Towards an Understanding of Star Formation: Scaling Relations in the ISM

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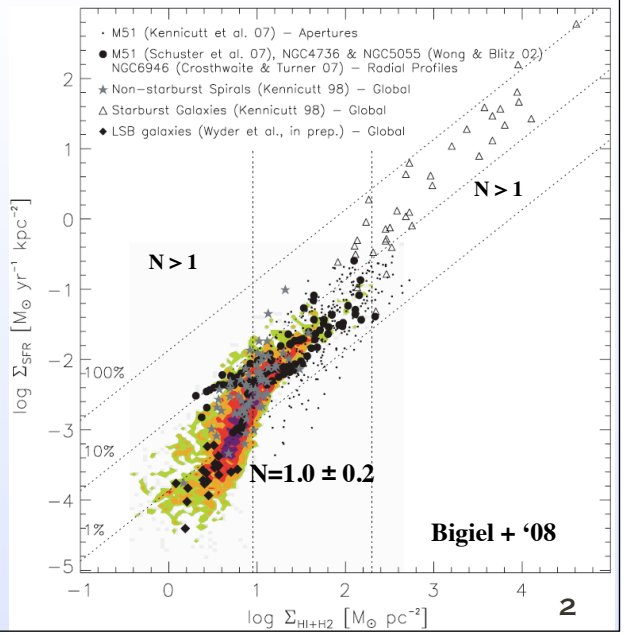
The Kennicutt-Schmidt Relationship

$$\Sigma_{SFR} \propto \Sigma_{gas}^{N}$$

Schmidt ‘59
Buat + ‘89
Kennicutt ‘89
Kennicutt ‘98
Hunter + ‘98
Boselli + ‘02
Wong & Blitz ‘02
Boissier + ‘03
Heyer + ‘04
Leroy + ‘05
Kennicutt + ‘07
Leroy + ‘08
Bigiel + ‘08
Blanc + ‘09
Verley + ‘10
Daddi + ‘10
Genzel + ’10
Liu + ‘11
Schruba + ’11
Rahman + ’12
Leroy + ’13
Momose + ’13...

Kennicutt & Evans 2012
(and references therein)



Overview

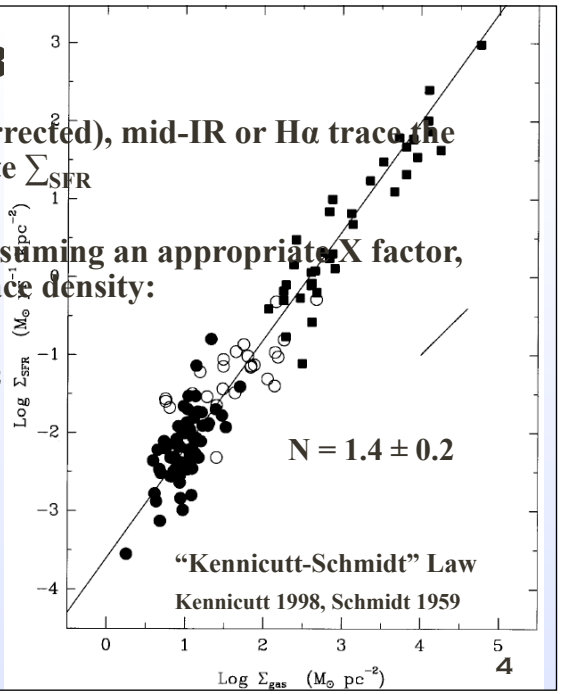
- The Kennicutt-Schmidt (KS) Relationship
- Previous Results
- Fitting the KS relationship: Evidence for diffuse molecular gas
- Outlook: other scaling relations
- Summary

KS: Ob

- FUV (extinction corrected), mid-IR or Hα trace the Star Formation Rate $\sum_{SFR}$
- HI and CO lines, assuming an appropriate X factor, trace total gas surface density:
  - $\sum_{gas} = \sum_{HI} + \sum_{H2}$

Observations find:

$$\sum_{SFR} \propto \sum_{gas}^{N}$$



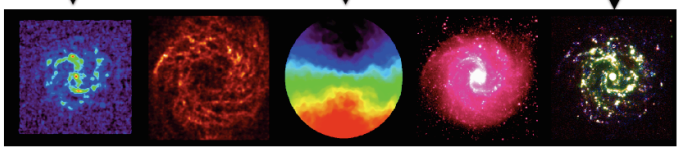
HERACLES

A Multiwavelength View of SF in Disks

Molecular Gas
Peak CO intensity
From HERACLES

Kinematics
Here from HI line
Also from CO

Recent Star Formation
Composite of **FUV** (GALEX),
mid-IR (SINGS/LVL),
and **Hα** (SINGS/LVL)



Atomic Gas
VLA 21cm data THINGS +
new & archival

Old Stars
Near infrared intensity
From SINGS and LVL

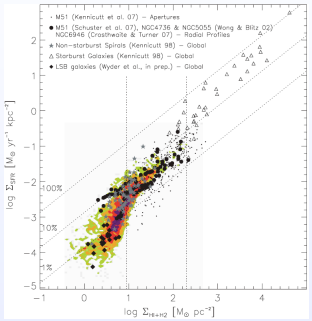
Leroy + '08, 09, Bigiel + 08

Kennicutt & Evans 2012
(and references therein)

KS Slope Estimates

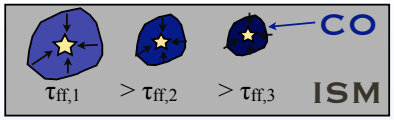
- At intermediate 10 $M_\odot$ pc^{-2} < Σ_{gas} < 100 $M_\odot$ pc^{-2}, Bigiel +'08 find N~1

- A linear relationship from resolved galaxies: STING, HERACLES, though with significant scatter
  (e.g. Bigiel + '08, Rahman + '12, Schruba + '12, Leroy + '13, etc...)



- Super-linear N~1.5 KS relationship from unresolved disks (Kennicutt '89, '98) and resolved observations (e.g. Kennicutt + '07, Liu + '11, Momose + '13)

Interpreting the KS Slope



Super-linear KS slope (N~1.5)

⇒ decreasing gas depletion time, or higher efficiency, with increasing GMC density

In both paradigms, CO traces star forming 'GMCs'

Depletion time τ_{dep} a key parameter for theories of star formation (Ostriker+, Dobbs+, Krumholz+, Hopkins+, ...)

Linear KS slope (N~1)

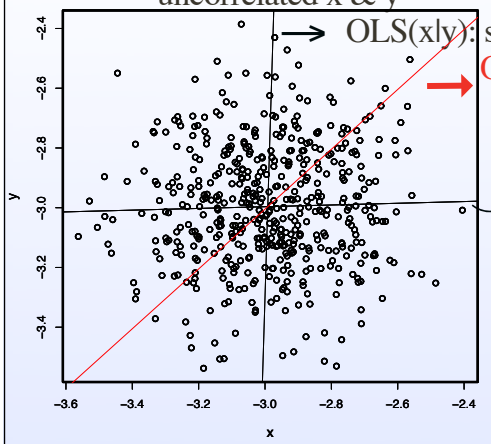
⇒ constant gas depletion time or efficiency of GMCs
(though observations indicate significant scatter)

Statistical Fitting

- Fitting method provides well defined statistics (OLS methods: y|x, x|y, bisector)
- Hierarchical modeling for hierarchical data
- Hierarchical Bayesian fitting rigorously treats uncertainties, providing PDFs of all fitted parameters
- Quantifying goodness of fit "By Eye"

Testing OLS Methods

uncorrelated x & y



OLS(x|y): slope = 36.4 +/- 0.04

OLS(bisector): slope = 1.0 +/- 0.04

OLS(y|x): slope = 0.03 +/- 0.05

Hierarchical Bayesian Fitting of KS Relationship

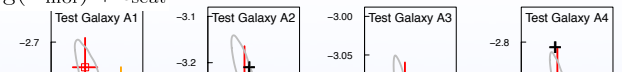
- Monte Carlo methods can account for statistical uncertainties. Bayesian inference is well suited for hierarchical problems, through MCMC methods (Kelly '07, Gelman + '04, Gelman & Hill '07, Kruschke '11)

- Developed and tested Bayesian method, accounting for uncertainties to fit KS parameters of individual galaxies and the population (Shetty + '13, '14)

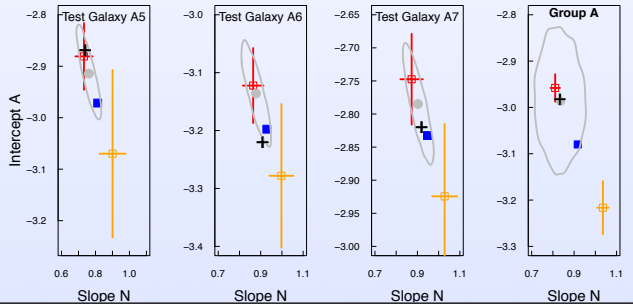
- Analysis of resolved observations using 7 HERACLES (Leroy + '09, Bigiel + '08) galaxies and 13 STING galaxies (Rahman + '12)

Testing the Hierarchical Bayesian Fit

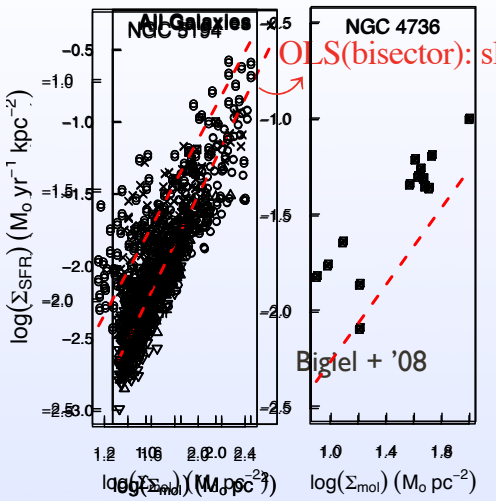
$$\log(\Sigma_{\rm SFR}) = A + N\log(\Sigma_{\rm mol}) + \epsilon_{\rm scat}$$



Subject	True A	True N	True $\sigma_{\rm scat}$	Bayes A	Bayes $2\sigma_A$	Bayes N	Bayes $2\sigma_N$	Bayes $\sigma_{\rm scat}$
Test Galaxy A1	−2.77	0.72	0.1	−2.79	[−2.9, −2.7]	0.74	[0.64, 0.84]	0.12
Test Galaxy A2	−3.21	0.88	0.1	−3.23	[−3.4, −3.1]	0.86	[0.76, 0.97]	0.12
Test Galaxy A3	−3.18	0.89	0.1	−3.14	[−3.3, −3.0]	0.89	[0.79, 0.99]	0.12
Test Galaxy A4	−2.81	0.78	0.1	−2.91	[−3.0, −2.8]	0.82	[0.72, 0.92]	0.12
Test Galaxy A5	−2.87	0.74	0.1	−2.91	[−3.0, −2.8]	0.76	[0.66, 0.86]	0.12
Test Galaxy A6	−3.22	0.91	0.1	−3.13	[−3.3, −3.0]	0.87	[0.78, 0.98]	0.12
Test Galaxy A7	−2.82	0.92	0.1	−2.78	[−2.9, −2.7]	0.90	[0.80, 1.00]	0.12
Group Parameters[1]	**−2.98**	**0.83**	-	**−2.99**	**[−3.2, −2.7]**	**0.84**	**[0.65, 1.0]**	0.12



The KS Relationship of the Bigiel + ’08 Sample



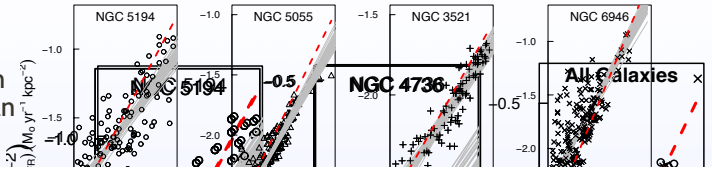
OLS(bisector): slope = 1.0 +/- 0.2

Bigiel + ’08

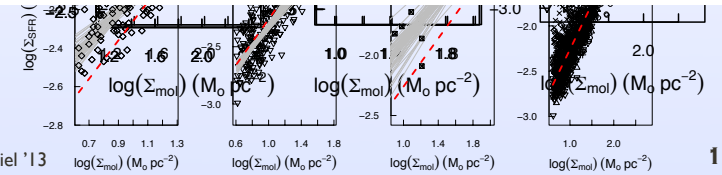
Bigiel + ’08

The KS Relationship of the Bigiel + '08 Sample

Gray lines: 50 random draws from the Bayesian posterior

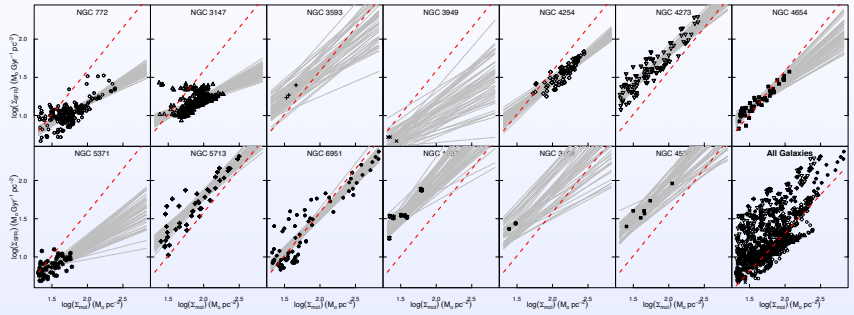


Subject	Bayes A	Bayes $2\sigma_A$	Bayes N	Bayes $2\sigma_N$	Bayes $\sigma_{\rm scat}$
NGC 5194 (M51)	-2.84	$[-3.0, -2.7]$	0.72	[0.62, 0.83]	0.06
NGC 5055	-3.20	$[-3.3, -3.1]$	0.87	[0.79, 0.95]	0.04
NGC 3521	-3.20	$[-3.4, -3.0]$	0.90	[0.76, 1.03]	0.05
NGC 6946	-2.81	$[-2.9, -2.7]$	0.78	[0.70, 0.86]	0.11
NGC 628	-2.89	$[-3.1, -2.6]$	0.76	[0.51, 0.95]	0.05
NGC 3184	-3.24	$[-3.4, -3.1]$	0.92	[0.79, 1.10]	0.05
NGC 4736	-2.83	$[-3.2, -2.4]$	0.92	[0.67, 1.20]	0.08
Group Parameters	$\mathbf{-3.00}$	$\mathbf{[-3.3, -2.7]}$	**0.84**	**[0.63, 1.0]**	0.14



Bigiel + '08
Shetty, Kelly, Bigiel '13

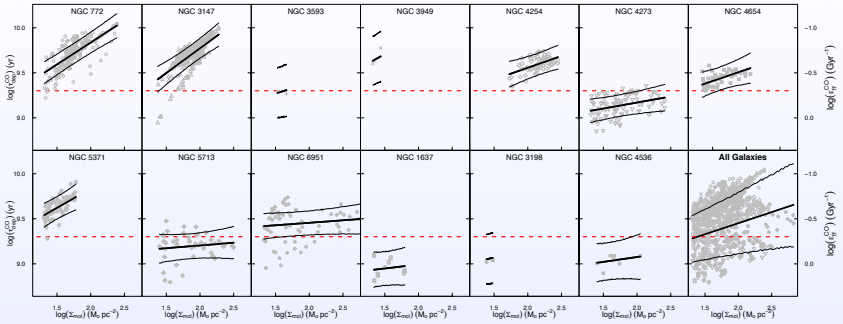
The KS Relationship of the STING Sample



Individual slopes range from 0.42 - 0.95
Mean Slope = 0.76; 2σ=[0.58 - 0.94]

Rahman +'11, '12,
Shetty + '14

Depletion times $\tau_{dep}^{CO} = \Sigma_{gas}/\Sigma_{SFR}$



Rahman + '12 STING Sample

⇒ No Universal depletion time

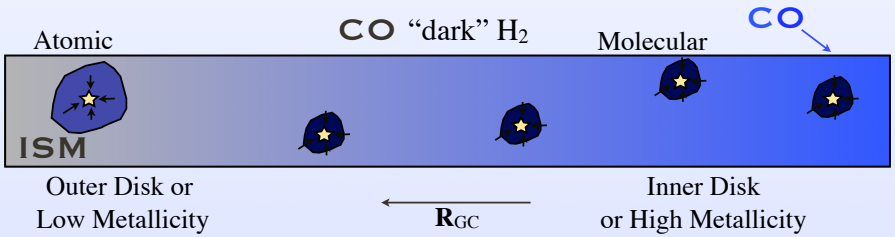
(Bigiel+'08, Leroy+'09, Schruba+'11, Rahman+'12, etc...)

⇒ 2 Gyr not a representative T_{dep}^{CO} , but T_{dep}^{CO} increases with Σ_{gas}, as traced by CO

Shetty + '13,'14a

Interpreting the variable & sub-linear KS Slope

- No evidence for an "Universal" KS slope: magnetic fields, stellar content, metallicity, molecular gas fraction all affect SF properties of given galaxy
- Significant evidence for sub-linear relationship, for most individual galaxies and for both ensembles: CO tracing some gas that is not associated with star formation?



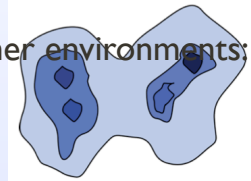
Diffuse Molecular Gas?

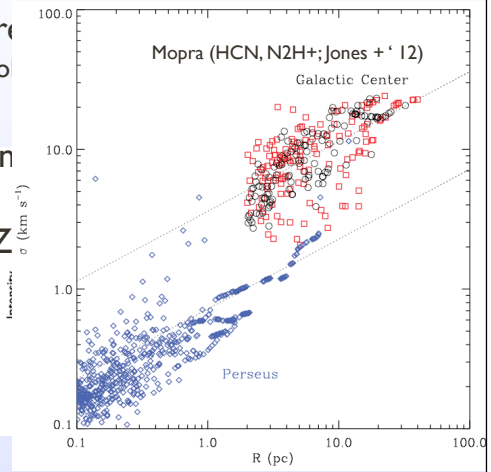
- Presence of non-star forming molecular gas postulated by Elmegreen (1993). Chemistry matters, including metallicity, UV radiation field, ambient density, etc...
- M51 the most sublinear slope (0.72) in Bigiel + '08 sample (see also Blanc + '09): Broad wings in CO suggestive that 50% of emission is from a diffuse molecular component (Pety+ '13, see also Hughes, Meidt, Schinnerer + '13).
- From GRS survey (Jackson + '06), significant fraction of CO luminosity not assigned to 'GMCs'. After accounting for distance ambiguity, quantify the mass fraction...? (Roman-Duval, Clark, RS, Klessen).

Shetty, Clark, Klessen, '14, In Prep

Outlook: Quantifying the structure of the ISM

- Other scaling relations, other tracers
- Decomposing the structure cores: "dendrograms" (Roso
- Scaling relation: Larson's lin
- Other environments: CMZ





Shetty + '12

Summary

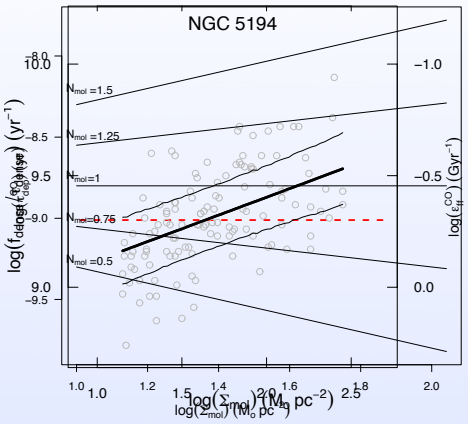
- Extragalactic observations: 2 datasets evidence a mean sub-linear KS relationship, and sub-linear slopes for most galaxies (Shetty + '13,'14a)

- Implications:

  - $\mathbf{T_{dep}}$ = 2 Gyr not representative timescale
  - $\mathbf{T_{dep}}$ increases with CO traced surface density
  - indicative of a diffuse CO component? (Shetty + '14b)

- Detailed observations, including various tracers, along with statistical analyses will further our understanding of star formation in the ISM

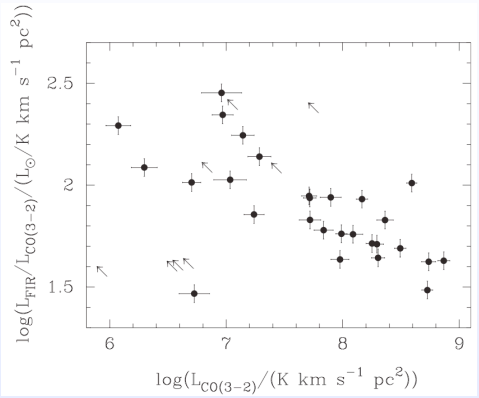
Variable Depletion Times?



- If CO is solely tracing clouds, then clouds have different properties, such as densities or SFRs
- X_{co} varies? X_{co} decreasing with Σ_{mol}. X_{co} - Σ_{mol} relationship must vary between galaxies...
- Presence of diffuse molecular gas, either diffuse (unbound?) clouds, or a pervasive component

Shetty + '14b, In Prep

Evidence for diffuse molecular gas

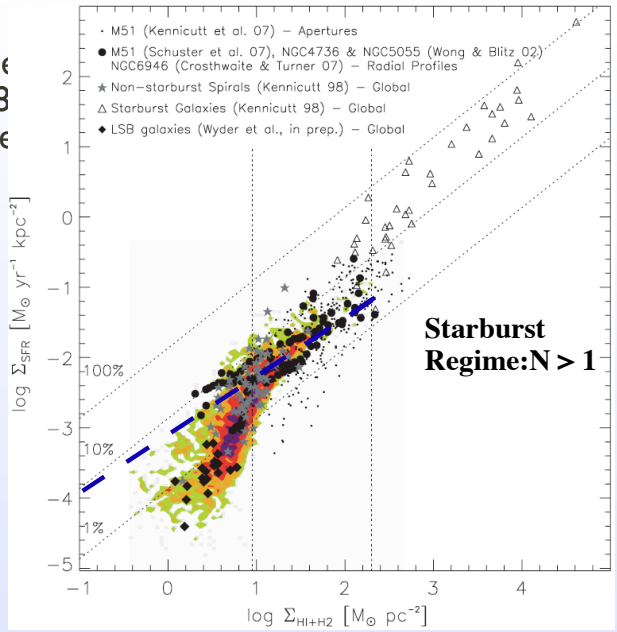


- From CO (J=3-2) NGLS, inverse correlations between SF efficiency and molecular gas density
- Higher $^{12}CO/^{13}CO$ ratio from unresolved extra-galactic observations compared to Galactic GMCs suggestive of diffuse component (Wilson & Walker '94)

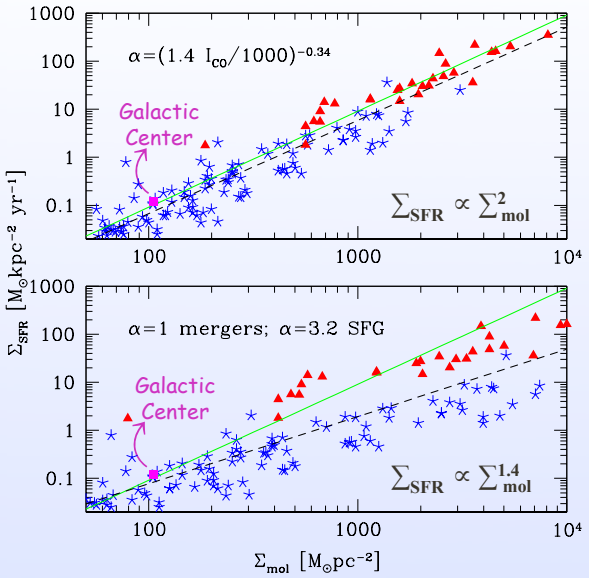
Wilson + '12

Importance of Starburst Galaxies for Global Fits

- Even without hie
  '08 sample [0.88
  relationship (She
- By eye fit...?
- Theory of Star Formation Self-Regulation (Ostriker + '10, Ostriker & Shetty '11 Kim et al. '11, '13, Shetty & Ostriker '12)



Self-Regulation in Observed Systems?



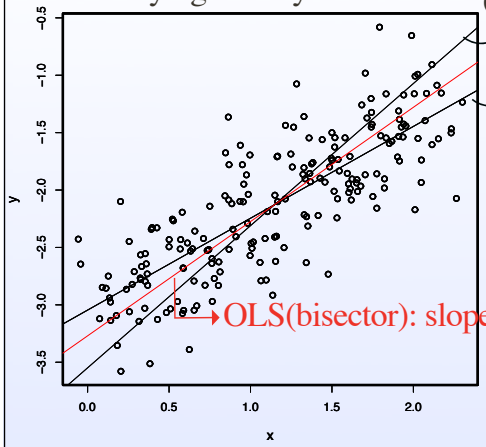
Star forming galaxies and merger systems from Genzel + '10

Galactic Center from Yusef-Zadeh + '09

Continuous X factor? (Shetty + 11a,b, Narayanan + '11,'12)

Testing OLS Methods

Underlying data: y = -3 + 0.75x



OLS(x|y): slope = 1.2 +/- 0.04

OLS(y|x): slope = 0.8 +/- 0.04

OLS(bisector): slope = 1.0 +/- 0.04

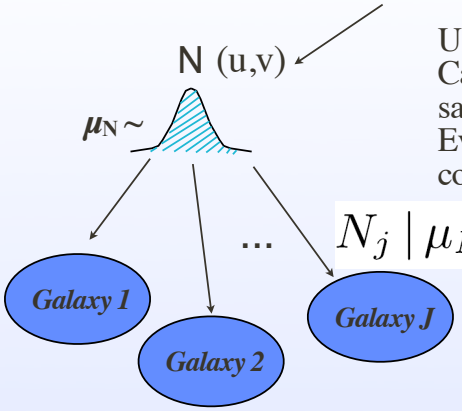
Shetty, Kelly, Bigiel '13

⇒ Bisector does not provide accurate parameter estimates of y = A + Nx

⇒ Bisector usually overestimates slope for N~1

Hierarchical Modeling

Additional level for population parameters



Using Markov Chain Monte Carlo (MCMC) techniques to sample all distributions. Evaluate the likelihood, and construct the posterior PDF.

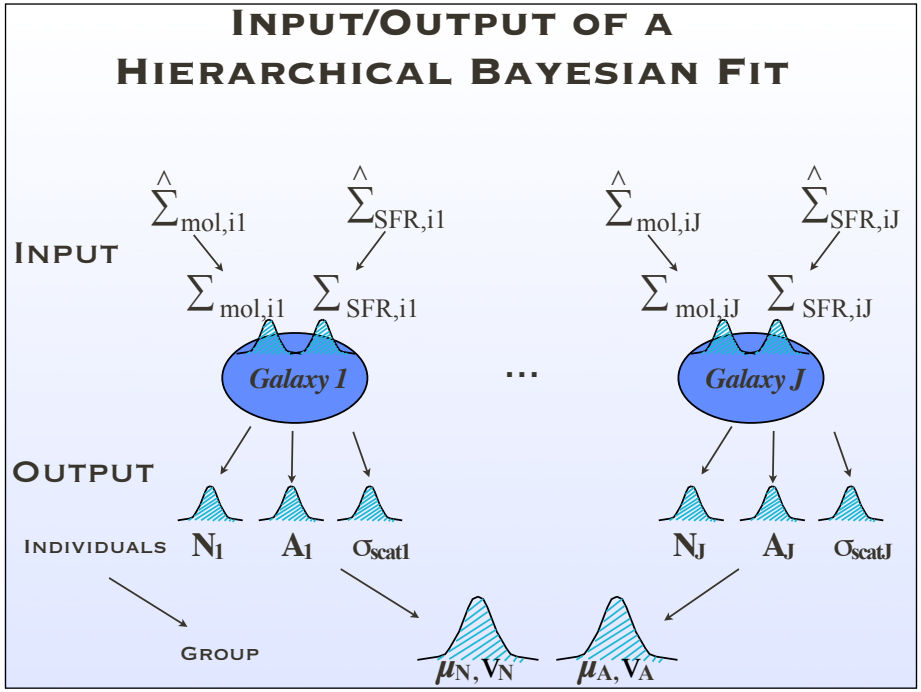
$$N_j \mid \mu_N, v_N \sim \mathcal{N}(\mu_N, v_N)$$

Similarly for A_j, etc...

$$\log \Sigma_{\mathrm{SFR,ij}} | A_j, N_j, \Sigma_{\mathrm{mol,ij}}, \sigma^2_{\mathrm{scat,j}} \sim \mathcal{N}(A_j + N_j \log \Sigma_{\mathrm{mol,ij}}, \sigma^2_{\mathrm{scat,j}})$$

Caveats

- Diffuse emission affecting SFR? (Kennicutt + '07, Liu + '11)
- Conversion factors...?
  - e.g. X factor, old stellar population, IMF...?
  - Correlations b/w parameters (Shetty, Kelly, Bigiel '13)?
- slope and scatter depend on scale
  - Schruba + '11, Kruijssen & Longmore '13
- Single dish for STING (checked NGC 4254 in Shetty + '13b)


INPUT/OUTPUT OF A
HIERARCHICAL BAYESIAN FIT
INPUT
OUTPUT
INDIVIDUALS
GROUP
Galaxy 1
Galaxy J
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