Signature of Past Star Forming Activity in the Central Molecular Zone of Our Galaxy

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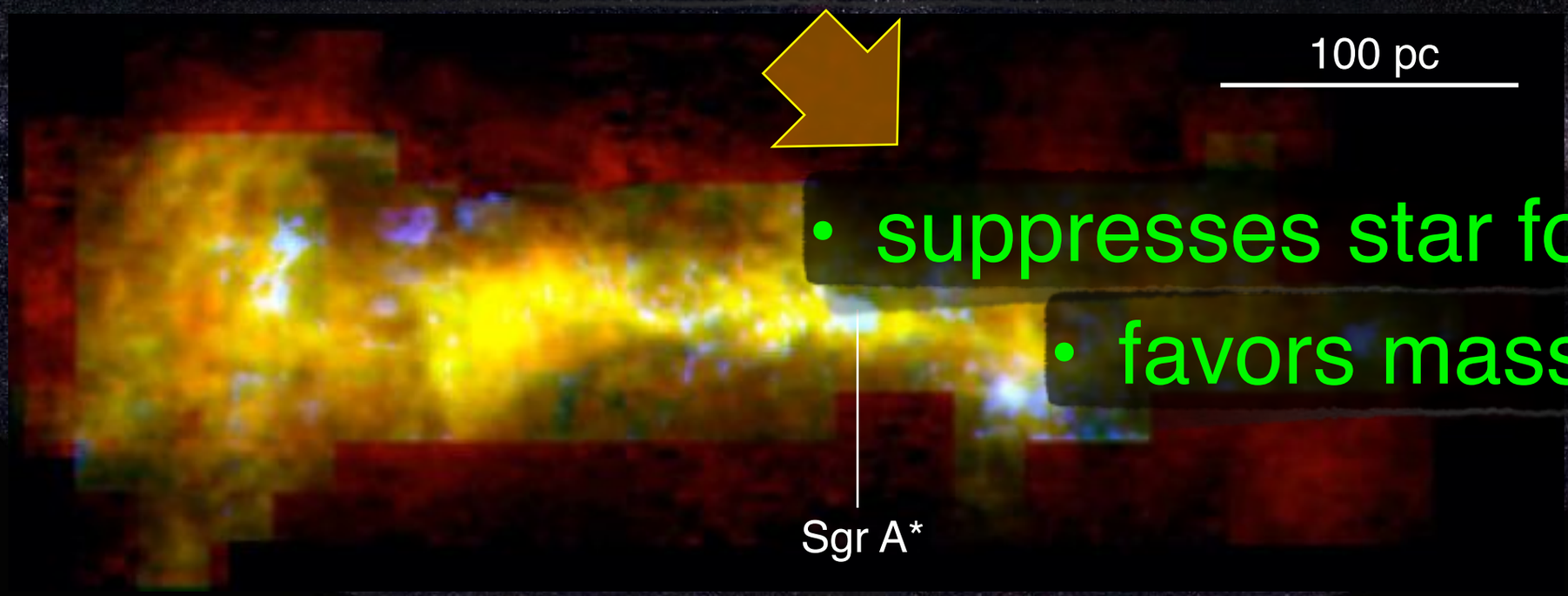
Central Molecular Zone

- Inner 200 pc of the Milky Way Galaxy
- Dense (n_{H2}>10^4 cm^{-3}) and warm (T_k>30 K) molecular gas (M_{gas}=5x10^7 M_{sun})
- Highly turbulent (ΔV>15 km s^{-1})



- suppresses star formation
- favors massve stars

Young Massive Clusters

- Arches Cluster
  - M_{ini} ~ 2x10^4 M_{sun}
  - age = 2–4 Myr
- Quintuplet Cluster
  - M_{ini} ~ 2x10^4 M_{sun}
  - age = 3–5 Myr

IMF: top-heavy or normal

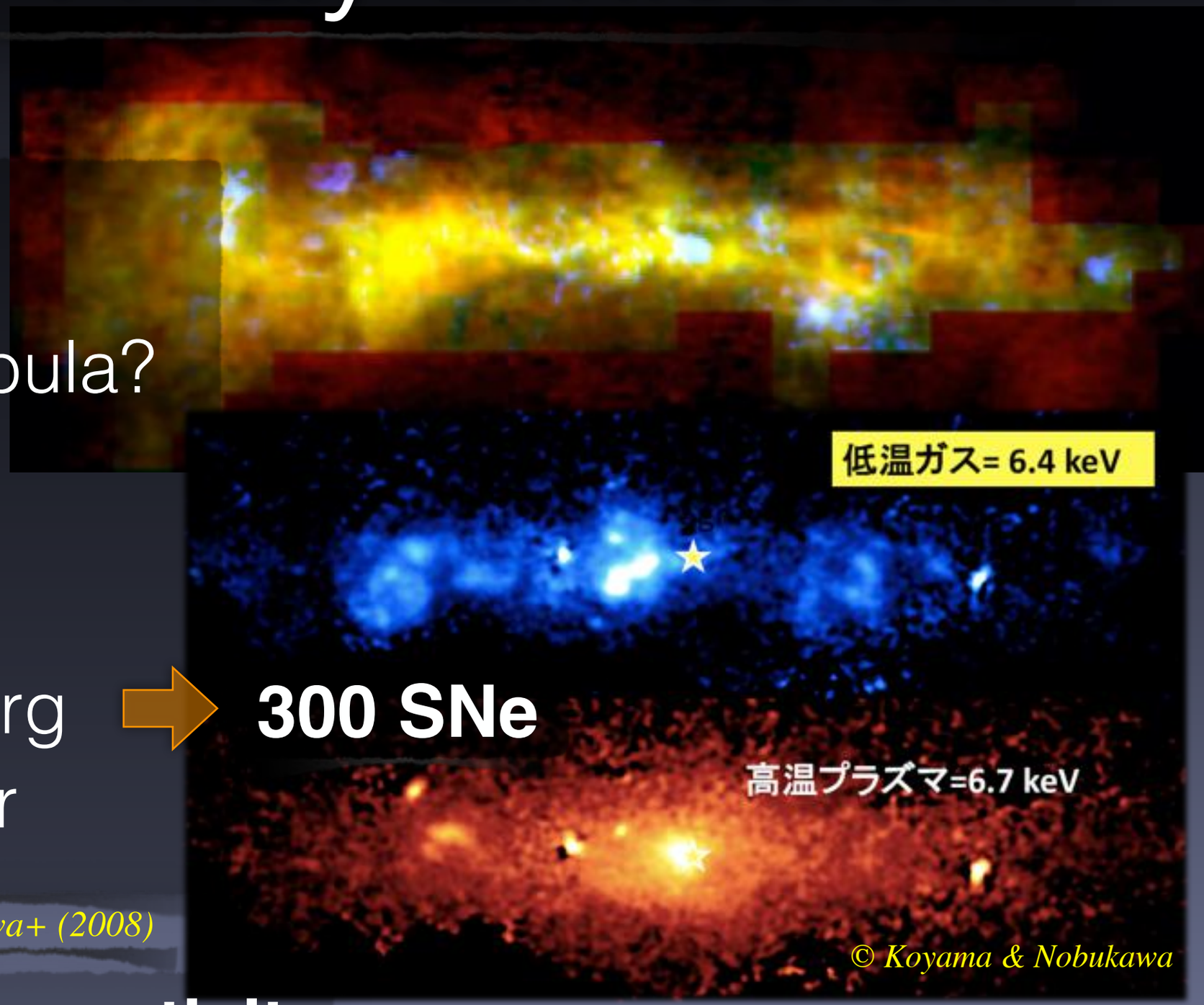
Figer+ (1999)

Star formation is currently taking place

Diffuse X-ray Emission

- Fe 6.4 keV line
  - Reflection nebula?
- Fe 6.7 keV line
  - kT = 6.6 keV
  - E_{th} = 3x10^{53} erg
  - t_{eq} ~ 5–10 Myr

Nobukawa+ (2008)

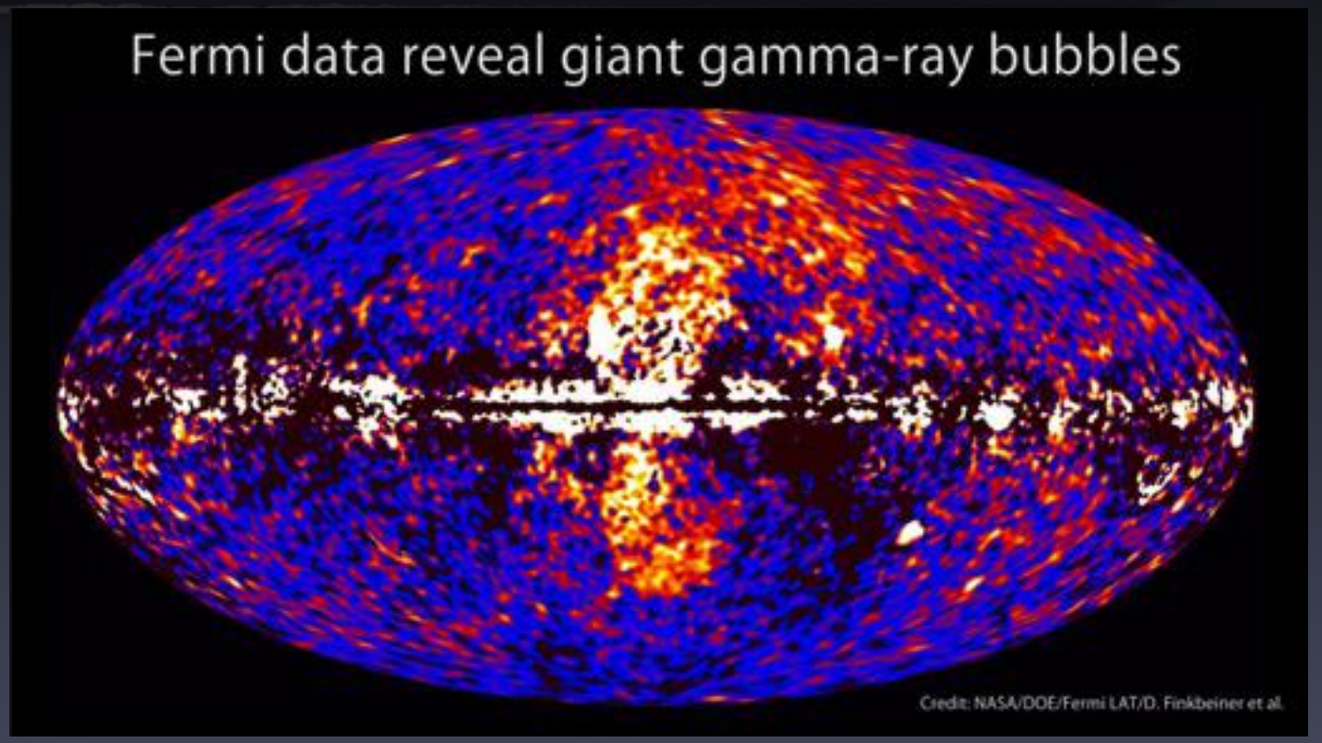


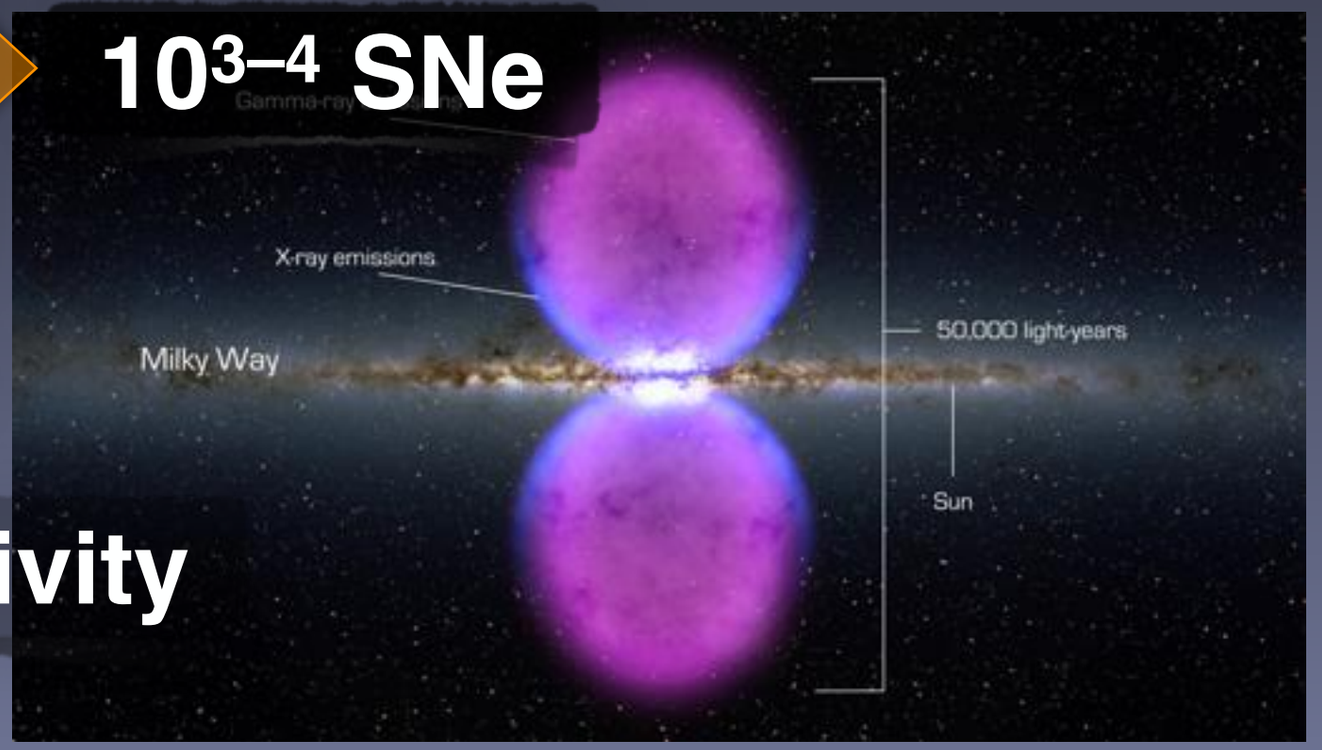
Past star forming activity

Fermi Bubbles

- γ-ray (1–20 GeV)
- X-ray / radio
- kT ~ 2 keV
- E_{kin} = $10^{54–55}$ erg
- t_{exp} ~ 10 Myr

Su+ (2010)



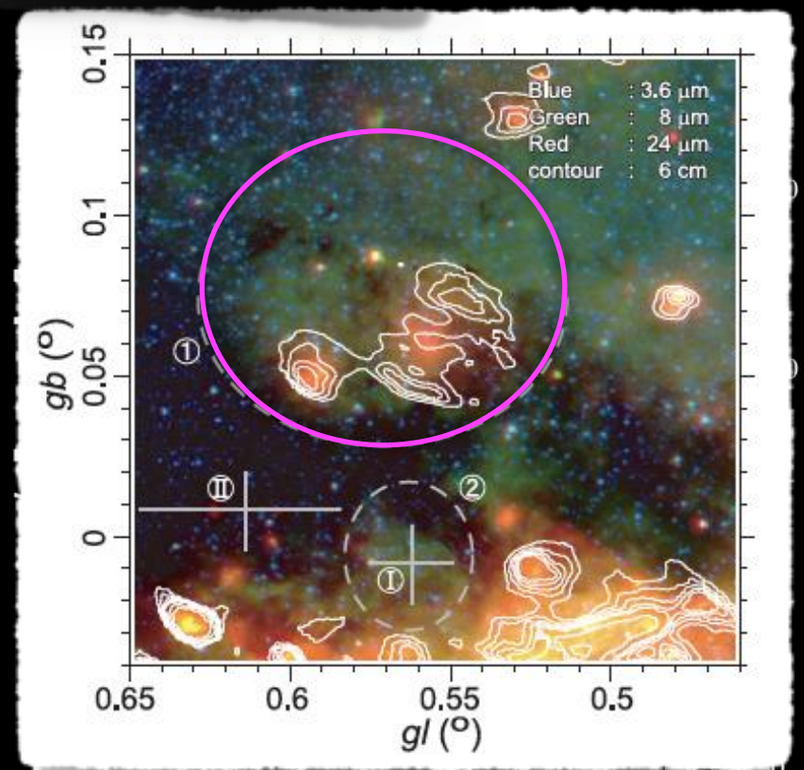


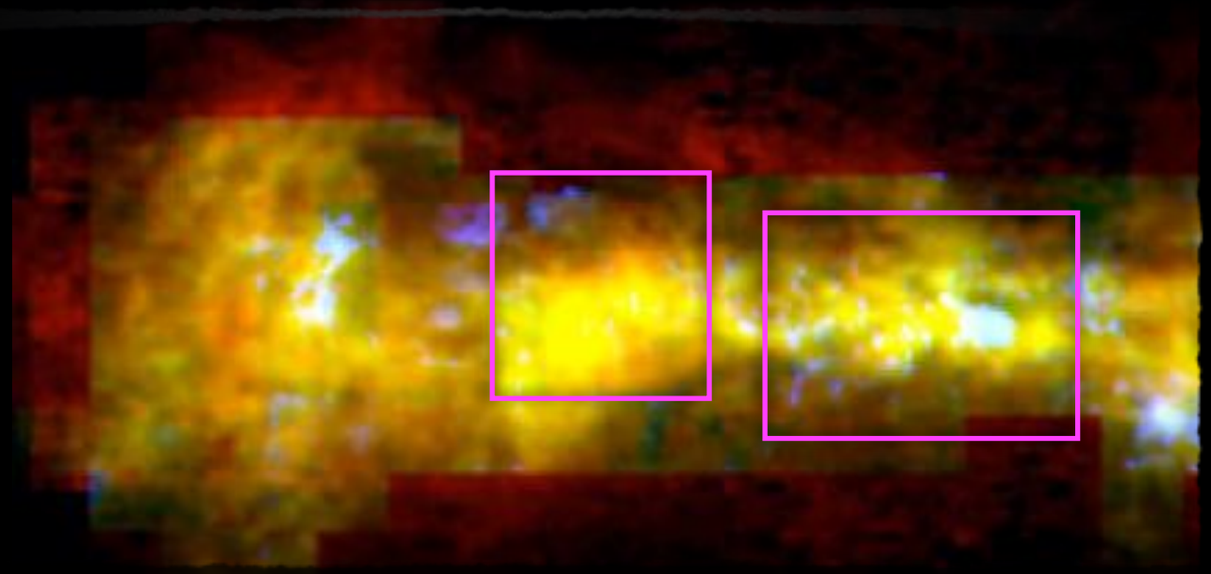
Starburst/quasar **activity**

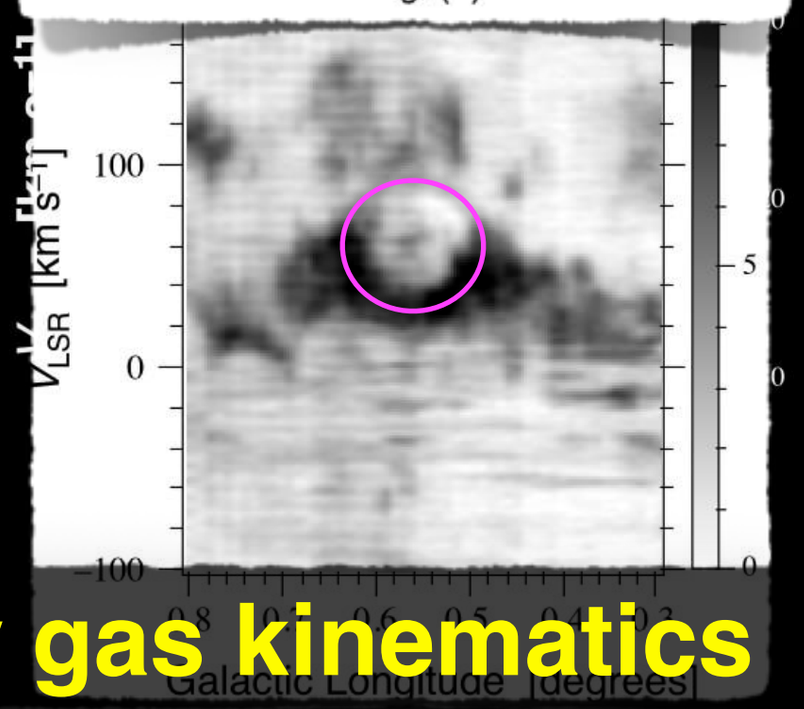
Expanding Shells

- Radio Arc region
  - *Oka et al. 2001, PASJ, 53, 779*
- Sgr B1 region
  - *Tanaka et al. 2009, PASJ, 61, 461*

Accelerated by SNe and SWs







Star formation can be traced by gas kinematics

Topics

Detections of

- Two Molecular Bubbles
- Intermediate-mass Black Hole Candidate

in the Central Molecular Zone

CO Imagings of the CMZ

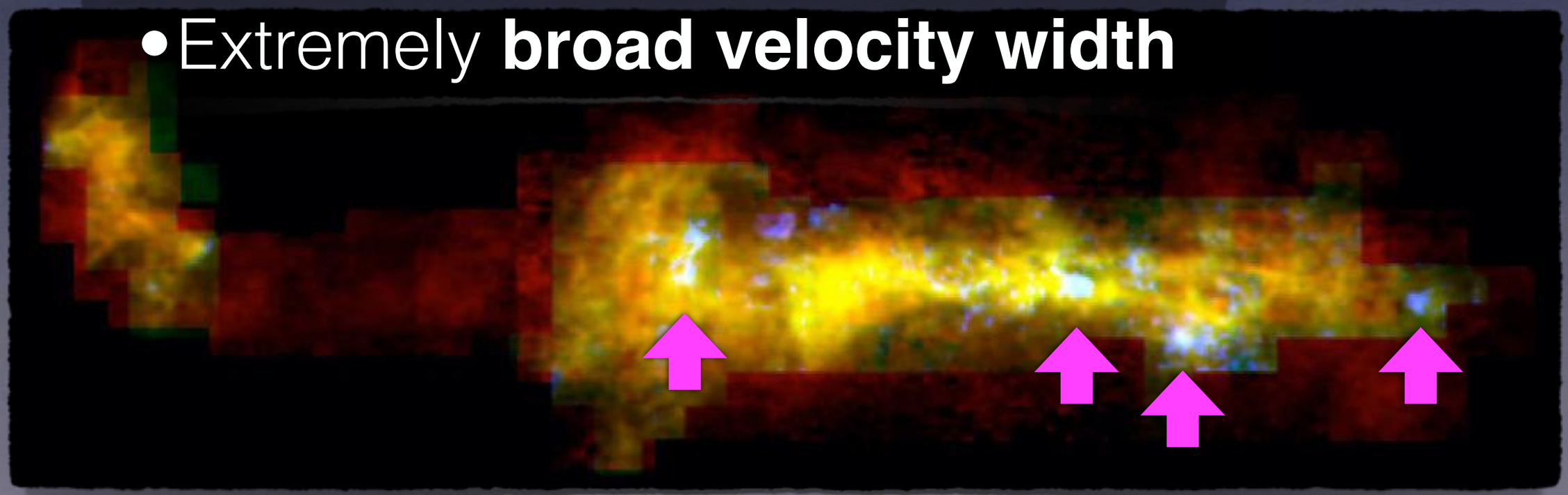
- NRO 45 m survey
  - CO *J*=1–0 (115 GHz)
  - *Oka et al. 1998, ApJS, 118, 455*
- ASTE survey
  - CO *J*=3–2 (346 GHz)
  - *Oka et al. 2012, ApJS, 201, 14*

Red: CO *J*=1–0
Green: CO *J*=3–2
Blue: $R_{3-2/1-0} \geq 1.5$

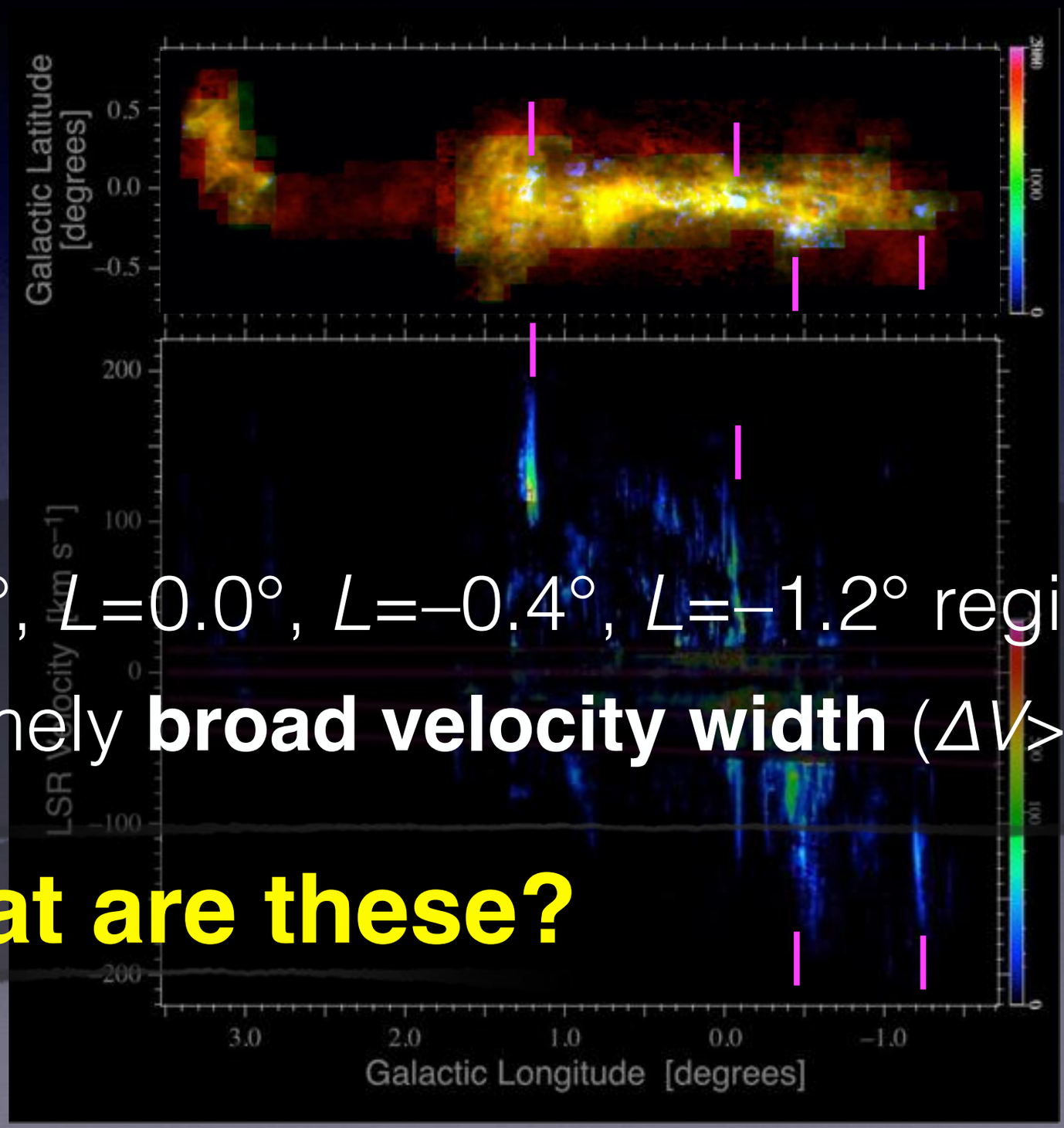
High $R_{3-2/1-0}$ Regions

Oka et al. 2012, ApJS, 201, 14

- $R_{3-2/1-0} \geq 1.5$: **dense and warm** gas
  - $T_k \geq 50$ K, $n(H_2) \geq 10^4$ cm^{-3}
  - [$N_{CO}/dV = 10^{17}$ cm^{-2} (km s^{-1})$^{-1}$]
- L=+1.3°, L=0.0°, L=–0.4°, L=–1.2° regions
  - Extremely **broad velocity width**



High $R_{3-2/1-0}$ Regions



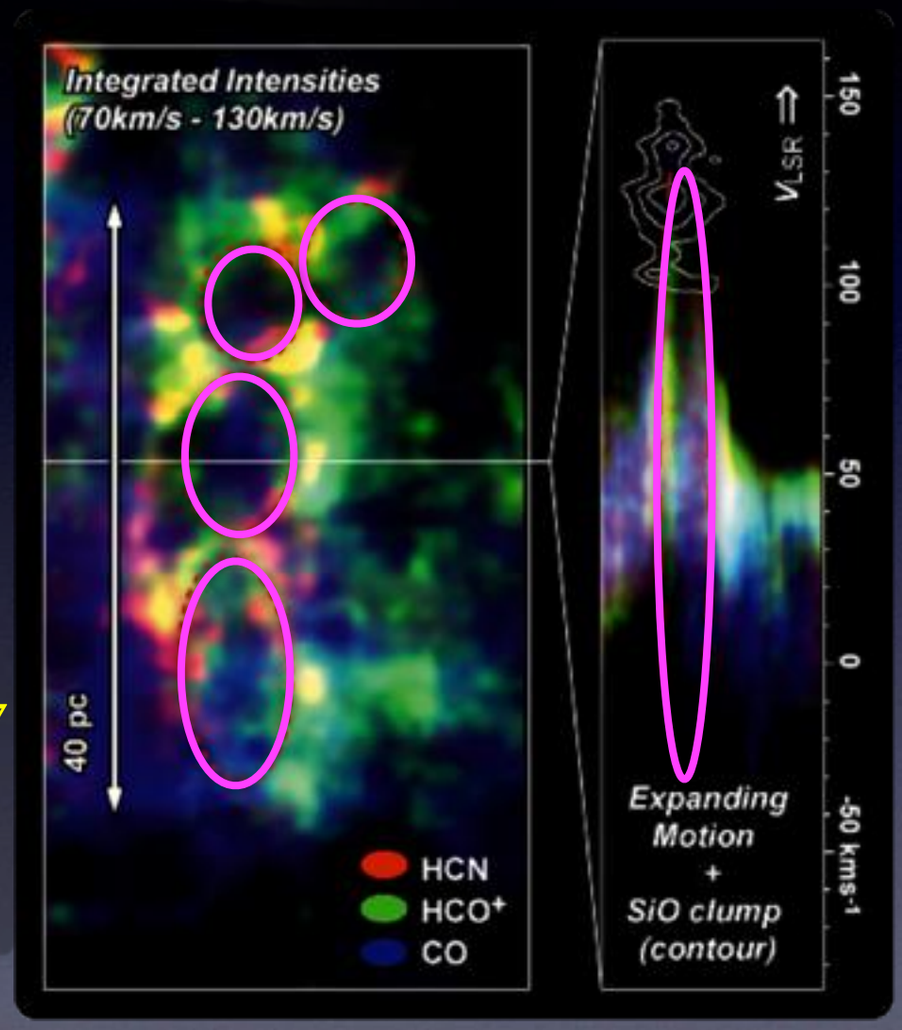
- L=+1.3°, L=0.0°, L=−0.4°, L=−1.2° regions
  - Extremely **broad velocity width** (ΔV>100 km s^{-1})

What are these?

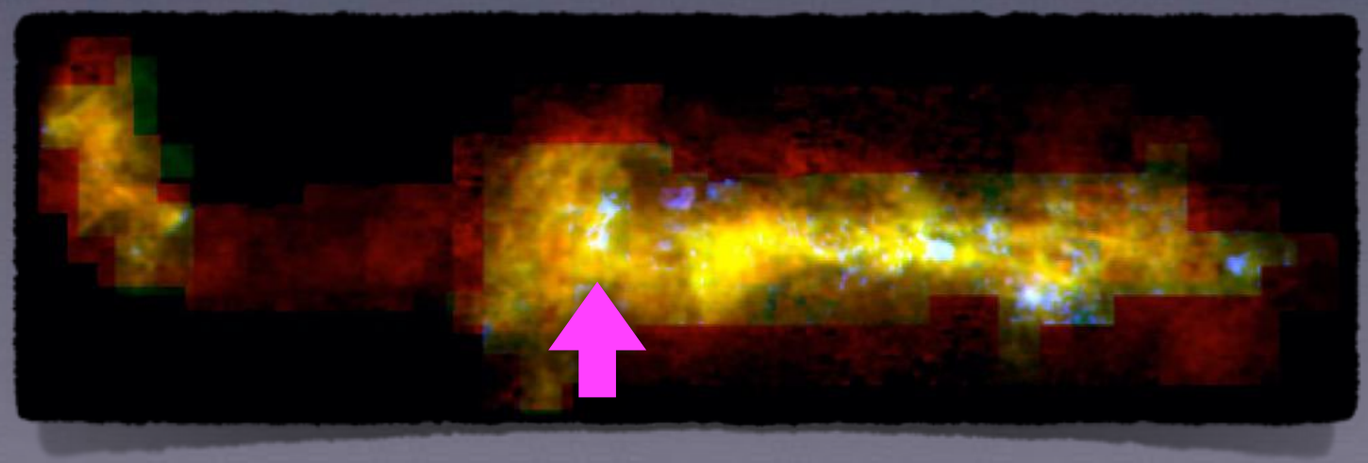
L=+1.3° Region

High-velocity compact cloud

- HVCC CO 1.27+0.01 *Oka et al. 2001*
  - Two clear expanding shells
  - t_{exp} = 6x10^4 yr
  - E_{kin} = 2x10^{52} erg
- Nine Expanding shells *Tanaka et al. 2007*
  - Shocked gas at high-vel. ends



Molecular Bubble (1)

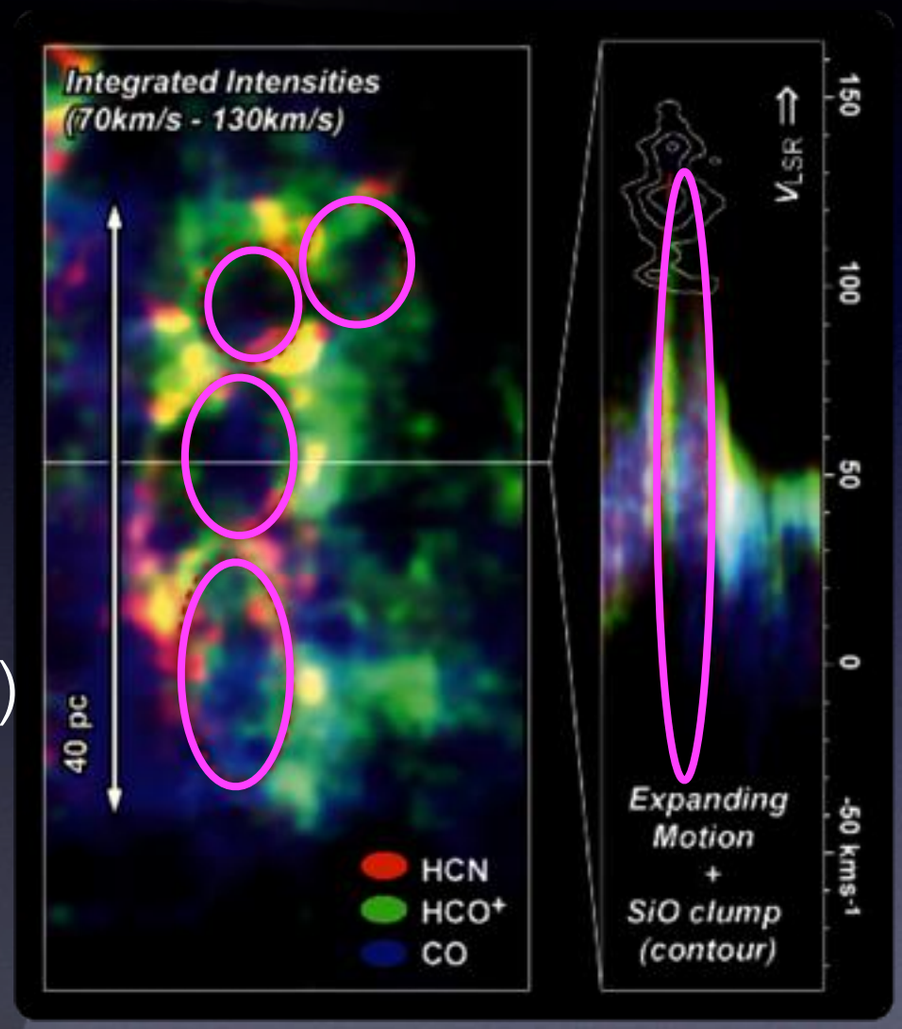


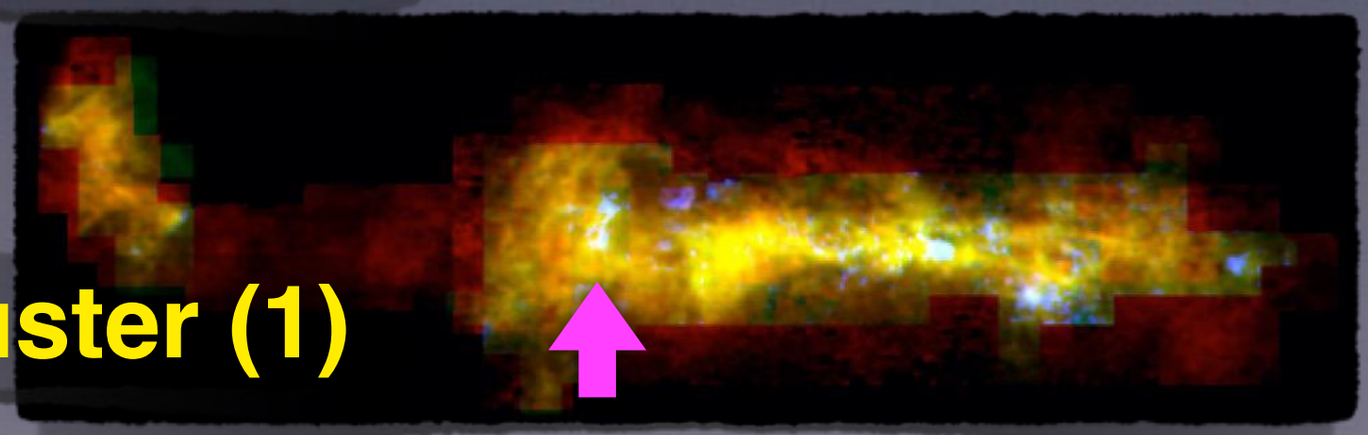
L=+1.3° Region

- HVCC CO 1.27+0.01 *Oka et al. 2001*
  - t_{exp} = 6x10^4 yr
  - E_{kin} = 2x10^{52} erg
- Energetics
  - N_{SN} ~ 20 η^{-1} (η~0.3; *Crocker et al. 2011*)
  - SNR ~ 10$^{-3.5}$ η^{-1} yr^{-1}
  - Salpeter IMF (α=2.35)

M_{Cl} ~ 10$^{6.1}$ η^{-1} M_{sun}

Unusually Massive Cluster (1)

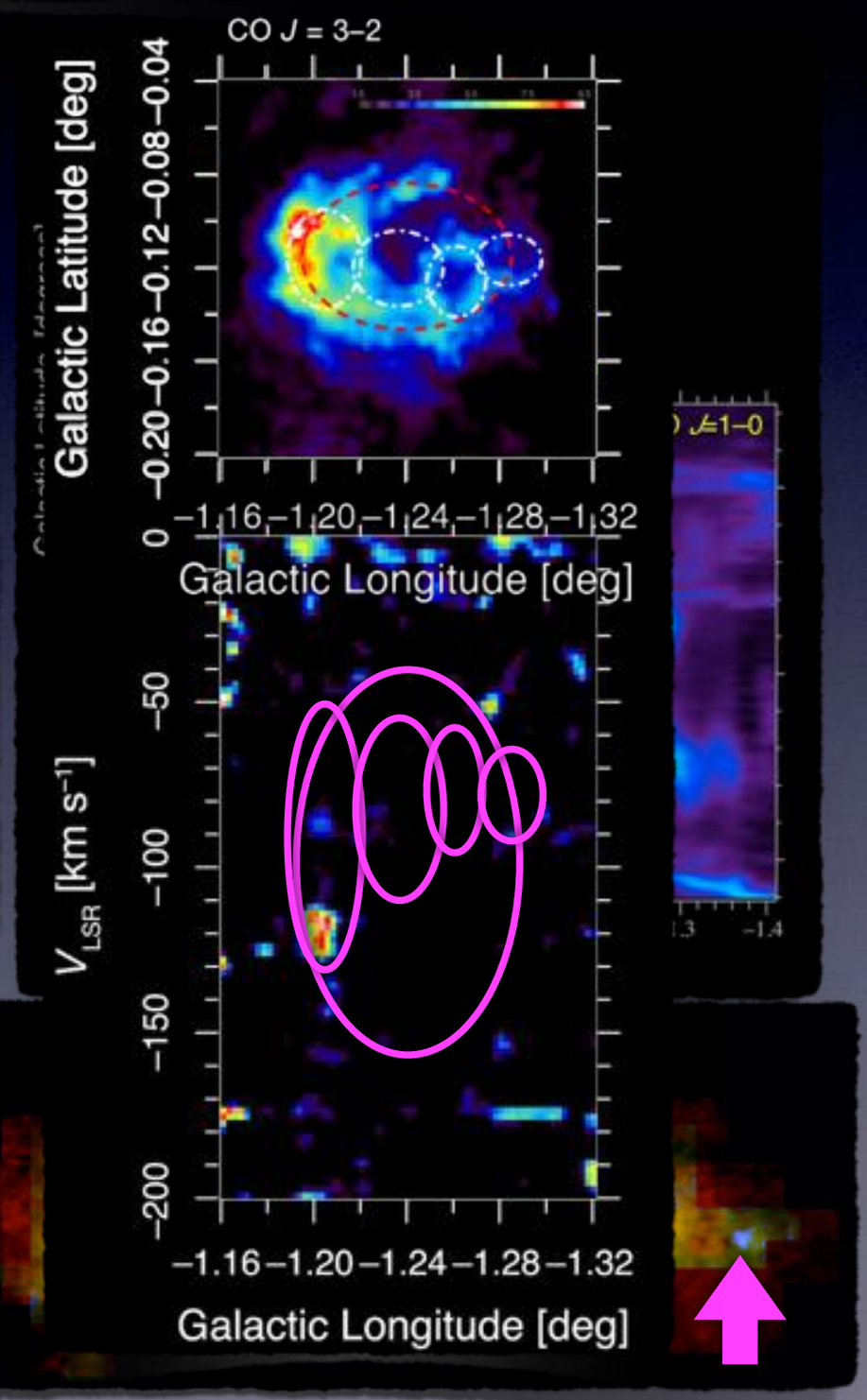




L=–1.2° Region

- HVCC CO–1.21–0.12 *Oka et al. 2012*
  - Clear expanding shell
  - t_{exp} ~ 10^5 yr
  - E_{kin} ~ 10^{52} erg
- Five Expanding shells *Tsujimoto et al. 2017*
  - Aligned to the Galactic plane
  - Shocked gas at high-vel. end

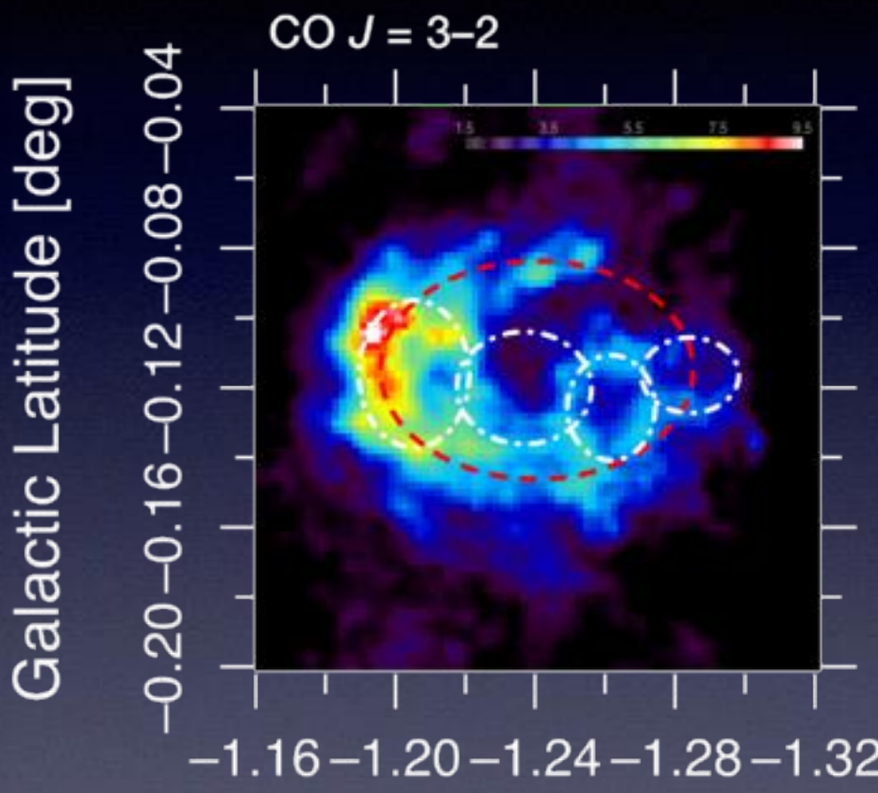
Molecular Bubble (2)

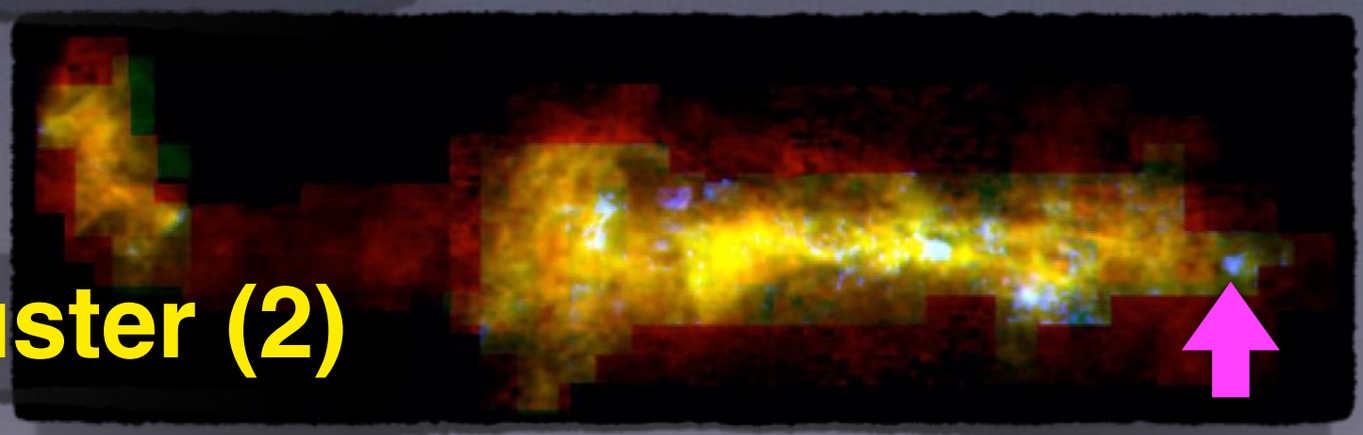


L=–1.2° Region

- HVCC CO–1.21–0.12 *Oka et al. 2012*
  - t_{exp} ~10^5 yr
  - E_{kin} ~10^{52} erg
- Energetics *Tsujimoto et al. 2017*
  - N_{SN} ~ 10 η^{-1} (η~0.3; *Crocker et al. 2011*)
  - *SNR* ~ 10^{-4} η^{-1} yr^{-1}
  - Salpeter IMF (α=2.35)

M_{cl} ~ $10^{5.6}$ η^{-1} M_{sun}

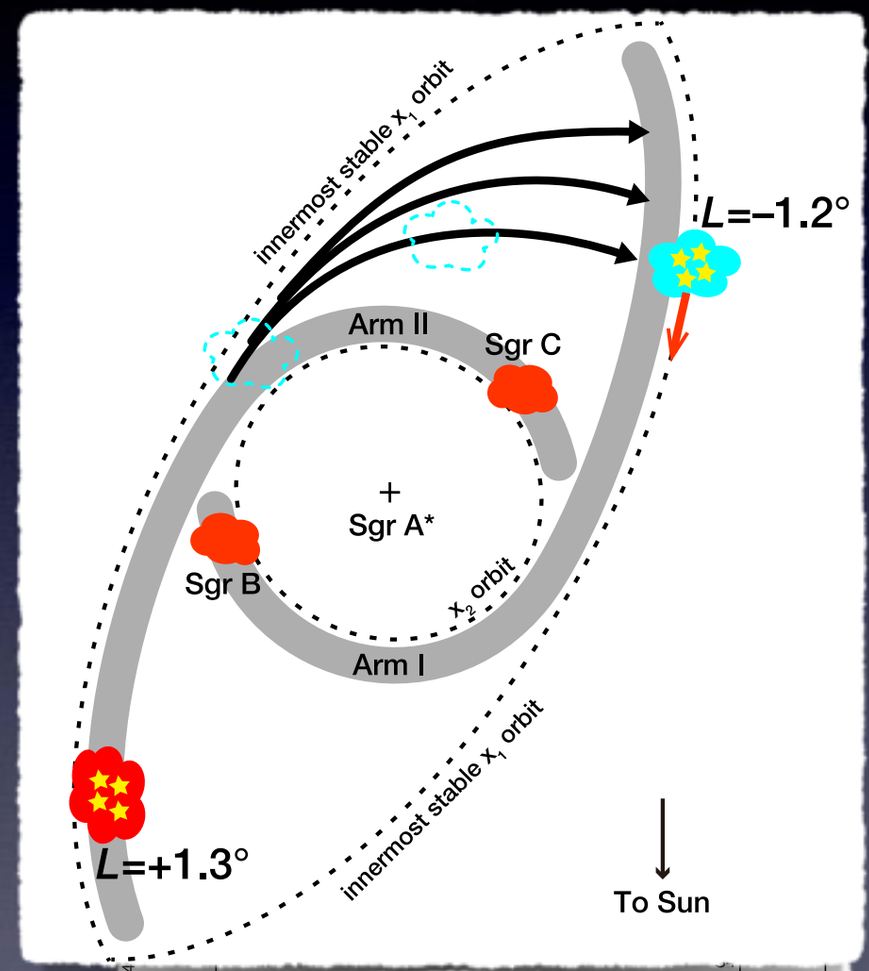


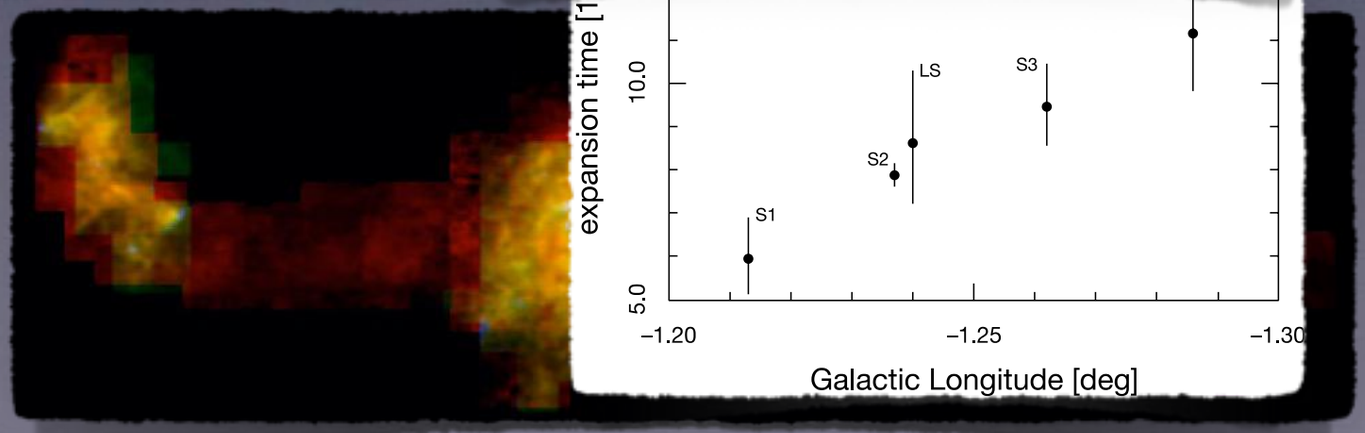


Unusually Massive Cluster (2)

L=–1.2° Region

- Expanding shells *Tsujimoto et al. 2017*
  - t_{exp} well correlates with l
- Gas orbits near ILR *Binney et al. 1991*
  - Cluster: innermost x_1 orbit
  - Gas: infalling from an orbit intersection





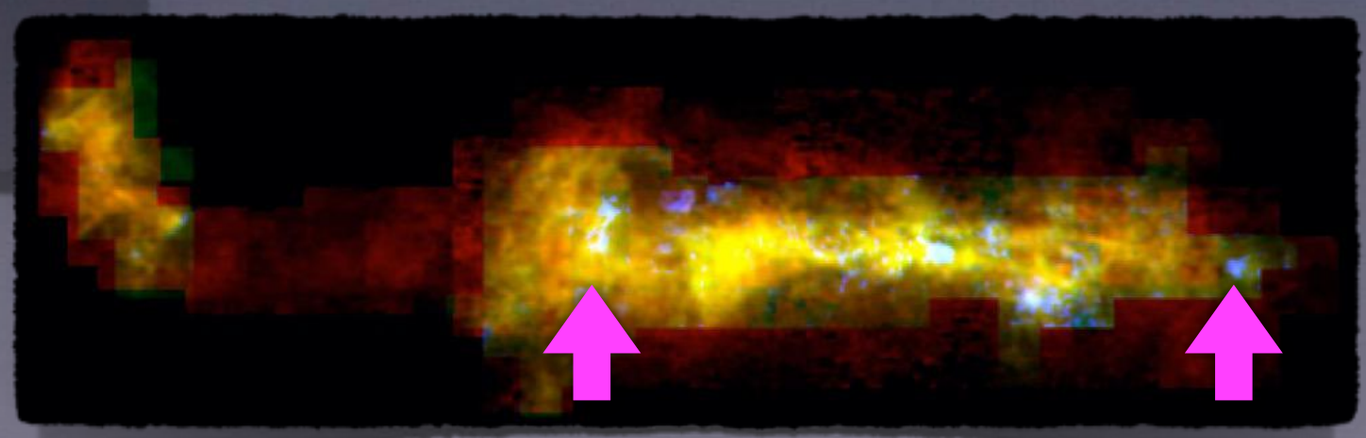
Nature of the Clusters

- No RC/IR counterpart → **age = 10–30 Myr**
- Expected Luminosity (α=1.7)
  - $L_{cl}(+1.3°) \sim 10^{7.8}\ \eta^{-1}\ L_{sun}$
  - $L_{cl}(-1.2°) \sim 10^{7.6}\ \eta^{-1}\ L_{sun}$
- Observed IR luminosity
  - $L_{IR}(+1.3°) \sim 10^{6.2}\ L_{sun}$
  - $L_{IR}(-1.2°) \sim 10^{5.8}\ L_{sun}$

- Expected Luminosity (α=2.35)
  - $L(+1.3°) \sim 10^{8.2}\ \eta^{-1}\ L_{sun}$
  - $L(-1.2°) \sim 10^{7.7}\ \eta^{-1}\ L_{sun}$

not consistent!

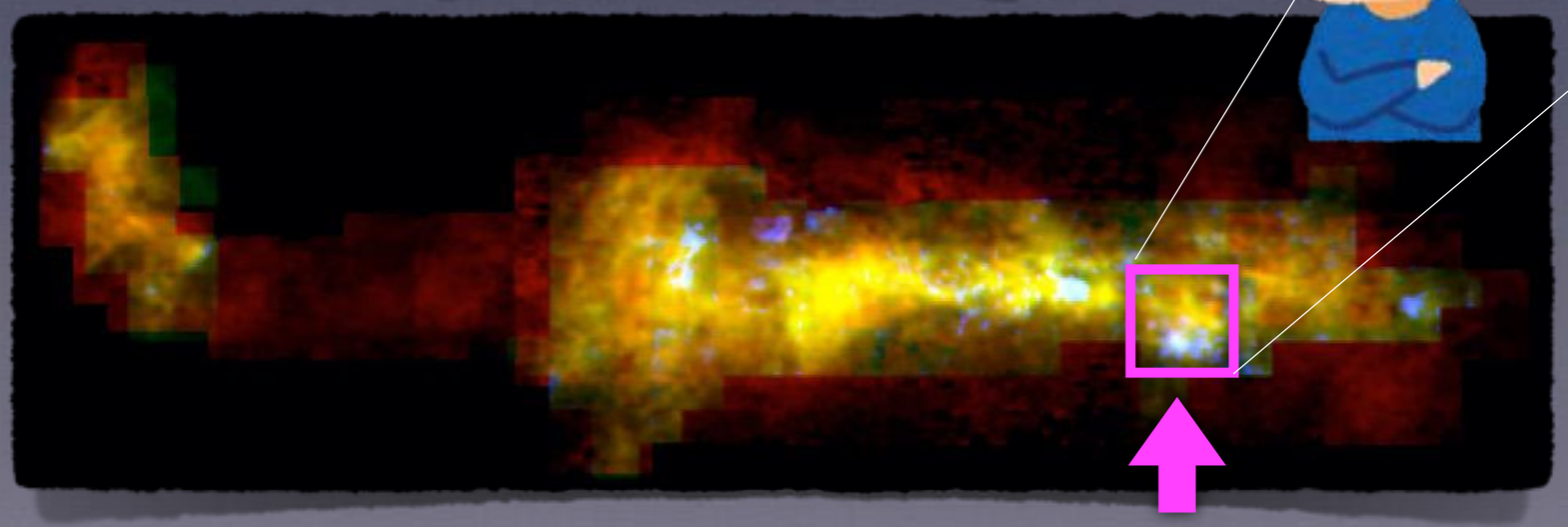
Top-heavy IMF?

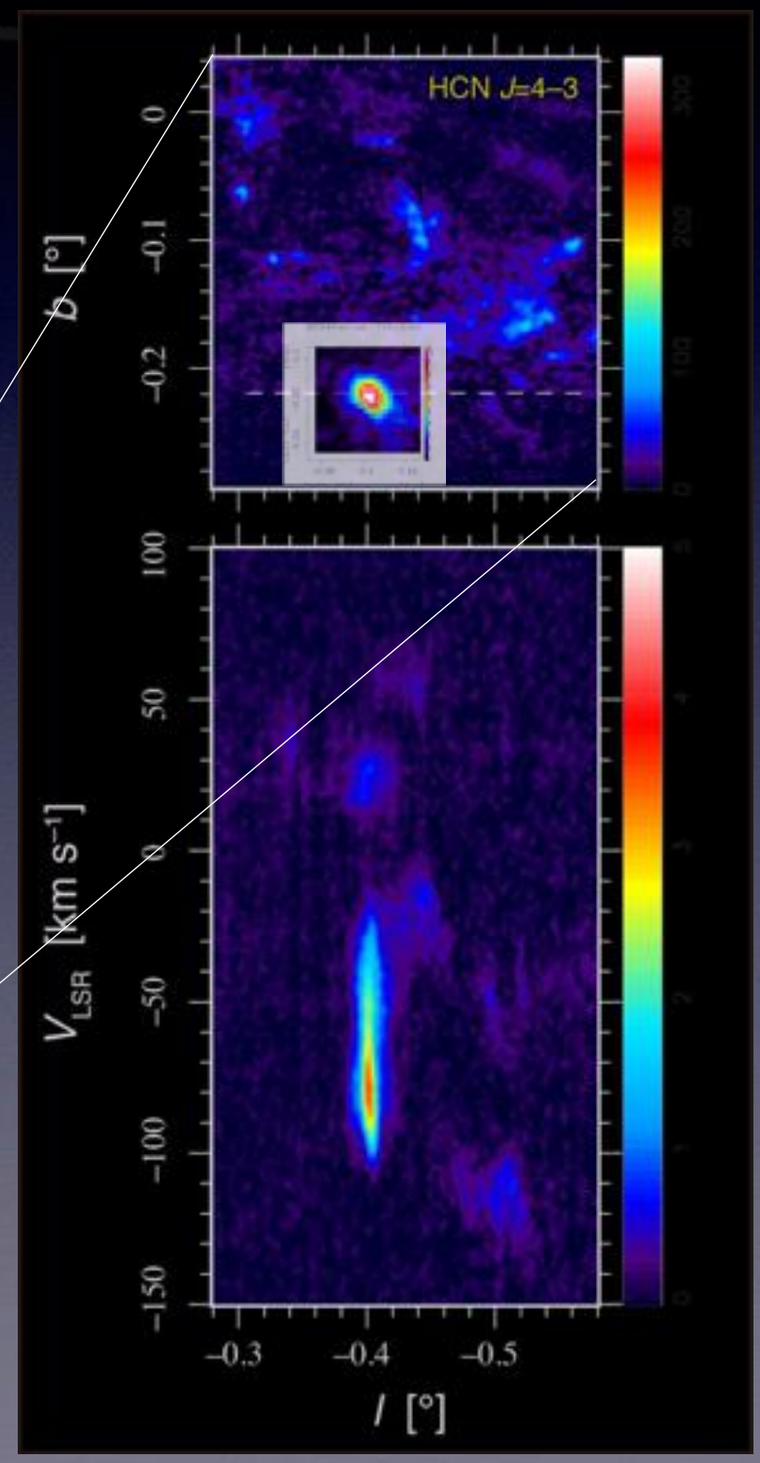


L=–0.4° Region

- HVCC CO–0.40–0.22
  - Compact appearance (d<3 pc)
  - Extremely-broad ΔV (>80 km s^{-1})
  - No counterpart

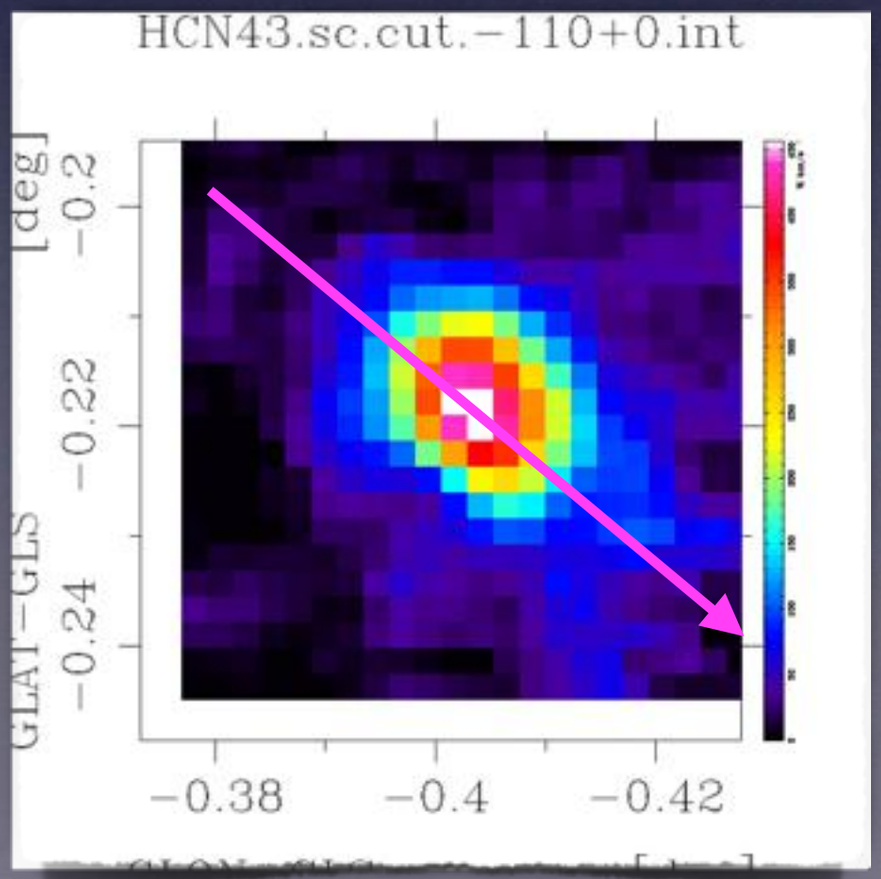
What is this?

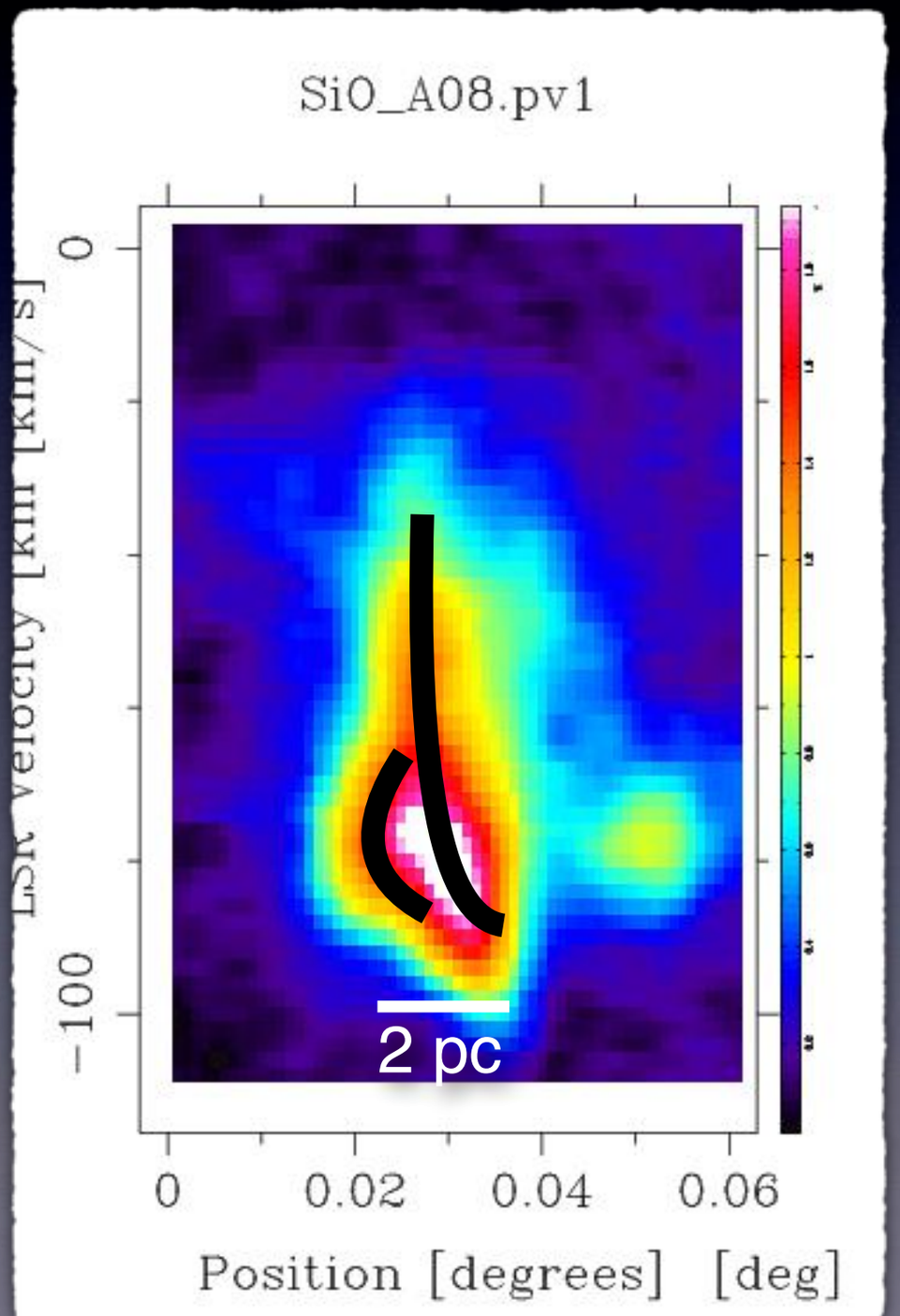




Kinematics

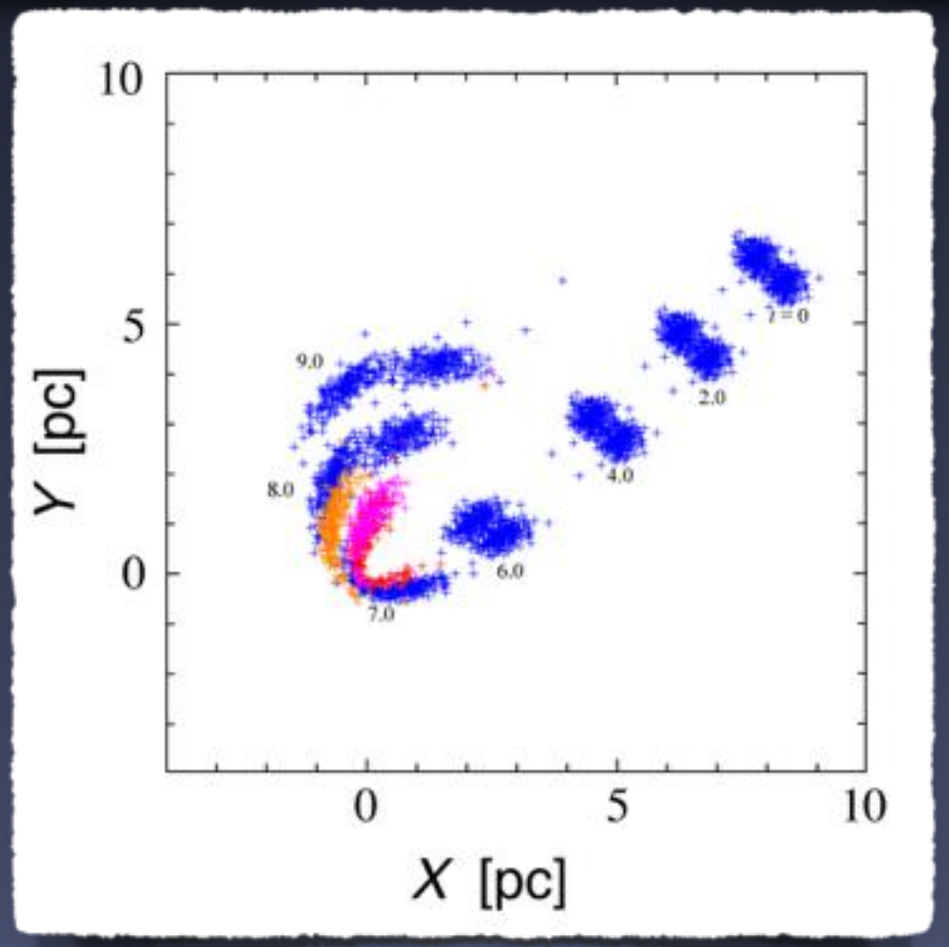
- Size ~ 2 pc
- Velocity gradient shift
- Eastern hump

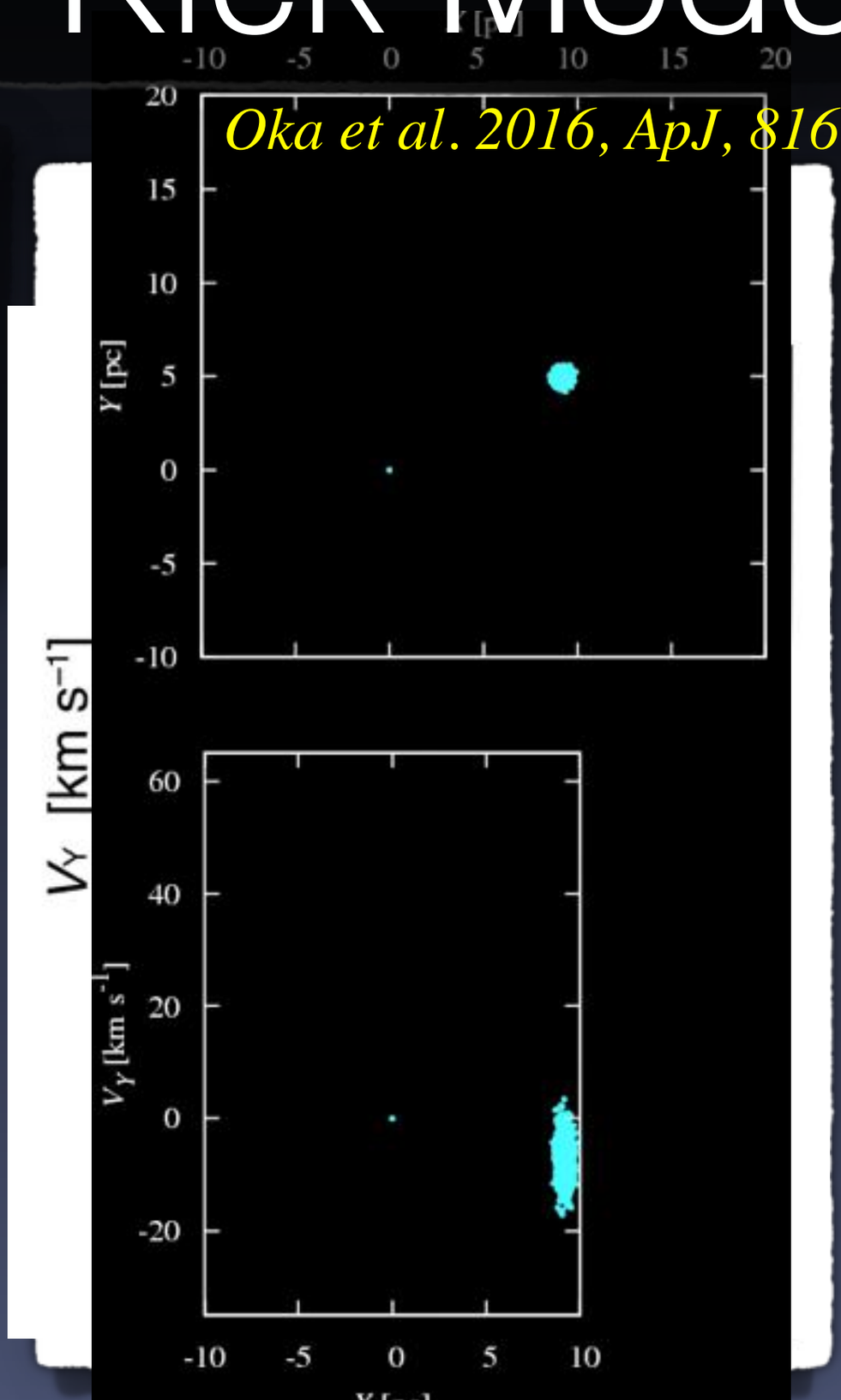




Gravitational Kick Model

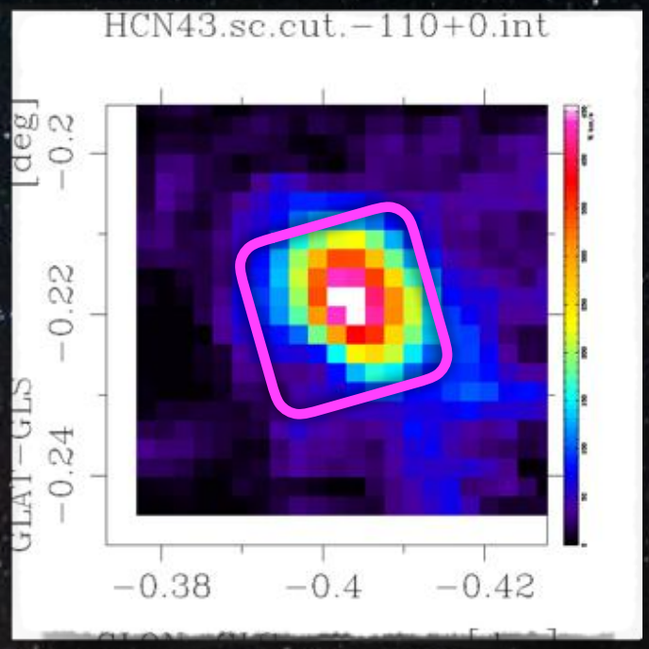
- $M = 10^5\ M_{\rm sun}$!
- $V_0 = 10$ km s^{-1}, $D = 10$ pc
- $b = 1.0$ pc, 1.8 pc
- $t \sim 7\text{x}10^5$ yrs

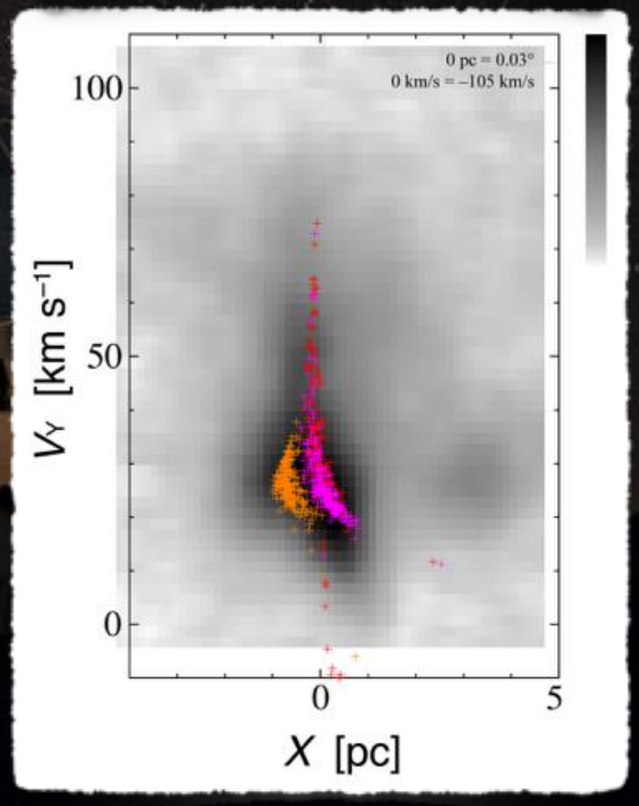




ALMA Band 6 Observations

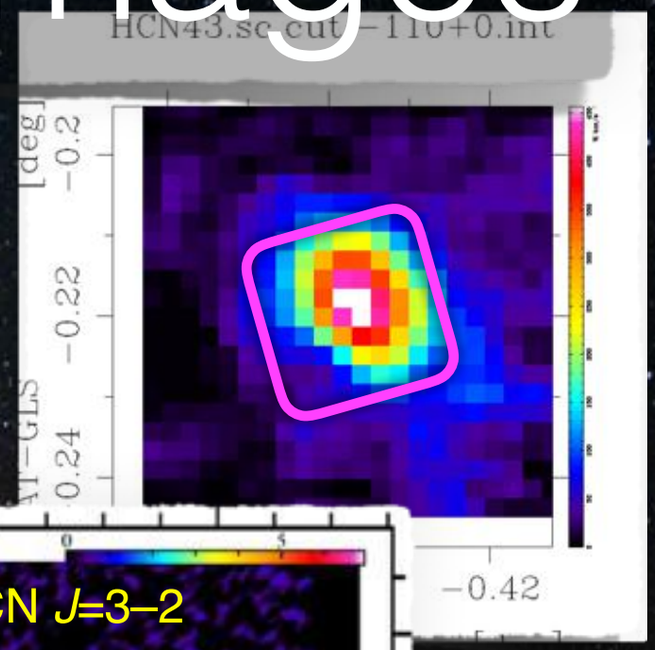
- CO *J*=2–1 : 230.538001 GHz
- HCN *J*=3–2 : 265.886432 GHz
- 12m array + 7m array
- HPBW = 1.7”x1.0”@231 GHz
  = 1.3”x0.5”@266 GHz
- 進捗
  - Nov. 2012: Approved Cycle 1 obs.
  - Oct. 2013: Transfer to Cycle 2
  - Dec. 2014: 7m data delivery
  - Apr. 2015: 12m data delivery

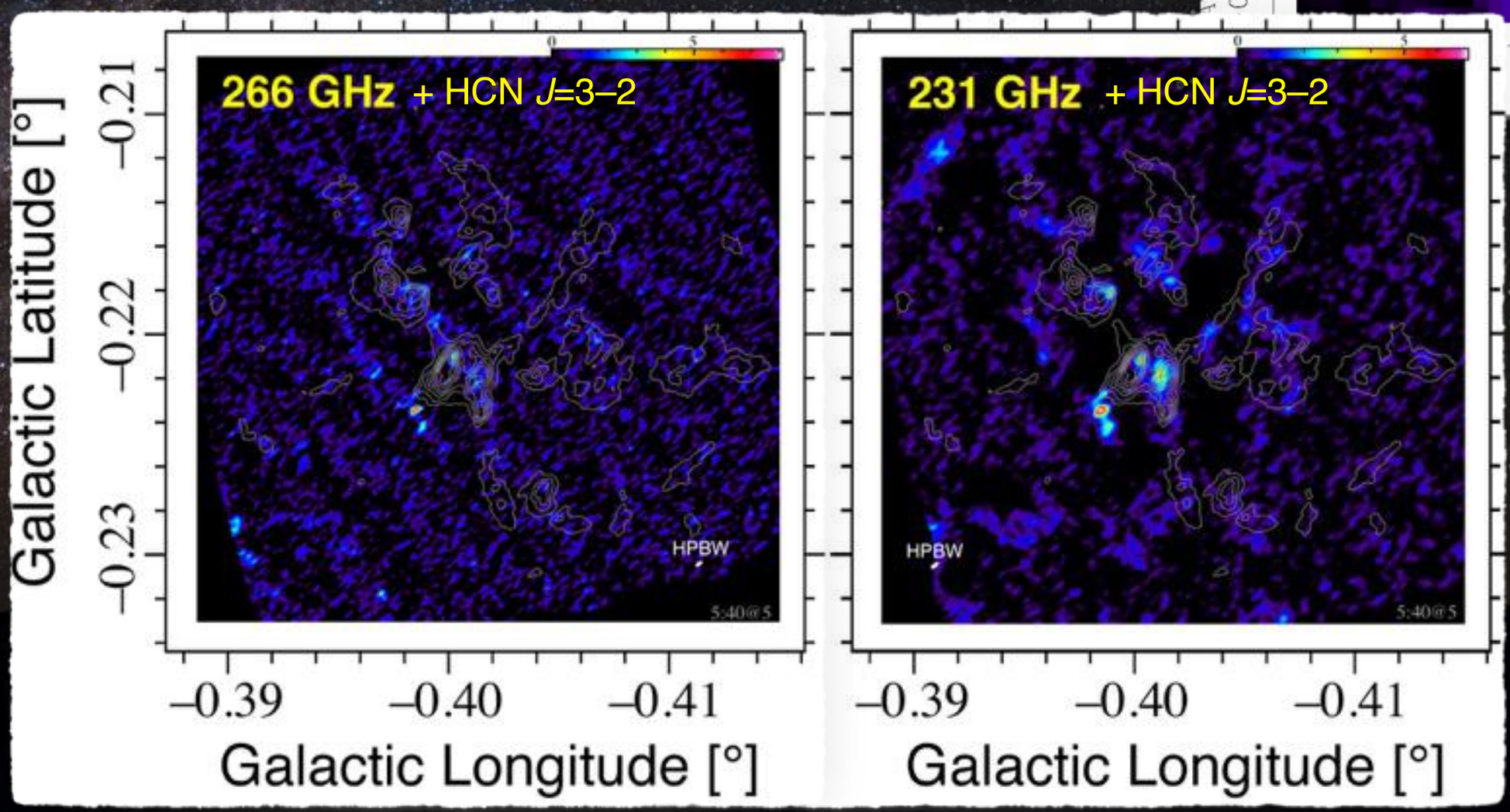




Radio Continuum Images

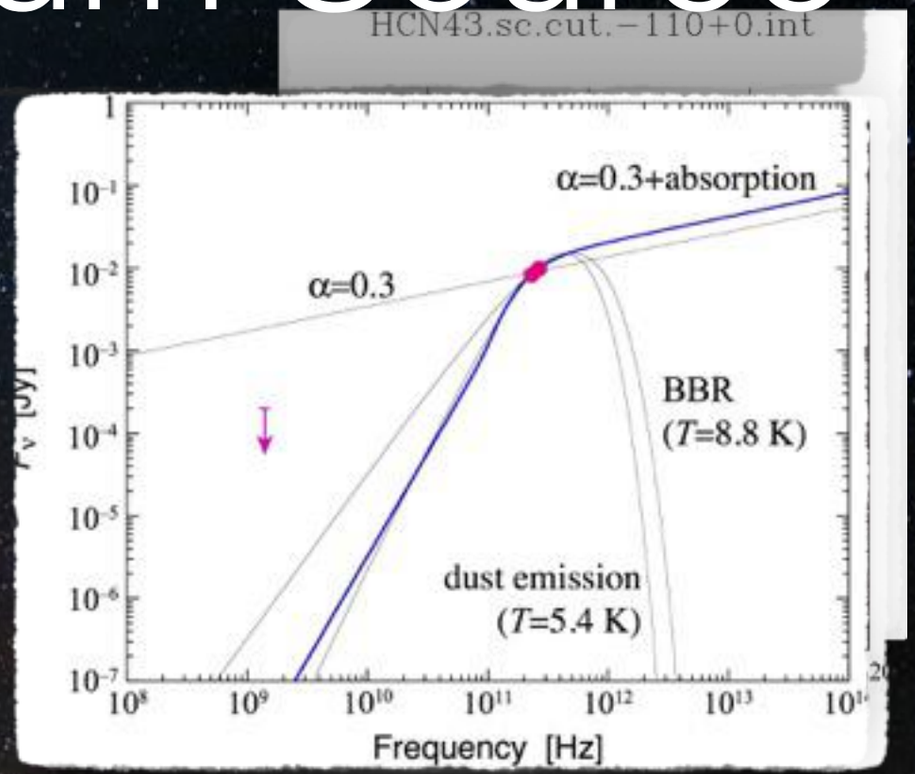
- Point-like source: CO–0.40–0.22*
- Size < $HPBW_{266}$ (=0.06x0.02 pc^2)

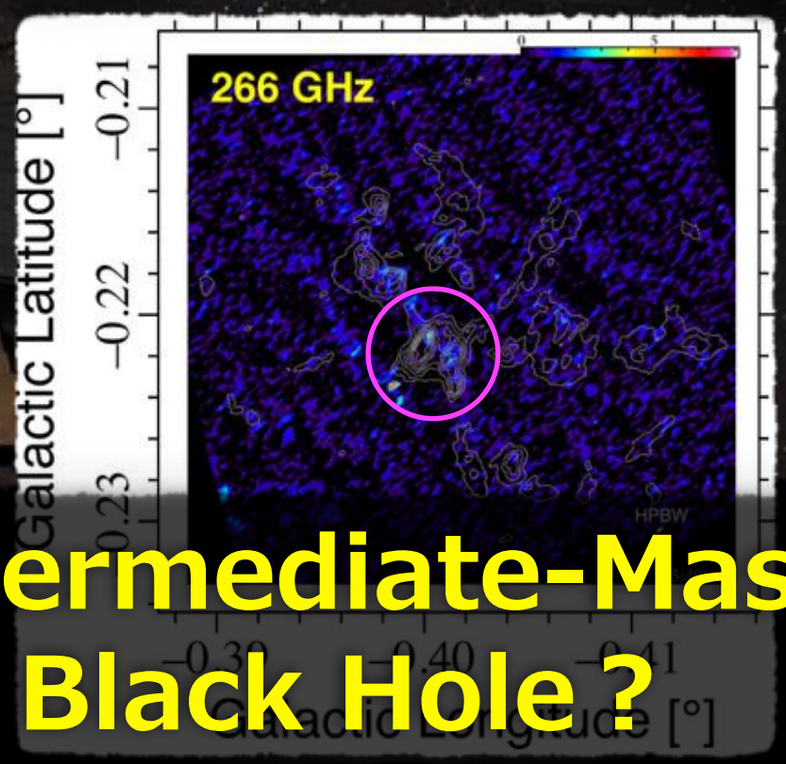




Point-like Continuum Source

- Fluxes
  - F_{231G} = 8.2±0.4 mJy
  - F_{266G} = 9.7±0.4 mJy (T_b~0.33 K)
    - α = 1.18±0.65 (~ 0.3 @Sgr A*)
  - F_X < 0.95 nJy





~~Ultra-compact HII region?~~
- EM >10^{11} cm^{-6} pc (<10^8 @UCHII)

~~Protoplanetary disk?~~
- T_d ~ 9 K (several 100 @PPD)

~~Submillimeter Galaxy?~~
- P_{ch} < 0.028 %

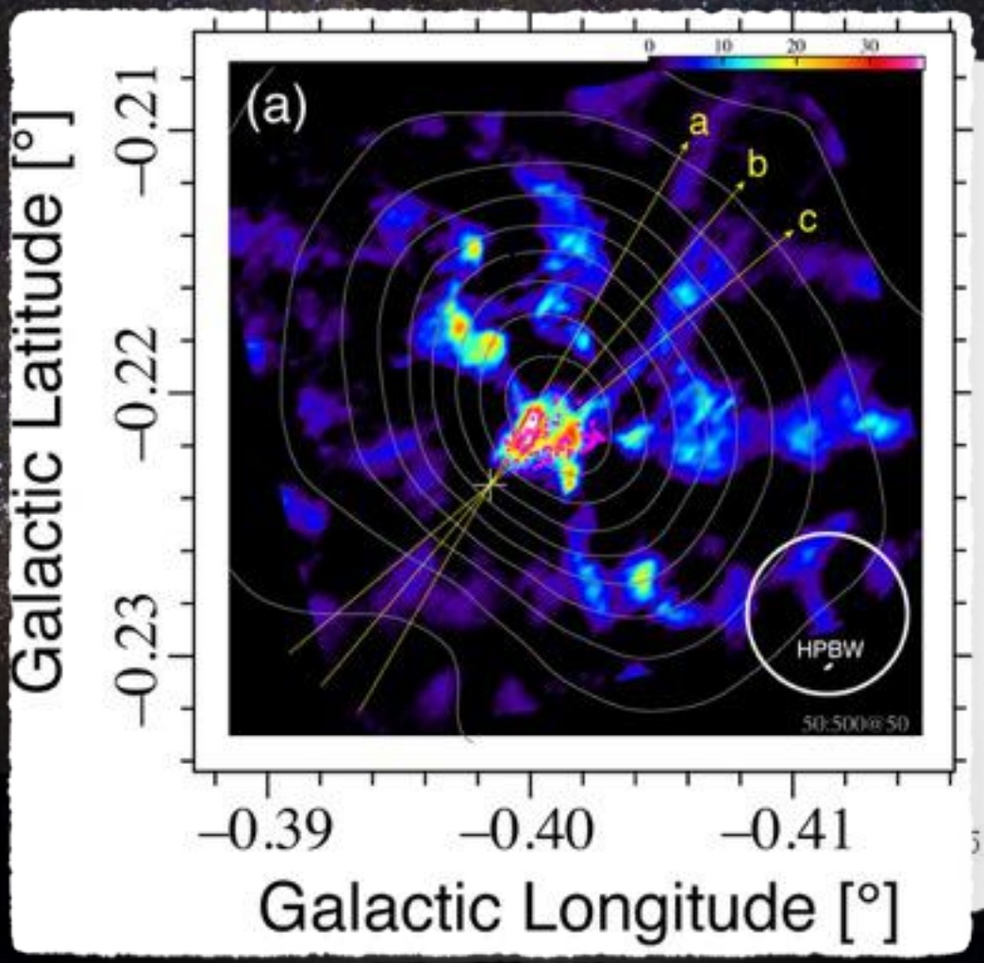
Intermediate-Mass Black Hole?

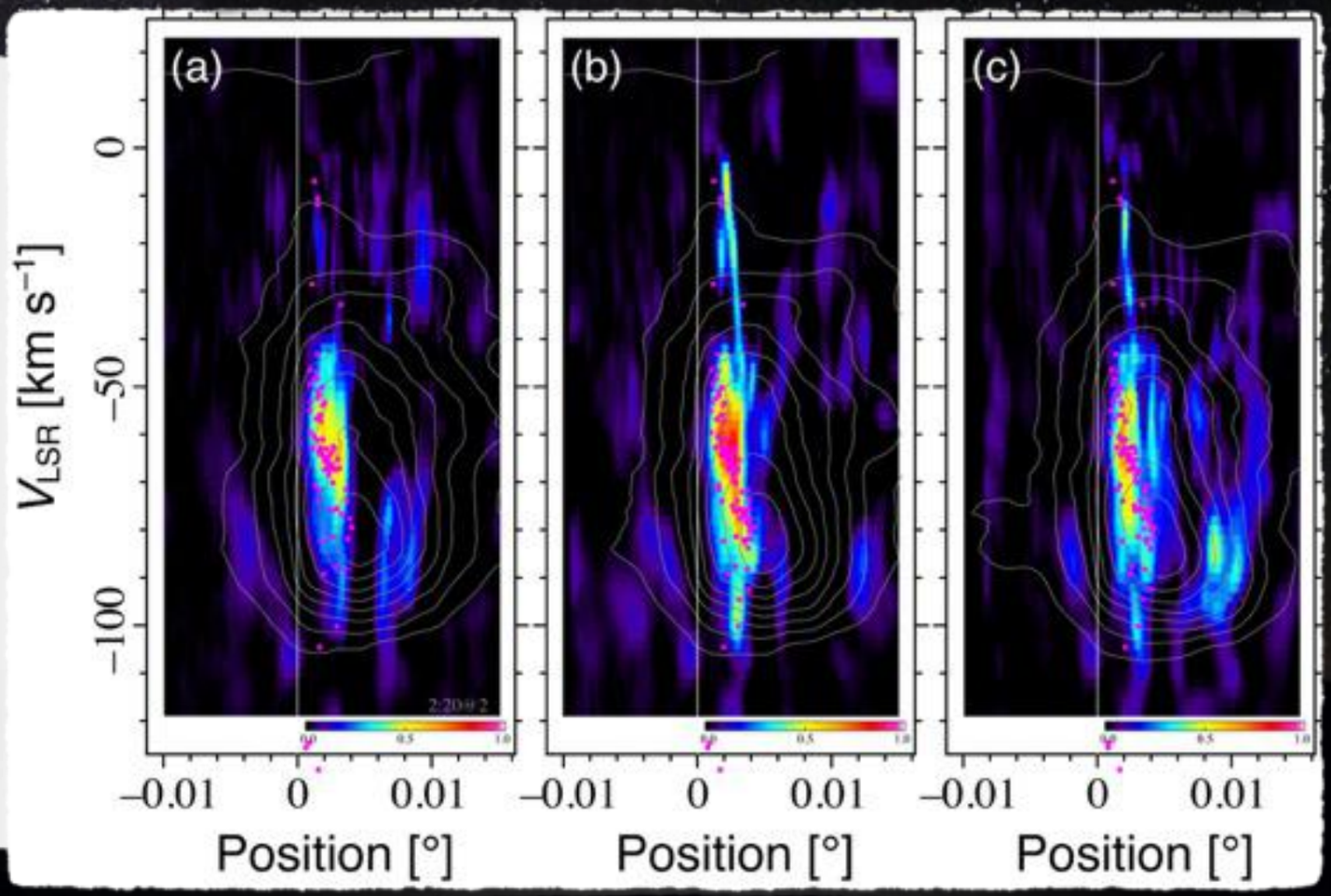
Gravitational Kick Model Revisited

Oka et al. 2017, NatAs

- 10^5 $M_{\rm sun}$ @CO–0.40–0.22*
- ϕ=45°, P.A.=41.6°, *i*=70°

reproduces very well





Formation/Evolution of SMBH

Ebisuzaki et al. 2001

- Starburst
  - Dense stellar clusters
- Runaway stellar coalescence
  - Intermediate-mass BHs
- Merging at GC
  - Supermassive BH

爆発的星形成

暴走的合体

高密度巨大星団

超大質量ＢＨ

Summary

We detected:

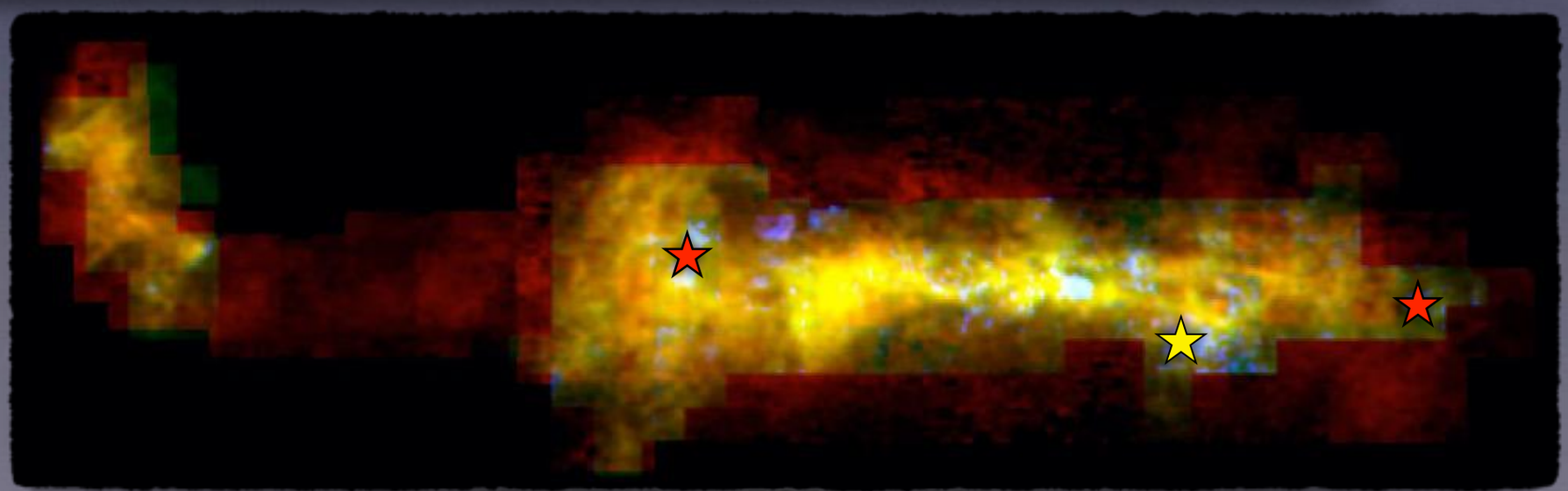
- Two molecular bubbles
  - embedded massive clusters
  - top-heavy IMF?

Oka et al. 2001, PASJ, 53,787
Tanaka et al. 2007, PASJ, 59, 323
Tsujimoto et al. 2017, ApJL submitted

- Intermediate-mass black hole candidate
  - M=10^5 $M_{\rm sun}$

Oka et al. 2016, ApJ, 816, L7
Oka et al. 2017, NatAs in press

in the central molecular zone of our Galaxy.



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ご静聴どうも有り難うございました。

Thank you for listening.