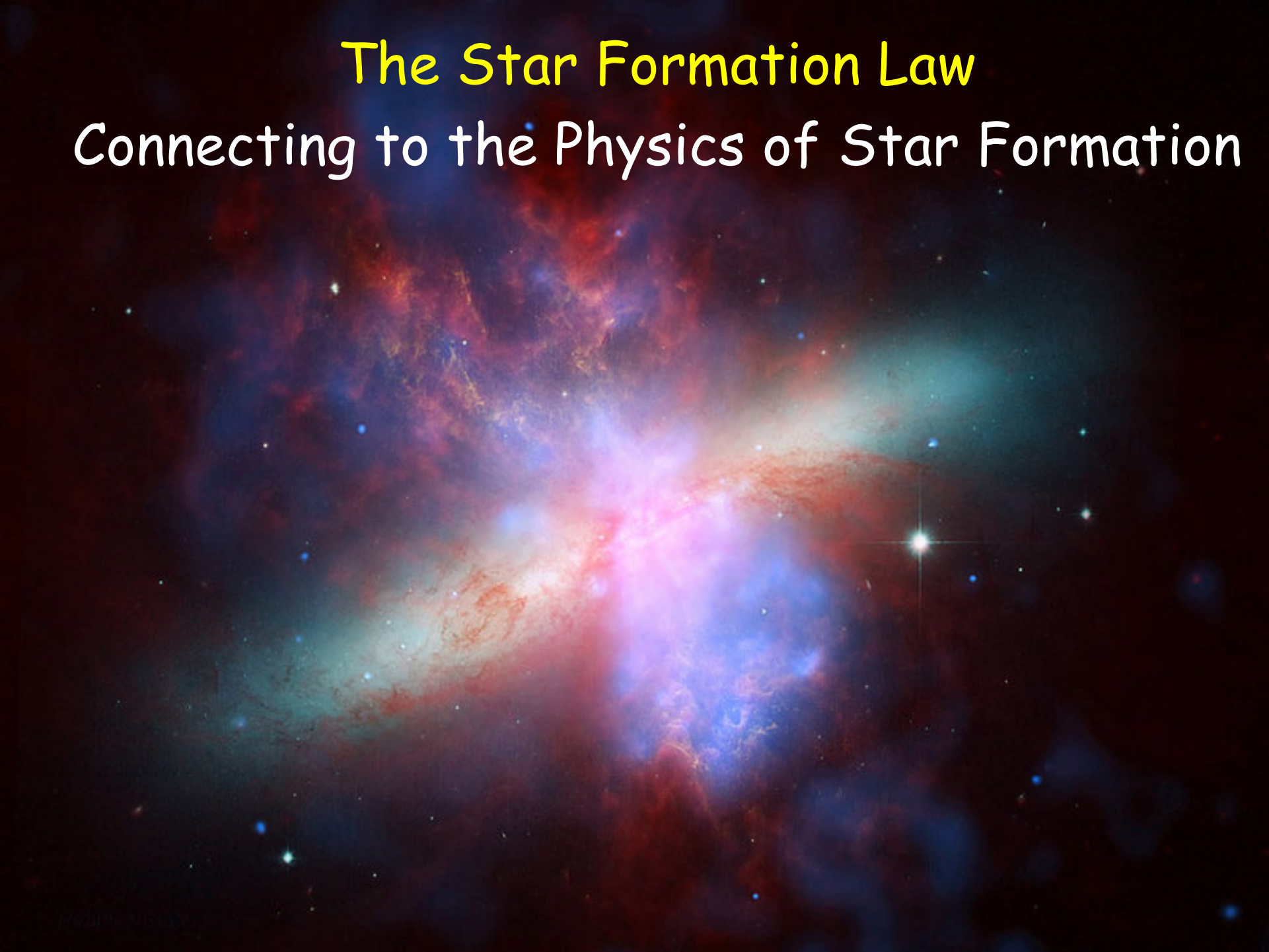
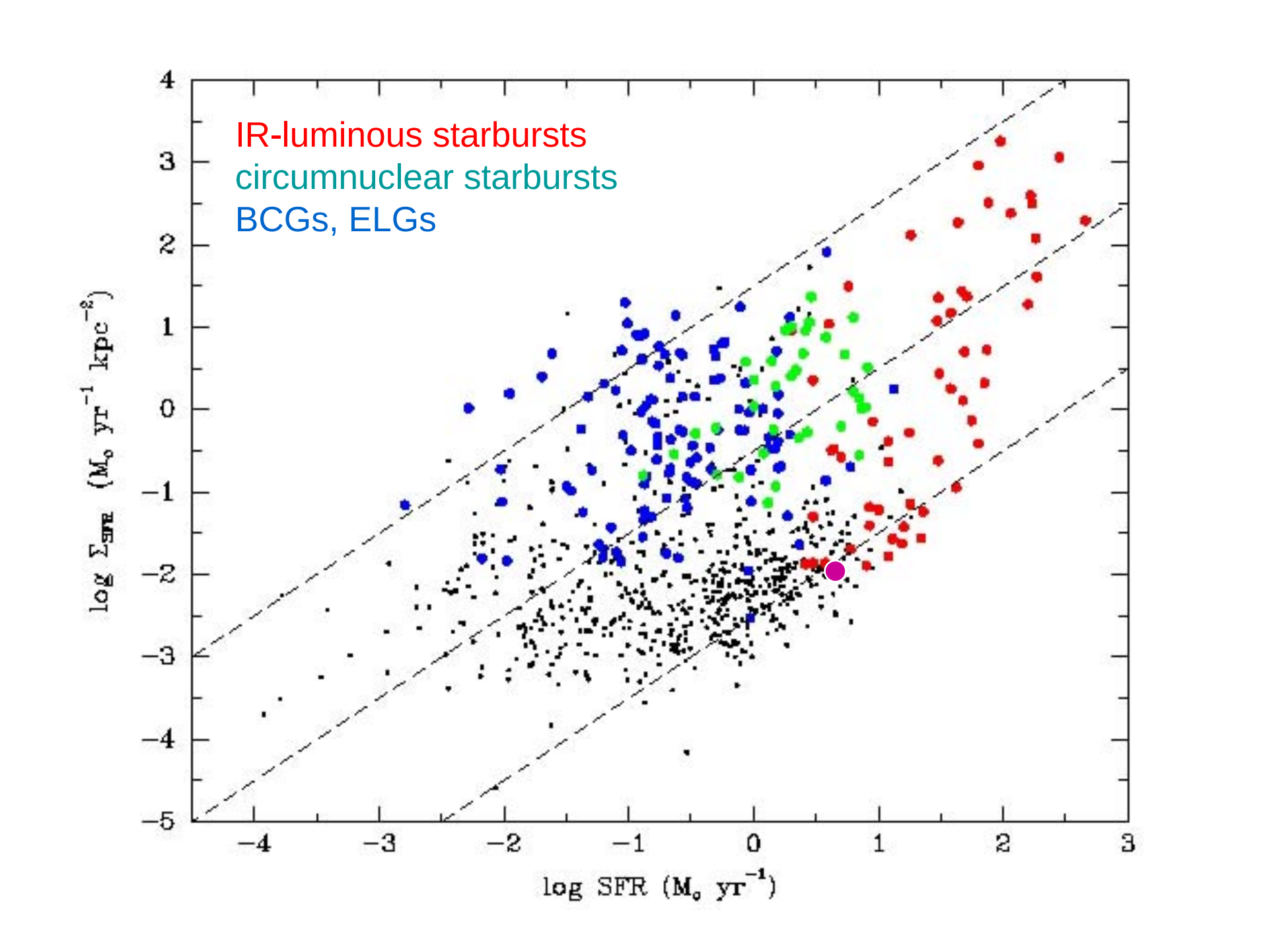
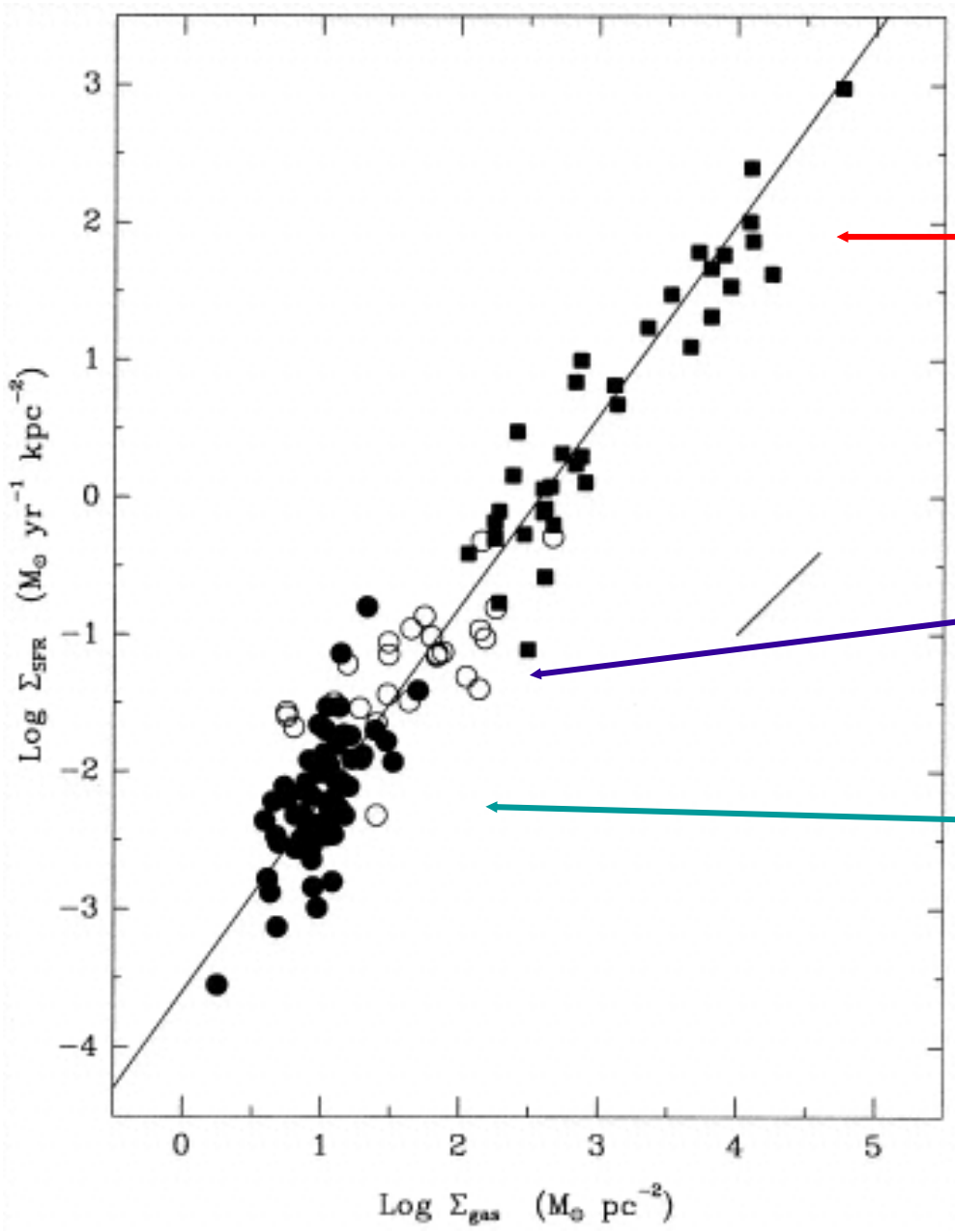
The Star Formation Law

Connecting to the Physics of Star Formation




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

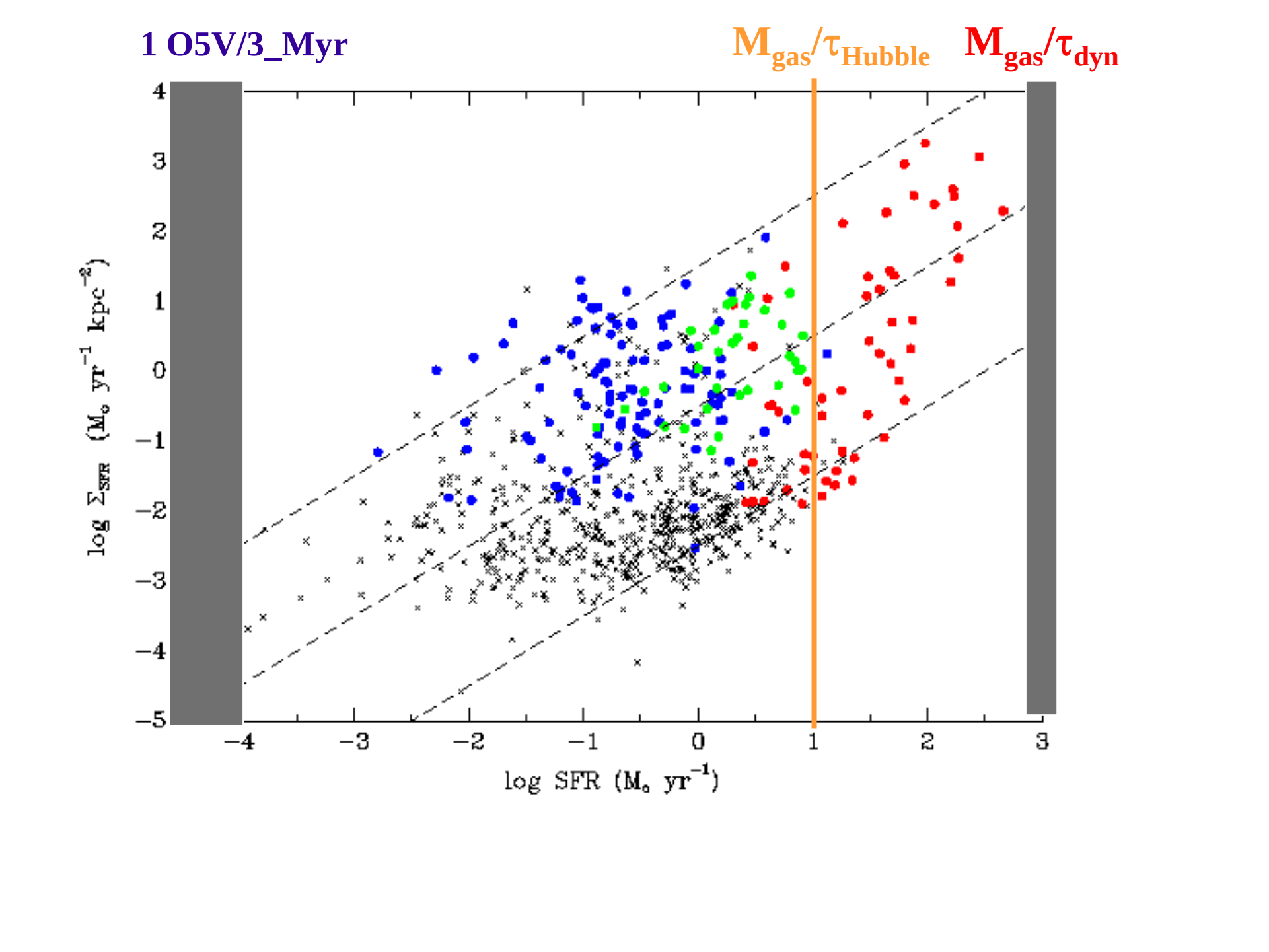


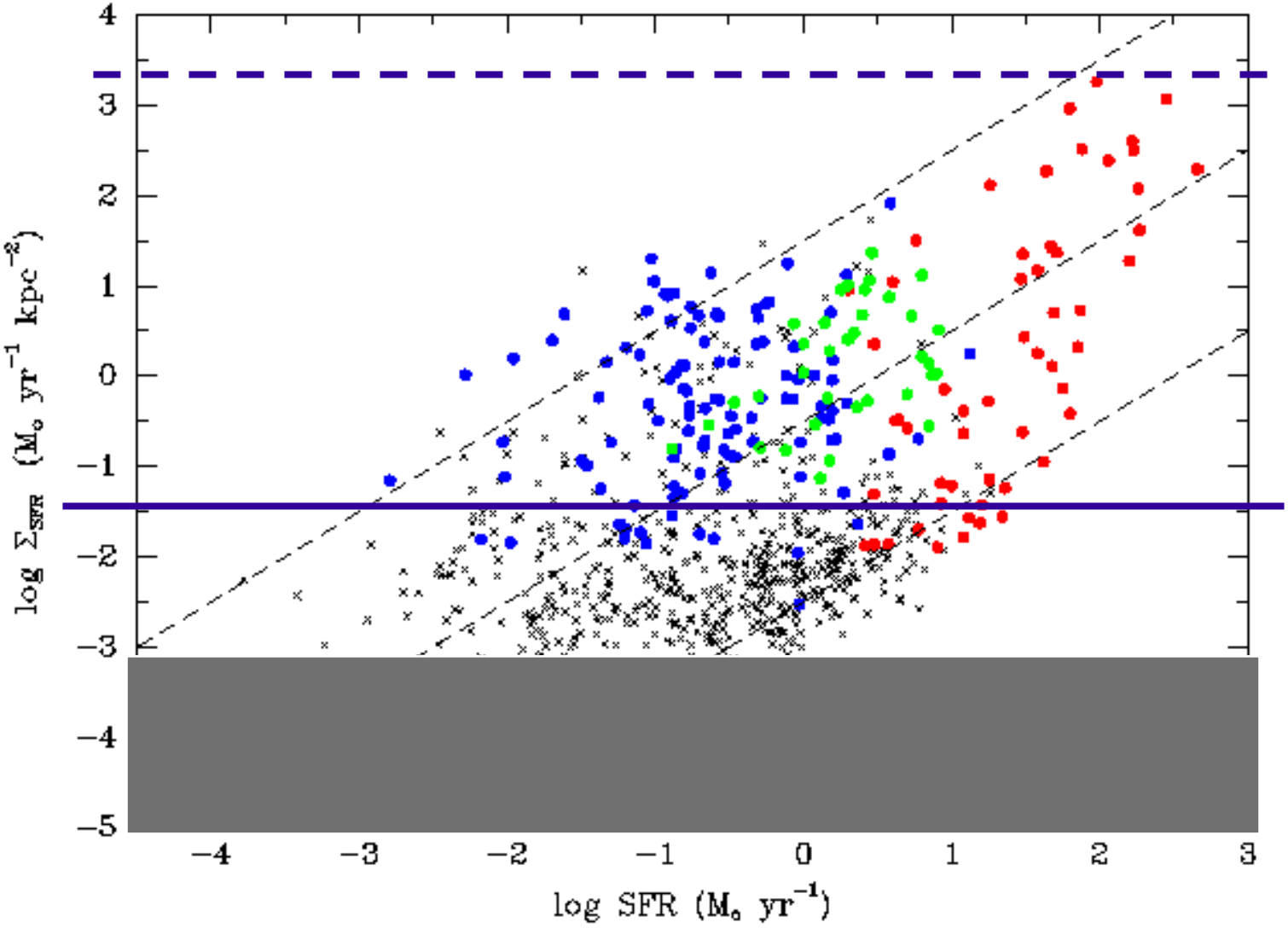
starbursts

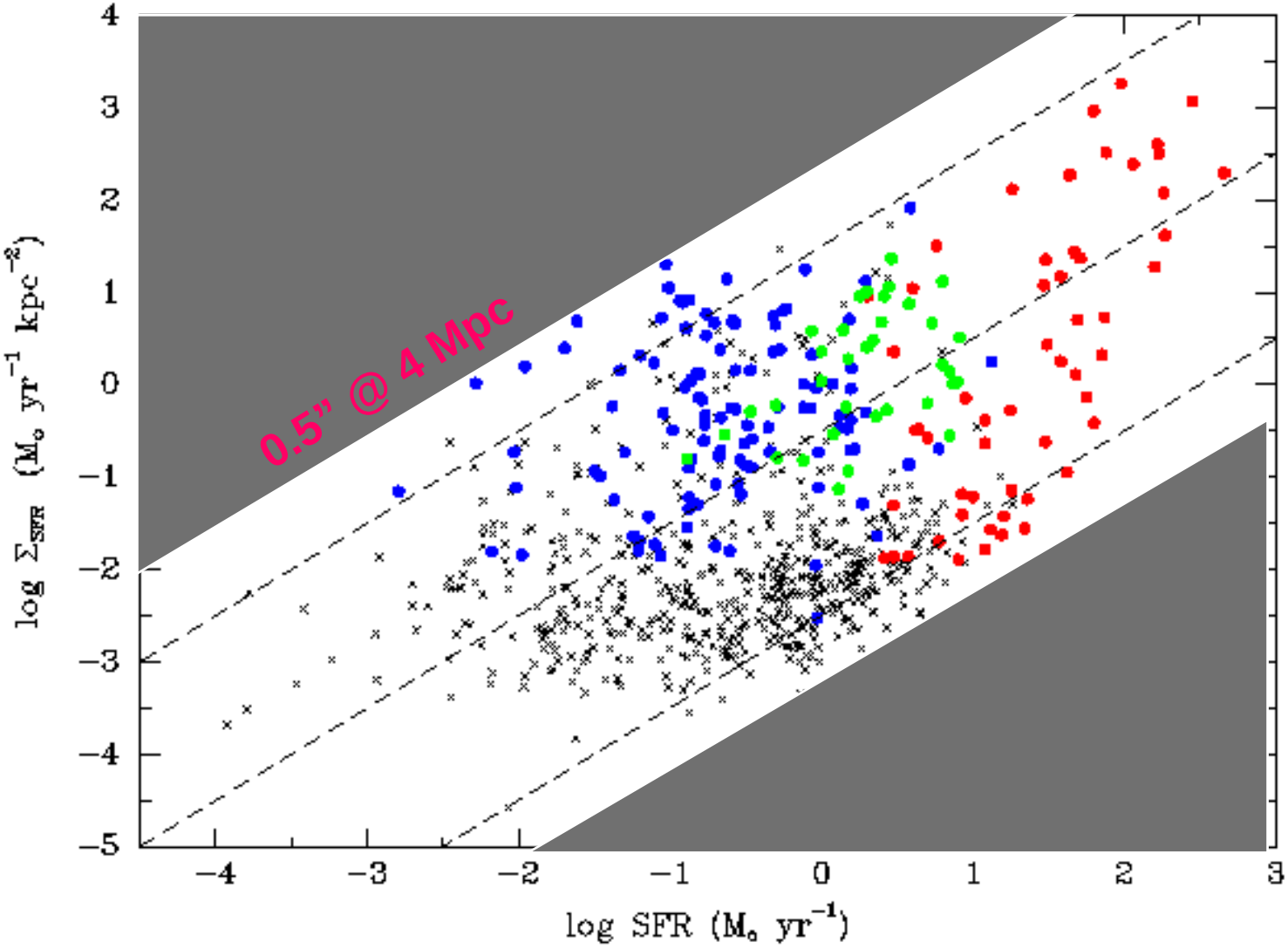
centres of discs

normal discs

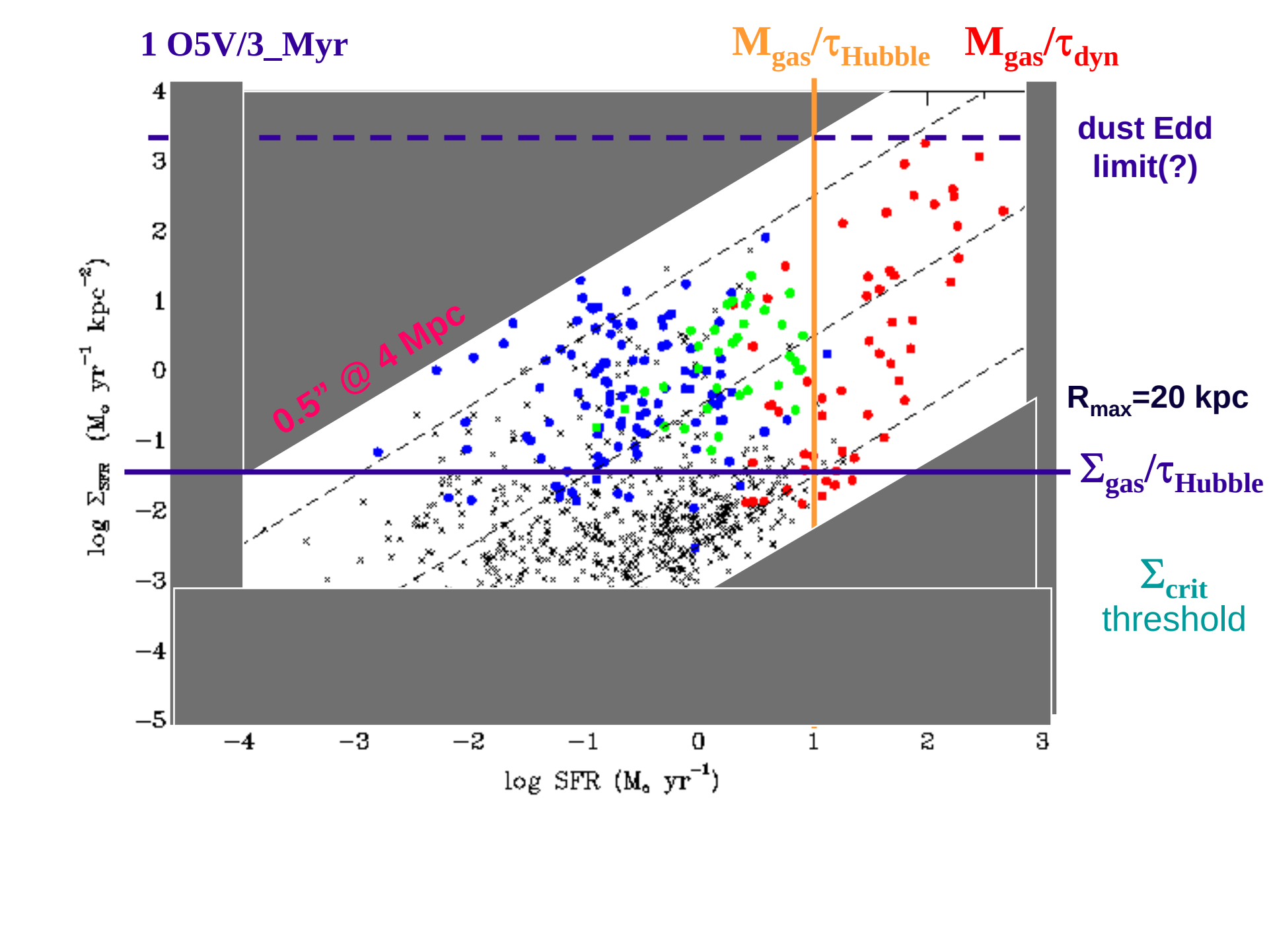
Kennicutt 1998, ApJ, 498, 541


1 O5V/3_Myr
M_{gas}/τ_{Hubble}
M_{gas}/τ_{dyn}
log Σ_{SFR} ($M_\odot$ yr^{-1} kpc^{-2})
log SFR ($M_\odot$ yr^{-1})
4
3
2
1
0
−1
−2
−3
−4
−5
−4
−3
−2
−1
0
1
2
3


dust Edd limit(?)
$\Sigma_{gas}/\tau_{Hubble}$
Σ_{crit} threshold
log Σ_{SFR} ($M_\odot$ yr^{-1} kpc^{-2})
log SFR ($M_\odot$ yr^{-1})
4
3
2
1
0
−1
−2
−3
−4
−5
−4
−3
−2
−1
0
1
2
3


0.5" @ 4 Mpc
log Σ_{SFR} ($M_\odot$ yr^{-1} kpc^{-2})
log SFR ($M_\odot$ yr^{-1})
4
3
2
1
0
−1
−2
−3
−4
−5
−4
−3
−2
−1
0
1
2
3

R_{max}=20 kpc

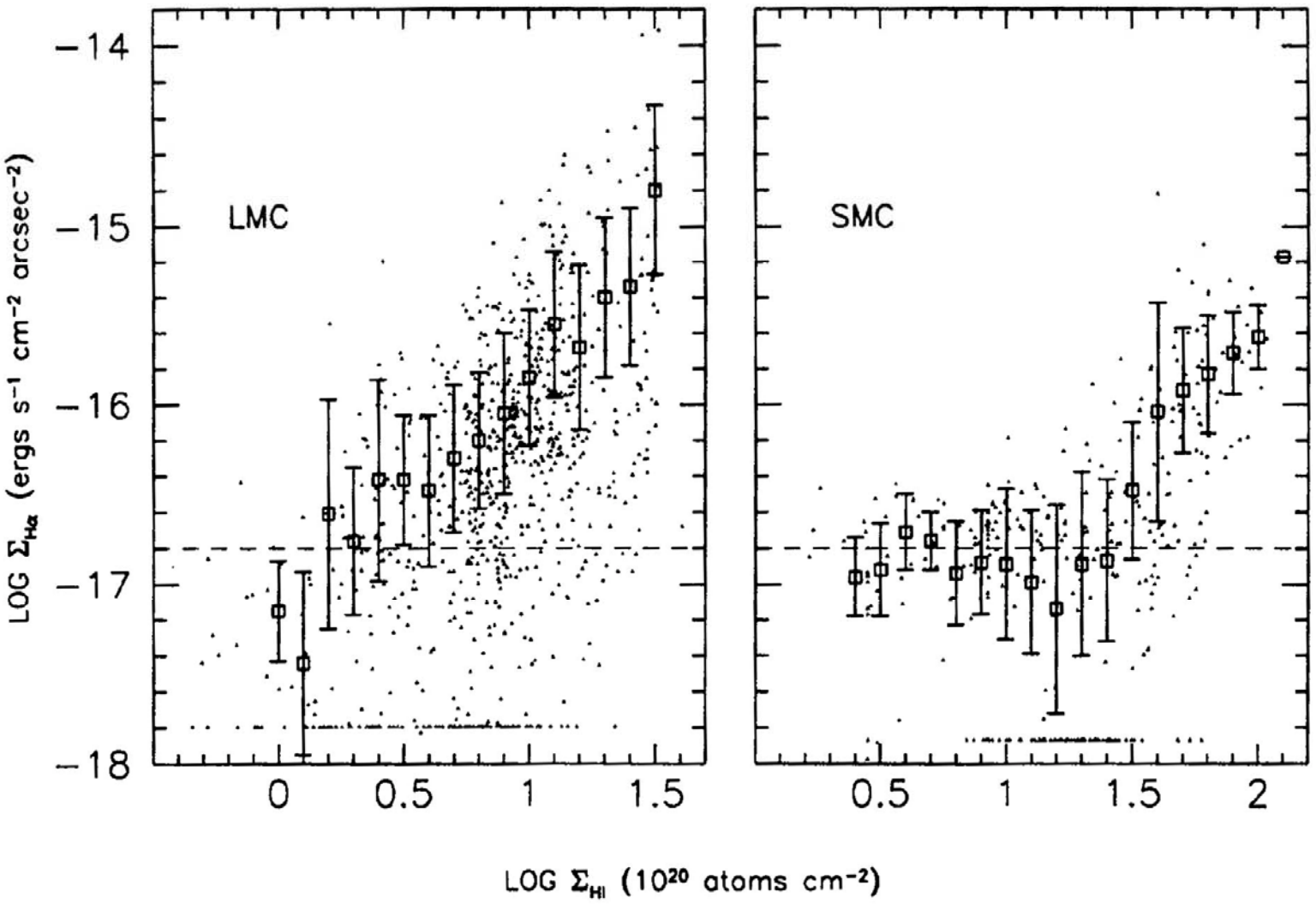

1 O5V/3_Myr
M_{gas}/τ_{Hubble}
M_{gas}/τ_{dyn}
dust Edd limit(?)
0.5" @ 4 Mpc
R_{max}=20 kpc
$\Sigma_{gas}/\tau_{Hubble}$
Σ_{crit} threshold
log Σ_{SFR} ($M_\odot$ yr^{-1} kpc^{-2})
log SFR ($M_\odot$ yr^{-1})
4
3
2
1
0
−1
−2
−3
−4
−5
−4
−3
−2
−1
0
1
2
3

Basic Observations

- Galaxies exhibit an immense diversity in SF properties, varying by $>10^7$ in SFR, SFR/mass and SFR/area
- SFR/area is correlated with gas surface density, following a truncated power law with index N = 1.4 +-0.1
  - scatter in relation is significant on all scales
  - tightest correlation with total density on large scales, and with molecular density on small scales (???)
  - 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 discs reside in the threshold regime at all radii

SF Law on Different Physical Scales

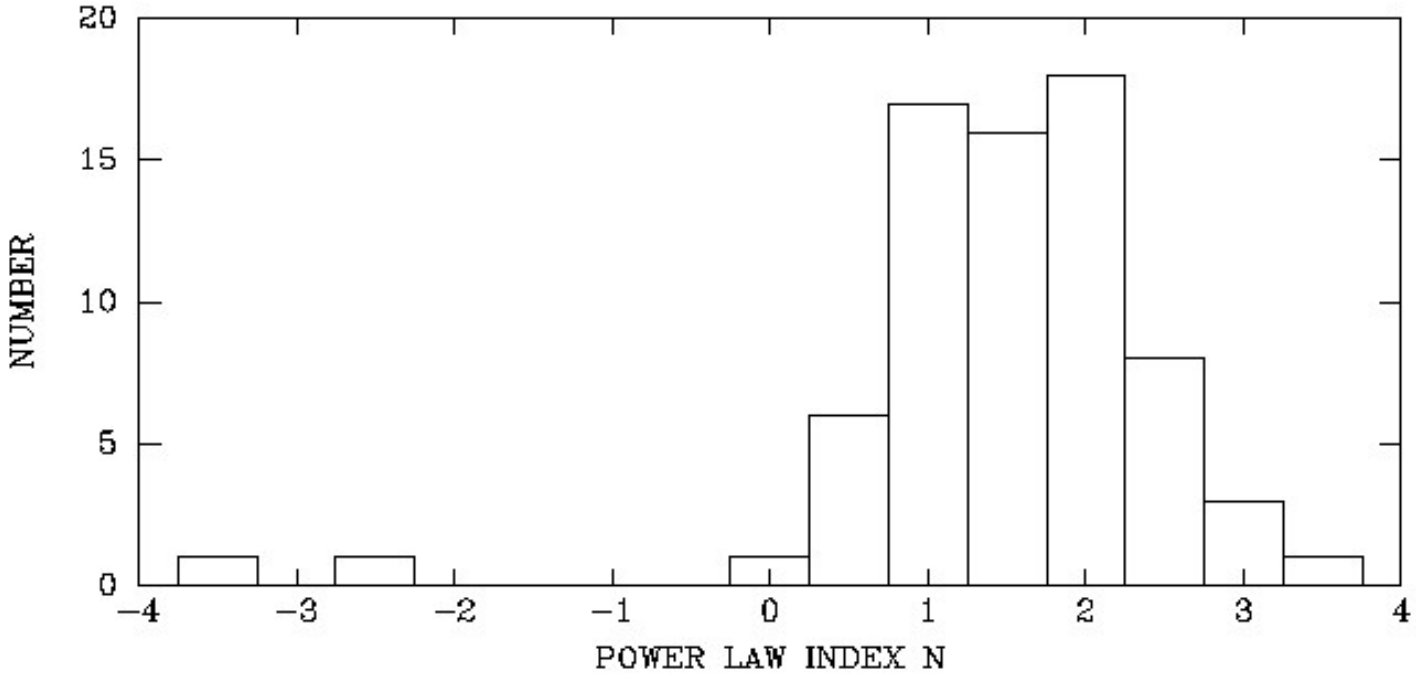
- Integrated (disc-averaged) law
  - parameterization of gas → star conversion rate on global scales, but little insight into physics of cloud/star formation
- Radial dependence of SFR on gas density
  - provides similar information to above, plus sensitivity to large-scale physical and dynamical parameters (e.g., metallicity, dynamical stability, H_2/HI ratio…)
- Local point by point relations
  - best probe of SFR regulation and SF efficiency on cloud scales, best chance to break parametric degeneracies
  - large scatter, with SF law only as statistical description
  - would expect convergence to linear relation (constant SF efficiency) on cloud scale??



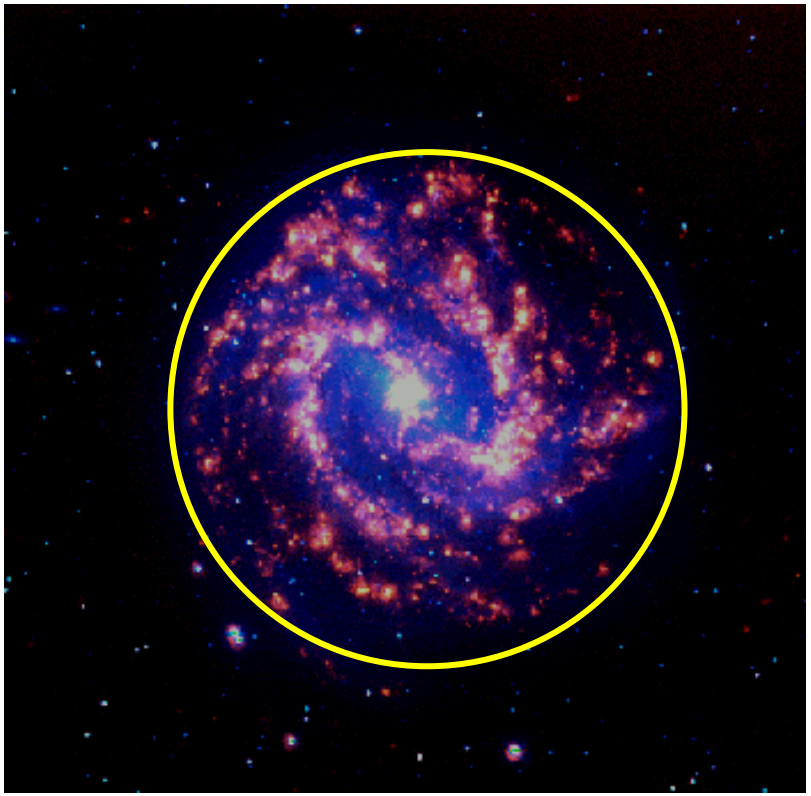
Kennicutt et al. 1995, *AJ*, 109, 594

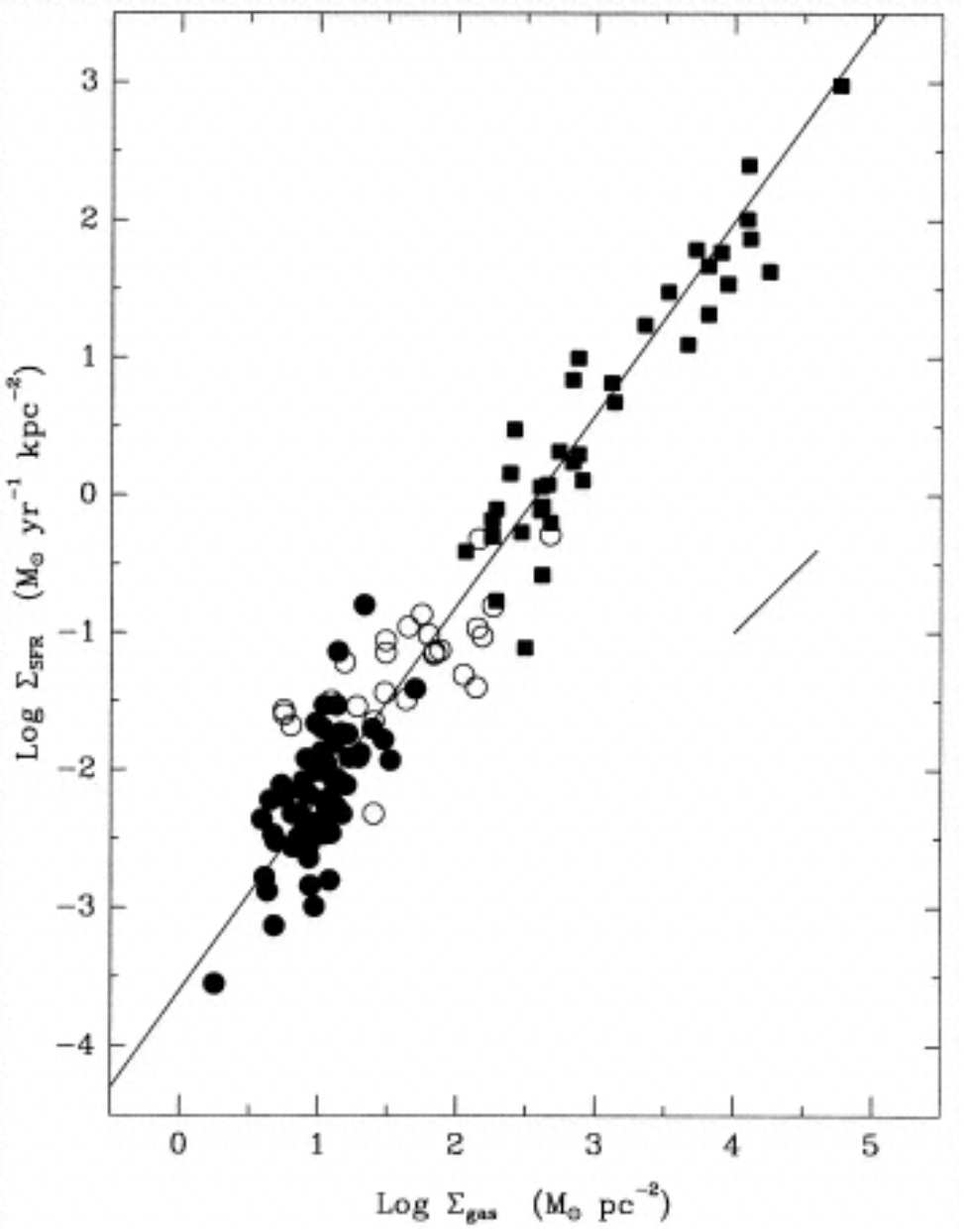
Schmidt Law

- Schmidt 1959, ApJ, 129, 243
- Schmidt 1963, ApJ, 137, 758



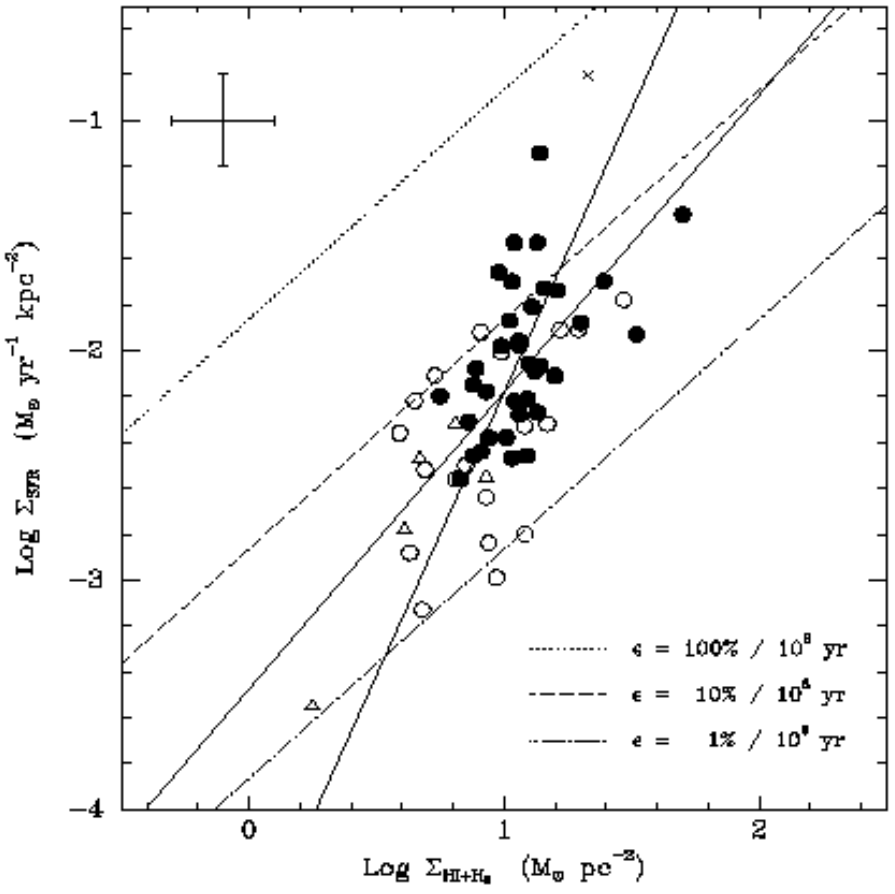
Kennicutt 1997, in The ISM in Galaxies (Kluwer)

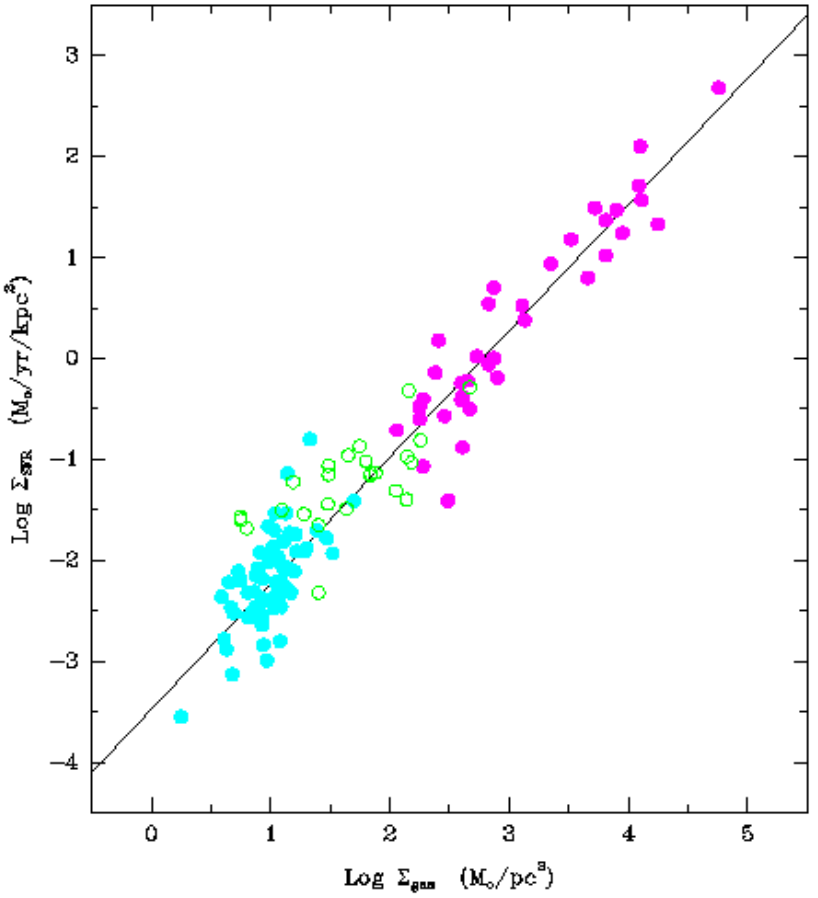



Log Σ_{SFR} ($M_\odot$ yr^{-1} kpc^{-2})
Log Σ_{gas} ($M_\odot$ pc^{-2})
3
2
1
0
−1
−2
−3
−4
0
1
2
3
4
5

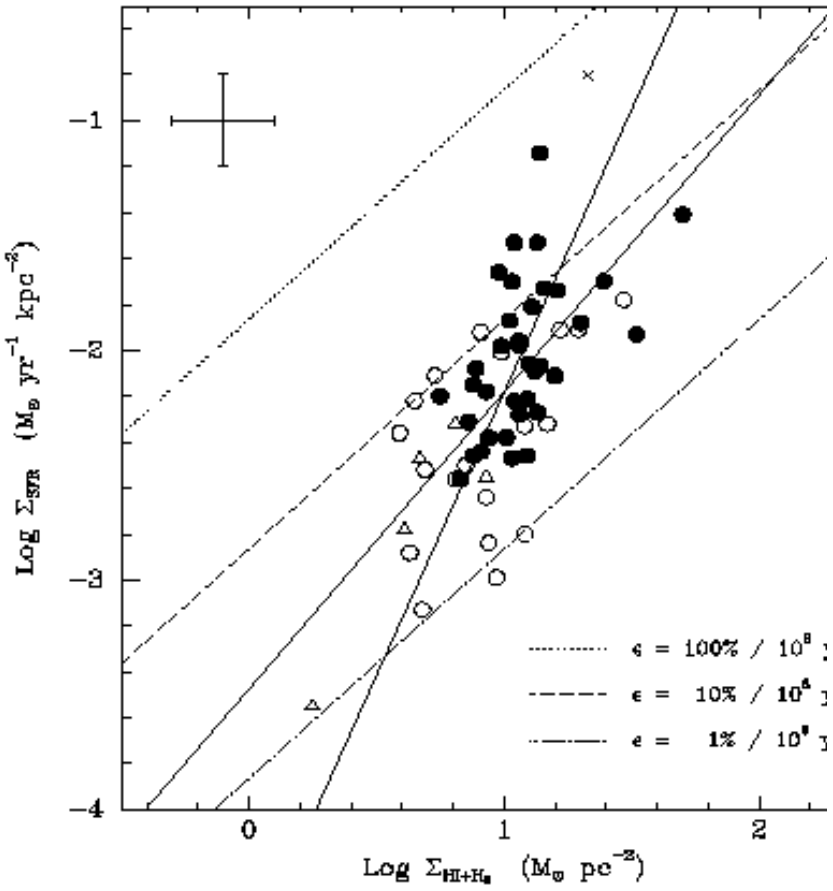
The Global Schmidt Law Revisited

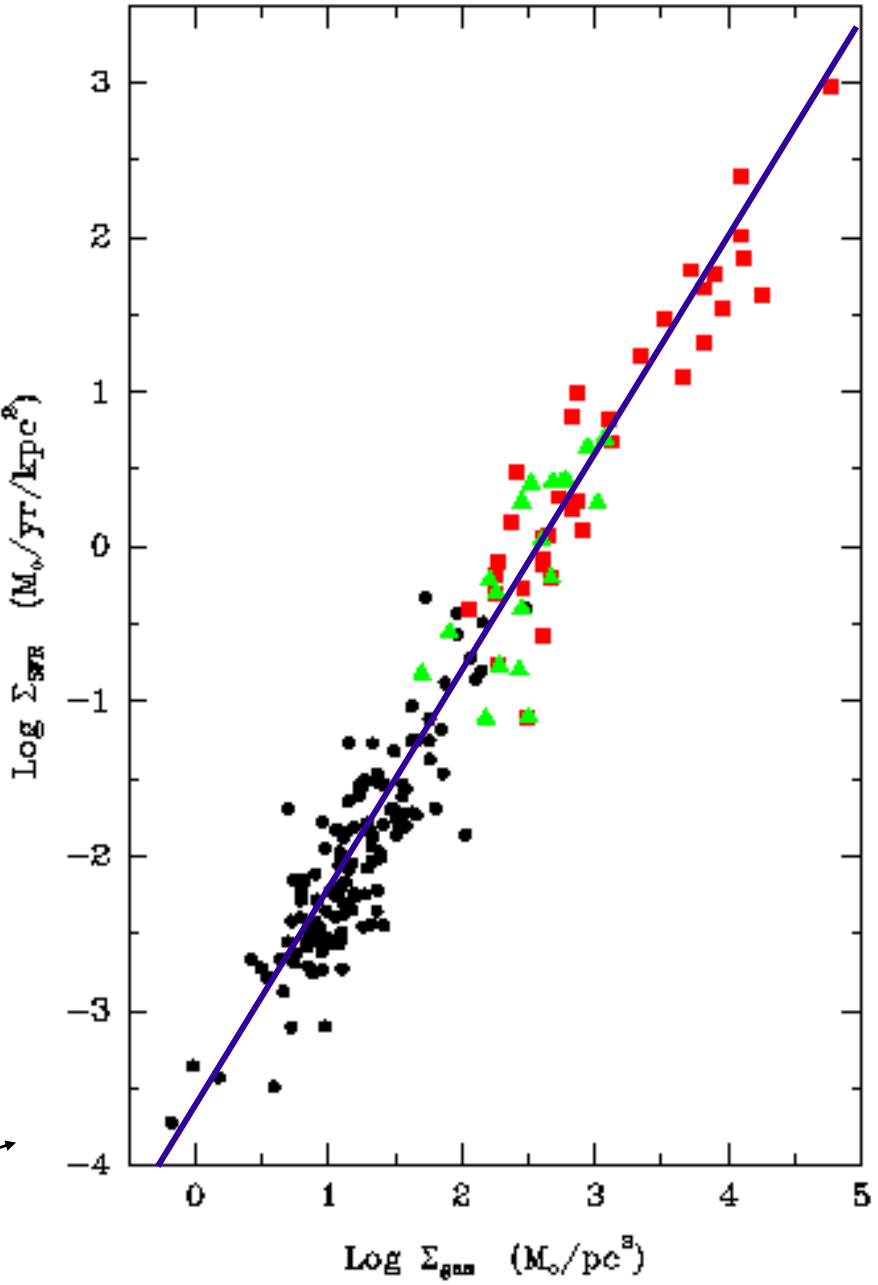
- analyze galaxies with spatially-mapped star formation (Hα, Pα, FIR), HI, and CO
- enlarged, diversified samples
  - normal galaxy sample 3x larger
  - larger ranges in gas and SFR densities
  - large subsamples of circumnuclear starbursts, low-metallicity galaxies incorporated
- densities averaged within active SF regions
- explicit corrections for [NII], extinction
- point-by-point analysis of SINGS + BIMA SONG galaxies



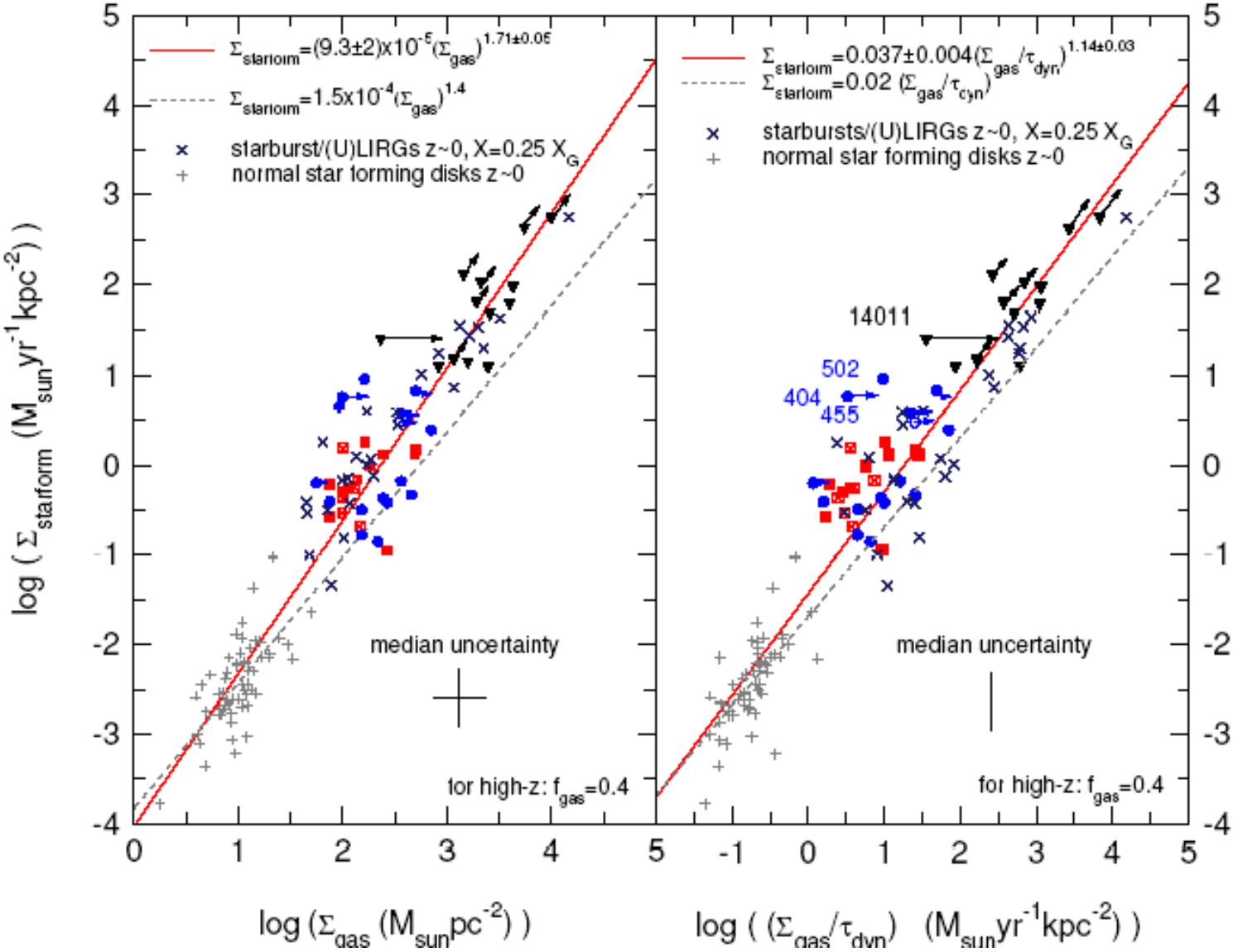


Kennicutt 1998, ApJ, 498, 541



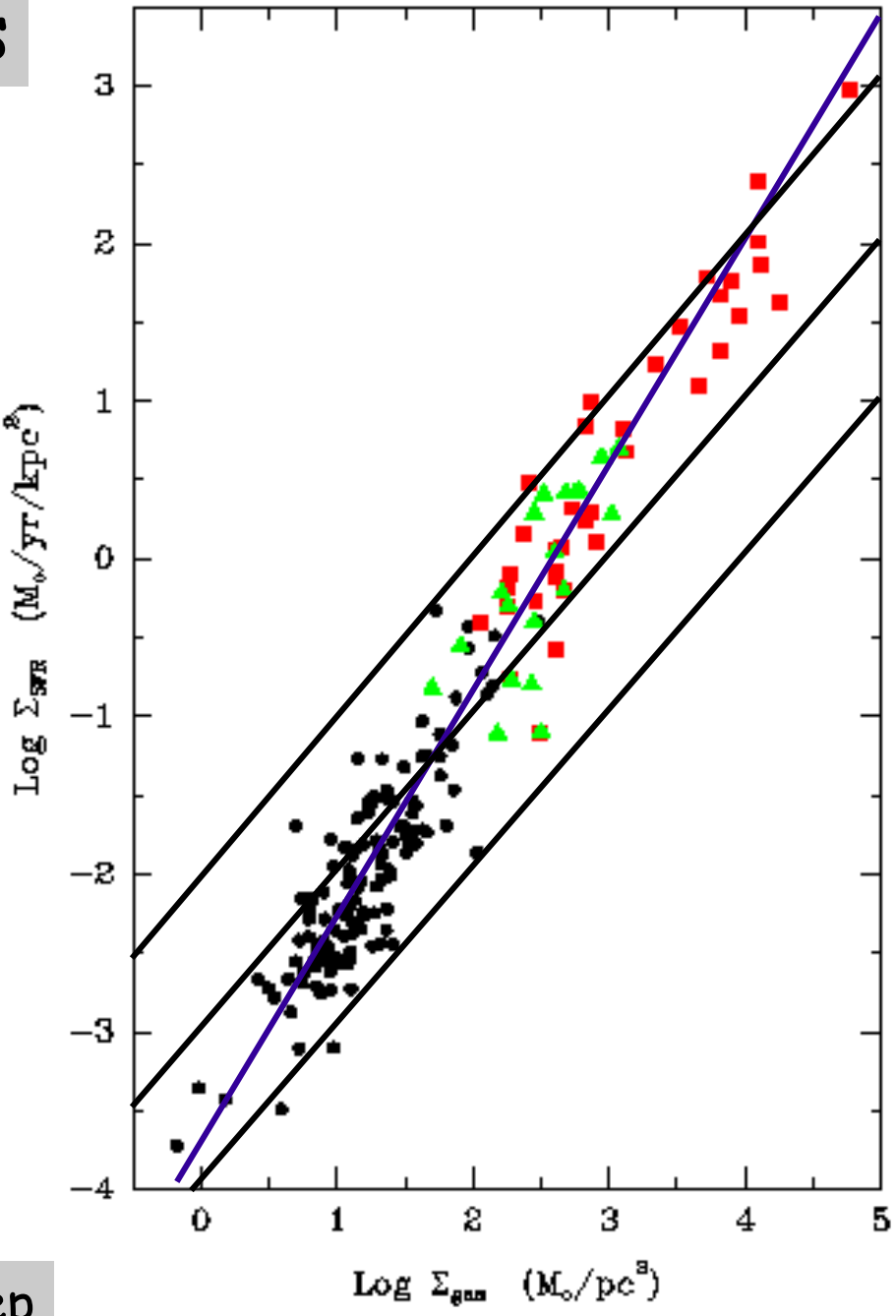


RCK et al., in prep



Bouche et al. 2007, ApJ, 671, 303

Global SFEs

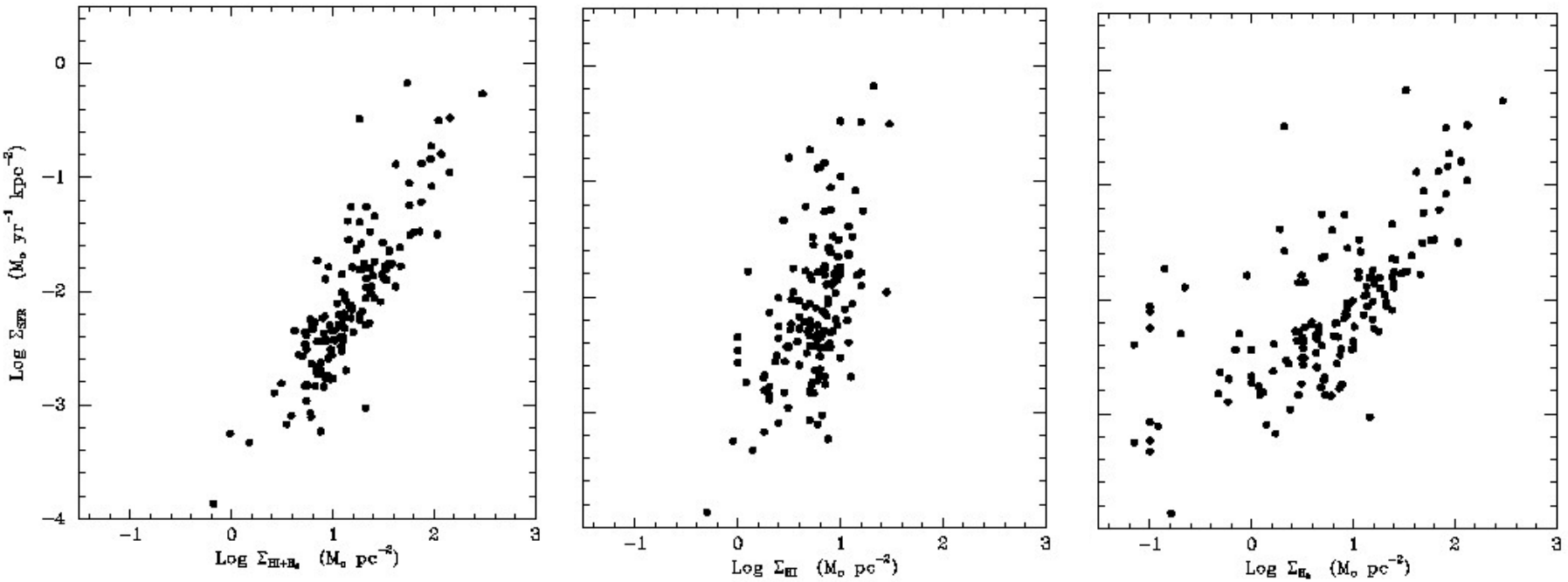


100% per 10^8 yr

10% per 10^8 yr

1% per 10^8 yr

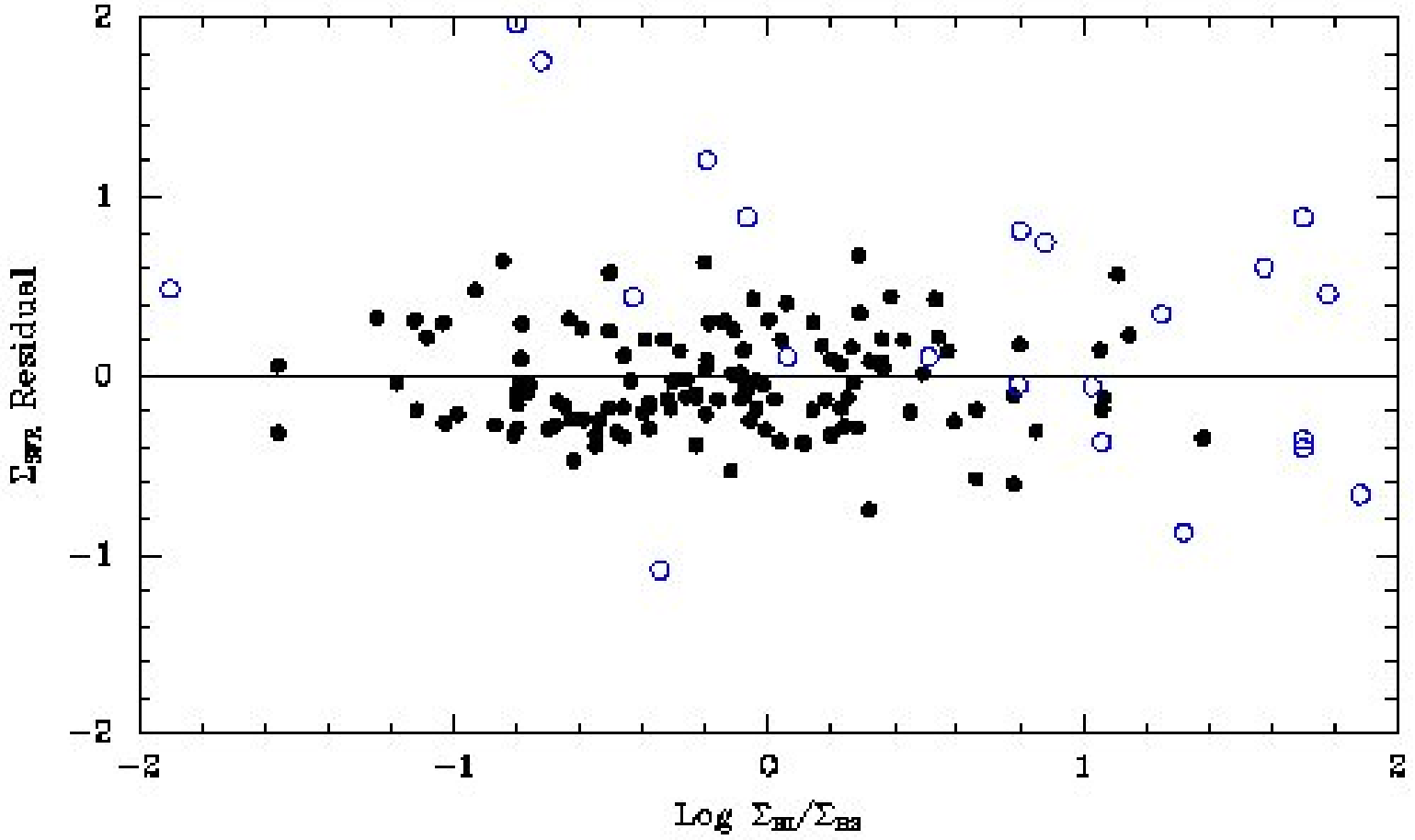
RCK et al., in prep



HI+H_2 HI H_2

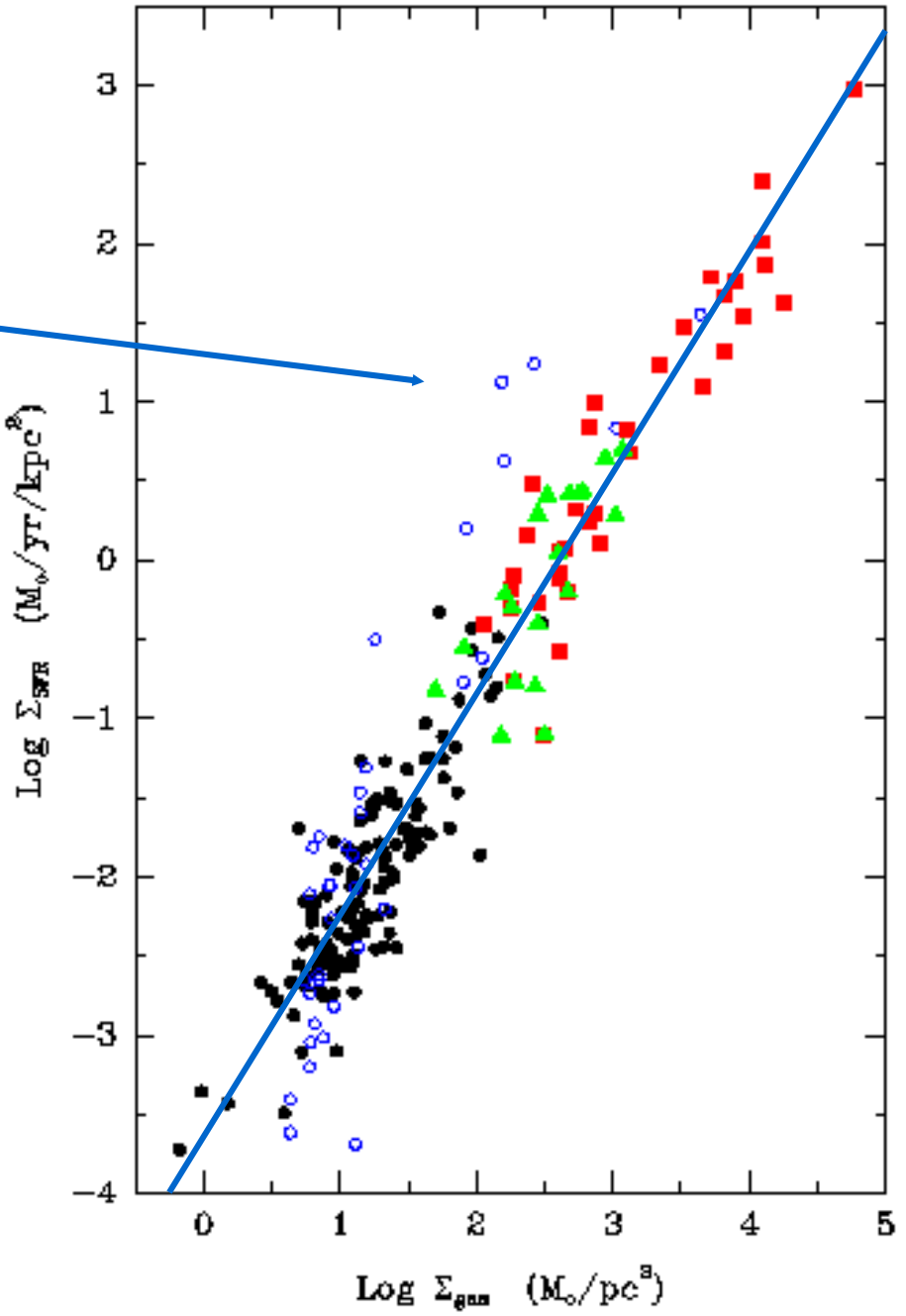
RCK et al., in preparation

Residuals vs HI/H2 Fraction



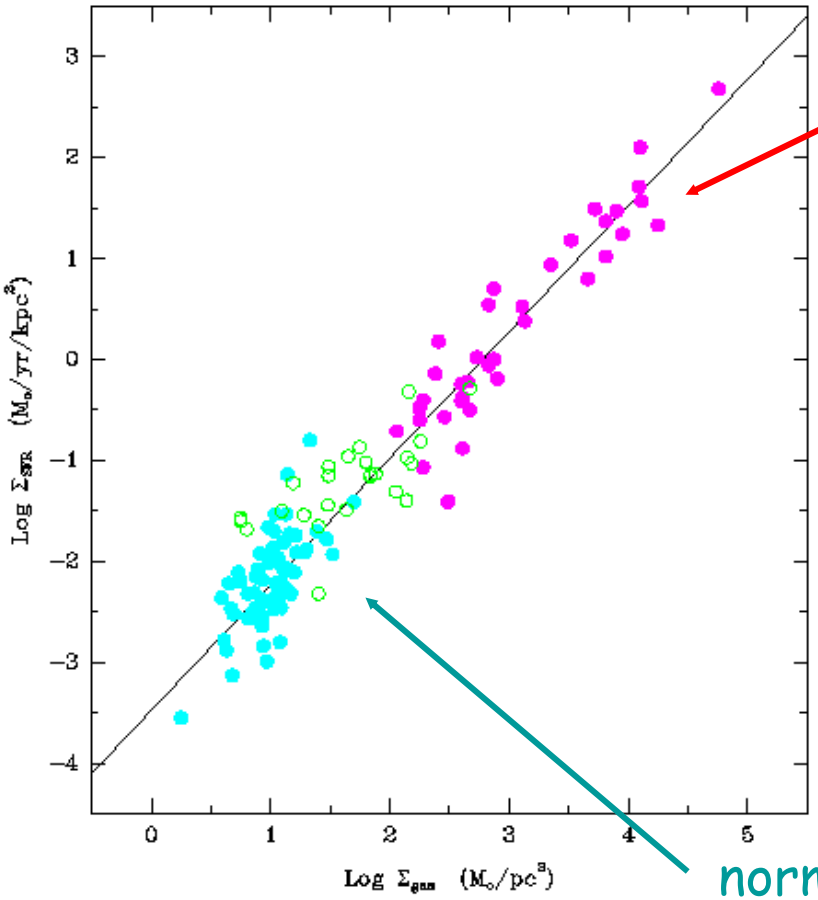
RCK et al., in preparation

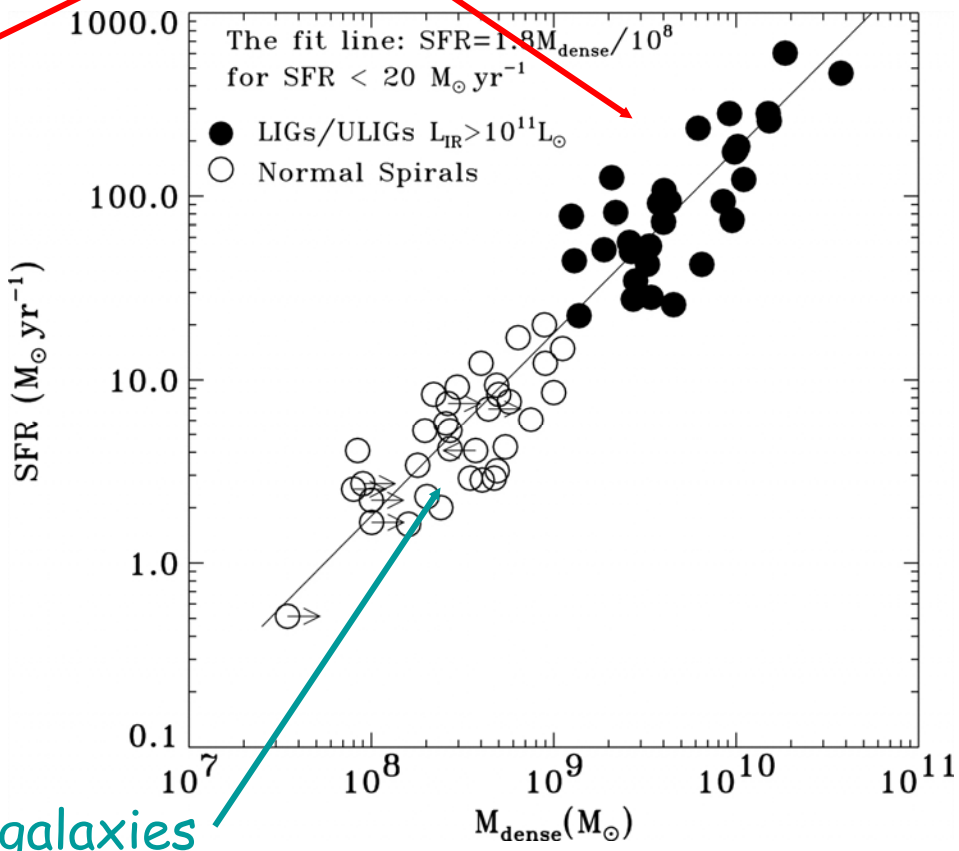
metal-poor dwarf galaxies



RCK et al., in preparation

starbursts

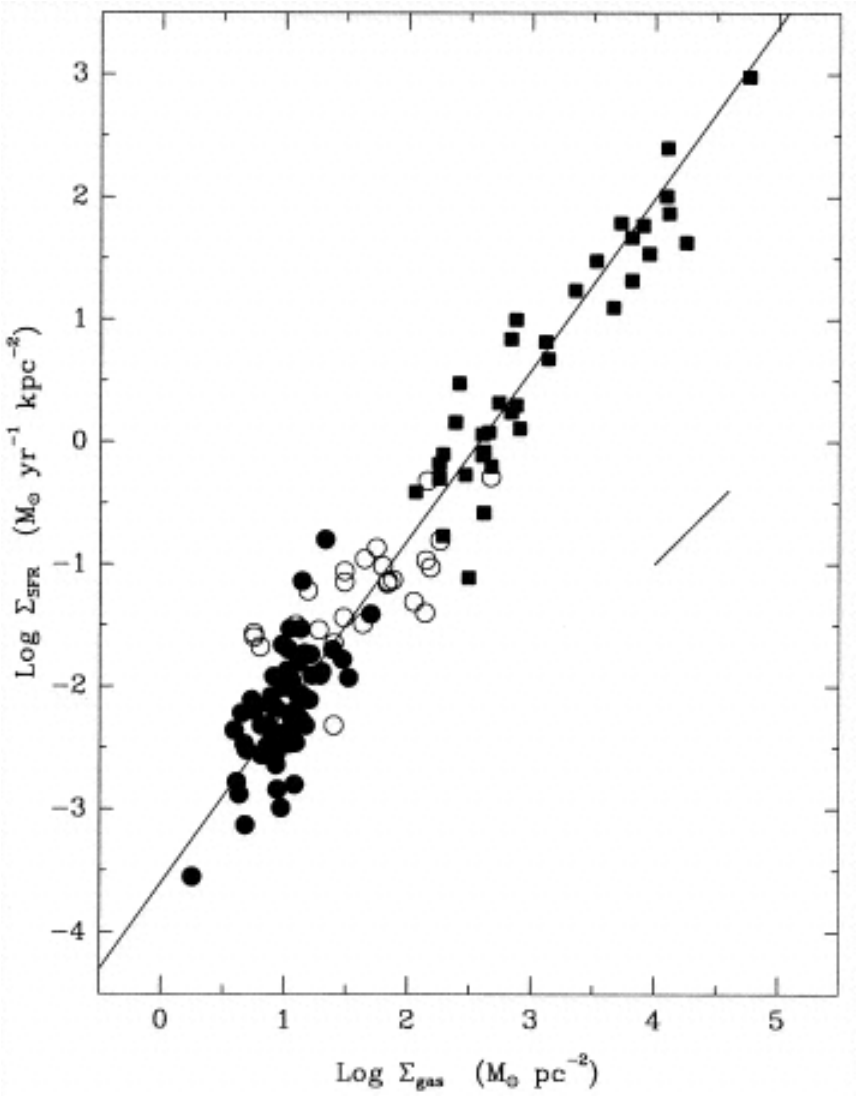


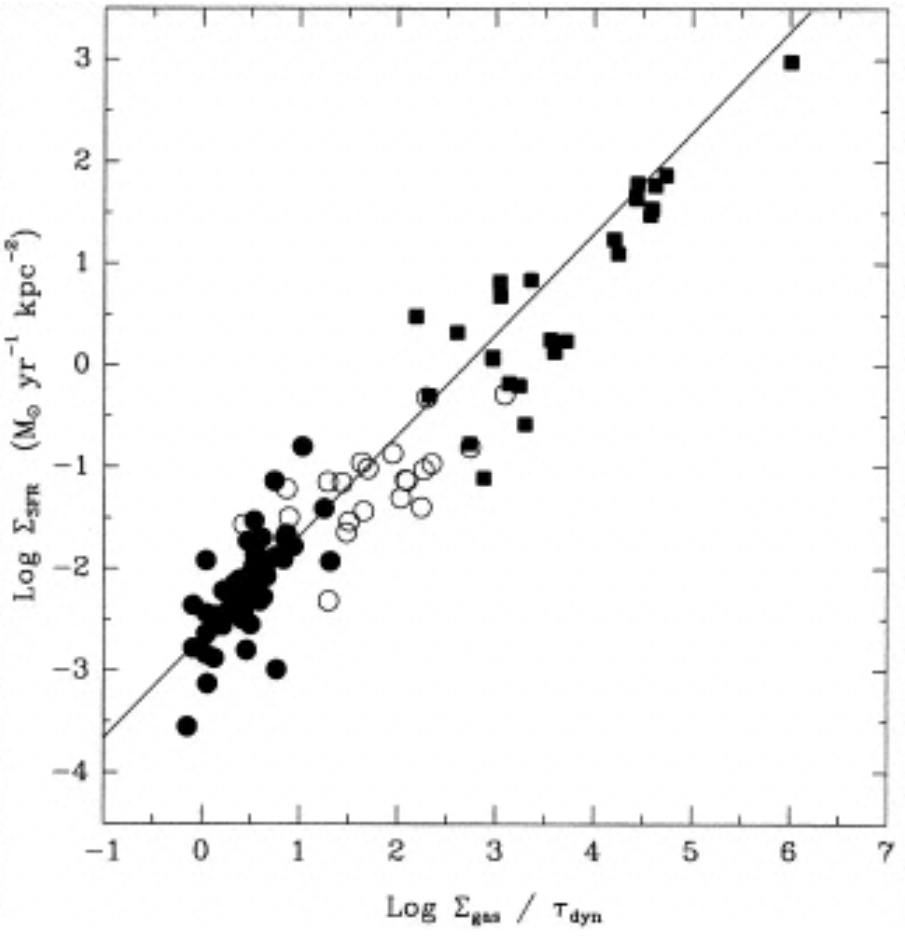


normal galaxies

Kennicutt 1998, ApJ, 498, 541

Gao, Solomon 2004, ApJ, 606, 271





"Schmidt law":

SFR vs gas density power law

"Silk law":

SFR vs gas density/dynamical time

The Spatially Resolved Star Formation Law in M51

Kennicutt et al. 2007, ApJ, submitted

- Use spatially-resolved measures of CO, HI, and SFR to characterize SFR vs gas surface density relation on a point-by-point basis

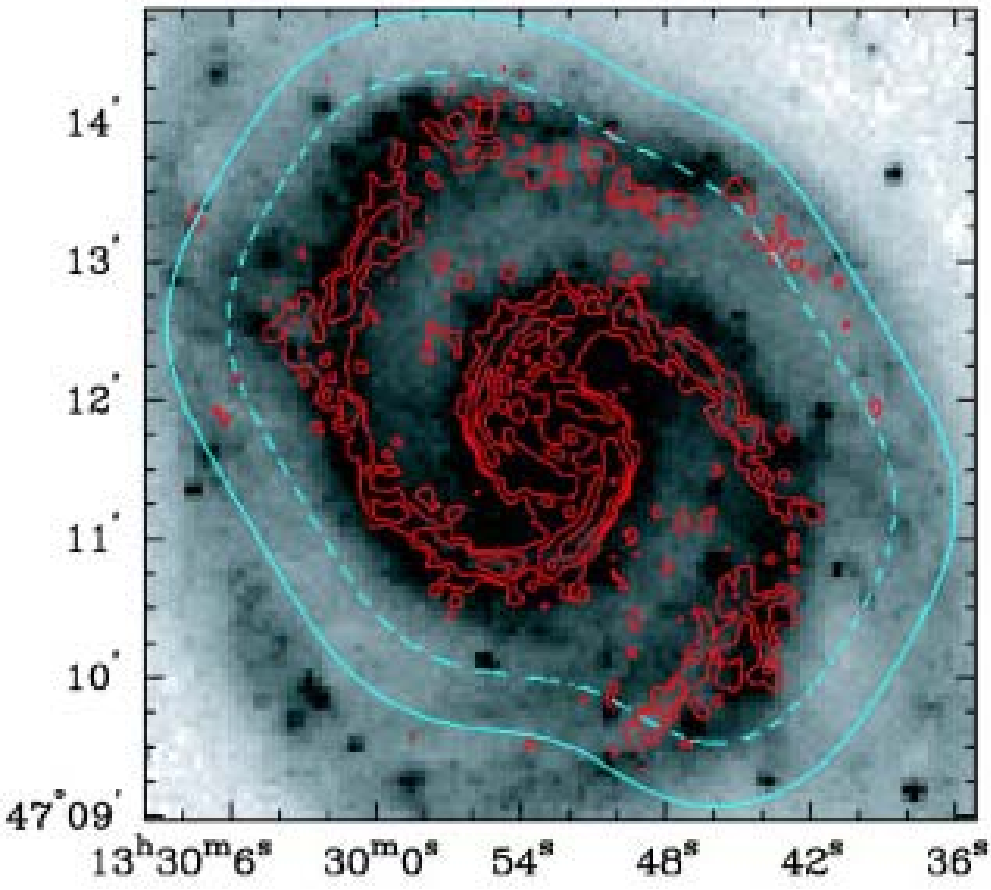
- Use combinations of Hα + Pα and Hα + 24 μm emission to correct for extinction in SFR measurements

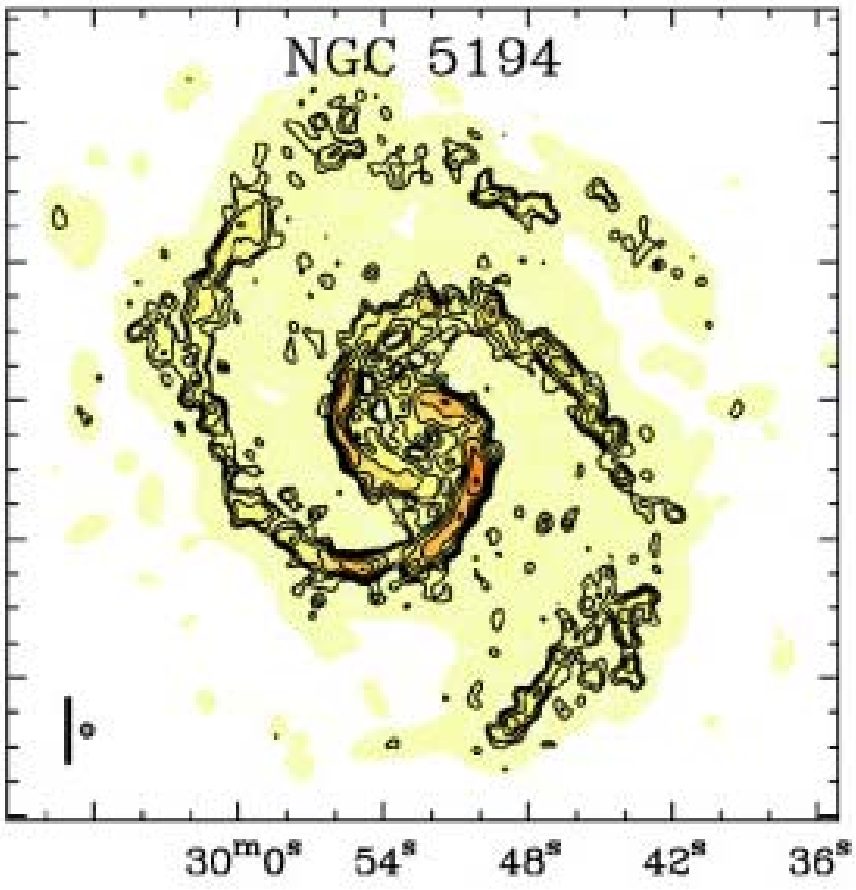
- Probe scales from 300 - 1850 pc (IR/HII regions to unbiased sampling of the disk)

Calzetti et al. 2005, ApJ, 633, 871

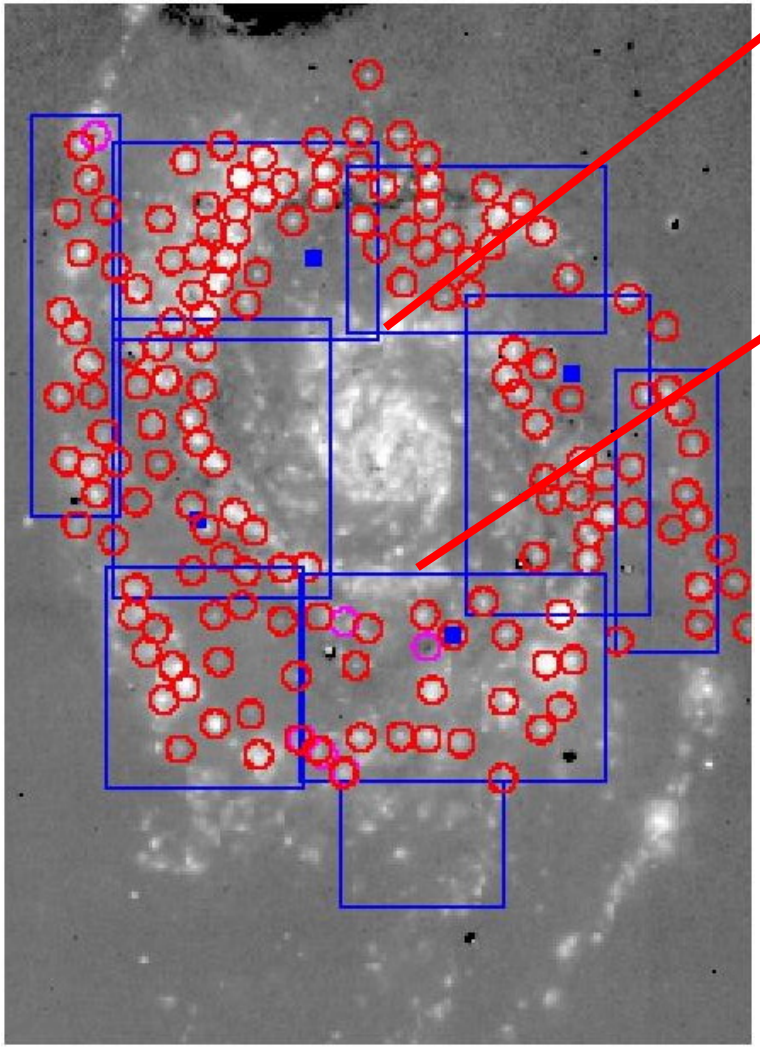
M51: BIMA SONG Survey

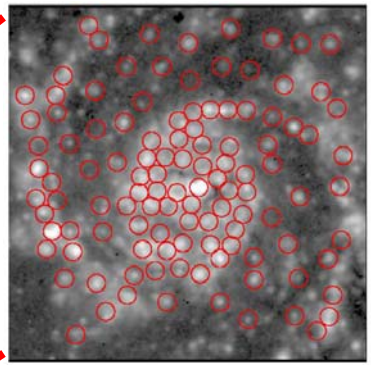
Helfer et al. 2003

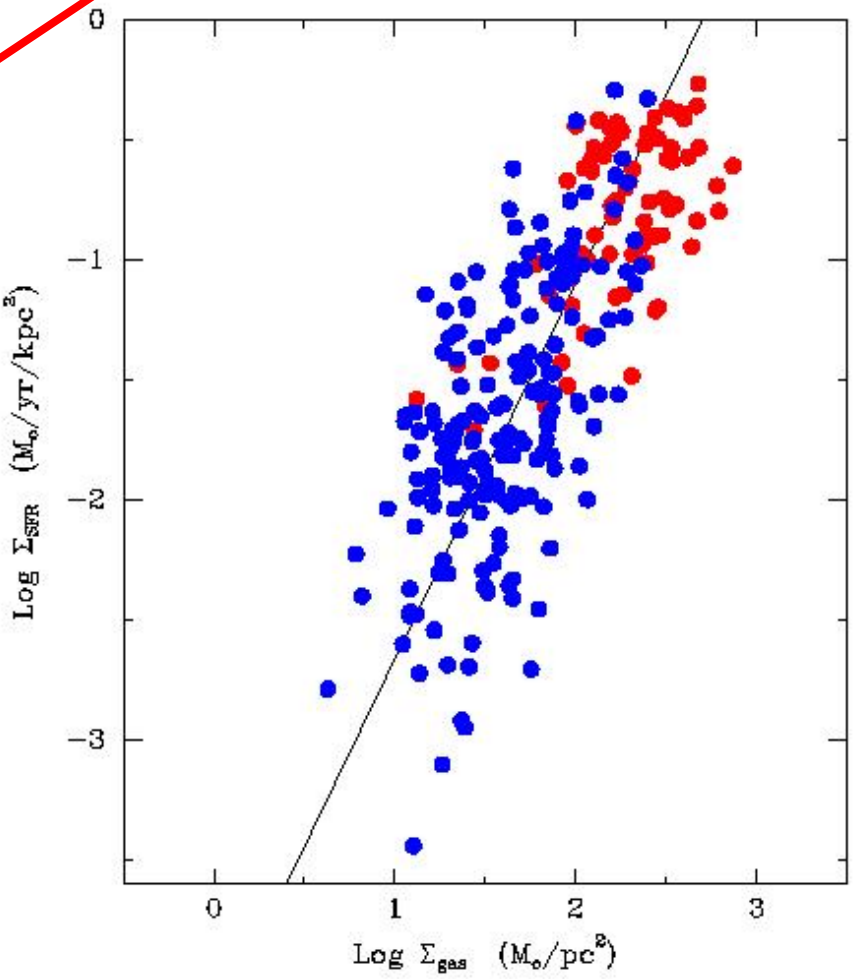




Local Schmidt Law in M51

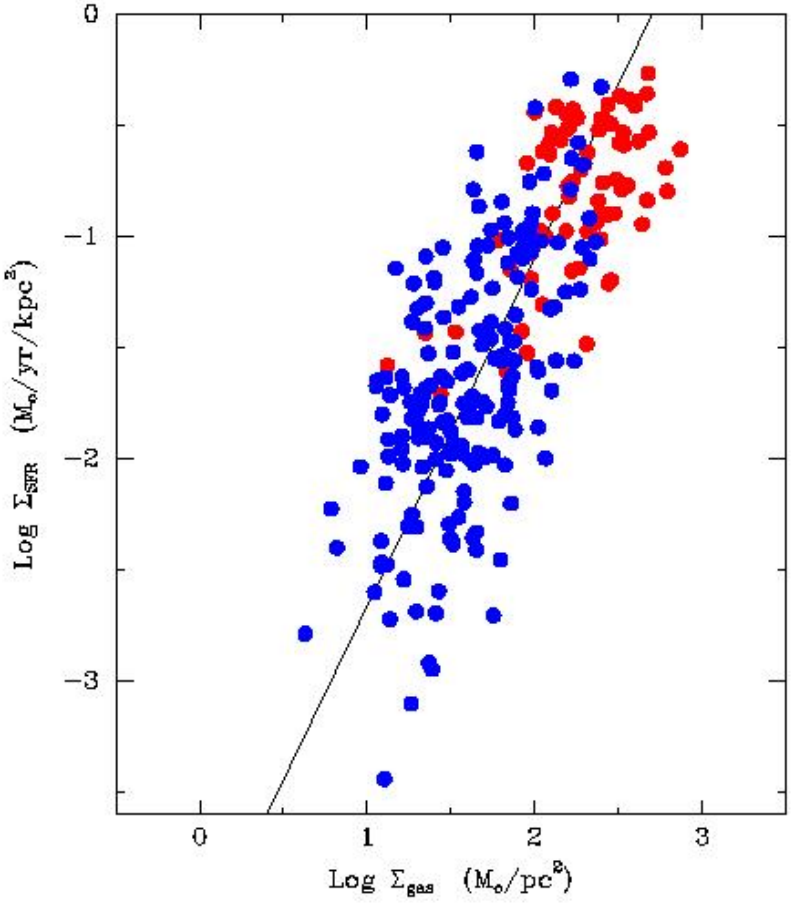


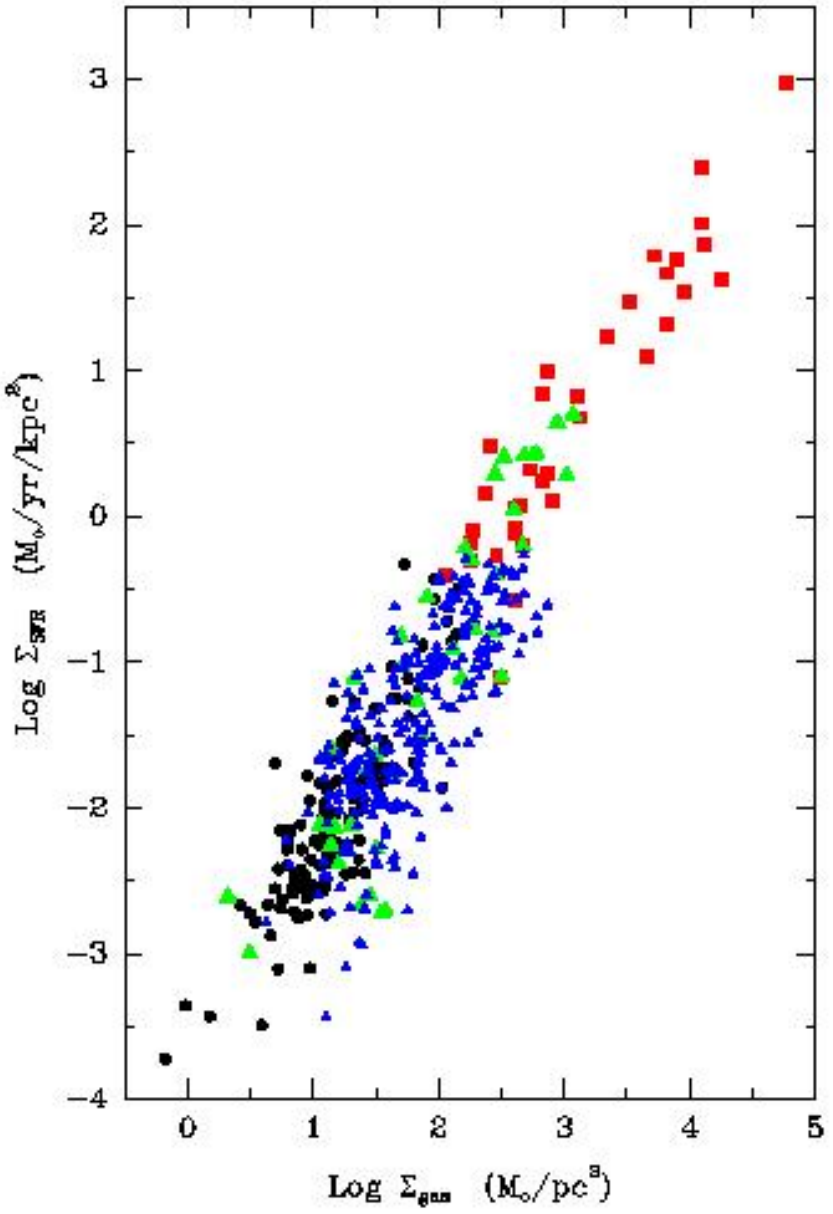




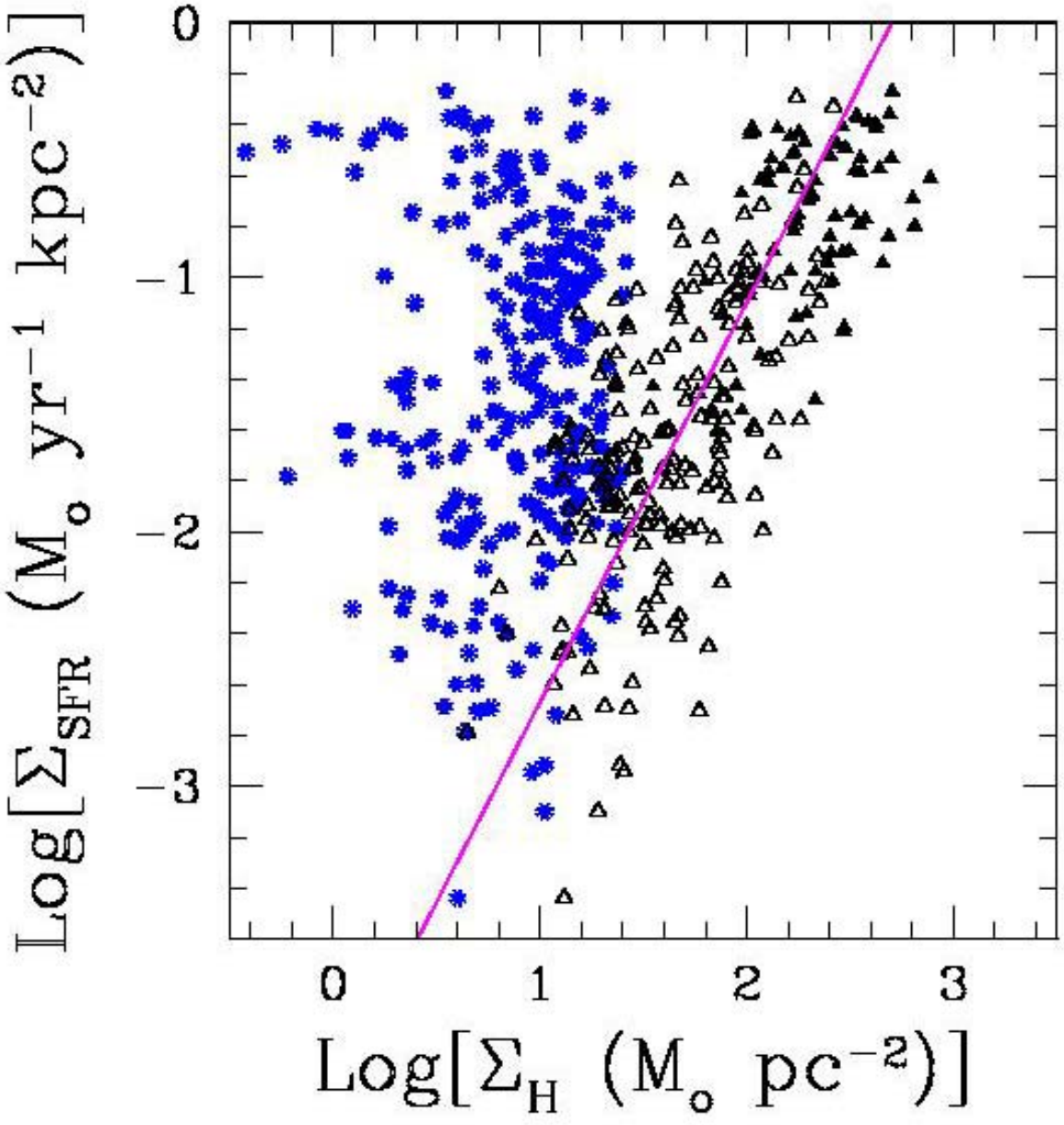
Kennicutt et al. 2007, ApJ, 671, 333

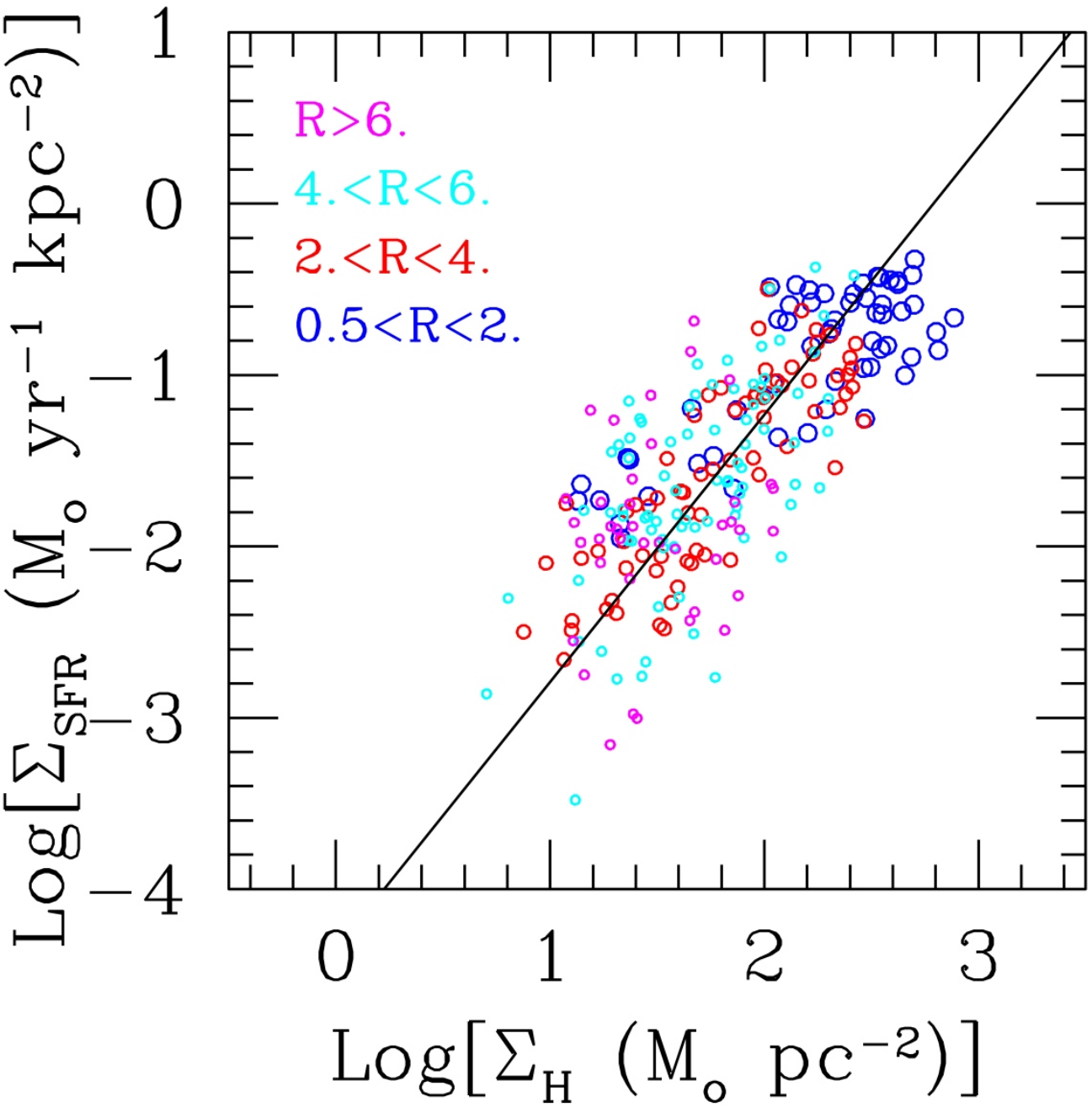
Local Schmidt Law in M51

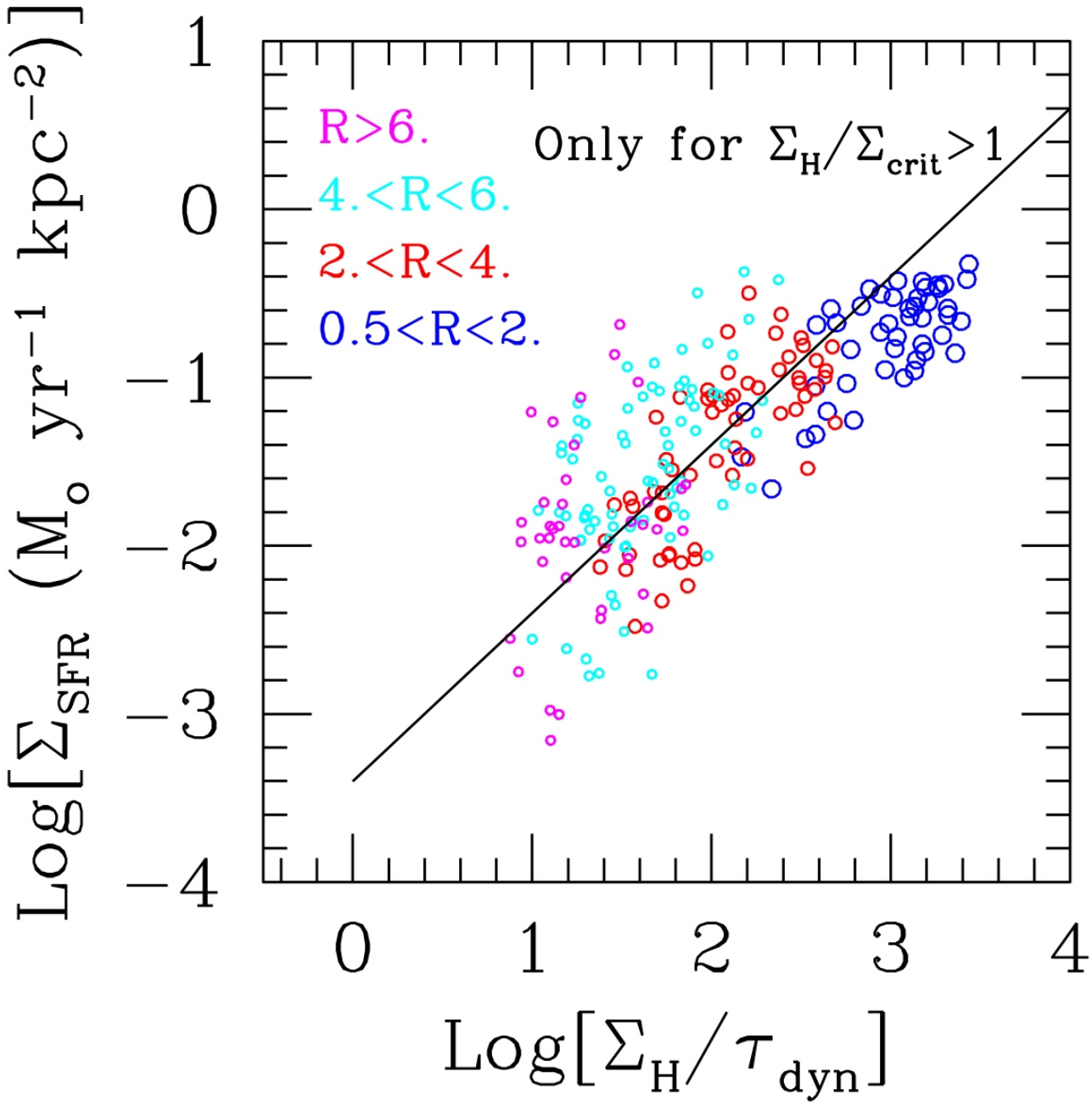


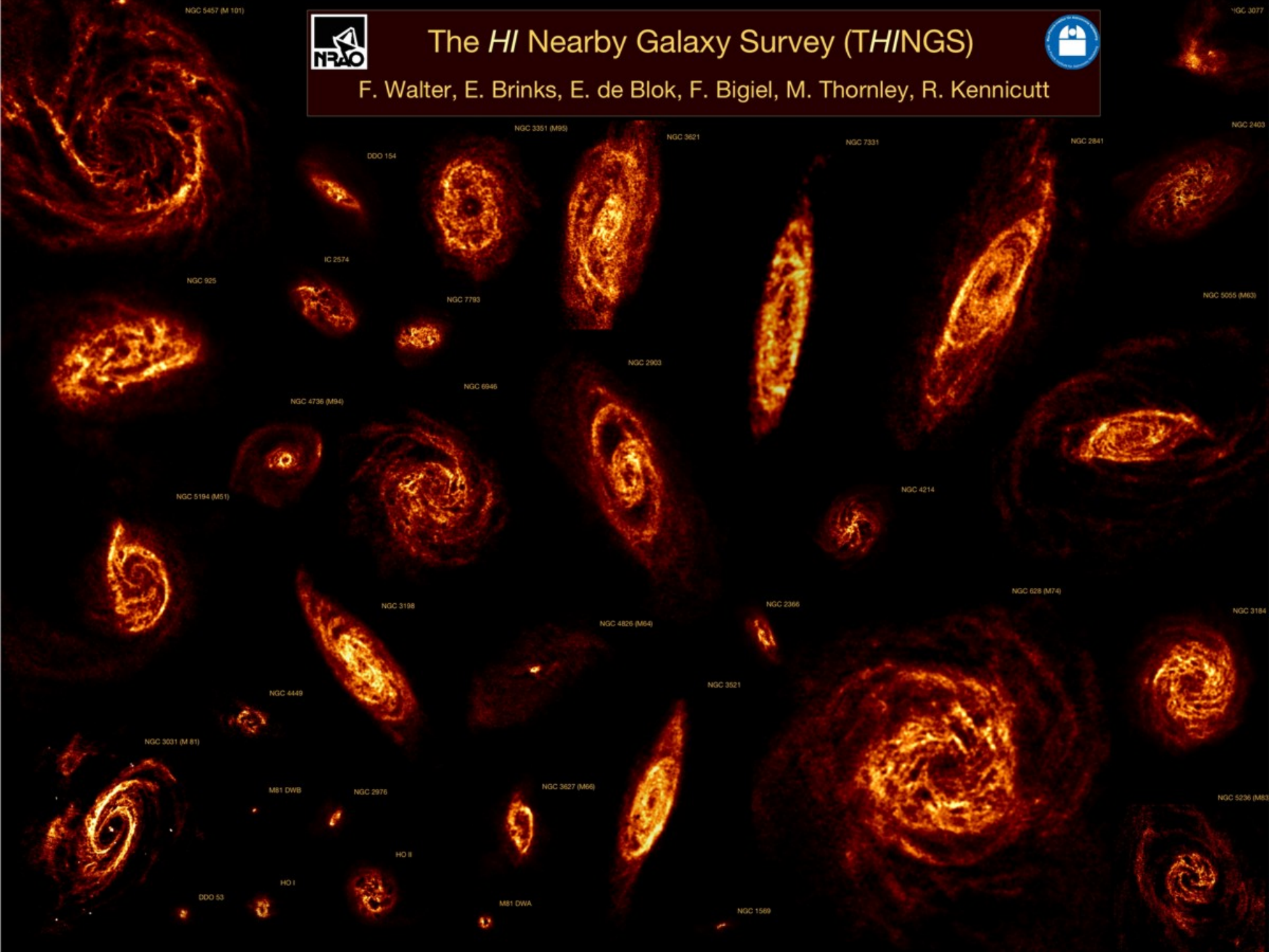


Kennicutt et al. 2007, ApJ, 671, 333

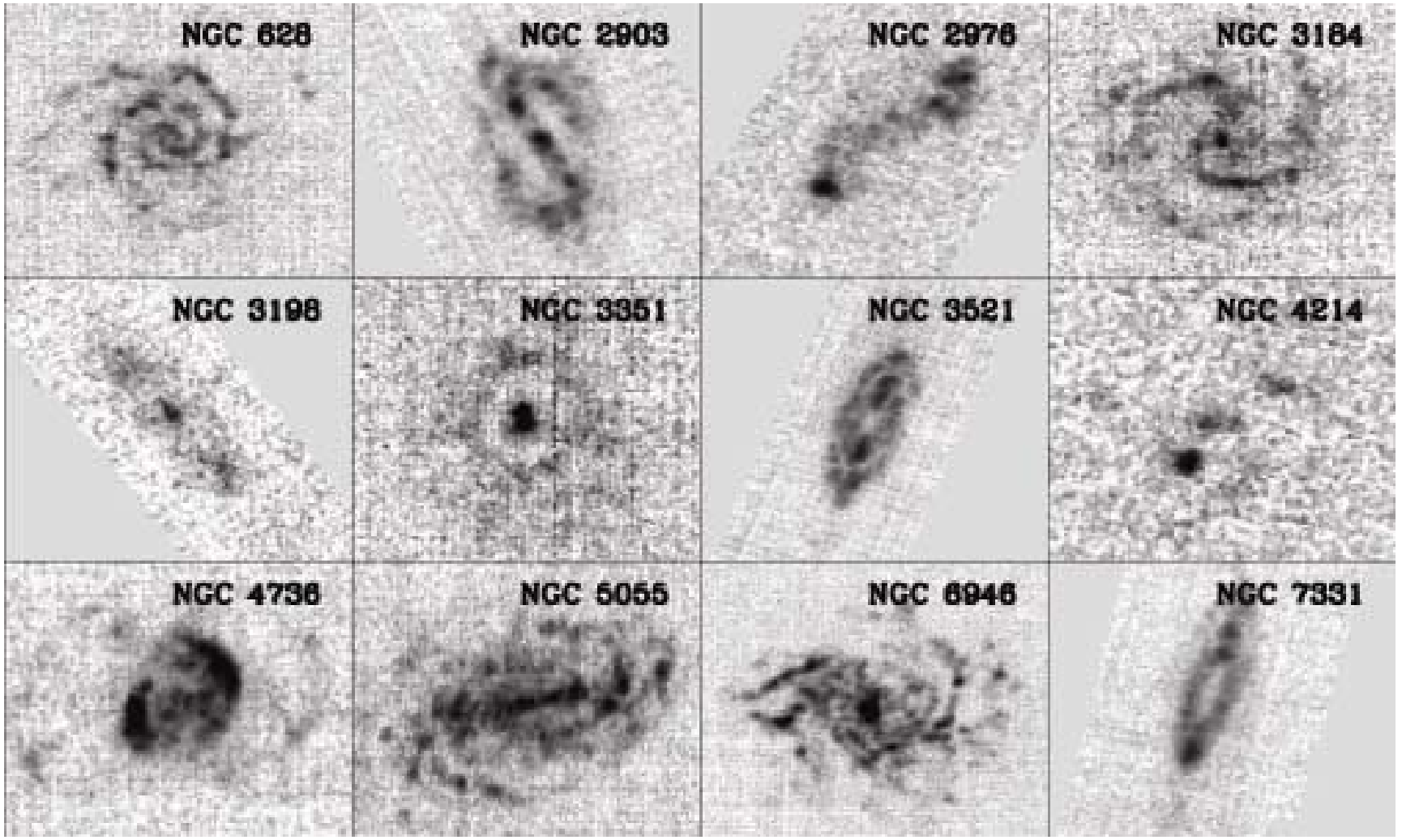

Log[Σ_{SFR} (M_o yr^{-1} kpc^{-2})]
0
−1
−2
−3
0
1
2
3
Log[Σ_H (M_o pc^{-2})]


R>6.
4.<R<6.
2.<R<4.
0.5<R<2.
1
0
−1
−2
−3
−4
0
1
2
3
Log[Σ_SFR (M_o yr^−1 kpc^−2)]
Log[Σ_H (M_o pc^−2)]

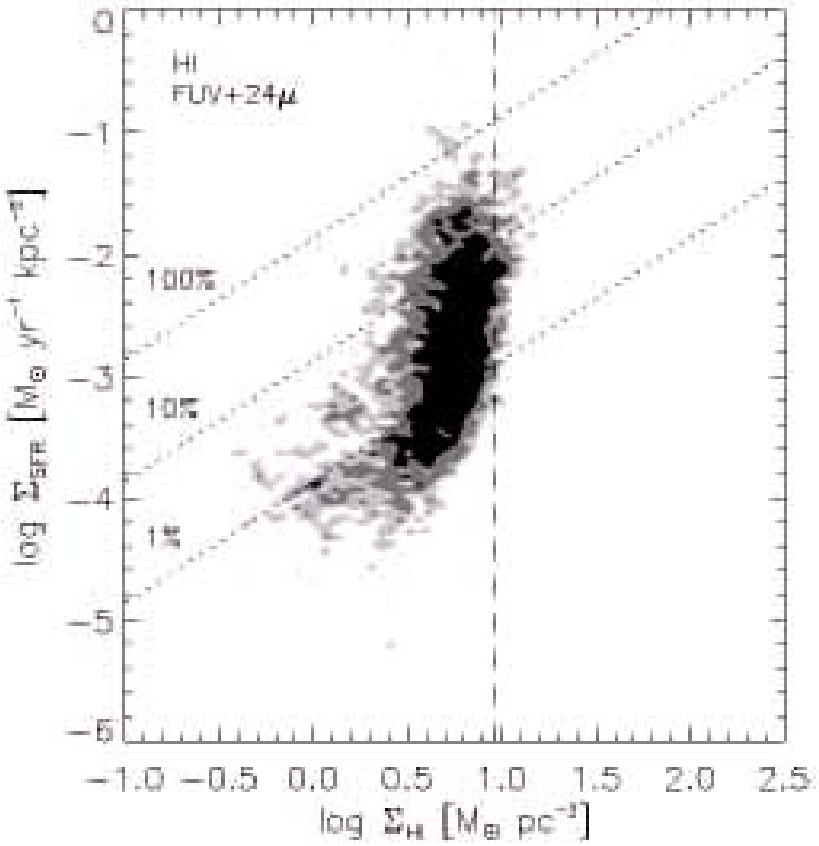

R>6.
4.<R<6.
2.<R<4.
0.5<R<2.
Only for $\Sigma_H/\Sigma_{crit}>1$
$\mathrm{Log}[\Sigma_{SFR}\ (M_o\ yr^{-1}\ kpc^{-2})]$
$\mathrm{Log}[\Sigma_H/\tau_{dyn}]$
1
0
−1
−2
−3
−4
0
1
2
3
4

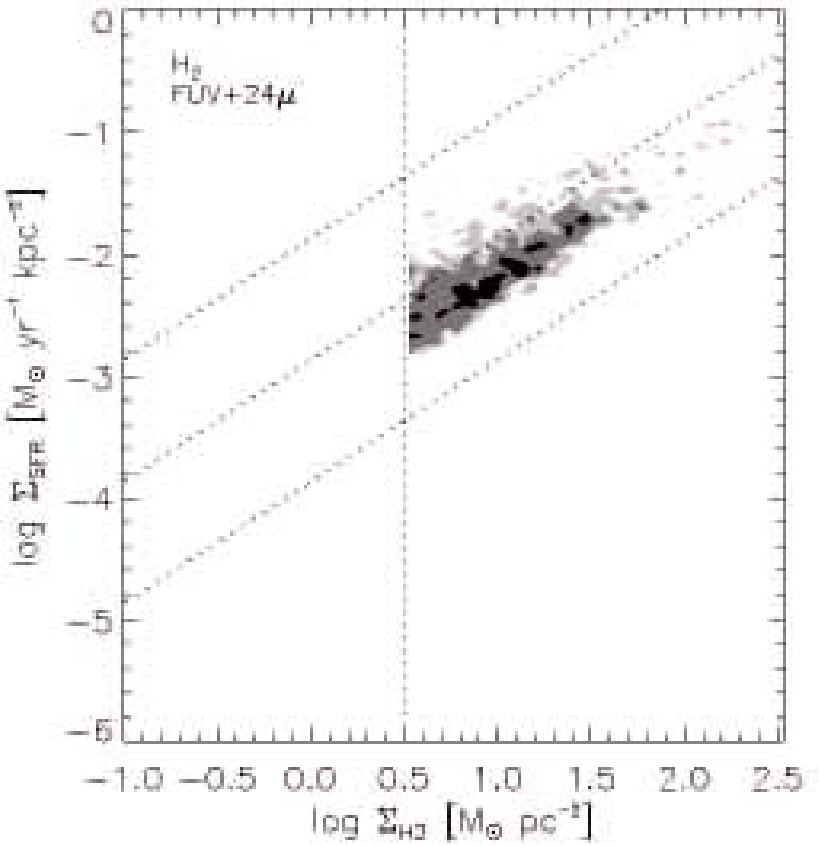

The HI Nearby Galaxy Survey (THINGS)
F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt
NRAO
NGC 5457 (M 101)
NGC 3077
NGC 3351 (M95)
NGC 3621
DDO 154
NGC 7331
NGC 2841
NGC 2403
IC 2574
NGC 925
NGC 7793
NGC 5055 (M63)
NGC 2903
NGC 6946
NGC 4736 (M94)
NGC 5194 (M51)
NGC 4214
NGC 628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

HERACLES CO 2-1 Survey

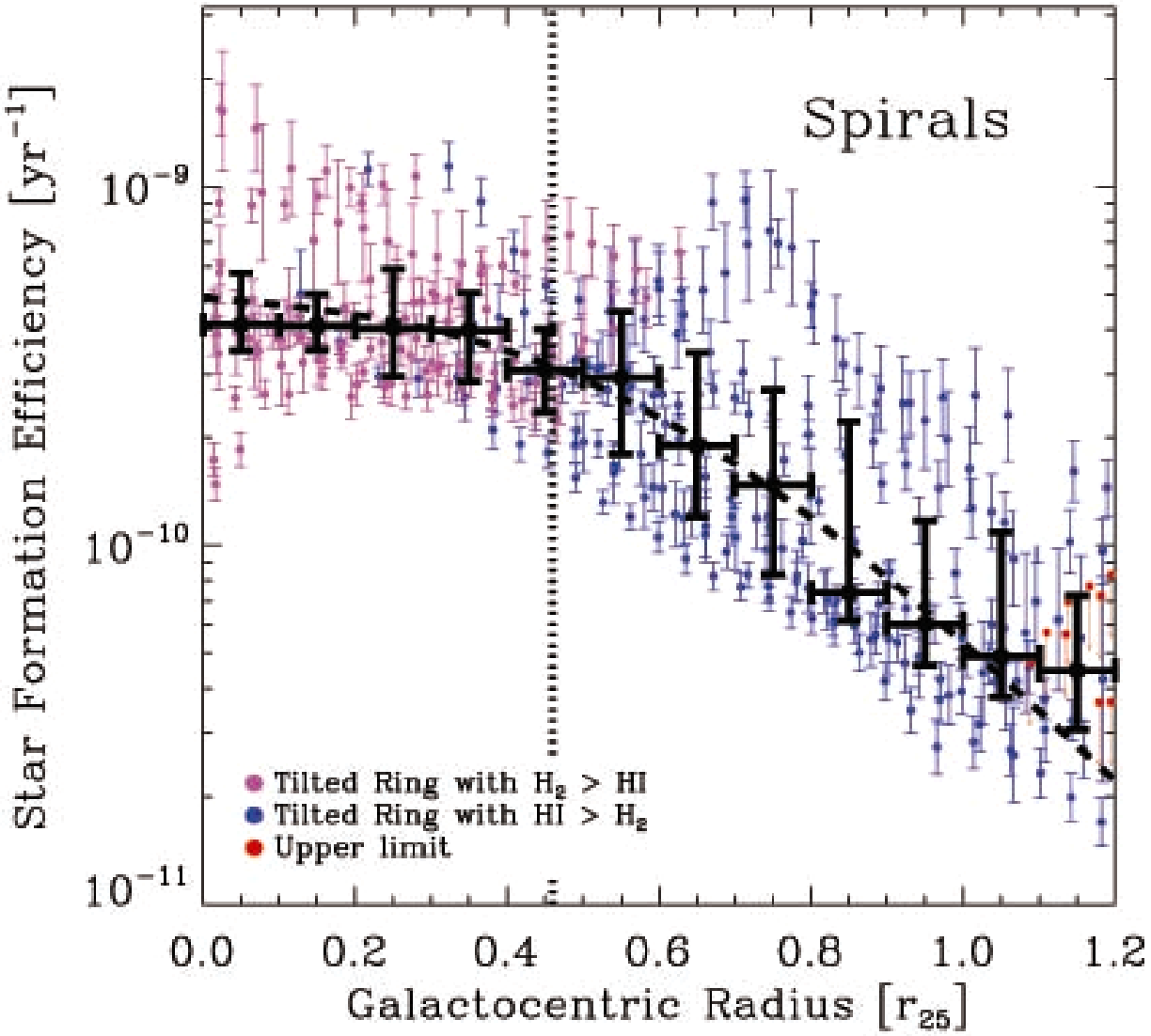


Leroy et al. 2008, submitted to AJ

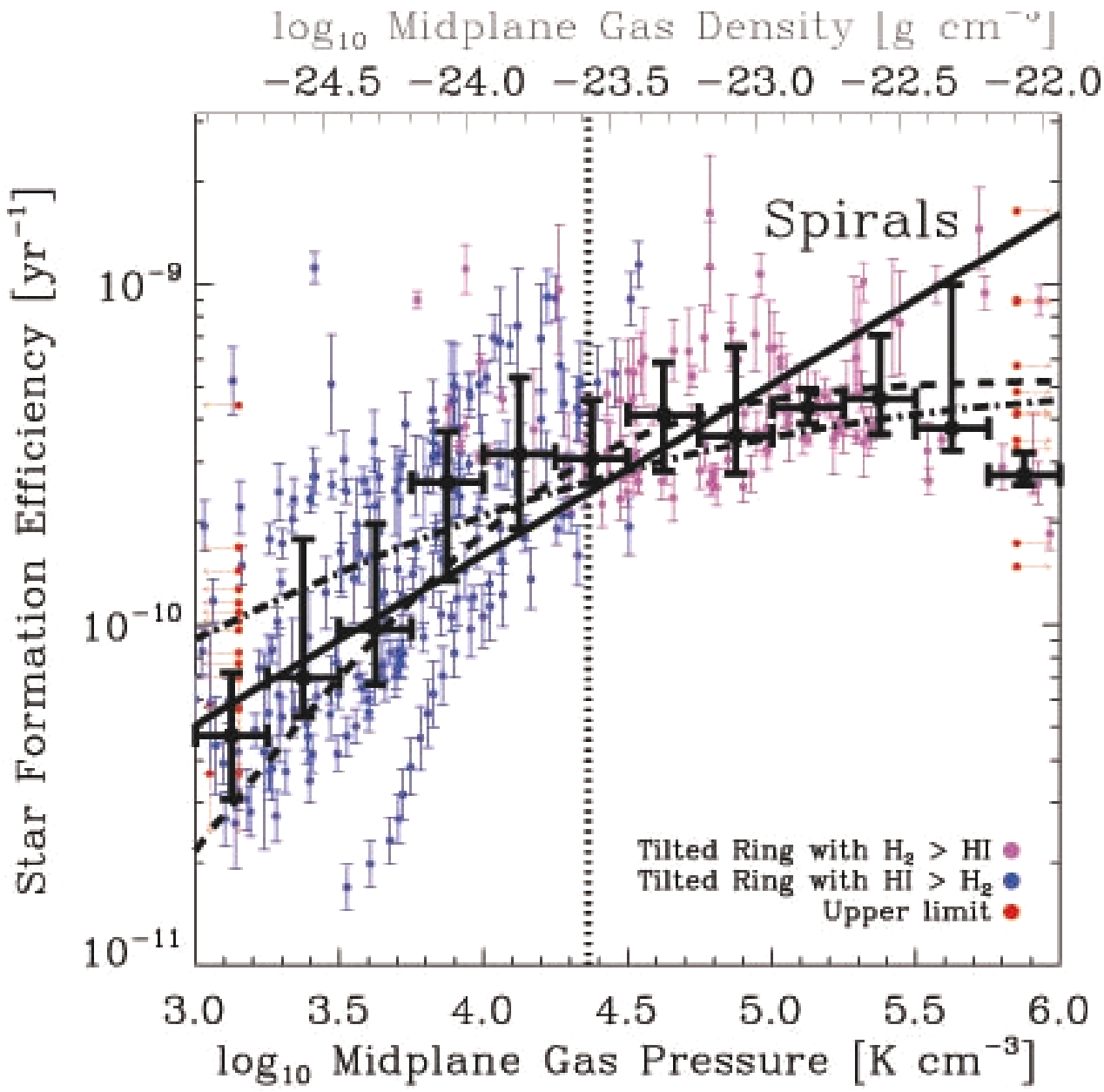




Biegel et al. 2008, submitted to AJ



Leroy et al. 2008, submitted to AJ


log10 Midplane Gas Density [g cm−3]
−24.5 −24.0 −23.5 −23.0 −22.5 −22.0
Spirals
Star Formation Efficiency [yr−1]
10−9
10−10
10−11
Tilted Ring with H2 > HI
Tilted Ring with HI > H2
Upper limit
3.0 3.5 4.0 4.5 5.0 5.5 6.0
log10 Midplane Gas Pressure [K cm−3]

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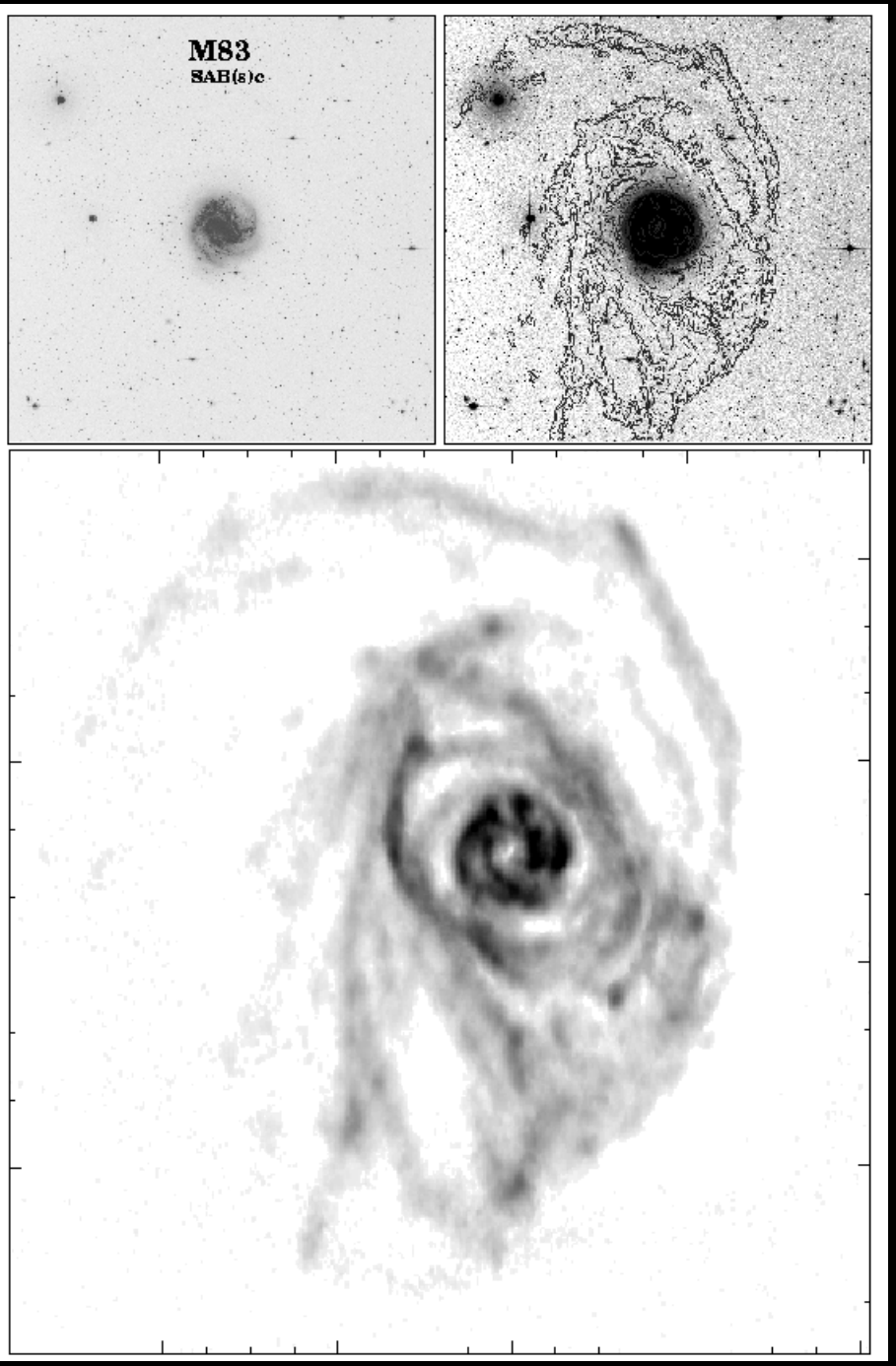
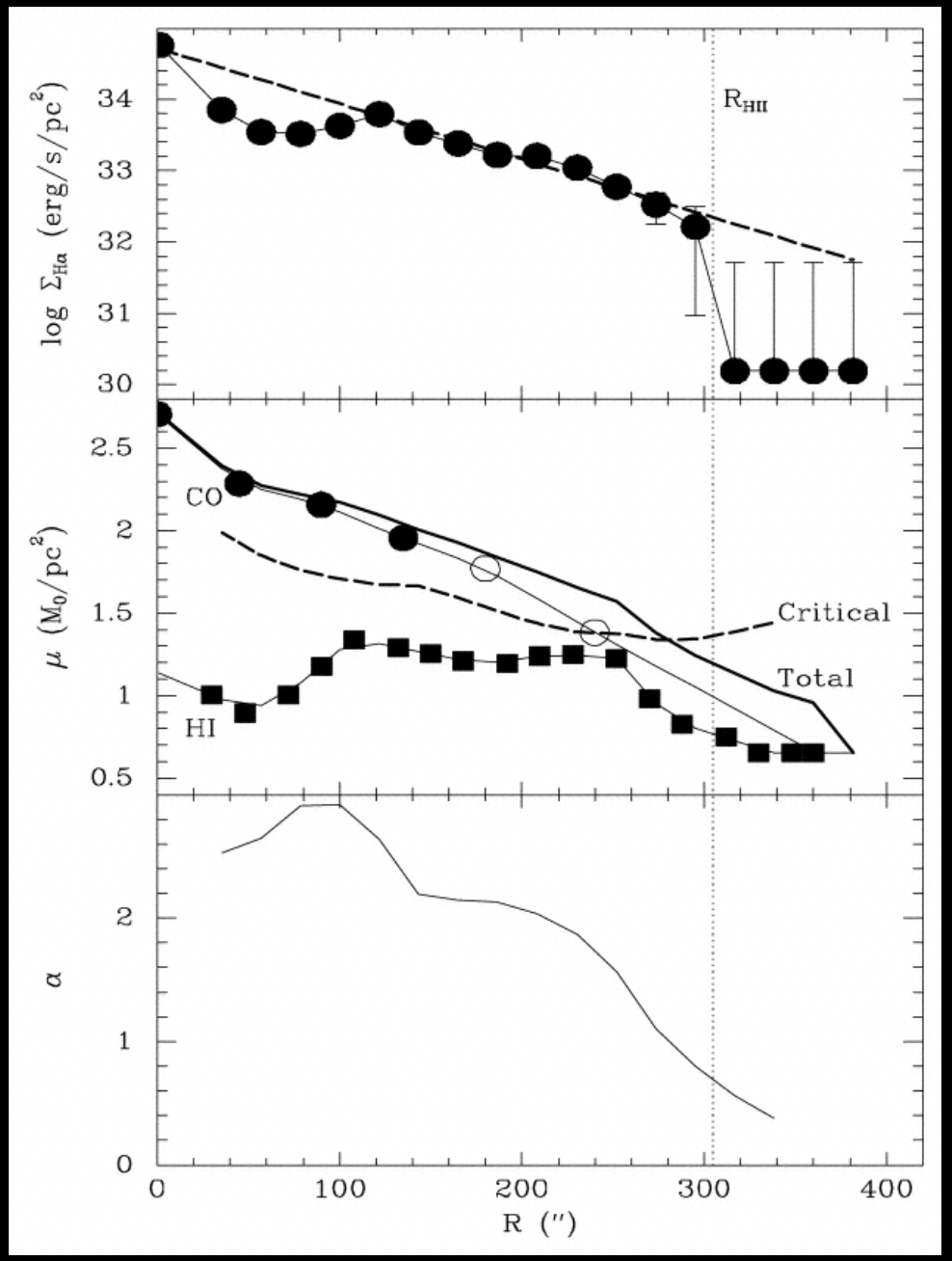
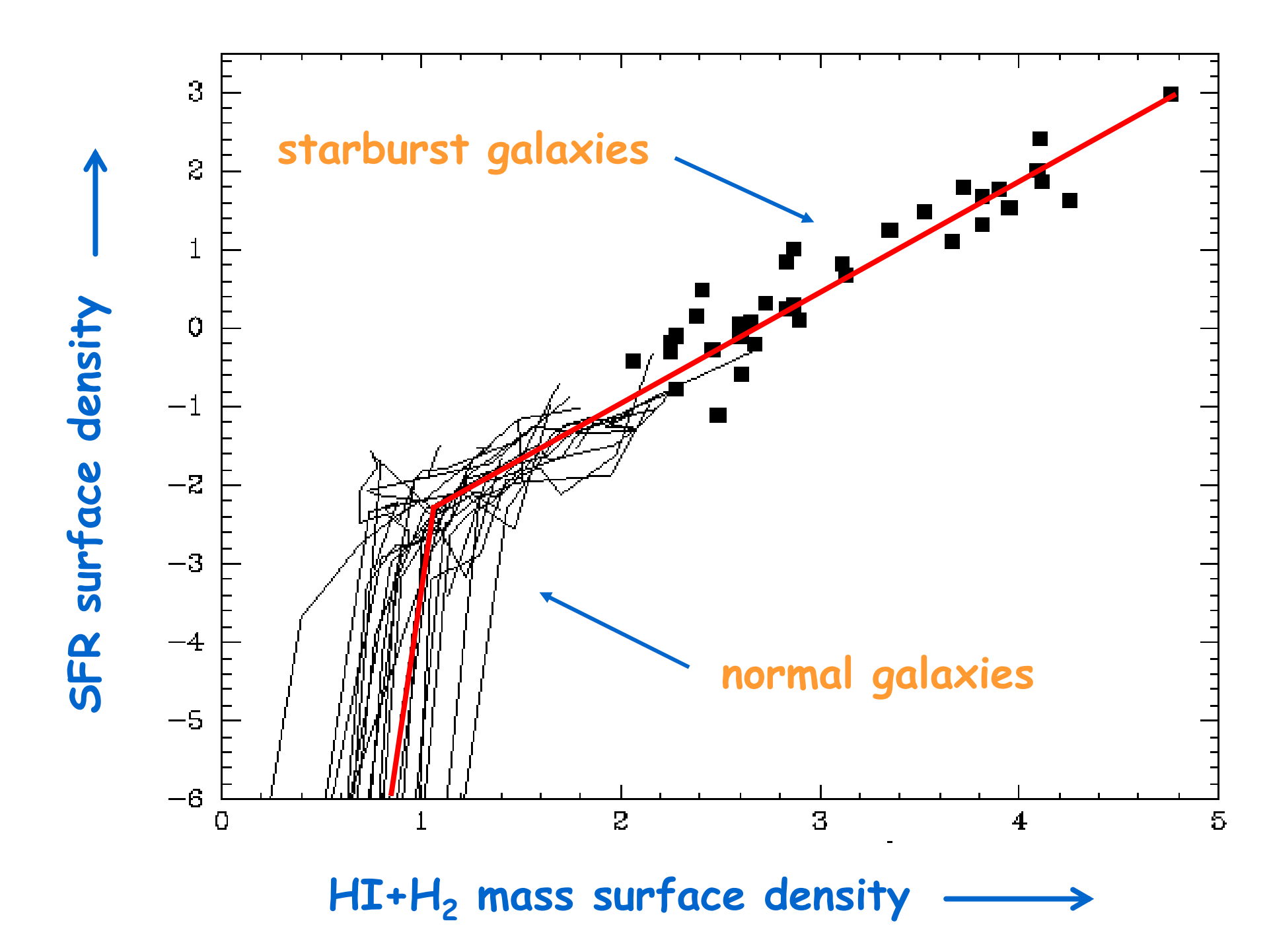


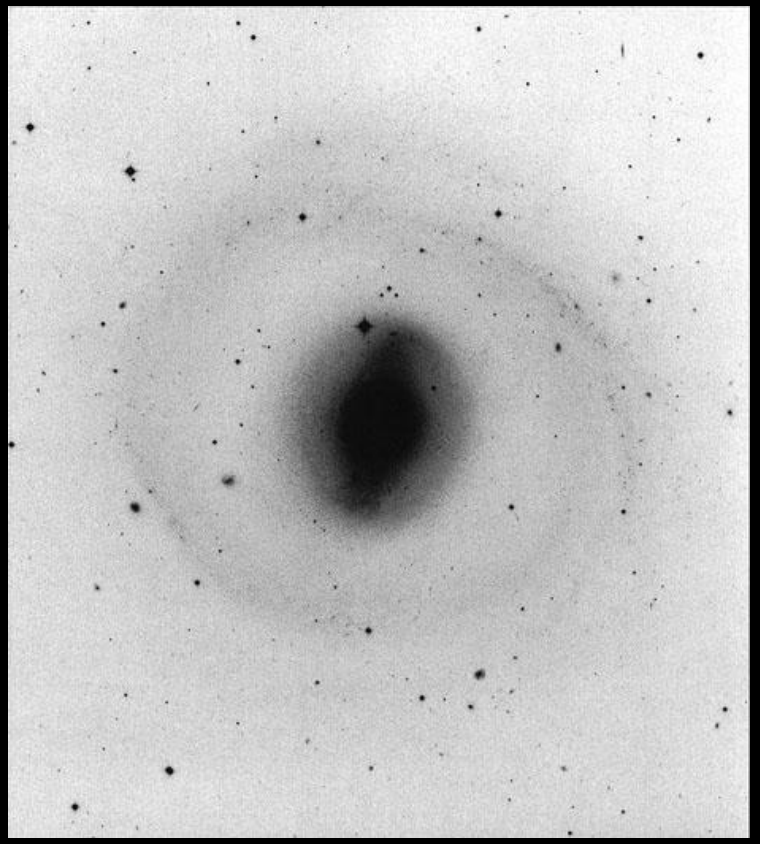
Crothswaite et al. 2003

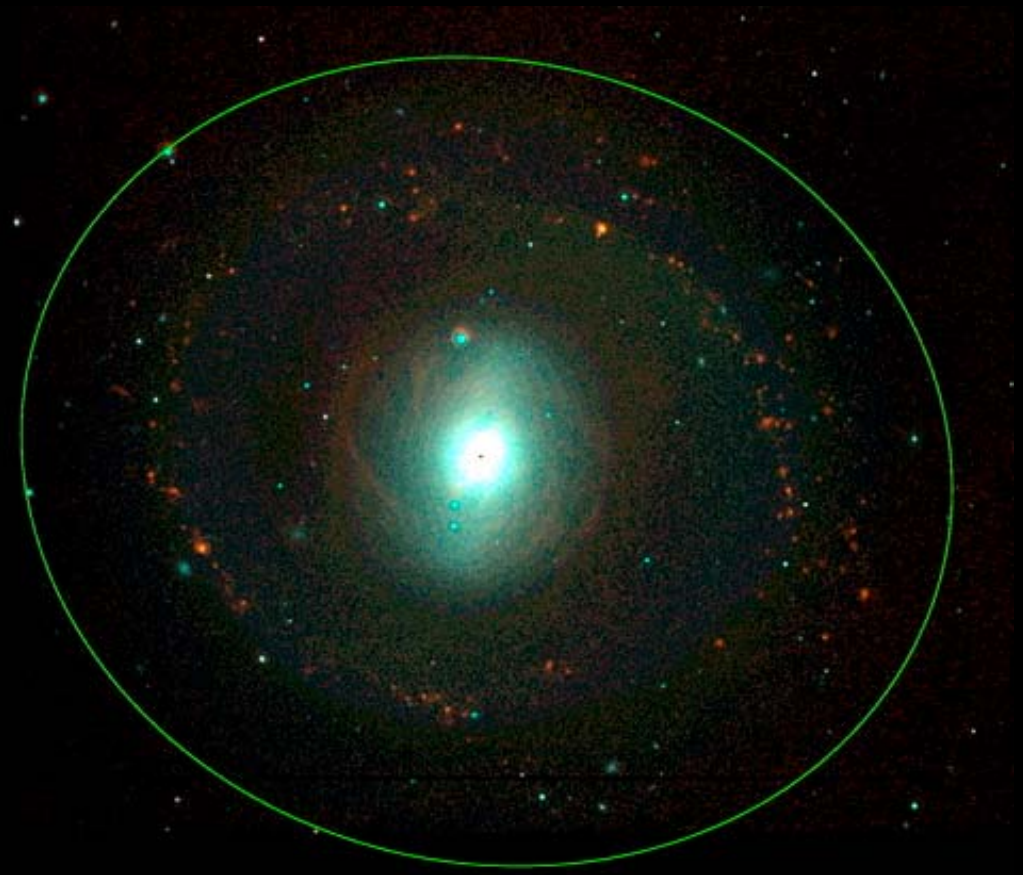


Martin & Kennicutt 2001, ApJ, 555, 301


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

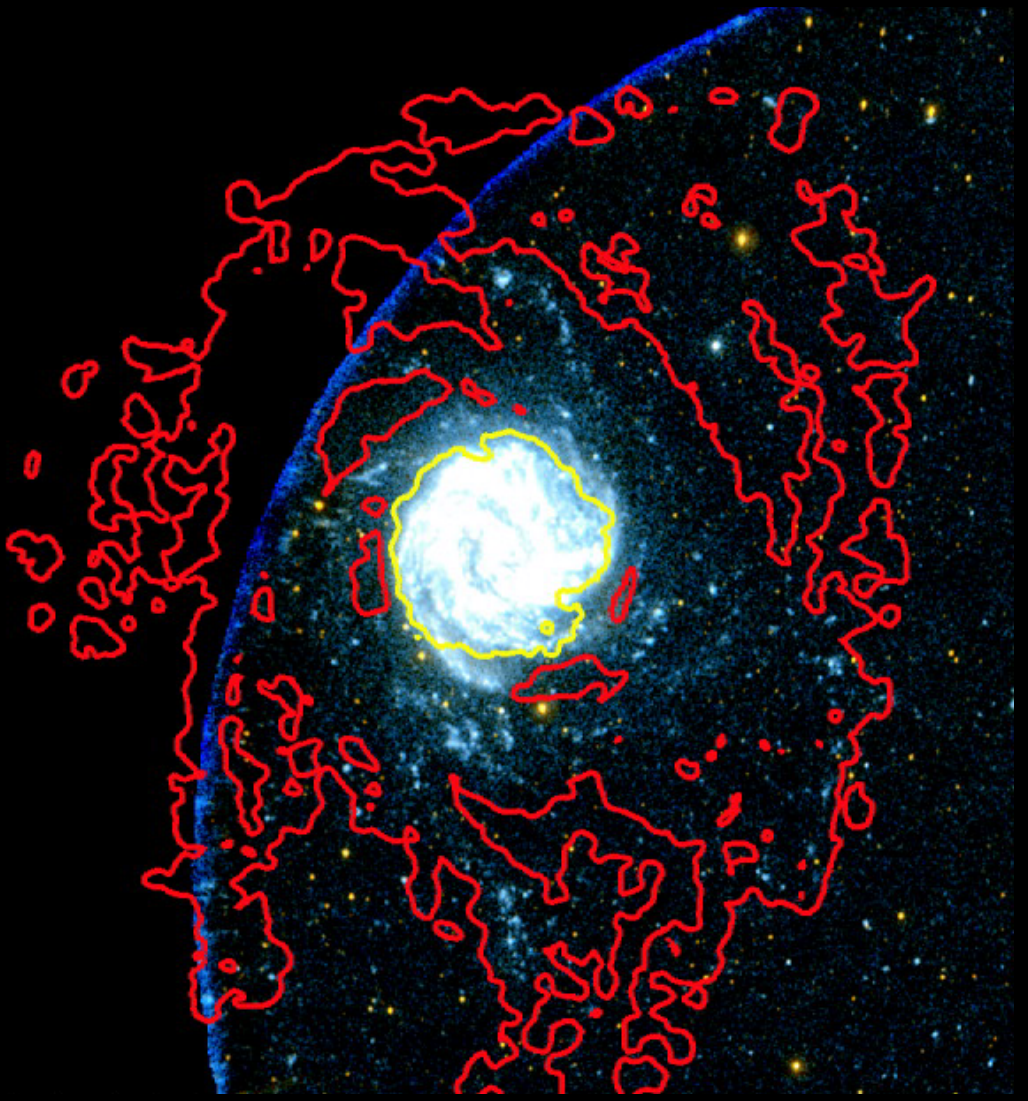
NGC 1291





Blue: Carnegie Atlas
Sandage & Bedke 1994

Hα + R: SINGG survey
Meurer et al. 2006



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)

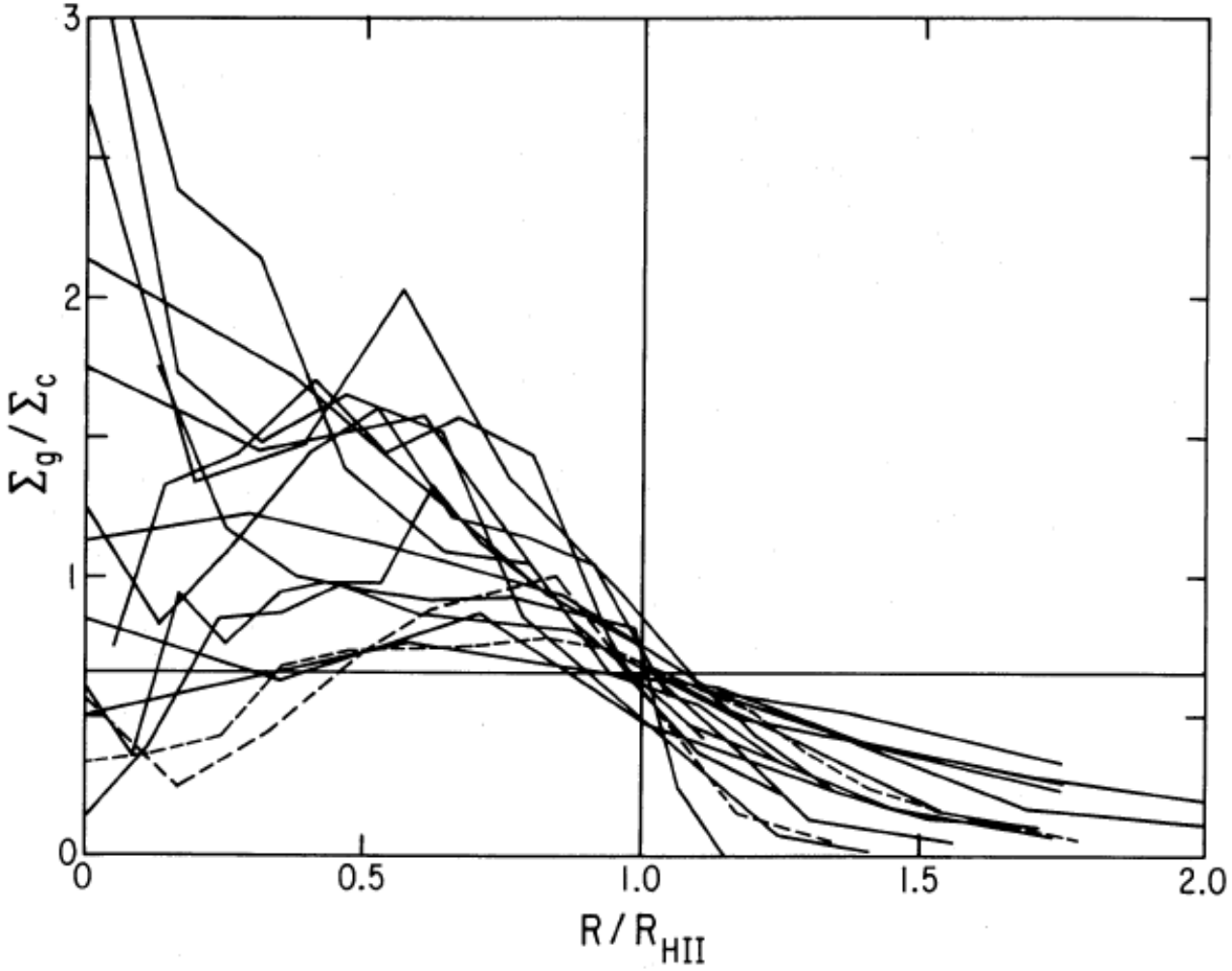
- transition to cold phase triggers gravitational instabilities

Pressure-regulated H_2 instabilities?
(Elmegreen, Parravano 1994; Blitz, Rosolowski 2006)

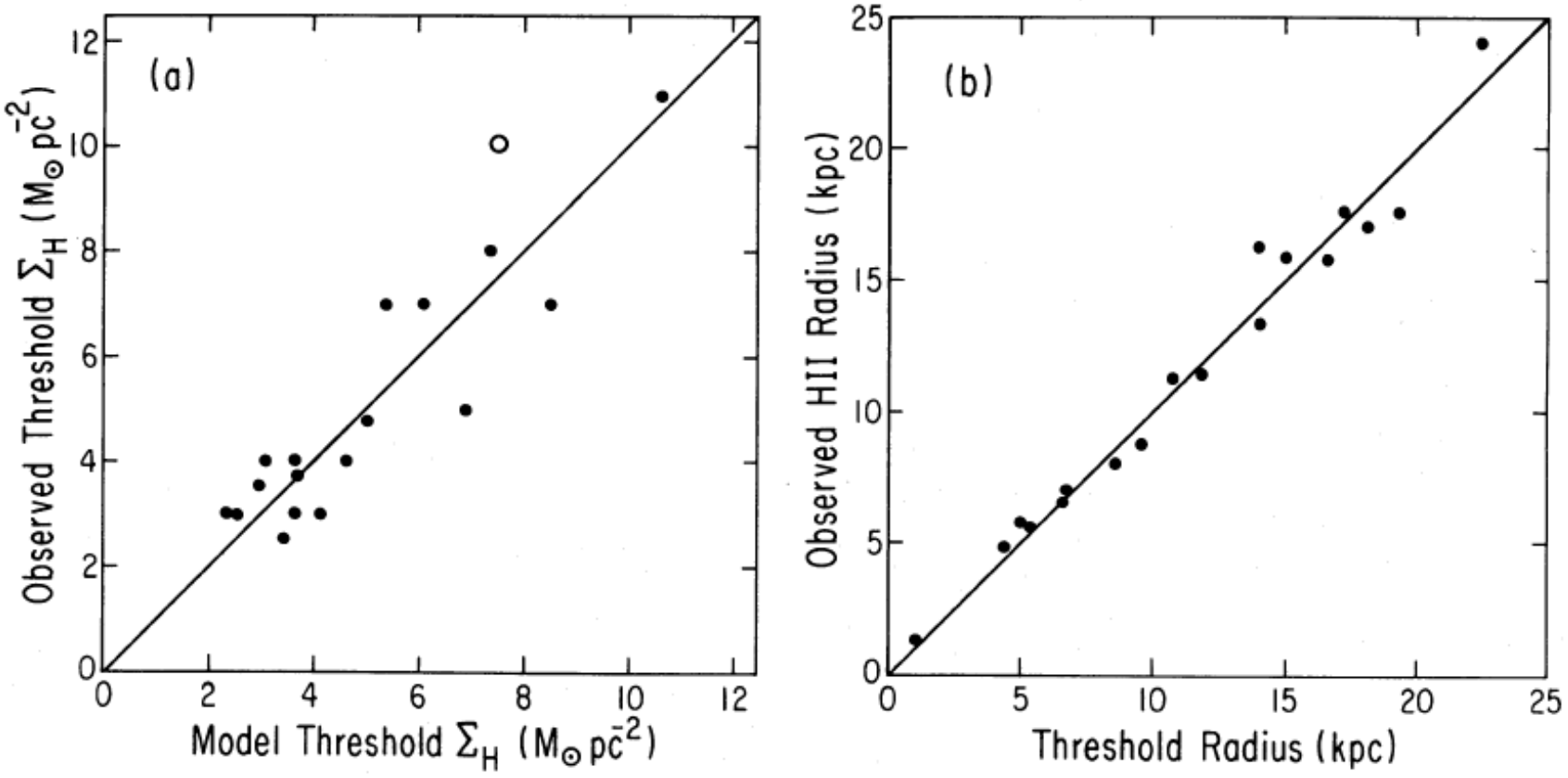
- SFR controlled by formation of H_2, with SFR ~ Σ_{H2}

Fragmentation threshold? (Krumholz & McKee 2008)

$1/Q_{gas}$ vs Radius: Active Star-Forming Discs

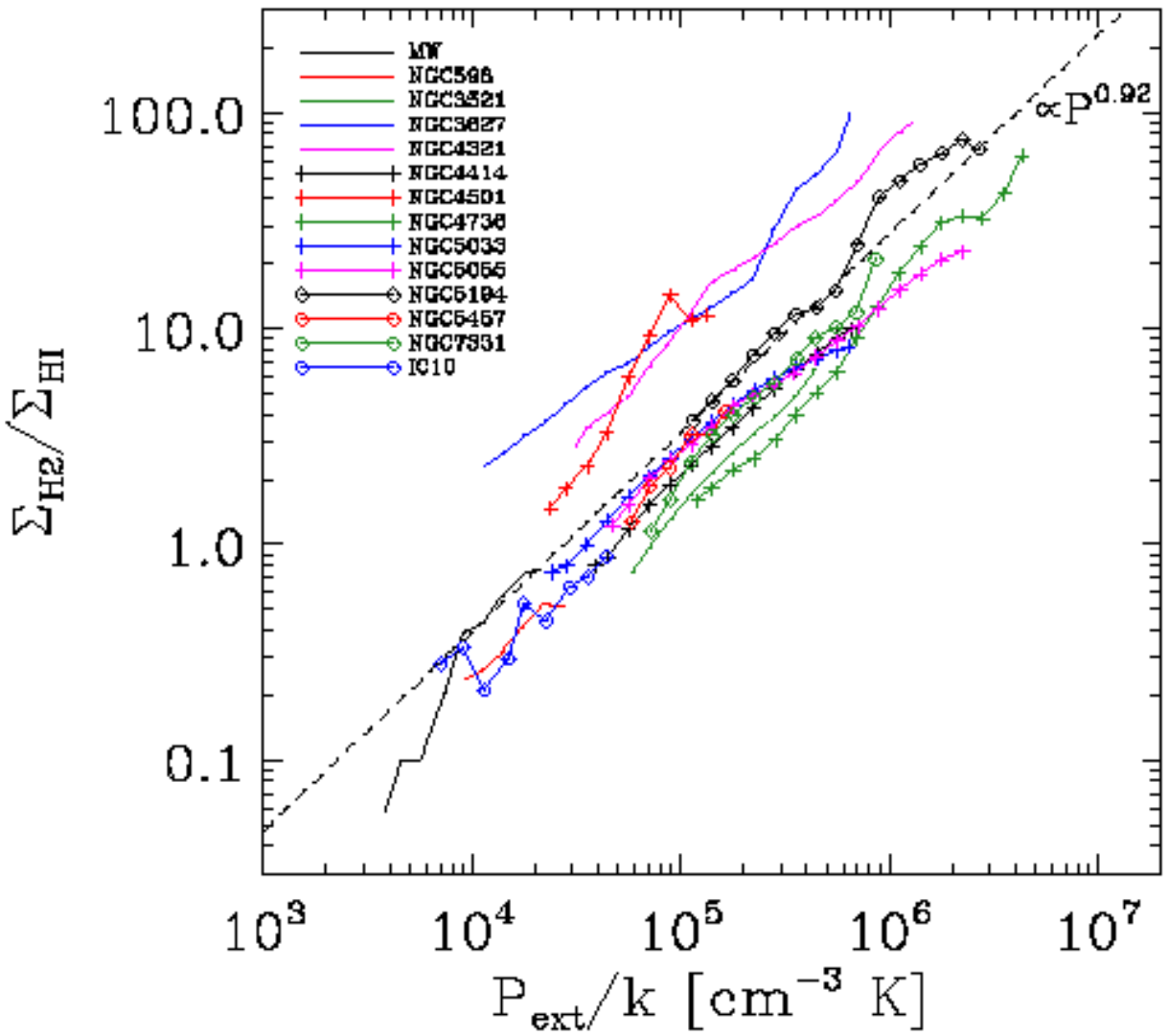


Kennicutt 1989, ApJ, 344, 685



Kennicutt 1989, ApJ, 344, 685

"pressure law"



Blitz & Rosolowsky 2006, ApJ, 650, 933

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)

Questions: Schmidt Law

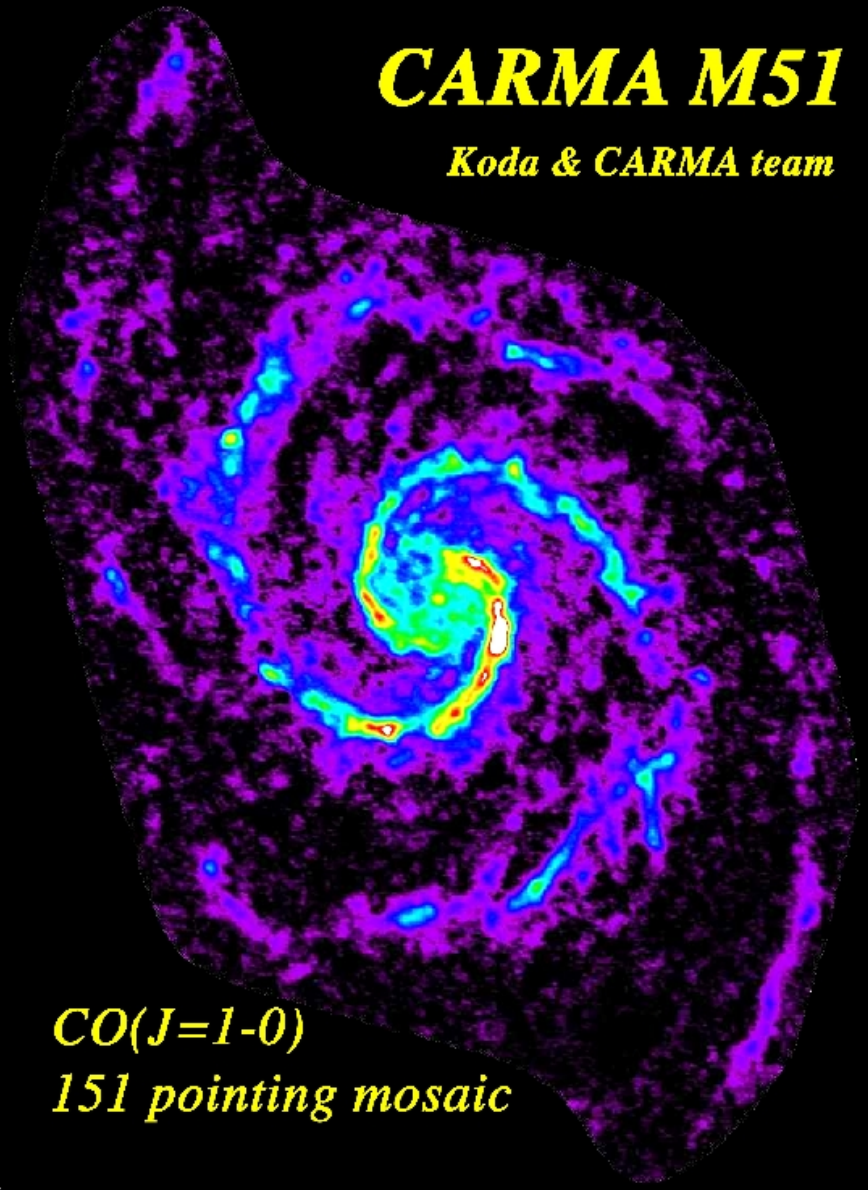
- Is the Schmidt law correlation really this good?
  - do all galaxies follow the same Schmidt law?
  - is the scatter driven by a second parameter?
- Is the global Schmidt law the result of a more fundamental underlying SF scaling law?
  - over what range of physical scales is the law valid?
- Is the SFR correlated more strongly with the total (atomic + molecular) surface density or with the molecular surface density alone?
- What is the physical origin of the relation?

Final Thoughts

- Multiwavelength observations have fuelled a revolution in observations of star formation on galactic scales
  - precise SFRs
  - large, complete, unbiased samples at low and high redshift
- Accurate measures of cold gas (esp. H_2) critical for further progress
- Integration of Galactic and extragalactic studies
  - define empirical trends over full range of ISM conditions
  - define structure of SF clouds in different environments
  - constrain systematic variations in IMF
  - timescales for cloud formation, fragmentation, destruction
  - role of star clustering
  - apply, test theories for large-scale SF

CARMA M51

Koda & CARMA team



CO(J=1-0)
151 pointing mosaic