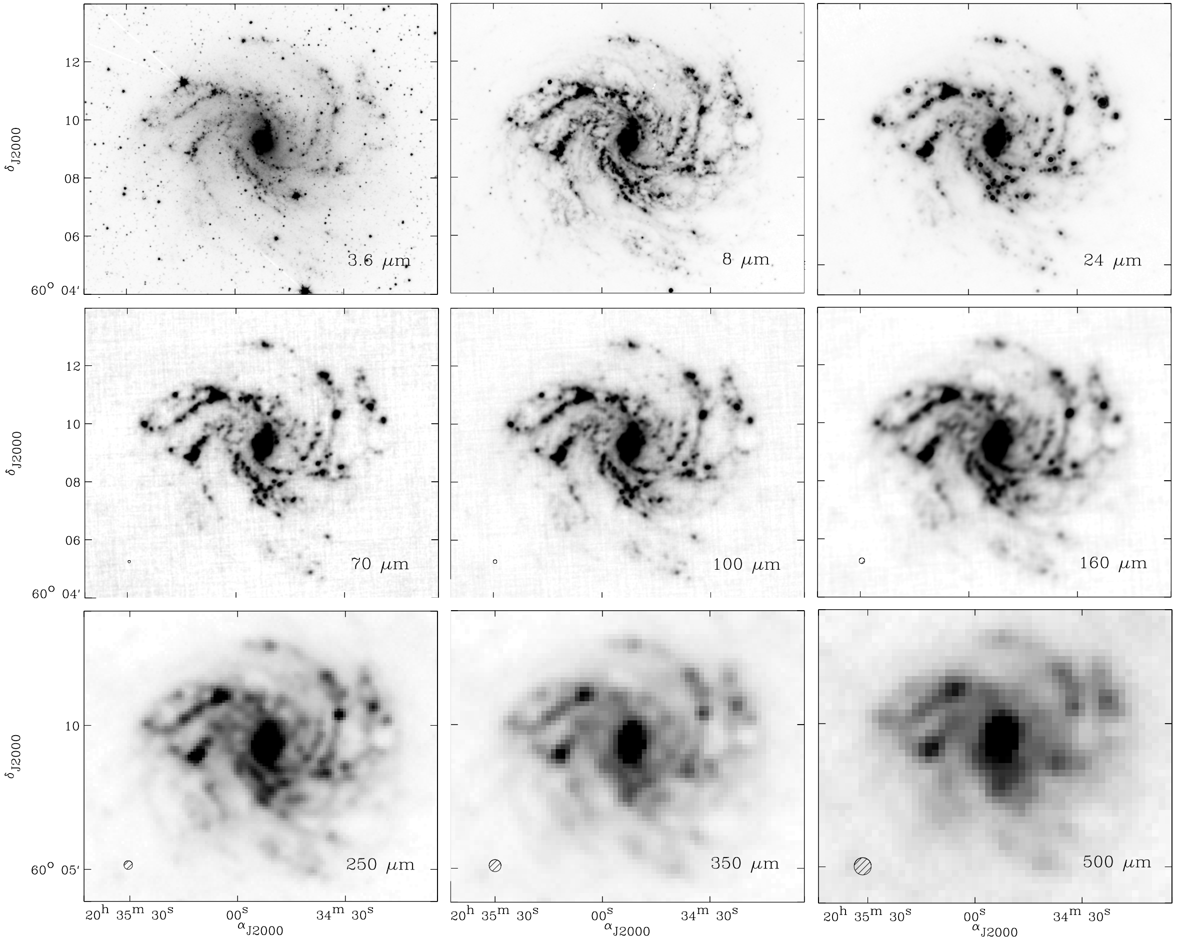
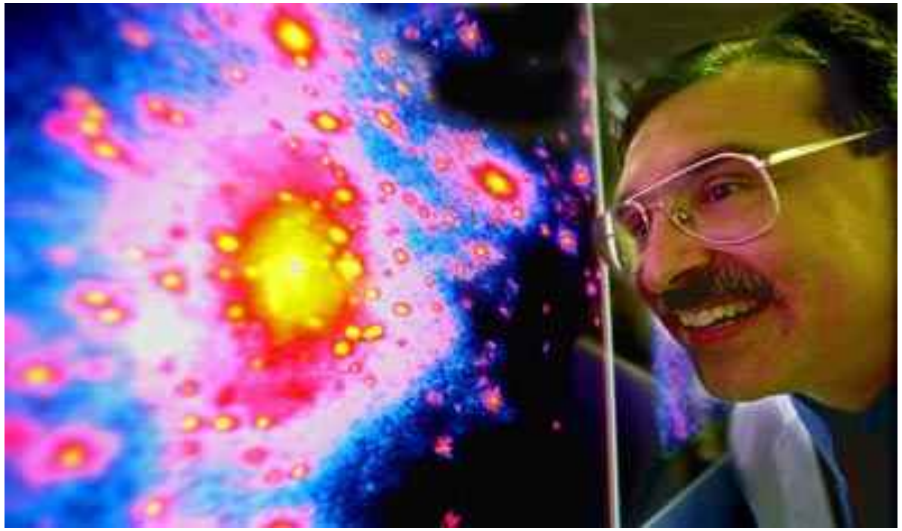
Galaxy-Wide Star Formation Processes
(and a brief conference overview)

Robert Kennicutt
Institute of Astronomy
University of Cambridge

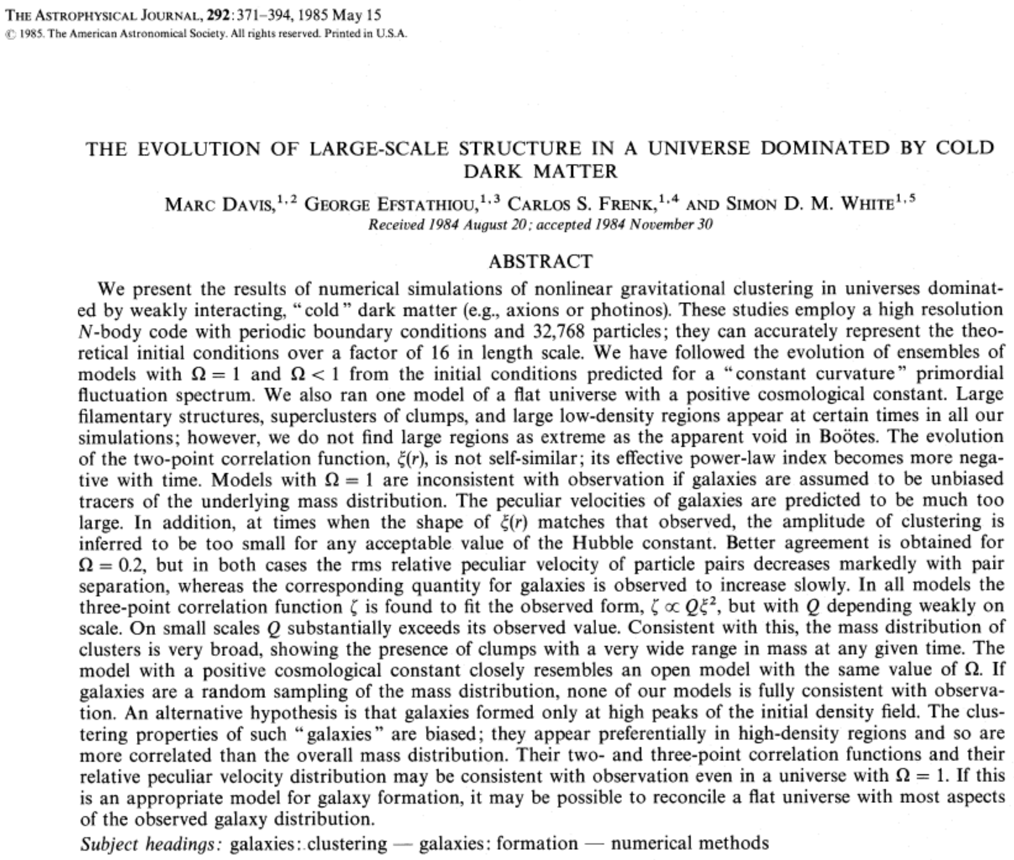


Galaxy Formation: An International Conference

…and a not-Festschrift for our conference co-organisers



"Gang of Four" Receives $500,000 Gruber Cosmology Prize for Reconstructing How the Universe Grew



THE ASTROPHYSICAL JOURNAL, **292**: 371–394, 1985 May 15

THE EVOLUTION OF LARGE-SCALE STRUCTURE IN A UNIVERSE DOMINATED BY COLD DARK MATTER

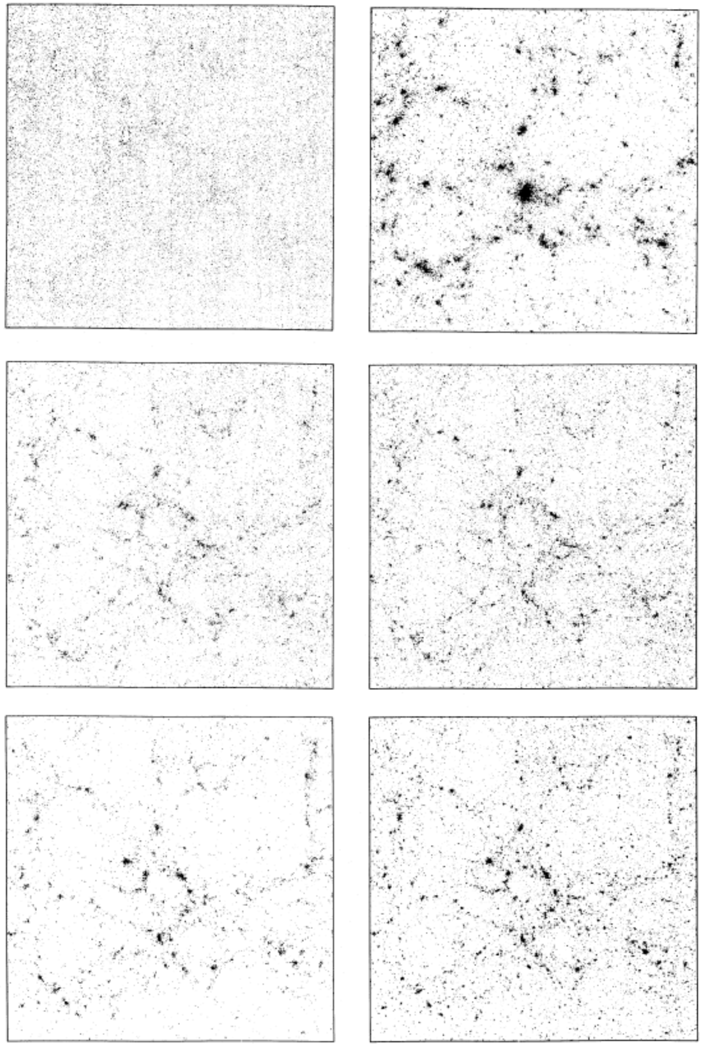
MARC DAVIS,[1,2] GEORGE EFSTATHIOU,[1,3] CARLOS S. FRENK,[1,4] AND SIMON D. M. WHITE[1,5]

Received 1984 August 20; accepted 1984 November 30

ABSTRACT

We present the results of numerical simulations of nonlinear gravitational clustering in universes dominated by weakly interacting, "cold" dark matter (e.g., axions or photinos). These studies employ a high resolution *N*-body code with periodic boundary conditions and 32,768 particles; they can accurately represent the theoretical initial conditions over a factor of 16 in length scale. We have followed the evolution of ensembles of models with $\Omega = 1$ and $\Omega < 1$ from the initial conditions predicted for a "constant curvature" primordial fluctuation spectrum. We also ran one model of a flat universe with a positive cosmological constant. Large filamentary structures, superclusters of clumps, and large low-density regions appear at certain times in all our simulations; however, we do not find large regions as extreme as the apparent void in Boötes. The evolution of the two-point correlation function, $\xi(r)$, is not self-similar; its effective power-law index becomes more negative with time. Models with $\Omega = 1$ are inconsistent with observation if galaxies are assumed to be unbiased tracers of the underlying mass distribution. The peculiar velocities of galaxies are predicted to be much too large. In addition, at times when the shape of $\xi(r)$ matches that observed, the amplitude of clustering is inferred to be too small for any acceptable value of the Hubble constant. Better agreement is obtained for $\Omega = 0.2$, but in both cases the rms relative peculiar velocity of particle pairs decreases markedly with pair separation, whereas the corresponding quantity for galaxies is observed to increase slowly. In all models the three-point correlation function ζ is found to fit the observed form, $\zeta \propto Q\xi^2$, but with Q depending weakly on scale. On small scales Q substantially exceeds its observed value. Consistent with this, the mass distribution of clusters is very broad, showing the presence of clumps with a very wide range in mass at any given time. The model with a positive cosmological constant closely resembles an open model with the same value of Ω. If galaxies are a random sampling of the mass distribution, none of our models is fully consistent with observation. An alternative hypothesis is that galaxies formed only at high peaks of the initial density field. The clustering properties of such "galaxies" are biased; they appear preferentially in high-density regions and so are more correlated than the overall mass distribution. Their two- and three-point correlation functions and their relative peculiar velocity distribution may be consistent with observation even in a universe with $\Omega = 1$. If this is an appropriate model for galaxy formation, it may be possible to reconcile a flat universe with most aspects of the observed galaxy distribution.

Subject headings: galaxies: clustering — galaxies: formation — numerical methods



The Astrophysical Journal, 379:52–79, 1991 September 20

GALAXY FORMATION THROUGH HIERARCHICAL CLUSTERING

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Received 1990 December 10; accepted 1991 March 28

ABSTRACT

We develop analytic methods for studying the formation of galaxies by gas condensation within massive dark halos. Our scheme applies to cosmogonies where structure grows through hierarchical clustering of a mixture of gas and dissipationless dark matter. It is an elaboration of the ideas of White & Rees. We adopt the simplest models consistent with our current understanding of N-body work on dissipationless clustering, and of numerical and analytic work on gas evolution and cooling. We also employ standard models for the evolution of stellar populations, and construct new models for the way star formation heats and enriches the surrounding gas. Although our approach is phenomenological, we avoid assumptions which have no clear physical basis. Our methods allow us to predict star formation as a function of location and time, and so the following properties of the galaxy population: current star formation rates and halo X-ray luminosities; current luminosity functions both for galaxies and for virialized systems; relations between present luminosity, circular velocity, metallicity, and stellar or total M/L ratio; the history of the OB star contribution to the metagalactic ionizing flux; and the distribution of faint blue (star-forming) galaxies in both apparent magnitude and redshift. In this paper we give detailed results only for a cold dark matter universe with $\Omega = 1$ and $H_0 = 50$ km s^{-1} Mpc^{-1}, although our methods are easily applied to other models. Even for this case, predictions depend strongly on the mean baryon density, on the fluctuation amplitude, on the models for heating and metal enrichment by massive stars, and on the initial mass function with which stars form. Our most successful models require a large baryon fraction ($\Omega_b/\Omega \gtrsim 0.1$) and efficient heating and enrichment of halo gas. They then approximately reproduce the characteristic luminosities of galaxies and of galaxy clusters, the observed relations between galaxy properties, and the kind of bias needed to reconcile $\Omega = 1$ with the observed kinematics of galaxy clustering. However, the amplitude of this bias is too small, and additional sources of bias must be invoked. Our luminosity functions contain significantly more faint galaxies than are observed. This is a serious discrepancy which may be alleviated by starbursts in dwarf galaxies, by selective merging of such systems, and by observational selection against low surface brightness dwarfs. Successful models form their stars late, typically more than half of them since $z = 1$, making the epoch of galaxy formation easily accessible to observation.

Subject headings: galaxies: clustering — galaxies: formation — galaxies: stellar content — galaxies: structure

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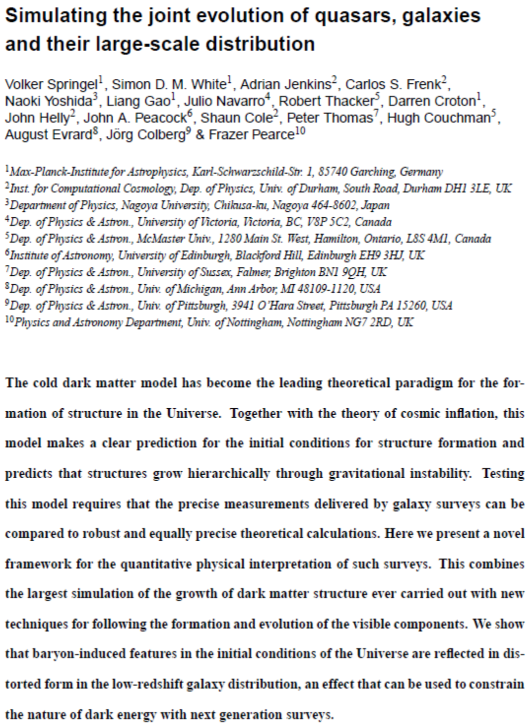

Simulating the joint evolution of quasars, galaxies and their large-scale distribution

Volker Springel[1], Simon D. M. White[1], Adrian Jenkins[2], Carlos S. Frenk[2],
Naoki Yoshida[3], Liang Gao[1], Julio Navarro[4], Robert Thacker[5], Darren Croton[1],
John Helly[2], John A. Peacock[6], Shaun Cole[2], Peter Thomas[7], Hugh Couchman[5],
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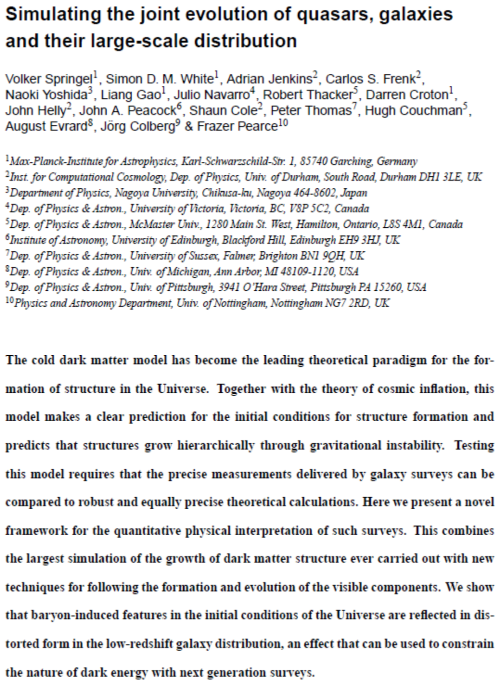
The cold dark matter model has become the leading theoretical paradigm for the formation of structure in the Universe. Together with the theory of cosmic inflation, this model makes a clear prediction for the initial conditions for structure formation and predicts that structures grow hierarchically through gravitational instability. Testing this model requires that the precise measurements delivered by galaxy surveys can be compared to robust and equally precise theoretical calculations. Here we present a novel framework for the quantitative physical interpretation of such surveys. This combines the largest simulation of the growth of dark matter structure ever carried out with new techniques for following the formation and evolution of the visible components. We show that baryon-induced features in the initial conditions of the Universe are reflected in distorted form in the low-redshift galaxy distribution, an effect that can be used to constrain the nature of dark energy with next generation surveys.



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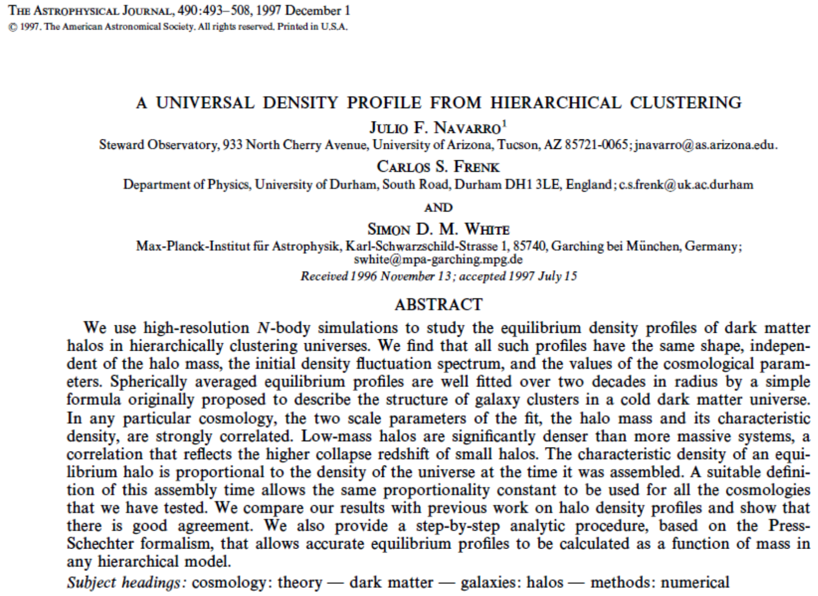

The Astrophysical Journal, 490:493–508, 1997 December 1

A UNIVERSAL DENSITY PROFILE FROM HIERARCHICAL CLUSTERING

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Received 1996 November 13; accepted 1997 July 15

ABSTRACT

We use high-resolution N-body simulations to study the equilibrium density profiles of dark matter halos in hierarchically clustering universes. We find that all such profiles have the same shape, independent of the halo mass, the initial density fluctuation spectrum, and the values of the cosmological parameters. Spherically averaged equilibrium profiles are well fitted over two decades in radius by a simple formula originally proposed to describe the structure of galaxy clusters in a cold dark matter universe. In any particular cosmology, the two scale parameters of the fit, the halo mass and its characteristic density, are strongly correlated. Low-mass halos are significantly denser than more massive systems, a correlation that reflects the higher collapse redshift of small halos. The characteristic density of an equilibrium halo is proportional to the density of the universe at the time it was assembled. A suitable definition of this assembly time allows the same proportionality constant to be used for all the cosmologies that we have tested. We compare our results with previous work on halo density profiles and show that there is good agreement. We also provide a step-by-step analytic procedure, based on the Press-Schechter formalism, that allows accurate equilibrium profiles to be calculated as a function of mass in any hierarchical model.

Subject headings: cosmology: theory — dark matter — galaxies: halos — methods: numerical

Causes for Celebration: Theory and Simulation

- A single model/paradigm which extends from inflation, CMB, and large scale structure to the formation and evolution of galaxies(!)
- Steady progress in resolving the challenges and "crises" of earlier years
  - N-body achieving state of the art(?)
  - "concordance cosmology" eliminated much room for mischief and solved some problems (e.g., "faint blue galaxy problem")
  - incorporation of gas physics, cooling
    - direct treatment of "bias"
    - importance of accretion modes
    - "cooling" and "angular momentum" crises partially resolved?
  - semi-analytical framework for incorporating star formation, feedback, and confronting models with observations

Causes for Celebration: Observation

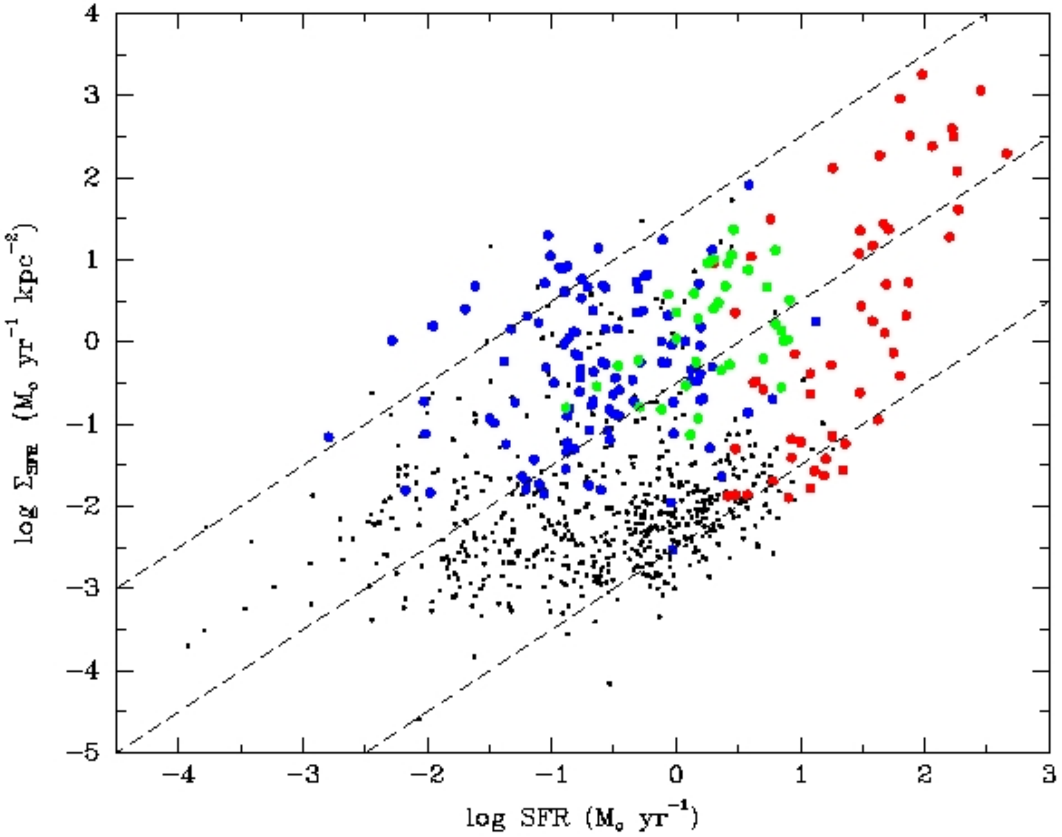
- Extraordinary observational progress
  - a fully filled, dust-corrected cosmic SFR history
  - resolution of most of the cosmic background
  - major progress toward cosmic histories of (stellar) masses, galaxy sizes, metal abundances, environmental evolution
  - statistical power of mega-surveys, especially in low-z observations, and a new quantitative framework
  - growing inventory of detailed stellar pops histories locally
  - beginnings on histories of cold baryon masses and kinematics
  - steady progress toward quantifying “sub-grid” scaling laws

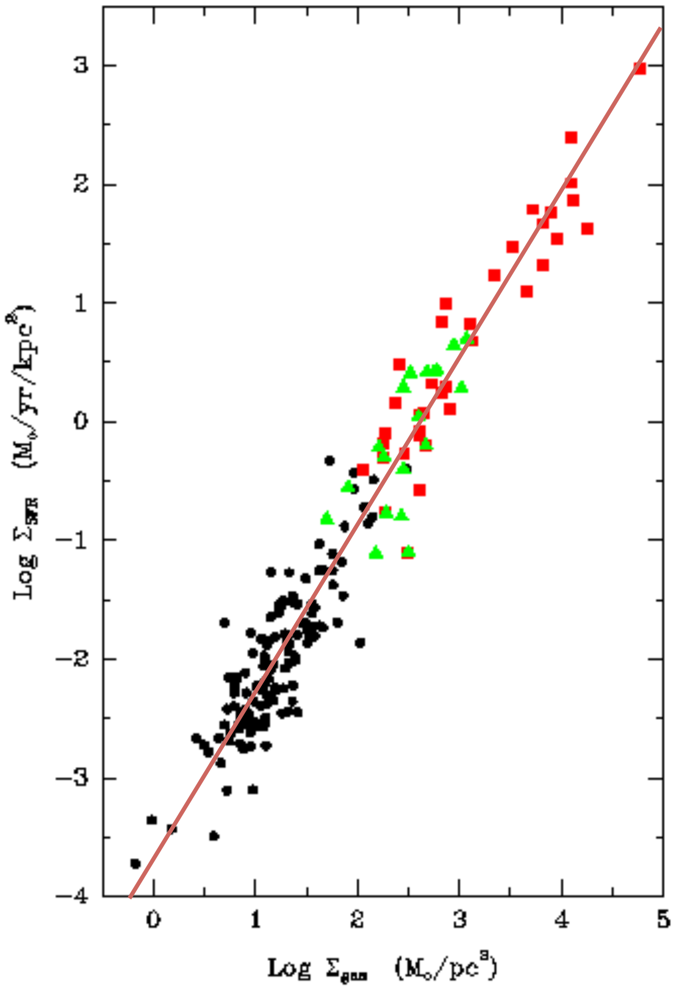
Assurances of Steady Work Ahead

- The foundation of our theoretical construct is still largely based on unobserved (or ill understood) phenomena
  - dark energy, dark matter, dark baryons, cold accretion, stellar feedback, NFW profiles, AGN feedback

- Uncomfortable reliance on primitive “subgrid” ingredients
  - IMF, cooling prescriptions, SF laws, feedback recipes
  - connection of galactic-scale to SMBH-scale processes embryonic
- Some problems just don’t seem to go away
  - overcooling/angular momentum; dwarf galaxy deficit; rapid growth of massive galaxies, SMBHs, metals, dust; reionising background
- Lack of information on cold baryon evolution a major handicap, but that is about to change
- The devil may live in the details of the sub-grid processes

Galaxy-Wide Star Formation:
the case study of the Schmidt law

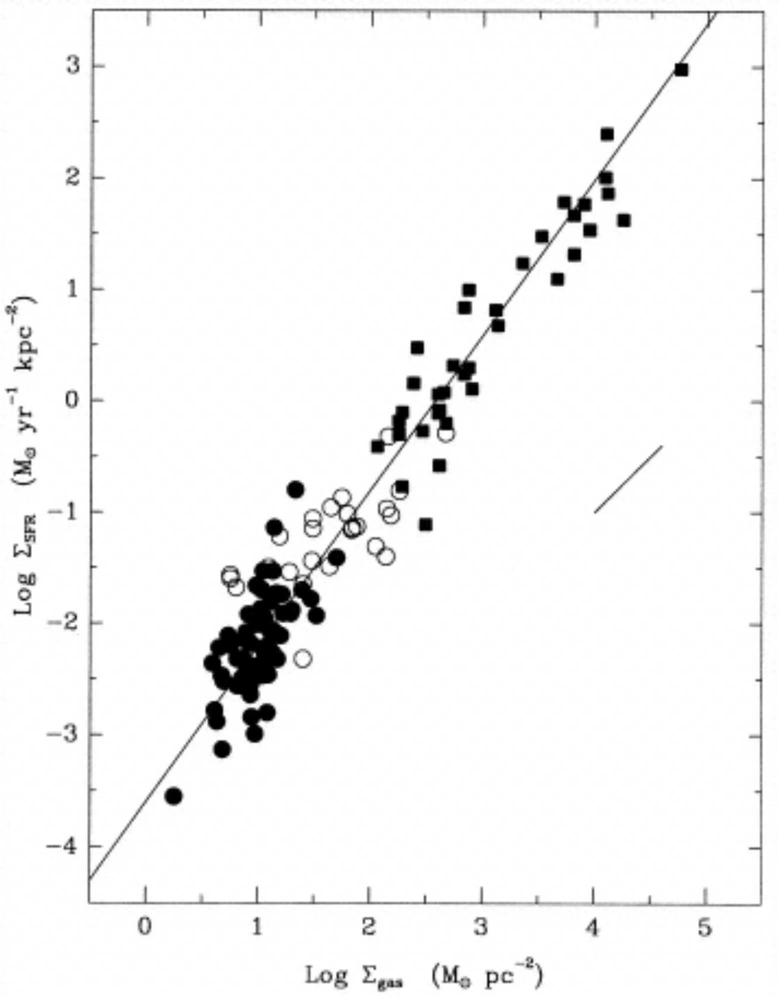




Kennicutt & Evans, ARAA, in prep

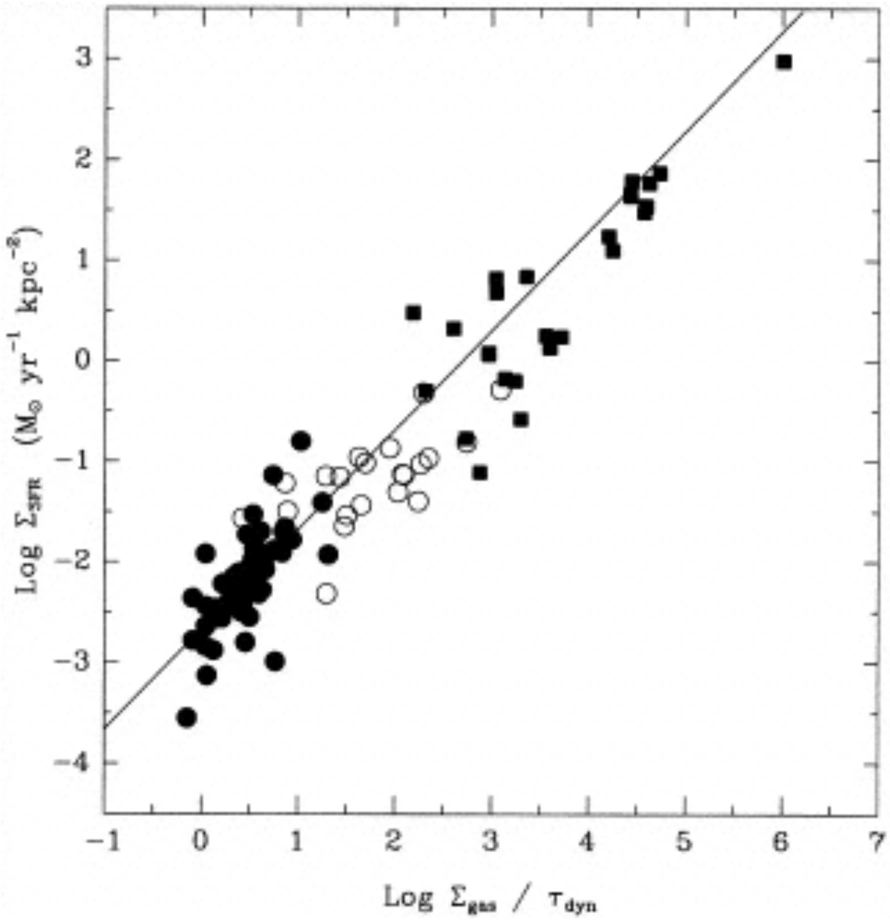
But what does it mean, and where can it be applied?

- spatially resolved and gas phase-resolved studies needed



Schmidt law:

SFR vs gas density power law

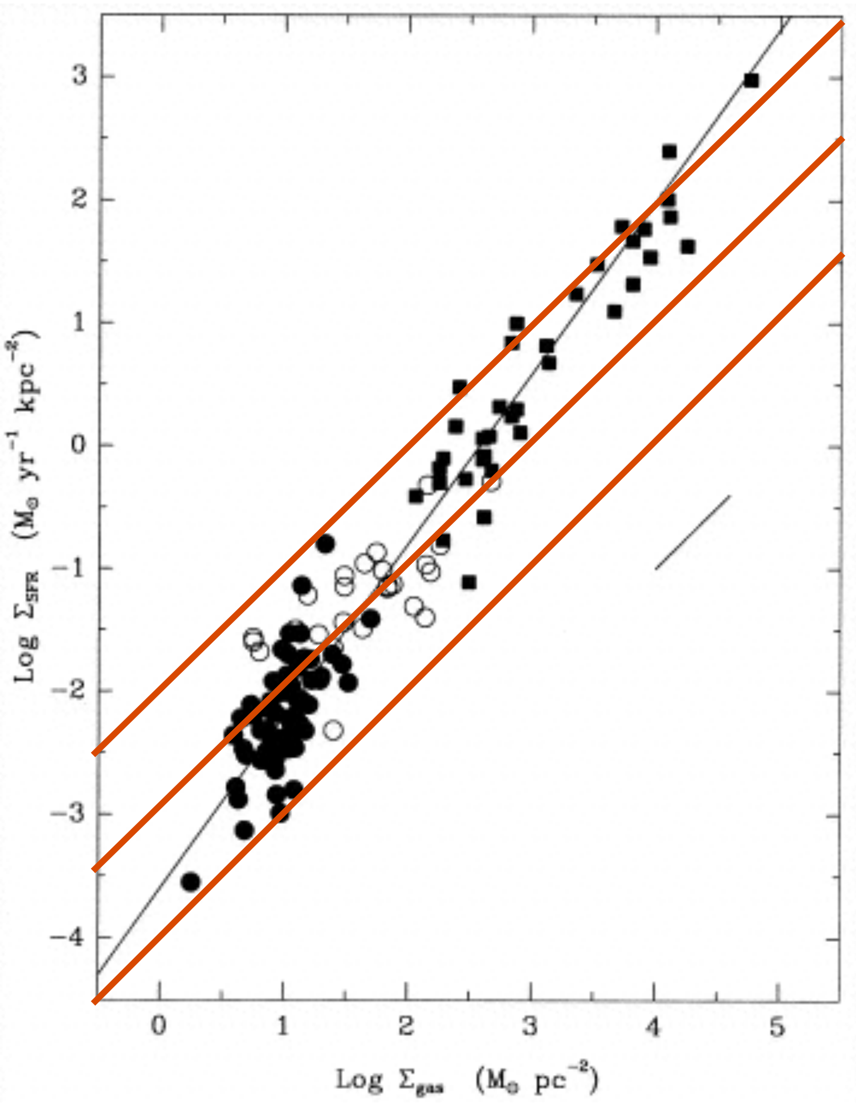


SFR vs gas density/dynamical time

Kennicutt 1998

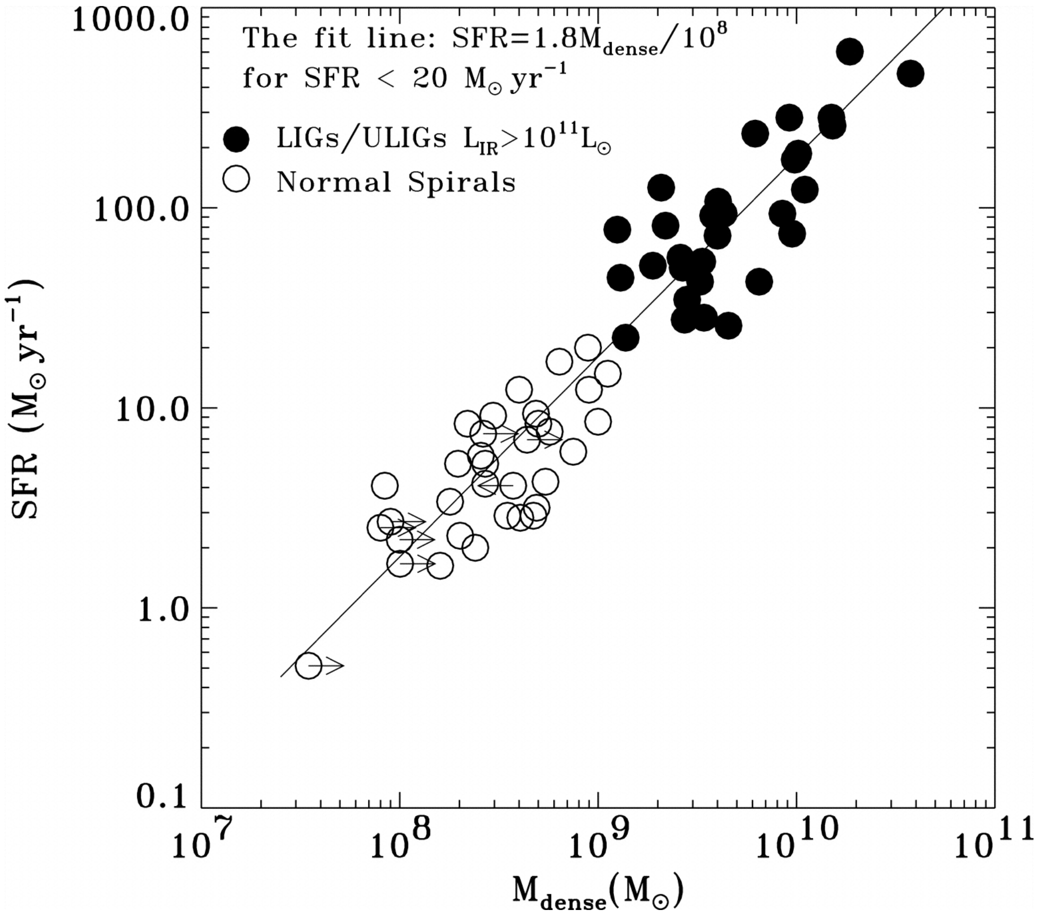
But what does it mean, and where can it be applied?

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

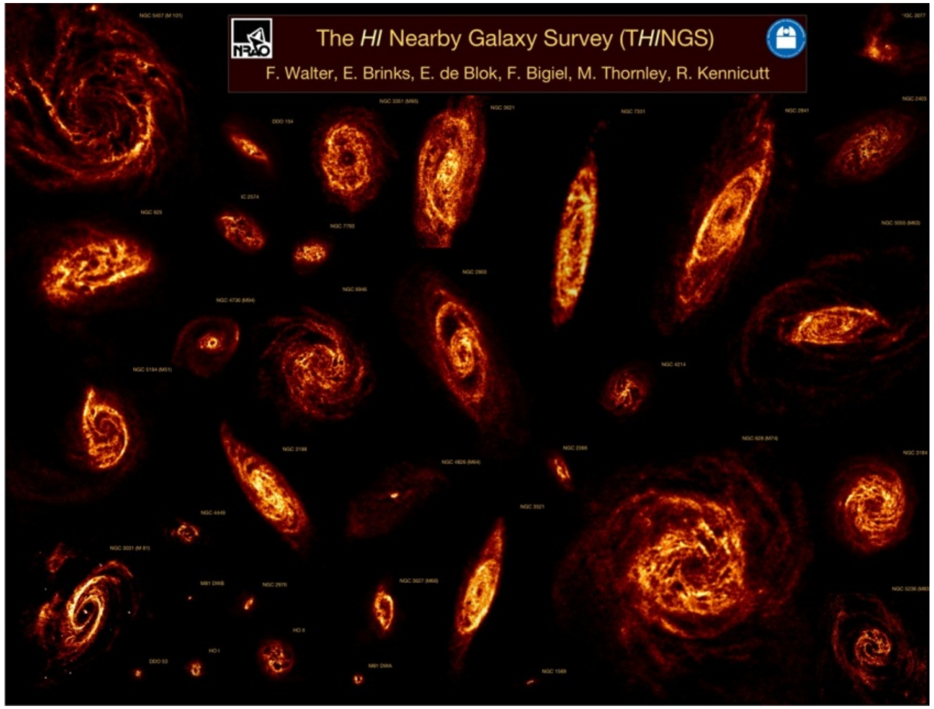


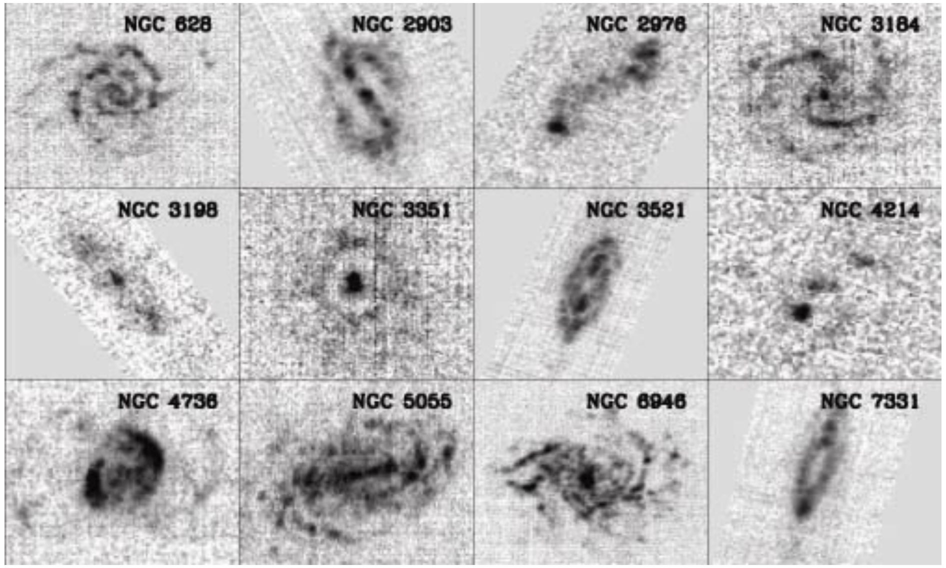
Kennicutt 1998

SFR/M(HCN) ~ const

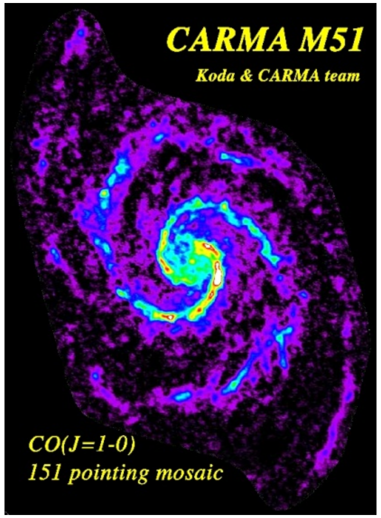


Gao, Solomon 2004



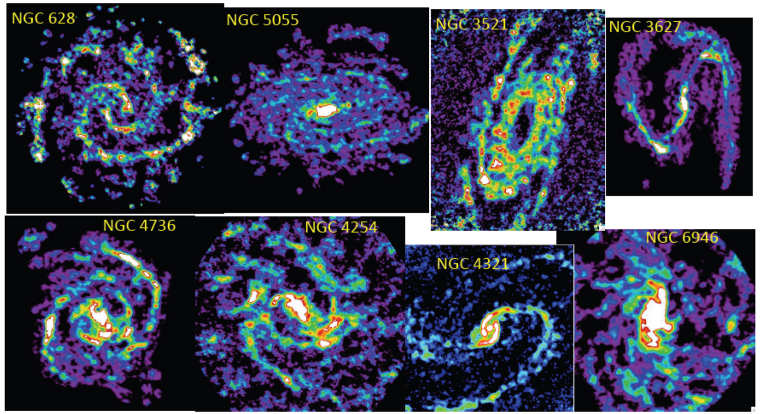


HERACLES CO 2-1 survey (IRAM)

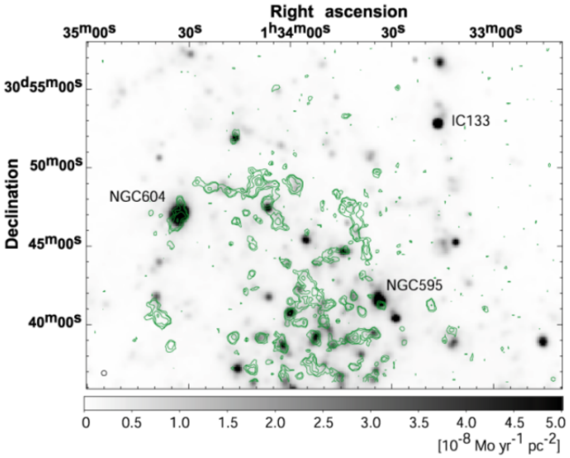


Obs. and Data Reduction in Progress

- CARMA: 10 completed + 3 half done.
- Nobeyama 45m telescope: 17 observed

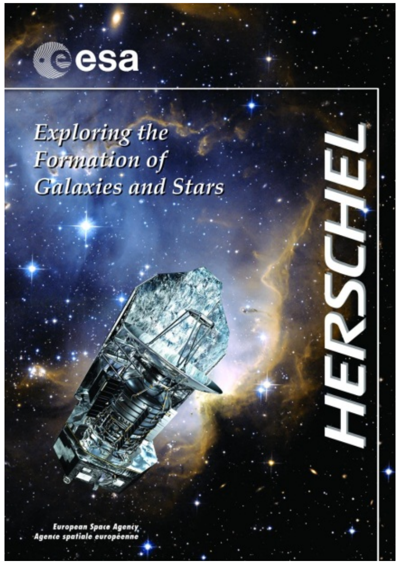


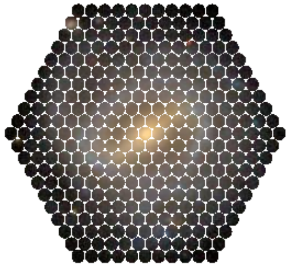
by Misty La Vigne; Fumi Egusa; Rieko Momose; Masahiro Fukuhara; Guilin Liu; Jin Koda



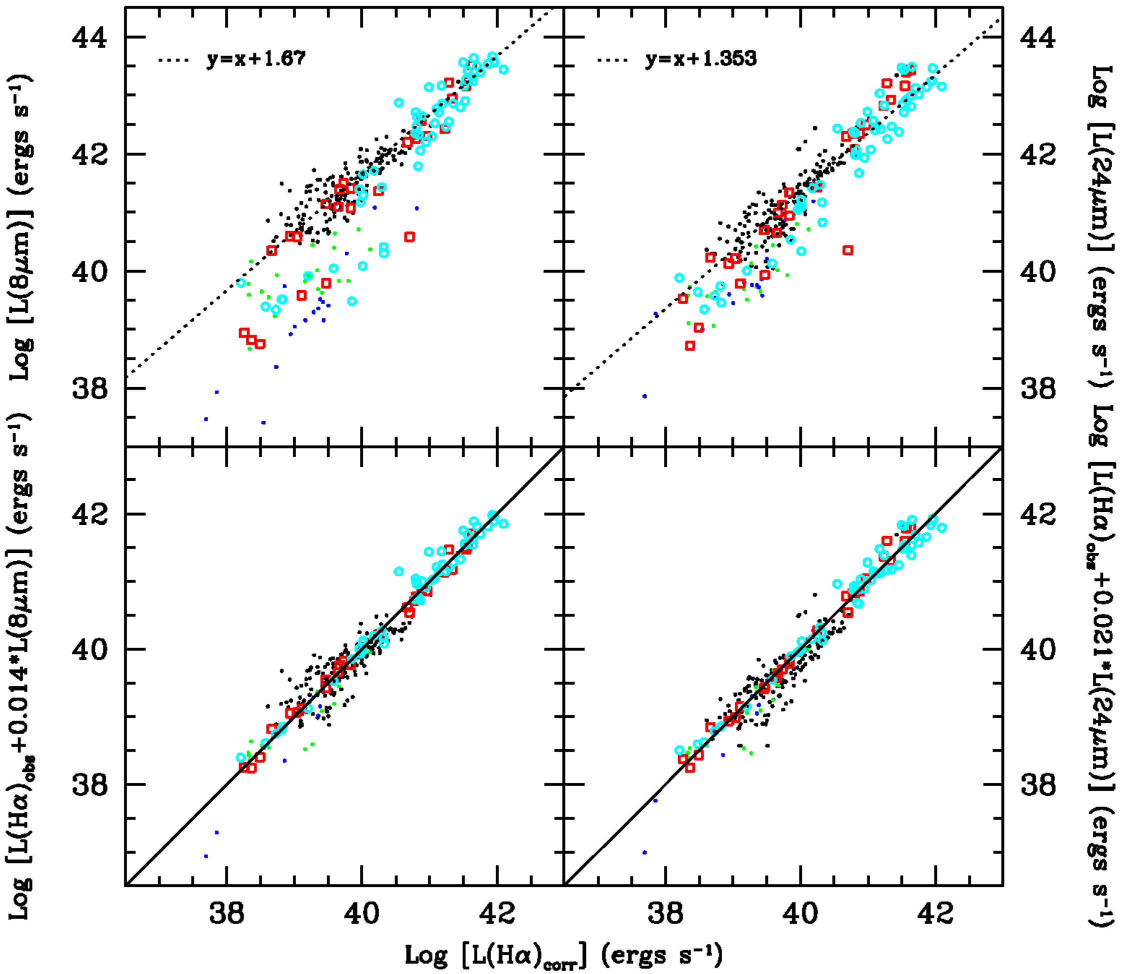
Nobeyama CO survey of M33

Multiwavelength observations provide dust-free SFR tracers





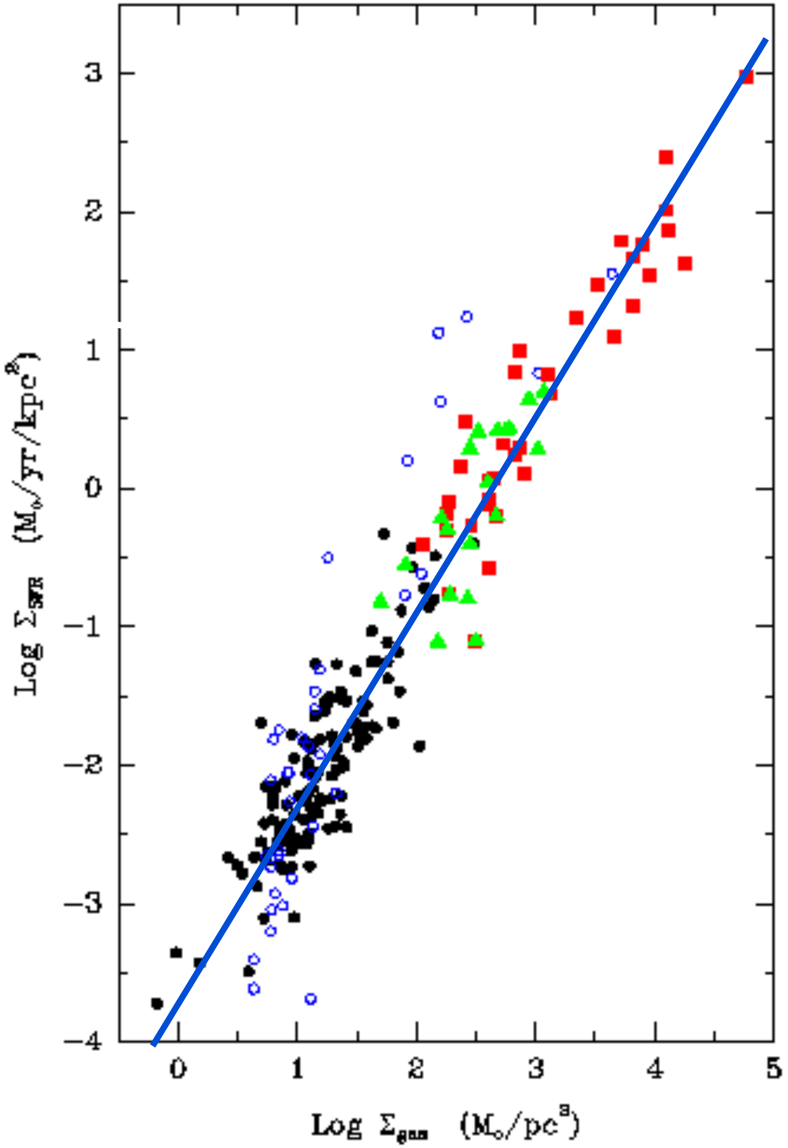
CALIFA Survey



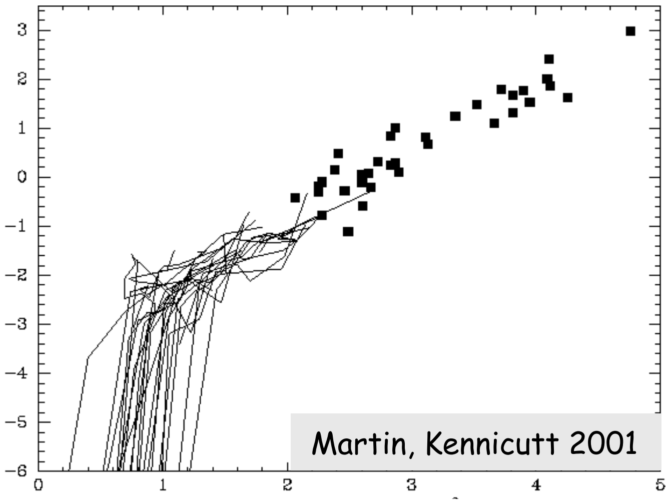
Kennicutt et al. 2009

Consistent Results (mostly)

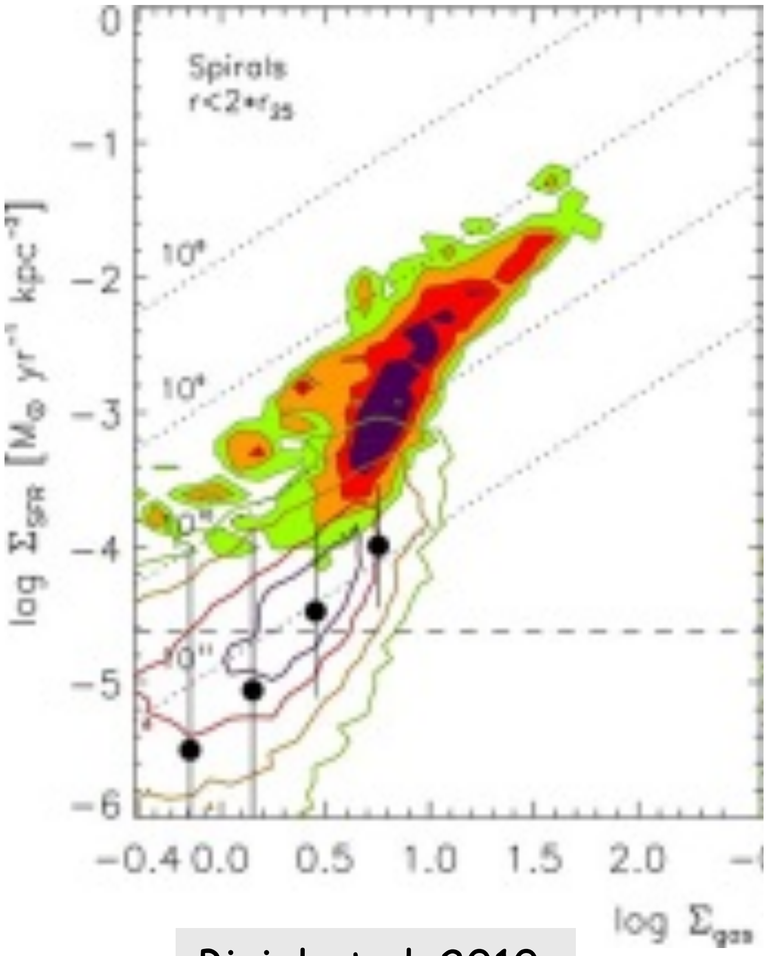
- Global non-linear Schmidt law confirmed (N = 1.4-1.5)
  - threshold present at low density (e.g., LSB's, outer HI discs)
  - non-linear behaviour seen in total and molecular gas laws (latter somewhat dependent on X_{CO})
  - low-metallicity dwarf galaxies deviate from main law (X_{CO}?)
- Low-density thresholds seen in Σ_{SFR} vs Σ_{gas} relations
- Local SFR uncorrelated with HI gas density



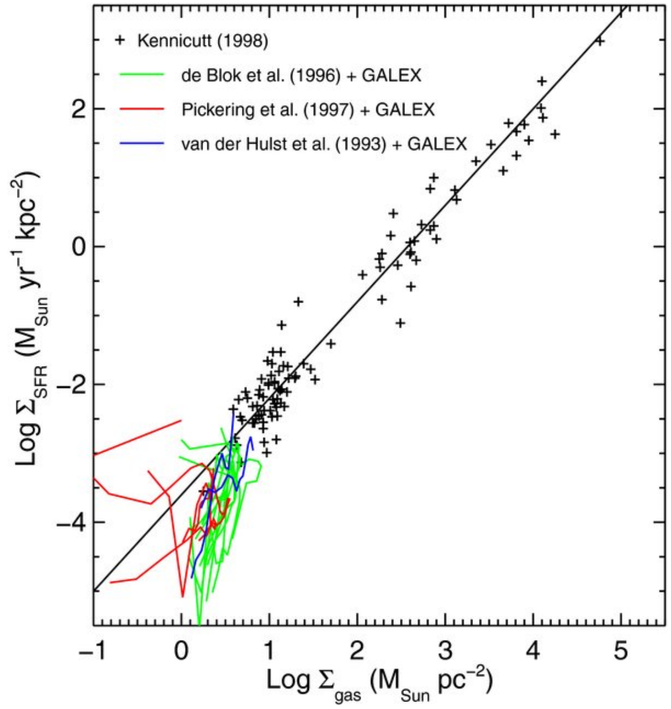
Confirming Evidence for SF Thresholds



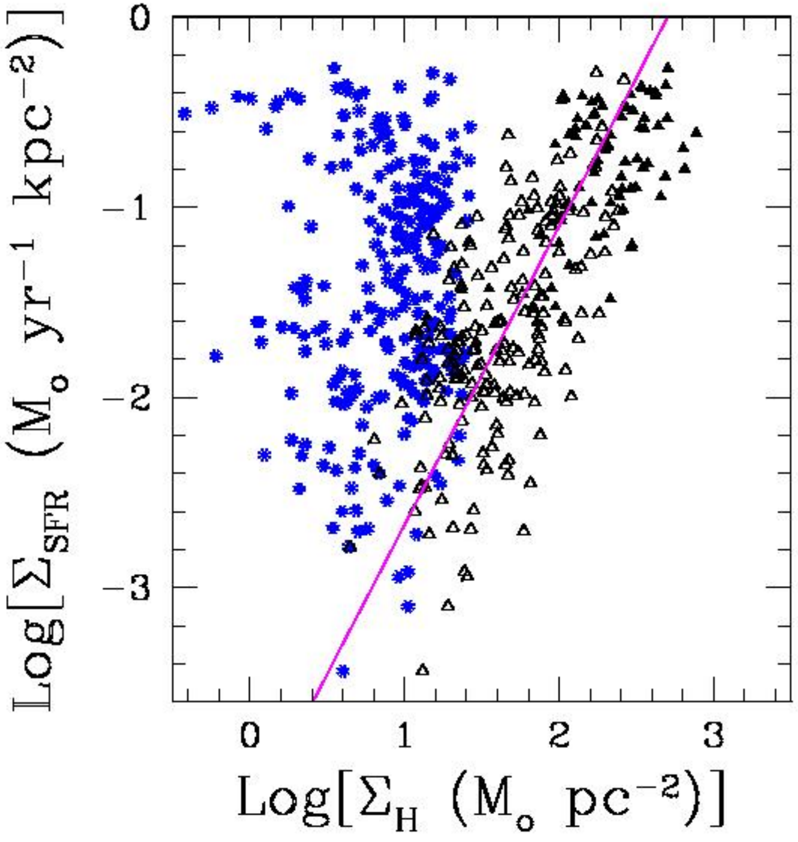
Martin, Kennicutt 2001



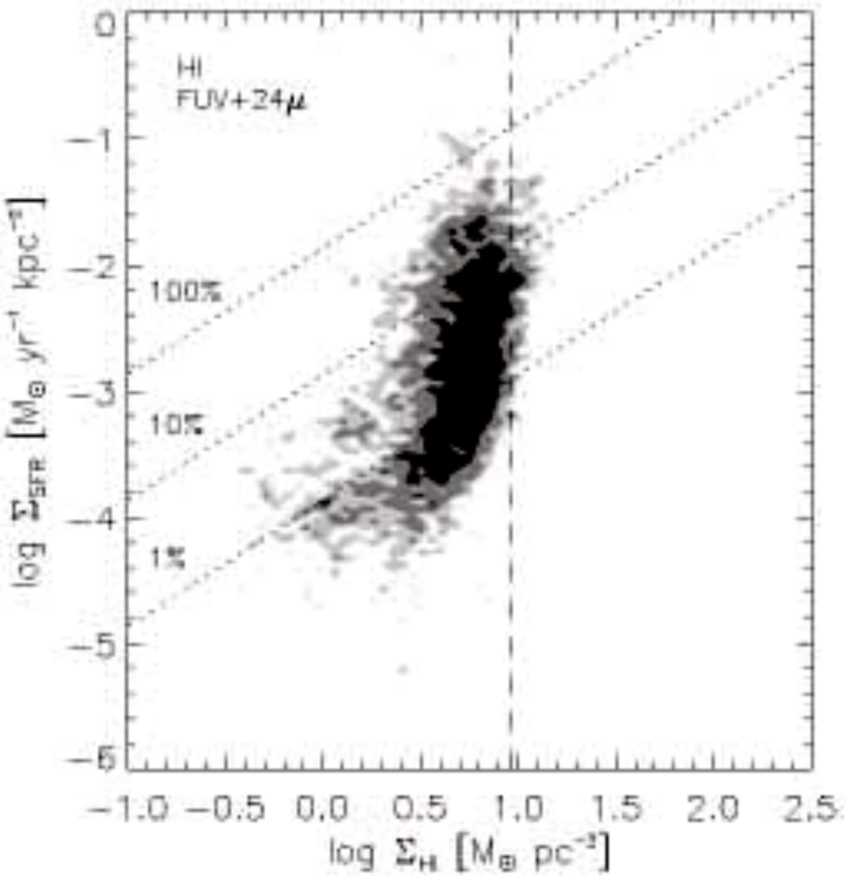
Bigiel et al. 2010



Wyder et al. 2009



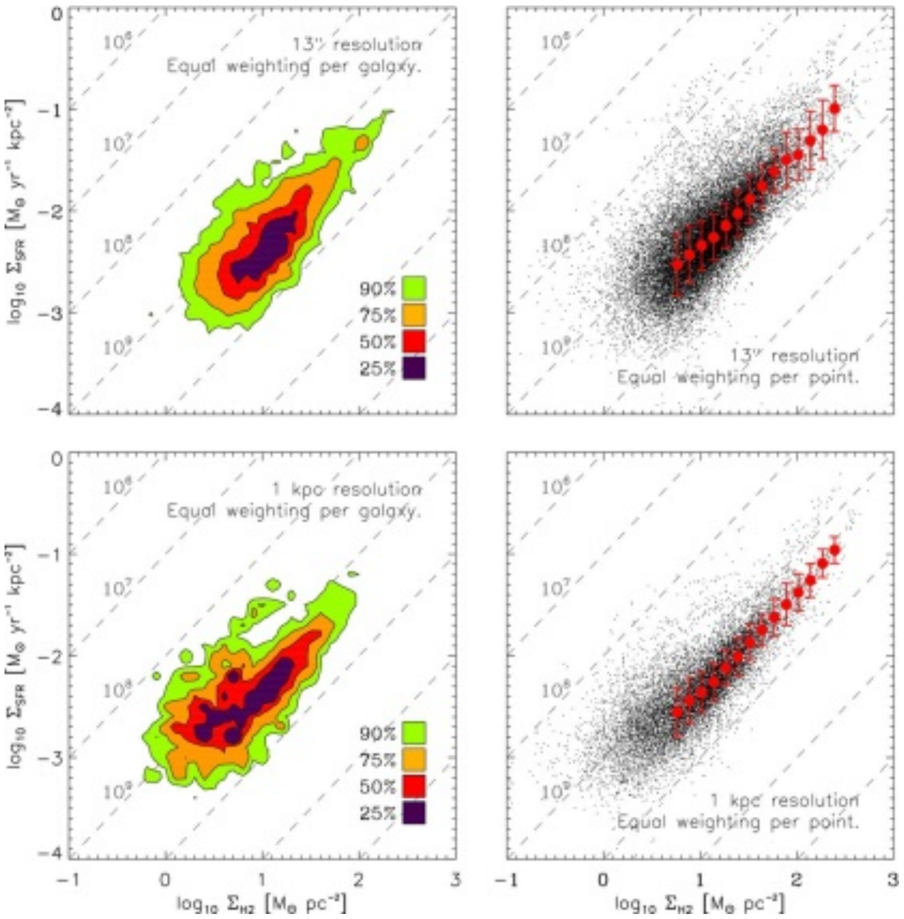
Kennicutt et al. 2007 (M51)



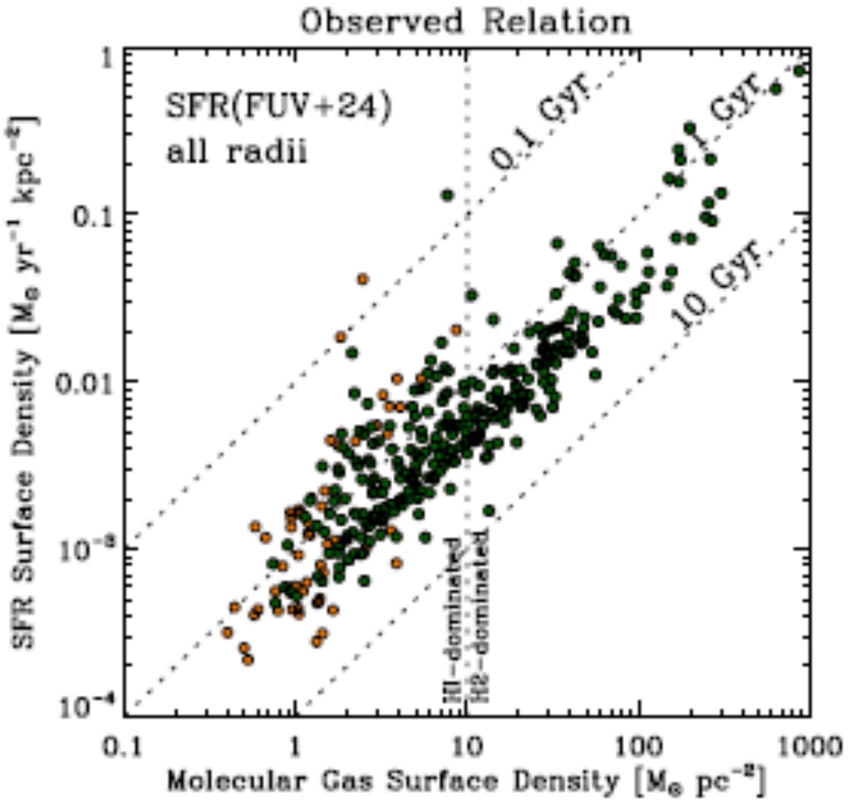
Biegel et al. 2008 (THINGS)

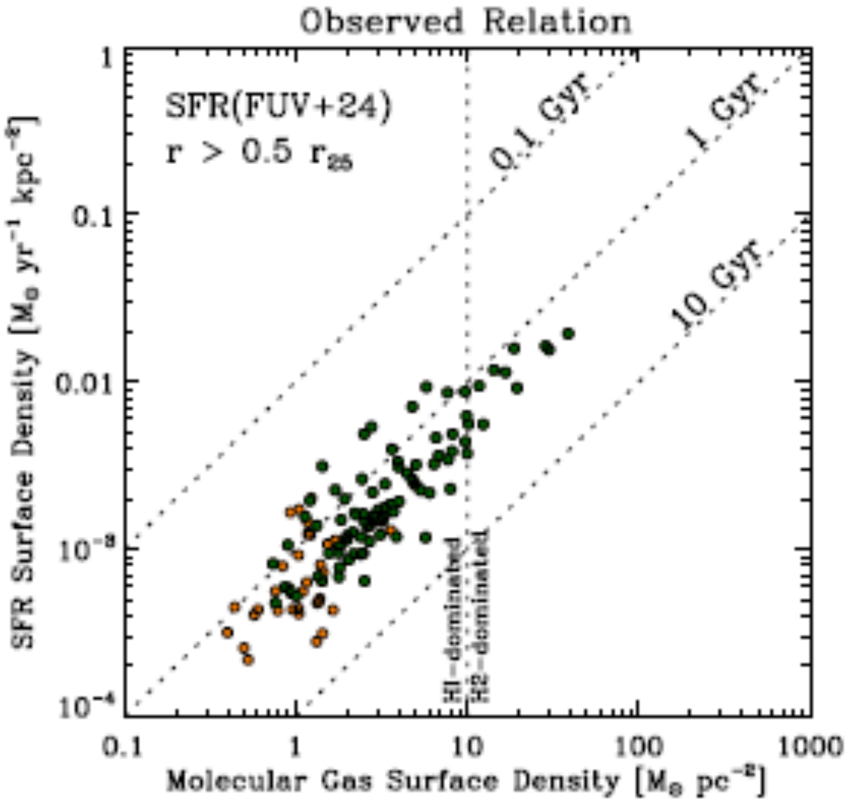
Inconsistent Results

- Several studies of the local SF law suggest a constant ratio of SFR to molecular gas density from CO(2-1)
  - implies that any non-linearities in global SFR law arise from HI – H_2 conversion
  - implies constant dense core (HCN) fraction everywhere
- Results inconsistent with very high SF efficiencies in starbursts
  - requires a second mode, with either non-linear high-density regime or a separate high-efficiency regime
  - transition density near point where global SF density approaches that in GMCs
- Or problem could be observational--other groups find non-linear SF law in CO. Differences coupled to method used to measure SFRs



Bigiel et al. 2011





Schruba et al. 2011

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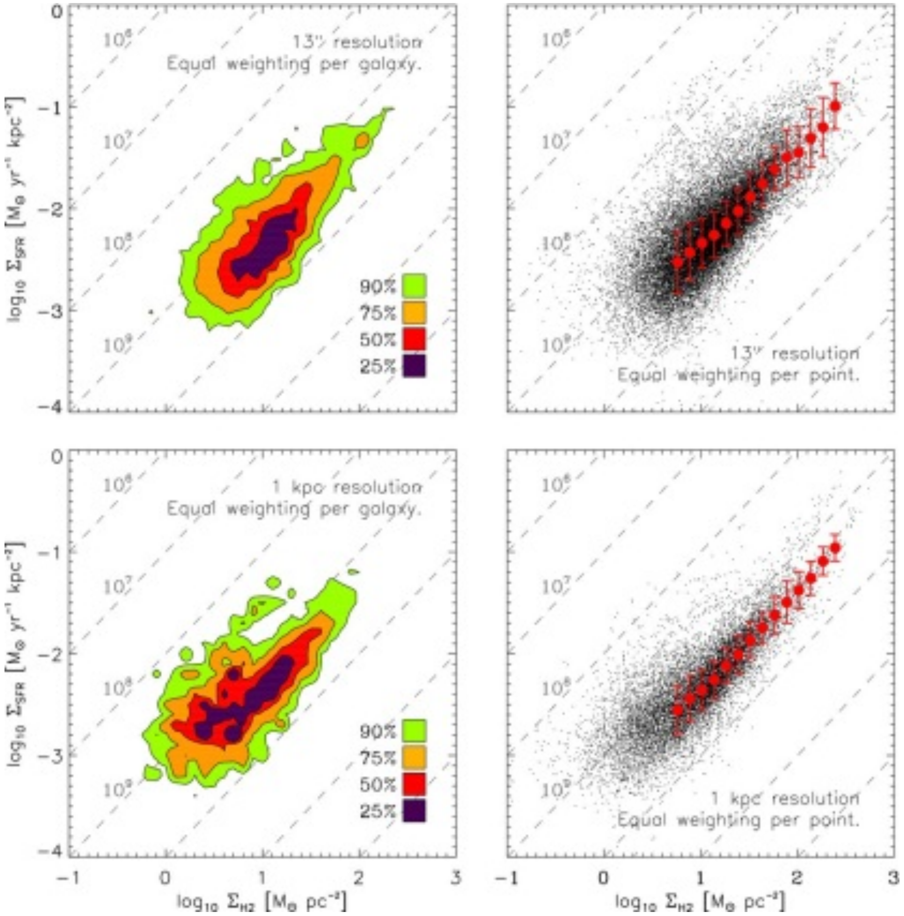
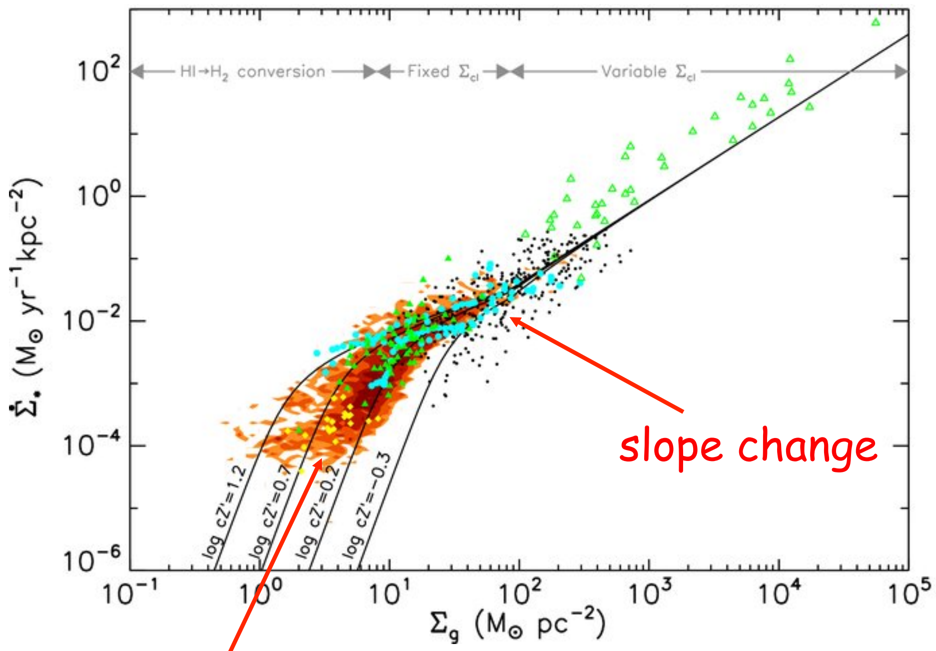
- Other groups find non-linear SF law in CO, differences coupled to method used to measure SFRs



Bigiel et al. 2011

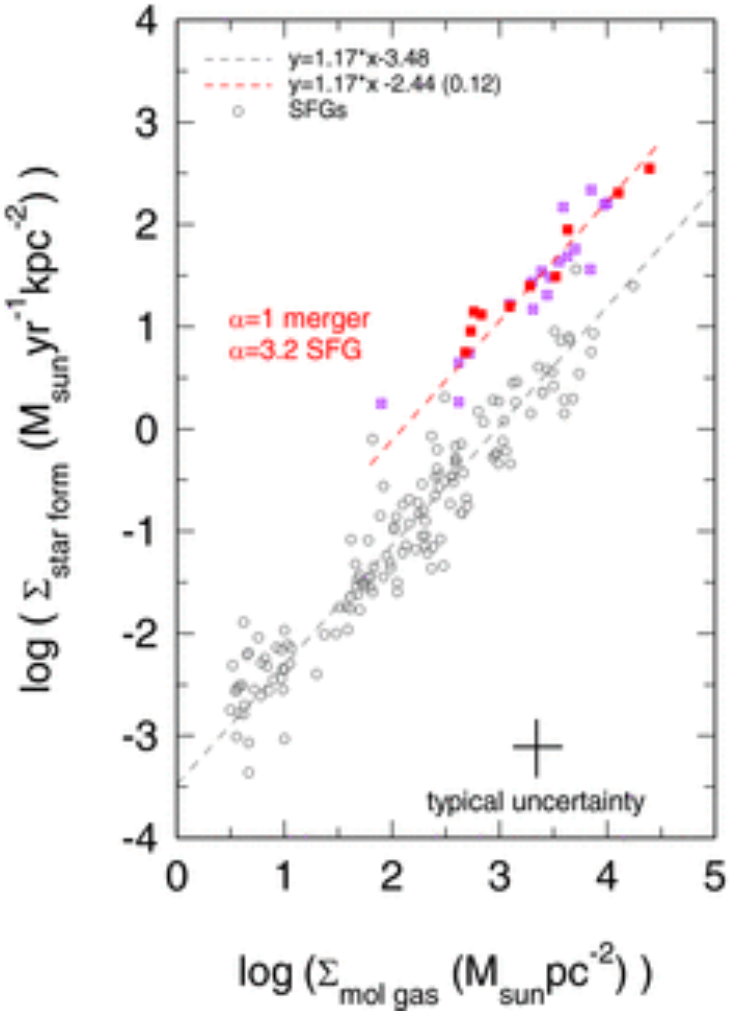
Two Ways to Reconcile



slope change

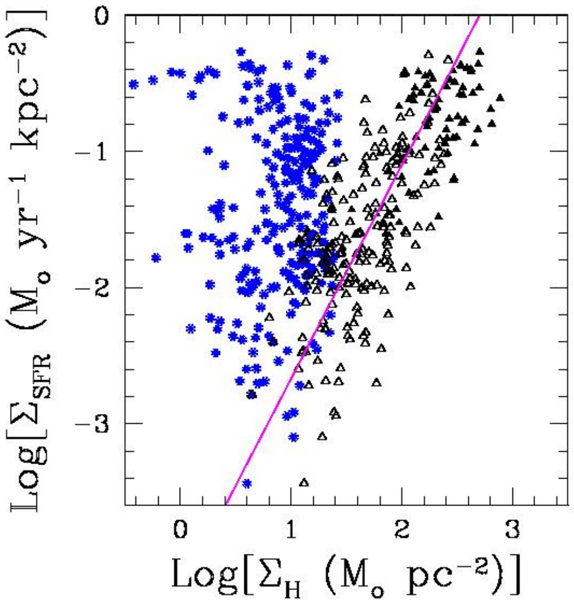
thresholds from UV shielding, not gravity

Krumholz et al. 2009

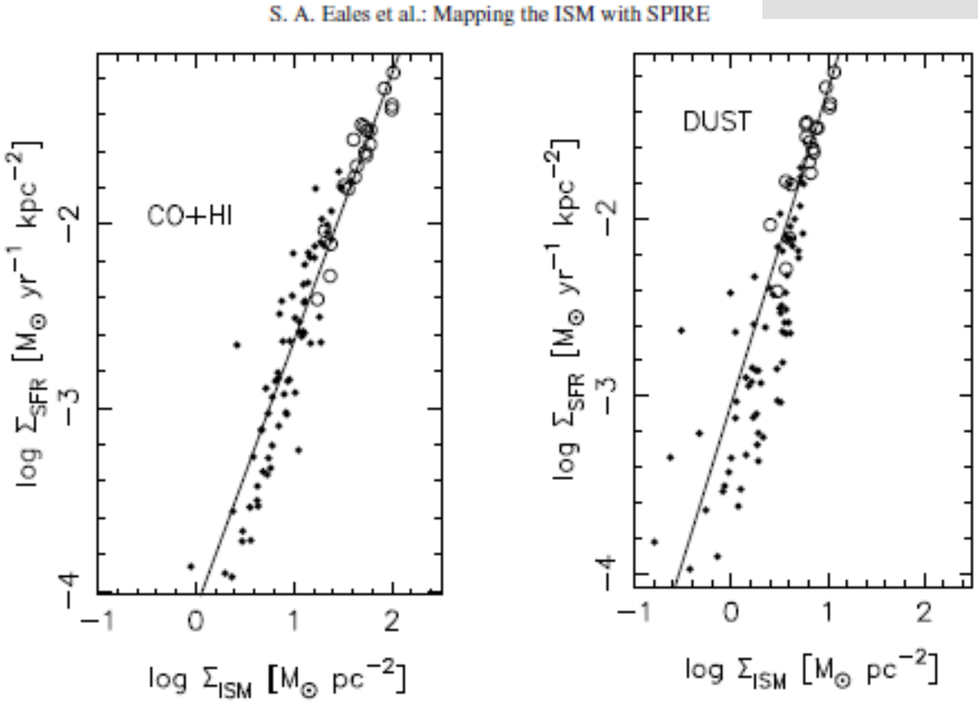


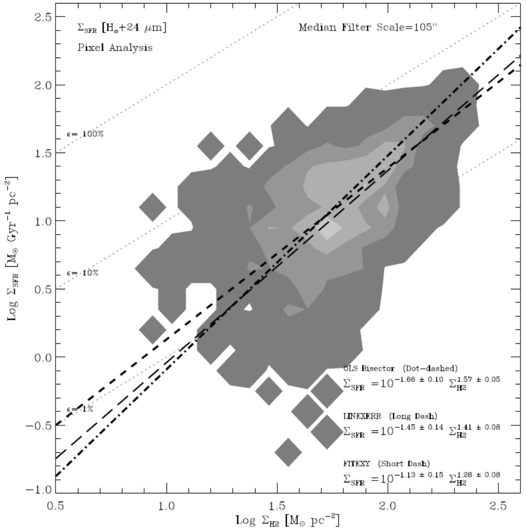
Genzel et al. 2010

Kennicutt et al. 2007

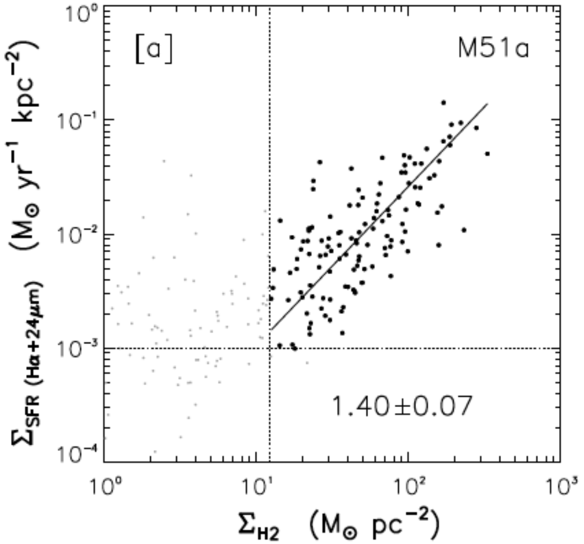


Eales et al. 2010





Rahman et al. 2011

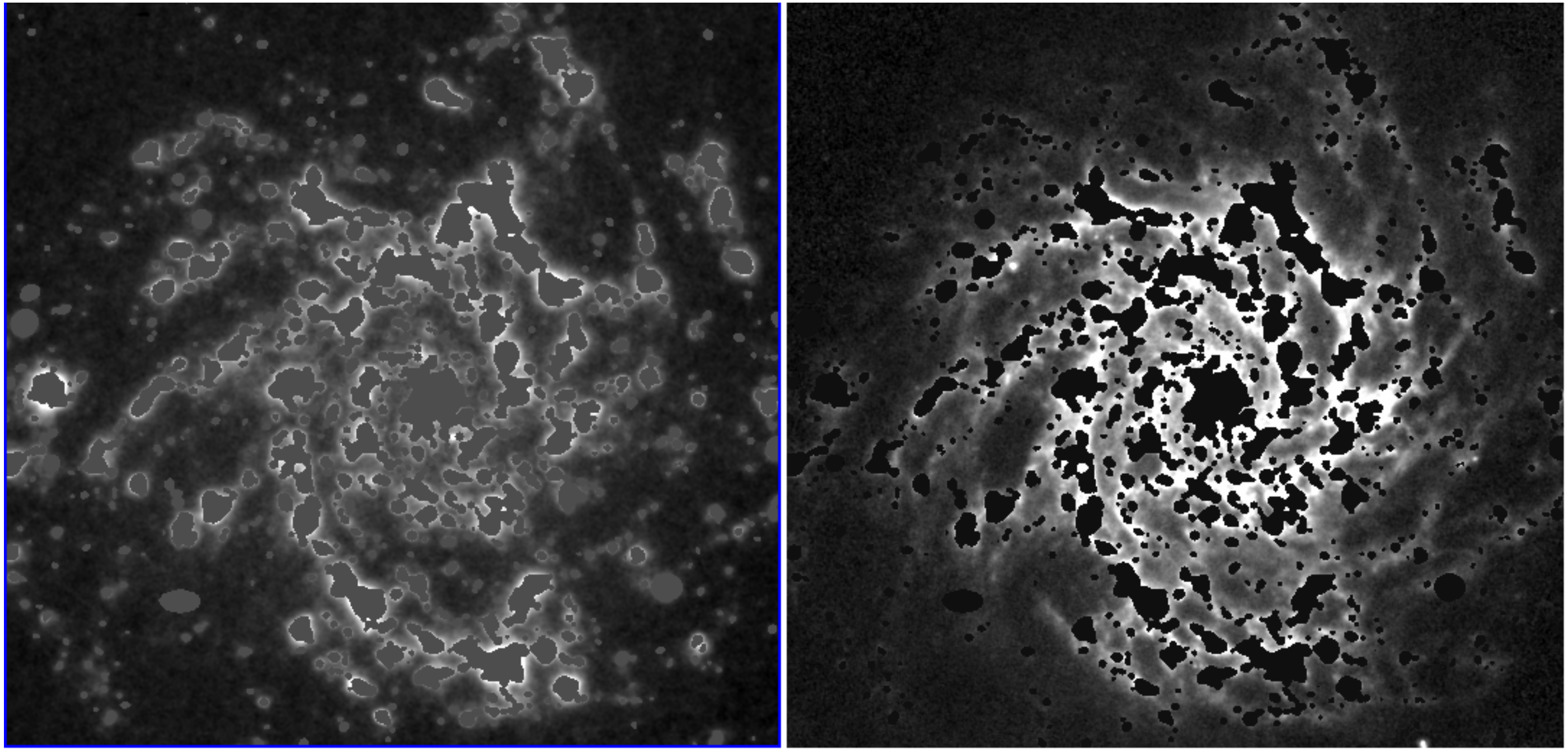


Liu et al. 2011

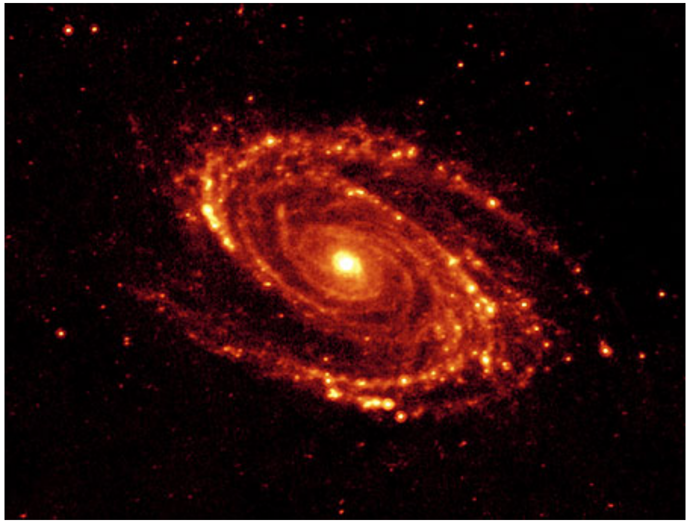
The Challenge: Spatially-Resolved SFRs

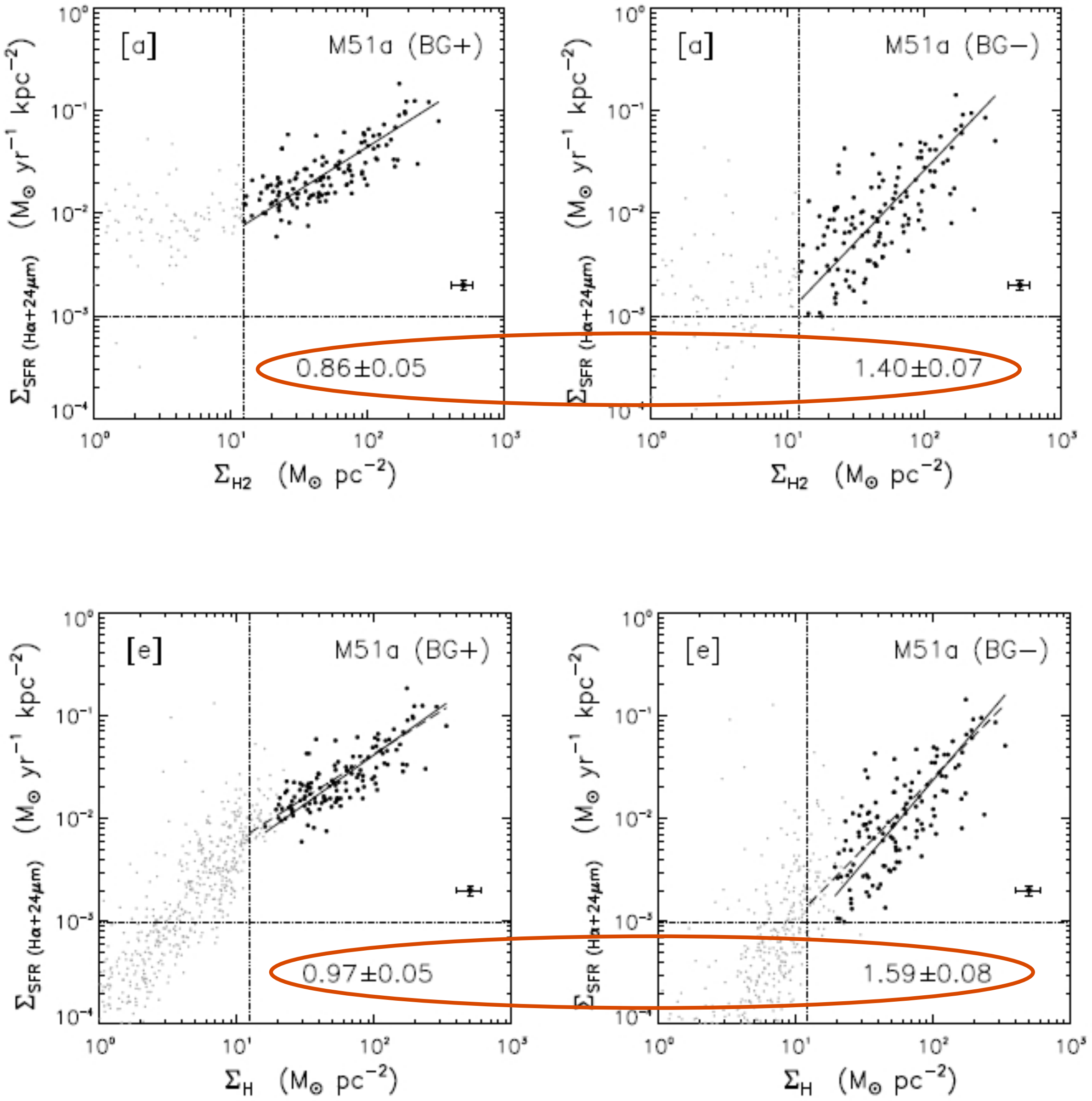
- the robustness of galaxy-wide SFRs rests several approximations:
  - averaged over full range of region ages
  - IMF is fully populated, well represented
  - dust geometry effects average out
  - SFR averaged over a galaxy roughly steady with time, so age sensitivity of tracers (Hα, UV, IR) can be ignored
- extending this approach to a “SFR map” uncovers several systematic effects:
  - local emission dependent on small number statistics of individual stars, “cosmic variance” (especially for Hα, other ionised gas tracers)
  - variations in dust geometry add scatter to “SFRs”
  - age of stellar population varies locally, altering Hα/UV/IR emission per unit SFR
  - Hα and dust emission trace gas, not stars
  - diffuse emission produces false “star formation” signal far away from any young stars
  - meaning of “SFR” itself ill defined on local scales

Contamination by diffuse emission



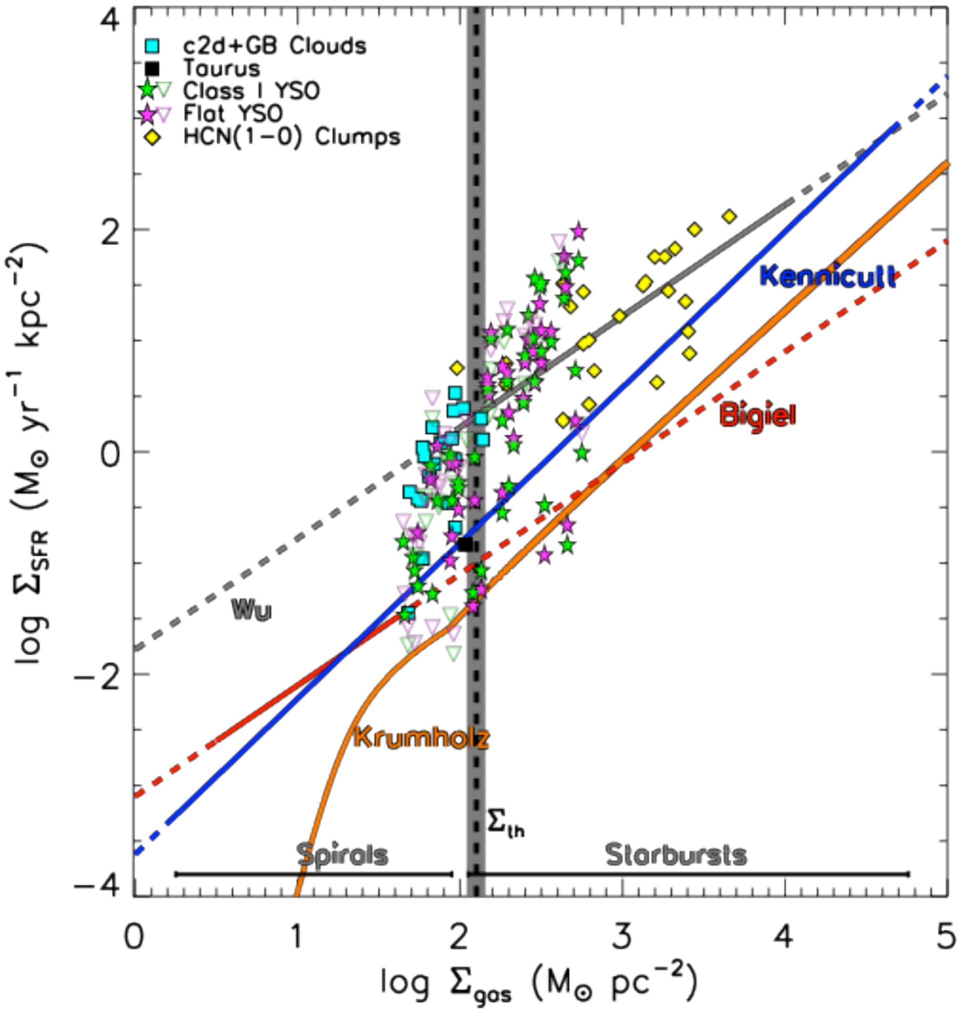
- Difficult problem that requires masking out of clustered regions of star formation (HII regions/clusters) and separate diffuse SF-associated PAH emission associated from non-SF diffuse PAH emission (Crocker et al., in prep.)





Liu et al. 2010

The "SF Law" Within Clouds



Fit with broken powerlaw with slopes of 4.6 below and 1.1 above a turnover Σ_{gas} = 129+-14 M_{sun} pc^{-2}. (see Lada et al. 2010)

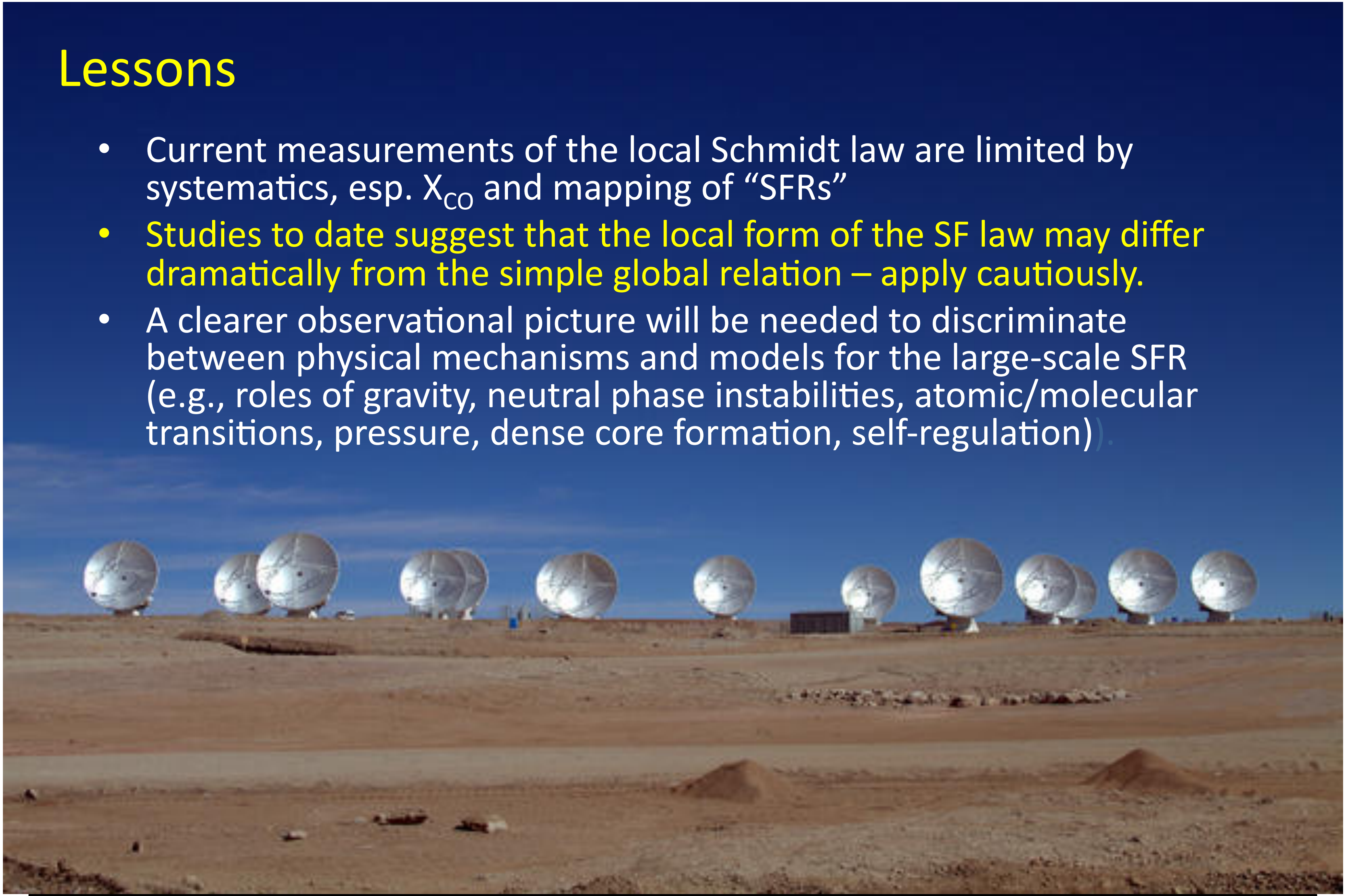
Gutermuth et al. favor continued rise with
$\Sigma_{SFR} \sim \Sigma_{gas}^2$ throughout.

All agree: well above all exgal relations except for dense gas relation.

Heiderman et al. 2010

Lessons

- Current measurements of the local Schmidt law are limited by systematics, esp. X_{CO} and mapping of “SFRs”
- Studies to date suggest that the local form of the SF law may differ dramatically from the simple global relation – apply cautiously.
- A clearer observational picture will be needed to discriminate between physical mechanisms and models for the large-scale SFR (e.g., roles of gravity, neutral phase instabilities, atomic/molecular transitions, pressure, dense core formation, self-regulation)).



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