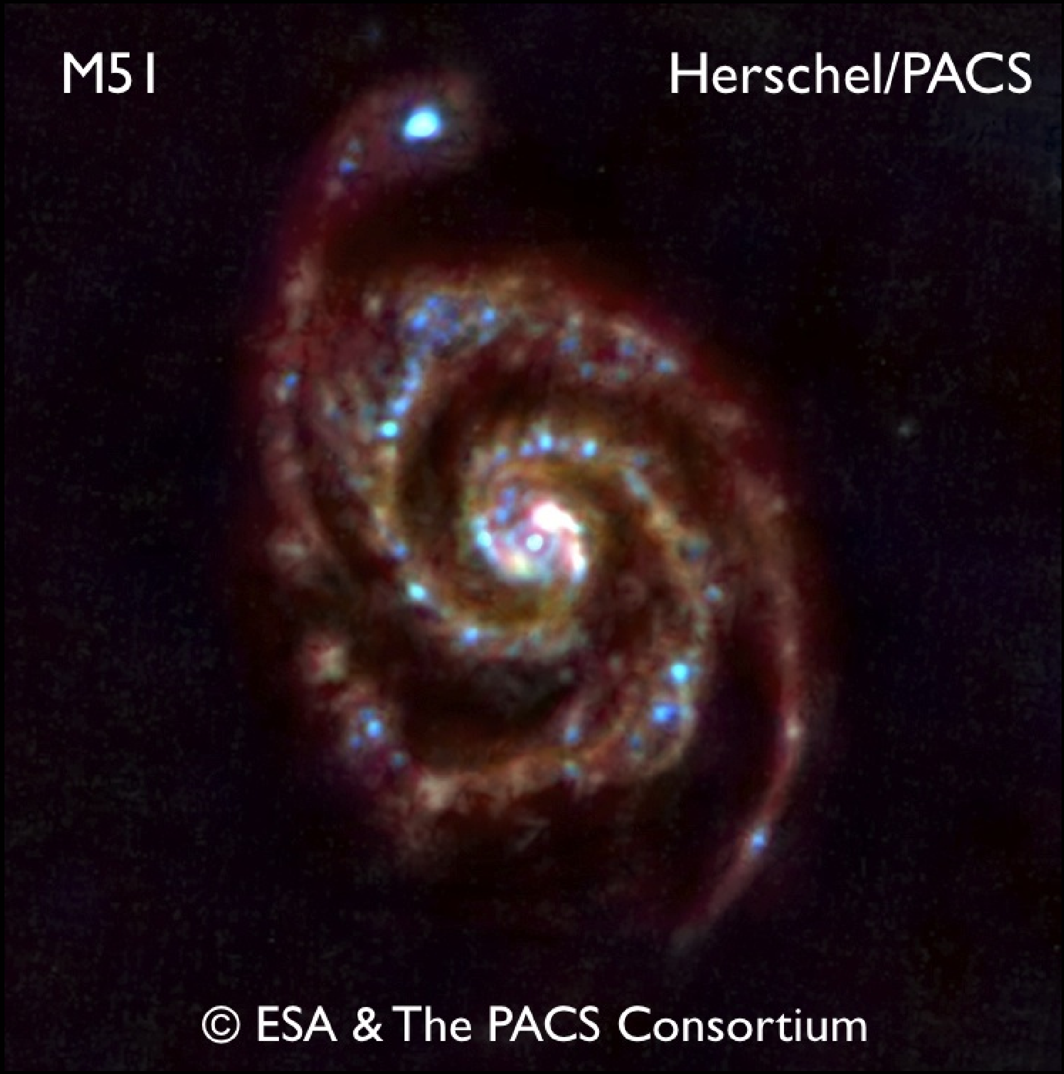
SFR@50
Lessons from the First 50 Years

Robert Kennicutt
Institute of Astronomy
University of Cambridge



THE ASTROPHYSICAL JOURNAL

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ASTRONOMICAL PHYSICS

VOLUME 129 MARCH 1959 NUMBER 2

THE RATE OF STAR FORMATION

Maarten Schmidt*
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology
Received October 29, 1958

$$\rho_{SFR} = a\ \rho^{n}_{gas}$$

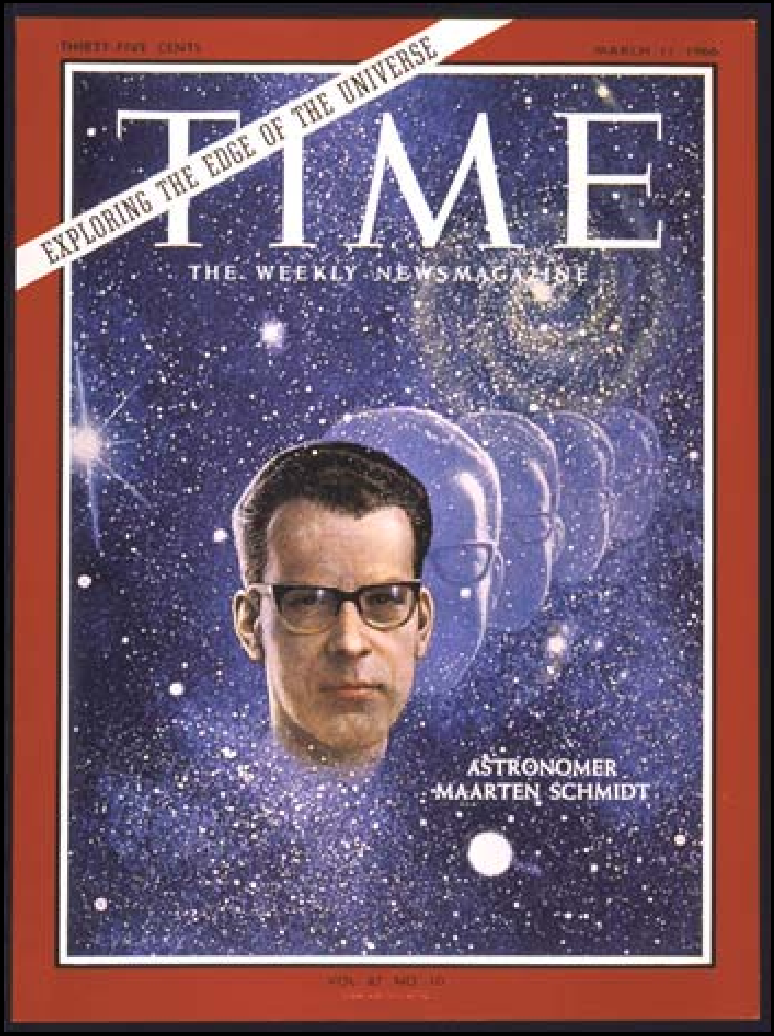
THE RATE OF STAR FORMATION. II. THE RATE OF FORMATION OF STARS OF DIFFERENT MASS

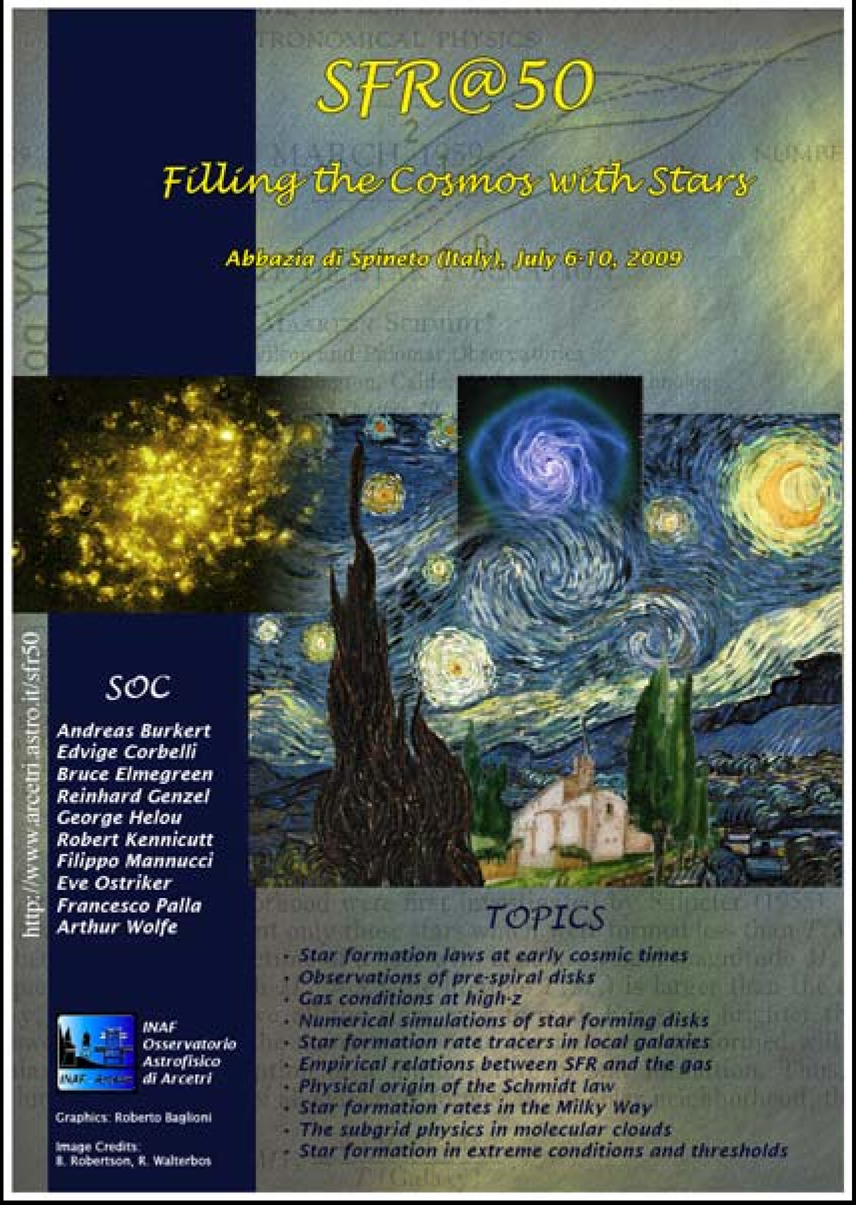
Maarten Schmidt
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology
Received October 8, 1962

$$\Sigma_{SFR} = A\ \Sigma^{N}_{gas}$$

Stages of Scientific Discovery

- Discovery (that eureka moment, "Holy ----!")
- Characterisation, phenomenology
  - number counts, classification (Types I, II, III, Ia, IIc…), channel maps, "JPEG science", "MPEG science"
  - complete samples, correlations, trends
- Synthesis, integration
  - theoretical interpretation (observational confirmation)
  - acceptance, widespread application, second-order discoveries, (over)interpretation
- Maturation, challenge, conflict
  - skepticism, contradition
  - professional amnesia and dementia, re-discovery


EXPLORING THE EDGE OF THE UNIVERSE
TIME
THE WEEKLY NEWSMAGAZINE
ASTRONOMER
MAARTEN SCHMIDT


SFR@50
Filling the Cosmos with Stars
Abbazia di Spineto (Italy), July 6-10, 2009
http://www.arcetri.astro.it/sfr50
SOC
Andreas Burkert
Edvige Corbelli
Bruce Elmegreen
Reinhard Genzel
George Helou
Robert Kennicutt
Filippo Mannucci
Eve Ostriker
Francesco Palla
Arthur Wolfe
TOPICS
· Star formation laws at early cosmic times
· Observations of pre-spiral disks
· Gas conditions at high-z
· Numerical simulations of star forming disks
· Star formation rate tracers in local galaxies
· Empirical relations between SFR and the gas
· Physical origin of the Schmidt law
· Star formation rates in the Milky Way
· The subgrid physics in molecular clouds
· Star formation in extreme conditions and thresholds
INAF
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Astrofisico
di Arcetri
Graphics: Roberto Baglioni
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B. Robertson, R. Walterbos

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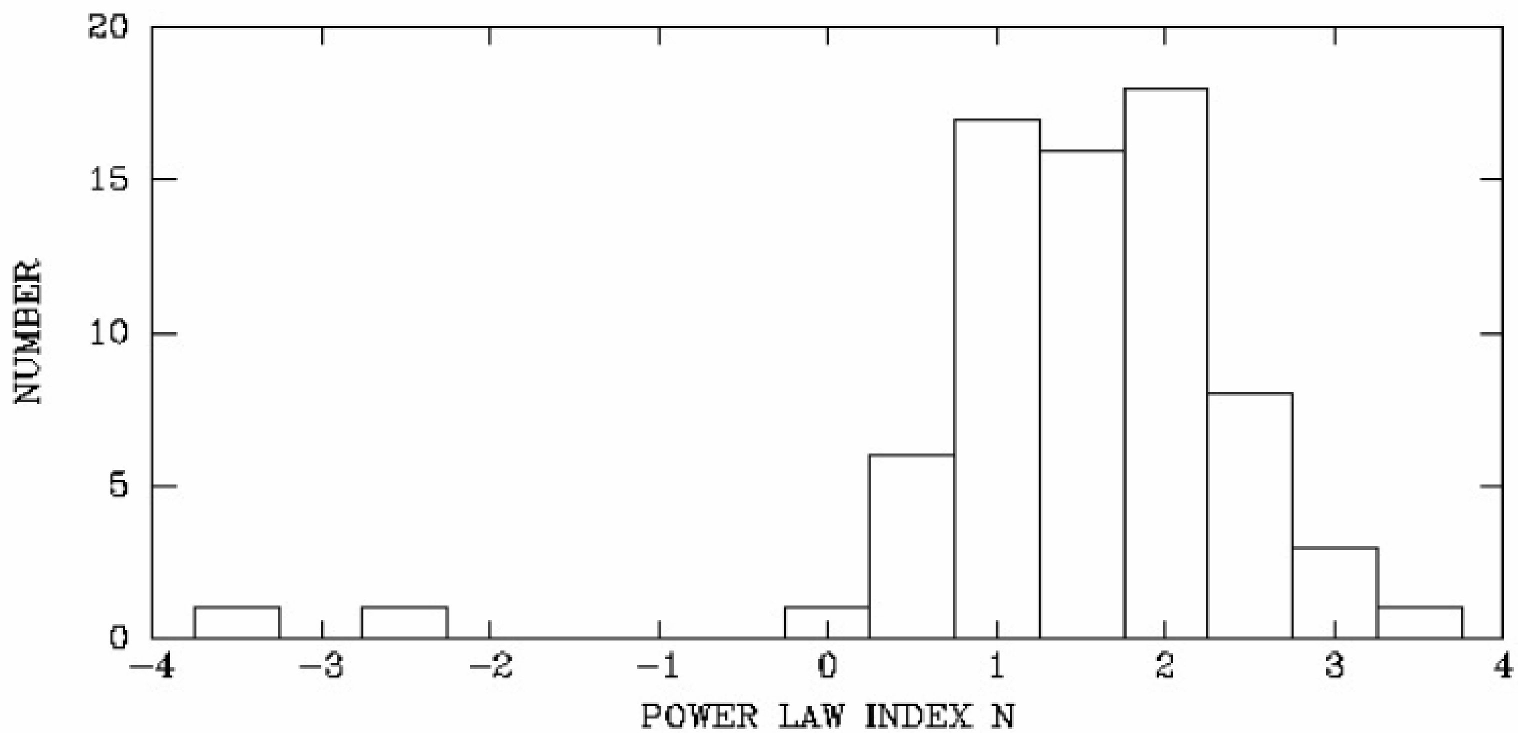
Derived Values of Schmidt Power-Law Index N
1960 - 1995



Kennicutt 1997

cf. Madore 1977, MNRAS, 178, 1

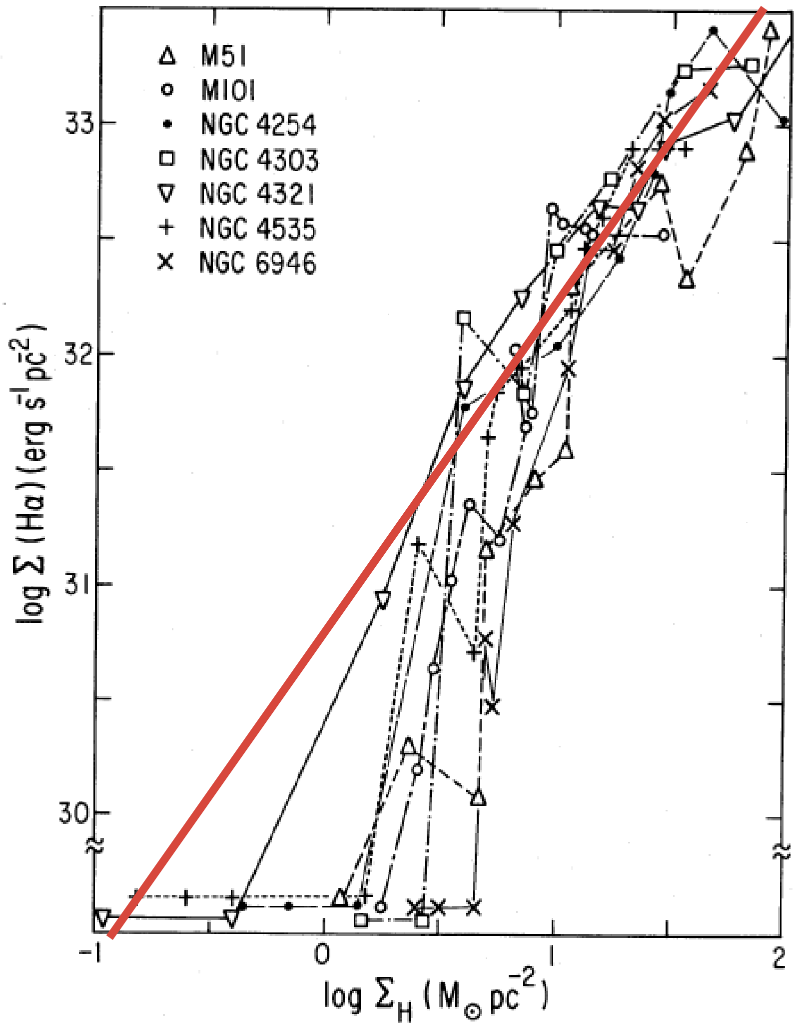
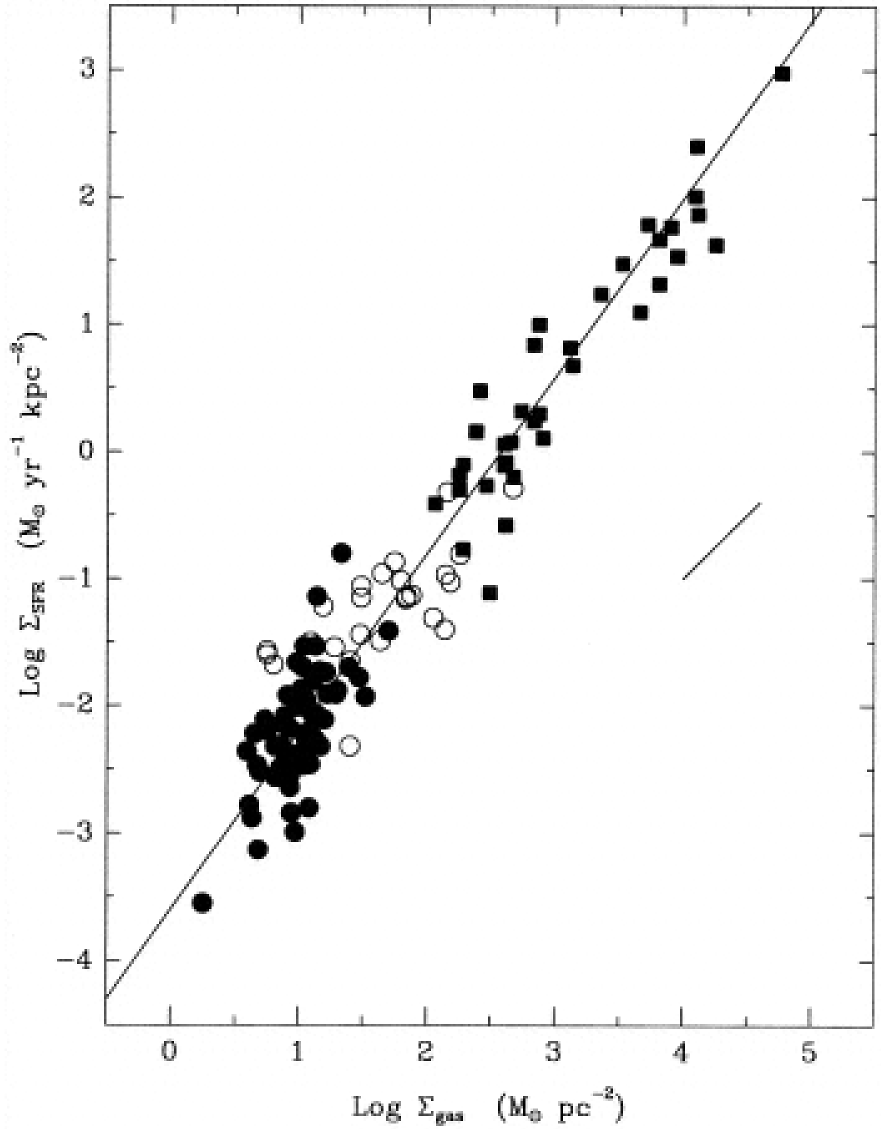
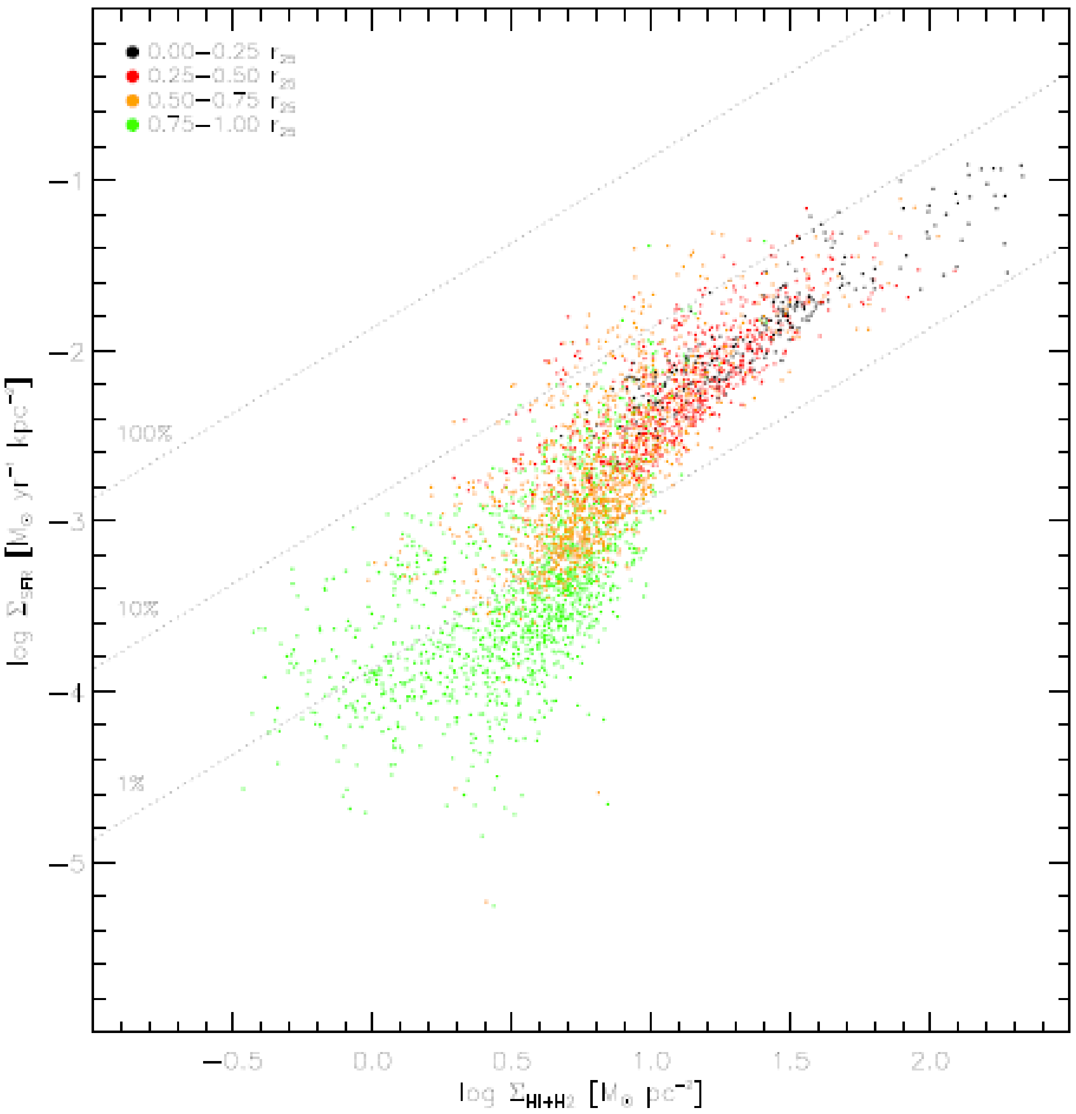
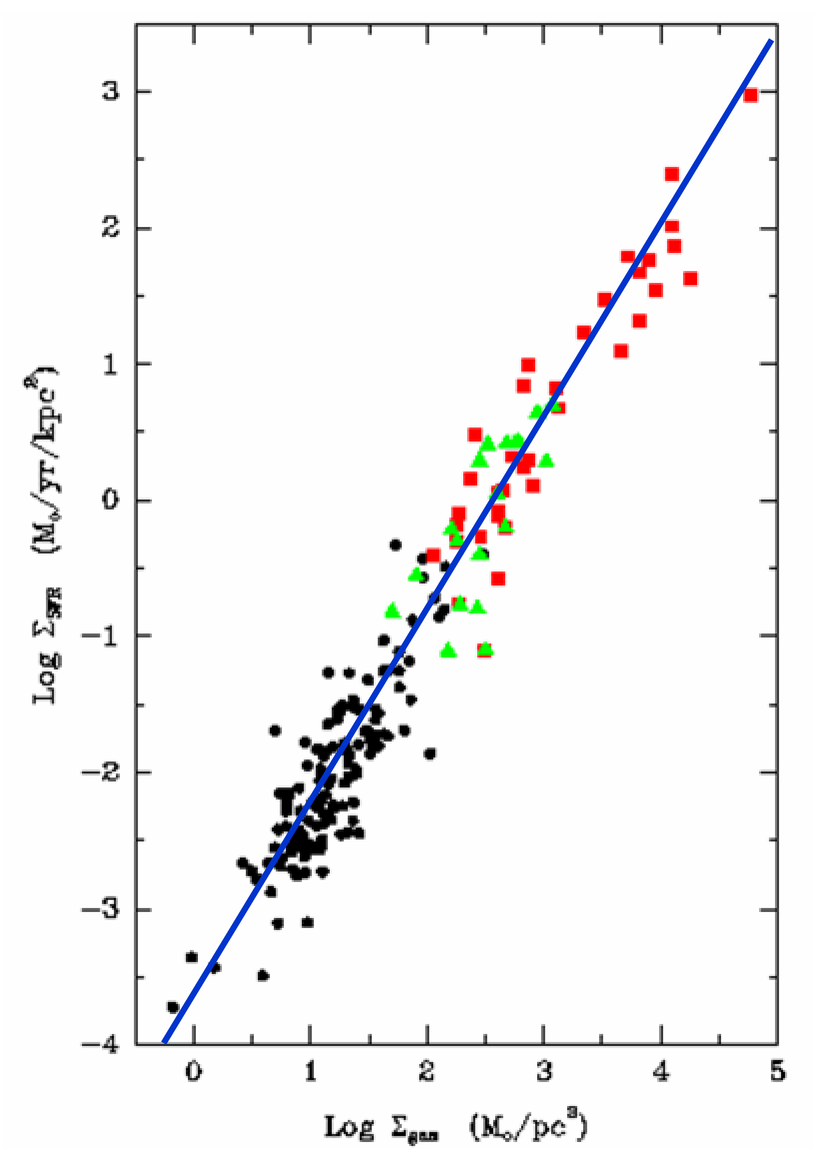


FIG. 8.—Dependence of Hα surface brightness on total (H I + H_2) hydrogen surface density, for seven giant Sc galaxies. Each point represents the Hα and gas densities averaged at a given galactocentric radius, and lines connect points at adjacent radii. The points at the bottom denote regions where no Hα emission was detected.

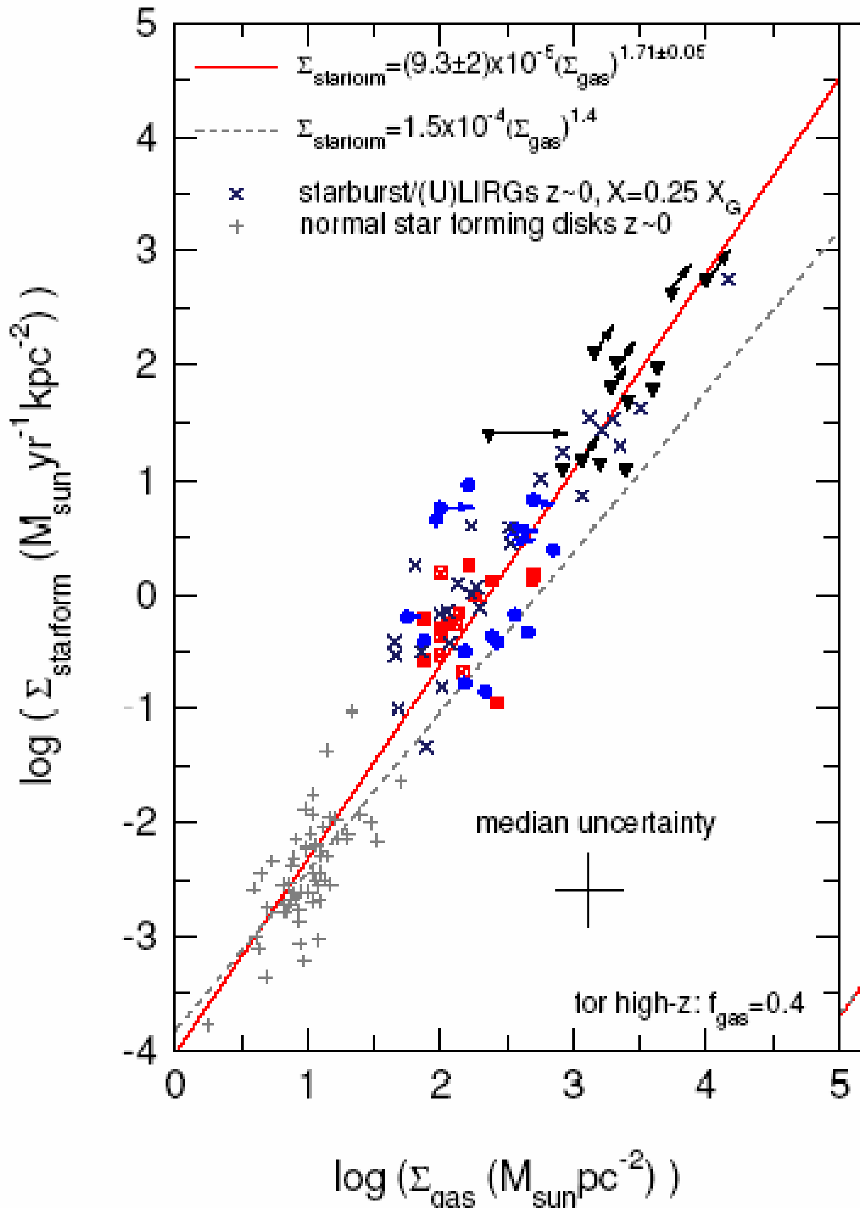




Bigiel et al. 2008, AJ, 136, 2846

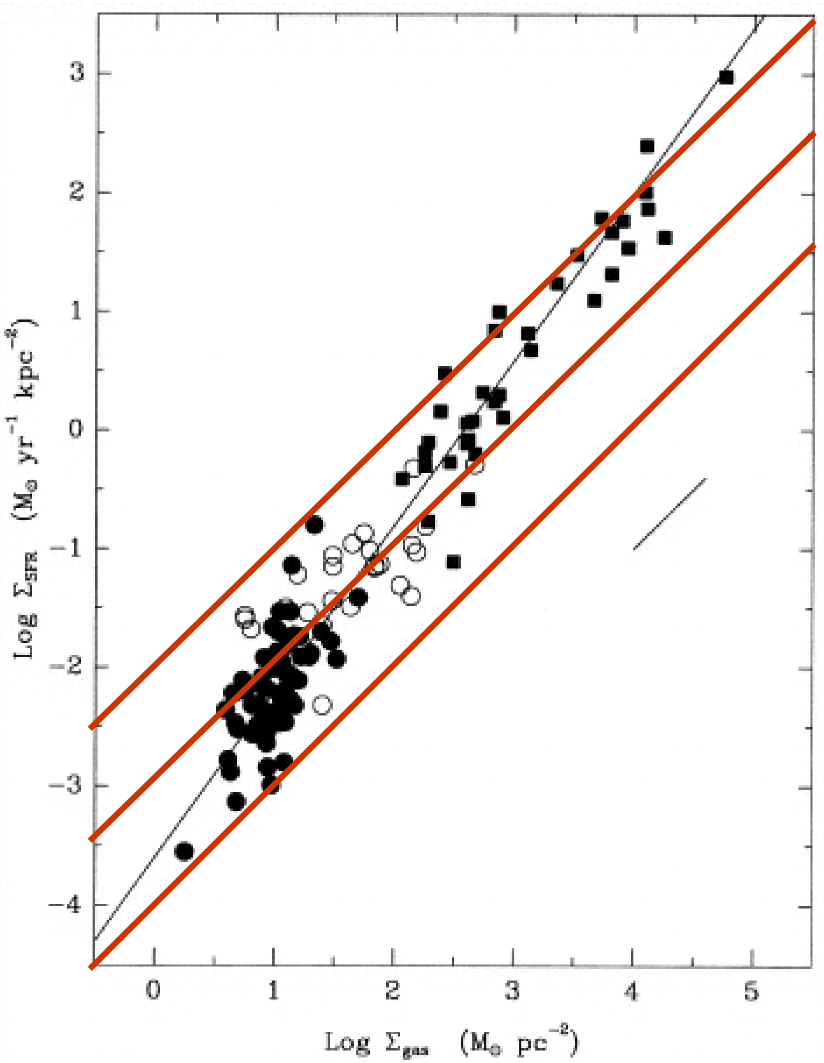


Kennicutt 2009, in prep



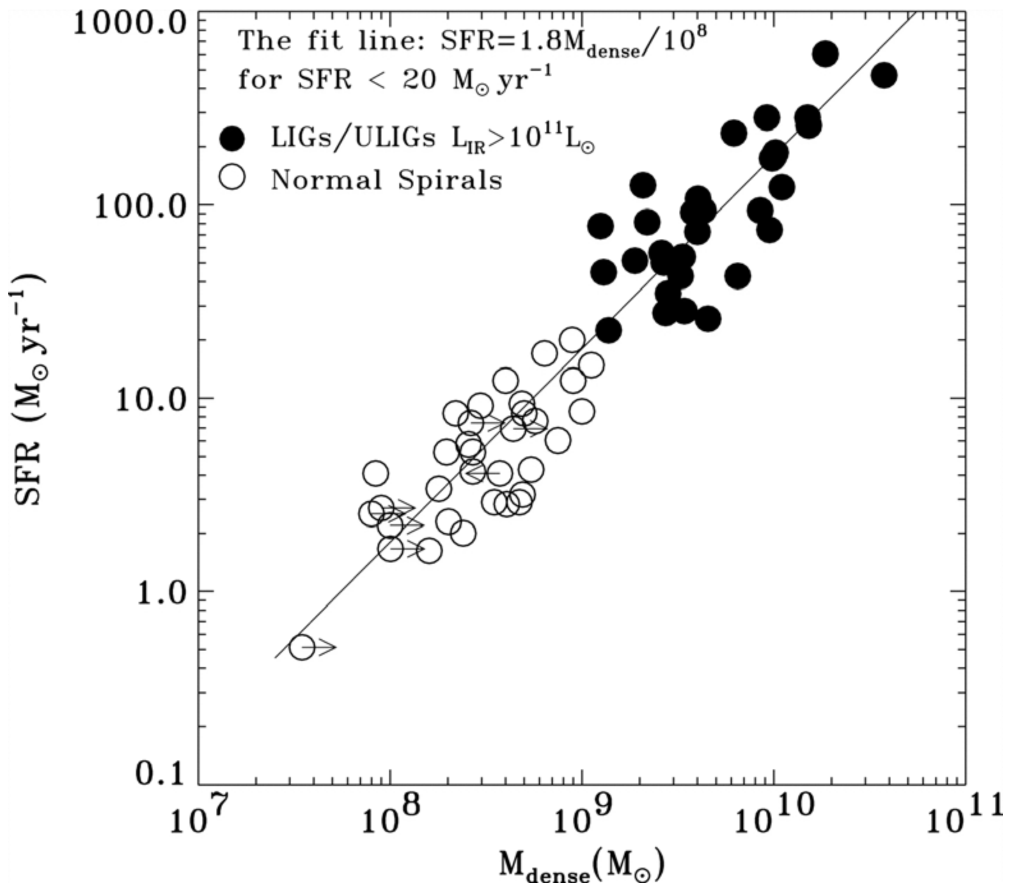
Bouche et al. 2007, ApJ, 671, 303

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



Kennicutt 1998, ApJ, 498, 541

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

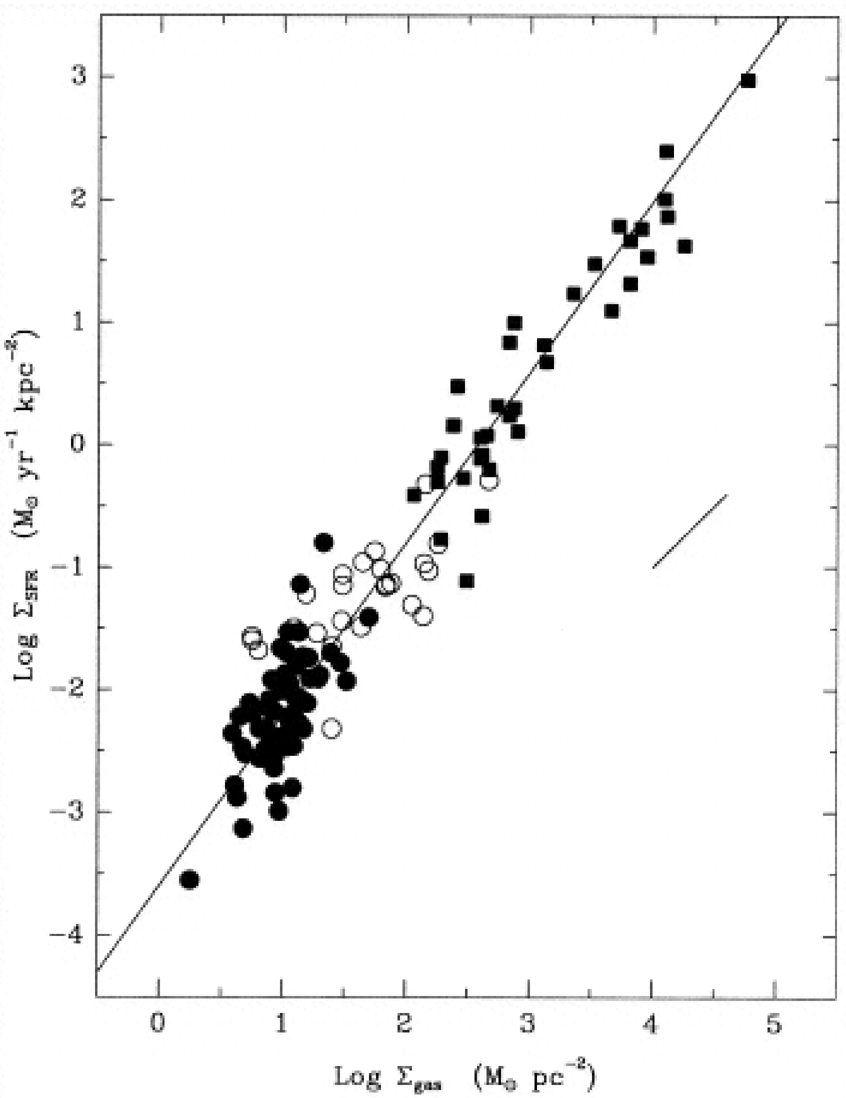


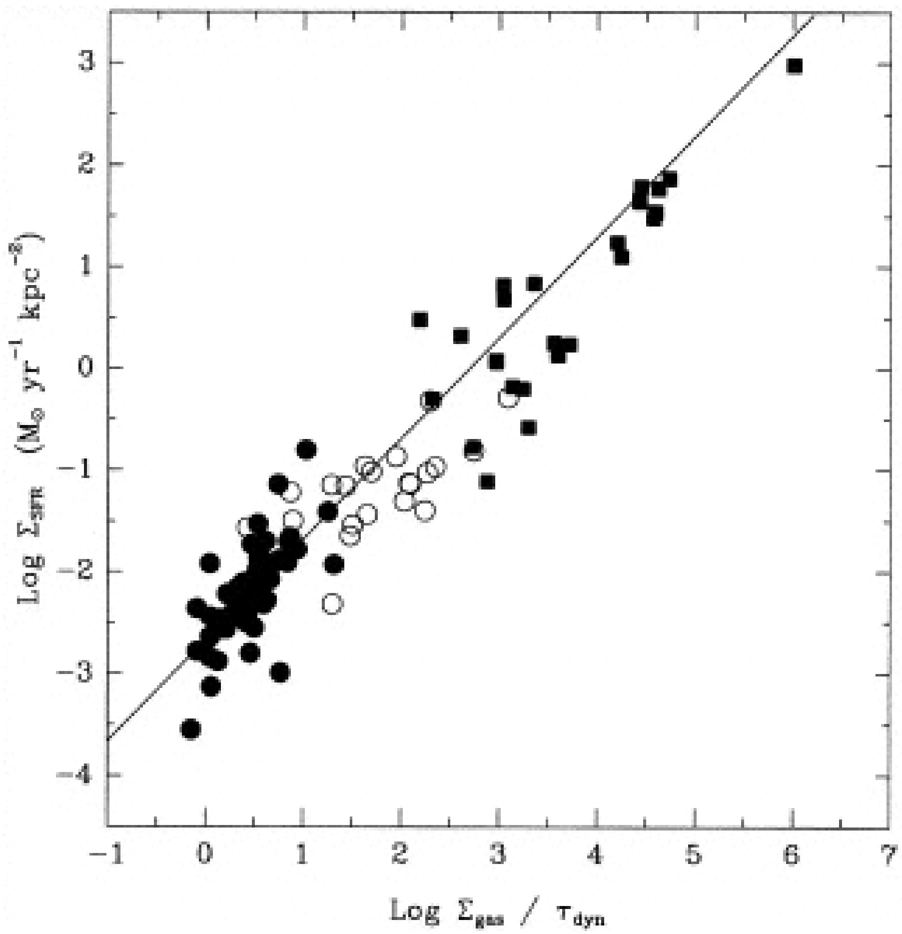
Gao, Solomon 2004, ApJ, 606, 271

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)





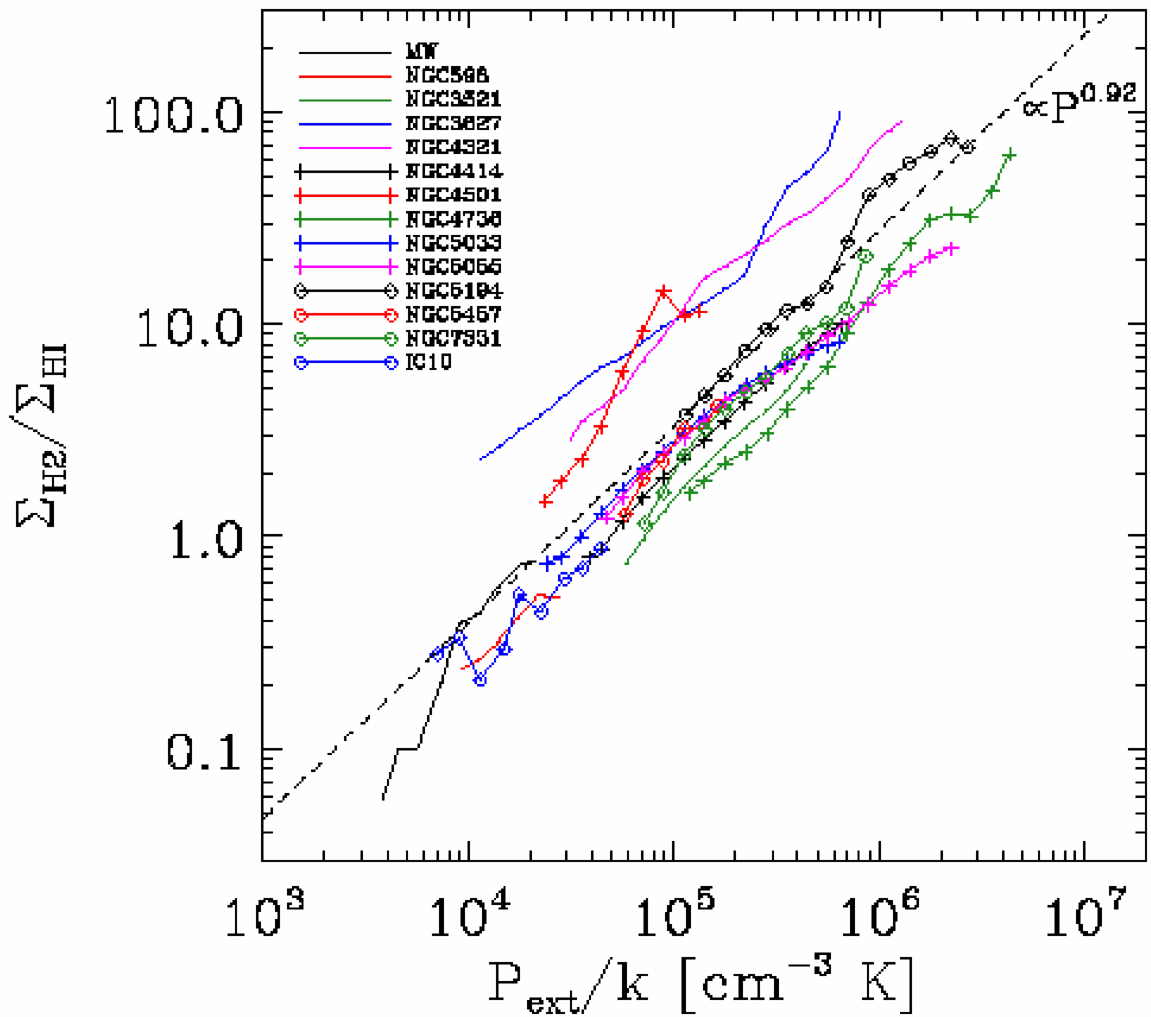
"Schmidt law":

SFR vs gas density power law

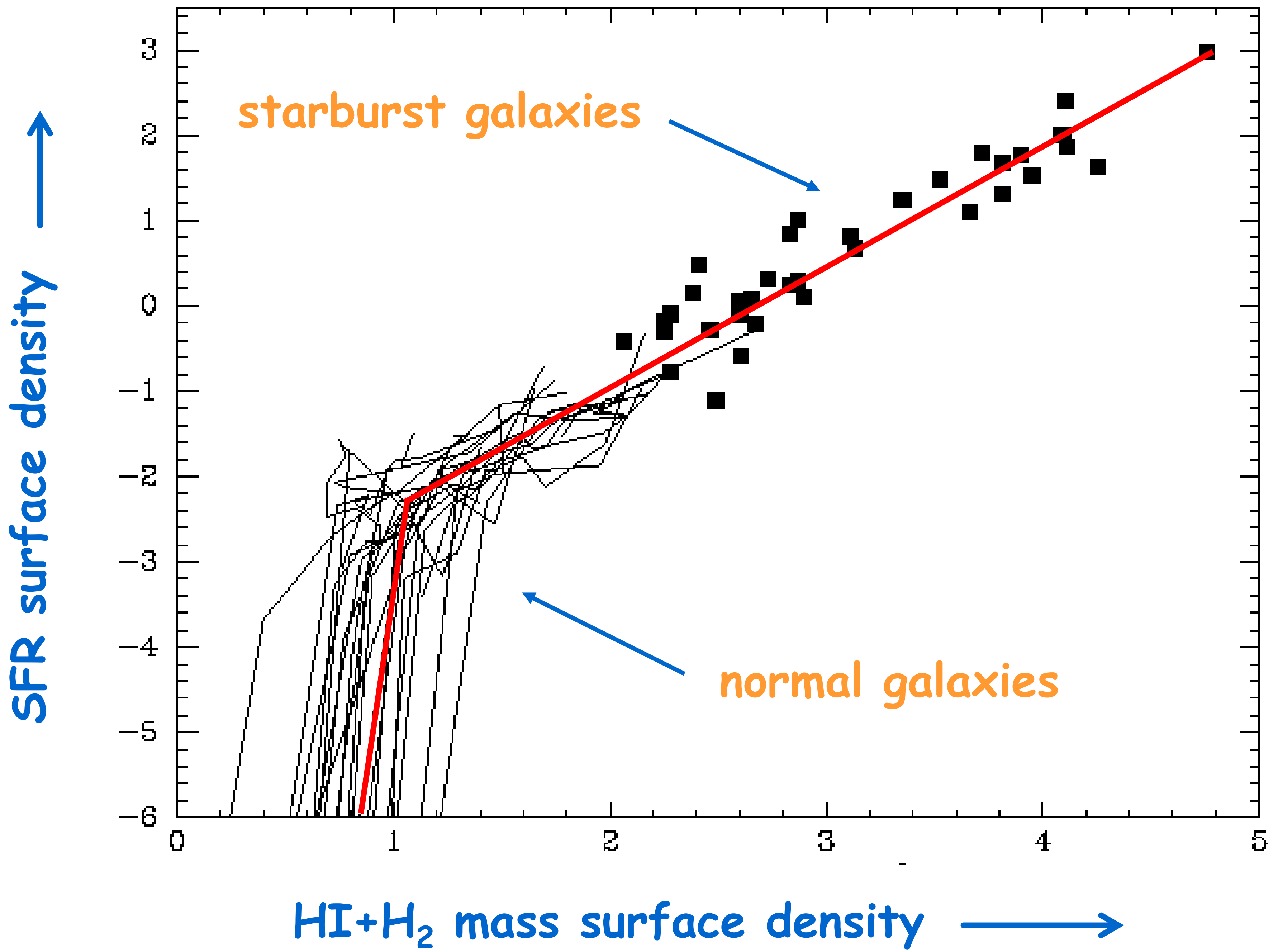
"Silk law":

SFR vs gas density/dynamical time

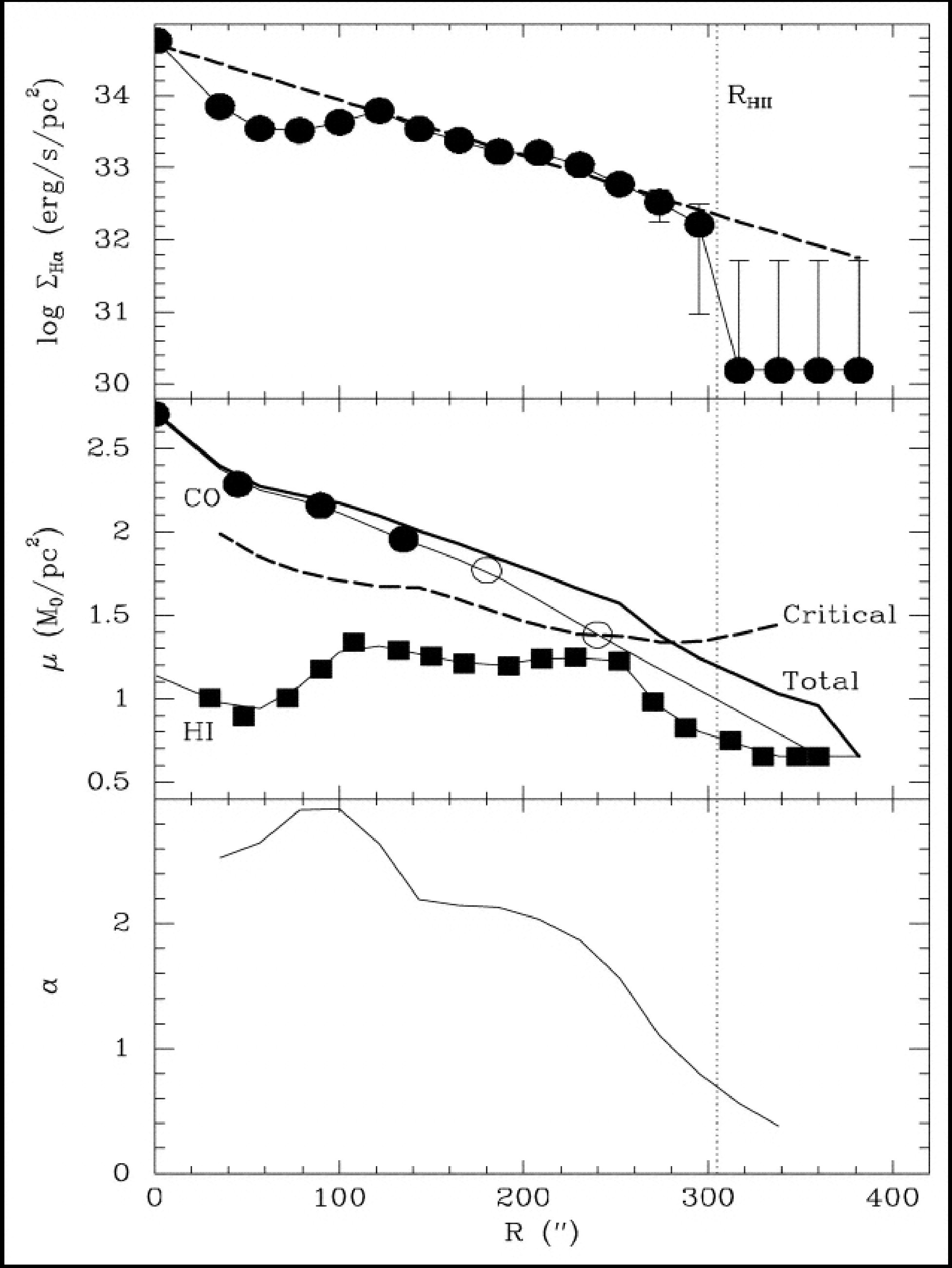
"pressure law"

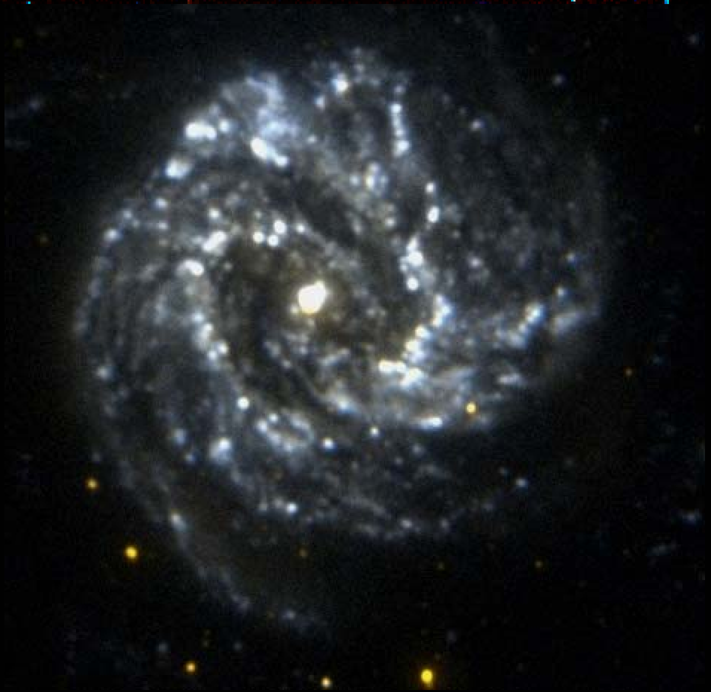


Blitz & Rosolowsky 2006, ApJ, 650, 933



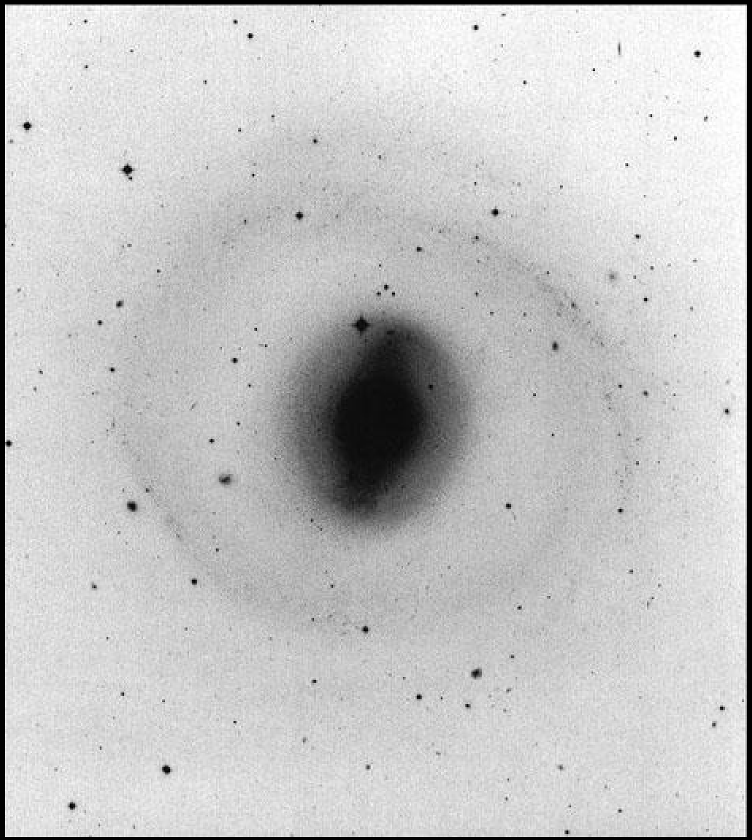
starburst galaxies
normal galaxies
SFR surface density
HI+H2 mass surface density
3
2
1
0
−1
−2
−3
−4
−5
−6
0
1
2
3
4
5

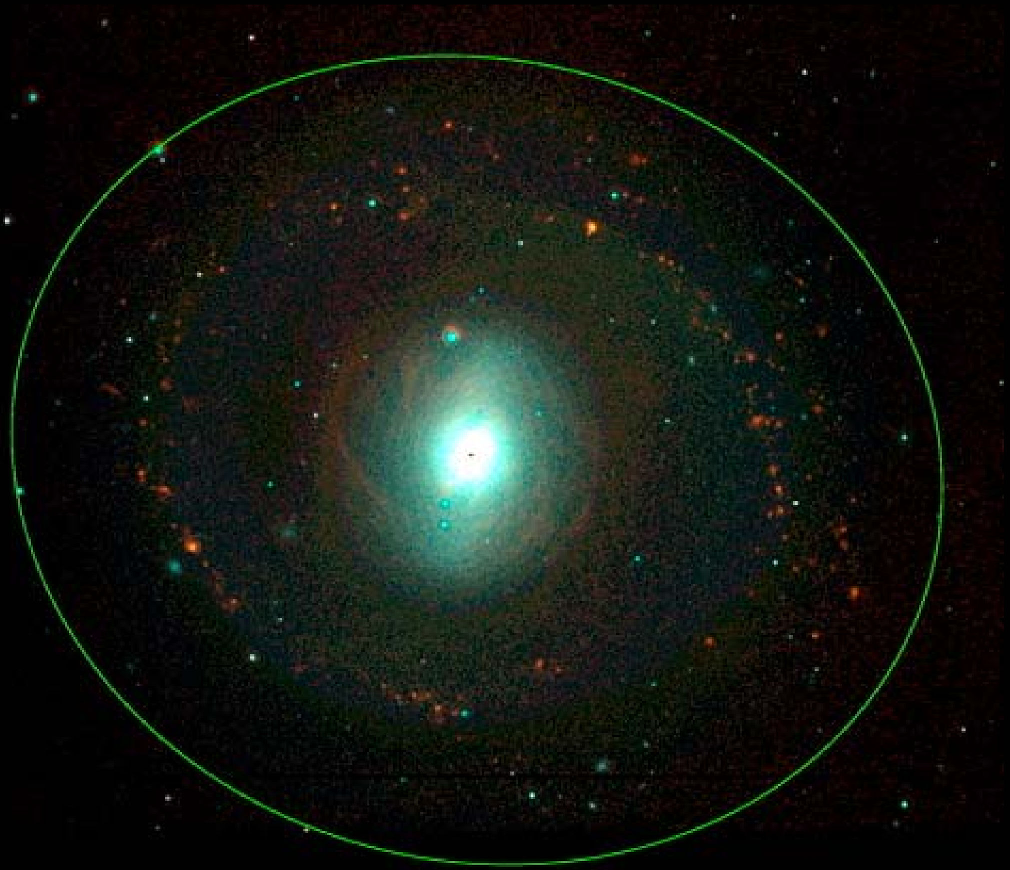




Martin & Kennicutt 2001

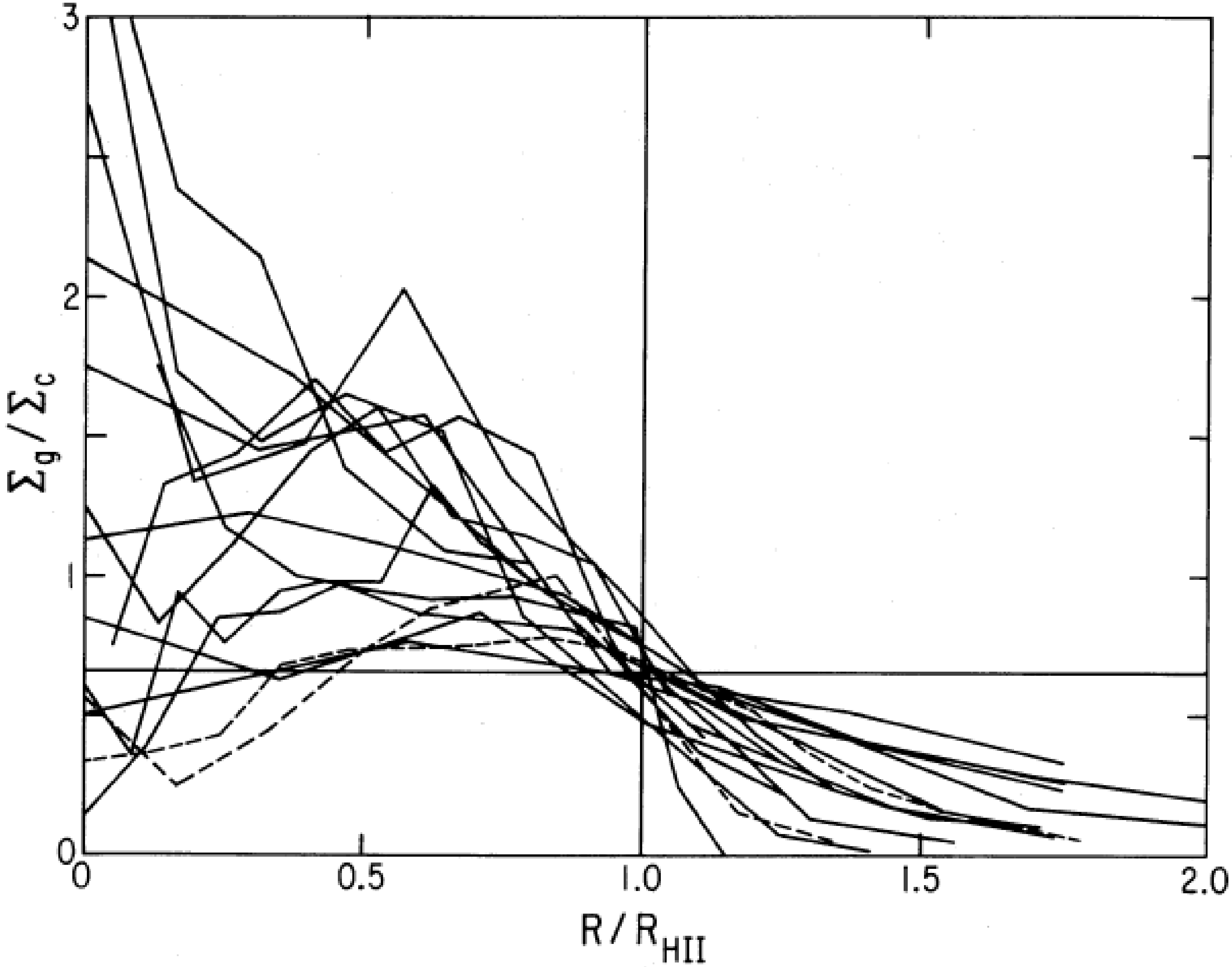
NGC 1291





Blue: Carnegie Atlas
Sandage & Bedke 1994

Hα + R: SINGG survey
Meurer et al. 2006



Kennicutt 1989, ApJ, 344, 685

Basic Picture, Oversimplified

- The SFR/area is correlated with gas surface density, following a truncated Schmidt power law with index N = 1.4 +-0.1
  - the correlation of with dense gas (e.g., HCN) is roughly linear
- The Schmidt law shows a turnover below a threshold surface density that varies between galaxies.
  - in gas-rich, actively star-forming galaxies this transition is seen as a radial transition in the SFR/area
  - some gas-poor disks reside in the threshold regime at all radii
  - the threshold radii and densities in most galaxies are consistent with a Q~1 gravitational stability criterion

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Complications, Issues, Questions

- Physical explanation of thresholds
- Nature and existence(!) of thresholds
  - do Hα and UV emissivities trace SFR?
- Extension of Schmidt law to local scales?
- Is the SF law fundamentally a correlation with HI, H_2, or total gas density?

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)

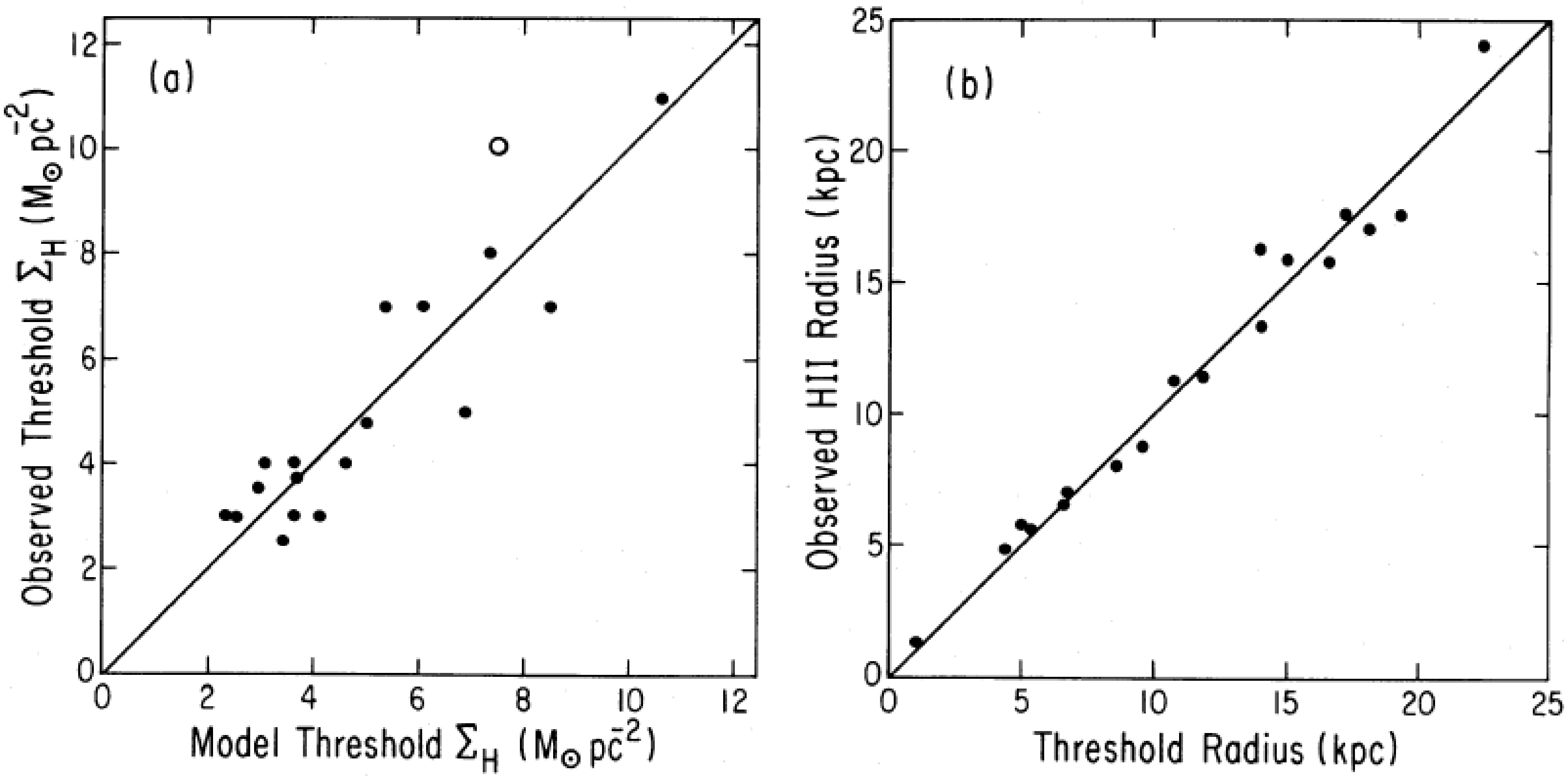
- transition to cold phase triggers gravitational instabilities

Pressure-regulated H_2 instabilities?

(Elmegreen, Parravano 1994; Blitz, Rosolowski 2006)

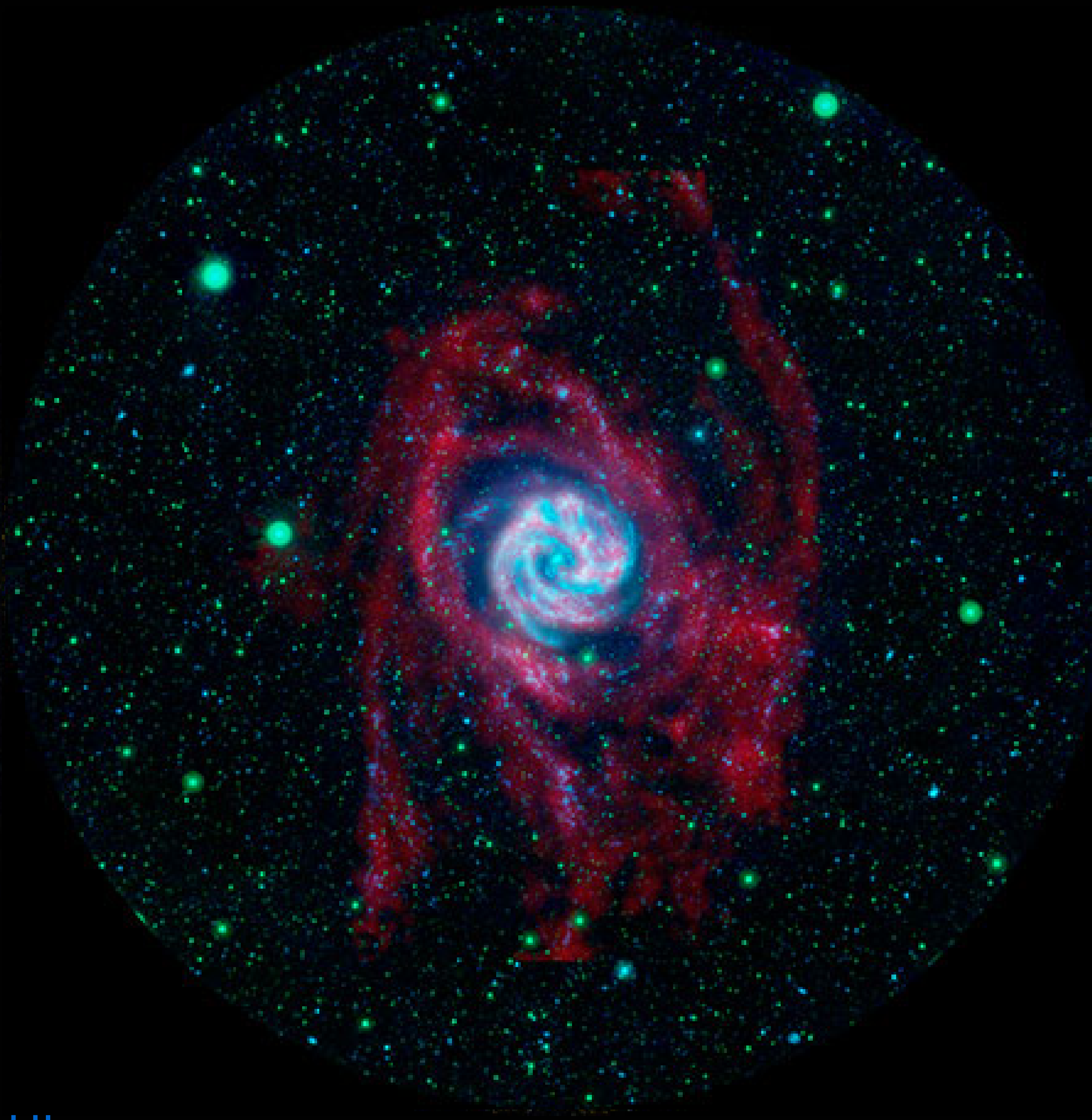
- SFR controlled by formation of H_2, with SFR ~ Σ_{H2}

Fragmentation threshold? (Krumholz & McKee 2008)



Kennicutt 1989, ApJ, 344, 685

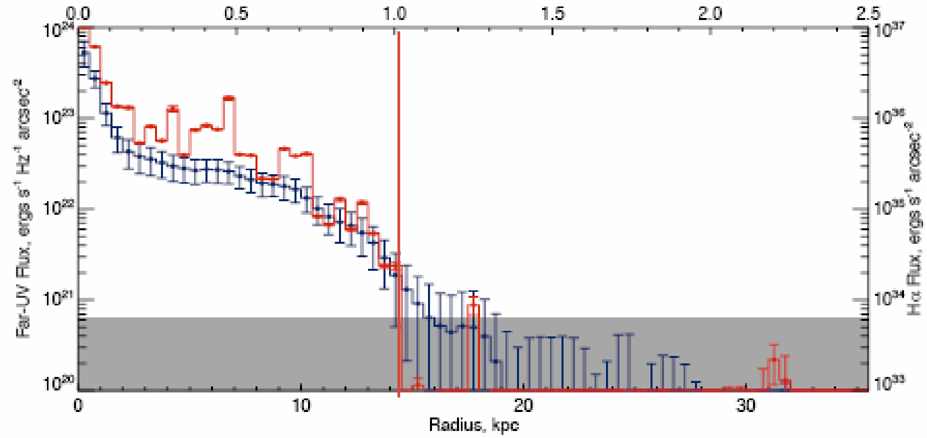
"XUV Discs"



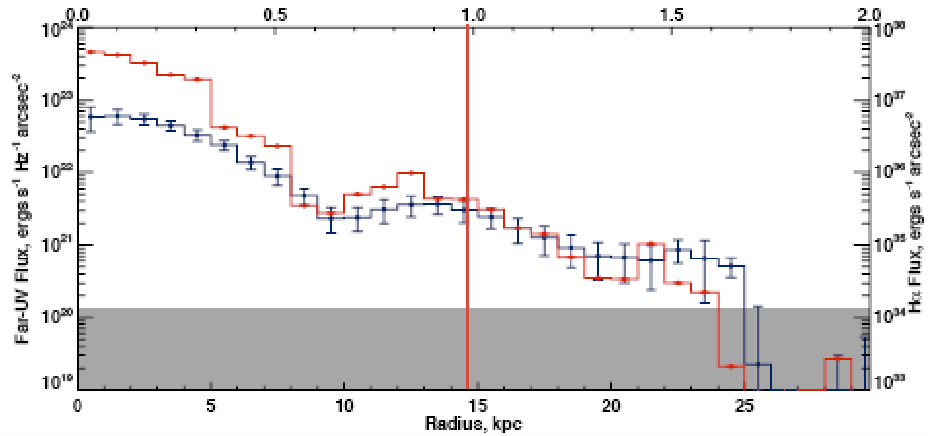
M83 = NGC 5236

GALEX FUV/NUV + VLA HI

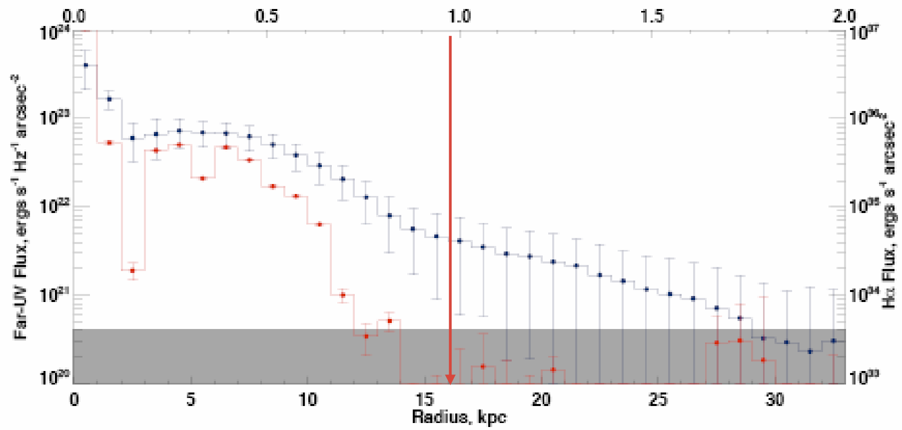
NGC 925
truncated in UV + Hα

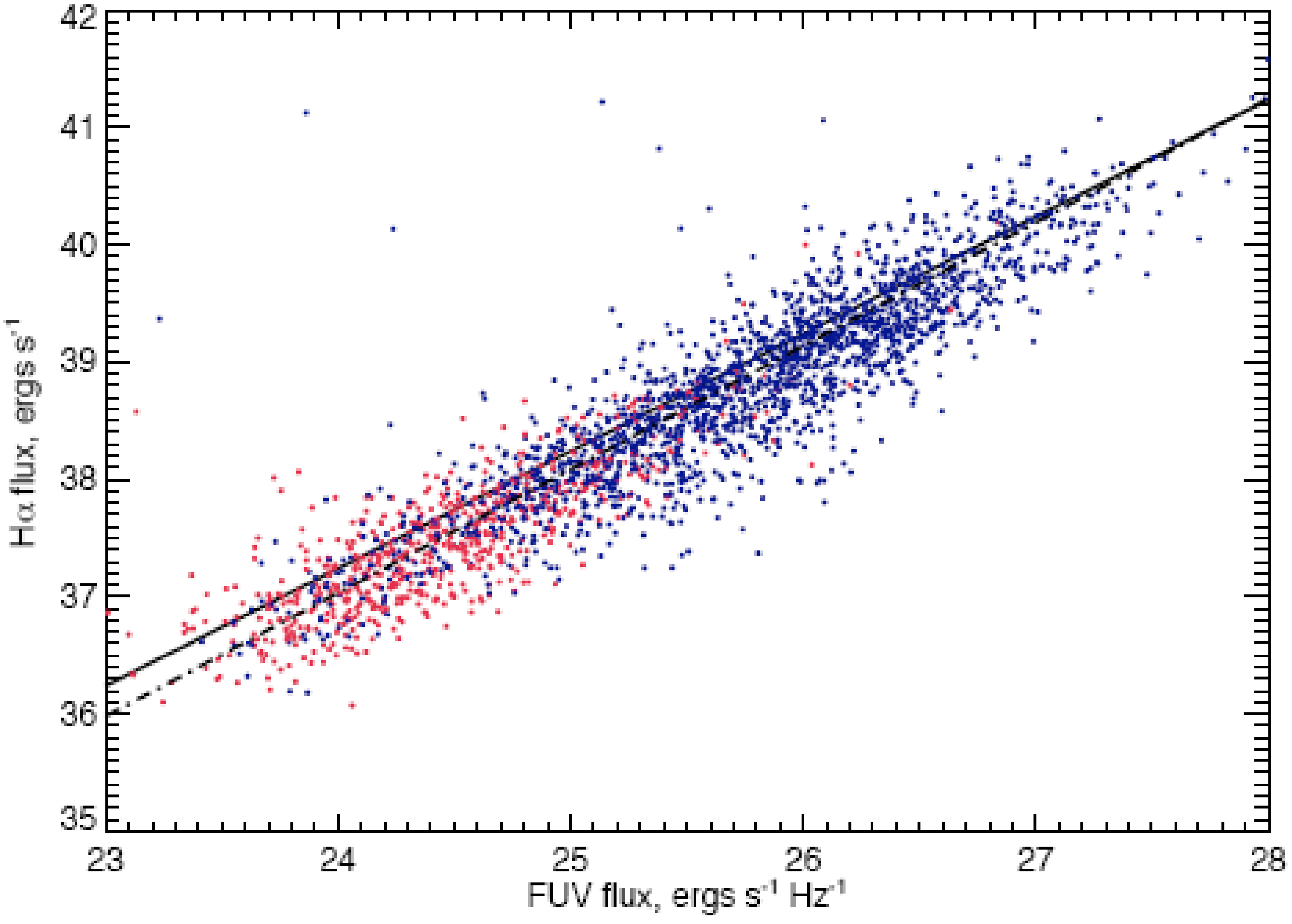


NGC 3621
extended in UV + Hα



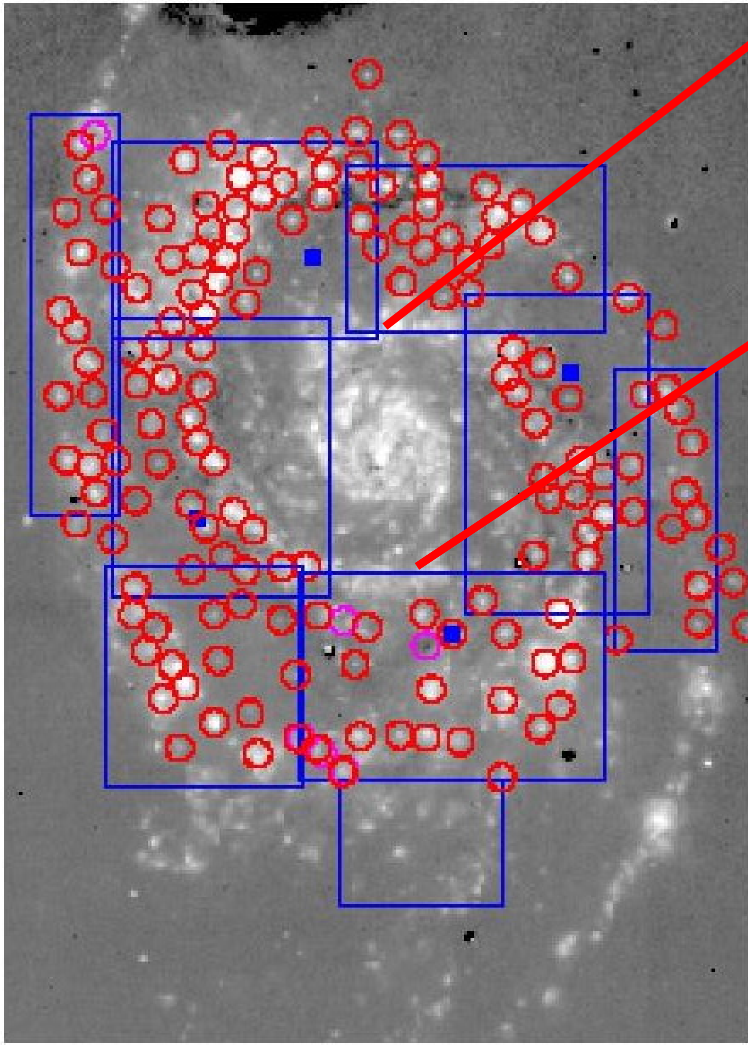
NGC 2841
truncated in Hα
extended in UV

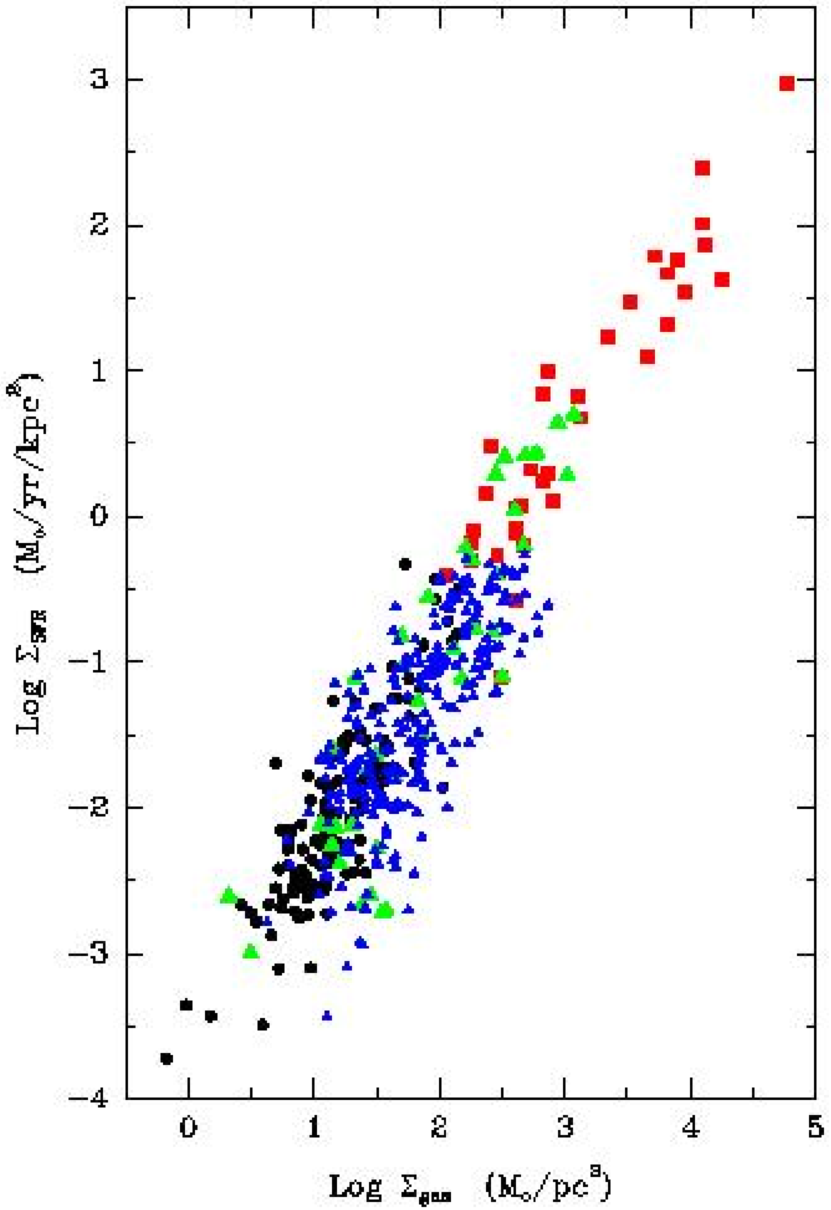




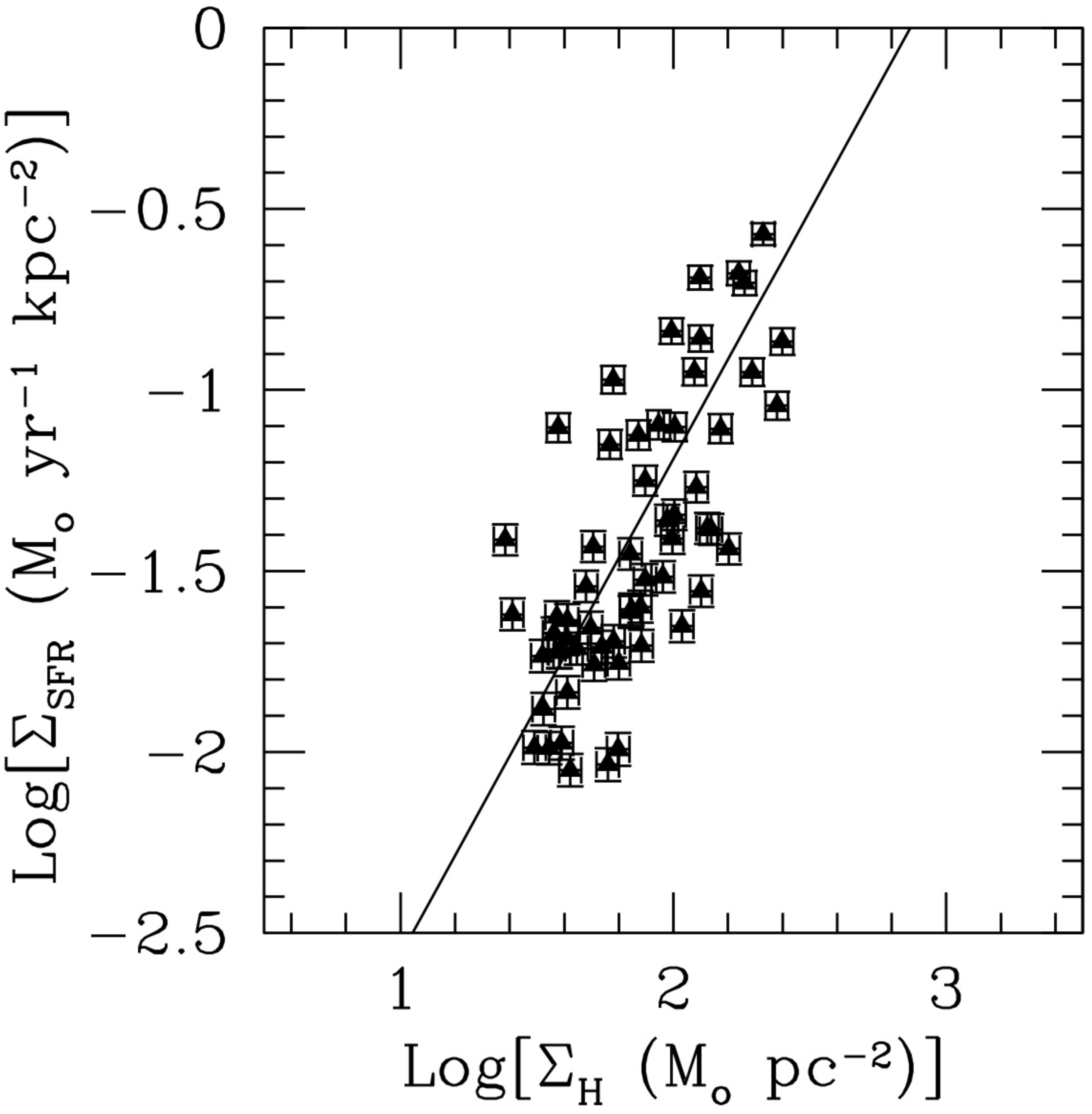
- Hα/UV properties vary continuously with luminosity
- No evidence for transition between inner/outer discs (except M83)

Local Schmidt Law in M51

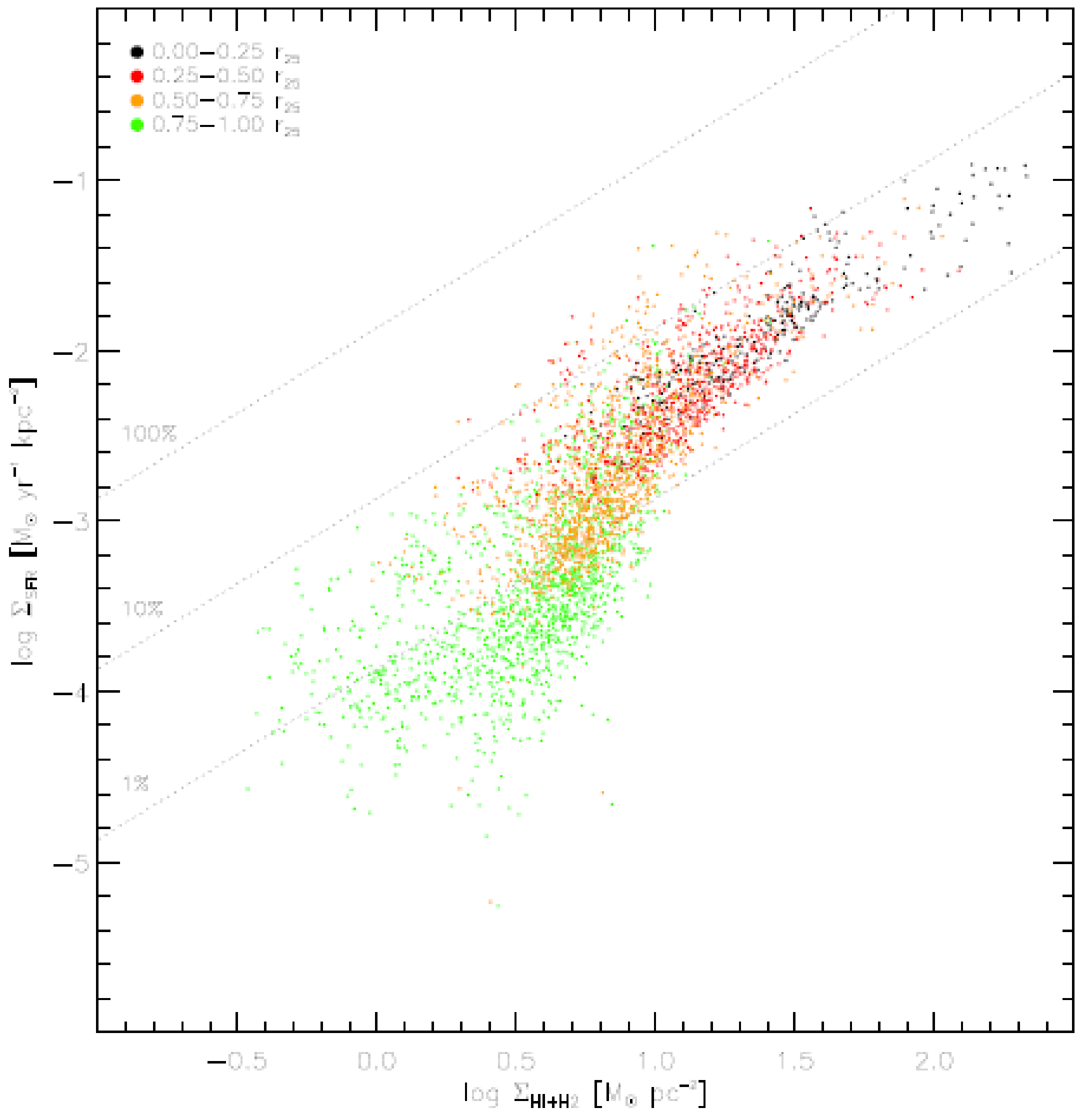




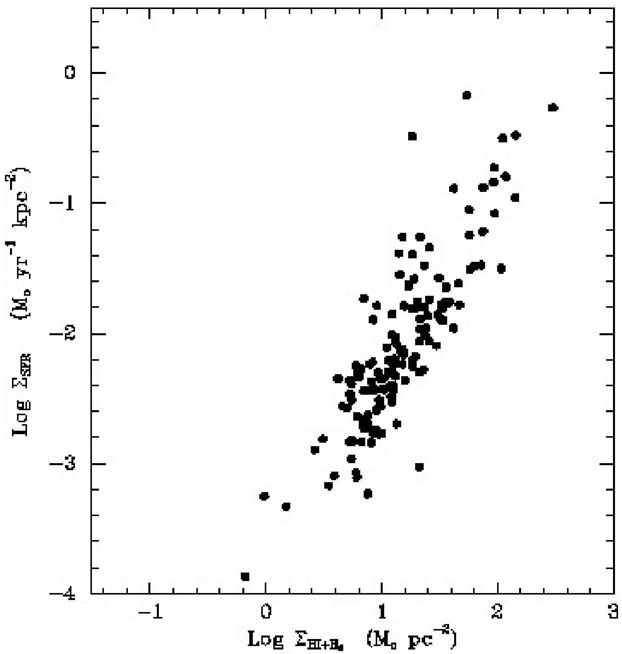
Kennicutt et al. 2007, ApJ, 671,333



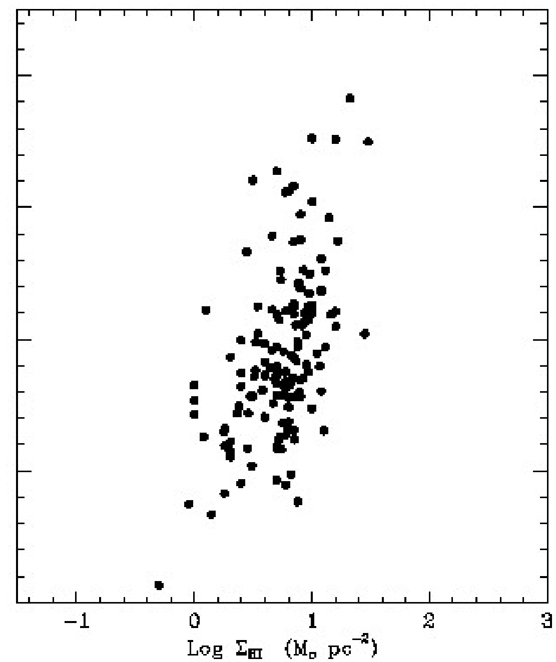
0
−0.5
−1
−1.5
−2
−2.5
1
2
3
Log[Σ_SFR (M_o yr^−1 kpc^−2)]
Log[Σ_H (M_o pc^−2)]



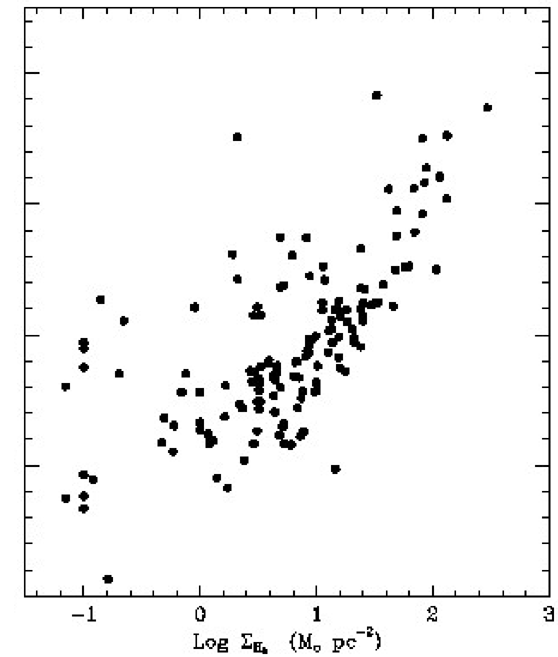
Bigiel et al. 2008, AJ, 136, 2846



HI+H_2

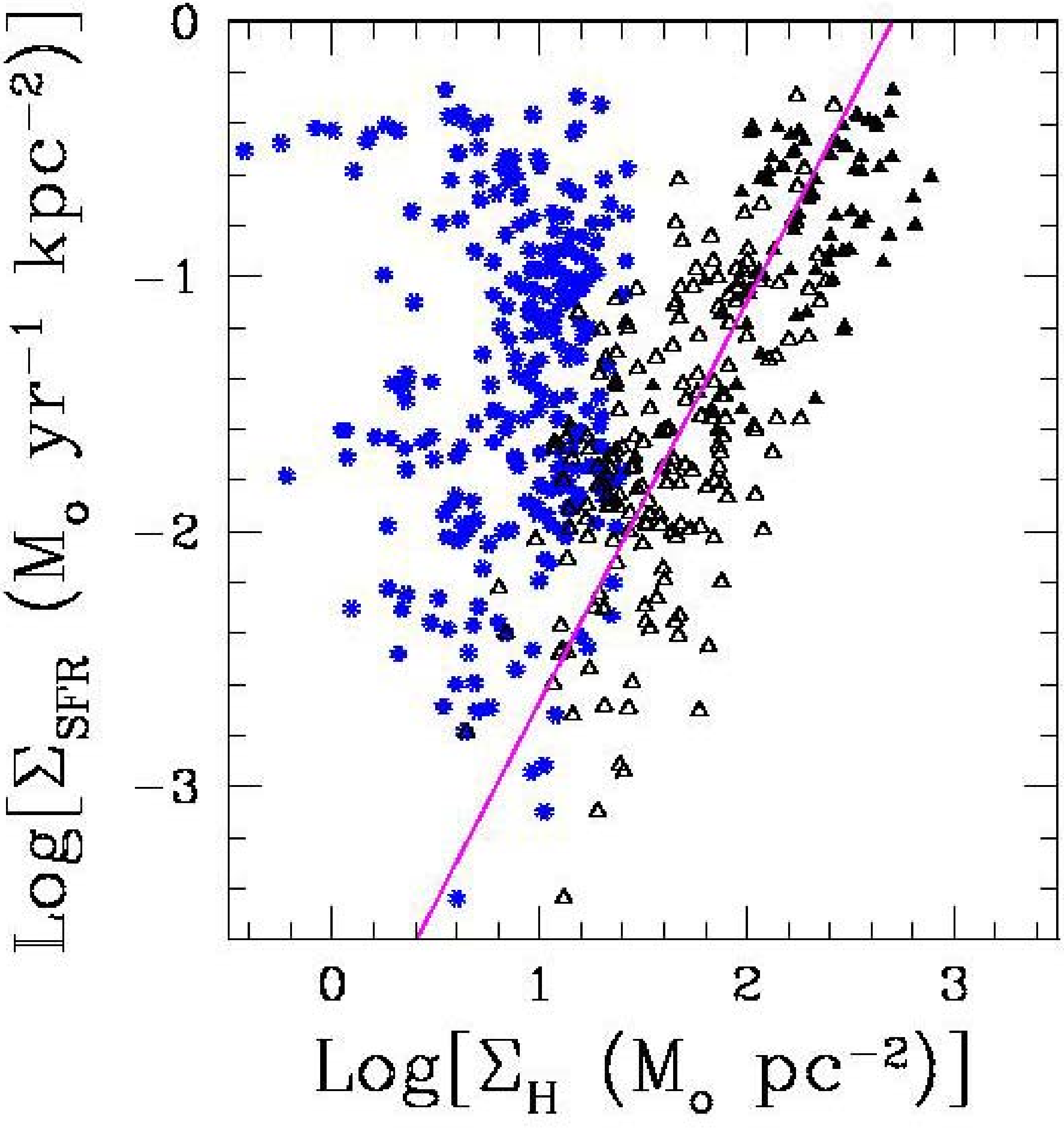


HI

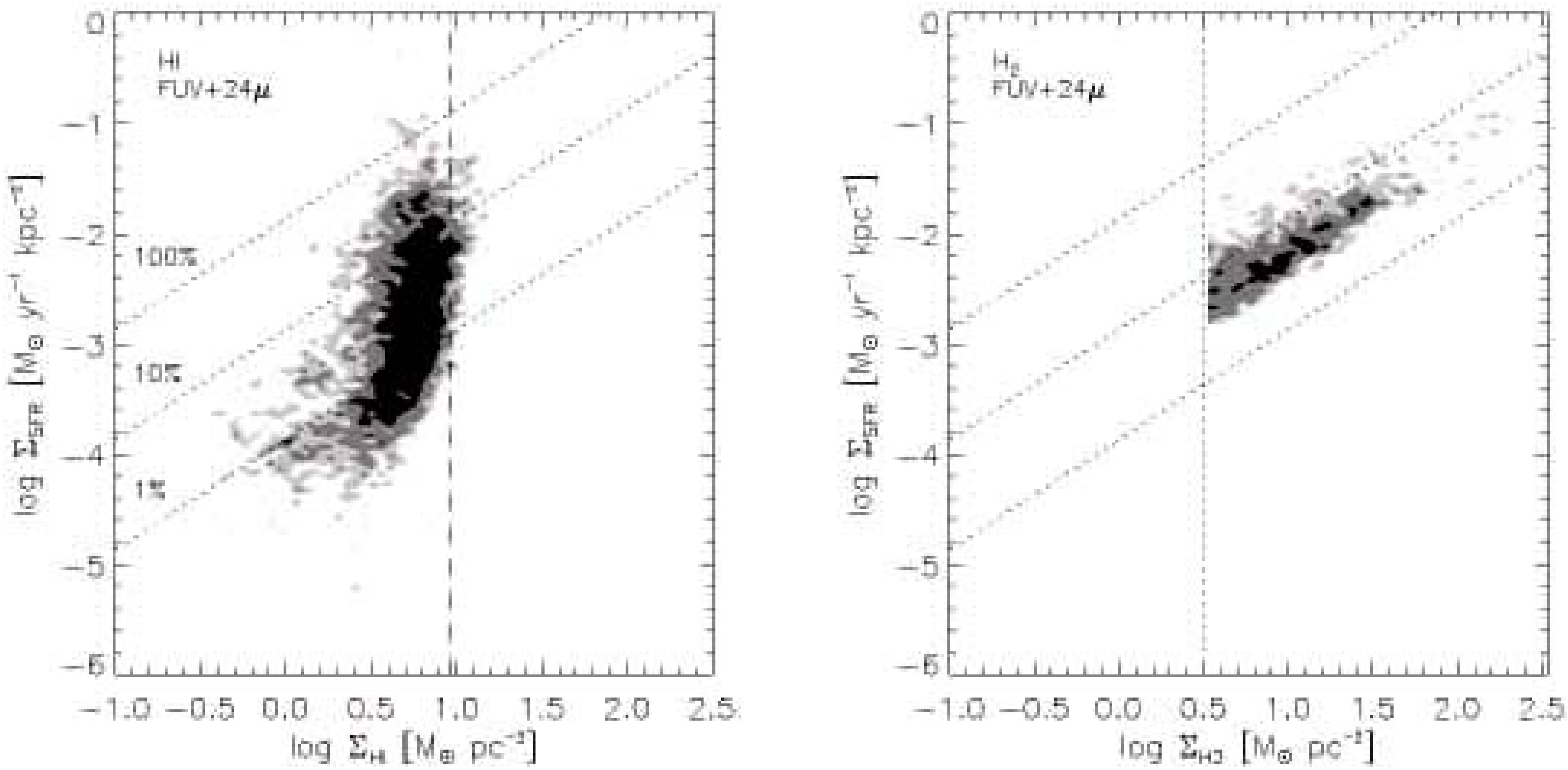


H_2

RCK, in preparation



0
−1
−2
−3
0
1
2
3
Log[Σ_SFR (M_o yr^-1 kpc^-2)]
Log[Σ_H (M_o pc^-2)]

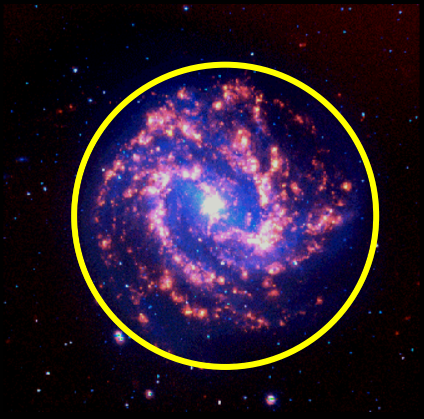


Bigiel et al. 2008, AJ, 136, 2846

Lessons Learned

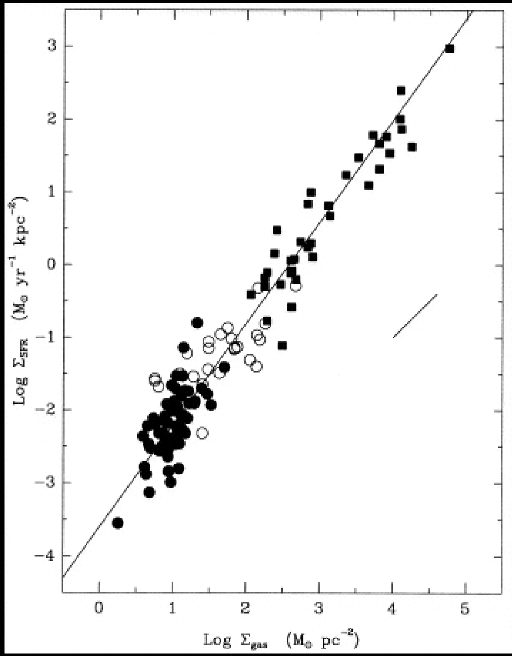
- Scales matter – the empirical nature and physical character of the Schmidt law ought to depend on linear scale, from the cloud scale to galactic scales.
- Systematic effects in observables may still dominate the nature of the SF law correlations
  - gas densities sensitive to presumed behaviour of CO/H_2 conversion factor
  - applicability of SF tracers strongly dependent on scale
  - systematics may dominate interpretation of SFR measures in low surface brightness (sub-threshold) regime
- Beware of confusion between correlation and causation

Scales Matter: Global Scales (~1-20 kpc)



- provide valuable recipes for theory, simulations

- probe nonlinear dependences of cloud and star formation on ISM density



BUT

– observables integrated over vast range of local physical conditions, important features (e.g., thresholds) may be washed out

- may characterise "thermodynamic laws" of SF at best, but little contact with SF physics

Cloud Scale (~1-50 pc)

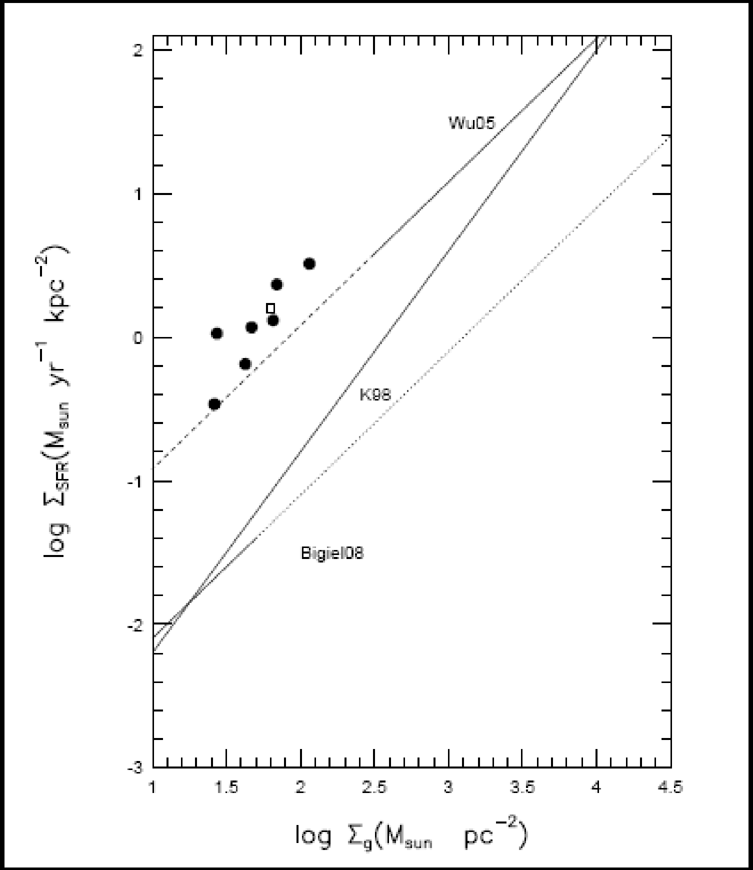
- direct probes of physical processes on the SF scale

- ~linear law expected if SFE is constant

BUT

- observables are fundamentally different, formed stellar mass vs cloud mass, not the SFR

- results sensitive to choice of SF and gas tracers



Evans et al. 2009, ApJS, 181, 321

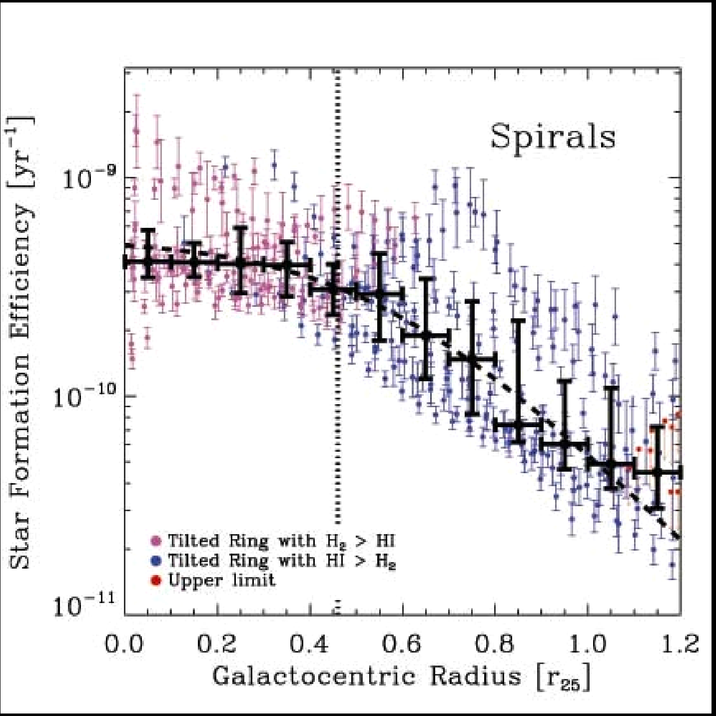
Sub-Disc Scale (~0.05-1 kpc)

- should see transition from SFE regime in clouds to nonlinear cloud formation regime

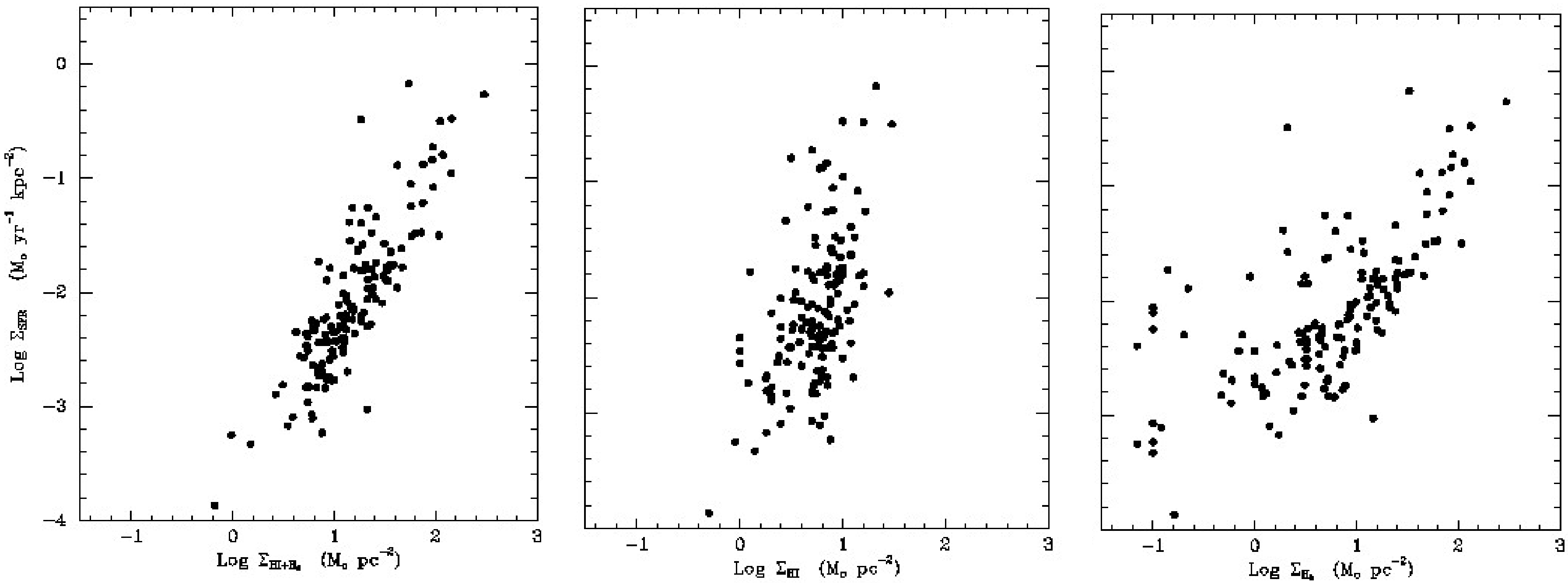
- spatial resolution in discs breaks some degeneracies in interpretation of relations

BUT

– care still needed when interpreting observed correlations



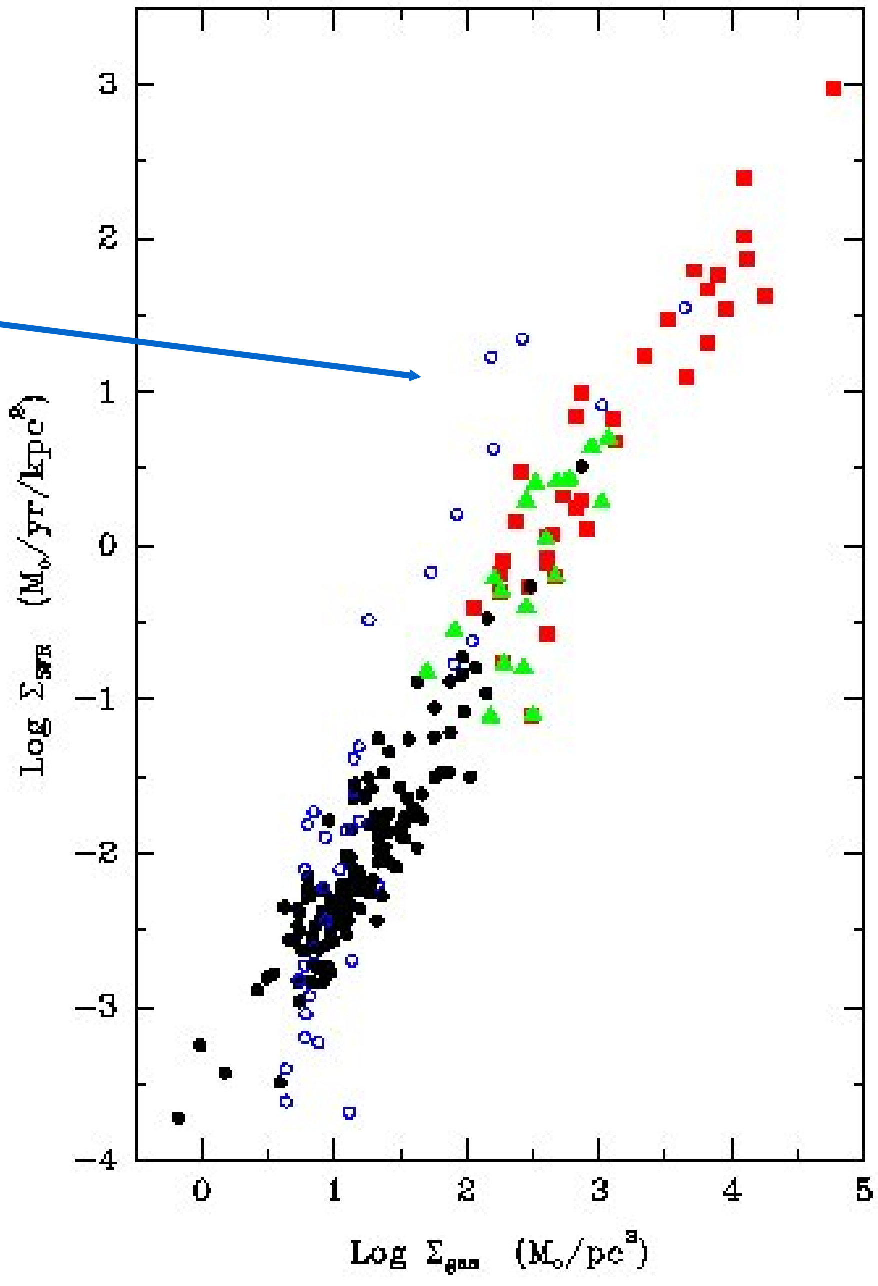
Leroy et al. 2008, AJ, 136, 2782

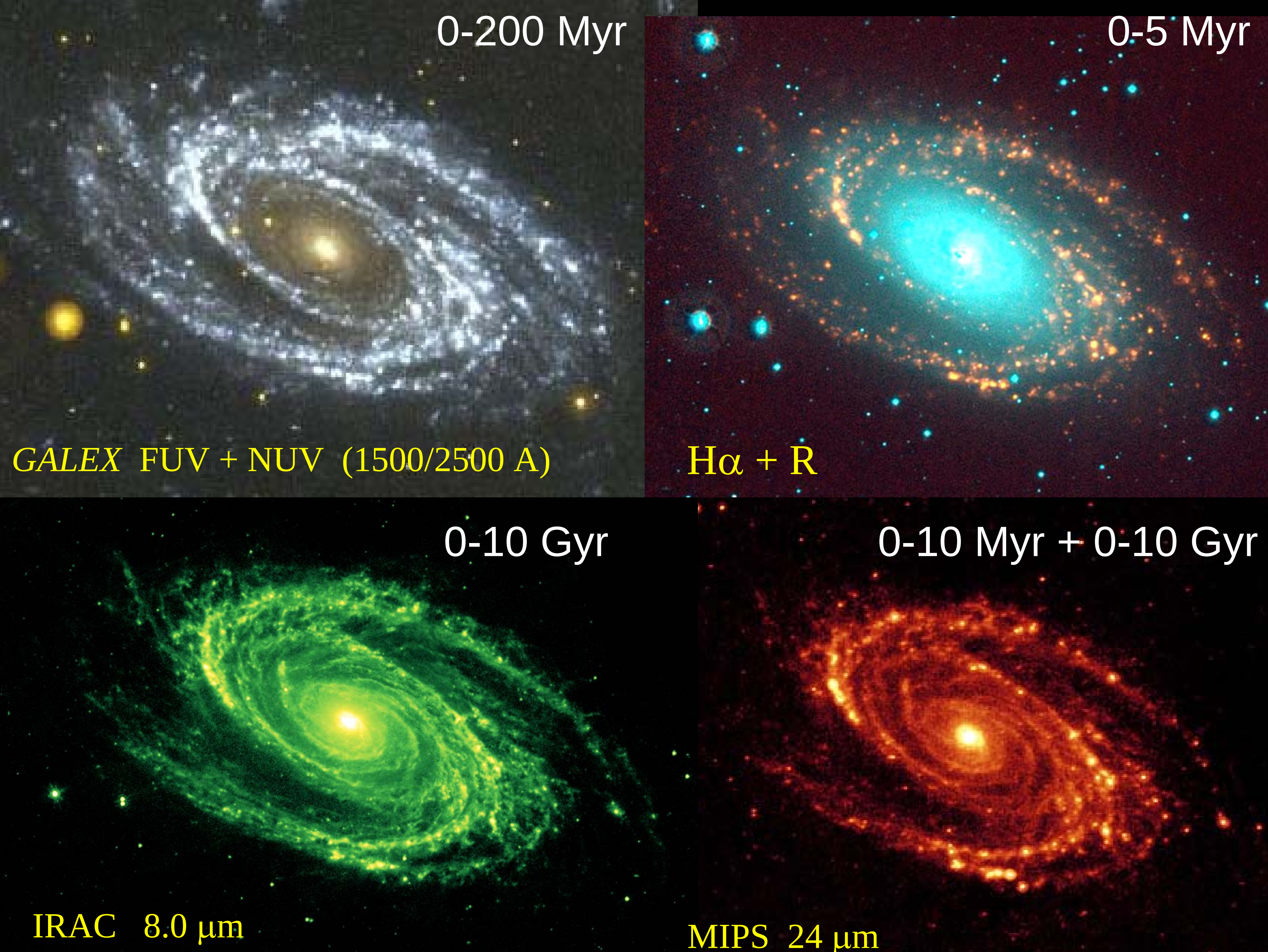


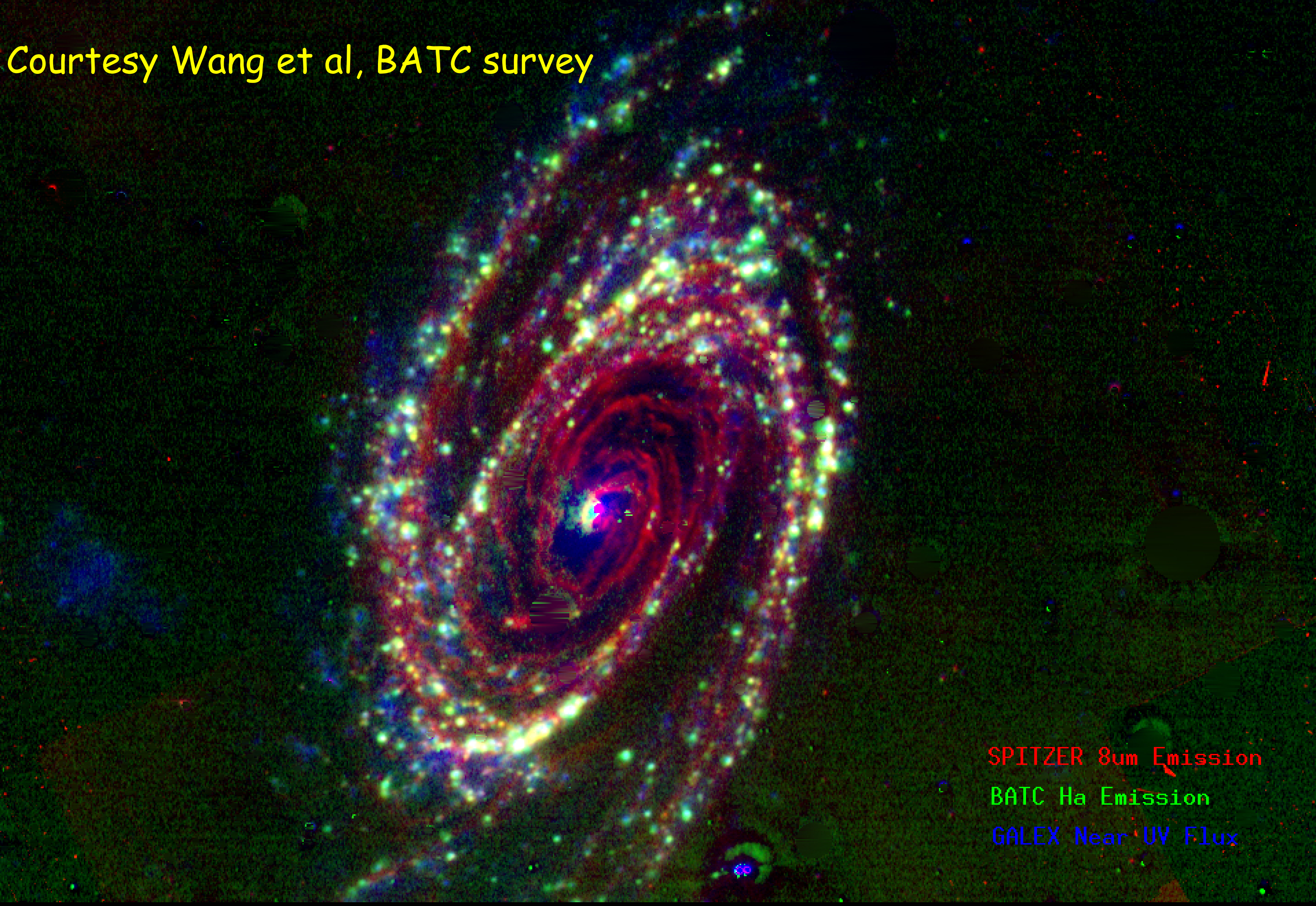
HI+H_2 HI H_2

RCK, in preparation

metal-poor dwarf galaxies




0-200 Myr
GALEX FUV + NUV (1500/2500 A)
0-5 Myr
Hα + R
0-10 Gyr
IRAC 8.0 μm
0-10 Myr + 0-10 Gyr
MIPS 24 μm

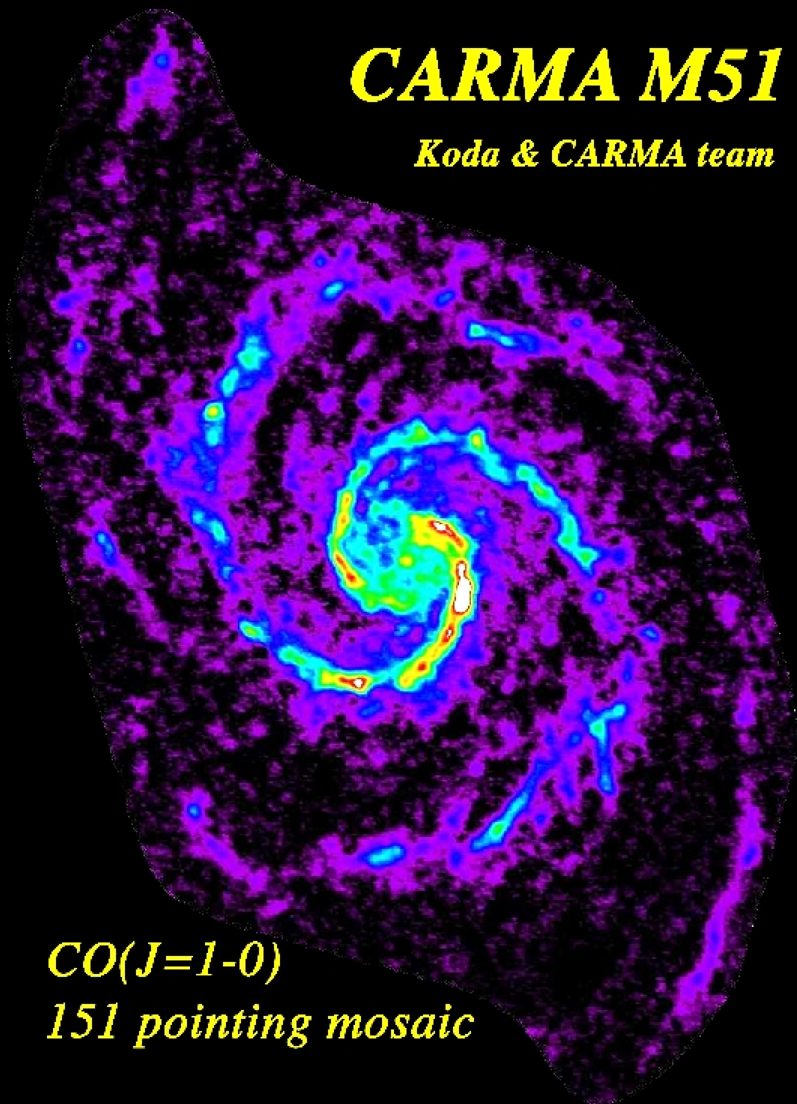


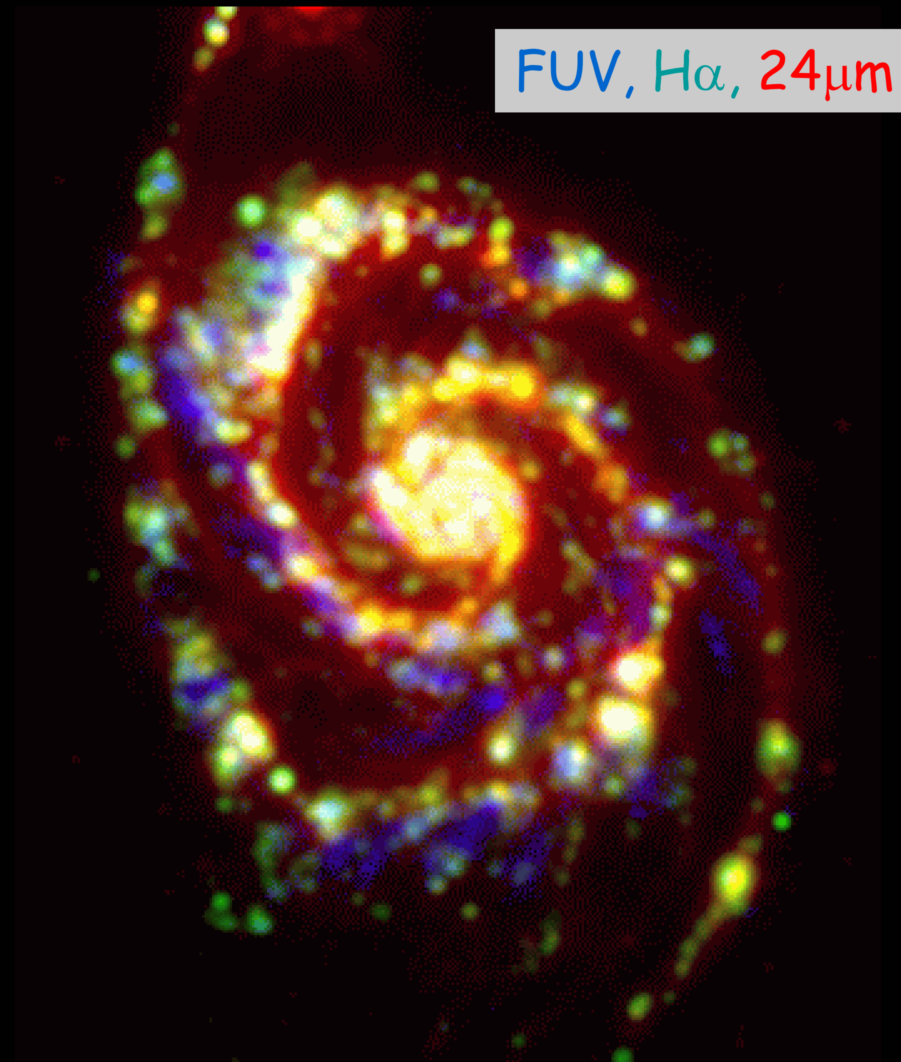
cf. Madore 1977, MNRAS, 178, 1

Correlation vs Causation

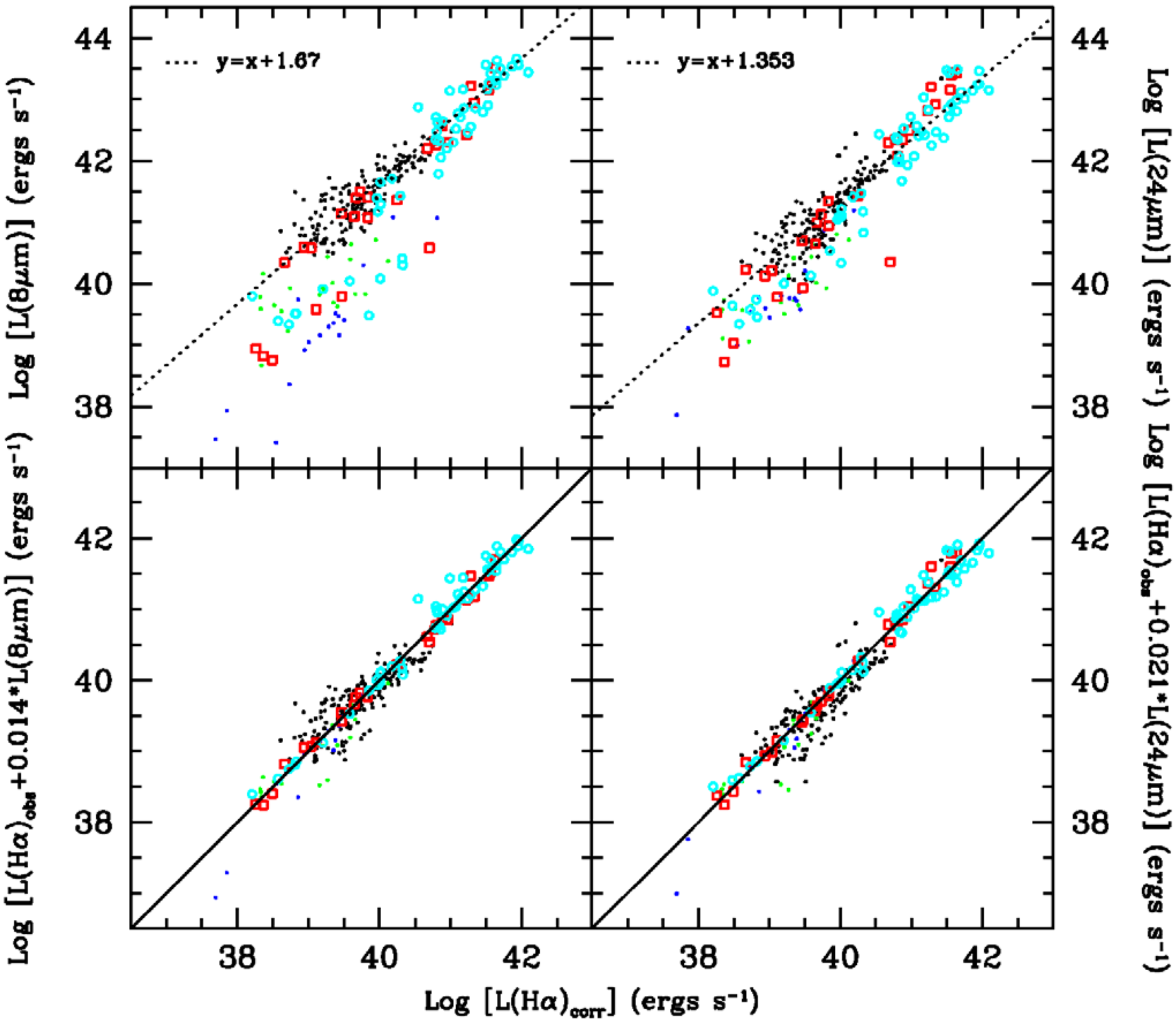
- Beware the treacheries of correlation vs causation!
  - For a Q ~ 1 disk: $\Sigma_{gas} \sim \kappa c/\pi G$

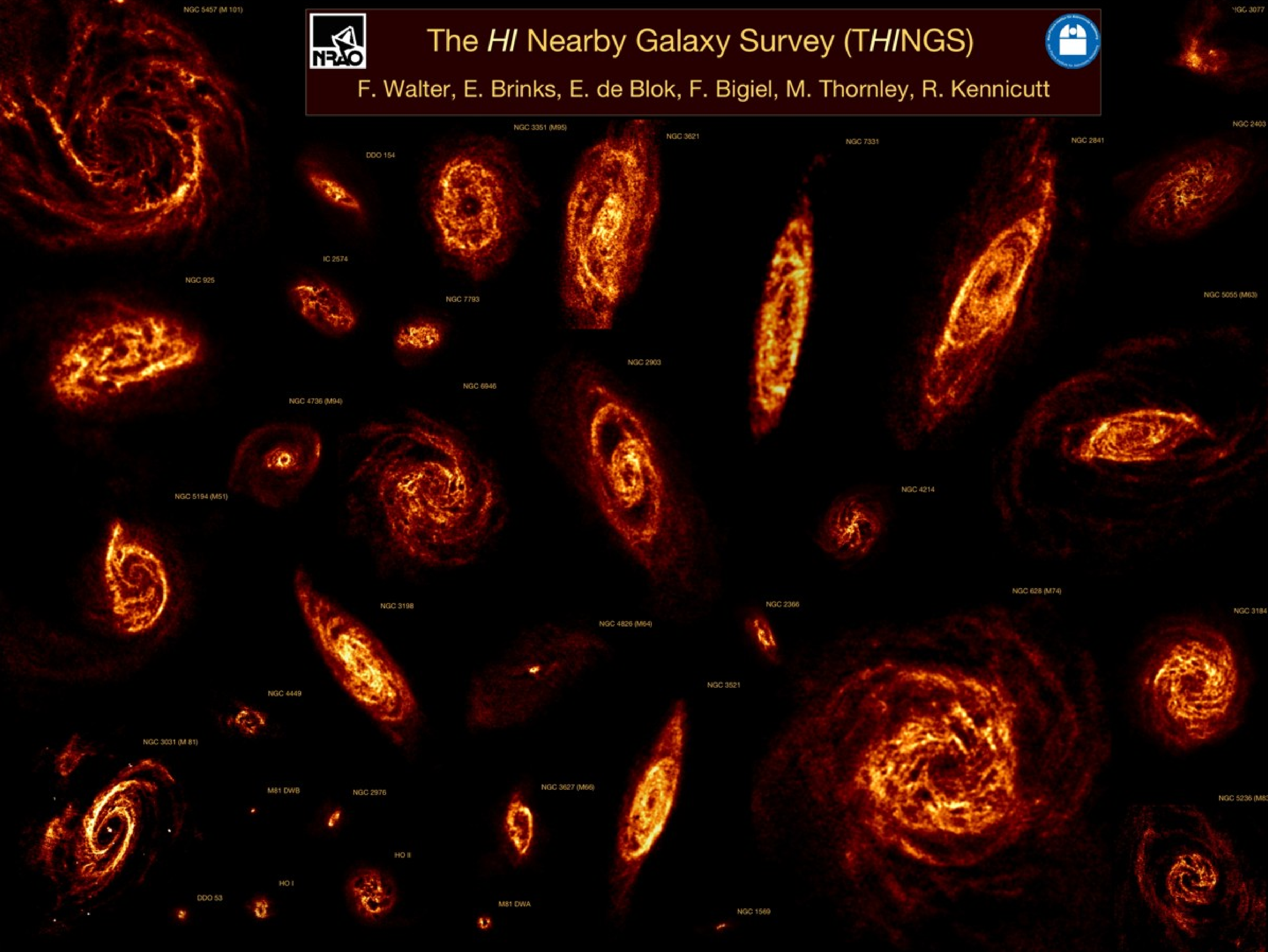
    $\kappa \propto \Omega$ so $\Sigma_{gas} \propto \Omega$
  - Likewise: $\Sigma_{gas} \propto \Sigma_{tot}$, so $P \propto \Sigma^2$
  - Also, for local Galactic ISM pressures, Σ_{crit} for self-gravitating clouds is approximately the same as Σ_{crit} for self-shielding of molecular clouds
  - And--- in SF regions much of HI may be a photodissociation product of UV radiation on H_2


CARMA M51
Koda & CARMA team
CO(J=1-0)
151 pointing mosaic

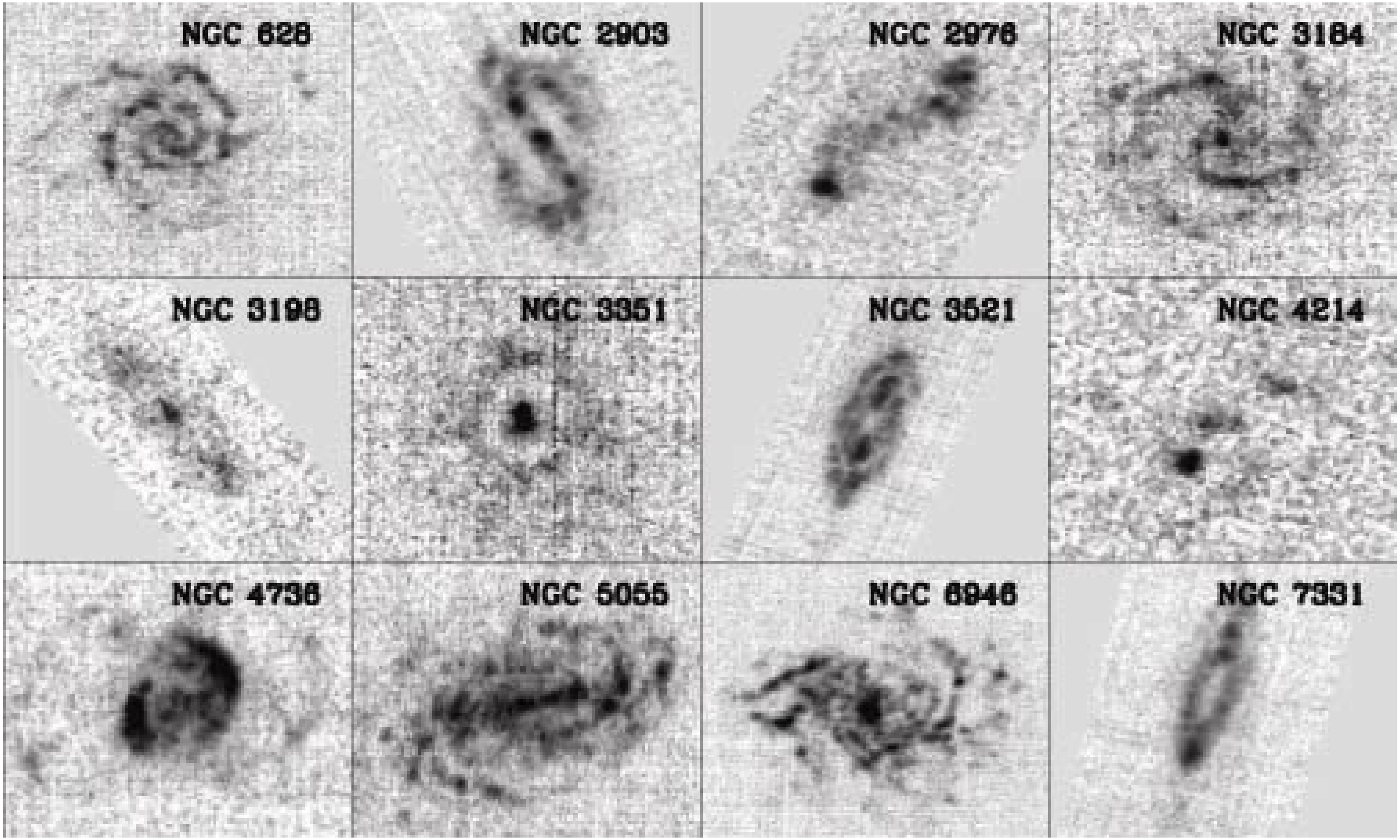

FUV, Hα, 24μm

SINGS Sample: 8 μm and 24 μm

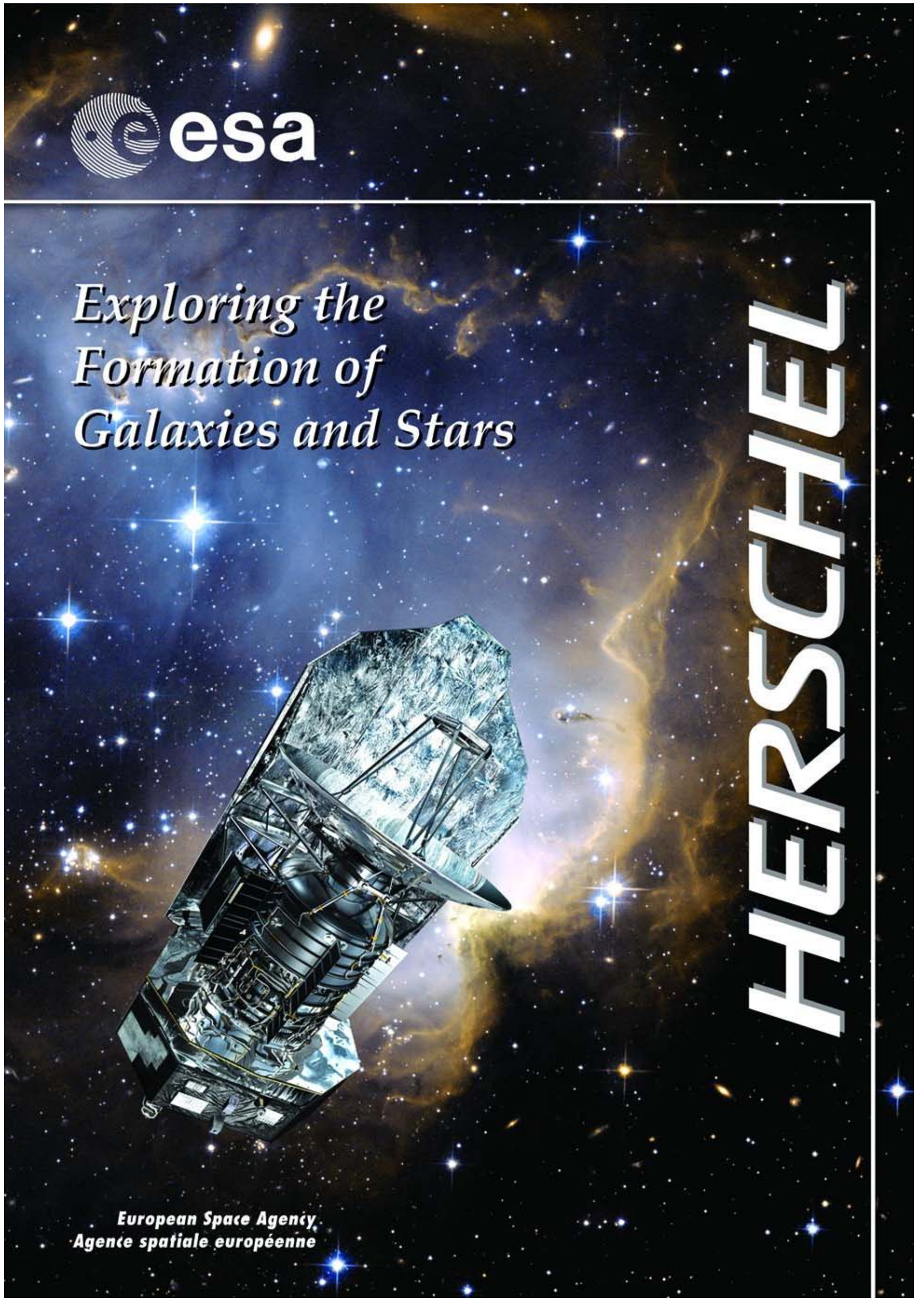



The HI Nearby Galaxy Survey (THINGS)
F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt
NRAO
NGC 5457 (M 101)
NGC 3351 (M95)
NGC 3621
NGC 7331
NGC 2841
NGC 2403
DDO 154
IC 2574
NGC 925
NGC 7793
NGC 5055 (M63)
NGC 2903
NGC 6946
NGC 4736 (M94)
NGC 5194 (M51)
NGC 4214
NGC 628 (M74)
NGC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

HERACLES CO 2-1 Survey



Leroy et al. 2009, AJ, 137, 4670



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