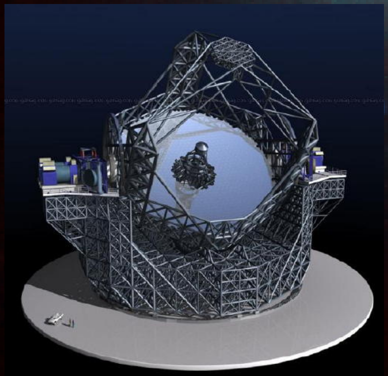
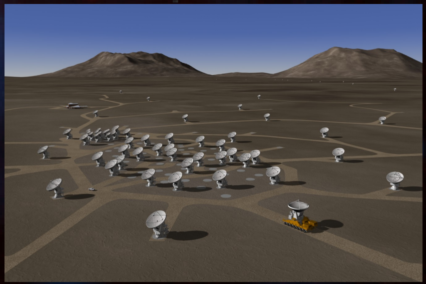
Star Formation in Galaxies
From Re-ionization to the Present



Robert Kennicutt
Institute of Astronomy
University of Cambridge

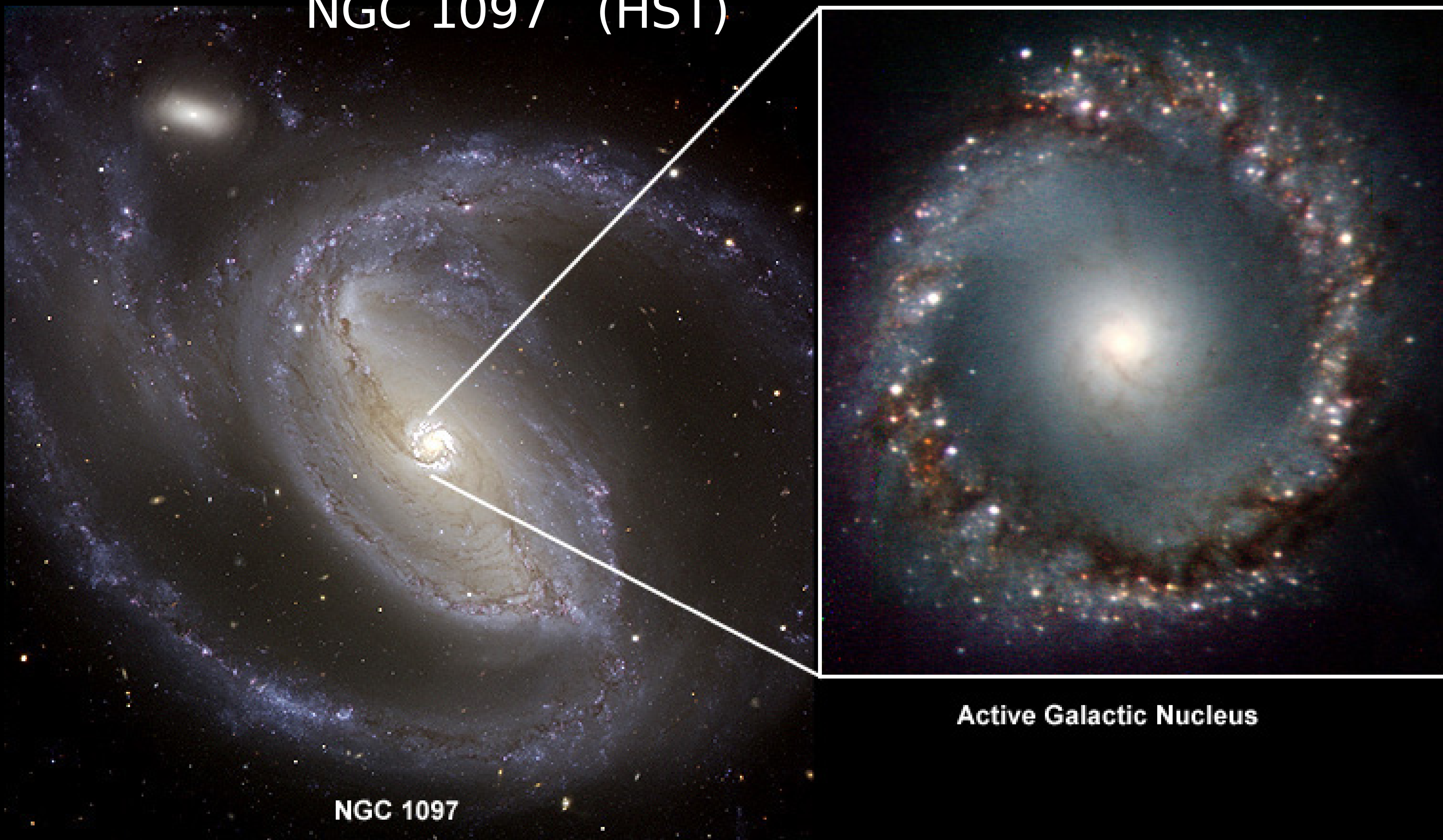


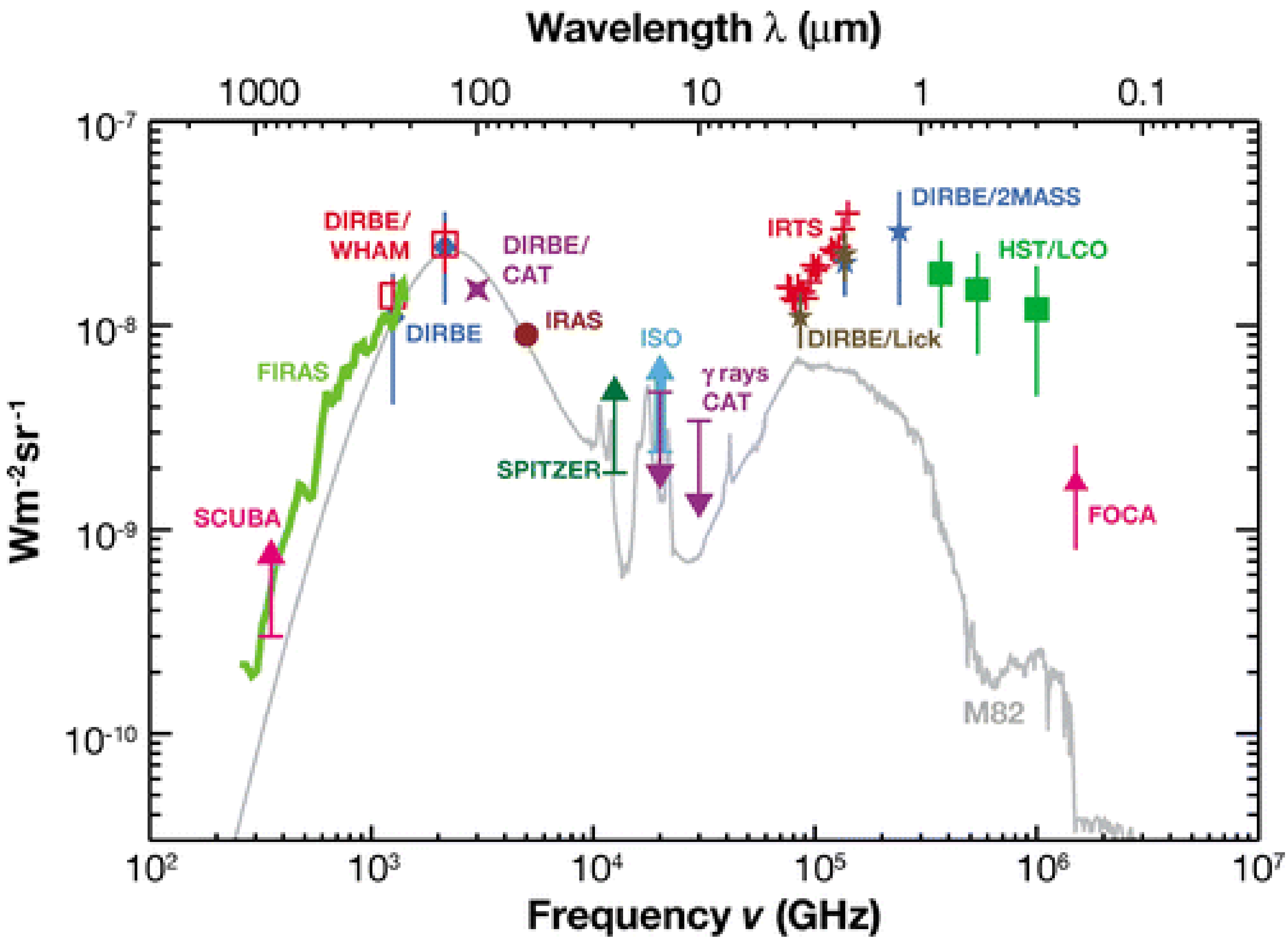
Outline

- What do we know?
- What don't we understand?
- Some key questions, experiments for ALMA, ELT
- General thoughts

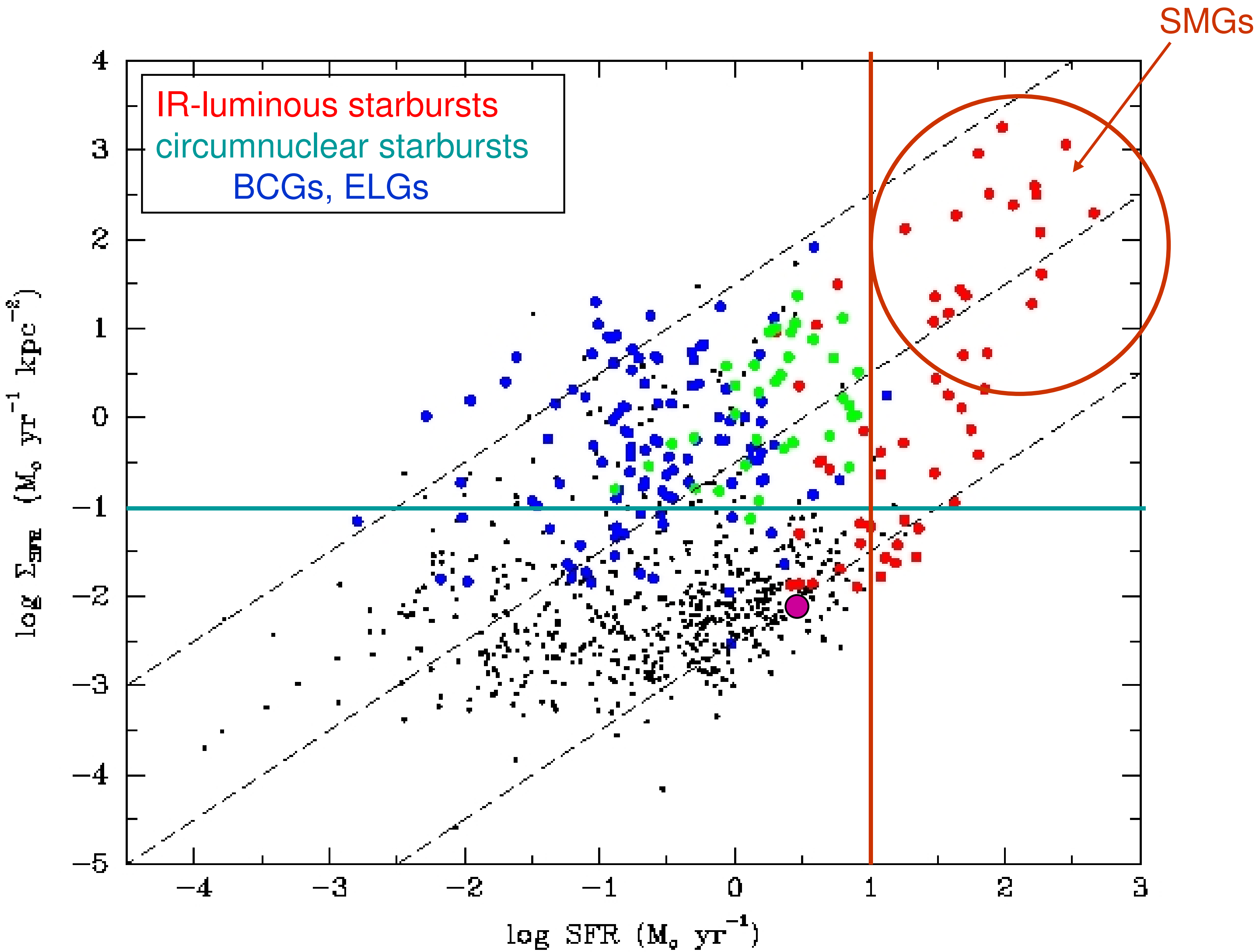
Two Asymptotic Modes of Star Formation

NGC 1097 (HST)



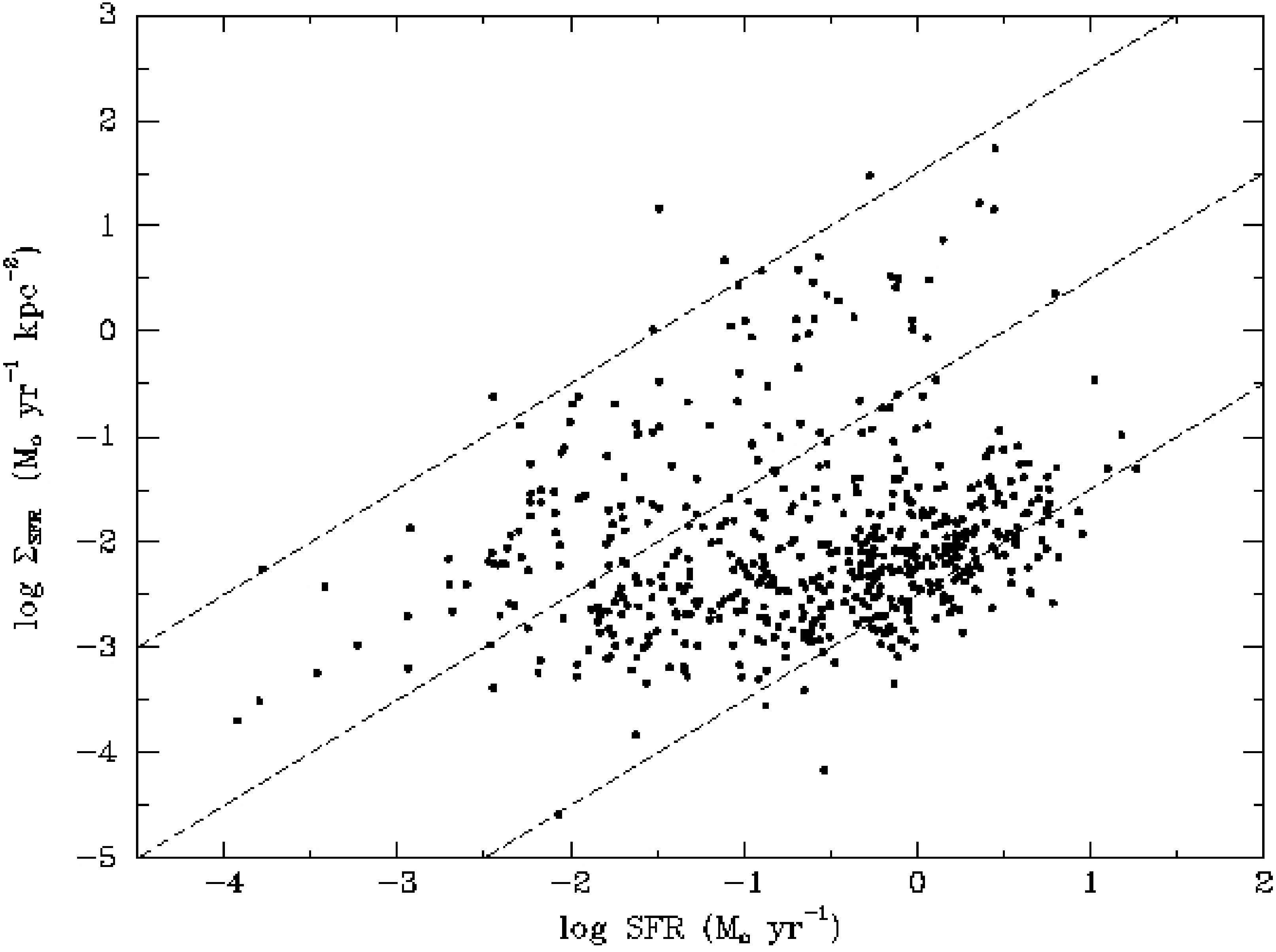


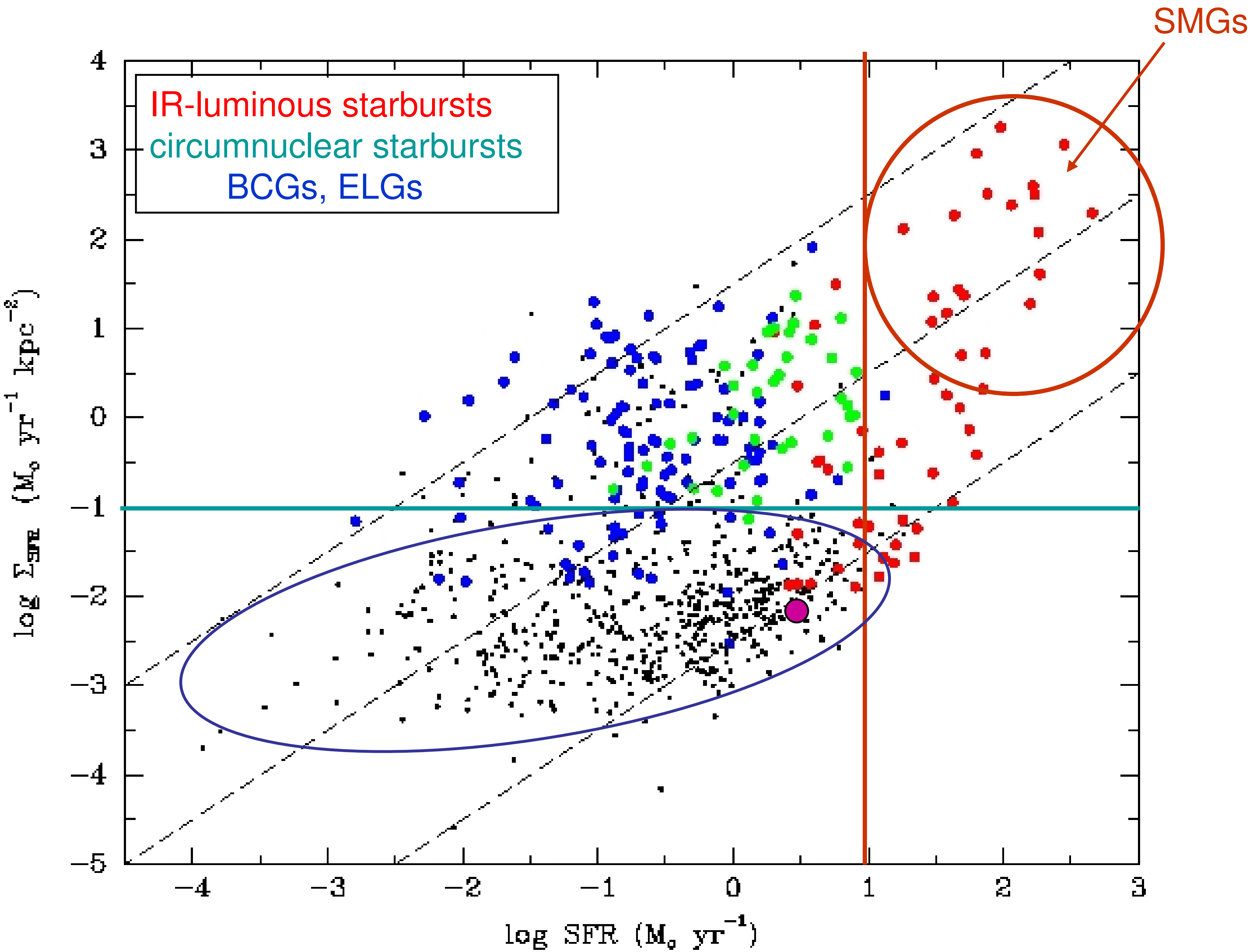
Lagache, G et al. 2005
Annu. Rev. Astron. Astrophys. 43: 727–68



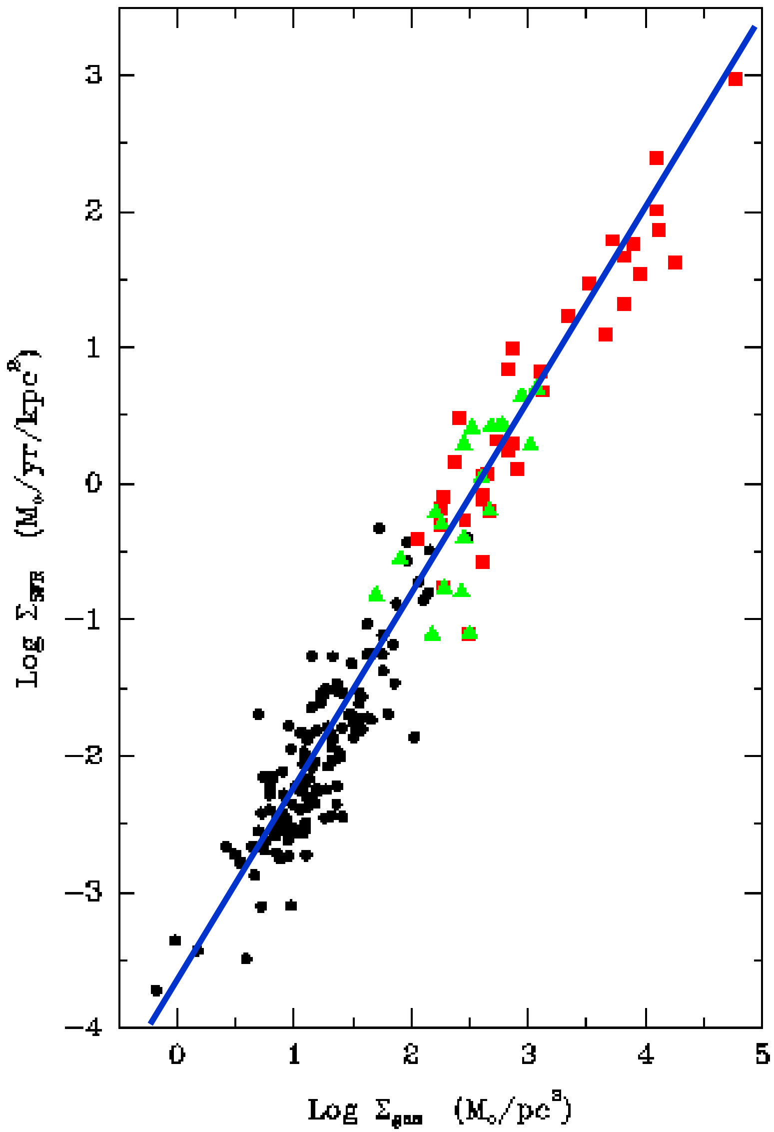
SMGs
IR-luminous starbursts
circumnuclear starbursts
BCGs, ELGs
log Σ_SFR (M_o yr^-1 kpc^-2)
log SFR (M_o yr^-1)
4
3
2
1
0
−1
−2
−3
−4
−5
−4
−3
−2
−1
0
1
2
3

11 Mpc Sample (RCK et 07) + Hα Galaxy Survey (James et 03)

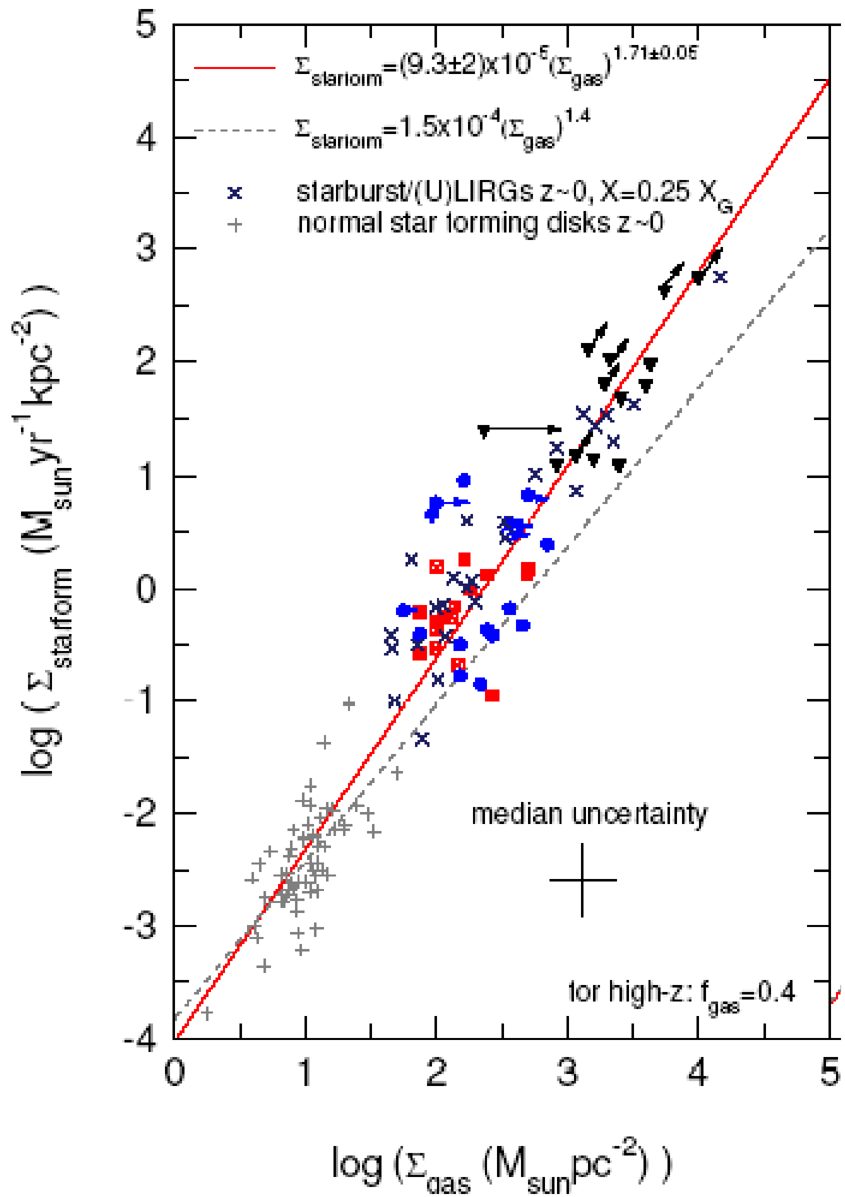




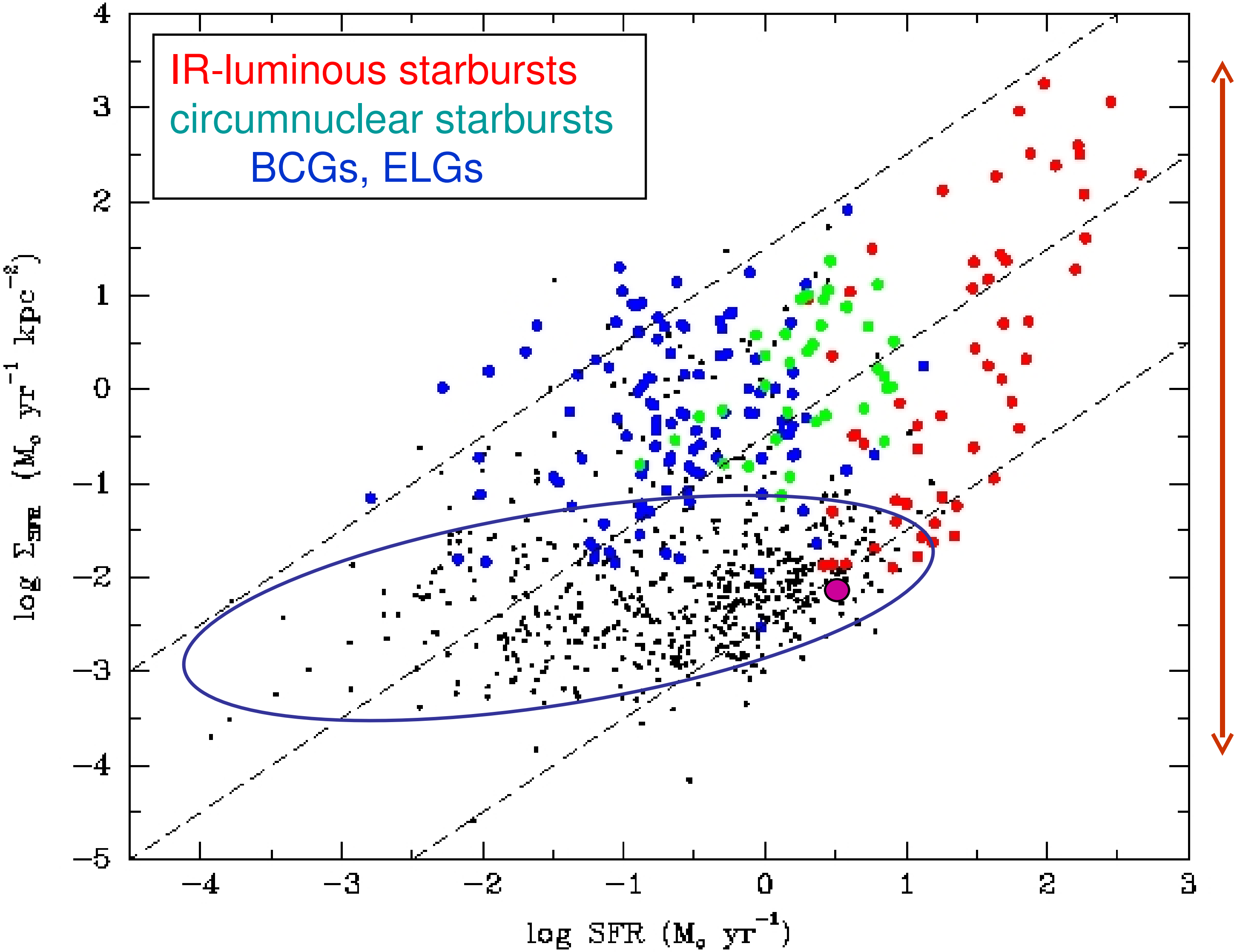
SMGs
IR-luminous starbursts
circumnuclear starbursts
BCGs, ELGs
log SFR (M☉ yr⁻¹)
log Σ_SFR (M☉ yr⁻¹ kpc⁻²)



Kennicutt 1998



Bouche et al. 2007

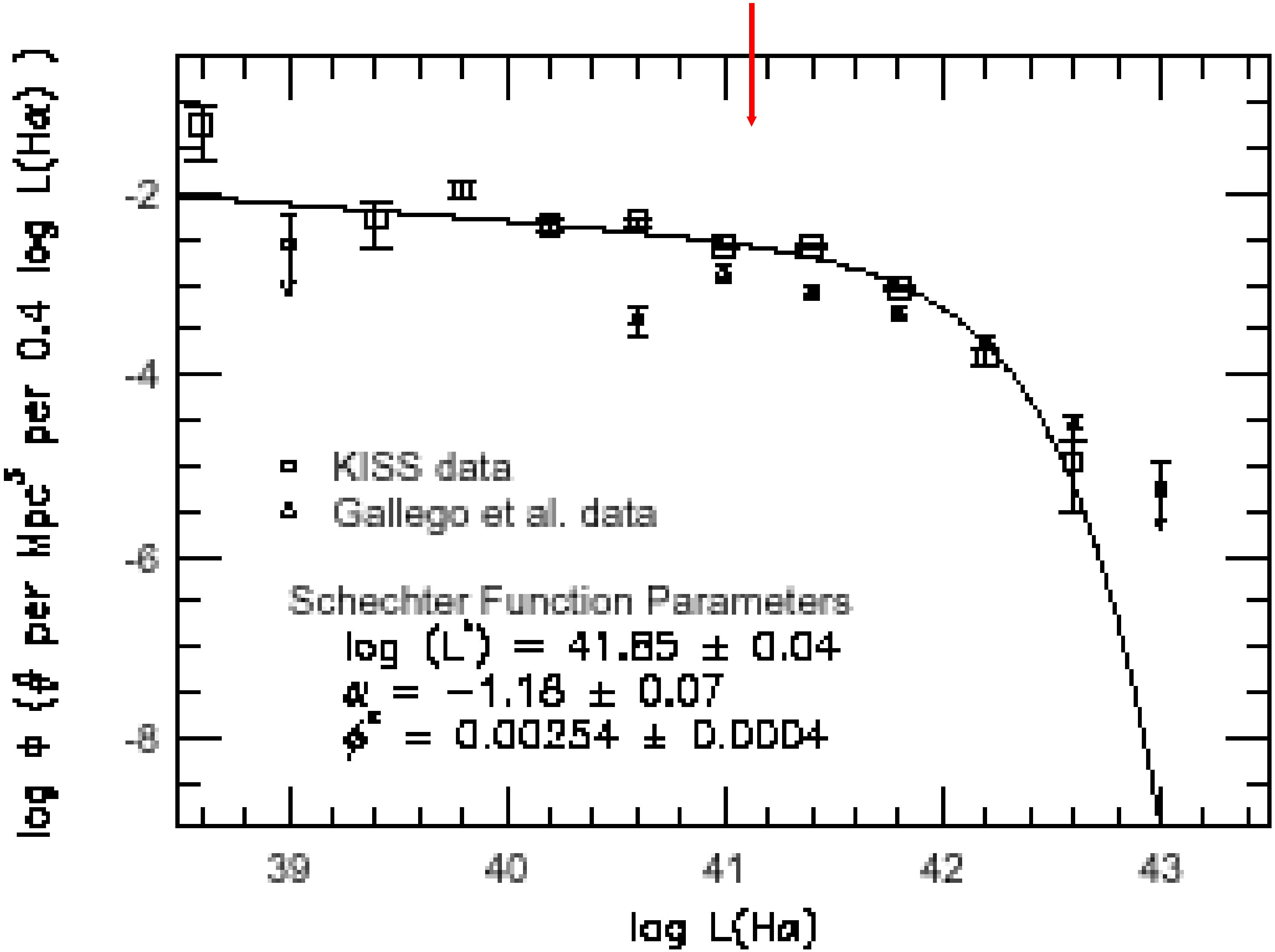


10^7 in Σ_{SFR}

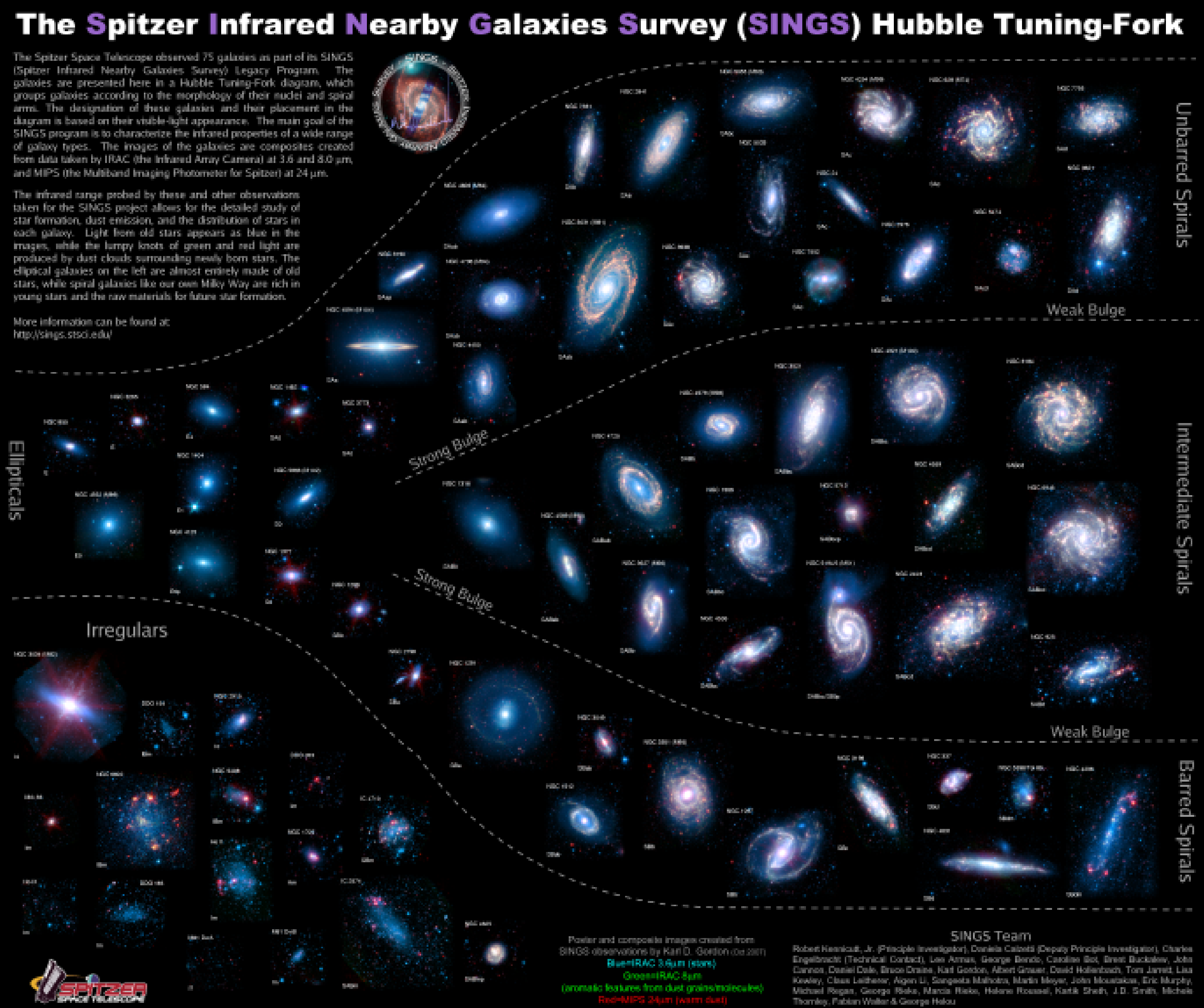
10^5 in Σ_{gas}

10^{10} in P_{hyd}

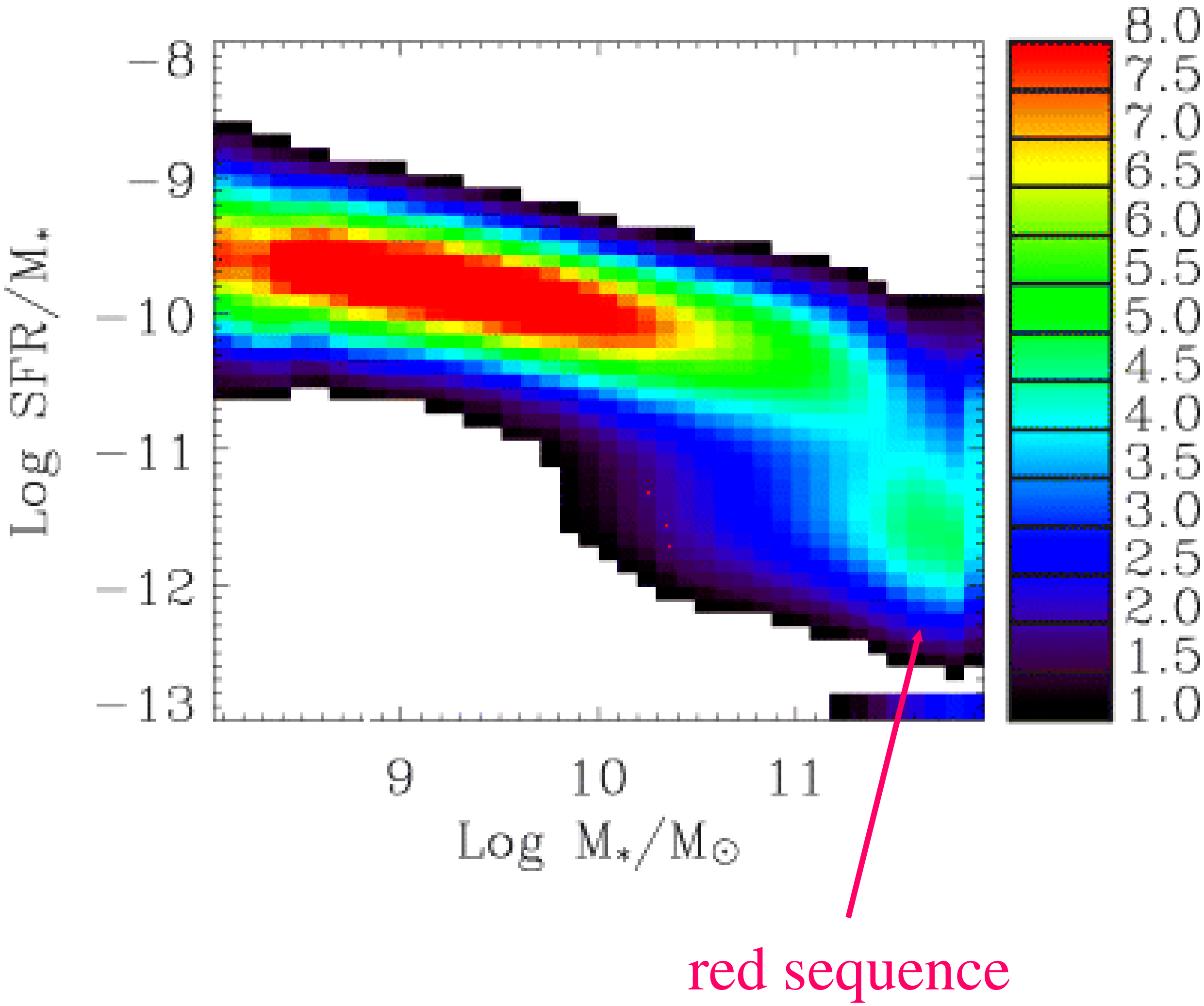
SFR* ~5 M_o/yr



Gronwall 1998

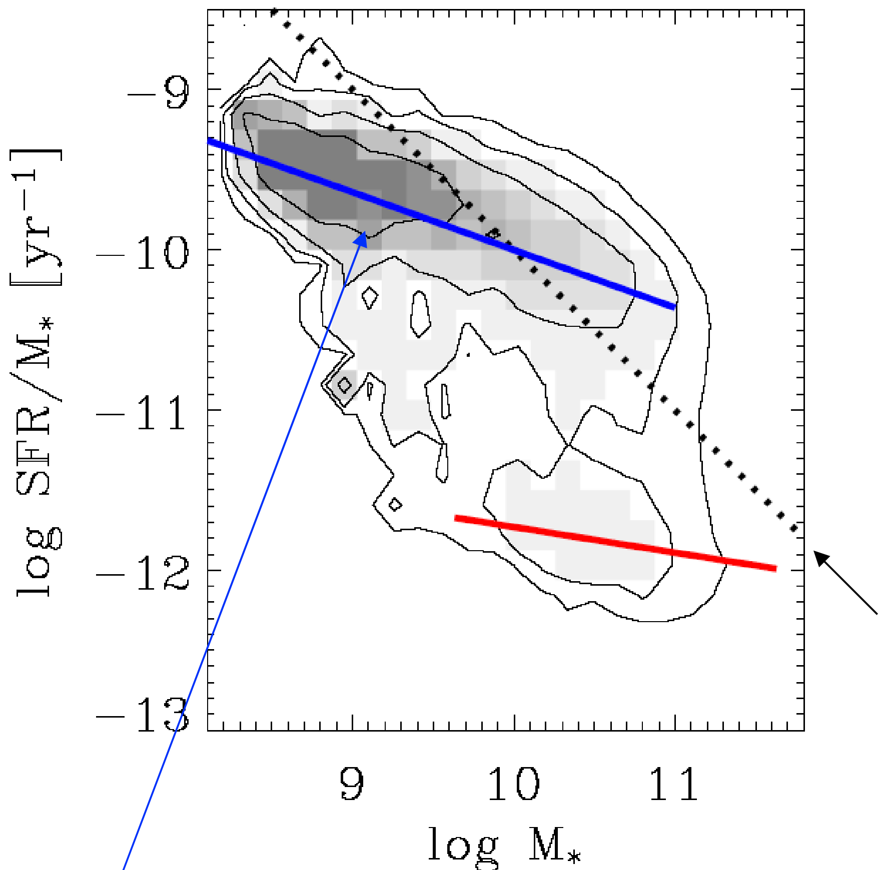

The Spitzer Infrared Nearby Galaxies Survey (SINGS) Hubble Tuning-Fork
The Spitzer Space Telescope observed 75 galaxies as part of its SINGS (Spitzer Infrared Nearby Galaxies Survey) Legacy Program. The galaxies are presented here in a Hubble Tuning-Fork diagram, which groups galaxies according to the 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
Intermediate Spirals
Strong Bulge
Weak Bulge
Barred Spirals
Ellipticals
Irregulars
Poster and composite images created from SINGS observations by Karl D. Gordon (Oct 2007)
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

SFRs for 100,000 galaxies with Sloan!



Brinchmann et al. 2006, MNRAS, 351, 1151

SFR/M_* vs. M_* Distribution: Star-Forming Sequence



$$SFR \propto M_*^{2/3}$$

$SFR = 1\ M_\odot\ yr^{-1}$

Salim et al. (2007)
Noeske et al. (2007)

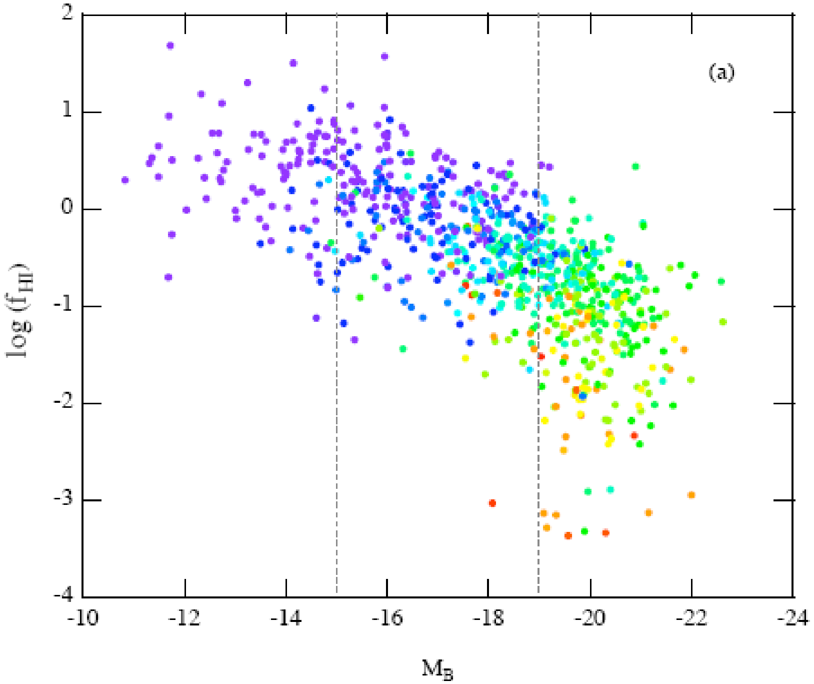
see also
Brinchmann et al. (2004), Feulner et al. (2006)

$$\log SFR/M_* = -0.35(log M_* - 10) - 9.83$$

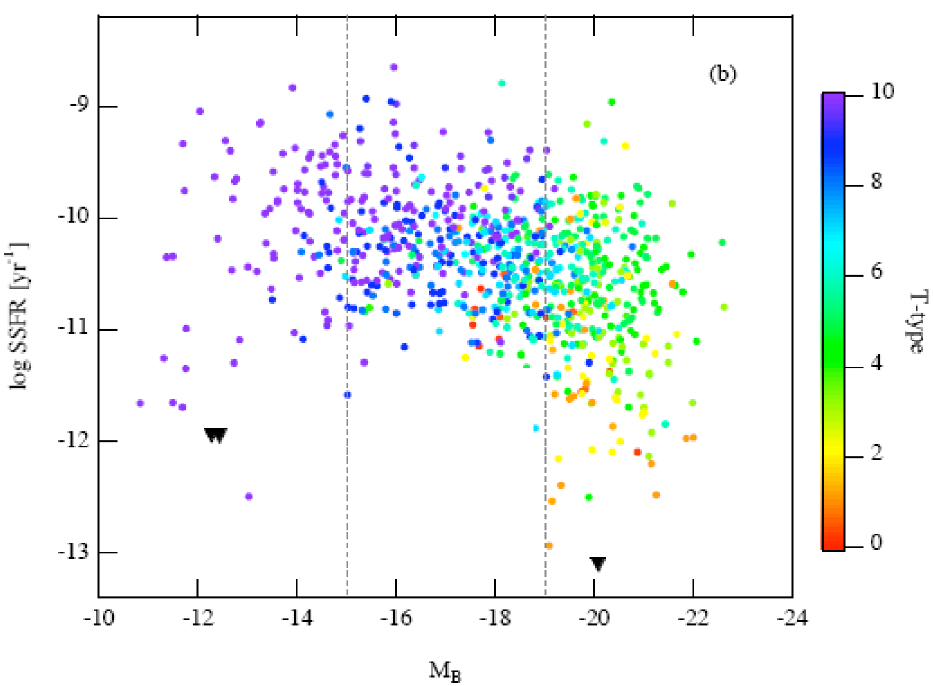
Schimminovich 2007

Main driver of SFR trends is cold gas supply
(except in dwarf galaxies)

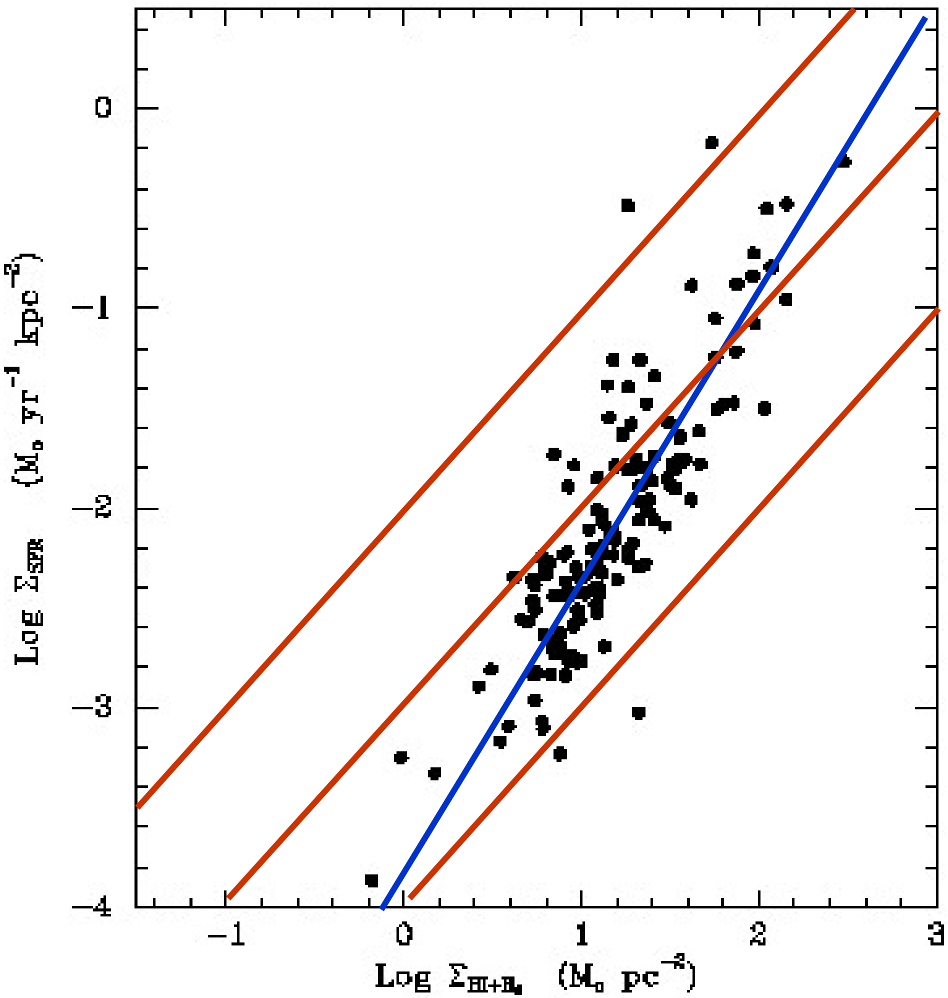
HI/stellar mass ratio



SFR/mass



Bothwell & Kennicutt 2009, in prep



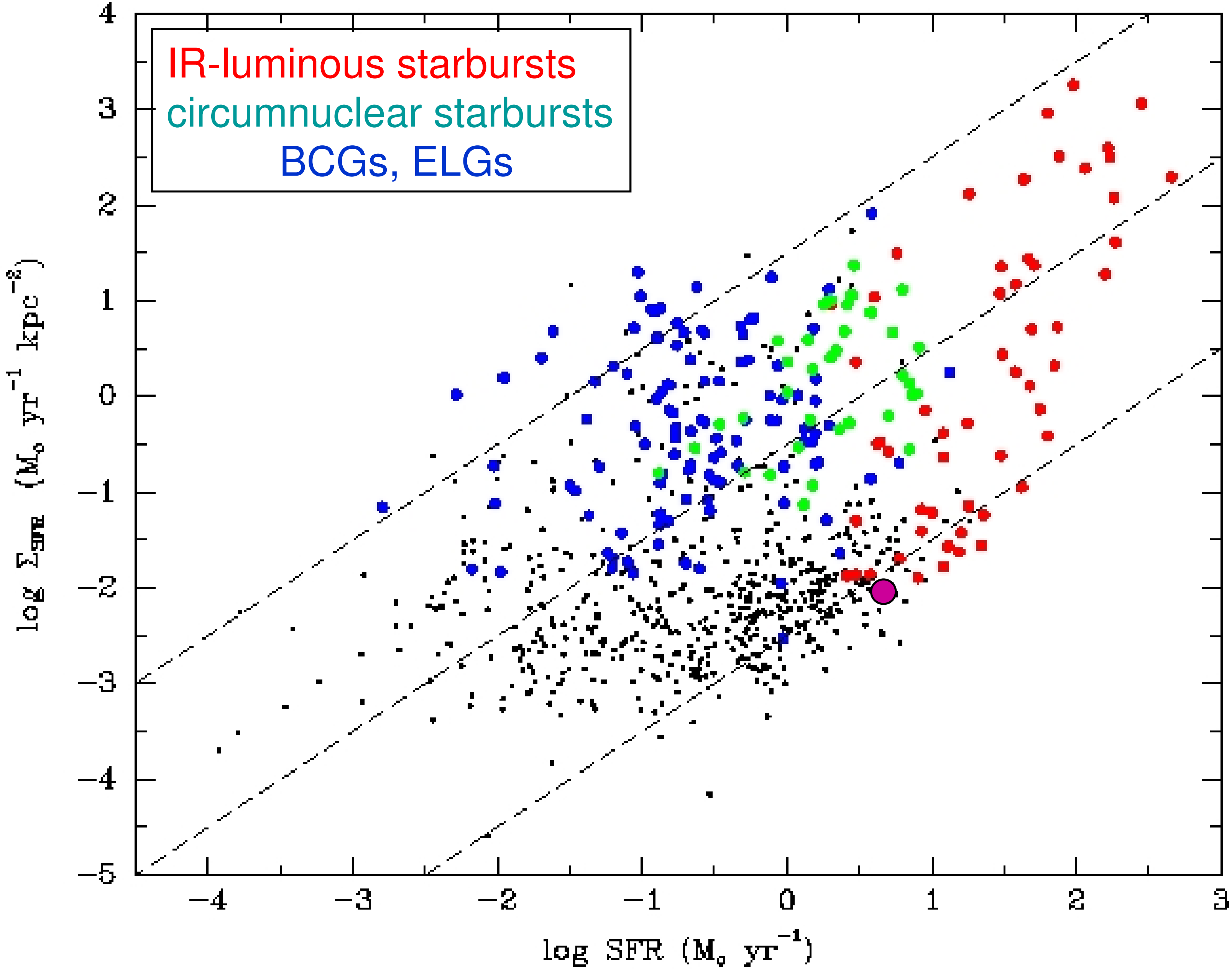
average SFR/area

average cold gas density

<SFE> ~4%/10^8 yr

<τ_{gas}> ~ 2.5 Gyr

<τ_{disk}> ~5-10 Gyr



IR-luminous starbursts
circumnuclear starbursts
BCGs, ELGs
log Σ_SFR (M⊙ yr^-1 kpc^-2)
log SFR (M⊙ yr^-1)
4
3
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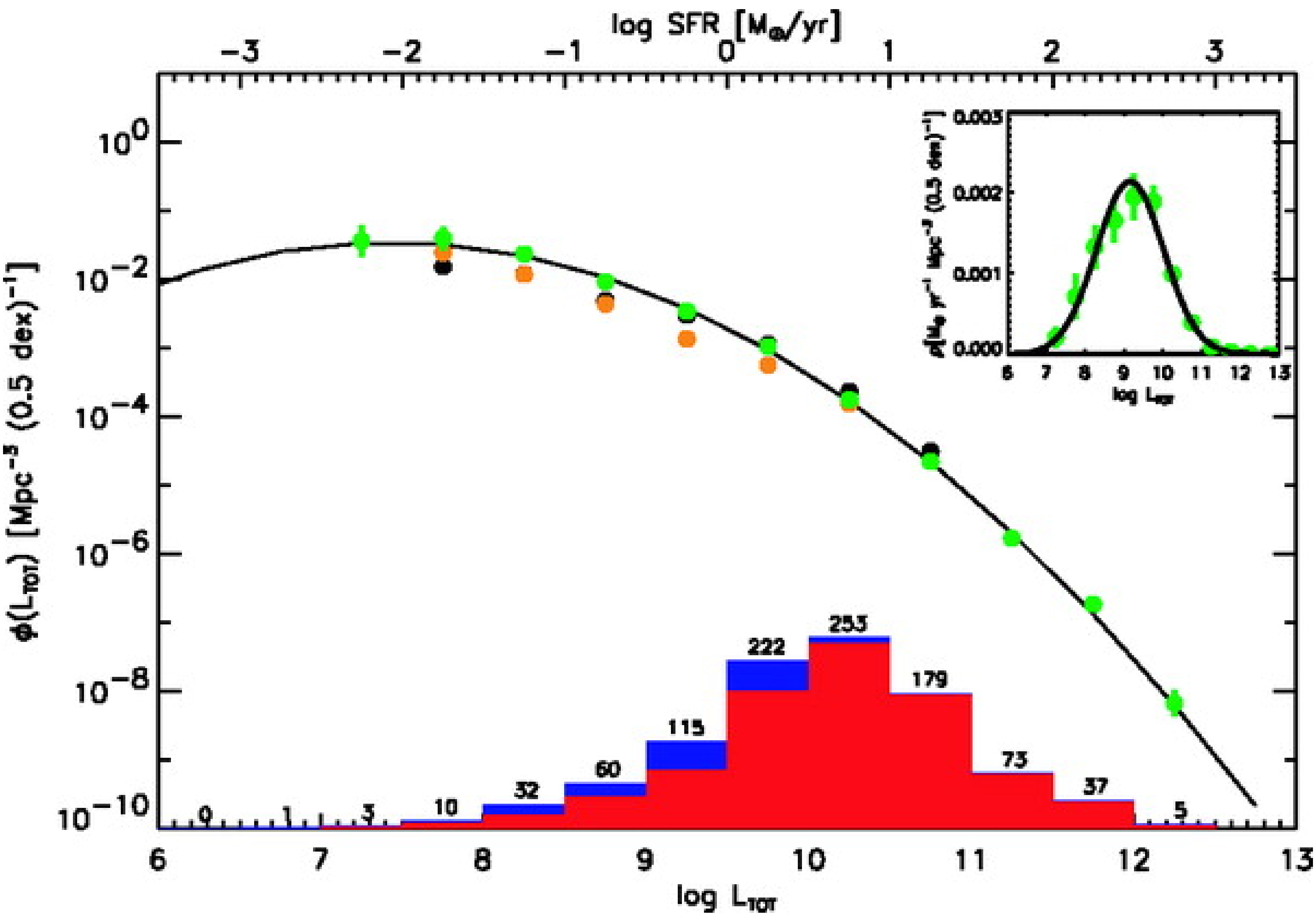
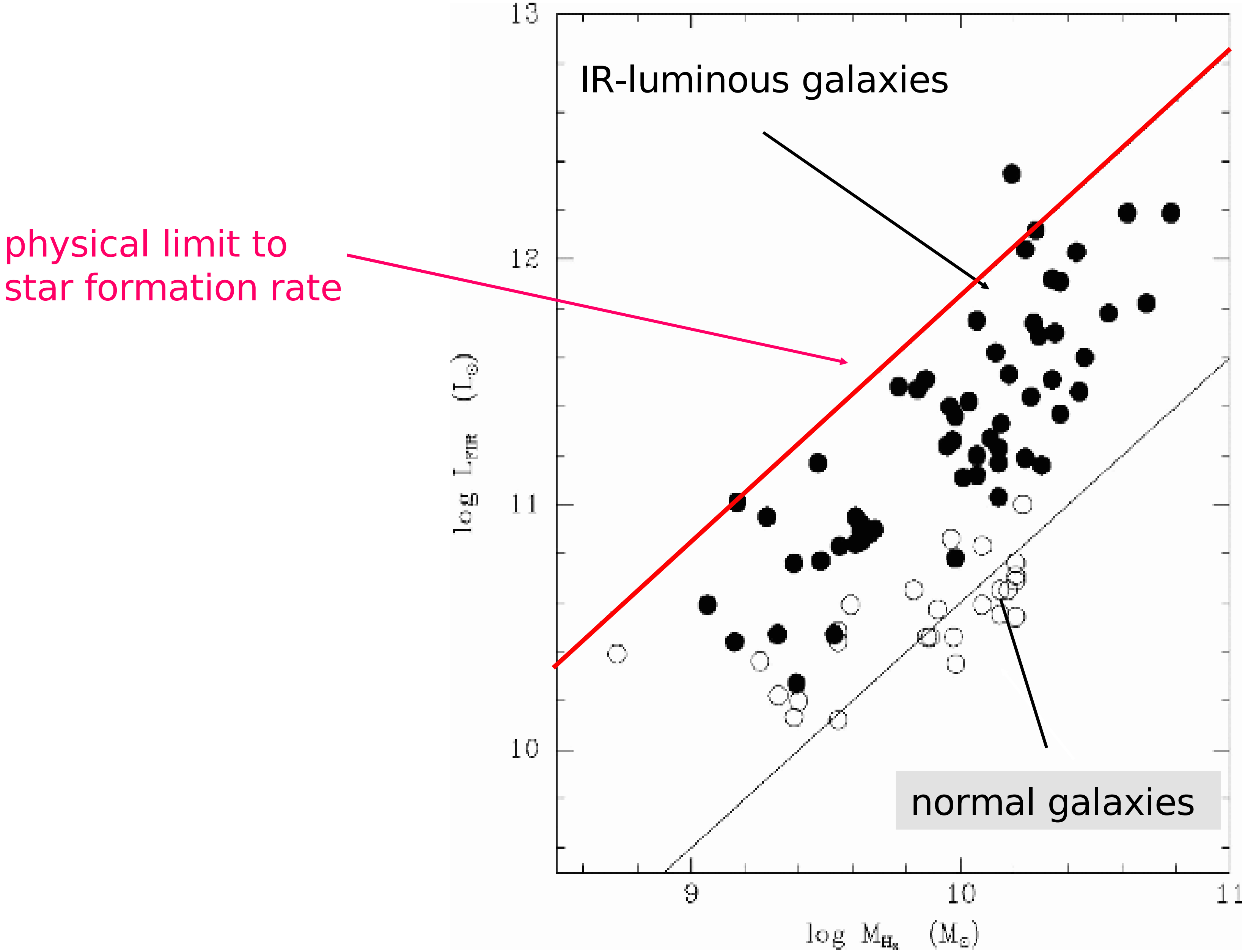
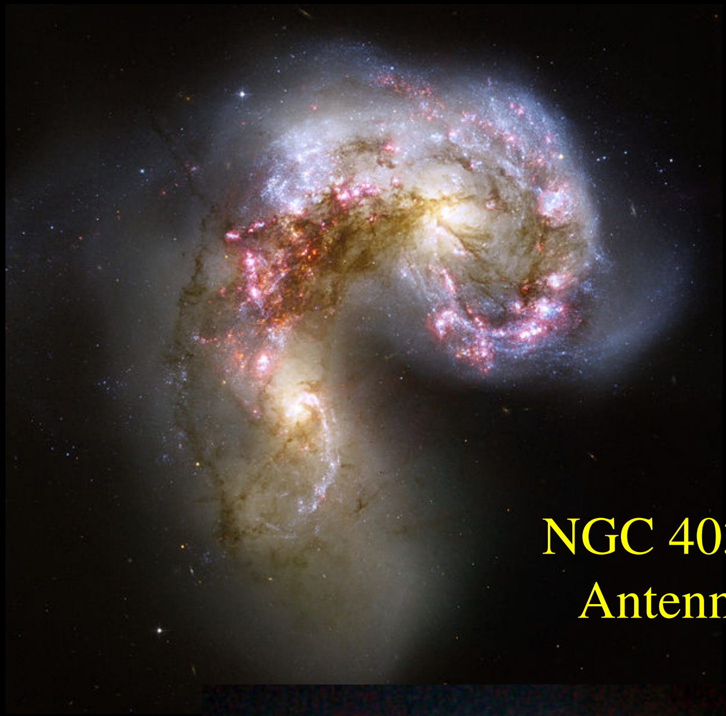
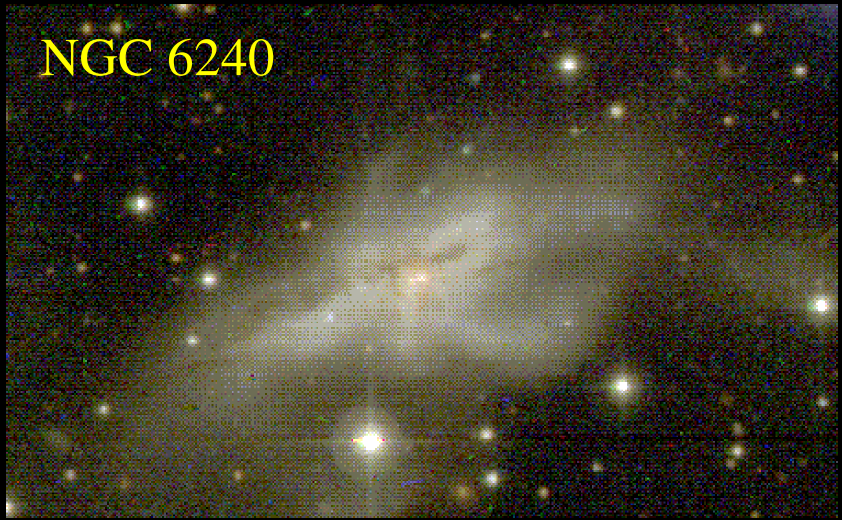


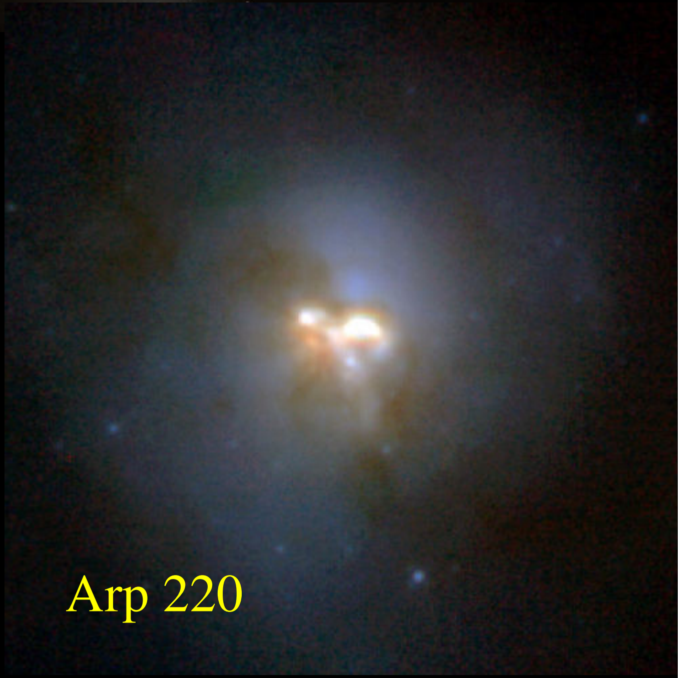
Martin et al. 2005

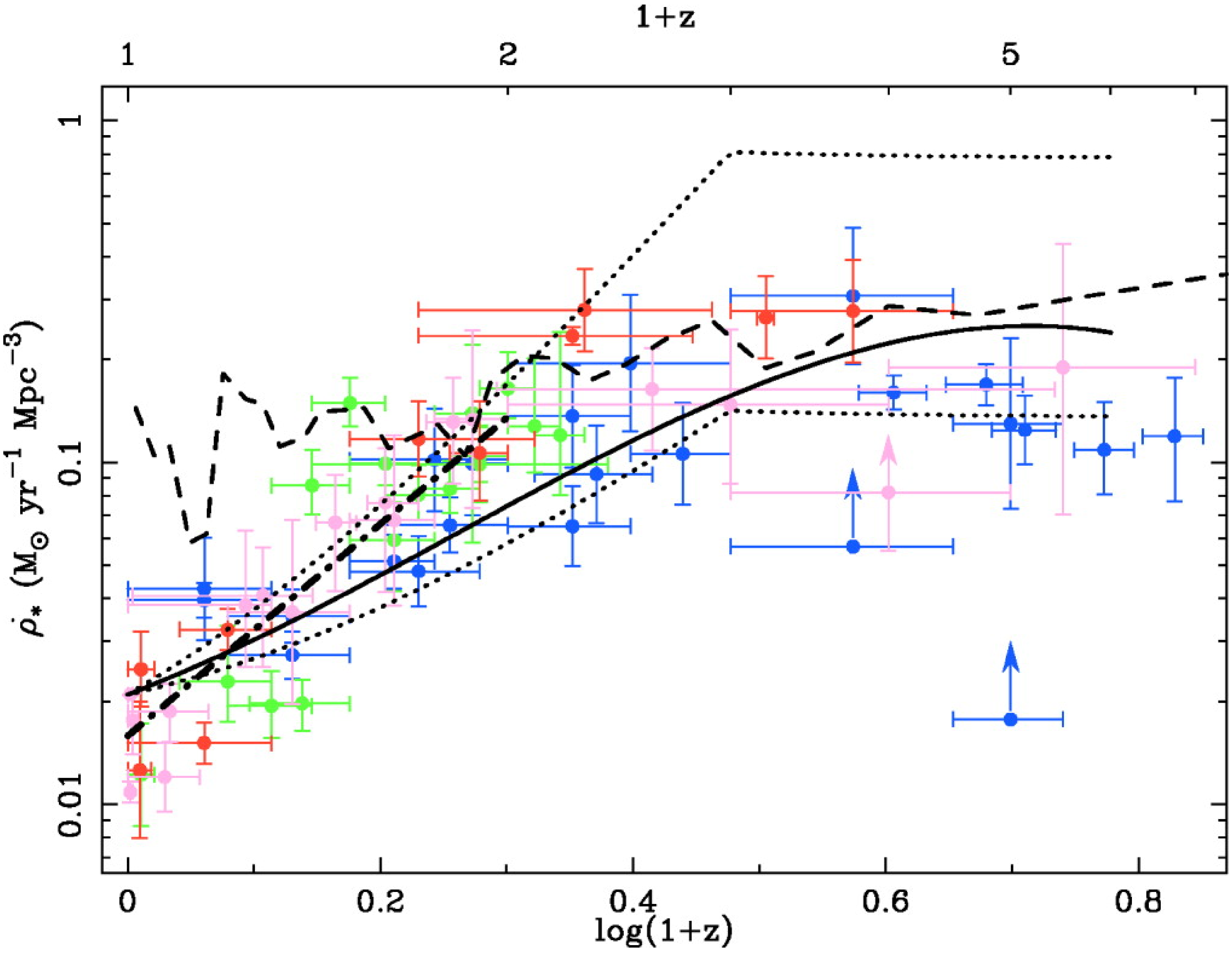

physical limit to
star formation rate
IR-luminous galaxies
normal galaxies
13
12
11
10
log L_FIR (L_⊙)
9
10
11
log M_H2 (M_⊙)


M82

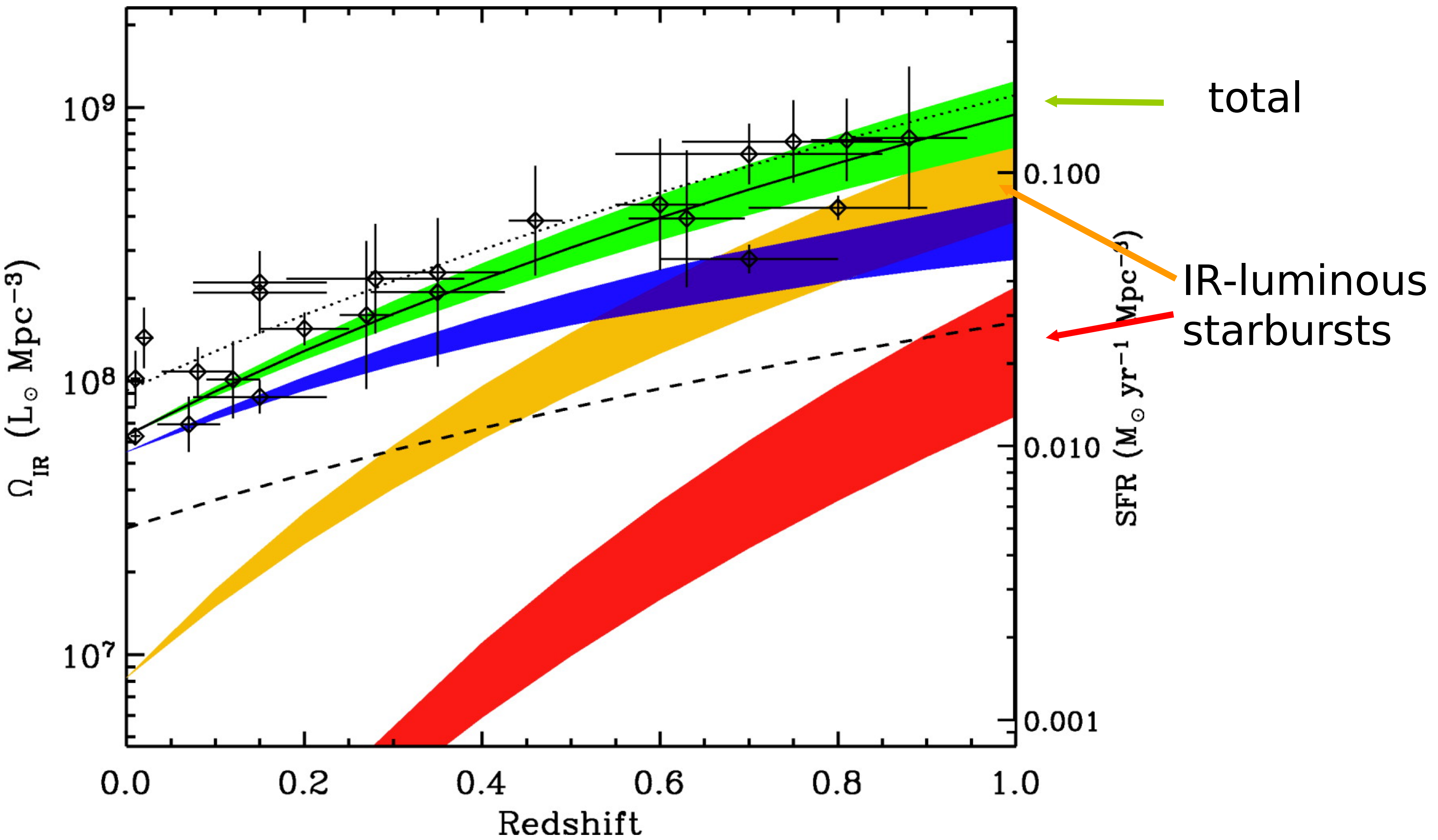

NGC 4038/9
Antennae


NGC 6240

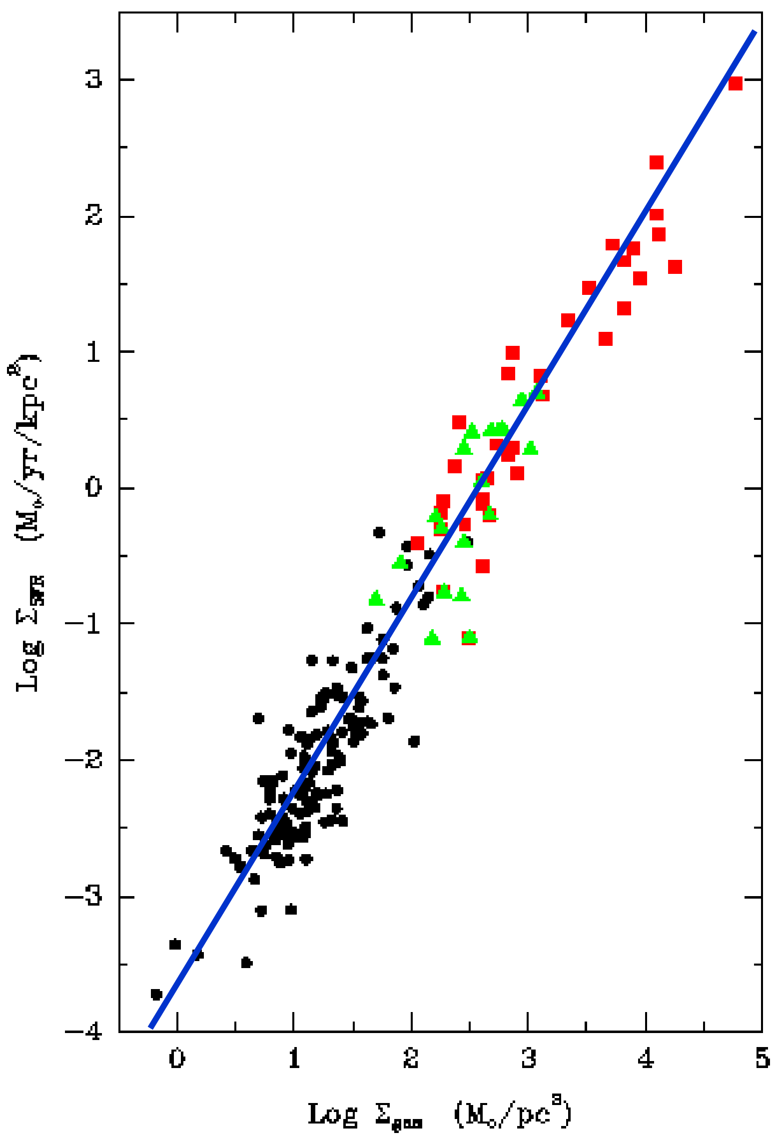

Arp 220



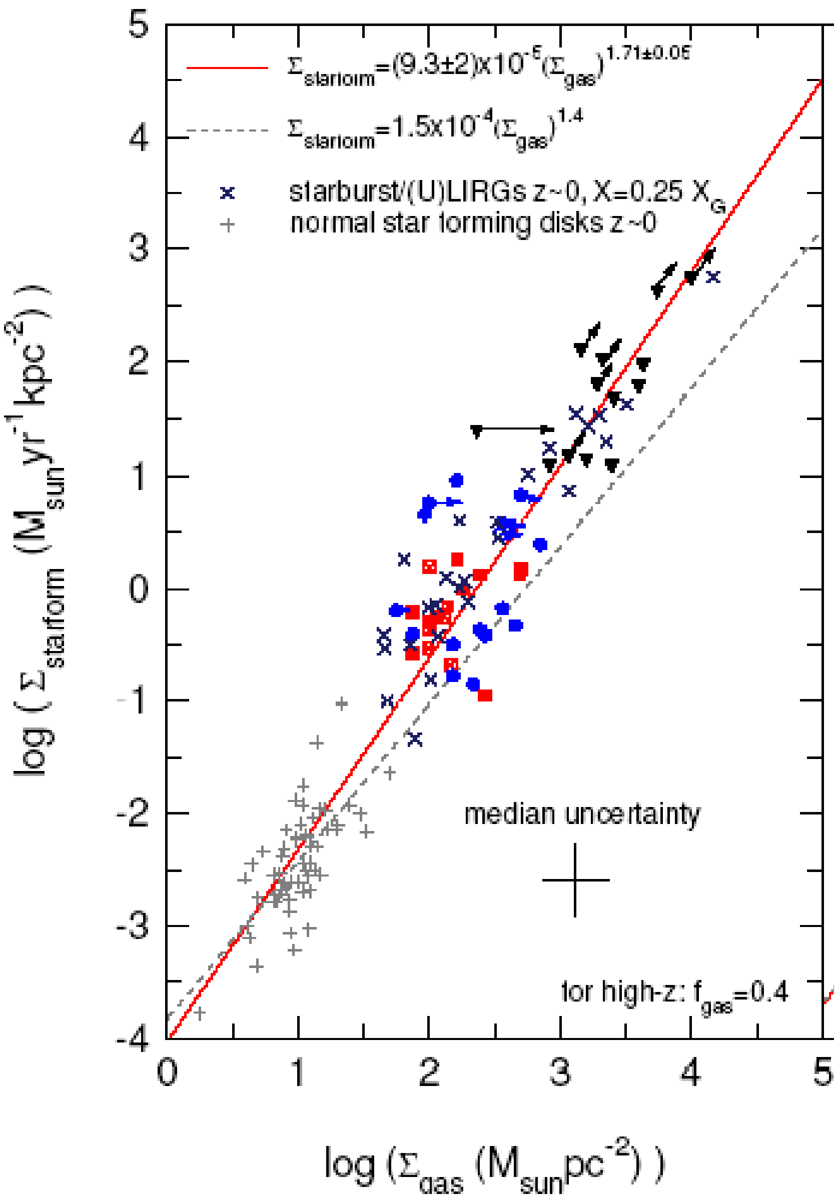
Hopkins 2004, ApJ, 615, 209



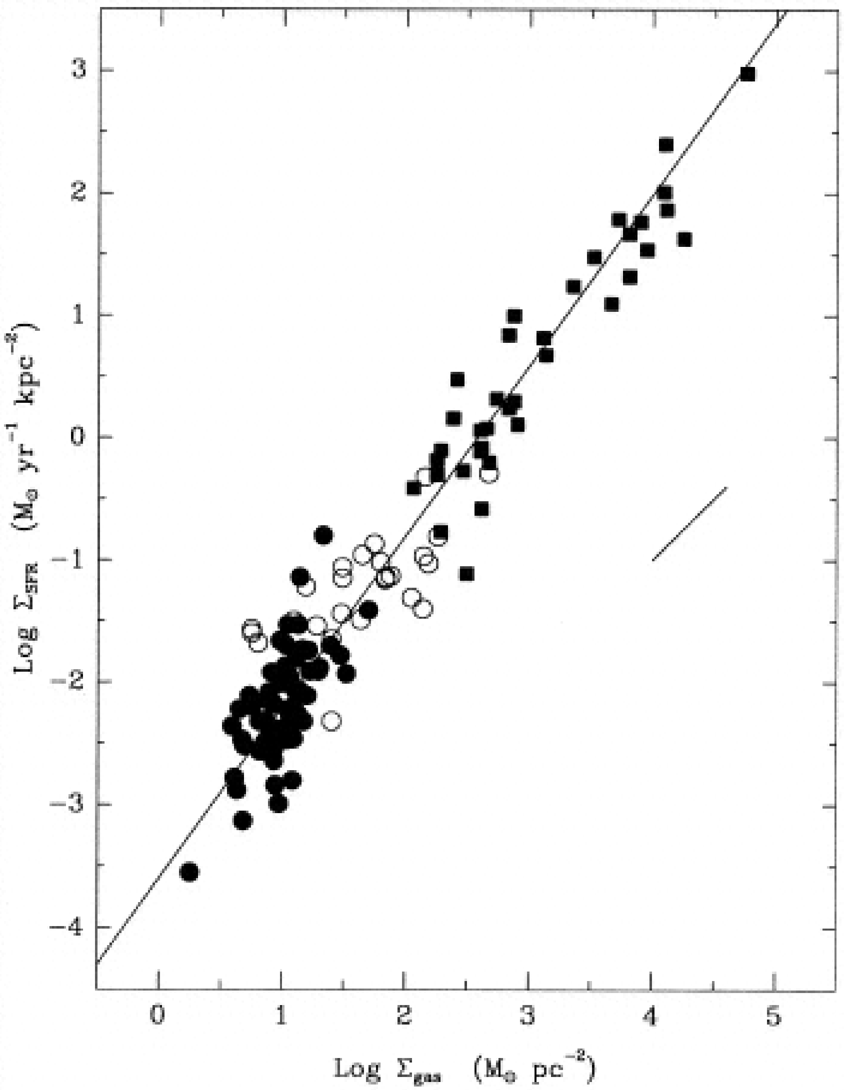
L'Floch et al. 2005, ApJ, 632, 169

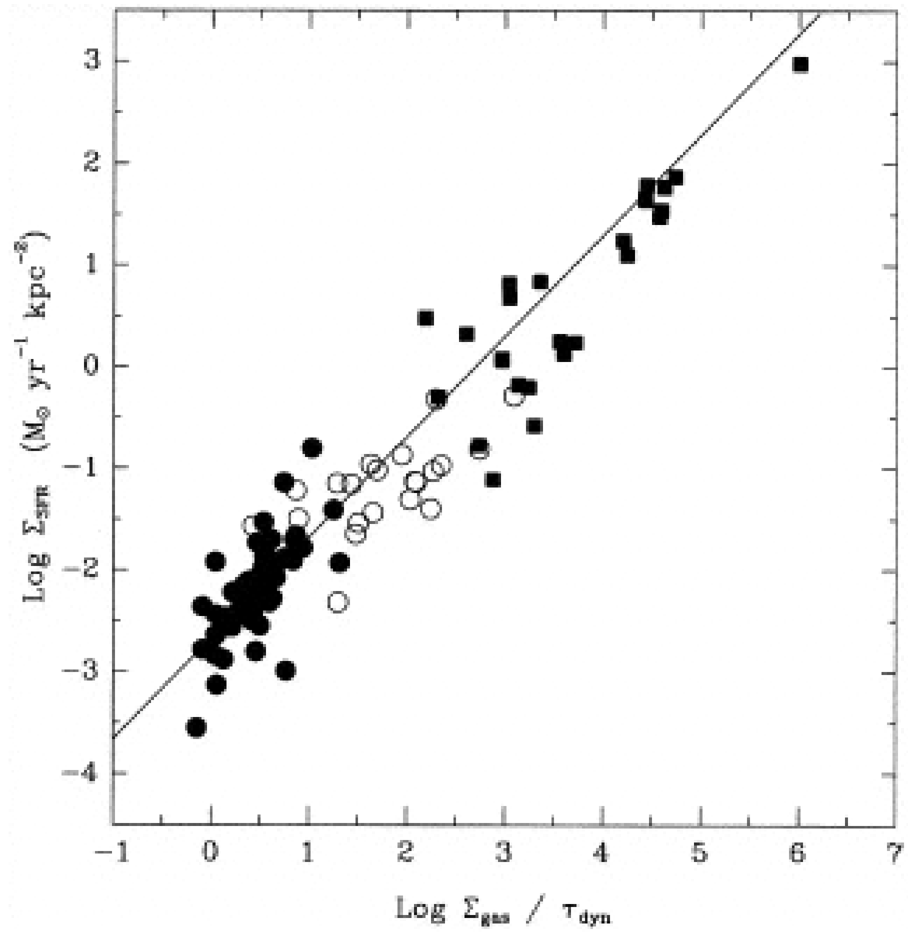


Kennicutt 1998



Bouche et al. 2007





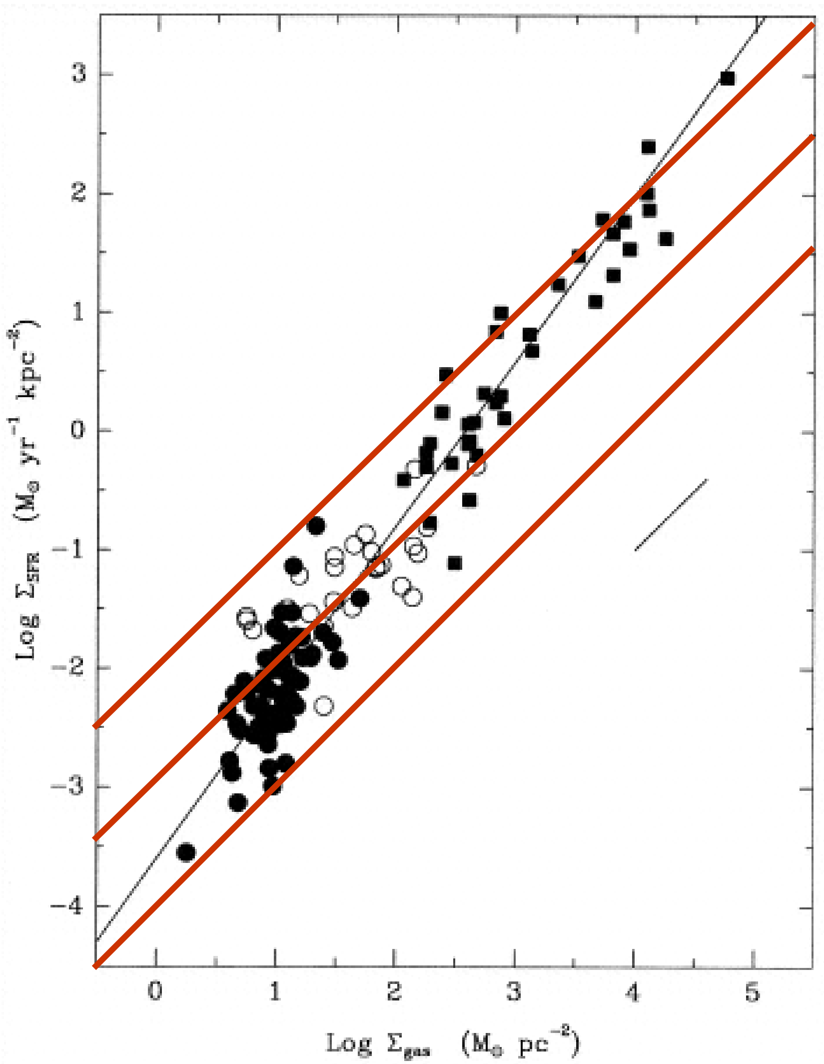
Schmidt law:

SFR vs gas density power law

SFR vs gas density/dynamical time

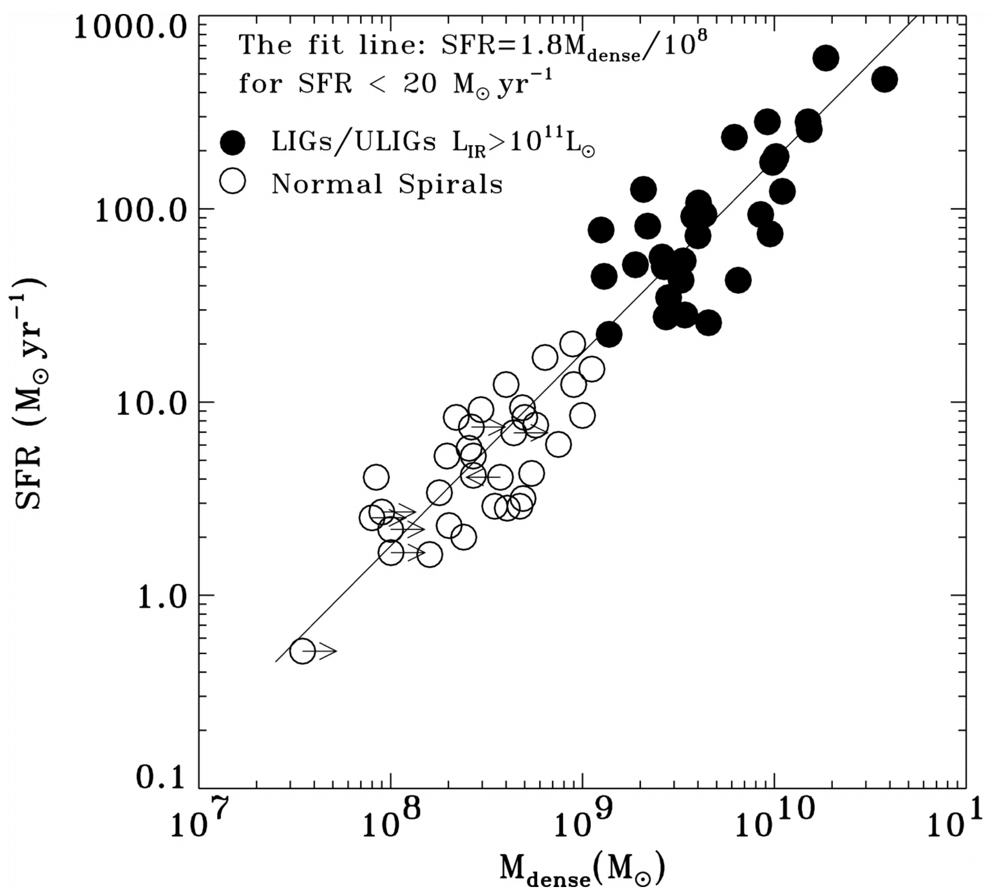
Kennicutt 1998, ApJ, 498, 541

$\Sigma_{SFR}/\Sigma_{gas} \sim \Sigma_{gas}^{0.5}$



Kennicutt 1998, ApJ, 498, 541

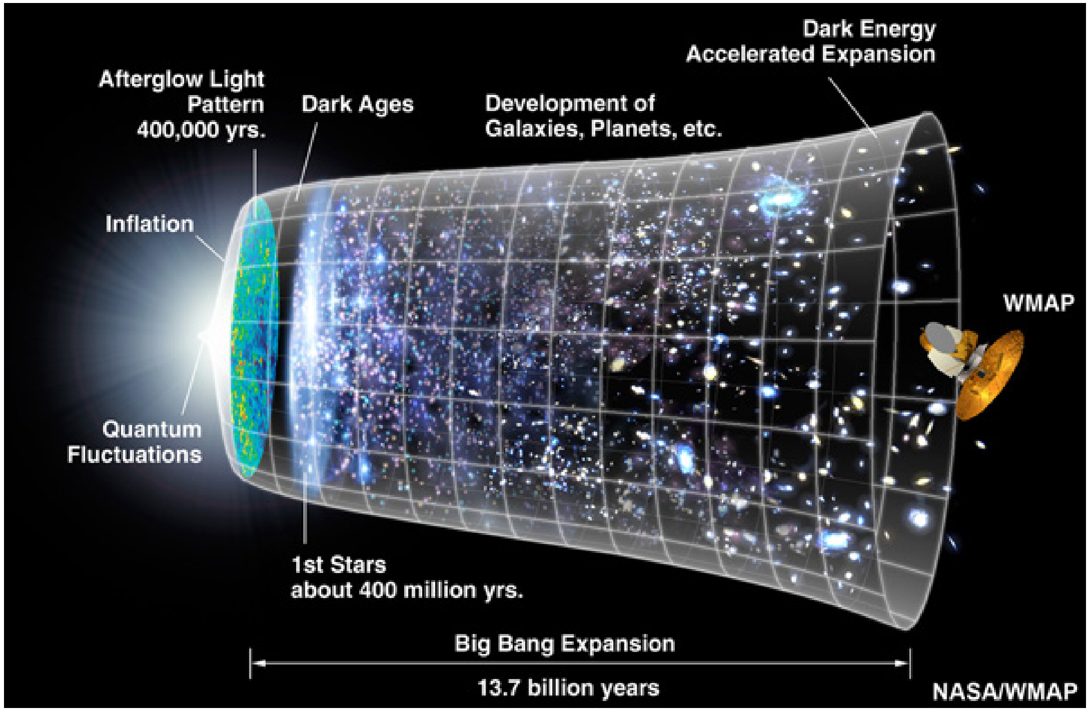
$\Sigma_{SFR}/\Sigma_{HCN} \sim$ const

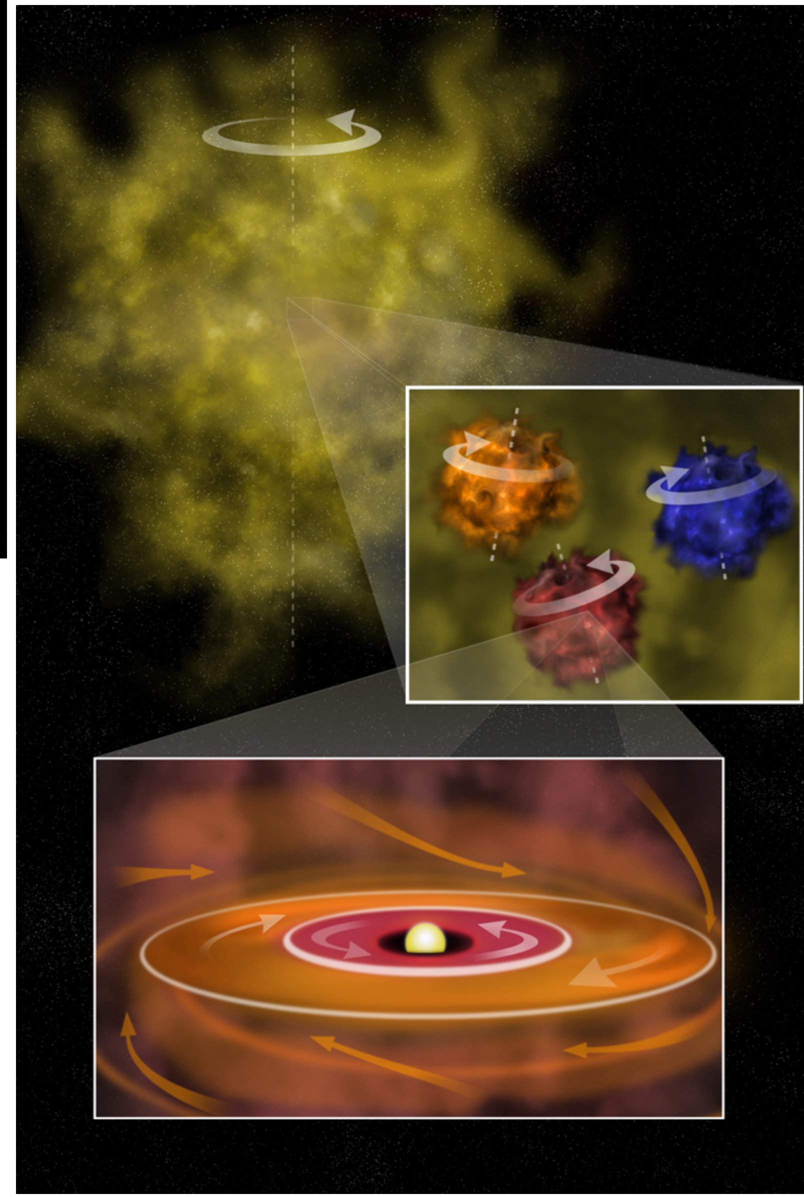


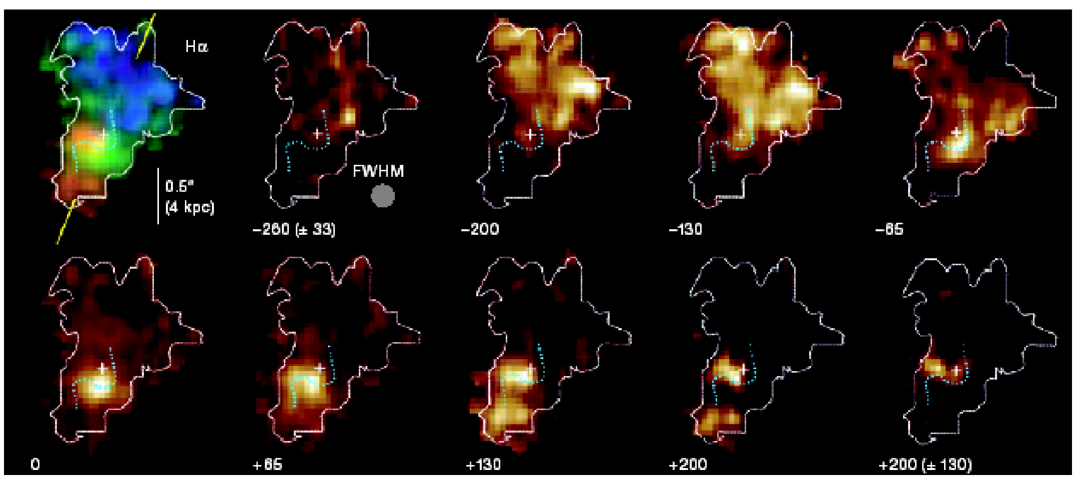
Gao, Solomon 2004, ApJ, 606, 271

Things We Don't Understand

- SF during the reionisation epoch
  - the first star formation
- Baryon accretion histories
  - role of slow accretion vs mergers
- Structure, dynamics, chemistry of star-forming clouds
- Fossil star formation histories from resolved stellar populations


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP

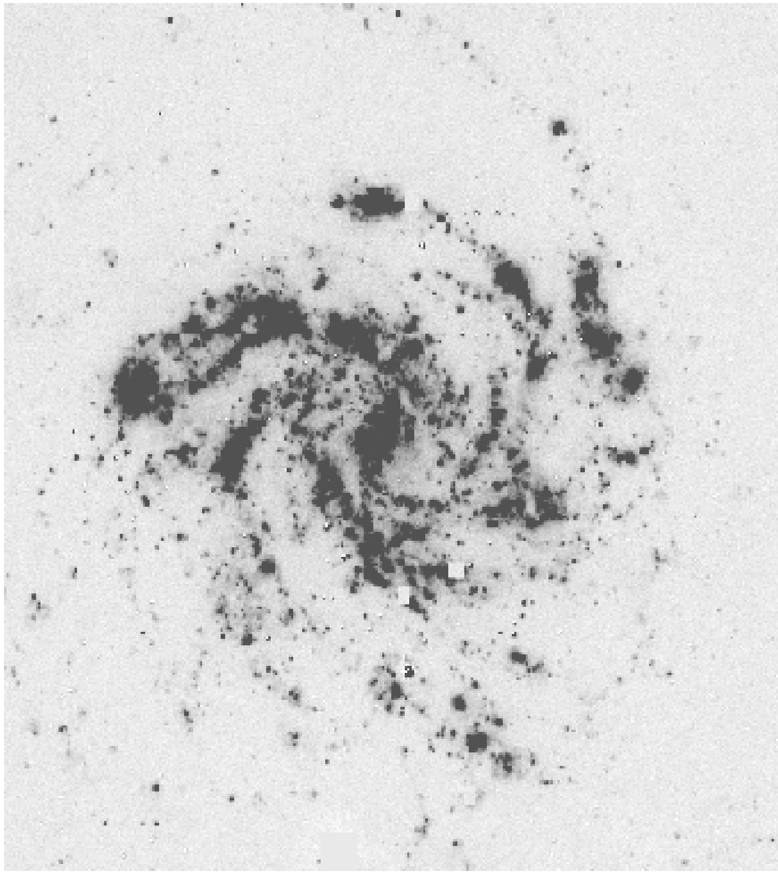



Hα
0.5"
(4 kpc)
FWHM
−260 (± 33)
−200
−130
−65
0
+65
+130
+200
+200 (± 130)

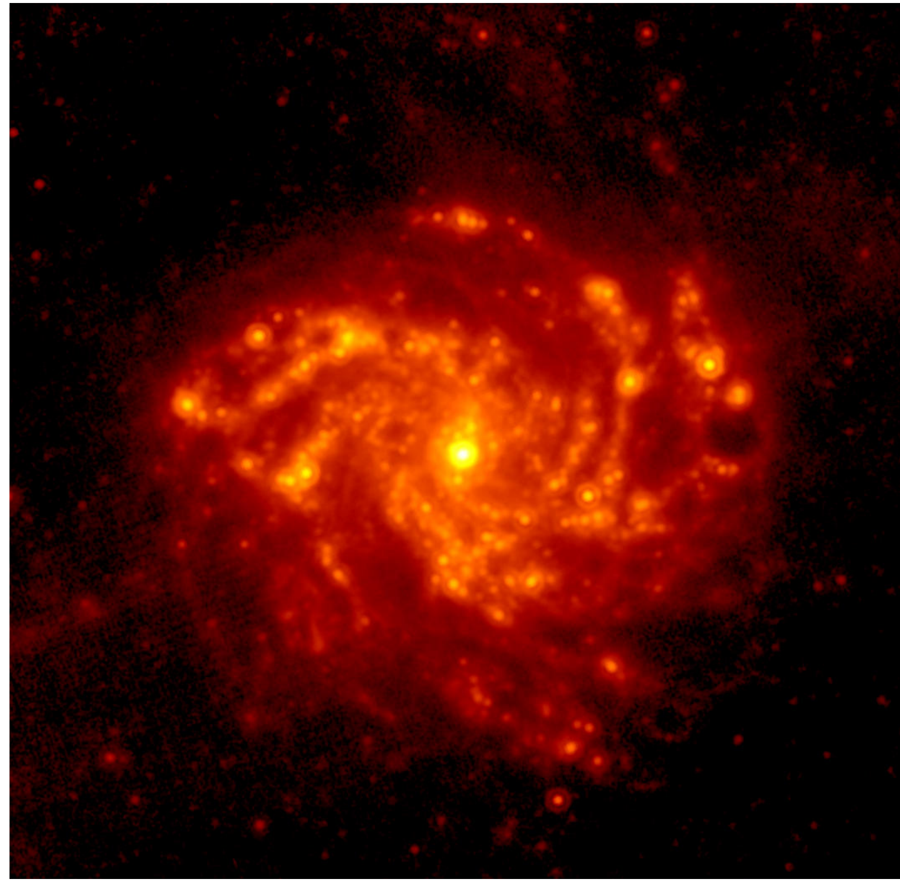
Things We Don't Understand

- How strong is the foundation?
  - 3 dirty acronyms: IMF, X_{CO}, τ_{gas}
- Where is the physics?
  - What drives the SFR on large scales?
  - What is the causation in the Schmidt law?
  - Are there multiple SF modes, how are they separated physically?
  - What sets the form and constancy of the IMF?
  - How do we connect to the physics of SF in Ewine's talk?

NGC 6946 Hα *vs* IR

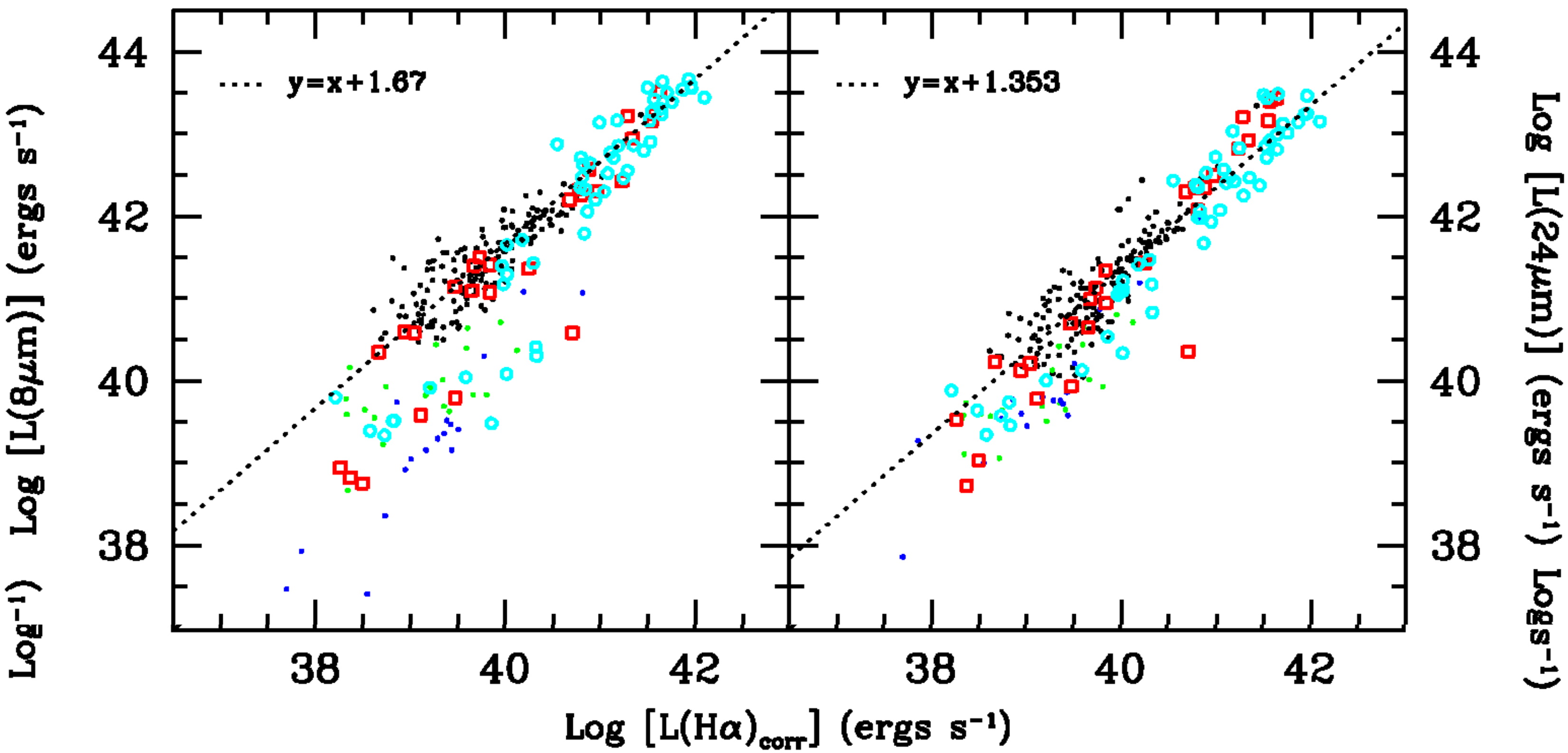


Ferguson et al 1998, ApJ, 506, L19

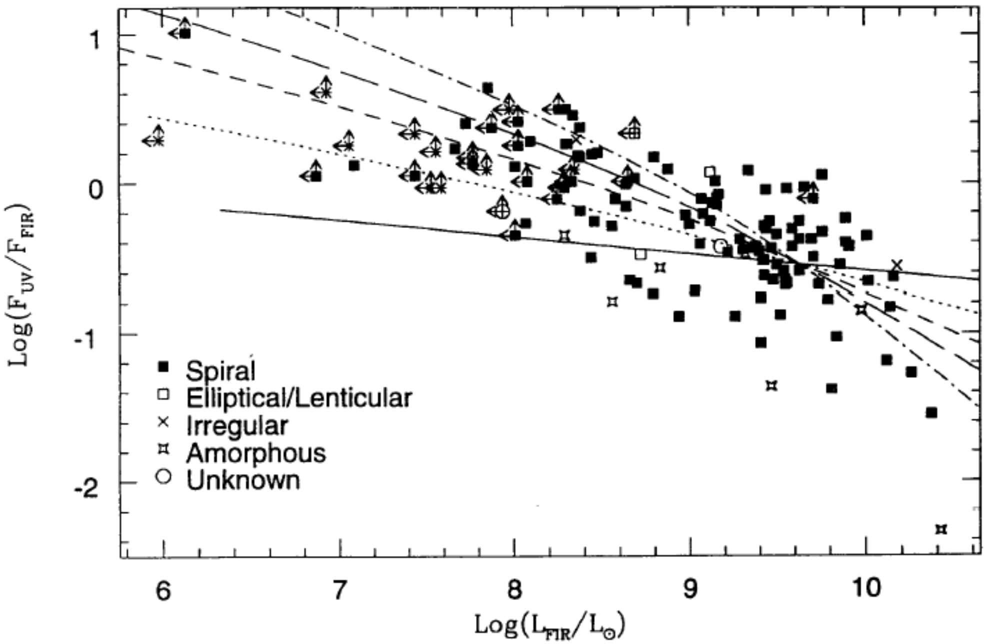


Spitzer MIPS 24μm

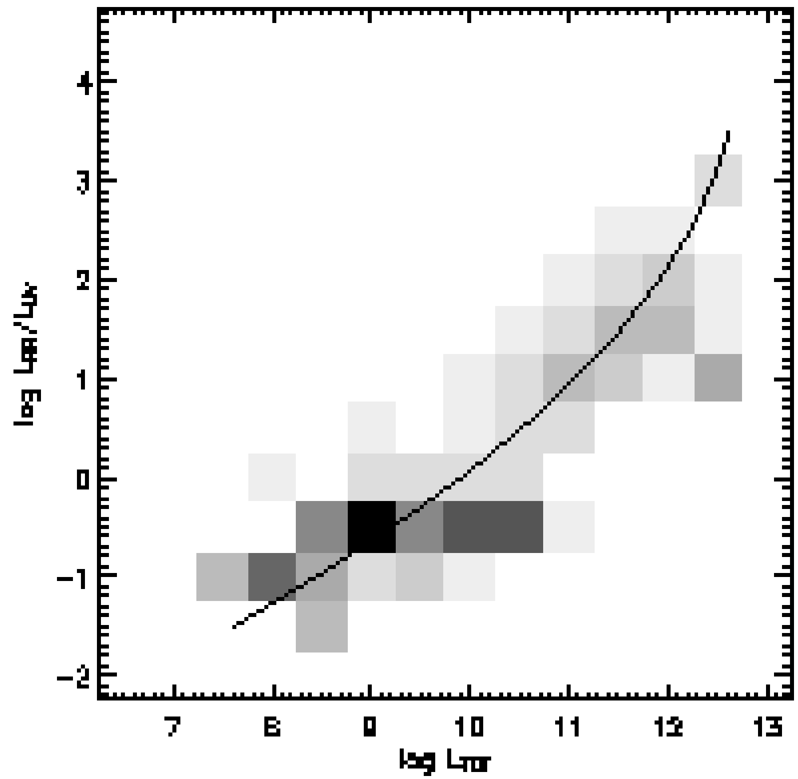
SINGS Sample: 8 μm and 24 μm



Kennicutt et al. 2009, ApJ, submitted

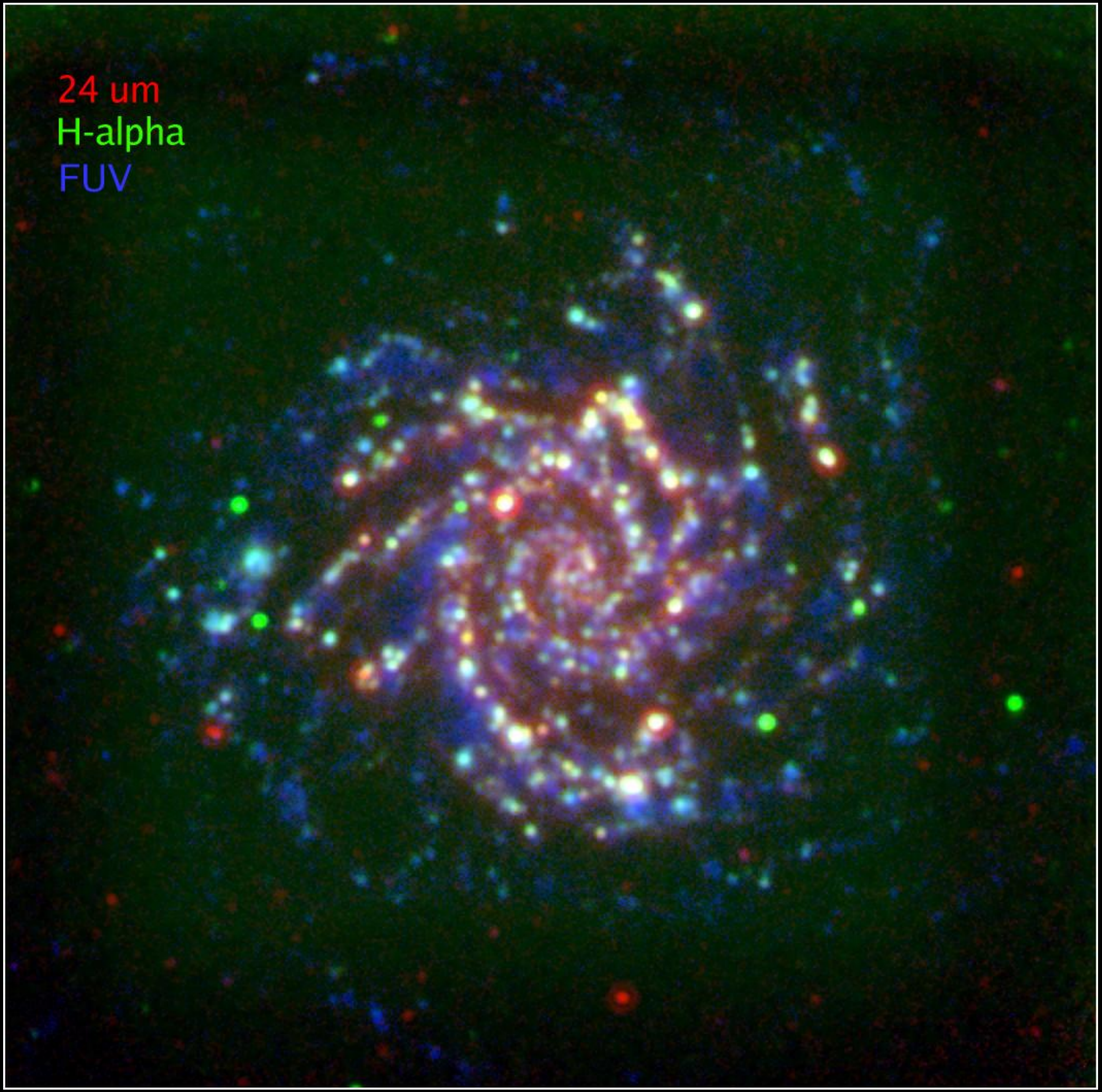


Wang & Heckman 1996, ApJ, 547, 965

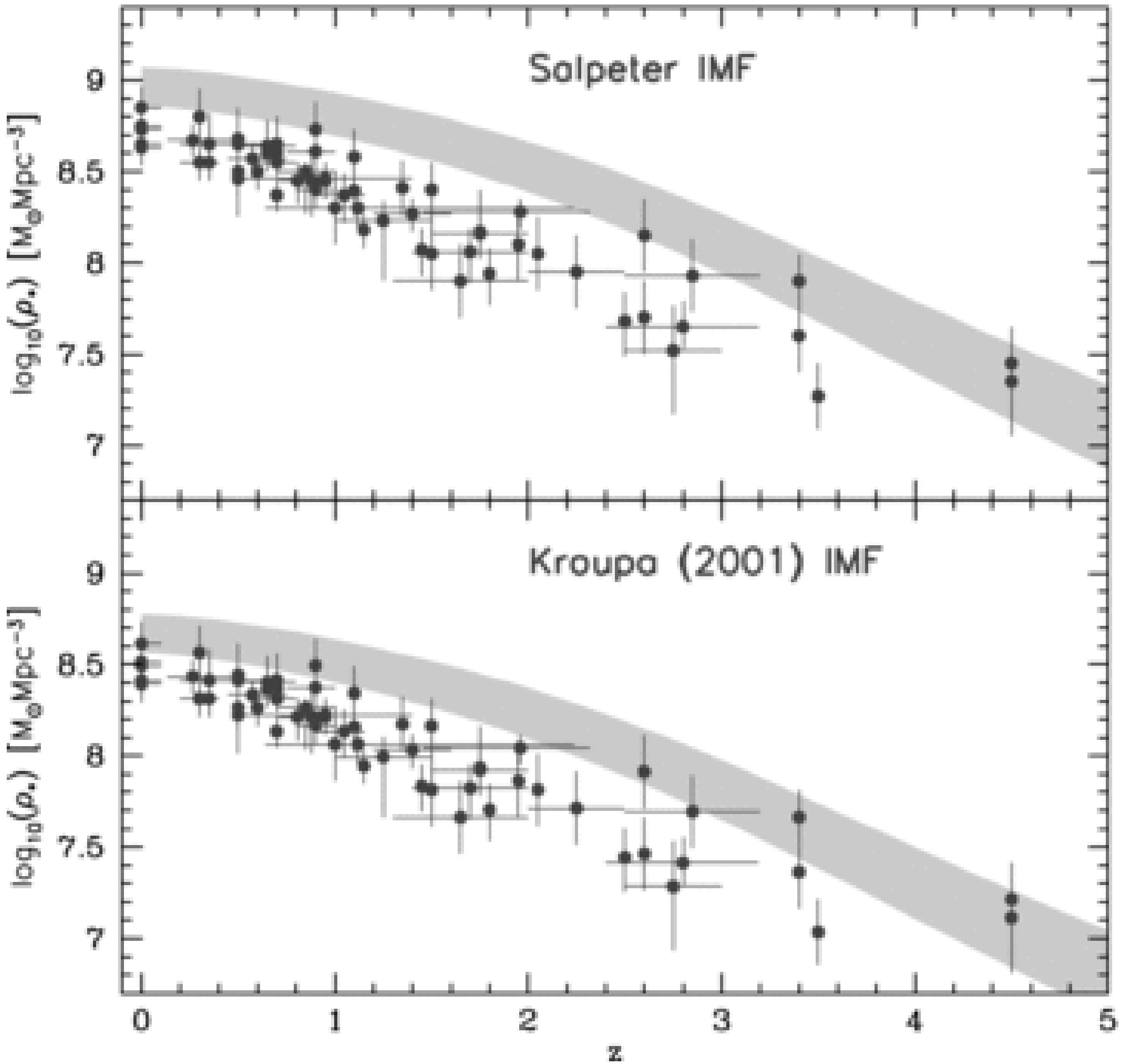


Martin et al. 2005, ApJ, 619, L59

NGC 628
(M74)

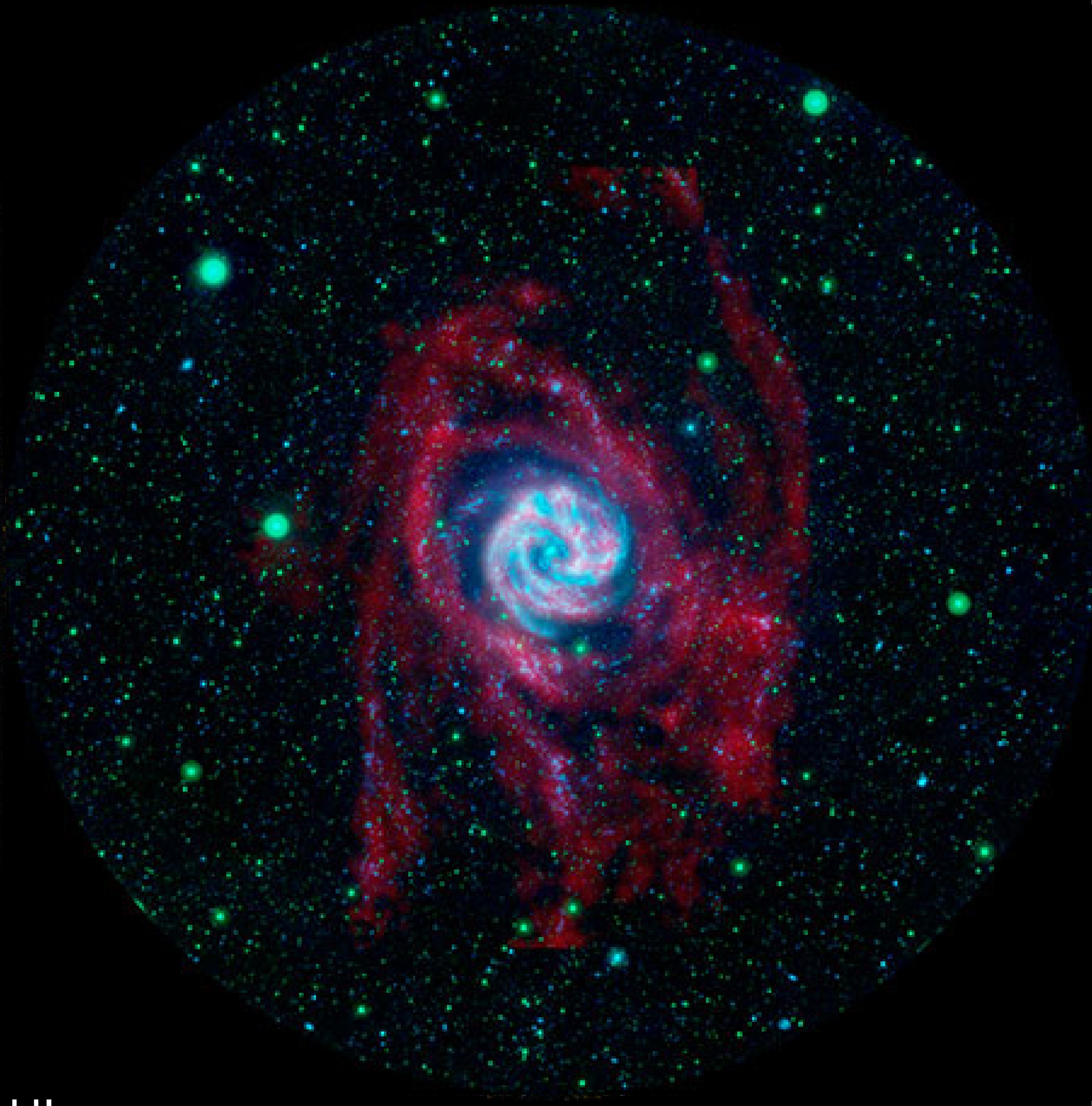


C. Tremonti
11HUGS Team



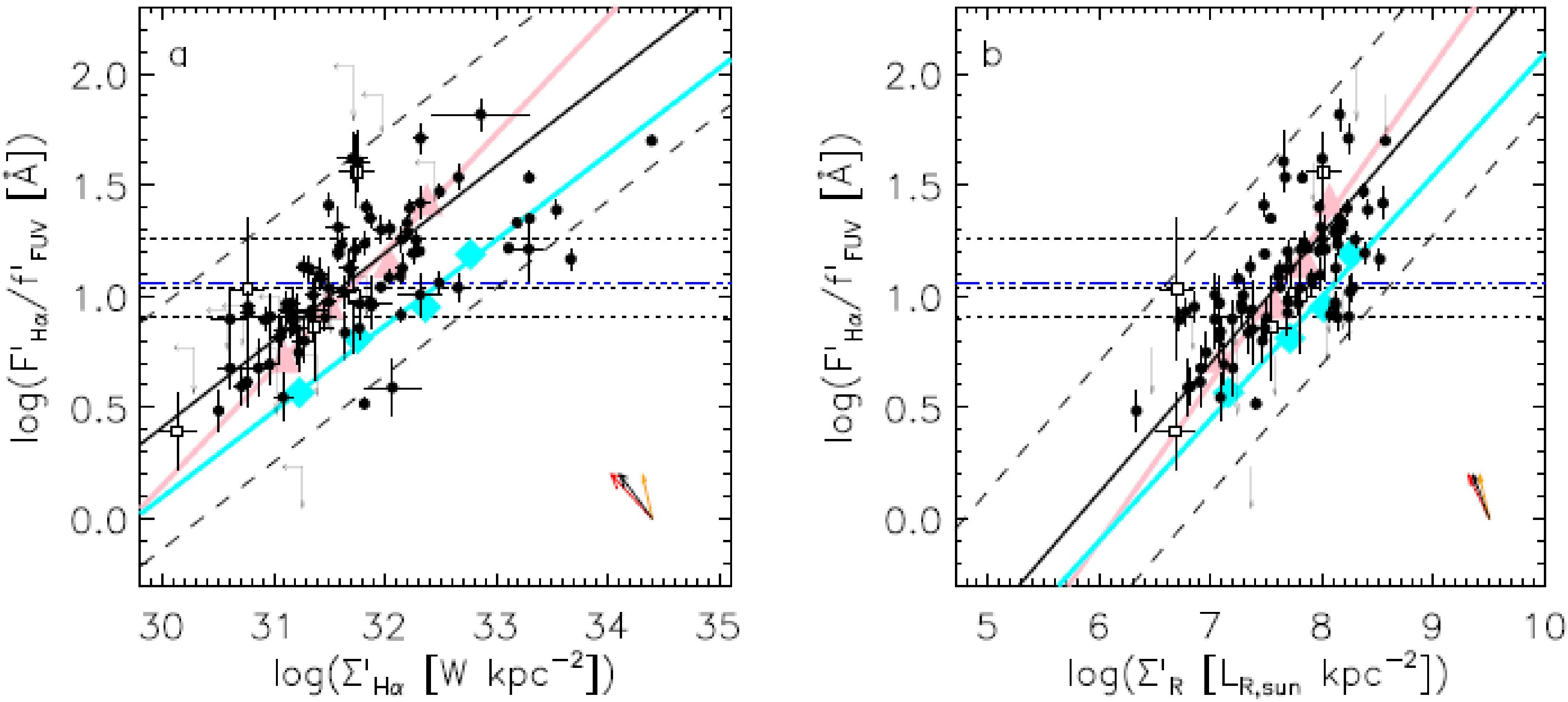
Wilkins et al. 2008

“XUV Discs”

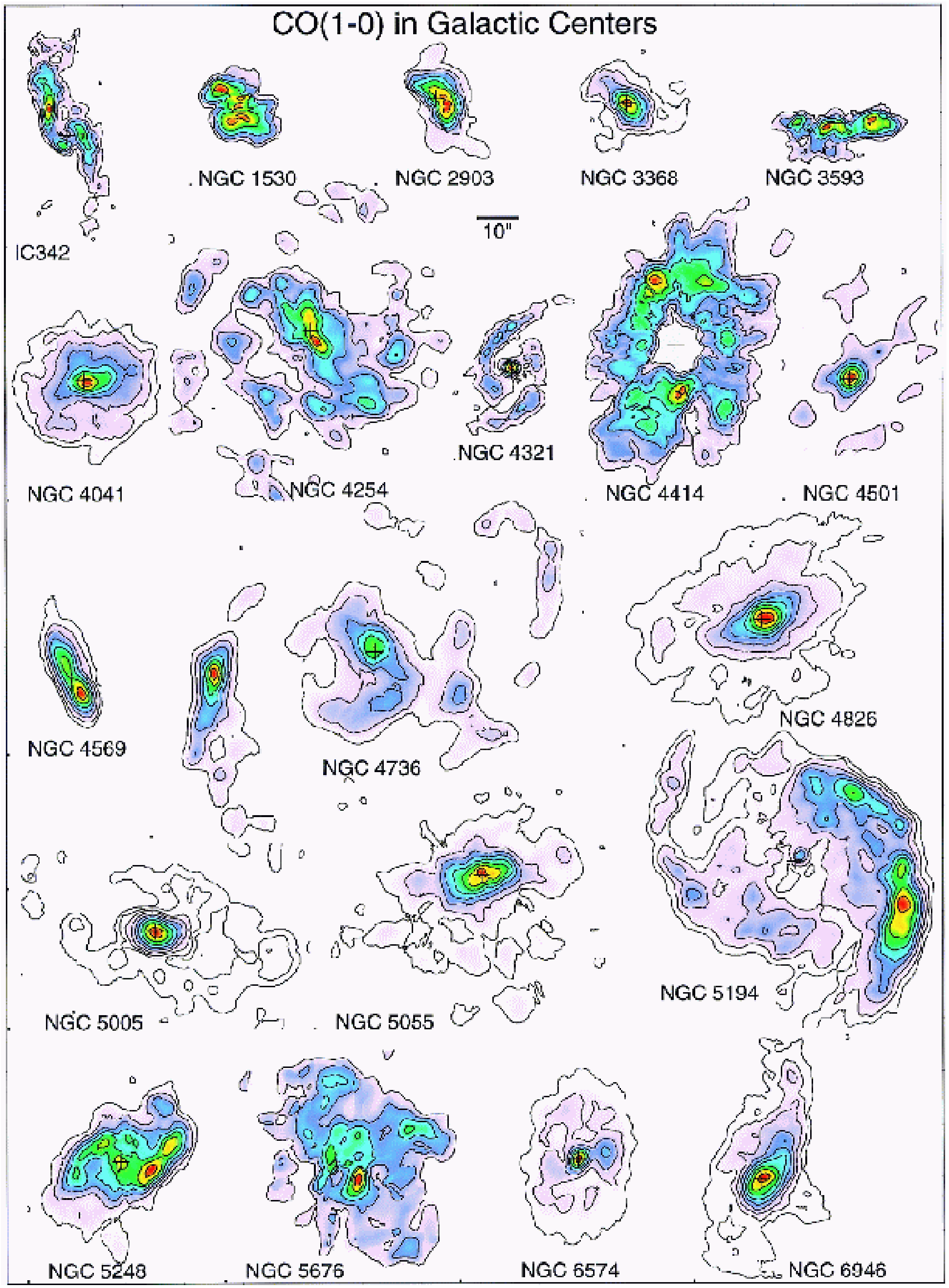


M83 = NGC 5236

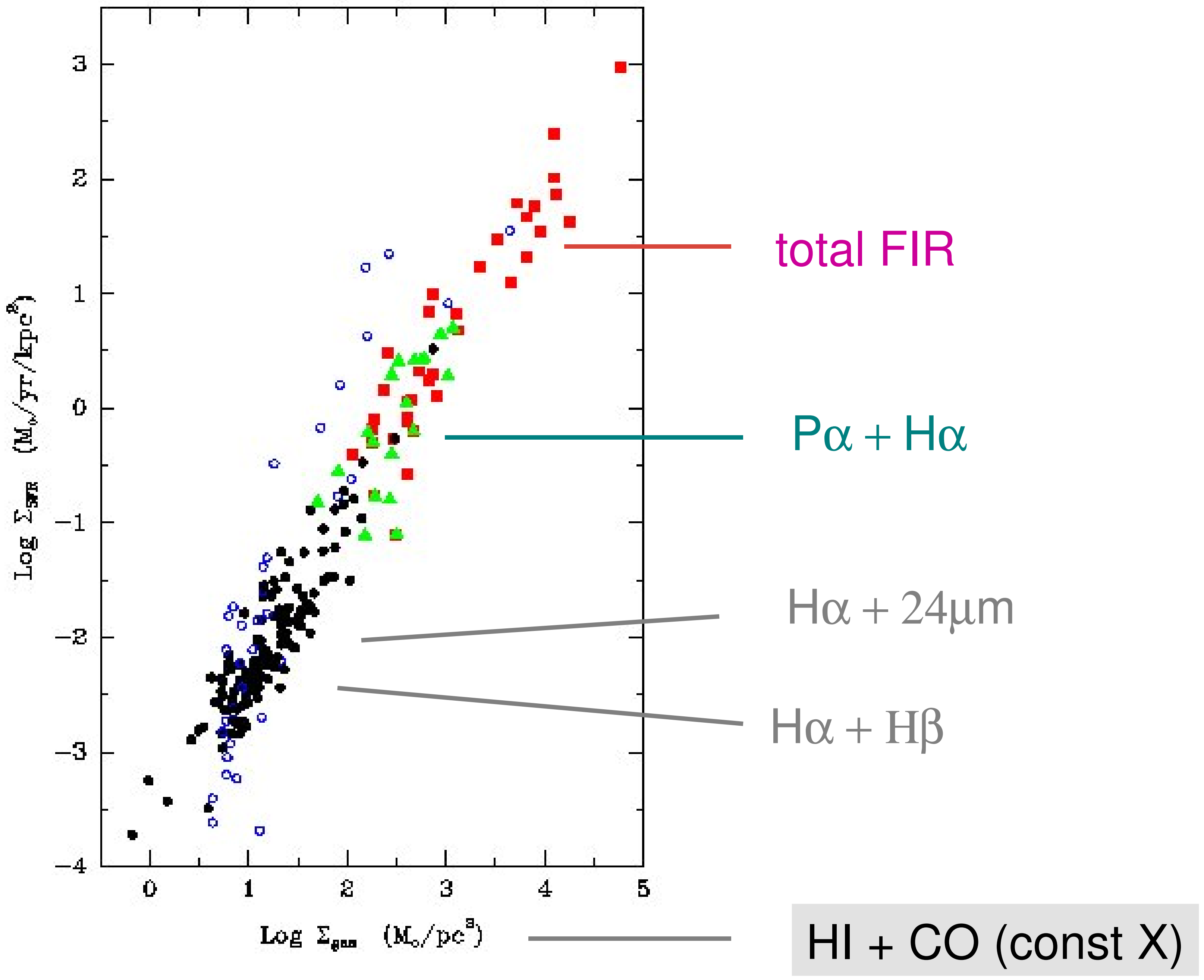
GALEX FUV/NUV + VLA HI



Meurer et al. 2009, arXive:0902:0384

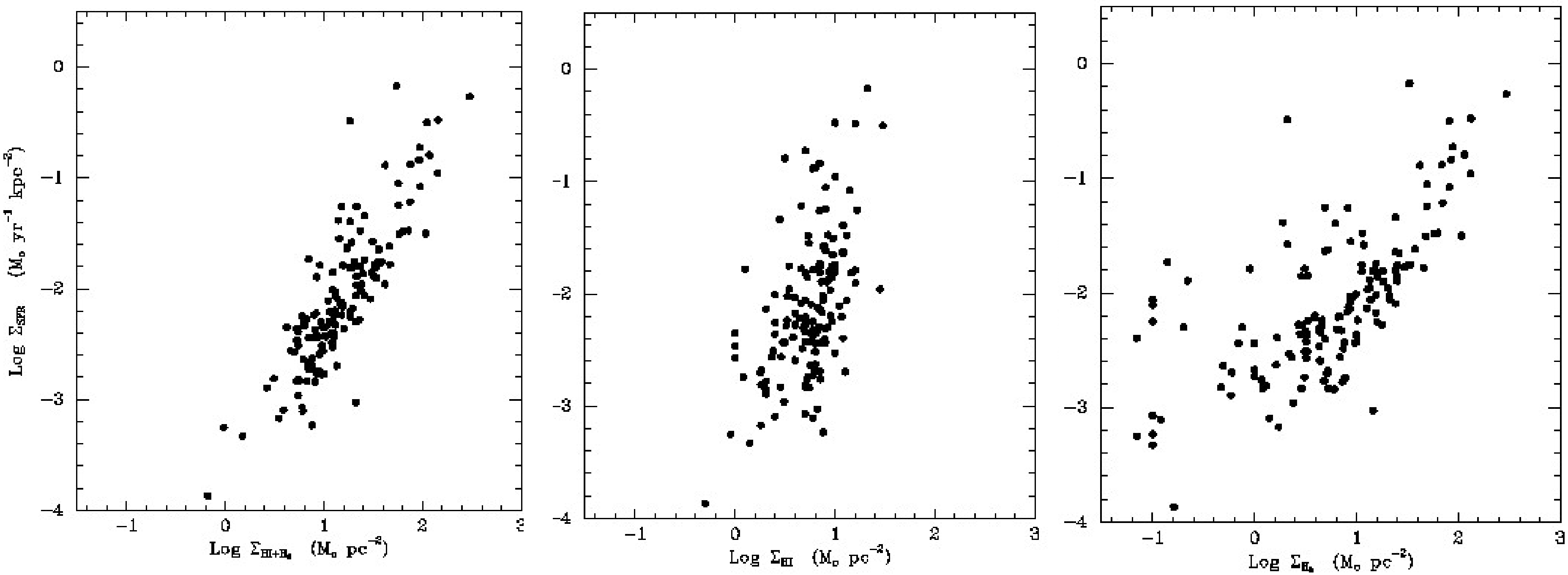


Sakamoto et al. 1999



total FIR
Pα + Hα
Hα + 24μm
Hα + Hβ
HI + CO (const X)

HI + H_2 HI H_2



Log Σ_SFR (M_☉ yr^-1 kpc^-2)
Log Σ_HI+H2 (M_☉ pc^-2)
Log Σ_HI (M_☉ pc^-2)
Log Σ_H2 (M_☉ pc^-2)
0
−1
−2
−3
−4
1
2
3

Physical Origin of Schmidt Law?

Self-gravity timescales

(Larson 1991, Elmegreen 2002, 2003)

Cloud-cloud collision rates (Tan 2000)

Gravitational instabilities + linear SFE

(Friedli et al. 1994, Li et al. 2005, 2006)

GMC PDF + turbulence

(Kravtsov 2003; Tasker & Bryan 2006)

Self-regulation via GMC turbulence

(Krumholz & McKee 2005)

Self-regulation via ISM pressure (Dopita 1985)

Self-regulation via ISM porosity (Silk 1997)

Physical Origin of SF Thresholds?

Gravitational instabilities?

(Quirk 1972, Kennicutt 1989)

– transition to bound clouds when gas disc becomes gravitationally unstable: $\Sigma_{crit} \sim 0.7 \kappa c/\pi G$

Cold phase thermal instabilities? (Schaye 2004)

– transition to cold phase triggers gravitational instabilities

Pressure-regulated H_2 instabilities?

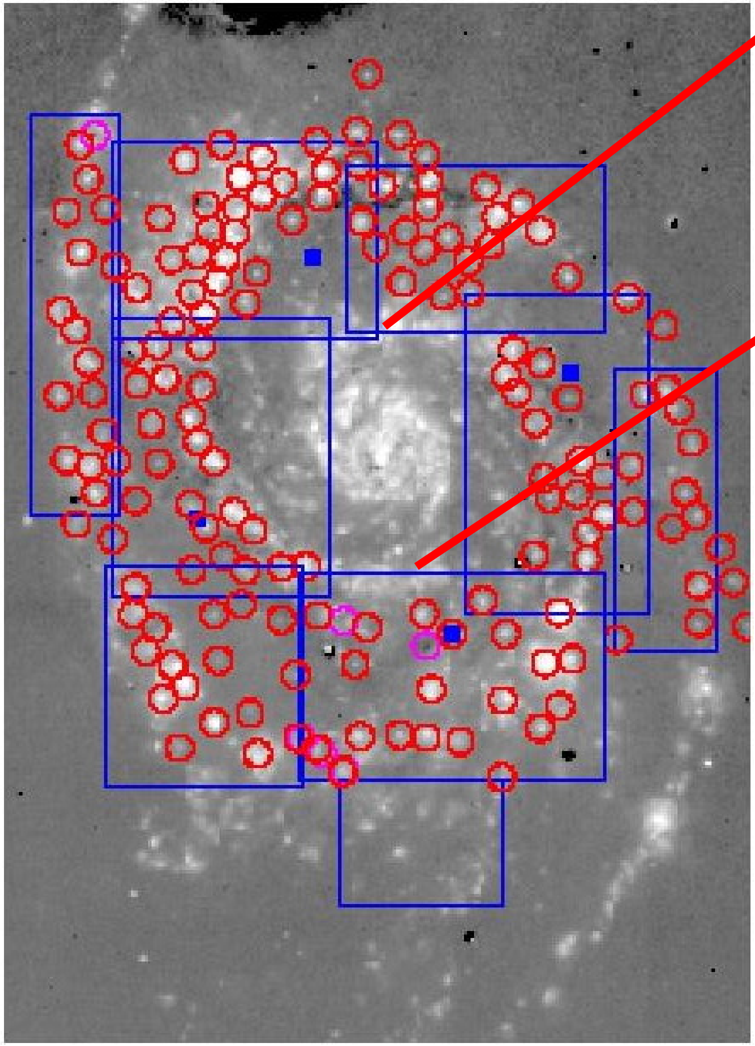
(Elmegreen; Parravano 1994; Blitz-Rosolowski 2006)

Fragmentation threshold? (Krumholz & McKee 2008)

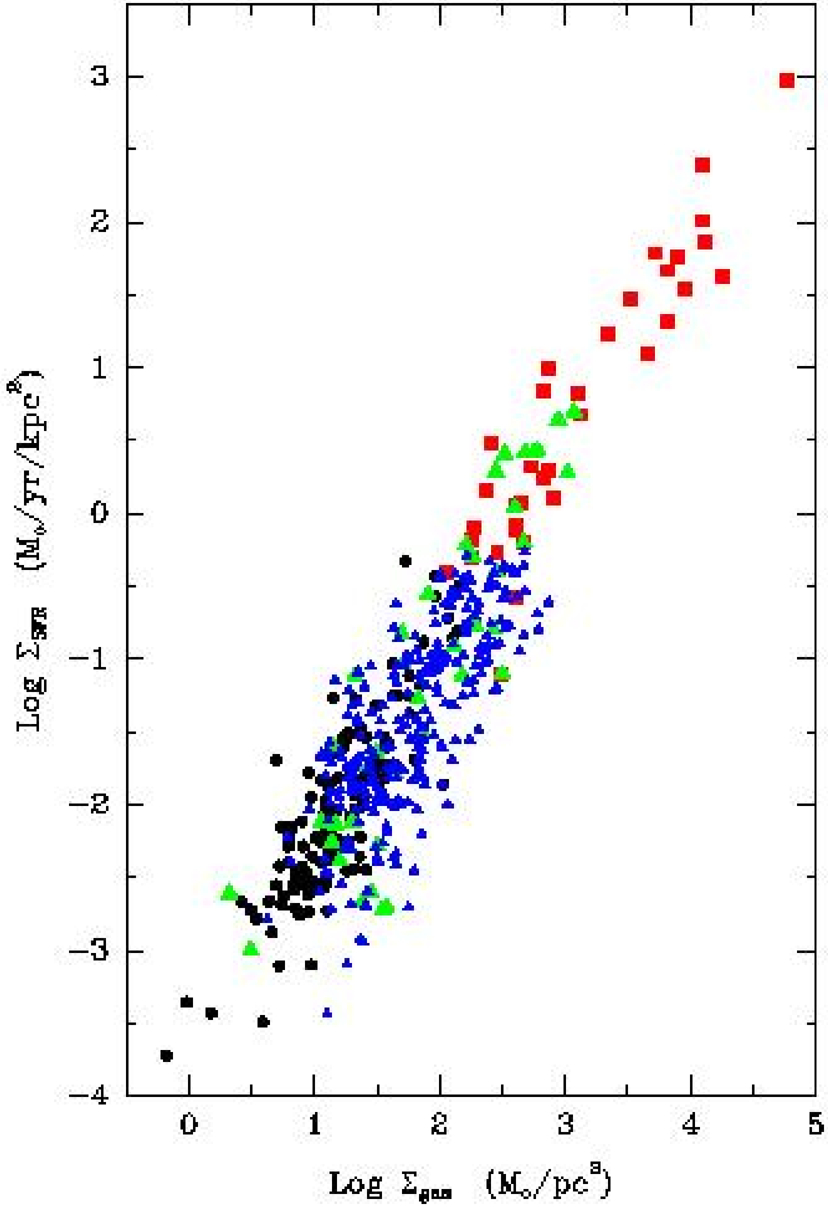
Things We Don't Understand

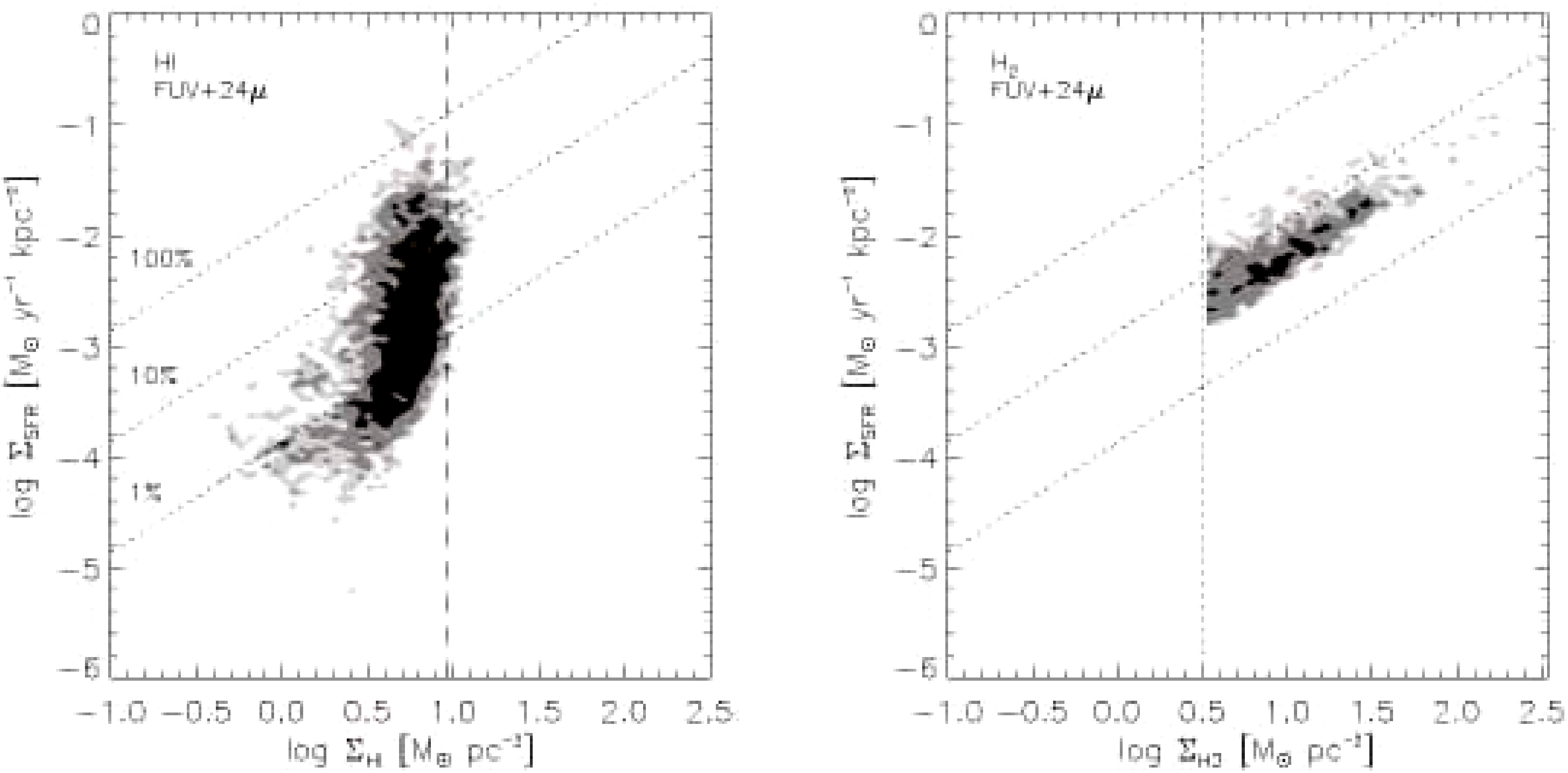
- How do the structure, mass spectrum, and dynamics of SF clouds vary in/among galaxies?
  - along the Hubble sequence, vs galaxy mass
  - vs clustering, from isolated clouds to Fabian's galaxy
  - near central black holes
- SF law
  - How does the global Schmidt law connect to SF on the cloud scale?
  - What are the nature and physical origin of SF thresholds?
  - What sets the fraction of cloud mass in dense cores?
- Systematics of star clustering in galaxies?
- Are there scaling laws for feedback?
  - What is the underlying physics?

Local Schmidt Law in M51



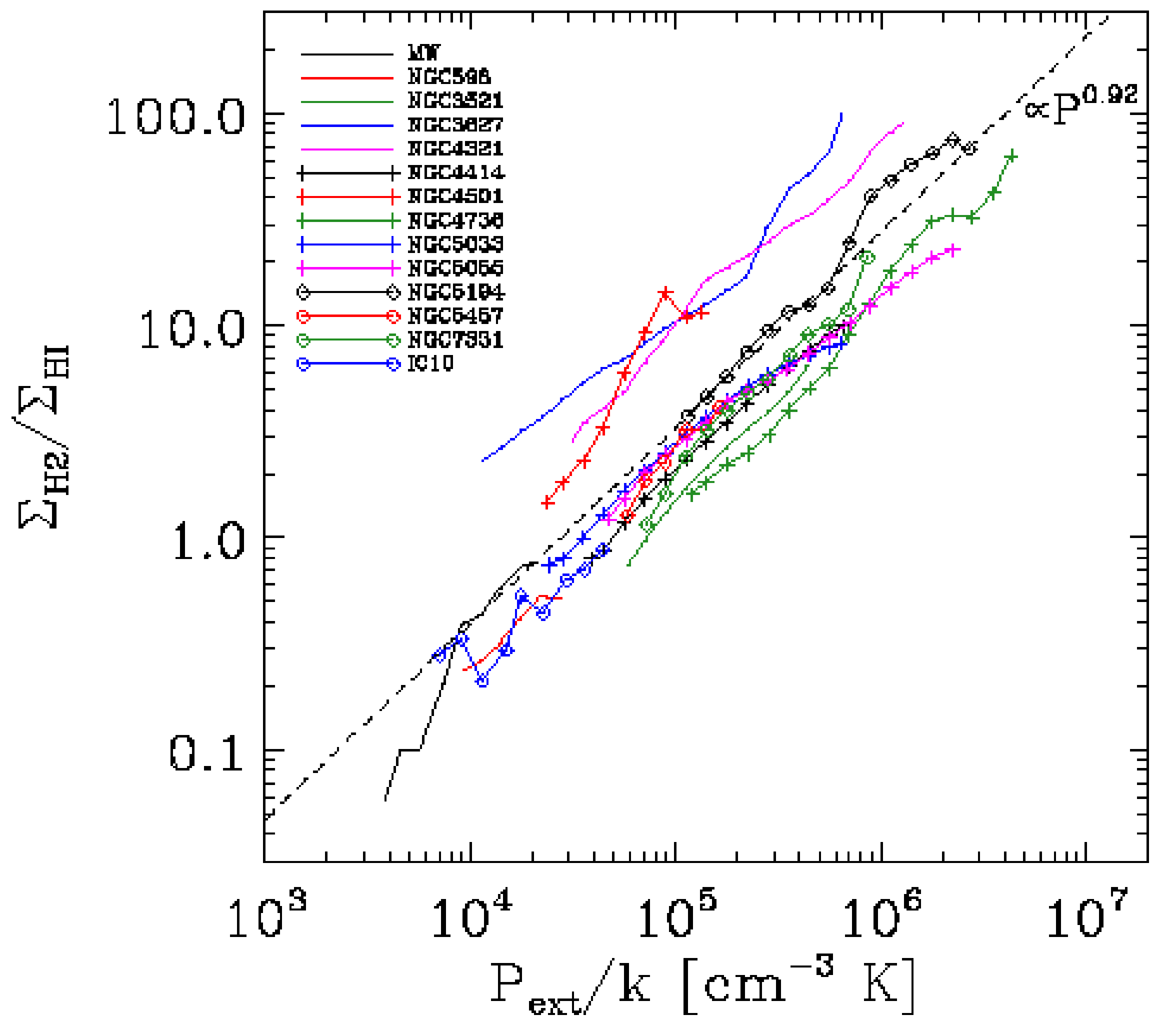
Kennicutt et al. 2007



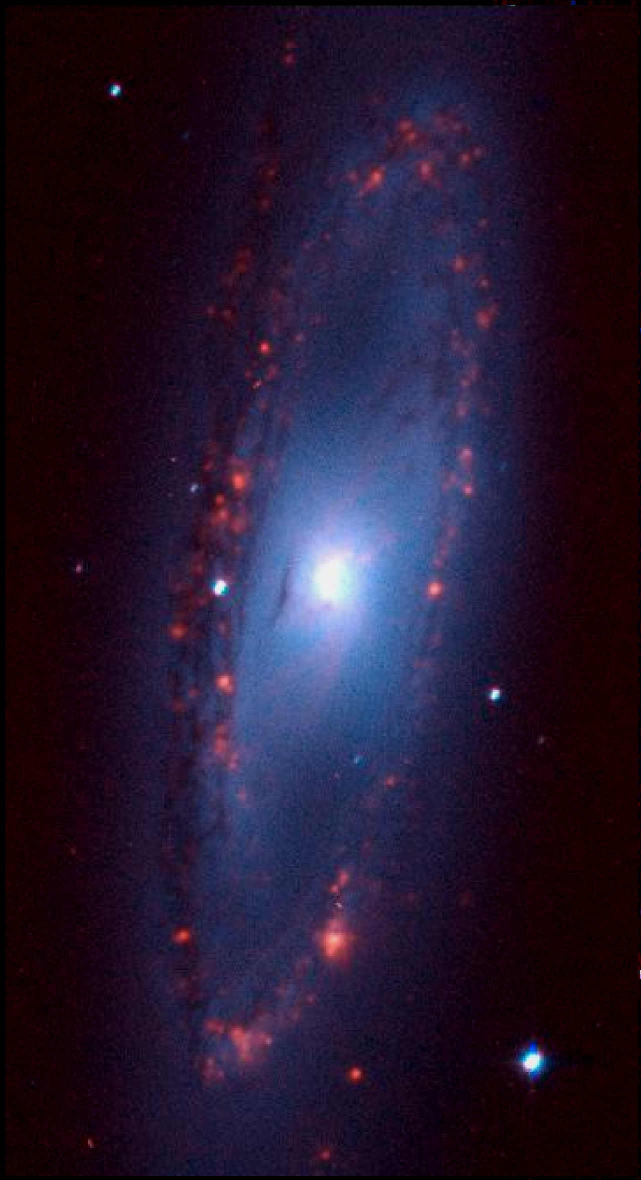


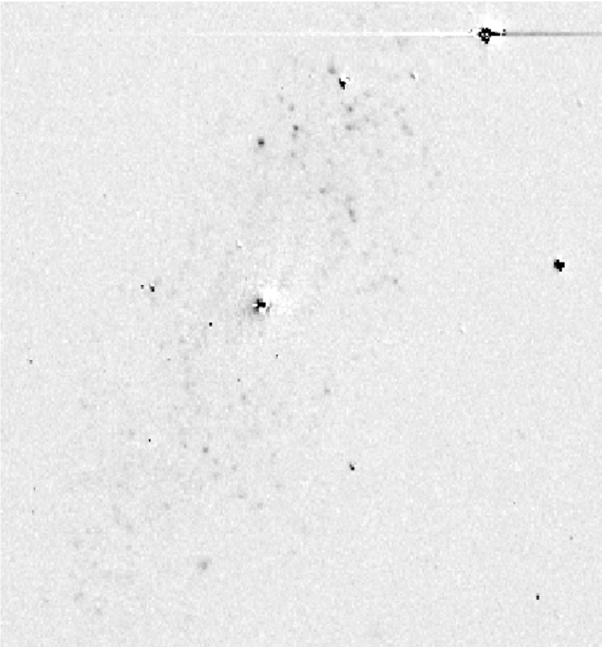
Biegel et al. 2008

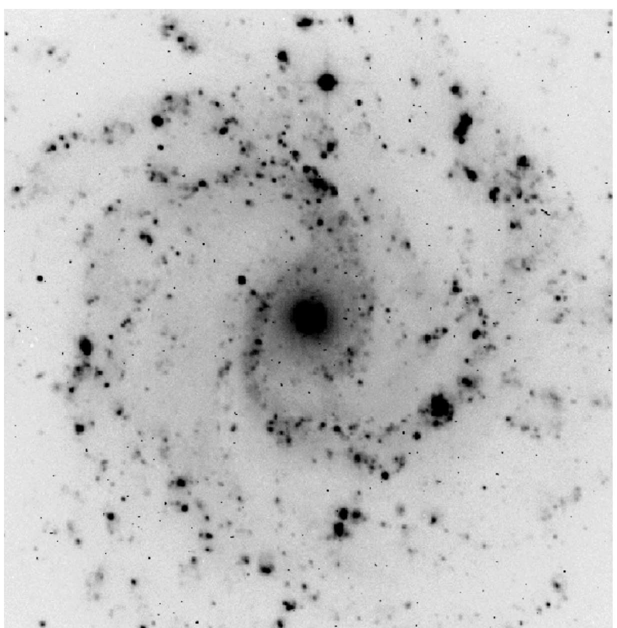
“pressure law”



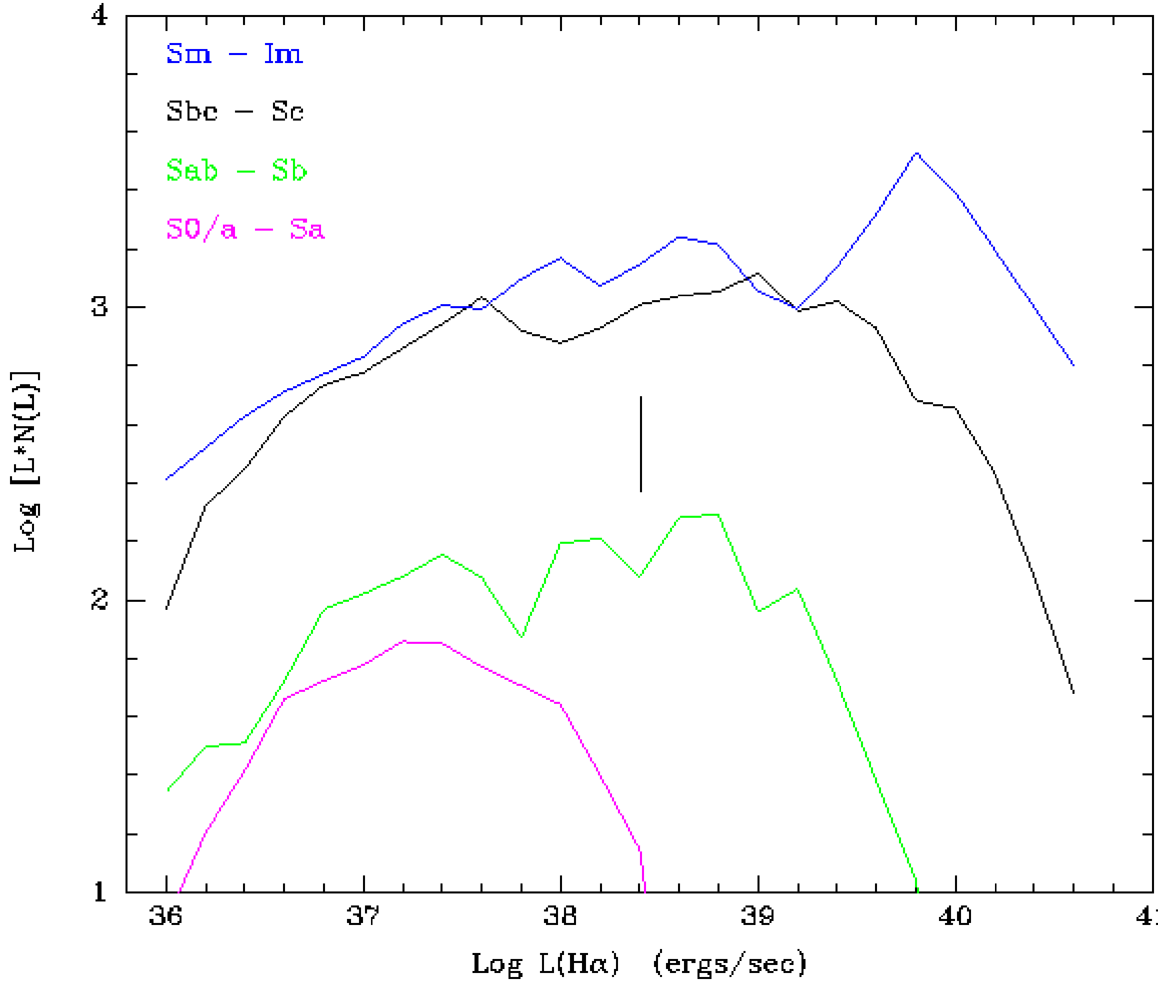
Blitz & Rosolowsky 2006, ApJ, 650, 933

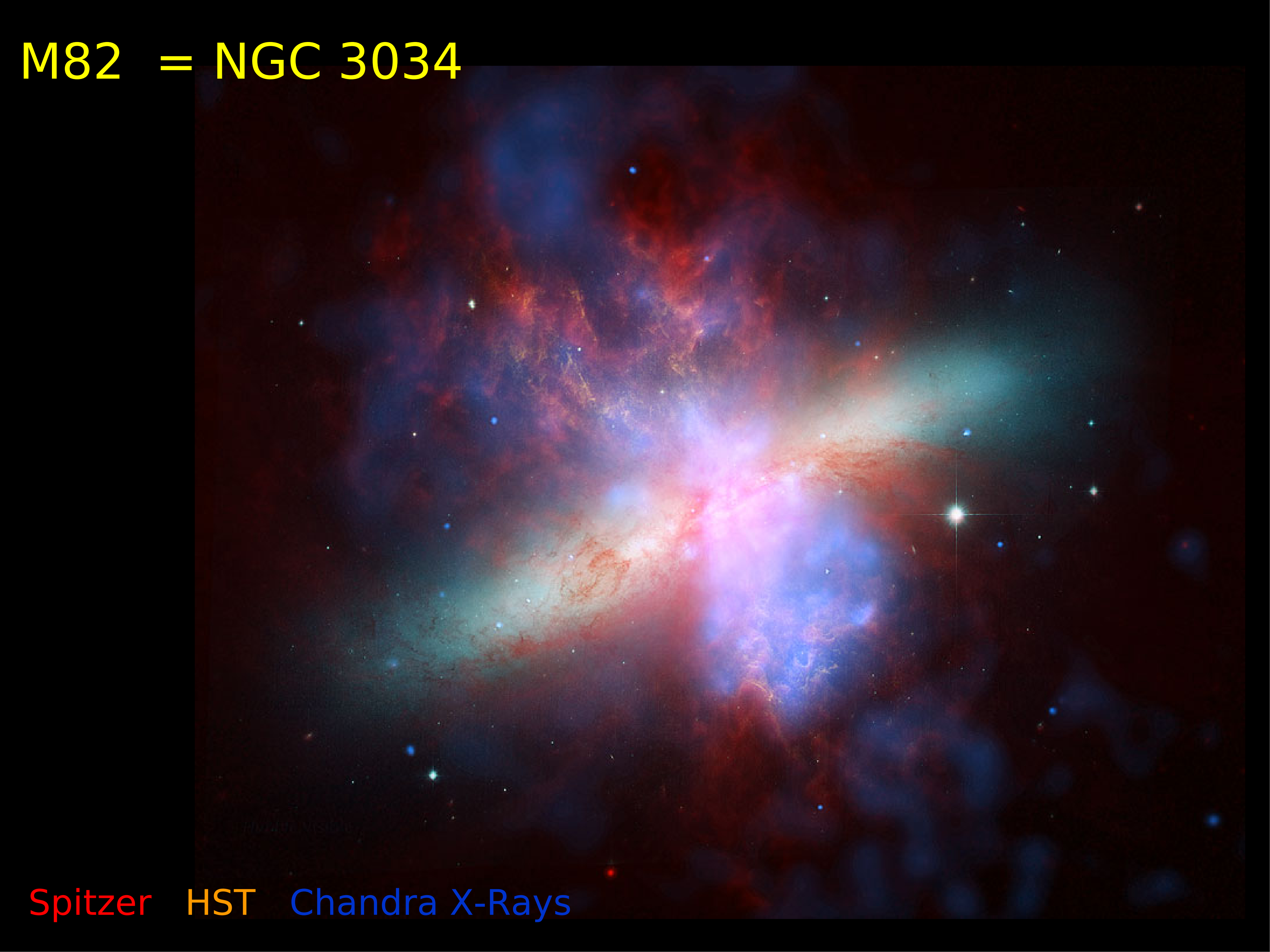




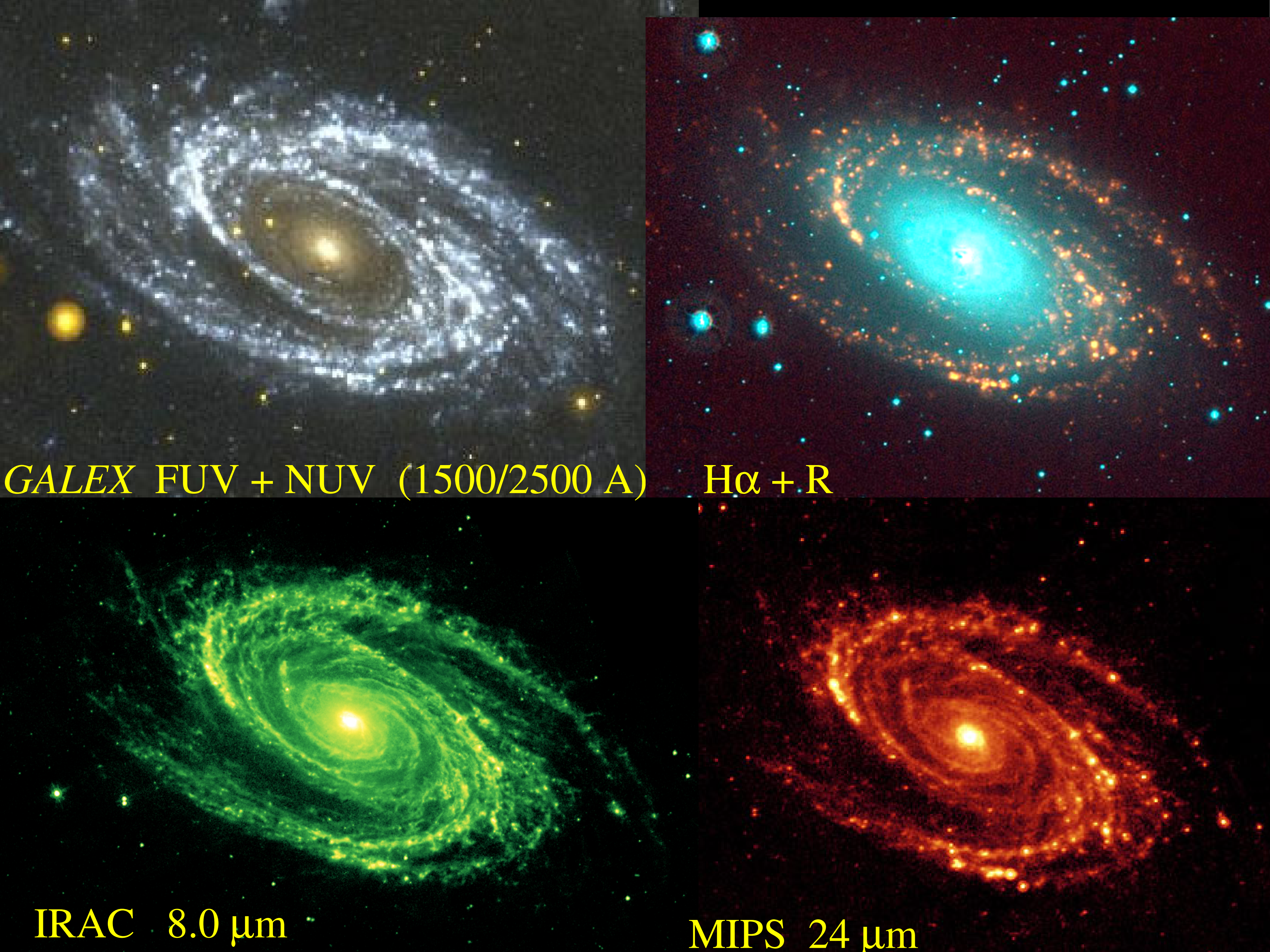
SFR increase reflects an increase in frequency of SF events, <u>and</u> a shift in the mass spectrum of single events



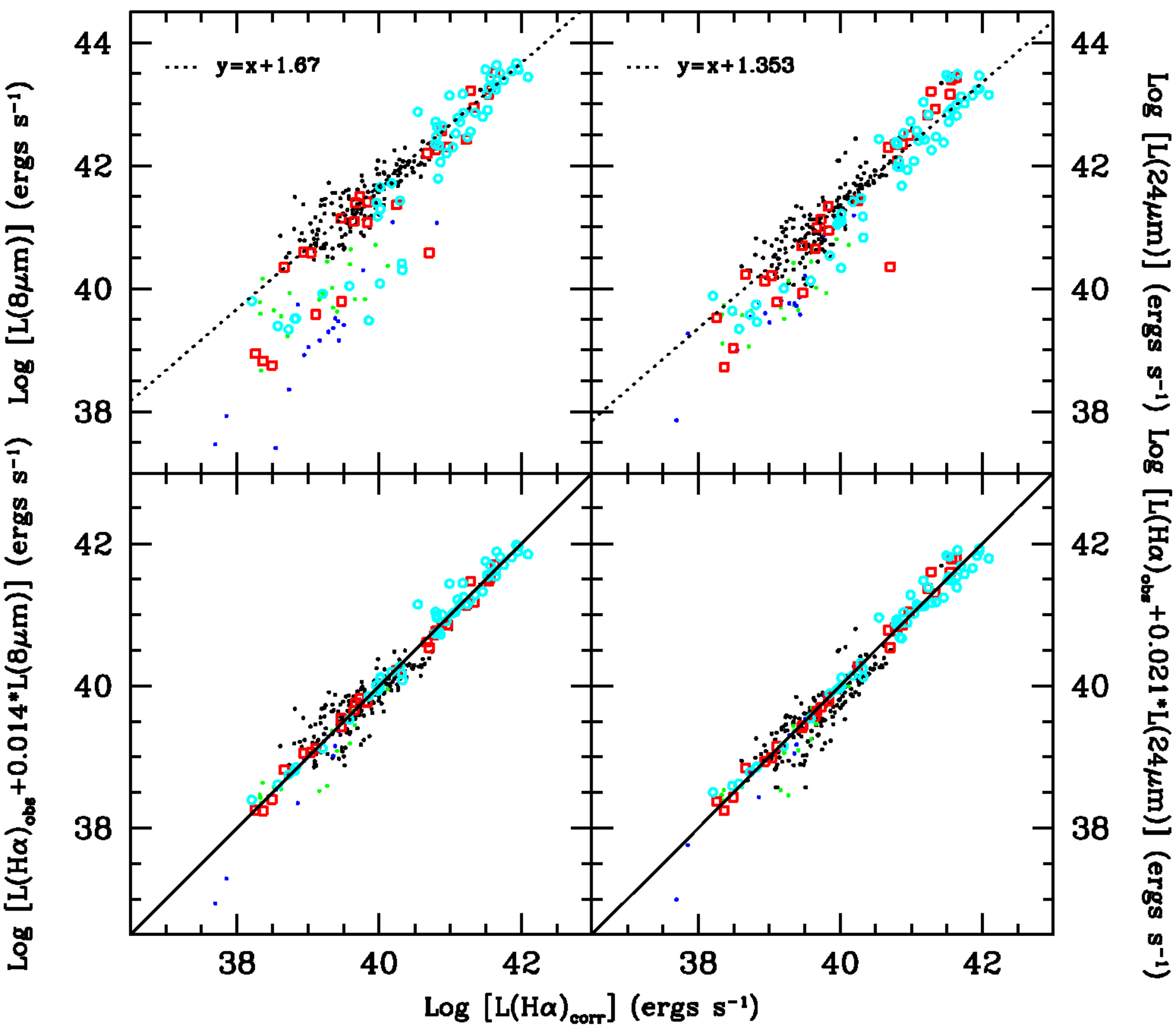

M82 = NGC 3034
Spitzer
HST
Chandra X-Rays

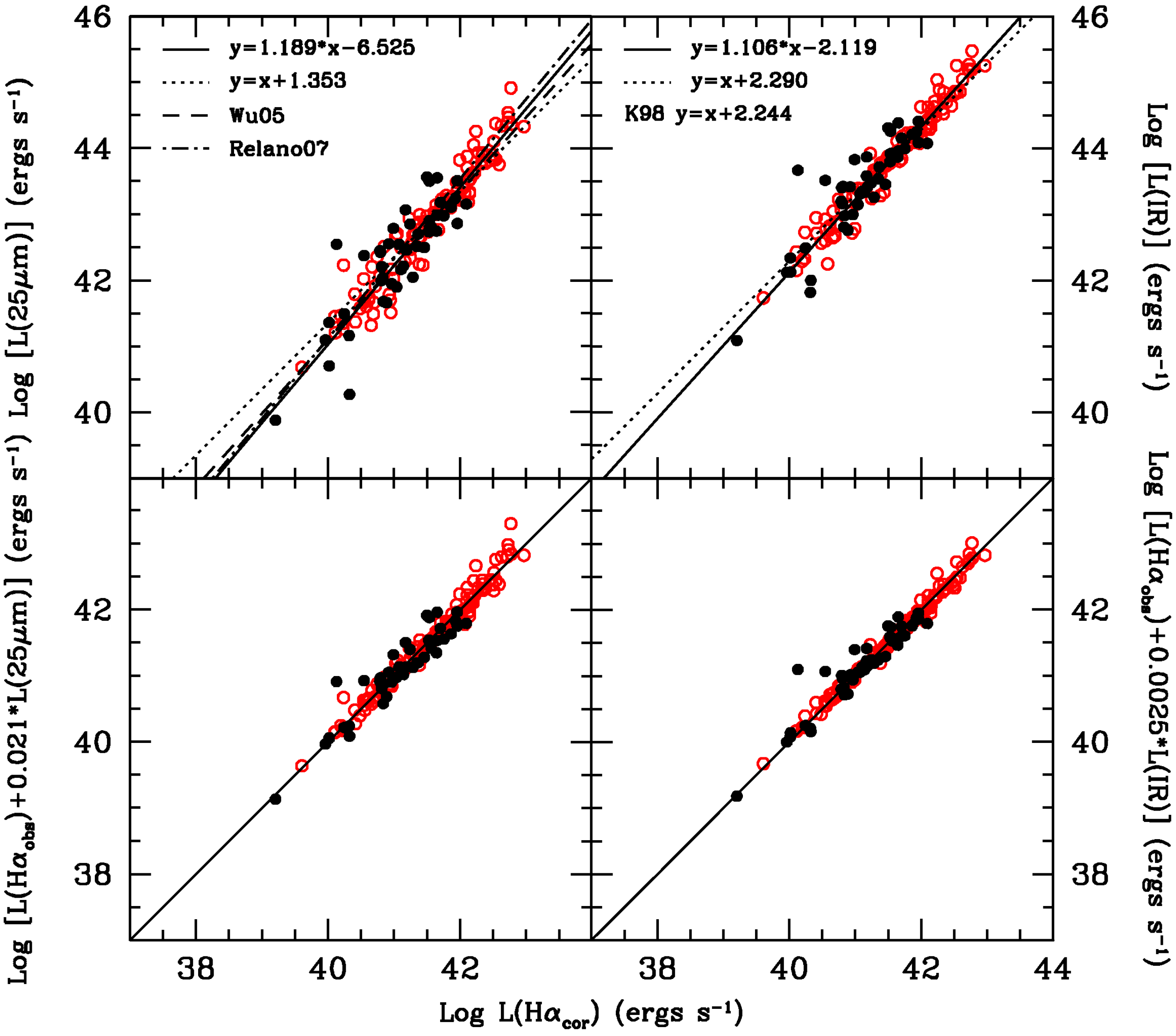
Key Applications (ELT + ALMA)

- Bolometric star formation rates
  - combining [UV, Hα, [OII]] flux with [8μm, 24μm, 70 μm, TIR, 1.4 - 5 GHz] flux of galaxy/knot can provide robust dust-corrected SFRs →
  - mix and match!
- Mate high-resolution imaging of young clusters with ALMA mapping of clouds + environments
  - trace temporal evolution of formation process, feedback
  - possible link of ISM to local ISM environment
  - especially powerful in high surface brightness circumnuclear regions


GALEX FUV + NUV (1500/2500 A)
Hα + R
IRAC 8.0 μm
MIPS 24 μm

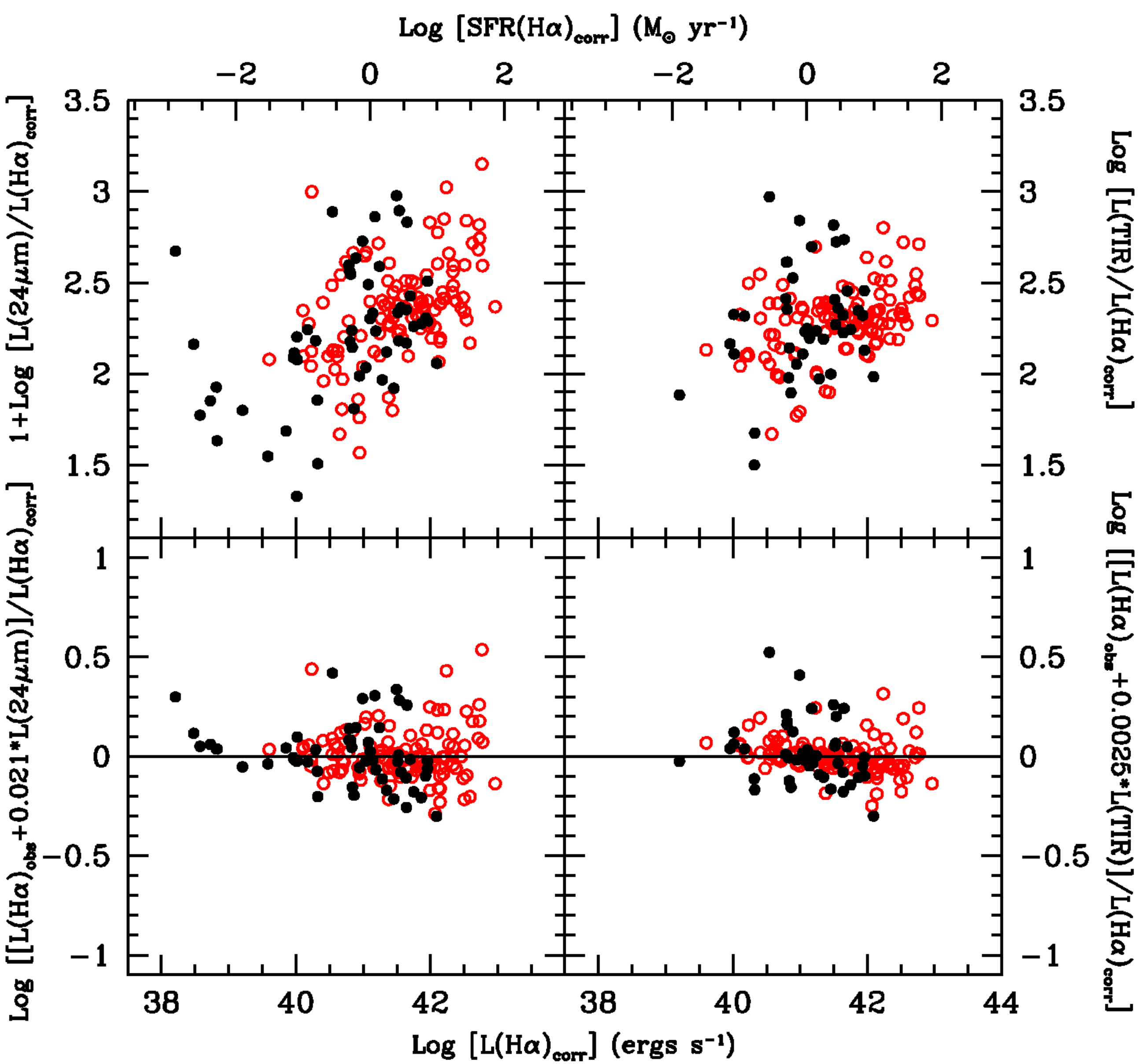
SINGS Sample: 8 μm and 24 μm

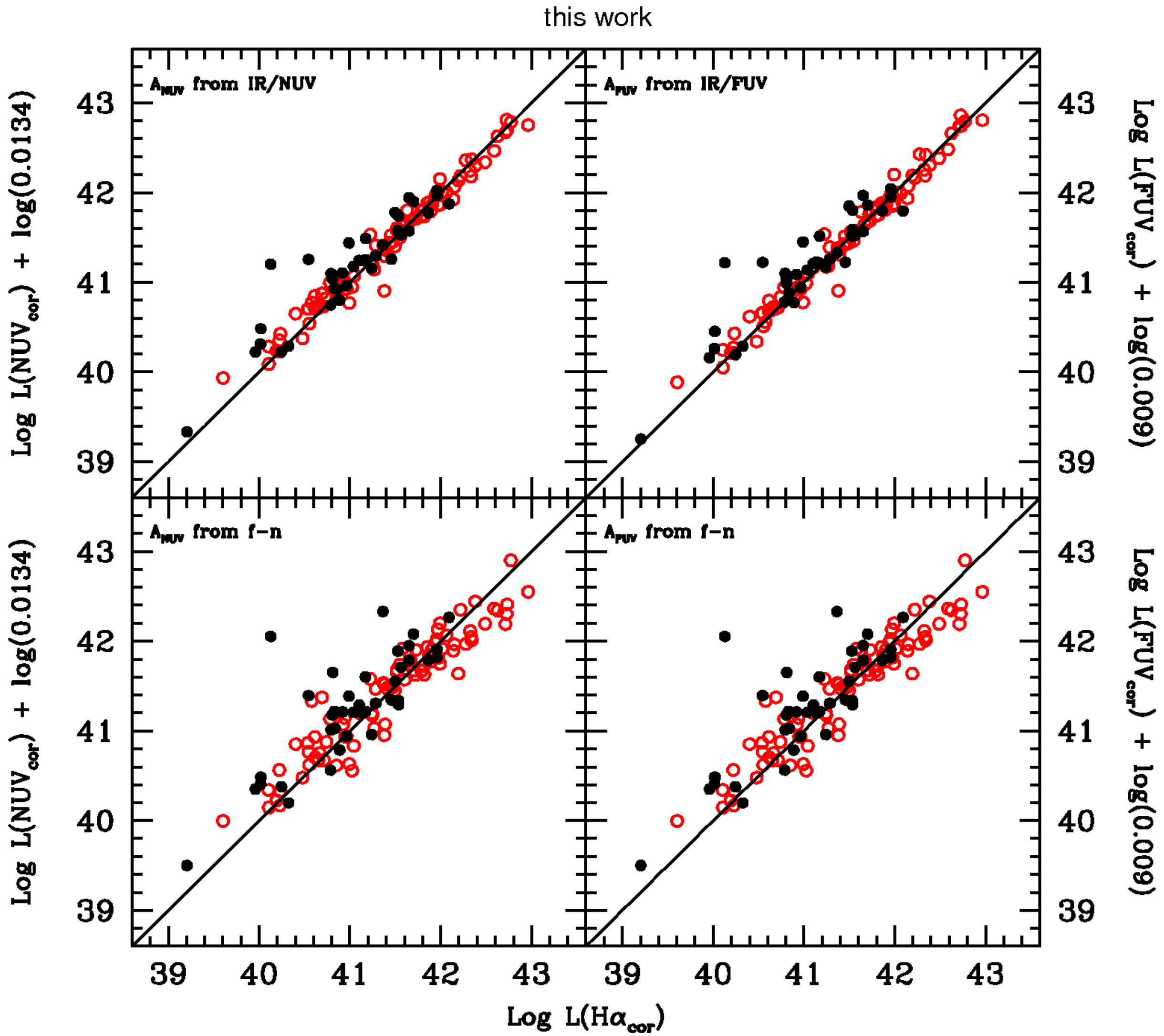




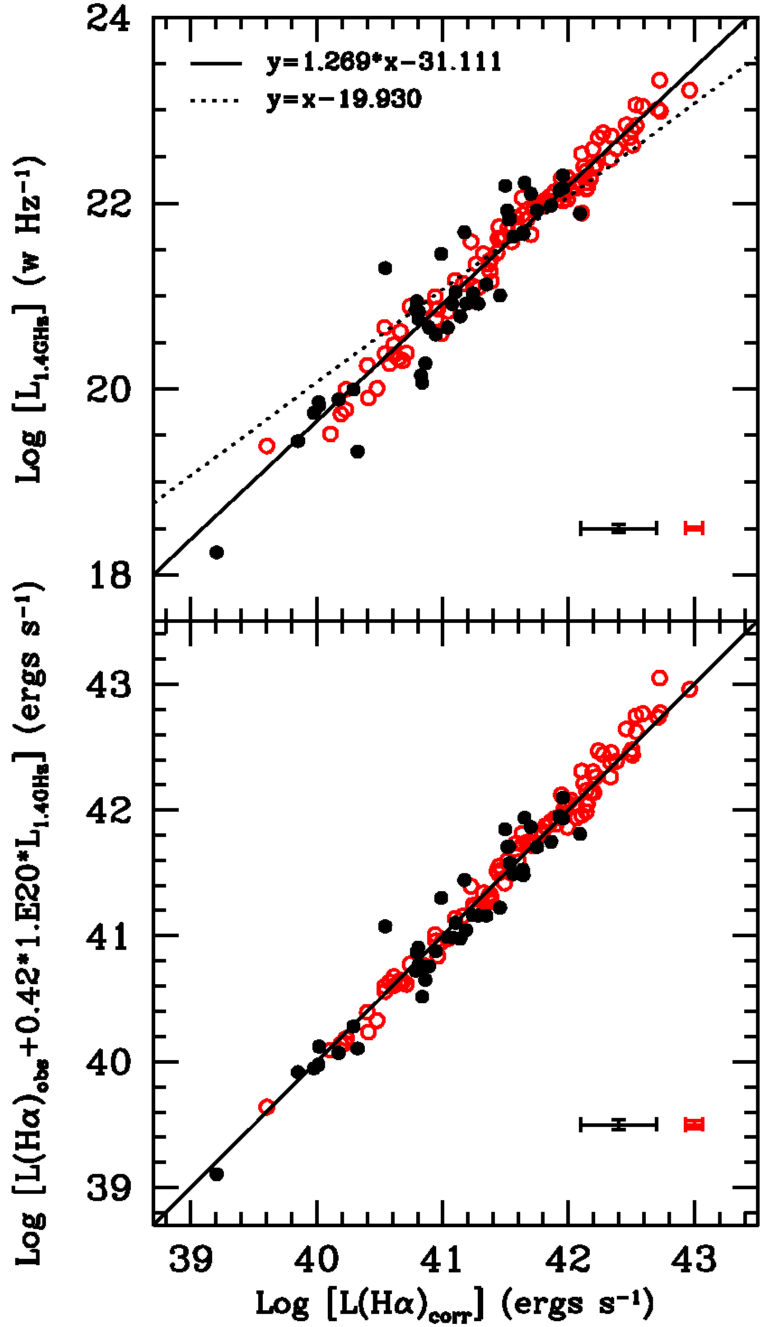
y=1.189*x−6.525
y=x+1.353
Wu05
Relano07
y=1.106*x−2.119
y=x+2.290
K98 y=x+2.244
Log [L(25μm)] (ergs s−1)
Log [L(IR)] (ergs s−1)
Log [L(Hα_obs)+0.021*L(25μm)] (ergs s−1)
Log [L(Hα_obs)+0.0025*L(IR)] (ergs s−1)
Log L(Hα_cor) (ergs s−1)

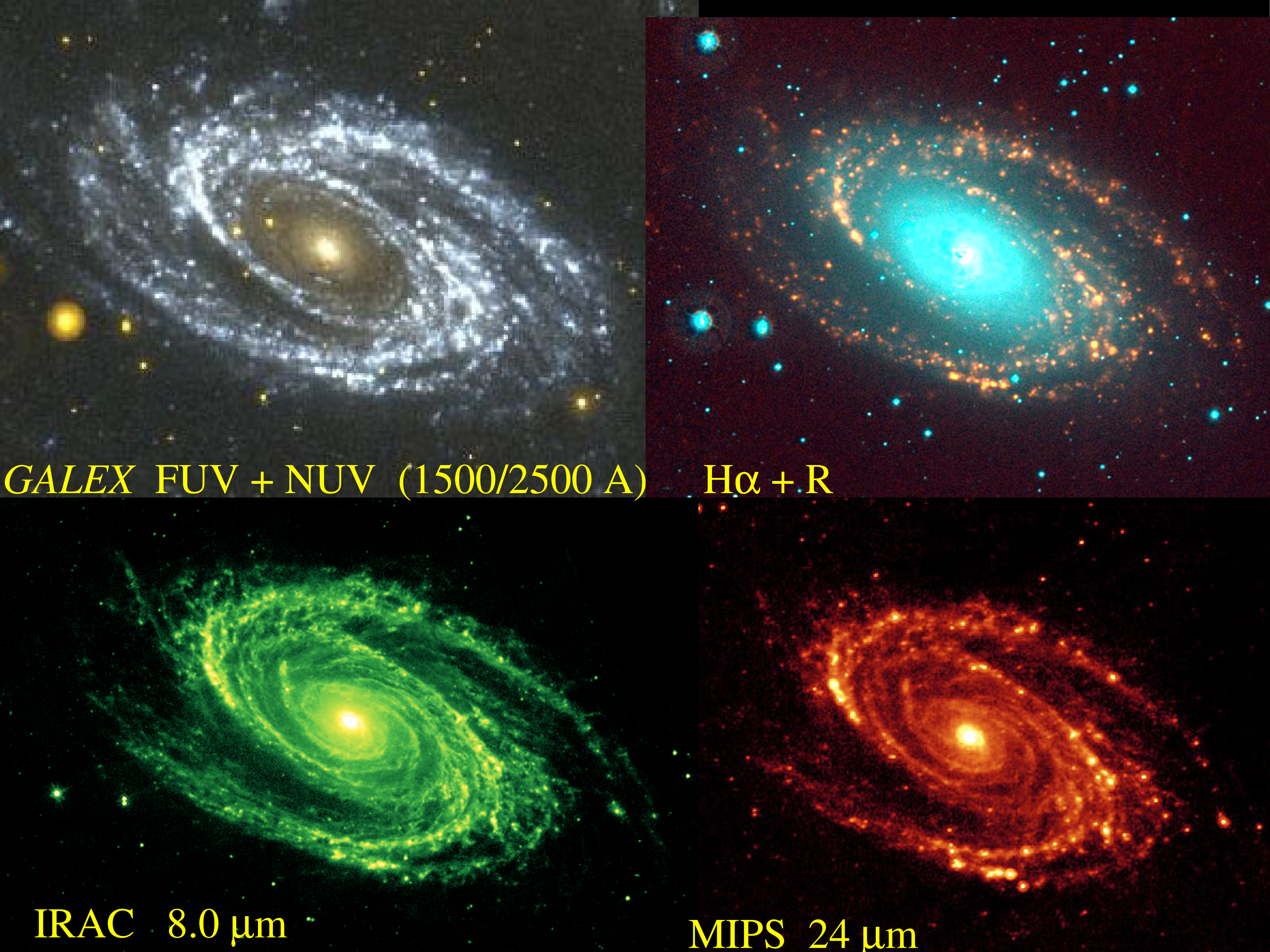
Residuals vs SFR




this work
A_{NUV} from IR/NUV
A_{FUV} from IR/FUV
A_{NUV} from f-n
A_{FUV} from f-n
Log L(NUV_{cor}) + log(0.0134)
Log L(FUV_{cor}) + log(0.009)
Log L($H\alpha_{cor}$)
39
40
41
42
43

Hα + 1.4 GHz Radio





GALEX FUV + NUV (1500/2500 A)
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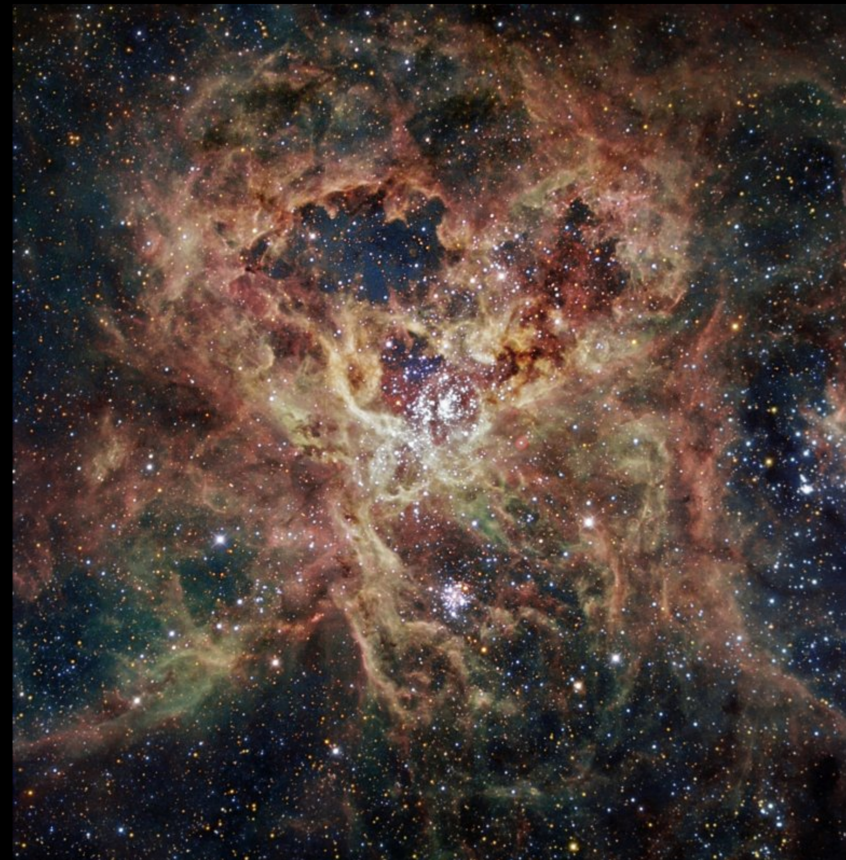
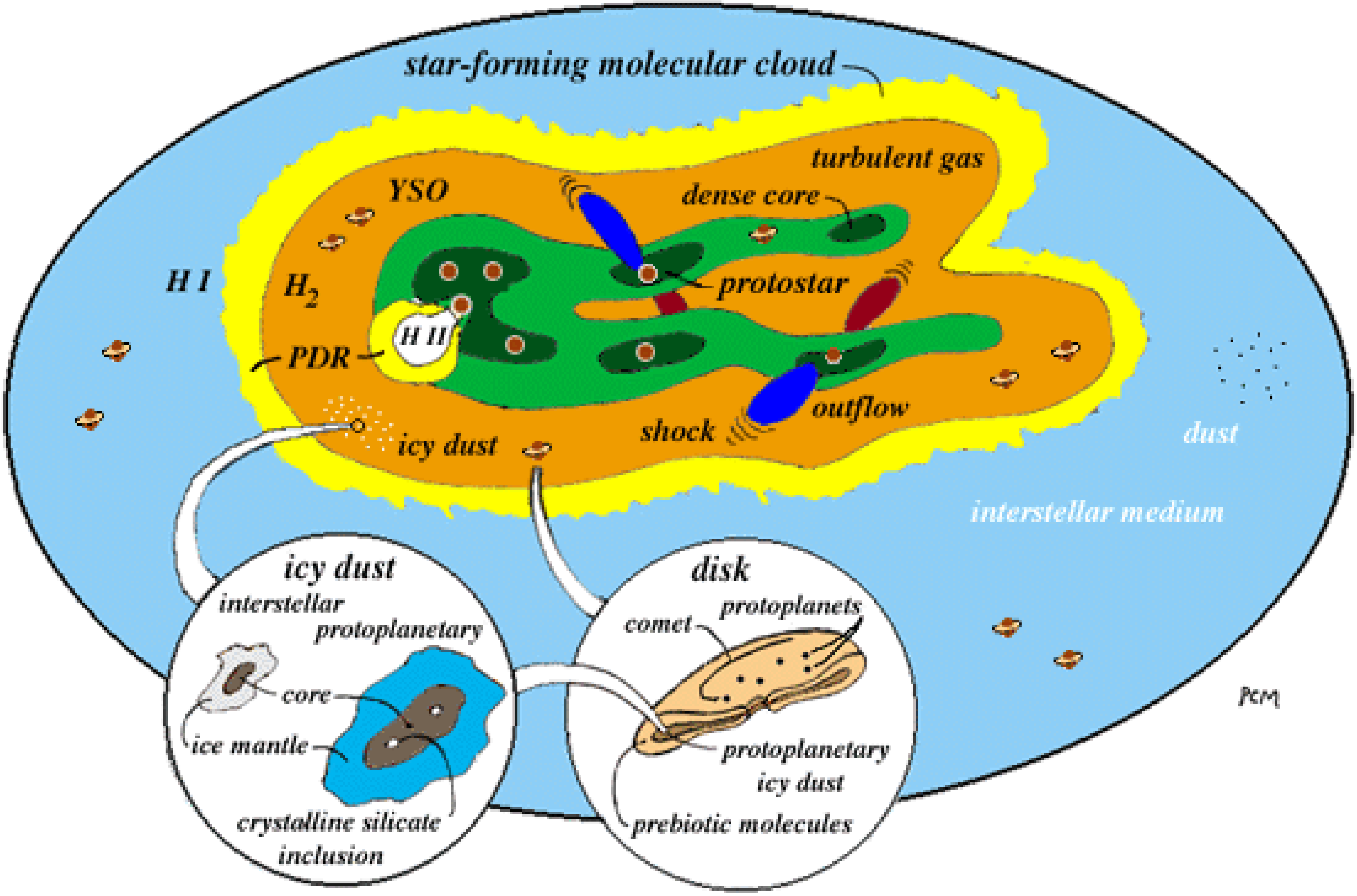
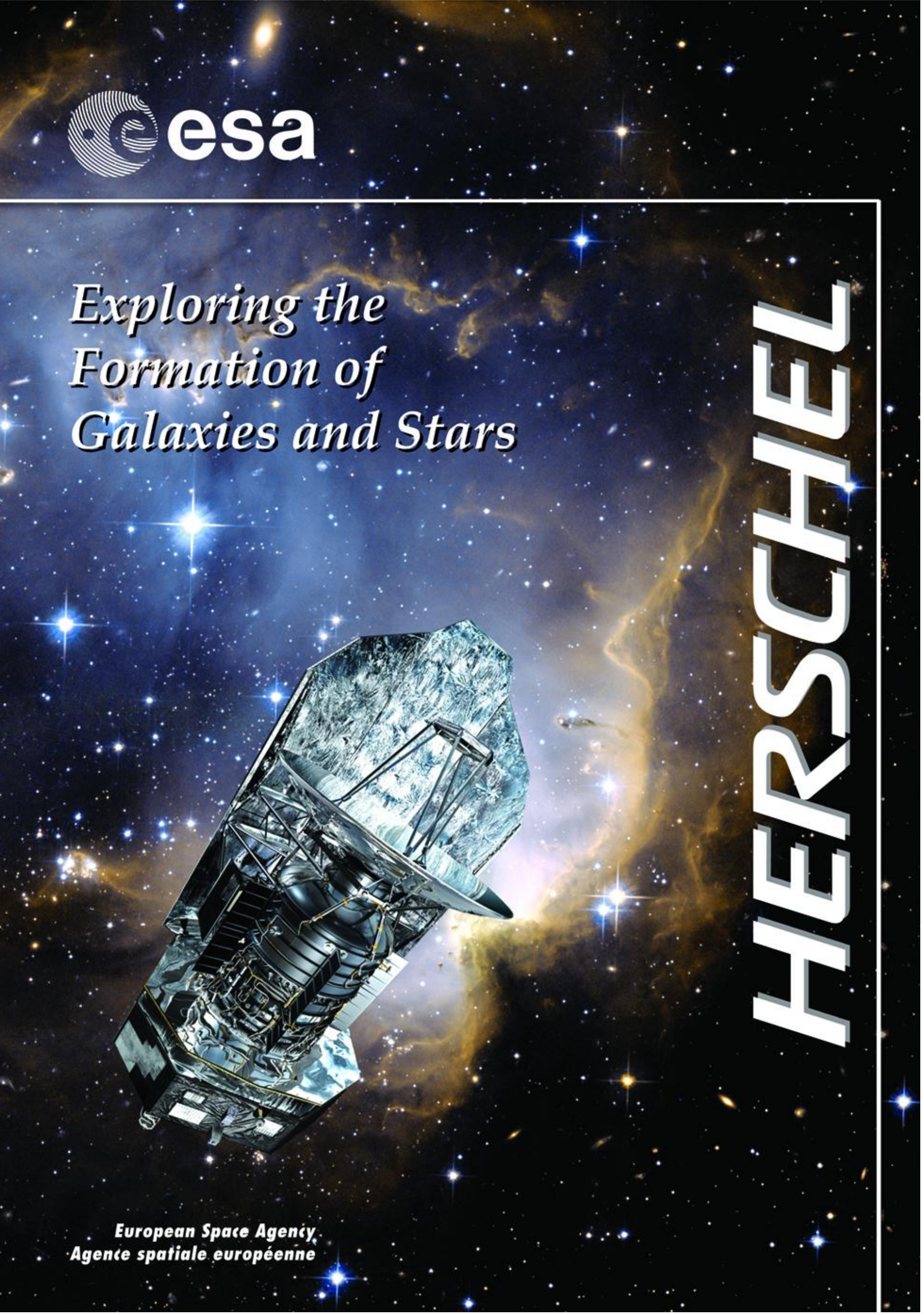


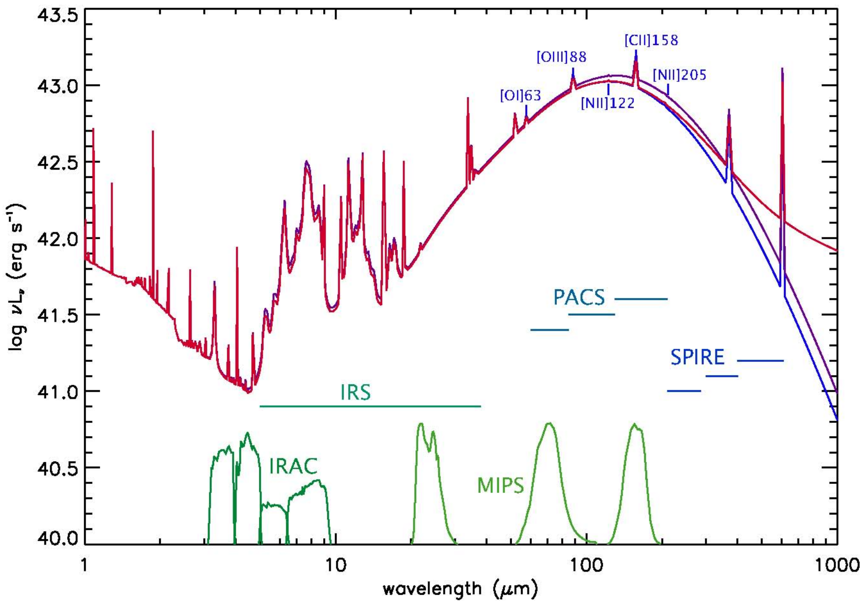
Key Applications (ALMA)

- Subarcsecond mapping of MCs in LMC, SMC
  - continuum, CO, HCN…
  - wide-field mapping (1”) and targeted high-resolution (0”.2)
- In-depth mapping of MCs in nearby galaxies
  - targets from dense circumnuclear regions (e.g., M83, NGC 253, NGC 4945) to quiescent galaxies
  - CO rotational ladder up to 6-5, isotopic transitions, high-density tracers
- MCs in low SFR galaxies (ellipticals, low surface brightness, dwarfs..)
- High-resolution mapping of centres of (U)LIRGs
  - CO mapping of star clusters, e.g., Antennae


star-forming molecular cloud
turbulent gas
YSO
dense core
H I
H_2
protostar
H II
PDR
outflow
shock
icy dust
dust
interstellar medium
icy dust
interstellar
protoplanetary
core
ice mantle
crystalline silicate
inclusion
disk
comet
protoplanets
protoplanetary
icy dust
prebiotic molecules
PCM

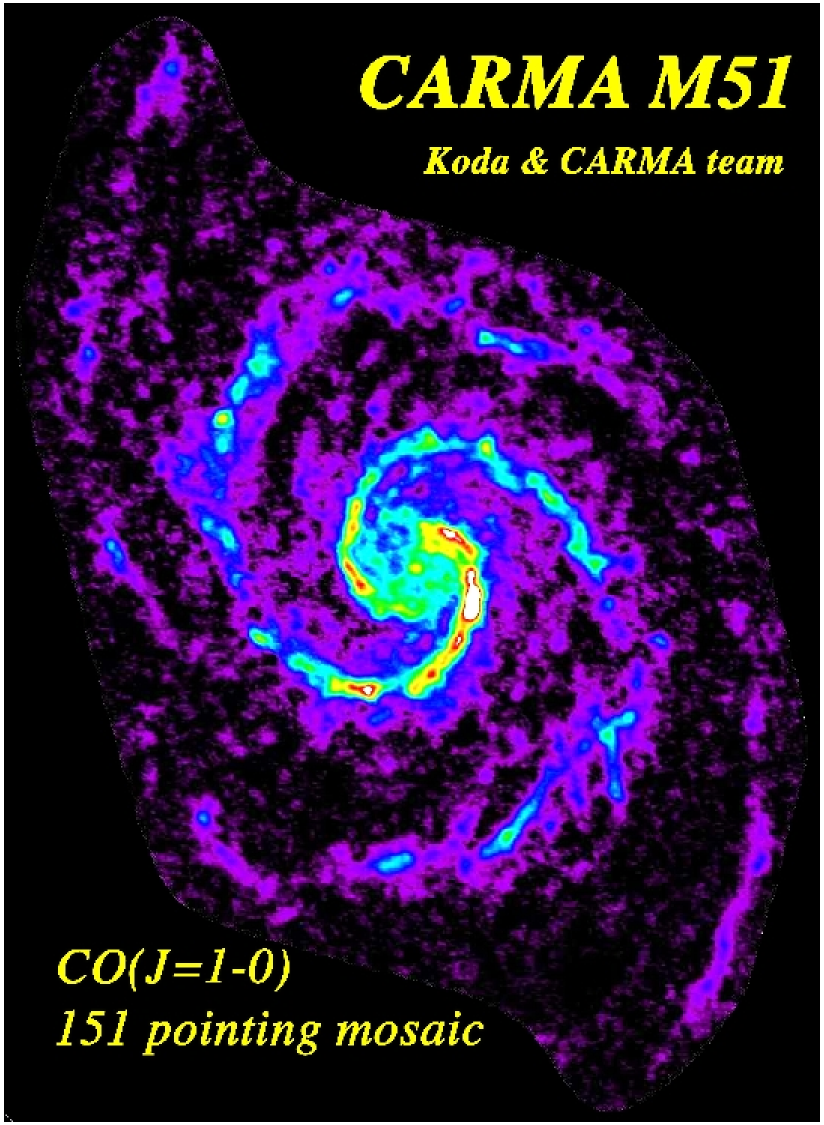


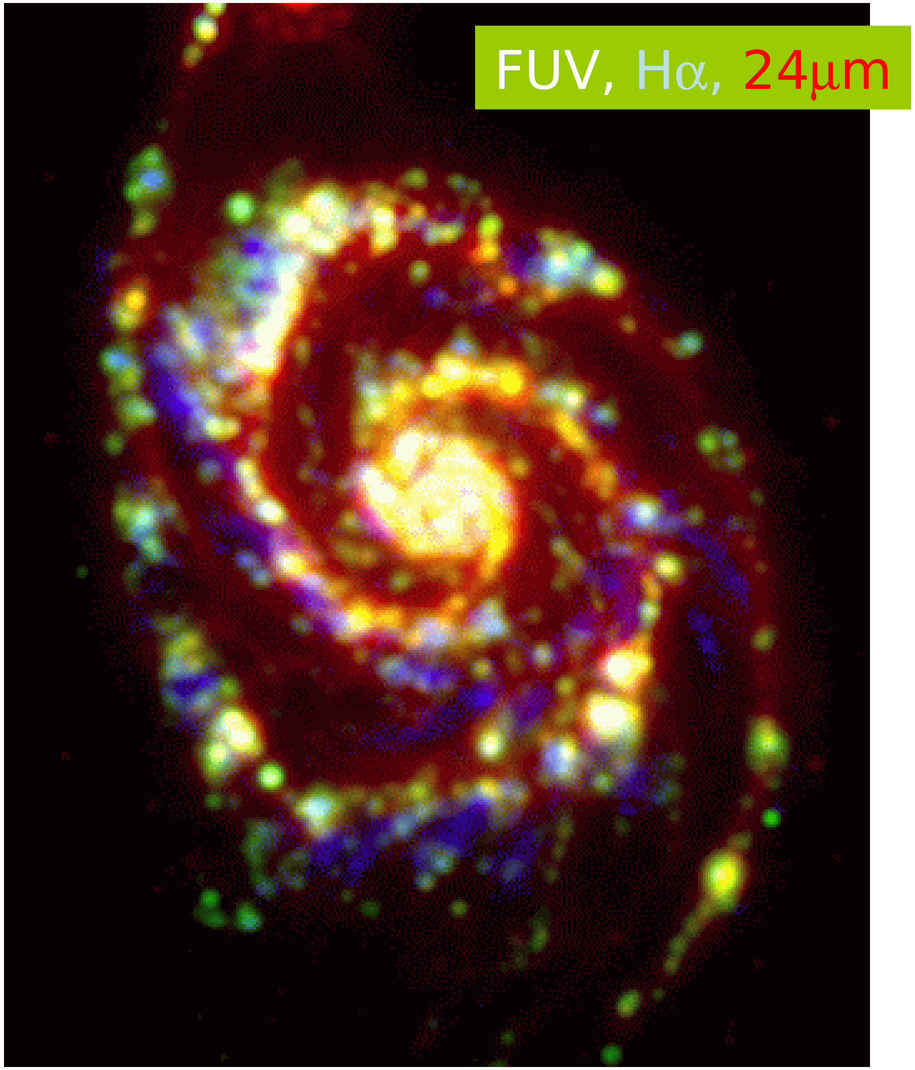
Key Insights on Nearby Galaxies: A Far-Infrared Survey with Herschel (KINGFISH)



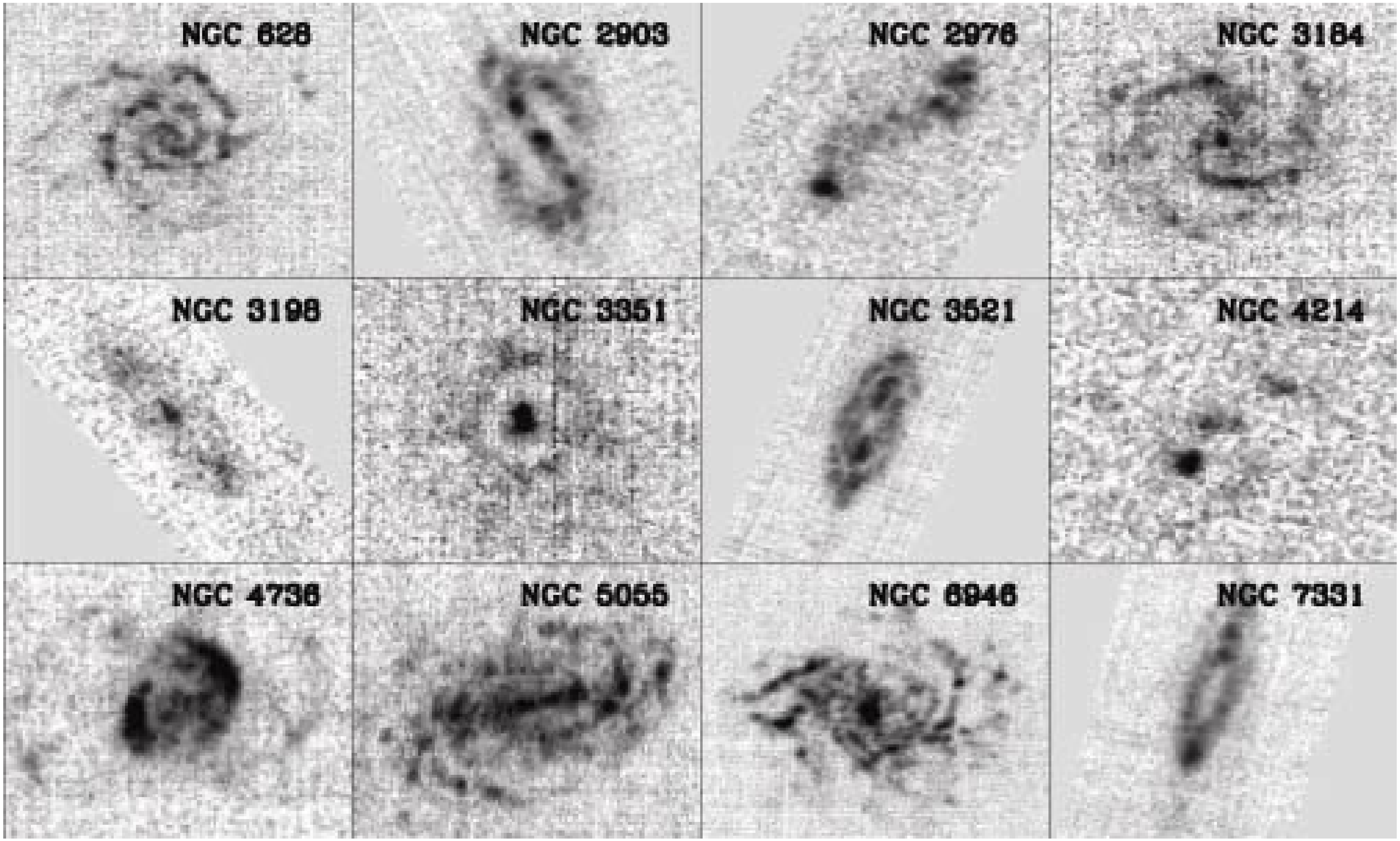
cold molecular gas

star formation

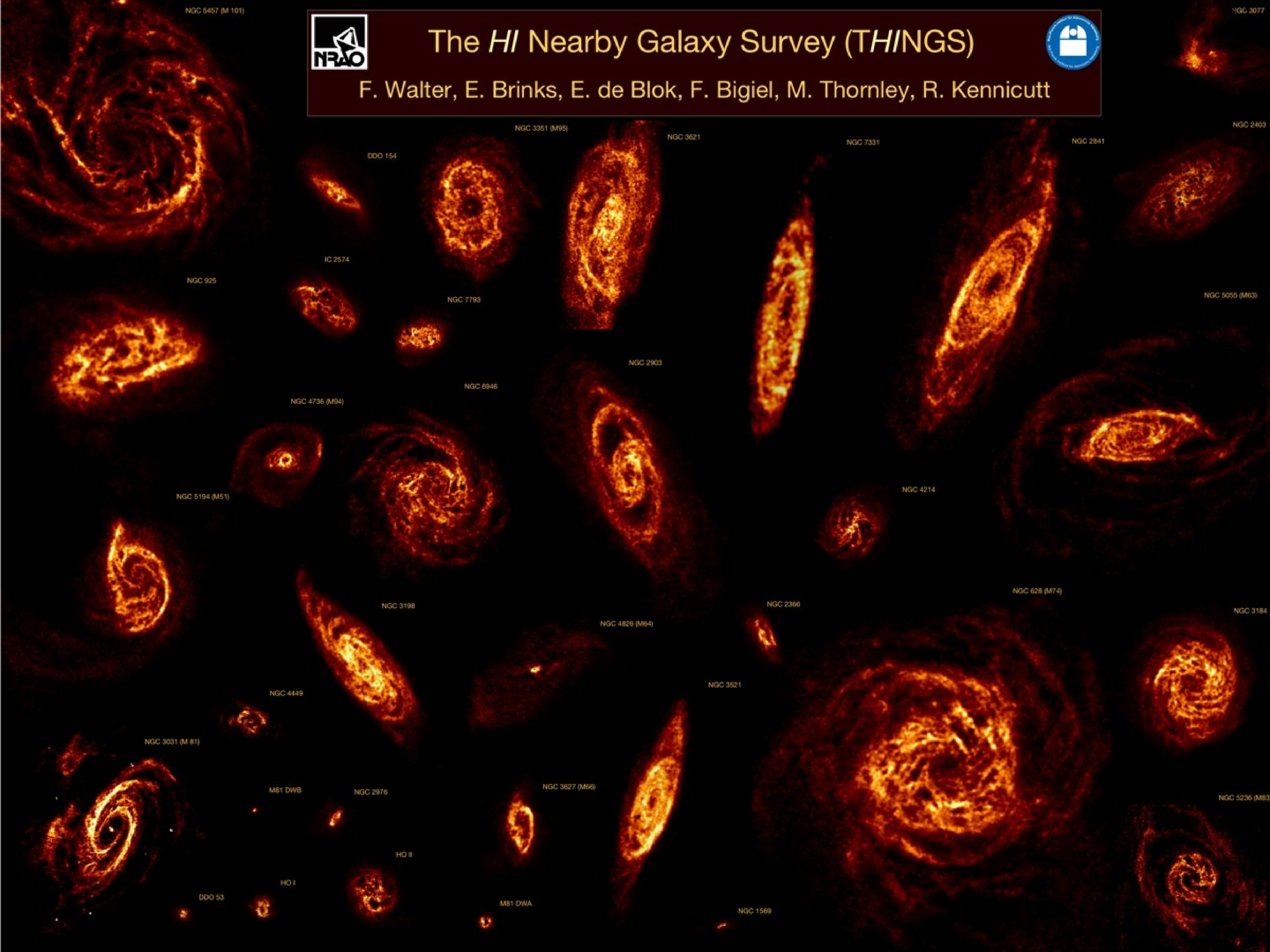




HERACLES CO 2-1 Survey



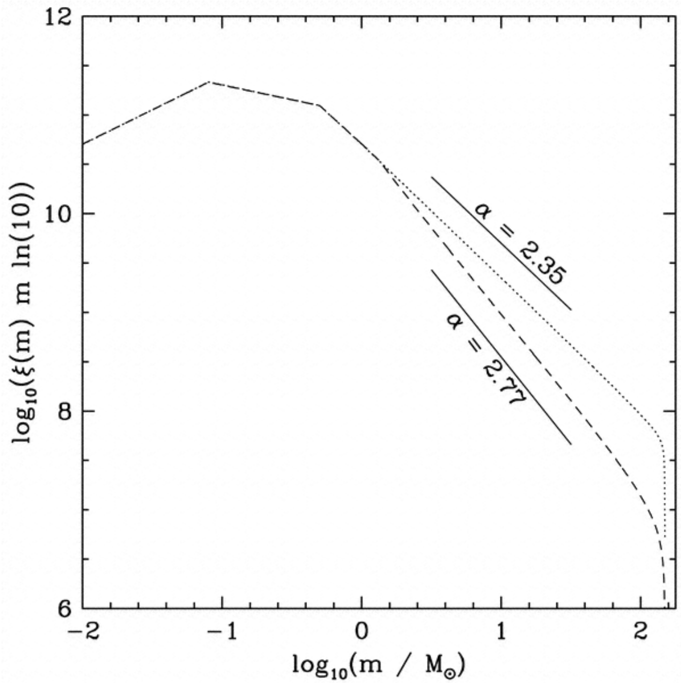
Leroy et al. 2008, submitted to AJ


The *HI* Nearby Galaxy Survey (TH*I*NGS)
F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt
NRAO
NGC 5457 (M 101)
IGC 3077
NGC 3351 (M95)
NGC 3621
NGC 7331
NGC 2841
NGC 2403
DDO 154
IC 2574
NGC 925
NGC 7793
NGC 5055 (M63)
NGC 2903
NGC 6946
NGC 4736 (M94)
NGC 5194 (M51)
NGC 4214
NGC 628 (M74)
NGC 3198
NGC 2366
NGC 3184
NGC 4826 (M64)
NGC 3521
NGC 4449
NGC 3031 (M 81)
M81 DWB
NGC 2976
NGC 3627 (M66)
NGC 5236 (M83
HO II
HO I
DDO 53
M81 DWA
NGC 1569

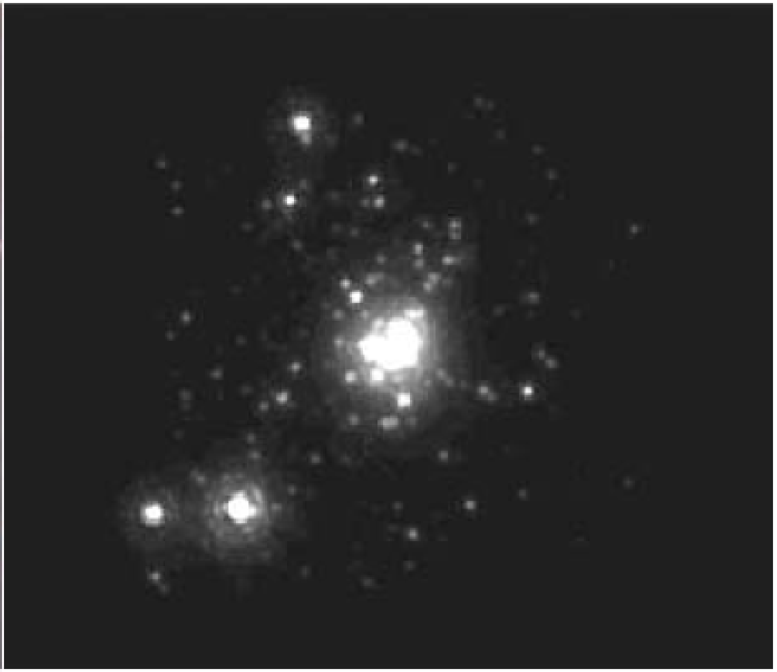
Key Applications (ELT)

- Deep IR imaging of star clusters
  - photometry down to H burning limit
  - trace IMF across full range of physical environments
- Star formation in the environment of black holes
  - circumnuclear star clusters
- Key parallel studies
  - resolved SF histories of nearby galaxies
  - chemical evolution studies (all redshifts)
  - stellar structure/evolution, esp. binaries
  - statistics and spectra of supernovae, GRB afterglows

Kroupa & Weidner 2003



GMT Science Case



General Observations

- High impact will come from fundamentals
  - IMF, extinction, CO/H_2, ISM structure, stellar physics
  - “systems” approach to optimising use of observing time?
  - critical path to full understanding may lead to 21 cm
- ALMA/ELTs will straddle boundaries of Galactic and extragalactic star formation
  - will cultures and approaches meet at last?
  - abolish/adjust traditional segregation in time allocation?
- Other instrumental synergies are critical for planning (JWST, EVLA, VLT/PdB/CARMA/LMT generation of instruments)