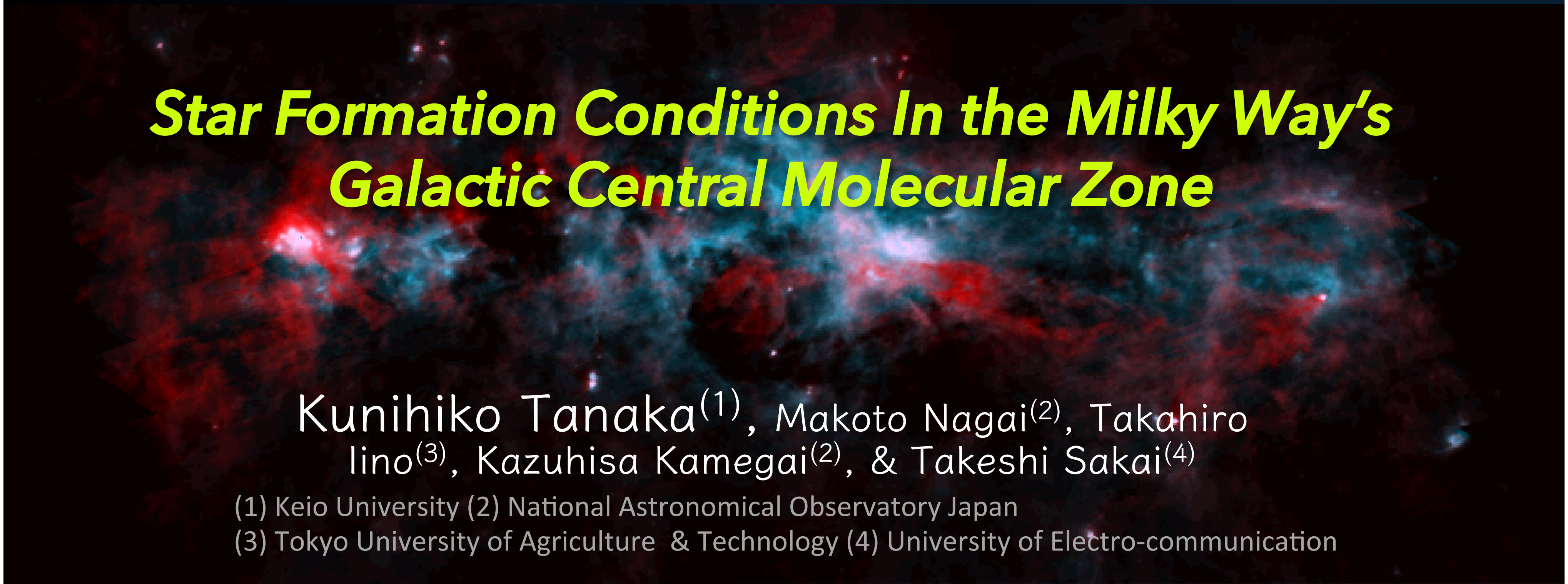

Star Formation Conditions In the Milky Way's Galactic Central Molecular Zone

Kunihiko Tanaka[(1)], Makoto Nagai[(2)], Takahiro Iino[(3)], Kazuhisa Kamegai[(2)], & Takeshi Sakai[(4)]

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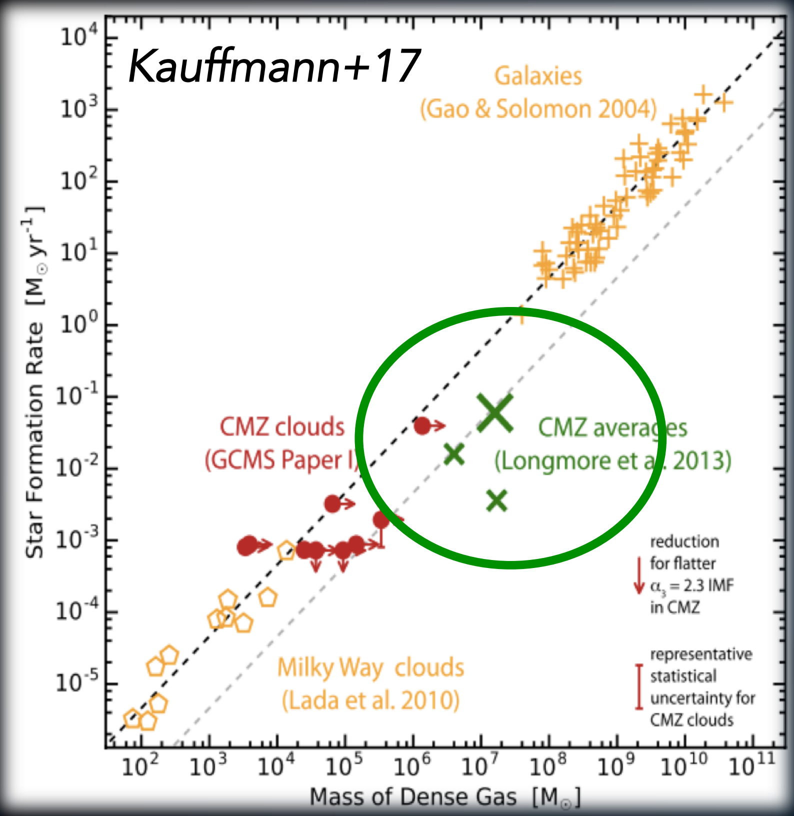
Inefficient SF in GC



- Star Formation *Efficiency* is 1–2 orders below the K-S Law for dense gas
  (e.g. *Kauffmann+17*)

- GC is a hostile environment for SF

& good sample for finding parameters of SF

  – Turbulence
  – Magnetic Field
  – Cosmic-Ray (e.g. *Kruijssen+14)*

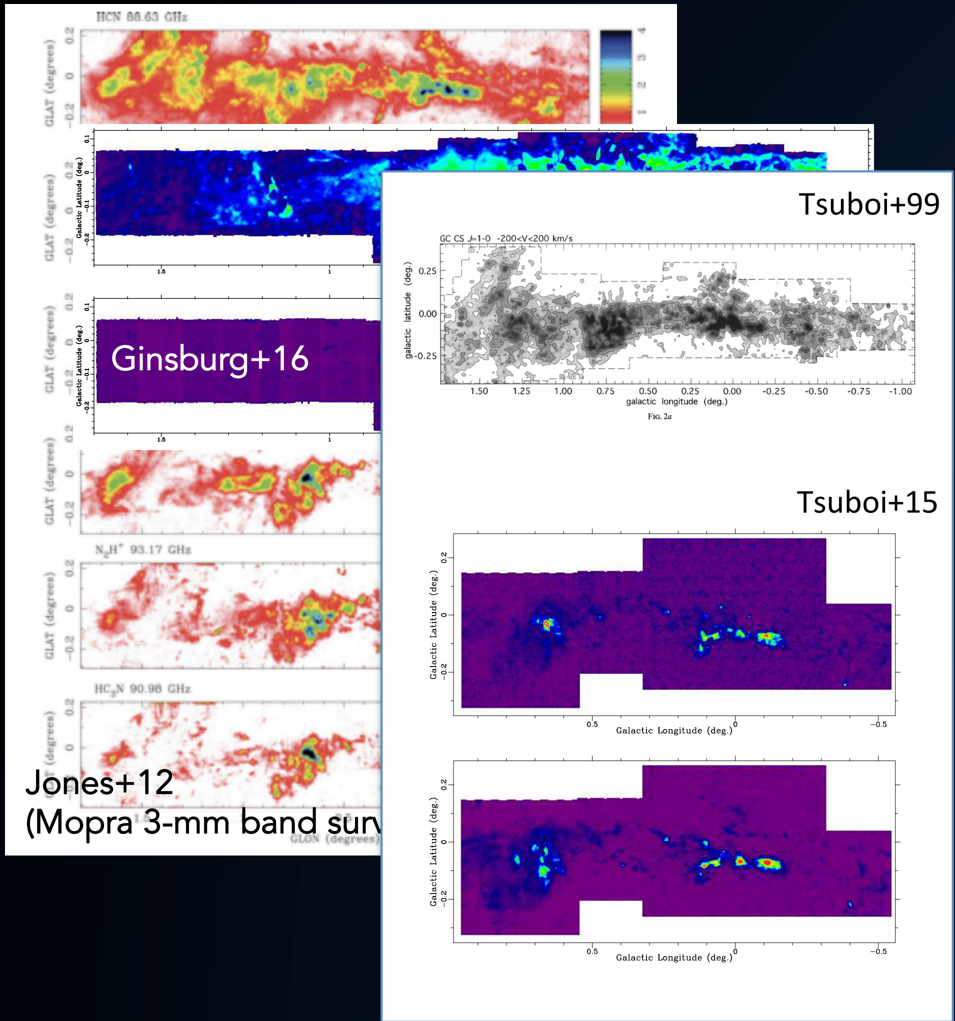
- Gas Volume density n_{H2}
  – SFR = $\boxed{\varepsilon_{ff}} \cdot M_{gas} \cdot \boxed{t_{ff}^{-1}}$

function of density? *function of density*

  – SFR $\propto M_{gas}$ (n_{H2}>10^4 cm^{-3})

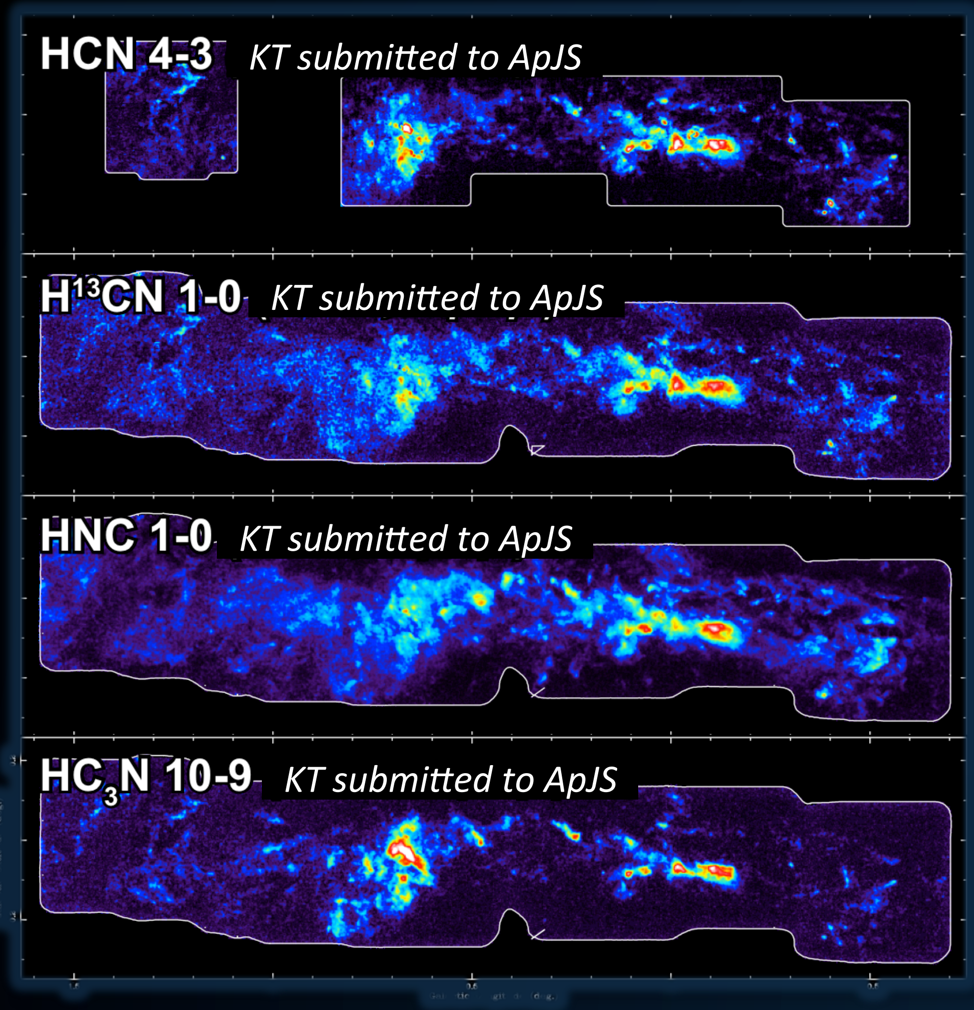
Density Measurement is Difficult

- Physical Condition Probes
  - gas surface density N_{H2} : submm-FIR dust
  - gas kinetic temperature T_{kin} : ammonia, H_2CO
  - gas volume density n_{H2} : ???
- We have to Solve *excitation equation* including full *parameter set*
  - (N_{H2}, T_{kin}, n_{H2}, filling factor, *molecular abundances*) x num. of voxel



Multi-line Analysis

- ASTE10-m & NRO45-m (*KT+ in prep.*)
  - HCN *J*=4–3
  - $H^{13}CN$ *J*=1–0 +
- Mopra 3-mm Survey (*Jones+ 2012*)
  - HCN *J*=1-0
  - HCO^+ *J*=1-0 +
- Apex Survey (*Ginsburg+16*)
  - *p*-H_2CO $J=3_{03}-2_{02}$, $J=3_{21}-2_{20}$ +
- NRO45m Survey (*Tsuboi+15*)
  - $H^{13}CO^+$ *J*=1-0 +



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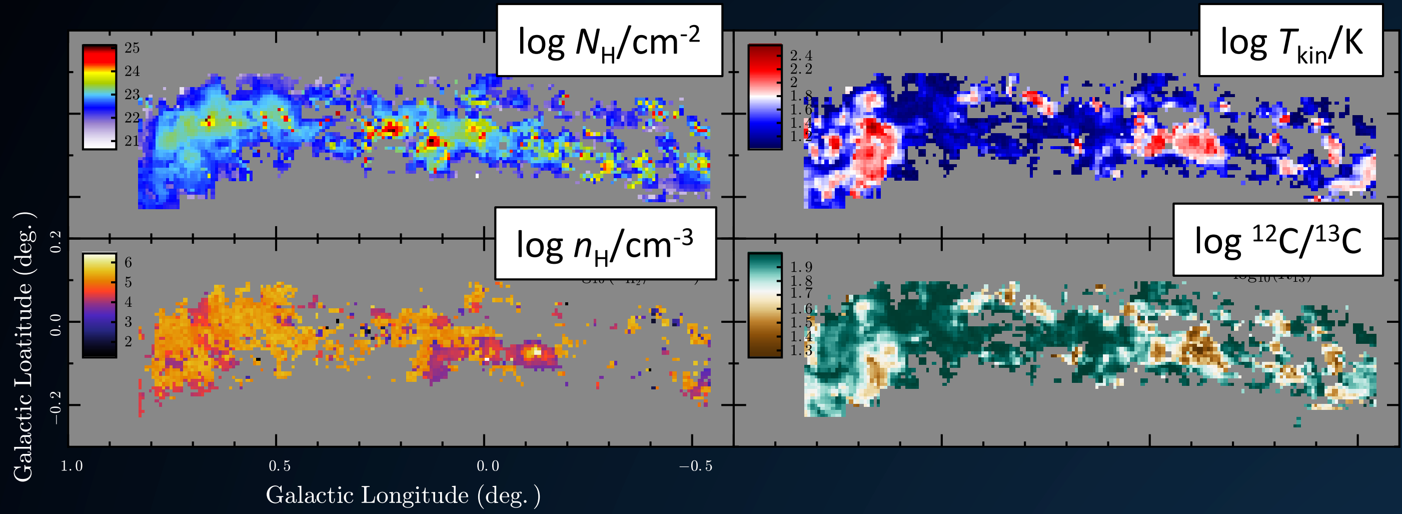
  - p-H_2CO $J=3_{03}$-2_{02}, $J=3_{21}$-2_{20} +
- NRO45m Survey (*Tsuboi+15*)
  - $H^{13}CO^+$ J=1-0 +

Maximum Likelihood(ML) Analysis



Likelihood Function :

$$P(\boldsymbol{x}|\boldsymbol{p}) \;\propto\; \prod_i \frac{1}{\delta_i} \exp\left[-\frac{1}{2}\left(\frac{x_i - F(\boldsymbol{p_i})}{\delta_i}\right)^2\right]$$

- Severely affected by systematic errors due to calibration errors, spectral baseline noises, breakdown of one-zone LVG approximation, ⋯

…But Systematic Errors cannot be included in ML analysis

factor for systematic errors

$$P(\boldsymbol{x}|\boldsymbol{p}) \propto \prod_i \frac{1}{\delta_i} \exp\left[-\frac{1}{2}\left(\frac{x_i - \boxed{\epsilon_i} \cdot F(\boldsymbol{p_i})}{\delta_i}\right)^2\right]$$

- Additional parammeter representing systematic errors are necessary
- Cannot be solved with ML method : d.o.f < 0

Hierarchical Bayesian Analysis

Kelly+12

Physical Parameters	Errors	Hyper-parameters
N_{H2} n_{H2} T_{kin}	e(HCN1-0)	Σ
R_{13} = [^{12}C]/[^{13}C]	e(HCN 4-3)	p_0
filling factor	e($H^{13}CN$ 1-0)	σ
x(HCN)	e(p-H_2CO 3_{03}-2_{02})	
x(p-H_2CO)	e(p-H_2CO 3_{21}-2_{20})	
…	…	

- Uses statistical properties of Parameters for inference
  - Variance-covariance of p : Σ
  - Voxel-mean of p : p_0
  - Std of systematic errors : σ

Posterior Probability

$$P(\boldsymbol{p},\boldsymbol{\epsilon},\boldsymbol{\theta}|\boldsymbol{I}) \propto P(\boldsymbol{I}|\boldsymbol{p},\boldsymbol{\epsilon})\cdot P(\boldsymbol{p},\boldsymbol{\epsilon}|\boldsymbol{\theta})\cdot P(\boldsymbol{\theta}) =$$

$$\prod_{i,j}\frac{1}{\delta_{i,j}}\exp\left[-\frac{1}{2}\left(\frac{\boldsymbol{x}_{i,j}-\epsilon_i\cdot F(\boldsymbol{p}_i)_j}{\delta_{i,j}}\right)^2\right]$$

$$\cdot\prod_{i,j}\frac{1}{\sigma_j\cdot\epsilon_{i,j}}\cdot\exp\left[-\frac{1}{2}\left(\frac{\ln\epsilon_{i,j}}{\sigma_j}\right)^2\right]$$

$$\cdot|\boldsymbol{\Sigma}|^{-\frac{N}{2}}\cdot\prod_{i}^{N}\left[1+\frac{1}{\nu}(\boldsymbol{p}_i-\boldsymbol{p}_0)^{\mathrm{T}}\cdot\boldsymbol{\Sigma}^{-1}\cdot(\boldsymbol{p}_i-\boldsymbol{p}_0)\right]^{-\frac{\nu+N_p}{2}}$$

$$\begin{cases}|R|^{-(N_p+1)}\cdot\prod_{k}^{N_p}\left[S_k^{-N_p}\left({R^{-1}}_{k,k}\right)^{-\frac{N}{2}}\right] & (for\ symmetric\ positive\ definite\ \boldsymbol{\Sigma})\\ 0 & (otherwise)\end{cases}$$

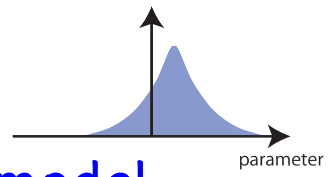
Joint (simultaneous) probability of

p : physical condition
e : errors
θ : statistical properties of *p* and *e*

on condition that *I* (line intensities) are known

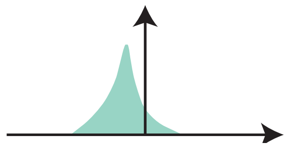
Posterior Probability

Likelihood =
degree of fitness of the model
to the observation



$$\prod_{i,j} \frac{1}{\delta_{i,j}} \exp\left[-\frac{1}{2}\left(\frac{\boldsymbol{x}_{i,j} - \epsilon_i \cdot F\left(\boldsymbol{p}_i\right)_j}{\delta_{i,j}}\right)^2\right]$$

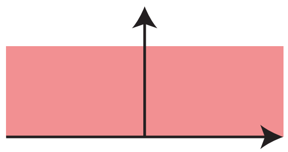
Prior functions:
Parameter ~ log-student (p_0, Σ)
Errors ~ log-normal $(0, \sigma^2)$



$$\cdot \prod_{i,j} \frac{1}{\sigma_j \cdot \epsilon_{i,j}} \cdot \exp\left[-\frac{1}{2}\left(\frac{\ln \epsilon_{i,j}}{\sigma_j}\right)^2\right]$$

$$\cdot |\boldsymbol{\Sigma}|^{-\frac{N}{2}} \cdot \prod_{i}^{N}\left[1 + \frac{1}{\nu}\left(\boldsymbol{p}_i - \boldsymbol{p}_0\right)^{\mathrm{T}} \cdot \boldsymbol{\Sigma}^{-1} \cdot \left(\boldsymbol{p}_i - \boldsymbol{p}_0\right)\right]^{-\frac{\nu+N_p}{2}}$$

Hyperprior functions:
"Any sets of (Σ, p_0, σ)
are equally possible"



$$\begin{cases} |R|^{-(N_p+1)} \cdot \prod_{k}^{N_p}\left[S_k^{-N_p}\left({R^{-1}}_{k,k}\right)^{-\frac{N}{2}}\right] \\ \quad (for\ symmetric\ positive\ definite\ \boldsymbol{\Sigma}) \\ 0 \\ \quad (otherwise) \end{cases}$$

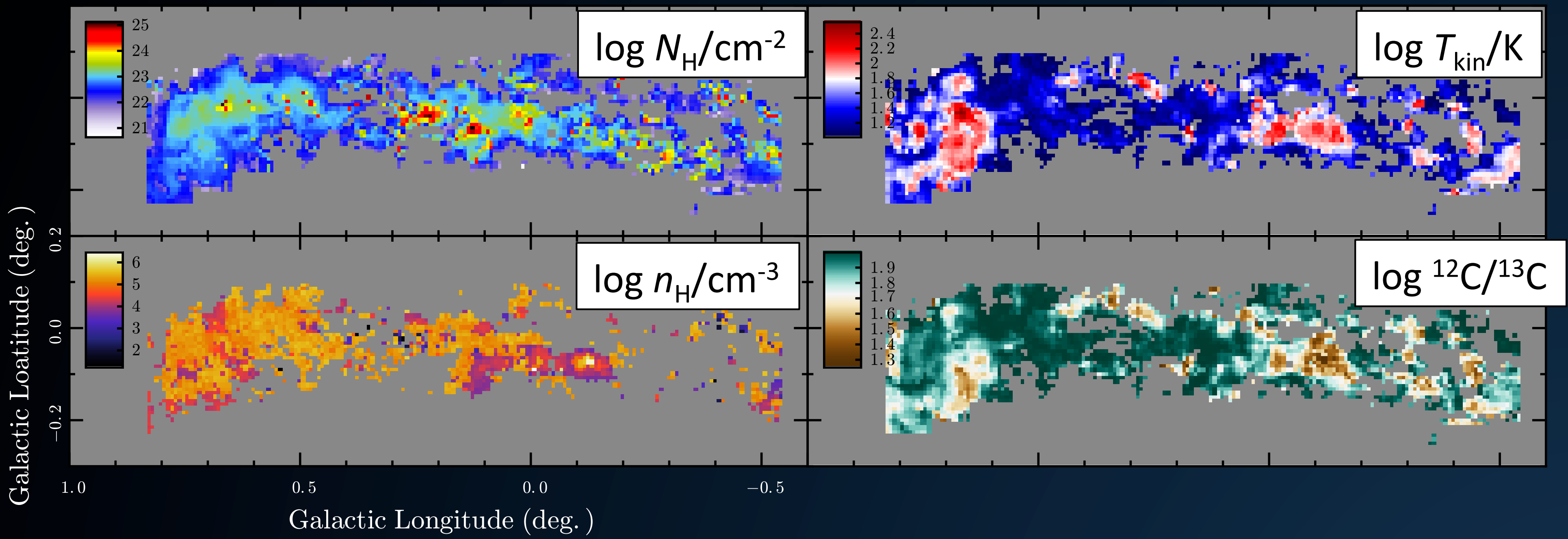
Marginal Posterior Probability

Eliminate `nuisance parameters' (e, θ) by performing integration

$$
\begin{aligned}
P\left(\boldsymbol{p}|\boldsymbol{I}\right) &= \int P\left(\boldsymbol{p},\boldsymbol{\epsilon},\boldsymbol{\theta}|\boldsymbol{I}\right)\cdot \mathrm{d}\boldsymbol{\epsilon}\cdot \mathrm{d}\boldsymbol{\theta} \\
&\propto \int P(\boldsymbol{I}|\boldsymbol{p},\boldsymbol{\epsilon})\cdot P\left(\boldsymbol{p},\boldsymbol{\epsilon}|\boldsymbol{\theta}\right)\cdot P\left(\boldsymbol{\theta}\right)\cdot \mathrm{d}\boldsymbol{\epsilon}\cdot \mathrm{d}\boldsymbol{\theta}
\end{aligned}
$$

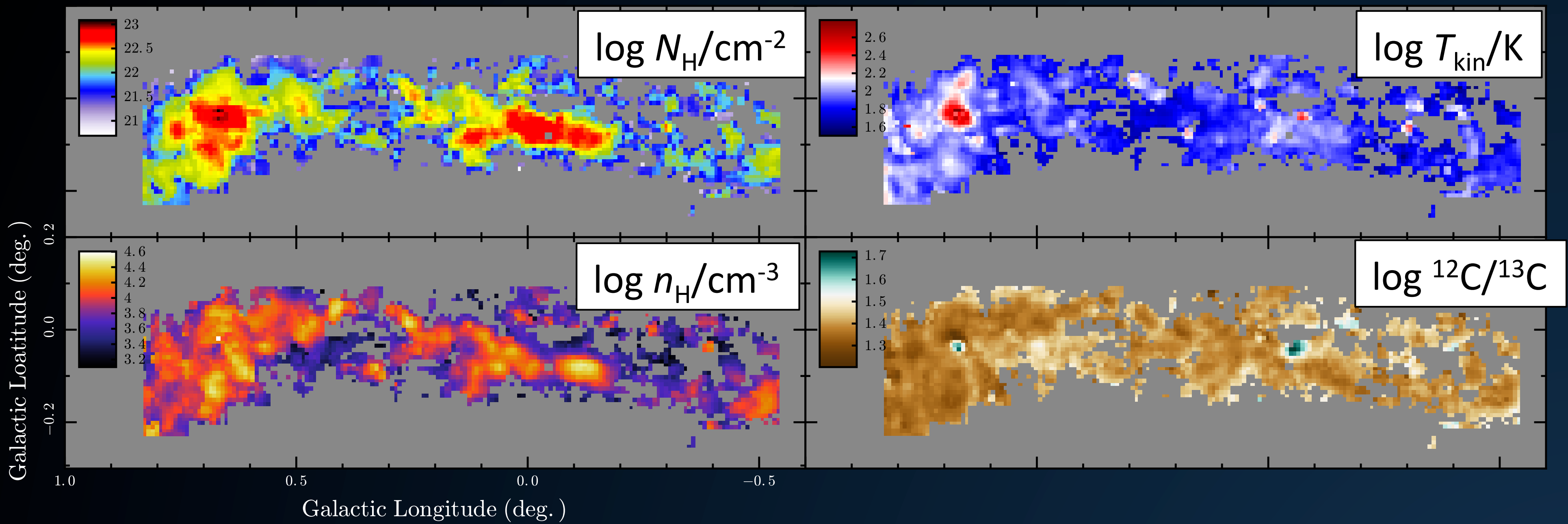
Integration is done using Marcov-Chain Monte Carlo (MCMC) method

ML Analysis



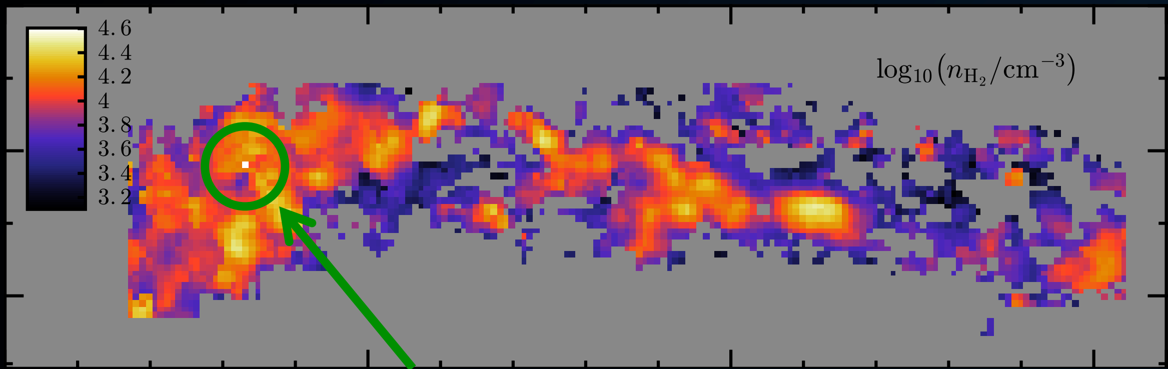
- *Severely affected by systematic errors due to calibration errors, spectral baseline noises, one-zone LVG approximation, ⋯*

HB Analysis (PDF median map)



- Artifacts are supressed

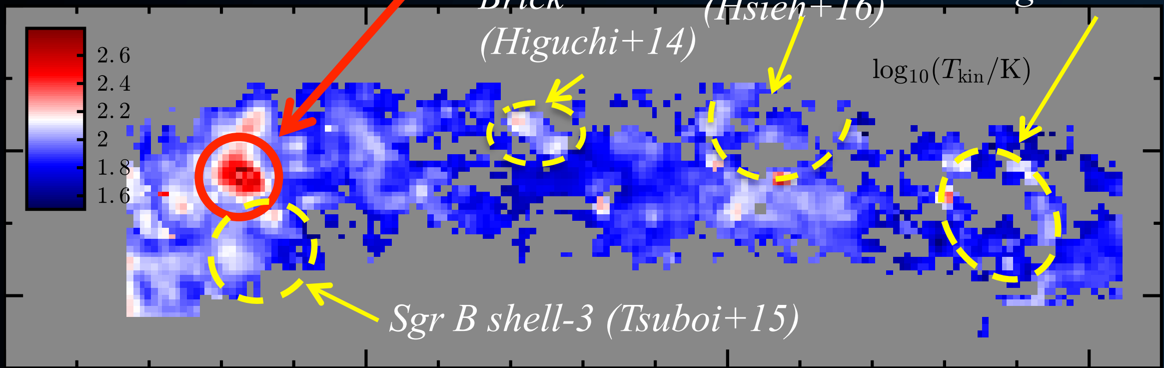
HB Analysis (PDF median map)



Volume density

No systematic difference between active SF regions and quiescent GMCs are detected (except for Sgr B2)

Sgr B2 cluster-forming region

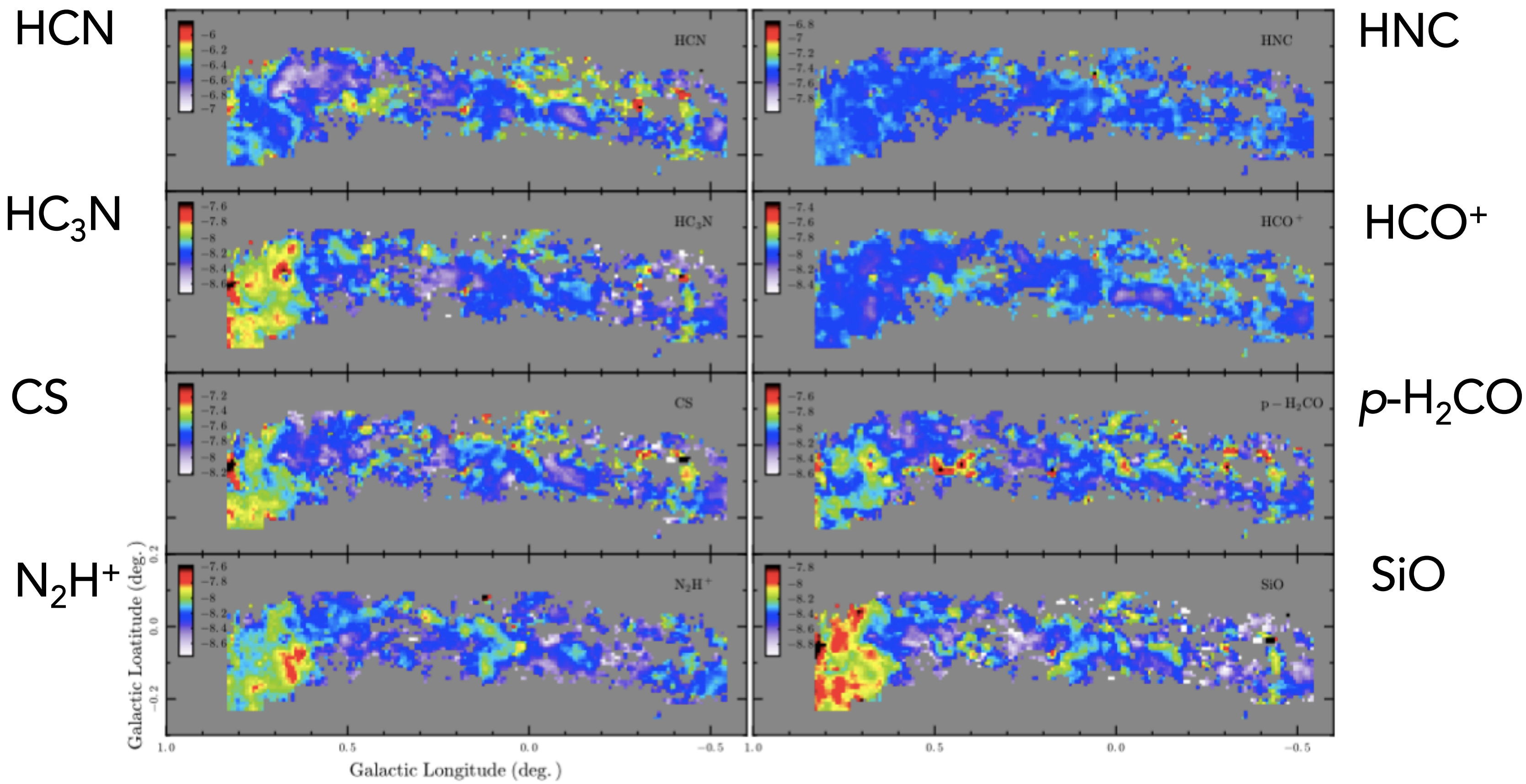


Gas Temperature

Warm regions without heating sources

→ Shock-heated gas

Molecular Abundance Map



Widespread Shock Chemistry

- Effects of shocks on the chemical & thermal processes in the GC clouds

Shock

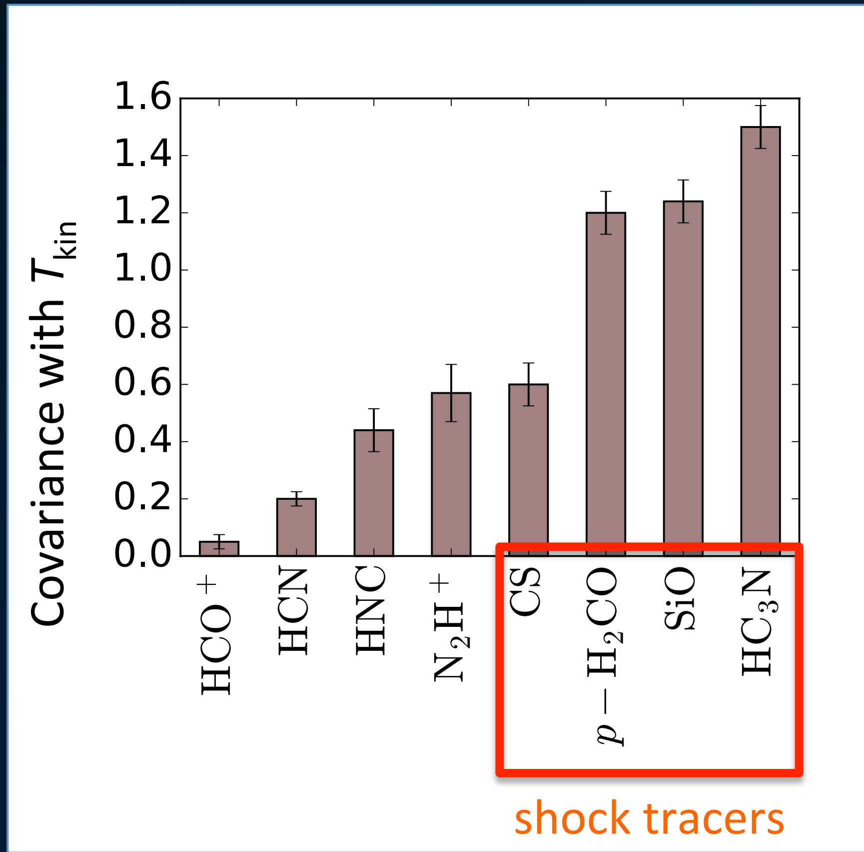
Mechanical Heating of Gas

Mechanical Sputtering of Dust Grain

V_{shock} > 20 km/s
Core sputtering
: SiO, CS

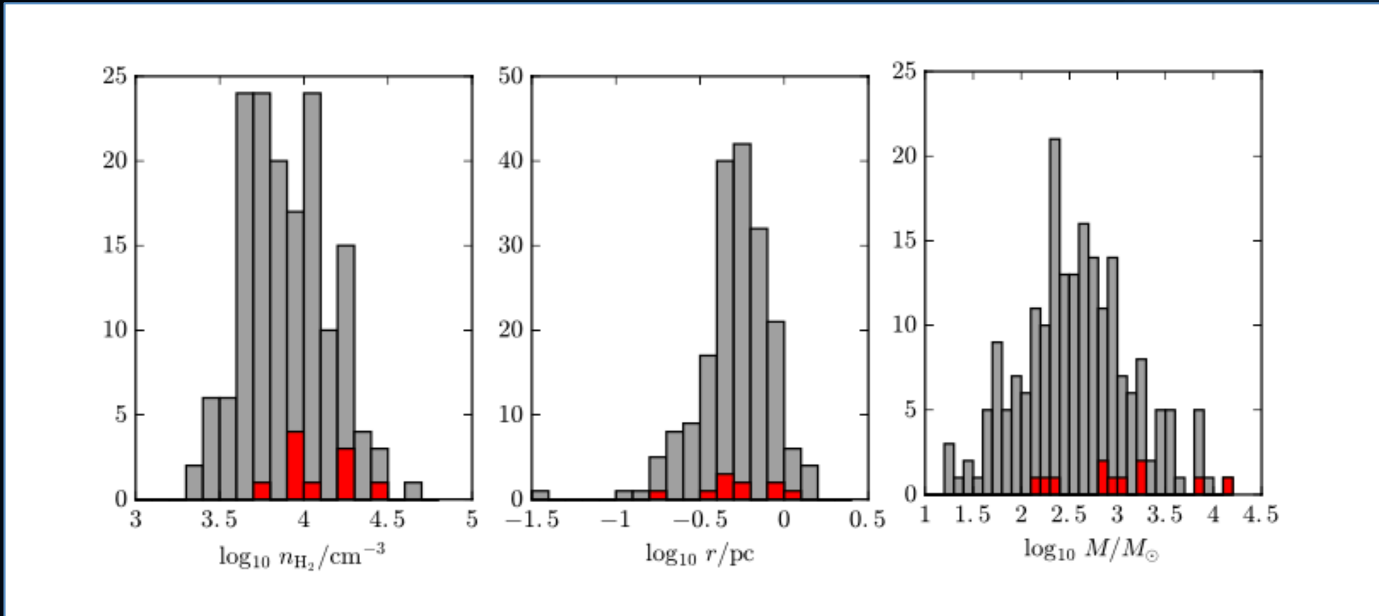
V_{shock} < 20 km/s
Mantle sputtering
: HC_3N, H_2CO

Requenna-Torres+06, Ao+13, Ginsburg+16

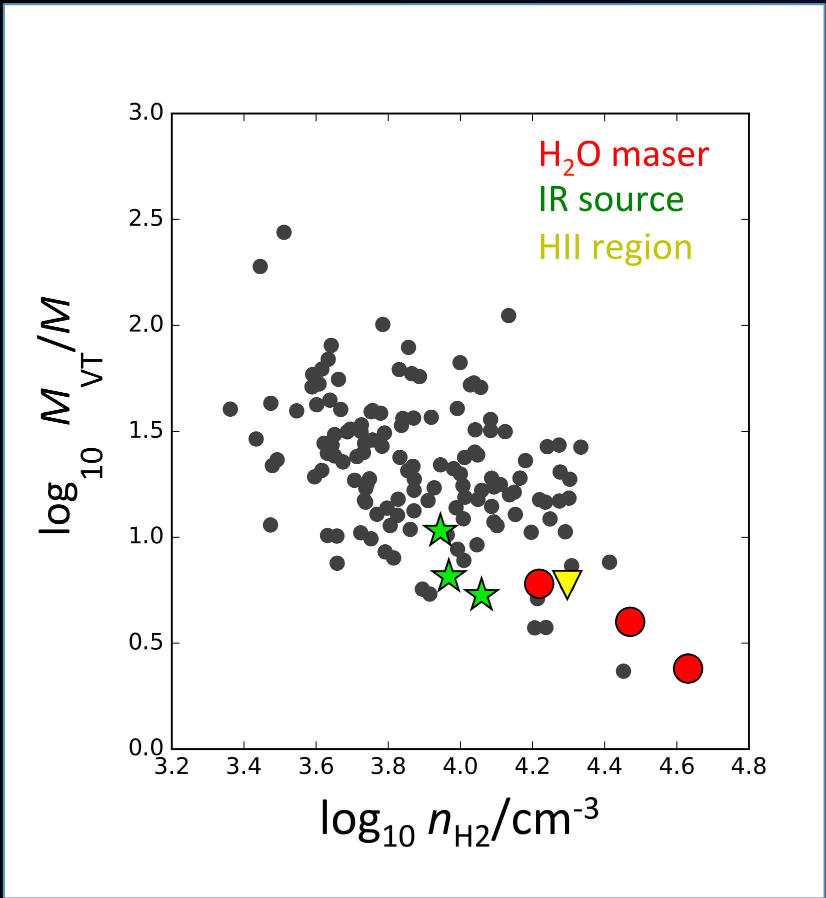


Physical Condition & Star Formation

- Identified 206 clumps from the HCN4-3 map
- Investigated correlation among *r*, d*v*, *M*, n_H, and T_kin



Principal Component & Linear Discrimination Analysis



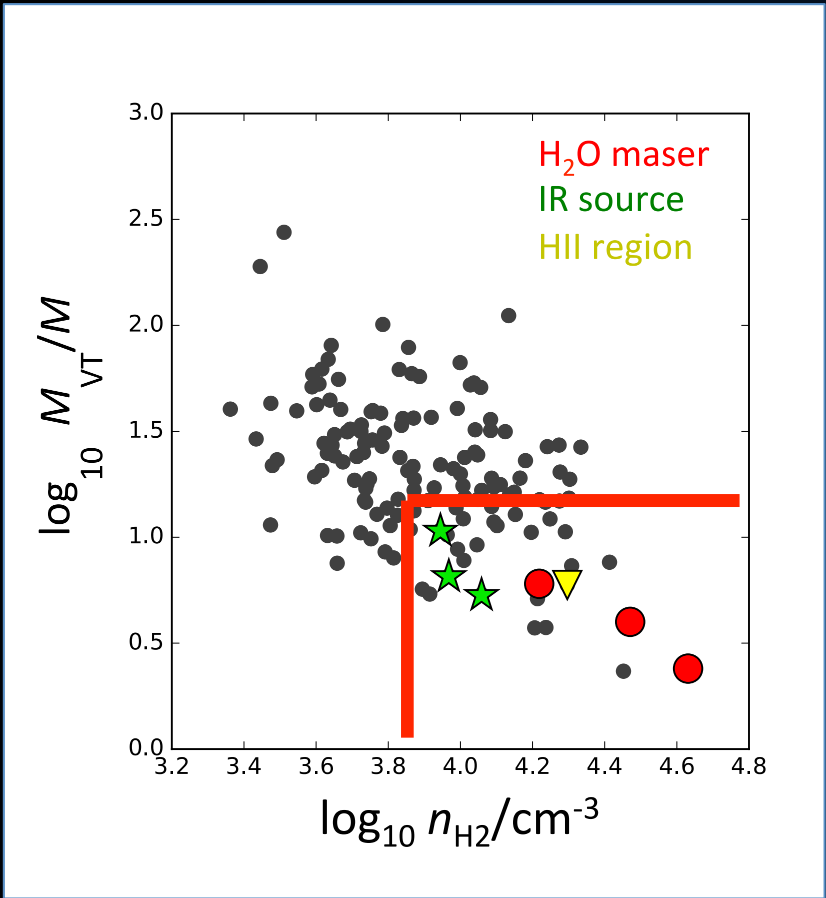
- Correlation 1: (PC5 = 0)

$$\boxed{r \cdot \Delta v^{1.15} \cdot M^{-0.71}} \cdot n_{\mathrm{H}_2}{}^{0.42} = Const.$$

Virial parameter $\alpha = r\, dv^2\, M^{-1}$ or

(Surface density per unit velocity)$^{-1}$

PCA & LDA results



- Correlation 1: (PC5 = 0)

$$\boxed{r \cdot \Delta v^{1.15} \cdot M^{-0.71}} \cdot n_{\mathrm{H}_2}{}^{0.42} = Const.$$

- Correlation 2:

$$\boxed{r \cdot \Delta v^{2.70} \cdot M^{-1.28}} \cdot n_{\mathrm{H}_2}{}^{-1.57} \sim P(SF)^{-1}$$

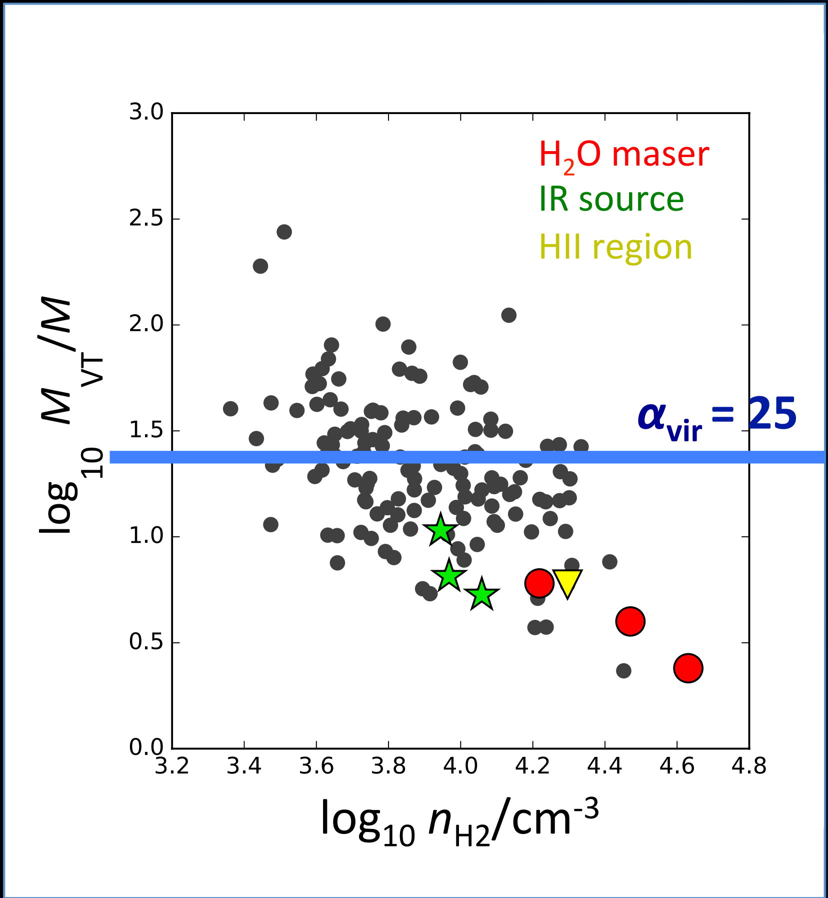
Virial parameter $\alpha = r\, dv^2\, M^{-1}$ or
(Surface density per unit velocity $)^{-1}$

- Qualitatively consistent with turbulent regulated SF

e.g. Krumoholz+05

Krumholz+05, Federrath+12

$$\frac{n_{\rm th}}{n_0} \sim \alpha_{\rm vir} \cdot \mathcal{M}^2 \cdot \left(1+\beta^{-1}\right)^{-1}$$



- n_{th} : threshold density
- n_0 : mean density ~ 10^4 cm^{-3}
- M : Mach Number ~ 20
- β : plasma beta ~ 0.1 (B=0.1 mG)
- α_{vir} : virial parameter ~ 25

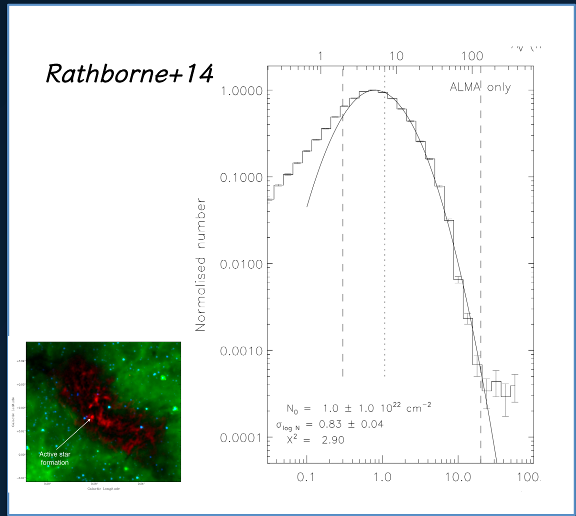
- n_{th} = 10^7 cm^{-3}
  (10^4 cm^{-3} for disk)
- critical overdensity factor ~ 10^3
  (10^2 for disk)

Reason of the low SFE in GC: *GC clouds are not dense enough to form stars against strong turbulent pressure support*

Potential Application of this Analysis

- Higher resolution analysis using ALMA data
  - density measurement of < 0.1 pc scale resolution data
  - Volume density PDF, detection of high density cores

- Application for extragalactic SF region



Summary

- Volume density distribution in 3-D (2-D in space + 1-D in velocity) space is calculated for the MW's central molecular zone
- New method using Hierarchical Bayesian Analysis is adopted for volume density measurement
- Effects of shocks on the thermal valance and molecular chemistry are confirmed
- Clumps with low virial parameter / high volume density tend to have higher probability of having SF signatures
- GC clumps are not dense enough to form stars against strong turbulent pressure support