

分子雲で見る天の川

鳥居 和史（国立天文台/野辺山宇宙電波観測所）

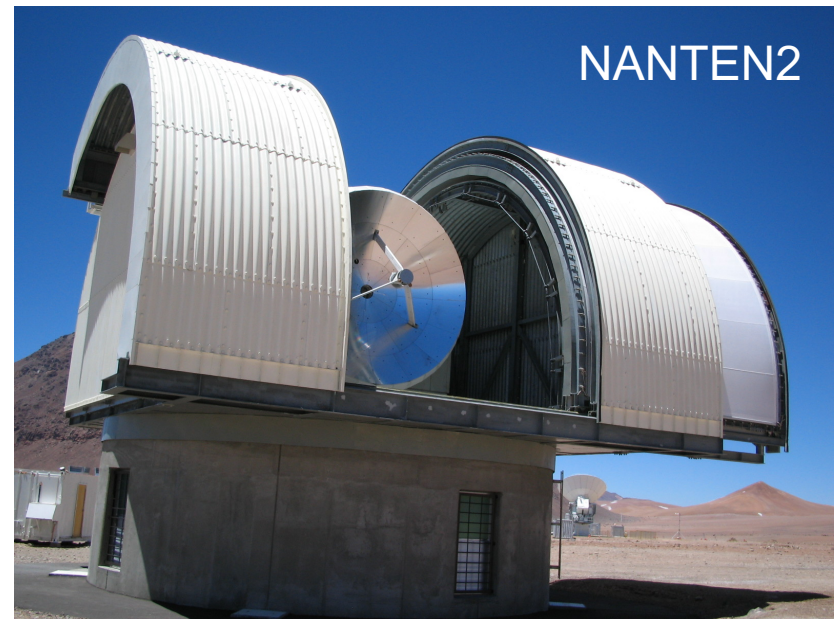
kazufumi.torii@nao.ac.jp

自己紹介

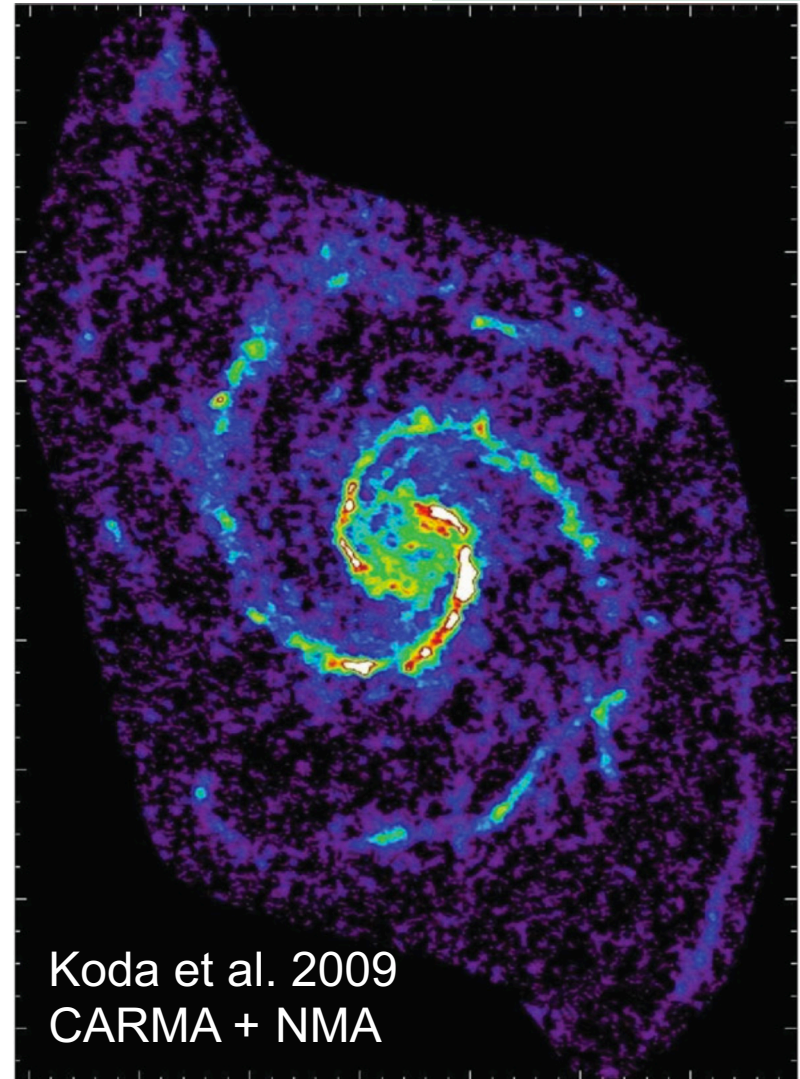
- 名古屋大学・A研
 - NANTEN2望遠鏡（チリ）
- 野辺山宇宙電波観測所
 - 45m電波望遠鏡

今日の話

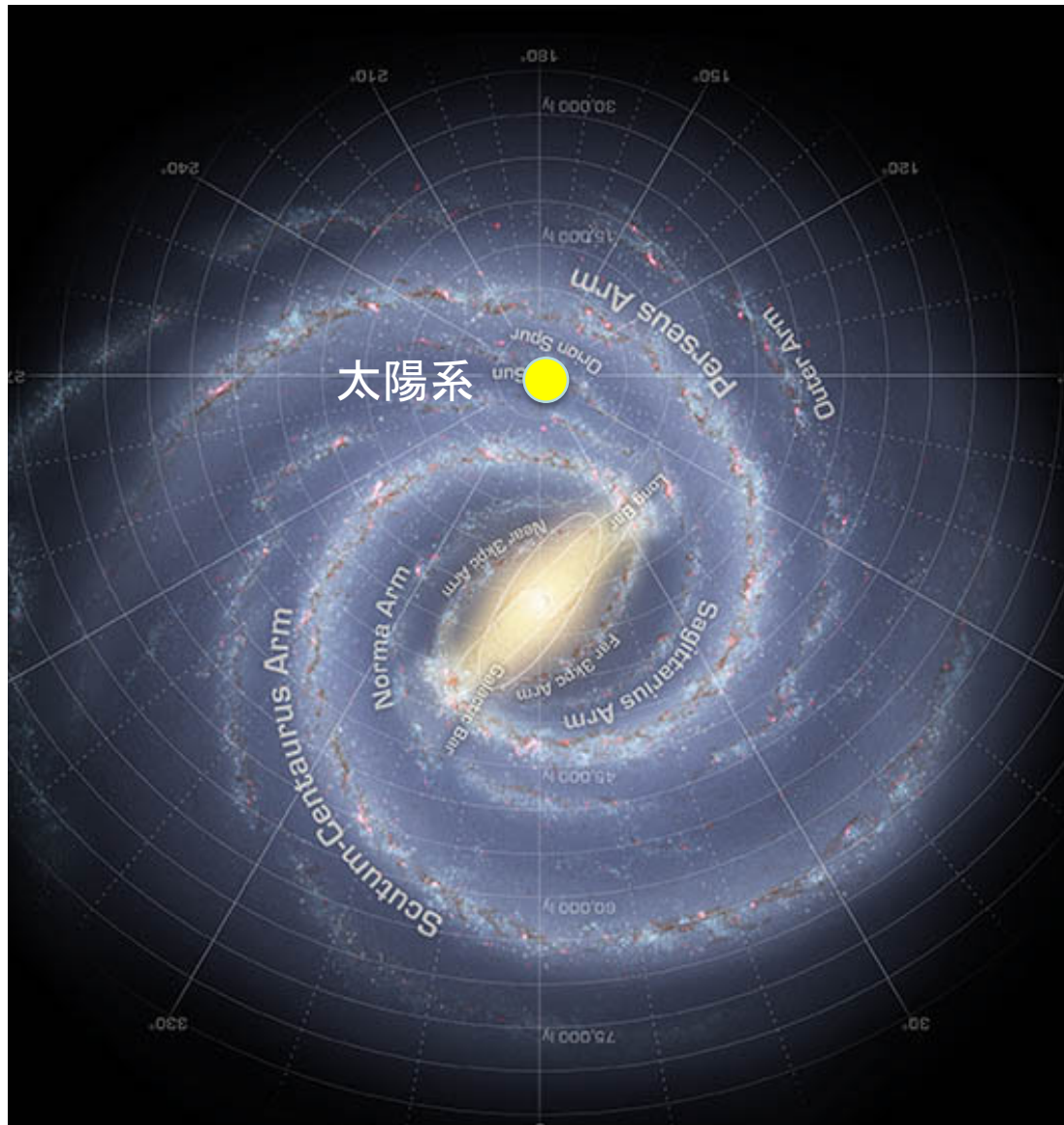
- 天の川の分子雲
 - 特にCOサーベイ
- 分子雲衝突と大質量星形成



分子雲

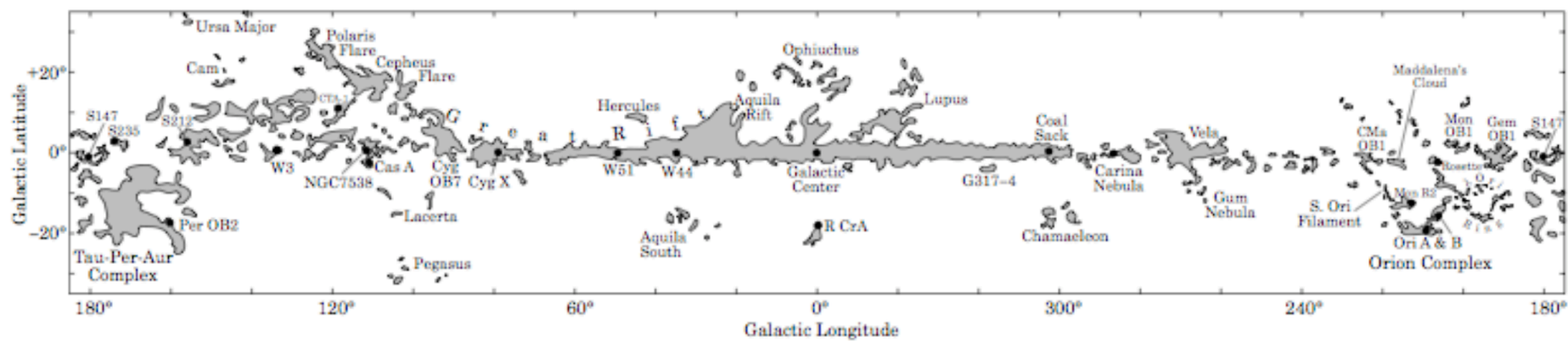
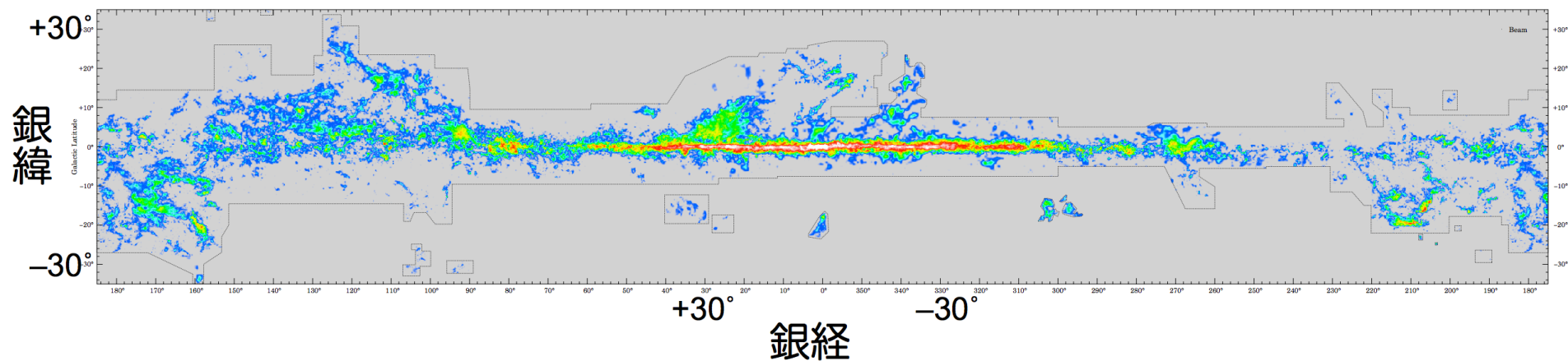


天の川銀河 (MilkyWay or MW)



- 全長： $3 \times 10^4 \text{ pc}$
- 太陽系から中心までの距離： 8500 pc
- 棒渦巻銀河

天の川の分子雲



Dame et al. 1987

天の川の分子雲

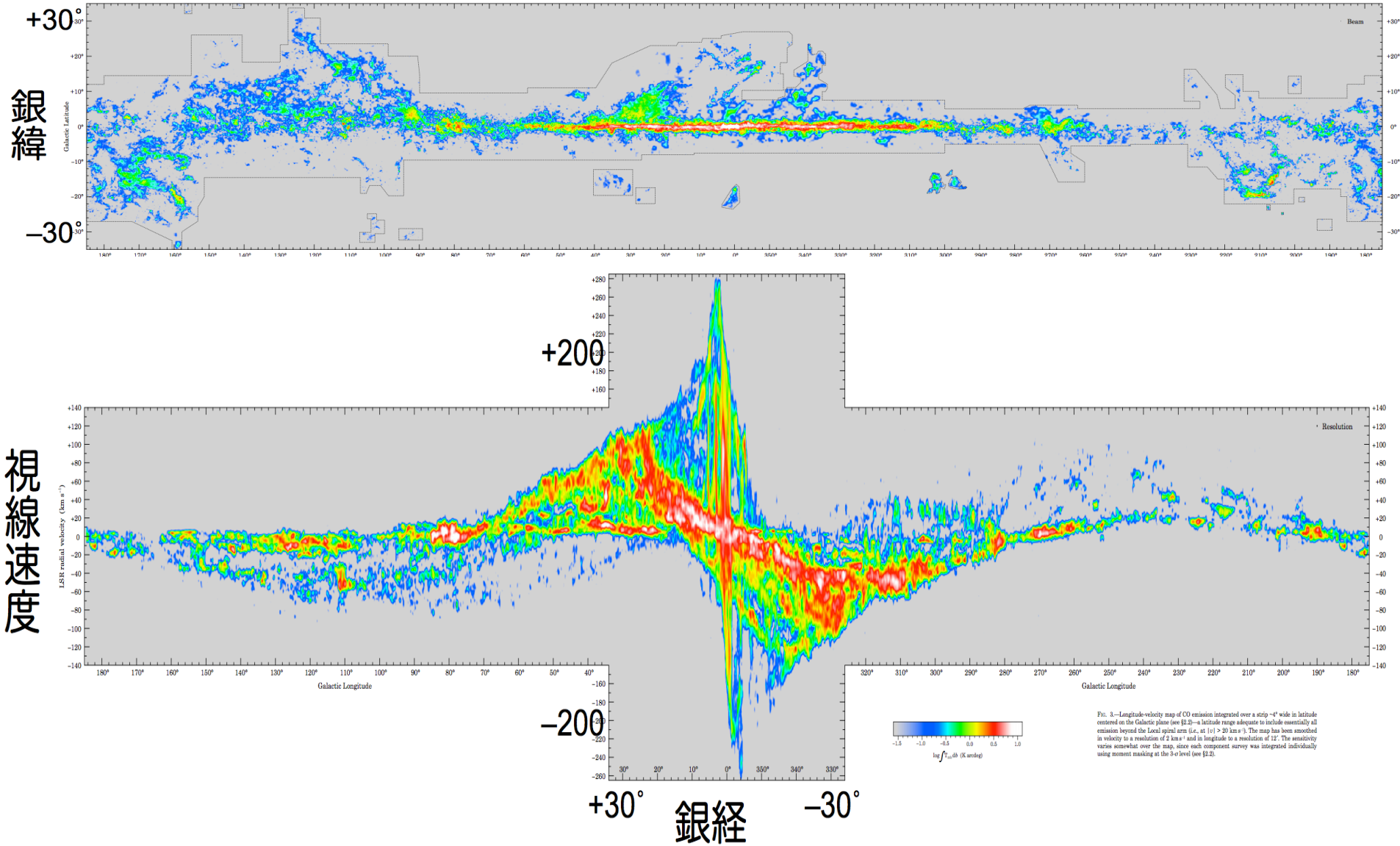
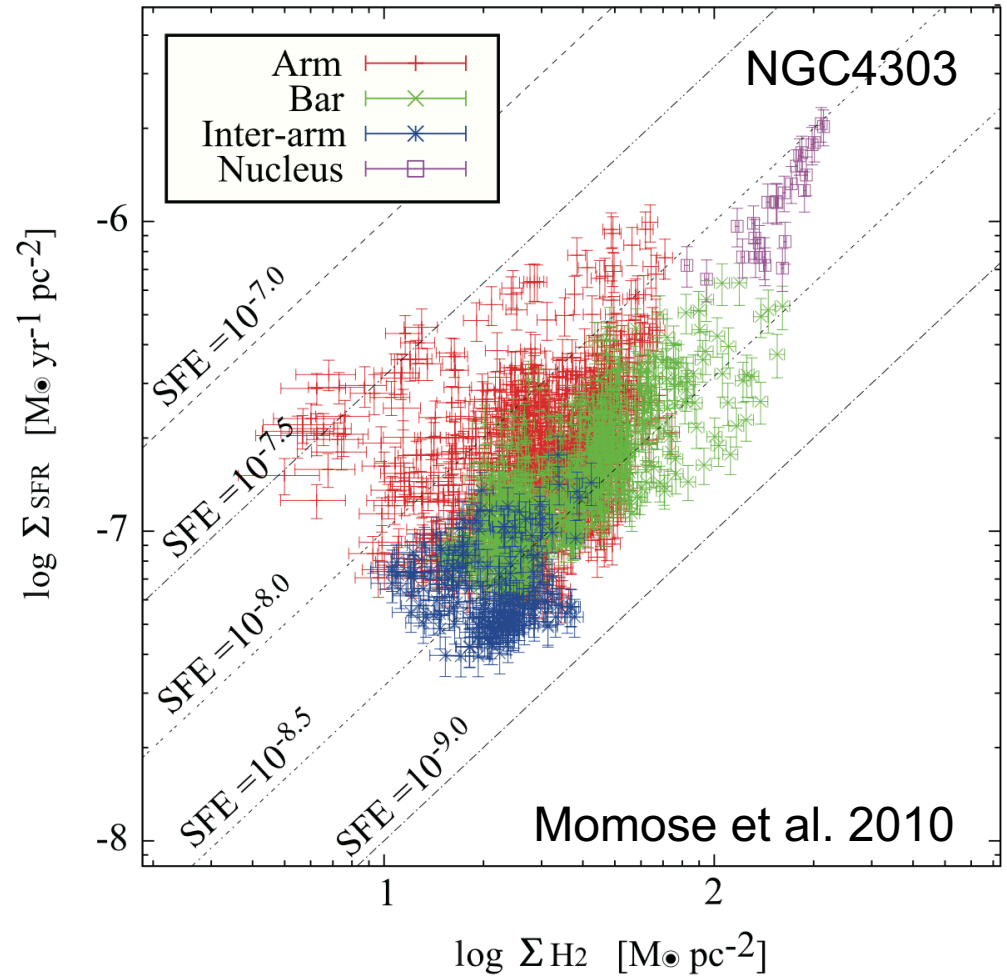
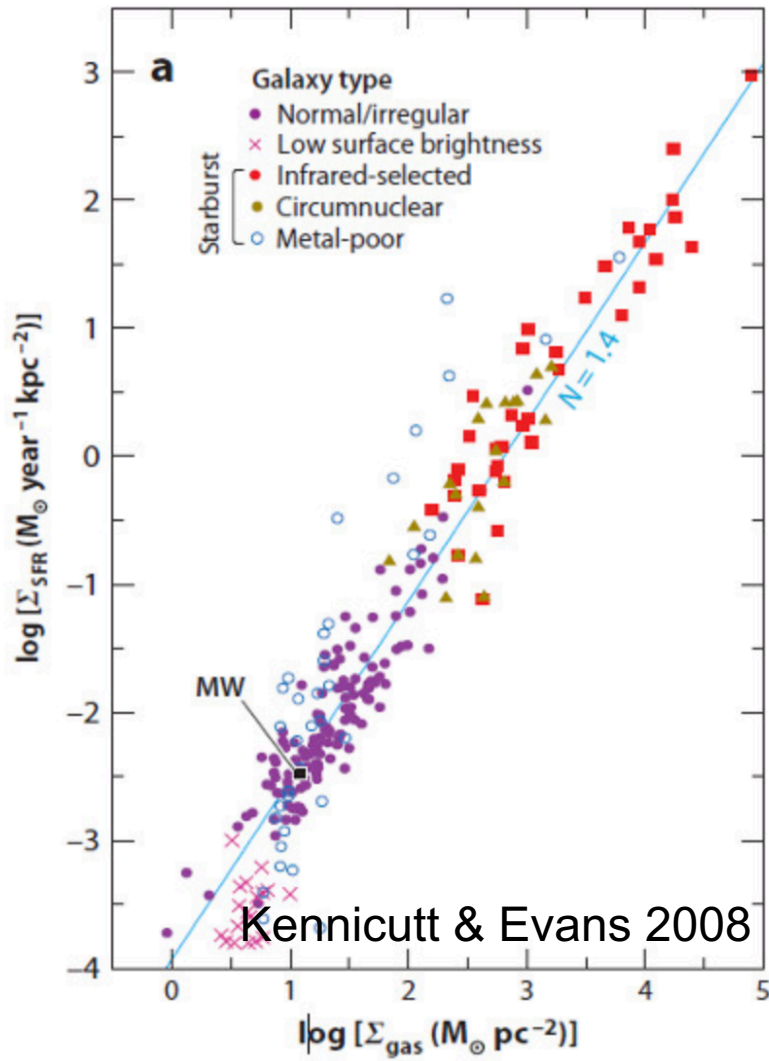


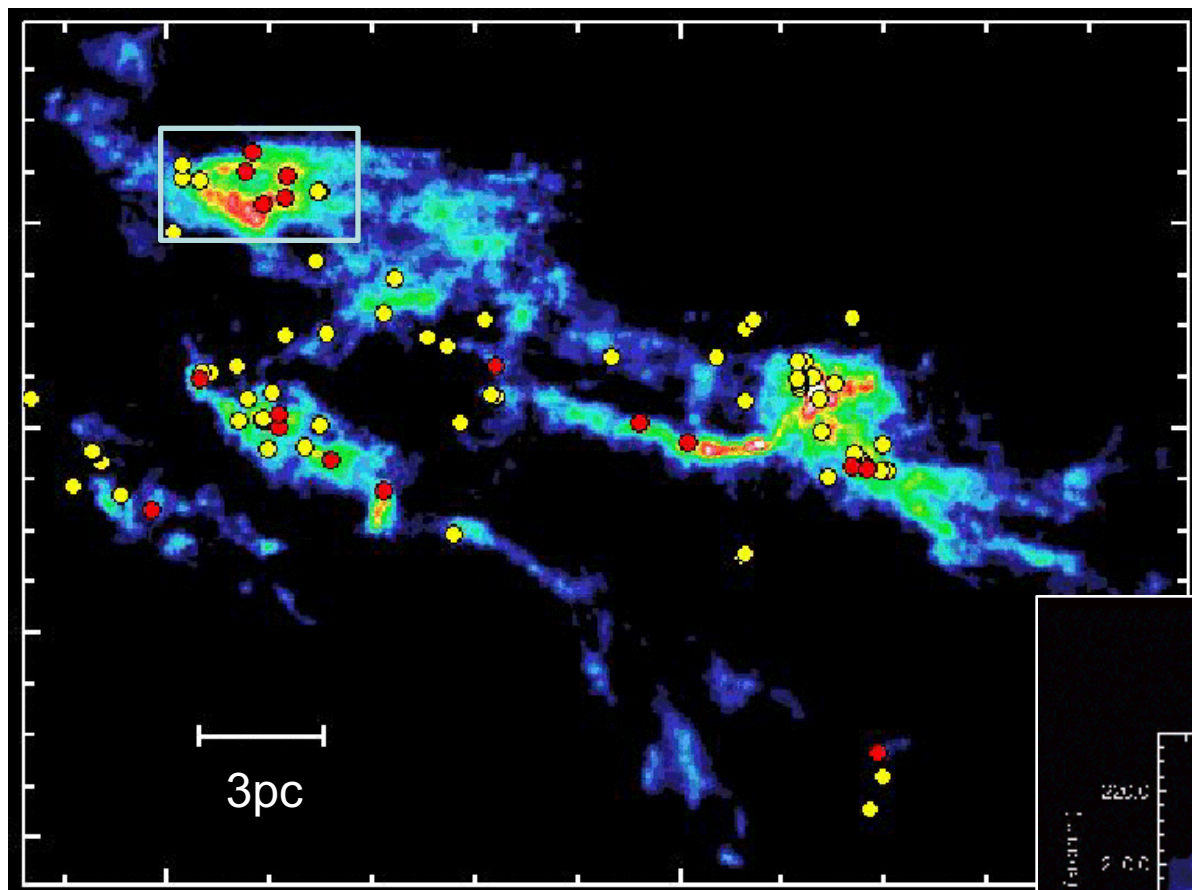
FIG. 3.—Longitude-velocity map of CO emission integrated over a strip $\sim 4^\circ$ wide in latitude centered on the Galactic plane (see §2.2)—a latitude range adequate to include essentially all emission beyond the Local spiral arm (i.e., at $|l| > 20^\circ$). The map has been smoothed in velocity to a resolution of 2 km s $^{-1}$ and in longitude to a resolution of $12'$. The sensitivity varies somewhat over the map, since each component survey was integrated individually using moment masking at the 3σ level (see §2.2).

銀河スケールの星形成; Kennicutt–Schmidt(KS)則

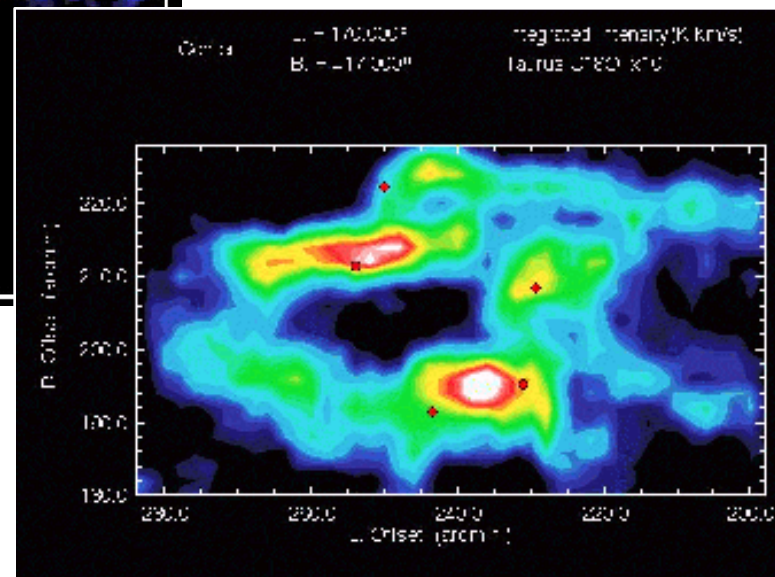


- ガスの面密度と星形成率（星形成の活発さ）との密接な関係
- 一方で銀河内では領域間で差

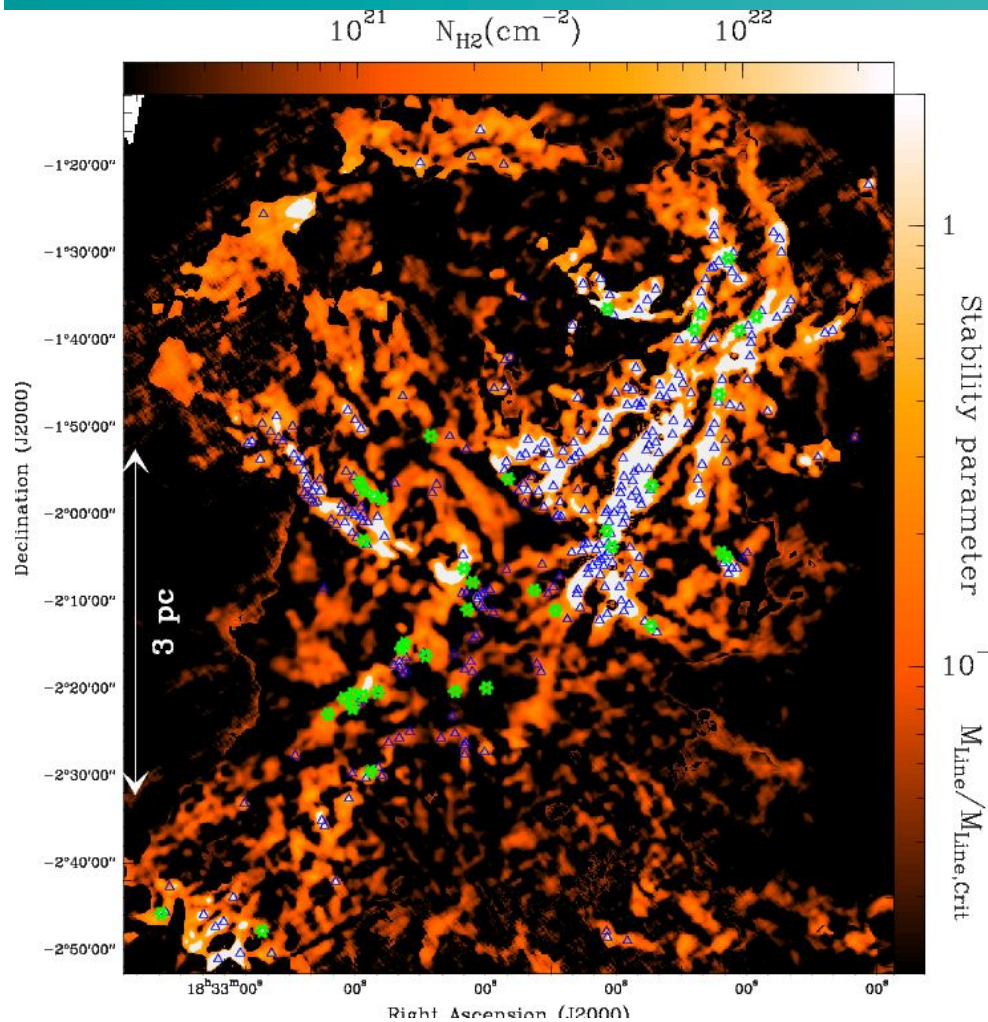
個々の分子雲中の星形成



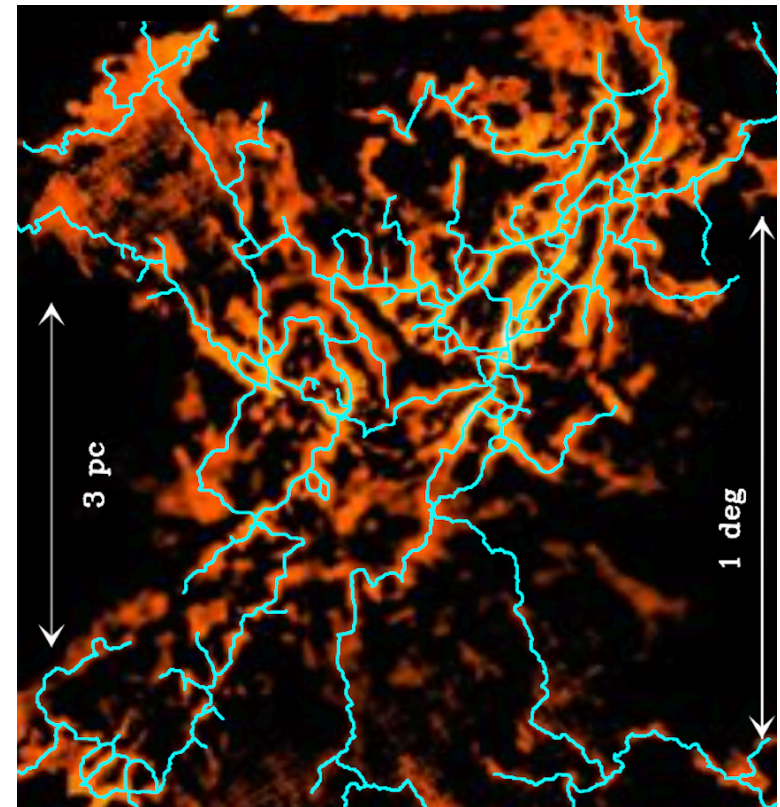
- おうし座分子雲
- 距離: 140pc
- 分子雲コア探査



個々の分子雲中の星形成



Andre et al. 2010



- 赤外線衛星Herschelの星間ダスト観測
- 幅0.1pcのフィラメント ($N_{\text{H}_2} > 7 \times 10^{21} \text{cm}^{-2}$, or $A_V > 8 \text{ mag.}$)の中で分子雲コア進化 → 星形成

天の川銀河の分子雲研究

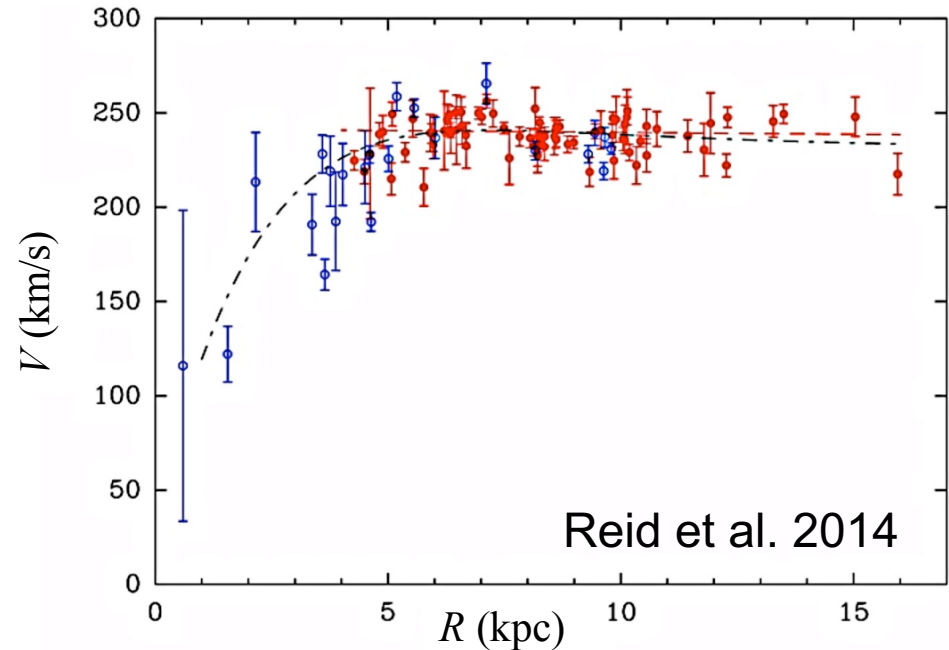
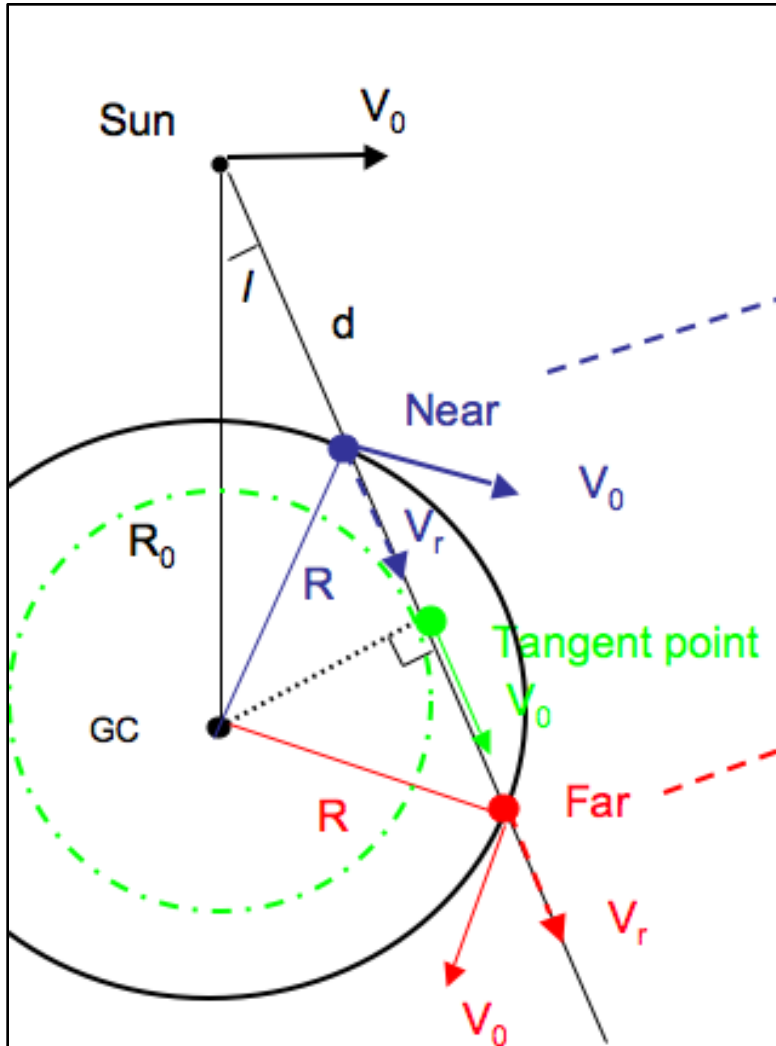
望み

- ・ 天の川銀河の星形成と星形成に関連する星間現象を明らかにしたい
- ・ 銀河一般の中での天の川銀河の位置付けを明らかにしたい
- ・ そのために天の川公式の分子雲データが欲しい

実態

- ・ 距離の問題が避け難く…
- ・ 分解能と観測範囲の両立の困難さ

天の川(銀河面)での距離の推定(運動学的距離)

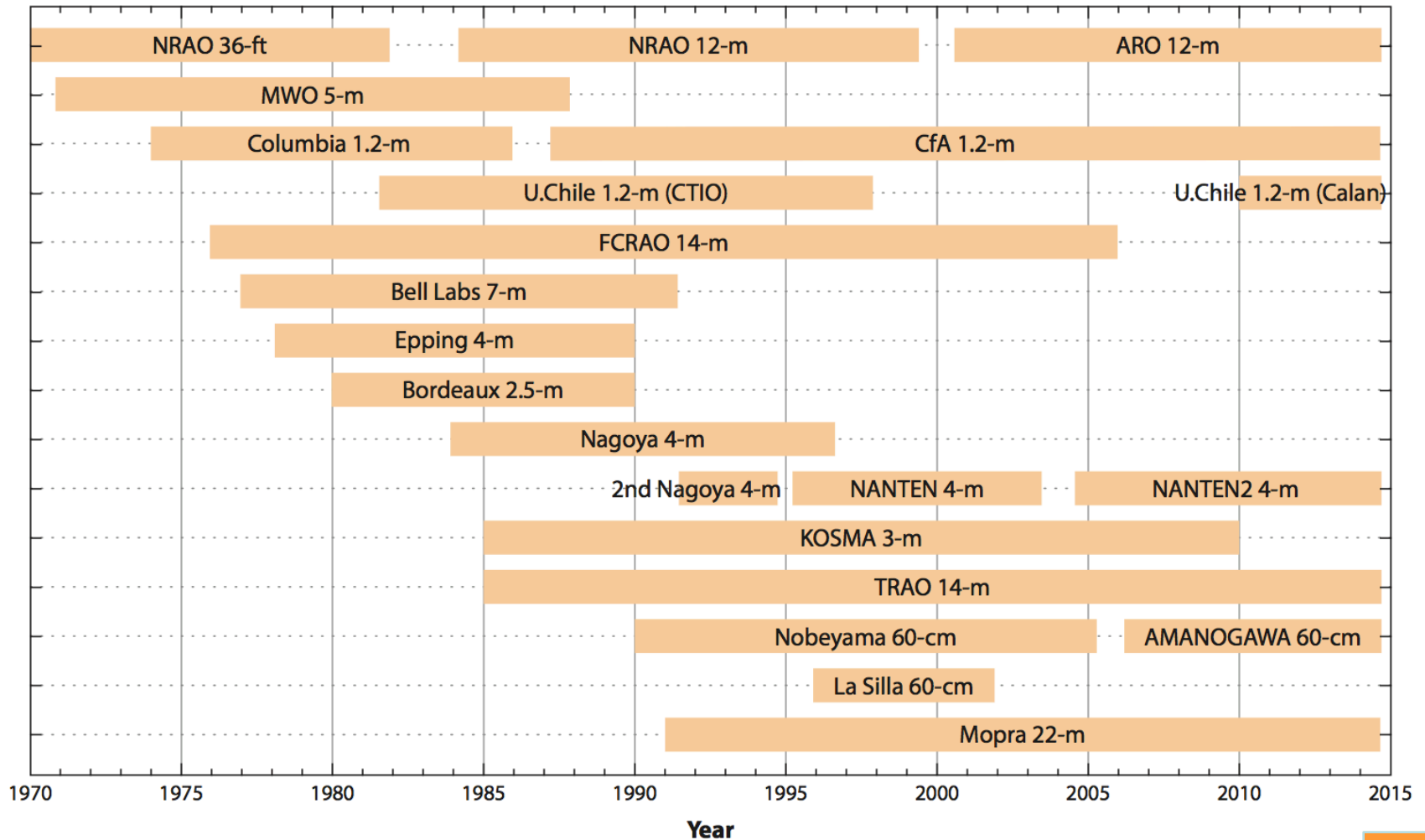


- 銀河の回転曲線から距離を推定
- 観測された輝線の視線速度と比較
- 問題点：Near-sideとFar-sideの2つの解が得られる
- 他の観測データと比較してNear or Farを解くなど



天の川(銀河面)COサーベイ

天の川COサーベイの歴史



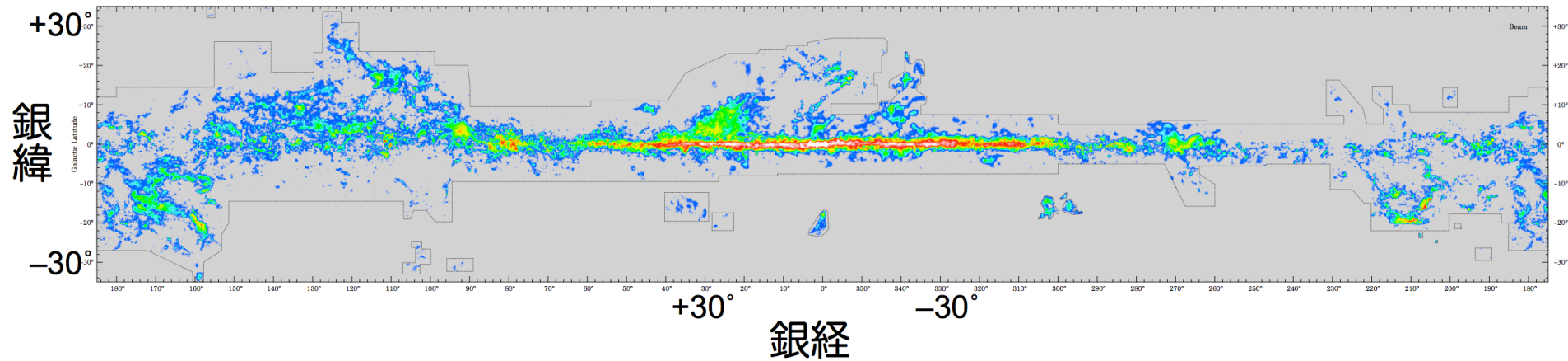
Heyer & Dame (2015)

FUGIN

ラインの選択

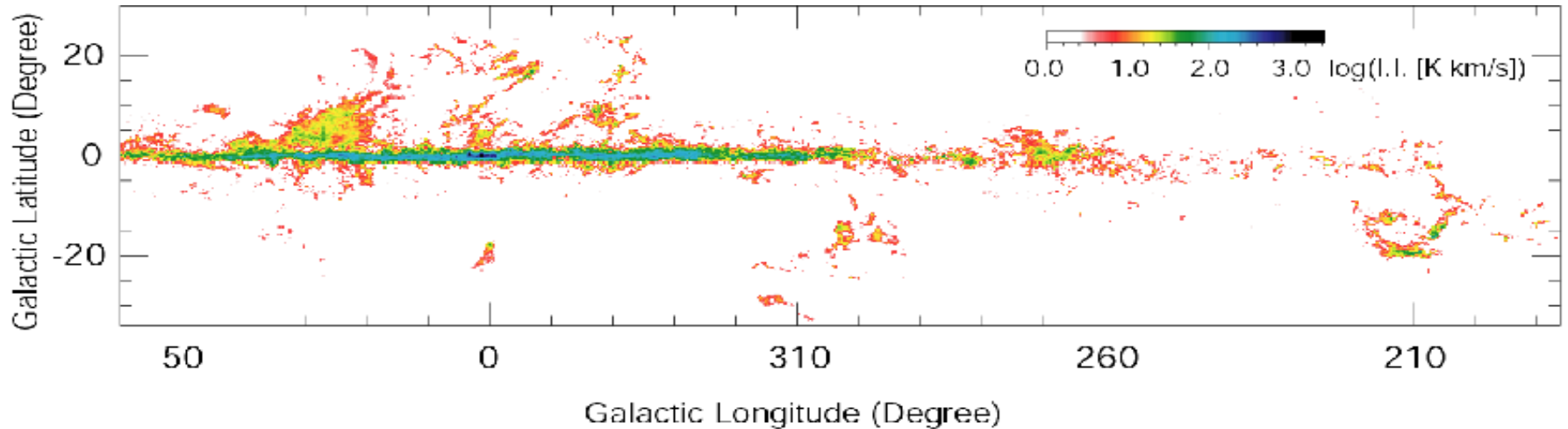
- ^{12}CO J=1-0 (115GHz)
 - 基本のライン。分子ガスの質量を測定(X-factor; Bolatto+13)。
- ^{13}CO J=1-0 (110GHz)
 - 基本のライン2。分子雲の比較的濃い場所。 ^{12}CO J=1-0と比べ空の条件が良い。
- C^{18}O J=1-0 (109GHz)
 - 星形成を伴うような分子雲の濃い領域に感度。
- CO J=3-2 (345GHz付近)
 - 分子雲の温度に敏感。 CO J=1-0データと比較して物理量（温度・密度）を推計（non-LTE解析）
 - 10-15m級の望遠鏡でも分解能20''を達成できる。
- CO J=2-1 (230GHz付近)

CfAサーベイ; Dame et al. (2001)



- CfA 1.2m
- ^{12}CO J=1-0
- もっとも多く使われている銀河面COサーベイデータ
- HPBW $\sim 8.6'$
- Grid size $\sim 8' - 16'$

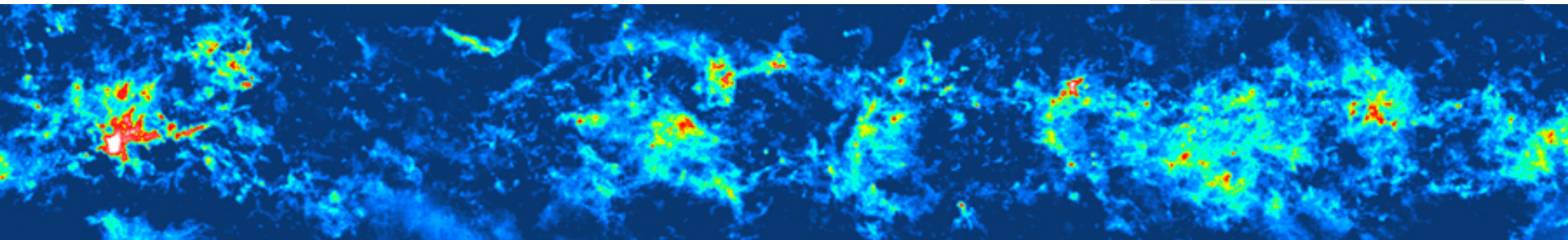
NANTENサーベイ



- NANTEN 4m
- $^{12}\text{CO } J=1-0$
- HPBW $\sim 2.6'$
- Grid size $\sim 2' - 4'$
- Galactic longitude $190^\circ - 60^\circ$

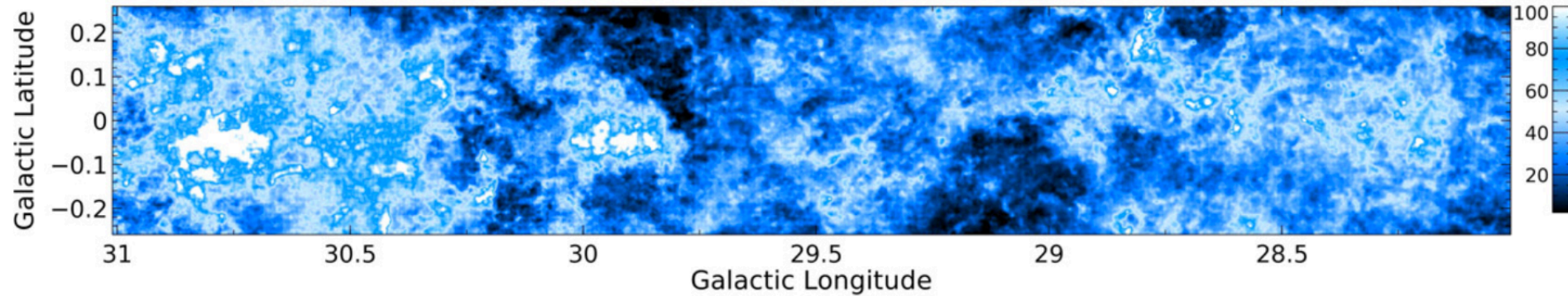


FCRAOサーベイ (Jackson et al. 2006)



- FCRAO 14m (Galactic Ring Survey; GRS)
- ^{13}CO J=1-0
- HPBW $\sim 46''$ (or $0.76''$)
- Nyquist sampling
- Galactic longitude $18^\circ - 55^\circ$
- Galactic latitude $-1^\circ - +1^\circ$

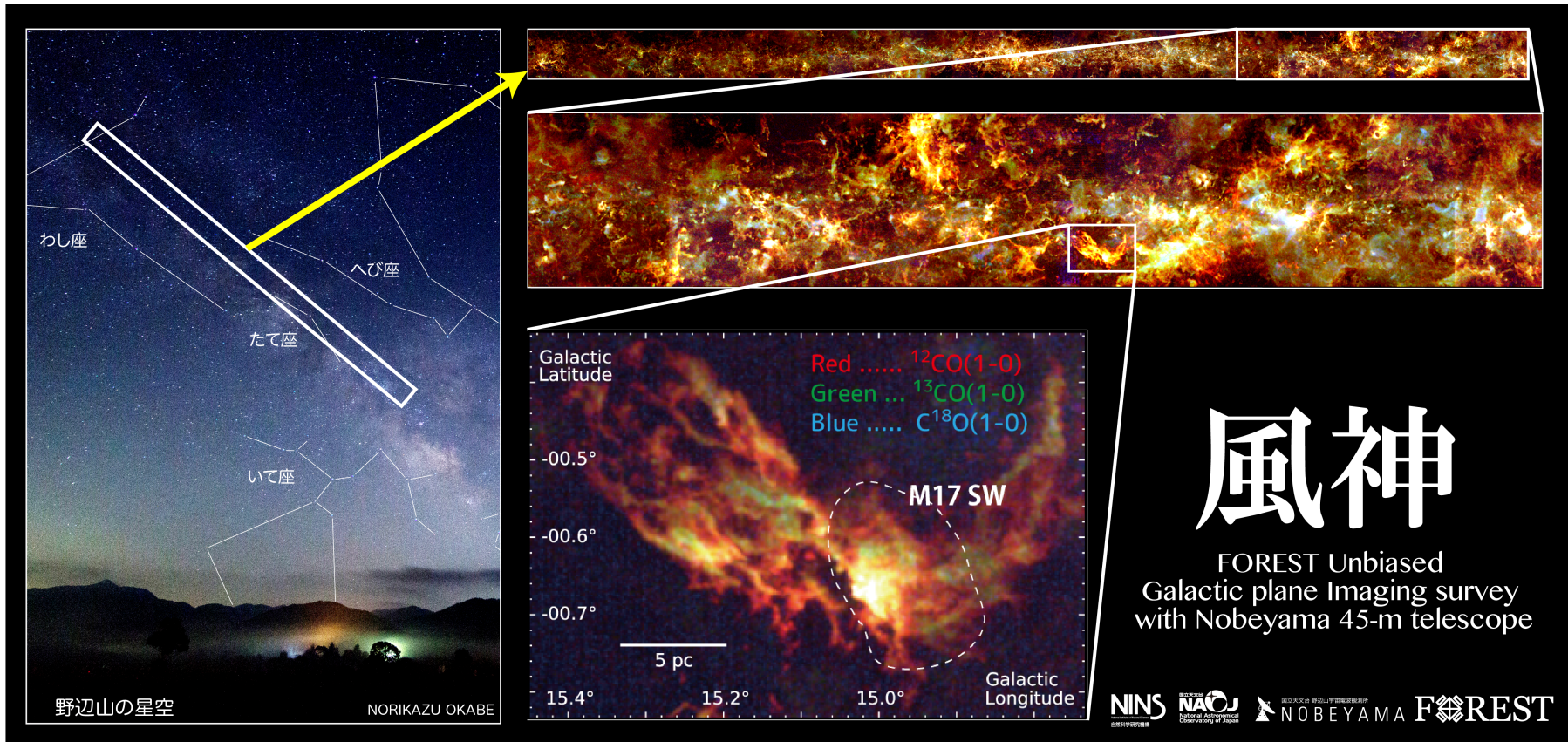
JCMTサーベイ (Dempsey+2013; Rigby+2016)



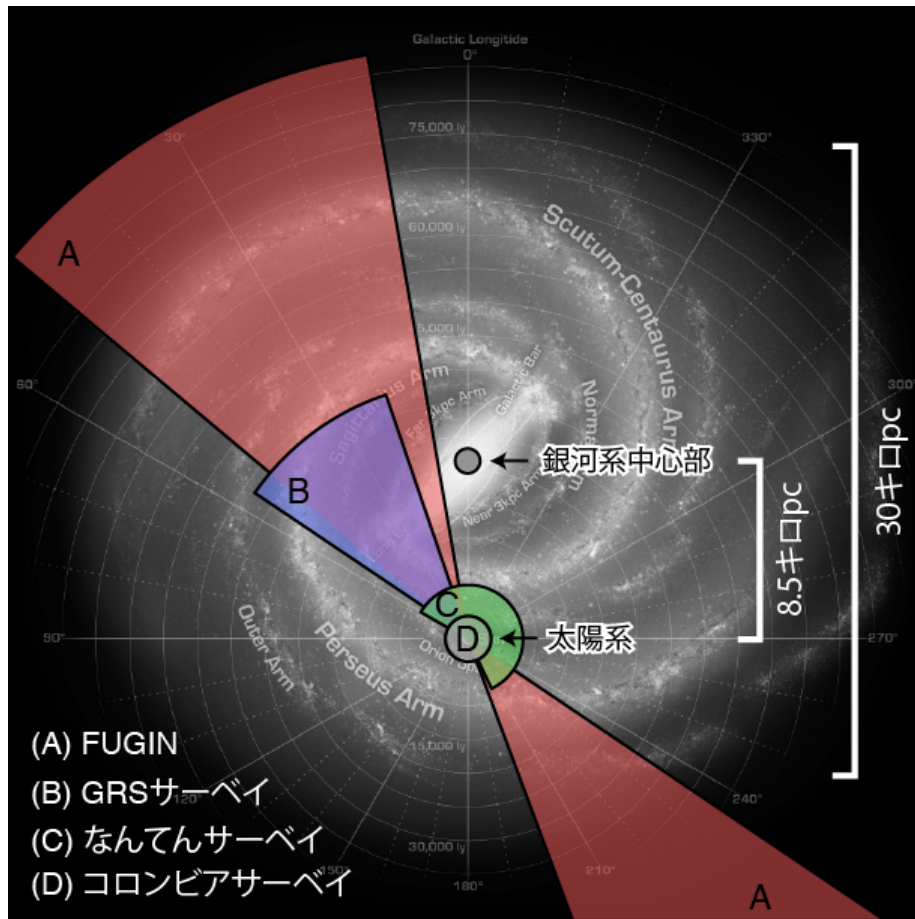
- JCMT 15m
- ^{12}CO J=3-2 (COHRS)
- ^{13}CO & C^{18}O J=3-2 (CHIMPS, CHIMPS2)
- HPBW $\sim 14''$
- Nyquist sampling
- Galactic longitude $10^\circ - 65^\circ$
- Galactic latitude $-0.25^\circ - +0.25^\circ, -0.5^\circ - +0.5^\circ$

NRO45mサーベイ FUGIN計画

FOREST Unbiased Galactic plane Imaging survey
with Nobeyama 45-m telescope



NRO45mサーベイ FUGIN計画



各サーベイが分解能2pc以下を達成できる範囲



- ^{12}CO , ^{13}CO , C^{18}O J=1-0
- HPBW $\sim 20''$ (or $0.33'$)
- Nyquist sampling
- $L \sim 10^\circ - 50^\circ, 198^\circ - 236^\circ$
- $B \sim -1^\circ - +1^\circ$

Japanese Virtual Observatory (JVO)でデータ公開中

<http://jvo.nao.ac.jp/portal/nobeyama/>

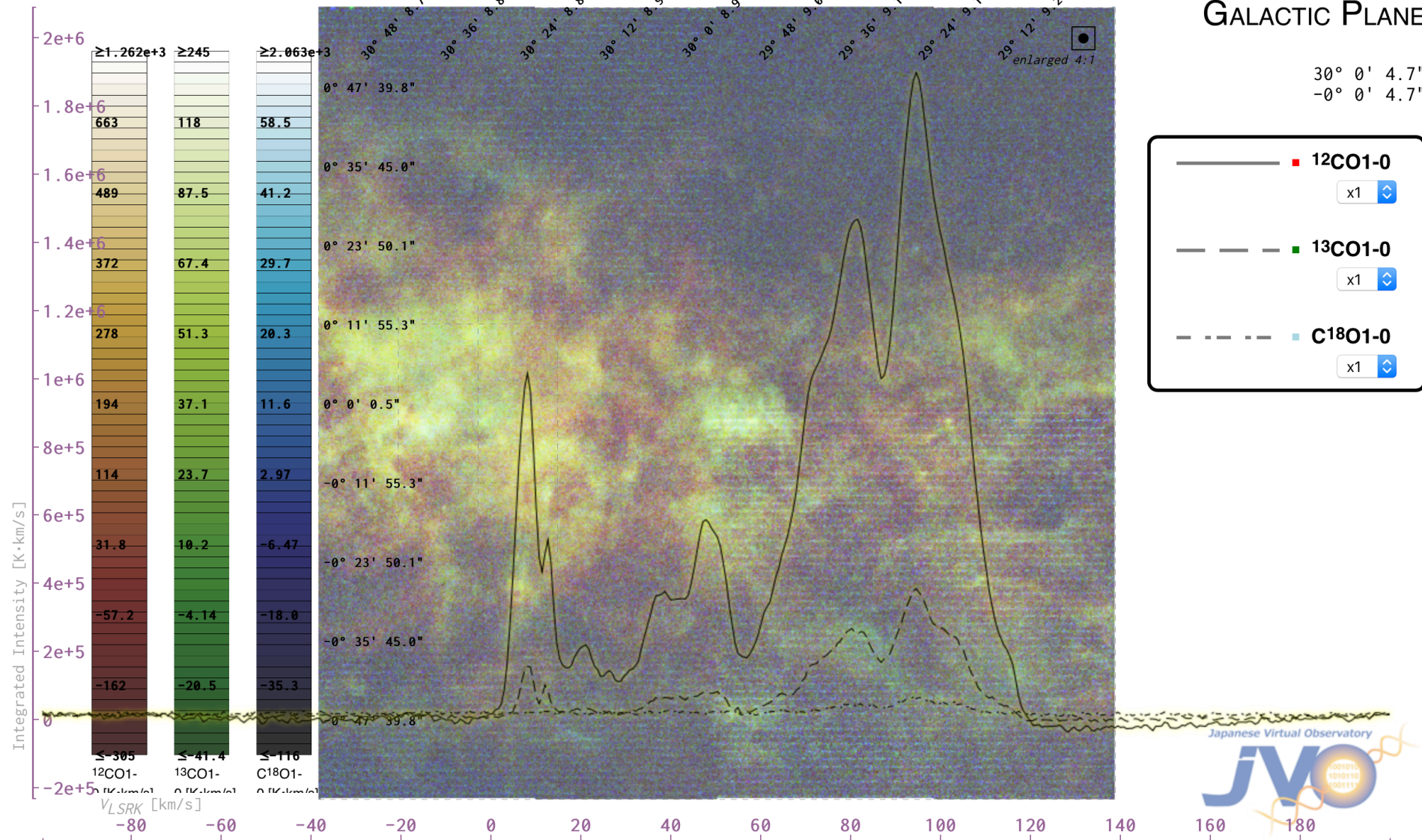
webQL on JVO

n/w latency: 28 ms fps: 36

SETTINGS

GALACTIC PLANE

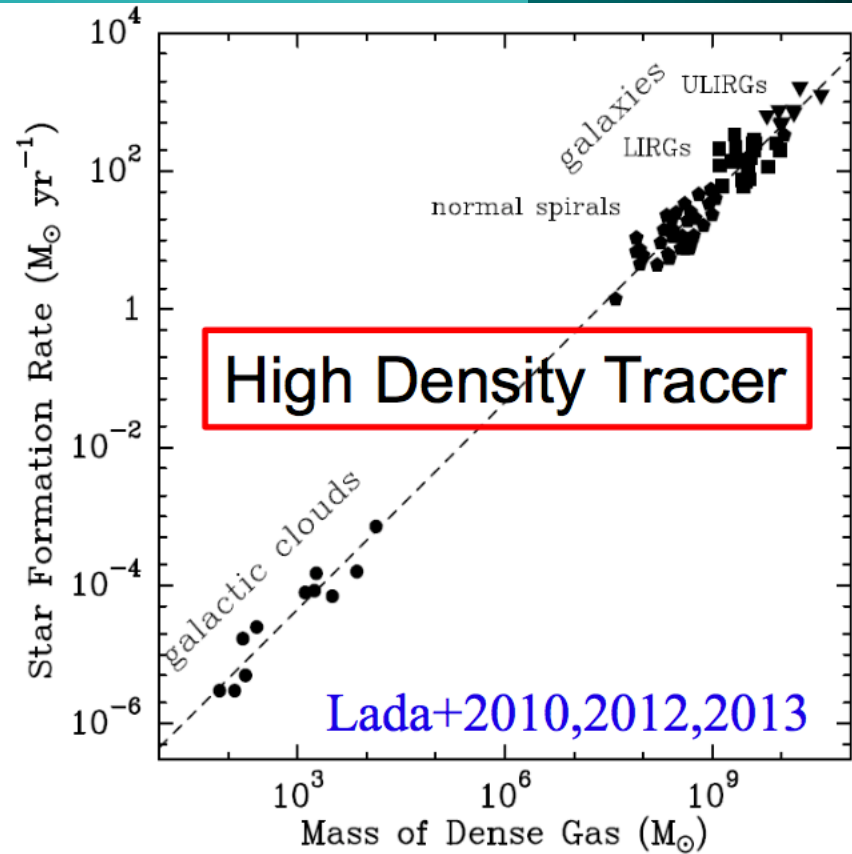
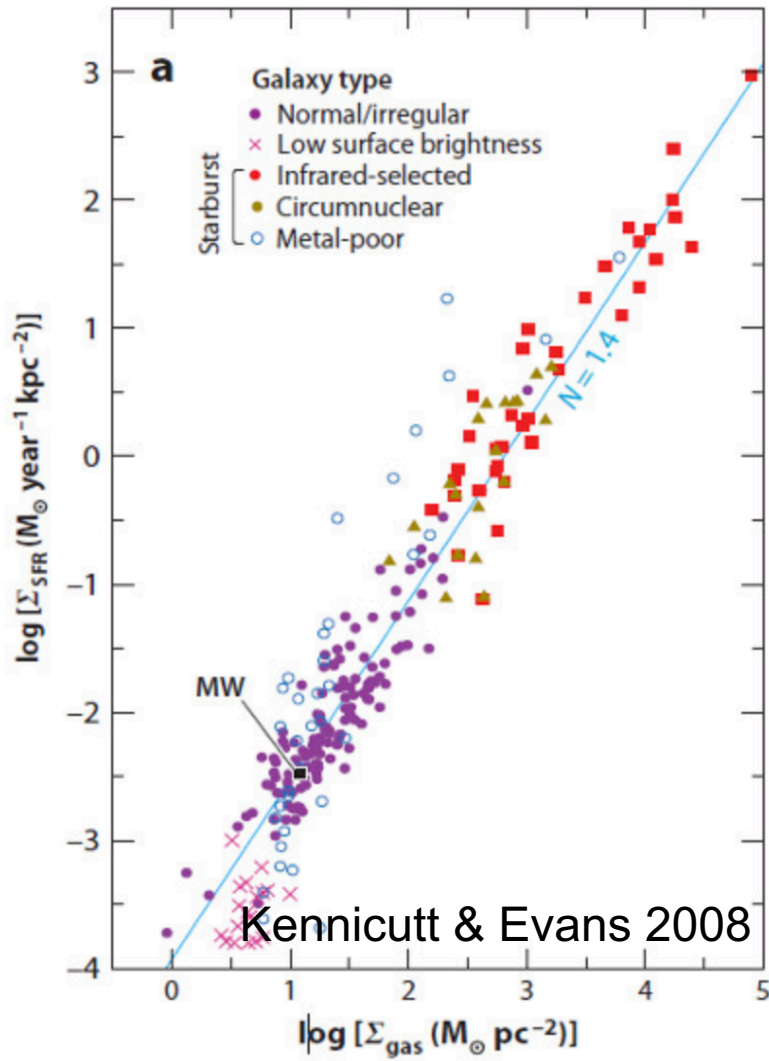
30° 0' 4.7"
-0° 0' 4.7"





FUGIN広域データ解析

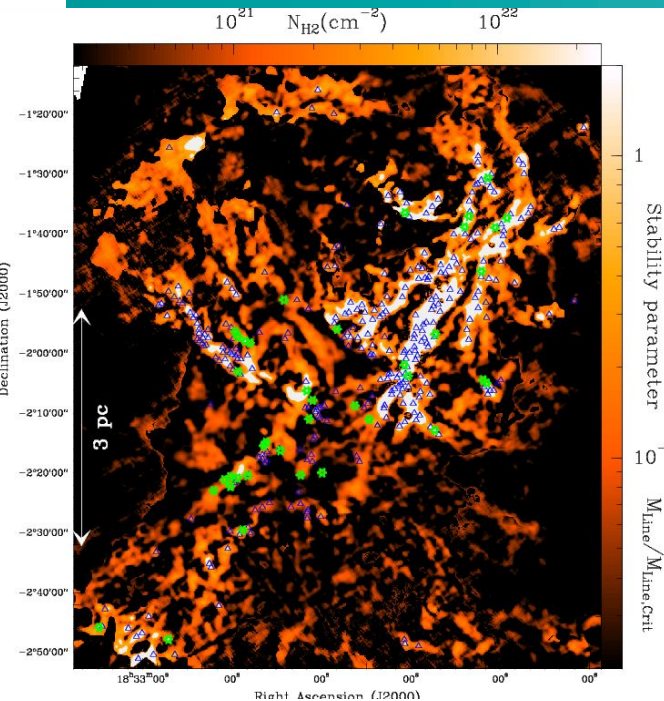
Kennicutt–Schmidt(KS)則



- Timescale: $M/(\text{SFR}) \sim 20\text{Myr}$
- See also Gao & Solomon 2004;
Wu+2005; Bigiel+2008,2010,2011,
Shimajiri+2017, etc.

Timescale: $\Sigma_{\text{gas}} / \Sigma_{\text{SFR}} \sim \text{Gyr}$

Star formation efficiency in dense gas



- Herschel Observation (e.g., Andre+14; Konyves+15)

$$M_{\text{core}} / M_{\text{filament}} < 15\%$$
- Star formation efficiency in Dense core: ϵ_{core}

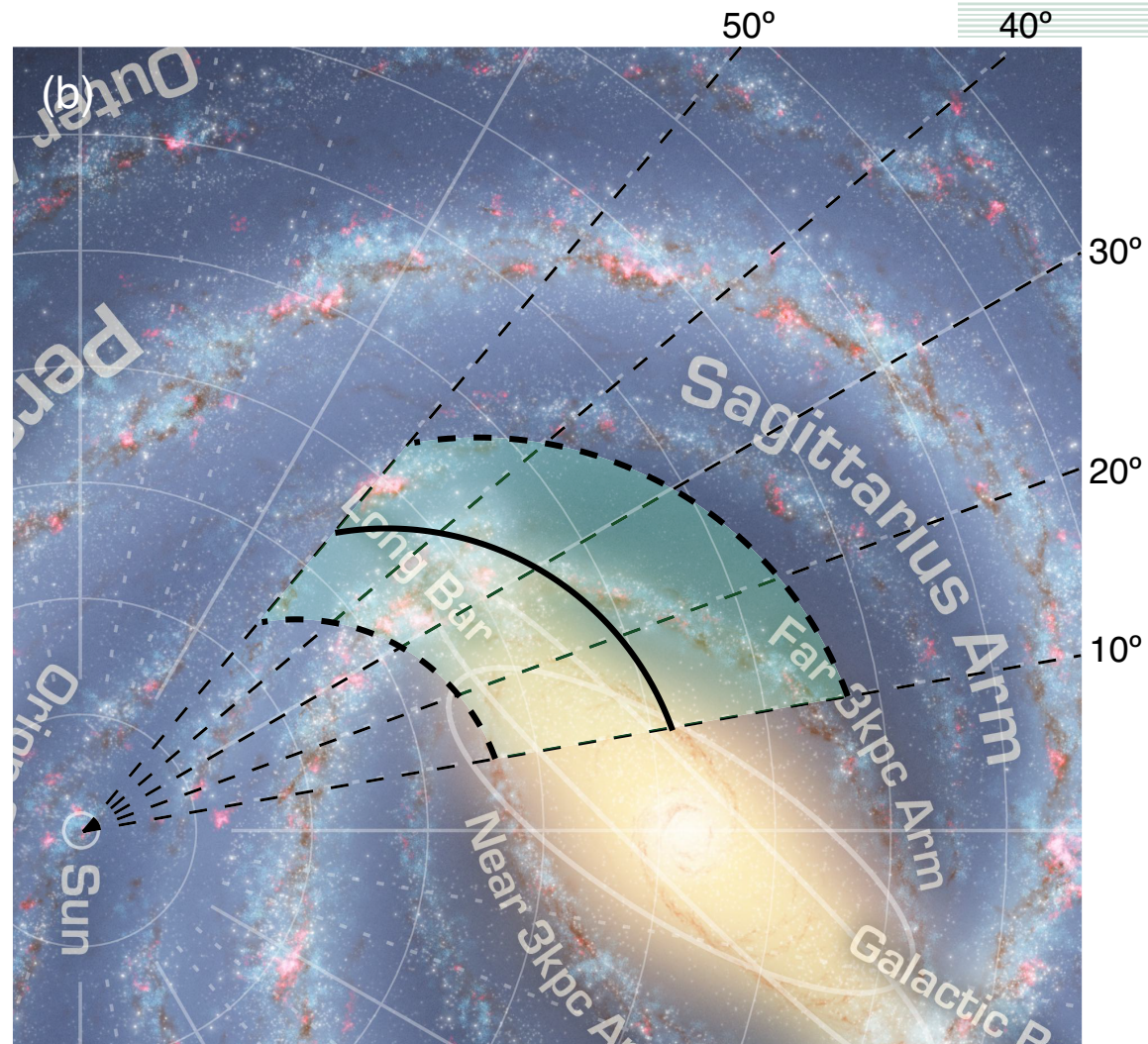
$$\epsilon_{\text{core}} \sim 33\%$$
- Star formation efficiency in a filament: $\epsilon_{\text{dense gas}}$

$$\epsilon_{\text{dense gas}} = M_{\text{core}} / M_{\text{filament}} \times \epsilon_{\text{core}} \sim 5\%$$

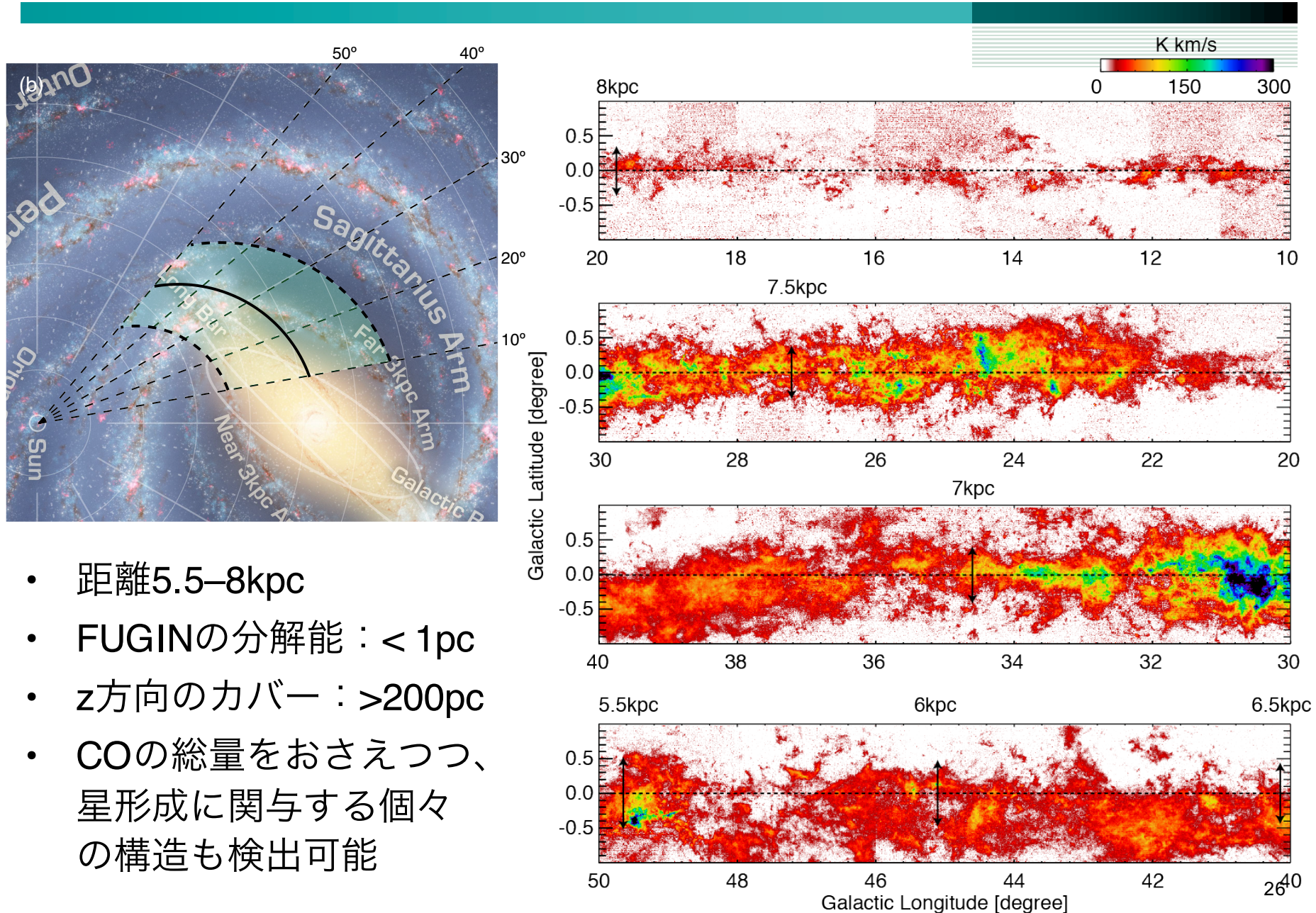
- Typical lifetime of dense cores $\sim 10^6$ yr (e.g., Andre+14)
- Consumption timescale of dense gas: $t_{\text{dense gas}}$

$$t_{\text{dense gas}}^{-1} \sim (10^6 \text{ yr})^{-1} \times \epsilon_{\text{dense gas}} = (20 \text{ Myr})^{-1}$$

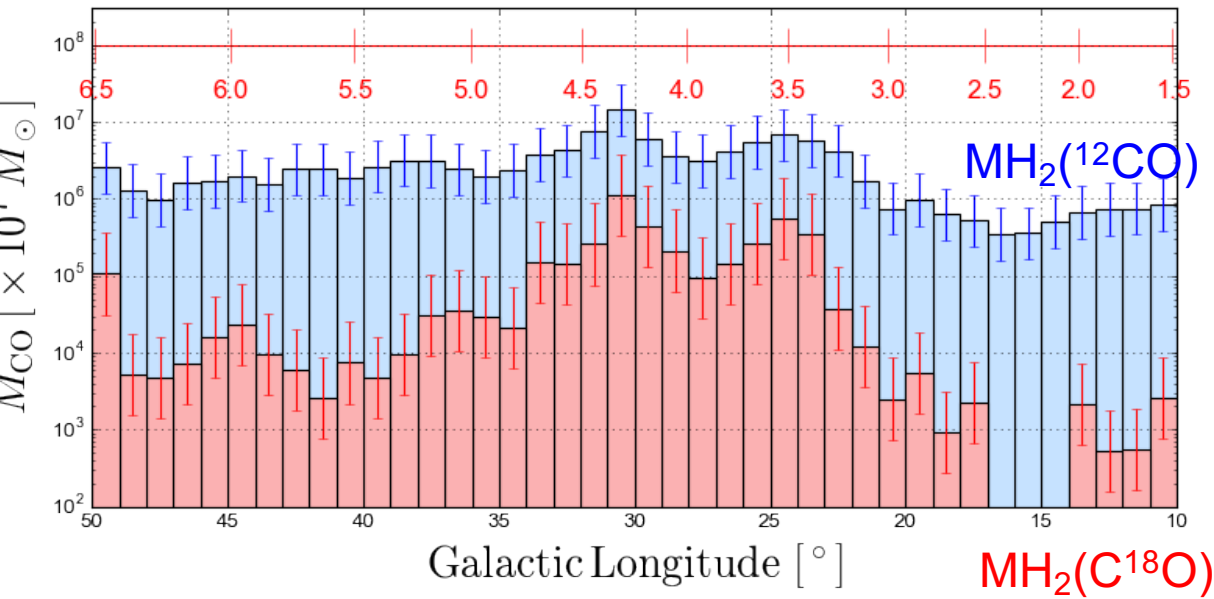
$$\rightarrow t_{\text{dense gas}} \sim 20 \text{ Myr (e.g., Andre+14; Lada+10)}$$



FUGIN ^{12}CO distribution



Mass distribution/Mass ratio distribution



- Total Mass (^{12}CO): $1.1 \times 10^8 M_{\odot}$
- Total Mass (C^{18}O): $4.1 \times 10^6 M_{\odot}$
- Ratio: $3.7 \pm 1.3 \%$

- 場所により 1 桁以上のずれ
- 系外銀河の理解と一致

ここまでのまとめ

- ・ FUGINは良いデータですよ（宣伝）
- ・ ざっくりと量的には「近傍銀河の理解」と「太陽系近傍の理解」を結べそう
- ・ じゃあその背景にある物理は？
- ・ ビッグデータへの直面
 - データ量そのものの爆発的増大 + 多波長解析の当たり前化
- ・ 新たな視点、アイデア、解析手法への需要の高まり
 - 例えば人工知能、機械学習
- ・ 理論面からのより強いサポートの必要性
- ・ 分野間連携の強化



分子雲衝突と大質量星形成

Cloud-cloud collisions

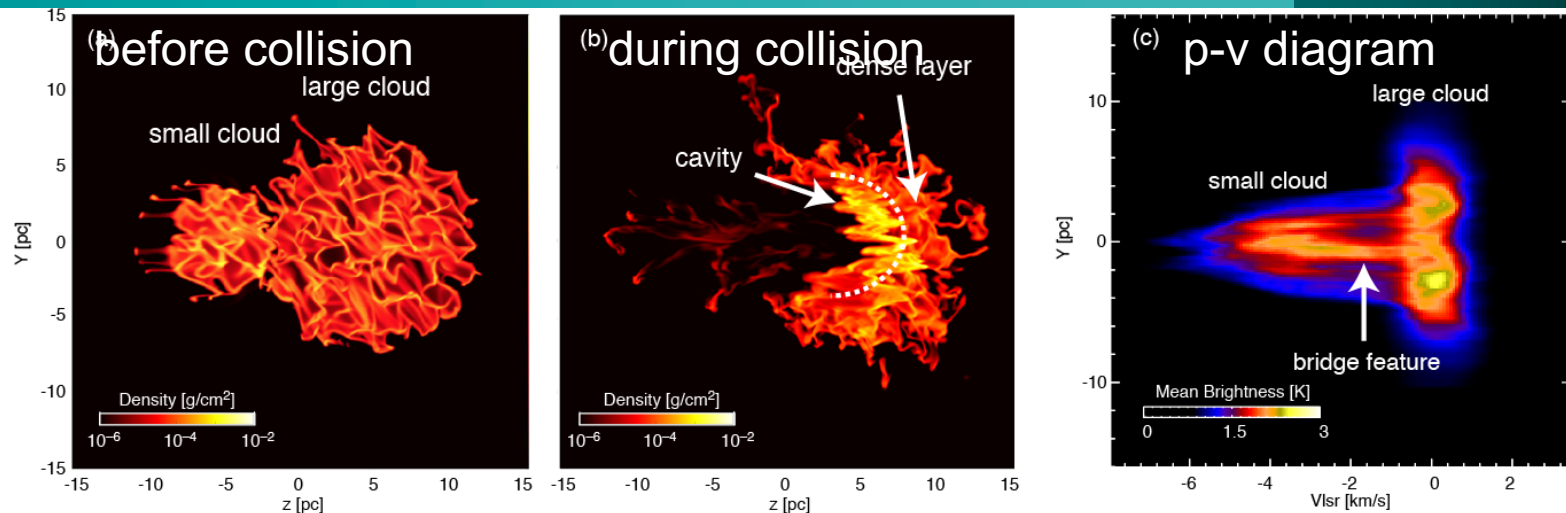
- Trigger of (massive) star formation

- NGC1333 (Loren 1976); SgrB2 (Hasegawa+1994)
- Galactic super star clusters (Furukawa+2010, Fukui+2014, 2016)
- HII regions (Torii+2011, 2015, 2017, Ohama+2017a, 2017b, etc.)
- Colliding velocities: $\sim 10\text{--}30$ km/s
- CCC-driven star formation is dominated by massive GMCs having masses $> 10^{5.5} M_{\odot}$, which accounts for a few 10% of the total star formation in the MW (Kobayashi et al. 2017)

- Merger/coagulation of clouds

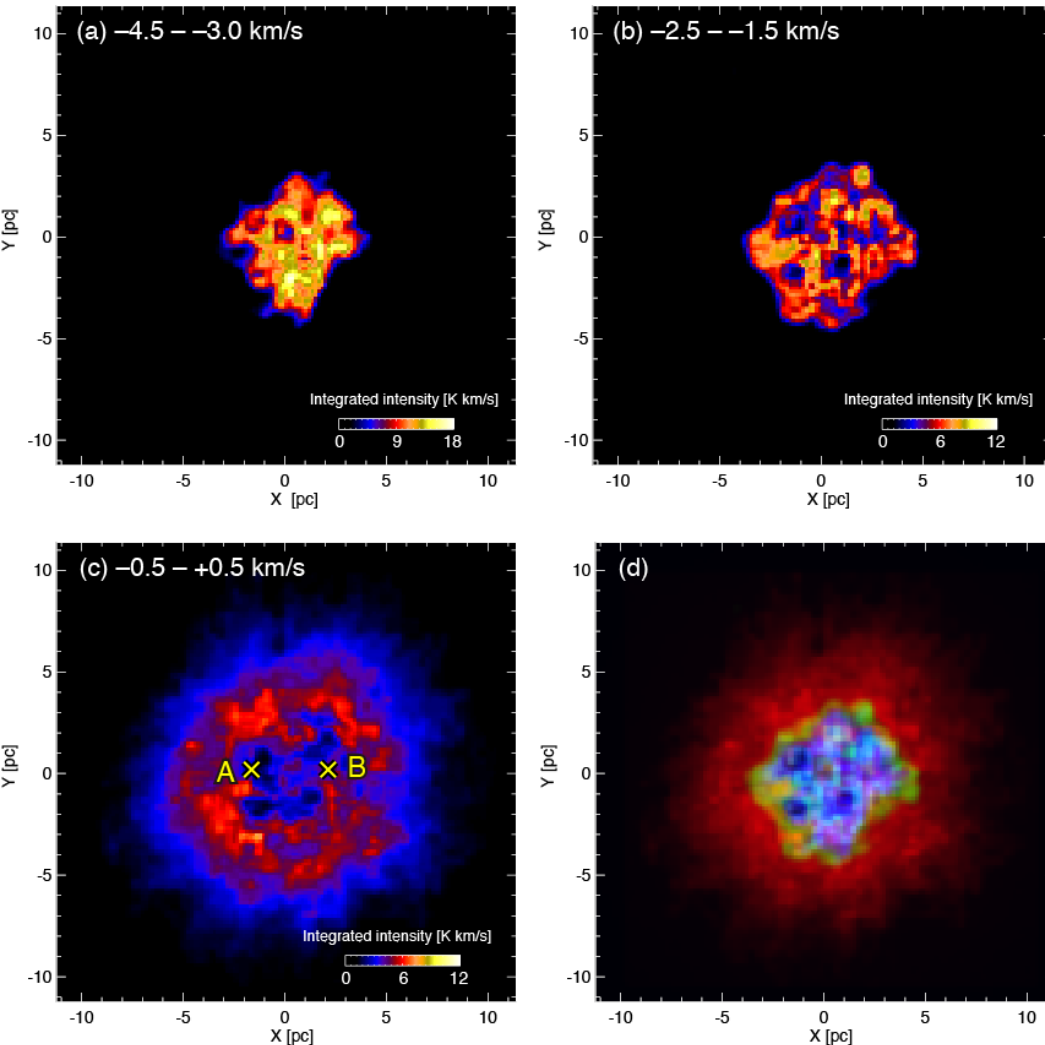
- Frequency of collisions in MW-like galaxies $\sim 7\text{--}10$ Myr (Tasker & Tan 11; Dobbs+15).
- Collision cooling to form giant clumps in gas-rich galaxy disk (Li 2017).
- Little impact on the evolution of ISMs (Dobbs+15).

Cloud-cloud collision (CCC) model



- Takahira+14, 18: Simulations of CCC between two dissimilar clouds.
- Haworth+15a, 15b: Synthetic CO J=1-0 observations with a radiative transfer code using the Takahira et al.'s data, in which the observer viewing angle is set to parallel to the colliding axis.
- When a smaller cloud drives into a larger cloud, a cavity is created on the larger cloud.
- In the p-v diagram, two velocity peaks separated by emissions with intermediate intensities (= broad bridge features) are observed.
- Bridge features are observable as long as the collision continues.

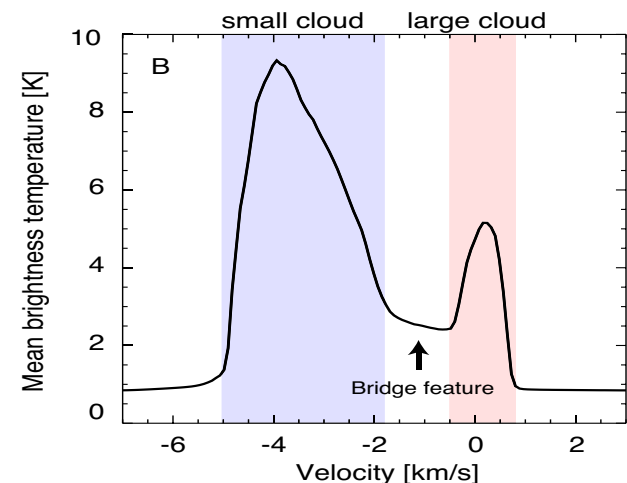
Cloud-cloud collision (CCC) model



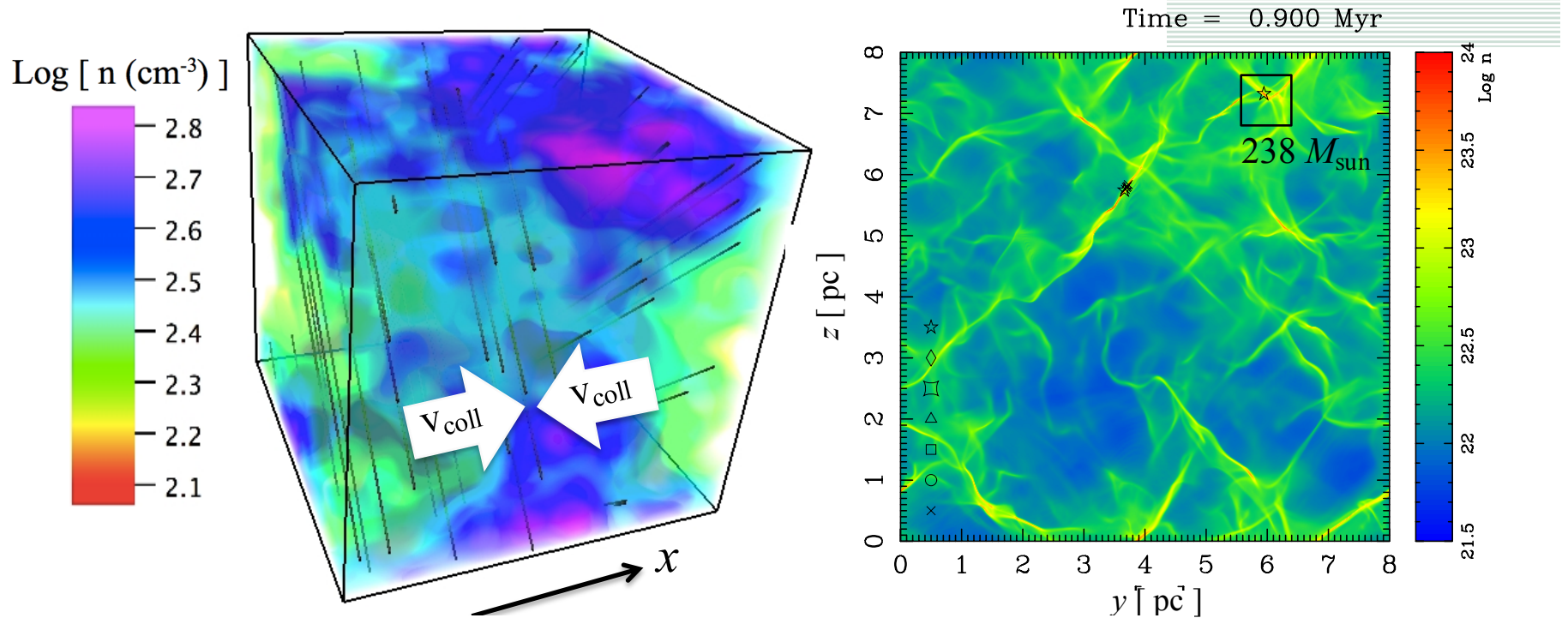
Torii+2017a

Spatial distributions of the molecular clouds based on the synthetic CO J=1-0 data.

- The larger cloud shows a ring-like gas distribution.
- The inner-radius of the ring corresponds to the size of the smaller cloud, showing complementary distribution between the two clouds.



MHD numerical calculations Inoue & Fukui (2013)



$$\dot{M} \sim \frac{M_J}{t_{ff}} = \frac{c_s^3}{G} \sim 2 \times 10^{-6} M_{\odot}/\text{yr} \left(\frac{T}{10K} \right)^{3/2}$$

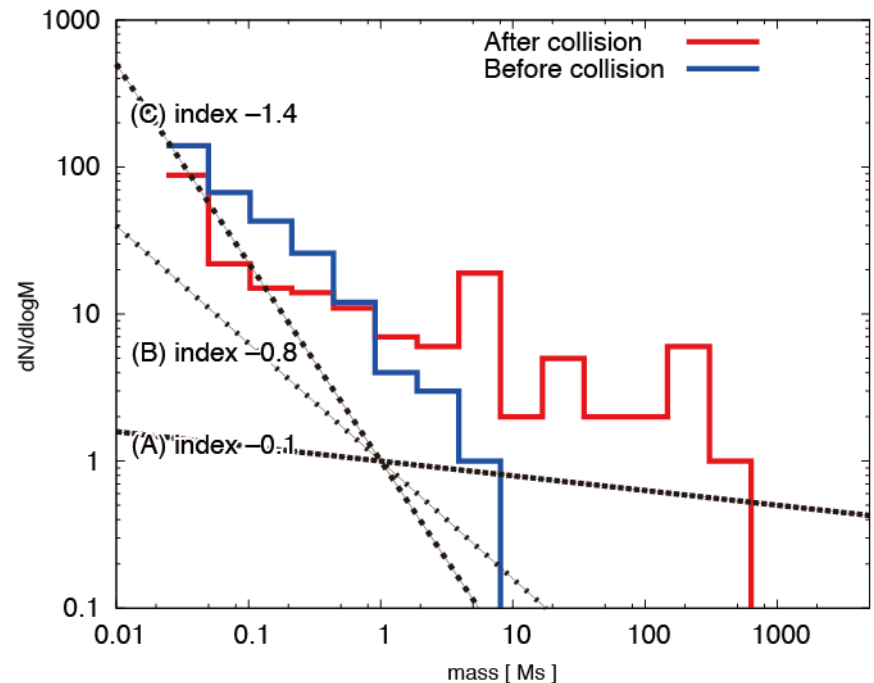
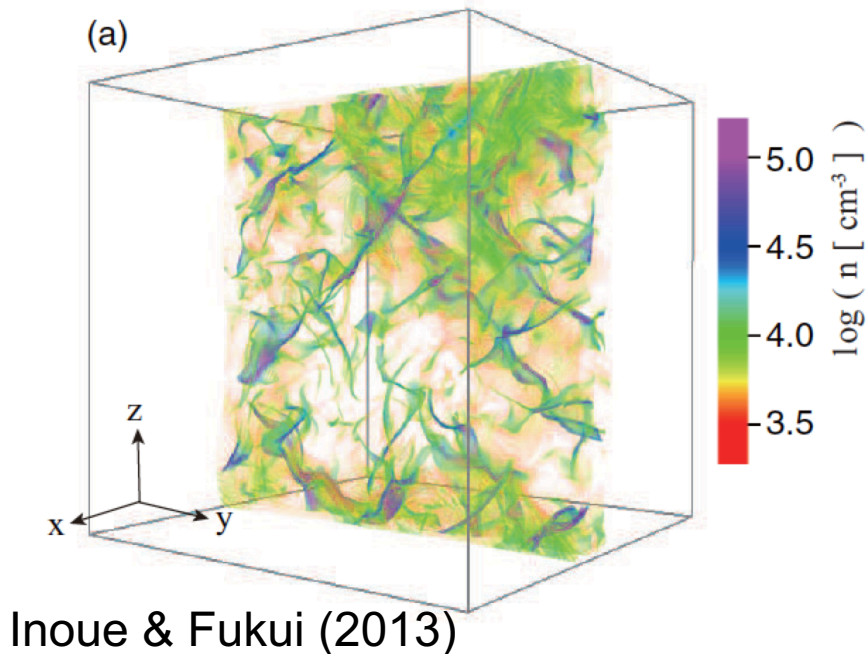
$$M_{J,\text{eff}} \approx (c_s^3 + c_A^3 + \Delta v^3) / (G^{3/2} \rho^{1/2}) \quad c_s^3 : c_A^3 : \Delta v^3 = 1 : 125 : 90$$

- Amplified magnetic field and gas turbulence increase dM/dt

$$dM/dt = 5 \times 10^{-4} - 4 \times 10^{-3}$$

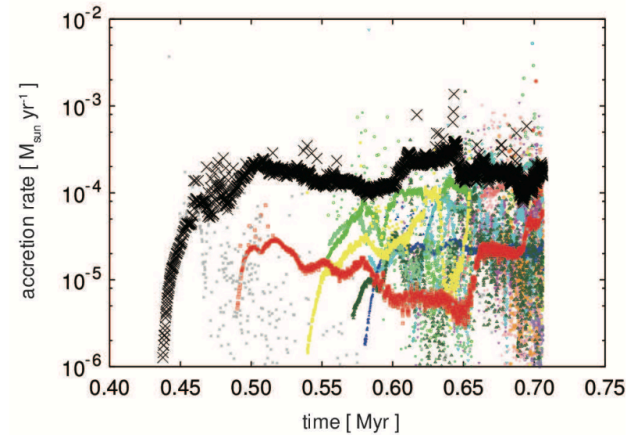
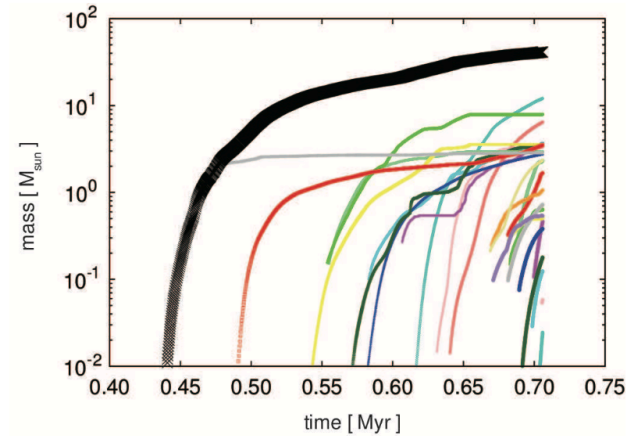
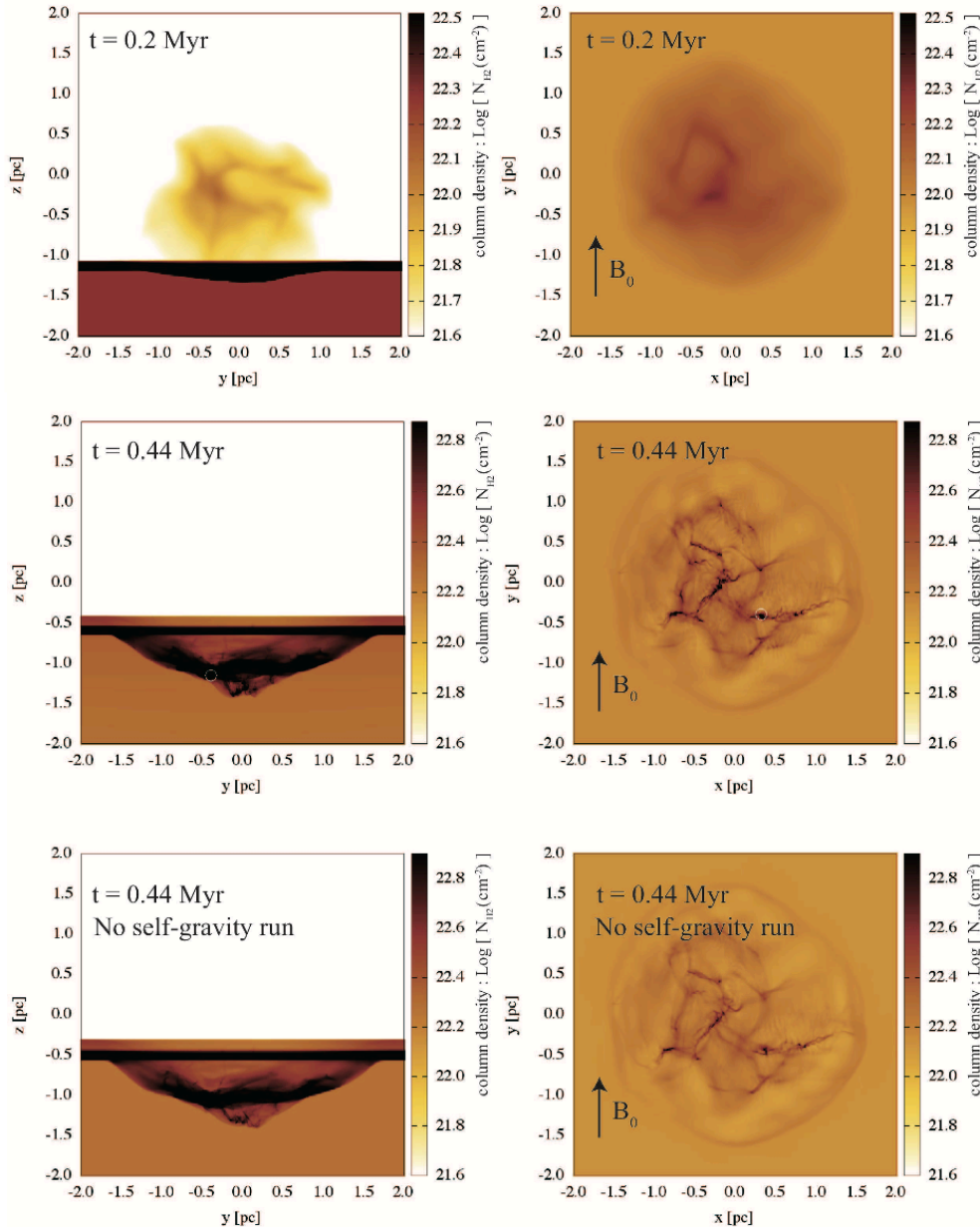
$$M_{\text{sun}}/\text{yr}$$

Core mass function in Inoue & Fukui (2013)



- Inoue & Fukui(2013)による分子雲衝突のMHD数値計算
- 衝突によりトップヘビーなCMFが予言
- 観測されたCMFと似たベキを再現

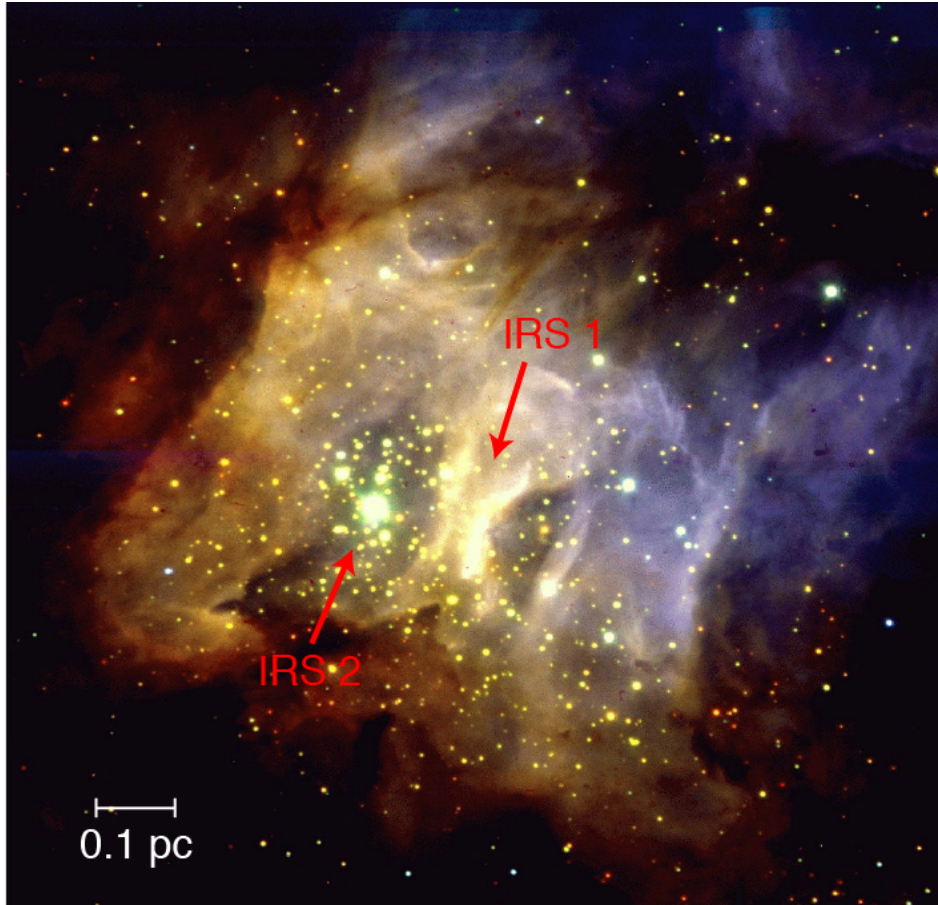
MHD numerical calculations (Inoue+2017)



- Formation of filaments within the colliding layer.
- Dense clumps with high $\dot{M}$ are formed.

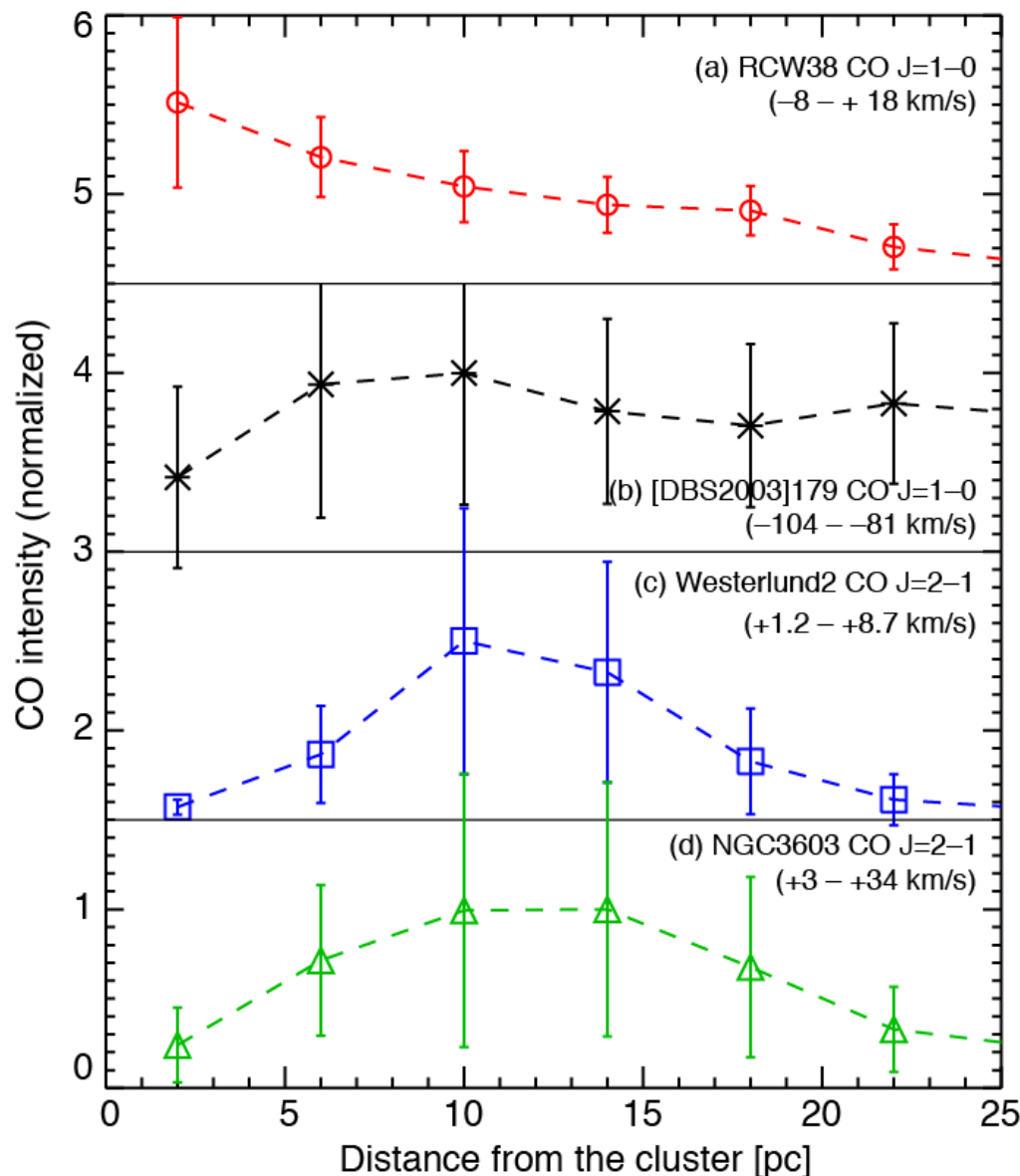


巨大星団での分子雲衝突3 (Fukui et al. 2016)



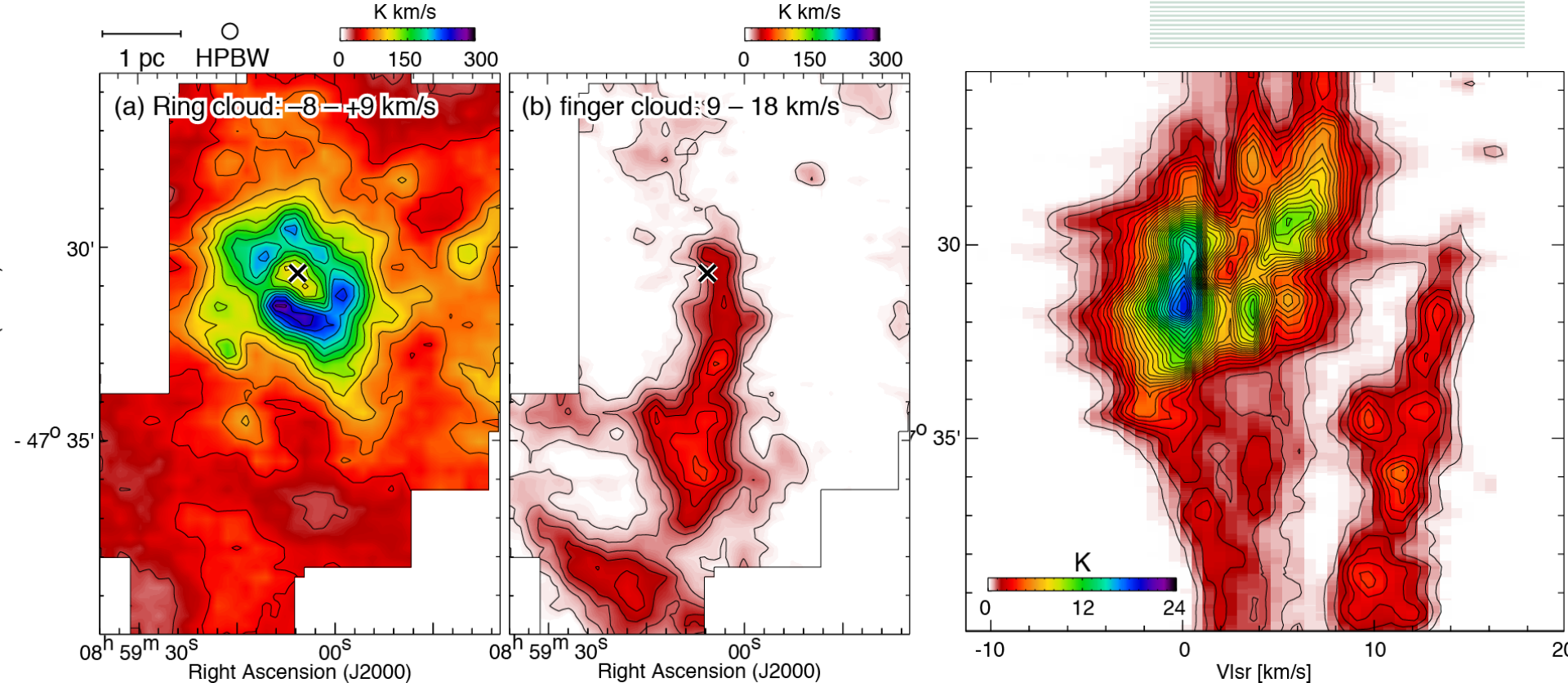
- 巨大星団RCW38
- 距離: $\sim 1.7\text{kpc}$
- 励起星: O5.5型星 (IRS2)
- O型星 (候補) : ~ 20 個
- 銀河系でもっとも若い巨大星団 ($\sim 0.1\text{Myr}$) (Fukui+16; Wolk+06)
- 星団中心方向に豊富な分子ガス

巨大星団での分子雲衝突3 (Fukui et al. 2016)



- 距離: $\sim 1.7\text{kpc}$
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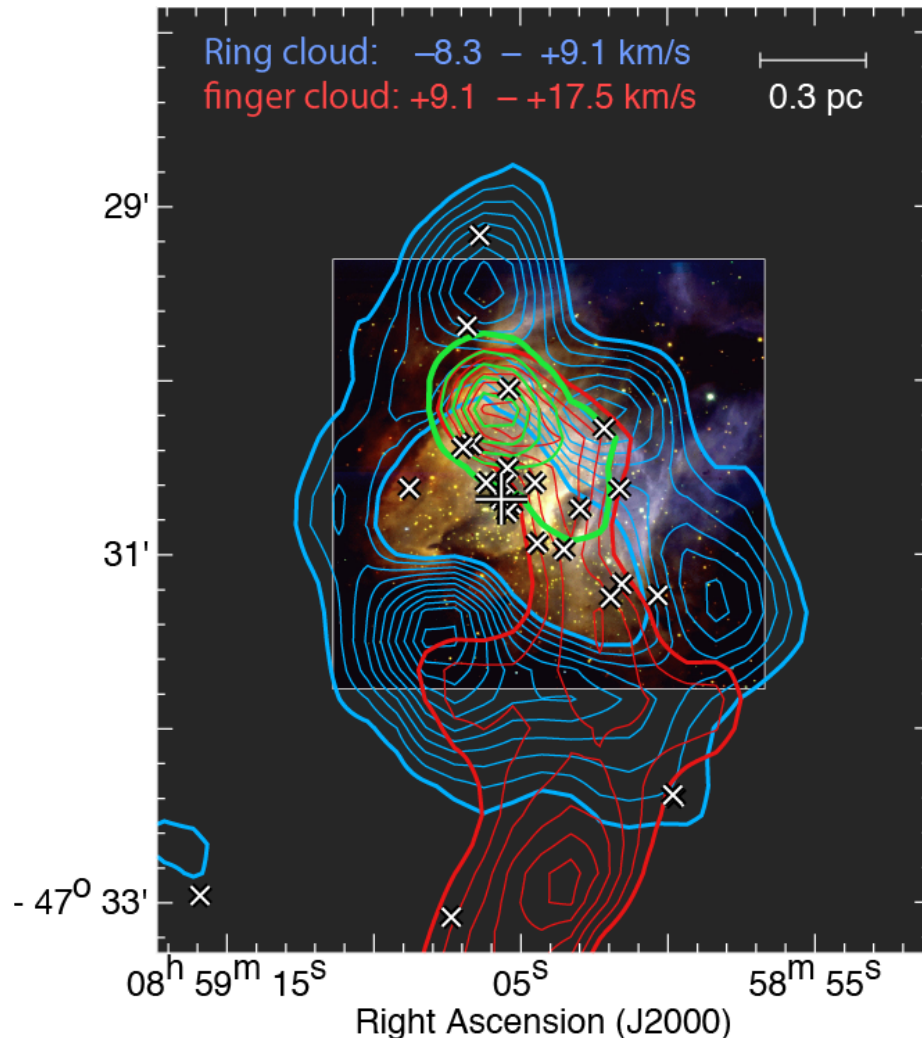
巨大星団での分子雲衝突3 (Fukui et al. 2016)



NANTEN2, Mopra, ASTEを用いたCO J=1-0, 3-2輝線観測
2つの速度の異なる分子雲

- Ring cloud (Blue-shifted), Finger cloud (Red-shifted)
- 速度差: ~ 12 km/s

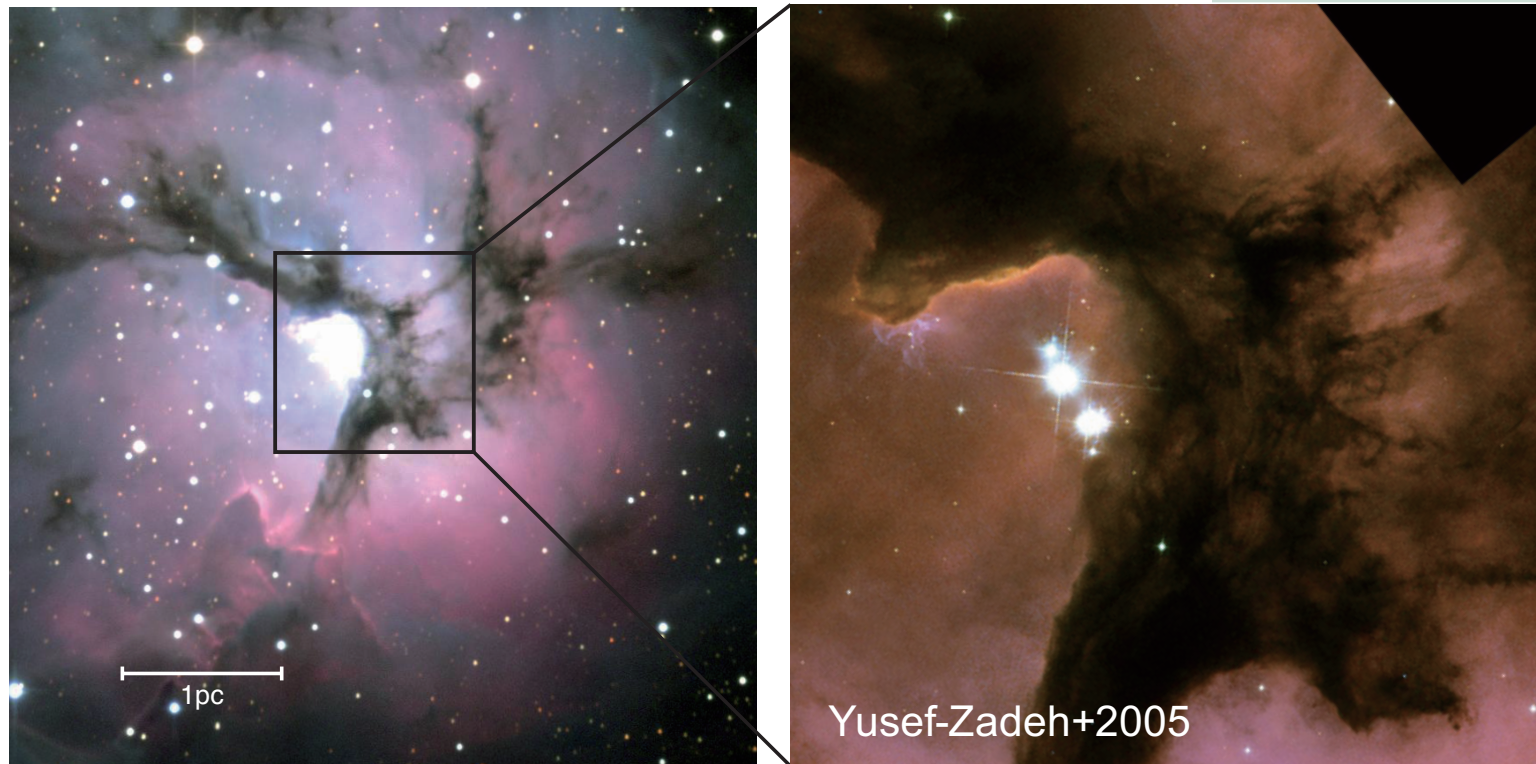
Observations in RCW38 (Fukui et al. 2016)



- Finger cloudの北端部とブリッジ構造の空間分布が一致
- ブリッジ構造とO型星の分布がおおよそ一致（やや北にオフセット）
- 先行研究からO型星の背後に多量の分子雲が分布 (e.g., Kaneda+2014)
- 高い柱密度($>10^{23}\text{cm}^{-2}$)をもつ Ring cloudと 10^{22}cm^{-2} 程度の Finger cloudの衝突
- 衝突箇所でO型星が形成
- 衝突のタイムスケール $\sim 0.1\text{Myr}$

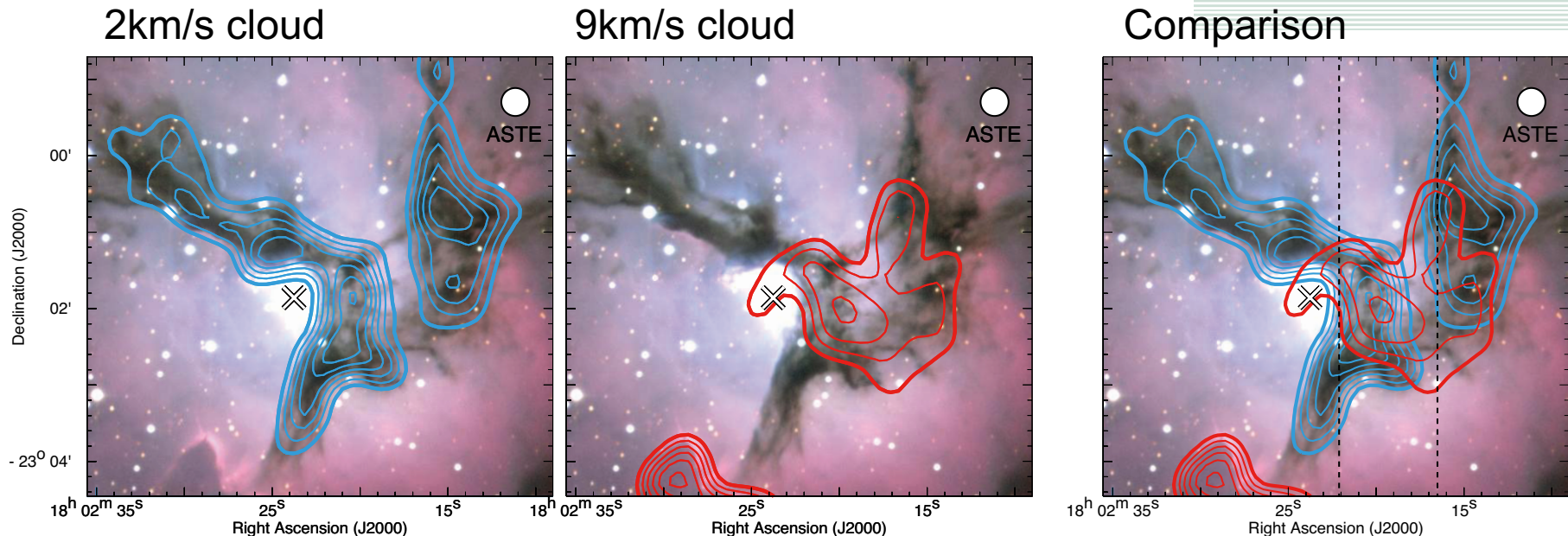


The Trifid Nebula, M20 (Torii+11, 17a)



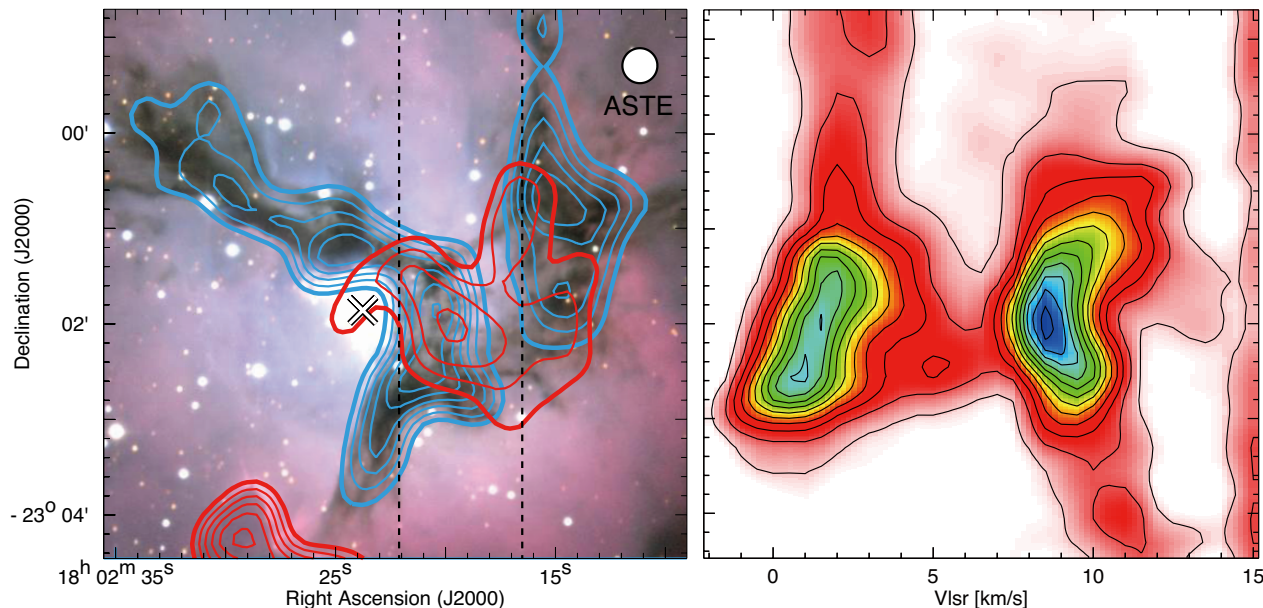
- $D \sim 1.7 \text{ kpc}$ (Lynds & Oneil 85)
- Very young: $\sim 0.3 \text{ Myrs}$ (Cernicharo+98)
- An exciting O7.5 star ($\sim 20 \text{ Mo}$)
- Low mass star formation (Rho+06; Cernicharo+98; Lefloch+08)

The Trifid Nebula, M20 (Torii+11, 17a)

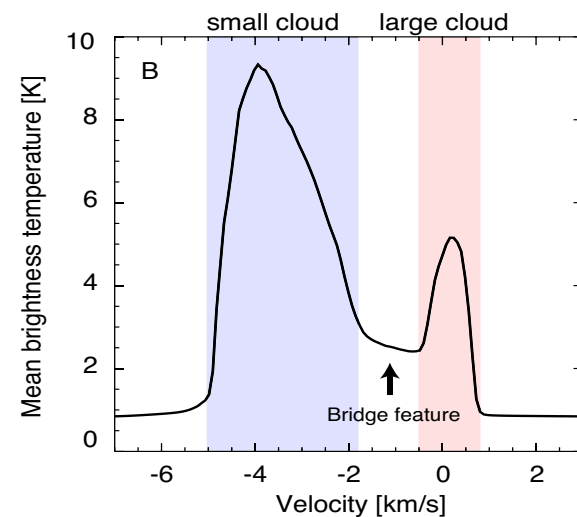
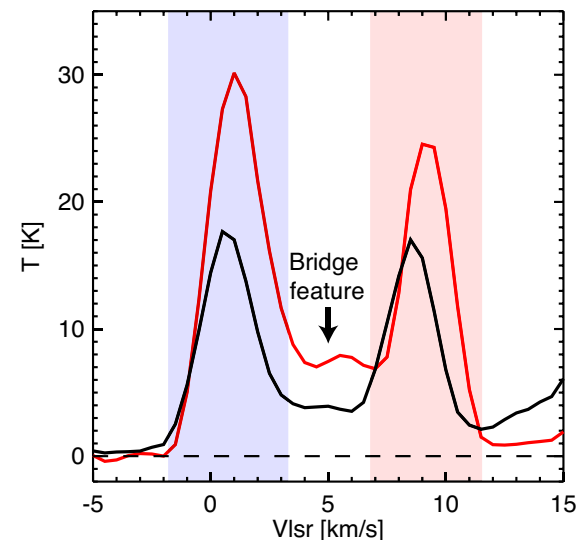


- Two clouds are associated with M20.
- 2km/s cloud corresponds to the dark lanes, indicating it is located in front of M20.
- 9km/s cloud is at the rear or at the inside of M20.
- The two clouds shows complementary distribution.

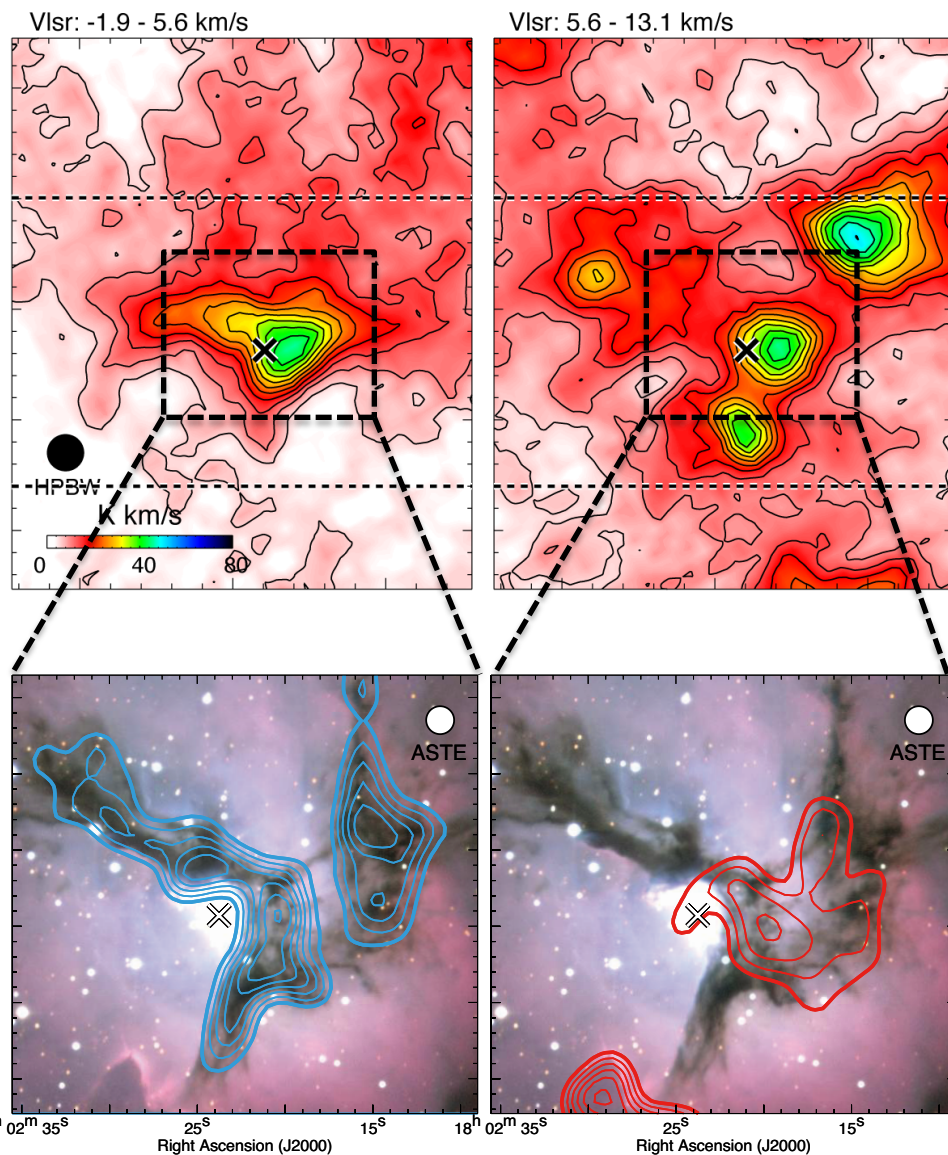
The Trifid Nebula, M20 (Torii+11, 17a)



- In the p-v diagram, the two clouds are connected by the intermediate intensity emission, indicating bridge feature.
- The CO profile shows a intermediate velocity feature, which cannot be interpreted as a wing feature, but resembles the model profile of the CCC simulation.



The Trifid Nebula, M20 (Torii+11, 17a)



- The two clouds have a total molecular mass of $\sim 1000 M_{\odot}$.
- A collision between two cloud with similar sizes.
- The timescale of the collision:
 $\sim 3 \text{ pc} / 10 \text{ km/s} \sim 0.3 \text{ Myr}$
- Consistent with the age of M20.

分子雲衝突のまとめ

- ・ 様々な形態の大質量星に適用できる可能性
- ・ 観測・理論について急速に整備が進む
 - 観測の背景には分子雲サーベイデータの存在
 - 観測的診断法も理解が進んできた
- ・ 大規模サンプリングも現実味
- ・ 銀河の星形成史との総合的理解
 - 分子雲衝突が担う星形成率は？星の質量の関数として
- ・ 原始星形成からフィードバックによる母体ガス散逸までの一般モデル構築

まとめに変えて: メッセージ、ないし独り言

- ・ 銀河面、分子雲に限らずサーベイは（辛いけど）楽しい
- ・ 可能な限り前提・先入観を排除した観測
- ・ 膨大な統計
- ・ お宝探しも魅力的
- ・ 宇宙に対する人類の原始的な向き合い方
 - 夜空を眺めてるだけで楽しい！
 - 未知の天体の発見にワクワクする！
- ・ 研究成果へとつなげることが大事