Star Formation in the Galactic Center Region

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- **Overview**
  1. **Small Scale ~ 0.5pc - few pc**
     - The stellar disk orbiting Sgr A* + the molecular ring
     - Partial accretion of passing molecular cloud
     - $\tau_{dynmaica} < \tau_{shear}$
  2. **On-going Star Formation in the Molecular Ring**
     - Methanol masers
     - Infancy of the molecular ring + in situ star formation
  3. **Large Scale ~ 200pc: Highlights of Spitzer Observations**
     - A population of YSOs
     - Star Formation Rate
     - $\tau_{dynmaical} > \tau_{shear}$
- **Conclusions**

Collaborators

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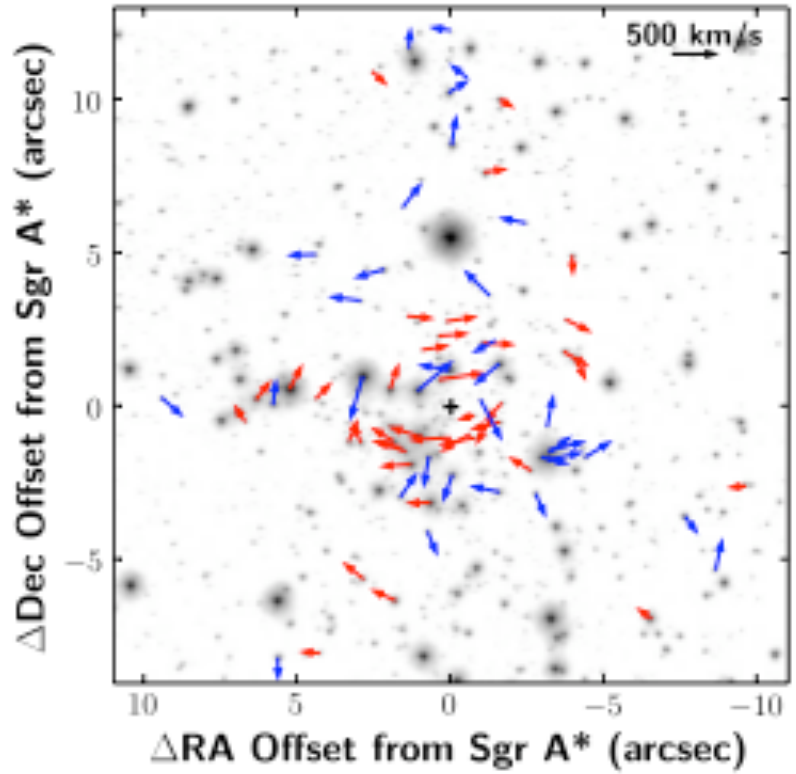
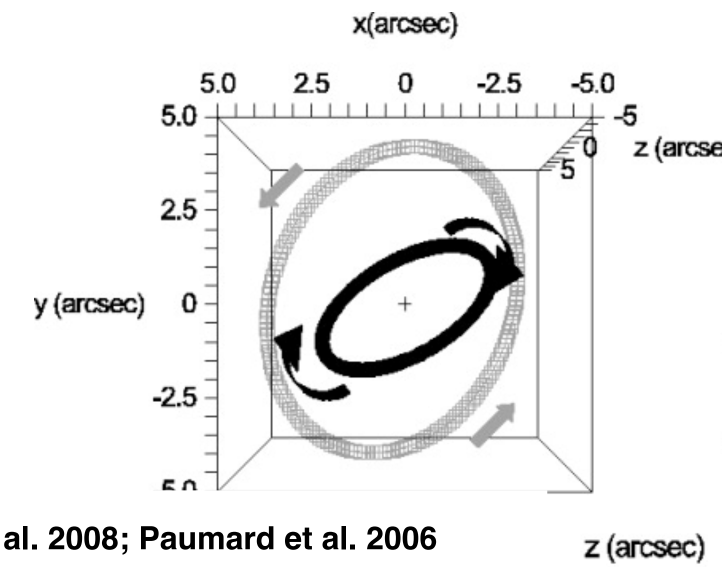
- M. Wardle

Stellar Disk 0.03–0.3 pc

- Majority of early type stars in one or two disks < 0.5pc
- Disks have moderate thickness (h/r~0.1)
- Stars have low-to-high eccentricities
- Coeval disks t=(6+/-2)x10^6 yrs
- Disk mass < 10^4 solar mass





Levin and Beloborodov 2003; Genzel et al. 2003; Lu et al. 2008; Paumard et al. 2006

Surprise!

Young stars so close to Sgr A*? (The paradox of youth)
Why formed in counter-rotating disks?

Two scenarios of star formation:

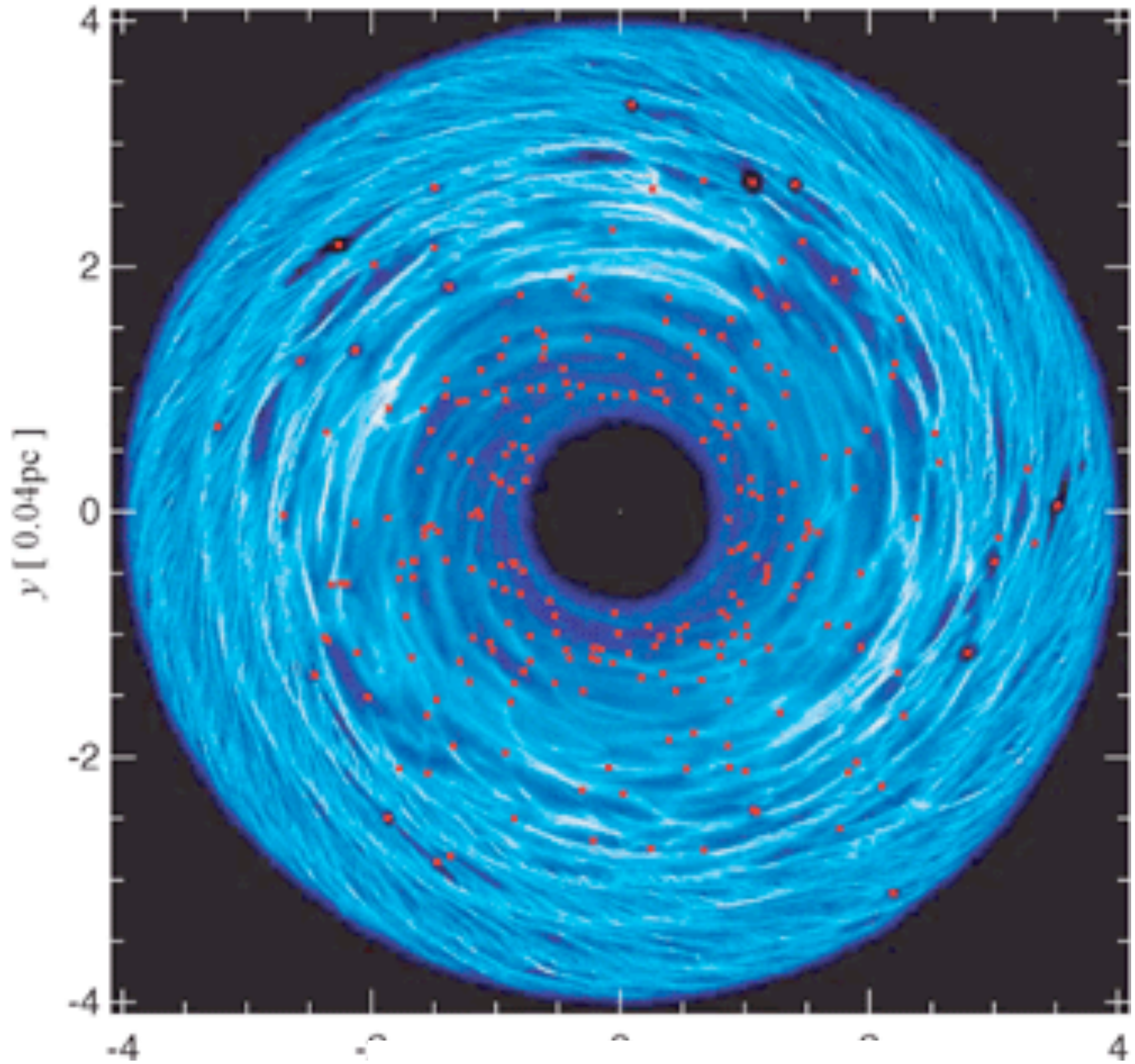
1. Migration: massive clusters will undergo dynamical friction (Gerhard 2001)
    - dynamical friction is too long
    - no massive stars beyond 0.5pc
    - disordered stellar orbits

2. In-situ: massive disk becomes Jeans unstable (preferred)

Stellar Disk Formation

- In-situ star formation
- Simulation of star formation in an accretion disk: efficent
- Snapshot of disk column density
- Red spots: stars > 3 solar mass

- Questions:
  - How do these disks get in there in the first place?
  - What about eccentric orbits?
  - The trajectory of a compact cloud less than 1pc at 100 km/s: highly rare
  - Compact cloud has no way of shedding its angular momentum



Nayakshin, Cuadra and Springel 2007

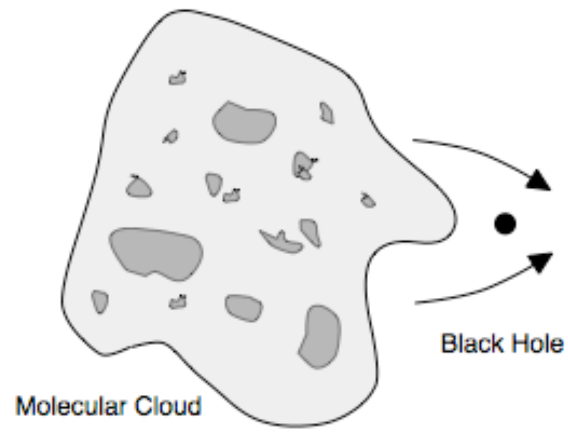
Molecular Cloud Engulfs Sgr A*

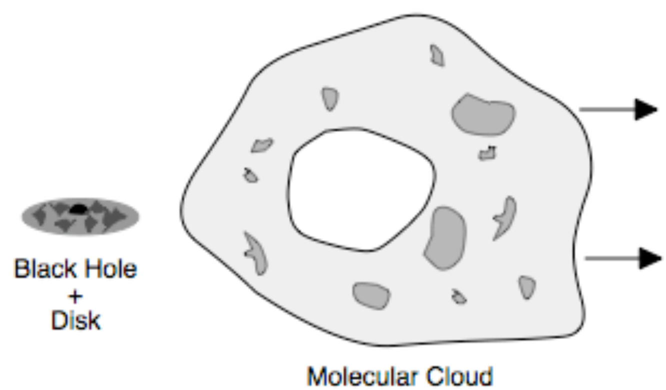
- Bondi-Hoyle: Inhomogeneous, extended cloud gravitationally focused

- Capture radius: 3pc
- 70% of angular momentum cancels out as r=3pc circularizes to 0.3pc

- Q<1 as the disk self-gravitates

- Cloud-cloud collisions: The circumnuclear ring (few pcs)





Wardle and FYZ (2008)

Mass-Radius Relationship

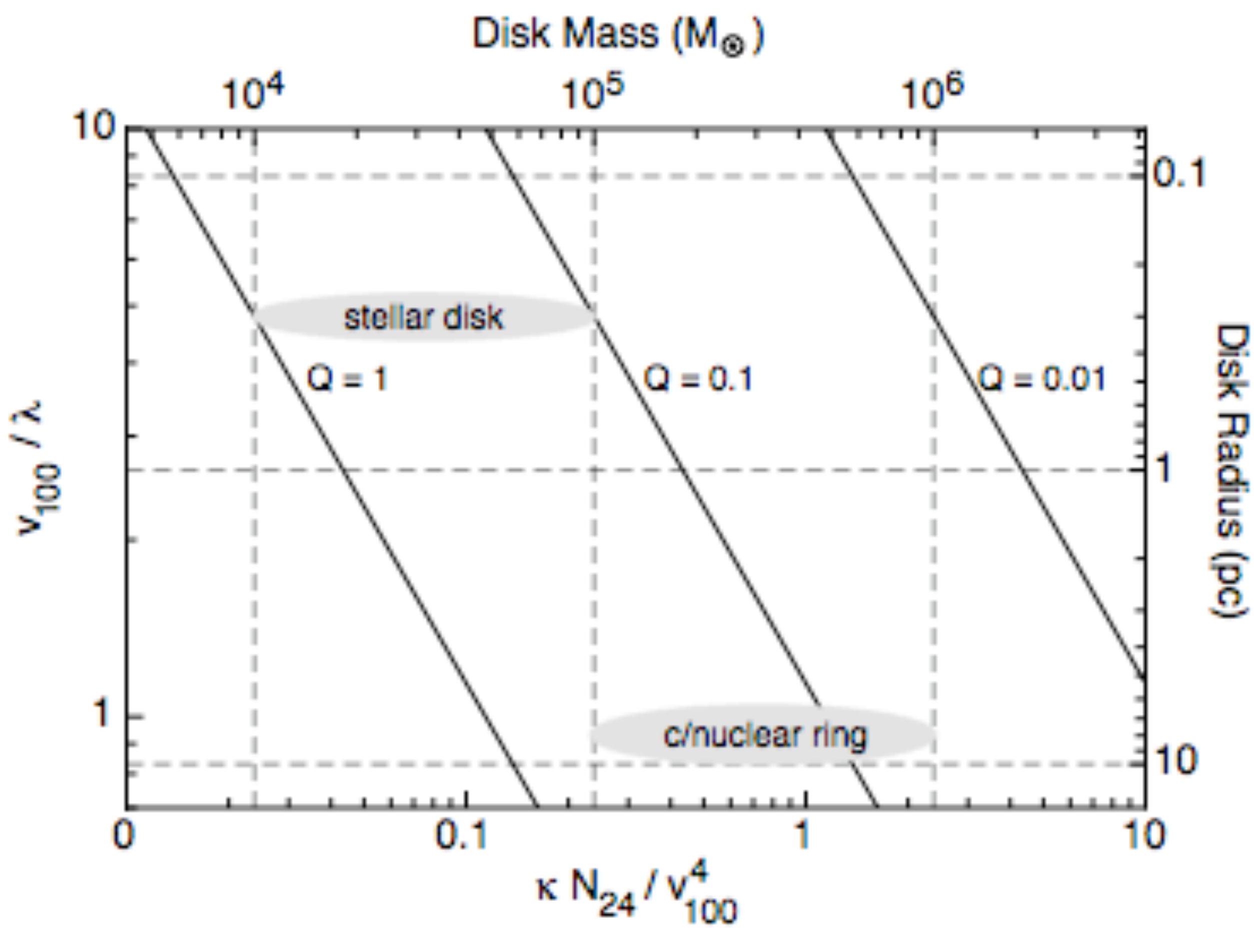
$$Q = \frac{c_s \Omega}{\pi G \Sigma_d} = 0.11\, T_{100}^{1/2} \frac{\lambda\, v_{100}^3}{\kappa N_{24}}$$

$Q = \tau_{dynamical} / \tau_{shear}$

λ: Fraction of angular momentum retained by the captured cloud ~0.3

κ: ratio of captured mass to accreted mass ~1

- Stars circularize with a range of eccentricities



Wardle and FYZ (2008)

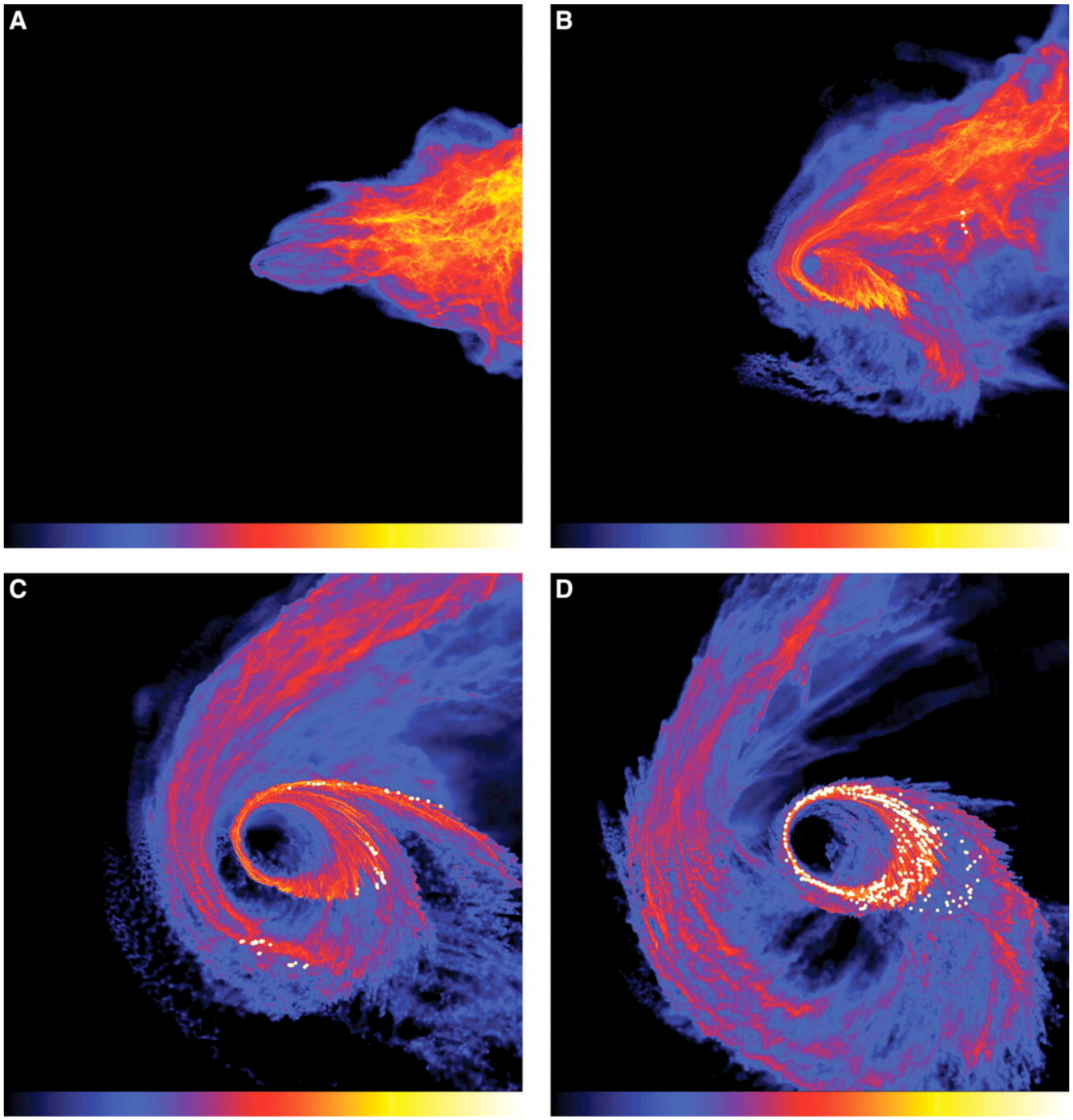
SPH Simulations: Formation of an Eccentric Disk

- Plunging of a 10^4 solar mass molecular cloud onto a 10^6 BH

- A: size 1.5 pc, t=3.2×10^4 yrs
- B: size 1pc, t=4.2×10^4 yrs
- C: size 0.5 pc, t=4.7×10^4 yrs
- D: size 0.5 pc, t=5.1×10^4 yrs

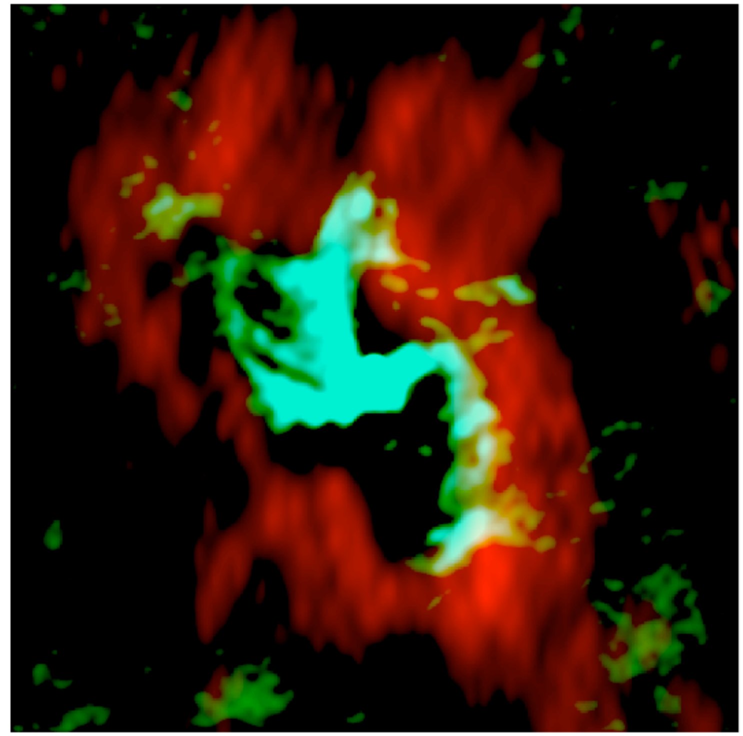
- Eccentric orbits

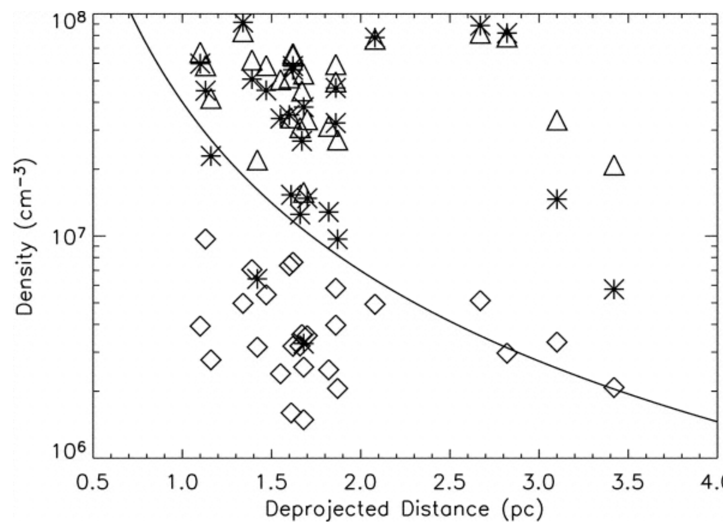
Bonnell and Rice (2008)



Molecular Ring Orbiting Sgr A*

- Kinematics: rotation with v~110 km/s
- Velocity dispersion ~27 km/s; Disturbed motion
- 26 dense cores
- size ~ 0.3x0.2 pc
- Velocity dispersion ~27 km/s
- Mass ~ 1.6x10^{4} Msolar
- Evidence for star formation?





~ few pcs

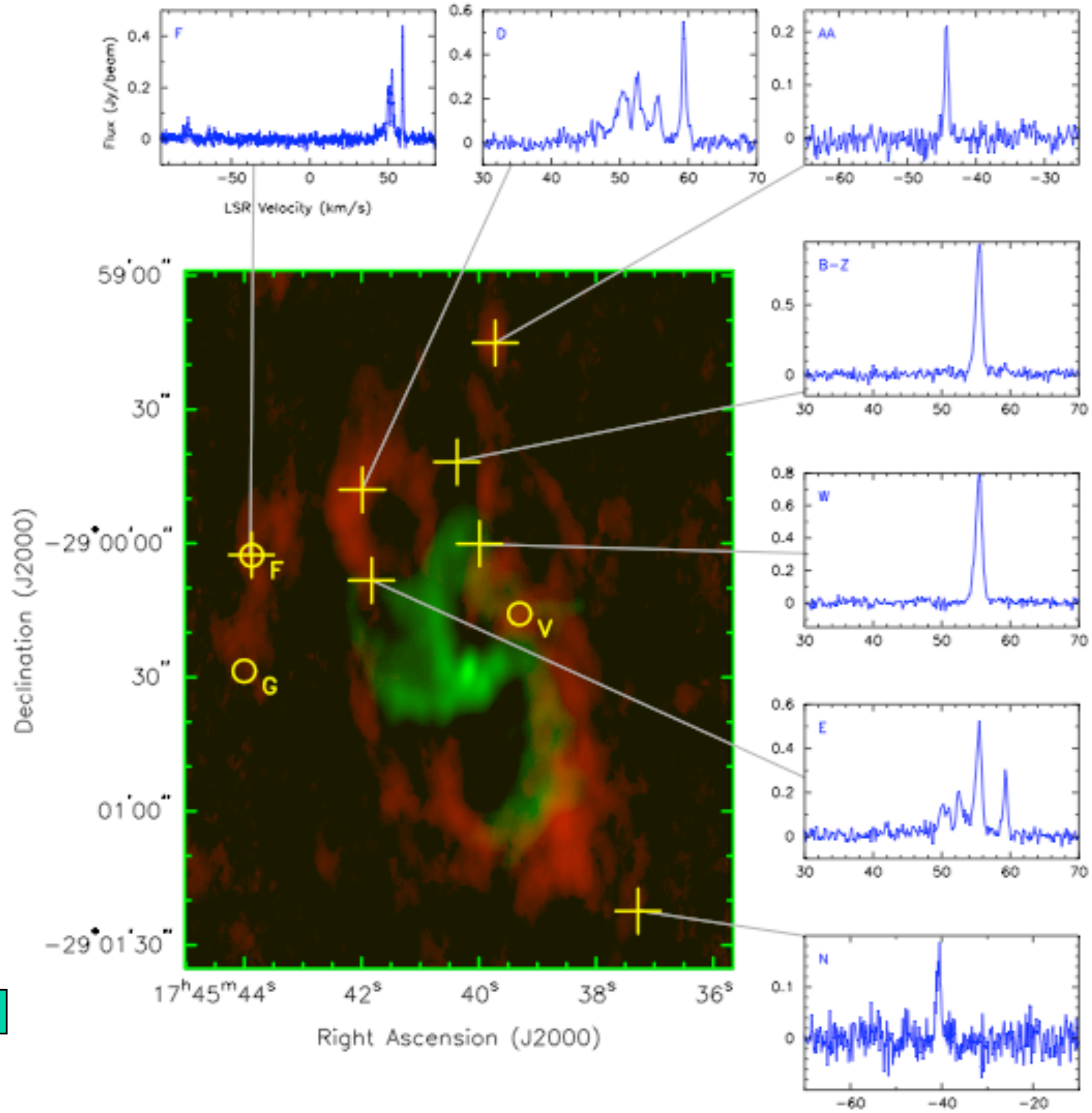
- Molecular Ring
  - –HCN(1-0) line

- Sgr A West
  - –Free-free emission at 1.3cm

Molecular Ring: H_2O and CH_3OH Emission

Detection of methanol and water maser emission with GBT

- Methanol Masers: signposts of on-going massive star formation
- Interstellar water masers: collisionally pumped at high densities



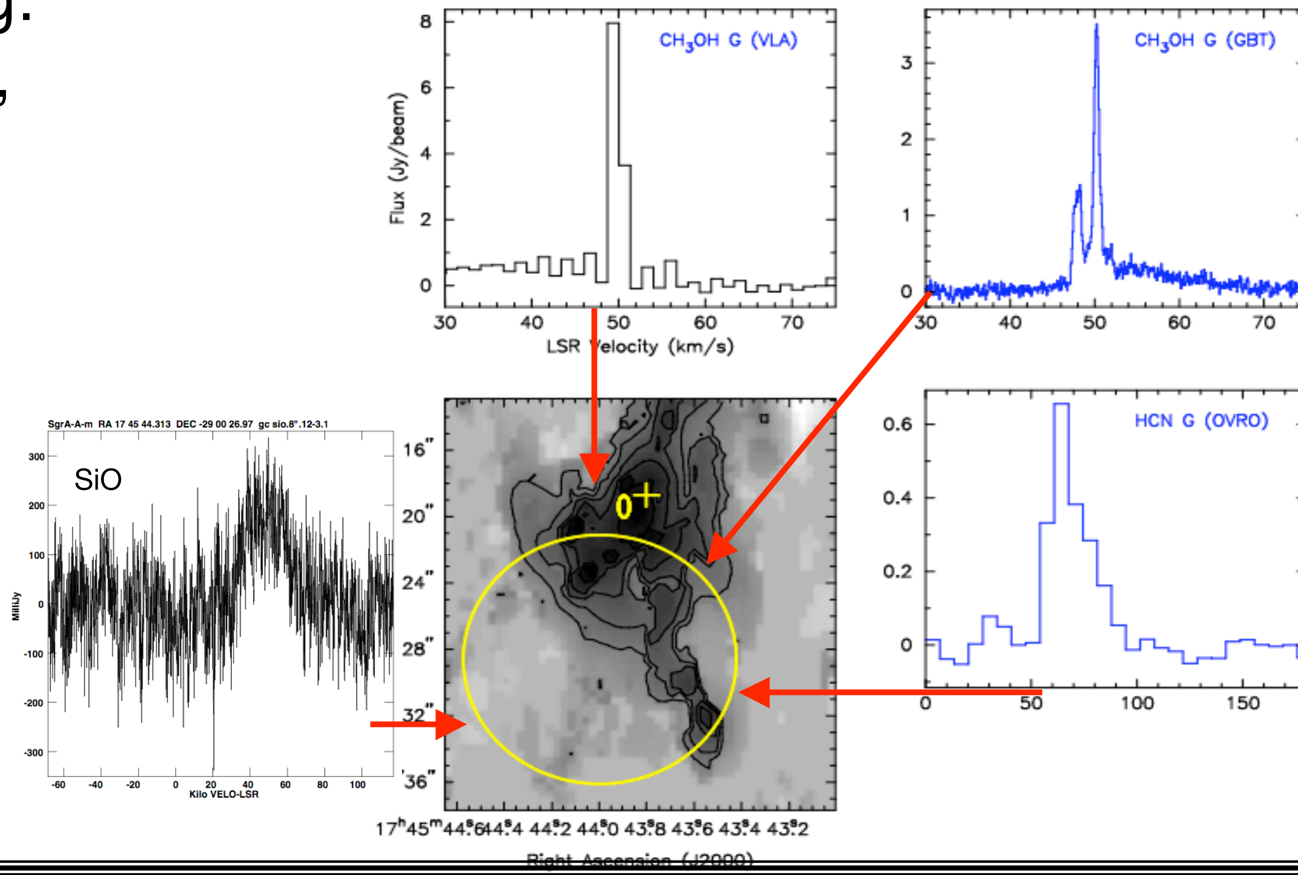
HCN

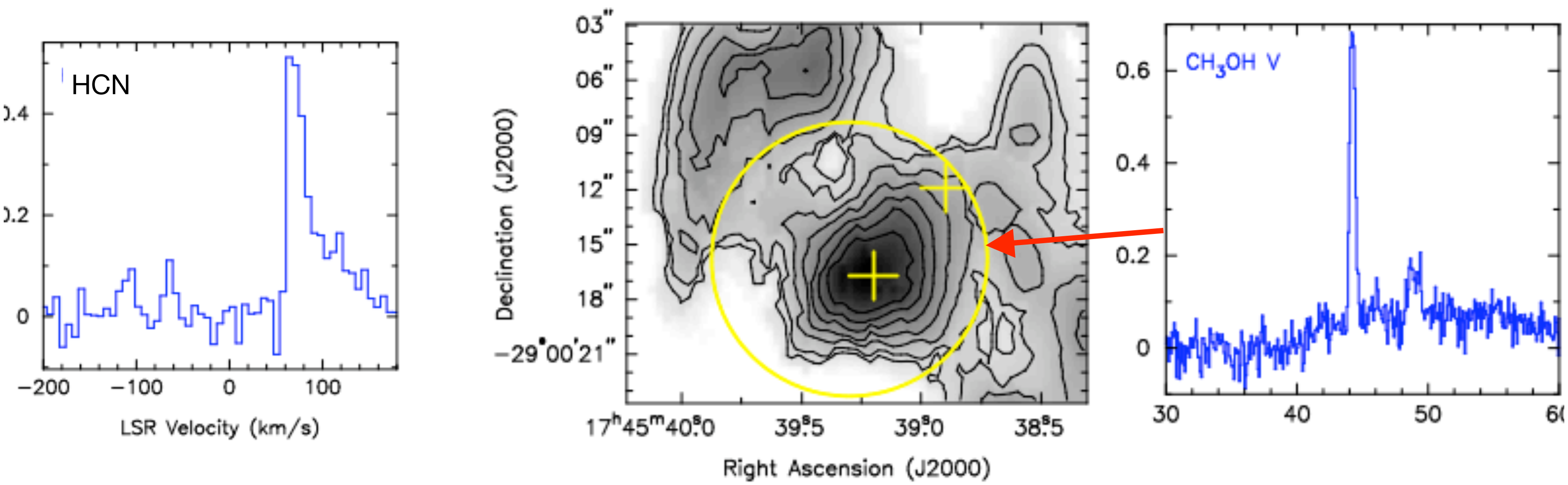
3.6cm

Molecular Ring: CH_3OH, HCN , SiO, H_2

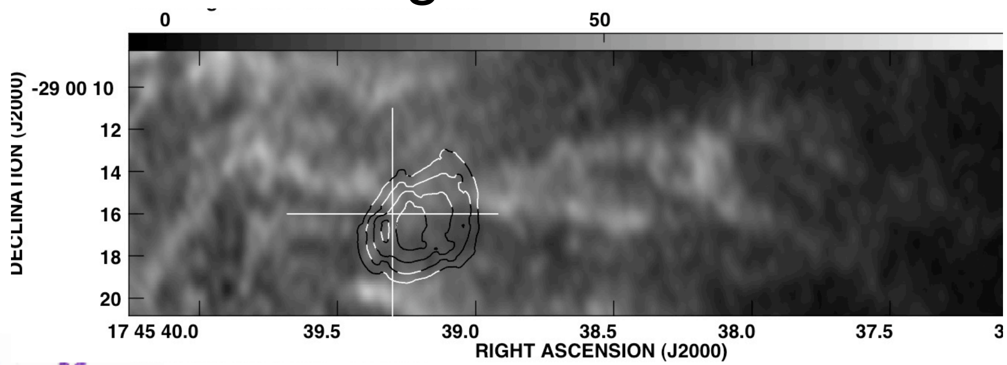
- CH_3OH:
  - Clump $d_{projected}$ ~0.6 pc
- Narrow line:
  - V~ 44 km/s & FWHM~ 0.35 km/s
  - Collisionally excited
- Broad line:
  - FWHM~ 25 km/s

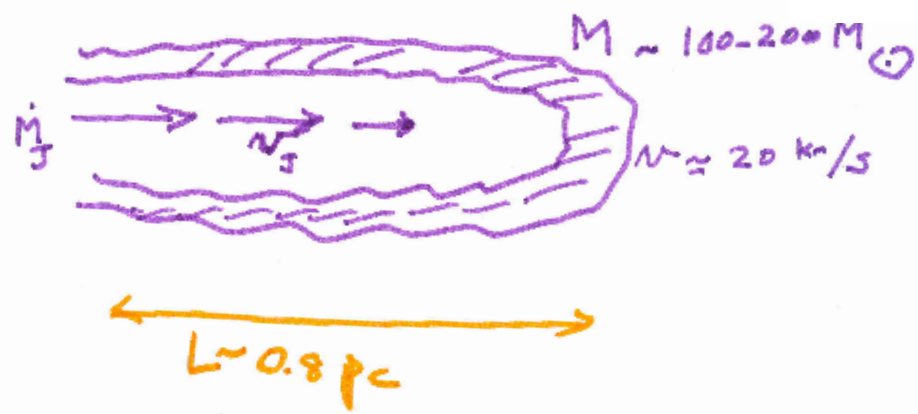
- HCN:
  - A red-shifted broad wing
- SiO:
  - Broad line emission





Protostellar Outflow in the Molecular Ring





Momentum deposited onto a cloud $\frac{M v}{\tau}$

Momentum deposited by the jet $\dot{M}_J v_J$

$$\tau = \frac{L}{v_J}$$

$$\dot{M}_J = \frac{M v}{L} \simeq 4 \times 10^{-3} M_\odot$$

Star Formation in the Nuclear Disk

- Jeans Mass

$$M_J \approx 0.53 \left(\frac{T}{10\,\mathrm{K}}\right)^{3/2} \left(\frac{n_{\mathrm{H}}}{10^6\,\mathrm{cm}^{-3}}\right)^{-1/2} M_\odot$$

- $M_J \sim 11\ M_{solar}$ when T~75K : consistent with massive stellar clusters

- Ambipolar diffusion time scale

$$t_{\mathrm{AD}} = \frac{R}{v_d} \approx 8 \left(\frac{x_e}{10^{-8}}\right)\ \mathrm{Myr}$$

- High ionization fraction: x_e $\Longrightarrow$ Suppression of star formation

- Cosmic ray ionization rate in the nuclear disk is high by 1-2 orders of magnitude

  H^+_3 and , H_3O^+ measurements (Oka et al. 2005; van der Tak et al. 2006)
  6.4 KeV Kα line emission from neutral Fe (FYZ et al. 2006)

ALMA opportunities

- Great uv coverage: wide range of angular scales in the GC
- Spectral imaging and mosaics for extended sources
- Chemistry of gas: PDR vs XDR $\Longrightarrow$ star formation
- Zeeman measerements: High B vs. Low B
- low-mass star formation: HH objects
- Band 1 is a must: ionized stellar winds+synchrotron

Conclusions

- Star Formation in the Nuclear Disk: Q < 1 and Q > 1
  - Stellar Disks and the molecular Ring:
    - In-situ star formation
    - Clouds passing through a strong potential
    - The ring is young
    - Star formation is being fed by clouds
  - A young population of YSO candidates
  - SFR ~ 0.08 M_{solar} /yr