Unveiling the Birth of Stars and Galaxies

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Cosmic Origins:
A Grand Challenge for 21st Century Astrophysics

- We are in the midst of a revolution in observing and understanding the birth of galaxies, stars, and planets, ranging from individual solar systems to cosmic scales, over all cosmic time

Eagle Nebula (M16), HST

protoplanetary disc around HL Tau
ALMA

- star formation (and the resulting energy releases) are critical agents in forming and shaping galaxies and the Hubble sequence

M94 = NGC 4736, HST

Hubble Extreme Deep Field

A Medley of Unveilings

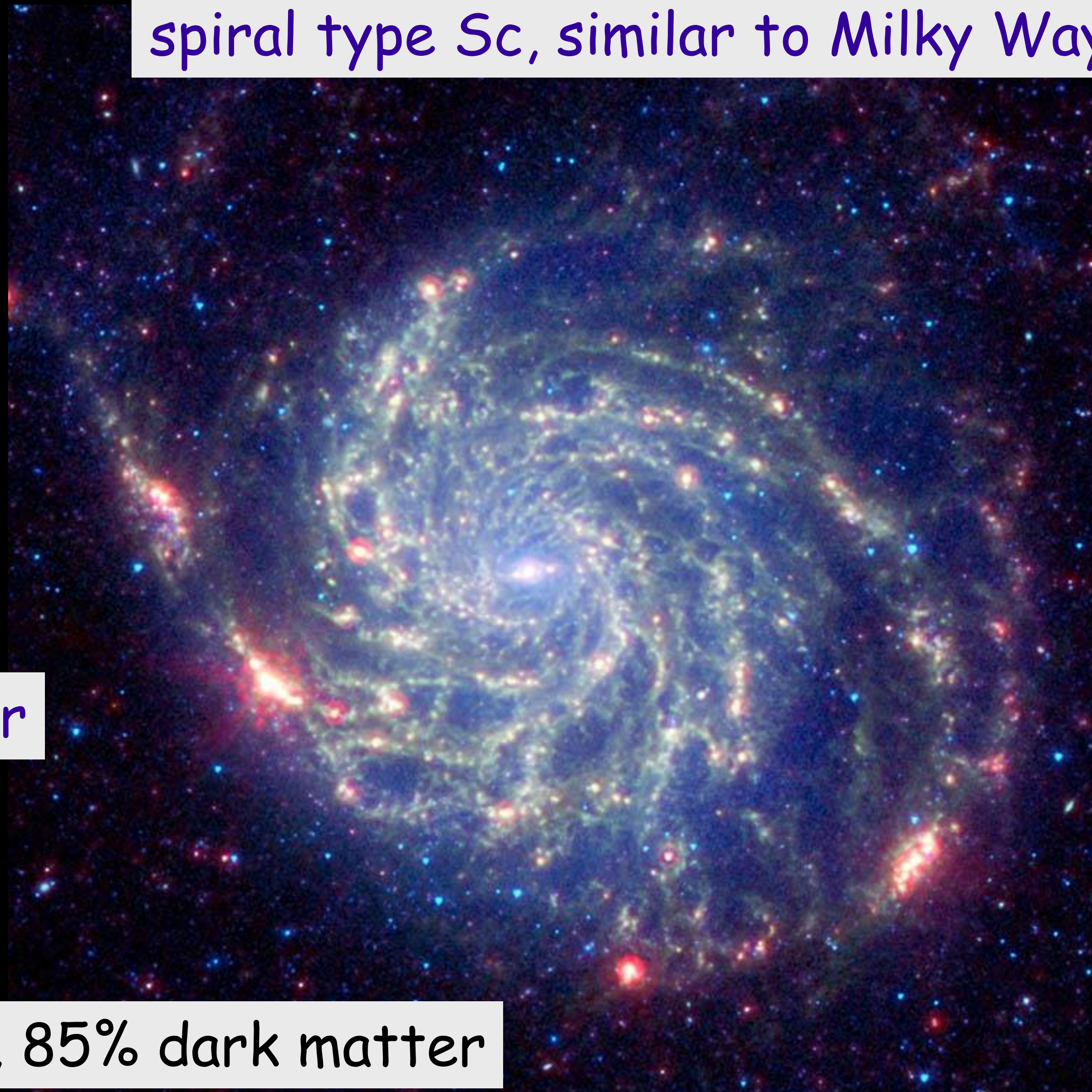
- the opening of the infrared universe, revealing the birth sites of stars previously hidden in the visible
- revealing and defining the diversity and demographics of star formation across the Universe
- exploring the most distant outskirts of the observable Universe, revealing the cosmic history of star and galaxy formation
- building a new theoretical cold dark matter driven paradigm for galaxy formation and evolution, extending from the Big Bang to the Milky Way today

Context: Galaxies

M101= NGC 5457 Fact Sheet

~23 million light years away

spiral type Sc, similar to Milky Way

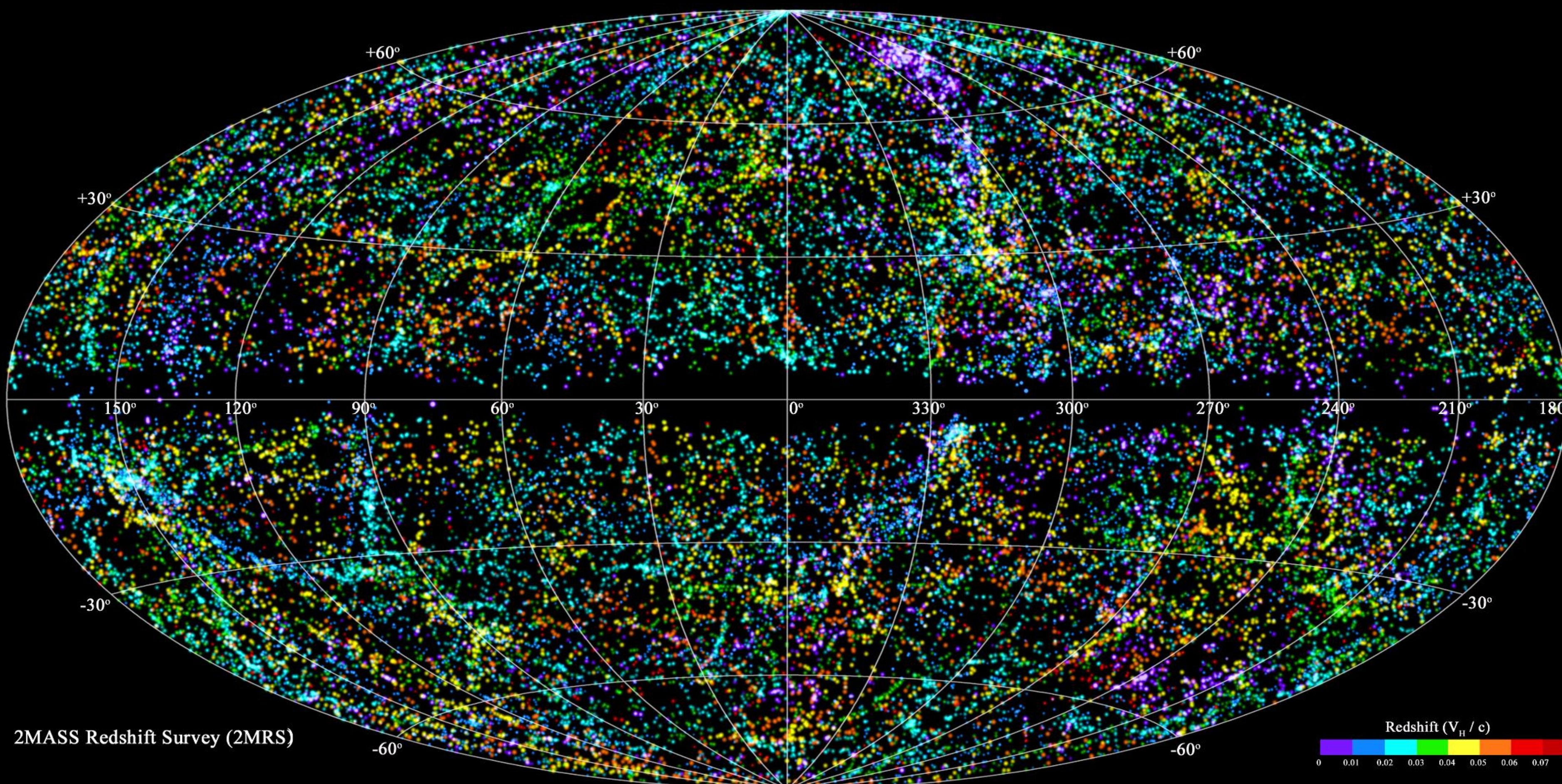


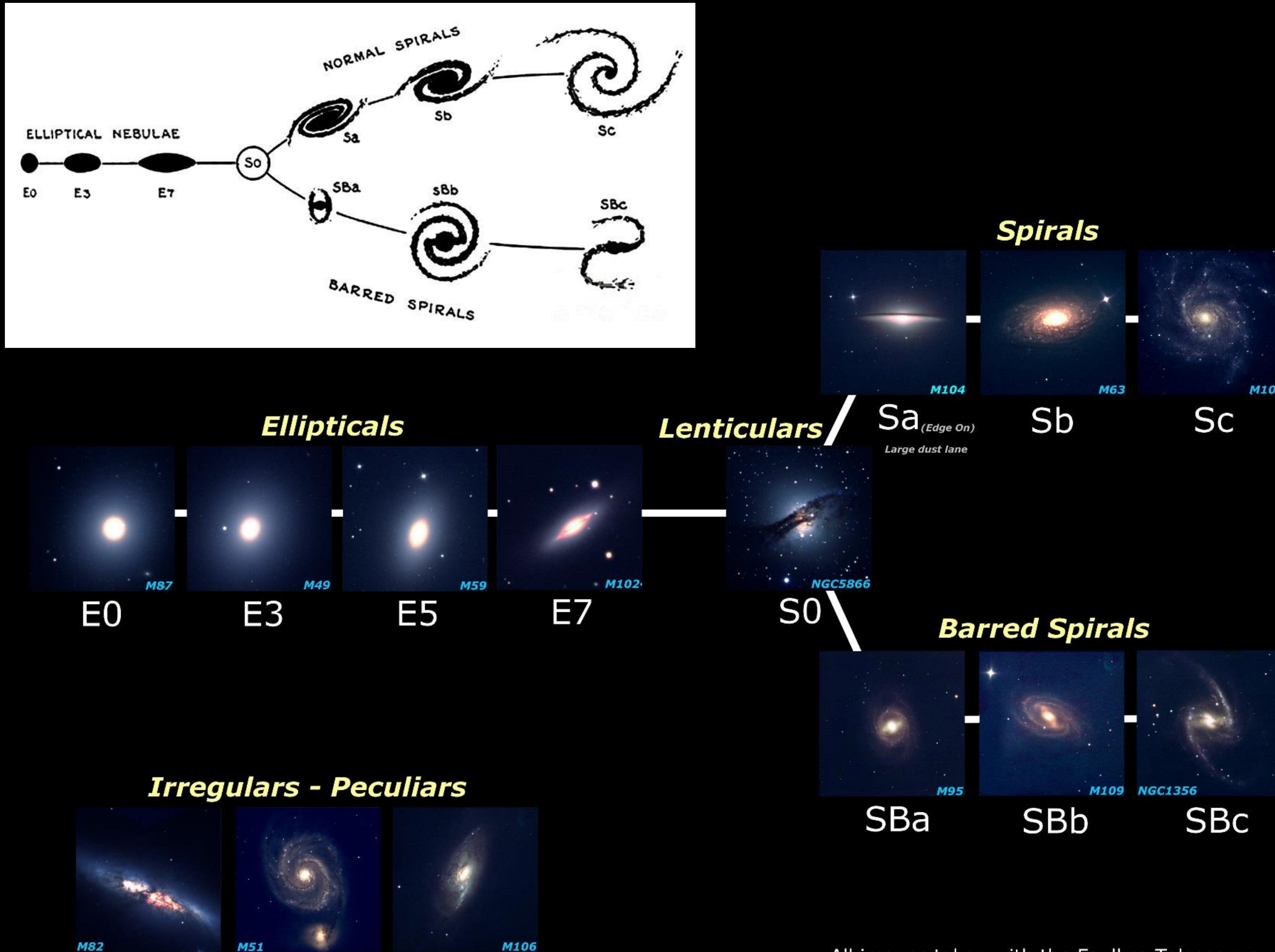
~100 billion stars

stellar ages 0-13 Gyr

~10% stars, 5% gas, 85% dark matter

Our Neighborhood: (within 1 billion light years [Gly])



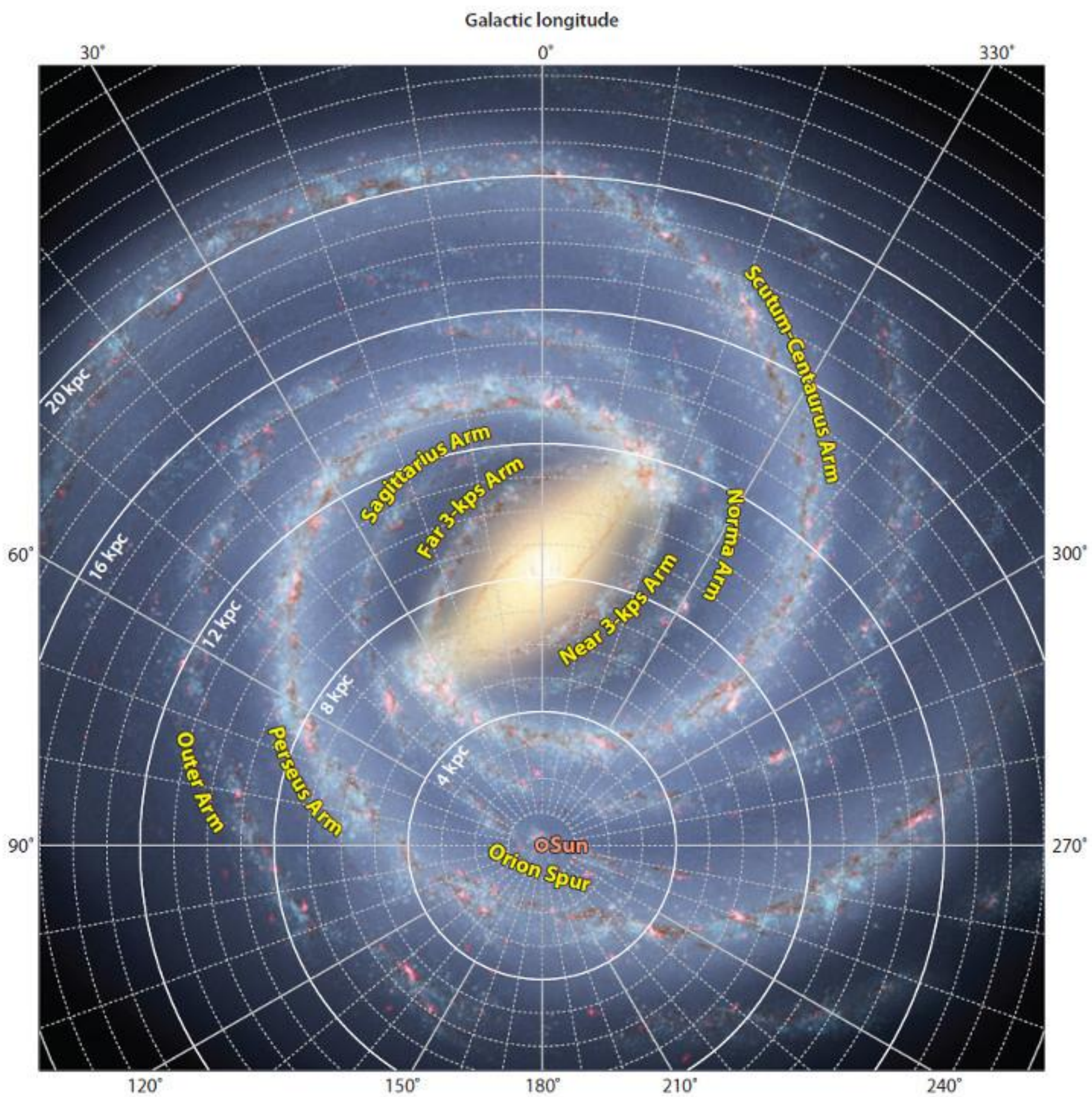


All images taken with the Faulkes Telescopes

College C.Perceret's astronomy workshop 2012

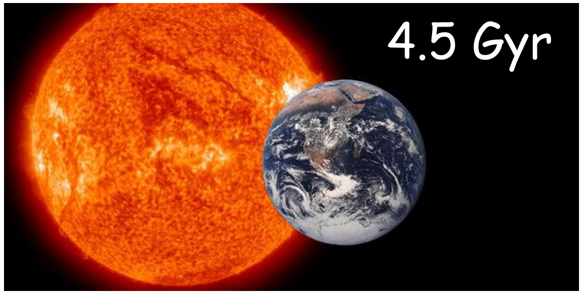
http://col21-perceret.ac-dijon.fr/col-astro

Milky Way (visualisation)



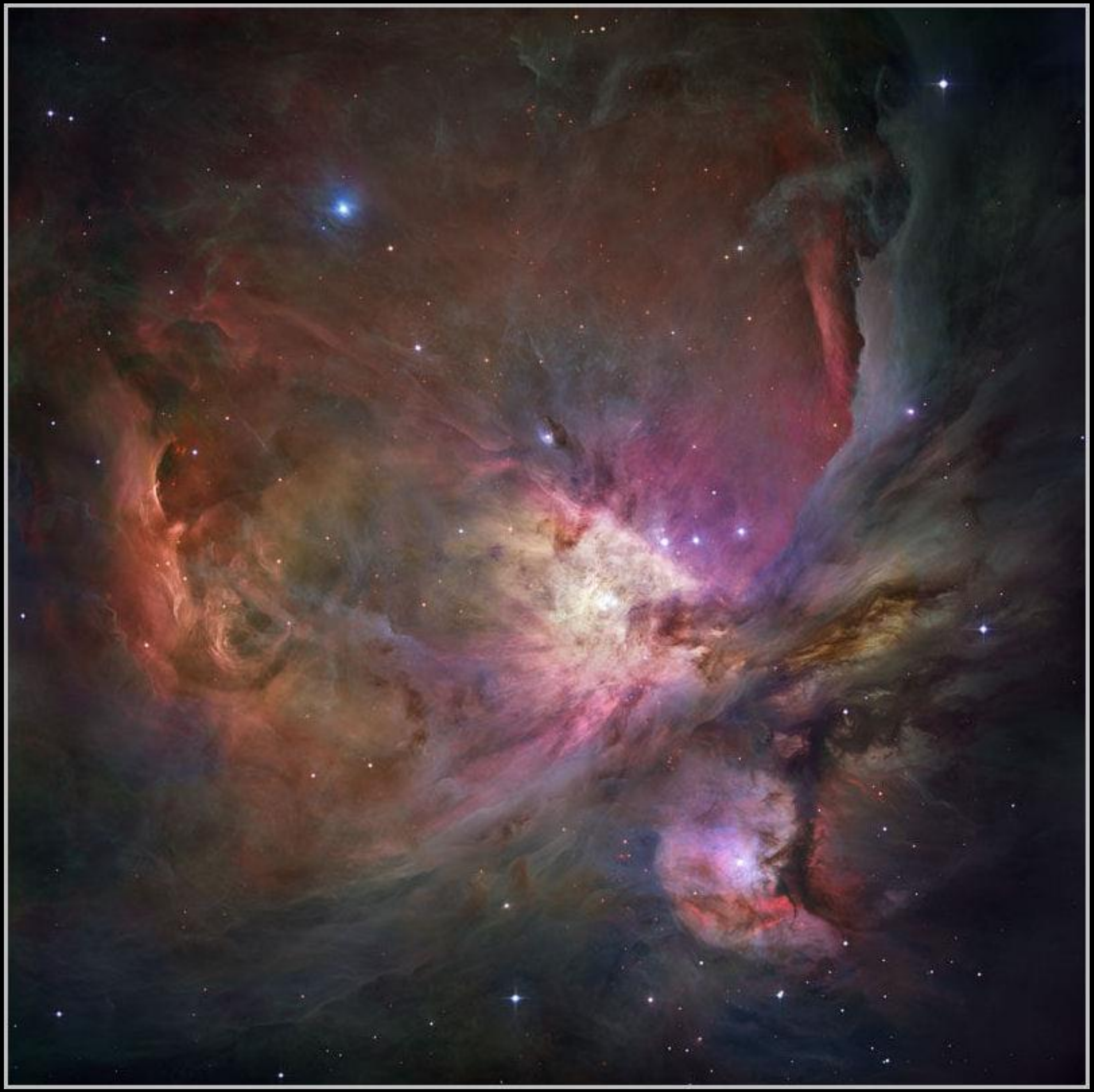
R Benjamin after R Hurt 2009

13 Gyr



0-1 Myr

Context: Star Formation



Orion nebula: HST

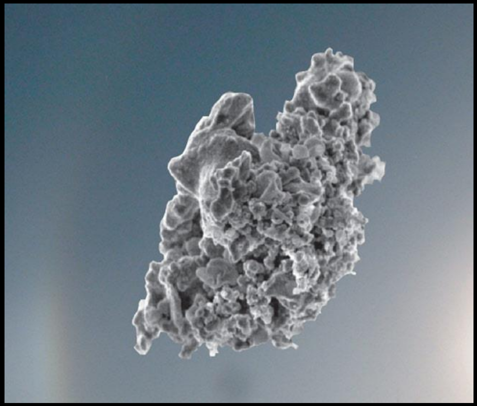
Orion Nebula Cluster: VLT

proplyds in Orion

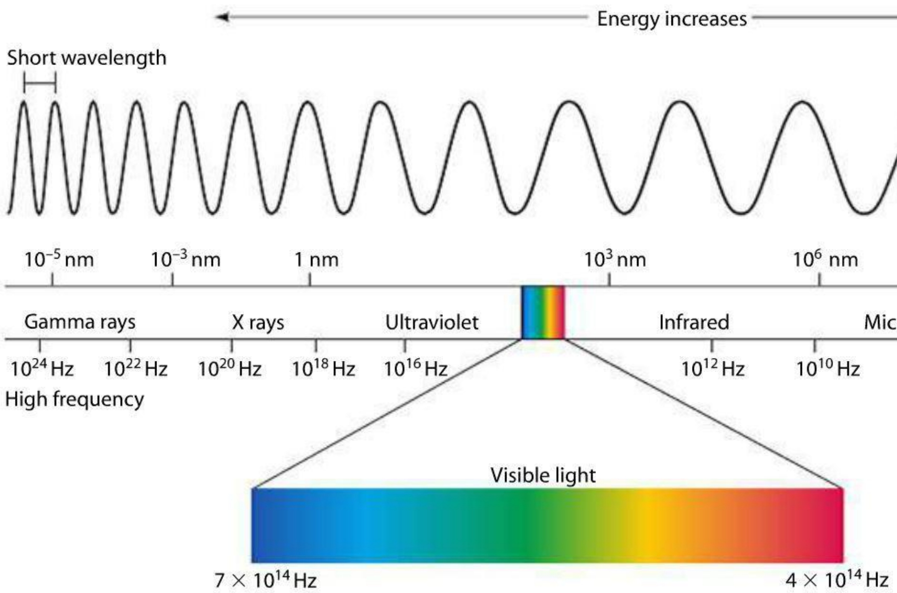
Context: The Veil…

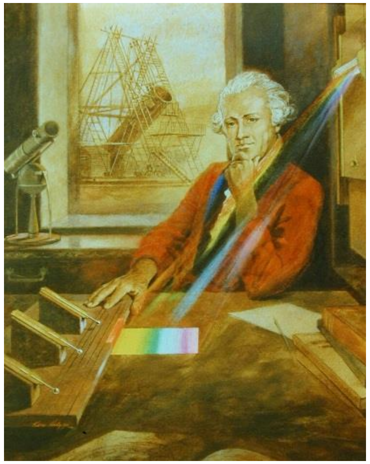
- interstellar space is <u>very</u> dusty (10000 ppm!)

- most dust particles are similar in size to waves of visible/ultraviolet light, so are highly absorbing

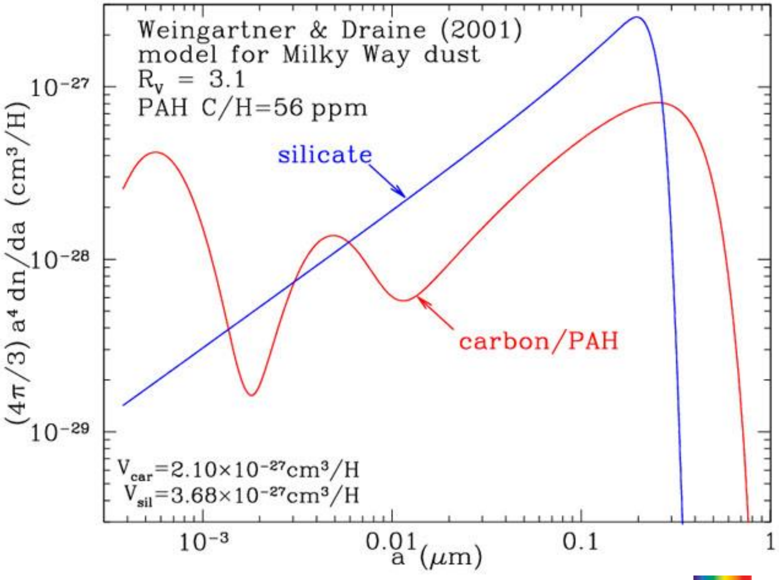


To penetrate the veil, observe the Universe in light waves that are larger than the dust grains, in the infrared





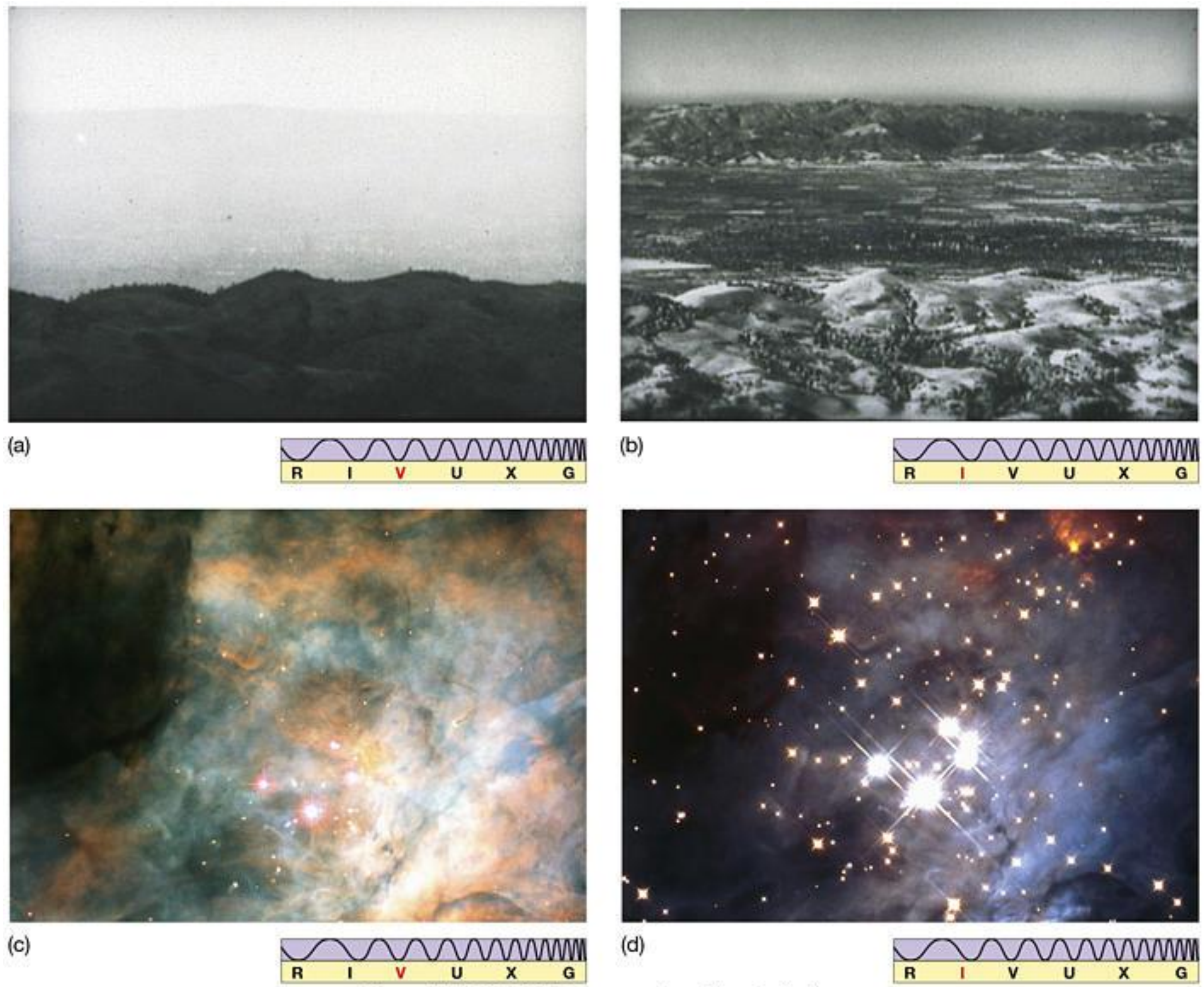
W Herschel 1800



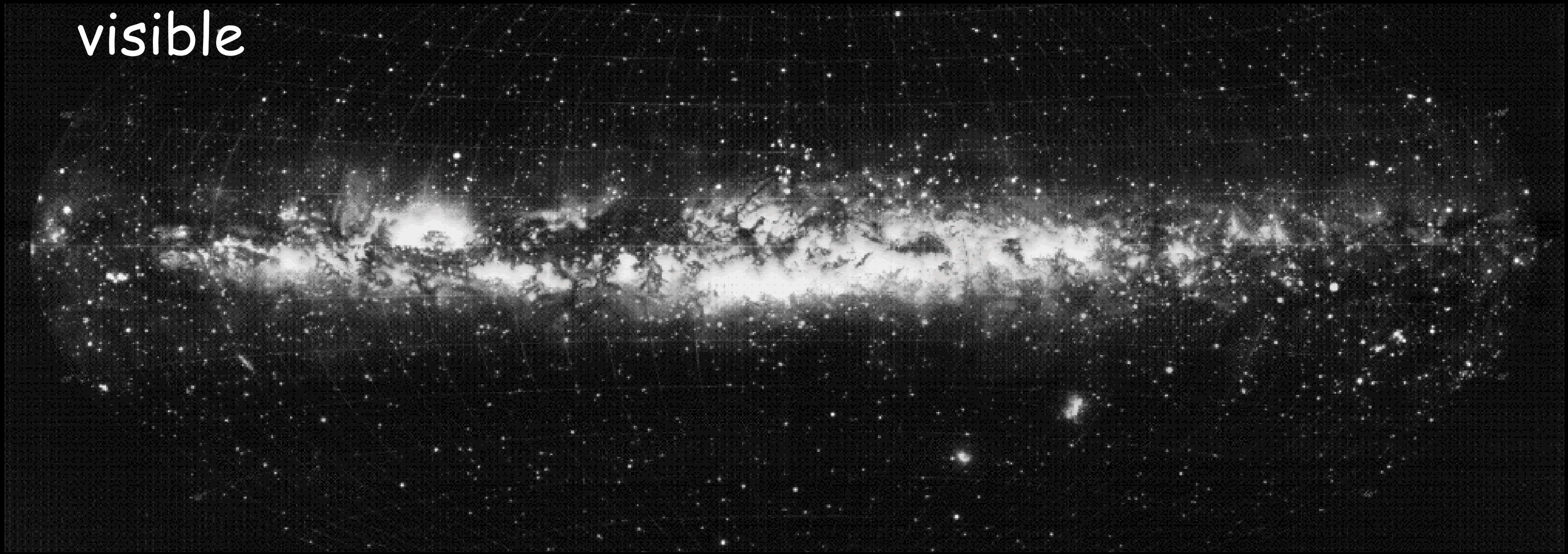
yellow light | **near-infrared**

San Jose Valley

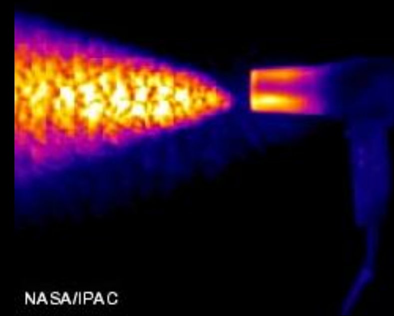
Orion nebula cluster

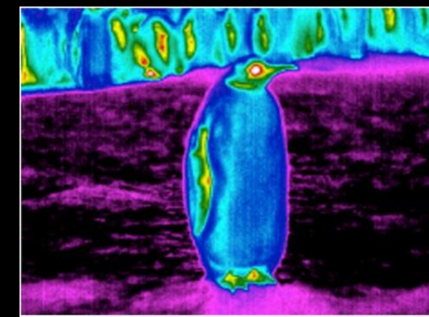


Milky Way in Visible Light and Near-Infrared

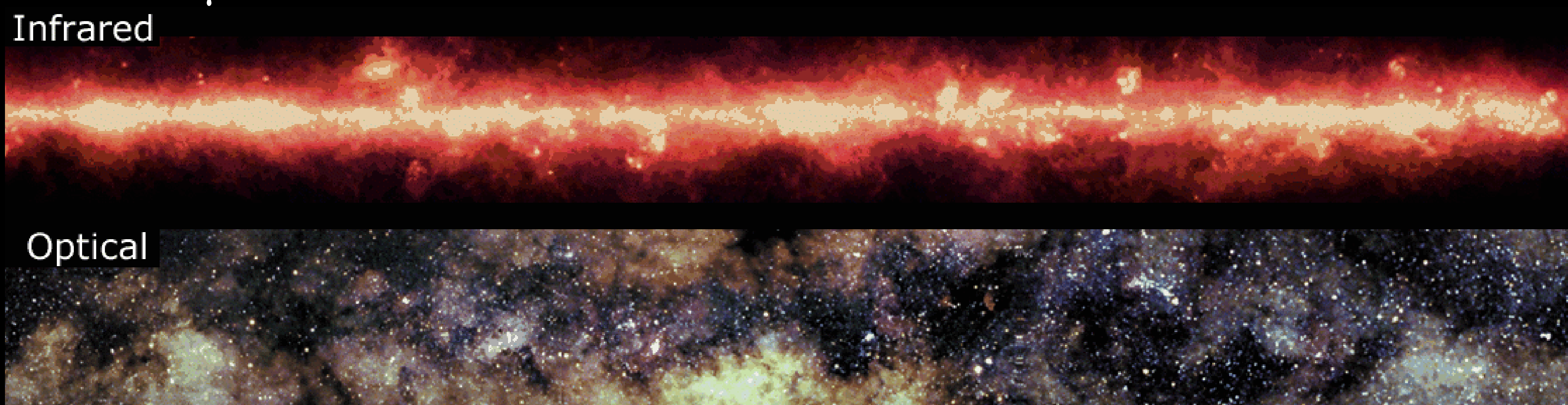


Another advantage: warm objects glow in the mid-far infrared



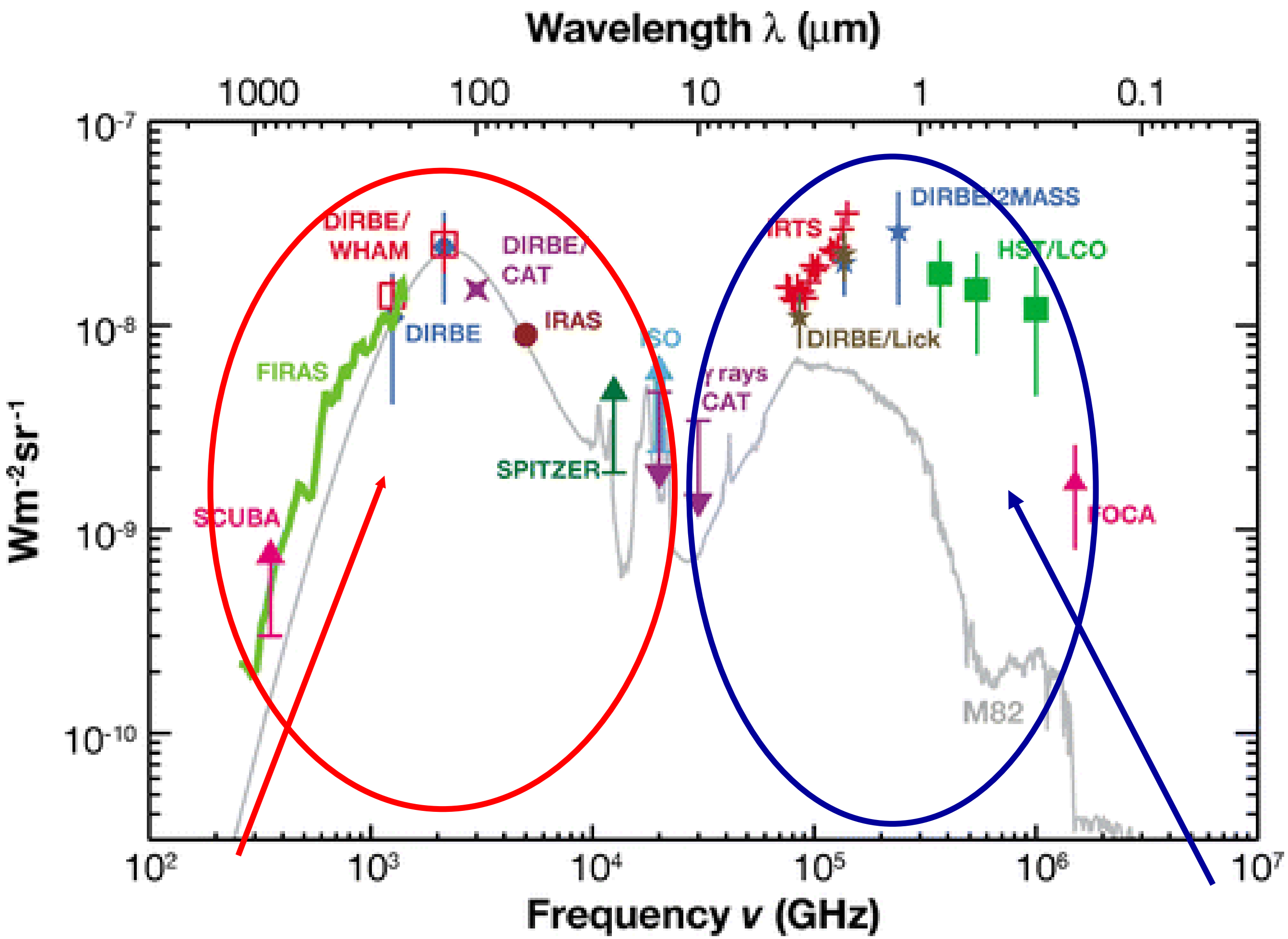


10-100 μm



Starlight "heats" interstellar dust to 5 – 100 K (-270 to -170 C), and the energy absorbed is re-emitted in the far-infrared.

0.0002% of the mass-energy of the Universe absorbs, re-emits half of its starlight!



dust-reprocessed starlight
(infrared, submillimetre)

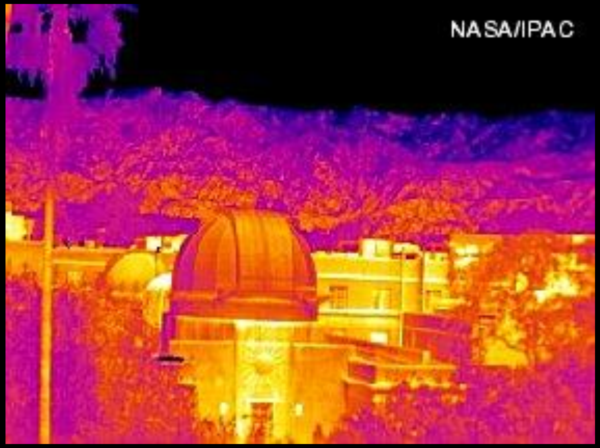
direct starlight
(visible, ultraviolet)

Why not build infrared telescopes on the ground?

- The earth's atmosphere blocks most infrared radiation

  (the greenhouse effect)

- Objects at room temperature are blazingly bright in the infrared!

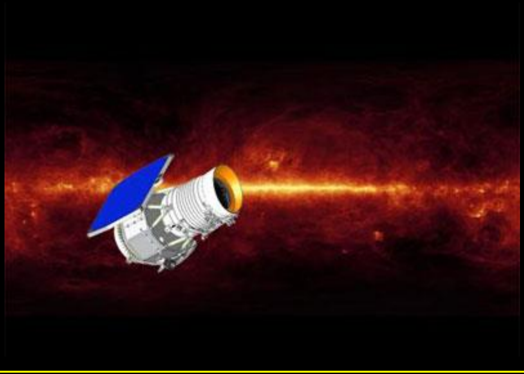


Solution: place a telescope in space

All-Sky Survey Telescopes

IRAS
1983
0.57m
12 – 100 μm

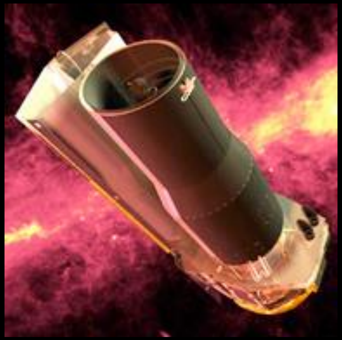
Akari (ASTRO-F)
2006
0.67m
1.8 – 180 μm



WISE
2009
0.4m
3.4 – 22 μm

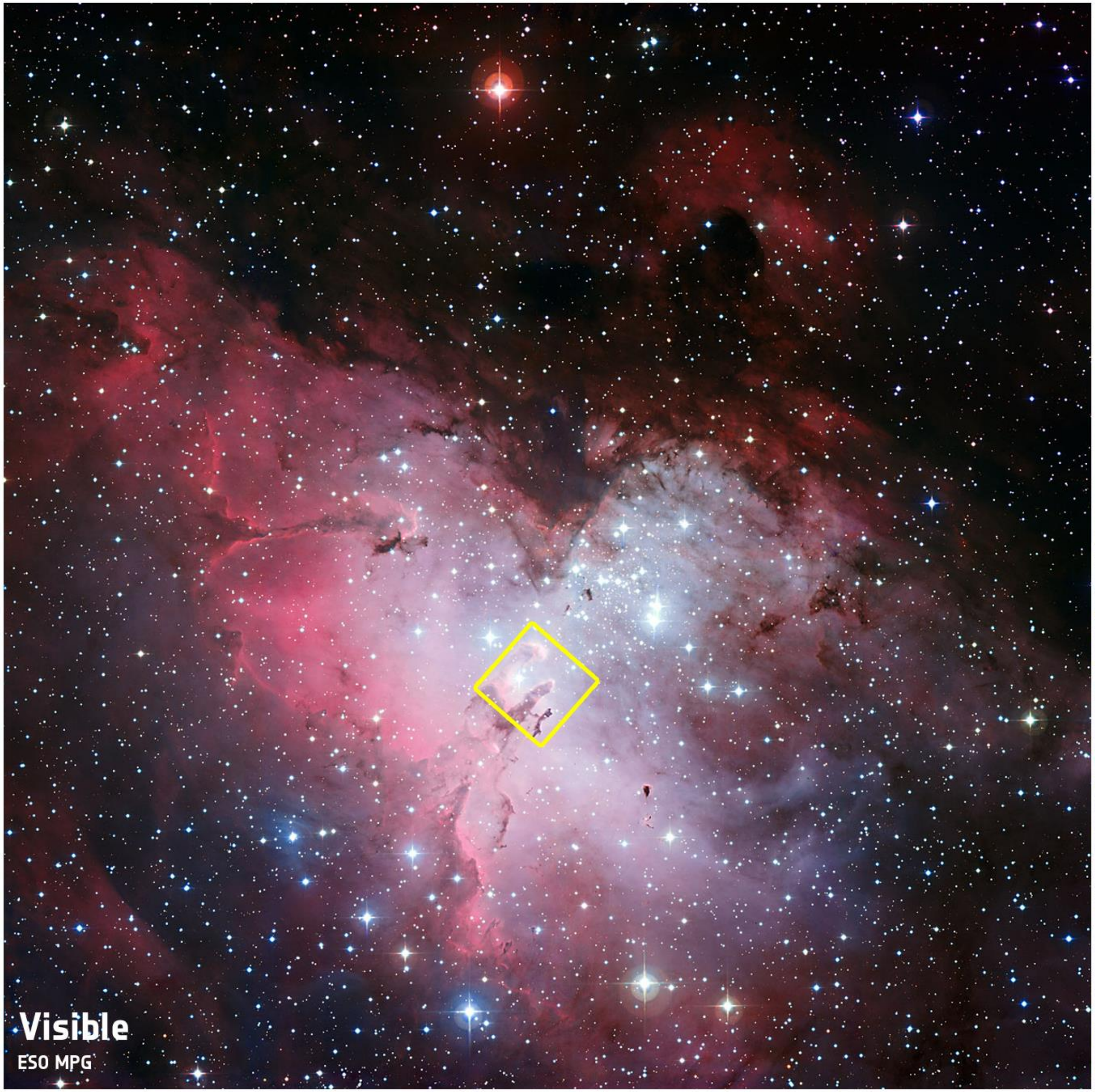
Space Observatories

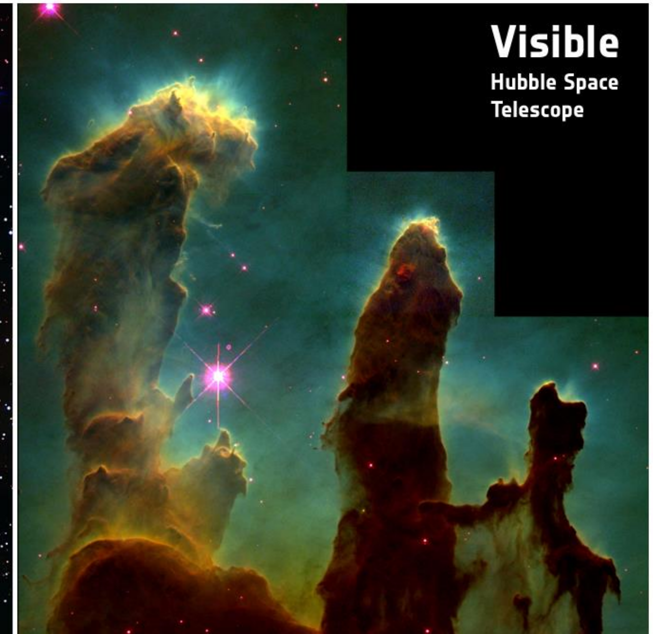
ISO
1995
0.6m
2.4 – 240 μm



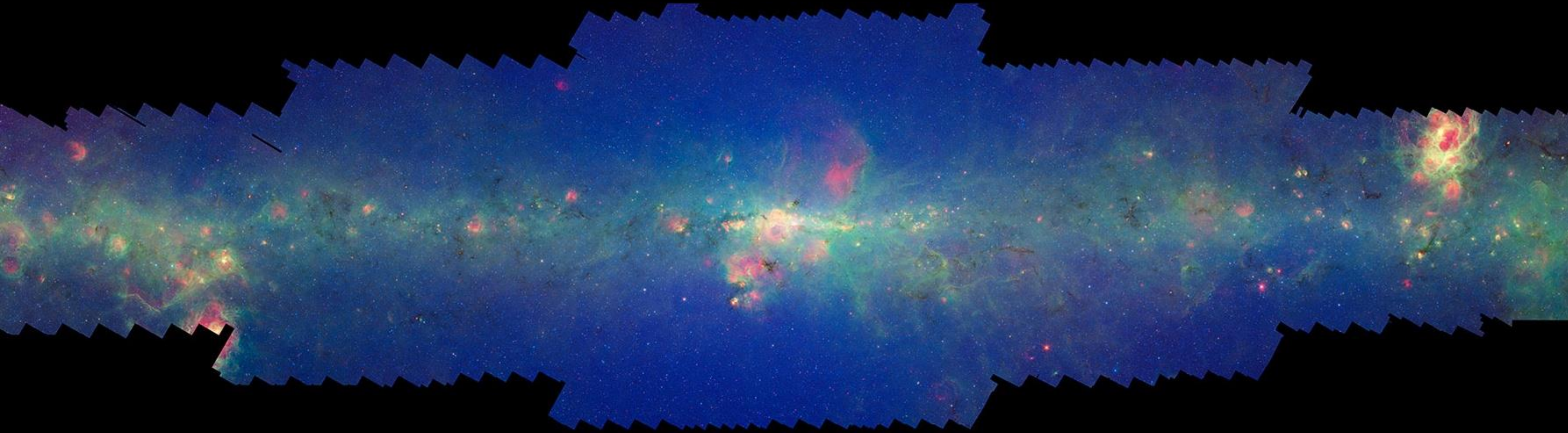
Spitzer
2003
0.8m
5 – 160 μm

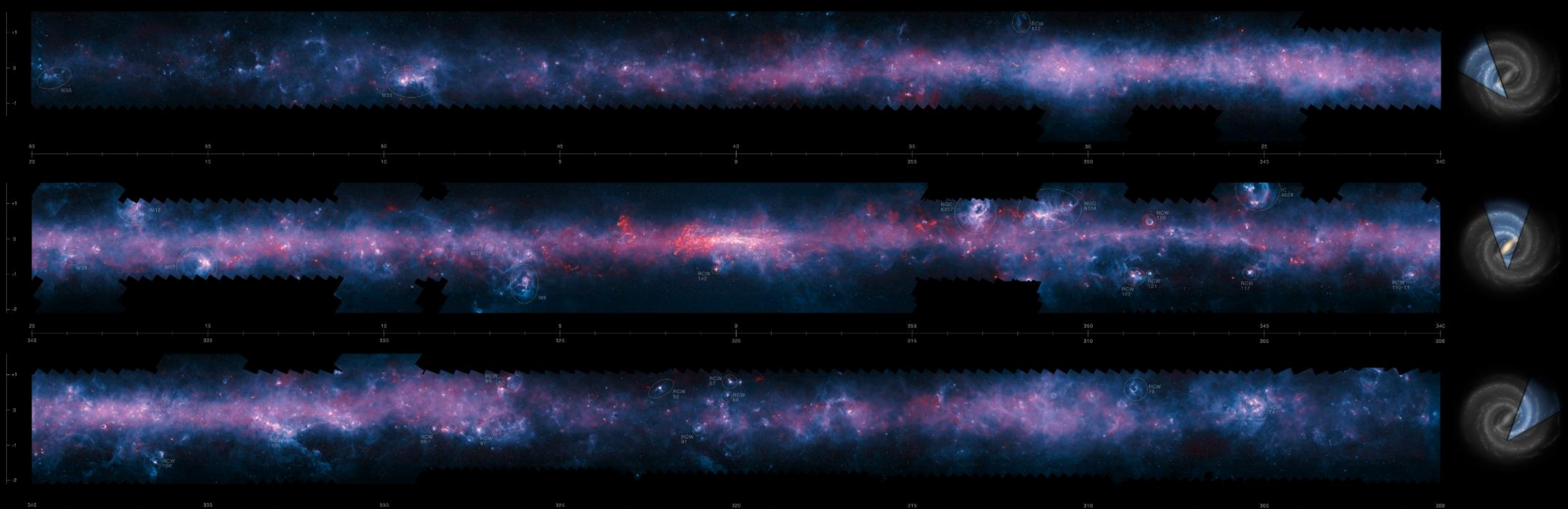
Herschel
2009
3.5m
57 – 672 μm


Visible
ESO MPG


Visible
Hubble Space Telescope

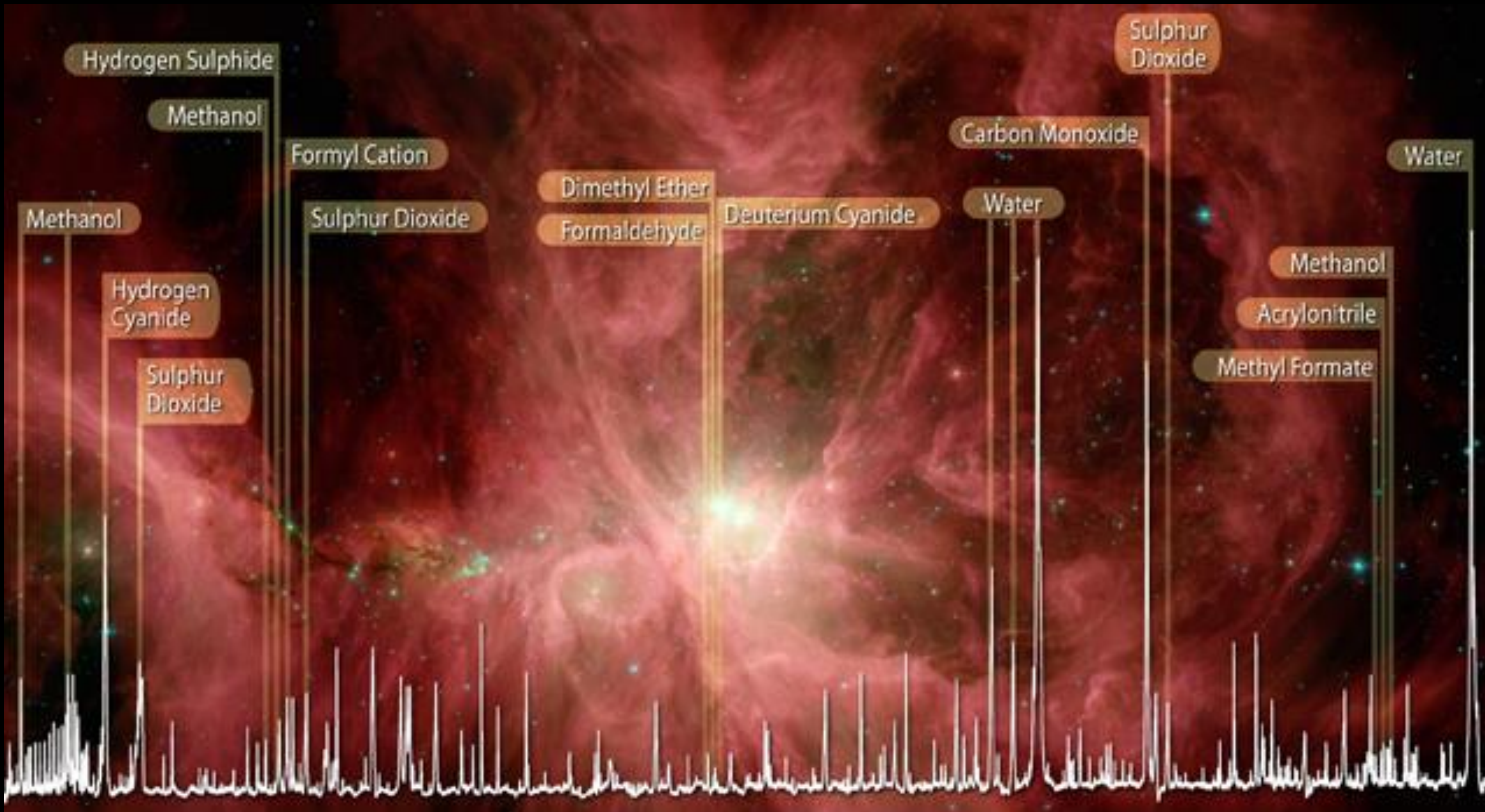

Near Infrared
ESO VLT

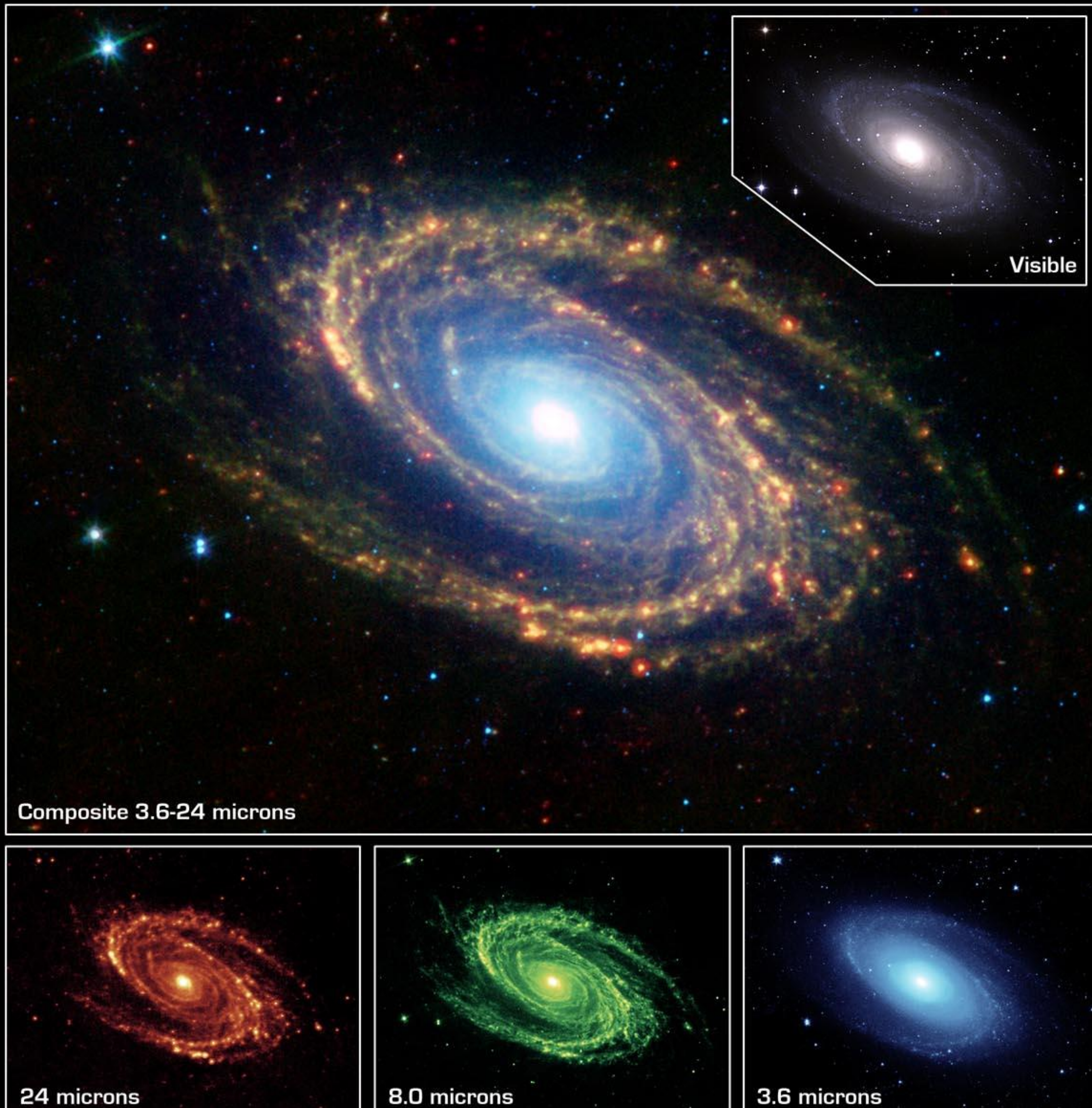




ATLASGAL

Infrared spectra reveal hundreds of thousands of molecular and atomic features, from every phase of the interstellar medium



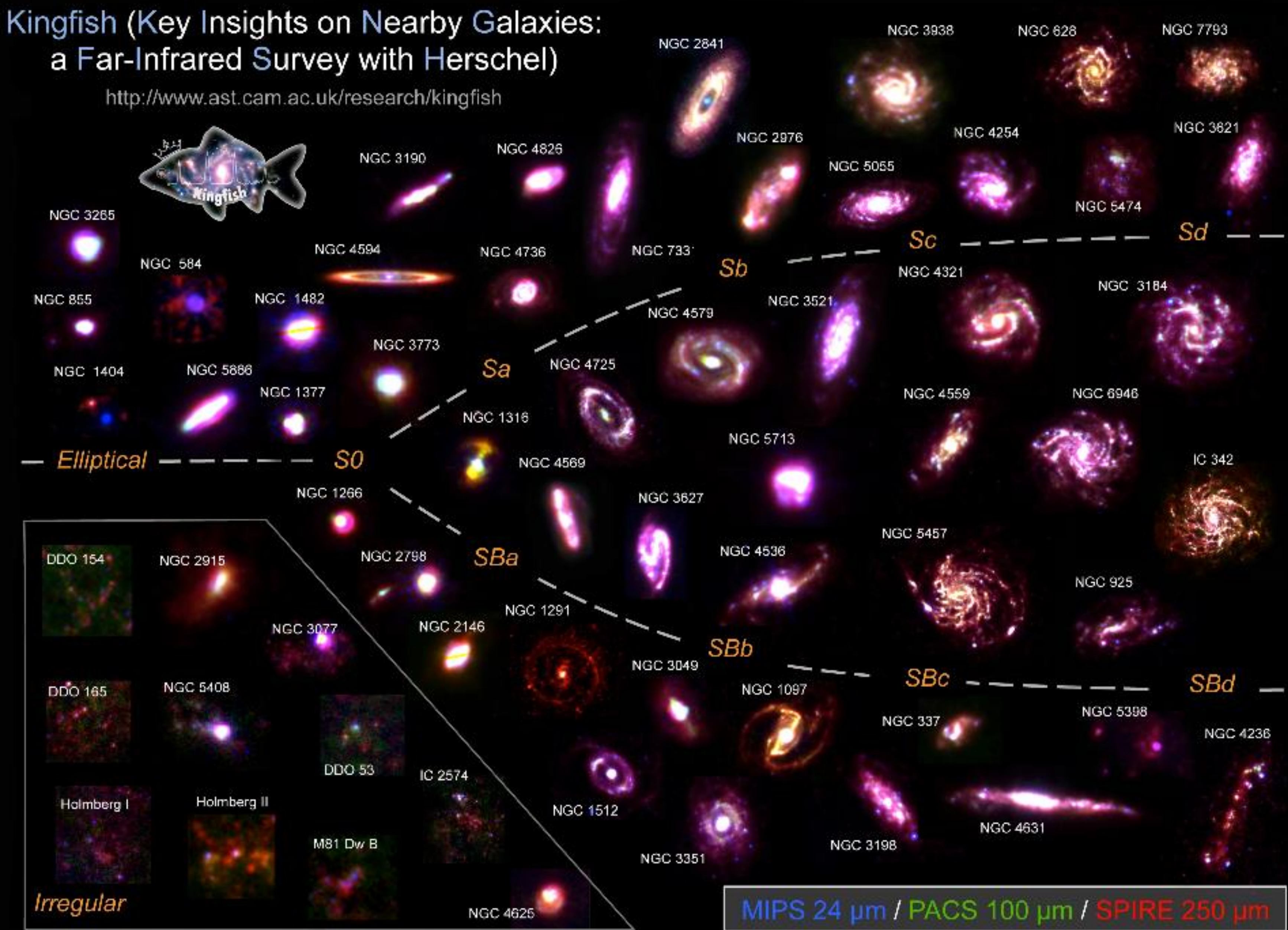


Spiral Galaxy M81 **Spitzer Space Telescope • MIPS • IRAC**

Inset: visible light (NOAO)

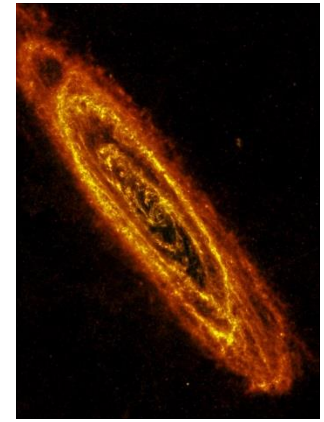
NASA / JPL-Caltech / K. Gordon (University of Arizona), S. Willner (Harvard-Smithsonian CfA) ssc2003-06

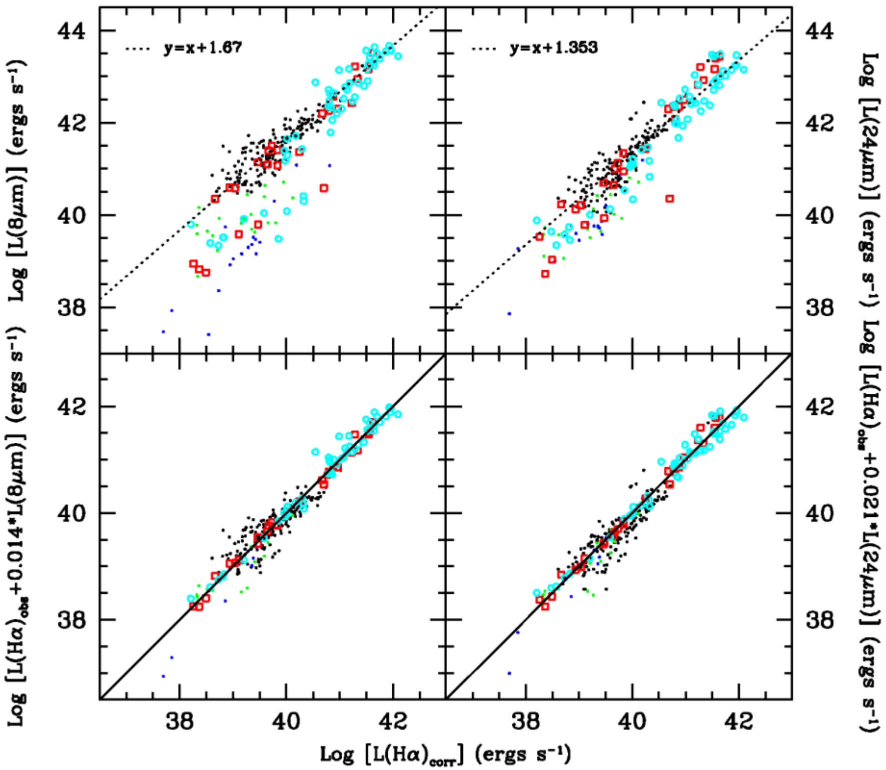
visible + ultraviolet + Hα

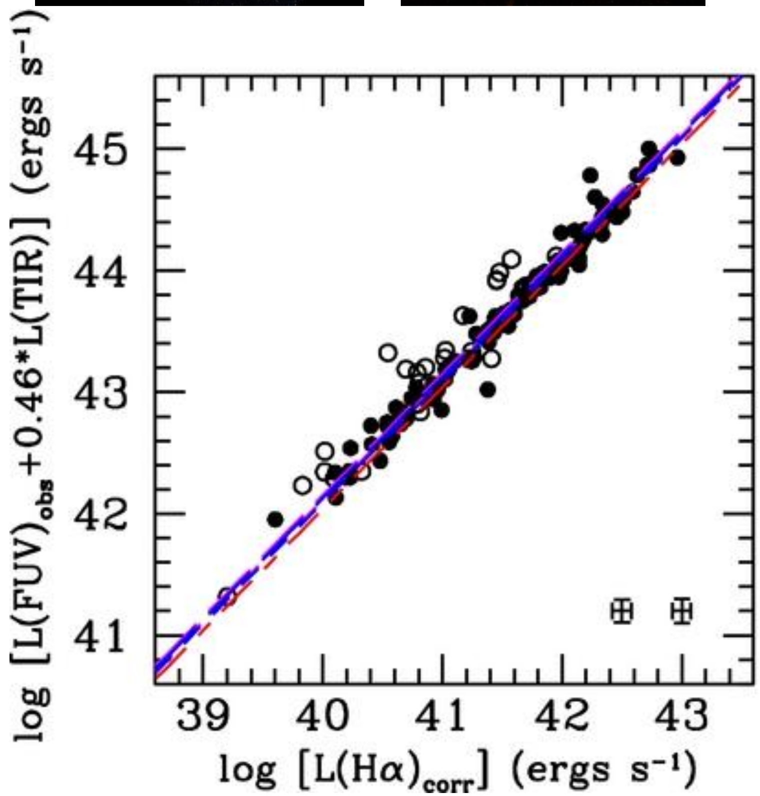


For an interactive version go to:
http://herschel.cf.ac.uk/kingfish

multiwavelength observations provide dust-free SF rate tracers, and the fraction of starlight attenuated by dust

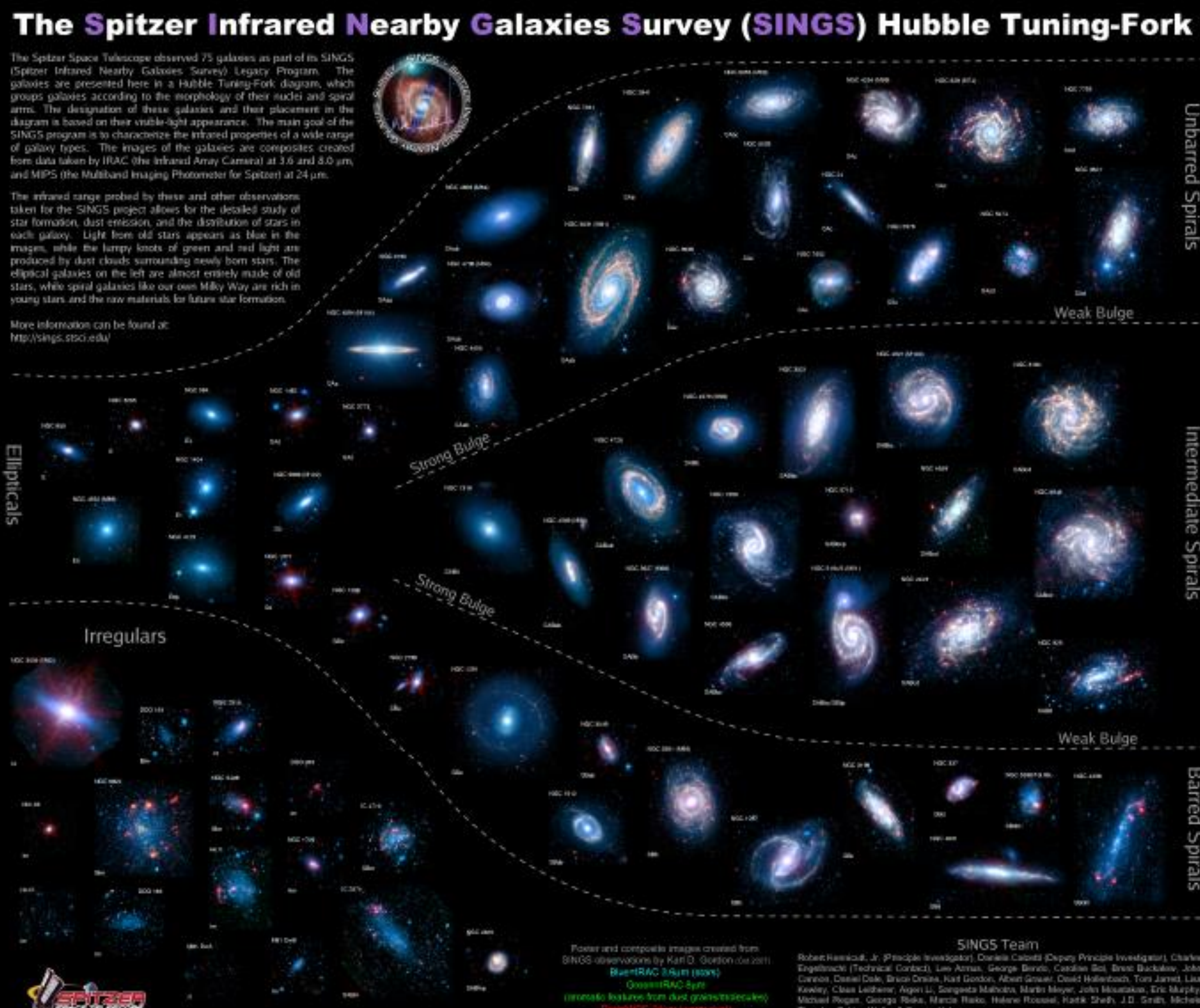






Kennicutt et al 2009

Hao et al 2011


The Spitzer Infrared Nearby Galaxies Survey (SINGS) Hubble Tuning-Fork
The Spitzer Space Telescope observed 75 galaxies as part of its SINGS (Spitzer Infrared Nearby Galaxies Survey) Legacy Program. The galaxies are presented here in a Hubble Tuning-Fork diagram, which groups galaxies according to the morphology of their nuclei and spiral arms. The designation of these galaxies and their placement in the diagram is based on their visible-light appearance. The main goal of the SINGS program is to characterize the infrared properties of a wide range of galaxy types. The images of the galaxies are composites created from data taken by IRAC (the Infrared Array Camera) at 3.6 and 8.0 μm, and MIPS (the Multiband Imaging Photometer for Spitzer) at 24 μm.
The infrared range probed by these and other observations taken for the SINGS project allows for the detailed study of star formation, dust emission, and the distribution of stars in each galaxy. Light from old stars appears as blue in the images, while the lumpy knots of green and red light are produced by dust clouds surrounding newly born stars. The elliptical galaxies on the left are almost entirely made of old stars, while spiral galaxies like our own Milky Way are rich in young stars and the raw materials for future star formation.
More information can be found at:
http://sings.stsci.edu/
Unbarred Spirals
Weak Bulge
Strong Bulge
Ellipticals
Intermediate Spirals
Strong Bulge
Weak Bulge
Irregulars
Barred Spirals
Poster and composite images created from SINGS observations by Karl D. Gordon
Blue=IRAC 3.6μm (stars)
Green=IRAC 8μm
(aromatic features from dust grains/molecules)
Red=MIPS 24μm (warm dust)
SINGS Team
Robert Kennicutt, Jr. (Principle Investigator), Daniela Calzetti (Deputy Principle Investigator), Charles Engelbracht (Technical Contact), Lee Armus, George Bendo, Caroline Bot, Brent Buckalew, John Cannon, Daniel Dale, Bruce Draine, Karl Gordon, Albert Grauer, David Hollenbach, Tom Jarrett, Lisa Kewley, Claus Leitherer, Aigen Li, Sangeeta Malhotra, Martin Meyer, John Moustakas, Eric Murphy, Michael Regan, George Rieke, Marcia Rieke, Helene Roussel, Kartik Sheth, J.D. Smith, Michele Thornley, Fabian Walter & George Helou
SPITZER SPACE TELESCOPE

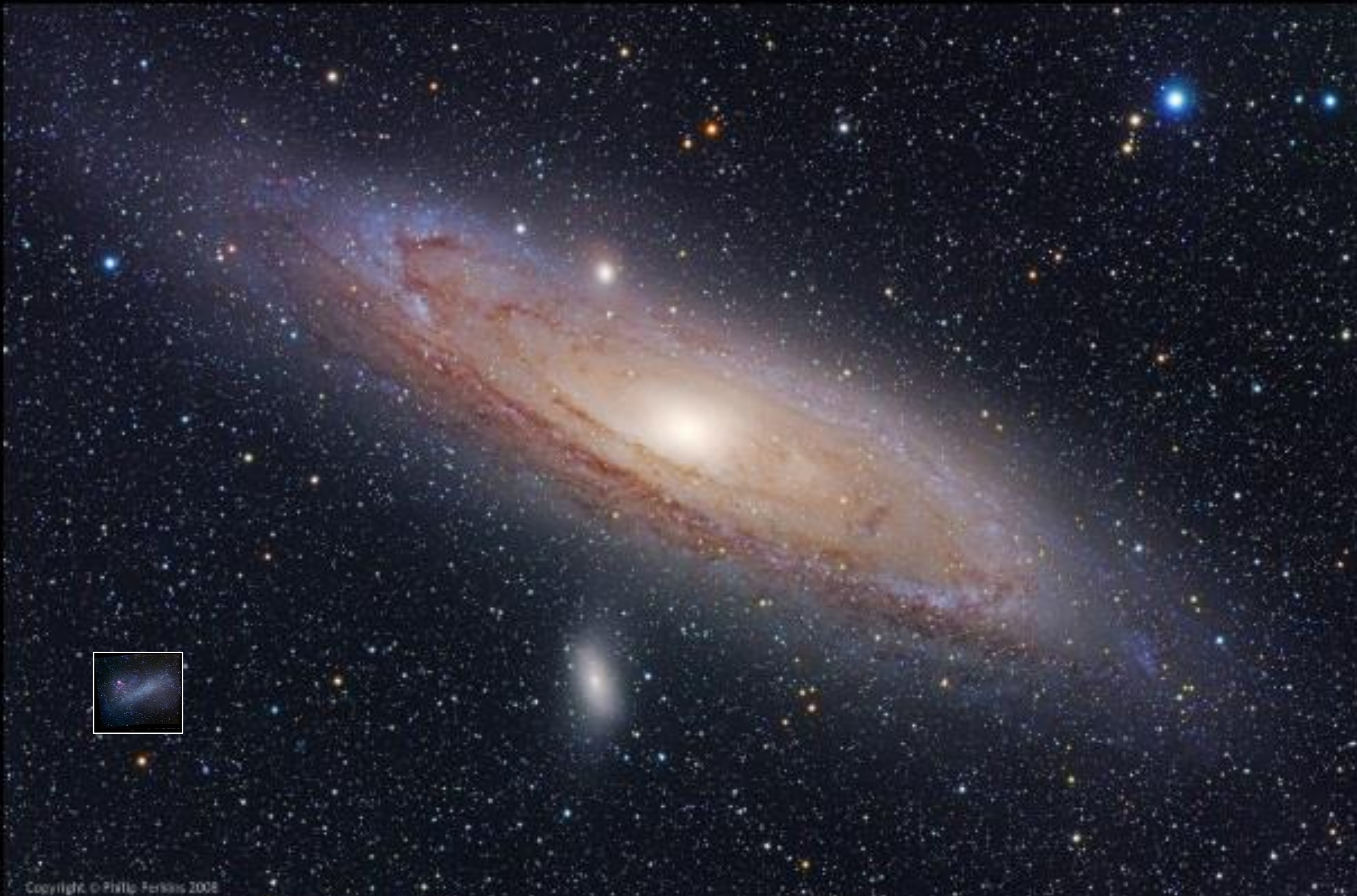
Case Studies: Two of our Nearest Neighbors

Andromeda Galaxy: M31

distance = 2.5 Mly   mass ~ 1.5 MW

Large Magellanic Cloud (LMC)

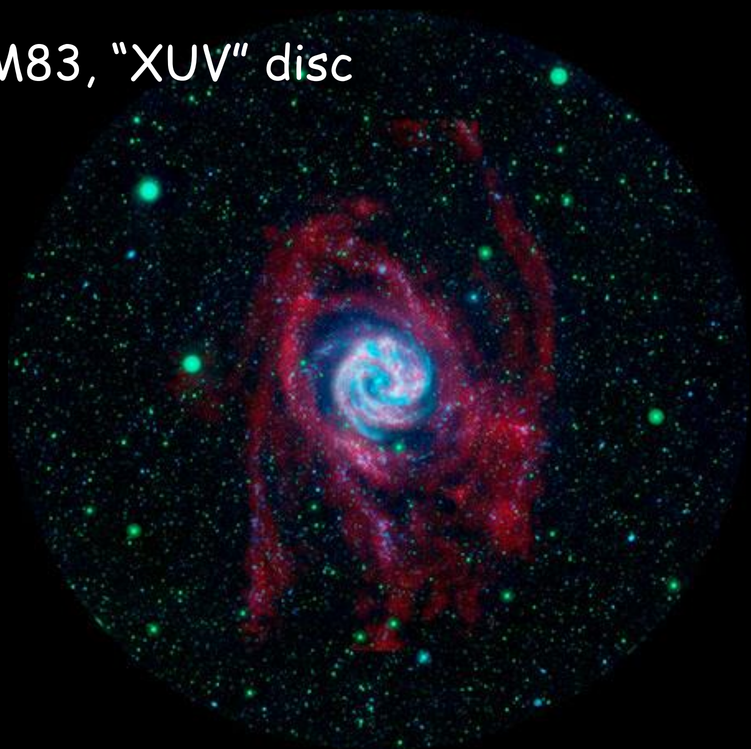
Distance = 0.16 Mly mass ~ 0.1 MW

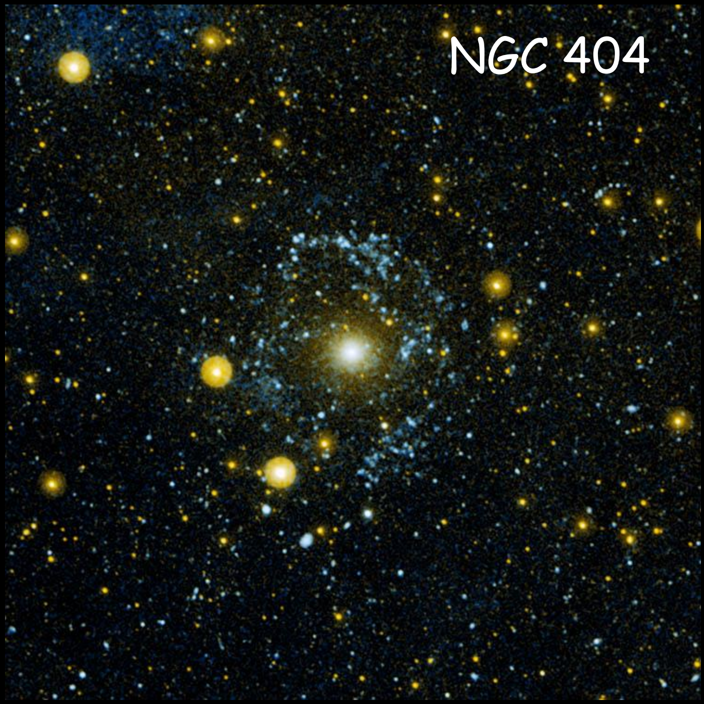

Copyright © Phillip Perkins 2008

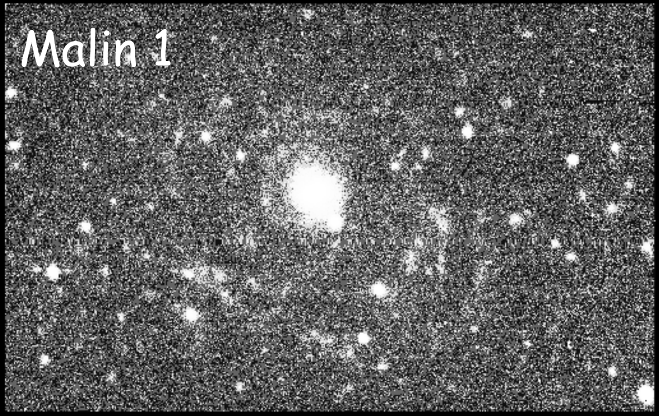
30 Doradus region
(HST)

>2,000 ionising stars
(vs 4 for Orion!)

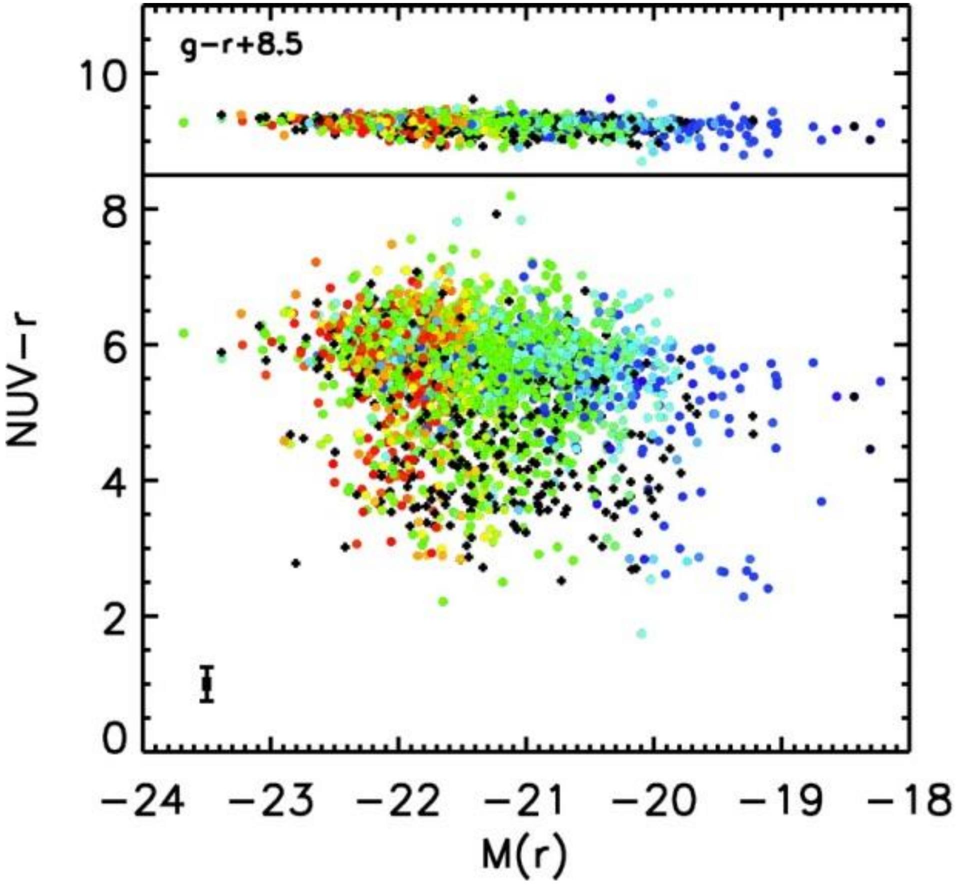
Star Formation in the Low Density Extreme

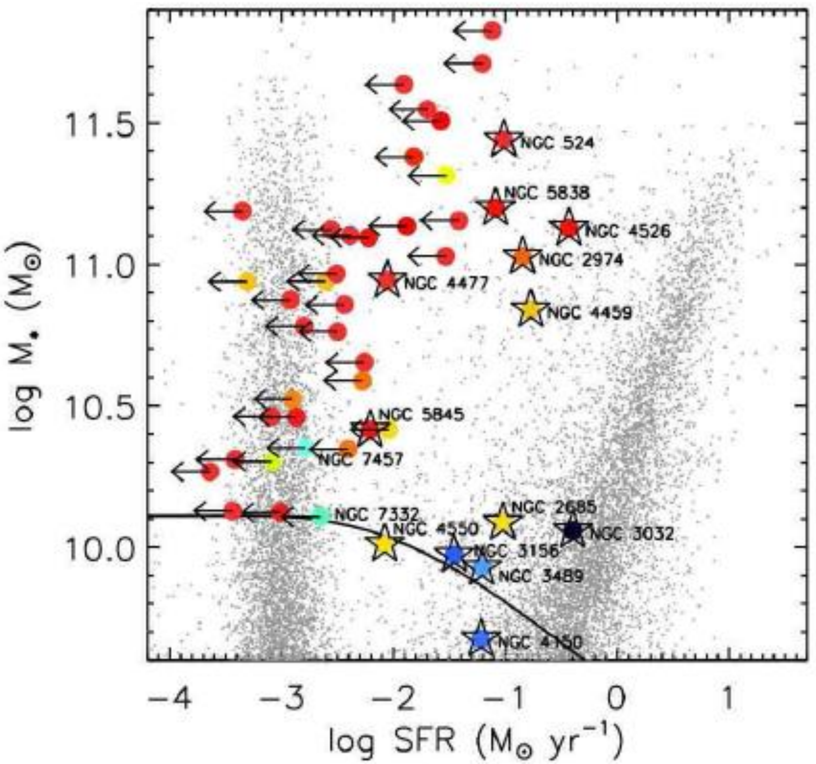






30% of E and S0 galaxies formed stars in last 300-500 Myr





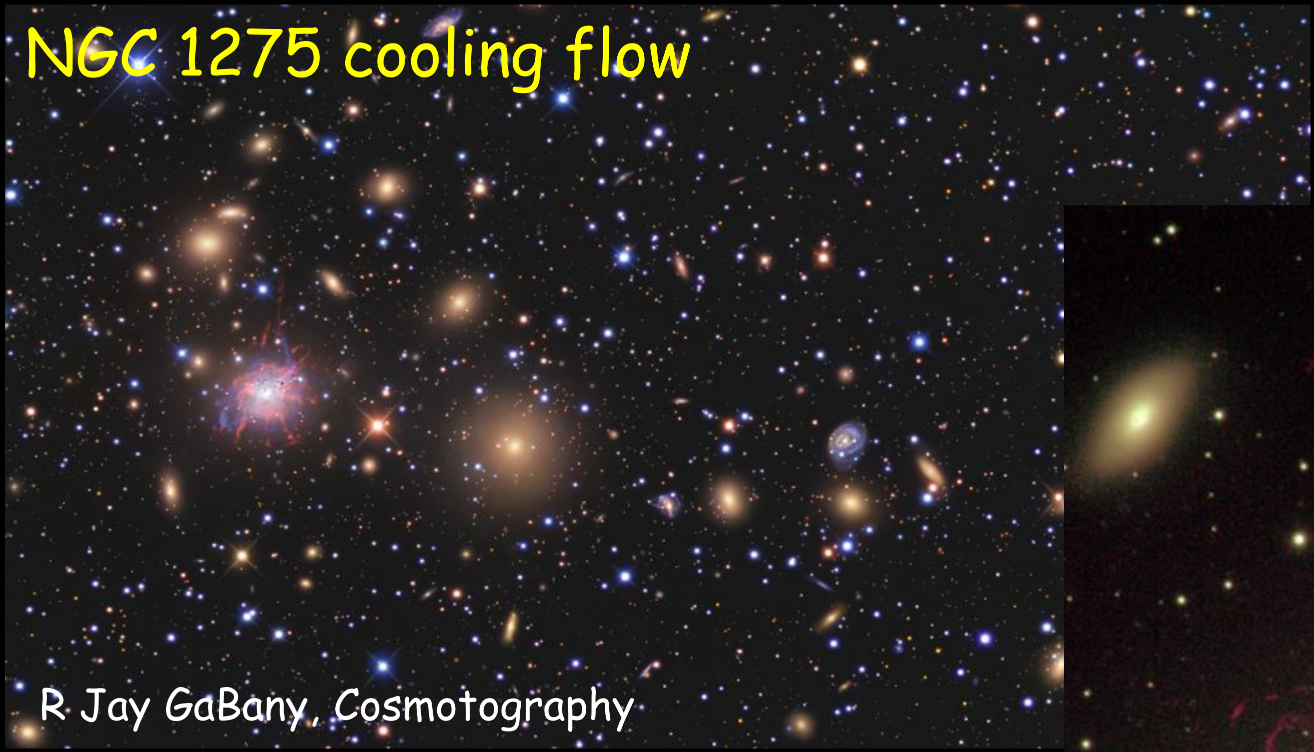
GALEX: Kaviraj et al. 2007

SAURON: Shapiro et al. 2010

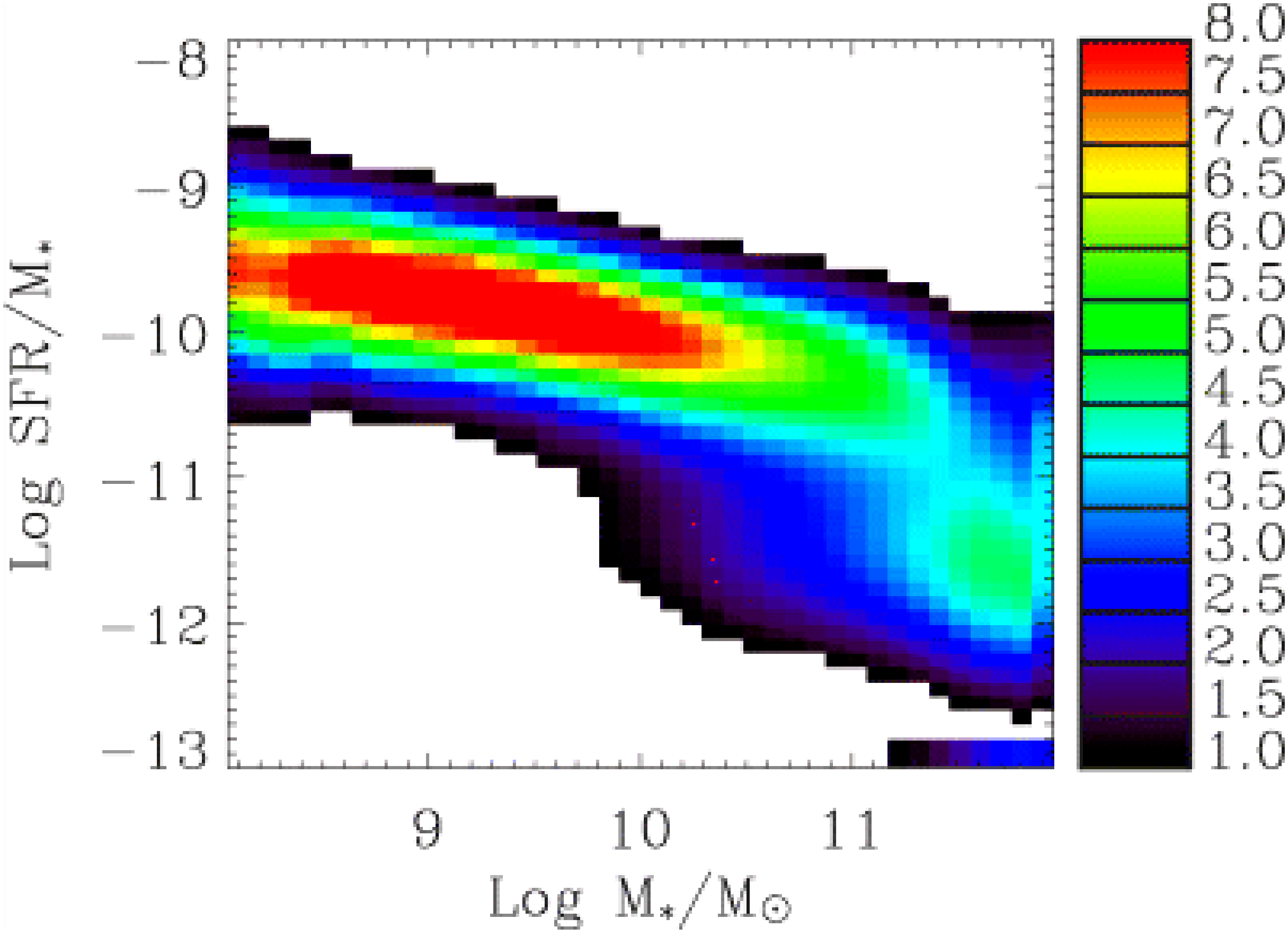
Perseus galaxy cluster: distance = 230 Mly

Kent Wood, Starlodge Observatory

NGC 1275 cooling flow

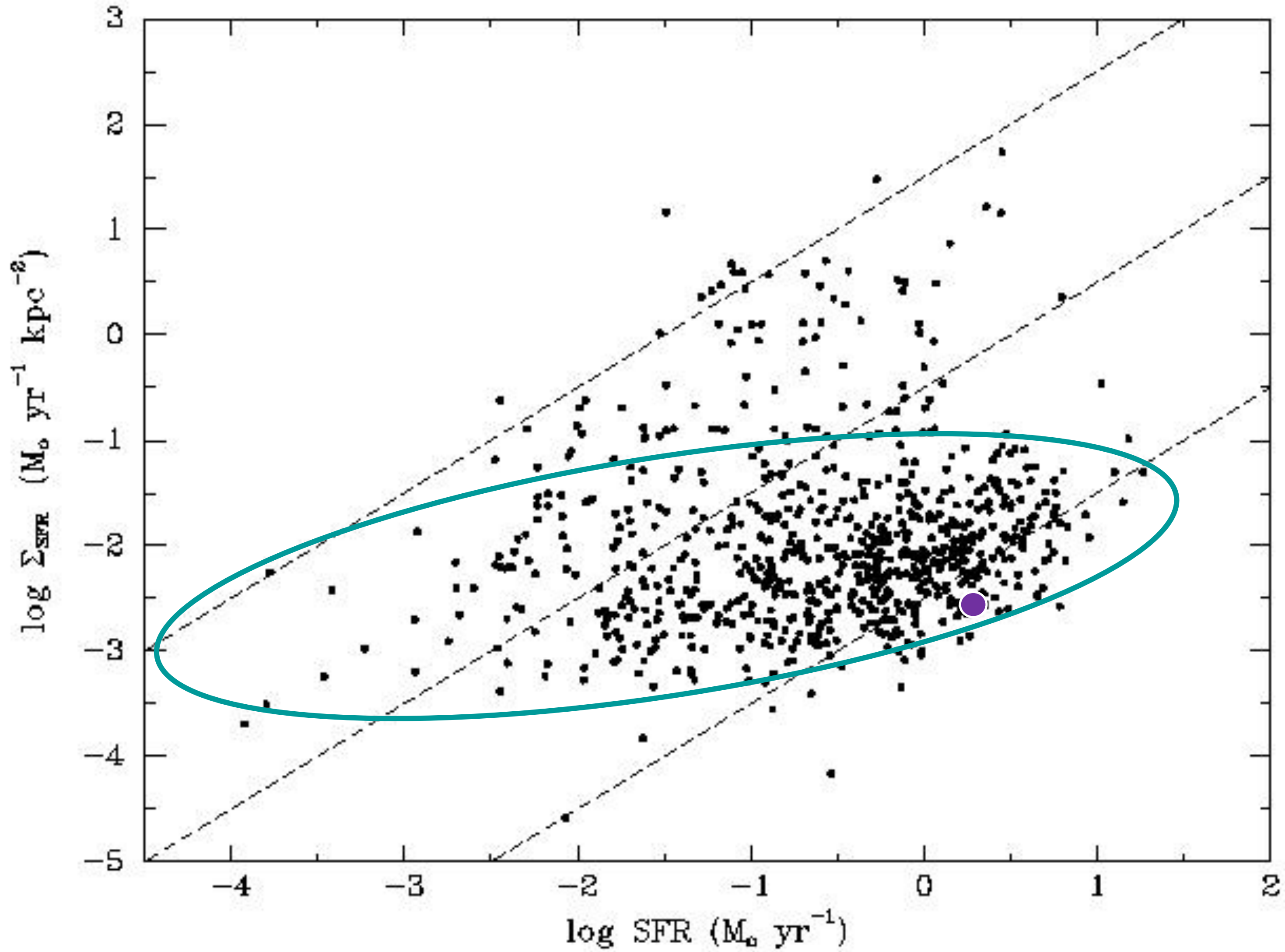


C. Conselice, WIYN telescope



Log SFR/M*
Log M*/M⊙
−8
−9
−10
−11
−12
−13
9
10
11
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0

11MPC + HαGS + SINGG+ Hameed + Goldmine Surveys

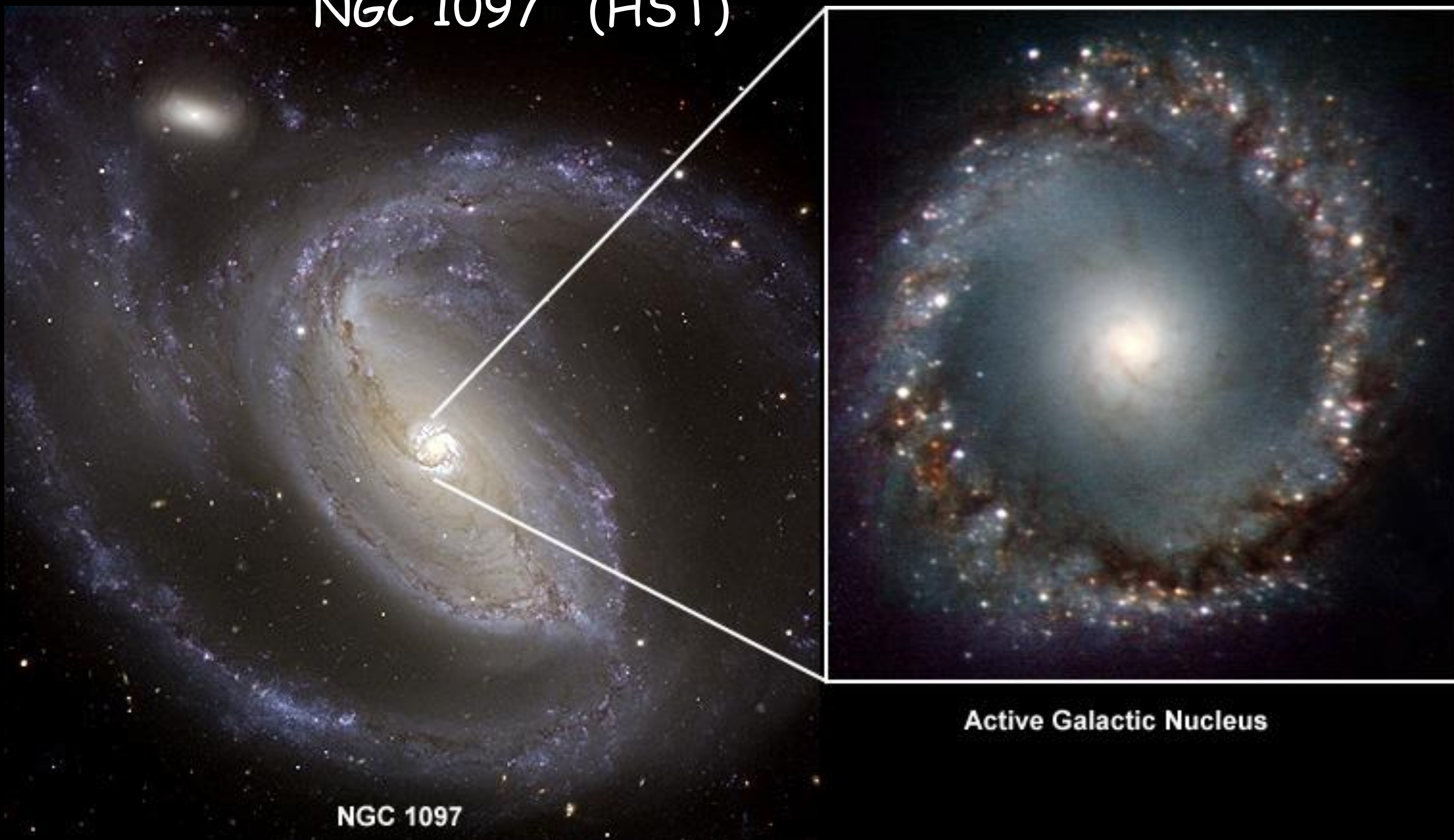


star formation rate per unit area

star formation rate

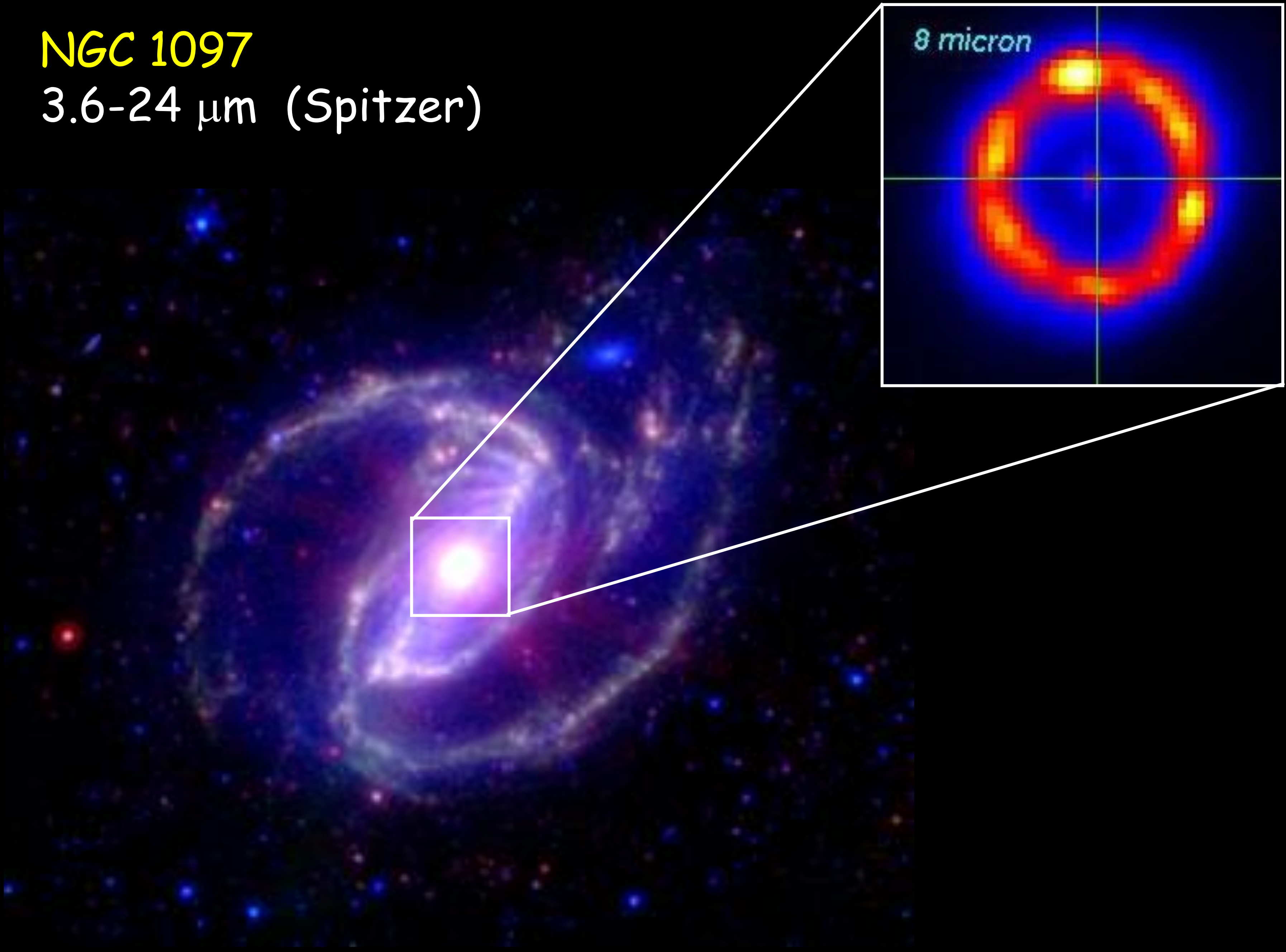
A Second Mode: Circumnuclear Star Formation

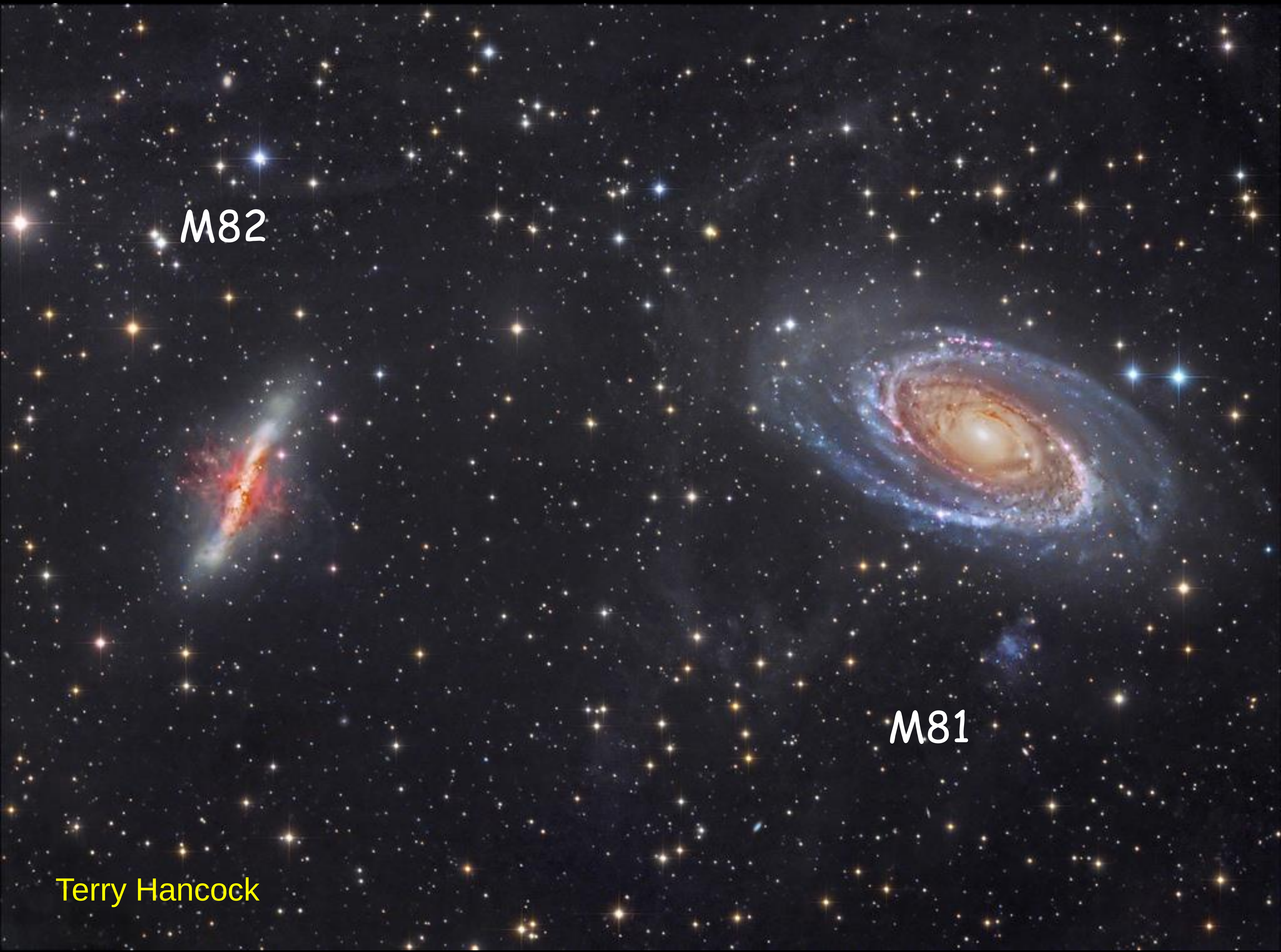
NGC 1097 (HST)



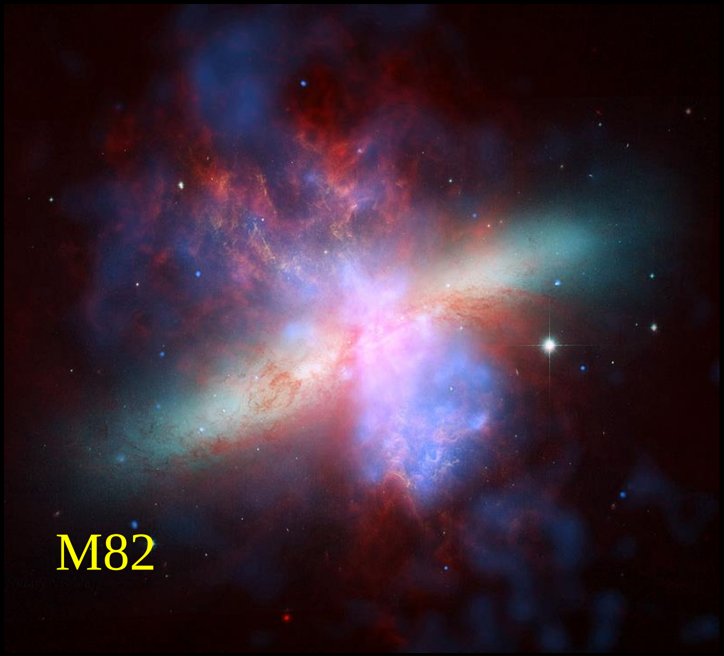
NGC 1097

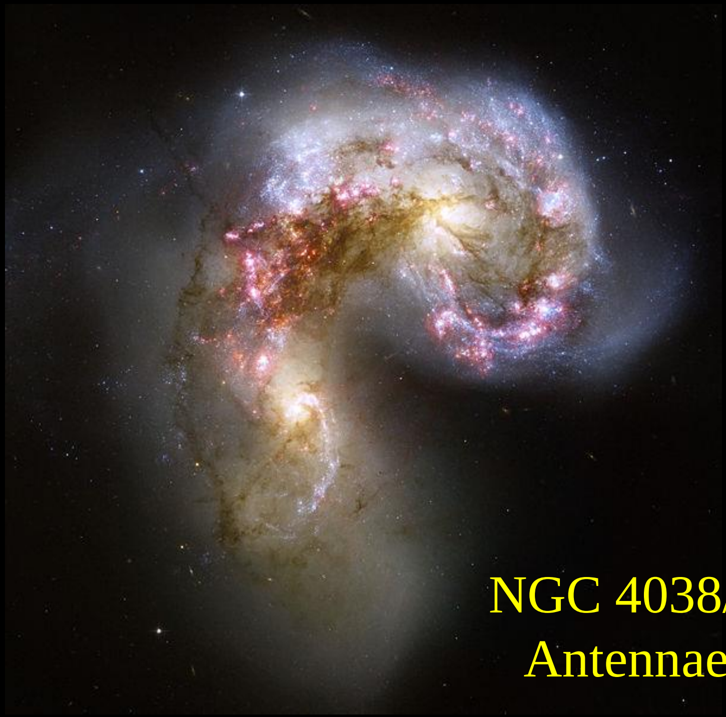
3.6-24 μm (Spitzer)

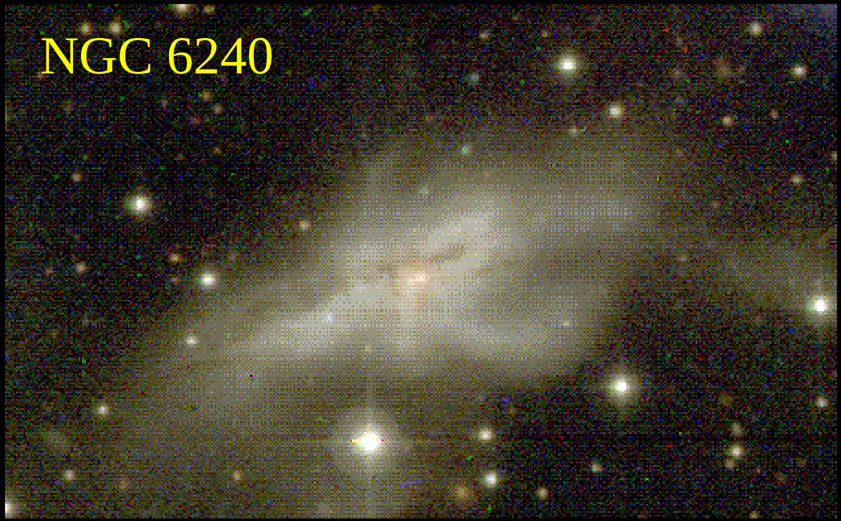


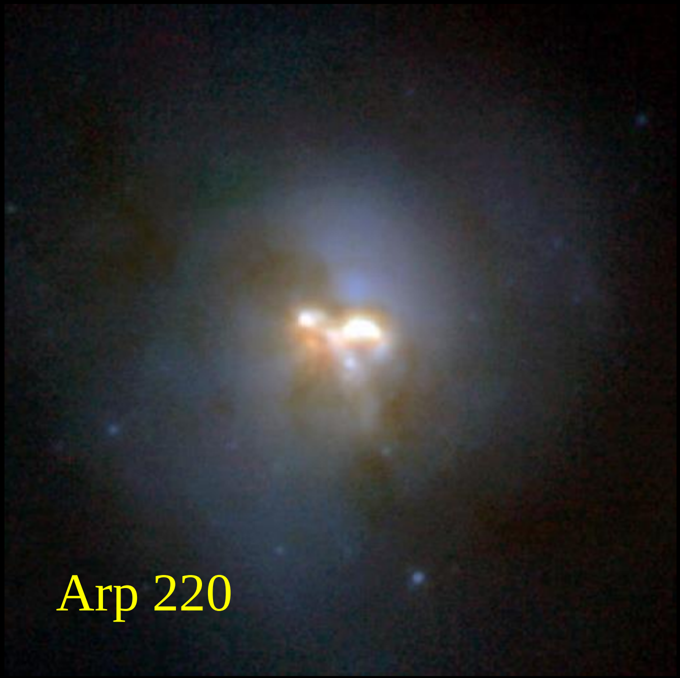

M82
M81
Terry Hancock

Infrared-Luminous, Ultraluminous Starburst Galaxies





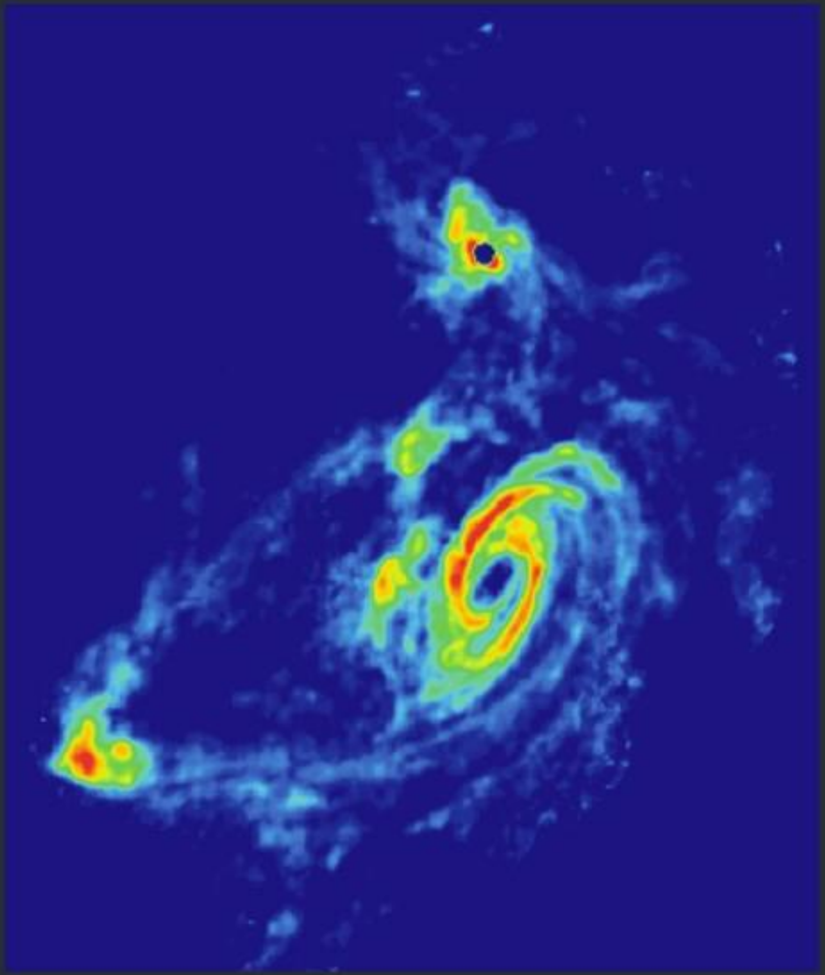


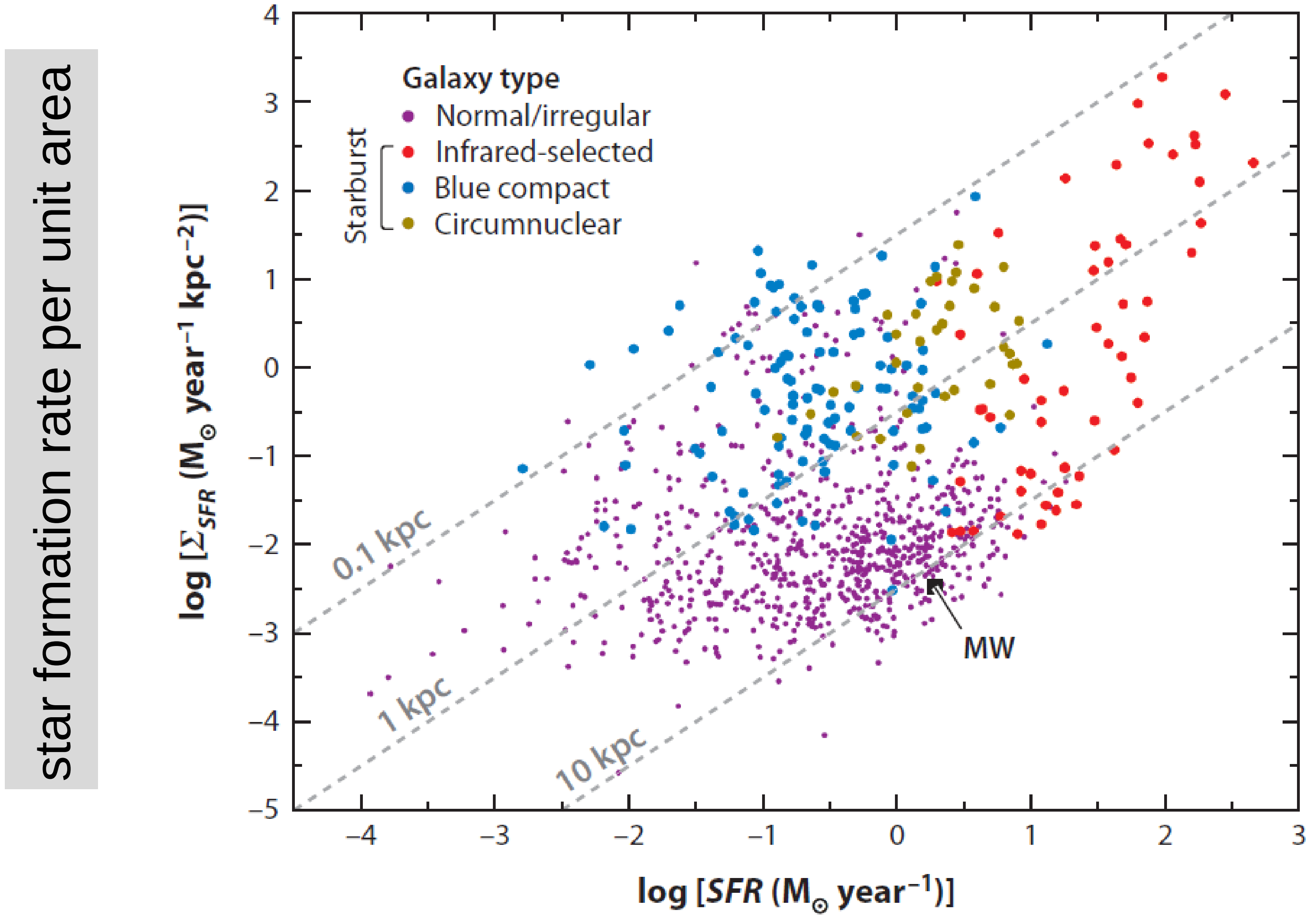


TIDAL INTERACTIONS IN M81 GROUP

Stellar Light Distribution

21 cm HI Distribution





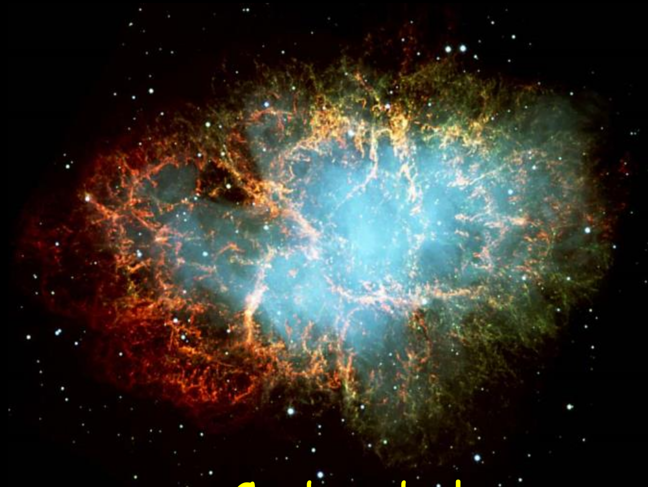
star formation rate

Kennicutt, Evans 2012

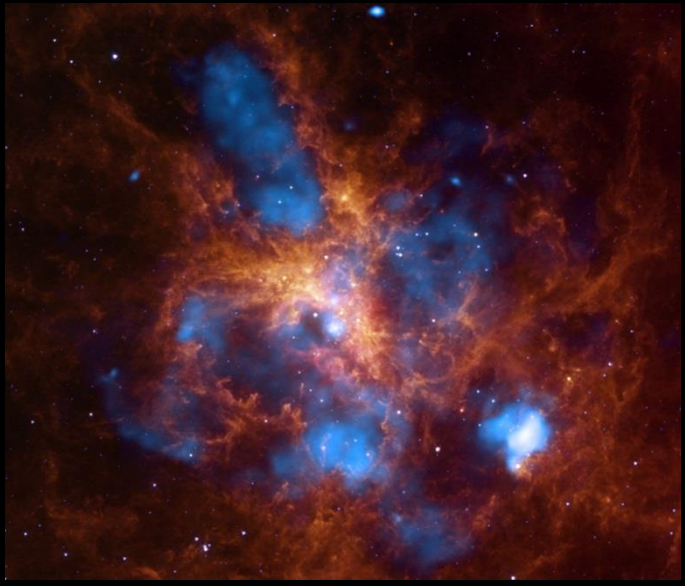
M82 = NGC 3034

Massive star formation is a highly exothermal process: "feedback"

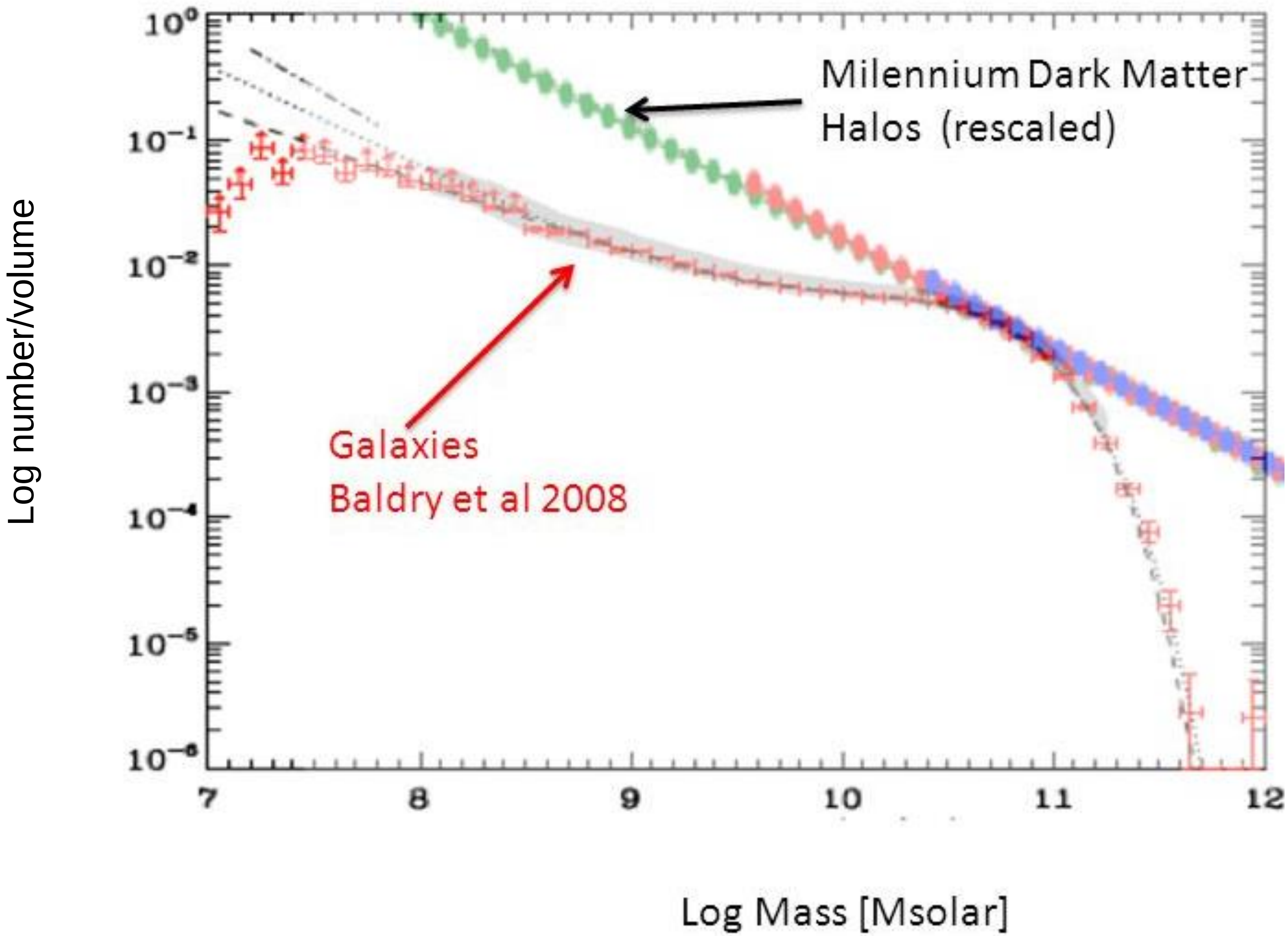
30 Doradus revisited

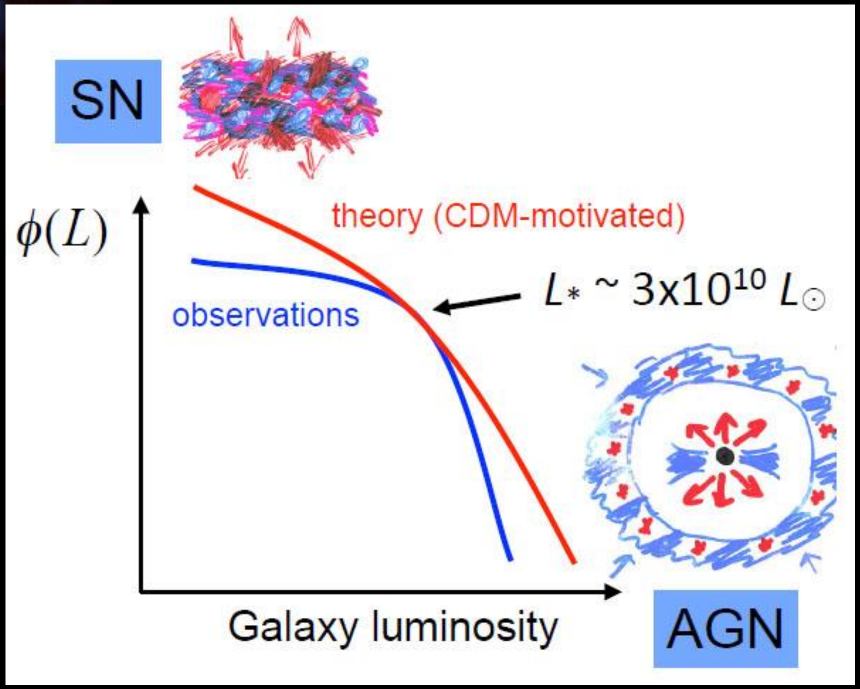


Crab nebula supernova remnant (SN1054)



feedback shapes galaxies





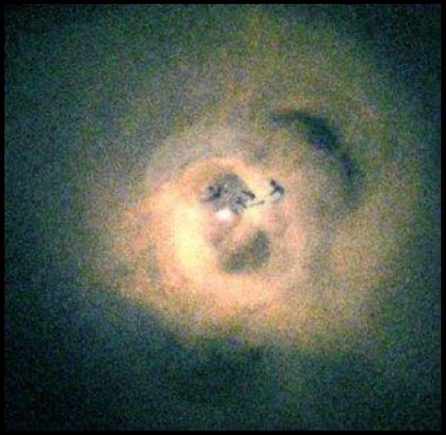
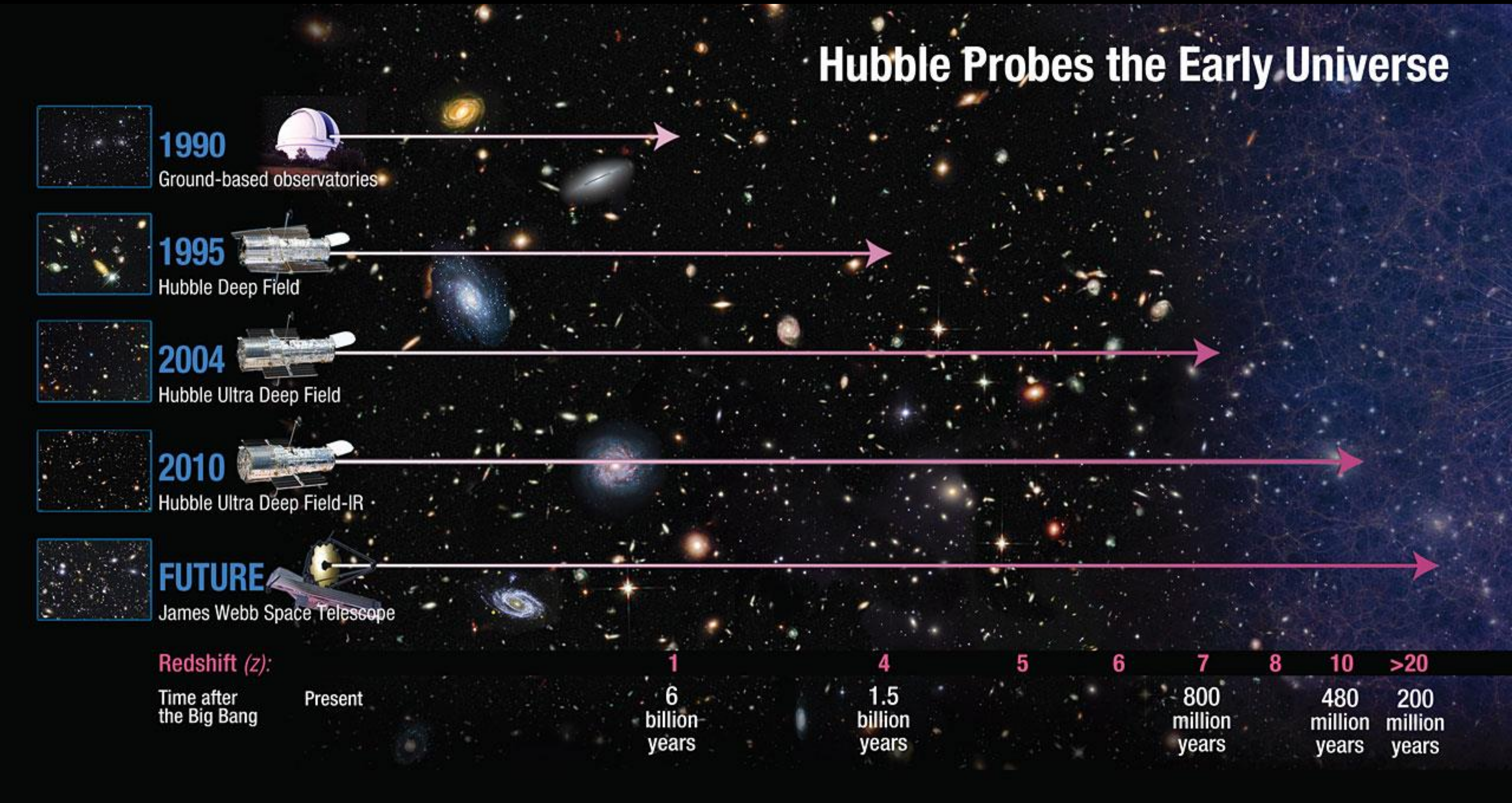
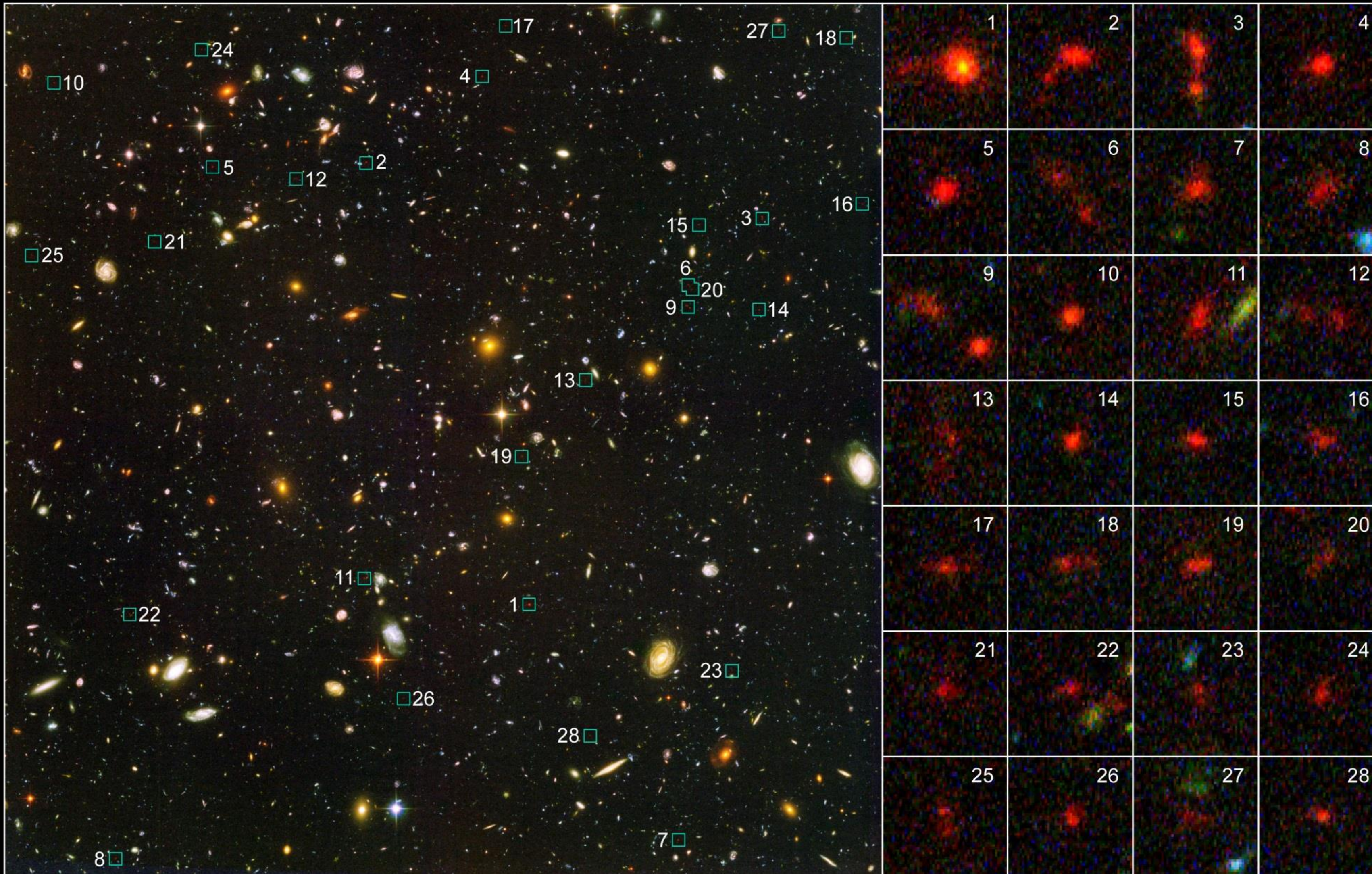


diagram by J Silk 2011



Hubble Probes the Early Universe
1990
Ground-based observatories
1995
Hubble Deep Field
2004
Hubble Ultra Deep Field
2010
Hubble Ultra Deep Field-IR
FUTURE
James Webb Space Telescope
Redshift (z):
1
4
5
6
7
8
10
>20
Time after the Big Bang
Present
6 billion years
1.5 billion years
800 million years
480 million years
200 million years



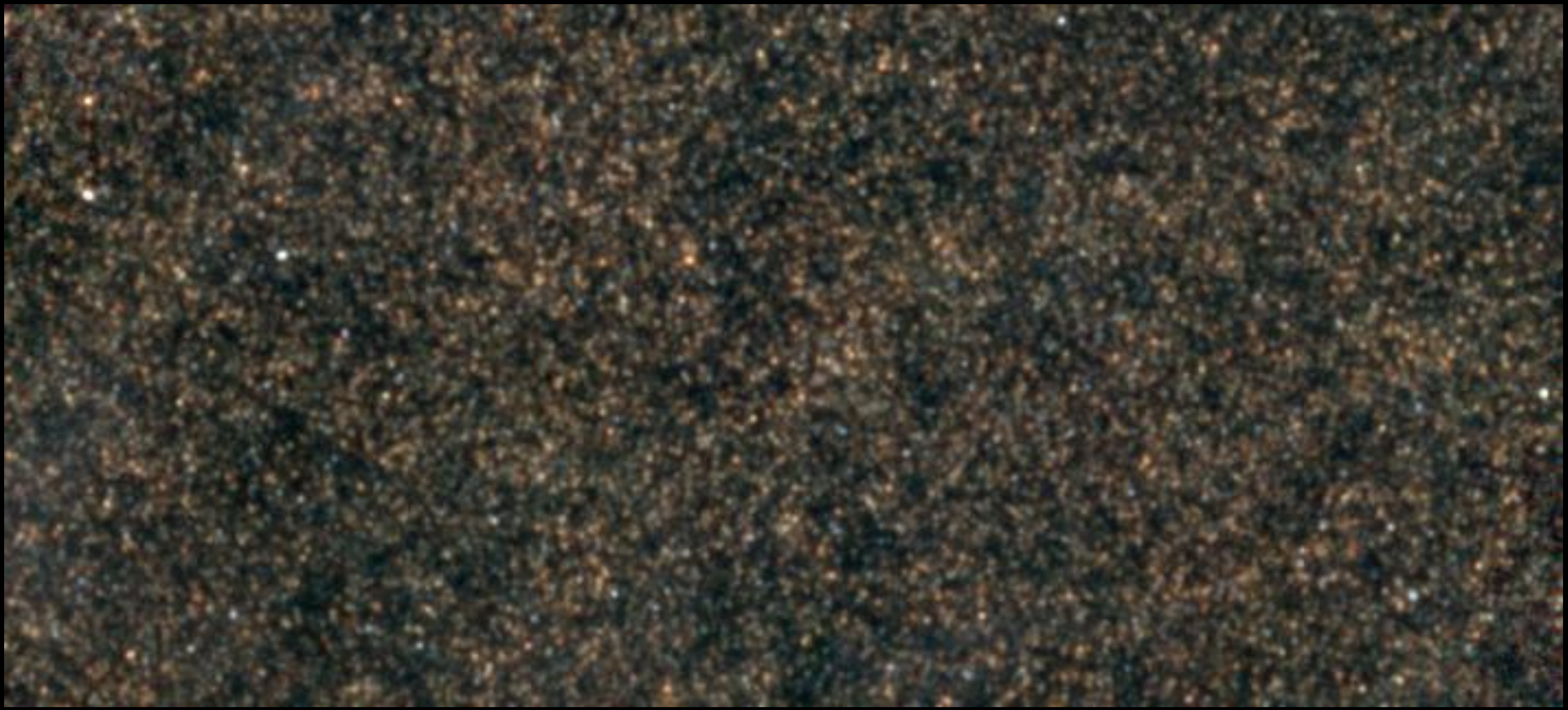
Distant Galaxies in the Hubble Ultra Deep Field

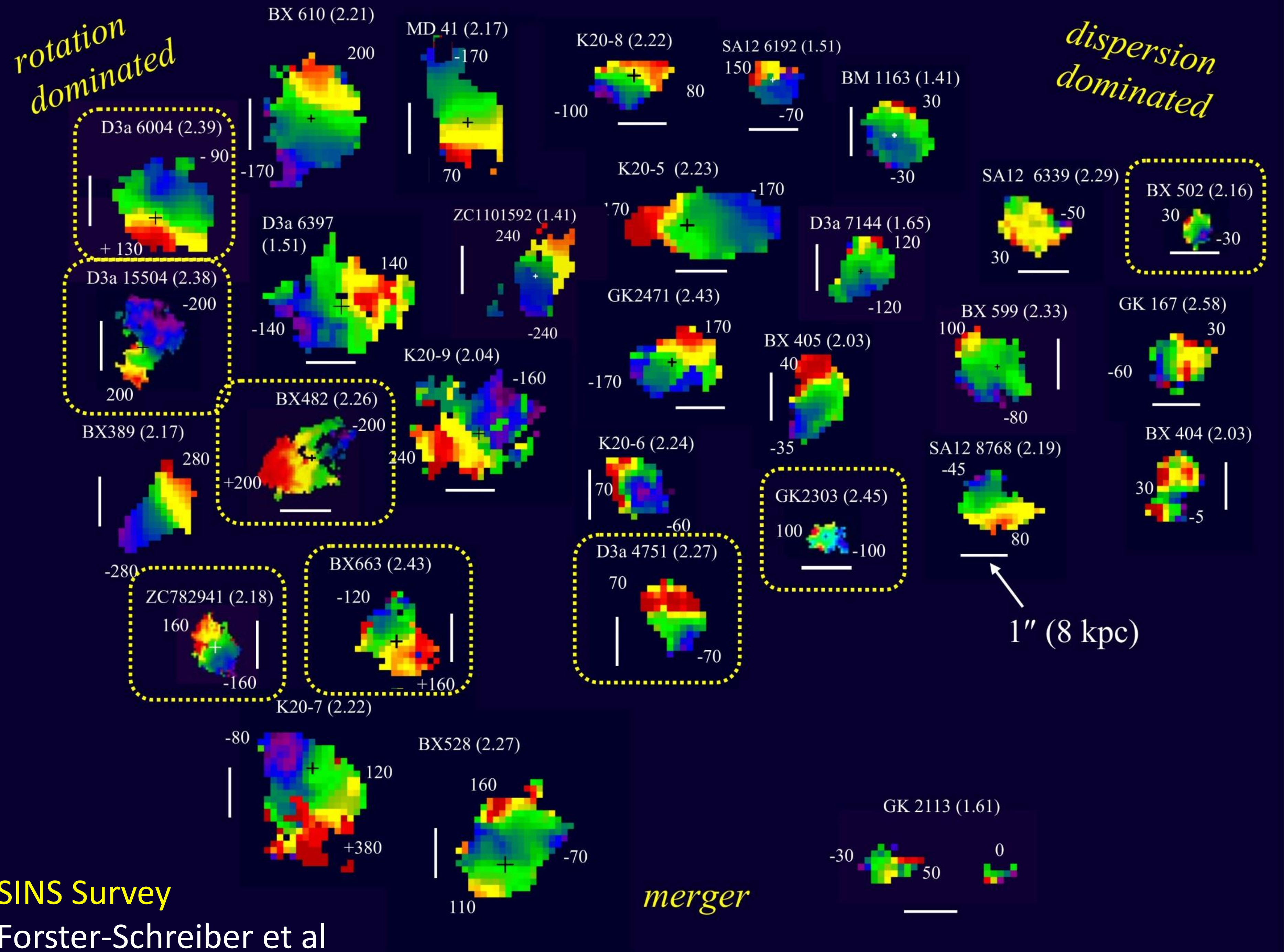
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, R. Bouwens and G. Illingworth (University of California, Santa Cruz)

STScI-PRC06-12

COSMOS Deep Field:
Herschel Space Observatory (HERMES)



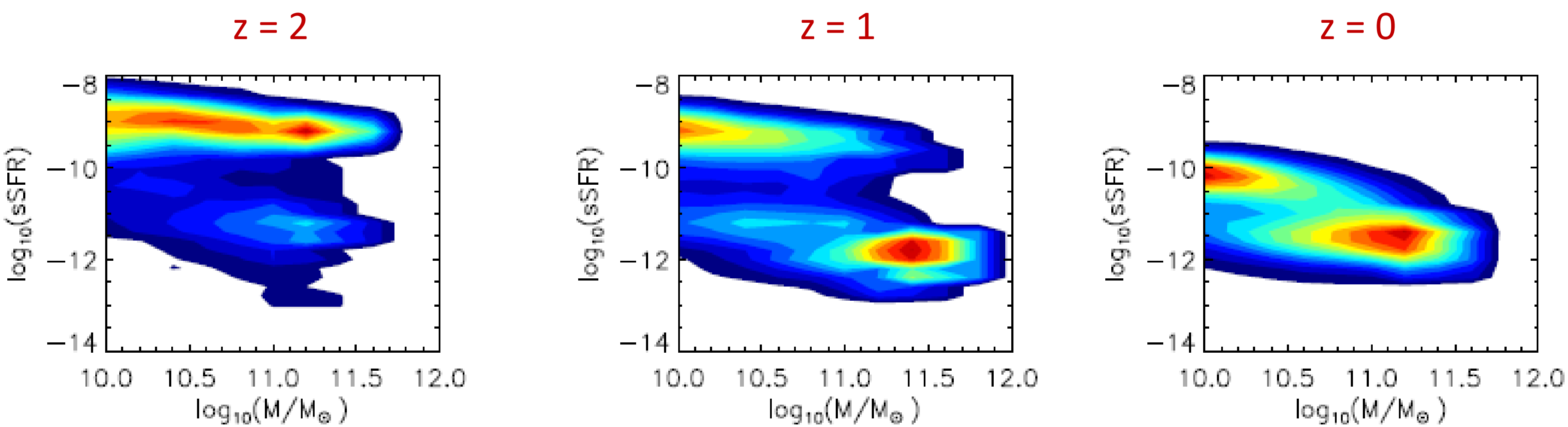


SINS Survey

Forster-Schreiber et al

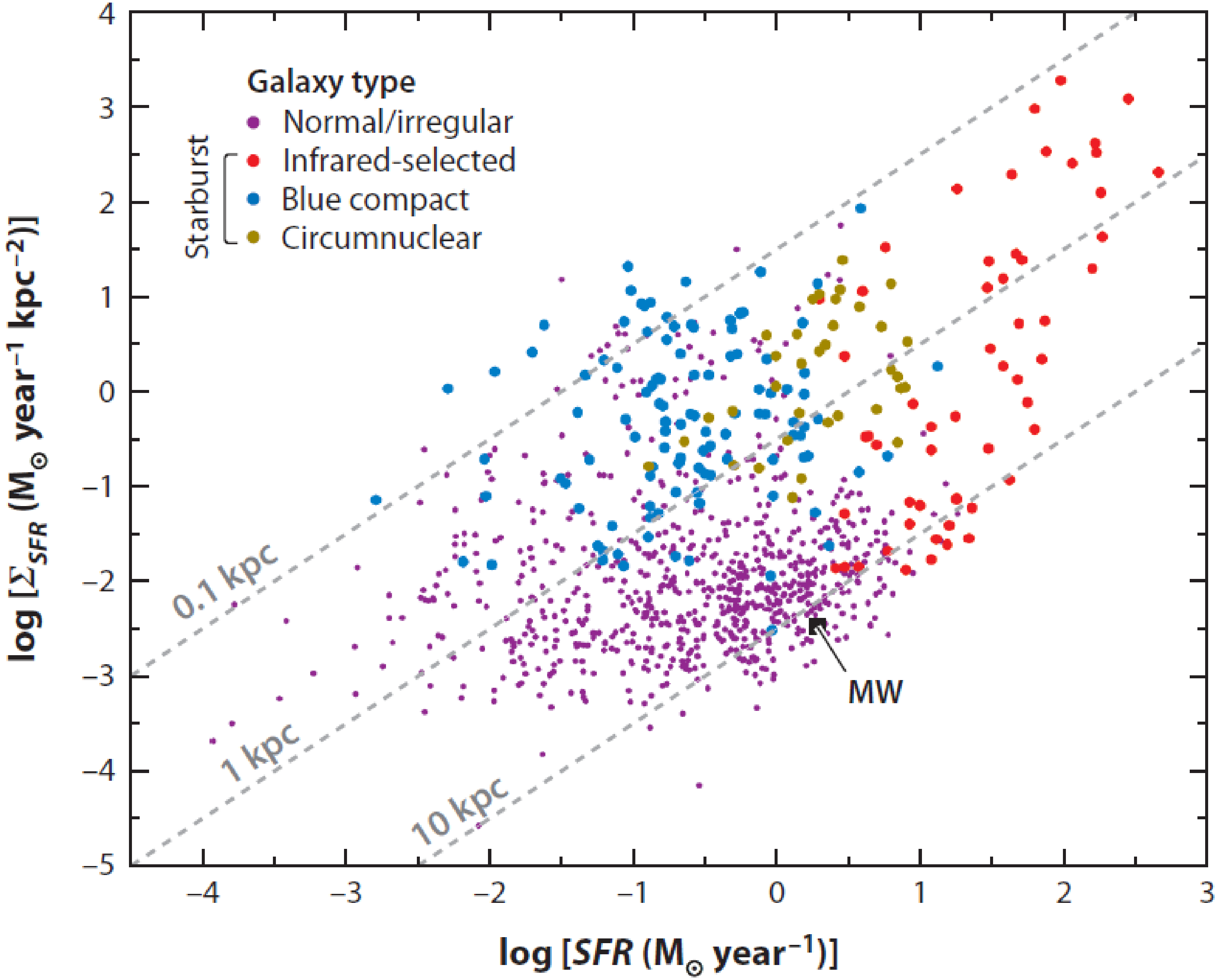
The average SFR/mass for "normal" galaxies increases with redshift

- by z = 2 many "quiescent" galaxies have SFR > 100 M_o/yr
- "normal" star formation at z=2 is a starburst by local definitions!



Ciambur et al 2013

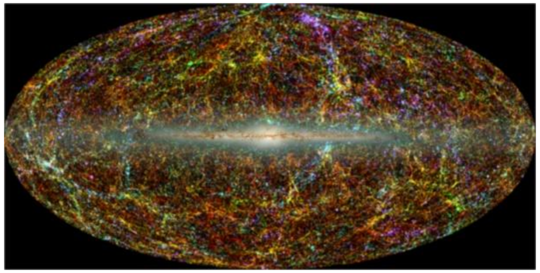
star formation rate per unit area

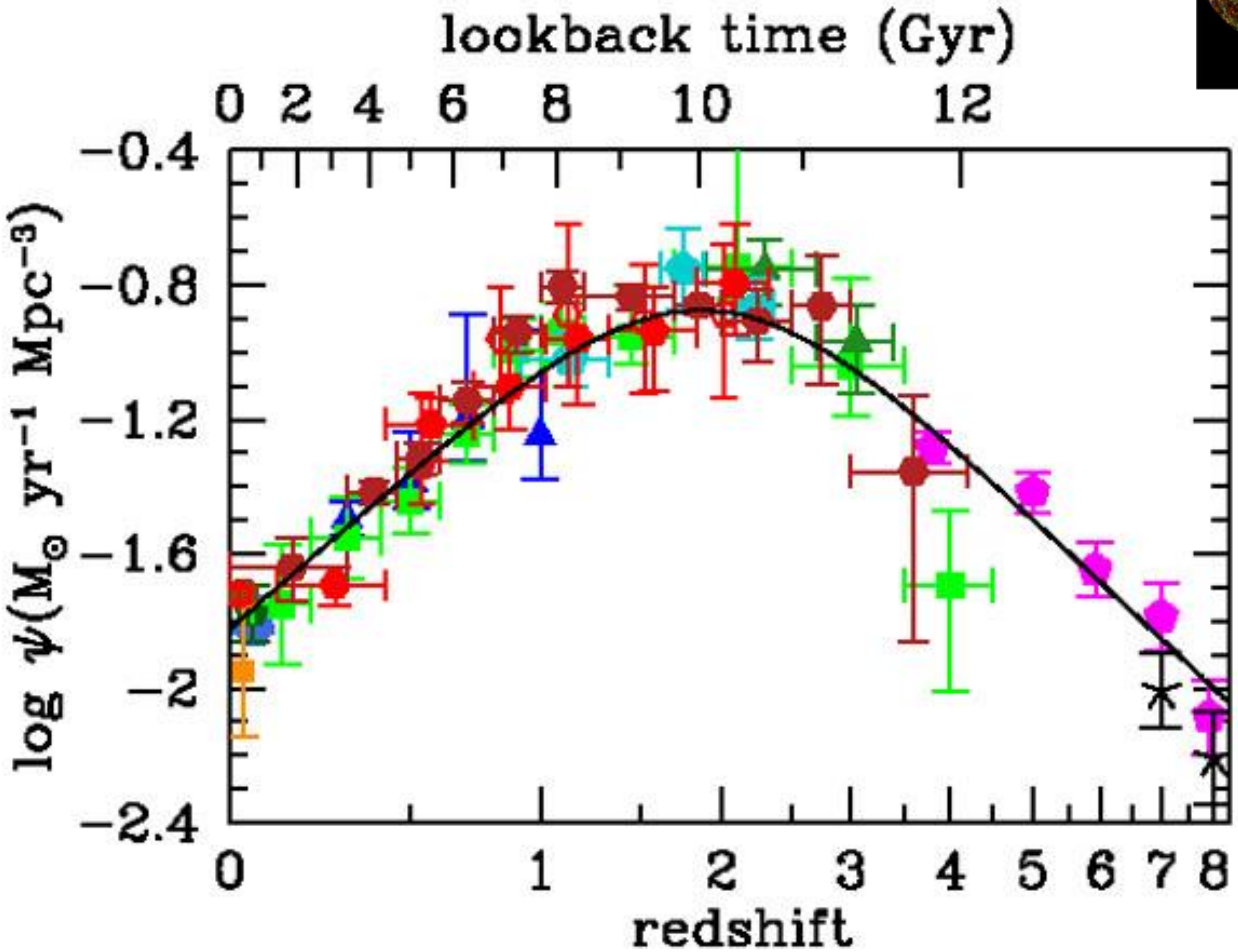


star formation rate

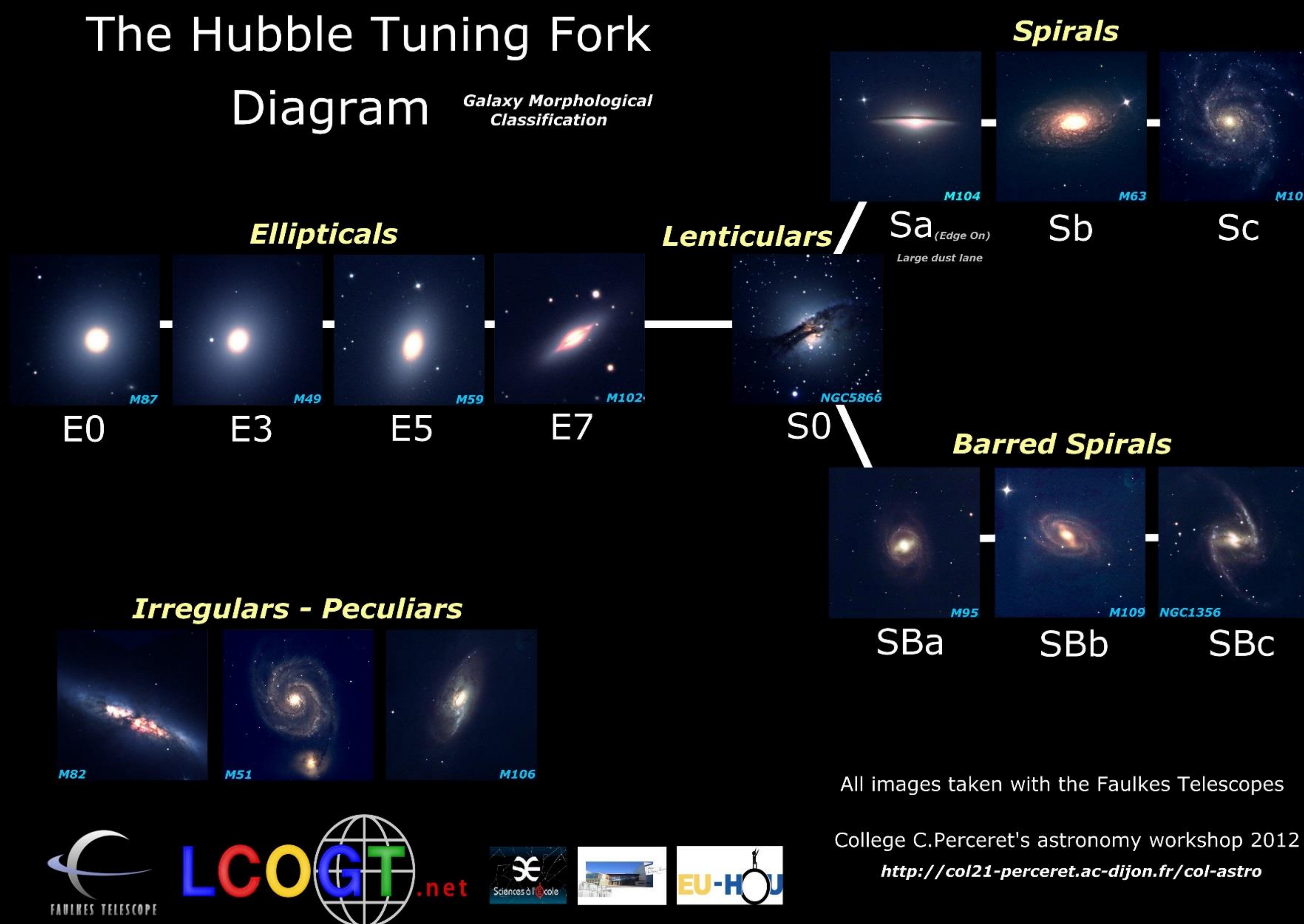
Kennicutt, Evans 2012

cosmic star formation history

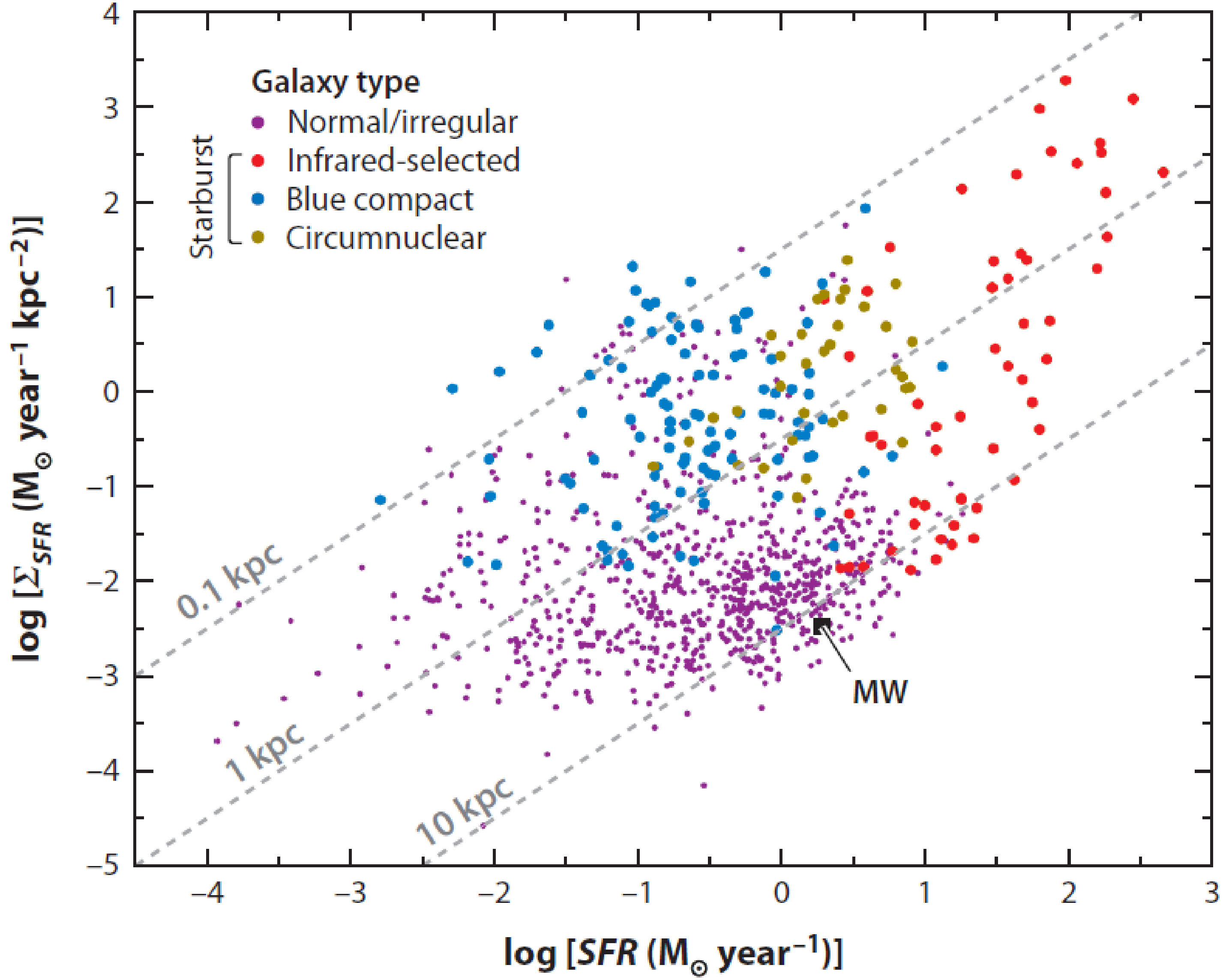




Madau & Dickinson 2014



The Hubble Tuning Fork Diagram
Galaxy Morphological Classification
Spirals
M104
M63
M101
Sa (Edge On)
Large dust lane
Sb
Sc
Ellipticals
Lenticulars
M87
M49
M59
M102
NGC5866
E0
E3
E5
E7
S0
Barred Spirals
M95
M109
NGC1356
SBa
SBb
SBc
Irregulars - Peculiars
M82
M51
M106
All images taken with the Faulkes Telescopes
College C.Perceret's astronomy workshop 2012
http://col21-perceret.ac-dijon.fr/col-astro
FAULKES TELESCOPE
LCOGT.net
Sciences à l'école
EU-HOU

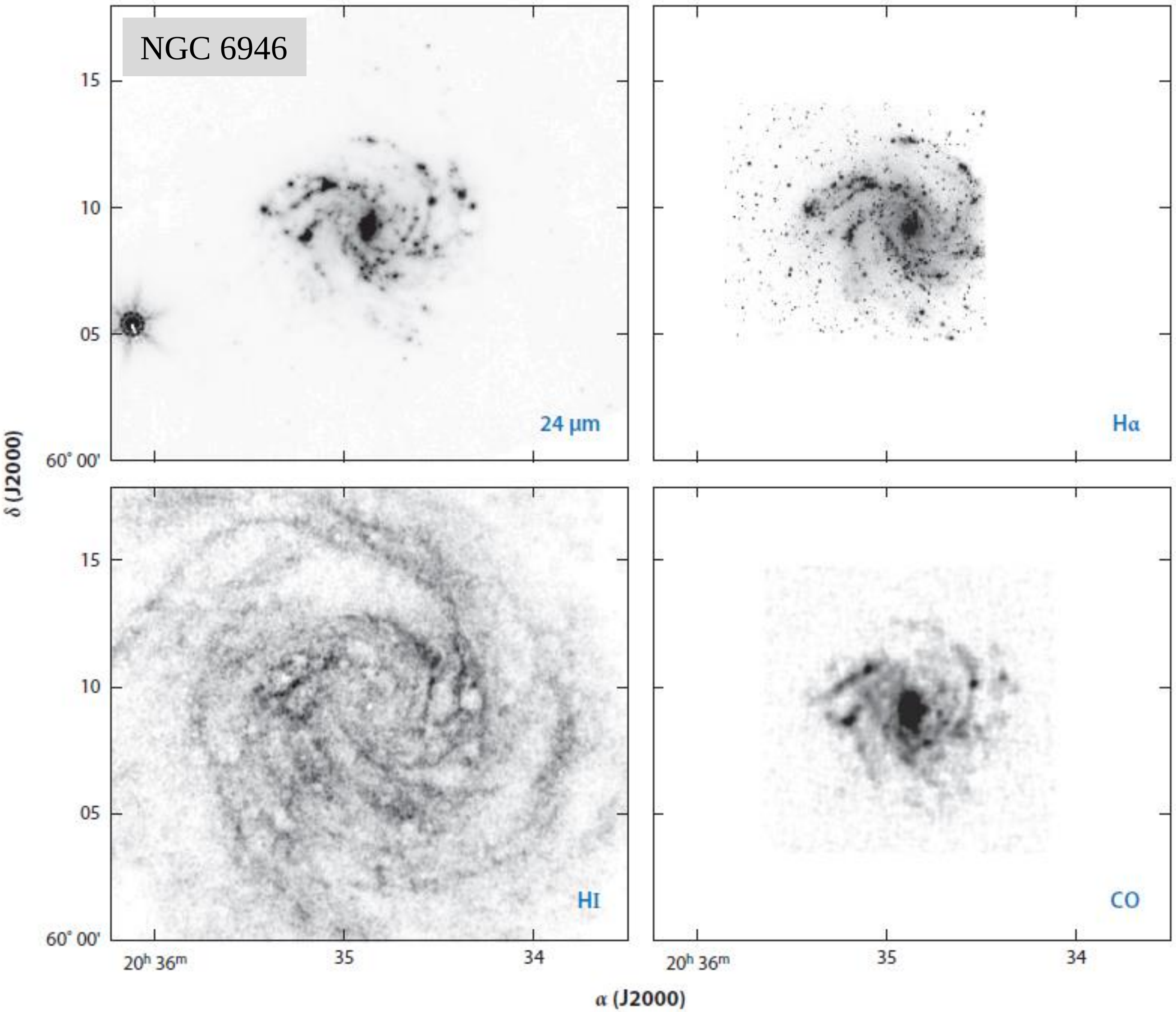


star formation rate per unit area

star formation rate

Kennicutt, Evans 2012

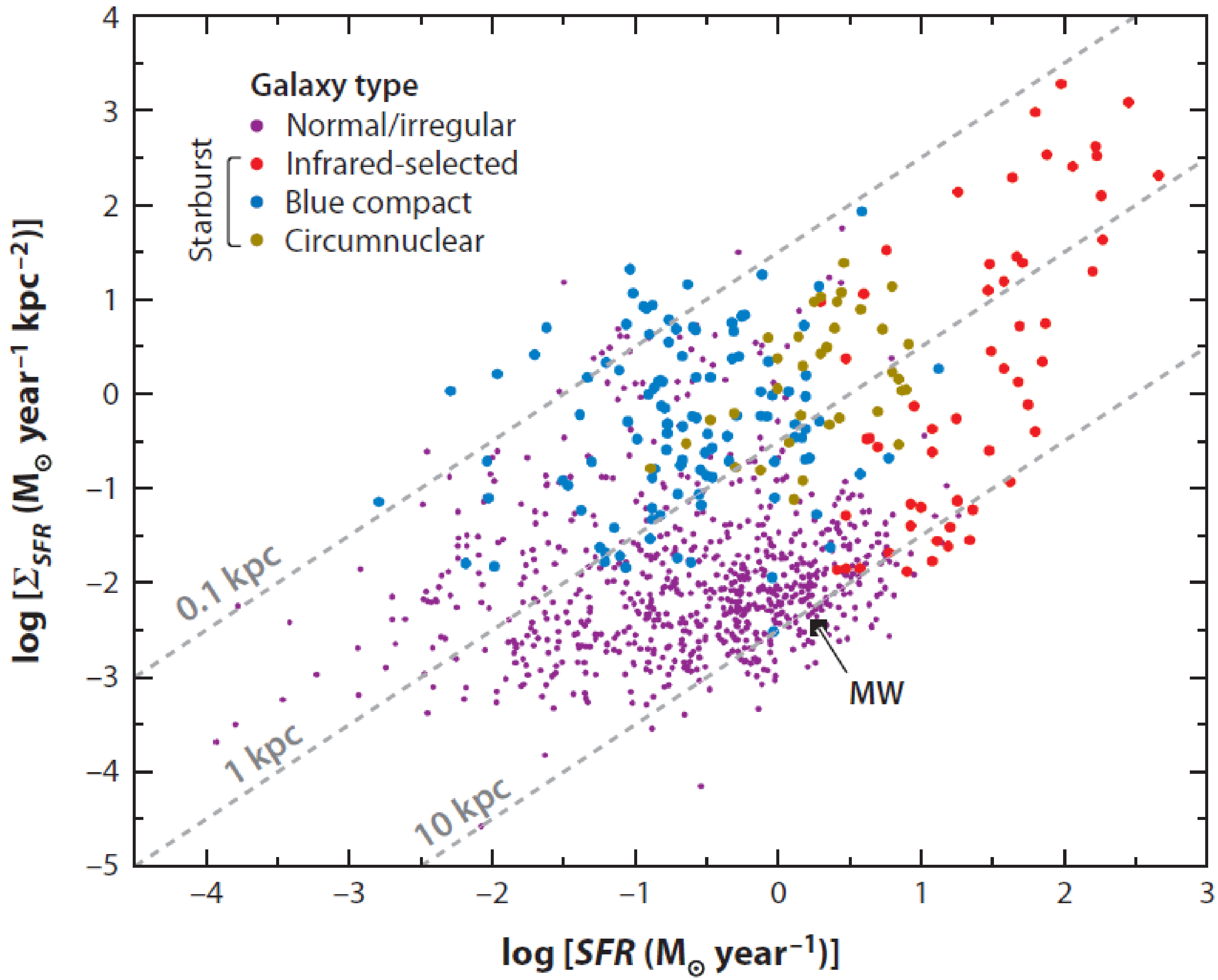
Spatially-Resolved Measurements of the SF Law



star formation

cold atomic, molecular gas

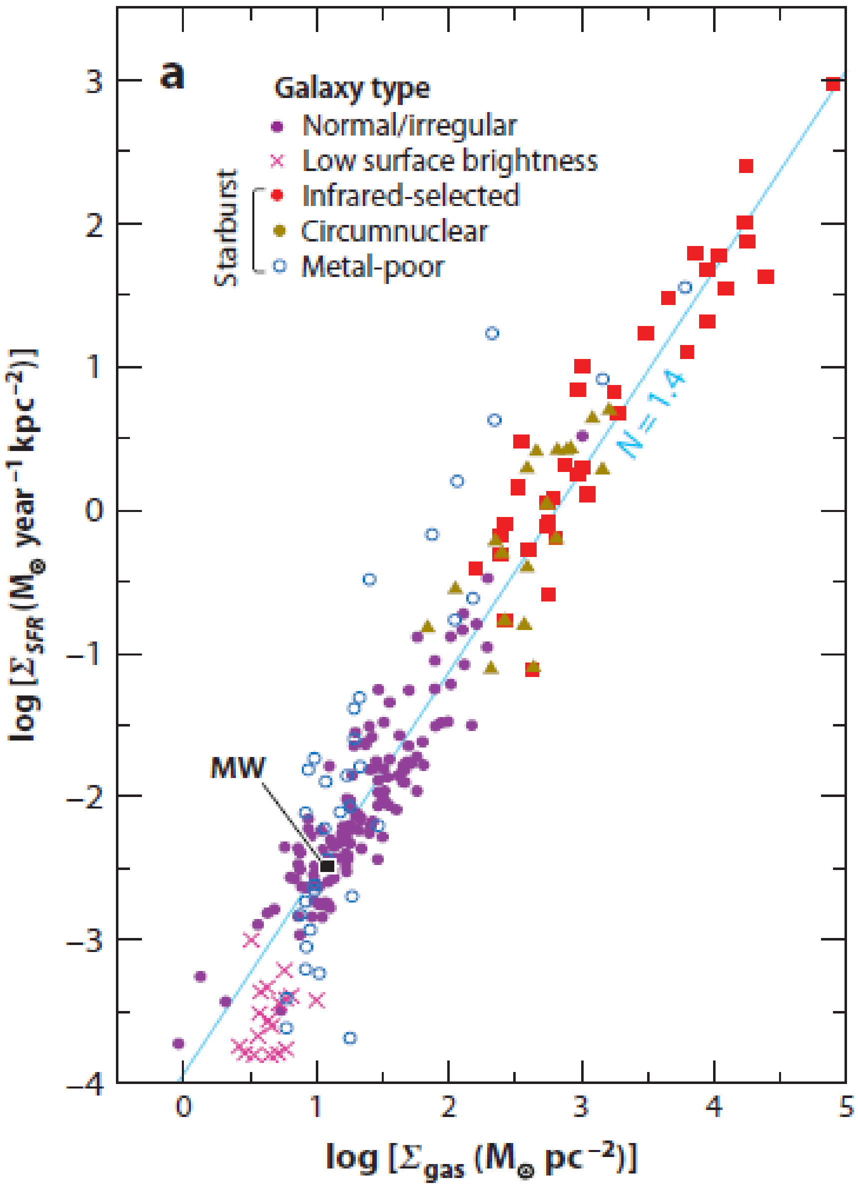
star formation rate per unit area



star formation rate

Kennicutt, Evans 2012

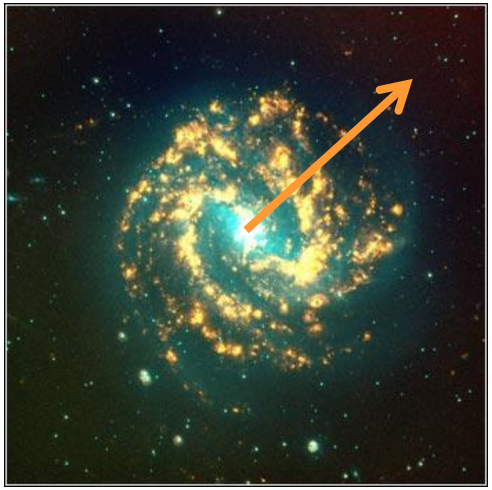
star formation rate per unit area

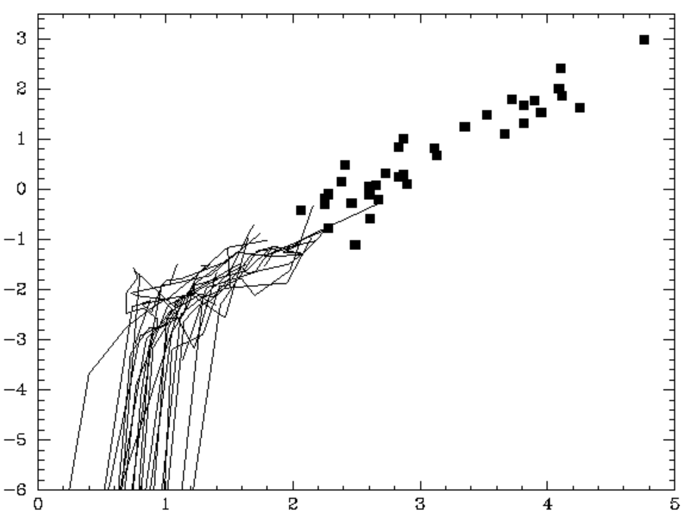


gas surface density ($HI+H_2$)

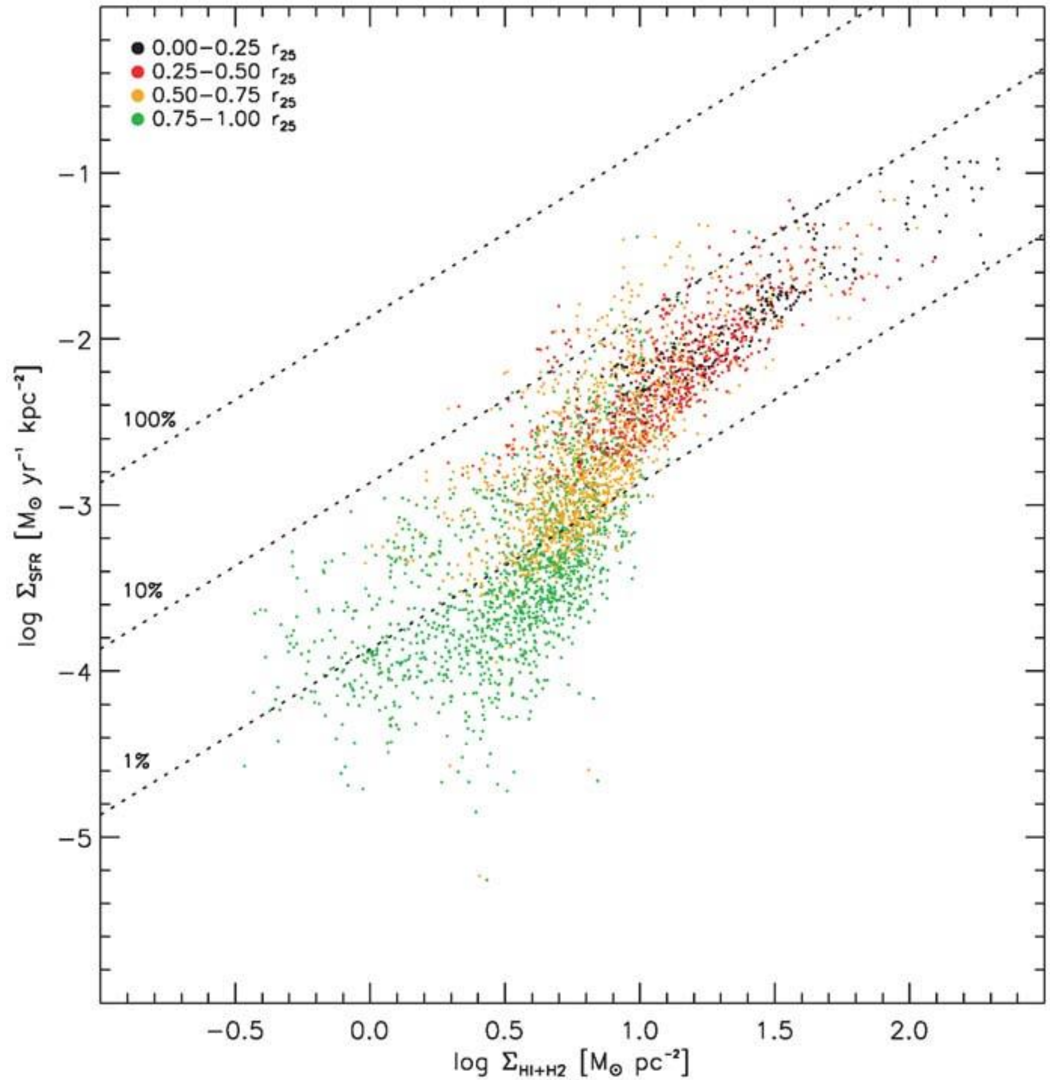
compressing the gas by 100x increases concentration of stars by 600-1000x

Kennicutt, Evans 2012





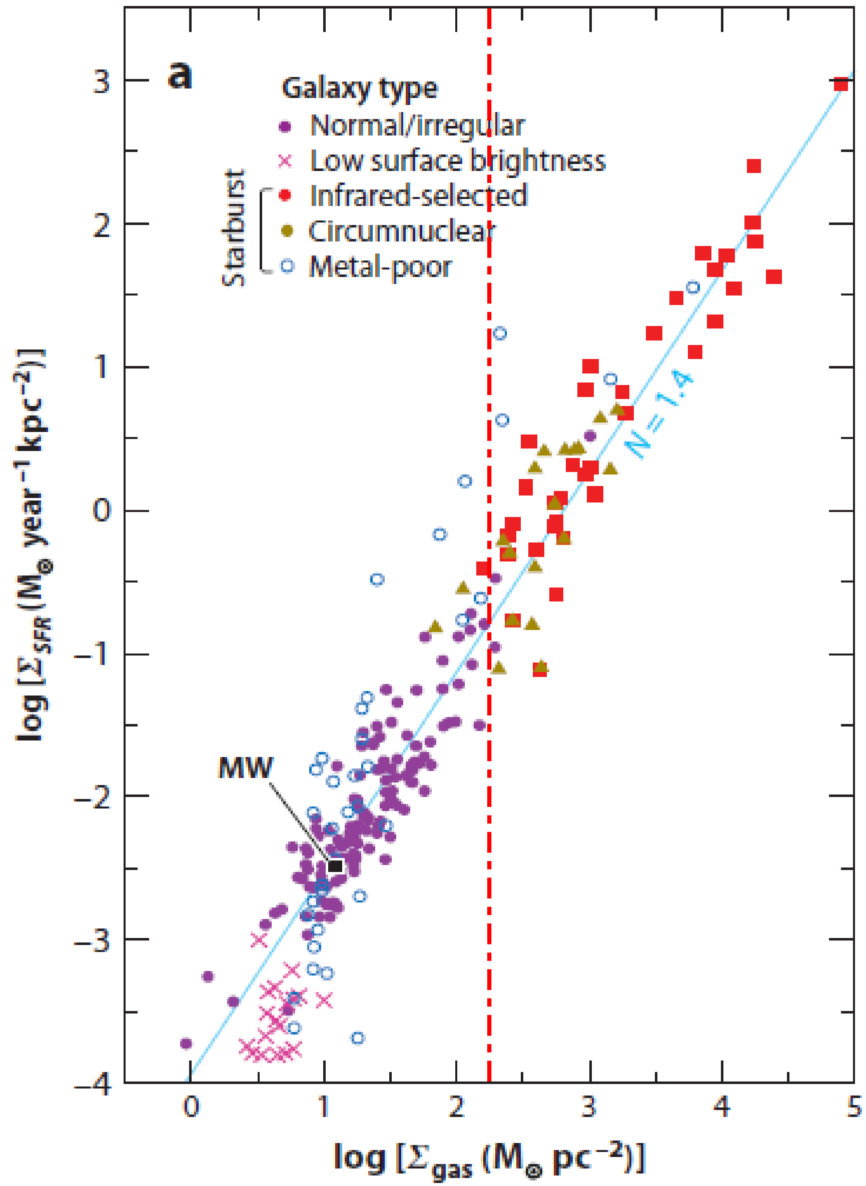
Martin & Kennicutt 2001



Bigiel et al 2008 (THINGS)

this helps explain:

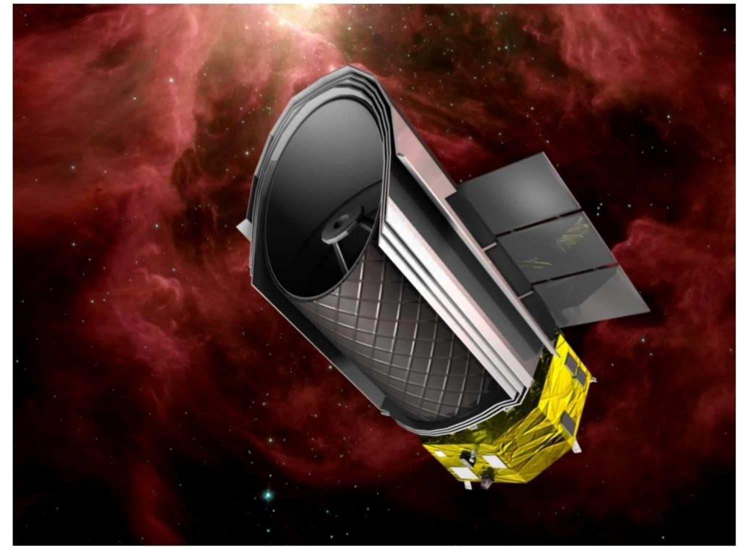
- high SFRs in starbursts
- high SFRs at high redshift
- faster evolution of massive galaxies
- inside out growth of galaxies
- dust obscuration of starburst regions



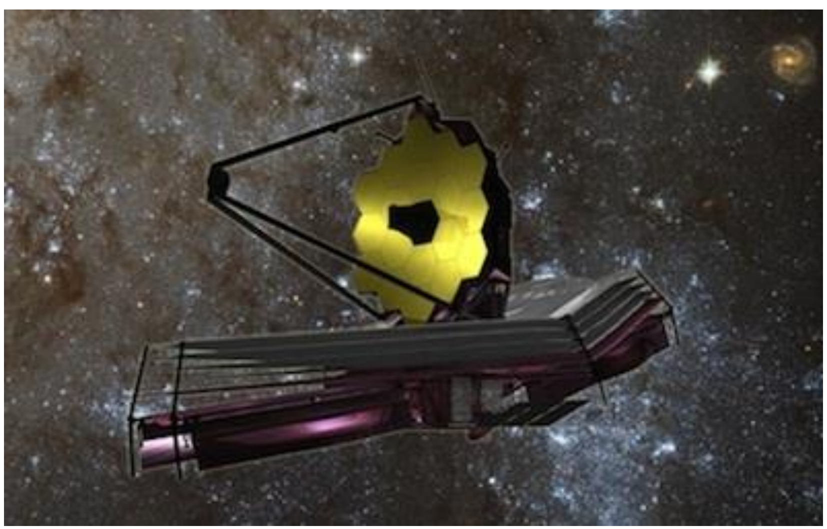
dust surface density (x100)

Kennicutt, Evans 2012

Atacama Large Millimetre Array (ALMA)



Space Infrared Telescope for Cosmology and Astrophysics (SPICA)



James Webb Space Telescope (JWST)