銀河における星形成則

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Outline

1. Introduction
    - Star formation in galaxies
    - Relation between SFR and gas density

2. Star formation law in GMC scale
3. Dependence on surface density of gas
    - High density regime
    - Low density regime
4. Dependence on volume density of gas

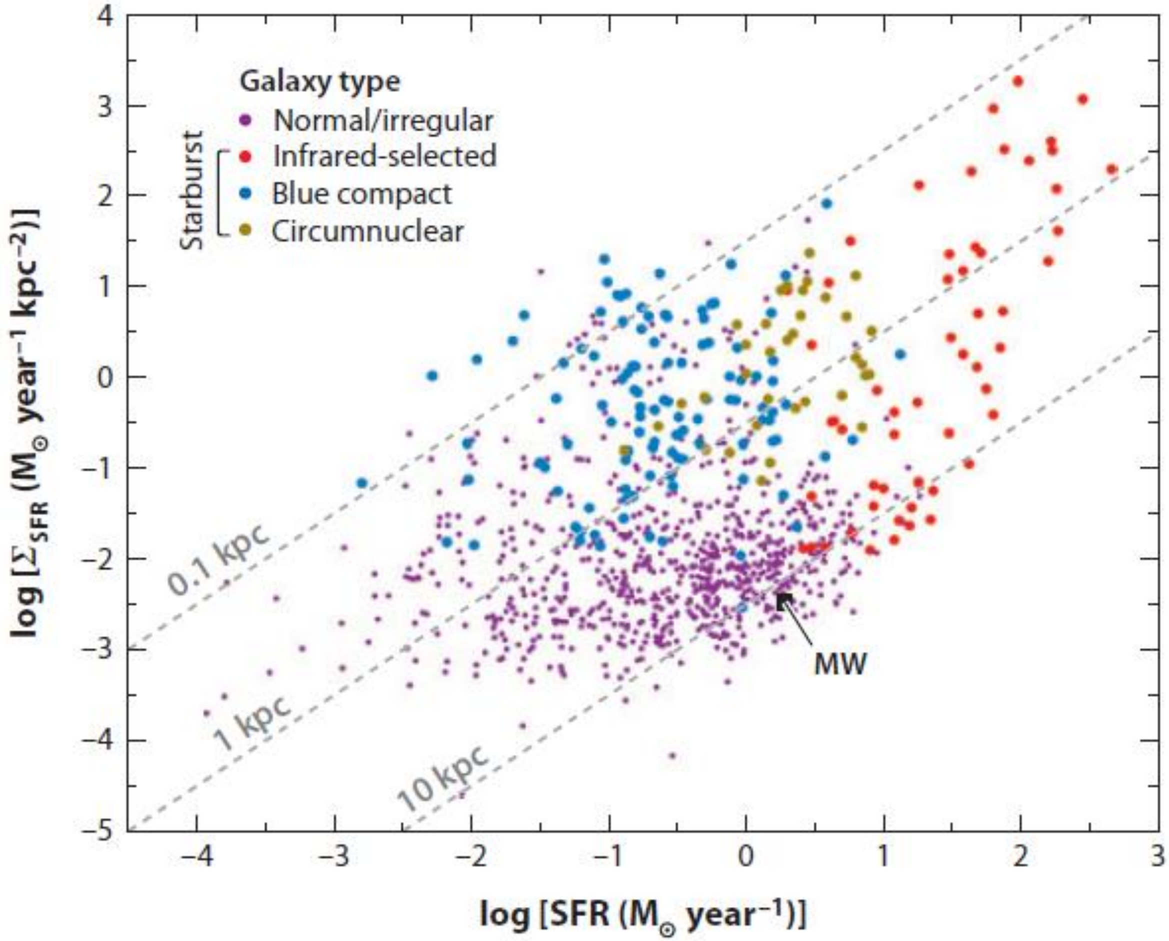
1. Introduction

Star formation in galaxies

- Normal galaxies
  - $\mathrm{SFR} < 20 M_{\odot} \mathrm{yr}^{-1}$
  - $\Sigma_{SFR} = \text{const.}$

- Starburst galaxies
  - SFR, Σ_{SFR}:

  10^2-10^3 times higher than normal galaxies

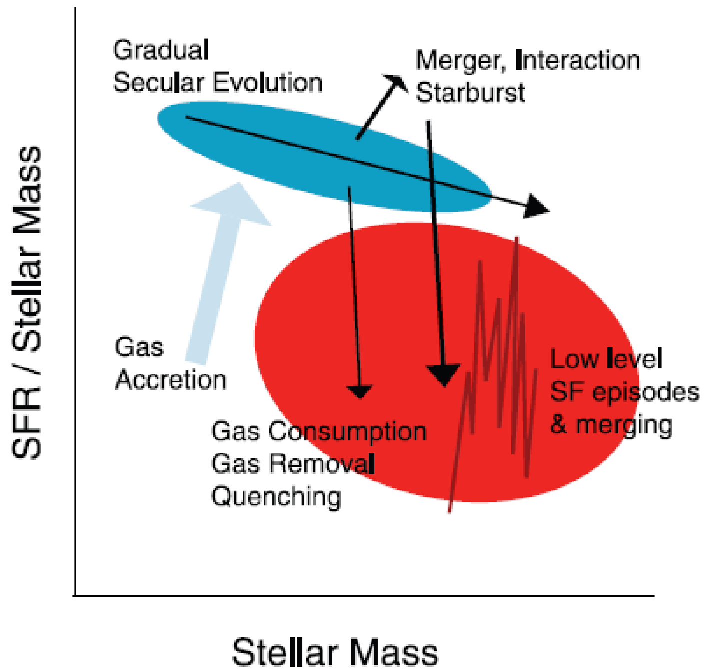


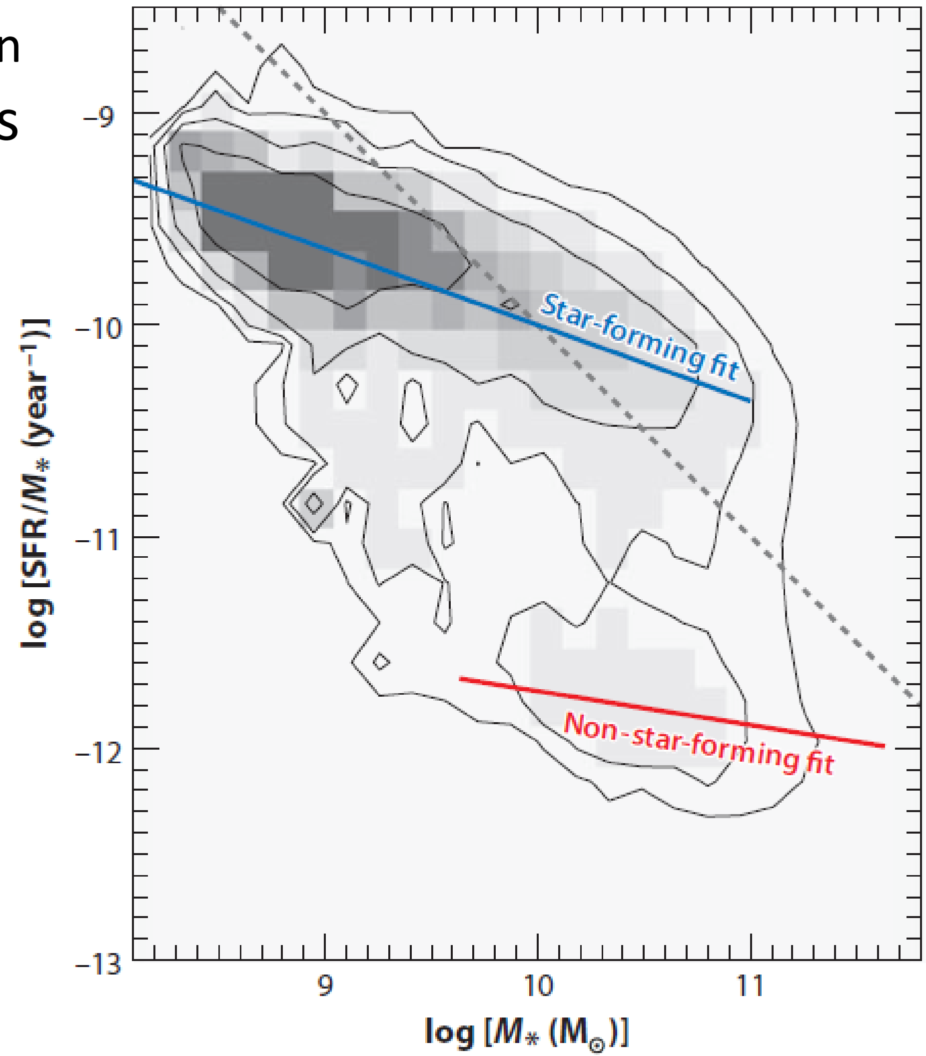
Kennicutt & Evans (2012)

Stellar mass vs. specific Star Formation Rate (SFR/M_*)

- Bimodality
  - Blue sequence： star formation
  - Red sequence： non star formation
- sSFR decreases with stellar mass
  - Difference in quantity（SFR）？
    quality（SFE）？

How do galaxies evolve from blue to red?



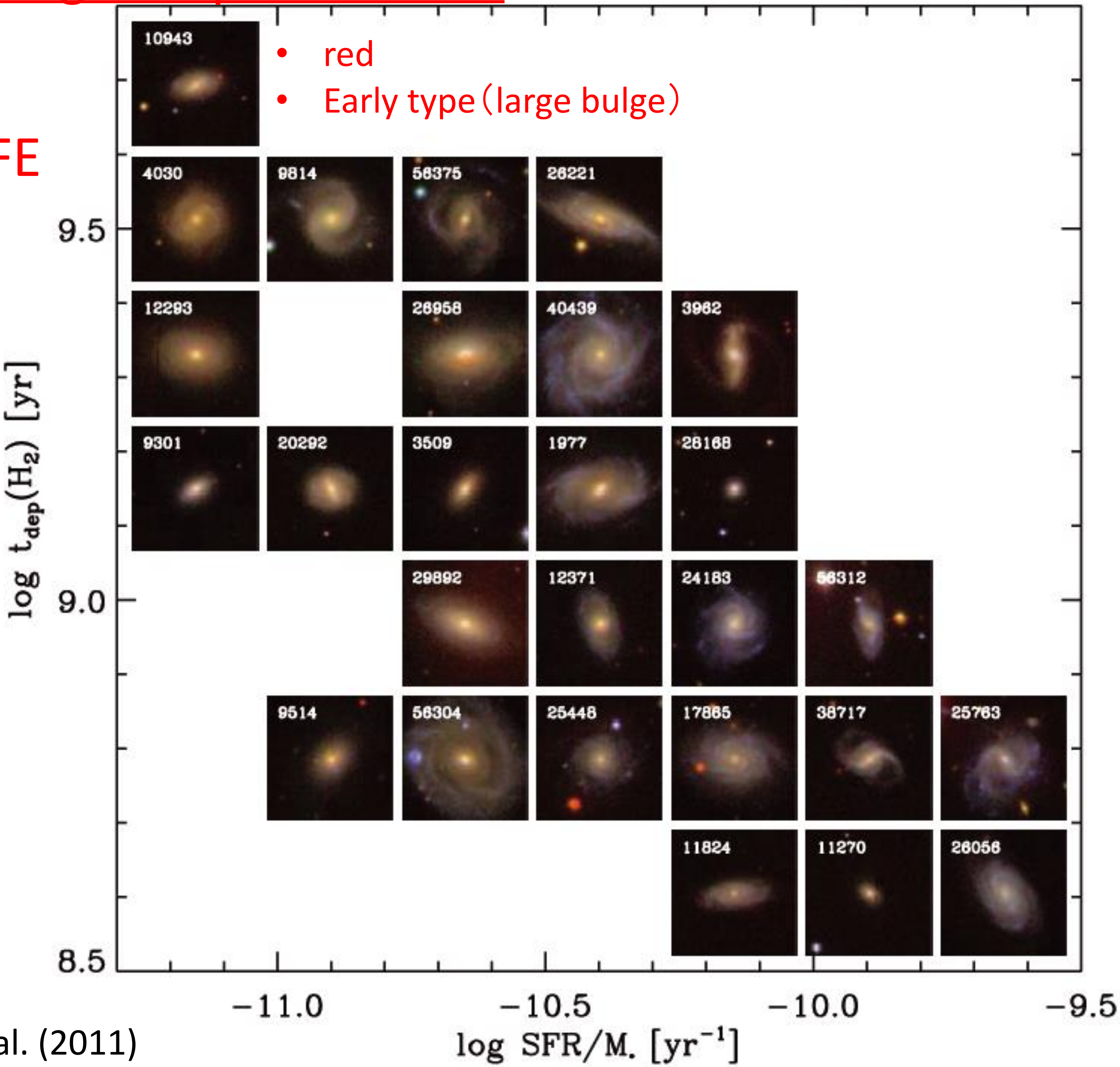


Schimoinovich et al. (2007)

sSFR vs. gas depletion time

Low SFE

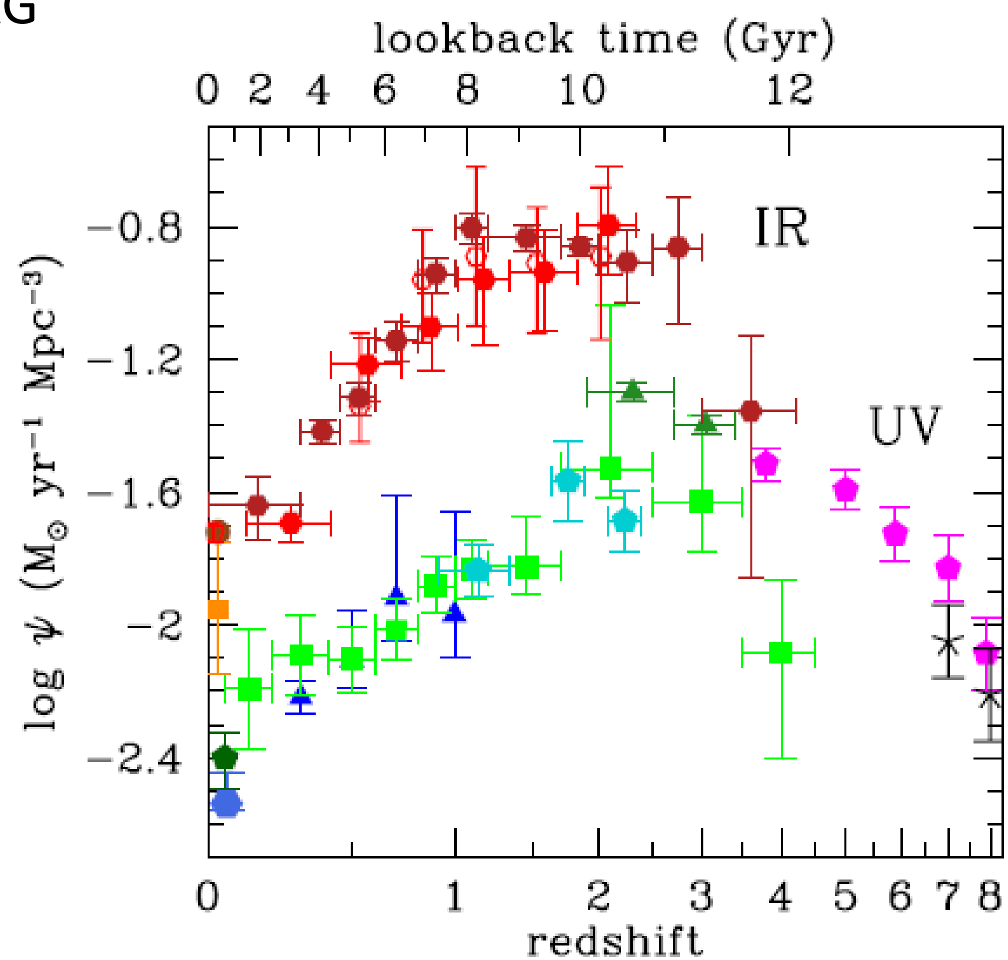
$$t_{\mathrm{dep}}(\mathrm{H_2}) = \frac{M(\mathrm{H_2})}{\mathrm{SFR}}$$



COLD GASS
Saintonge et al. (2011)

Cosmic star formation history

- SFR density ($M_{\odot}\mathrm{yr}^{-1}\mathrm{Mpc}^{-3}$)
  - Peak at z=1-3
  - (U)LIRG



Madau&Dickinson(2014)

Relation between SFR and gas density

Schmidt law： SFR vs. gas volume density

$\rho_{\mathrm{SF}} \propto \rho_{gas}{}^{N}$ $N \approx 2$（Schmidt 1959）

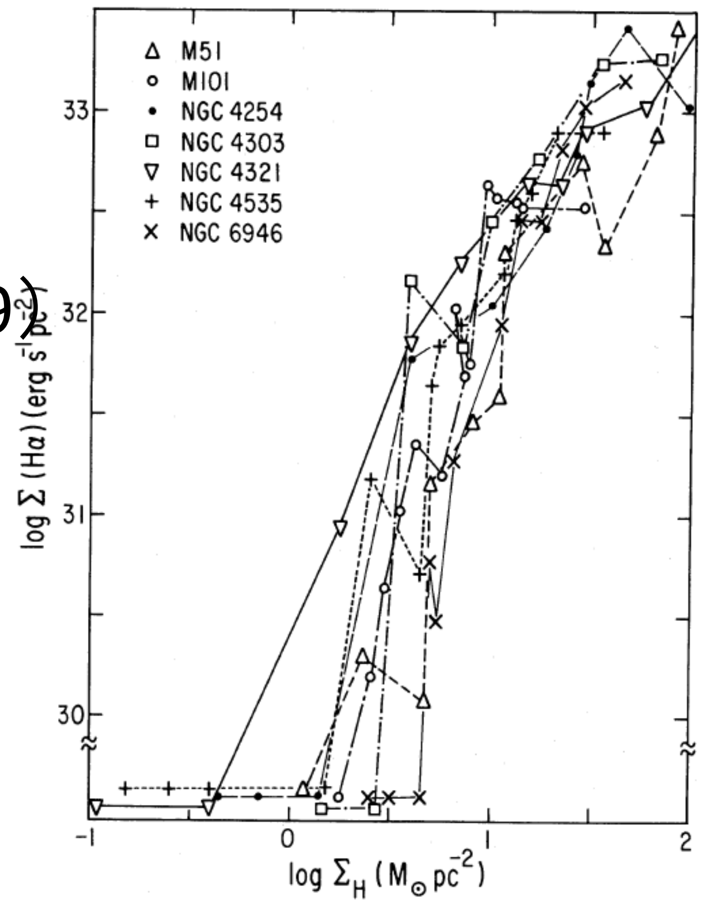
⬇

Kennicutt-Schmidt law：

Gas surface density（Kennicutt 1989）

$\Sigma_{\mathrm{SFR}} \propto \Sigma_{\mathrm{gas}}^{N}$ $N = 1.3 \pm 0.3$

- Critical surface density for star formation



Kennicutt (1989)

- Relation between properties of galaxies and star formation
  - Global
  - Radial distribution (sub-kpc scale)

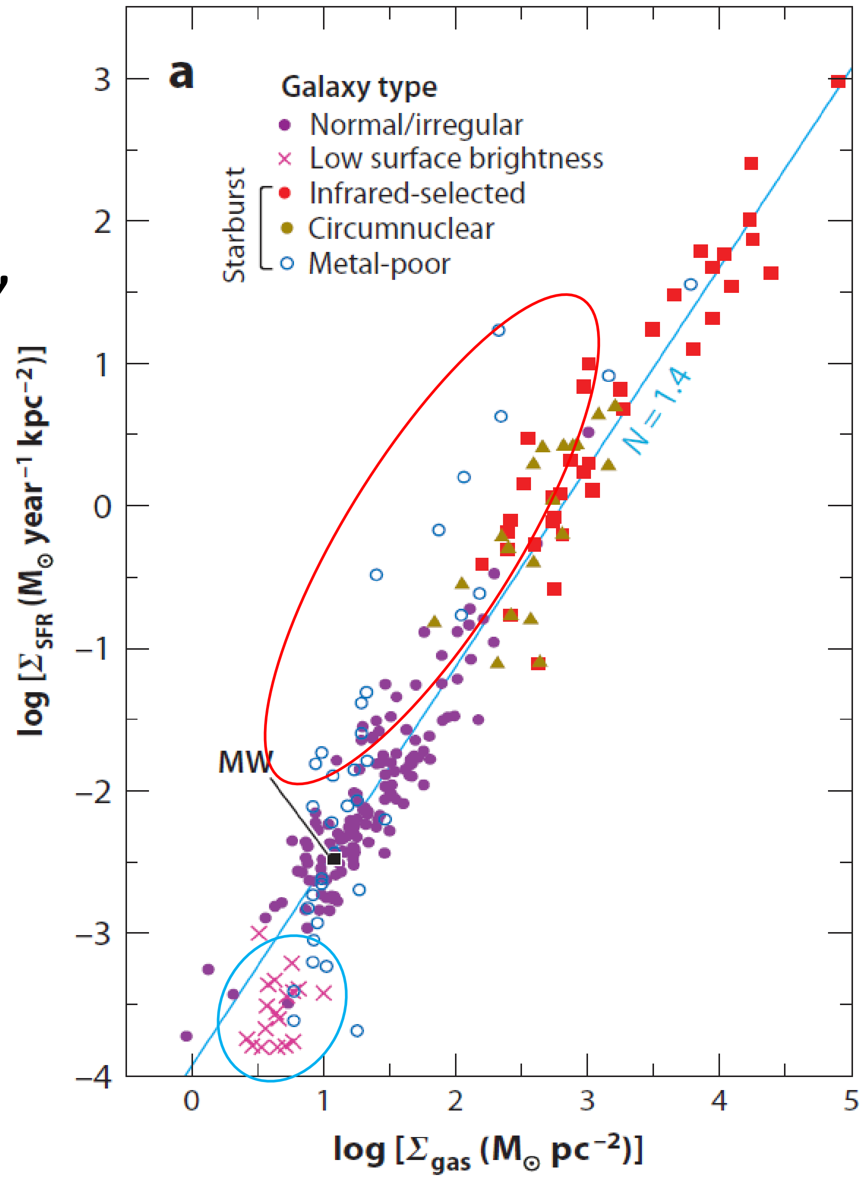
K-S law in global scale

- $\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^{N}$ $N \simeq 1.4 - 1.5$

($I_{\rm CO}$ -> $N(\rm H_2)$ conversion factor, $X_{\rm CO} = \rm const.$)

- Large offset of low metallicity galaxies ($Z < 0.3Z_{\odot}$)
  - Difference in $X_{\rm CO}$?

- Low-Surface-Brightness galaxies: Low SFR



(Kennicutt and Evans 2012)

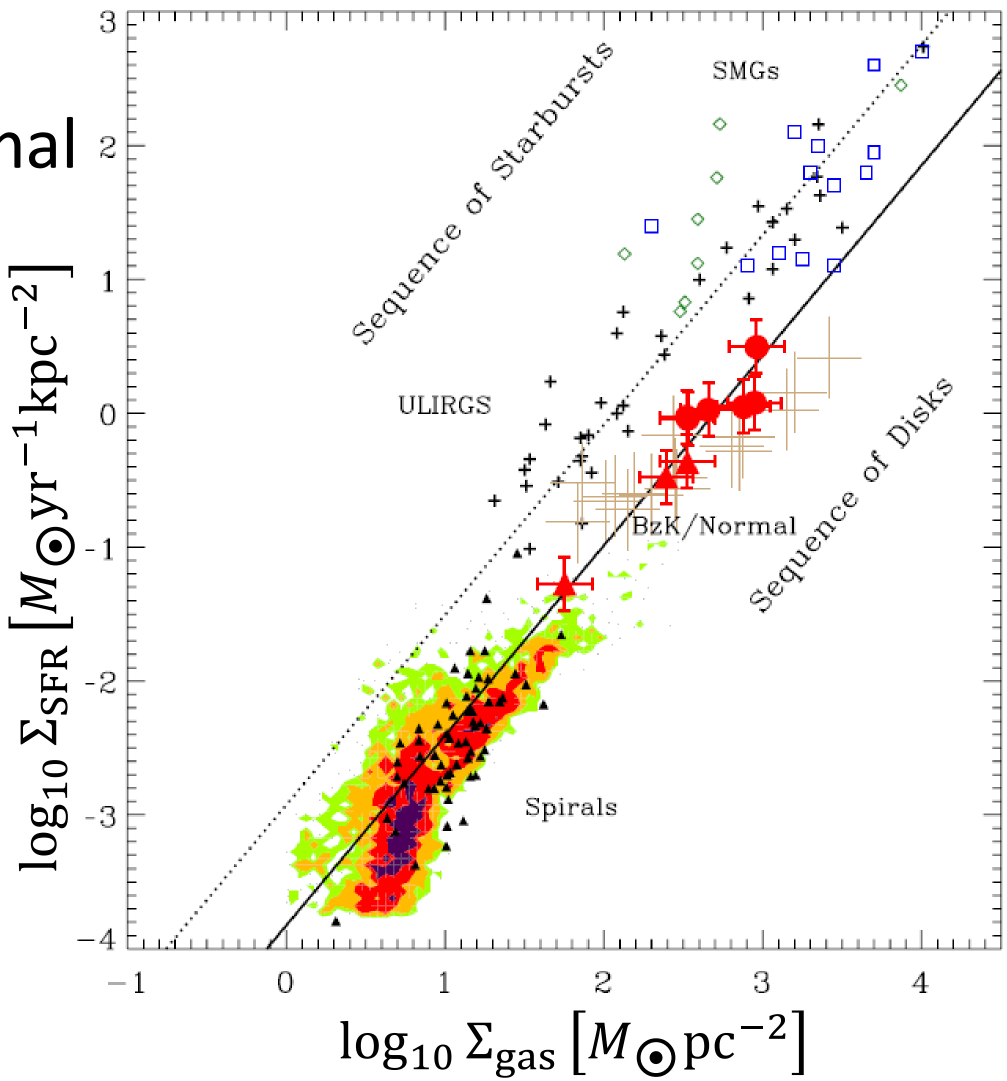
K-S law with distant galaxies ($z \geq 2$)

- Bimodal: Starburst vs. Normal

Note: not single $\alpha_{\rm CO}$

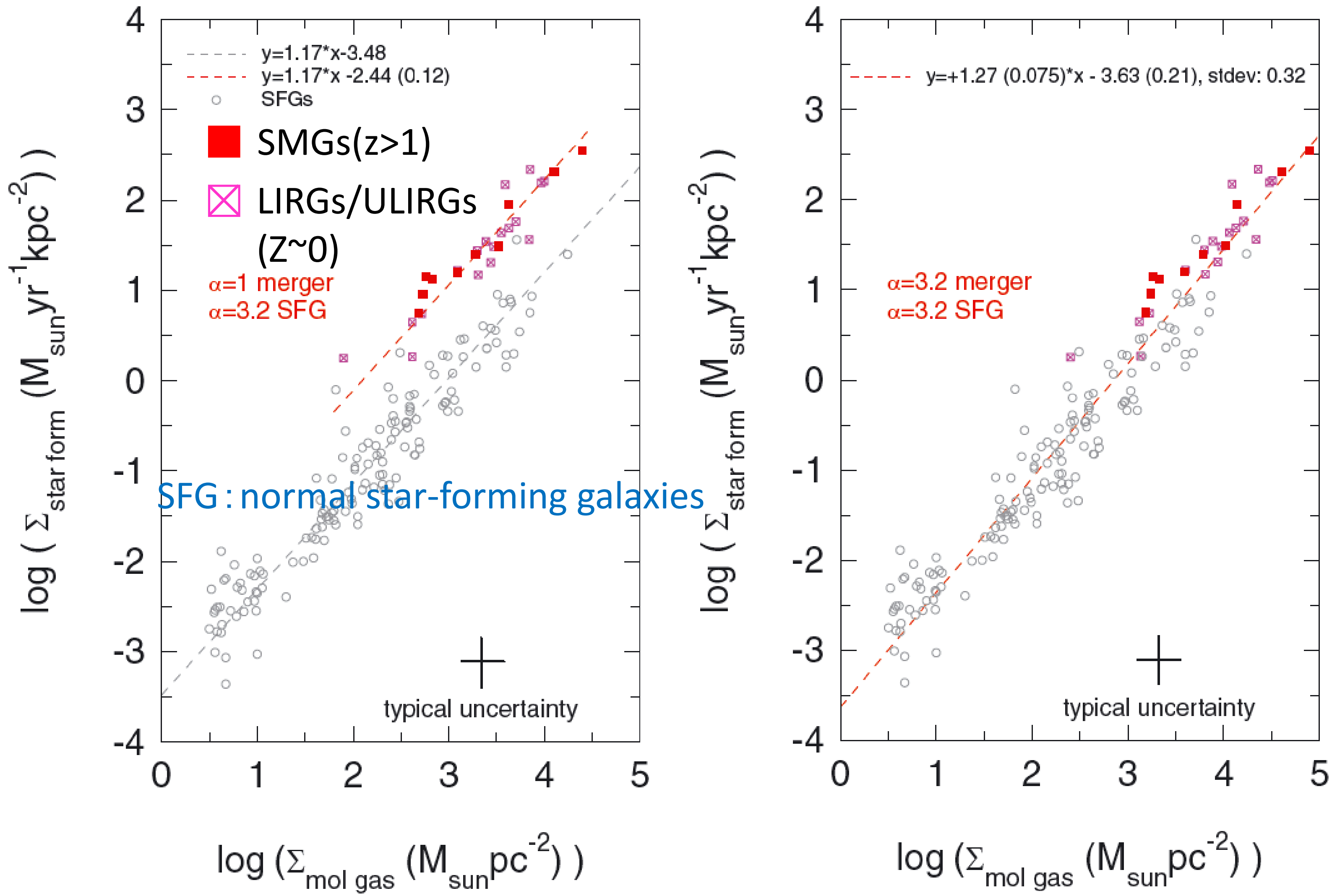
$L'_{\rm CO}$ -> $\Sigma(H_2)$

- normal@$z = 0.5 - 1.5$: $\alpha_{\rm CO}$=3.6
- Local spirals : $\alpha_{\rm CO}$=4.6
- ULIRGs, SMG/QSO : $\alpha_{\rm CO}$=0.8



Daddi et al. (2010)

- Dependence on α_{CO}
  - single $\alpha_{\mathrm{CO}} \Rightarrow$ unimodal

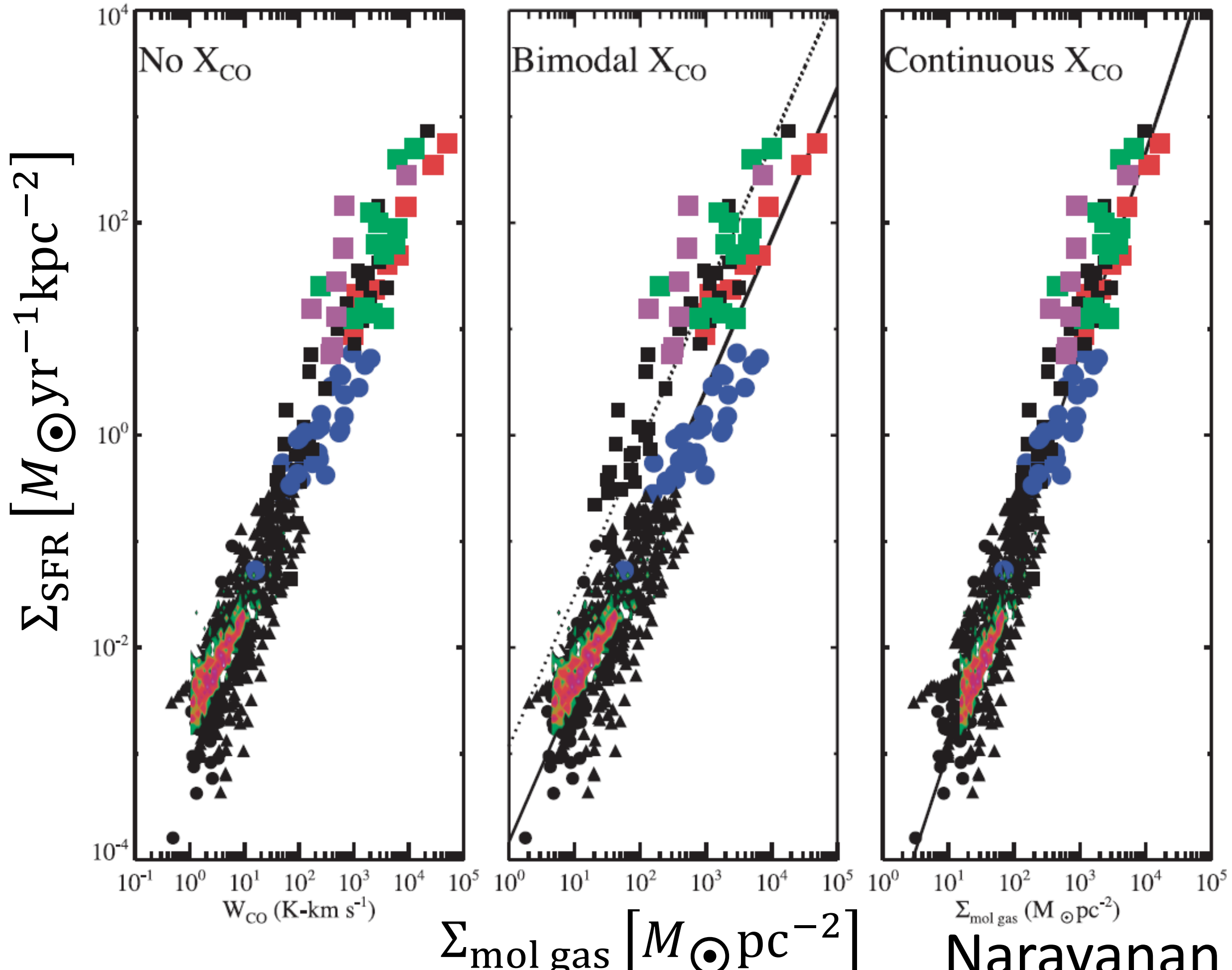


Genzel et al. (2010)

- α_{CO} depends on metallicity and CO intensity

$$X_{CO} = \frac{\min[4, 6.75 \times \langle W_{CO} \rangle^{-0.32}] \times 10^{20}}{Z'^{0.65}}$$ (Narayanan et al. 2012)

Bimodal ⇒ Unimodal with steeper slope



Narayanan et al. (2012)

Schmidt law by dense gas tracer

- Dense gas ⇒ star formation

  Critical density for excitation

  CO(1-0) 3×10^3 cm^{-3} @100K

  HCN(1-0) 4×10^6 cm^{-3} @30K

- SFR is proportional to dense gas mass

  $$L_{\mathrm{IR}} \propto L_{\mathrm{HCN}}^{1.00\pm0.05}$$

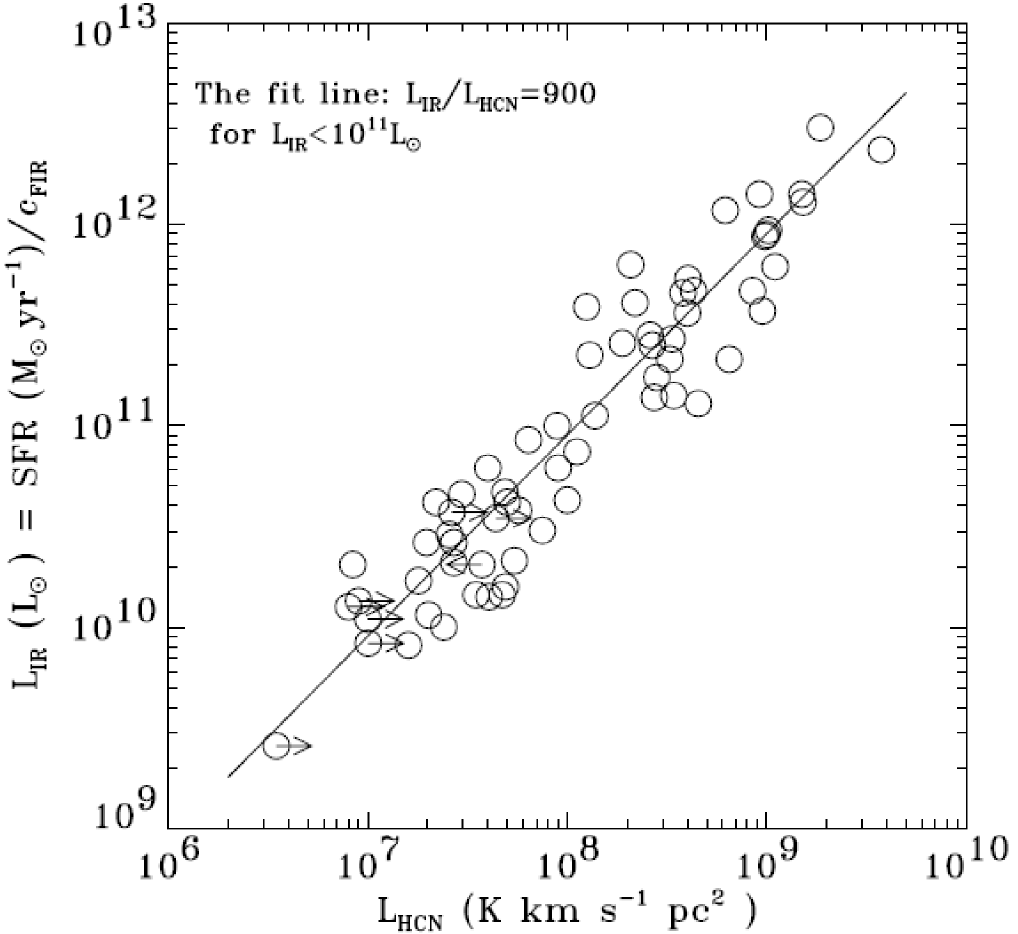
- If dense gas fraction increases with surface density of molecular gas

  ↓

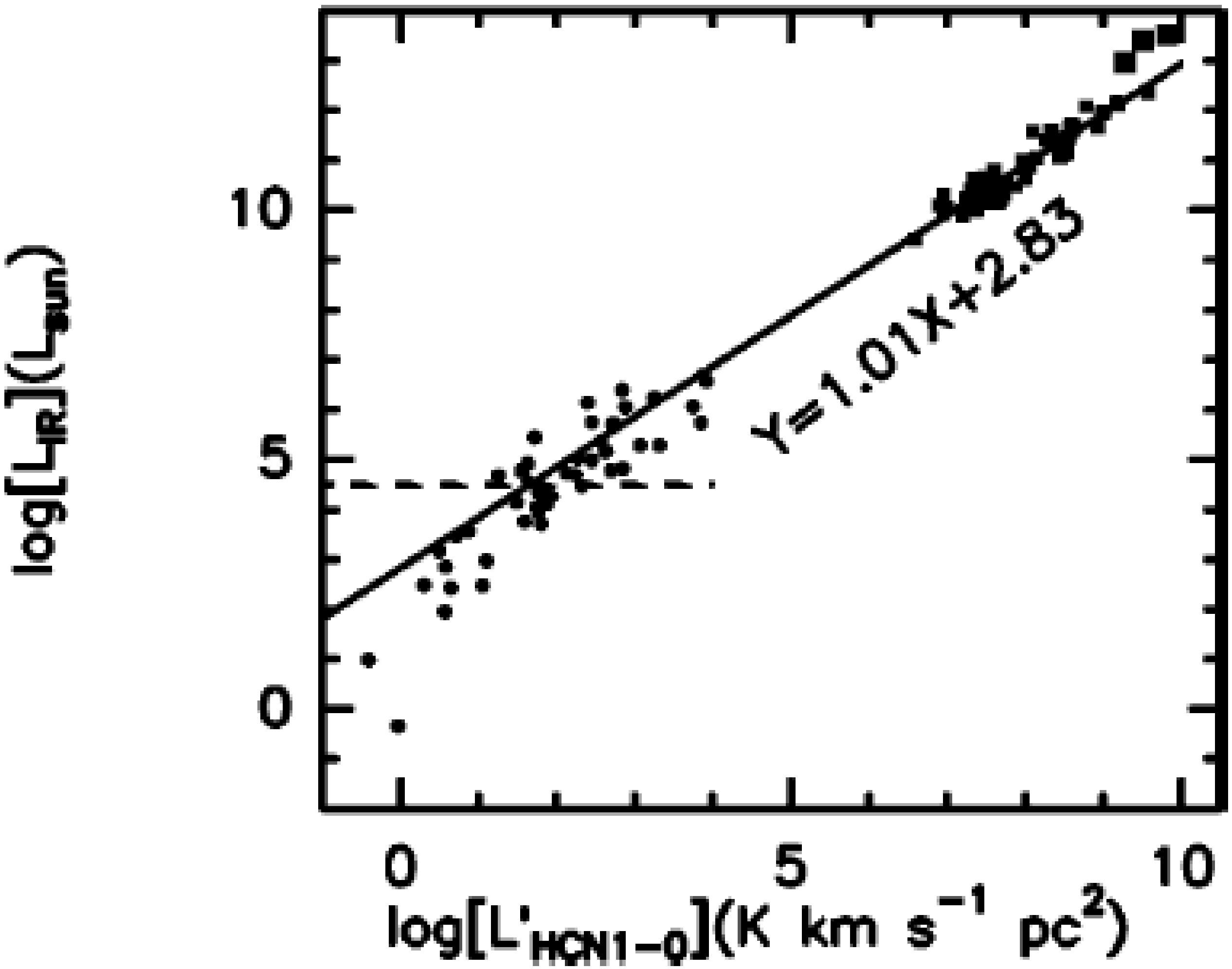
  higher SFE at higher $\Sigma_{\mathrm{H_2}}$

  ↓

  $\Sigma_{\mathrm{SFR}} \propto \Sigma_{\mathrm{H_2}}^{1.4}$ (non-linear for CO)



Gao & Solomon (2004)



Wu et al. (2005)

- Molecular cloud core to QSOs（order of ten!）

  Same relation（$L_{\mathrm{IR}} \propto L_{\mathrm{HCN}}$）?

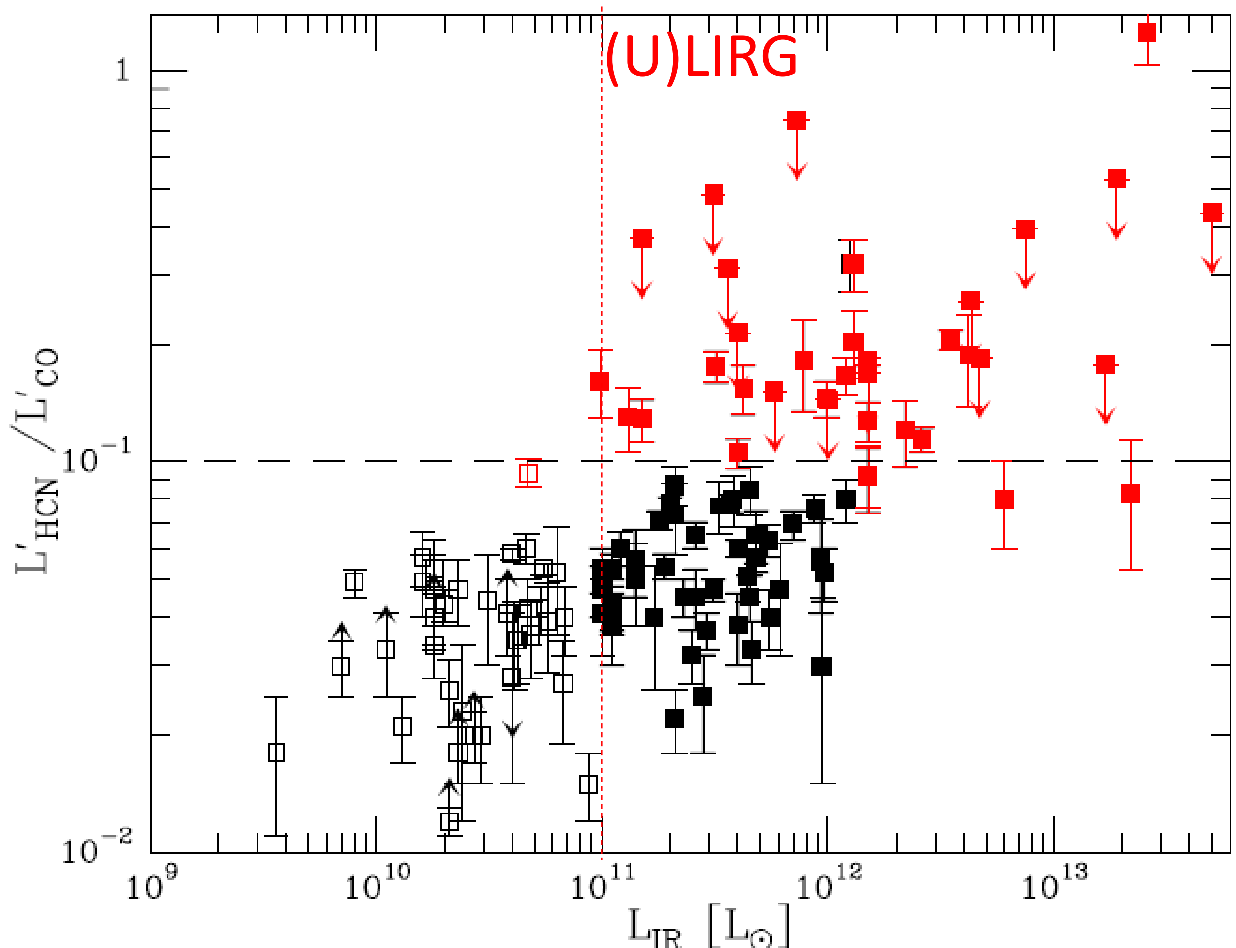
  ⇒ Star formation occurs beyond a certain critical density?

Higher HCN/CO in (U)LIRG

e.g., for normal conversion factor, $M_{\mathrm{dense}} > M_{\mathrm{gas}}$ in Arp220!

- HCN abundance?
- Excitation by IR radiation?

⇒ Small HCN-Σ_{dense} conversion factor



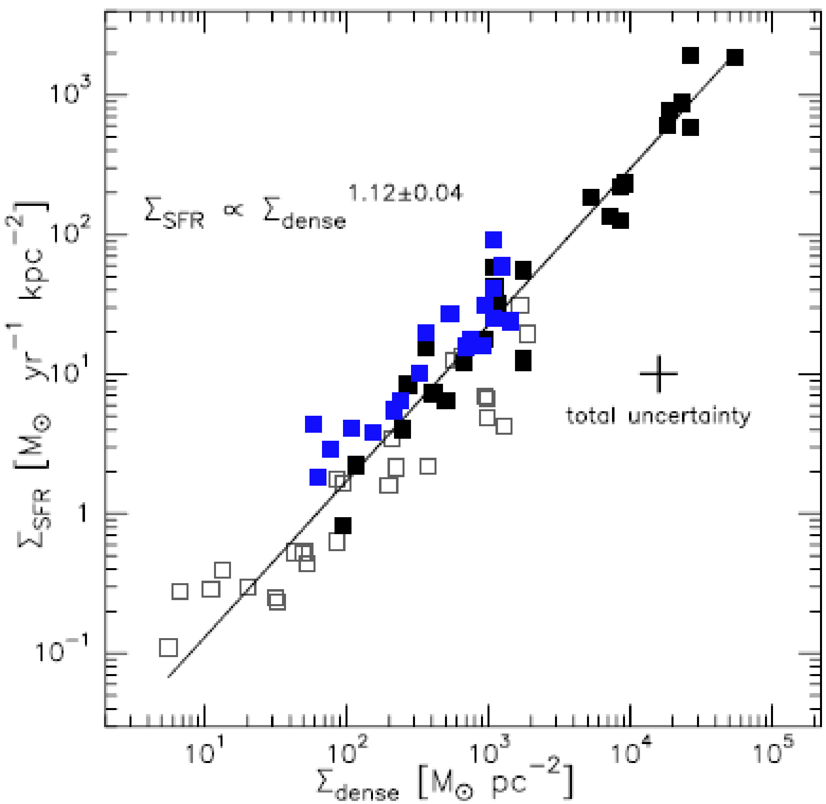
Garcia-Burillo et al. (2012)

Difference of HCN-Σ_{dense} conversion factor (α_{HCN}) between normal galaxies and ULIRG

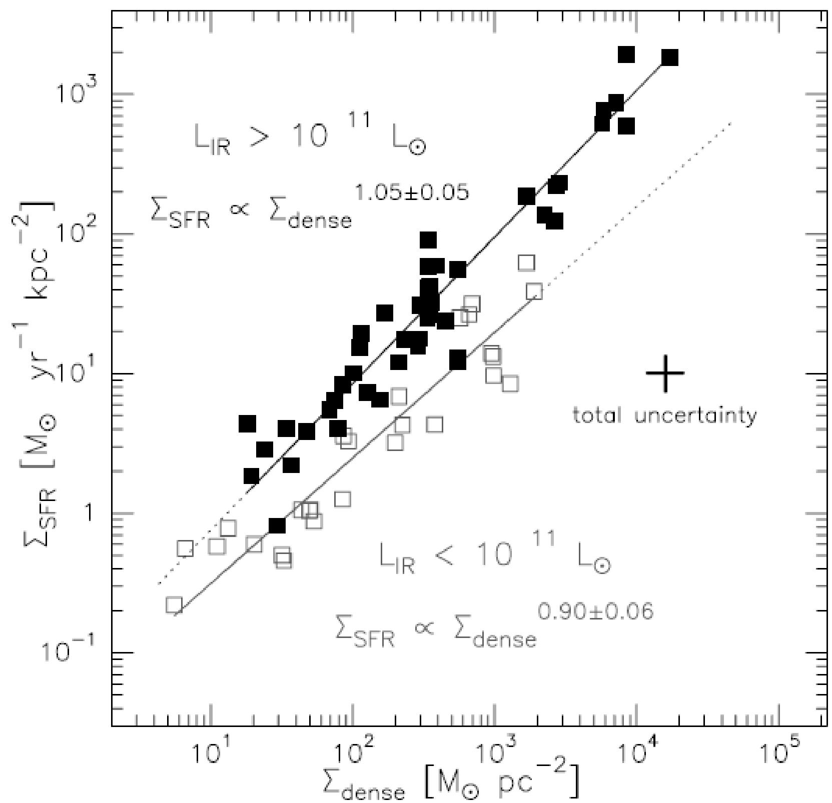
⇒ N>1 for all

⇒ Bimodality in K-S law by dense gas tracer?

Single α_{HCN}



1/3.2 for ULIRG (Same as CO)



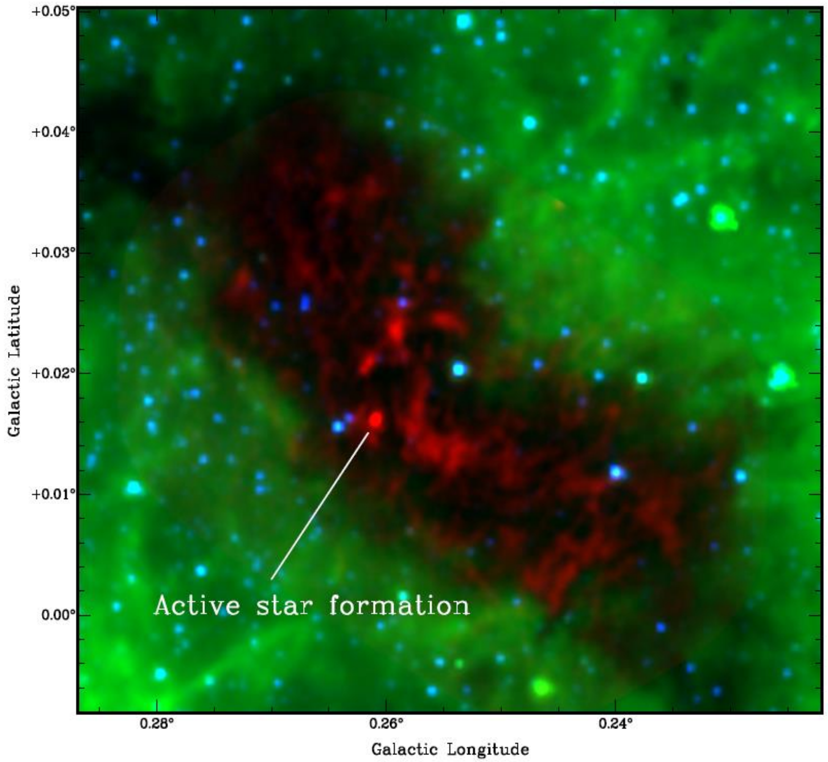
Garcia-Burillo et al. (2012)

Low $\mathrm{SFR}/M_{\mathrm{dense}}$ near the Galactic center

- Central Molecular Zone (CMZ) (R < 200 pc)
  - Low $\Sigma_{\mathrm{SFR}}/\Sigma_{\mathrm{dense}}$ （Rathborne et al. 2014）
  - G0.253+0.016： Star formation in a specific core ($> 10^6 \mathrm{cm}^{-3}$)

  ⇒High critical density for star formation?

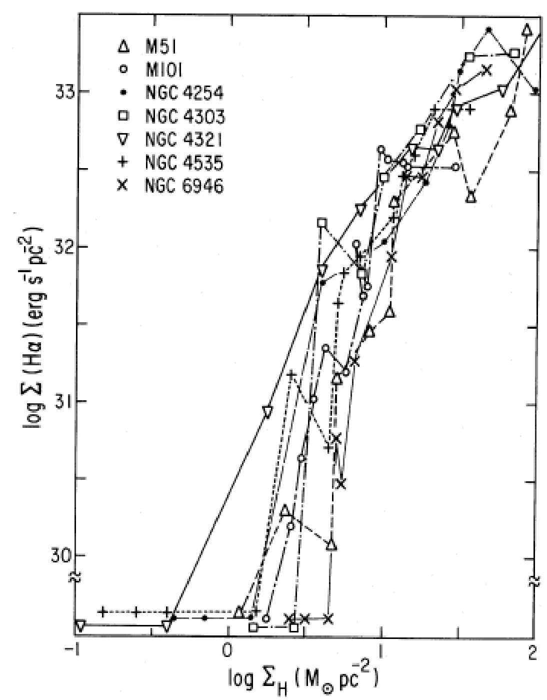
⇒Not simply $\mathrm{SFR} \propto M_{\mathrm{dense}}$?



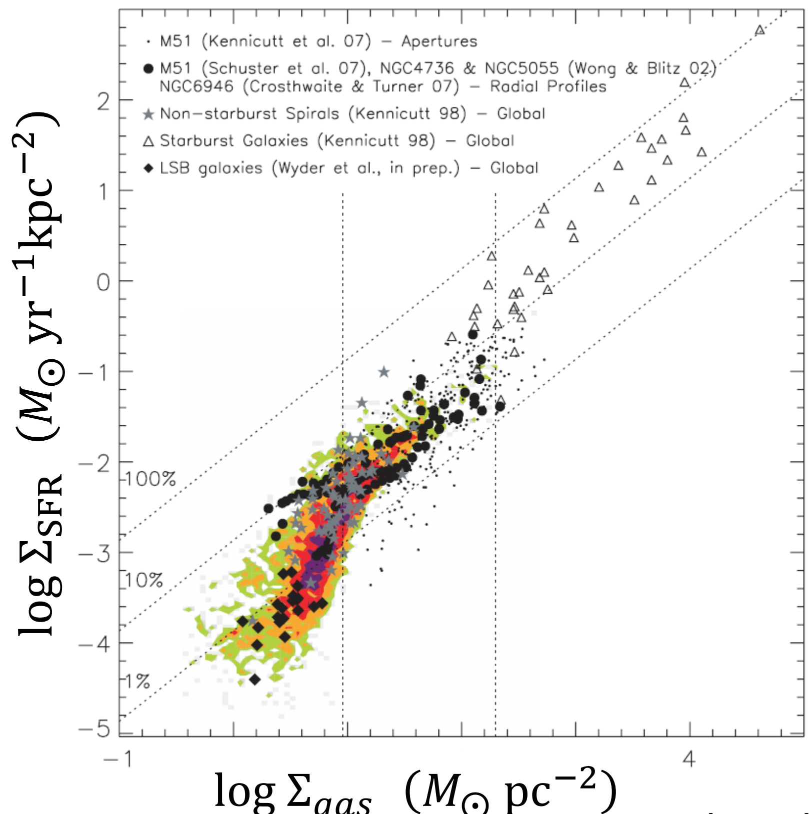
G0.253+0.016
Blue: 3.6μm
Green: 8.0μm
Red: 3mm
ALMA
Rathborne et al. (2014)

K-S law in sub-kpc scale

- Spatially resolved K-S law
  - and average of small-scale variation
- N=1.4-3.1(total gas), 1.0-1.4(molecular gas)
- Critical density for star formation ~a few $M_{\odot}\ \mathrm{pc}^{-2}$



Kennicutt (1989)



Bigiel et al. (2008)

Time scale of star formation

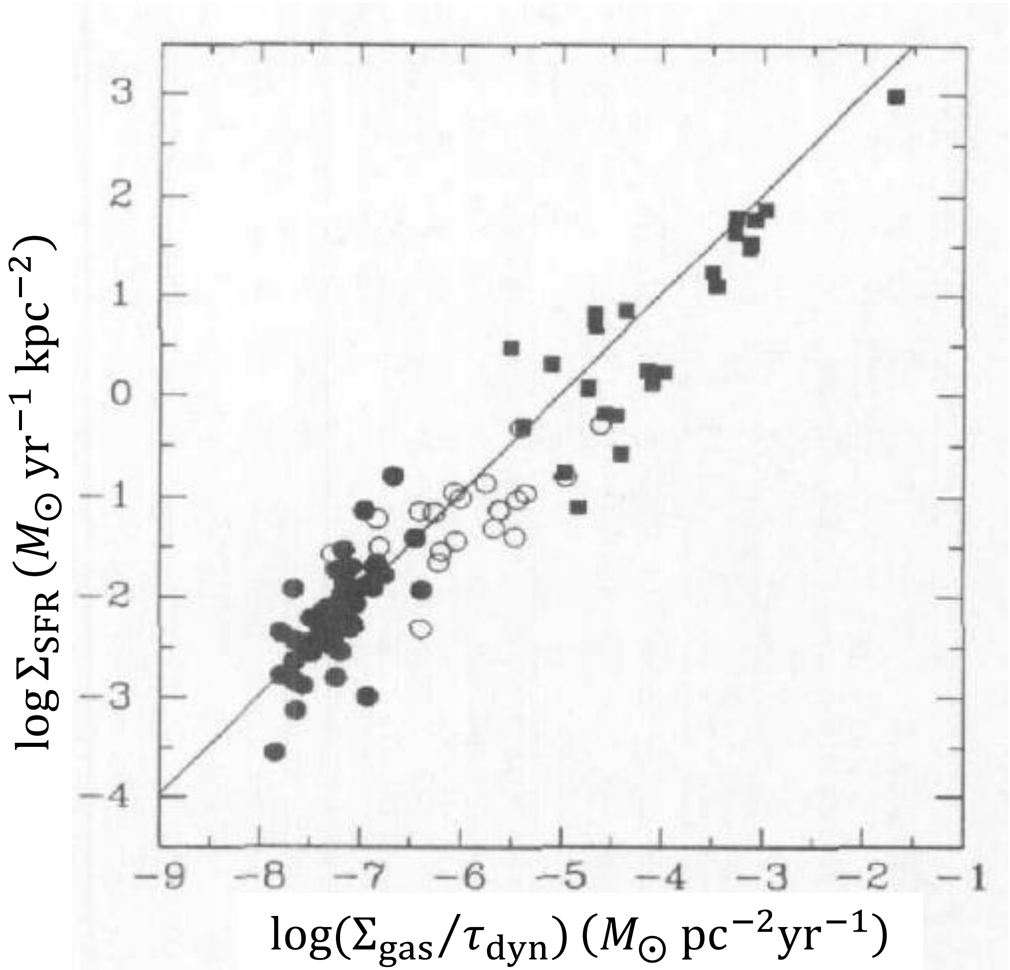
- Dynamical time $\tau_{\rm dyn}$:

One disk orbit time at half of the radius of the star-forming disk

$\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}/\tau_{\rm dyn}$

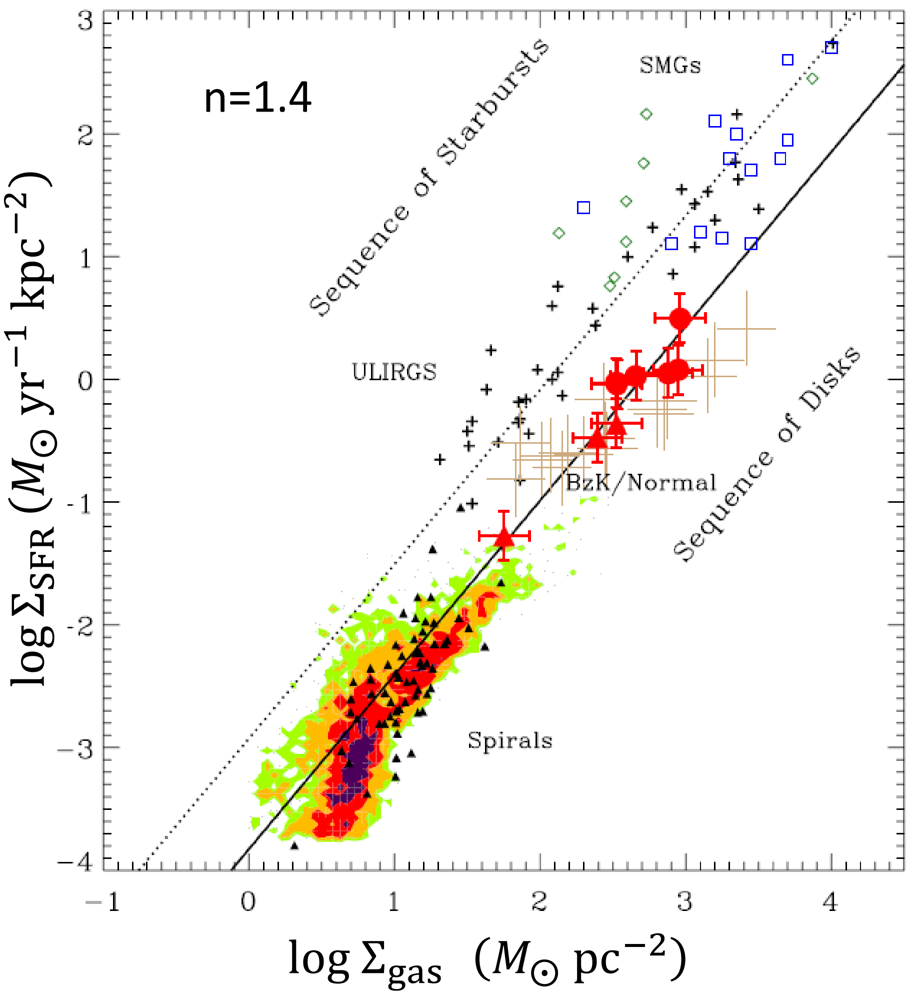
- A constant fraction of gas form stars per orbit

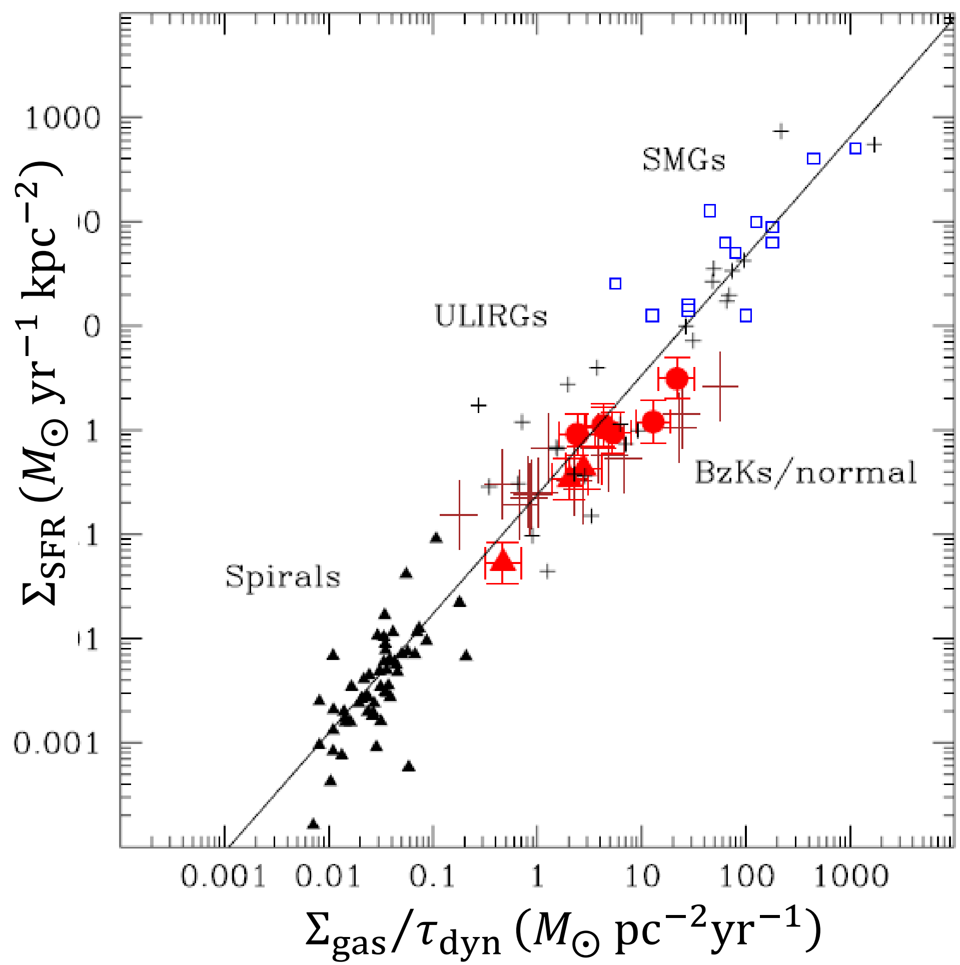
e.g., trigger by spiral arms?



Kennicutt (1998)

- $\Sigma_{\rm gas}/\tau_{\rm dyn}$: ULIRG/SMGs bimodal ⇒ unimodal
  - Galactic dynamics determine the relation? (Why?)





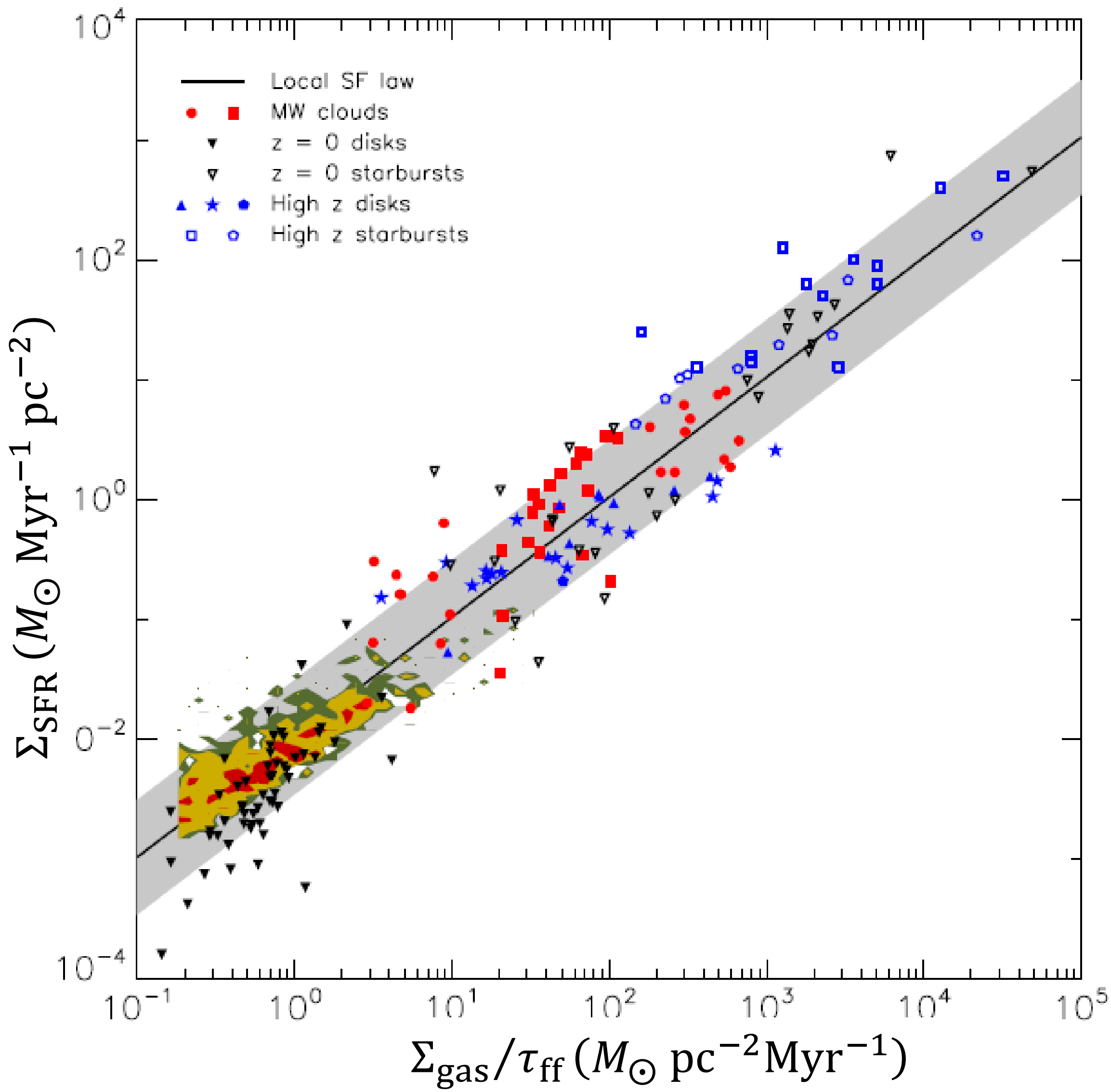
Daddi et al. (2010)

- Free fall time

$$\tau_{\mathrm{ff}} = \sqrt{\frac{3\pi}{32G\rho}}$$

$$\Sigma_{\mathrm{SFR}} \propto \Sigma_{\mathrm{gas}}/\tau_{\mathrm{ff}}$$

- SFR depends on the properties of molecular clouds?



Krumholz et al. (2012)

Physical interpretation of K-S law (1)

$$\rho_{\mathrm{SF}} \propto \frac{\rho_{\mathrm{gas}}}{\tau_{\mathrm{ff}}} \propto \frac{\rho_{\mathrm{gas}}}{\left(1/\sqrt{G\rho_{\mathrm{gas}}}\right)} \propto \rho_{\mathrm{gas}}^{1.5}$$

- If scale height of the galactic disk is constant

$$\Sigma_{\mathrm{SF}} \propto \Sigma_{\mathrm{gas}}^{1.5}$$

（But, we observe ensemble of molecular clouds.
In that case, $\Sigma_{\mathrm{SF}} \propto \Sigma_{\mathrm{gas}}$?）

Critical density for star formation

- Toomre criterion (Toomre 1964)
  - Critical density for gravitational instability in thin isothermal gas disk

$$\Sigma_c = \alpha \frac{\kappa\sigma}{3.36G}$$

σ: velocity dispersion, κ: epicyclic frequency

$$\kappa^2 = \left(R\frac{d\Omega^2}{dR} + 4\Omega^2\right)_{R_g}$$

R: radius, Ω: angular velocity

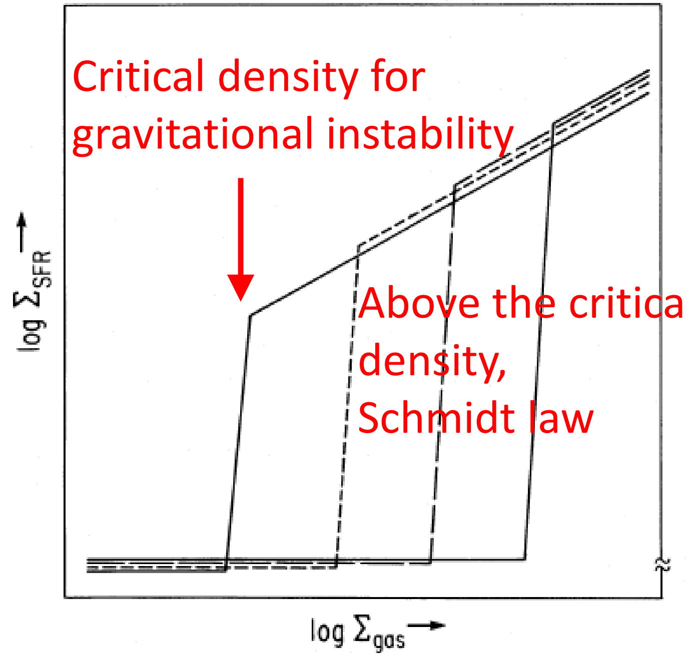
- Toomre Q parameter

$$\frac{\Sigma_c}{\Sigma} = Q = \alpha \frac{\kappa\sigma}{3.36G\Sigma}$$

$Q > 1$: stable $\qquad$ $Q < 1$: unstable

$\Sigma > \Sigma_c \Rightarrow$ star formation

by gravitational instability?



Physical interpretation of K-S law (2)

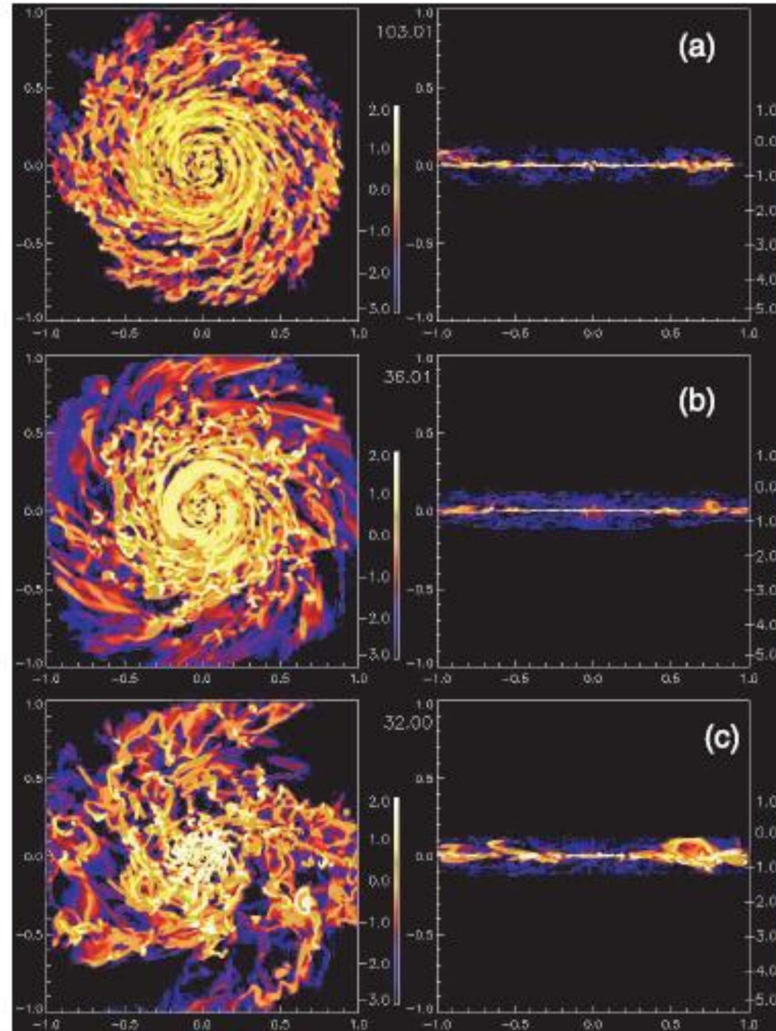
- Three-dimensional hydrodynamic simulations

⇒ Probability distribution function (PDF) of gas density

Star formation law

⇒ Relation between PDF of gas density and SFR

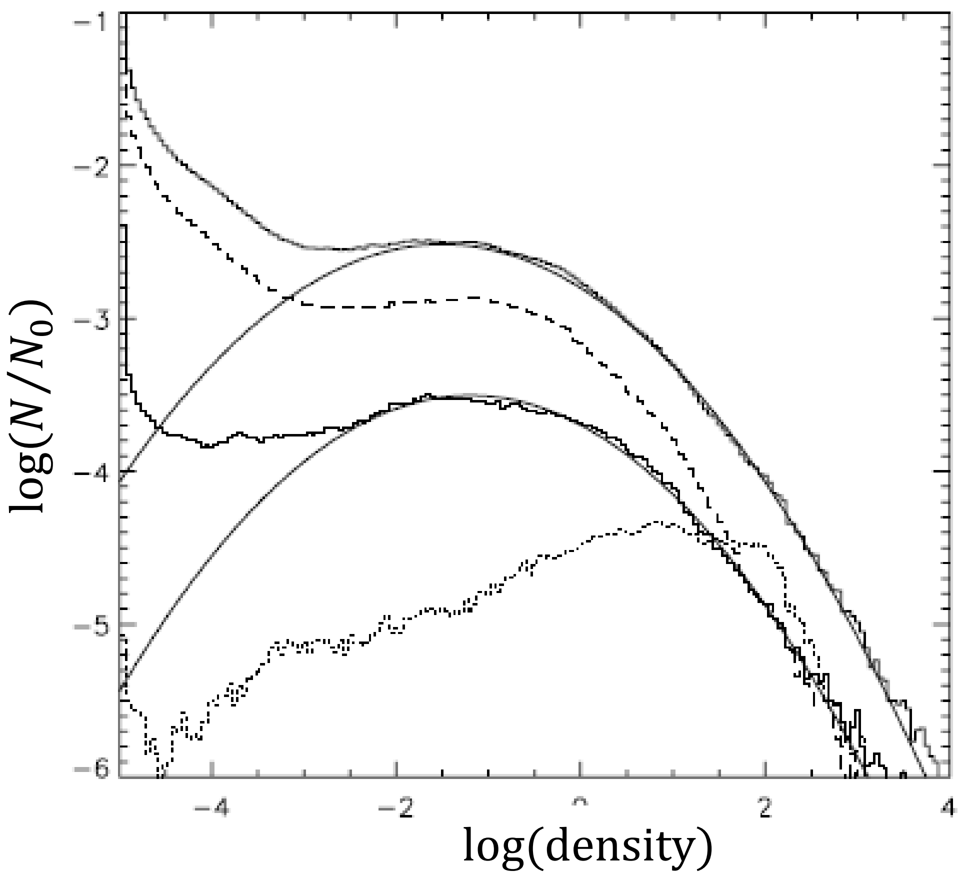
(Critical density, efficiency)



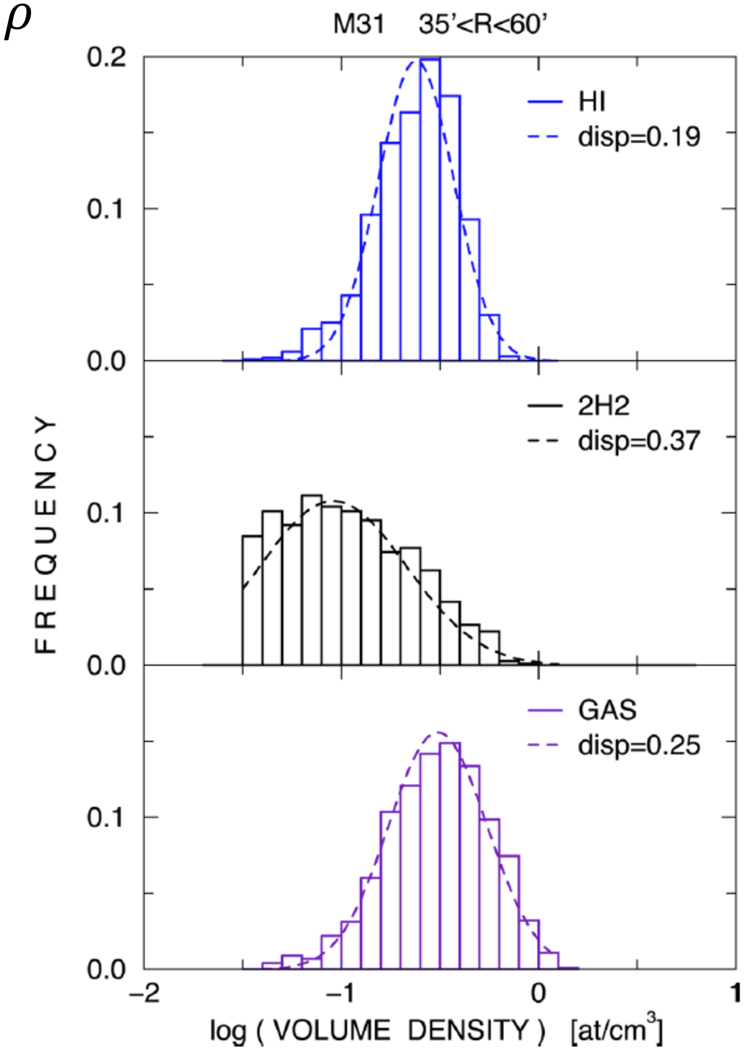
Wada & Norman (2007)

- If non-linear random processes determine density distribution
  ⇒ log-normal distribution（対数正規分布）

$$f(\rho)d\rho = \frac{1}{\sqrt{2\pi}\sigma} exp\left[-\frac{\ln(\rho/\rho_0)^2}{2\sigma^2}\right] d\ln\rho$$



Numerical simulation
(Wada and Norman 2007)



PDF of gas density in M31
(Berkhuijsen & Fletcher 2015)

- If stars are formed from dense gas above ρ_c with an efficiency ε_c,

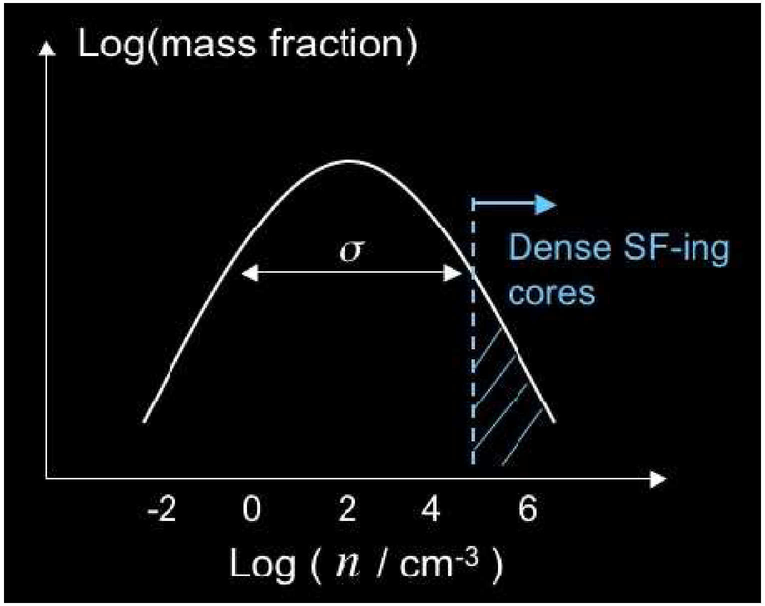
$$\dot{\rho}_* = \varepsilon_c (G\rho_c)^{1/2} f_c \langle\rho\rangle_V$$

ε_c : Star formation efficiency

ρ_c: Critical density for star formation

f_c : Fraction of gas above critical density

$\langle\rho\rangle_V$: Average density



- If PDF of gas density is log-normal $\Rightarrow$ f_c

SFR ⇒ a function of average density

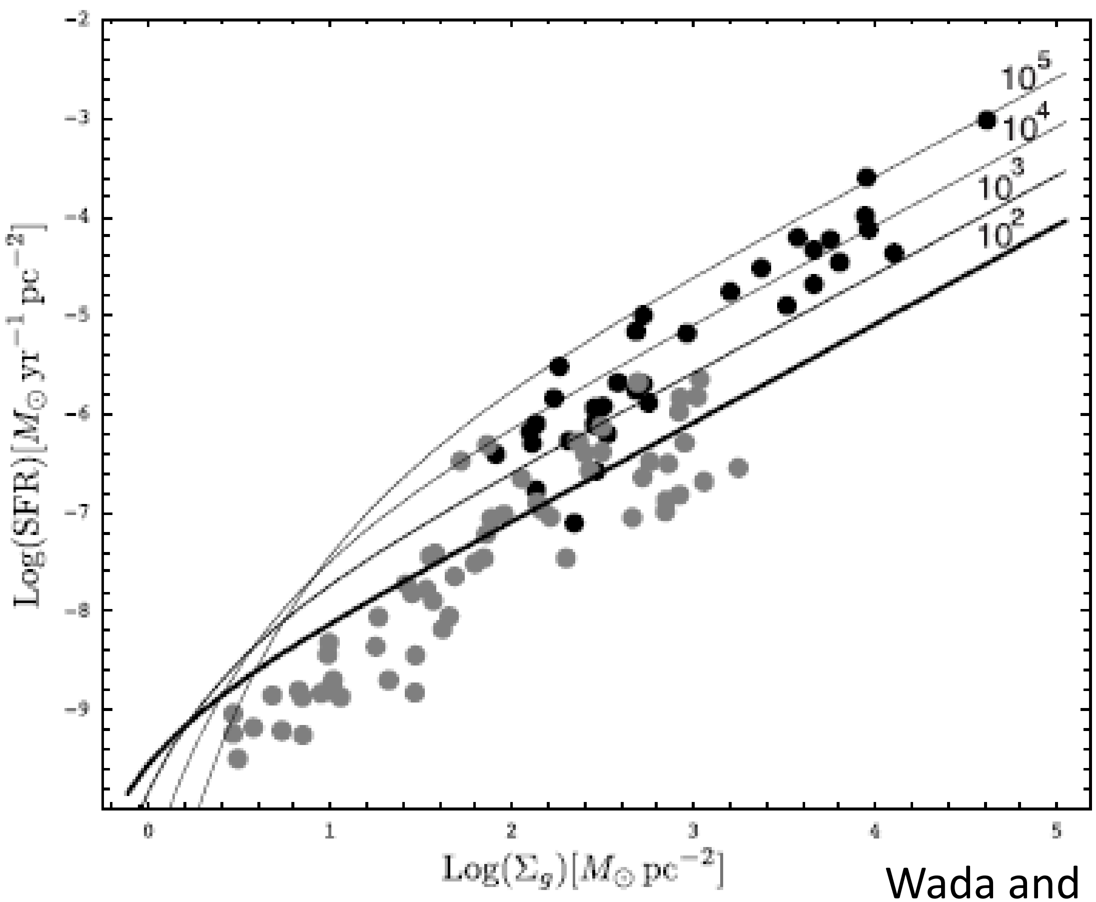
$$\dot{\rho}_*\left[\varepsilon_c, \left(\frac{\langle\rho\rangle_V}{1M_\odot \mathrm{pc}^{-3}}\right), \left(\frac{\rho_0}{1\mathrm{cm}^{-3}}\right), \left(\frac{\rho_c}{10^5\mathrm{cm}^{-3}}\right)\right]$$

$$= 3.6\times10^{-7}\varepsilon_c M_\odot \mathrm{yr}^{-1}\mathrm{pc}^{-3} \times \left[1 - Erf\left(\frac{\ln(\rho_c\rho_0/\langle\rho\rangle_V{}^2)}{2[\ln(\langle\rho\rangle_V/\rho_0)]^{1/2}}\right)\right]\rho_c{}^{1/2}\langle\rho\rangle_V$$

$$Erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt$$

- Consistent with observations
  - Steep slop at low density regime
  - $\sum_{SFR} \propto \sum_{gas}$ at high density regime
- Difference between Normal and starburst $\Rightarrow \varepsilon_c$?

  (What is the cause of the difference of ε_c?)



Wada and Norman (2007)

Physical interpretation of K-S law (3)

Critical density for star formation (Krumholz and McKee 2005)

- Star formation in clouds in virial equilibrium supported by turbulence

  $\sigma_l \propto l^{0.5}$ σ_l : velocity dispersion, l : size of molecular cloud

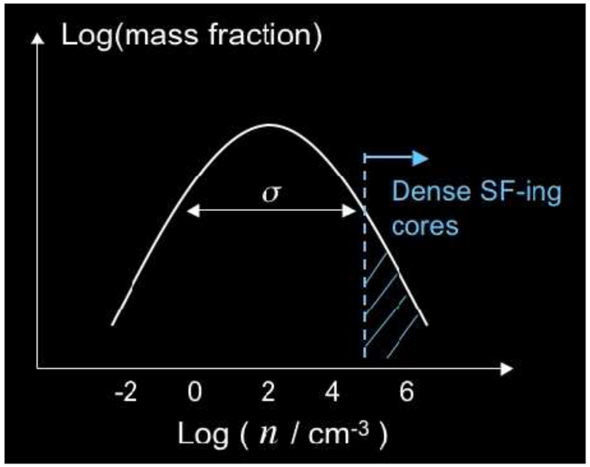
- PDF of gas density : log-normal
- Gravitational energy > turbulence energy ⇒ star formation

  ⇒ Jeans length < λ_s (velocity dispersion of turbulence = sound speed)

$$x = \frac{\rho}{\rho_0} > x_{crit} \equiv \left(\phi_x \frac{\lambda_{J0}}{\lambda_s}\right)^2$$

λ_{J0} : Jeans length of average density

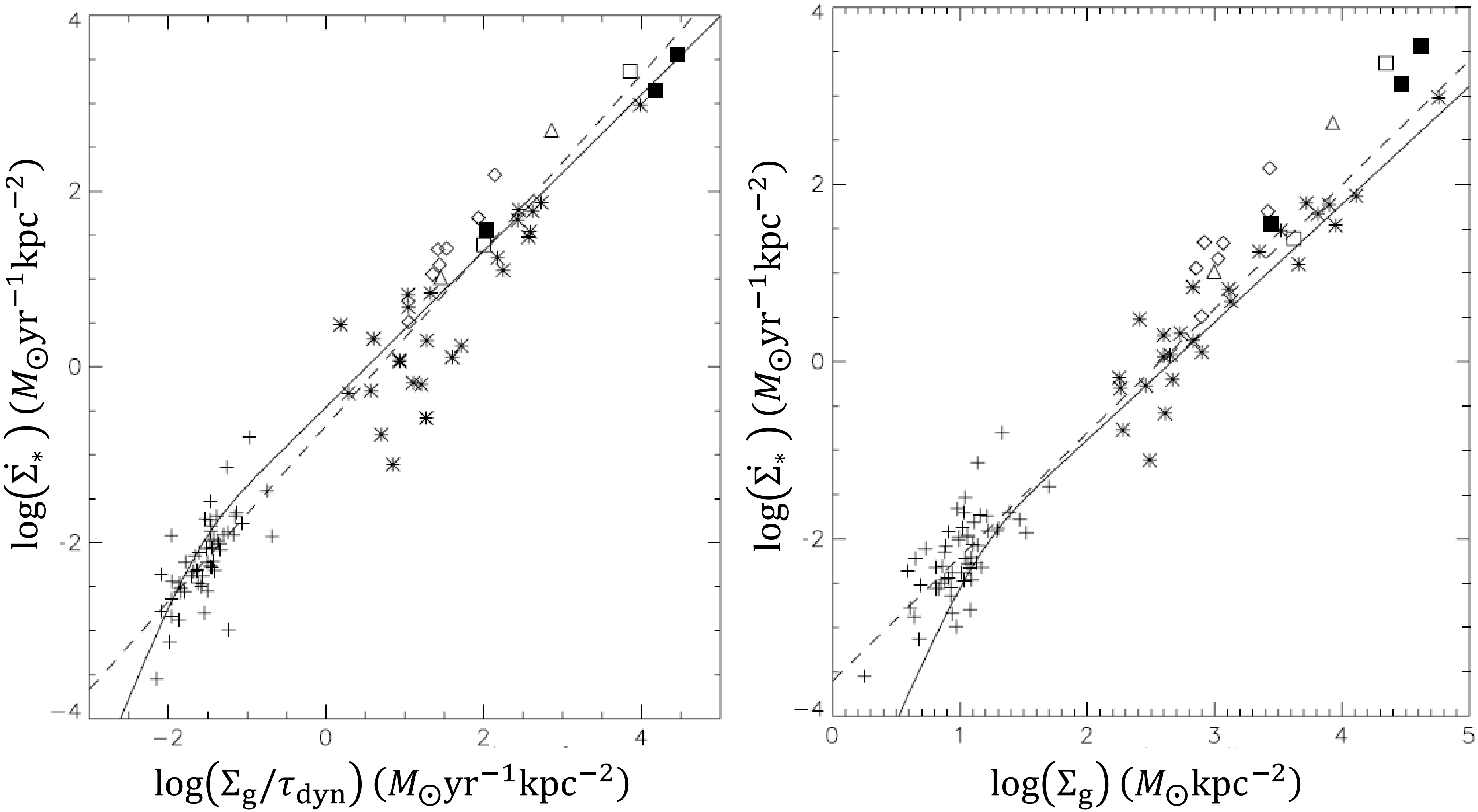
$\phi_x = 1.13$: fitted by simulations



⇒ Spatial variation of critical density

- Small λ_s ⇒ high critical density

  e.g., Galactic center



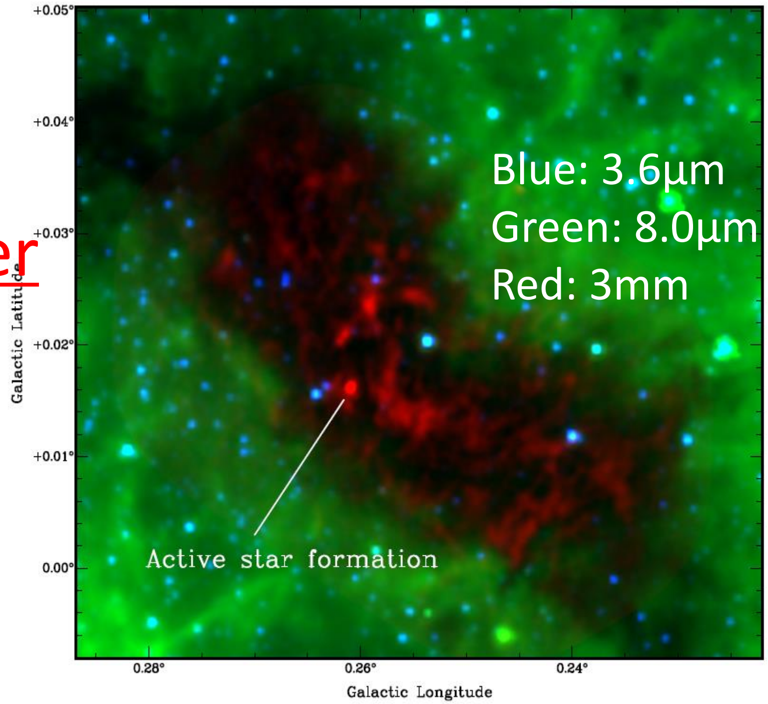
- Solid line：Krumholtz & McKee (2005)
- Dashed line：Kennicutt (1998)

Star formation near the Galactic cener

(Rathborne et al. 2014)（ALMA）

- Central Molecular Zone (CMZ)
  - Low $\Sigma_{\mathrm{SFR}}/\Sigma_{\mathrm{dense}}$

  ⇒ High critical density for star formation
    - G0.253+0.016
      - Star formation in the core with highest density ($> 10^6 \mathrm{cm}^{-3}$)



	Solar	G0.253+0.016	
Measured			
Mean, column density PDF (N_0)	$0.5\text{–}3.0 \times 10^{21}$ cm^{-2}	$86 \pm 20 \times 10^{21}$ cm^{-2}	7, 8
Dispersion, column density PDF ($\sigma_{\log N}$)	0.28–0.59	0.34 ± 0.03	7, 8
Critical volume density (ρ_{crit})	10^4 cm^{-3}	$>10^6$ cm^{-3}	3, 9, 8
Predicted (relative to solar neighborhood clouds)			
Mean, column density PDF (N_0)	1	100	
Dispersion, volume density PDF ($\sigma_{\log \rho}$)	1	1.2	
Critical volume density (ρ_{crit})	1	10^4	10, 11, 5

Note. The key properties are marked in bold.

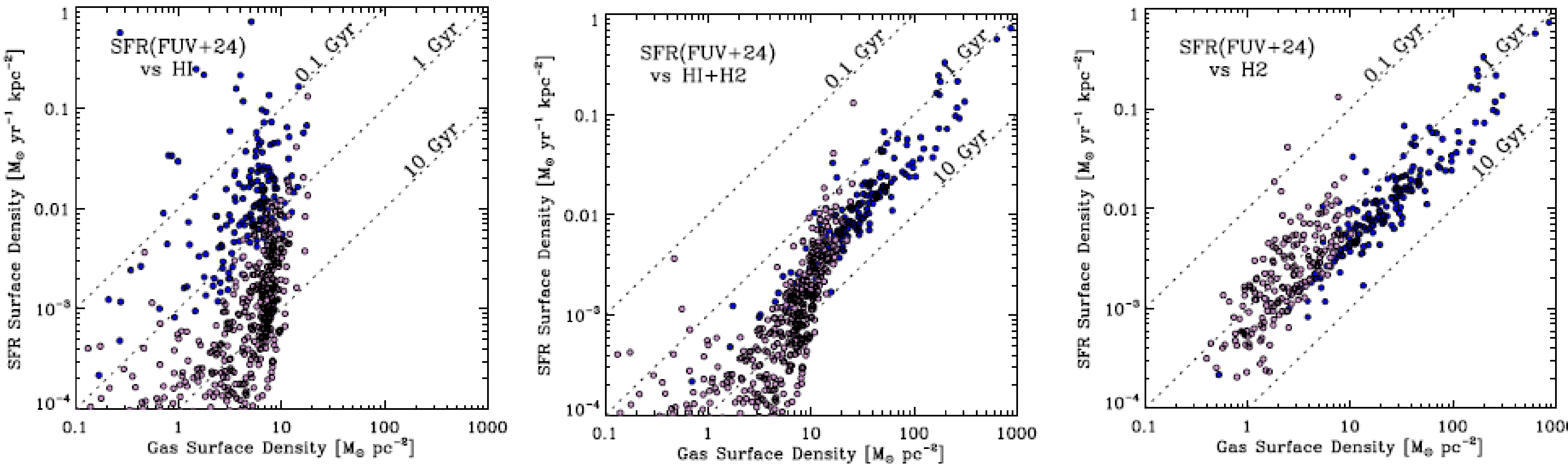
References. (1) Larson 2003; (2) Ao et al. 2013; (3) Lada et al. 2010; (4) Longmore et al. 2013; (5) Kruijssen et al. 2014; (6) Schneider et al. 2014; (7) Kainulainen et al. 2009; (8) this work; (9) Lada et al. 2012; (10) Krumholz & McKee 2005; (11) Padoan & Nordlund 2011.

Physical interpretation of K-S law (4)

- SFR vs. HI: no correlation
- SFR vs. H_2 : $\Sigma_{SFR} \propto \Sigma_{\mathrm{H_2}}{}^{1.0}$
- SFR vs. HI+H_2 : $\Sigma_{SFR} \propto \Sigma_{\mathrm{HI+H_2}}{}^{1.6}$ + Critical density for star formation

⇒ Star formation: Two processes

- HI -> H_2 ⇒ Critical density for H_2 formation
- Star formation from H_2 with a constant efficiency



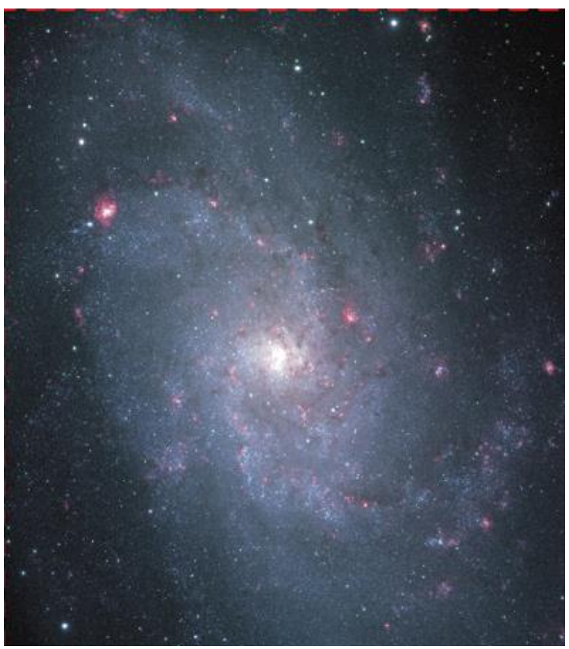
Schruba et al. (2011)

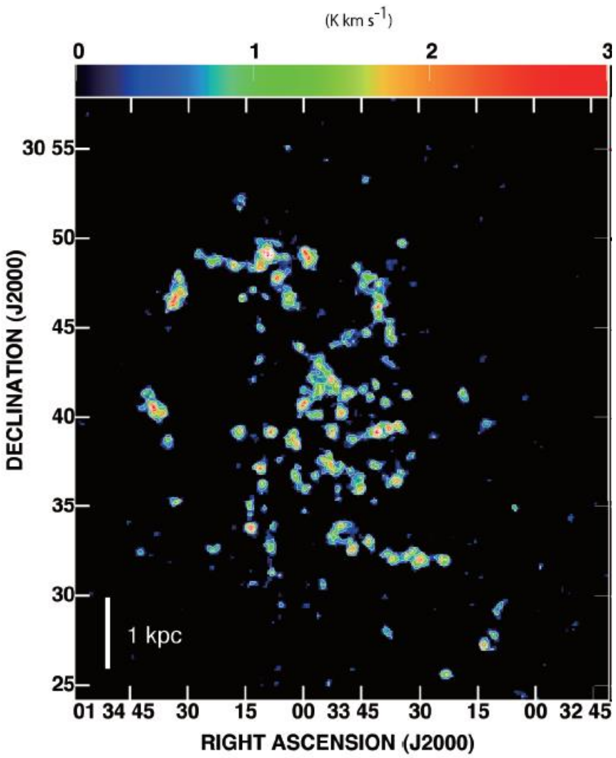
2. Star formation law in GMC scale
3. Dependence on surface density of gas
    - High density regime
    - Low density regime
4. Volume density of gas vs. SFE

2. K-S law in GMC scale (Onodera et al. 2009)

- K-S law
  - Global
  - Radial average

To what scale is the K-S law valid?



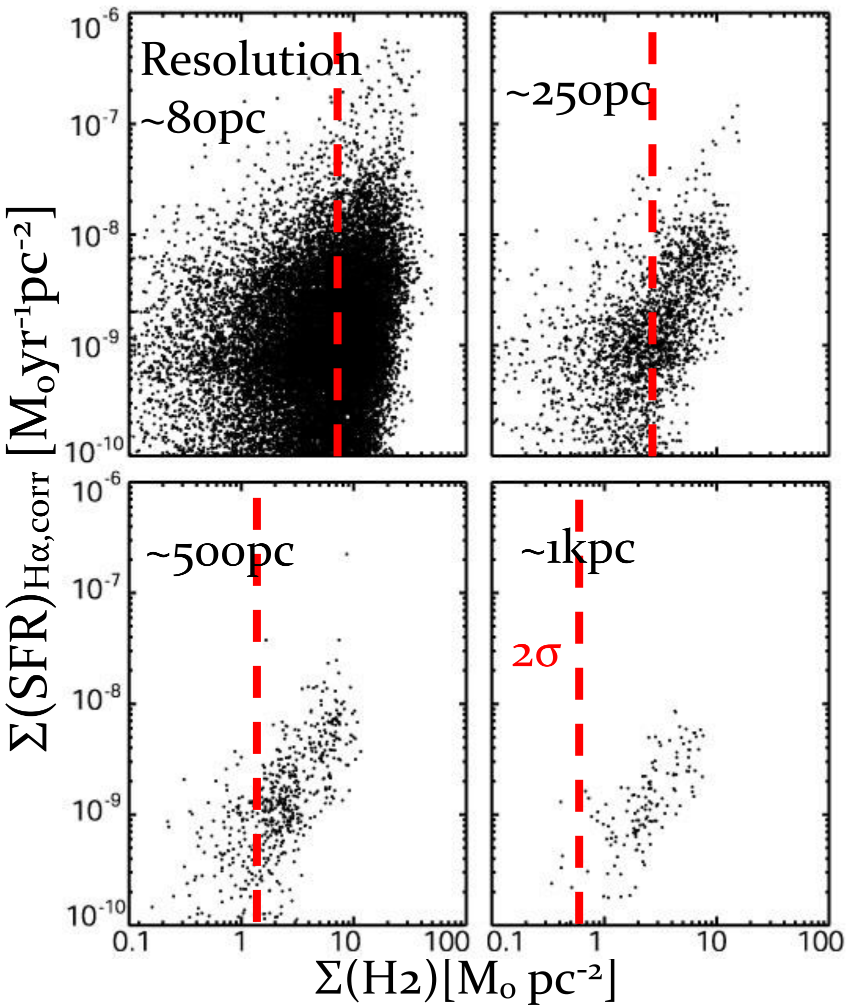


Spatial resolution
~80 pc
(GMC scale)

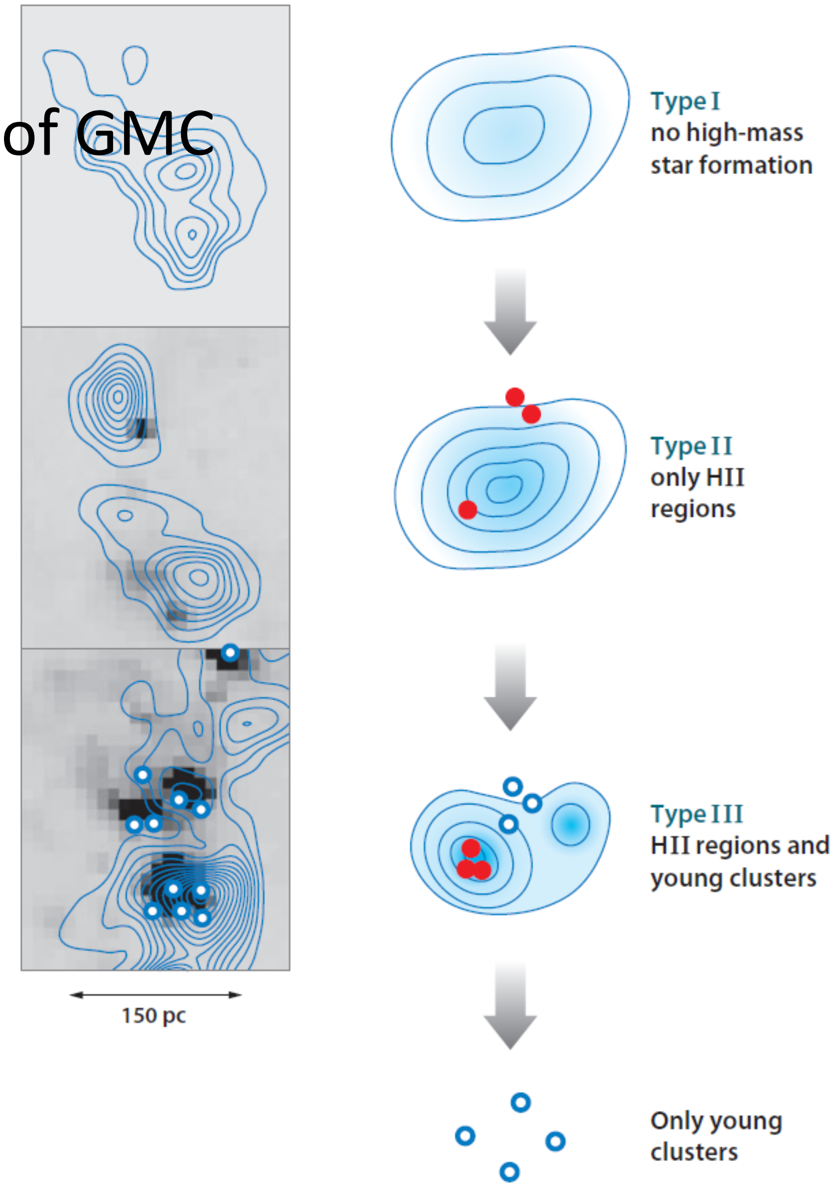
CO map of M33 (Tosaki et al. 2011)

K-S law in GMC scale

- Breakdown of K-S law
- Difference of evolutionary stage of GMC



M33: Onodera et al. (2009)

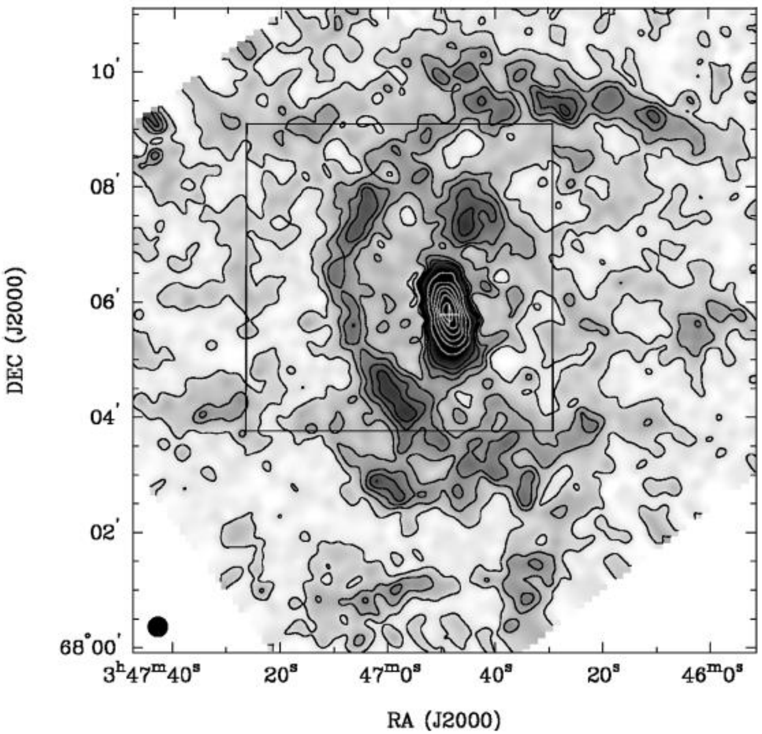


LMC:Fukui & Kawamura (2010)

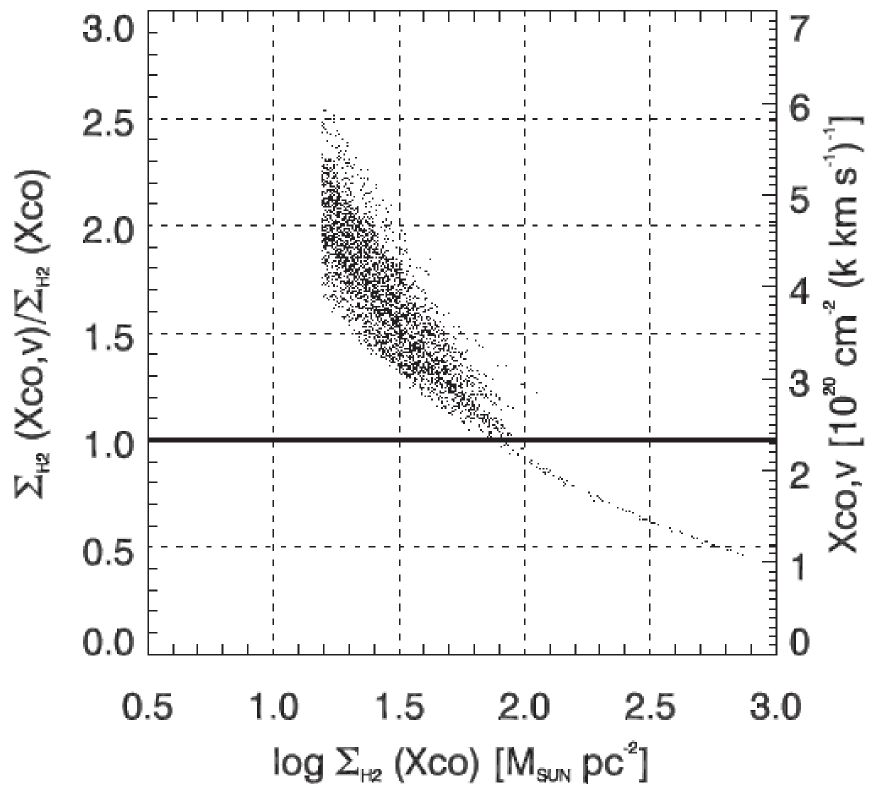
3. Dependence on surface density of gas
K-S law at high density region (Pan et al. 2014)

- Dependence of X_{CO} on metallicity and CO intensity

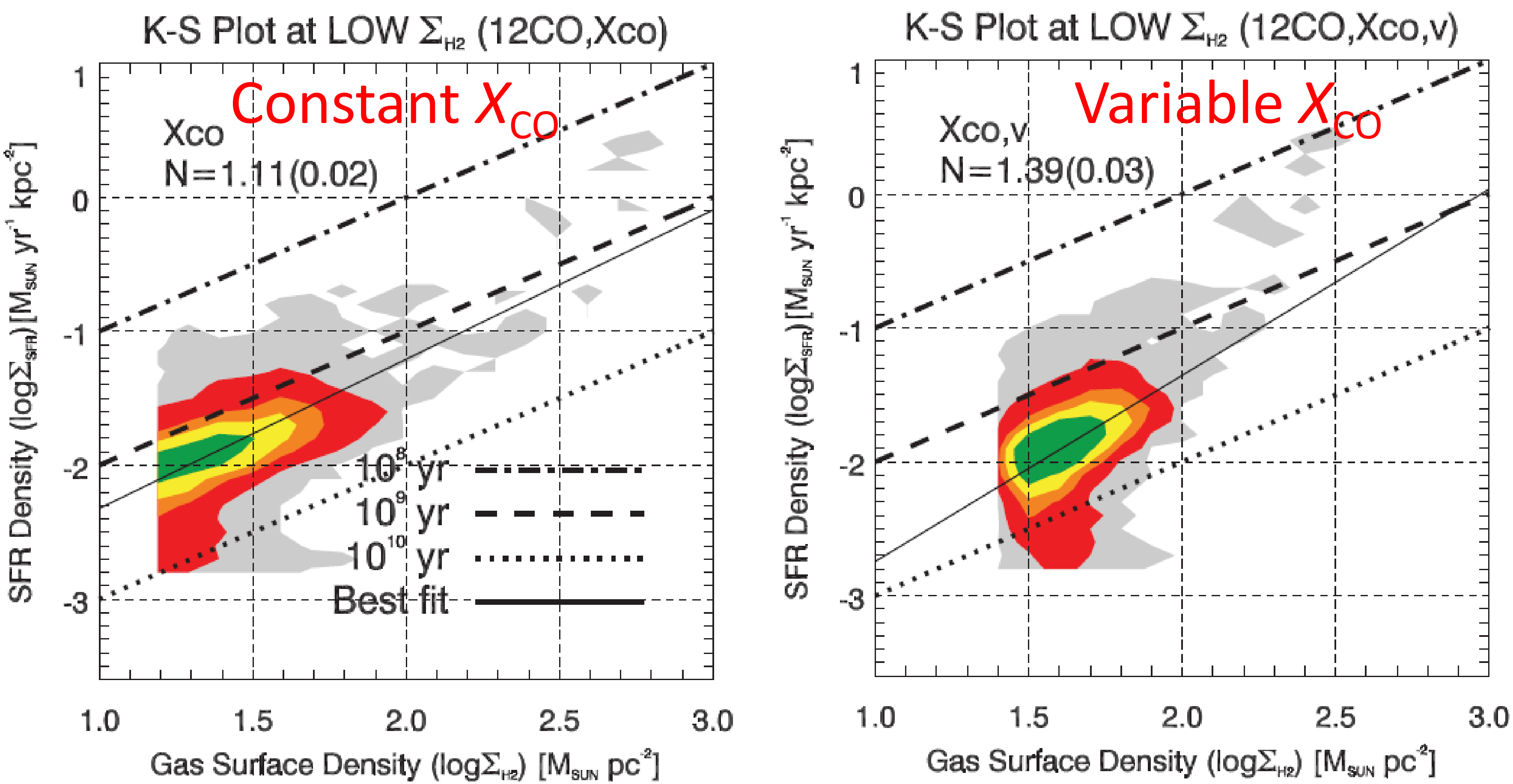
$$X_{\mathrm{CO},v} = \frac{\min\left[4, 6.75 \times \langle W_{\mathrm{CO}} \rangle^{-0.32}\right] \times 10^{20}}{Z'^{0.65}}$$ (Narayanan et al. 2012)



^{12}CO map of IC342 (Kuno et al. 2007)



- K-S law taking account of dependence of X_{CO} on metallicity and CO intensity
    - Higher power at high density region



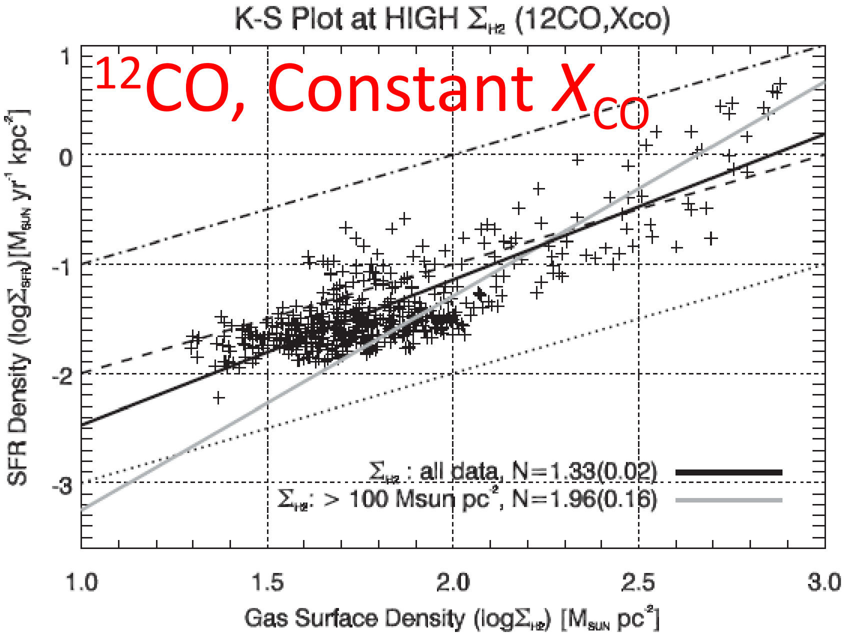
Comparison with optically thin ^{13}CO

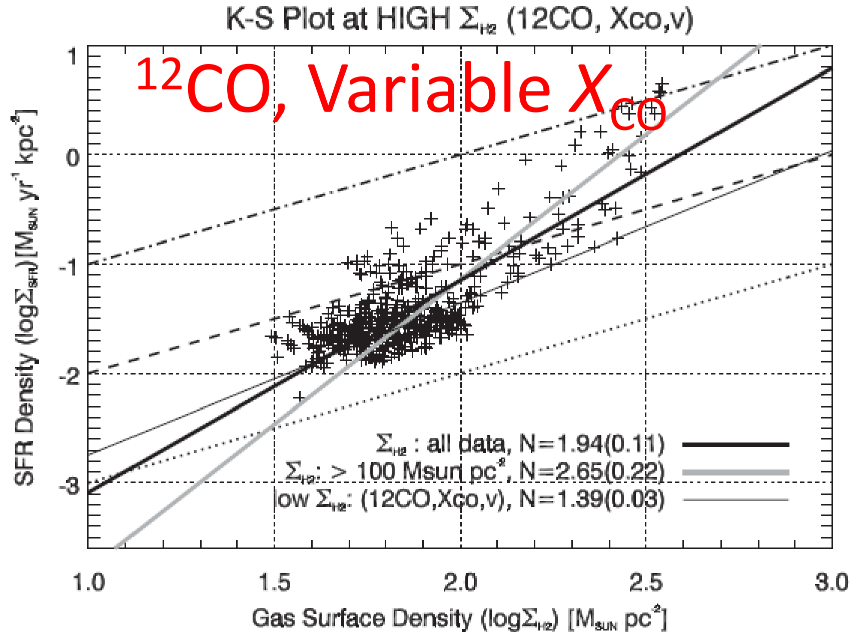
- ^{12}CO
  - Optically thick
    - Conversion factor ⇒ Gas mass
- ^{13}CO
  - Optically thin
    - LTE ⇒ Gas mass
  - Abundance variation

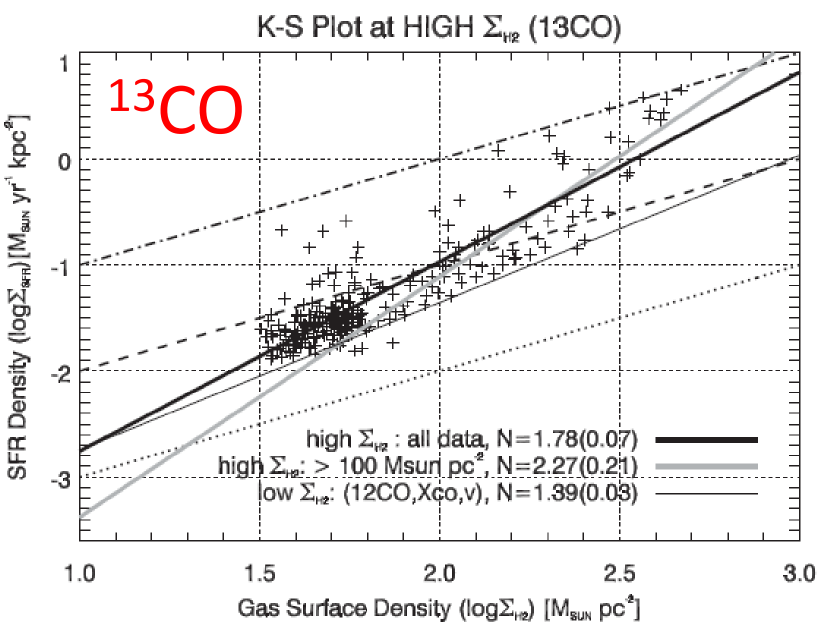
    Radial variation: center ⇒ high $^{13}CO/^{12}CO$
  - Temperature variation

    Dust temperature ⇒ Gas temperature

• Comparison with optically thin ^{13}CO





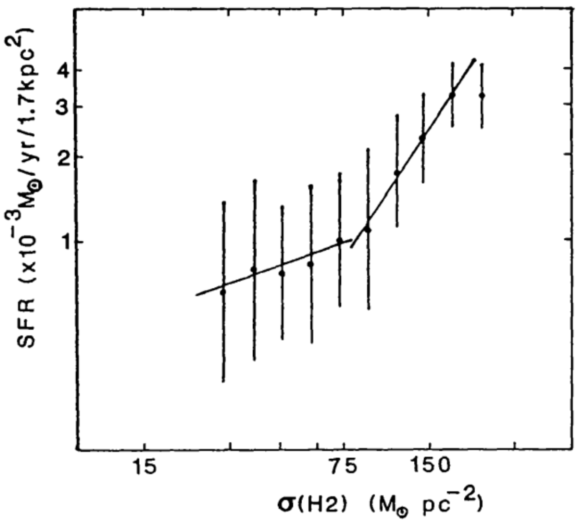


Same trend in ^{13}CO K-S law

[power, N]

	[all]	[>100Mo/pc^2]
^{12}CO, X_{CO} :	1.33	1.96
^{12}CO, $X_{CO,v}$:	1.94	2.65
^{13}CO :	1.78	2.27

- Star formation mechanisms
  - Low density region: Gravitational instability
  - High density region: Cloud-cloud collision



M51
(Nakai, Kuno et al. 1991)

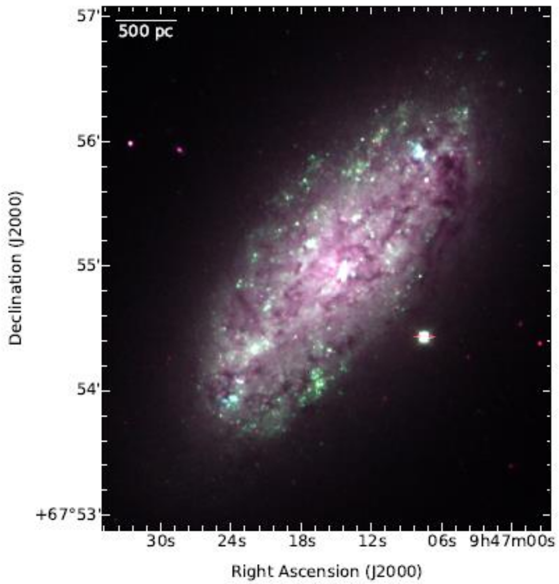
- GMC properties
  - High density region: ISM pressure ⇒ High density
    ⇒ Short free fall time

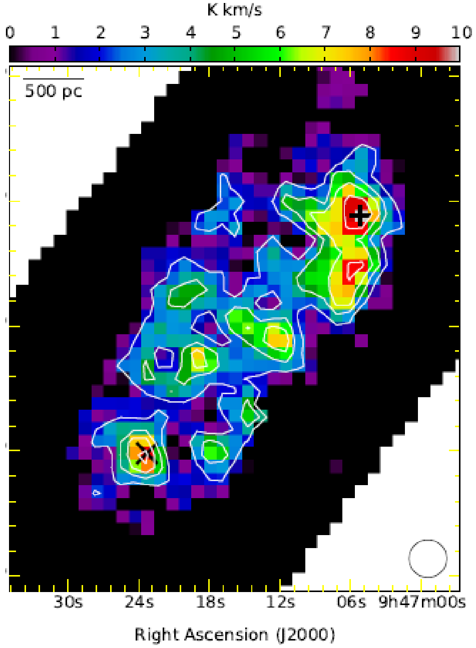
(Krumholz et al. 2009)

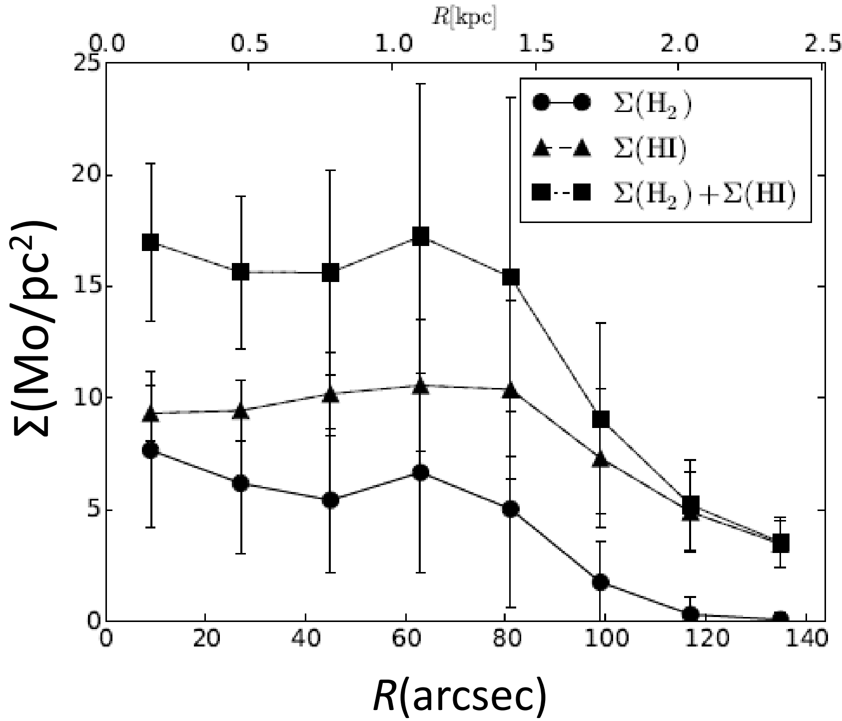
3. Dependence on surface density of gas
K-S law at low density region (Hatakeyama et al. 2017)

- NGC 2976
  - Nearby (3.56Mpc)
  - HI dominant

Good sample : HI ⇒ H_2 ⇒ Star formation

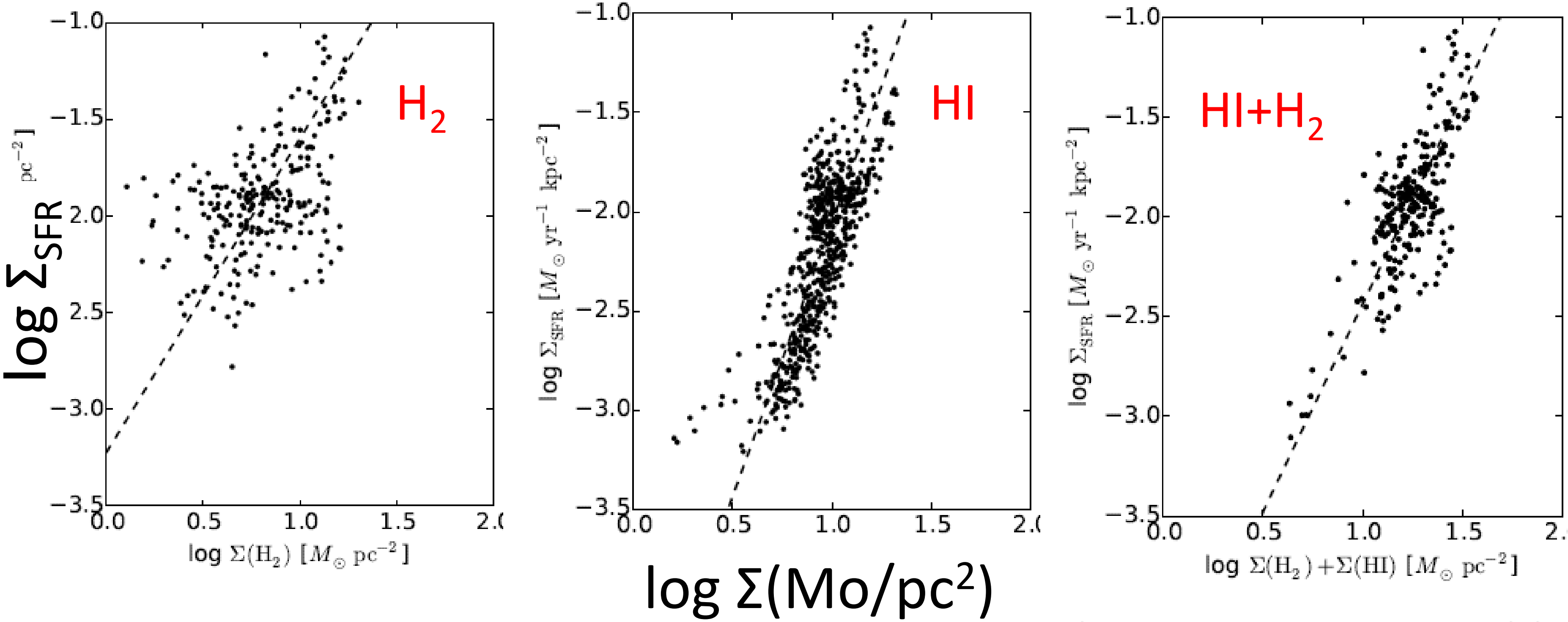






I_{CO} map obtained with NRO 45-m telescope

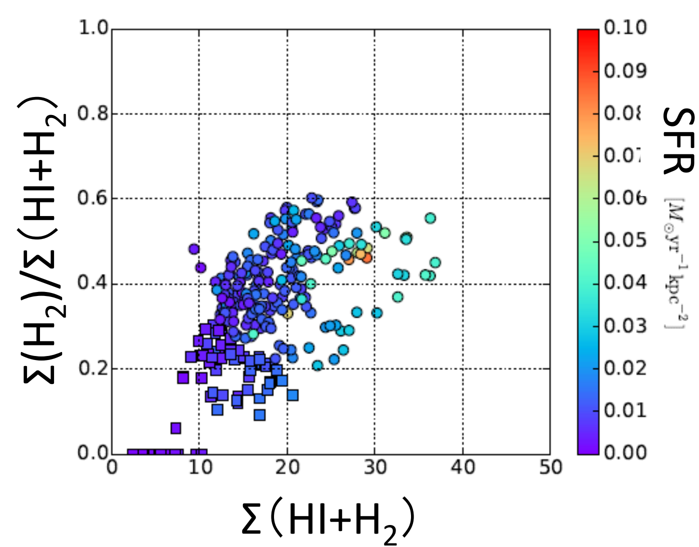
K-S law at low density region



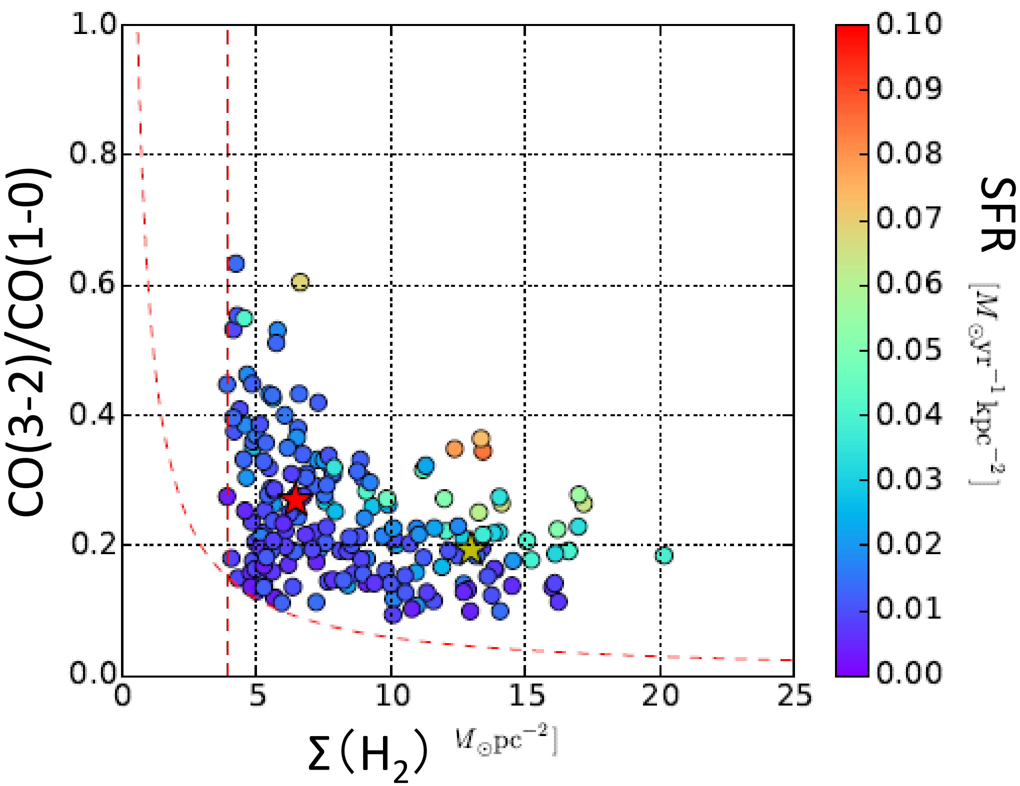
- HI
  - Saturated at $\Sigma \approx 10\ M_\odot \mathrm{pc}^{-2}$
  - Correlation with SFR (photoionization)?

⇒ Power: HI+H$_2$ > H$_2$

H$_2$ formation



- $\Sigma(H_2) > 10\ M_{\odot}\mathrm{pc}^{-2} \Rightarrow$ star formation?
  - Diffuse clouds ⇒ Self gravitating clouds ?

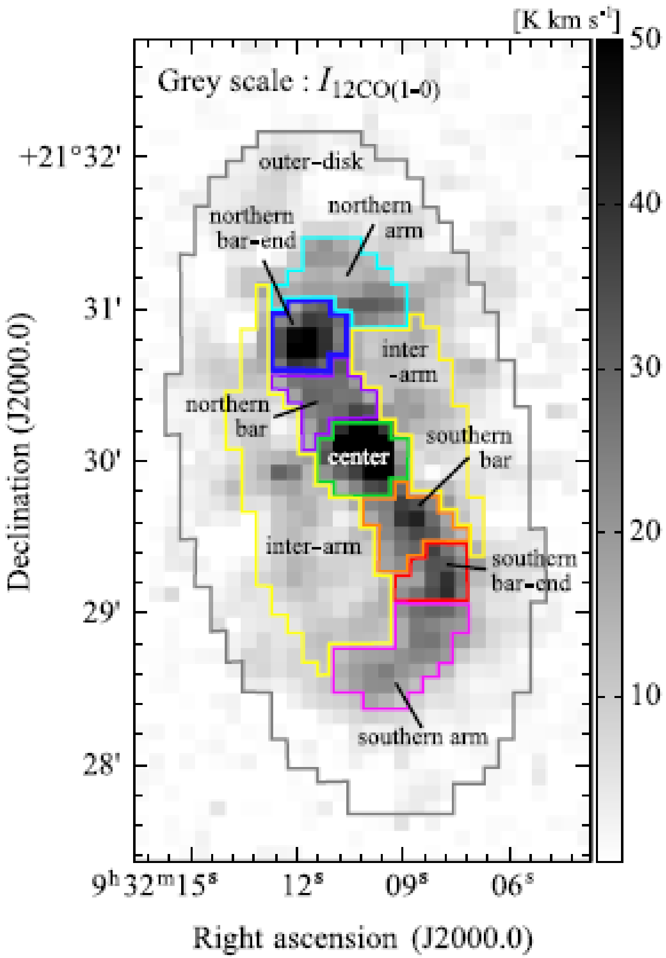


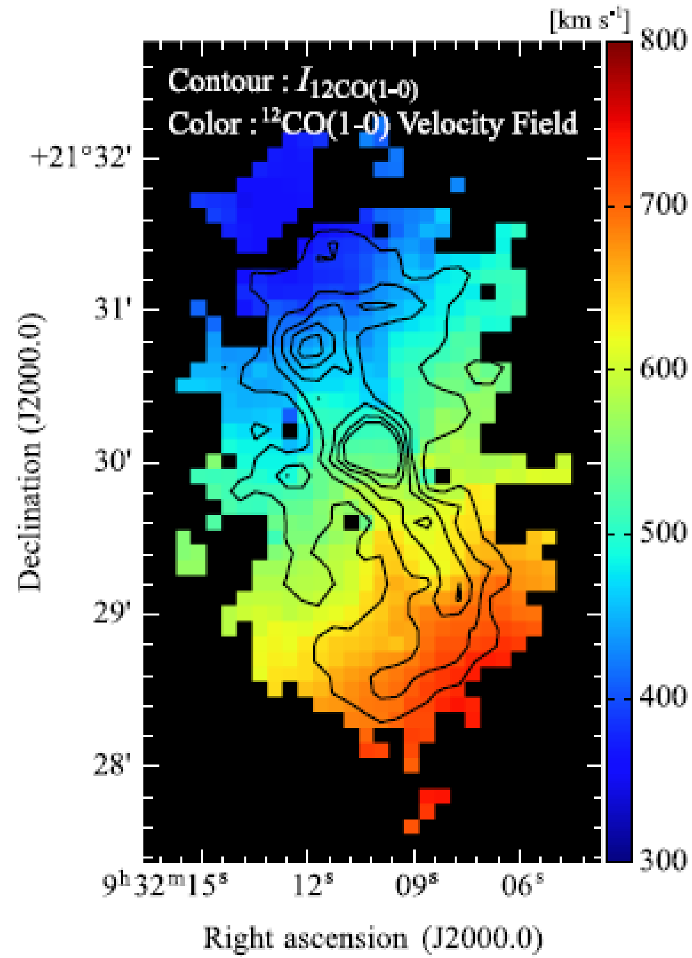
Star formation process

- $\Sigma(\mathrm{HI}) > 10\ M_{\odot}\mathrm{pc}^{-2}$: HI ⇒ H_2 (diffuse clouds)
- $\Sigma(\mathrm{H}_2) > 10\ M_{\odot}\mathrm{pc}^{-2}$: H_2 ⇒ self gravitating clouds ⇒ star

4. Volume density of gas vs. SFE (Muraoka et al. 2016)

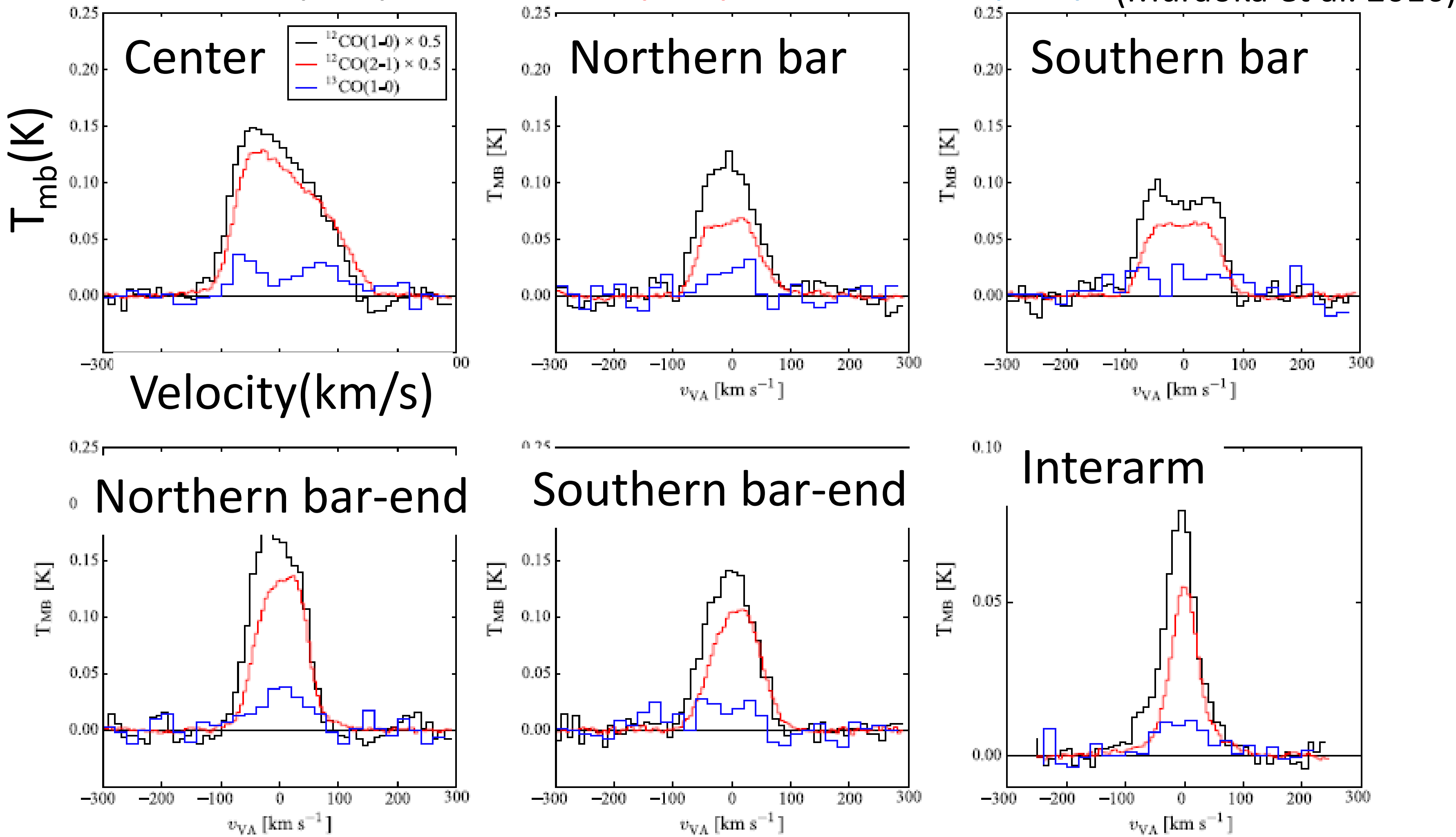
- NGC 2903
- $^{12}CO+^{13}CO$ mapping (COMING) ⇒ Physical properties





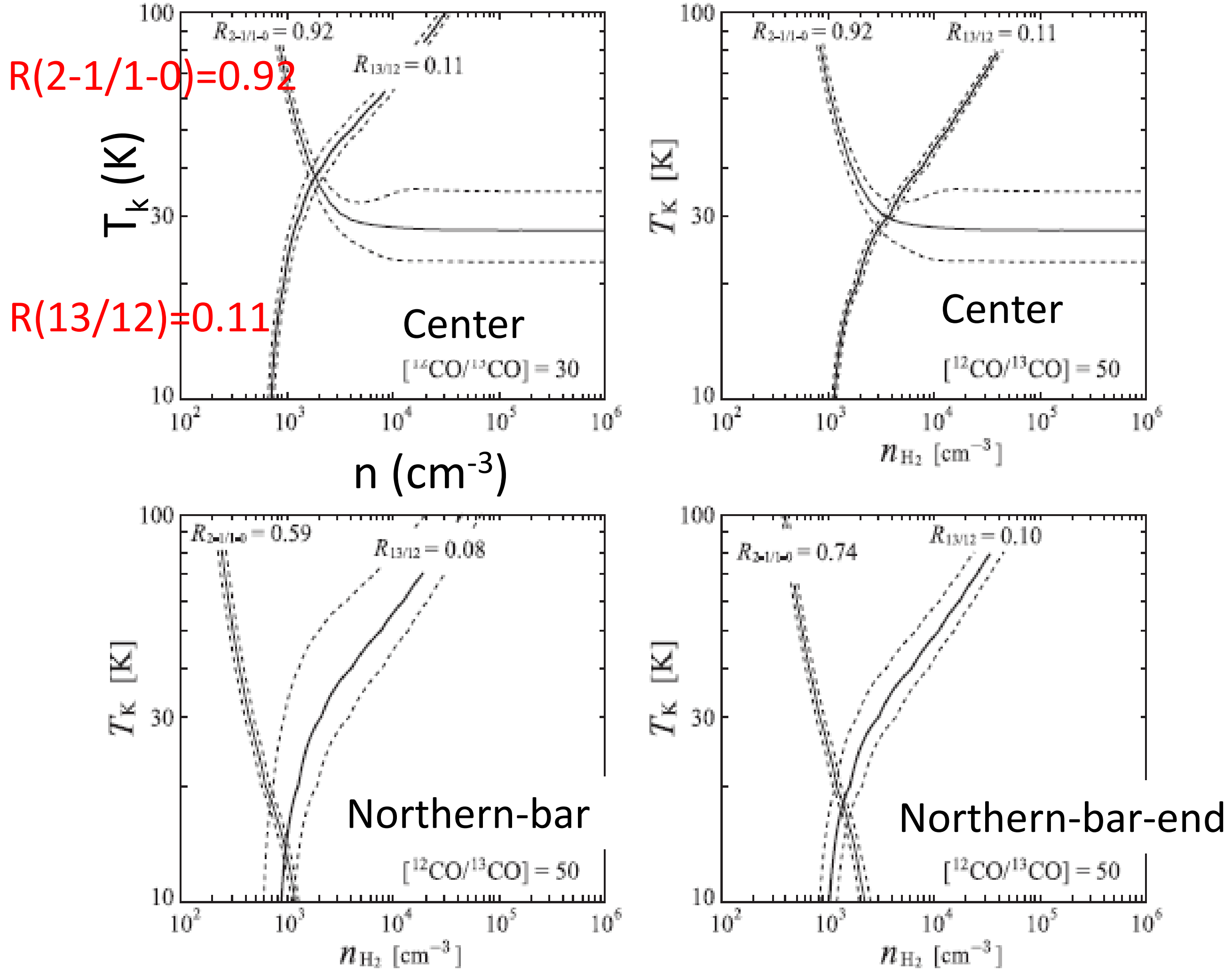
• Detection of ^{13}CO by stacking using ^{12}CO velocity

Black: ^{12}CO(1-0), Red: ^{12}CO(2-1), Blue: ^{13}CO(1-0) (Muraoka et al. 2016)



(^{12}CO(2-1): IRAM 30-m Leroy et al. 2009)

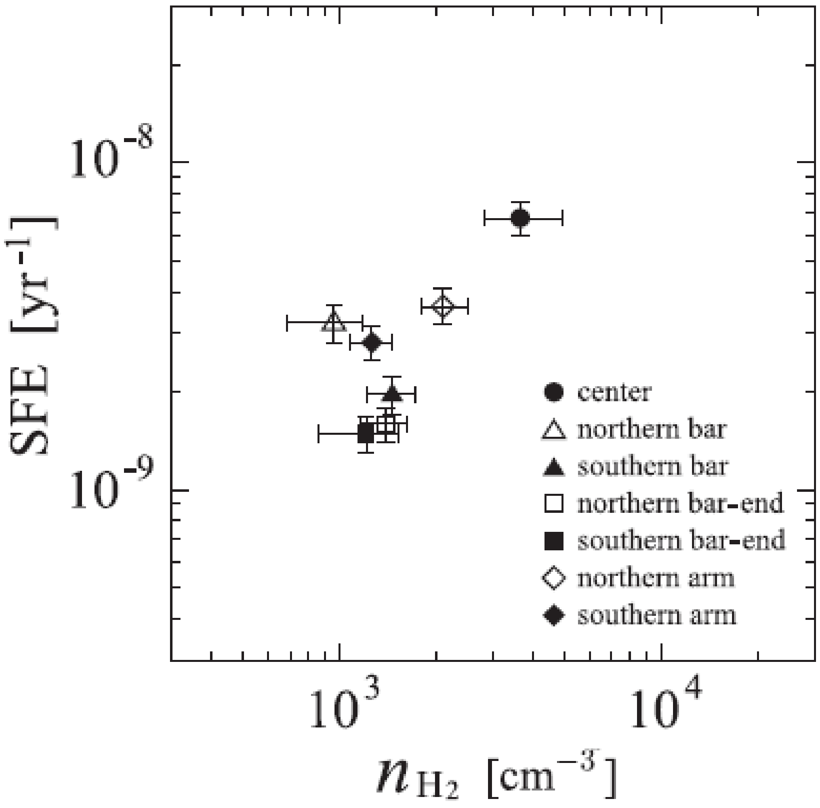
- Large Velocity Gradient (LVG) model
  - Abundance, Velocity gradient ⇒ density, temperature

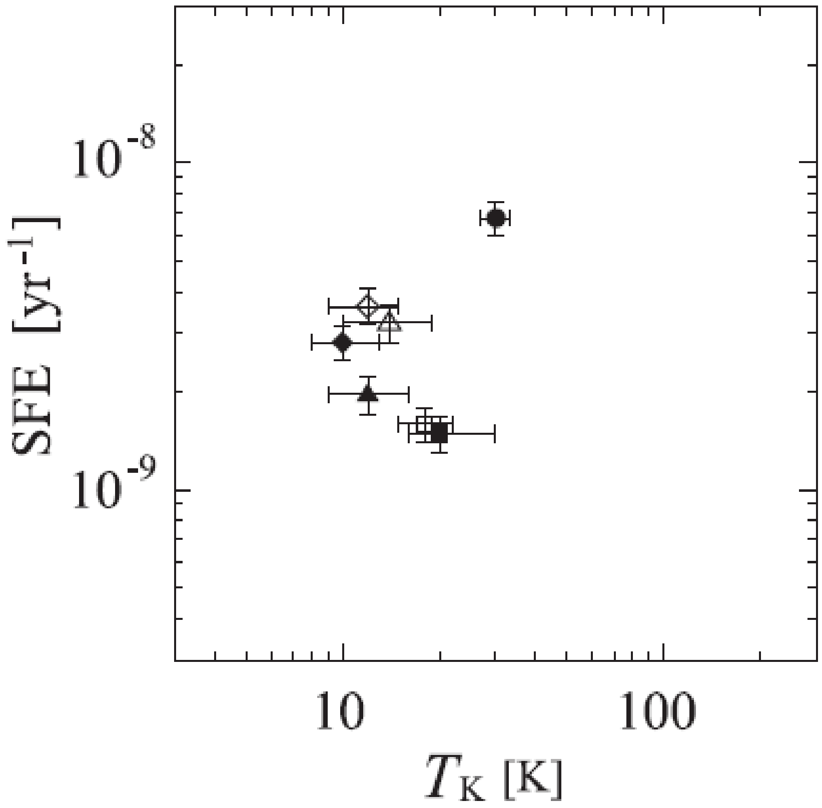


(Muraoka et al. 2016)

Volume density of molecular gas vs. SFE

- Higher volume density ⇒ Higher SFE





(Muraoka et al. 2016)

Summary

- Star formation law: one of the most fundamental relations to understand galaxy evolution
  - Gas phase (total gas, molecular gas, dense gas)
  - Galaxy type (e.g., normal vs. starburst)
  - Time scale of star formation
  - Spatial variation in galaxies
    (relation with galactic structures, such as spiral arm and bar)
  - Surface density ⇒ volume density
  - Effect of variation in conversion factor X_{co}