The Nuclear Star-Forming Ring of the Milky Way

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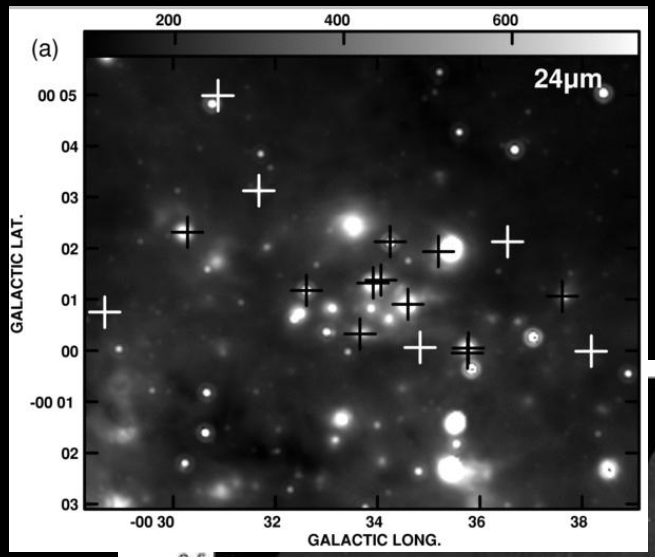
Recent Star Formation in the CMZ

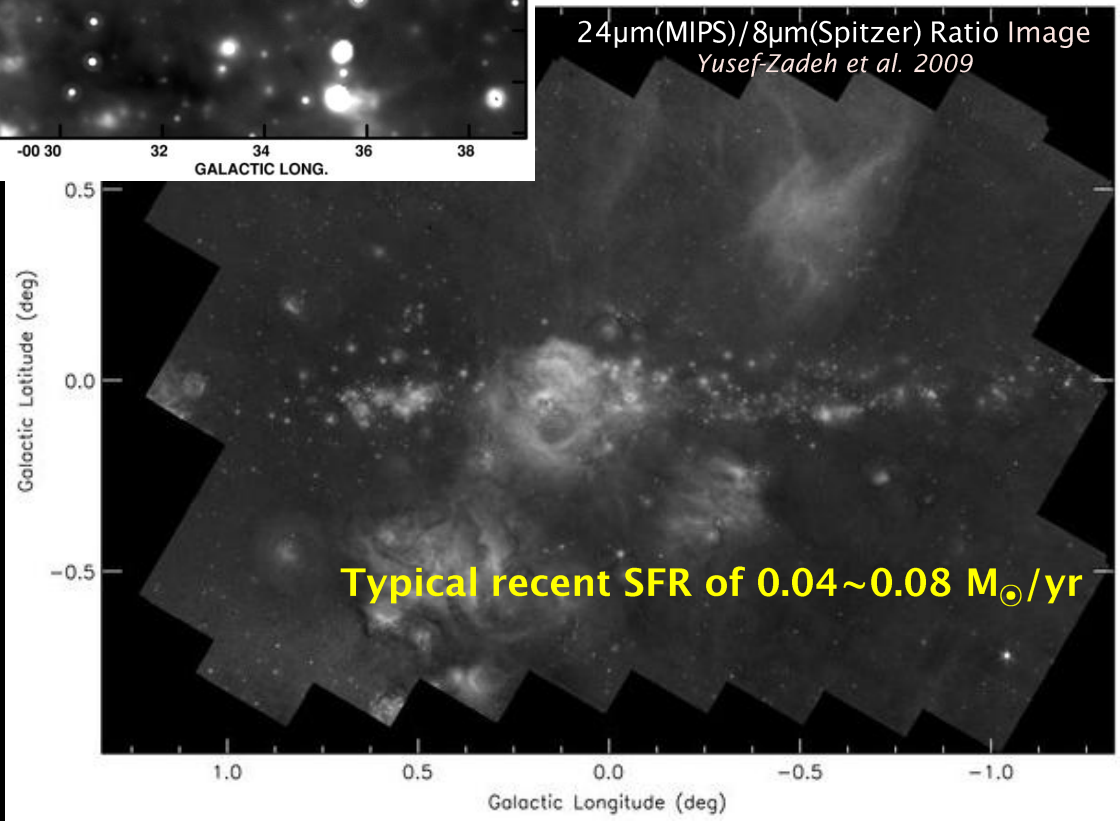
The Quintuplet (~Myr, ~10^4 $M_\odot$)
Figer et al. 1999

The Arches (~Myr, ~10^4 $M_\odot$)
Figer et al. 1999



G359.43+0.02 cluster of YSOs (~150 $M_\odot$)
Yusef-Zadeh et al. 2009

24μm(MIPS)/8μm(Spitzer) Ratio Image
Yusef-Zadeh et al. 2009

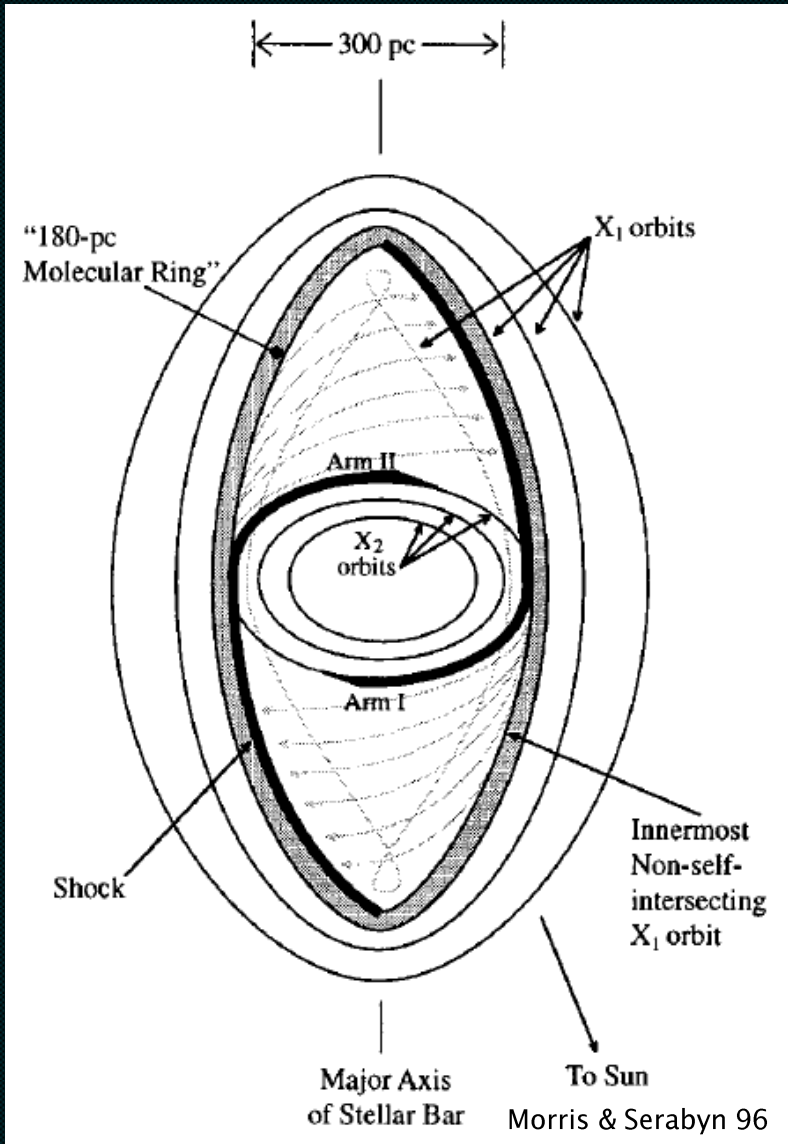


Typical recent SFR of 0.04~0.08 $M_\odot$/yr

Bar Potential and Star Formation

- Gas clouds experience compression in the cusps of innermost X1 orbits, lose orbital energy, and plunge to the X2 orbits inside.
- The infalling gas clouds get compressed even further when they collide with those already on the X2 orbits.
- This compression and subsequent cooling will transform the gas into molecular form (Binney et al. 1991) and eventually induce star formation.

- We have performed simulations of star formation in the CMZ to see if this scenario actually works.



Morris & Serabyn 96

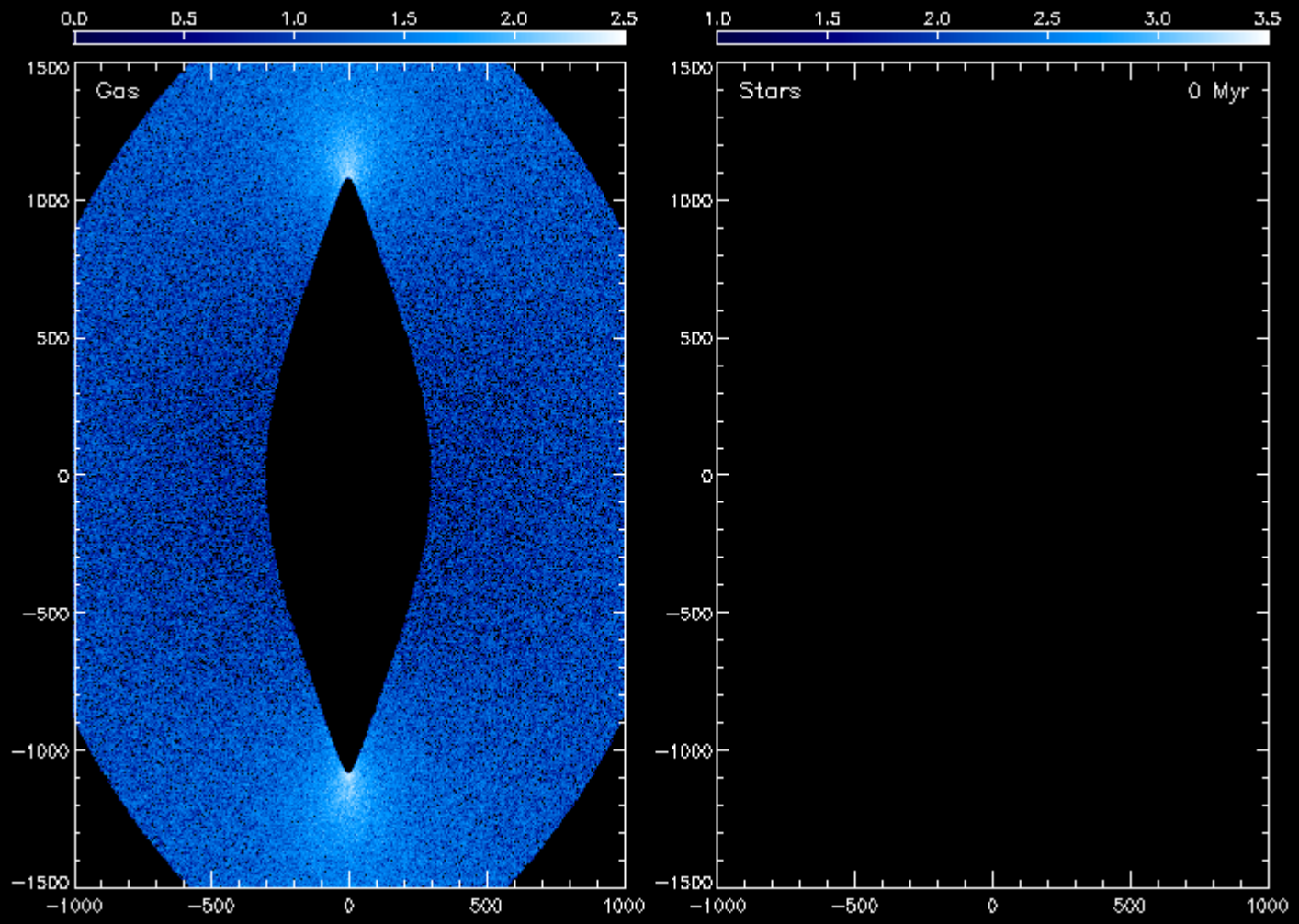
Simulations

- Code developed by T. Saitoh: ASURA
  - 3D SPH with self-gravity
  - Parallelized tree scheme
  - Uses GRAPE boards or Phantom-GRAPE (accelerated gravity routine on a machine-language level)
  - Cooling function for 10–10^8 K from Spaans & Norman (1997)
  - Heating by uniform FUV radiation (1–30x solar neighborhood values)
  - ***Star Formation :*** Spawn collisionless particles when
    - $n > n_{th}$
    - $T < T_{th}$
    - Converging flow $(\vec{\nabla} \cdot \vec{v} < 0)$
    - No heat increase by nearby SNs $(dQ \leq 0)$
  - SN feedback in forms of thermal energy addition

- Bar Potential
  - Power-law bulge with a m=2 bar

$$\rho = \rho_0 \left(\frac{r}{r_0} \right)^{-1.75} \left[1 + b_{22} P_{22}(\cos\theta) \cos 2\varphi \right]$$

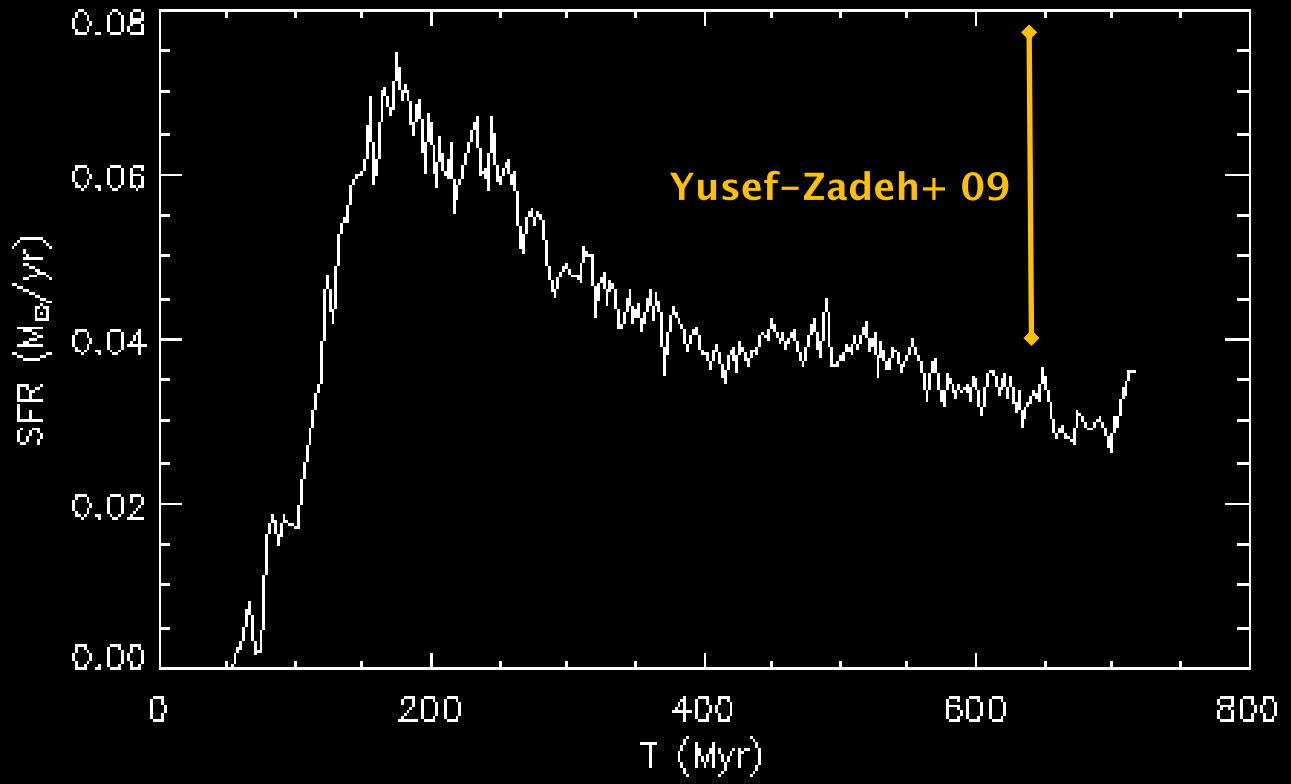
Standard Run



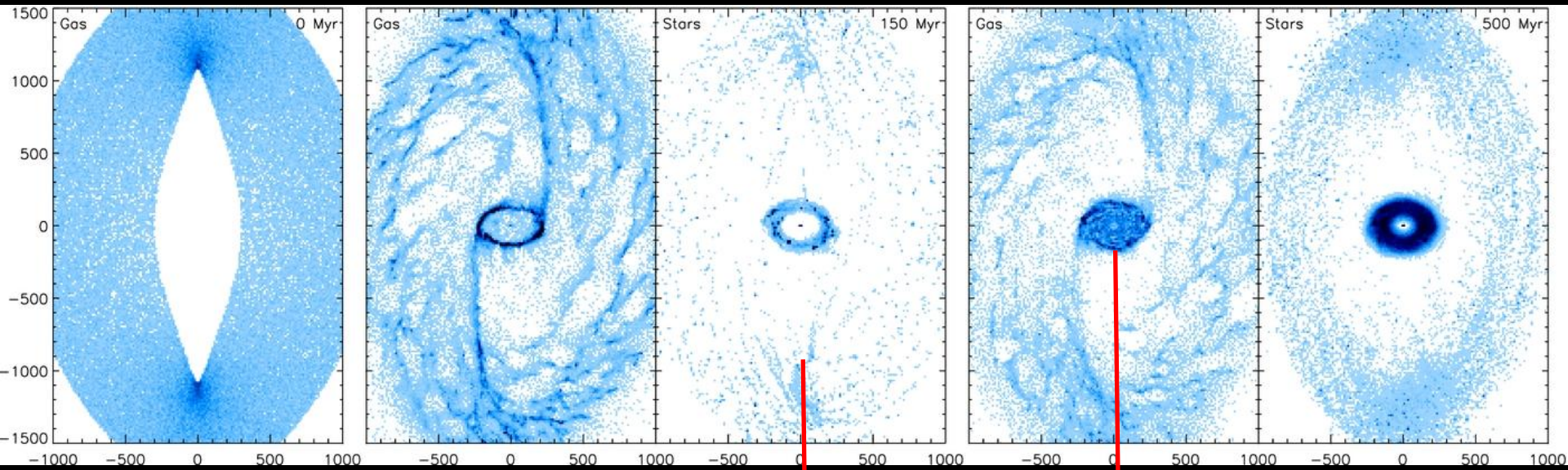
N=200k
M_{gas}=5x10^7 $M_\odot$
m_{SPH}=250 $M_\odot$
ε=3 pc

n_{th} =100 cm^{-3}
T_{th} =100 K
T_{cut}=10 K
C_* =0.033

Star Formation Rate



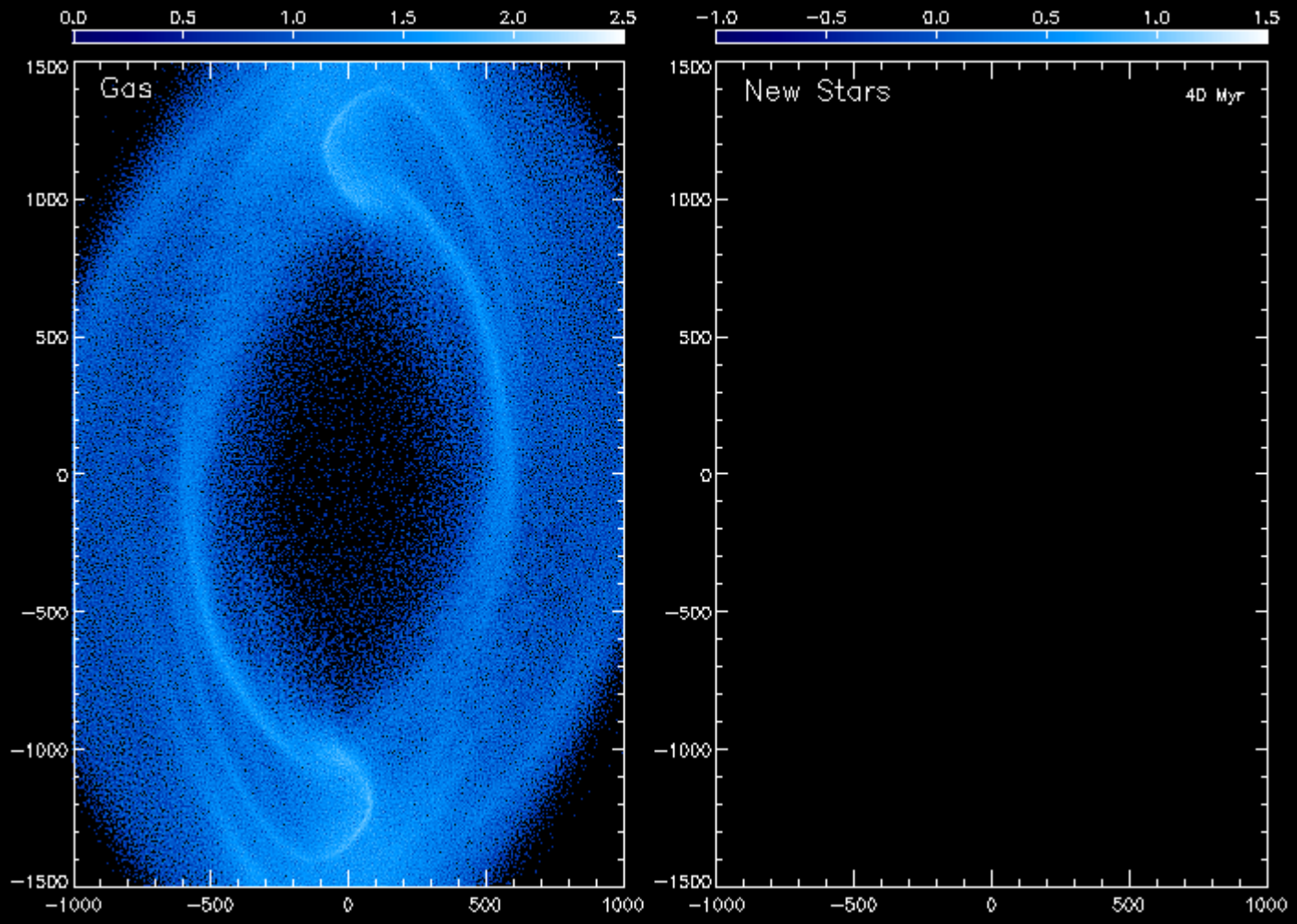
Dust Lanes, Star-Forming Ring, and the CMZ



Star formation in X1 region is quenched by strong FUV radiation from stars.

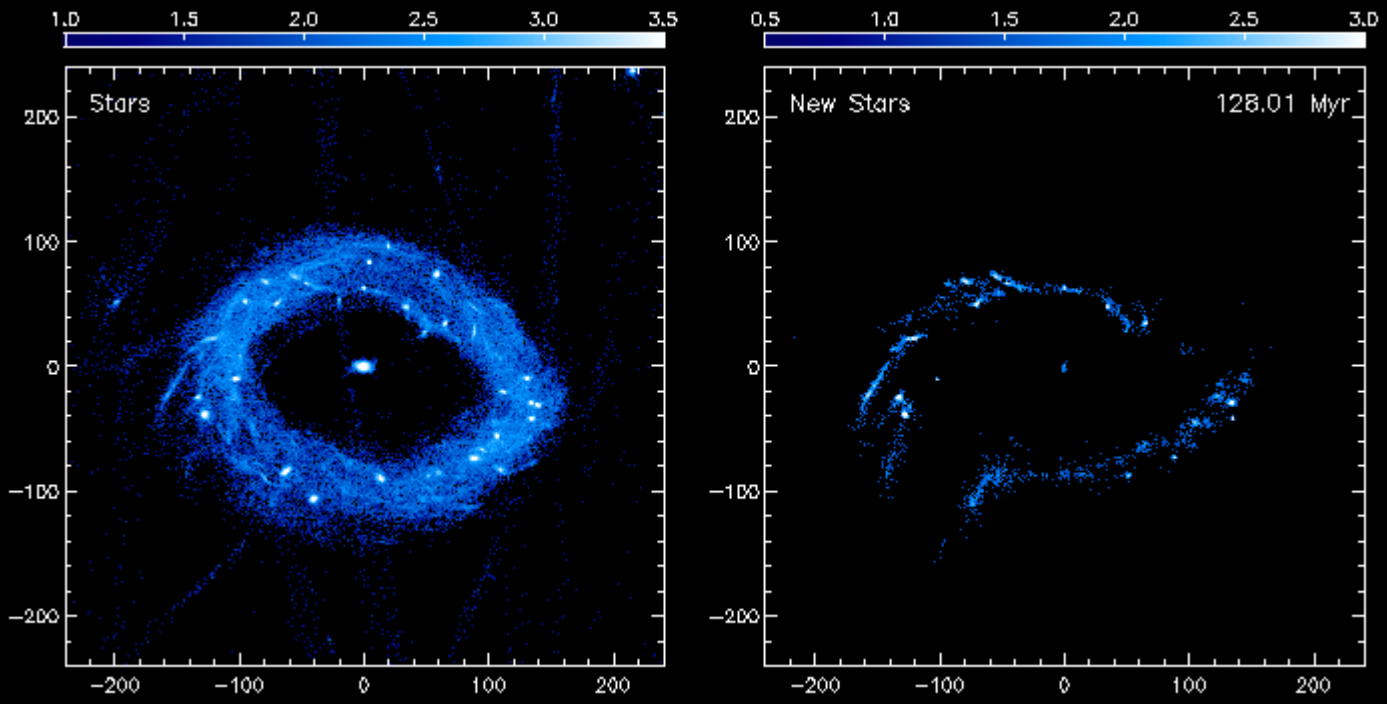
Our CMZ size, CMZ mass, and SFR are all consistent with observations!

Where do shocks take place?



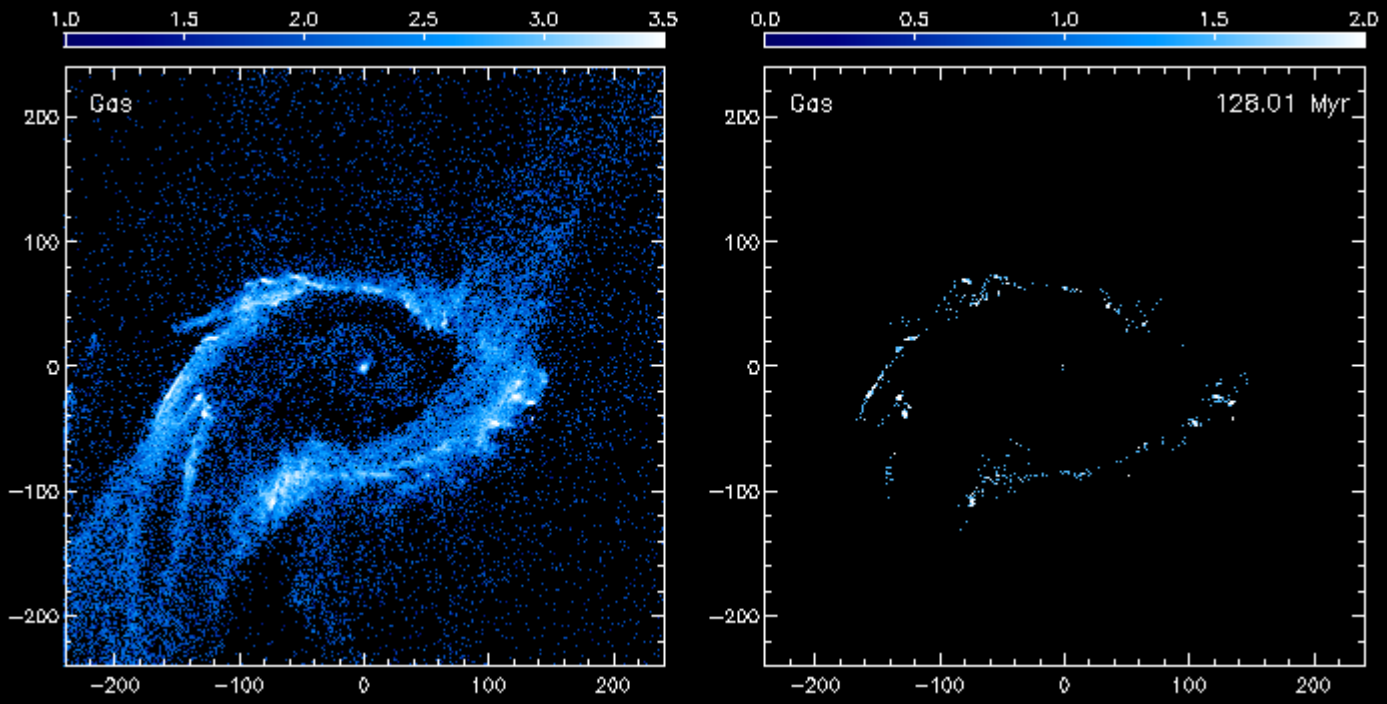
Star Clusters in the CMZ

Stars with ages < 1Myr

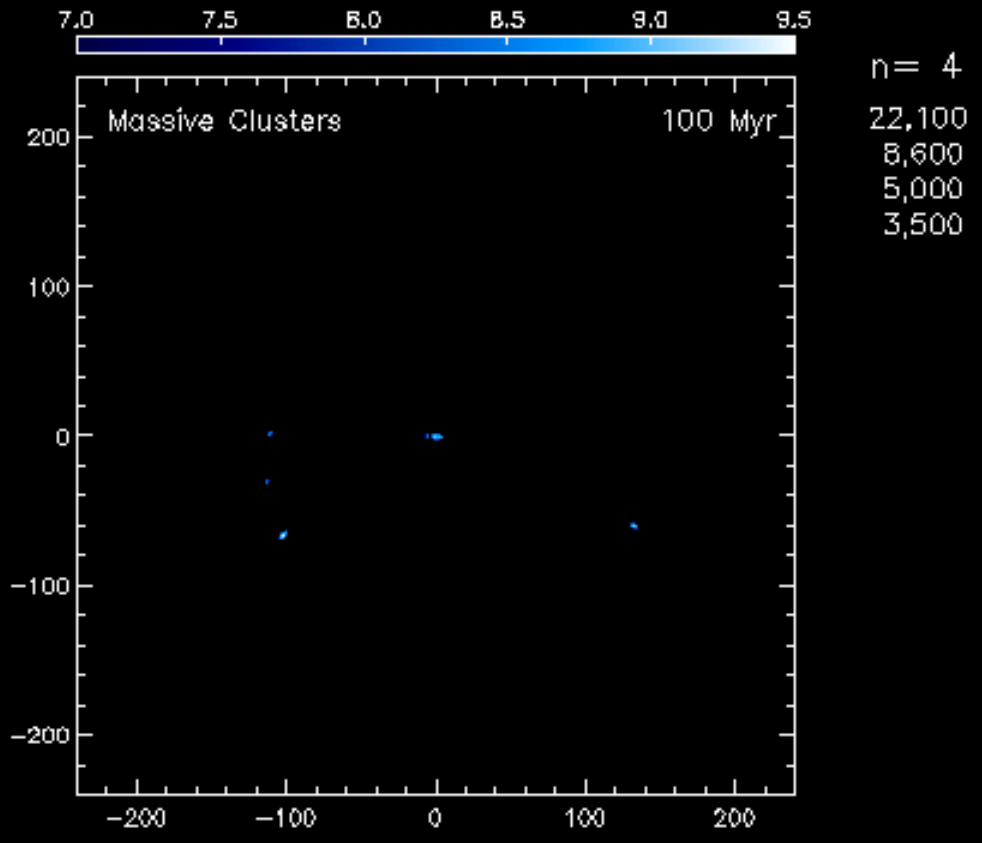


Beads on a string vs. Popcorn Models

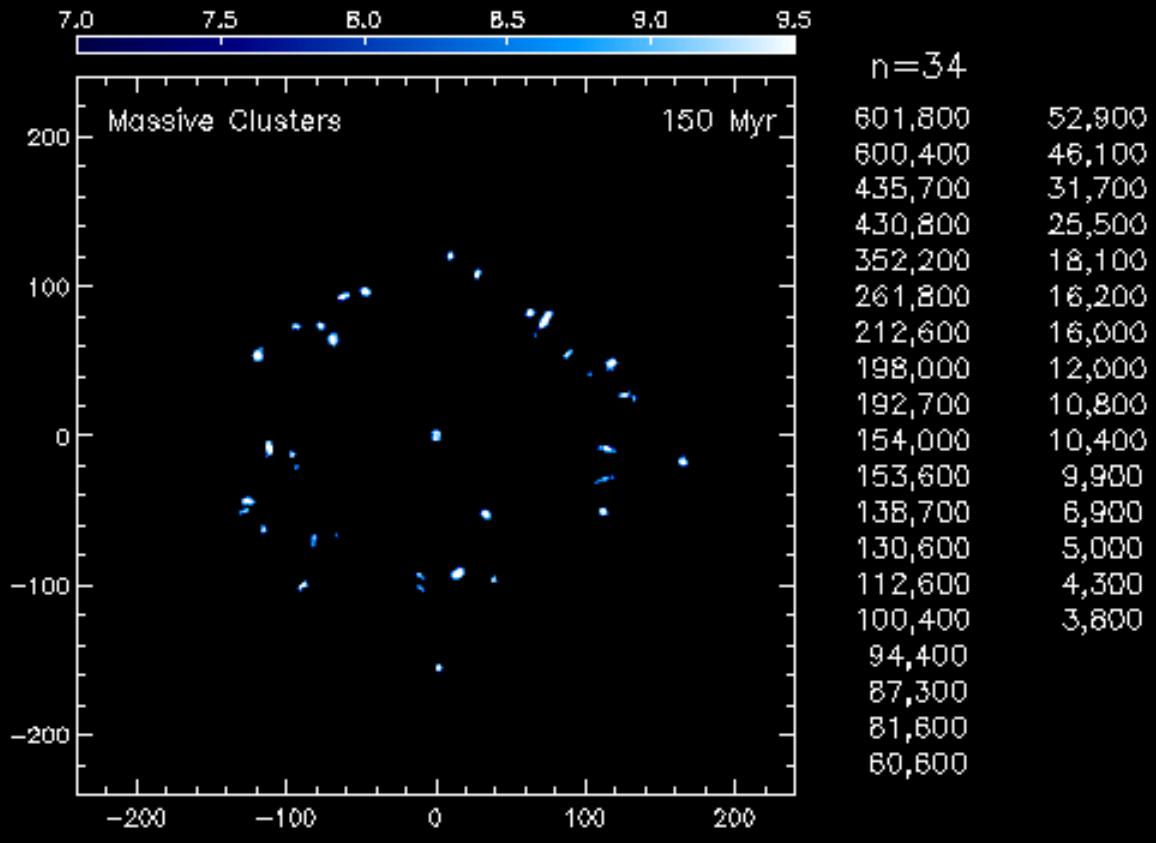
Stars with ages < 0.2Myr



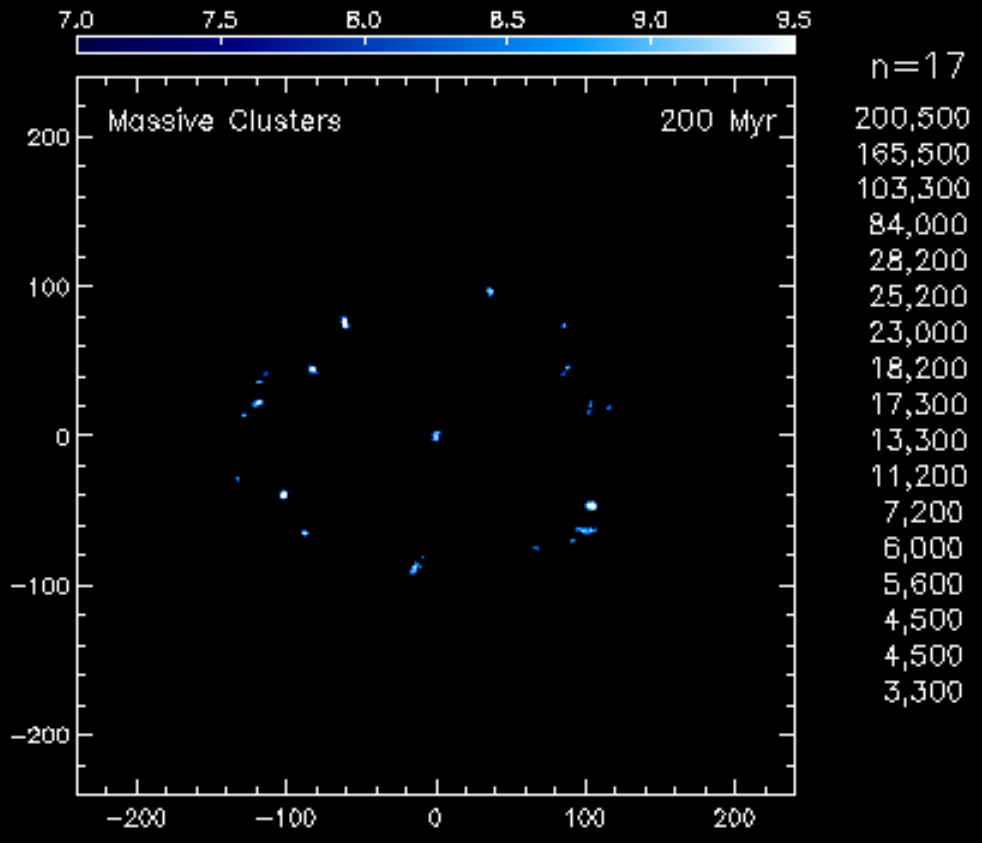
Massive Star Clusters



Massive Star Clusters



Massive Star Clusters



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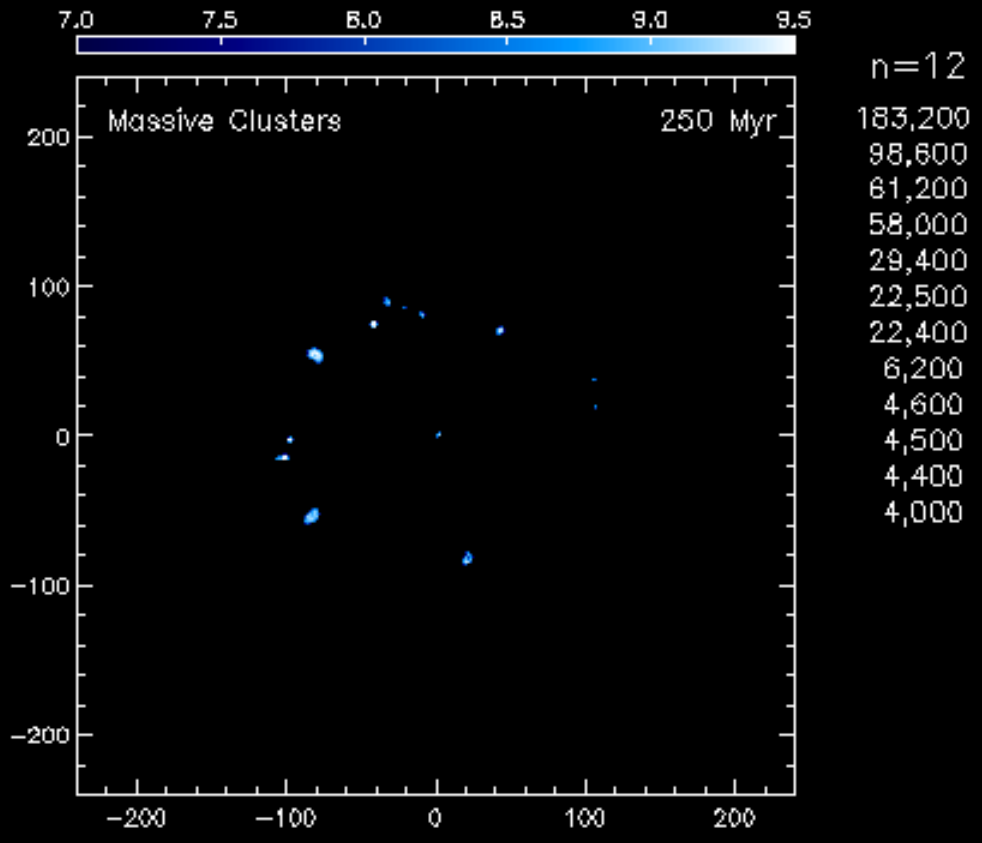
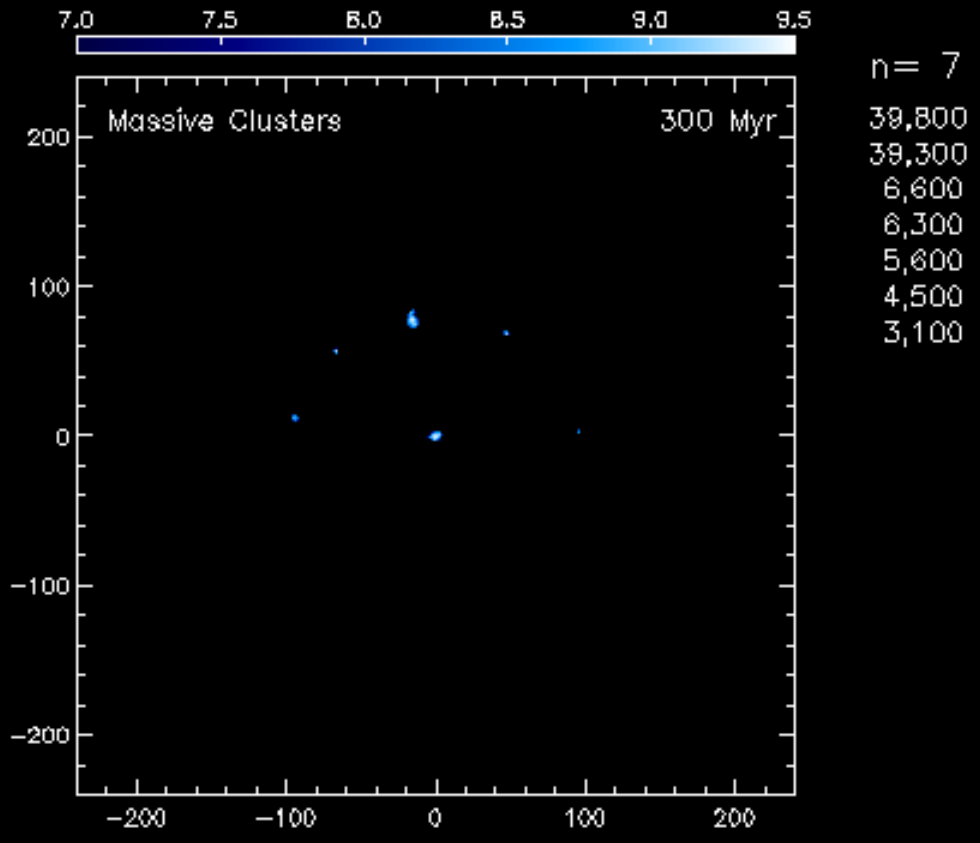


Massive Star Clusters



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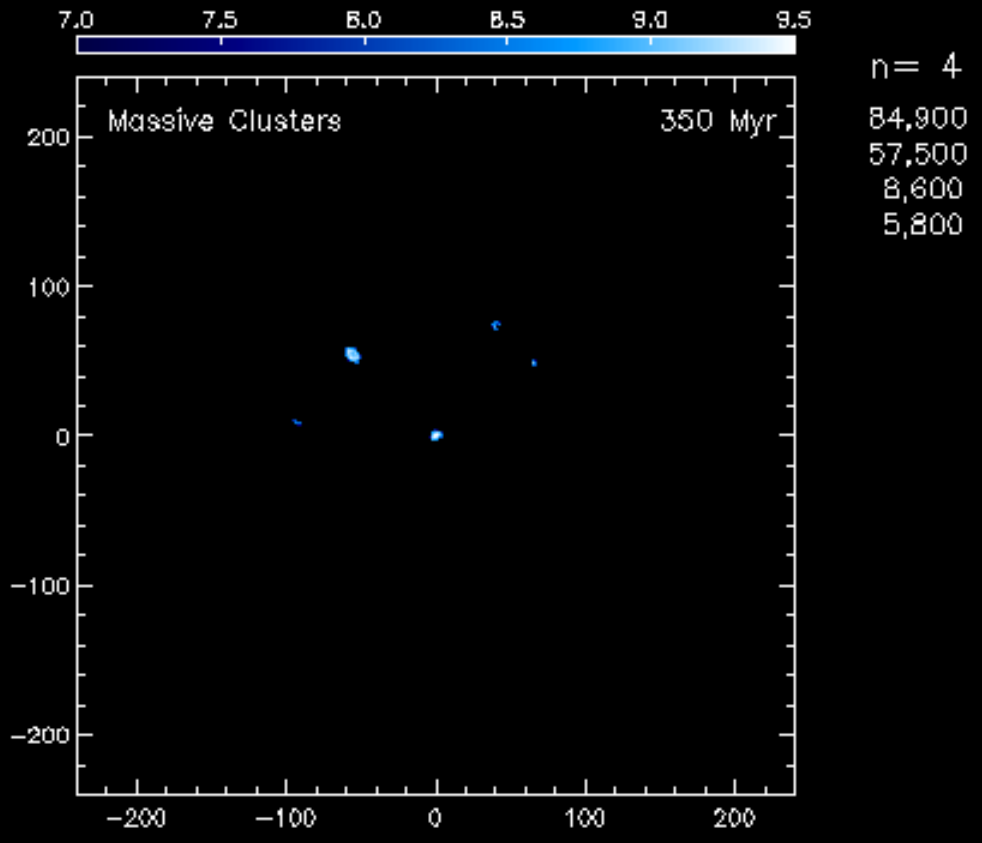
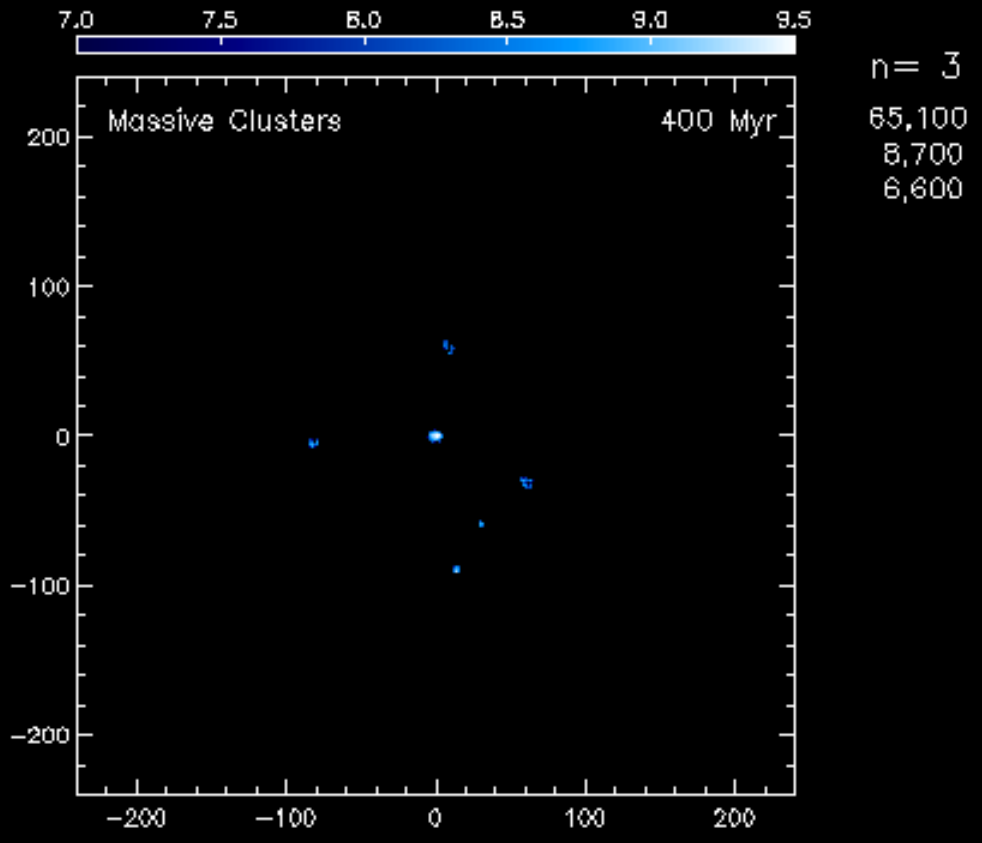
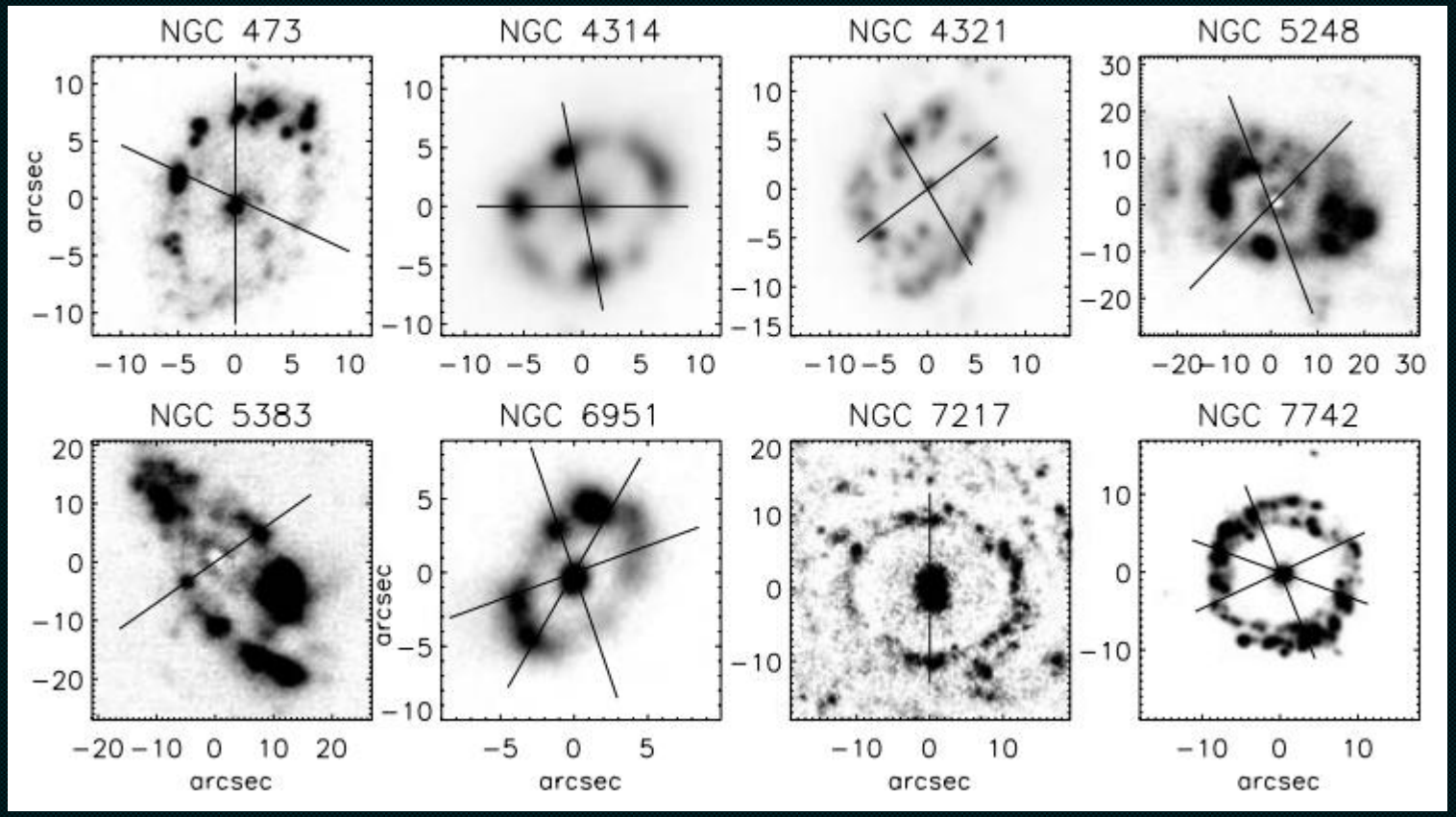


Massive Star Clusters



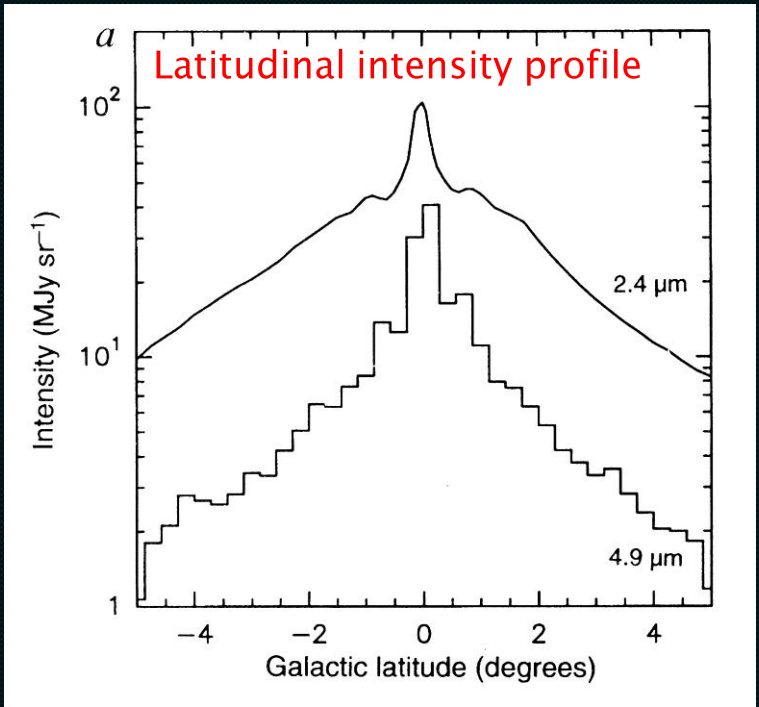
Nuclear Star-Forming Rings in External Galaxies



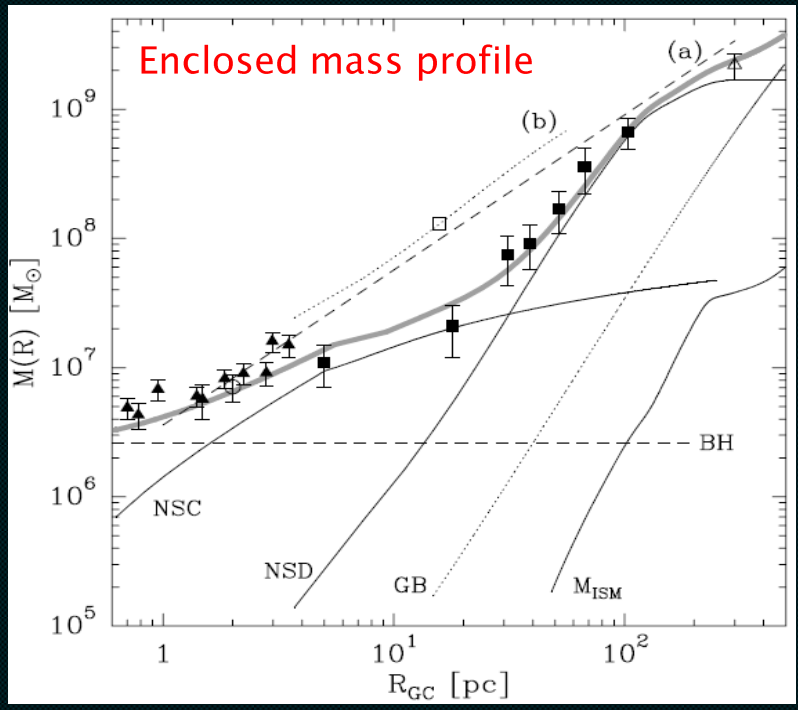
Sarzi+ 07

Result of Sustained Star Formation in the CMZ – The Nuclear Bulge

- Serabyn & Morris (1996) argued that star formation has been occurring in the CMZ throughout the lifetime of the Galaxy, and the resulting stellar population has been manifested as the *"nuclear bulge"*.
- With a constant SFR of the current value, the inner bulge would have accumulated a total mass of ~10^9 $M_\odot$.

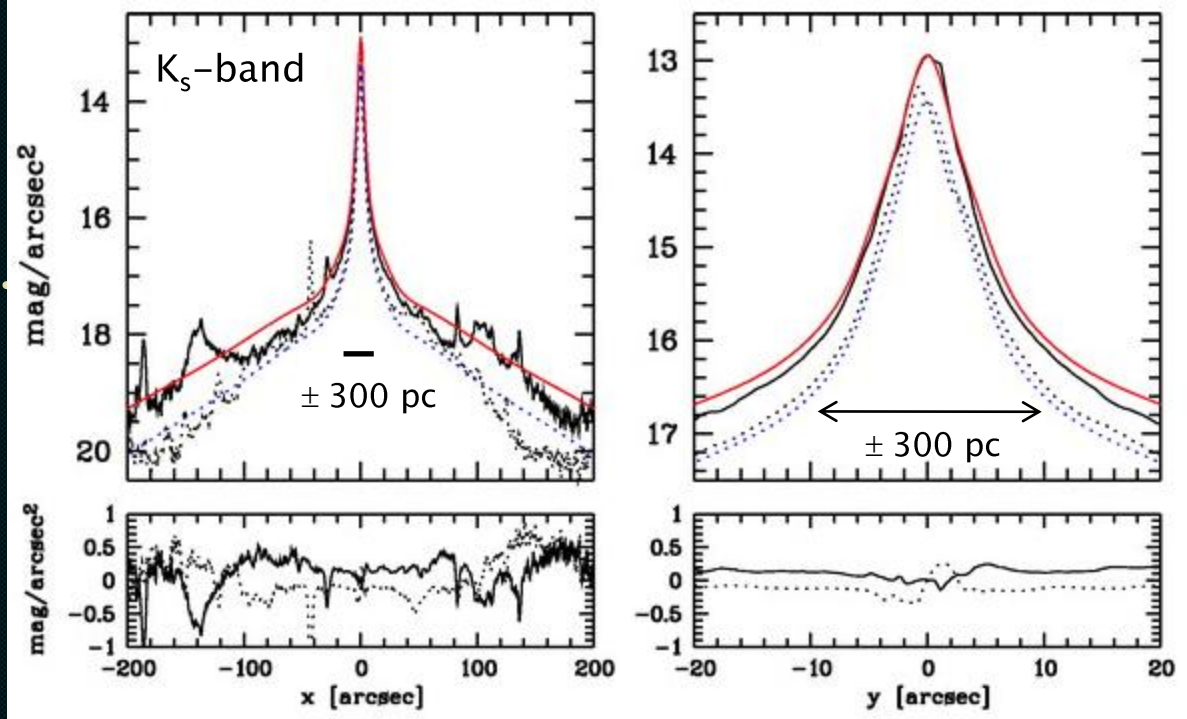


Serabyn & Morris 96

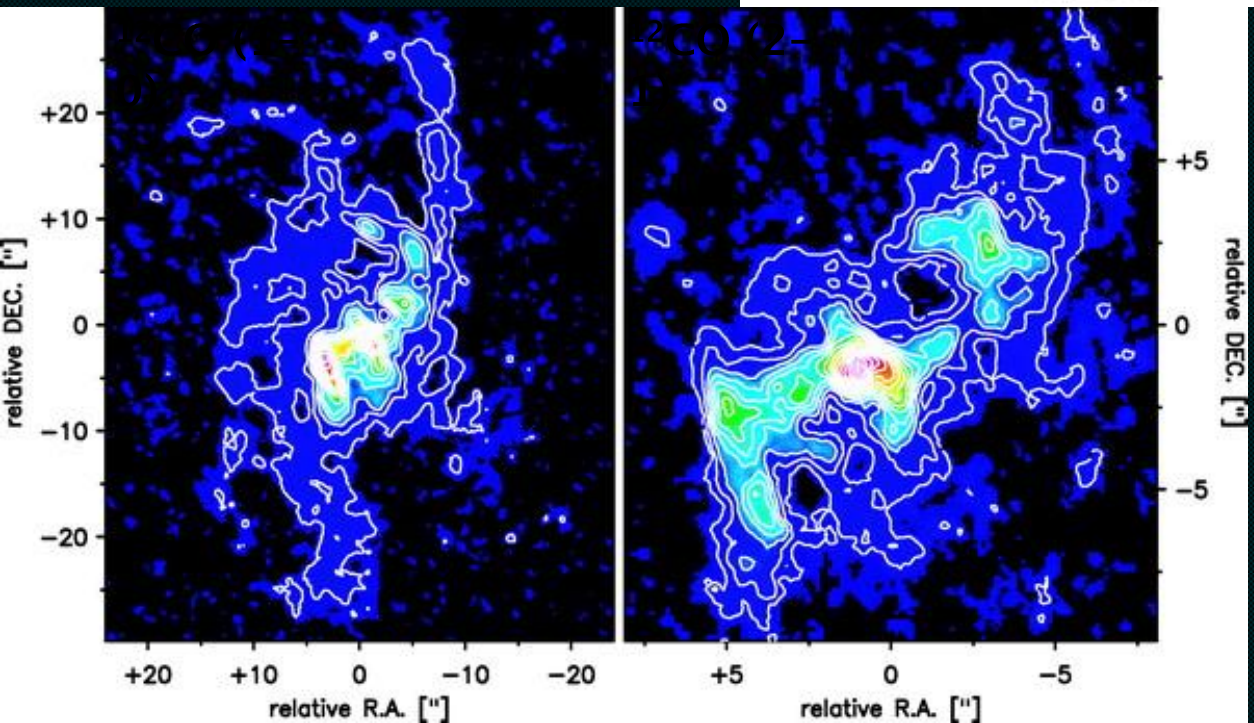


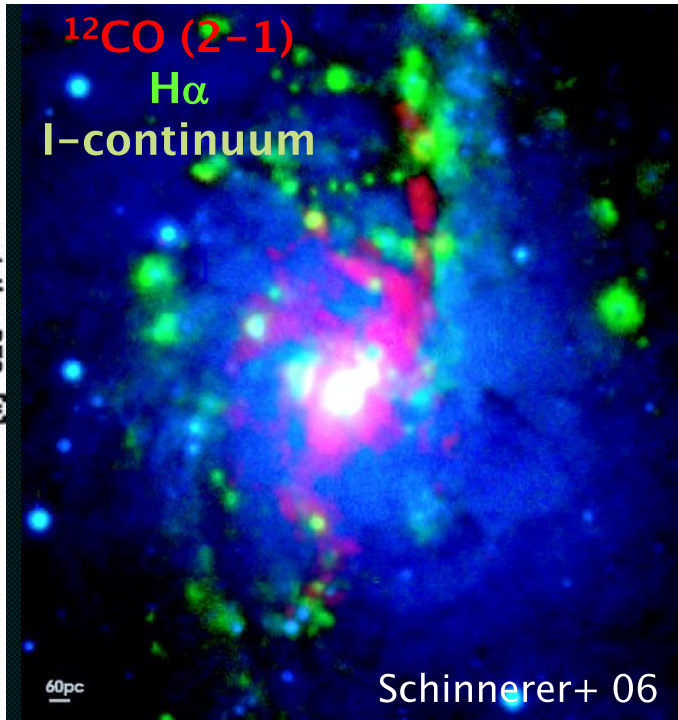
Launhardt+ 02

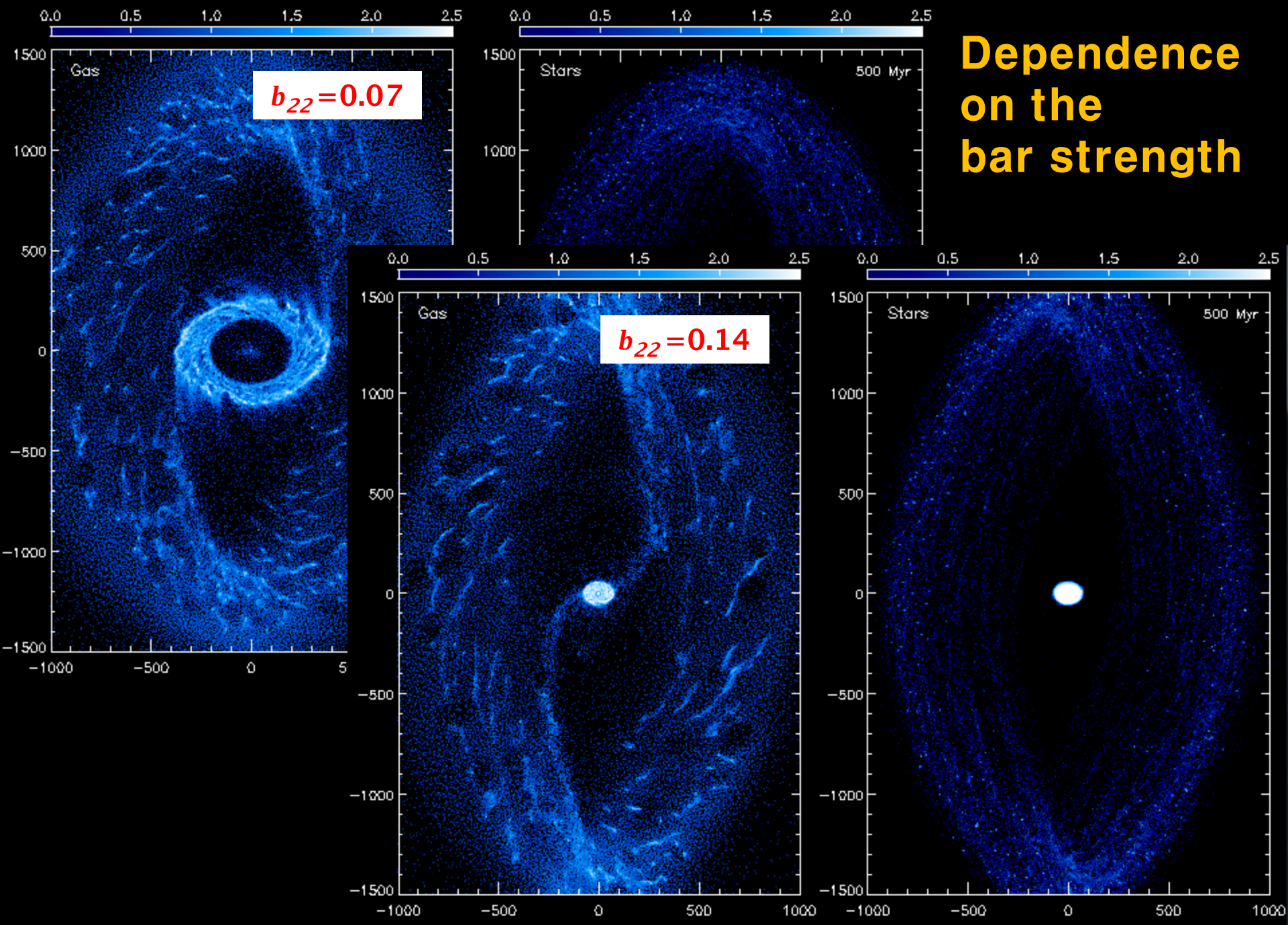
NGC 6946

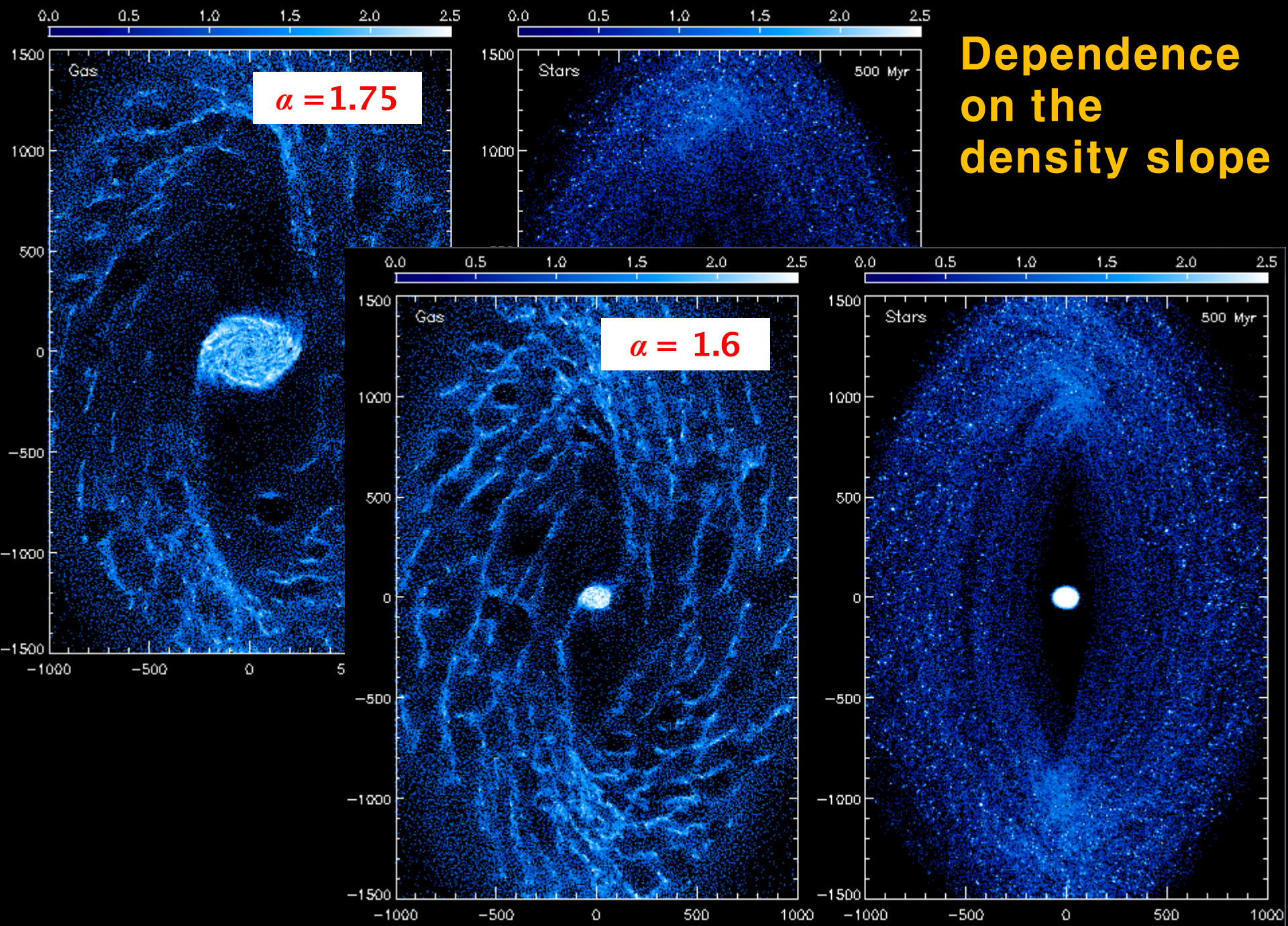


± 300 pc



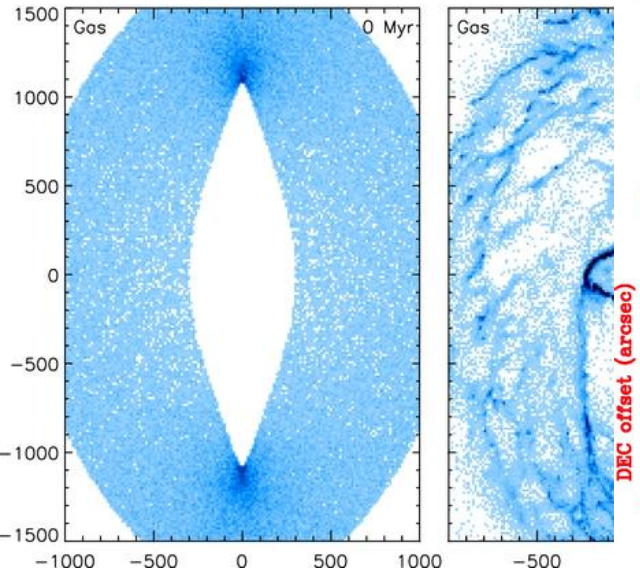


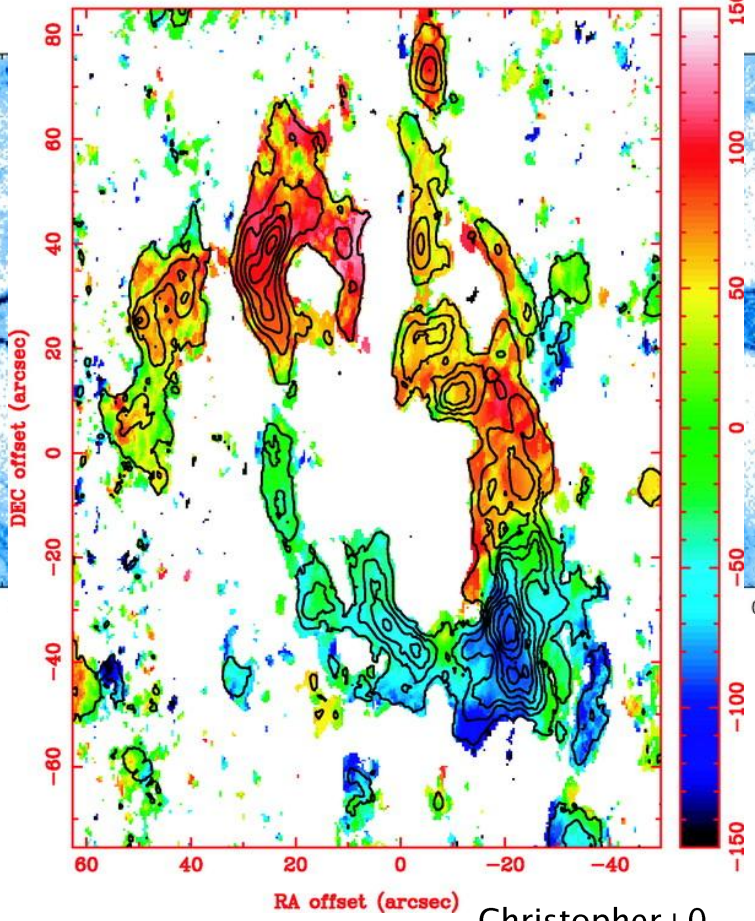

Dependence on the bar strength
Gas
b_{22}=0.07
Stars
500 Myr
Gas
b_{22}=0.14
Stars
500 Myr

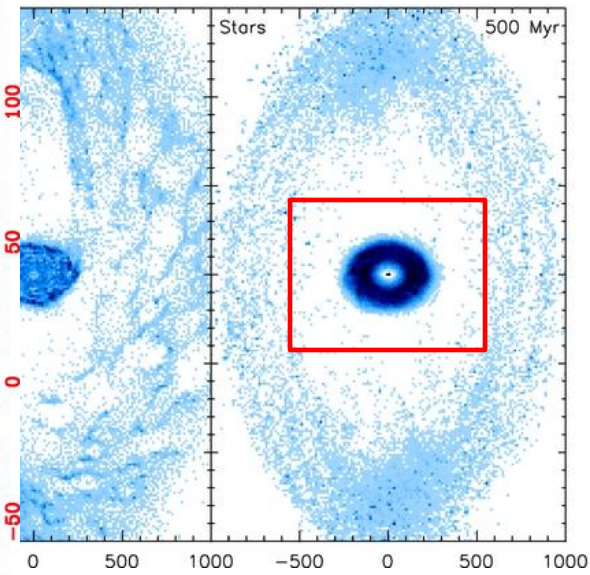

Dependence on the density slope
α =1.75
α = 1.6
Gas
Stars
500 Myr
0.0 0.5 1.0 1.5 2.0 2.5
1500
1000
500
0
−500
−1000
−1500
−1000 −500 0 500 1000

Elongated Nuclear Bulge – The Inner Bar?

The CircumNuclear Disk (~5 pc)

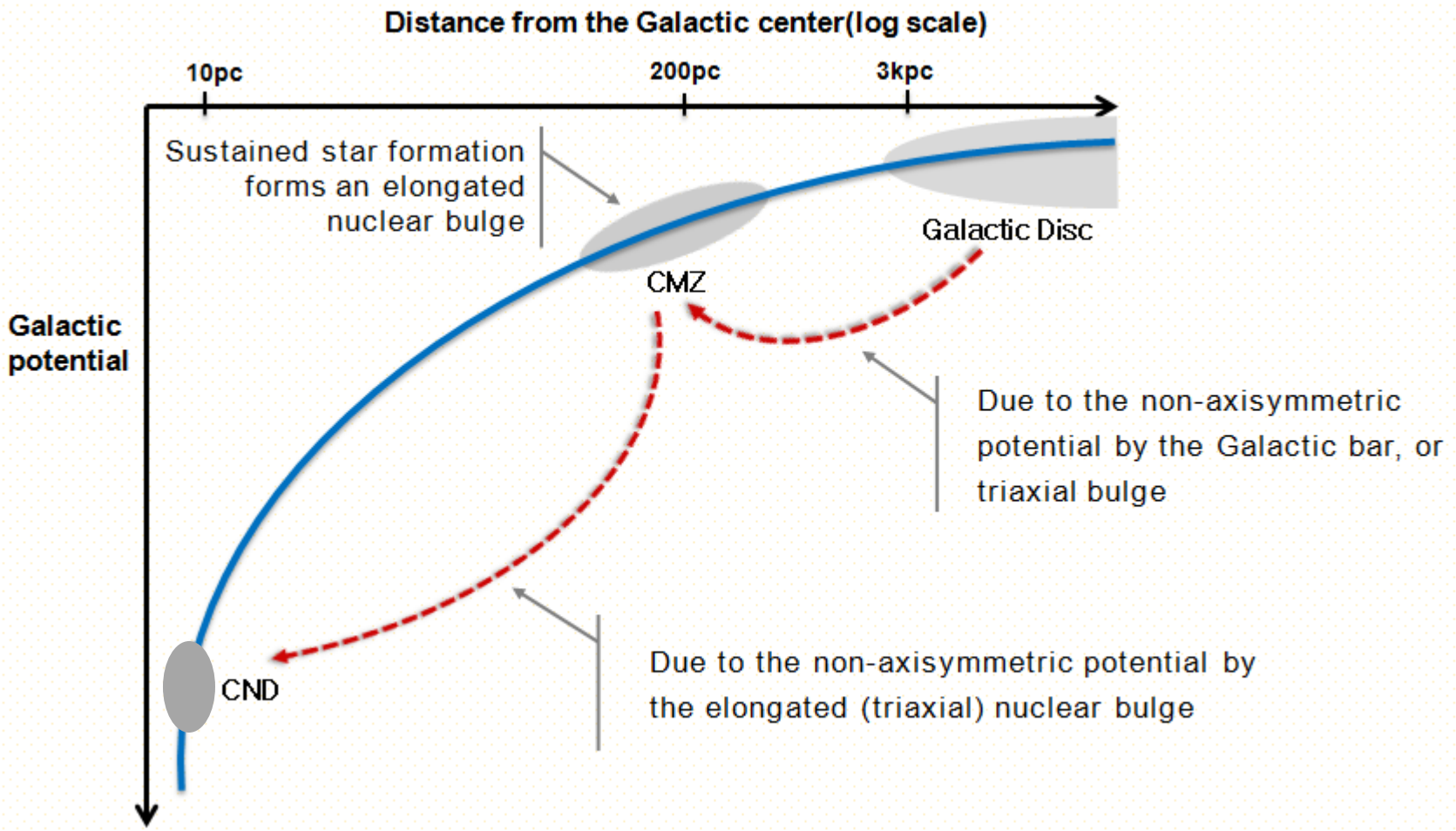




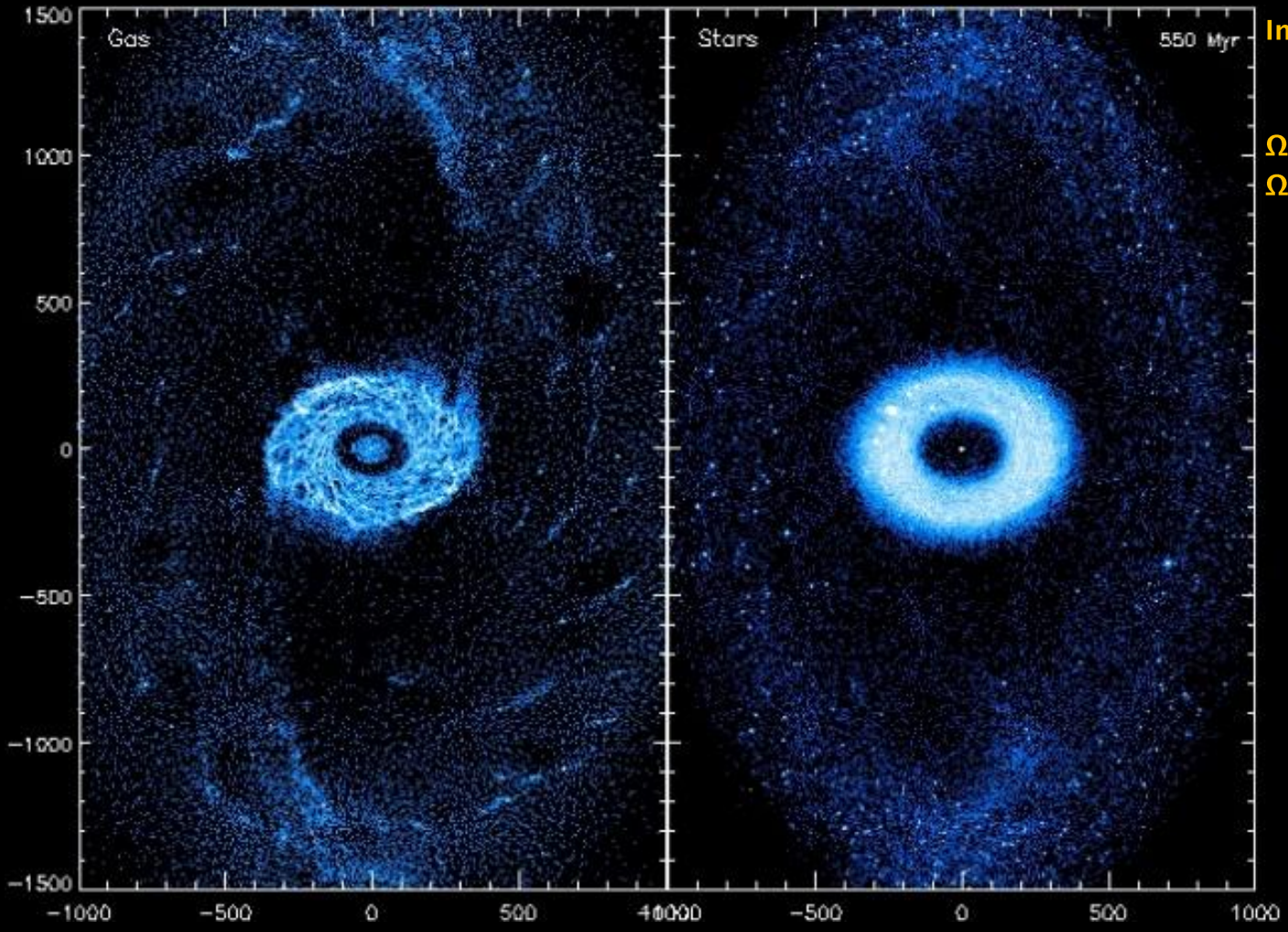


Christopher+05

Elongated Nuclear Bulge – The Inner Bar?



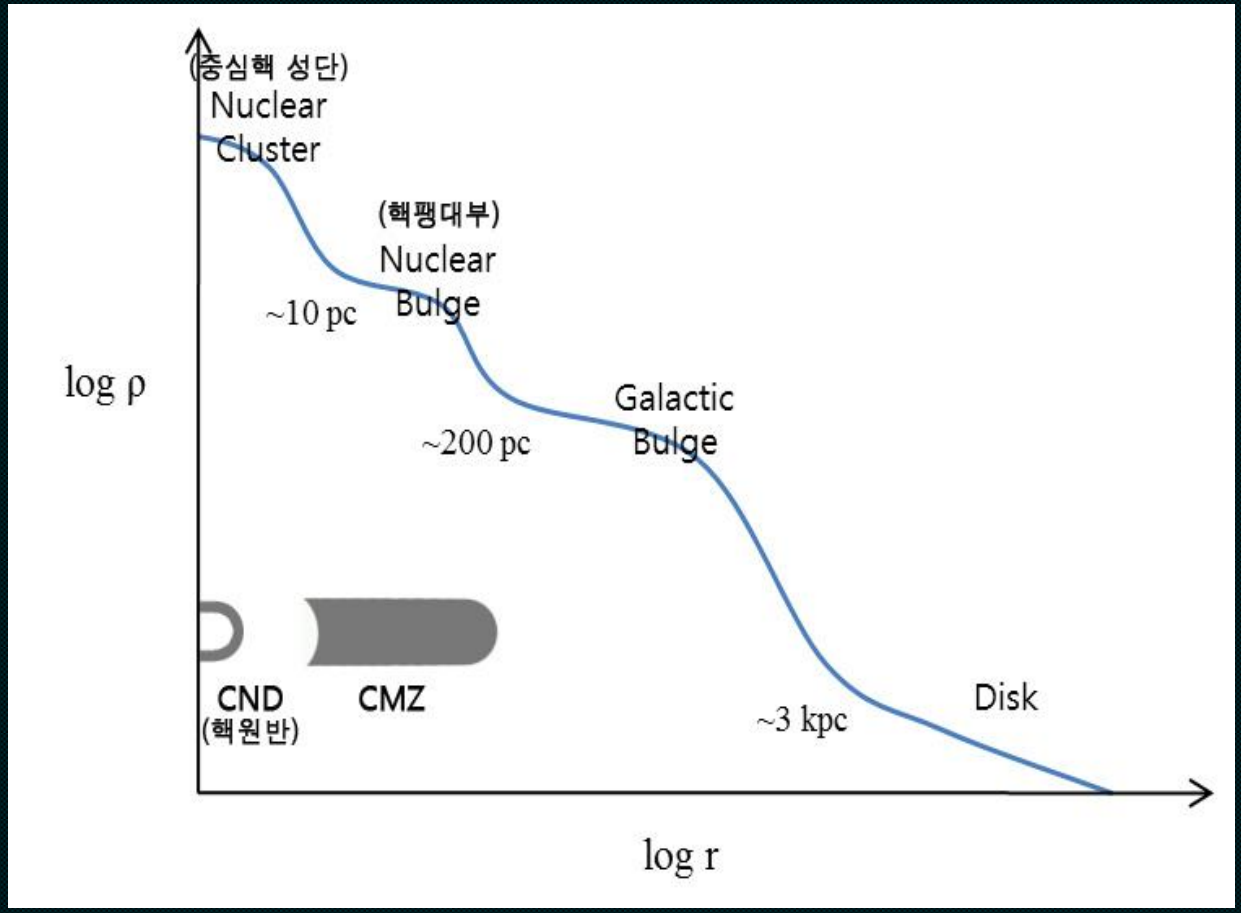
Gas Flow in Nested Bars (preliminary)



Inner bar axis ratio
= 3 : 1 : 1

Ω_{outer} = 63km/s/kpc
Ω_{Inner} =100km/s/kpc

The Inner Regions of the Milky Way



Summary

- Main results from the first hydrodynamic simulations for the CMZ with SF/feedback/self-gravity are
  - Bar potential indeed can compress gas to form stars .
  - SF takes place mostly in the inner 200 pc.
  - Obtained SFR, 0.05–0.1 $M_{\odot}$/yr, is consistent with recent YSO observations.

- These support the suggested connection between the CMZ and the stellar nuclear bulge.
  - (Obtained SFR) x (Lifetime of the Galaxy) ~ 10^9 $M_{\odot}$.
  - Consistent with the current NB mass, 1-2x10^9 $M_{\odot}$.

- The elongated nuclear bulge could transport the gas clouds in the CMZ further down to the CND.

Possible Origin of the Twisted Ring

- The HI disk, possibly a channel for gas migrating inward from the Galactic disk, is inclined by 10-20 deg.
- This inclination can be due to 1) interaction with massive objects (e.g., satellite galaxies) passing through the bulge, or 2) interaction with triaxial bulge (bar) that causes tipping instability.
- Gas clouds infalling from this inclined disk can have large initial vertical motions when colliding with the CMZ.