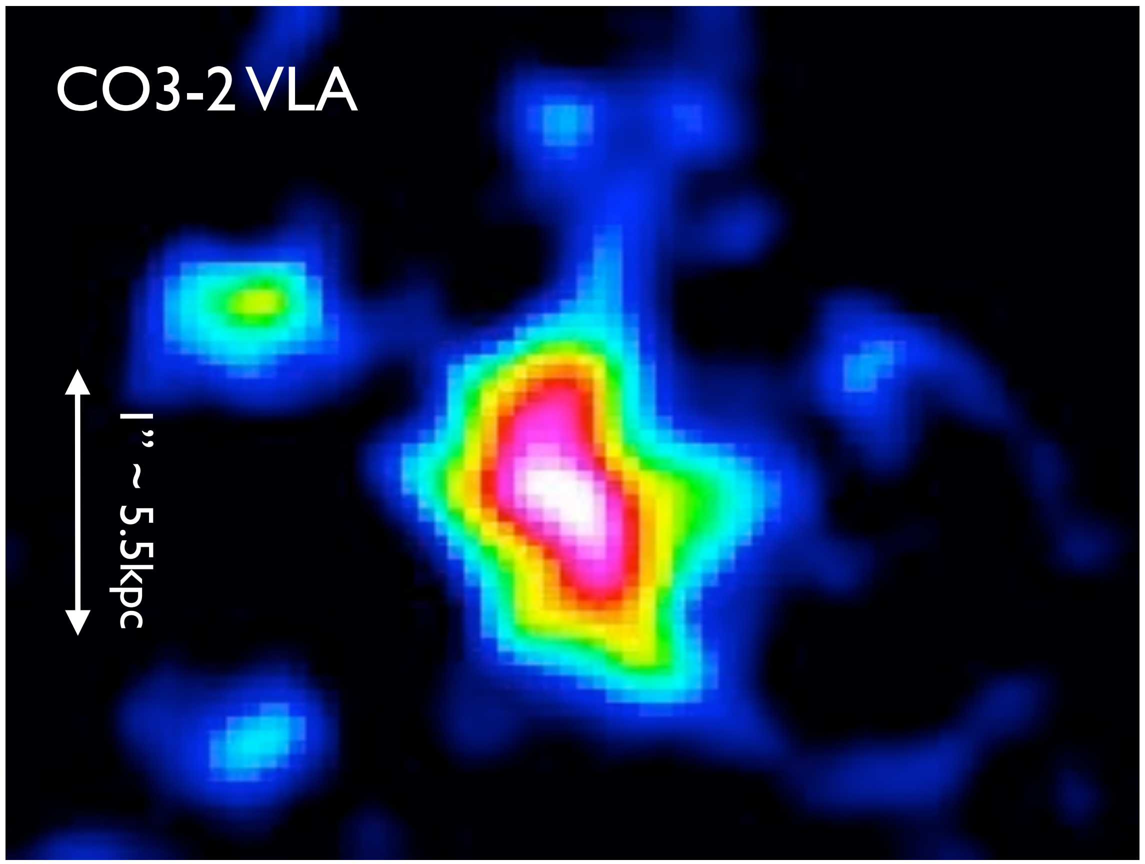
Leroy et al. 2009

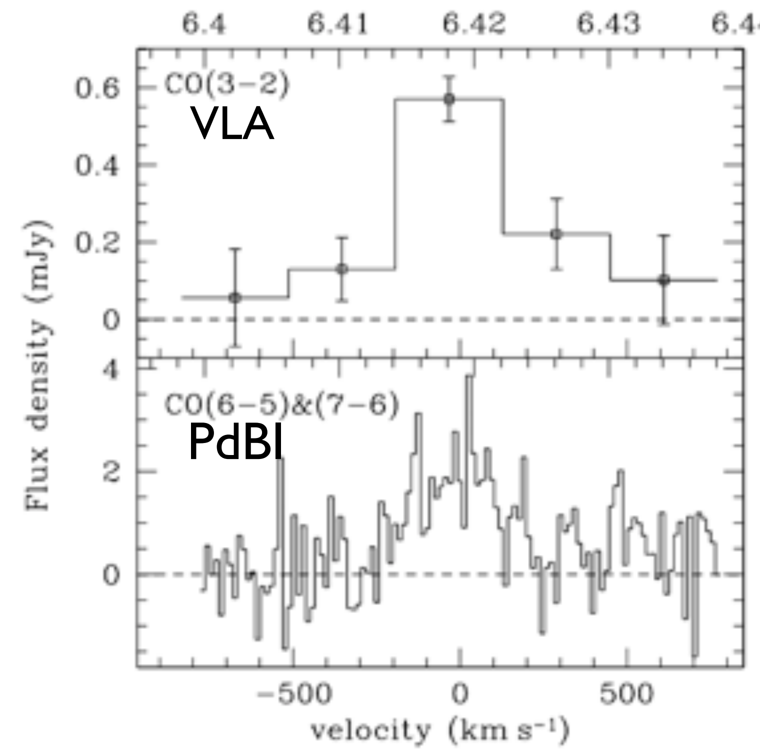
High fidelity maps reveal complex structure / gas in interarm regions



Schinnerer et al 2011

Molecular gas (CO) detected out to the most distant quasars (z=6.4)



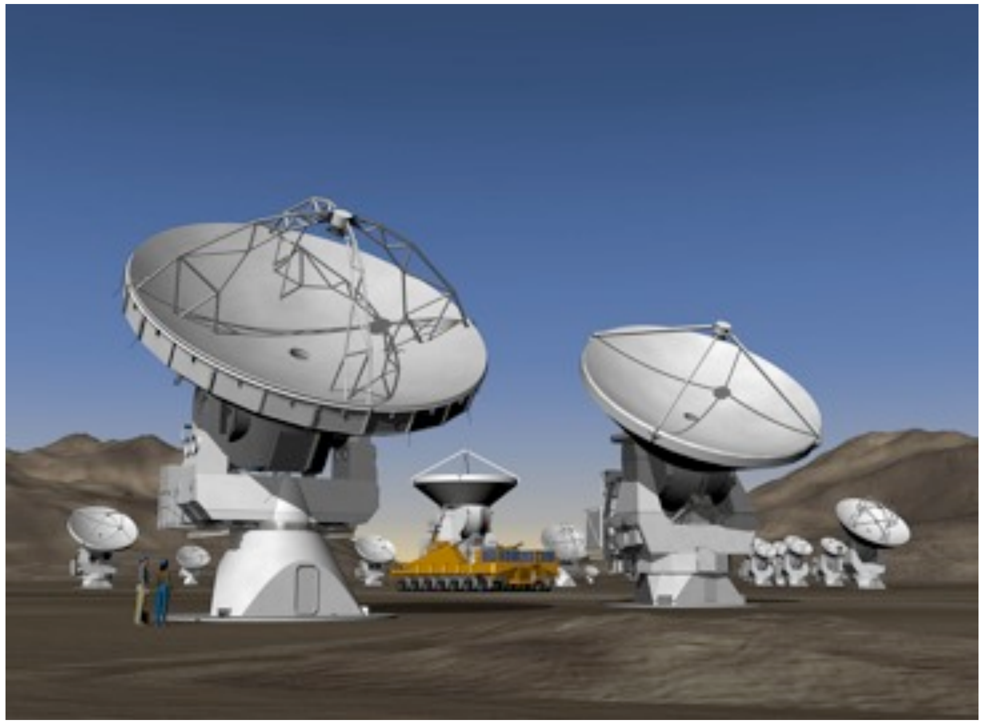


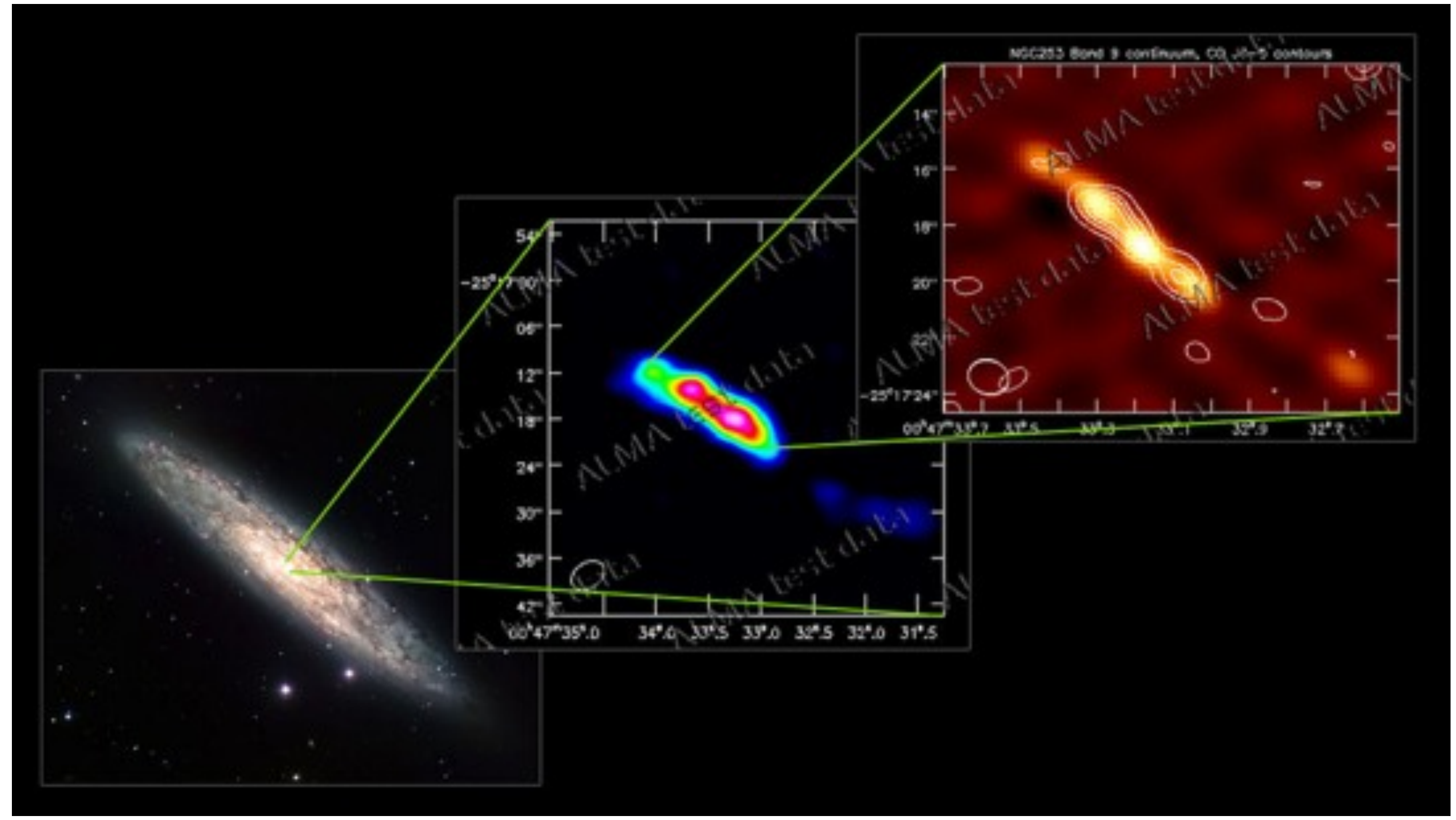
multiple transitions

- Size ~ 5.5 kpc
- $M(H_2) \sim 2\times10^{10}\ M_{sun}$
- $M_{dyn} \sim 5\times10^{10}\ M_{sun}$

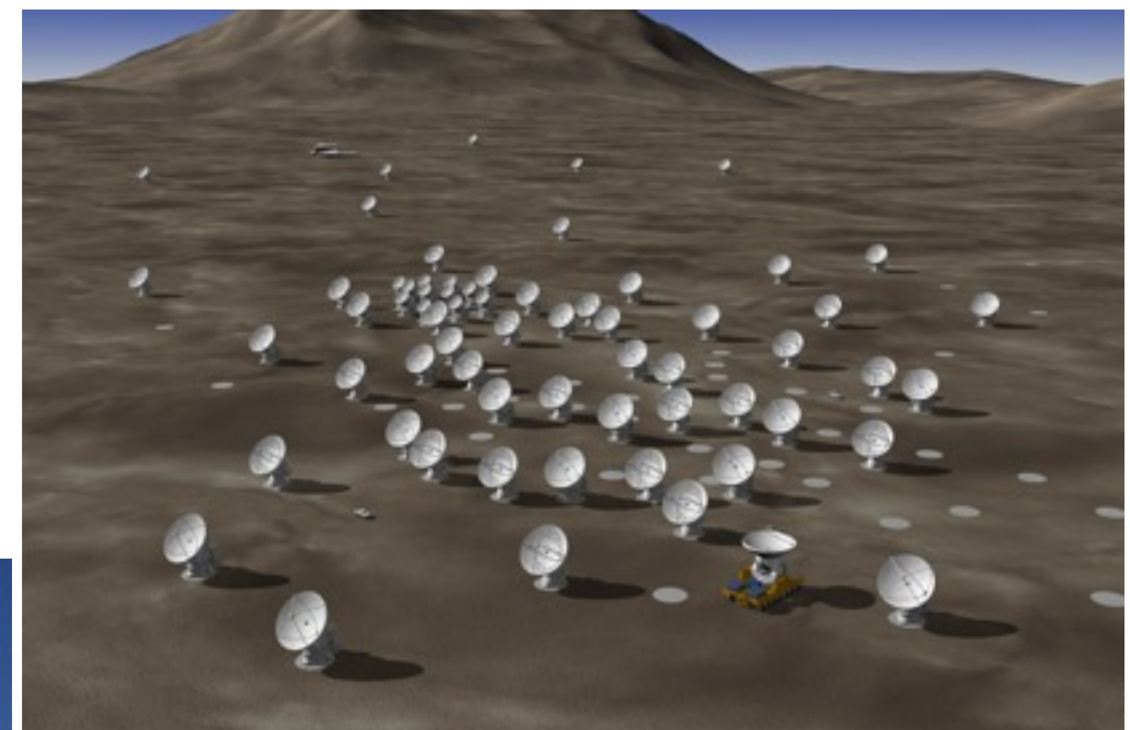
- FWHM = 305 km/s
- z = 6.419 +/- 0.001
- $M_{gas}/M_{dust} \sim 30$ (~ starburst gal.)

Walter et al. 2004



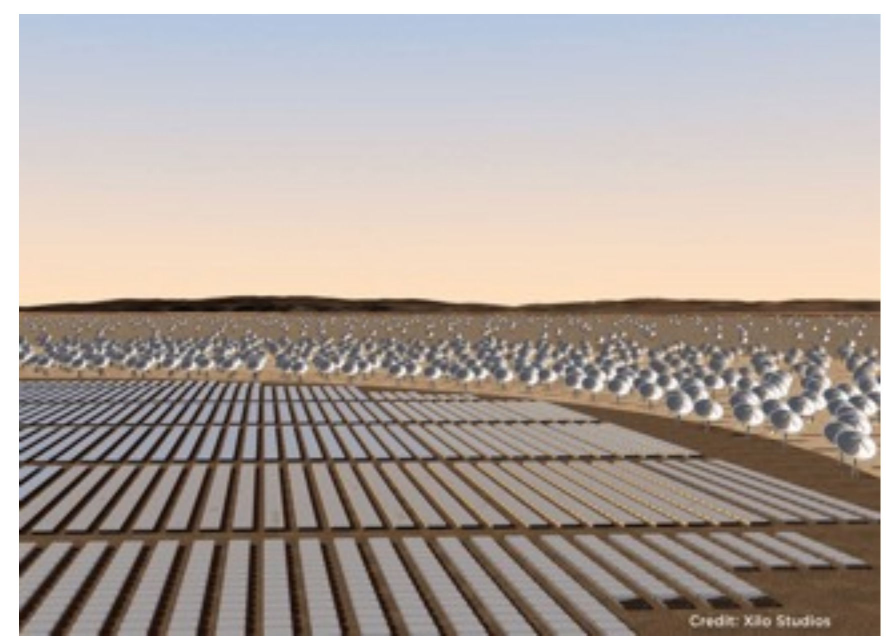


the future is now: ALMA

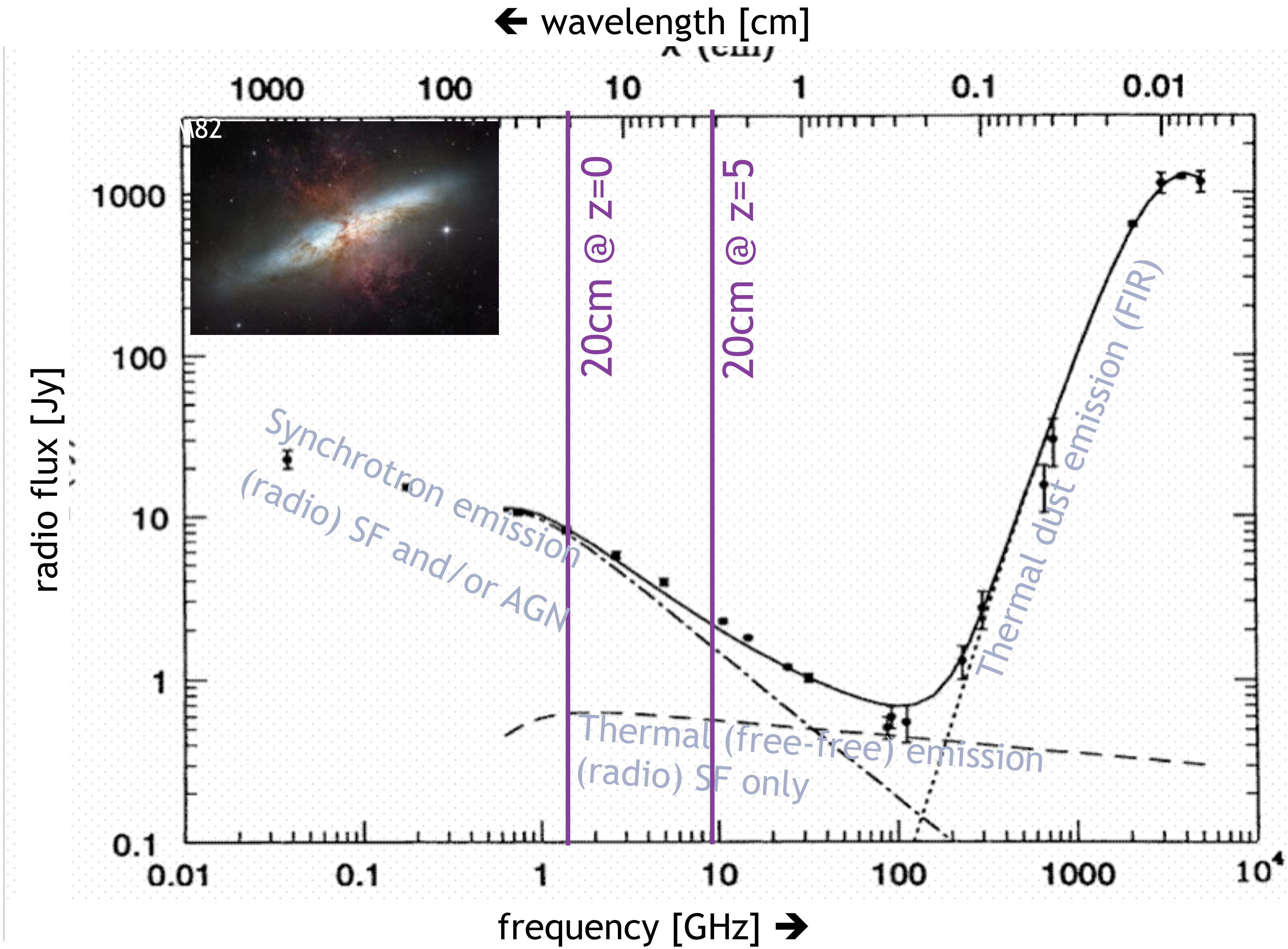


radio

the future: SKA



Origin of Radio Continuum Emission



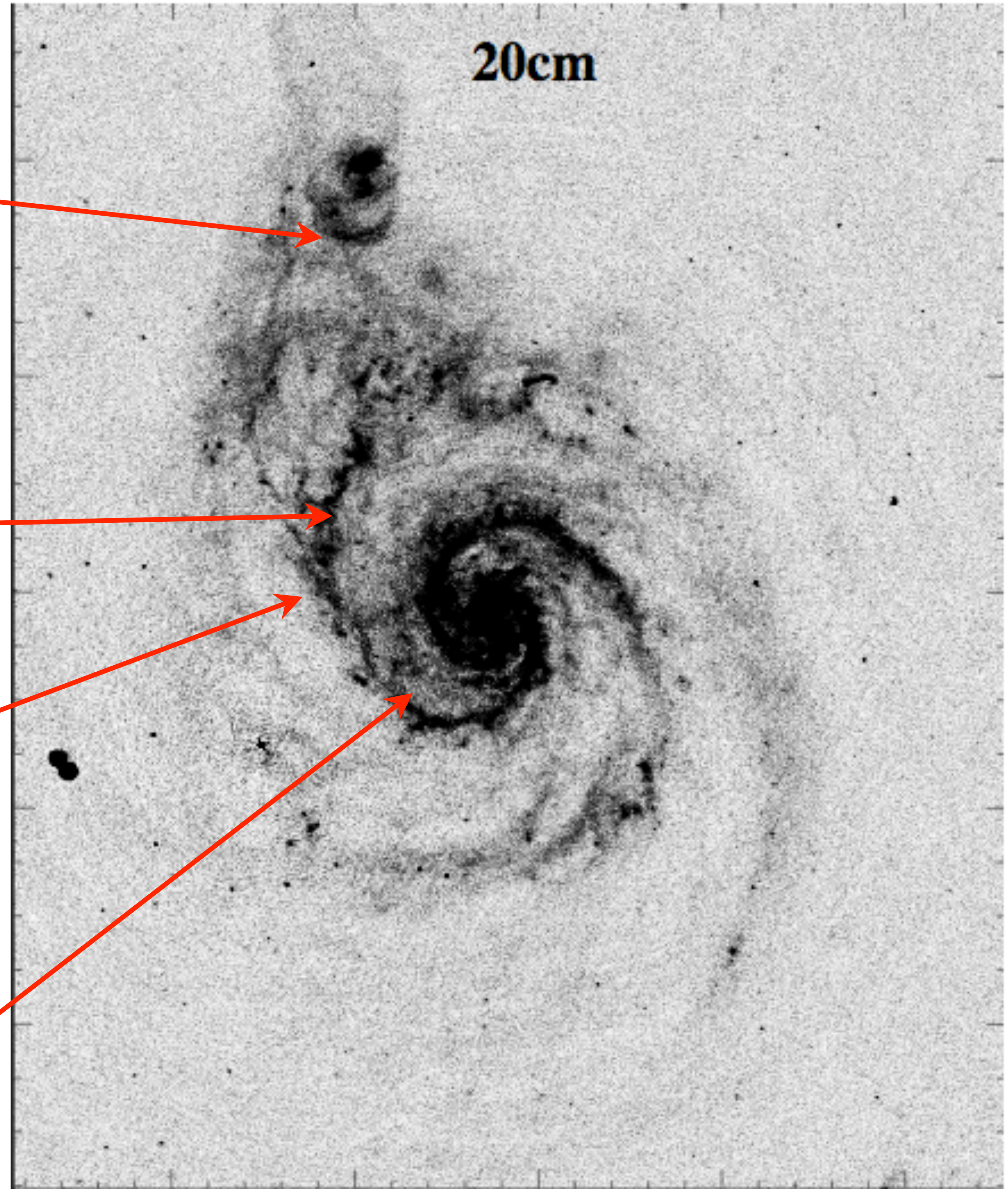
Radio – What do we see?

synchrotron
due to interaction
(no SF relation)

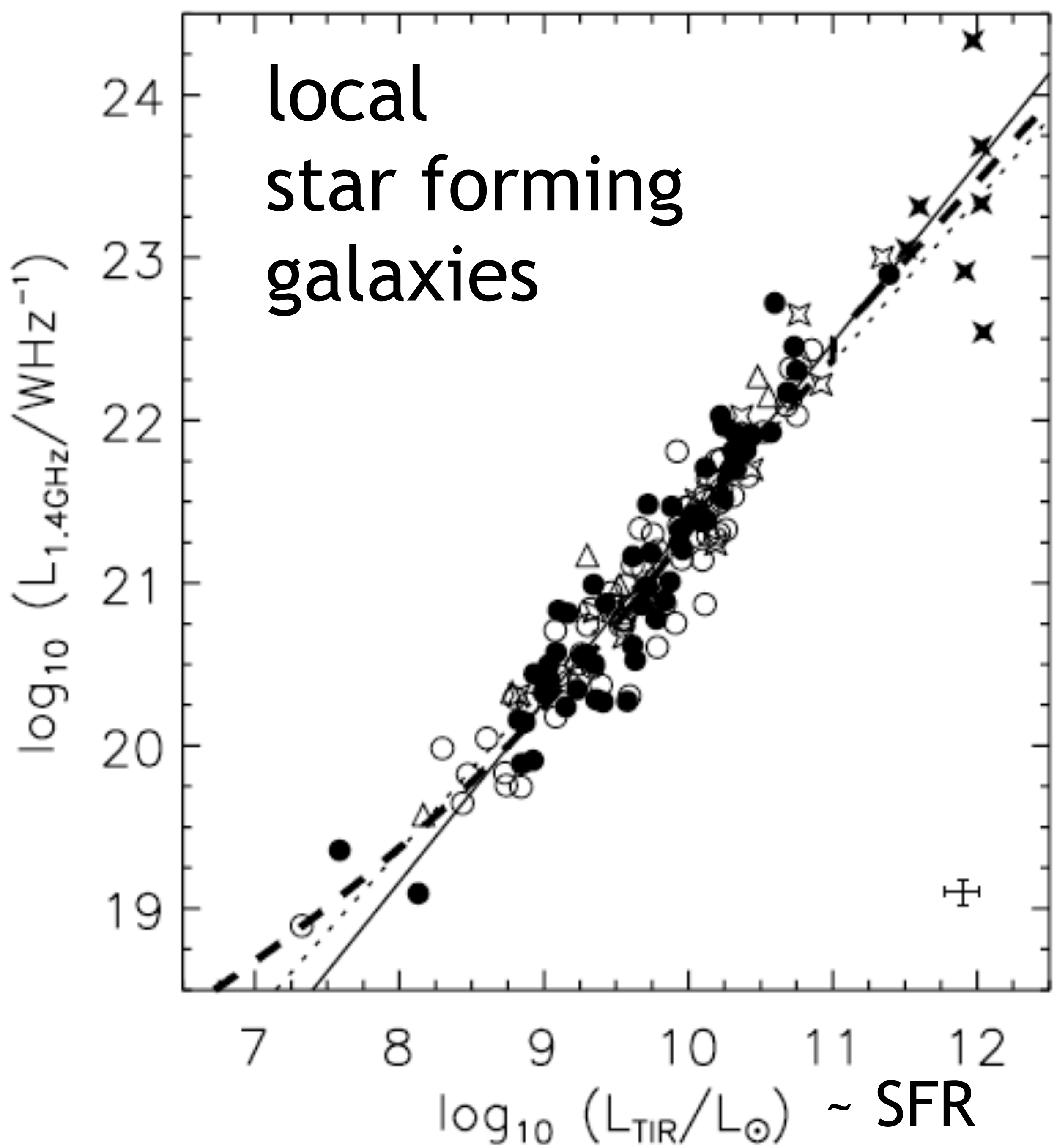
Thermal &
non-thermal
Due to SF region

Synchrotron
Diffusion from
SN

Synchrotron due
to spiral shocks
(no SF relation)



Empirically observed Radio-IR relation



$$q = log \frac{S[FIR]}{S[20cm]} = const$$

radio continuum traces very well (high-mass) star formation

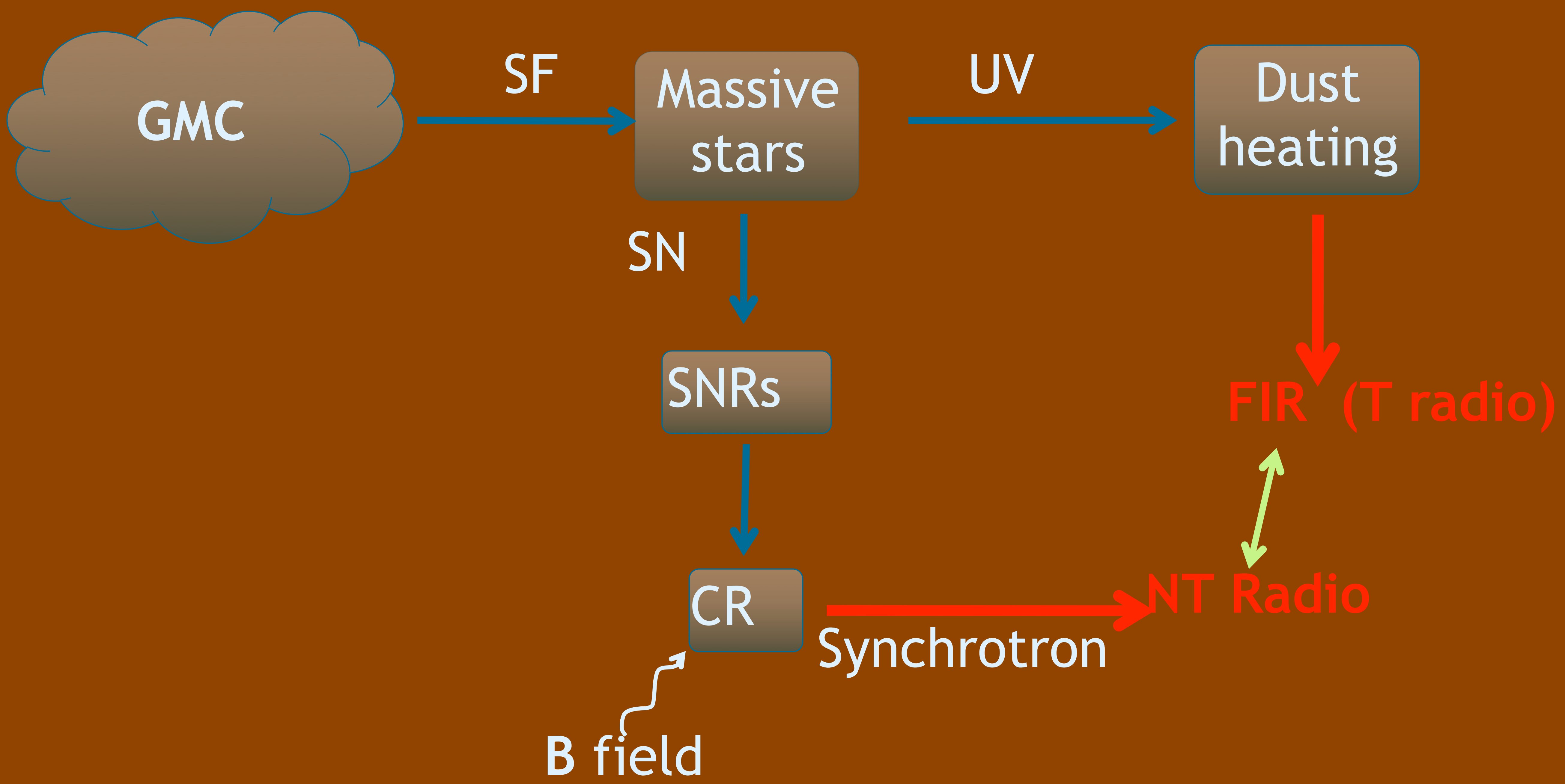
Over 4 orders of magnitude

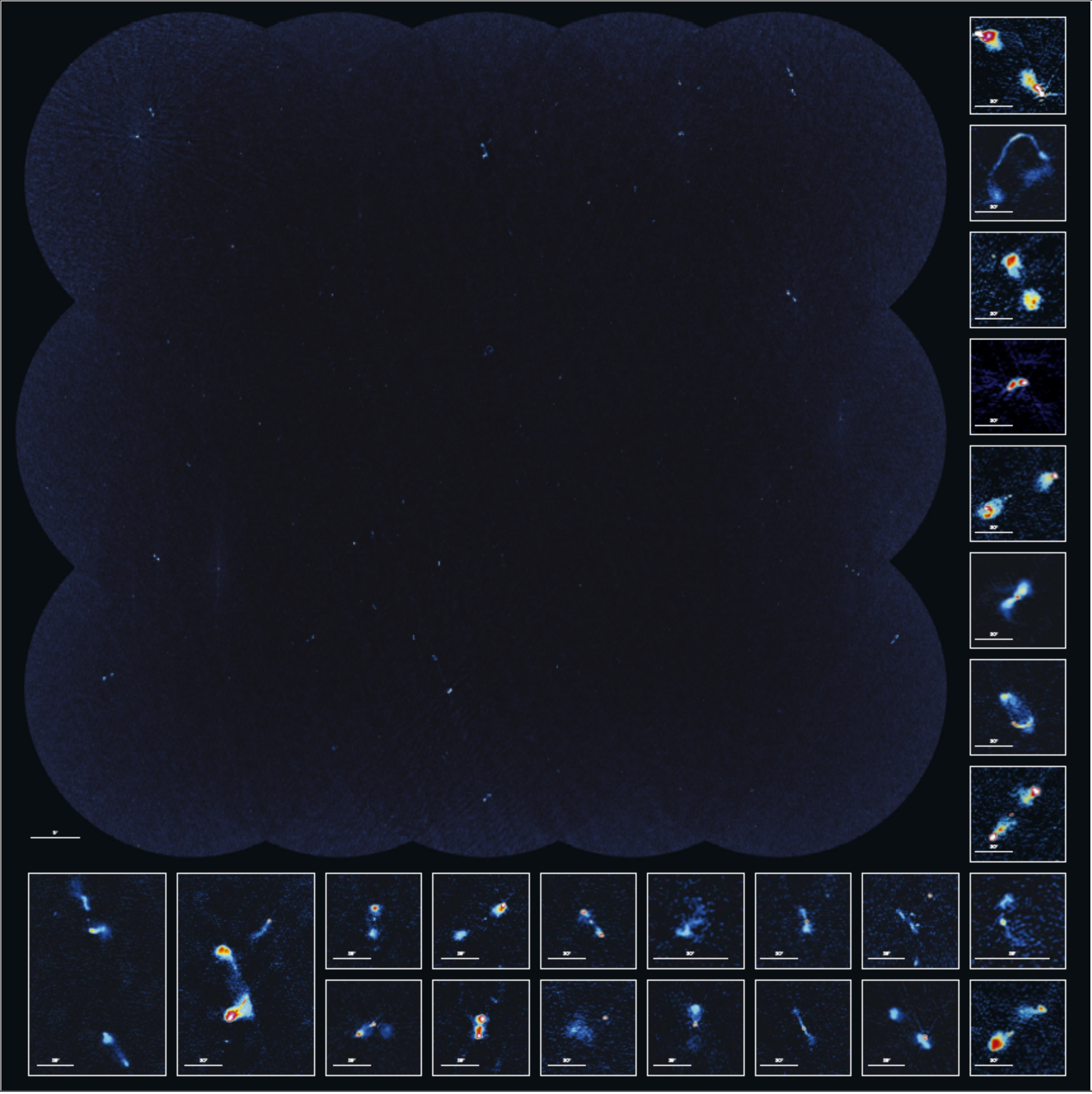
From starbursts to normal Star forming systems

Main driver: Star Formation

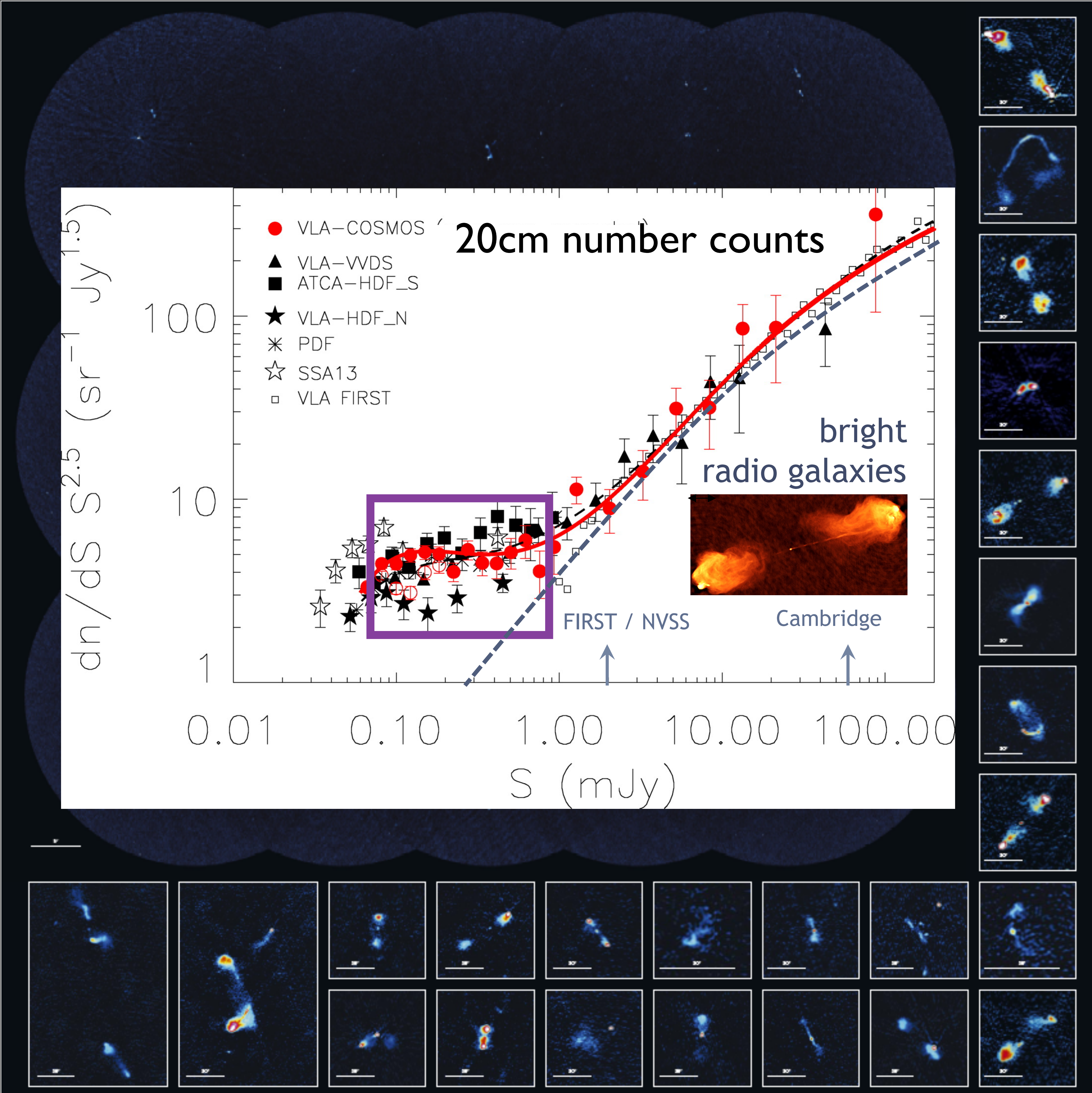
de Jong et al. (1985), Helou et al. (1985)
Bell (2003), Yun, Reddy, Condon (2001)

(possible) explanation of Radio-IR relation





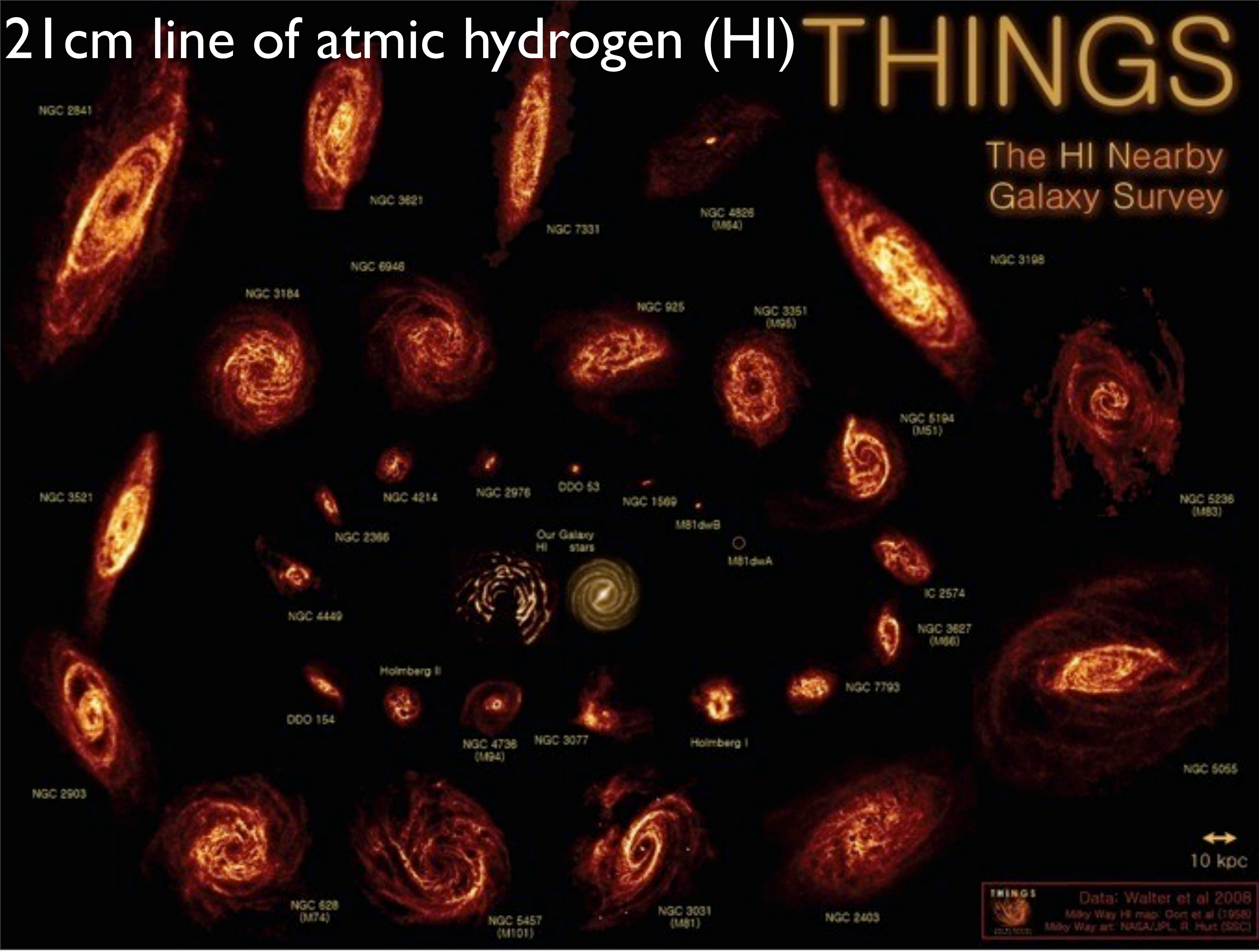
radio deep fields (here: COSMOS) mostly trace AGN/radio galaxy population...



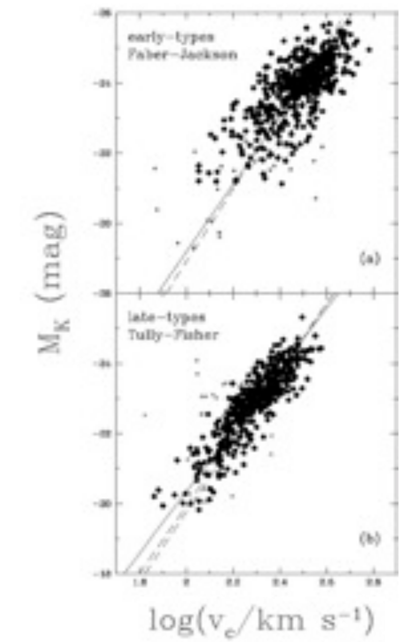
radio deep fields (here: COSMOS) mostly trace AGN/radio galaxy population...

...but star forming galaxies are entering at faintest flux levels

21cm line of atmic hydrogen (HI)

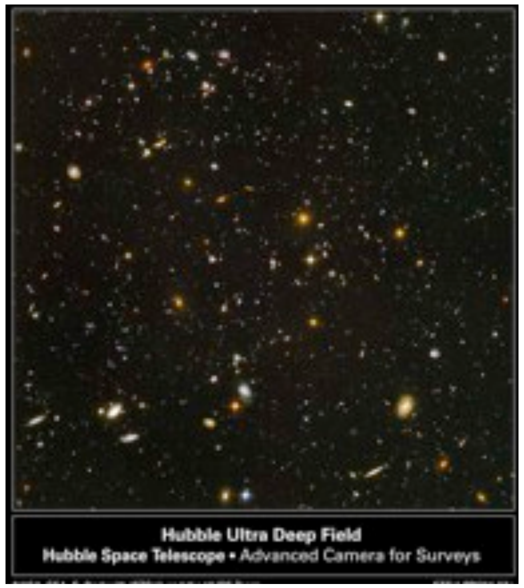


Questions that we want to address in this lecture are:

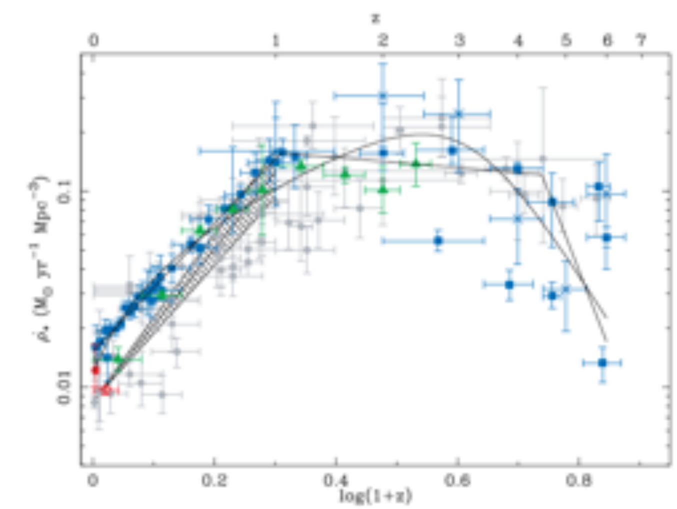


- why is the current population so regular

- when were the galaxies' masses assembled



- when/how did the stars form



- why do galaxies emit radiation over ~10 decades in frequency

- what do they do to the rest of the universe