E-ELT Science
Star Formation in the Local Volume

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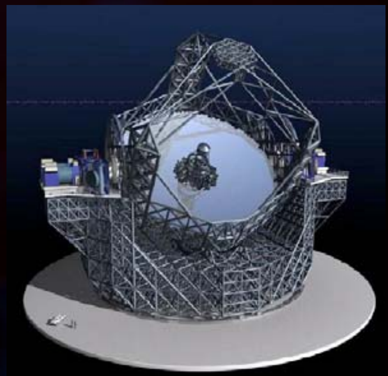
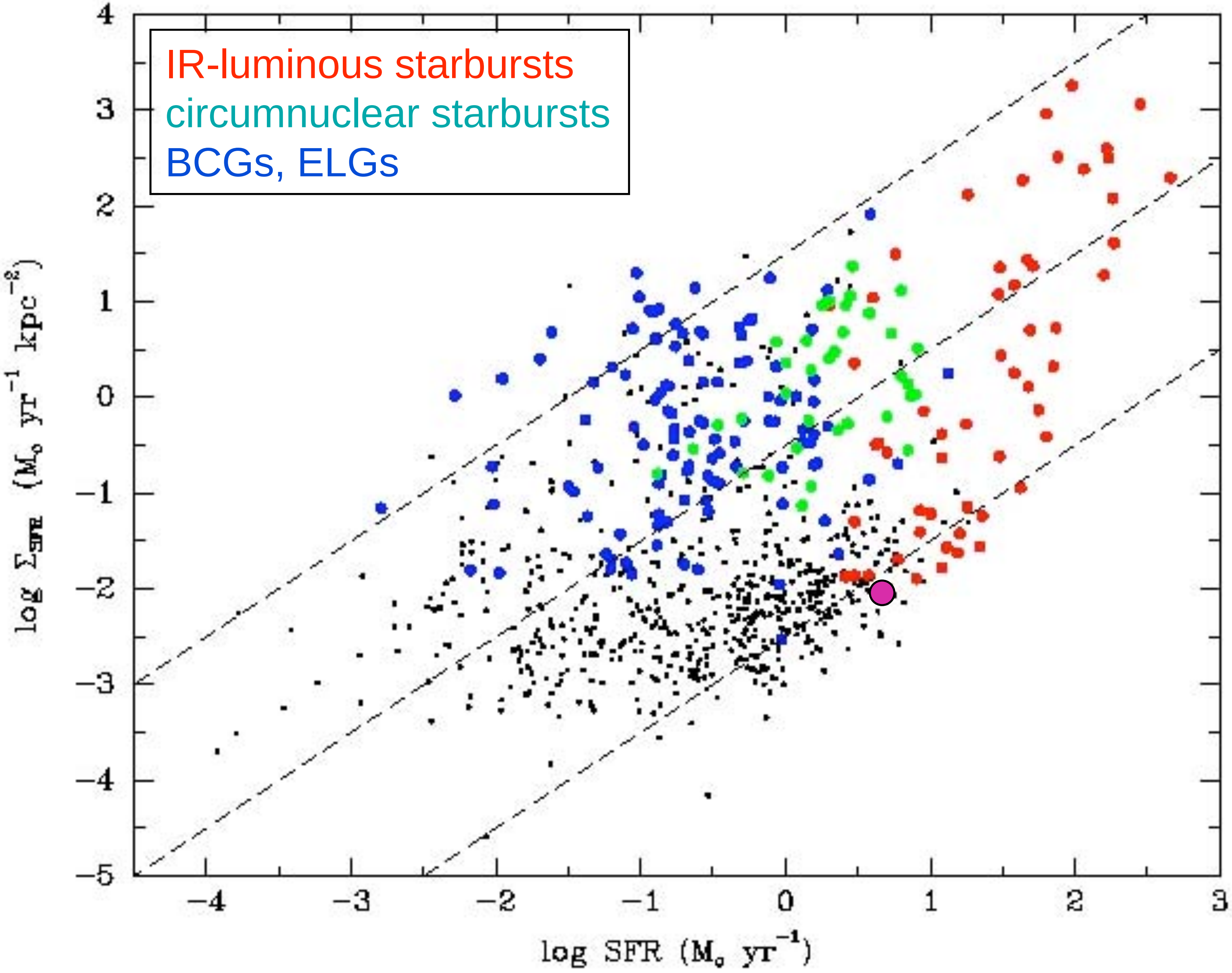


Outline

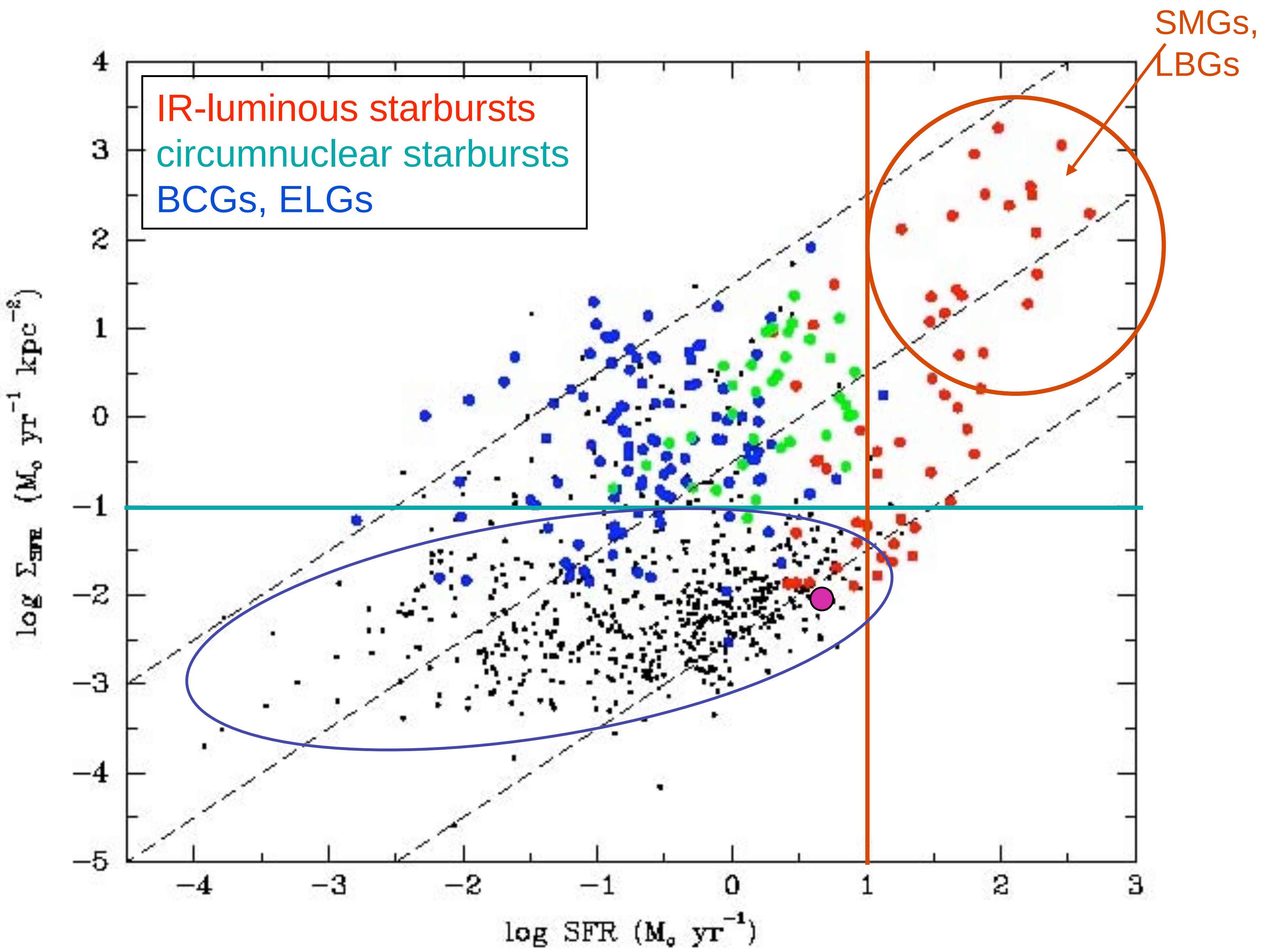
- Scientific context
- Key issues, problems
- Role of the E-ELT
- Questions and General Thoughts

Star Formation in Nearby Galaxies

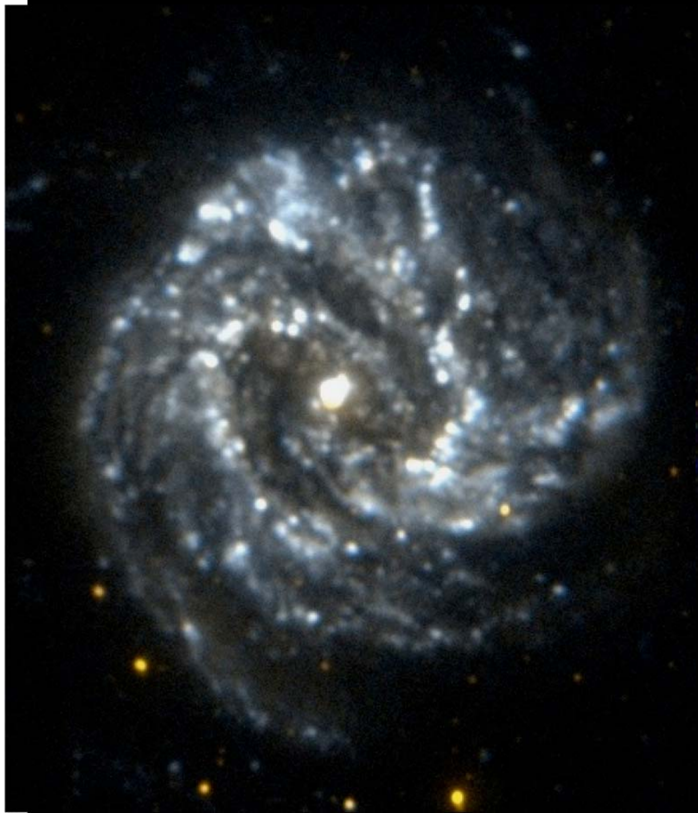
- Extend understanding of Galactic SF to larger scales, over a (much!) wider range of galactic environments
- On the critical path for understanding galaxy formation and evolution generally
- Address severe biases in lookback observations
  - galaxy mass, surface brightenss bias
  - stellar mass bias

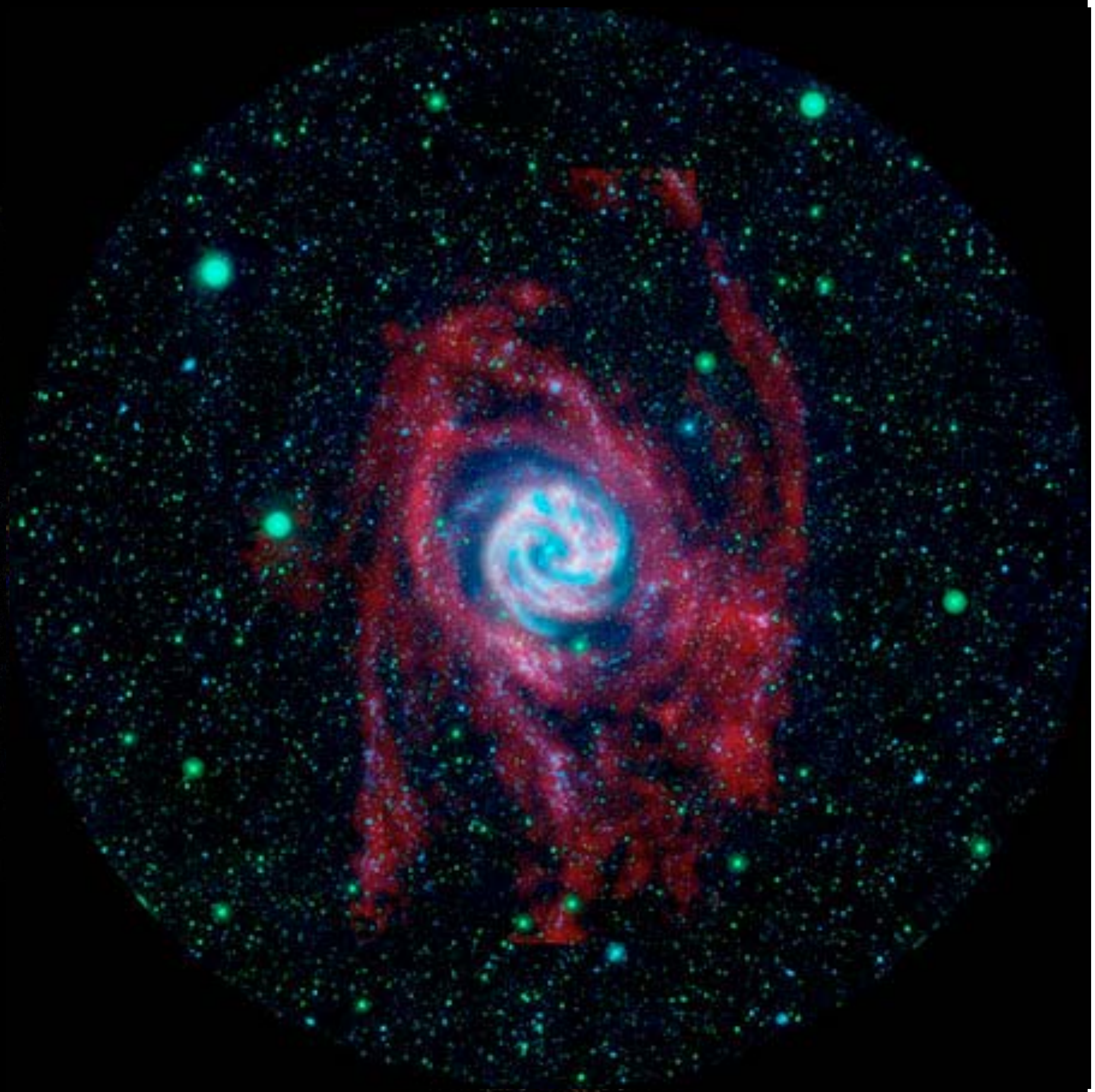


IR-luminous starbursts
circumnuclear starbursts
BCGs, ELGs
log Σ_SFR (M_o yr^-1 kpc^-2)
log SFR (M_o yr^-1)
4
3
2
1
0
−1
−2
−3
−4
−5
−4
−3
−2
−1
0
1
2
3


SMGs, LBGs
IR-luminous starbursts
circumnuclear starbursts
BCGs, ELGs
log SFR ($M_\odot$ yr^{-1})
log Σ_{SFR} ($M_\odot$ yr^{-1} kpc^{-2})
−4
−3
−2
−1
0
1
2
3
4
−5

"XUV Discs"

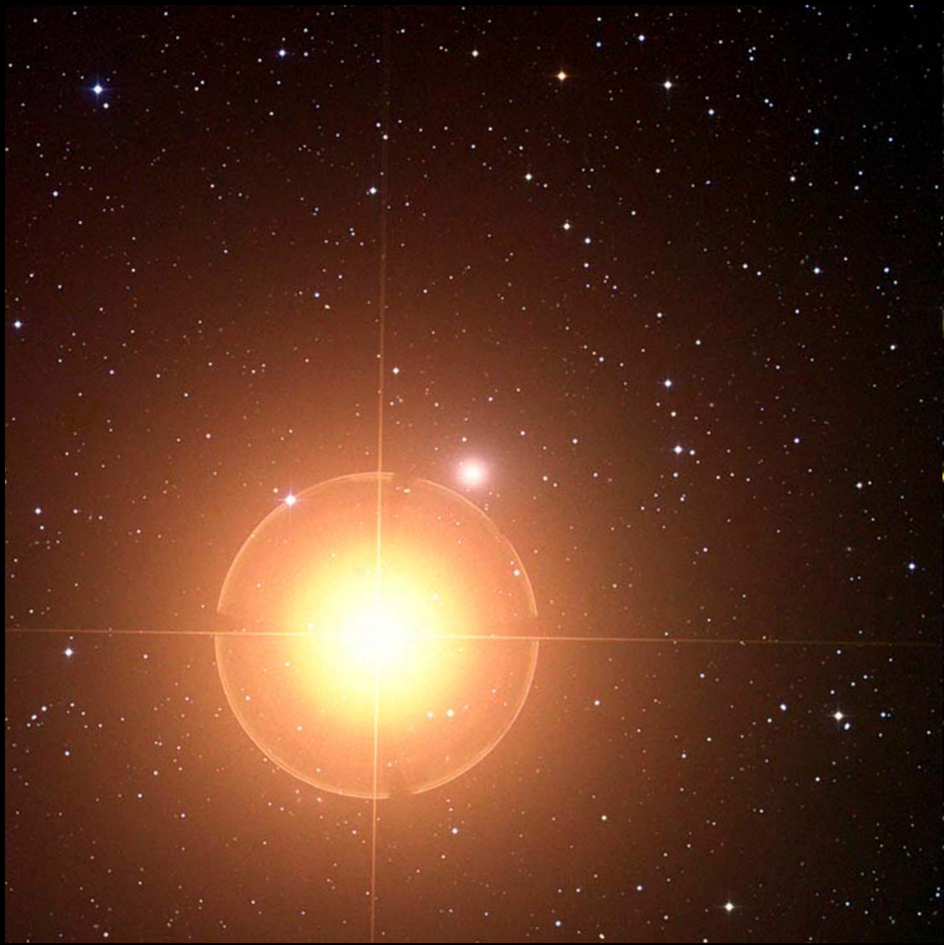




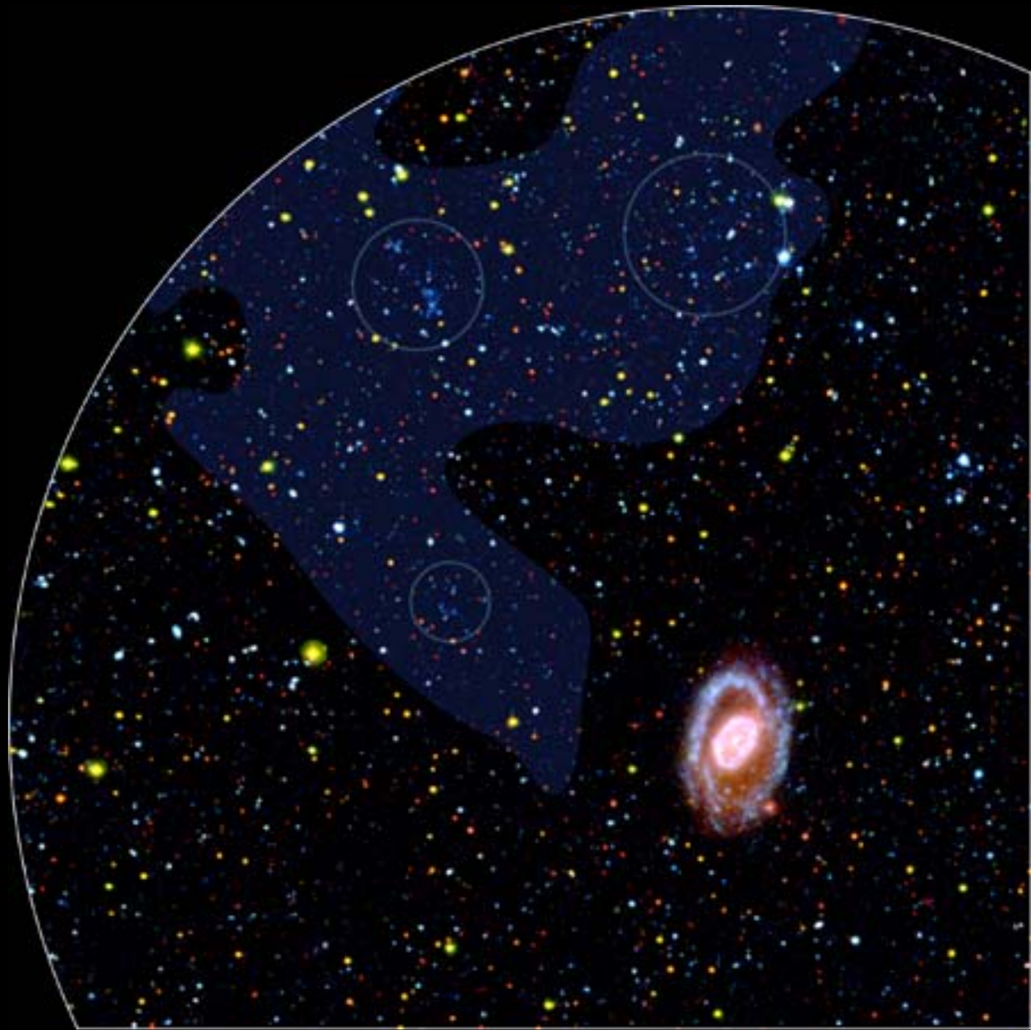
M83 = NGC 5236

GALEX FUV/NUV + VLA HI

star formation in NGC 404 (GALEX)

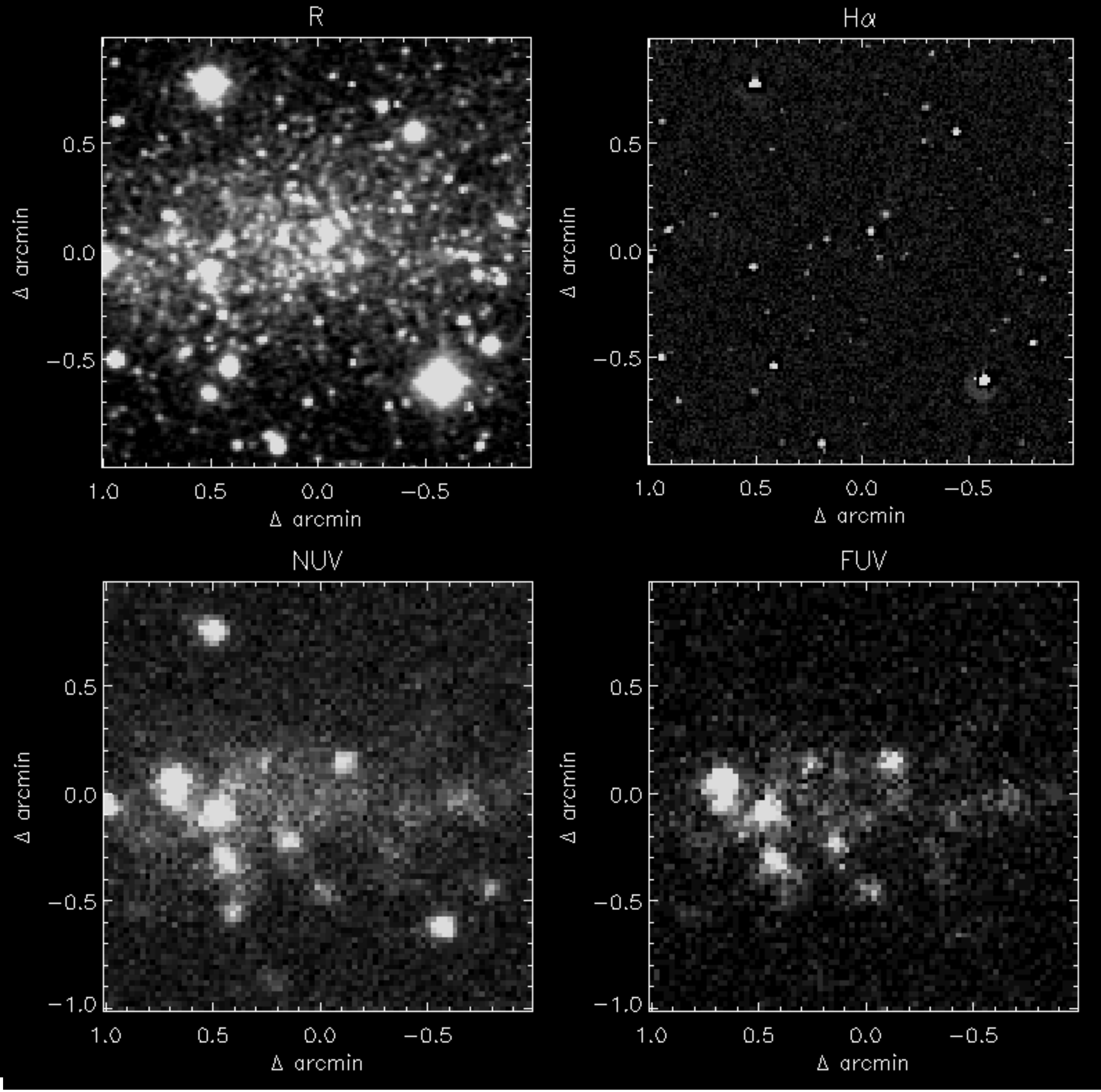


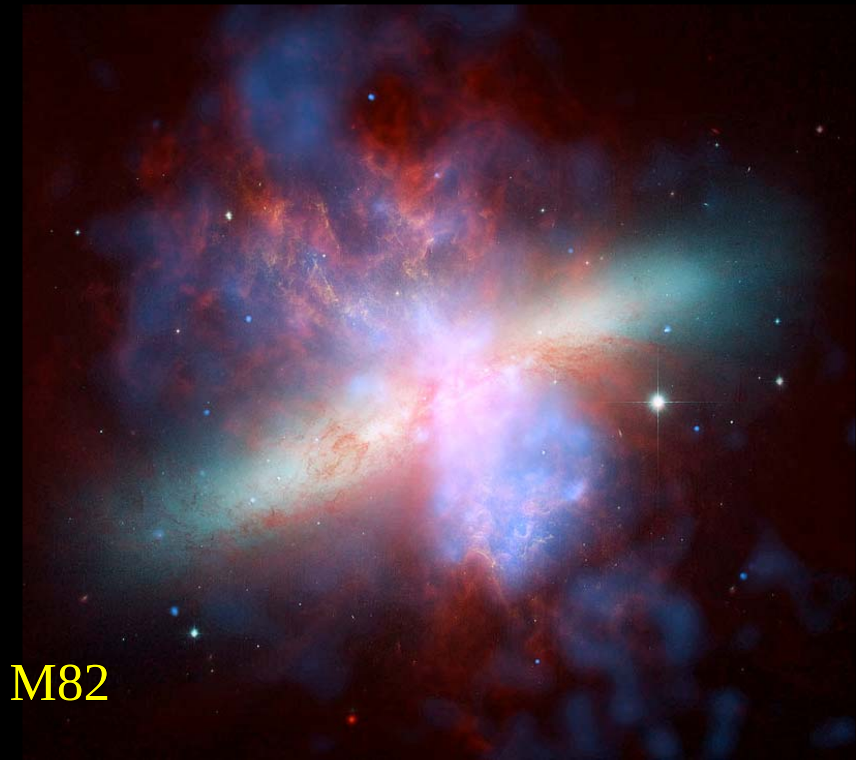
star formation in Leo HI cloud (GALEX)

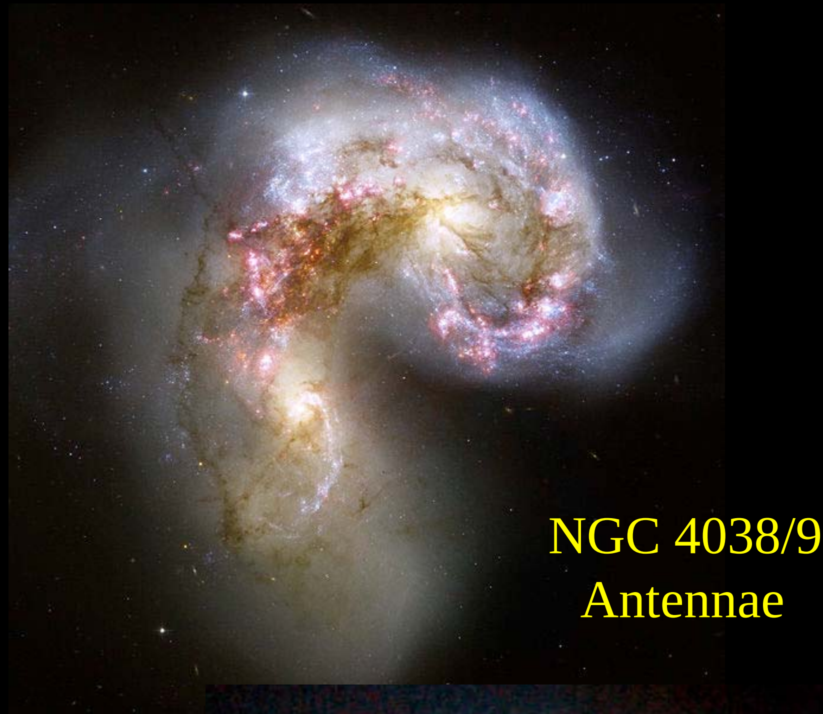


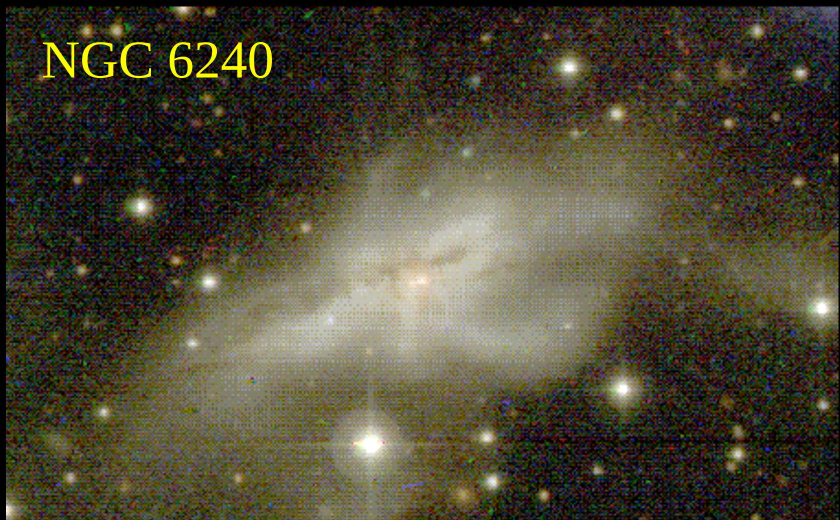
DDO 210

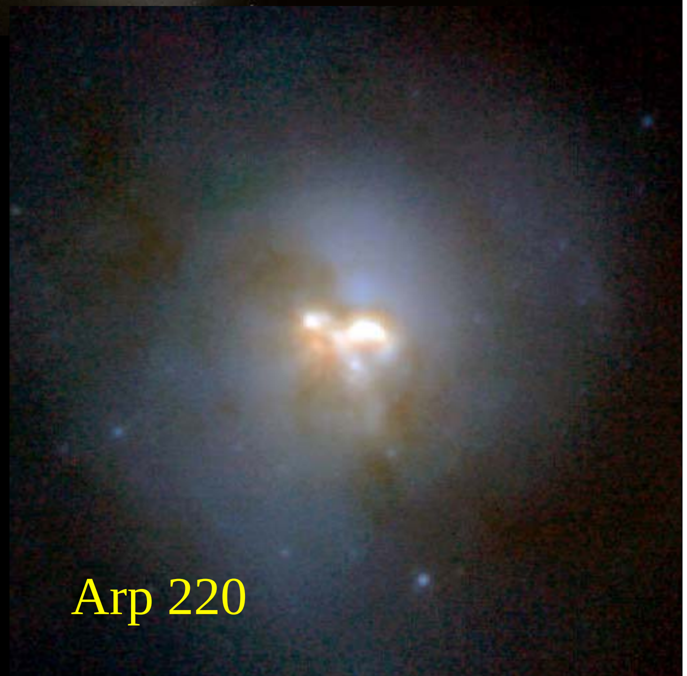
IB(s)m
M_B = -12:

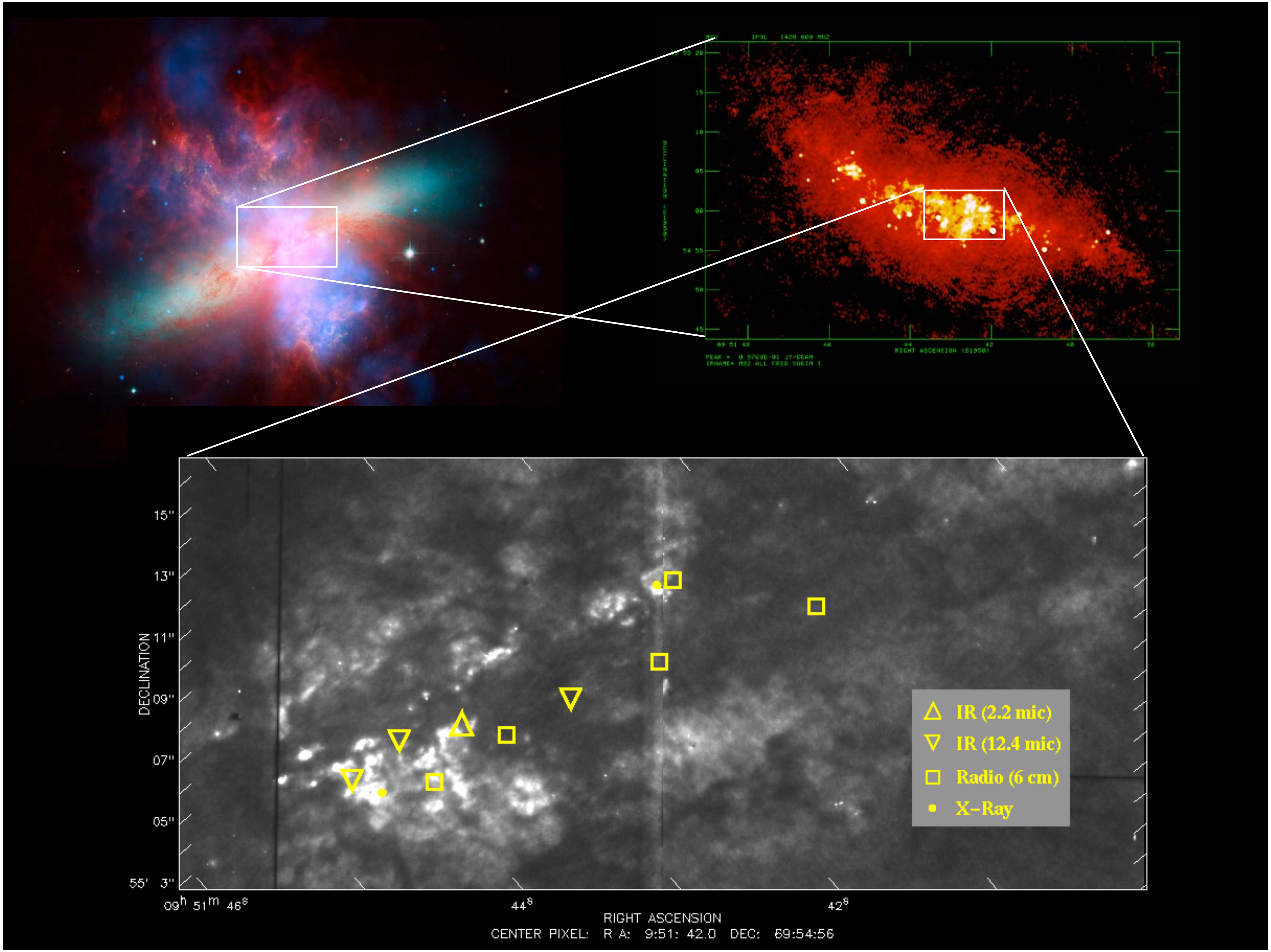



M82


NGC 4038/9
Antennae


NGC 6240

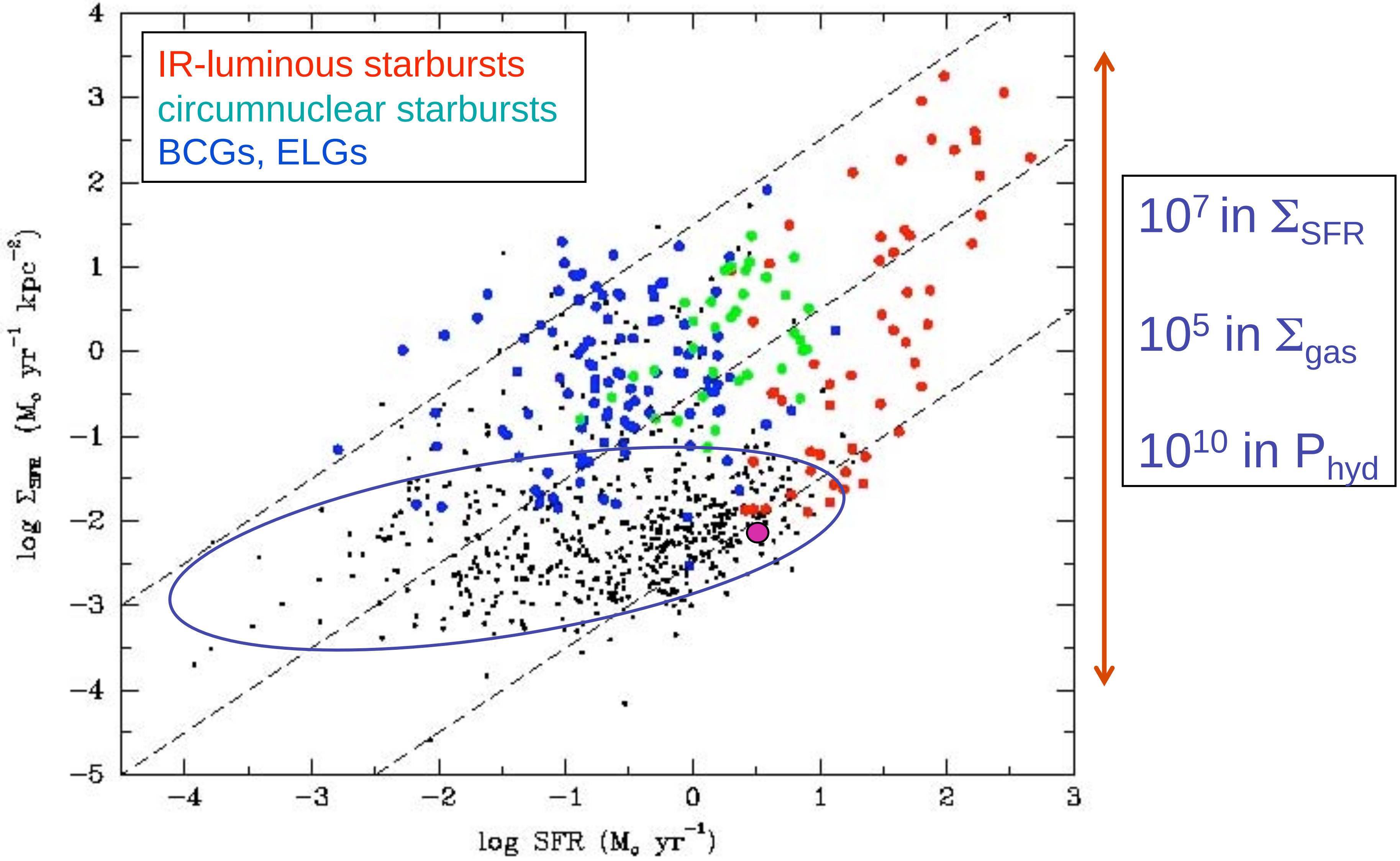

Arp 220

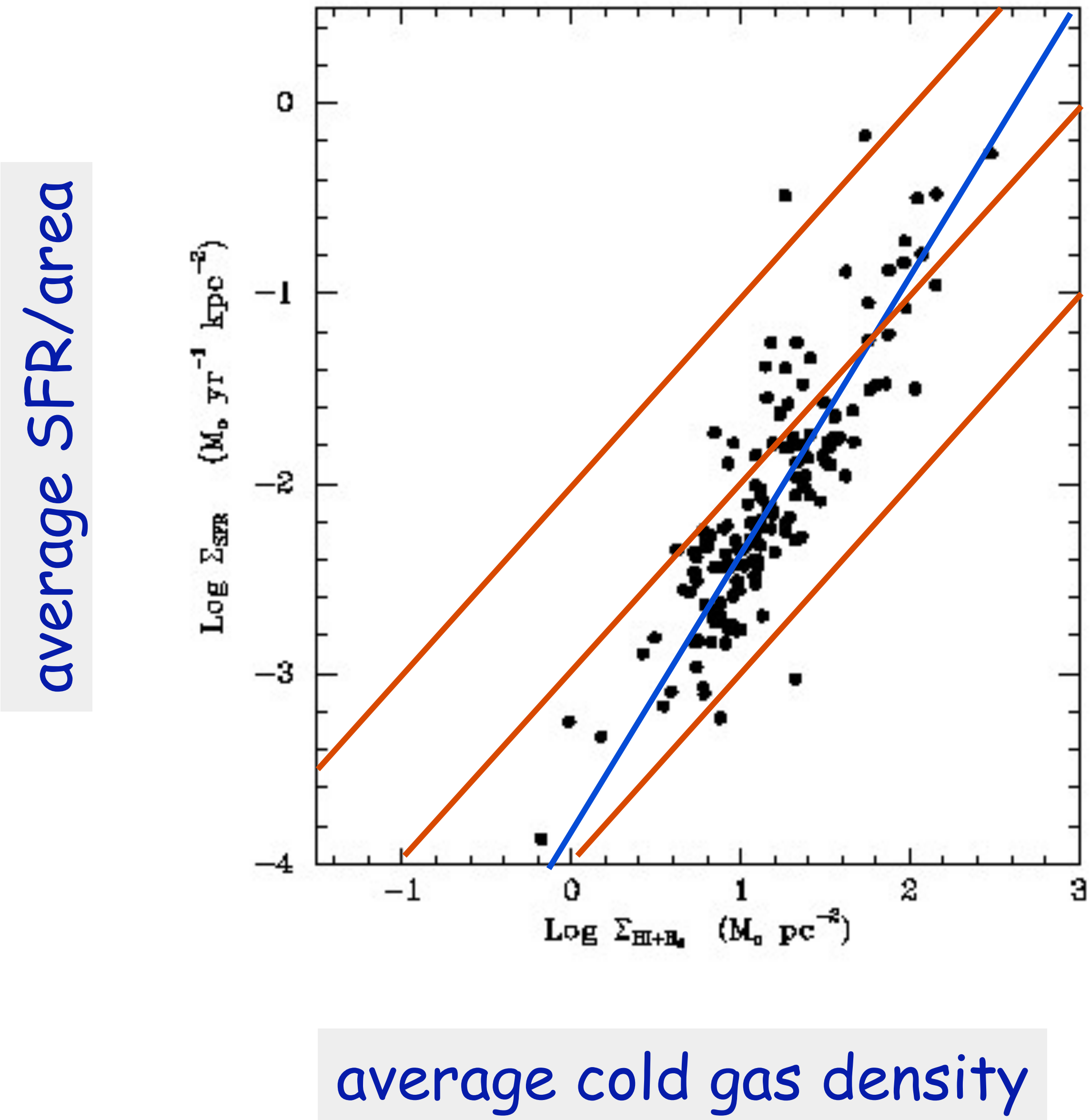


DECLINATION
15"
13"
11"
09"
07"
05"
55' 3"
09h 51m 46s
44s
42s
RIGHT ASCENSION
CENTER PIXEL: R A: 9:51: 42.0 DEC: 69:54:56
IR (2.2 mic)
IR (12.4 mic)
Radio (6 cm)
X-Ray

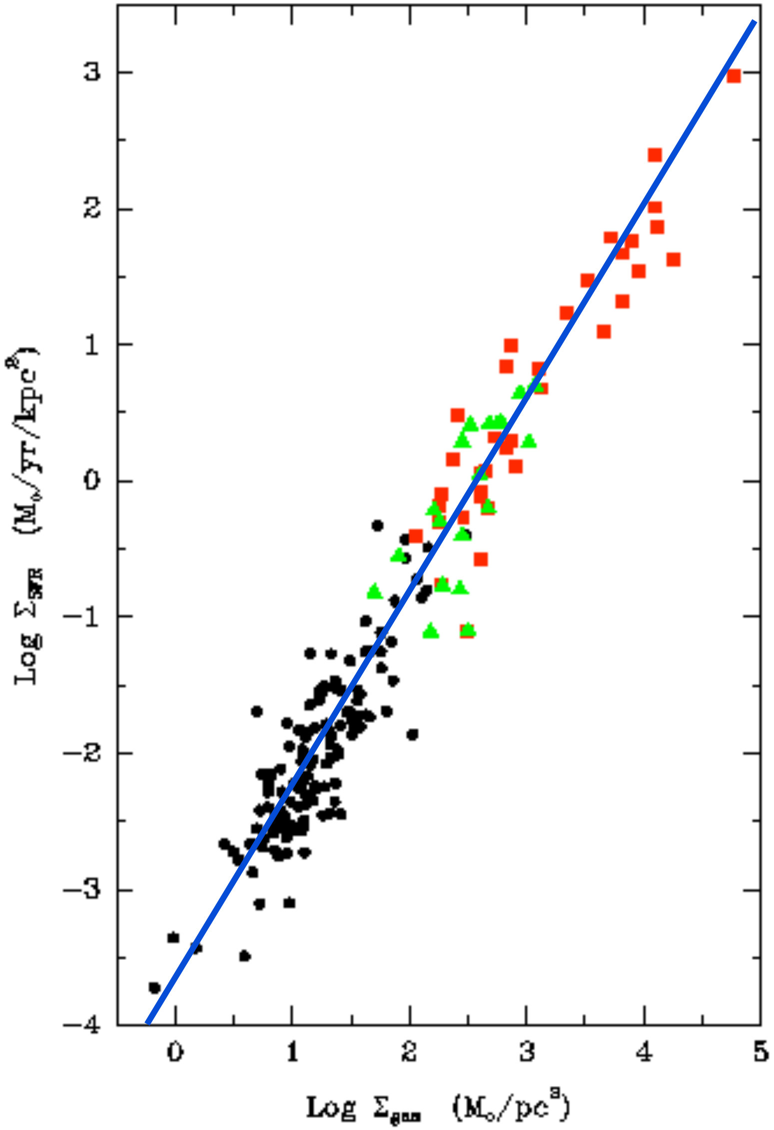
Star Formation in Nearby Galaxies

- Extend understanding of Galactic SF to larger scales, wider range of environments
- On the critical path for understanding galaxy formation and evolution generally
- Address severe biases in lookback observations

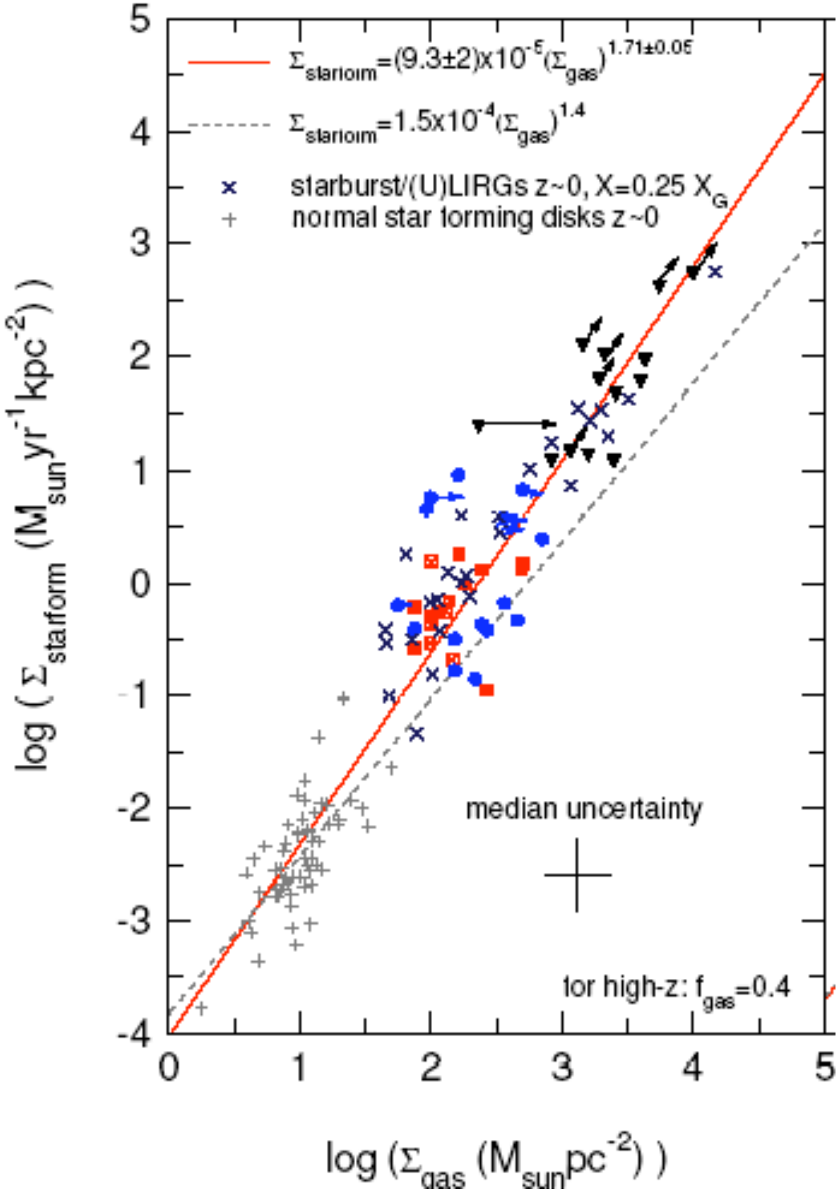

IR-luminous starbursts
circumnuclear starbursts
BCGs, ELGs
log Σ_{SFR} ($M_\odot$ yr^{-1} kpc^{-2})
log SFR ($M_\odot$ yr^{-1})
10^7 in Σ_{SFR}
10^5 in Σ_{gas}
10^{10} in P_{hyd}



<SFE> ~4%/10^8 yr
<τ_{gas}> ~ 2.5 Gyr
<τ_{disk}> ~5-10 Gyr

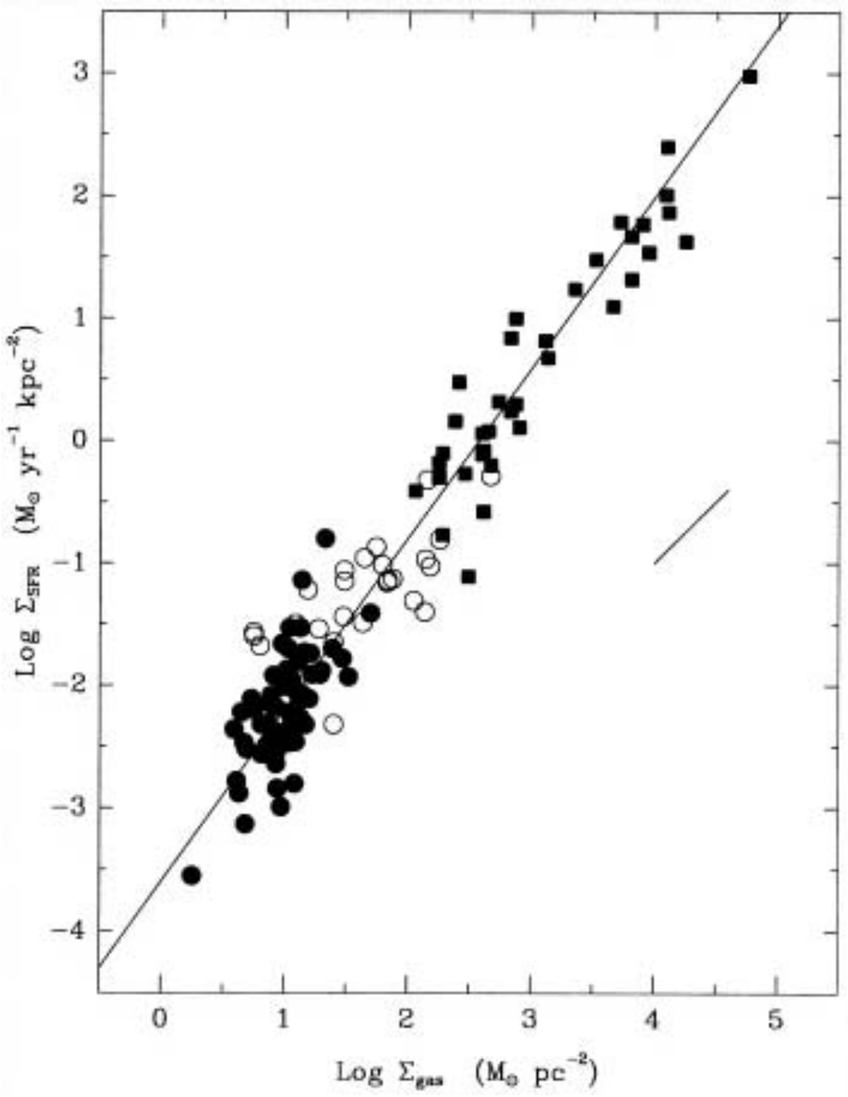


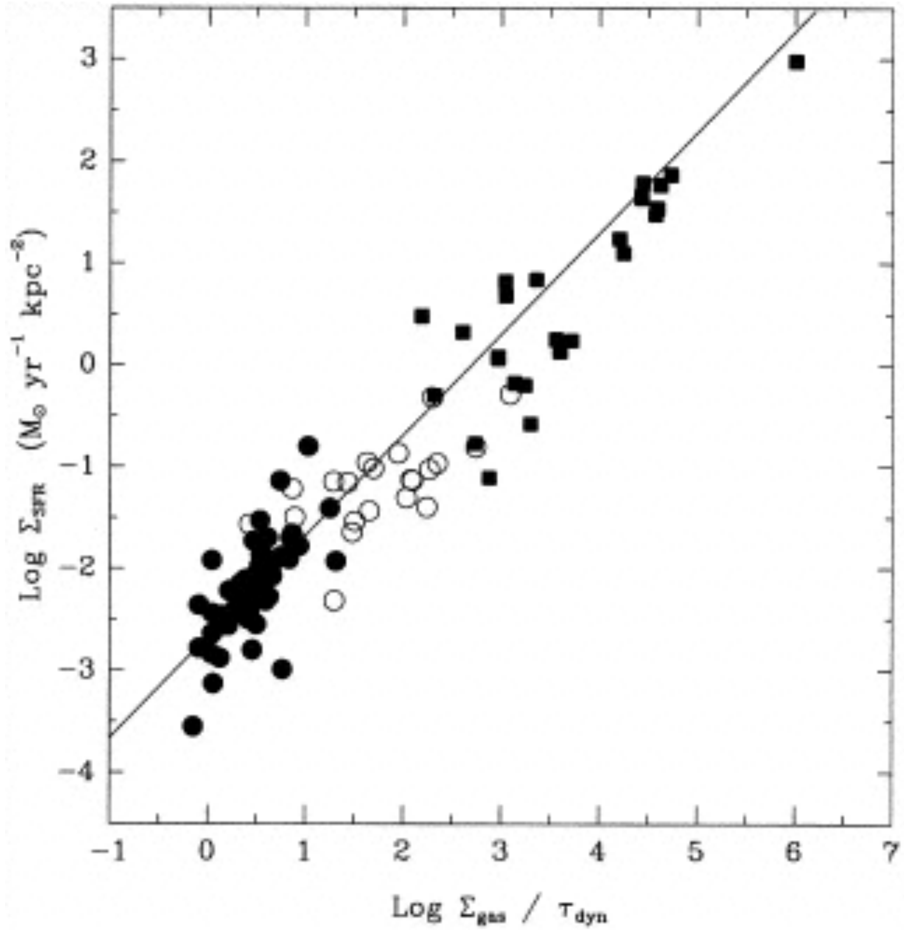
Kennicutt 1998



Bouche et al. 2007

The SF efficiency per dynamical time (or free-fall time) is roughly constant





Schmidt law:

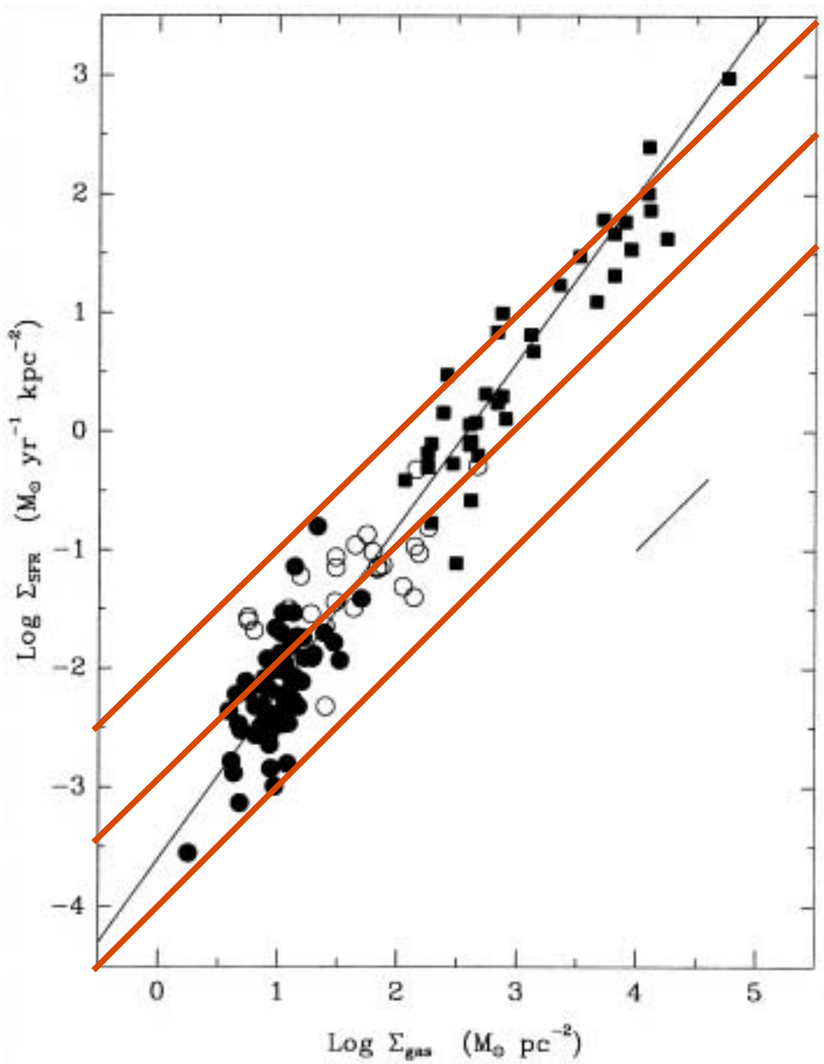
SFR vs gas density power law

SFR vs gas density/dynamical time

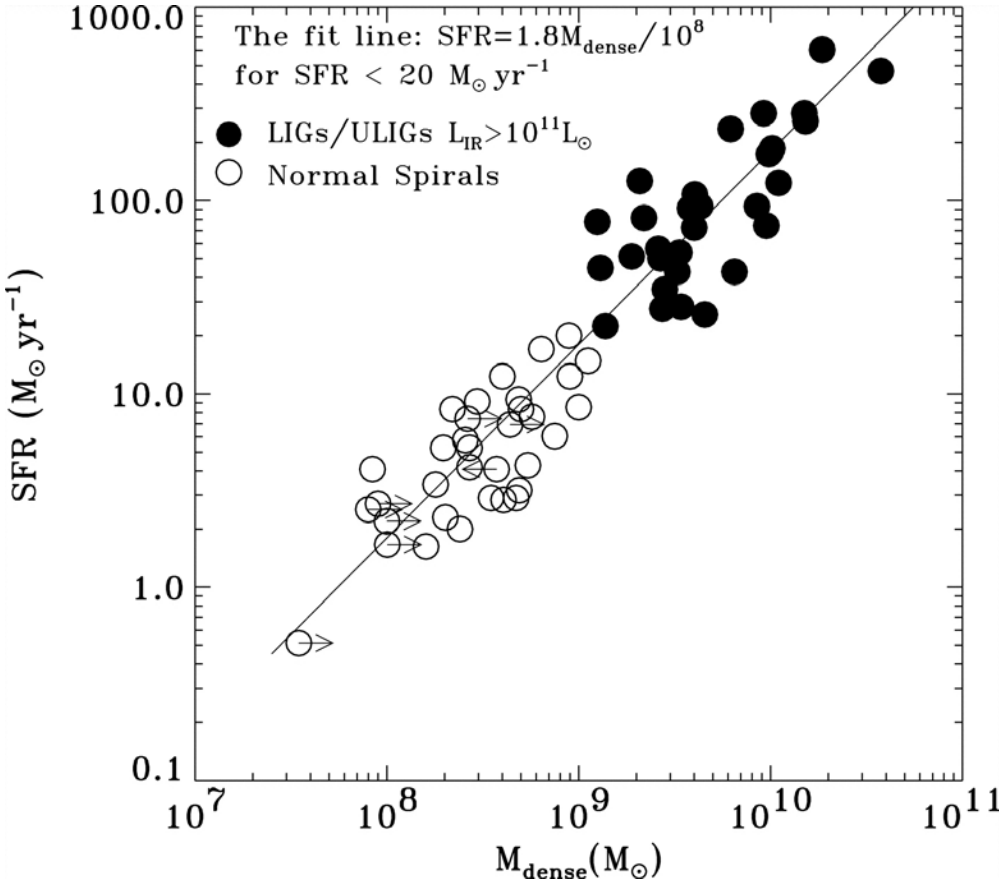
Kennicutt 1998, ApJ, 498, 541

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

The fraction of cold gas in dense cores scales with surface density



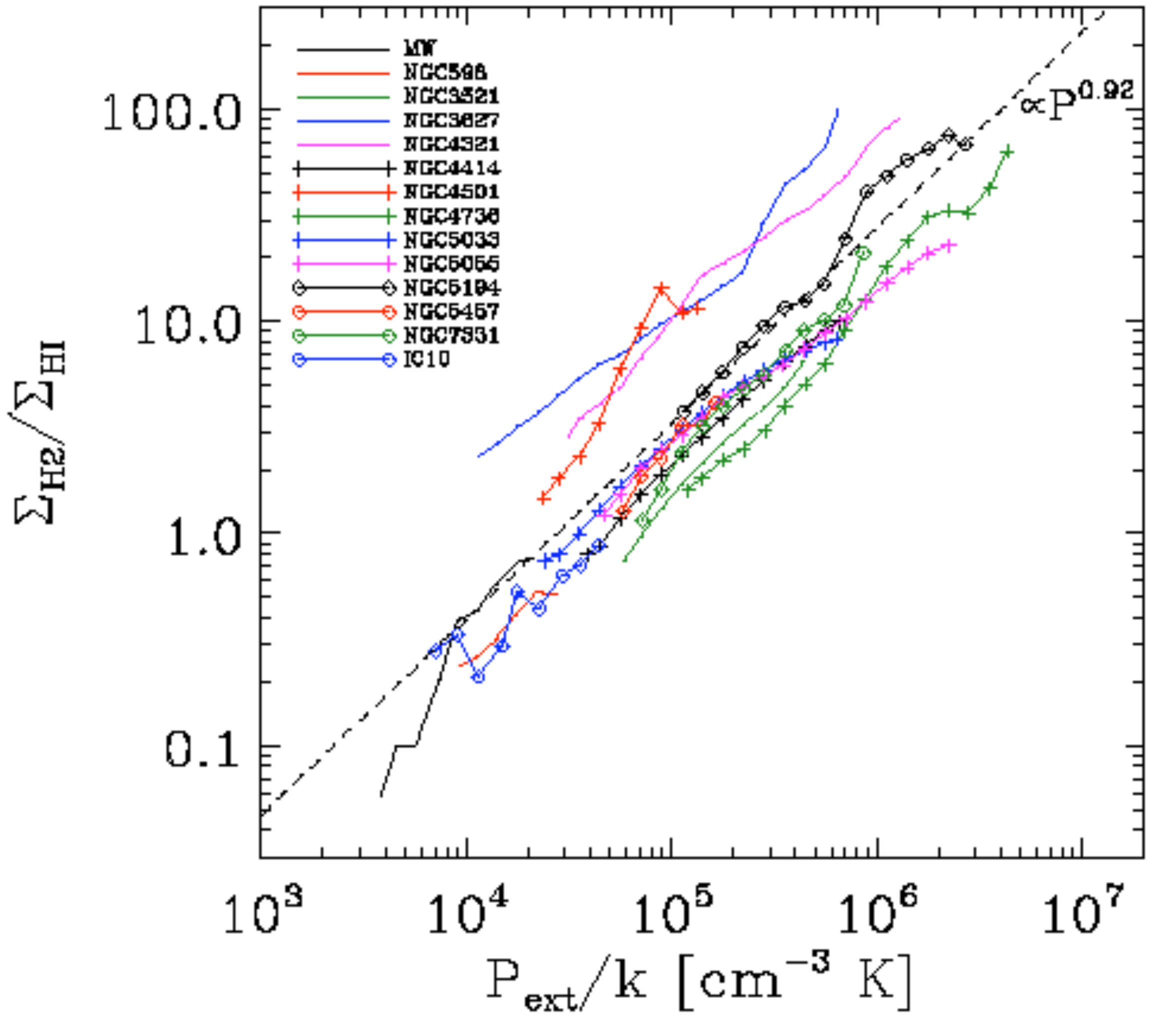
$\Sigma_{SFR}/\Sigma_{HCN} \sim$ const



Kennicutt 1998, ApJ, 498, 541

Gao, Solomon 2004, ApJ, 606, 271

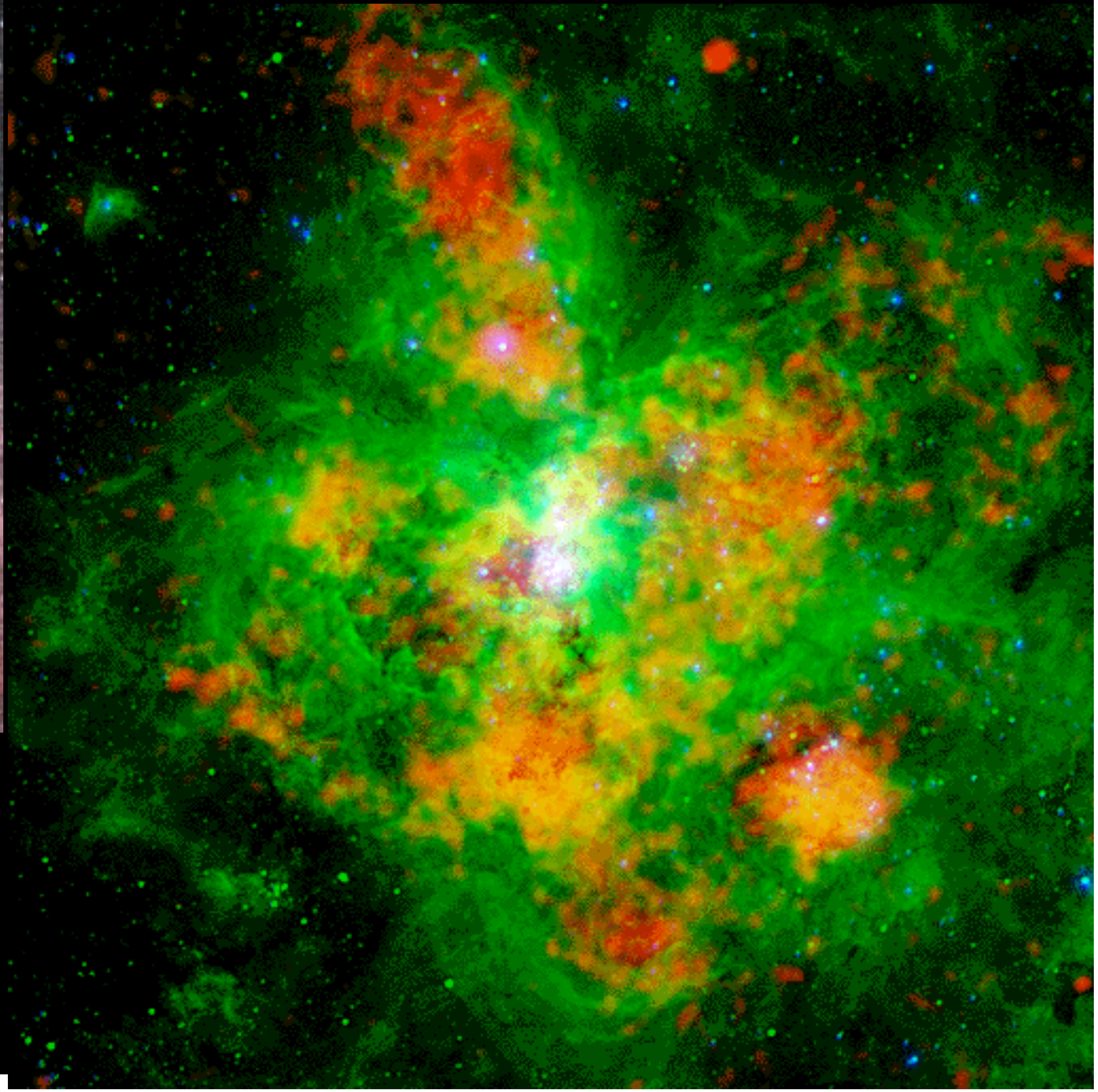
“pressure law”



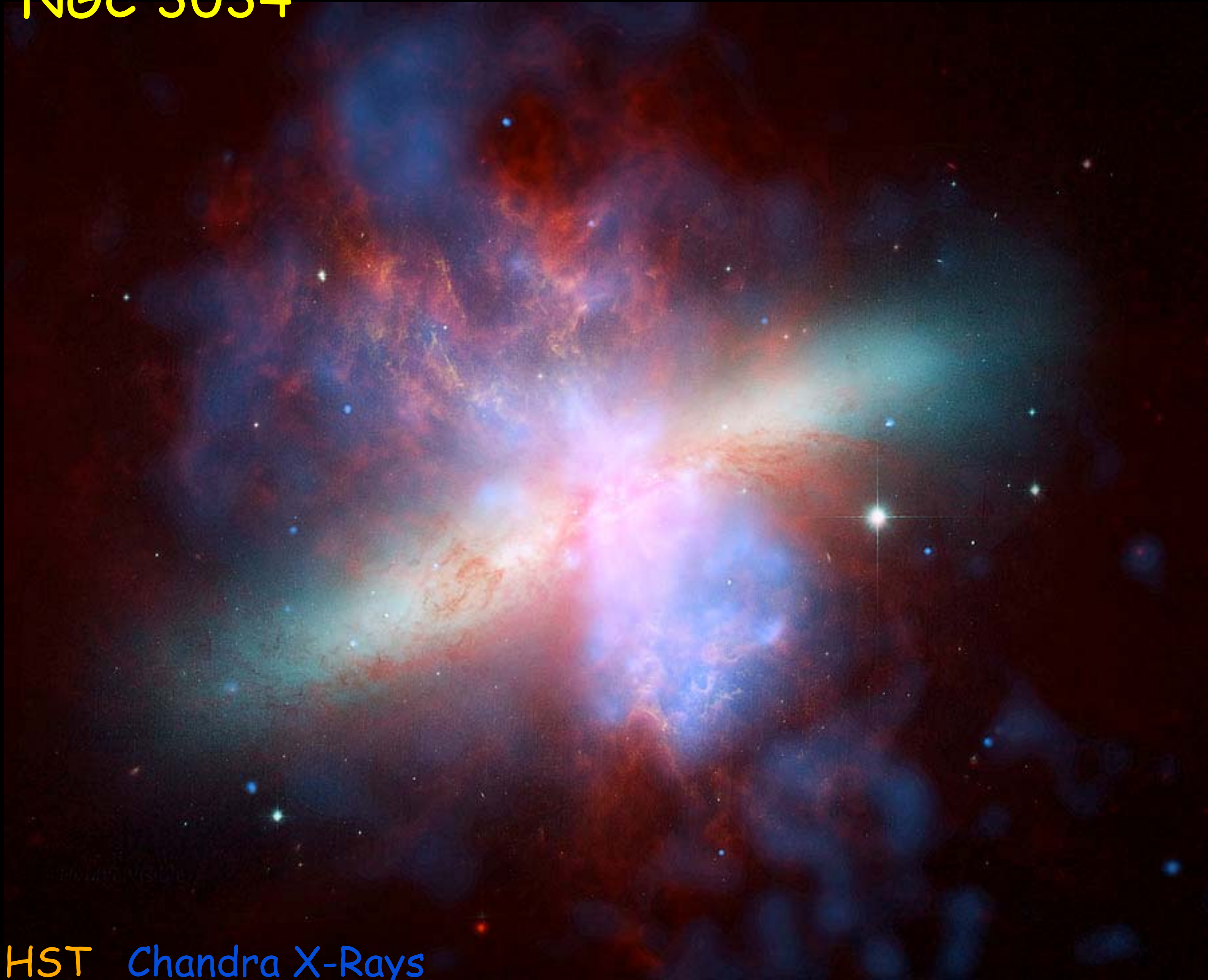
Blitz & Rosolowsky 2006, ApJ, 650, 933

Things We Don't Understand

- How strongly is our picture biased?
  - by galaxy mass, luminosity, surface brightness?
  - by stellar mass?
  - by star formation rate?
- How strong (shaky) is the observational foundation?
  - 3 dirty acronyms: **IMF, X_{CO}, τ_{dust}**
- 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?
  - What is the role of star clustering and collective feedback?
  - How do we connect to the physics of SF on single-cloud scales?

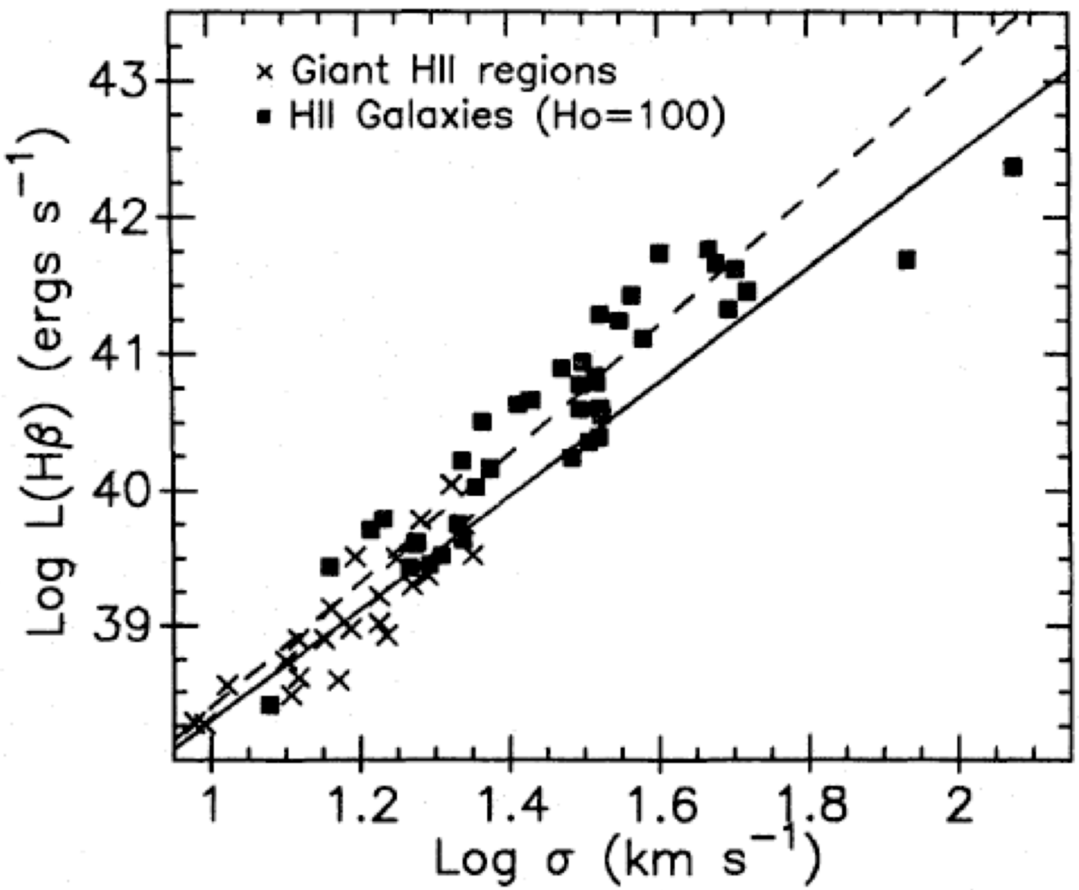


M82 = NGC 3034



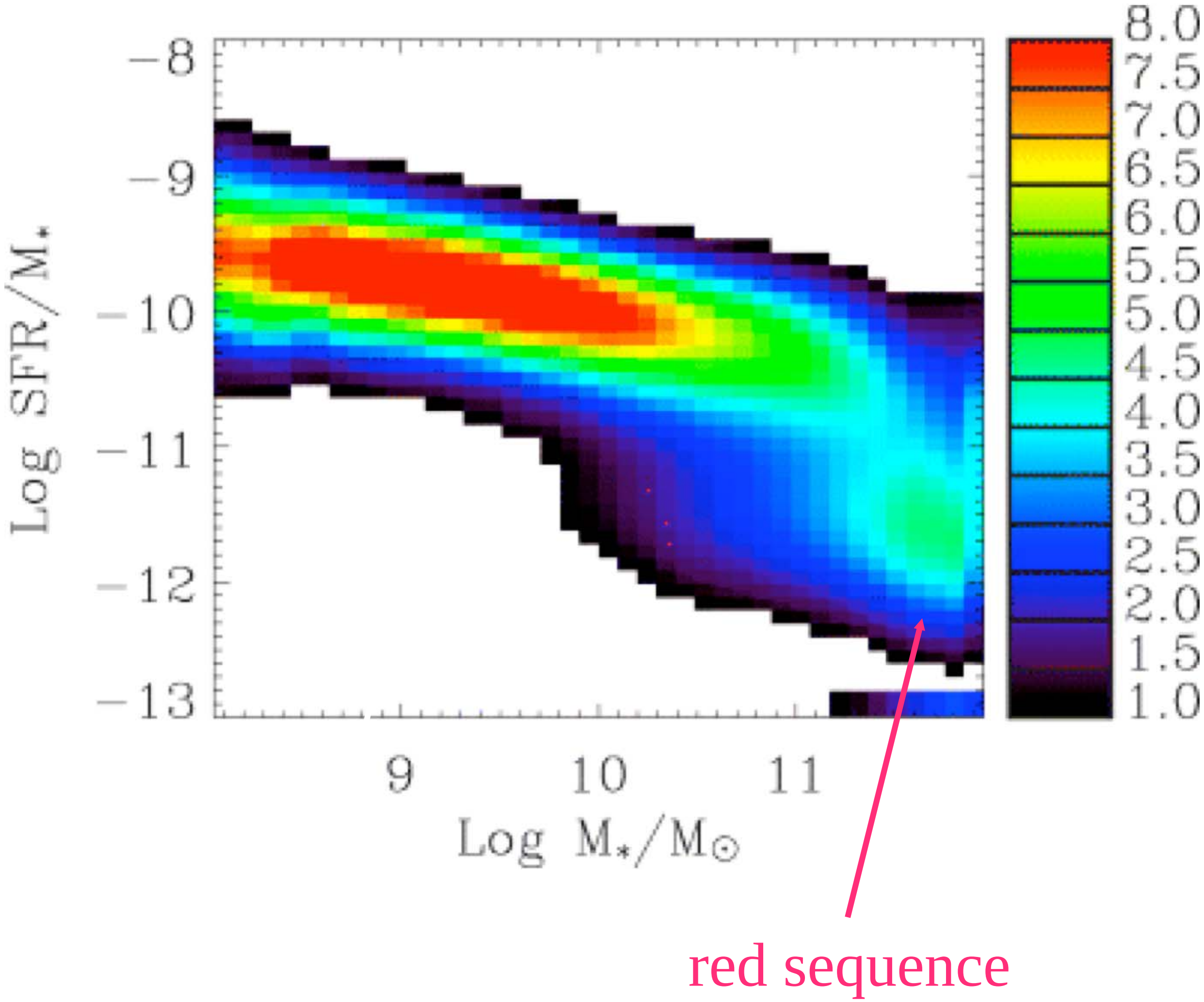
Spitzer HST Chandra X-Rays

Giant H II regions as distance indicators – II



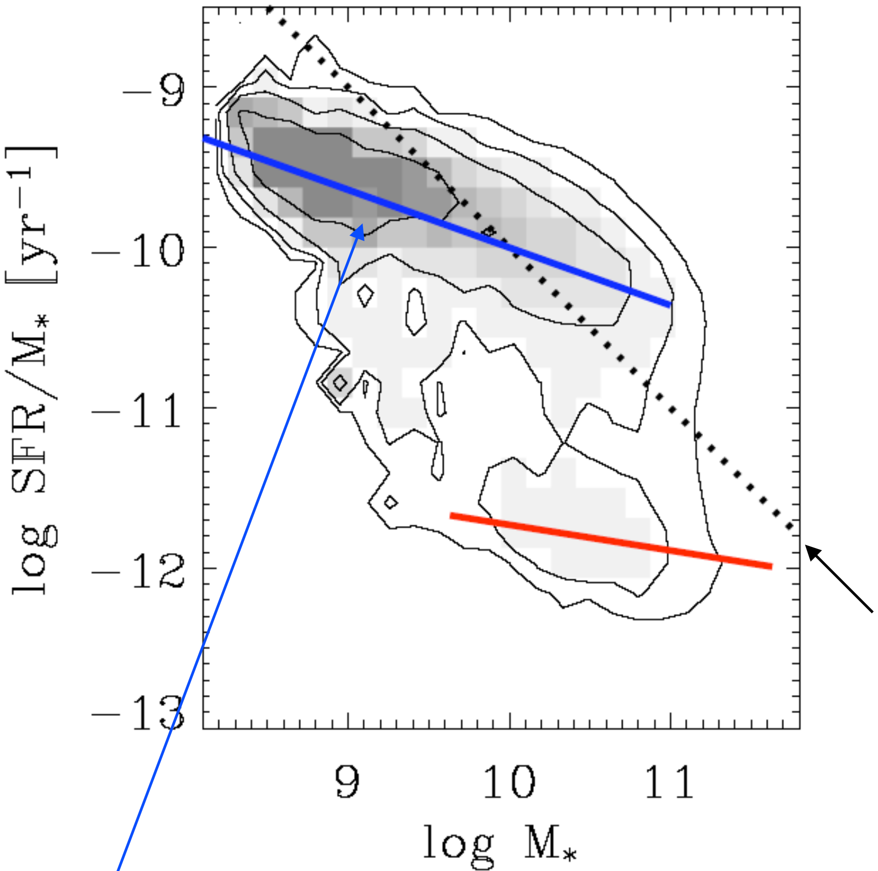
Melnick et al. 1988

SFRs for 100,000 galaxies with Sloan



Brinchmann et al. 2006, MNRAS, 351, 1151

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



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

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

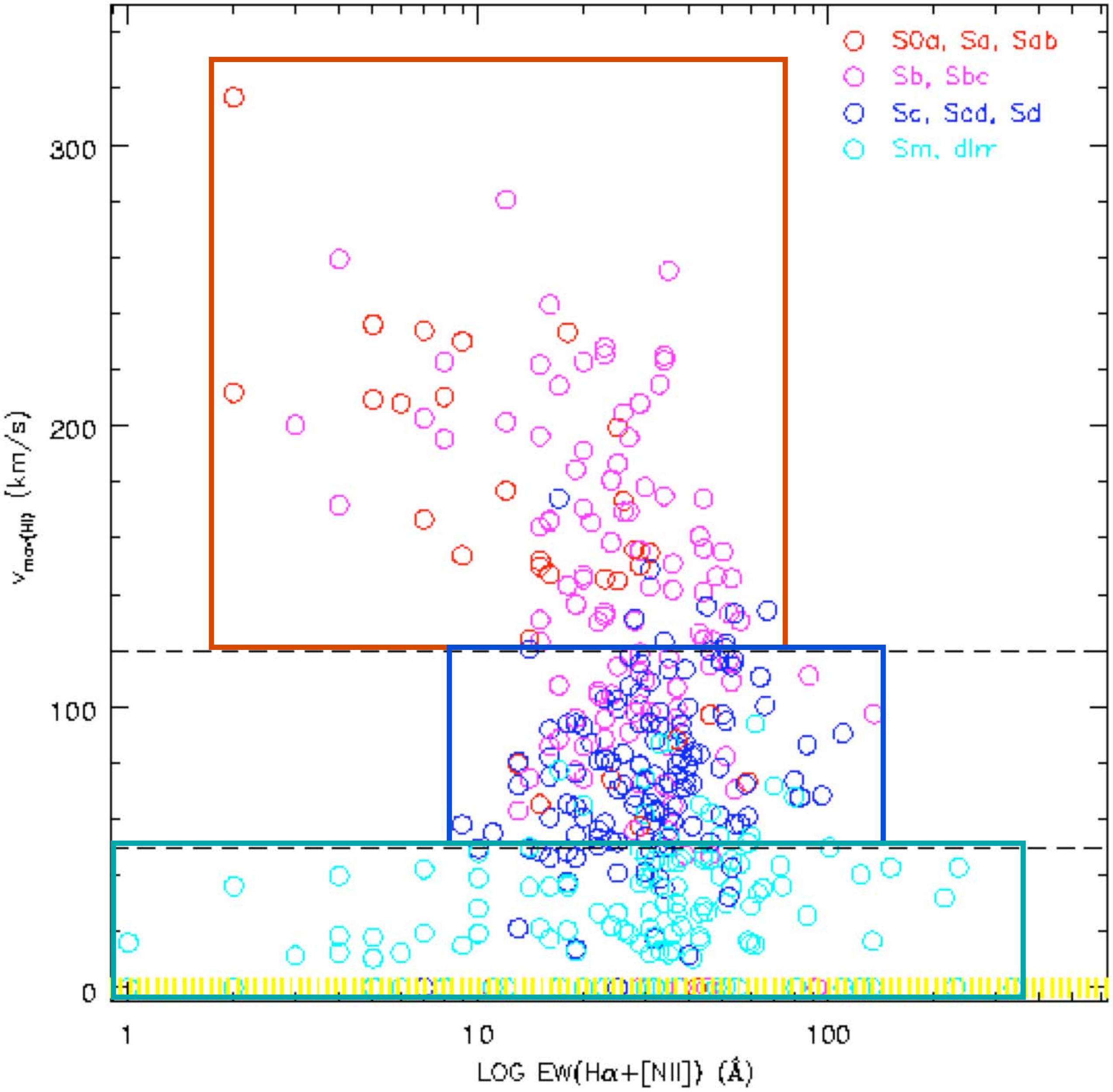
see also
Brinchmann et al. (2004),
Feulner et al. (2006)

$\mathrm{SFR} = 1\ \mathrm{M}_\odot\ yr^{-1}$

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

Schimminovich 2007

11HUGS Survey



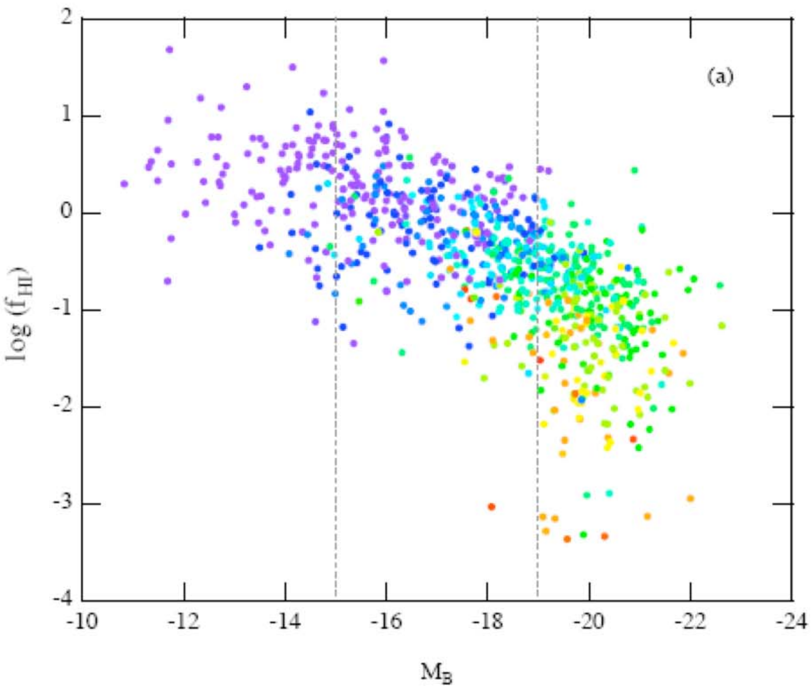
V_{circ}

SFR/mass

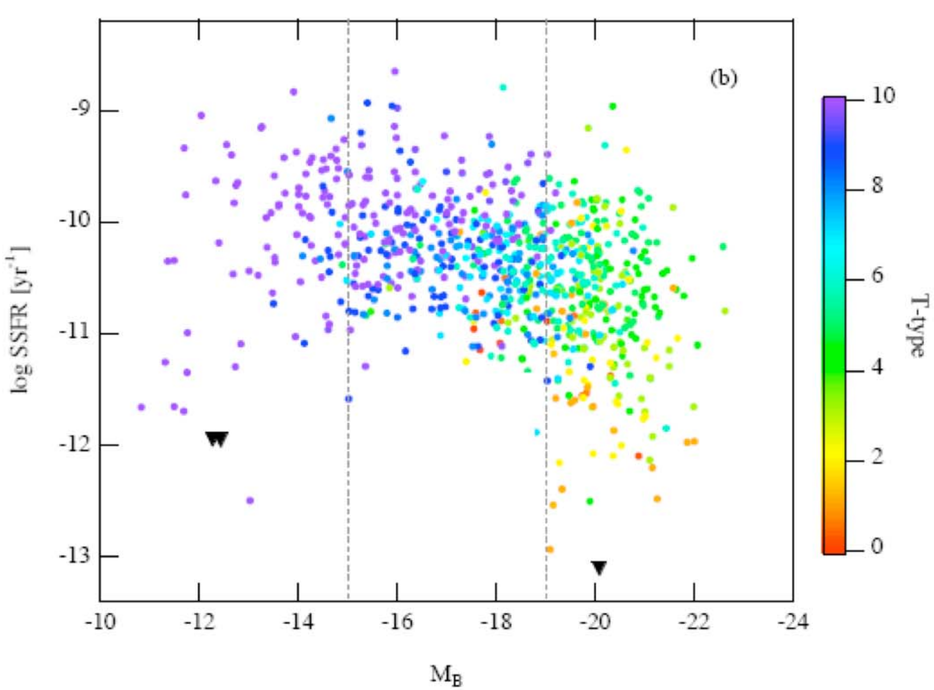
Lee et al. 2007, ApJL, 671, L113

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

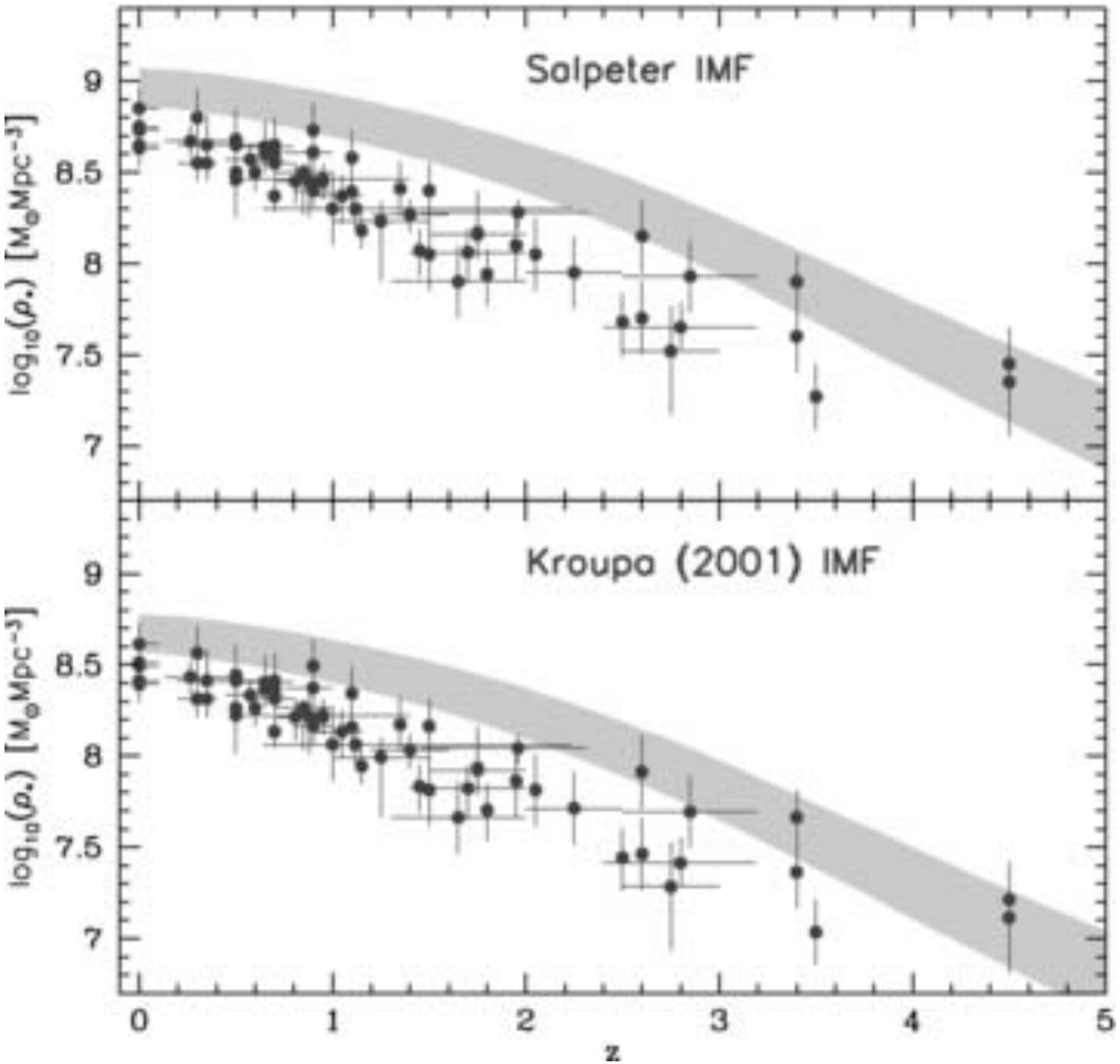
HI/stellar mass ratio



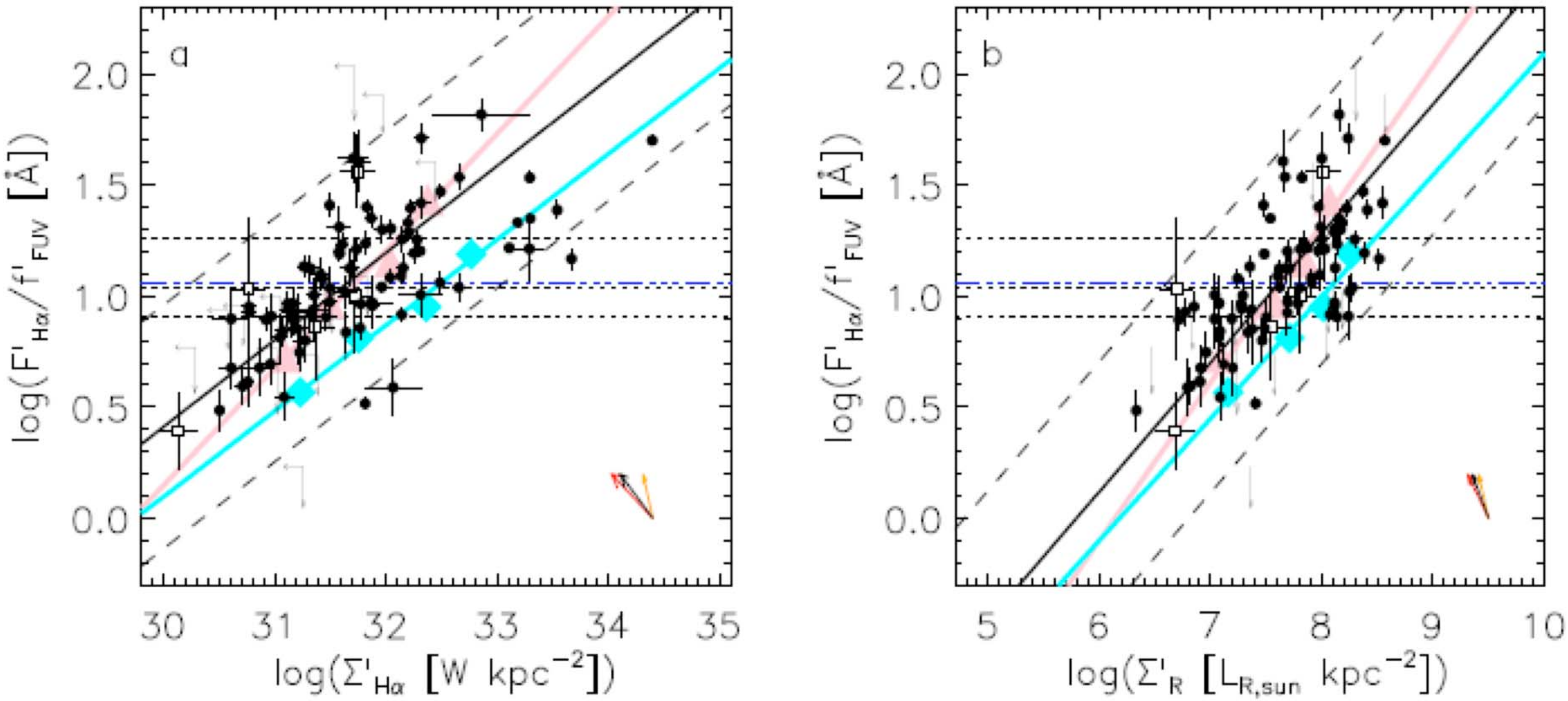
SFR/mass



Bothwell et al 2009, MNRAS, in press (arXiv0908.1122)



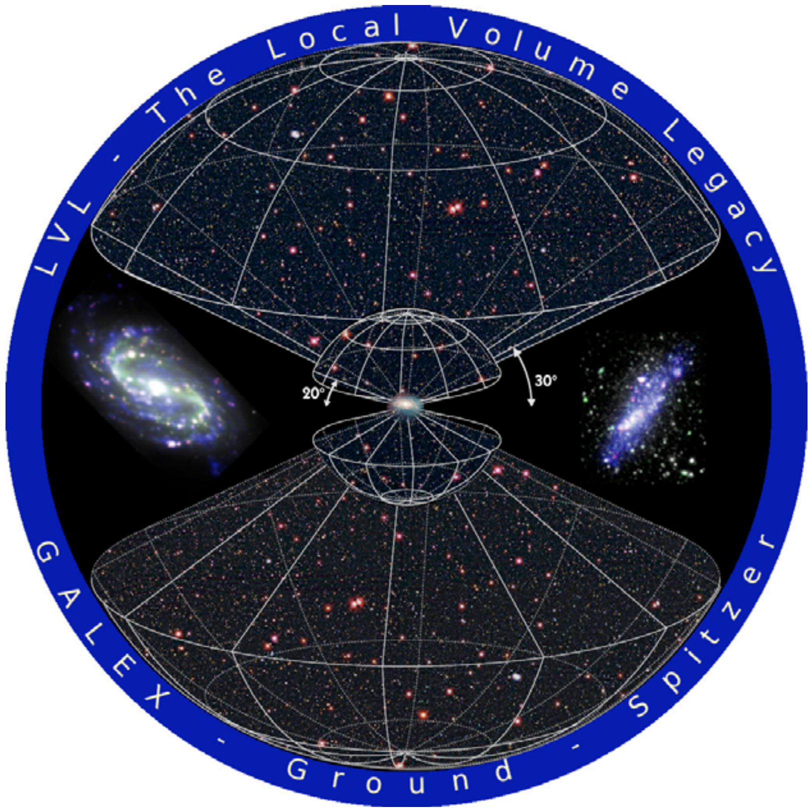
Wilkins et al. 2008

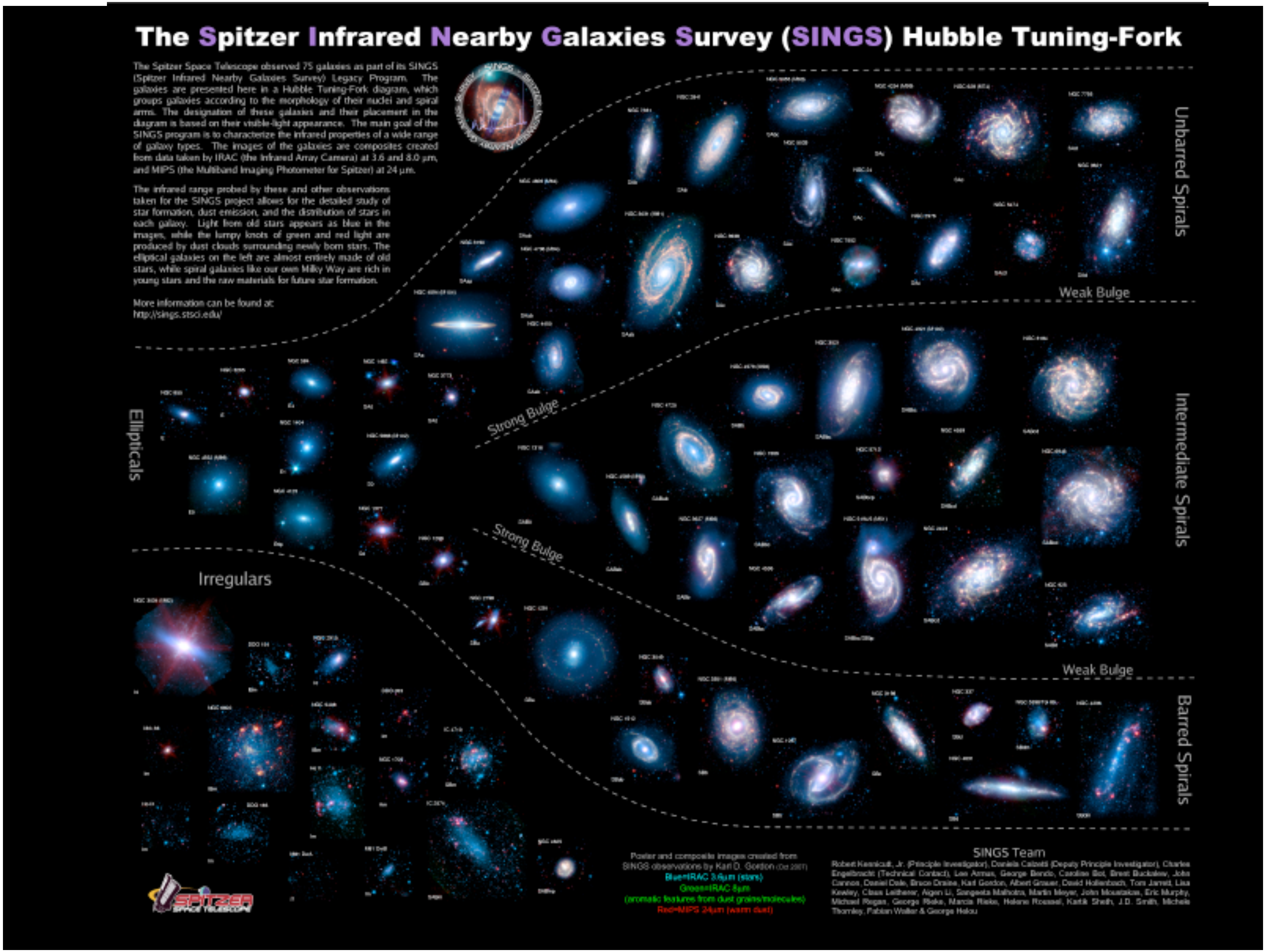


Meurer et al. 2009, arXiv0902:0384

Spitzer Local Volume Legacy

- Cycle 4 Spitzer Legacy project
- UV/Hα/IR Census of Local Volume
  - HST ANGST sample to 3.5 Mpc
    - all galaxies outside LG |b|>20
  - GALEX 11HUGS sample to 11 Mpc
    - all S0/a–Irr with |b|>30, B<15
- IRAC + MIPS imaging for 258 galaxies





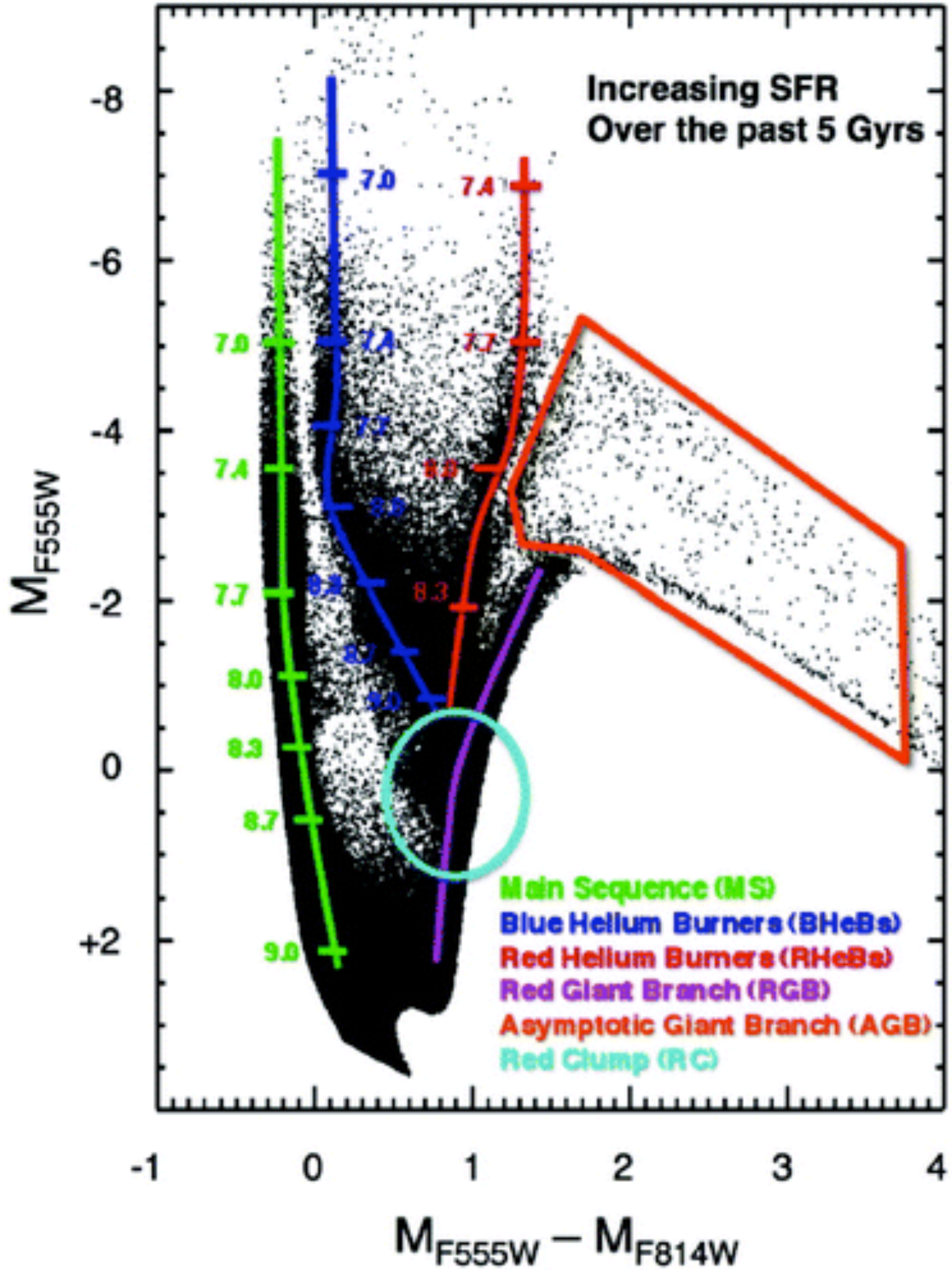
The Spitzer Infrared Nearby Galaxies Survey (SINGS) Hubble Tuning-Fork
The Spitzer Space Telescope observed 75 galaxies as part of its SINGS (Spitzer Infrared Nearby Galaxies Survey) Legacy Program. The galaxies are presented here in a Hubble Tuning-Fork diagram, which groups galaxies according to the 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
Intermediate Spirals
Strong Bulge
Ellipticals
Strong Bulge
Weak Bulge
Barred Spirals
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

Local Stellar Pops with E-ELT

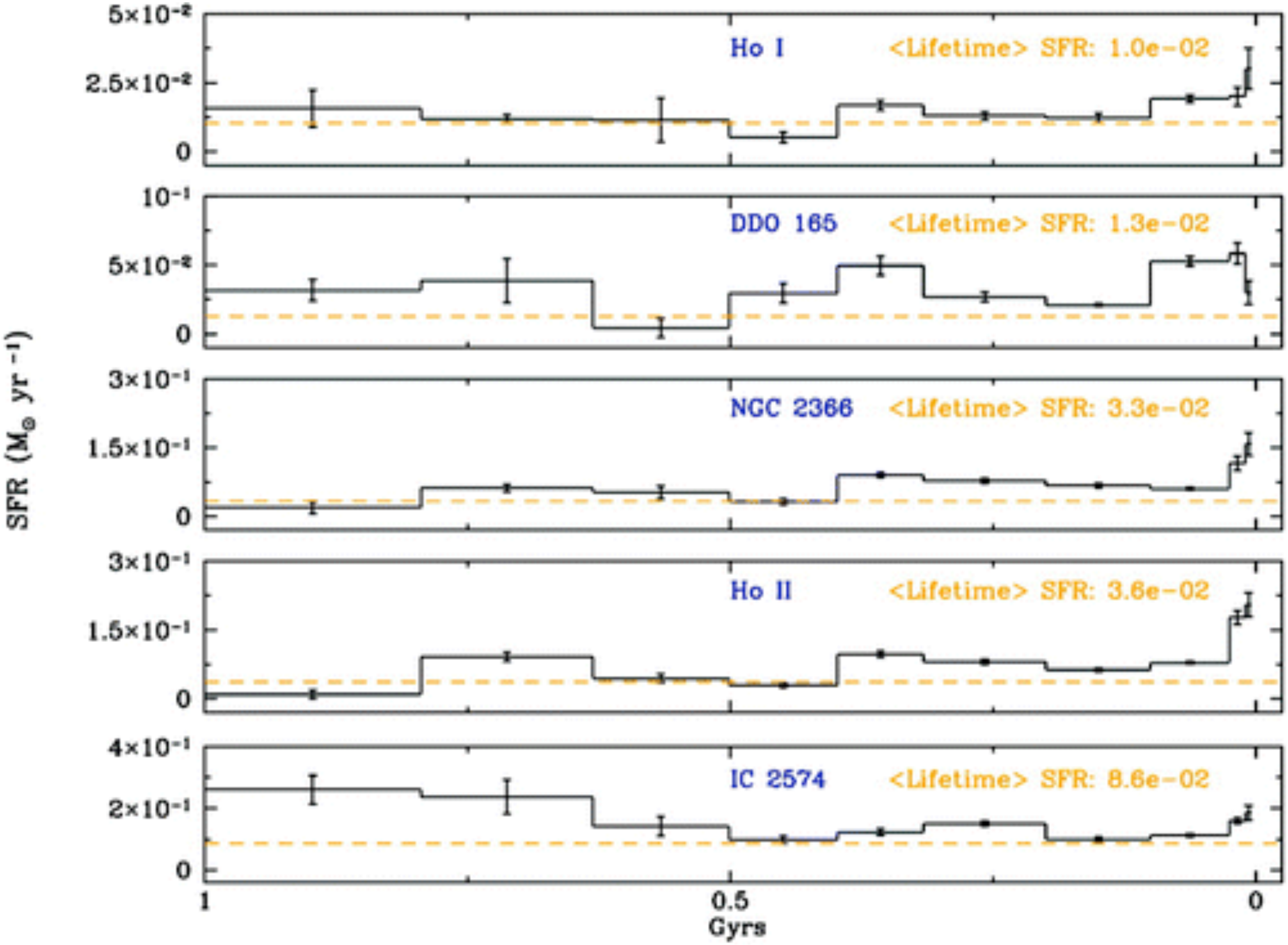
- Resolved SF histories of star-forming galaxies(?)
  - requires high-resolution CMDs

- IMF in clusters
  - systematic changes in M_{upper}?
  - systematic changes in turnover mass?
  - requires high-res imaging of young clusters; crowding an issue

- The physics of starbursts
  - high-res near-IR IFU imaging/spectra
  - mid-IR high-res imaging in lines and continuum
  - complementarity with ALMA especially powerful



Increasing SFR
Over the past 5 Gyrs
M_{F555W}
$M_{F555W} - M_{F814W}$
-8
-6
-4
-2
0
+2
-1
0
1
2
3
4
7.0
7.4
7.7
8.0
8.3
8.7
9.0
Main Sequence (MS)
Blue Helium Burners (BHeBs)
Red Helium Burners (RHeBs)
Red Giant Branch (RGB)
Asymptotic Giant Branch (AGB)
Red Clump (RC)



Weisz et al 2008

Local Stellar Pops with E-ELT

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- The physics of starbursts
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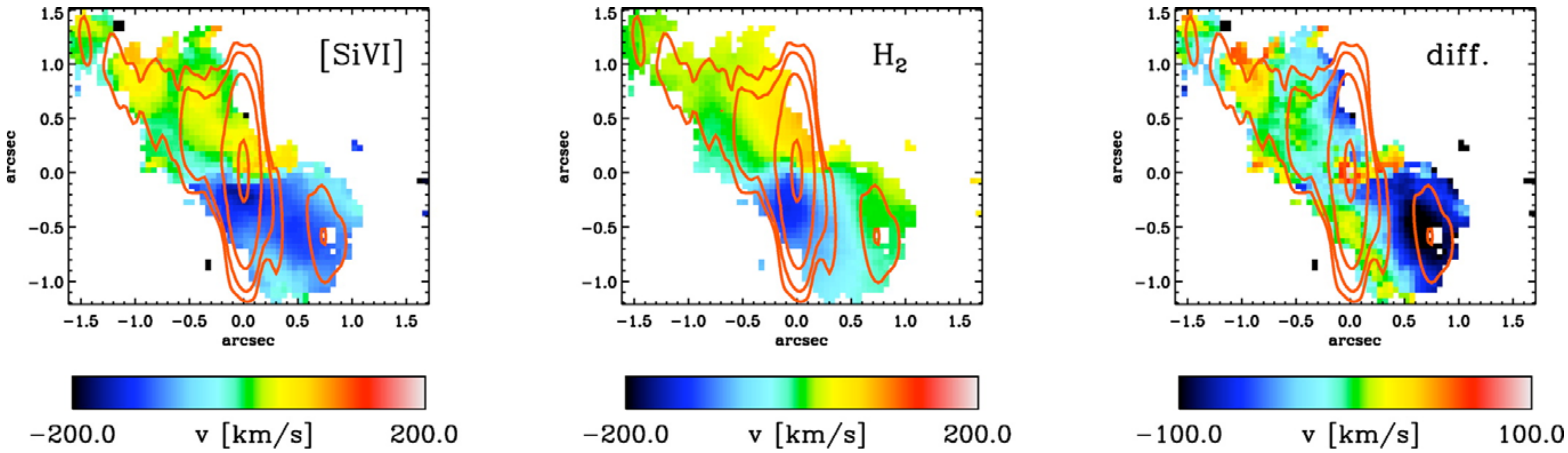
GMT Science Case

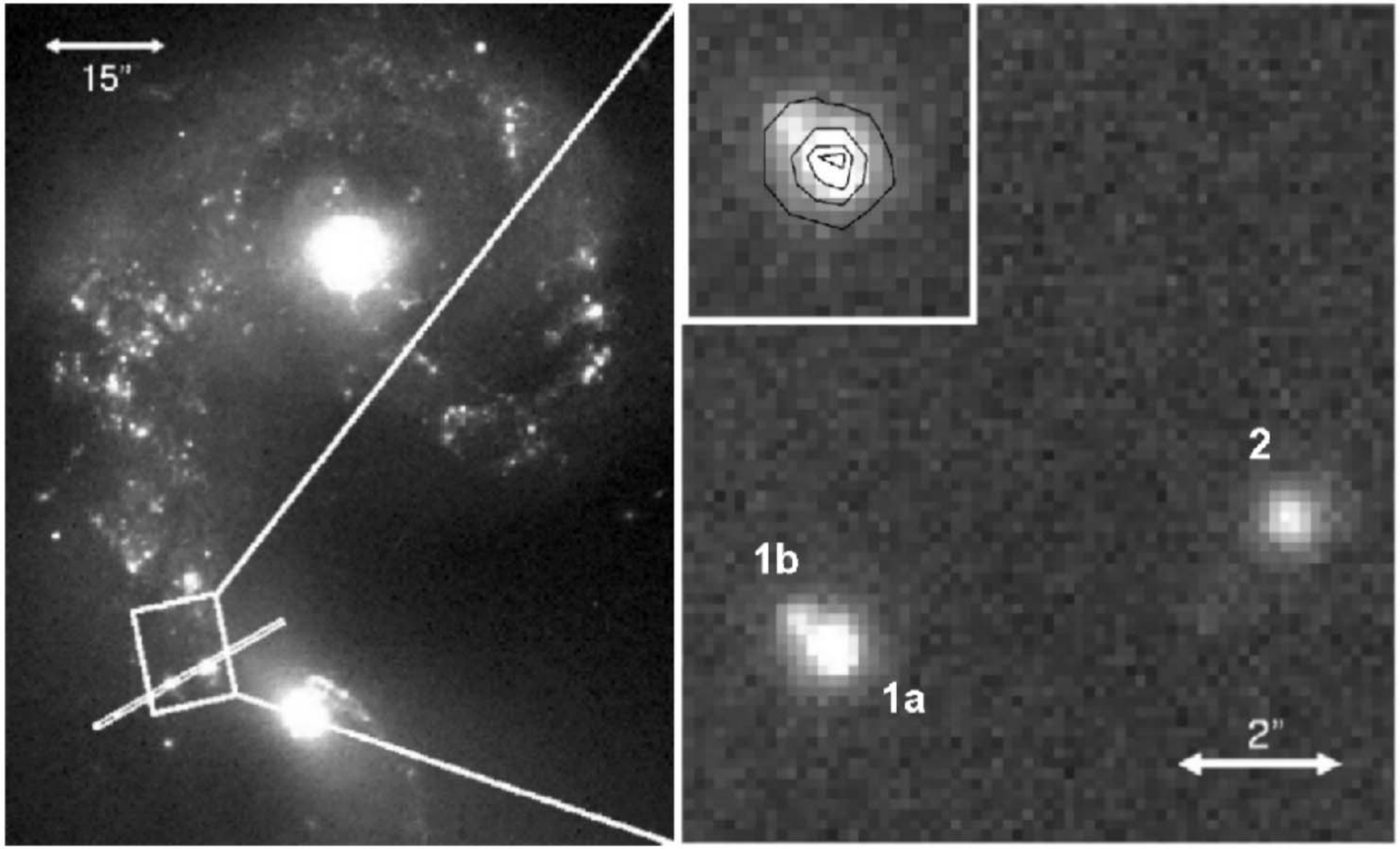
Cen A = NGC 5128
VLT + SINFONI



Neumayer et al (2007)

Antennae - NGC 4038/9

[NeII] 12.8mm, VLT + VISIR



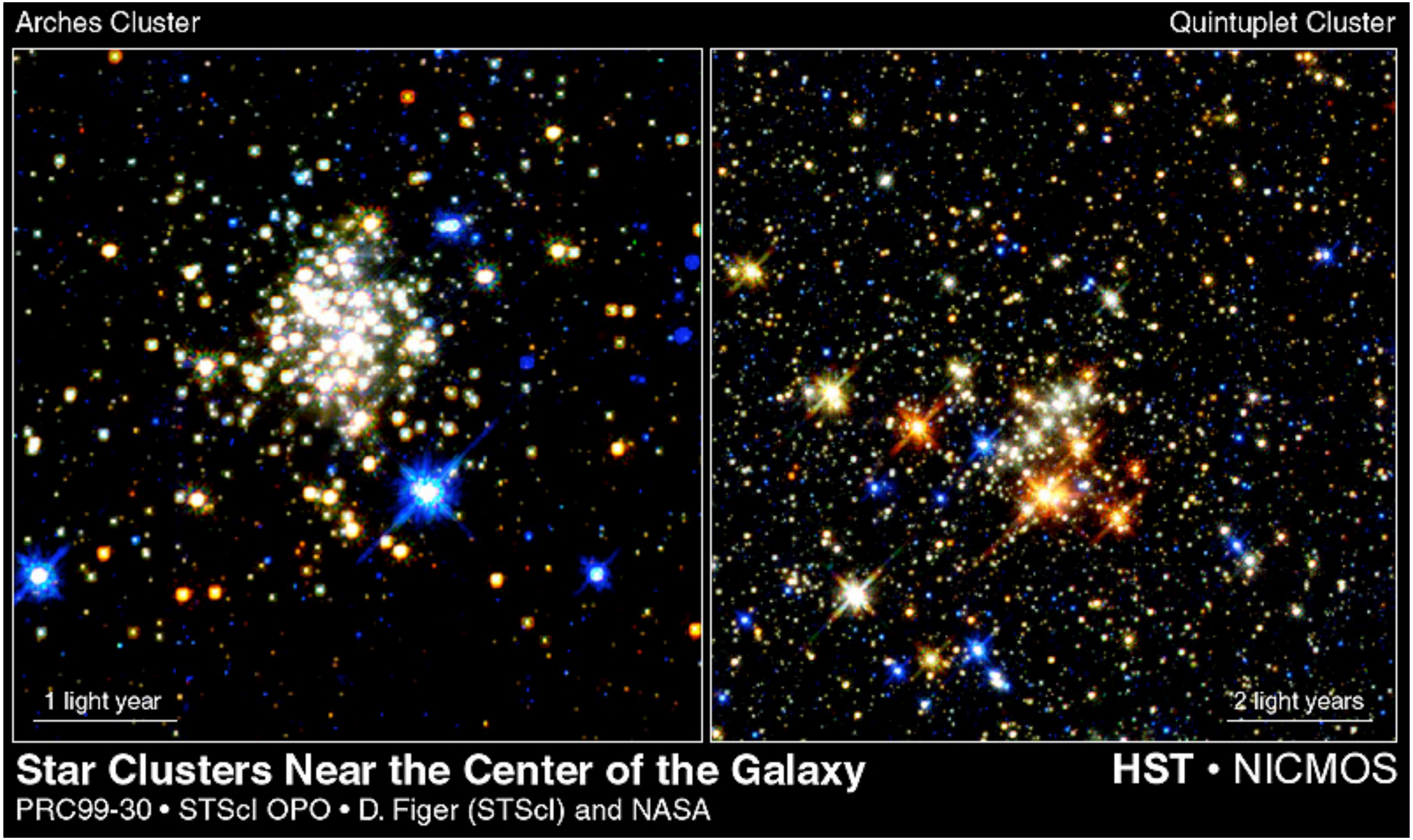
Snijders et al 2007

Summary of E-ELT Drivers

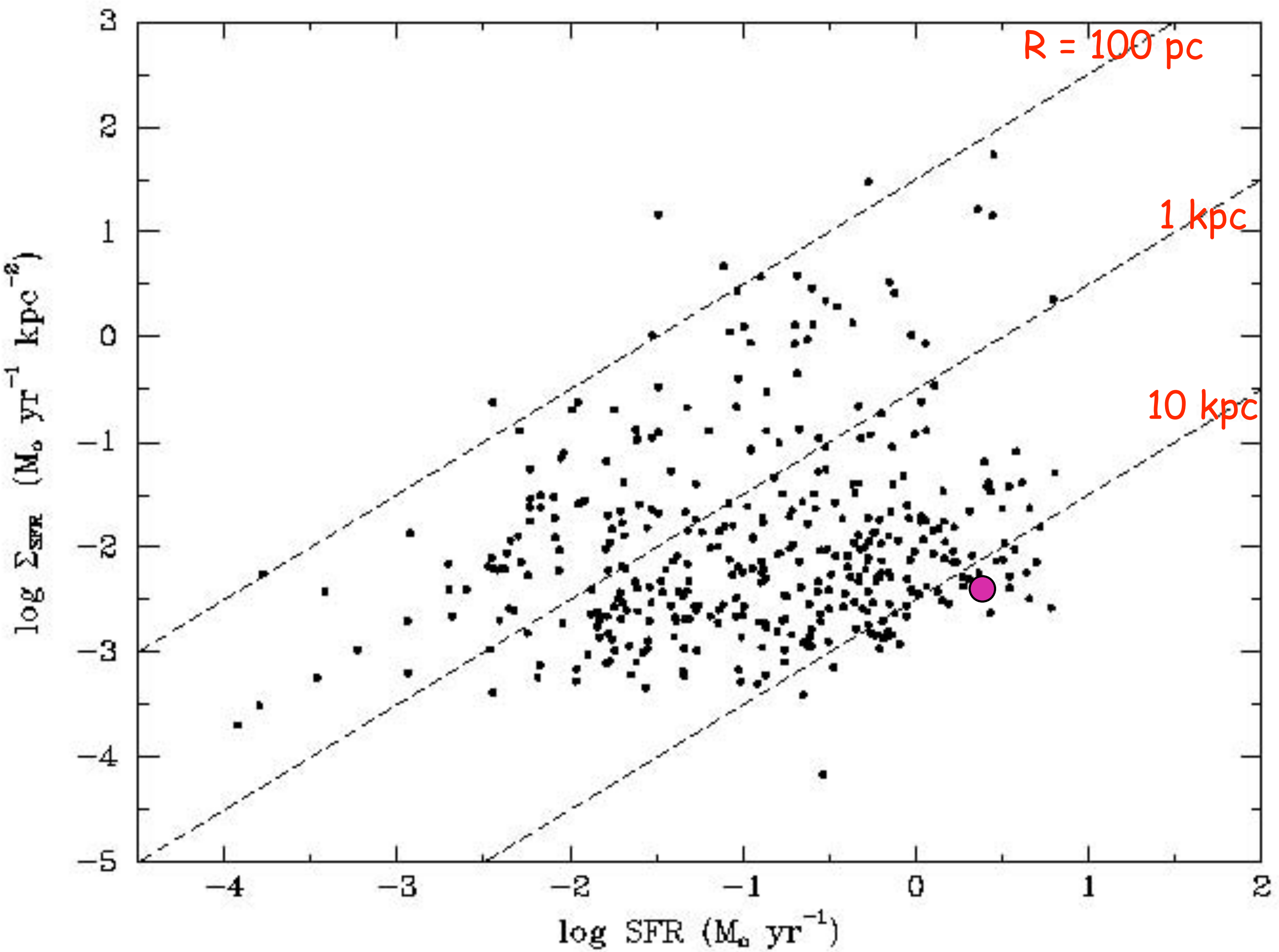
- High-res near-IR imaging + moderate-res spectroscopy
- Mid-IR imaging/spectroscopy
- "Wide-field" moderate resolution imaging for CMDs (presumably near-IR)

Parting Thoughts

- CMD work critically dependent on Strehl properties and stability of AO system – how limiting?
- Crowding problematic for youngest clusters, at all distances beyond LMC – how to address?
- Nature of Schmidt law dictates that most intense SF regions tend to be deeply embedded – mid-IR capability extremely powerful, unique

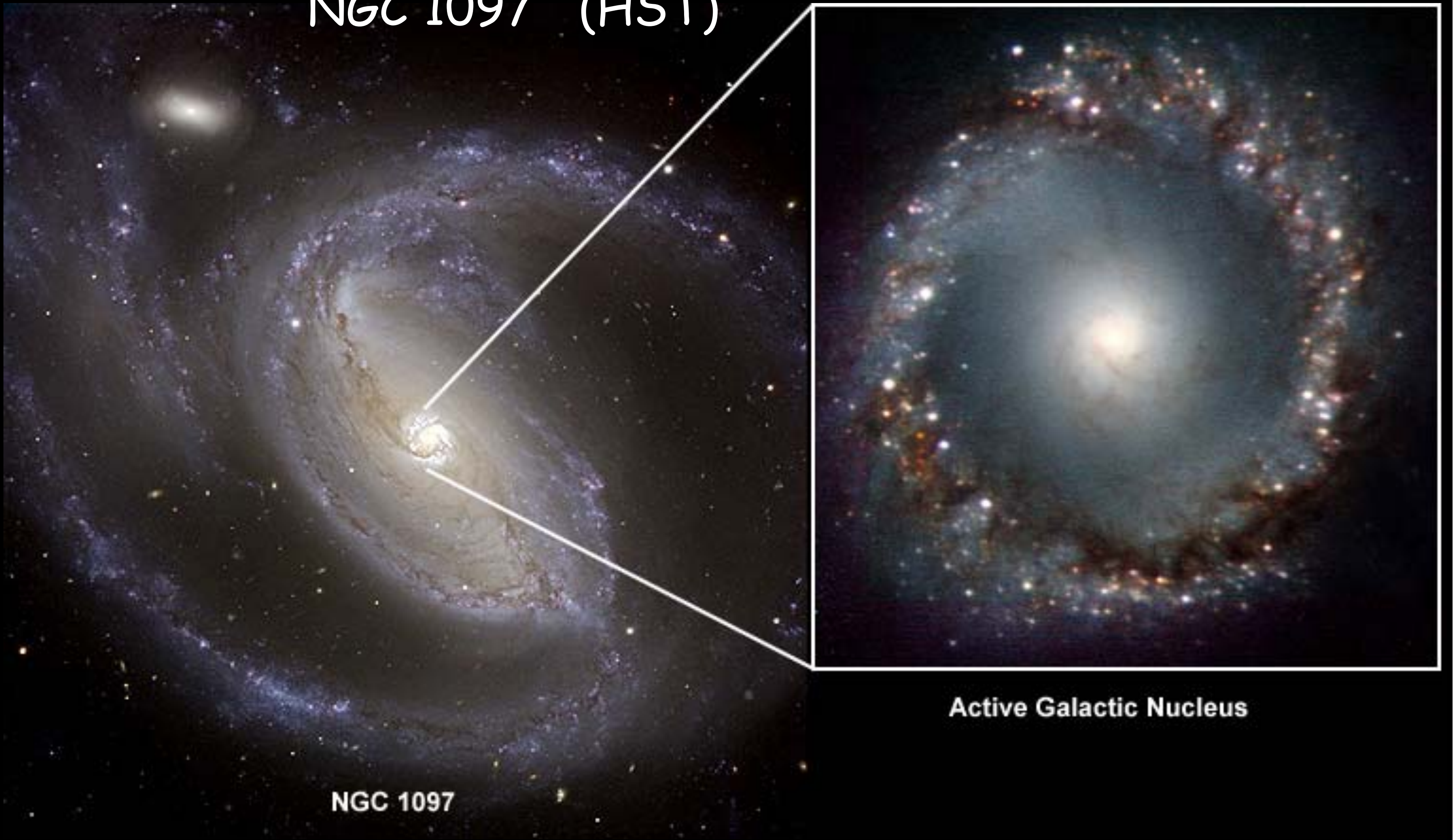

Arches Cluster
Quintuplet Cluster
1 light year
2 light years
Star Clusters Near the Center of the Galaxy
HST • NICMOS
PRC99-30 • STScI OPO • D. Figer (STScI) and NASA

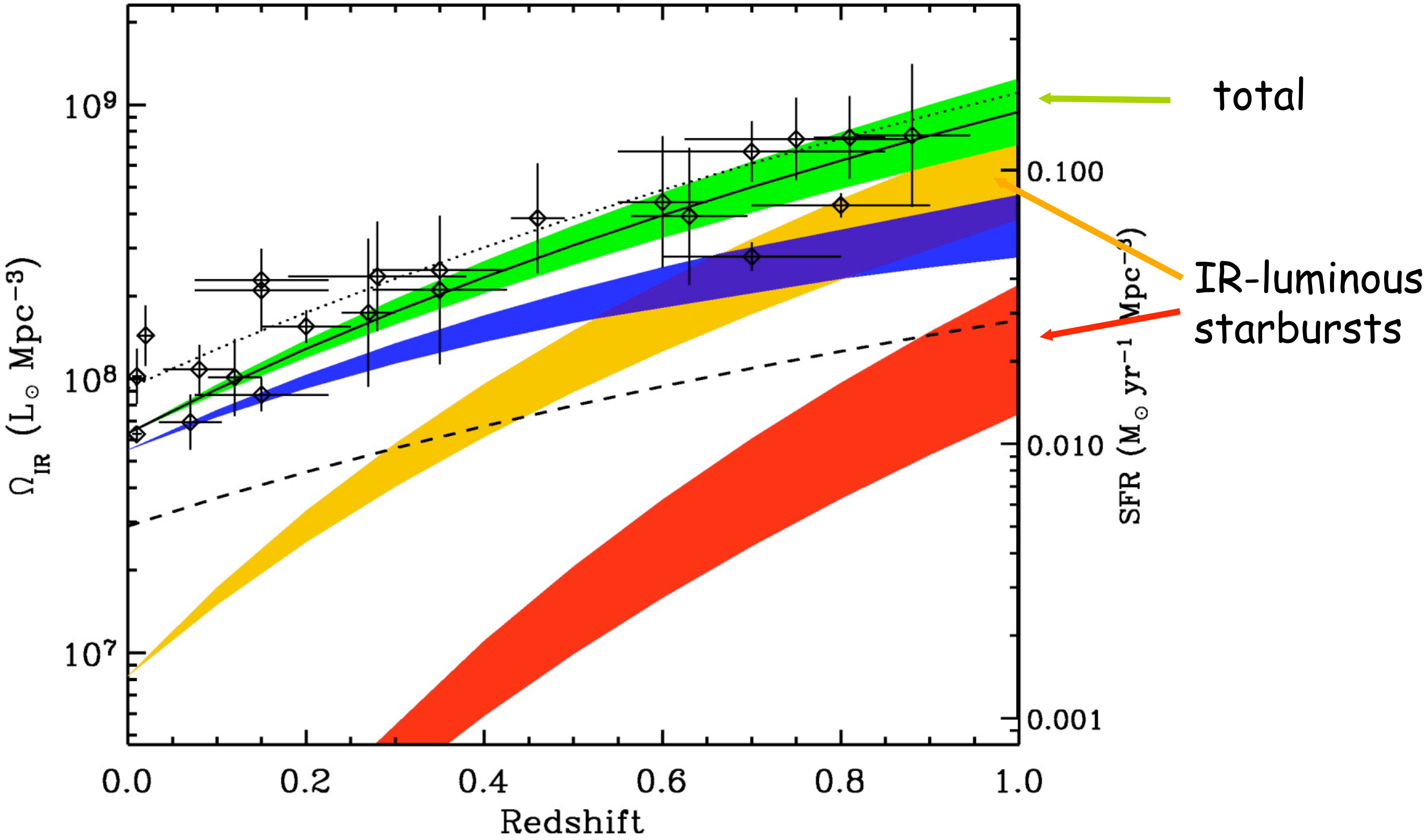
11 Mpc Hα Survey: (Kennicutt et al. 2007)



Two Asymptotic Modes of Star Formation

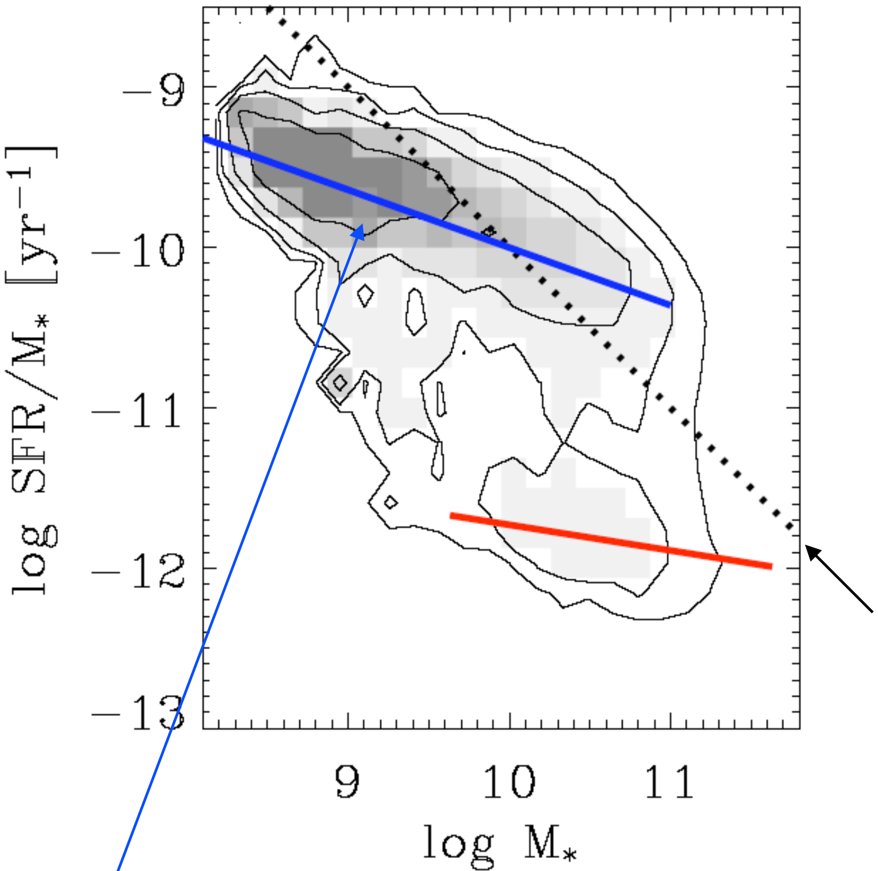
NGC 1097 (HST)





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

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



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

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

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

$\mathrm{SFR} = 1\ \mathrm{M}_\odot\ yr^{-1}$

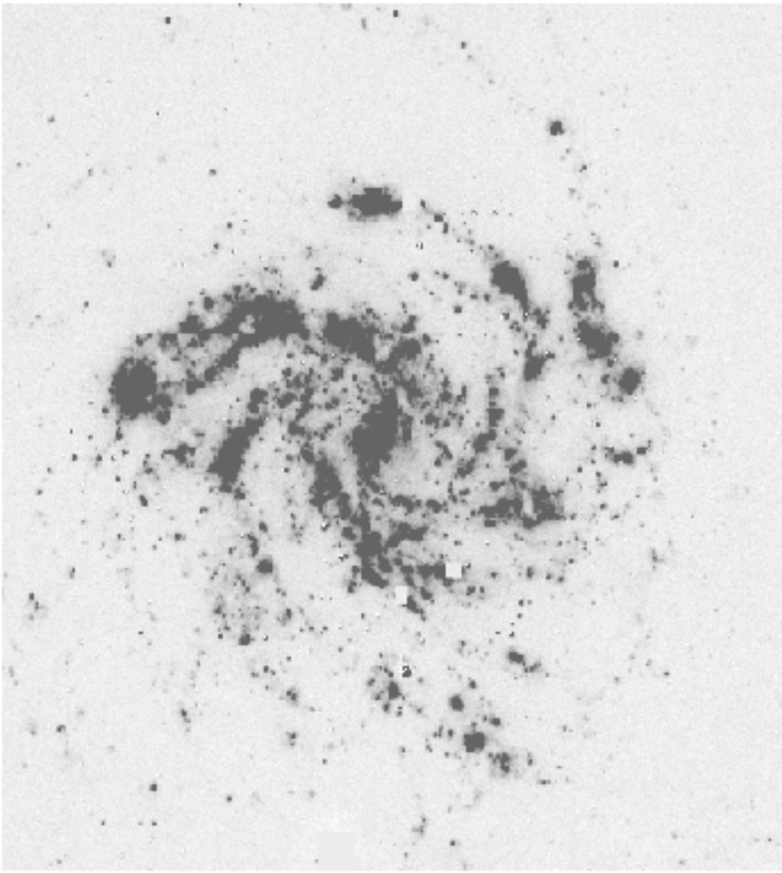
$$\log SFR/M_* = -0.35(log M_* - 10) - 9.83$$

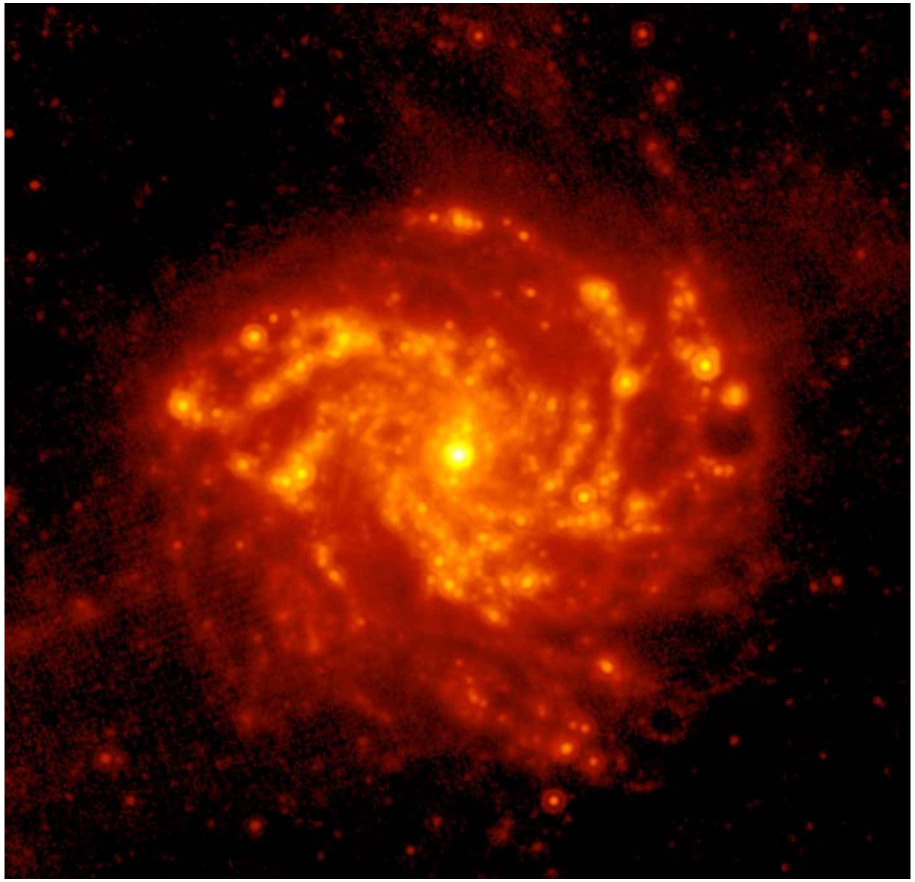
Schimminovich 2007

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

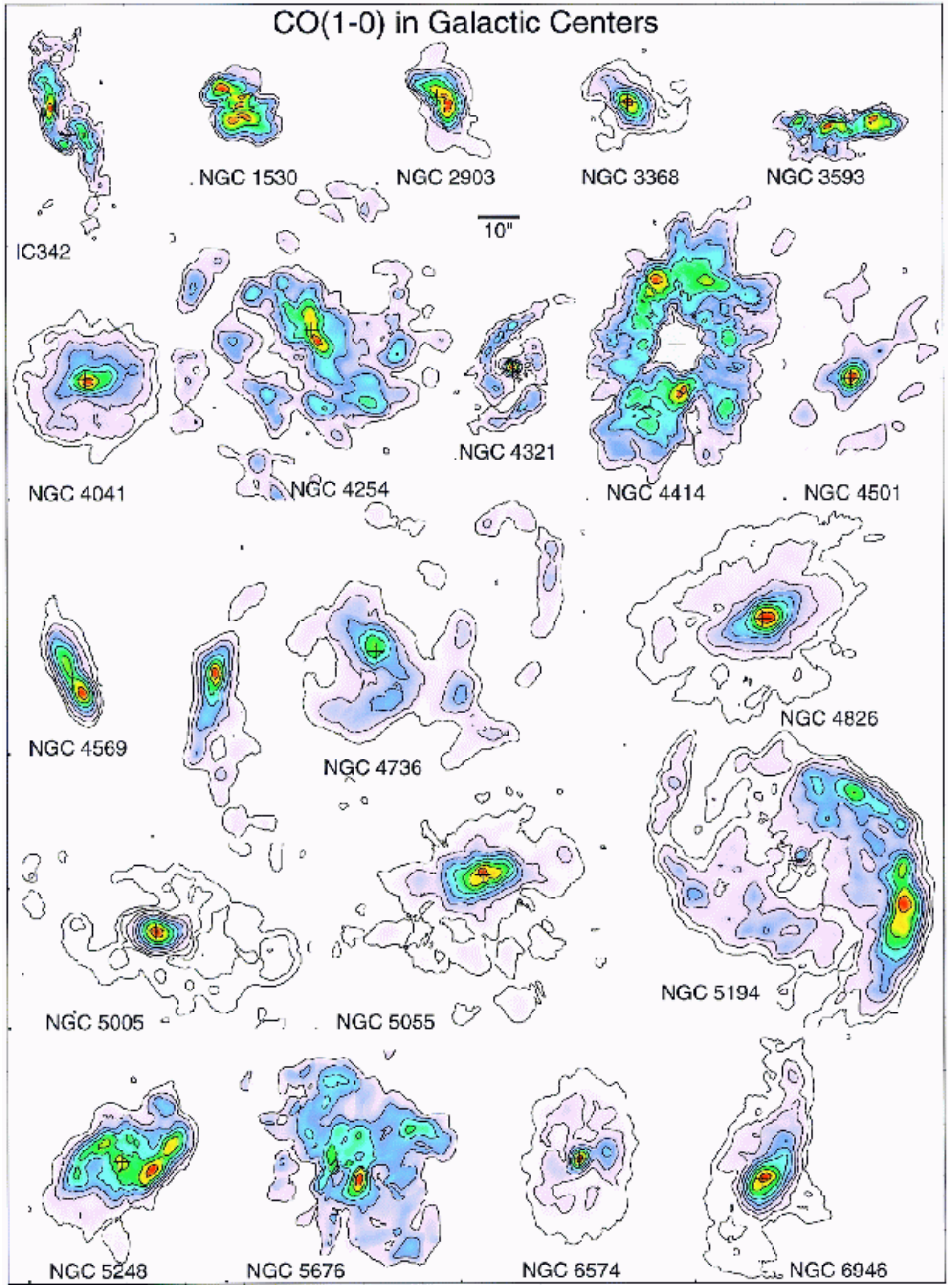
NGC 6946 Hα vs IR





Ferguson et al 1998, ApJ, 506, L19

Spitzer MIPS 24μm



Sakamoto et al. 1999

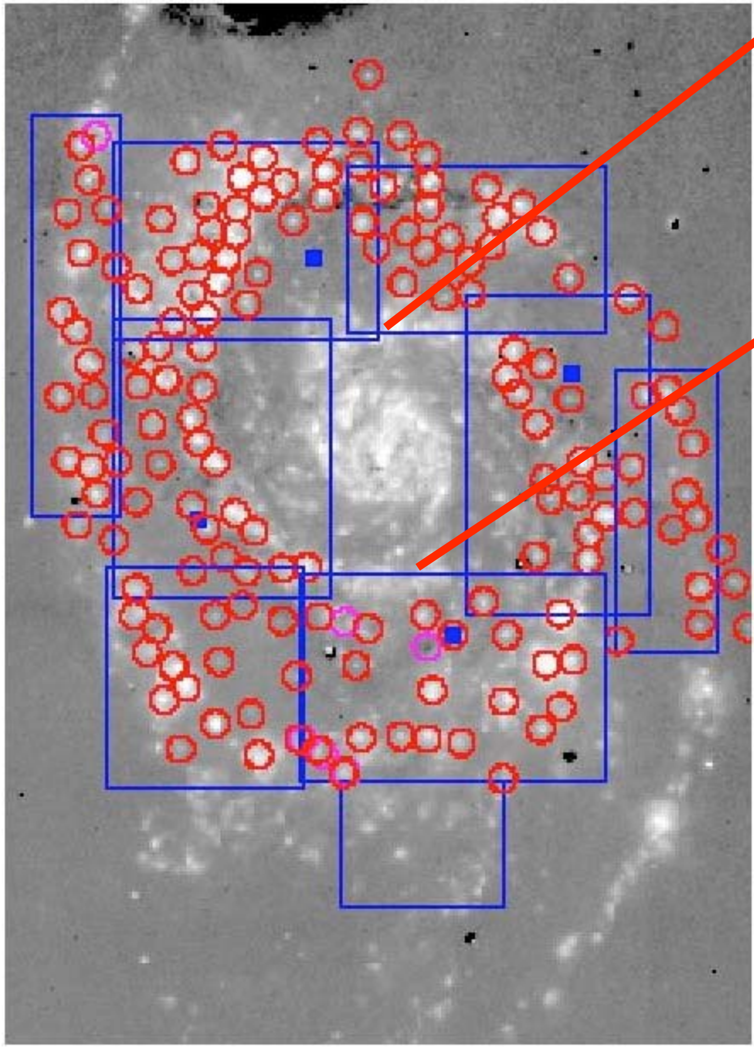
Things We Don't Understand

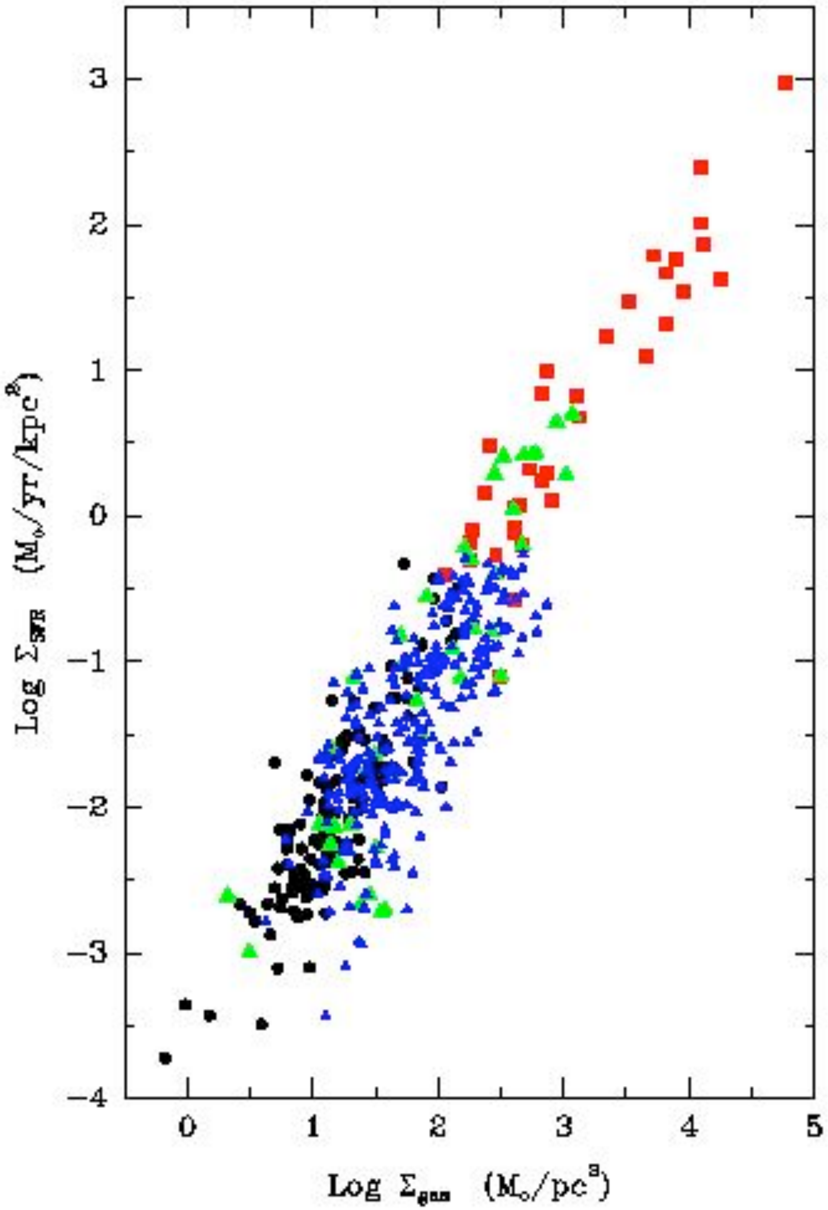
- How do the structure, mass spectrum, and dynamics of SF clouds vary in/among galaxies?
  - along the Hubble sequence, vs galaxy mass
  - vs clustering, from isolated clouds to Fabian's galaxy
  - near central black holes
- SF law
  - How does the global Schmidt law connect to SF on the cloud scale?
  - 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?

Things We Don’t Understand

- Three Dirty Acronyms: IMF, X_{CO}, τ_{dust}
  - robust SFR diagnostics
    - attenuation-corrected SFRs
    - systematics with Z/Z_o, P_{ISM}, B
  - extragalactic ISM
    - CO/H_2 and its behaviour →
    - systematics/evolution of cloud structure
  - IMF slope, turnover, mass limits
    - constrain variations vs redshift, SFR, pressure, clustering of SF
- Where is the physics?
  - How to we connect to the real physics of SF?

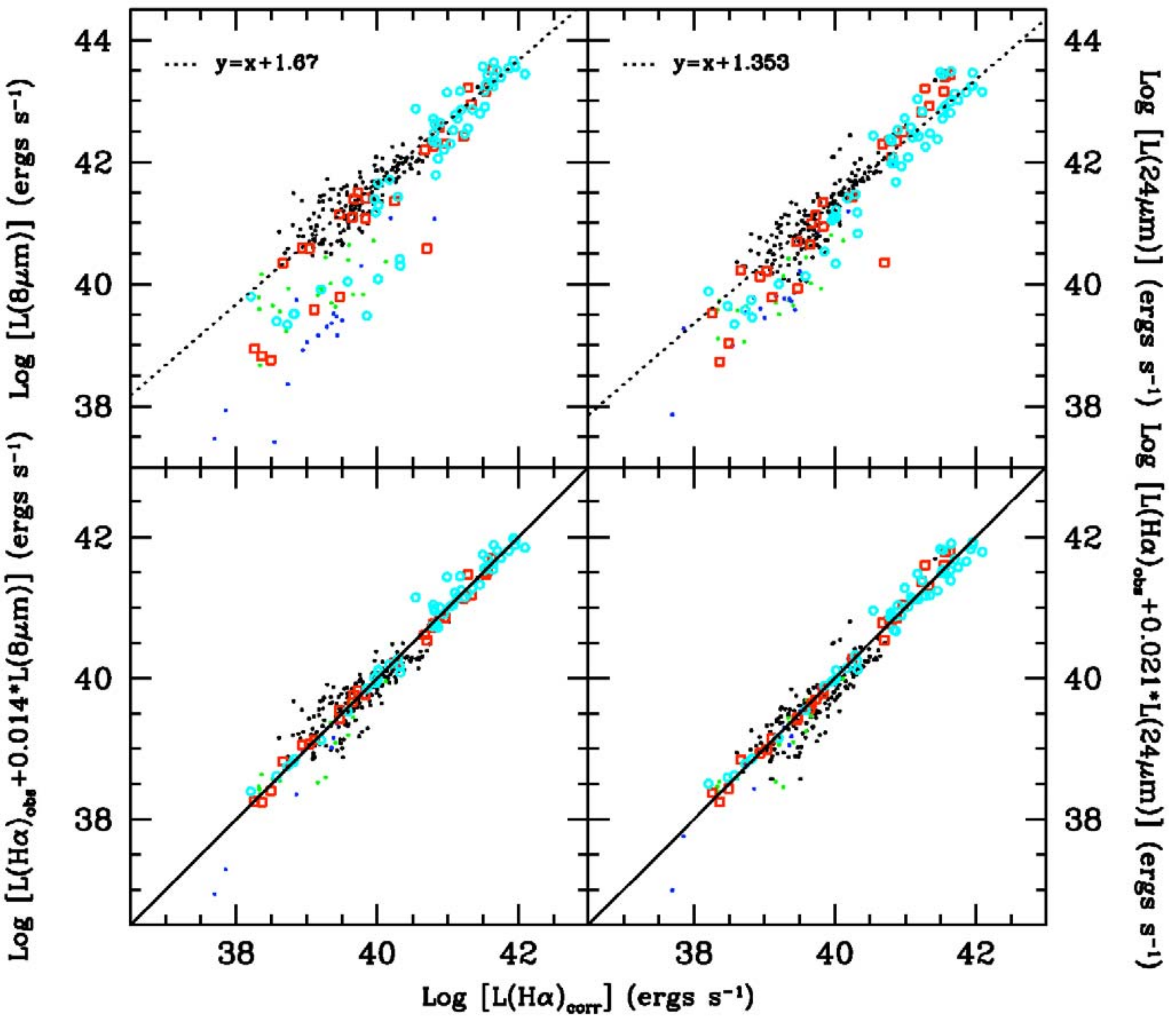
Local Schmidt Law in M51





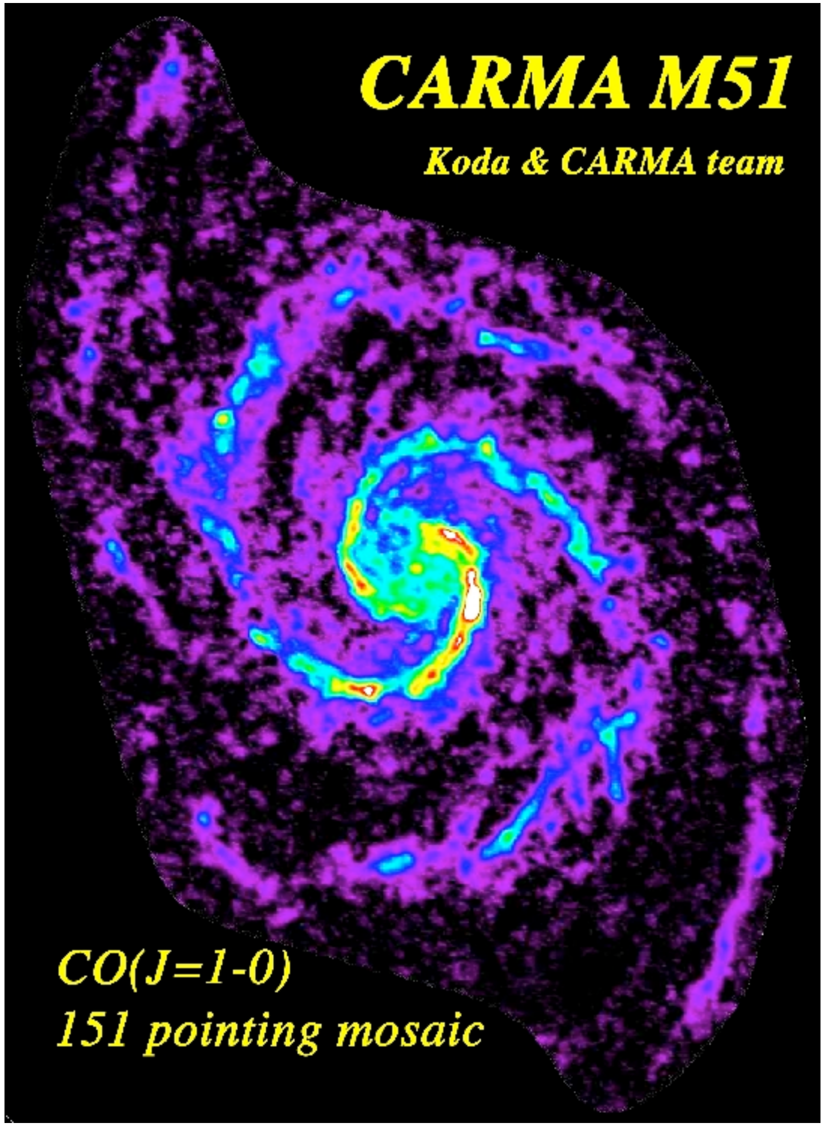
Kennicutt et al. 2007

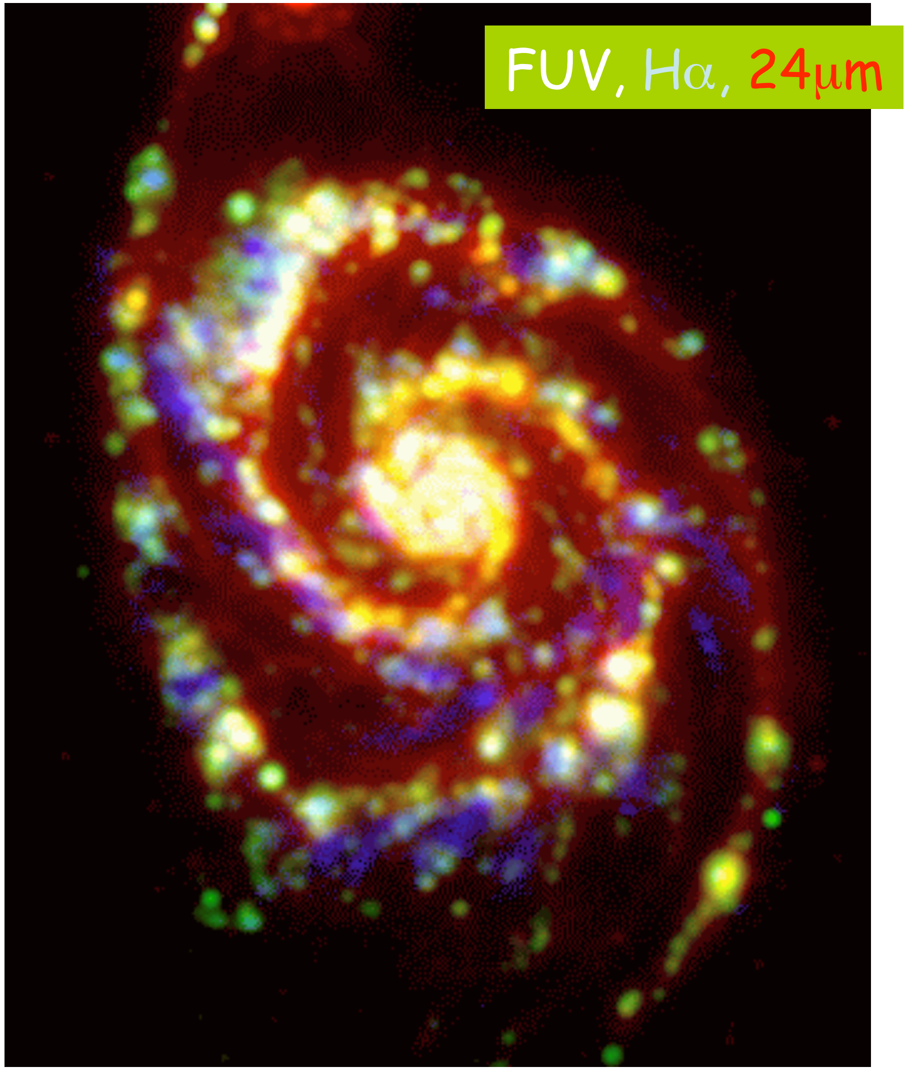
SINGS Sample: 8 μm and 24 μm



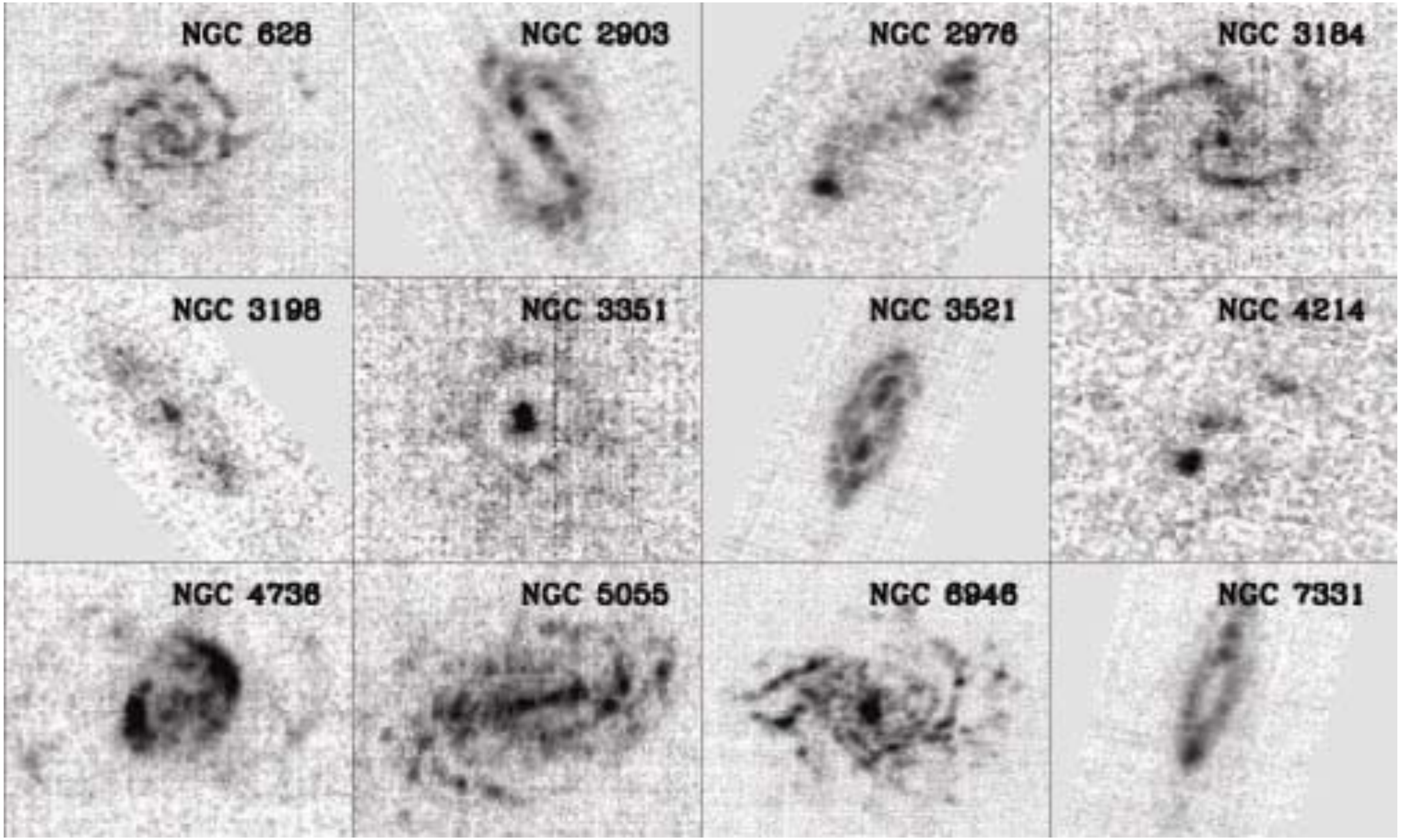
cold molecular gas

star formation

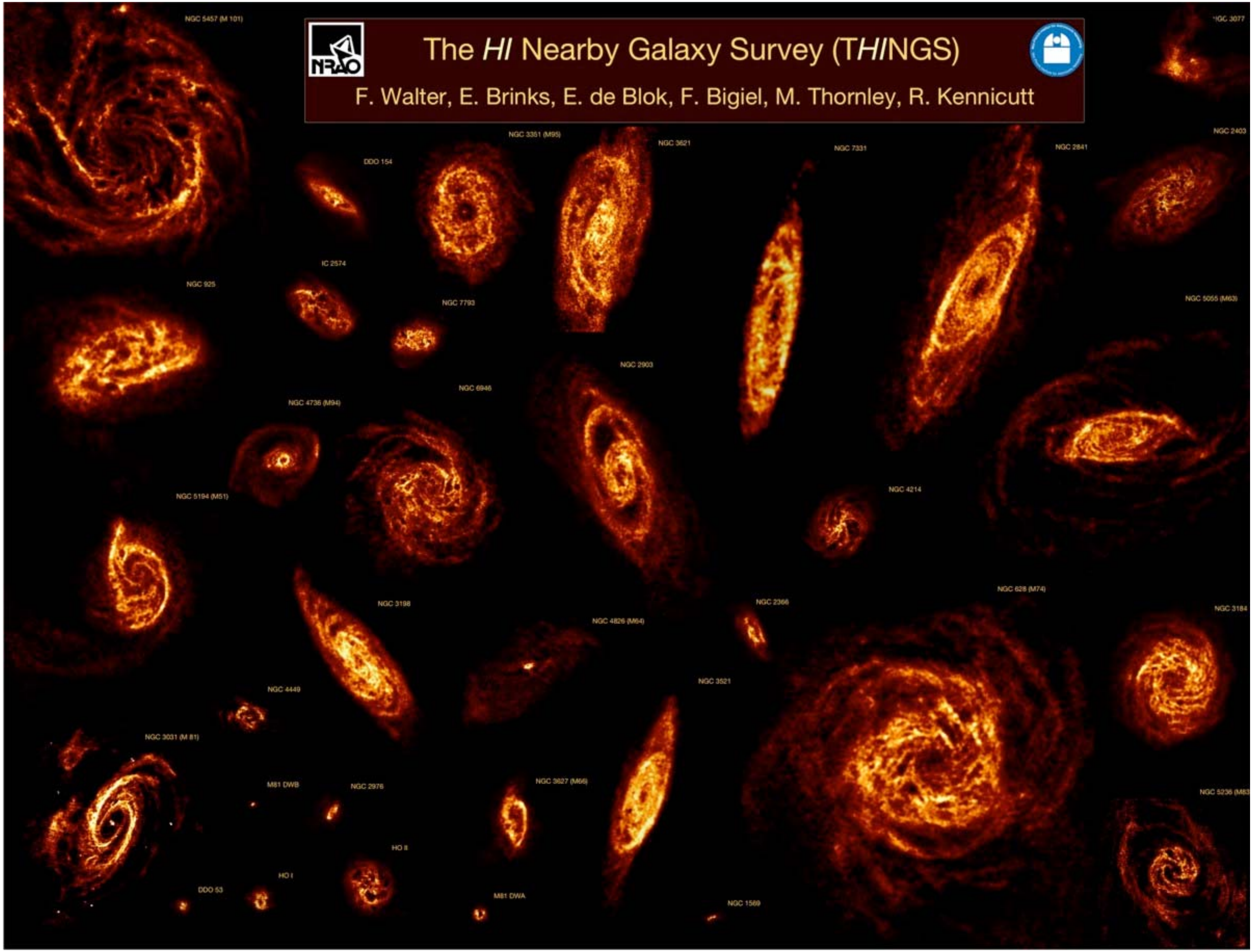




HERACLES CO 2-1 Survey



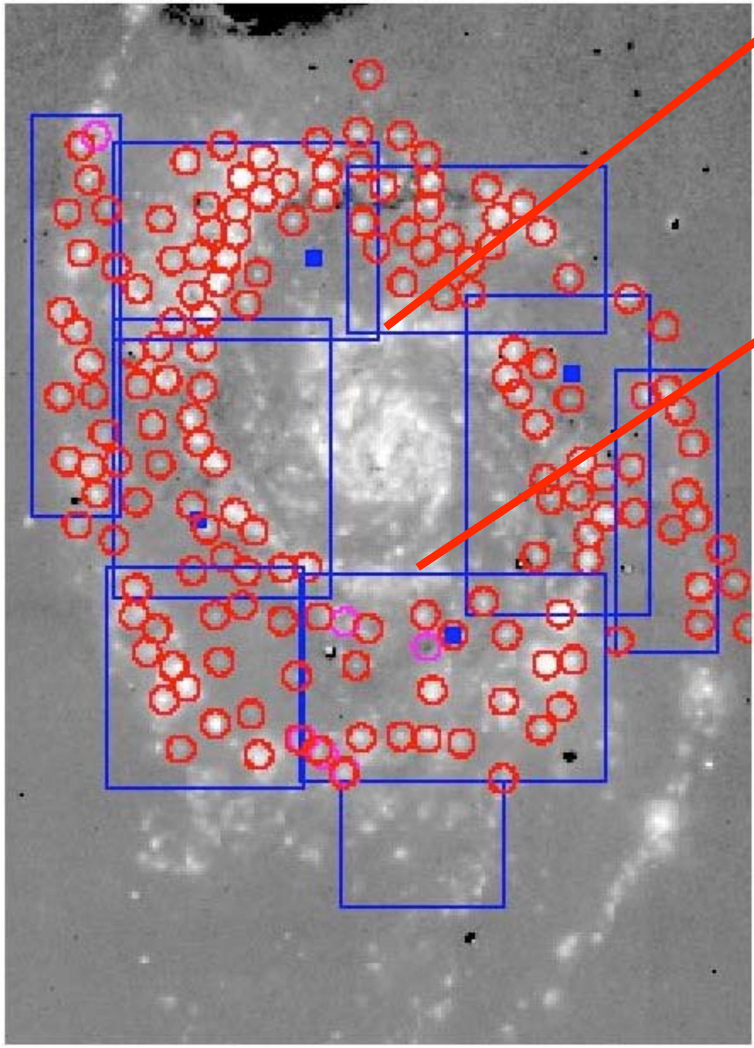
Leroy et al. 2008, submitted to AJ

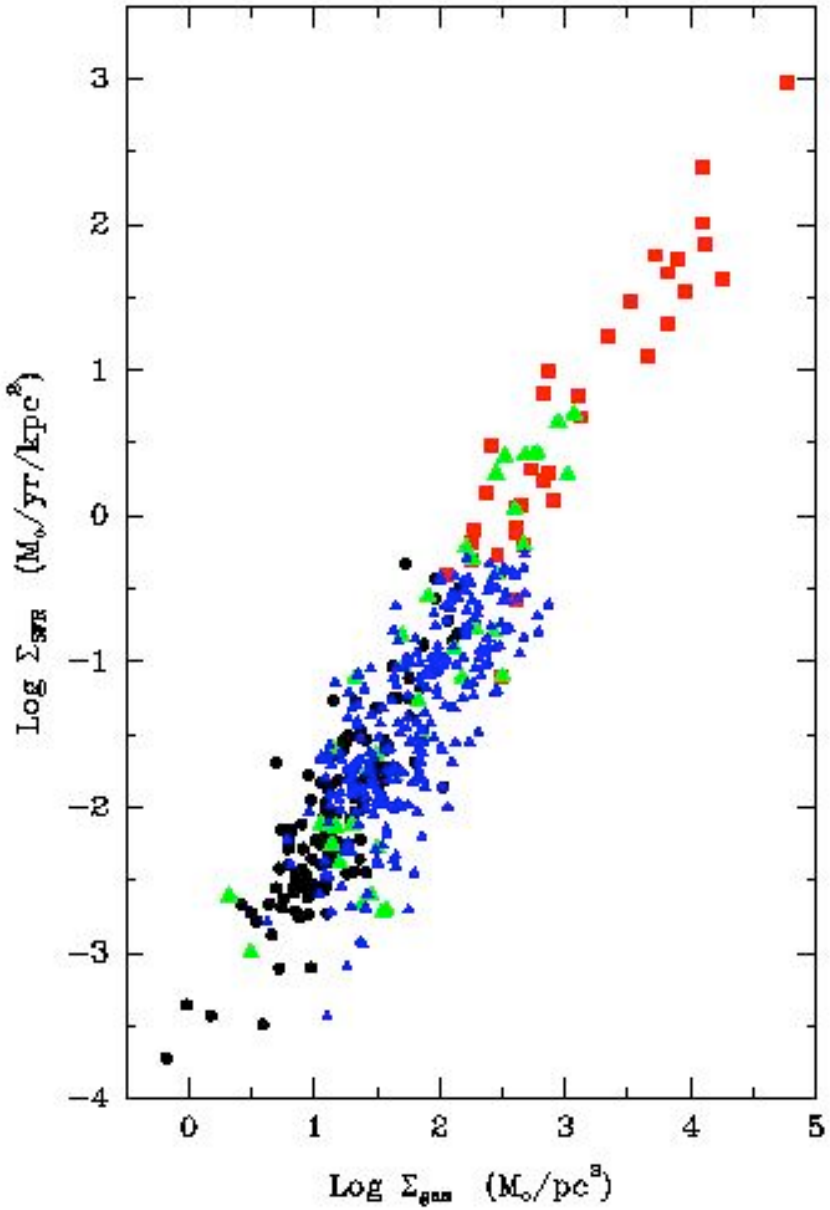

The HI Nearby Galaxy Survey (THINGS)
F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt
NGC 5457 (M 101)
DDO 154
NGC 3351 (M95)
NGC 3621
NGC 7331
NGC 2841
NGC 2403
IC 2574
NGC 925
NGC 7793
NGC 5055 (M63)
NGC 2903
NGC 6946
NGC 4736 (M94)
NGC 4214
NGC 5194 (M51)
NGC 628 (M74)
NGC 3198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

Local Schmidt Law in M51





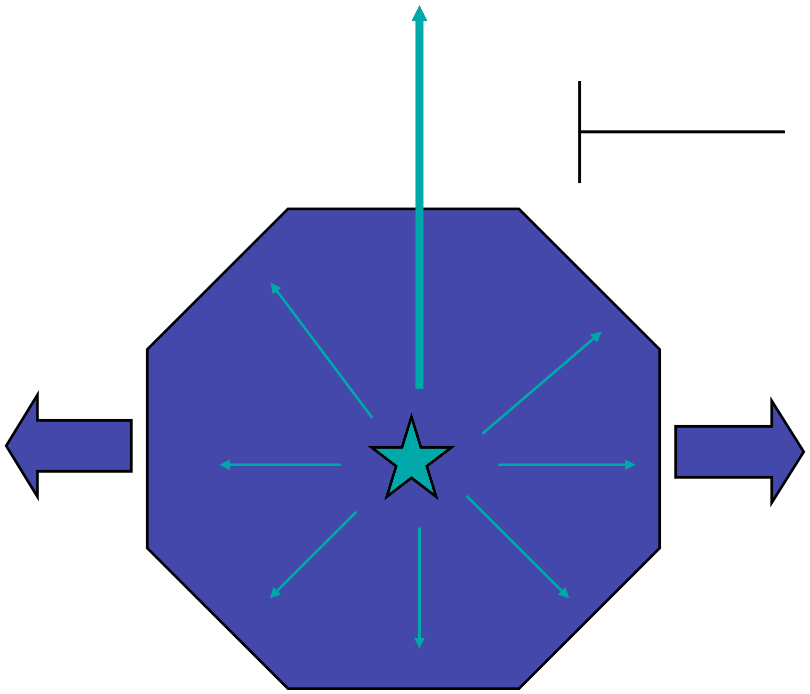
Kennicutt et al. 2007, ApJ, 671, 333

Method: Simple Energy Balance

Transmitted luminosity

$L(H\alpha)_{obs} = L(H\alpha)_{corr}\ e^{-\tau\,(H\alpha)}$

$L(H\alpha)_{obs} = \eta L(bol)\ e^{-\tau\,(H\alpha)}$



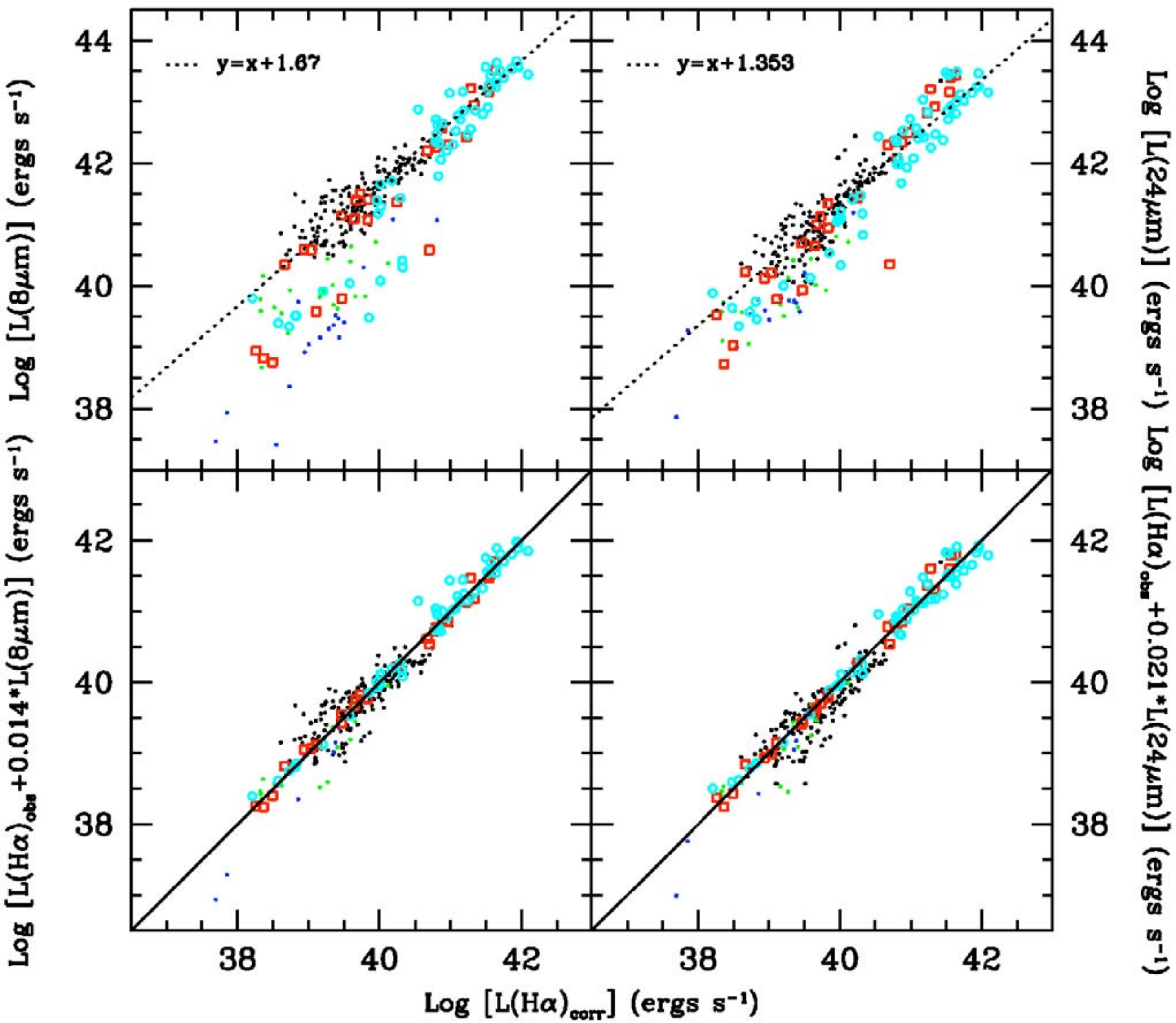
Dust re-emitted luminosity:

$L(TIR) = L(bol)\ (1 - e^{-\tau(eff)})$

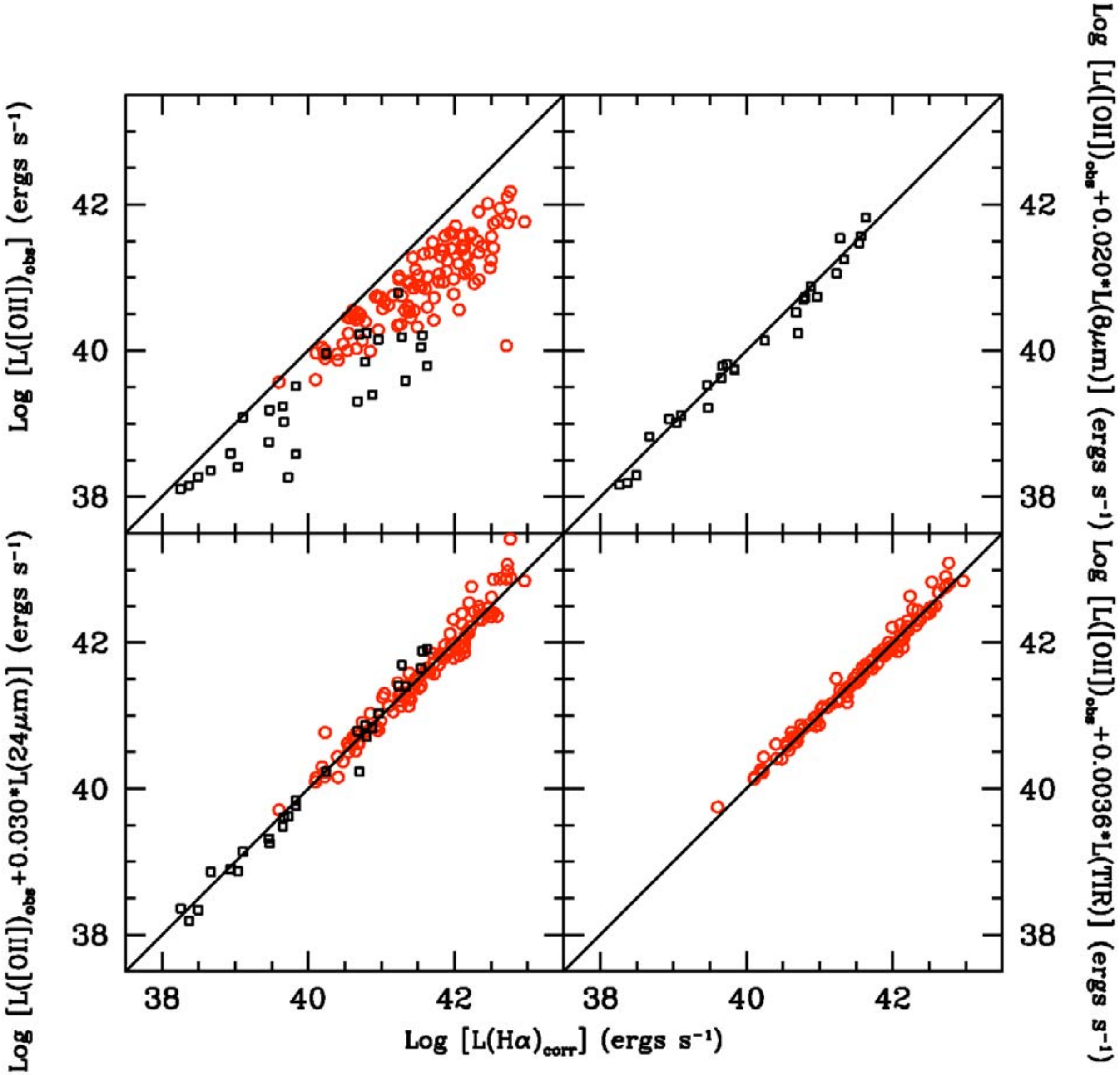
if $\tau(Ha) \sim \tau(eff)$

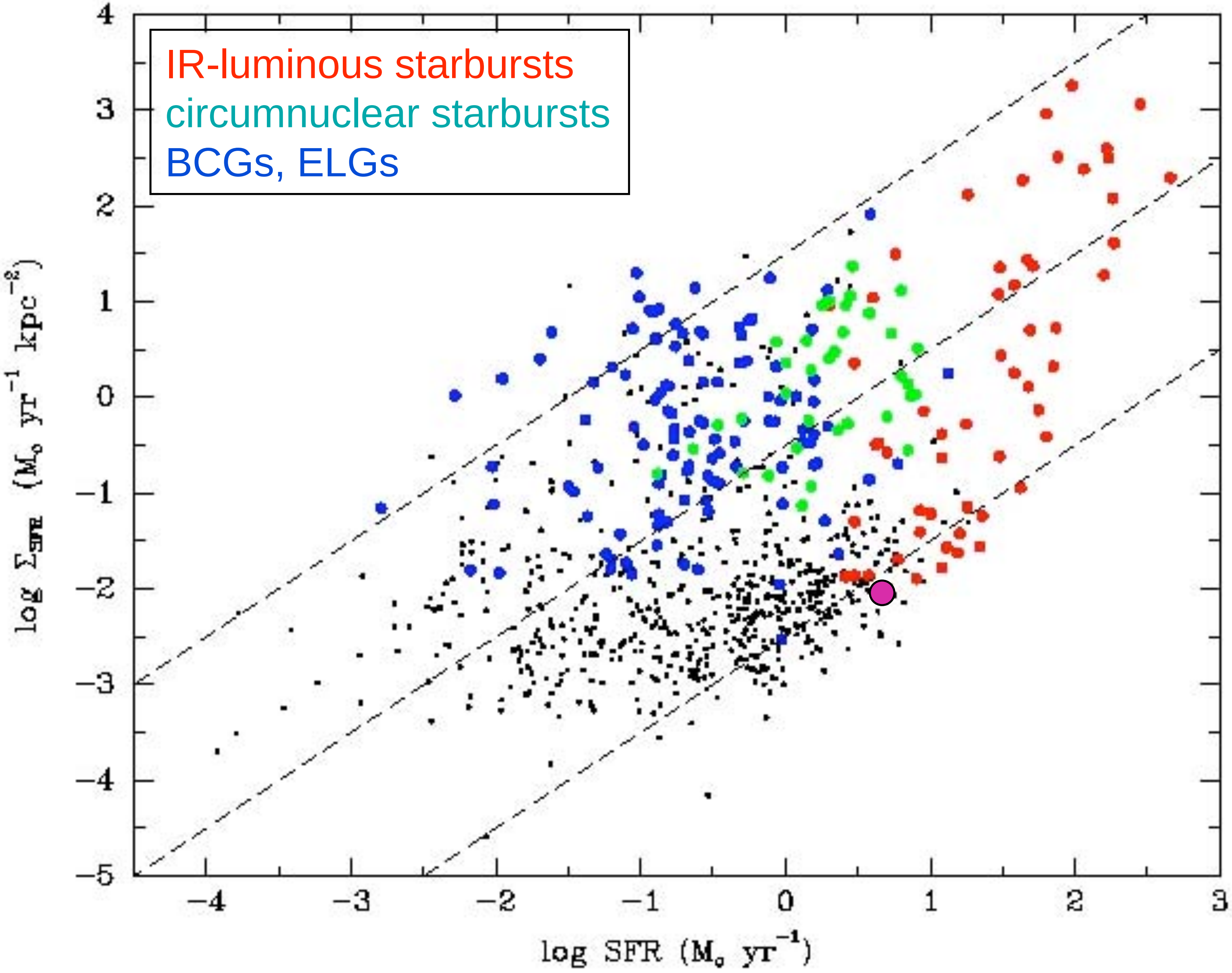
$L(H\alpha)_{corr} = L(H\alpha)_{obs} + \eta L(TIR)$

SINGS Sample: 8 μm and 24 μm



[OII] + 8μm, 24μm, TIR

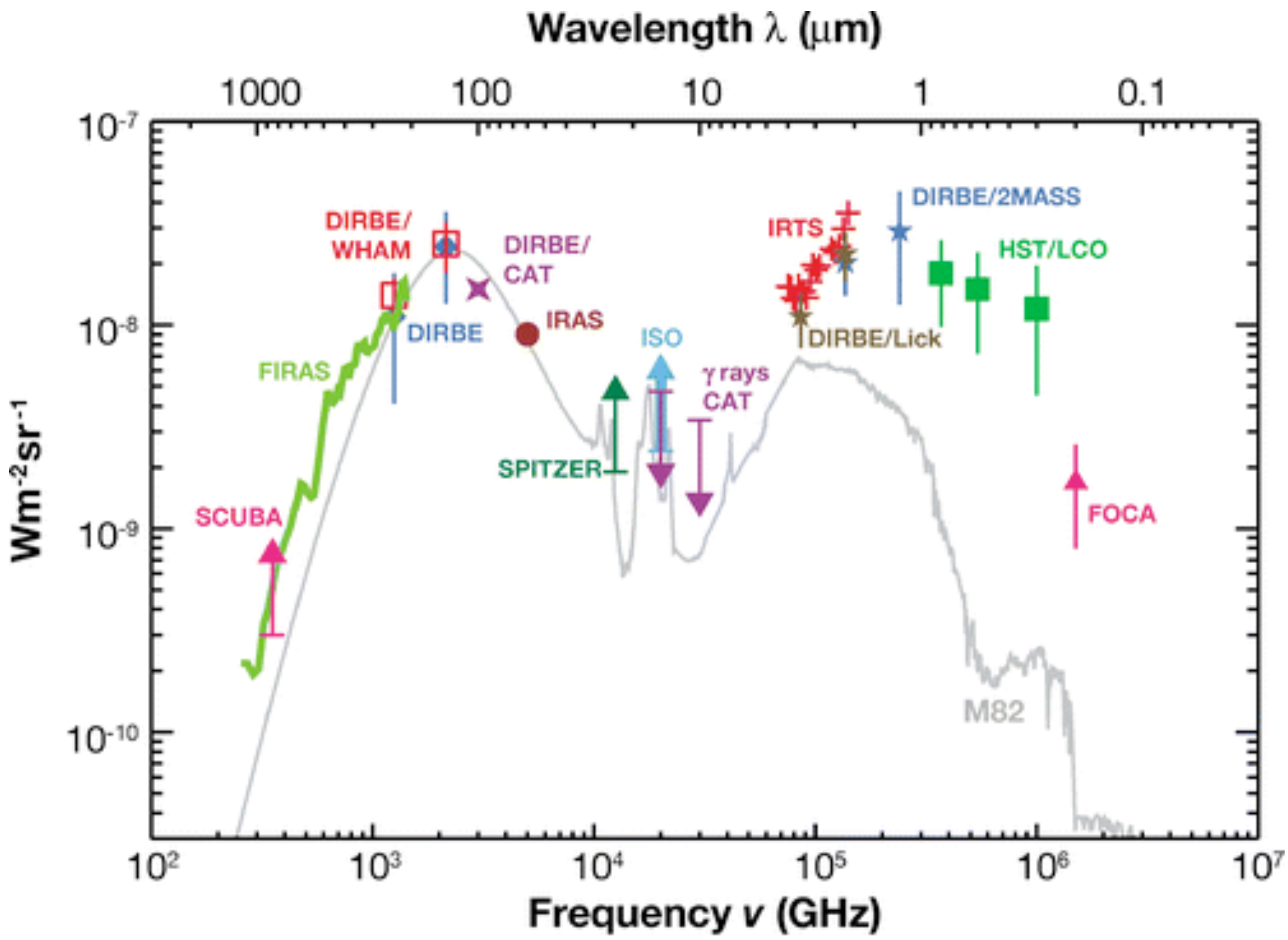




IR-luminous starbursts
circumnuclear starbursts
BCGs, ELGs
log Σ_SFR (M☉ yr⁻¹ kpc⁻²)
log SFR (M☉ yr⁻¹)
4
3
2
1
0
−1
−2
−3
−4
−5
−4
−3
−2
−1
0
1
2
3

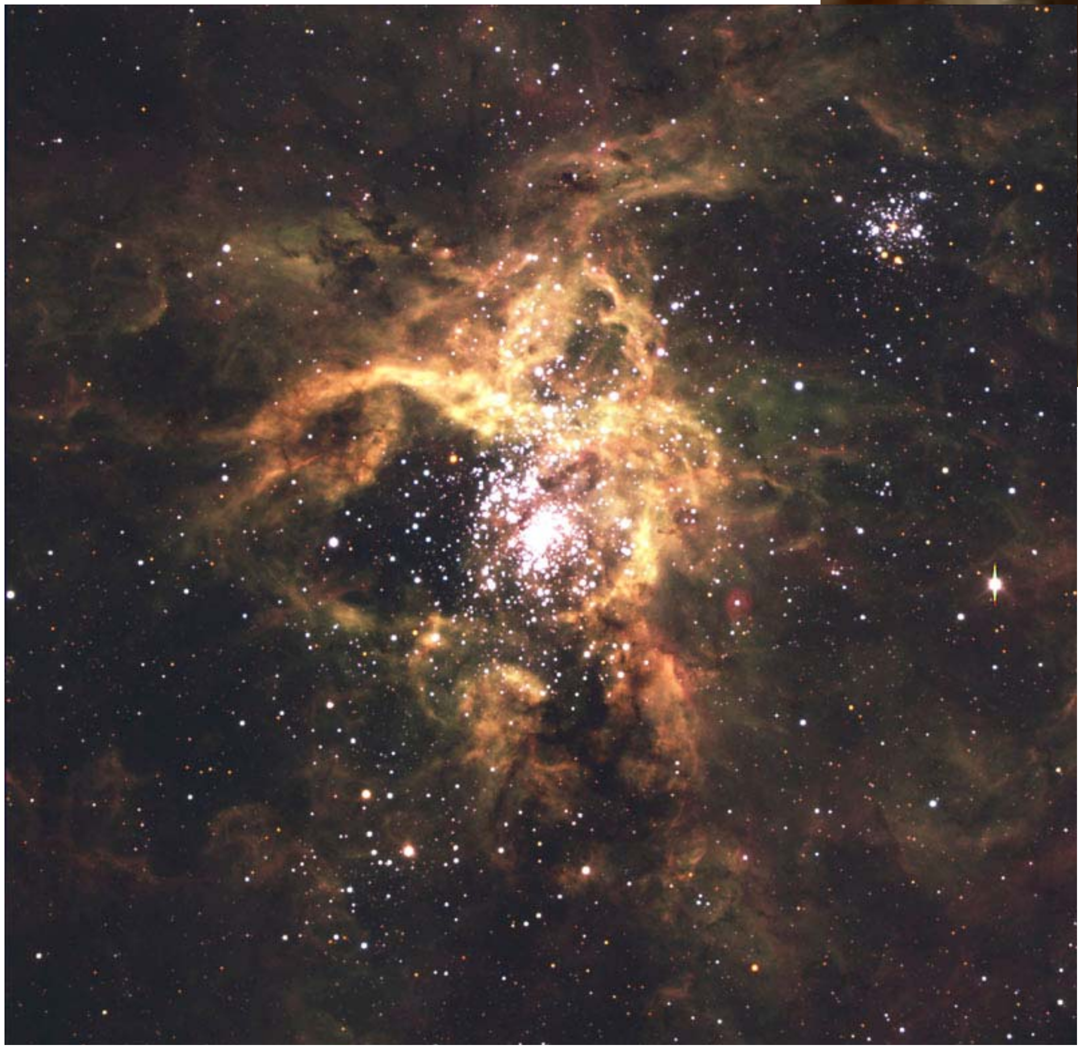
Key Applications (ELT + ALMA)

- 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 $\rightarrow$
  - 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

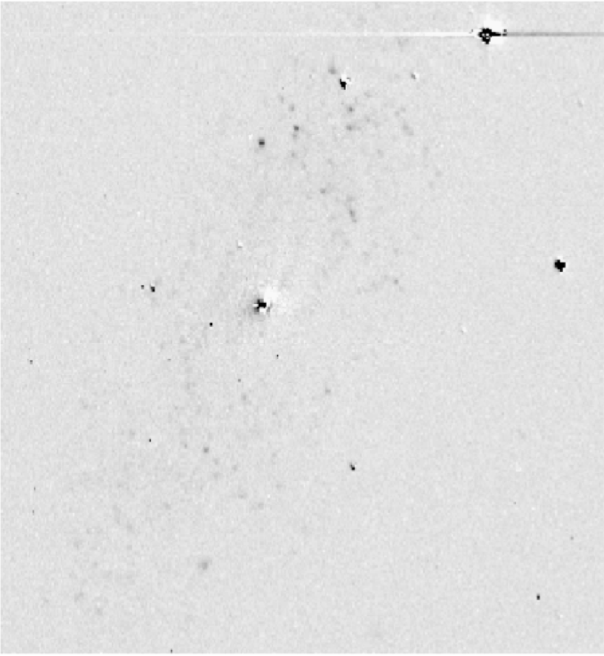


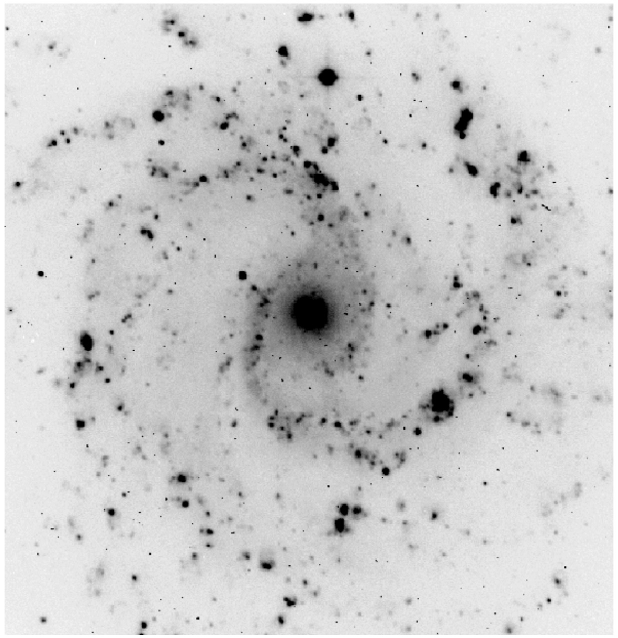
Lagache, G et al. 2005
Annu. Rev. Astron. Astrophys. 43: 727–68

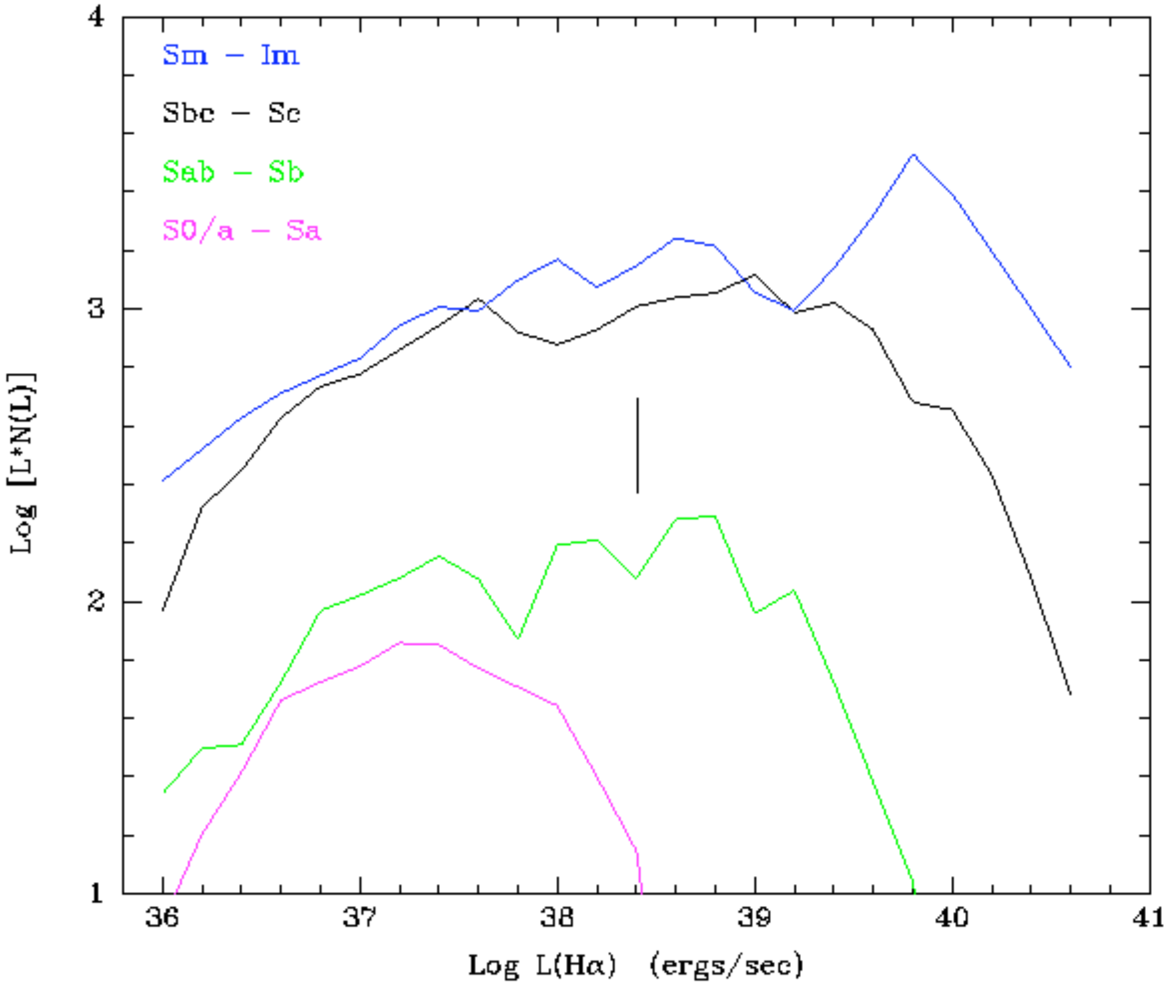
30 Doradus



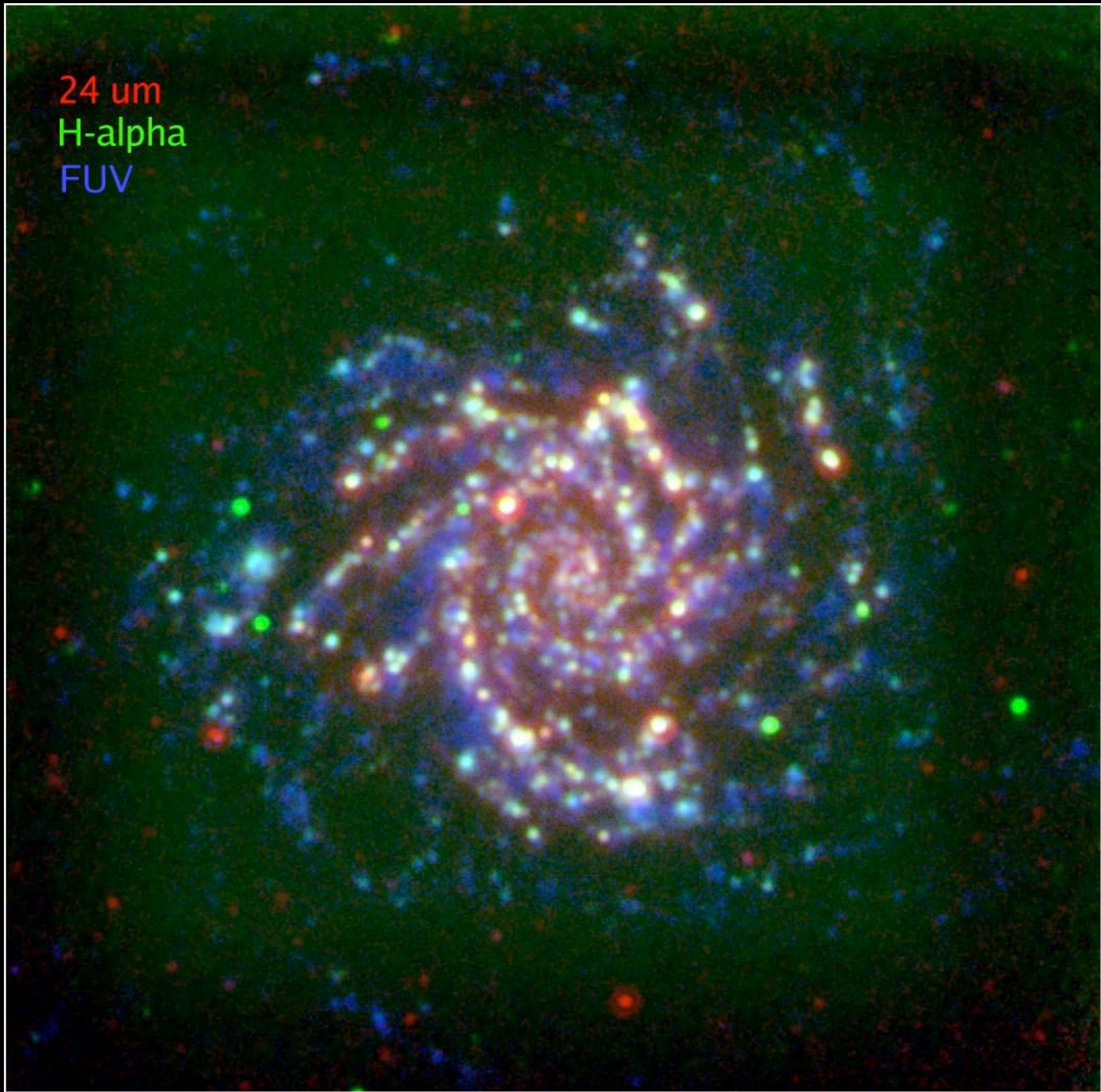
SFR increase reflects an increase in frequency of SF events, and a shift in the mass spectrum of single events





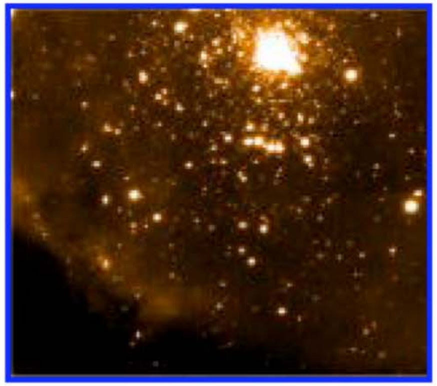


NGC 628
(M74)



C. Tremonti
11HUGS Team

E-ELT Science



Over the past five years the E-ELT science case has been developed by a substantial part of the the European astronomical community, largely under the auspices of the FP6 OPTICON network, led by Dr. Isobel Hook (Oxford) and Prof. Gerry Gilmore (Cambridge).

The E-ELT Science Working Group have consolidated the wide-range of science cases from the community and identified nine 'prominent' cases:

- Exo-planets (direct & indirect detection)
- The stellar initial mass function
- Stellar disks
- Resolved stellar populations
- Black holes
- The physics & evolution of galaxies
- The metallicity of the intergalactic medium
- 'First light' galaxies at the highest redshifts
- Dynamical measurement of the Universal expansion