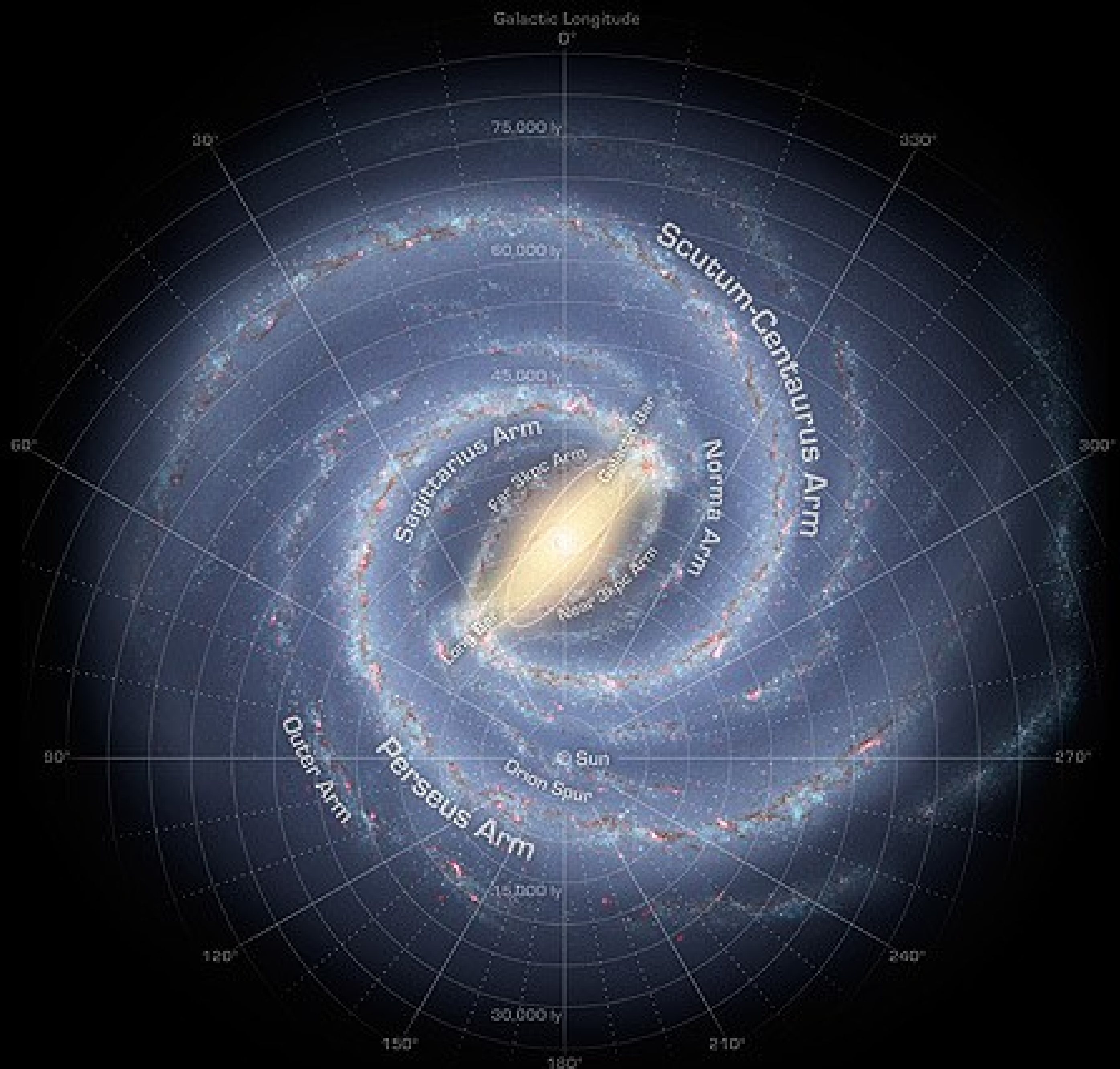
Star formation

Starburst Galaxies

Starting point: The Milky Way

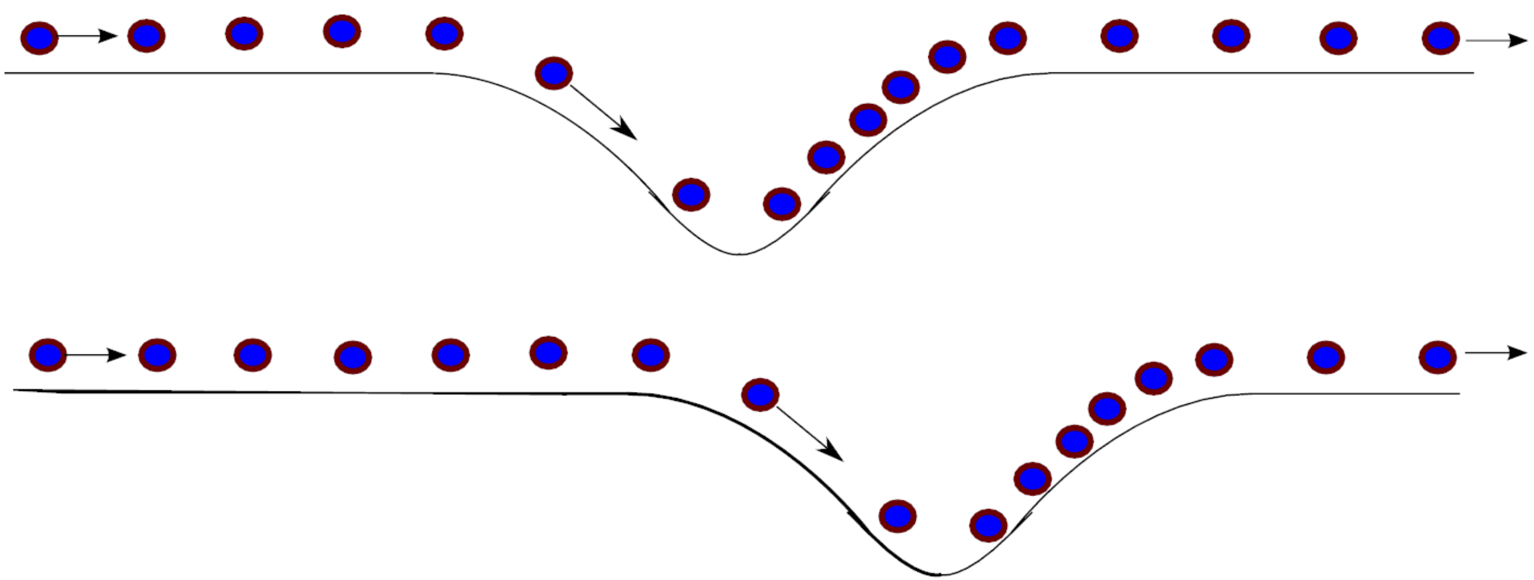


Spiral structure of the Milky Way derived from Spitzer observations

Star formation in spirals

• Spirals are small (~5%) density enhancements in the distribution of stars and interstellar clouds.

• In the Galactic rotation, stars and gas pass through the gravitational potential of the wave, first accelerating their motion, the decelerating it.



•The spiral is self-sustaining

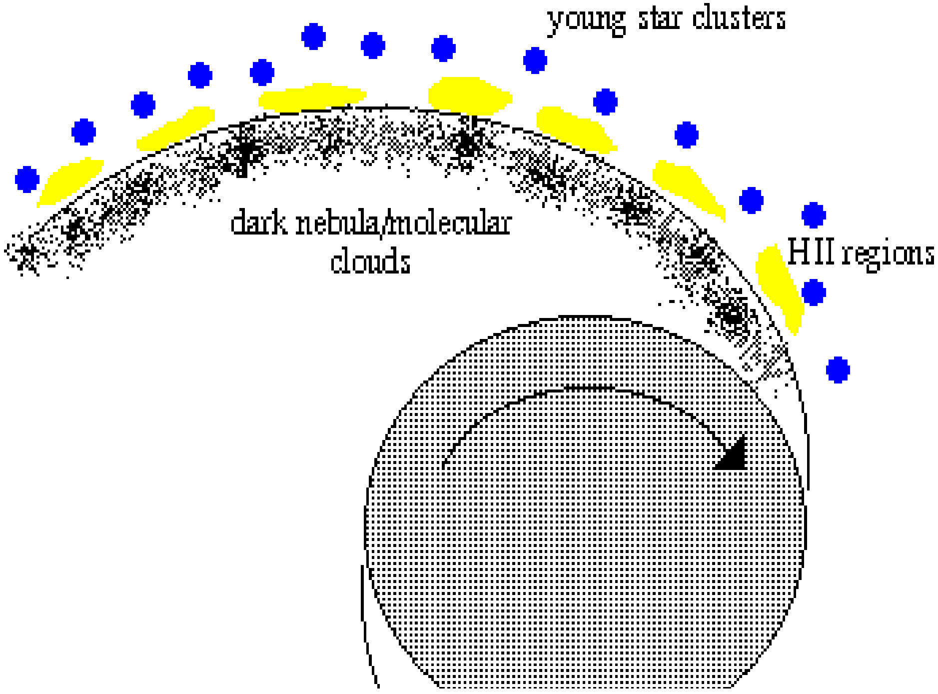
•It is always trailing to the Galactic rotation: v_{rel}=10-20km/s

Star formation in spirals

• Molecular clouds are compressed in the spiral
→ turn Jeans unstable → star formation

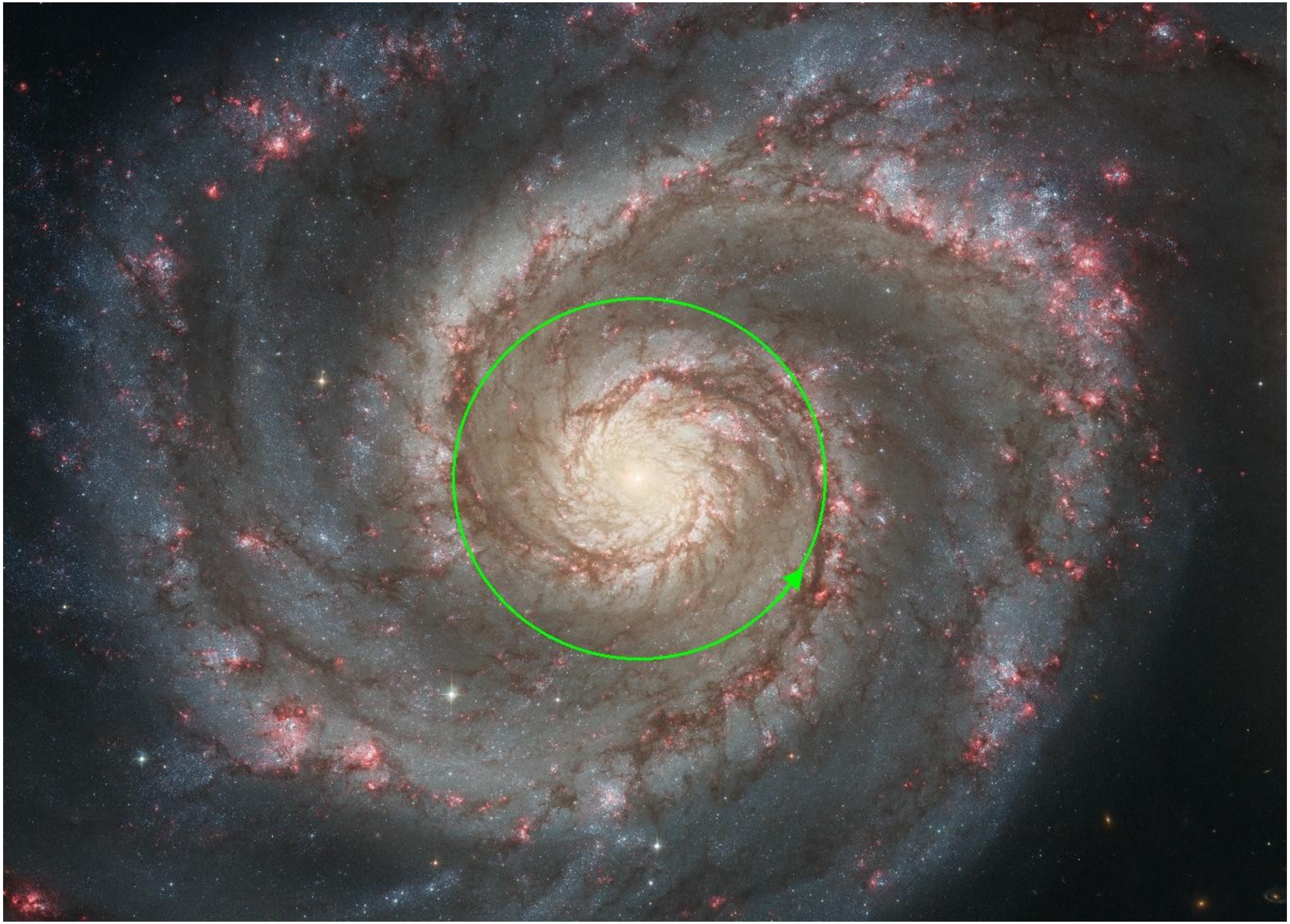
• Massive stars create HII regions and appear at the front edge of the spiral where they die.

• Low-mass stars live long enough to enter the inter-spirals space.



→ Spirals are bright in spite of the low density contrast.

Star formation in spirals

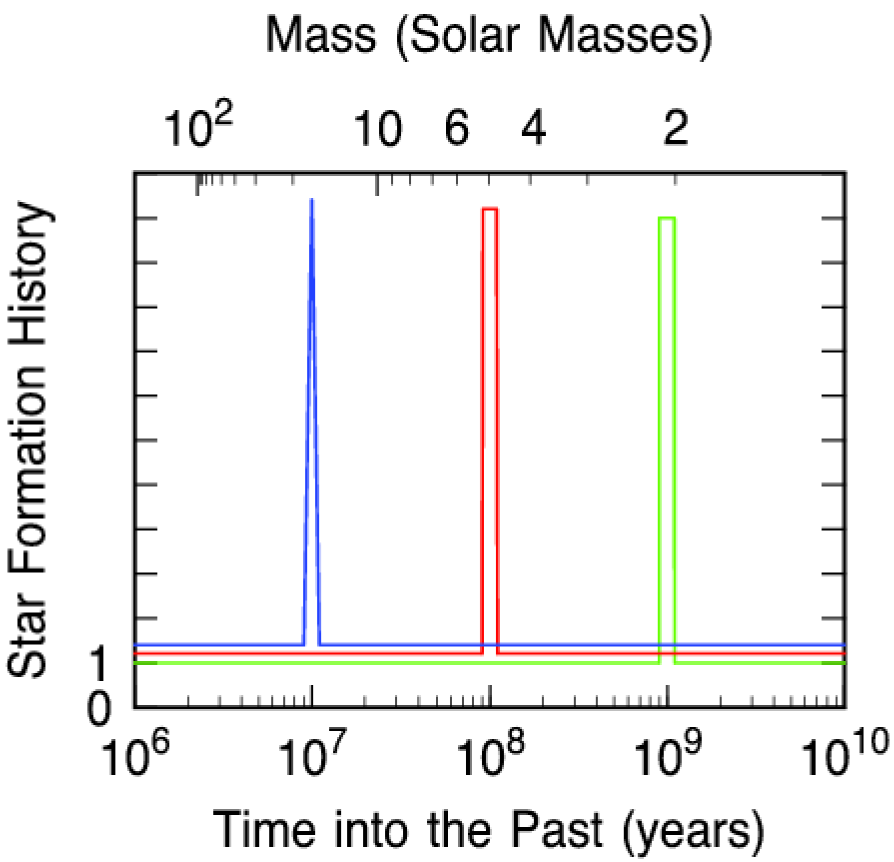


→ **Spirals are bright in spite of the low density contrast.**

Episodic star formation

Already considered in creation of IMF:

- Star formation is not continuous but varies by orders of magnitude, where high-mass stars are only formed for short periods



Starburst episodes

triggered e.g. by spiral density wave

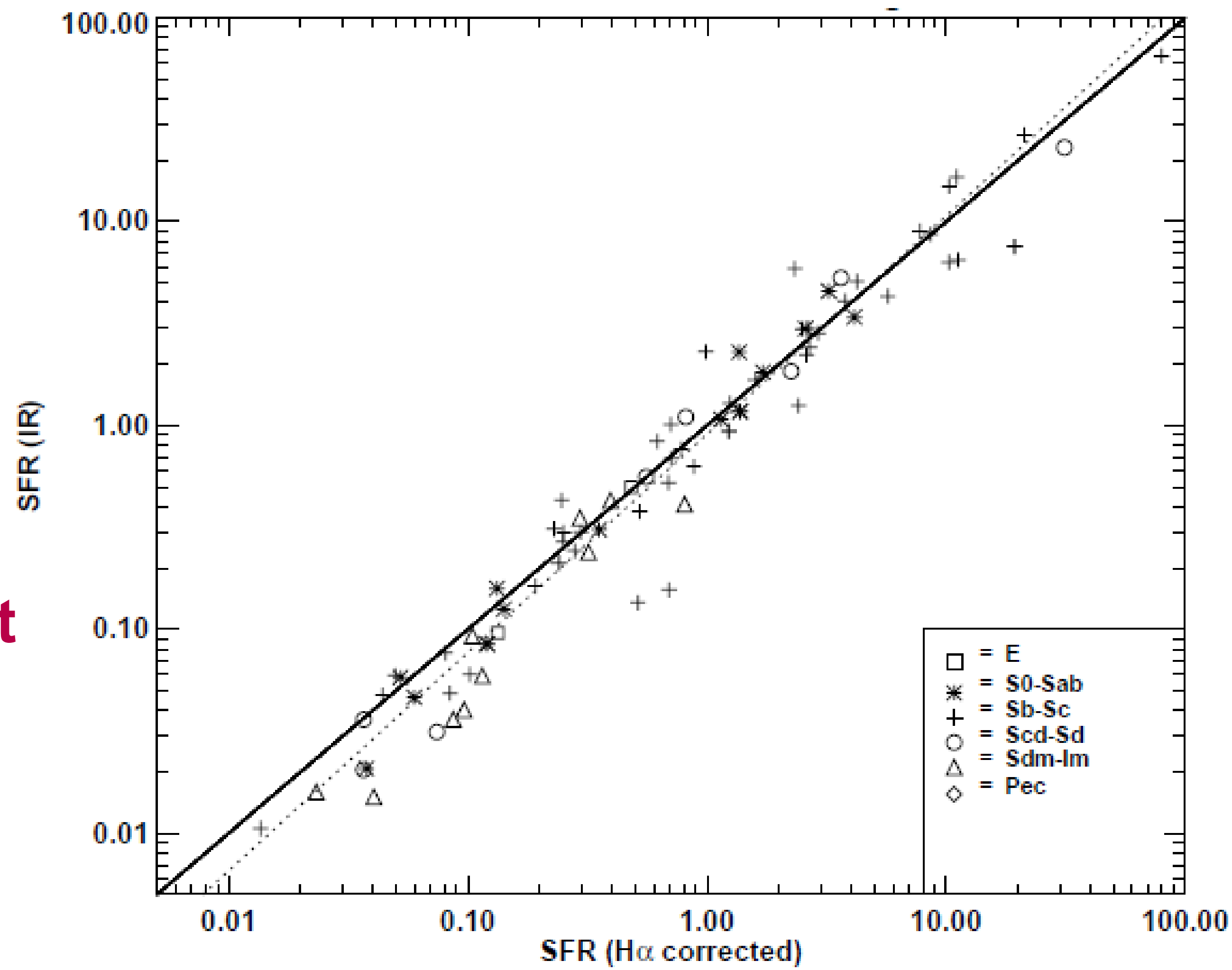
Measuring the SF activity

What are good tracers of star formation efficiency:

- Most measures based on extragalactic observations
  - Avoid line-of-sight confusion and galactic extinction

→ **FIR luminosity most reliable tracer**

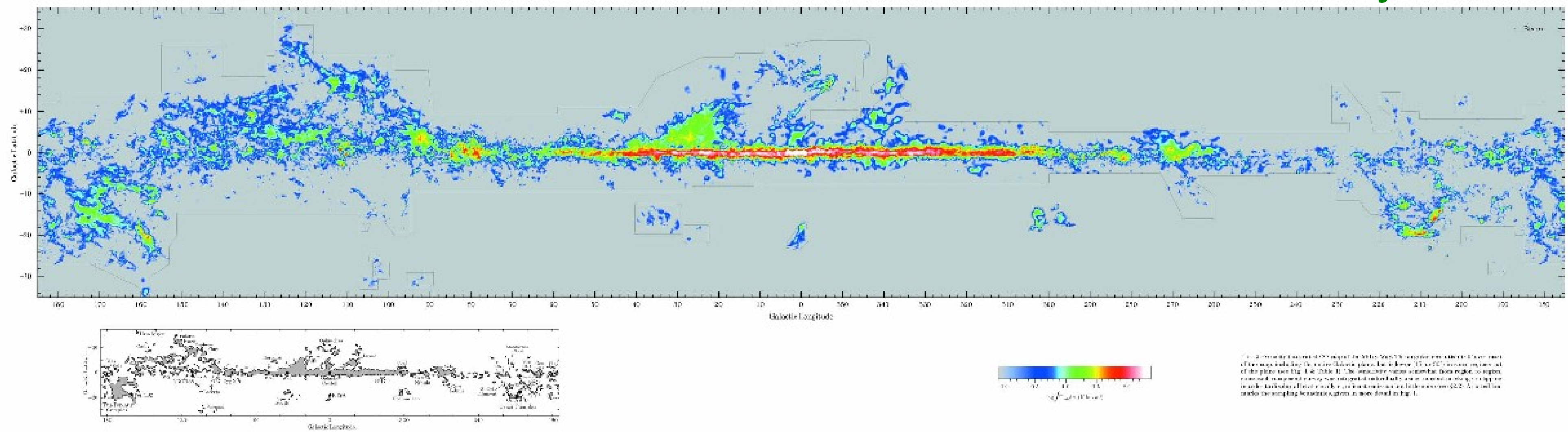
- Measures total energy input from densely embedded sources

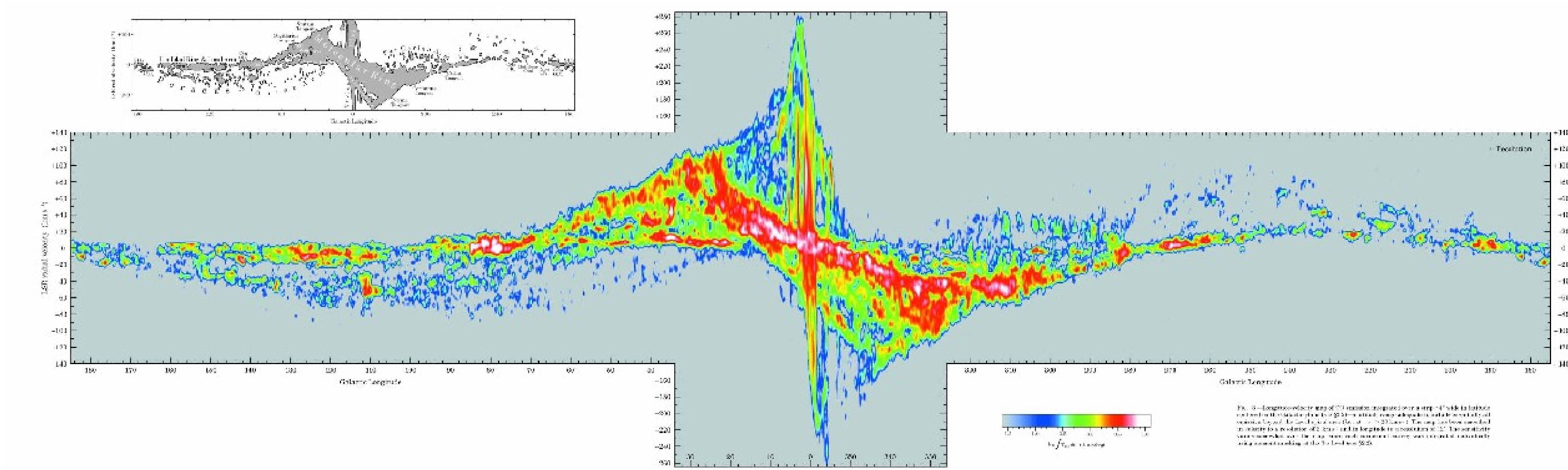


Kewley et al (2002)

Molecular clouds in the Milky Way

Distribution of molecular clouds able to form stars traced by CO:

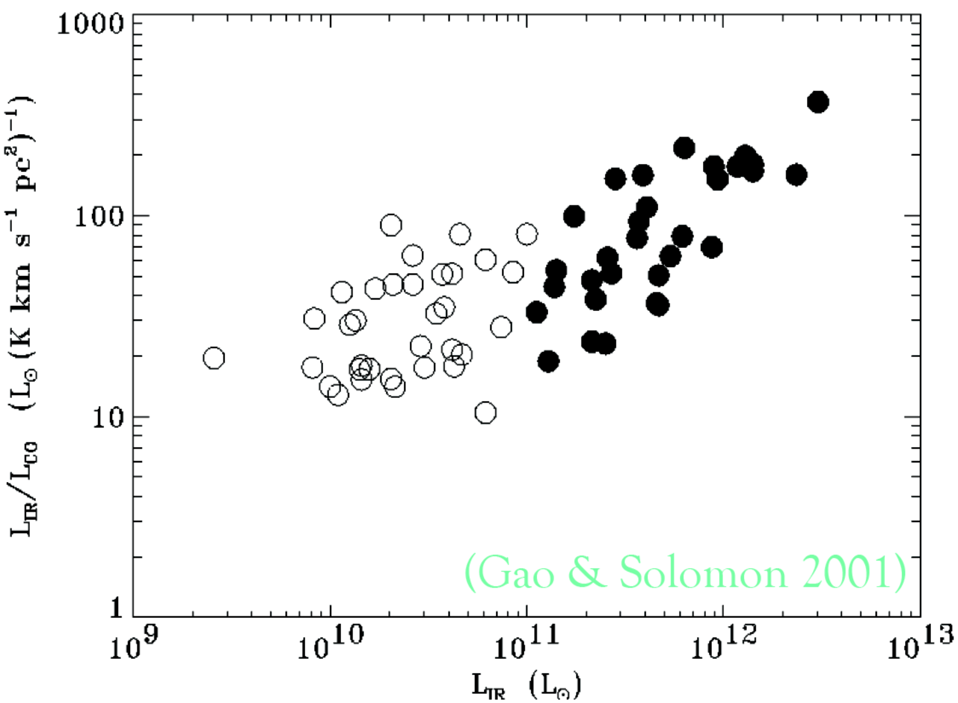


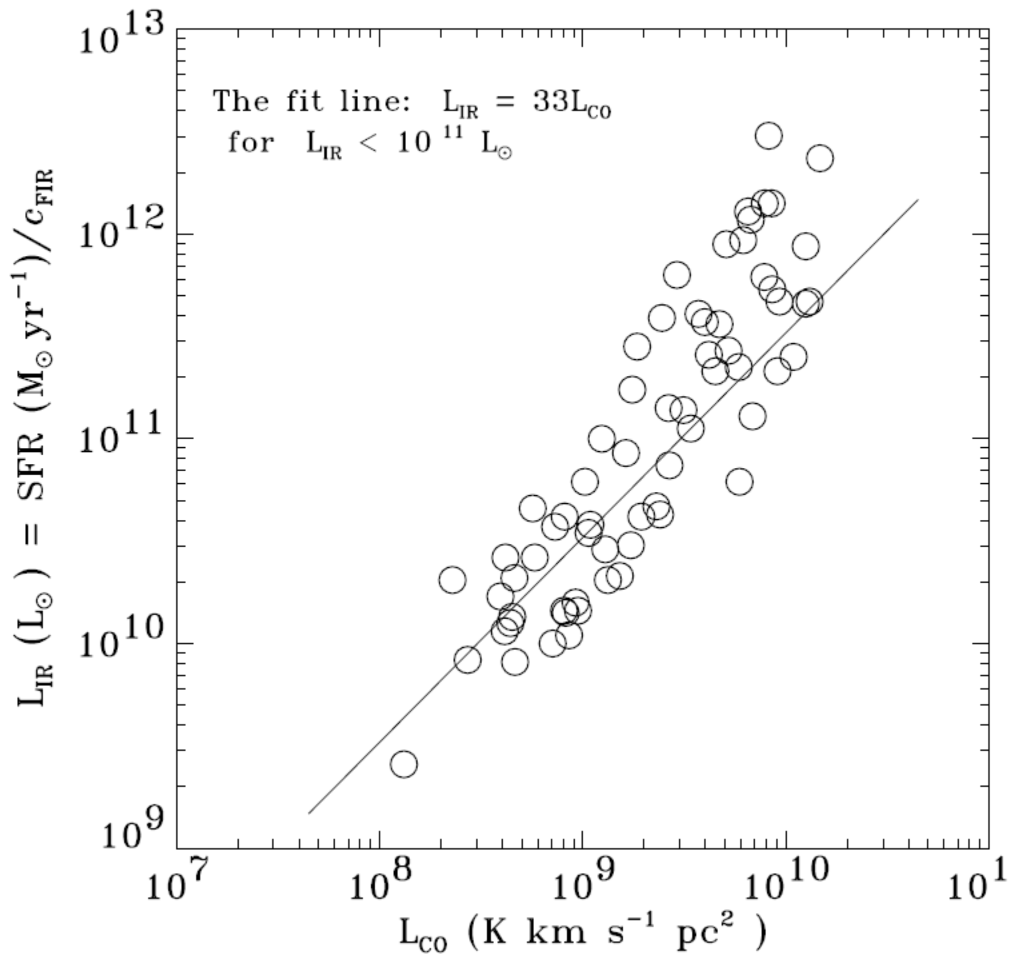


Measuring the SF activity

How much molecular cloud mass is transformed into stars?

- SFR approximately proportional to CO intensity
  - But, deviations at high intensities



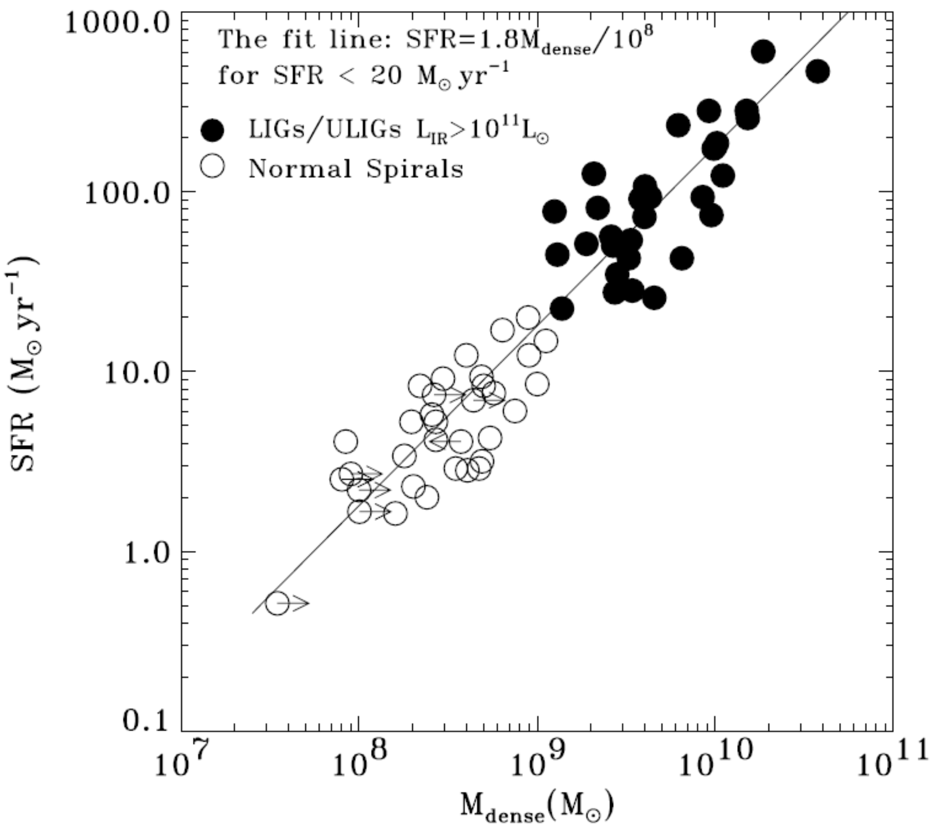


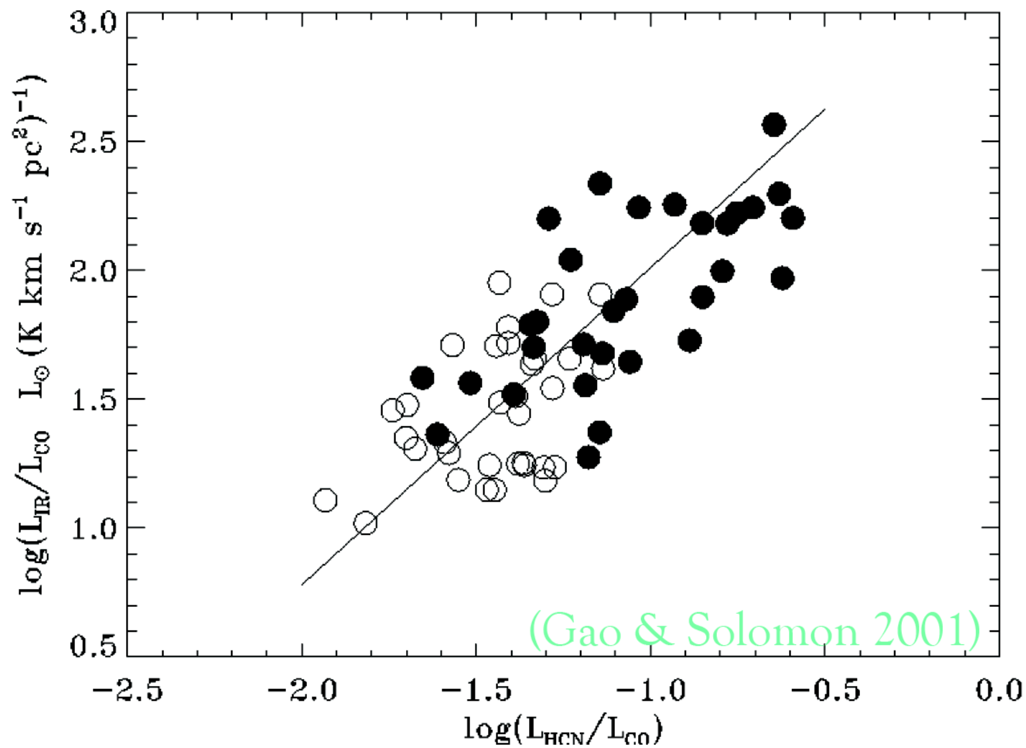
Gao & Solomon (2001)

Measuring the SF activity

How much molecular cloud mass is transformed into stars?

• SFR better correlated to high-density tracers





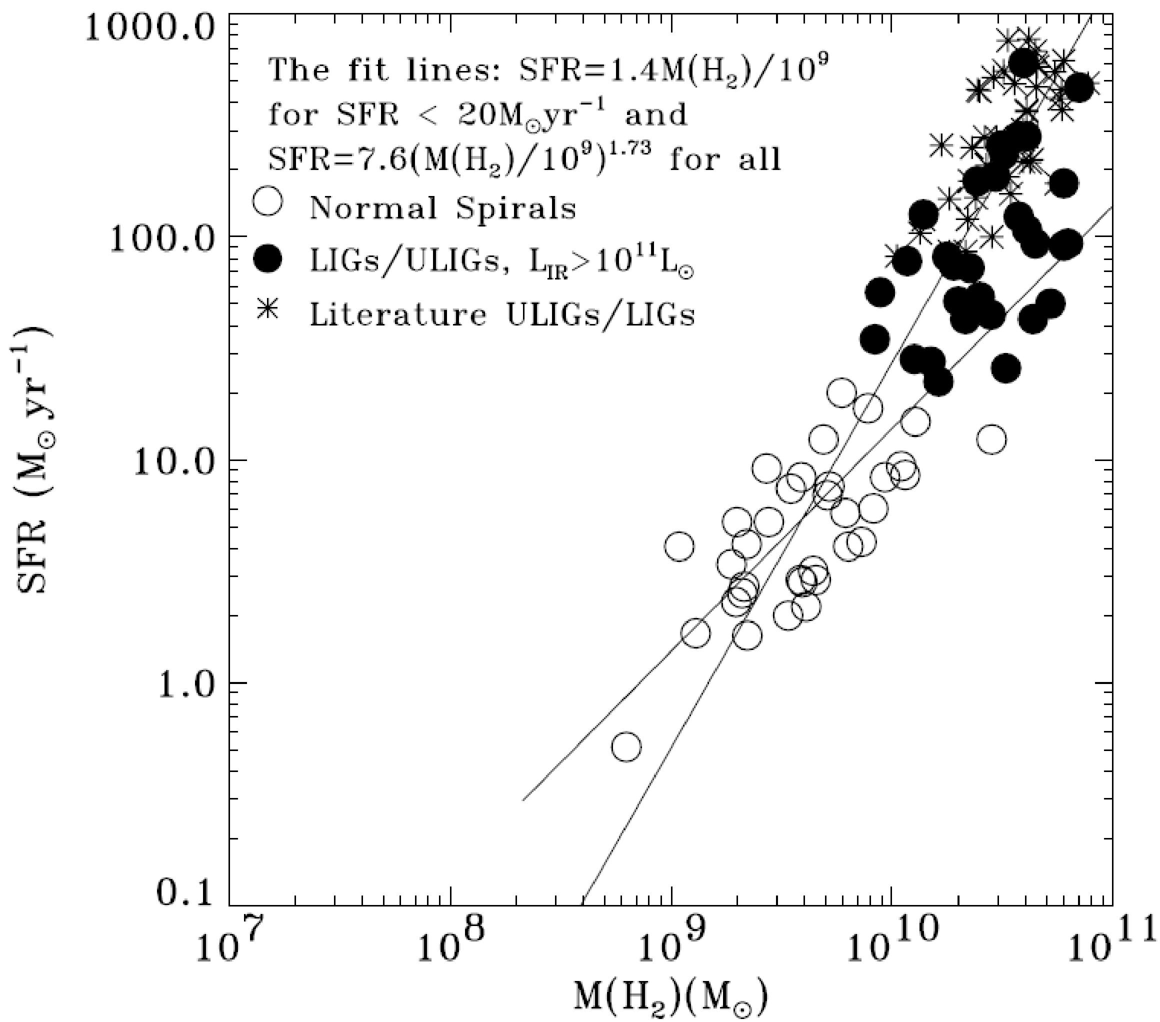
In most galaxies, we find a fixed efficiency for converting dense molecular gas into stars!

Gao & Solomon (2001)

Cause of global SF activity

Star formation rate:

- How much dense gas
  - is present in a galaxy?
  - can be compressed due to galaxy dynamics?
  - can be externally supplied
    - By accretion?
    - By galaxy mergers?
  - is replenished after SF consumes and ejects gas



Gao & Solomon (2001)

SF activity in the Milky Way

Accretion of material from high-velocity clouds not sufficient to replenish material that is ejected:

- Surface density and SFR in the Milky Way decreased over the last 5 Ga.
- $\Sigma_*(t) \sim t^{-(1+\beta)}$, $\beta \sim 2.2$

Fuchs et al (2009)

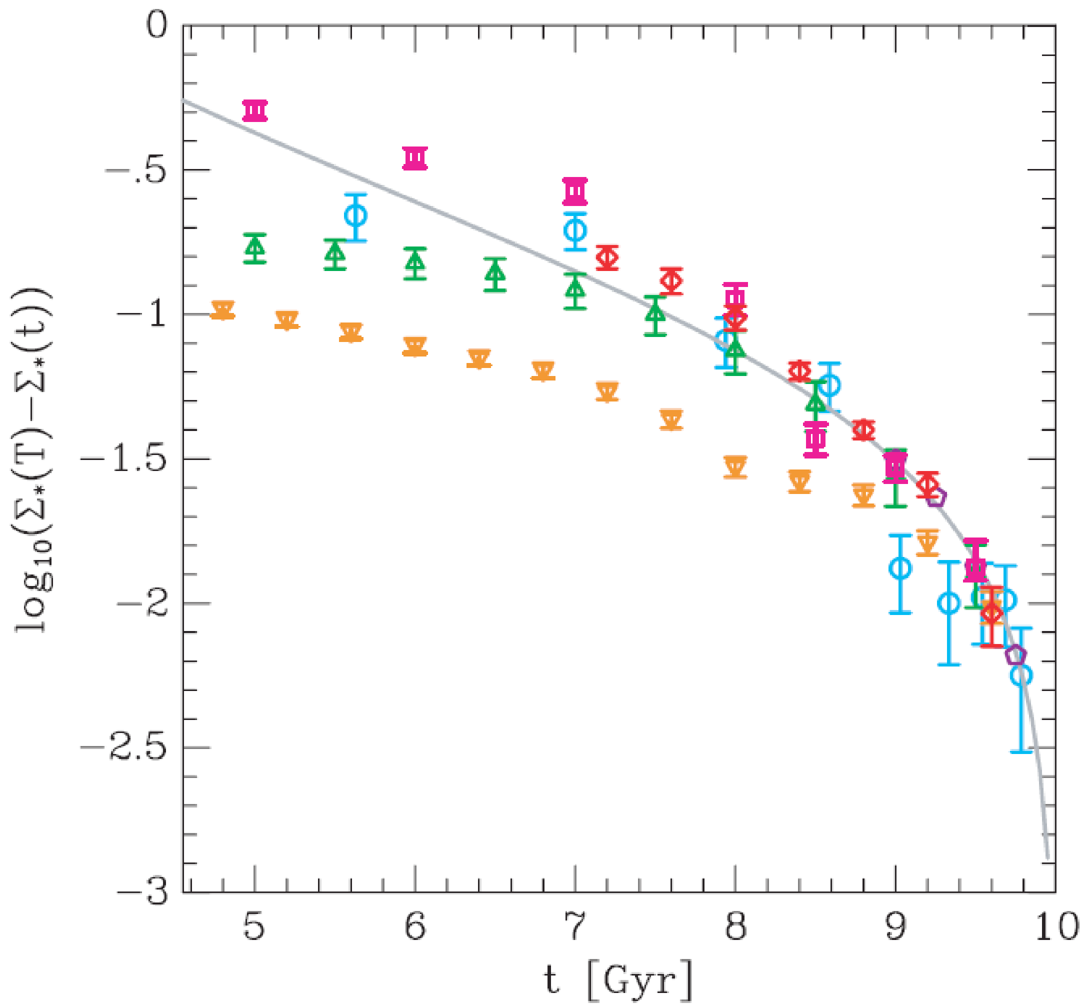
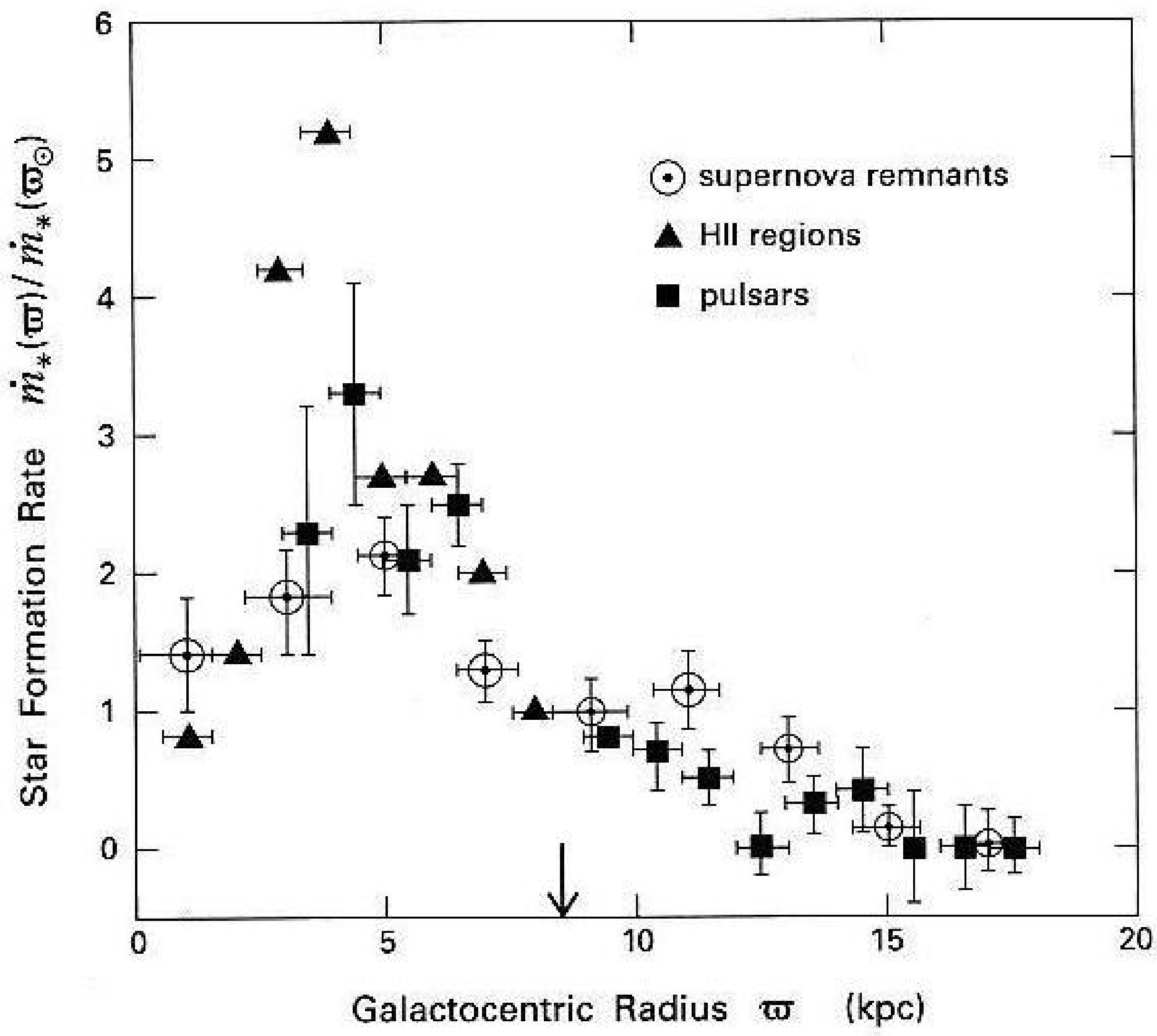


Figure 5. The relative SFH of the Galactic disk as determined in this work (circles, same as in Figure 3) compared with determinations by Cignoni et al. (2006; squares), de la Fuente Marcos & de la Fuente Marcos (2004; pentagons), Hernandez et al. (2000; rhombuses), Rocha-Pinto et al. (2000; downward triangles), and Vergely et al. (2002; upward triangles).

SF activity in the Milky Way



Local:
- $3\ 10^{-9}\ M_\odot\ a^{-1}\ pc^{-2}$
- Much higher in Galactic Ring

Global:
- $4\ M_\odot\ a^{-1}$
- $0.002\ M_\odot\ a^{-1}\ kpc^{-2}$

SF activity in the disk galaxies

The SFR is enhanced in the inner part of the disk:

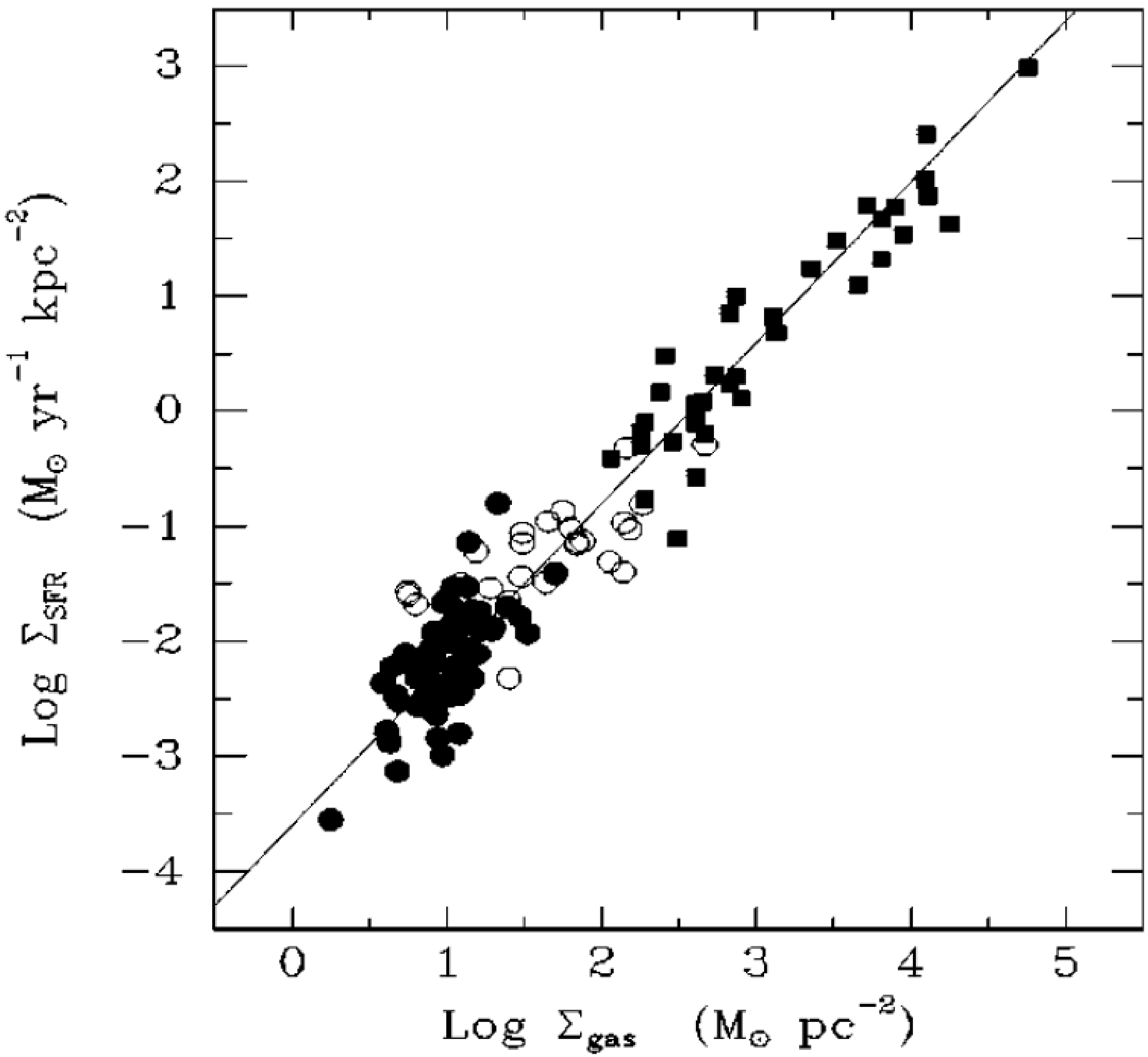
- The inflow of material through a bar drives an enhanced SF

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

The Schmidt-Kennicutt law

General relation between gas surface density and SFR:

- $\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^{1.4}$



Kennicutt (1998)

$$\Sigma_{\rm SFR} = 2.5 10^{-4} \left(\frac{\Sigma_{\rm gas}}{1 M_\odot {\rm pc}^{-2}} \right)^{1.4} M_\odot {\rm a}^{-1} {\rm kpc}^{-2}$$

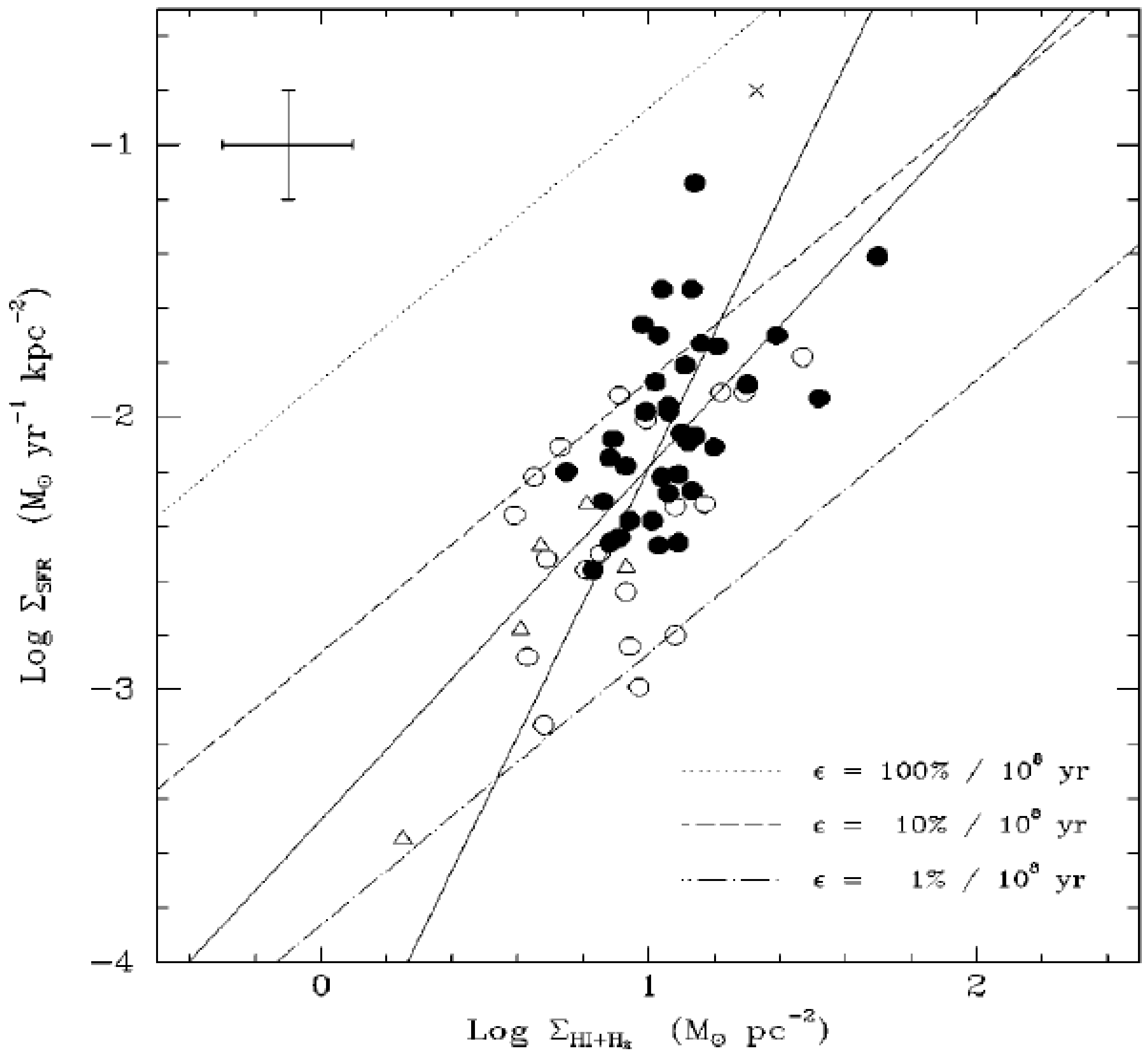
The Schmidt-Kennicutt law

$$\Sigma_{SFR} \propto \Sigma_{gas}^{1.4}$$

Exponent > 1 indicates a changing star-formation efficiency:

- Higher surface densities create
  - More dense gas
  - Higher SFR
  - Increased global SF efficiency

- High surface density galaxies can be ultra-luminous



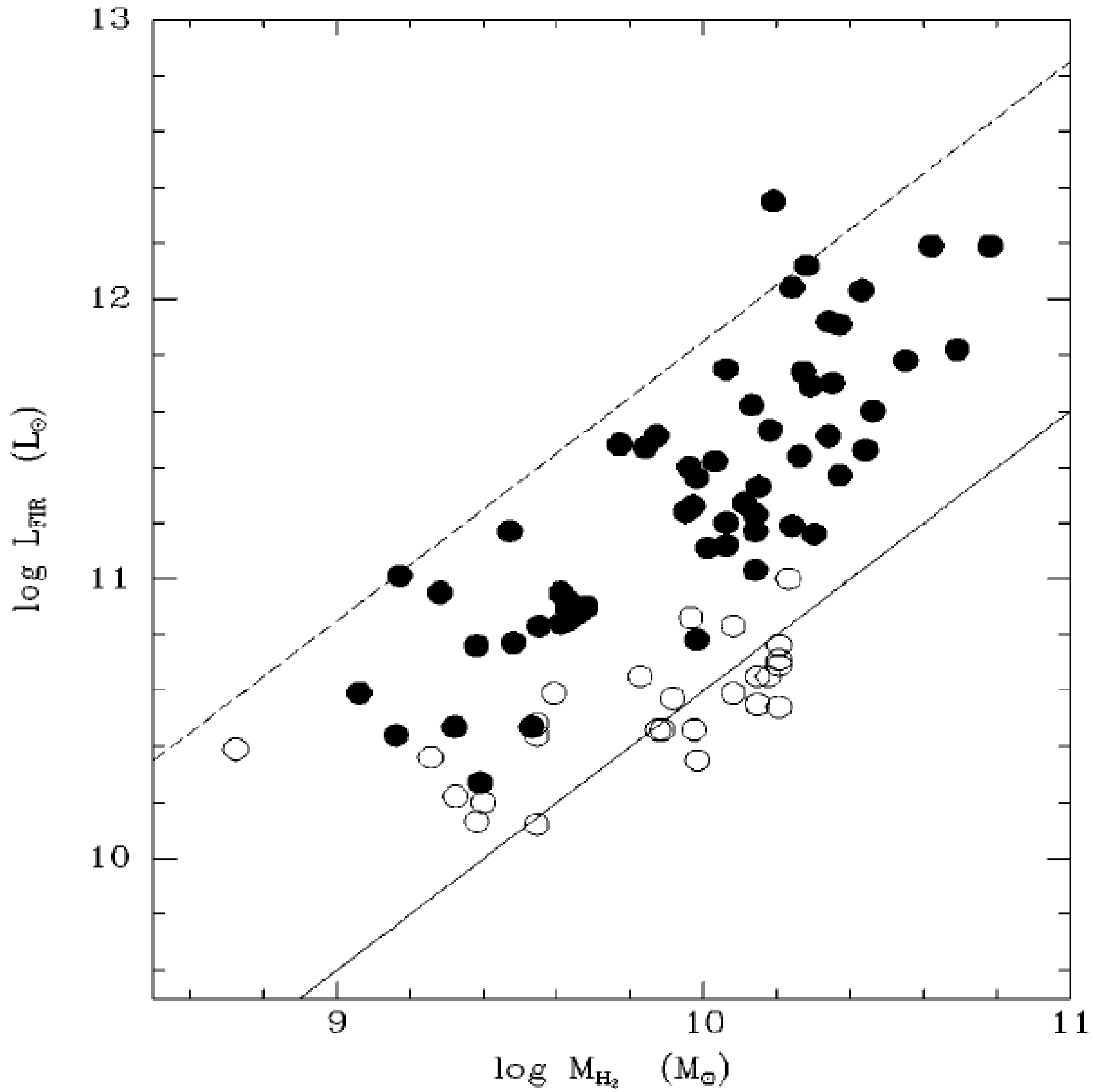
Kennicutt (1998)

The SF efficiency

The amount of dense interstellar material is the main parameter to determine the SFR

- But the SF efficiency also changes for a given amount of molecular material
  - Eventually determines whether a star-burst occurs

Star burst: SFR enhanced by factor 100 compared to average MW value



Kennicutt (1998)

The SF efficiency

The maximum star-burst

Mass that can be turned into stars in the ideal case:

- Assume free fall collapse: $$\dot{M}_{\mathrm{max}} = \frac{M_{\mathrm{gas}}}{\tau_{ff}} = M_{\mathrm{gas}}\sqrt{G\rho}$$

- Initially virialized clouds: $$\dot{M}_{\mathrm{max}} \approx 100 M_{\odot} \left(\frac{\sigma_v}{100\mathrm{km/s}} \right) \mathrm{a}^{-1}$$

→ quickly exhausting the available material

- Formation of many massive (OB) stars → strong winds
- SN rate enhanced by large factor
  - Example: NGC 253 SN every 5a

Cause of starburst

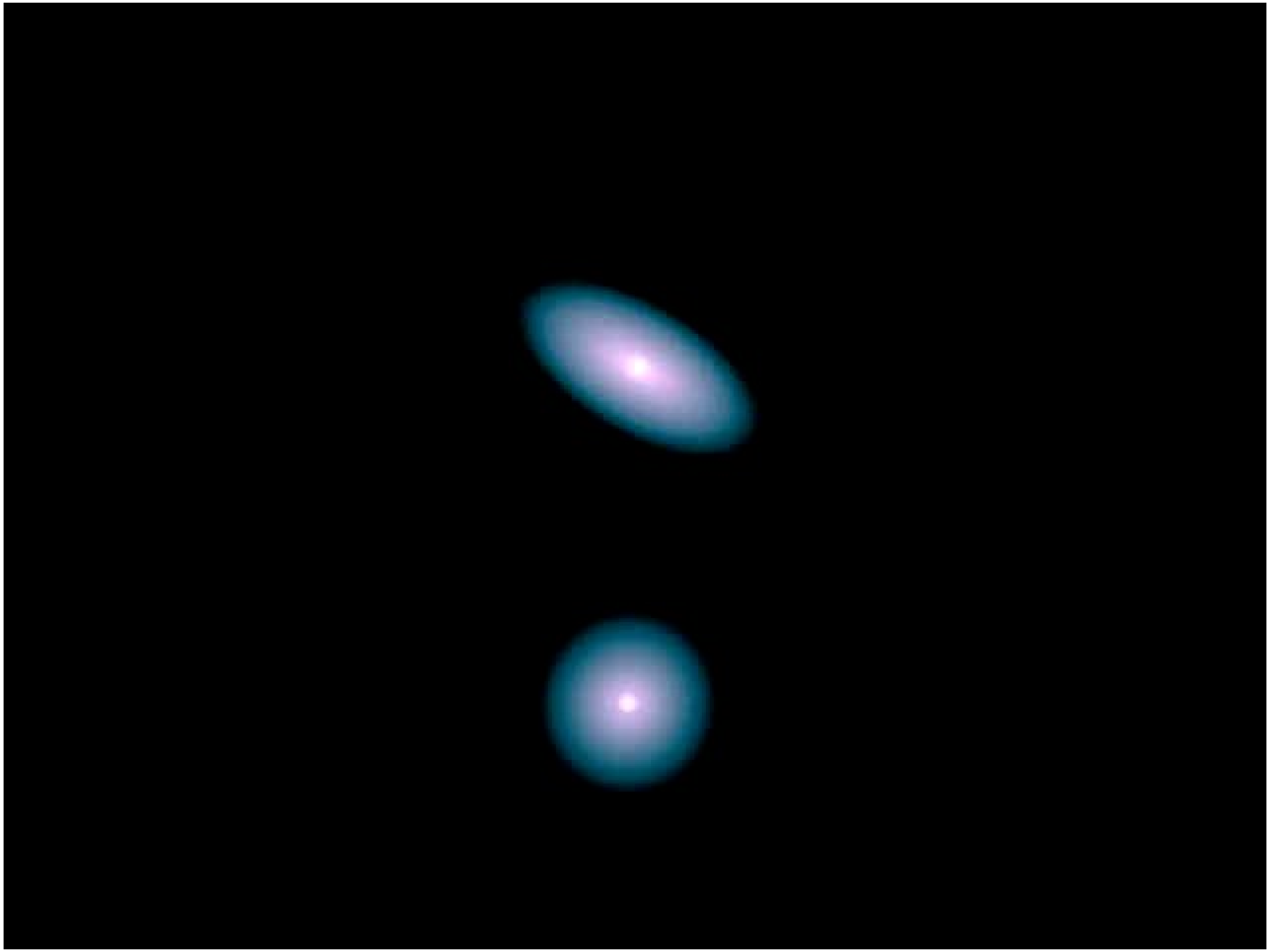
- Starburst requires
  - Additional feed of interstellar gas
  - Density enhancement due to compression
- Cause
  - Galaxy collisions
  - Active galactic cores

Pinwheel galaxy

Galaxy collisions are frequent and ubiquitous!

- Average distance between galaxies ~ 20 radii
  - Compare stars: 10^7 radii

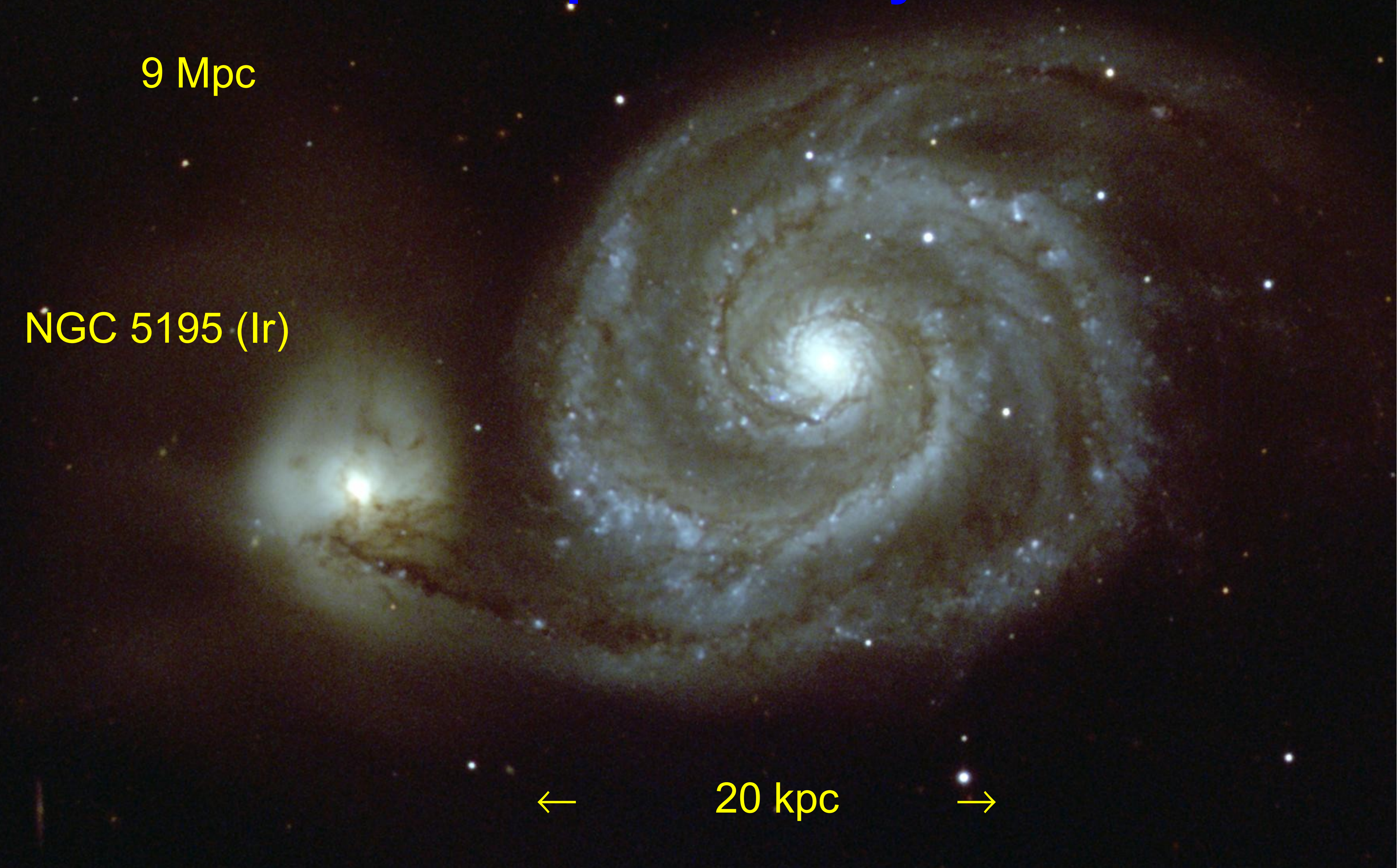
Galaxy collisions

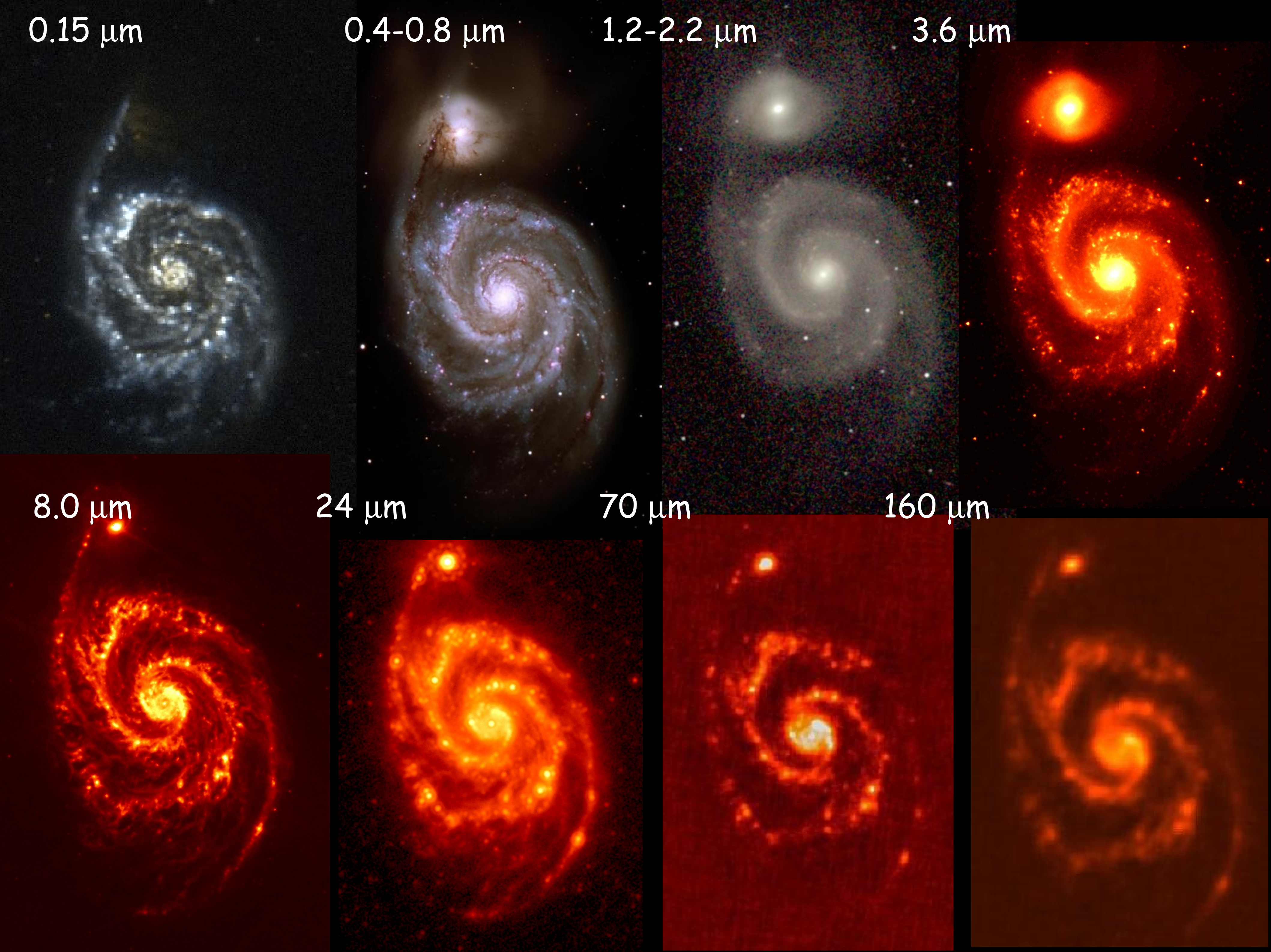


Simulation of the collision between Milky Way and M31 in about 5Ga.

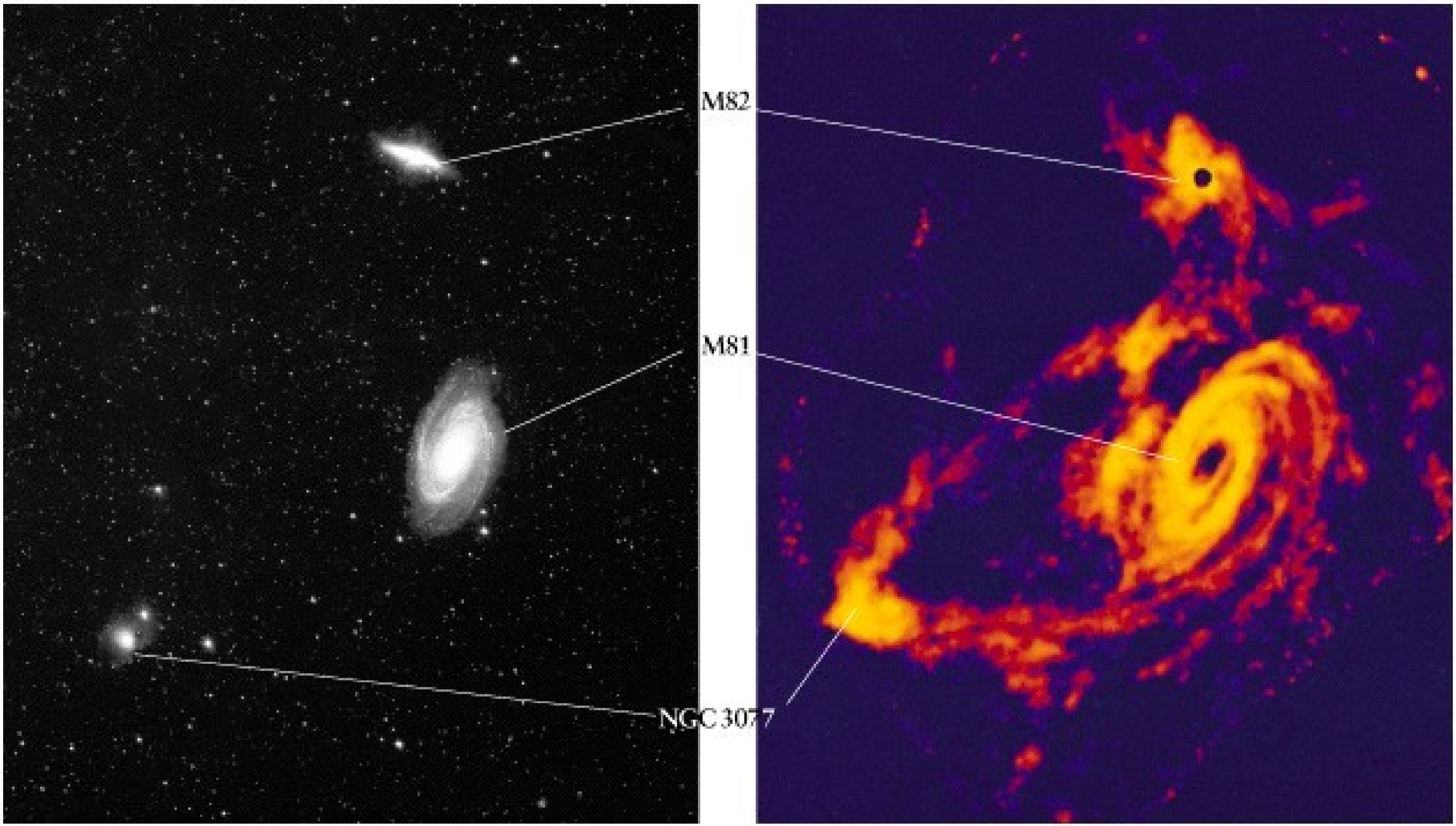
- Several periods of induced star burst
- Formation of an elliptical galaxy at the end

Observations of Galaxy collisions: The Whirlpool Galaxy M51




0.15 μm
0.4-0.8 μm
1.2-2.2 μm
3.6 μm
8.0 μm
24 μm
70 μm
160 μm

Observations of Galaxy collisions

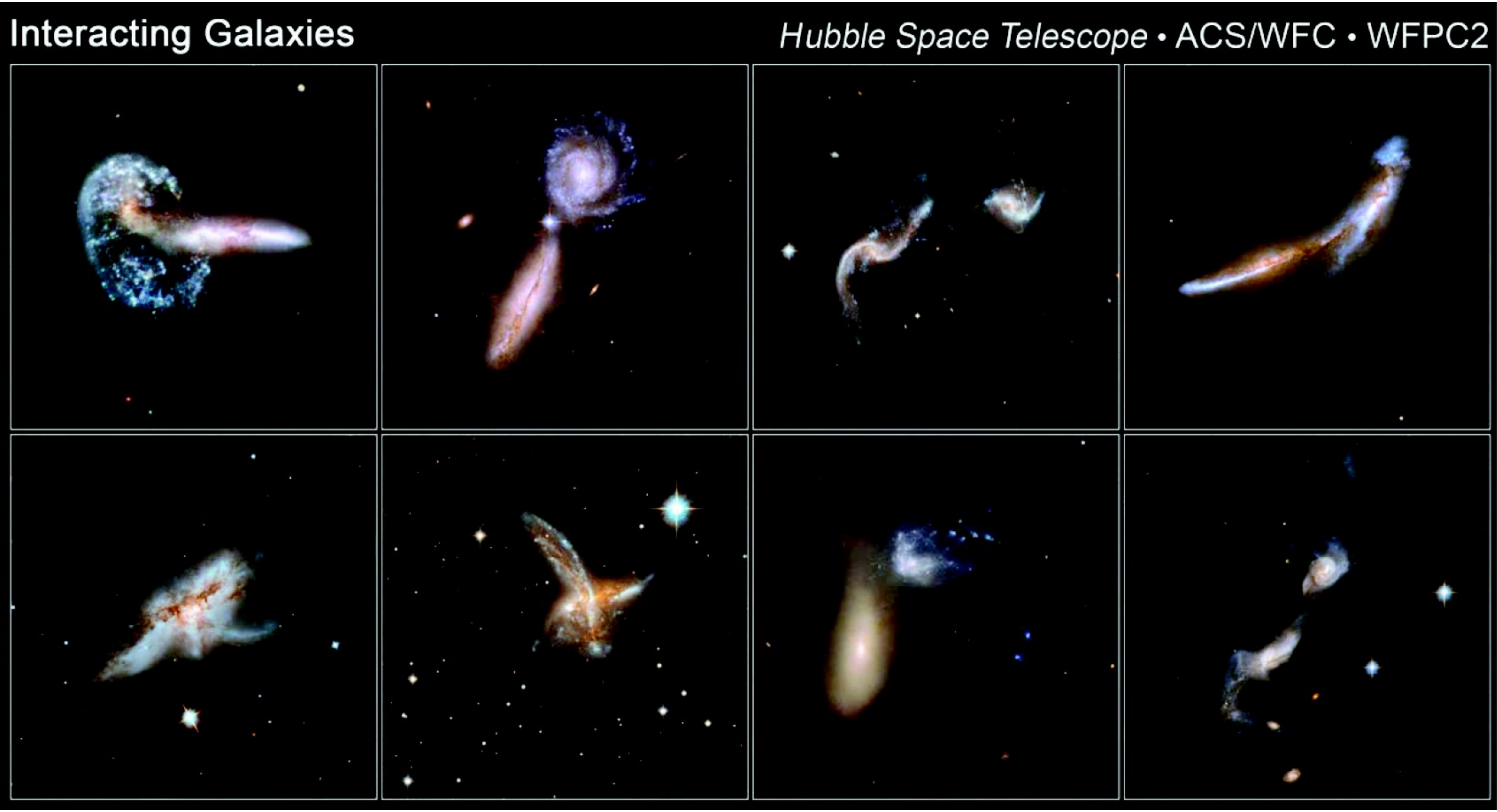


M82, M81 and NGC3077 in the optical

M82, M81 and NGC3077 in HI (radio)

The interaction is often only visible in gas tracers

Merging galaxies



A zoo of merging galaxies is known today

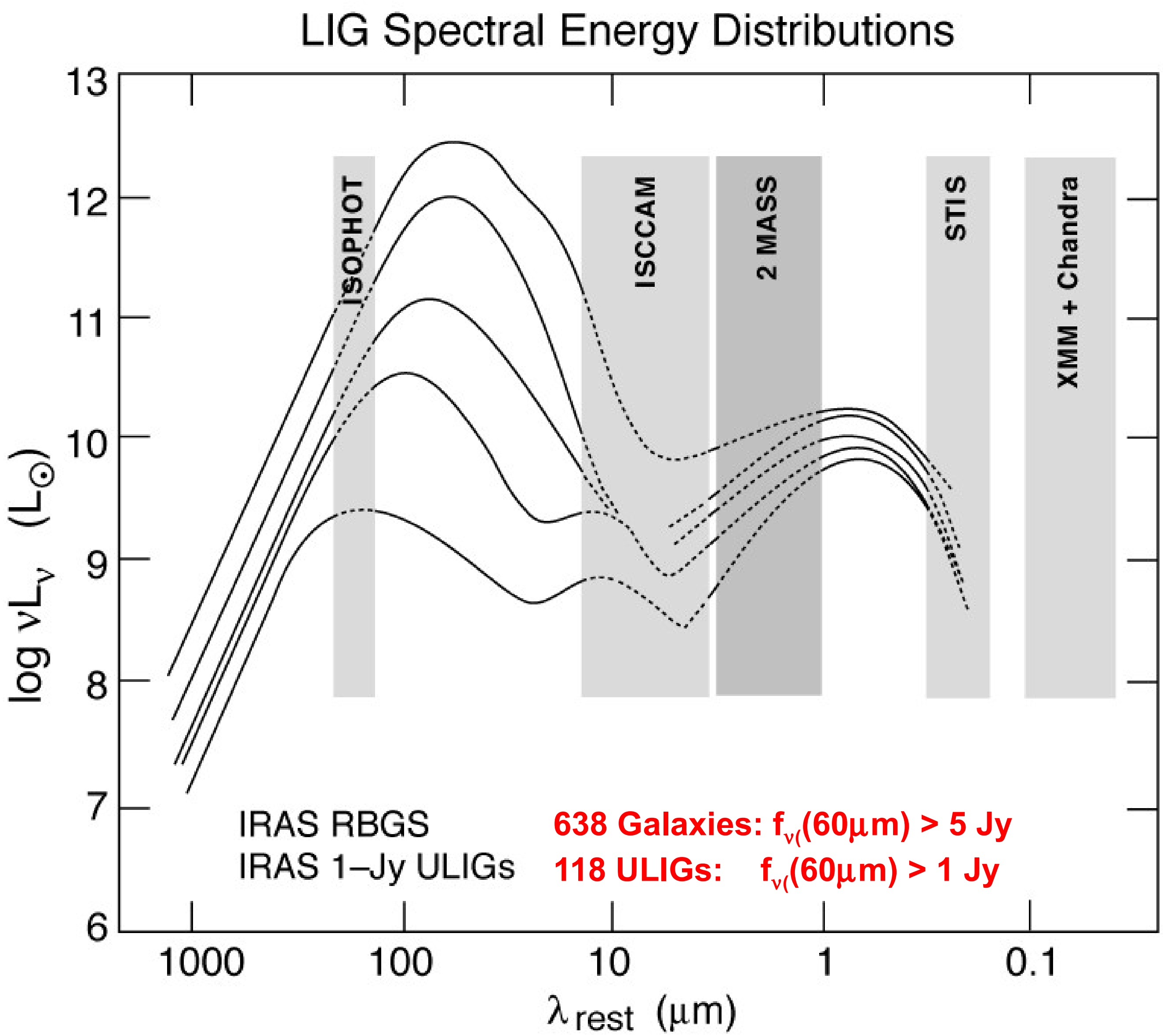
Evans (2005)

Starburst galaxies

Starburst = Infrared Luminous Galaxy!

Selection based on IRAS Intensities:

Radio-to-UV SEDs



"Infrared Galaxies" ≡ $(\nu f_\nu)_{IR} / (\nu f_\nu)_{opt} > 1$

Starburst galaxies

Starburst measured by infrared luminosity 8-1000 μm :

Name	L_{ir} [$L_\odot$]	$M(H_2)$ [$M_\odot$]	SFR (stars/a)
normal	10^{10}	10^{8}	1
LIRG	10^{11}	10^{9}	10
ULIRG	10^{12}	10^{10}	100
HLIRG	10^{13}	10^{11}	1000

Starburst galaxies

Starburst measured by infrared luminosity 8-1000 μm :

$$\text{ULIRGs:} \quad \left\langle \frac{L_{\mathrm{FIR}}}{M_{\mathrm{H_2}}} \right\rangle \approx 100 L_0 M_0^{-1}$$

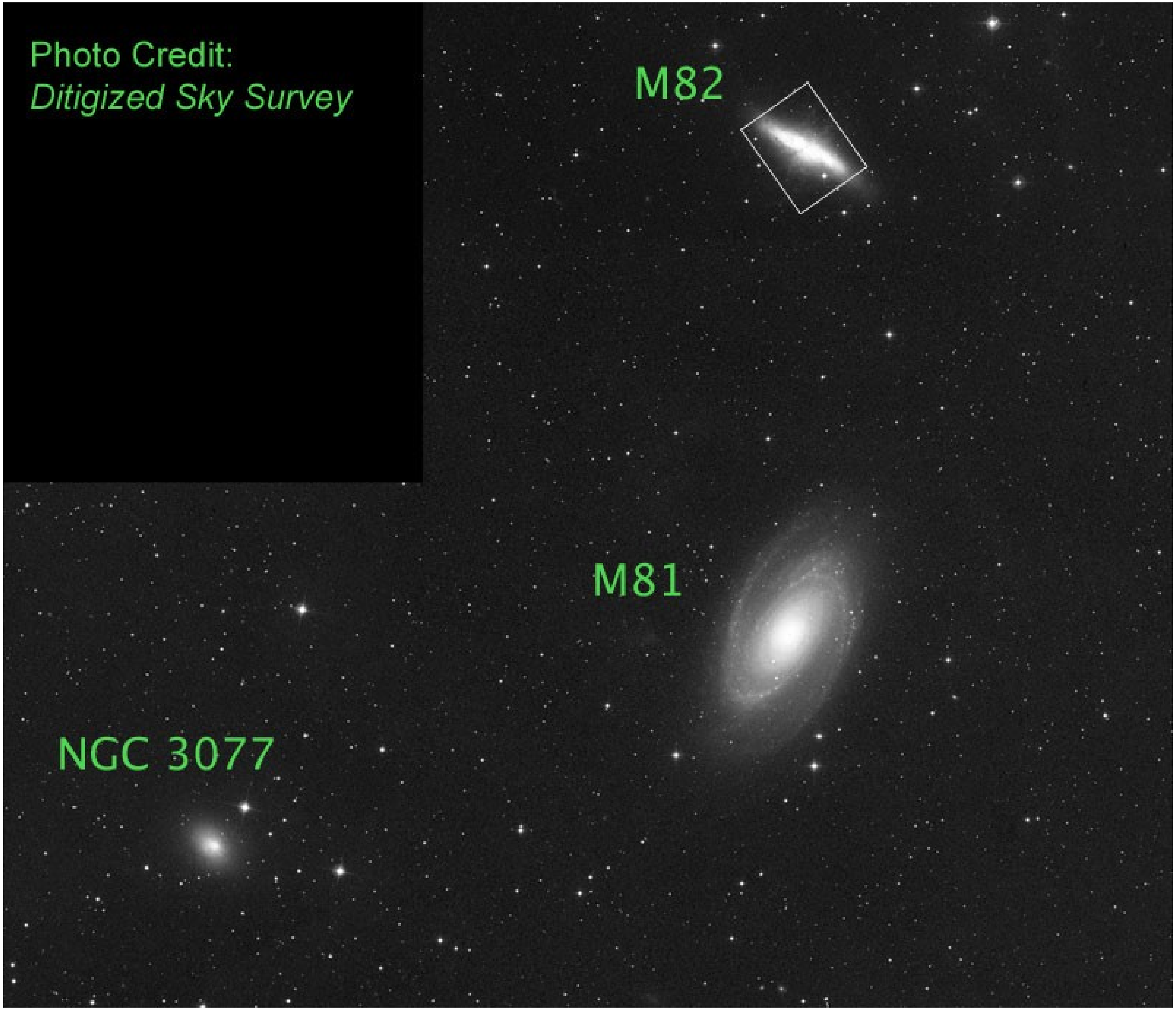
$$\text{Milky Way:} \quad \approx 1.5 L_0 M_0^{-1}$$

$$\text{Galactic GMCs:} \quad \approx 1.8 L_0 M_0^{-1}$$

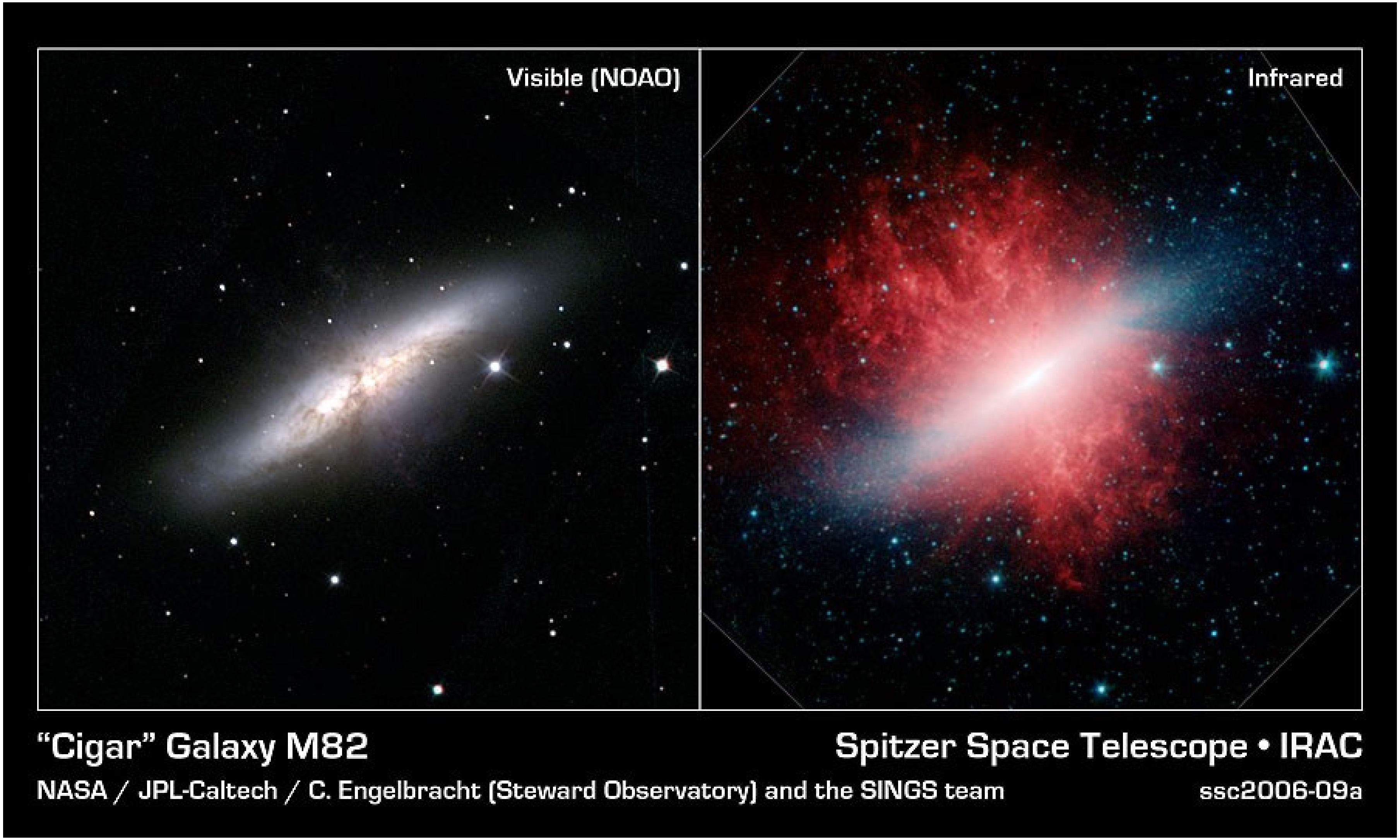
$$\text{OMC-1:} \quad \approx 54 L_0 M_0^{-1}$$

$$\text{Orion BN-KL:} \quad \approx 400 L_0 M_0^{-1}$$

M82 – a nearby starburst



M82 – a nearby starburst

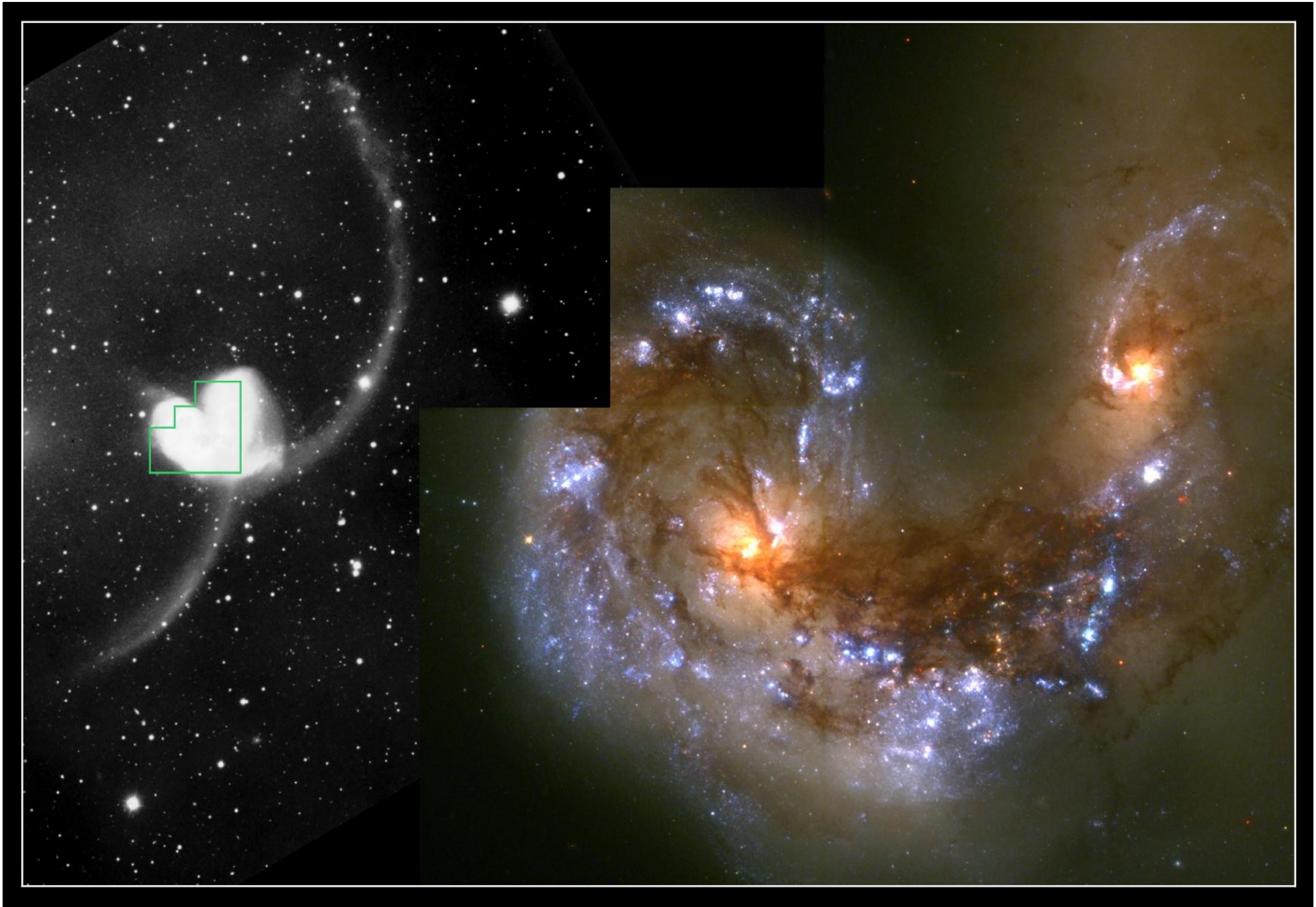


M82 – a nearby starburst

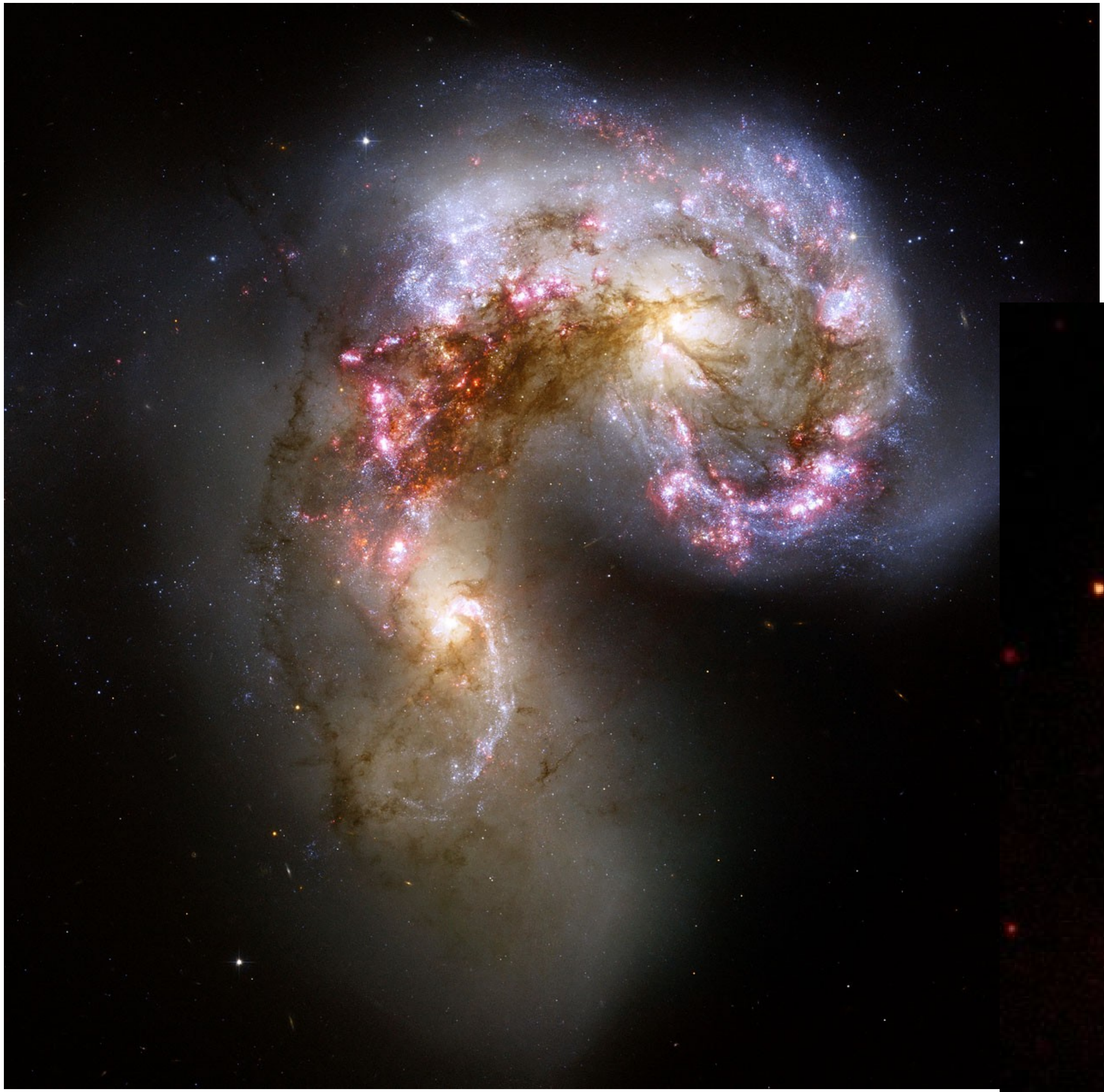
Red: Spitzer IR, Blue: Chandra X-ray

Antennae – a massive merger

Antennae – a massive starburst



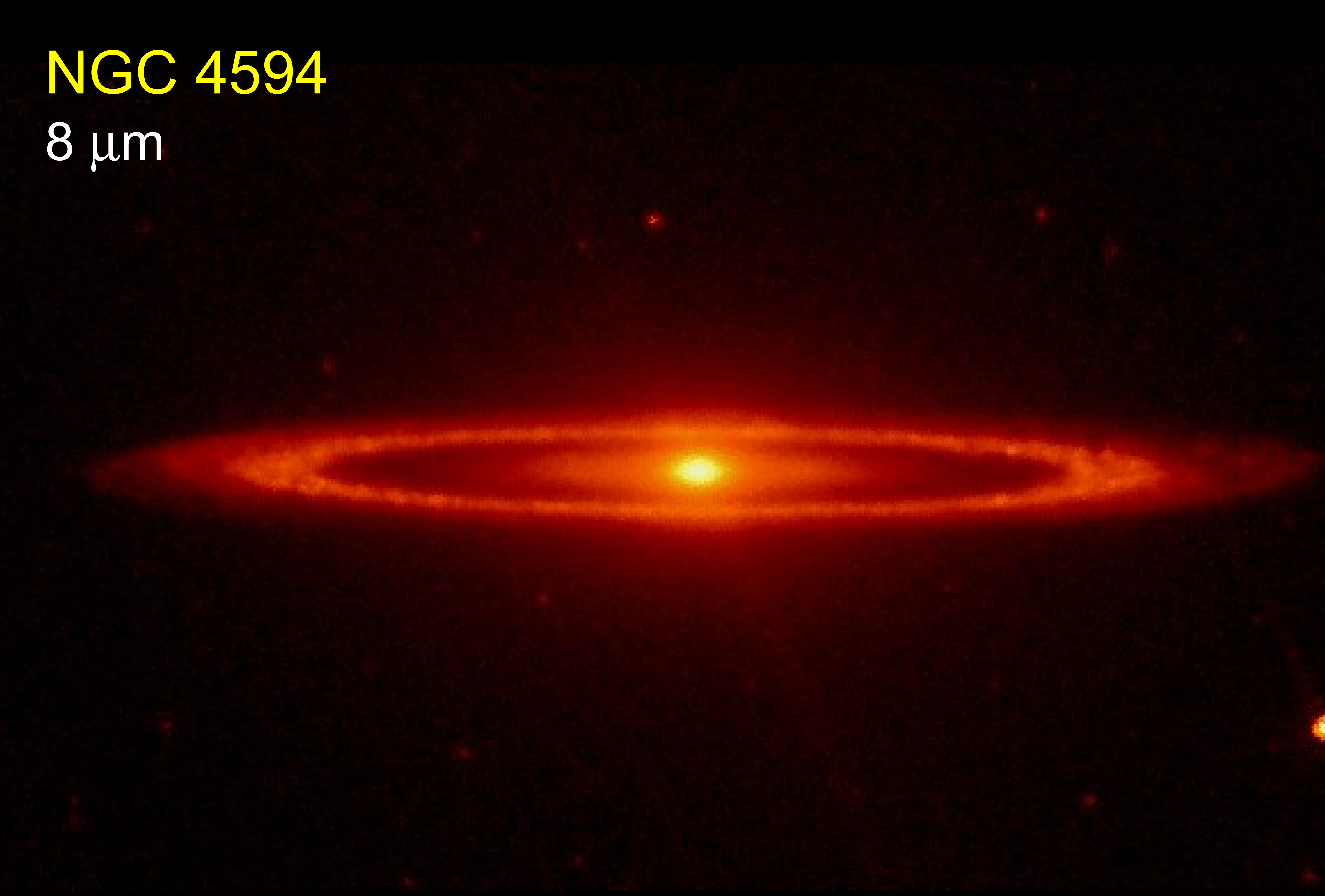
Antennae – a massive starburst



Optical image

Mid-Infrared

NGC 4594


NGC 4594
8 μm

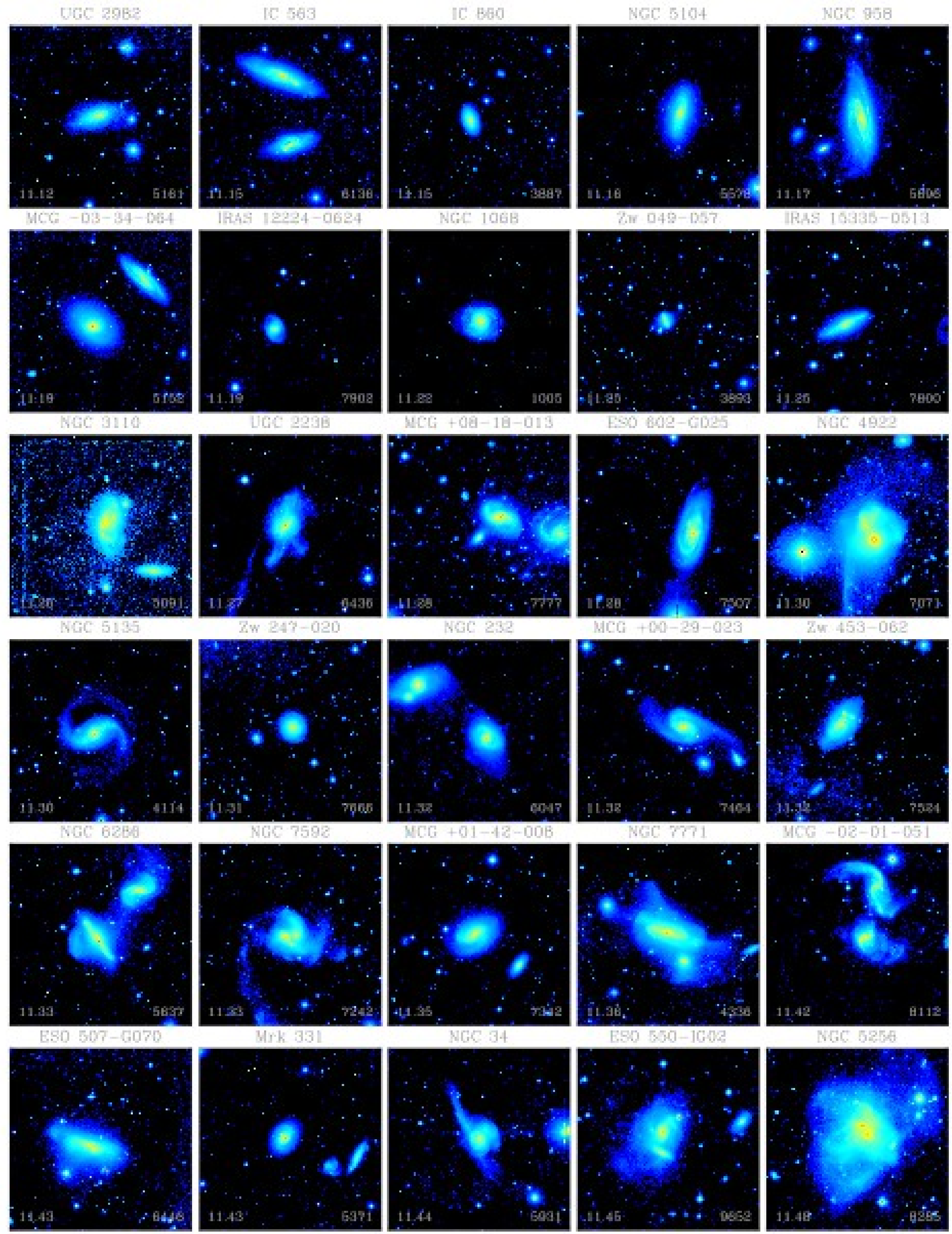

ible + Infrared

Optical Images of LIRGs

IRAS selected:
Log L_{IR} = 11 – 12

• Confirm merger origin of most star bursts

Ishida, ApJL (2003)

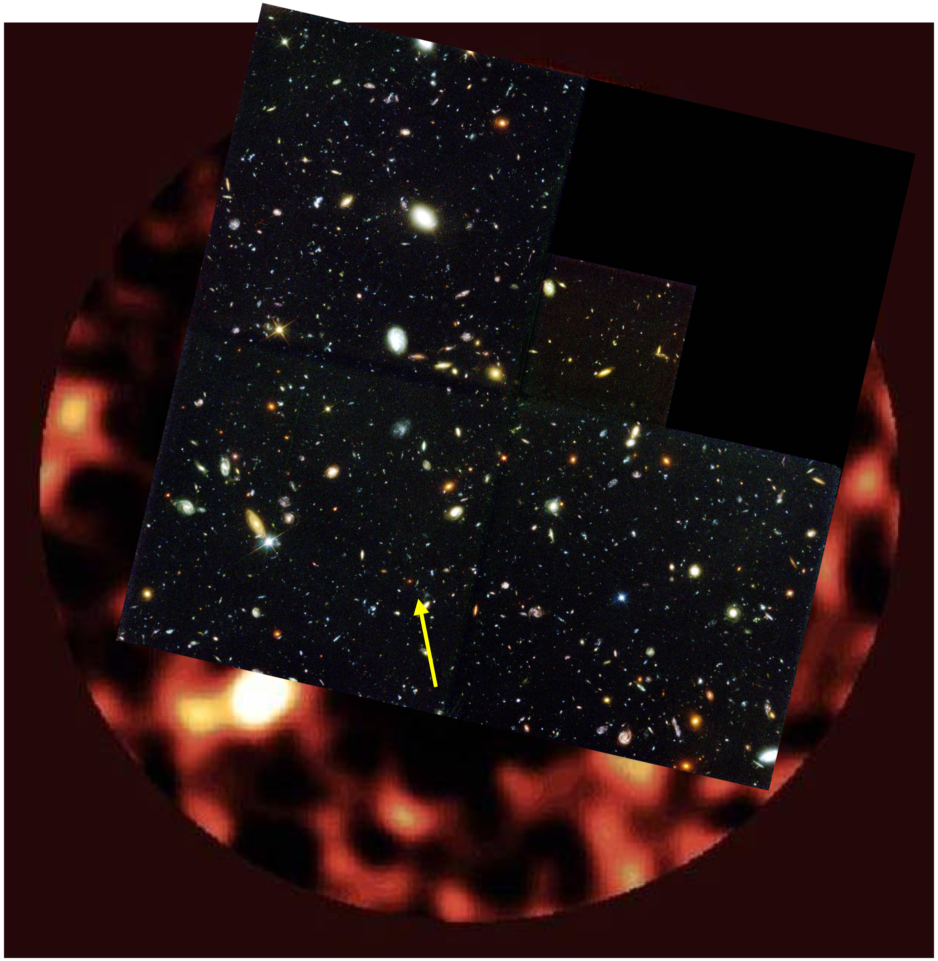


The far-infrared background

Large number of LIRGs and ULIRGs through the history of the universe provide a bright far-infrared background

→ permanent contamination of high-sensitivity observations with SPIRE onboard Herschel at wavelengths > 300μm

Optical counterparts for strong infrared sources identified only in a few cases

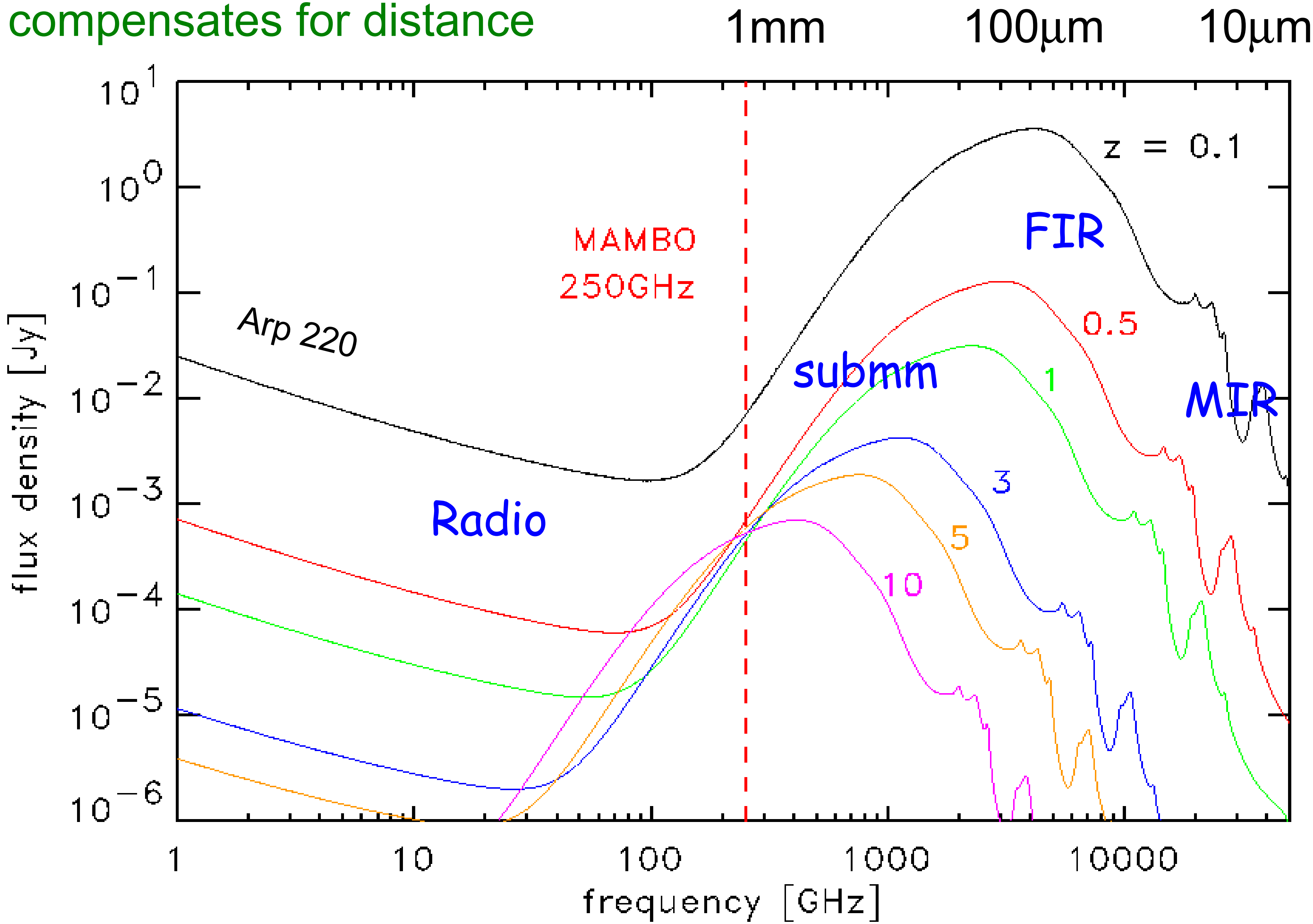


SCUBA 850μm

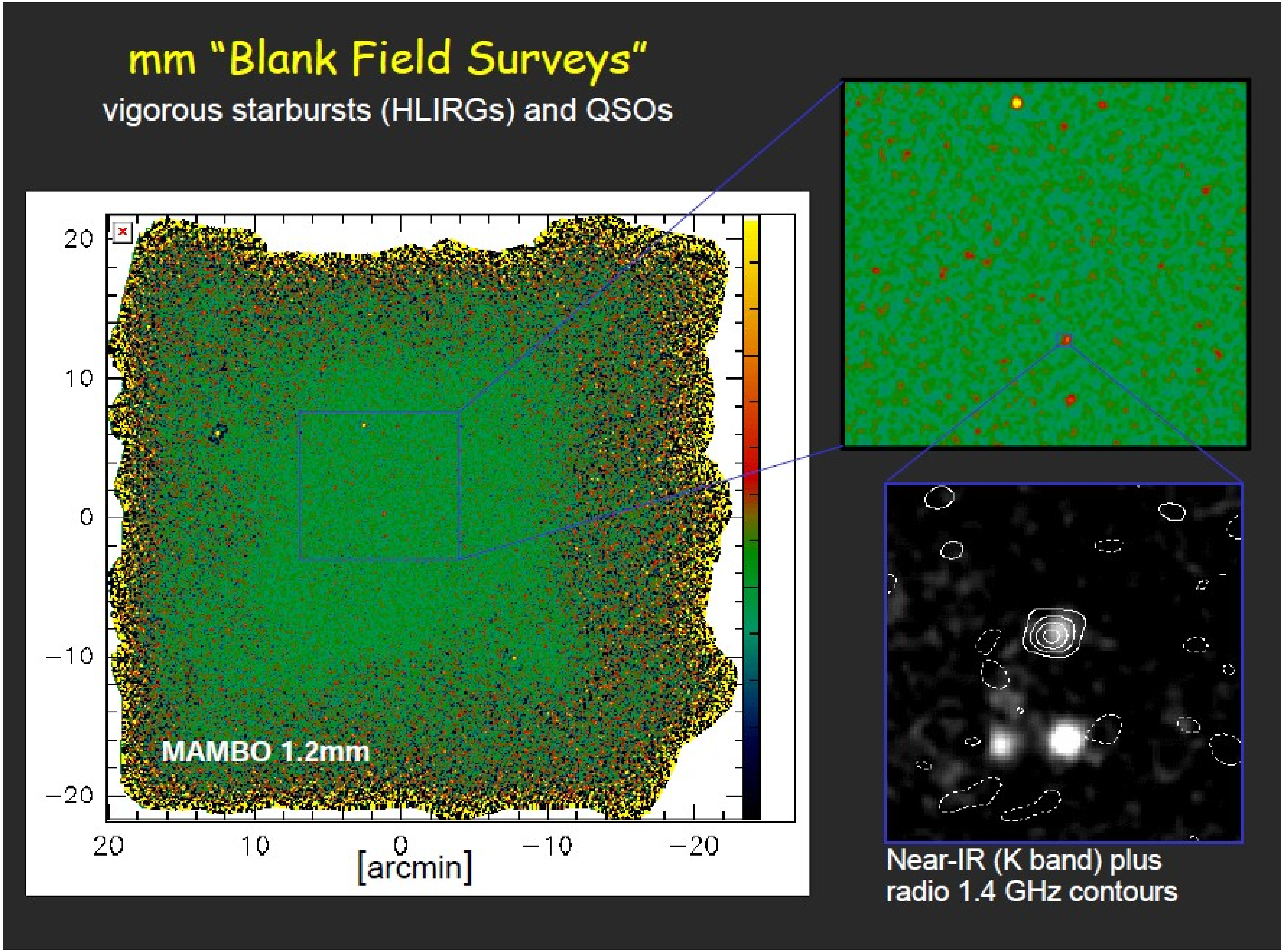
Optical/UV HST WFPC2: Helmut Dannerbauer

Search for LIRGs at high redshifts

The K-correction: at 1mm redshift compensates for distance

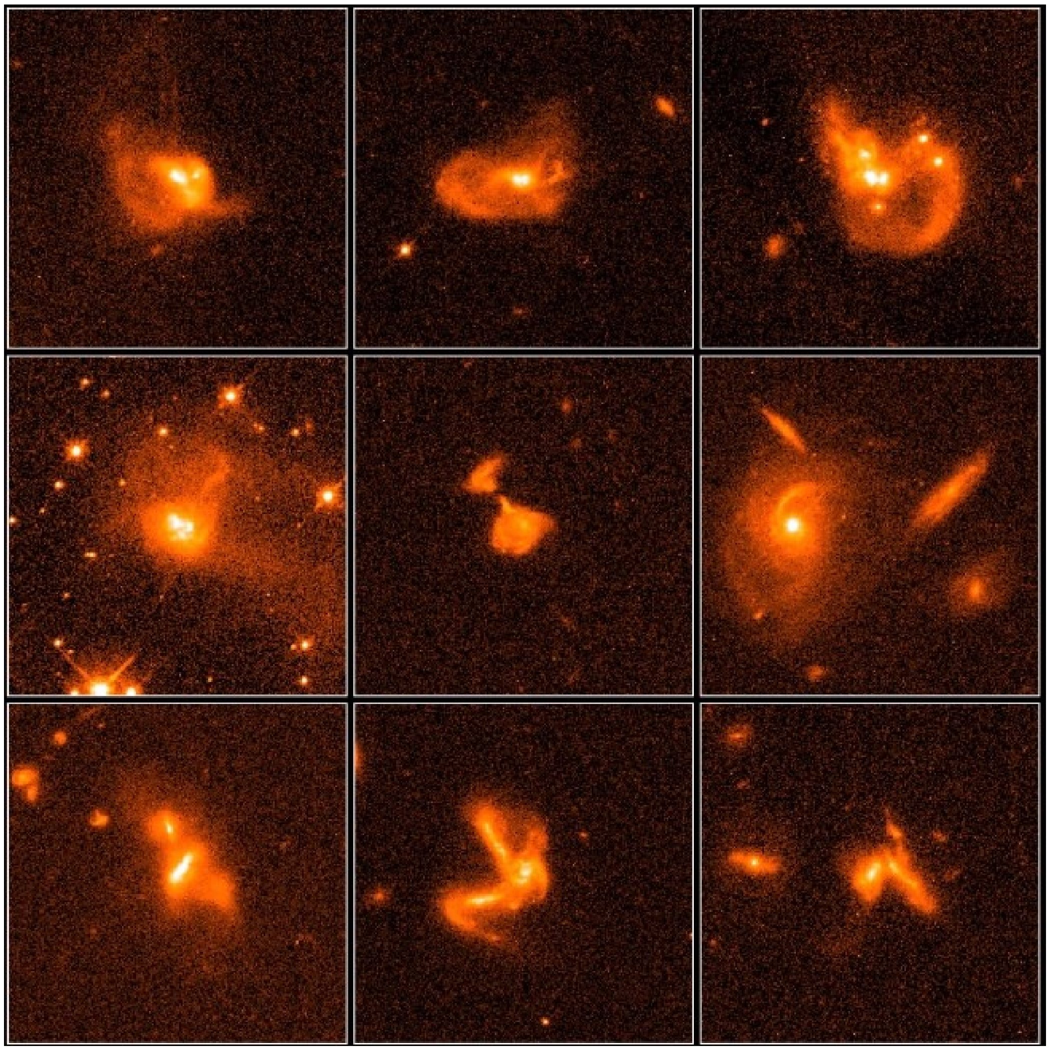


Search for LIRGs at high redshifts

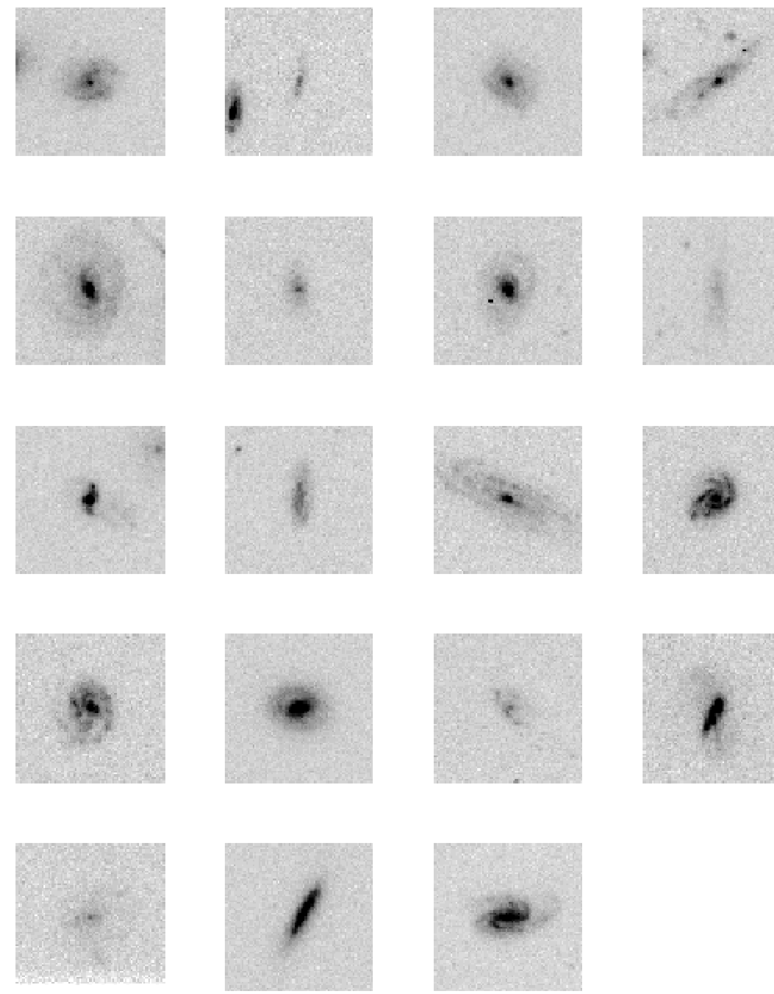


Galaxy Evolution

Galaxies at $z > 2$ are multiple with evidence of merging



Assembly of large Galaxies was evidently completed at $z<1$



The global star formation history

Star Formation Rate versus redshift z:

- The SFR was much higher at z ≥ 2.

- The early universe SF was deeper embedded
  - Larger amount of interstellar gas?