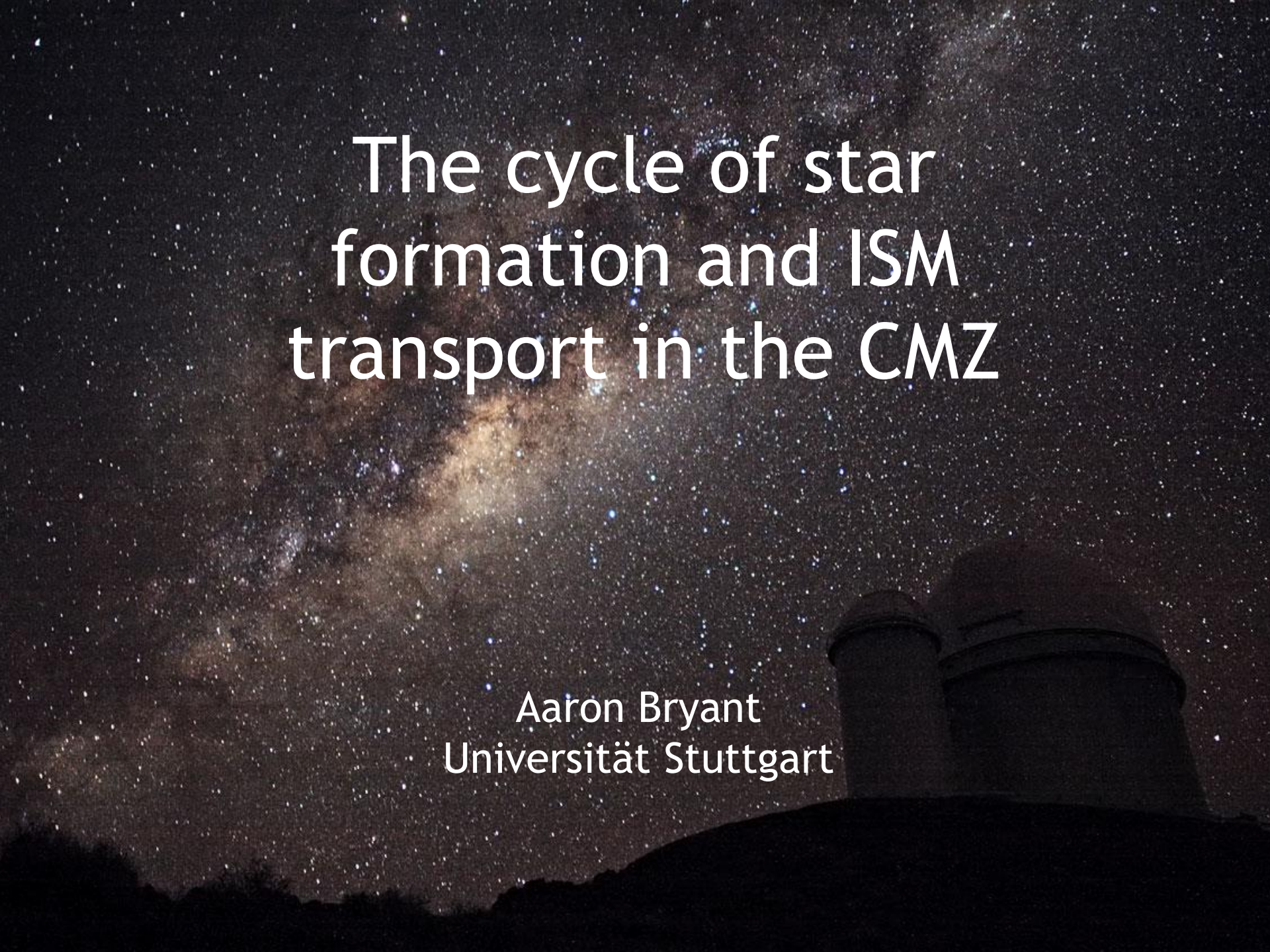
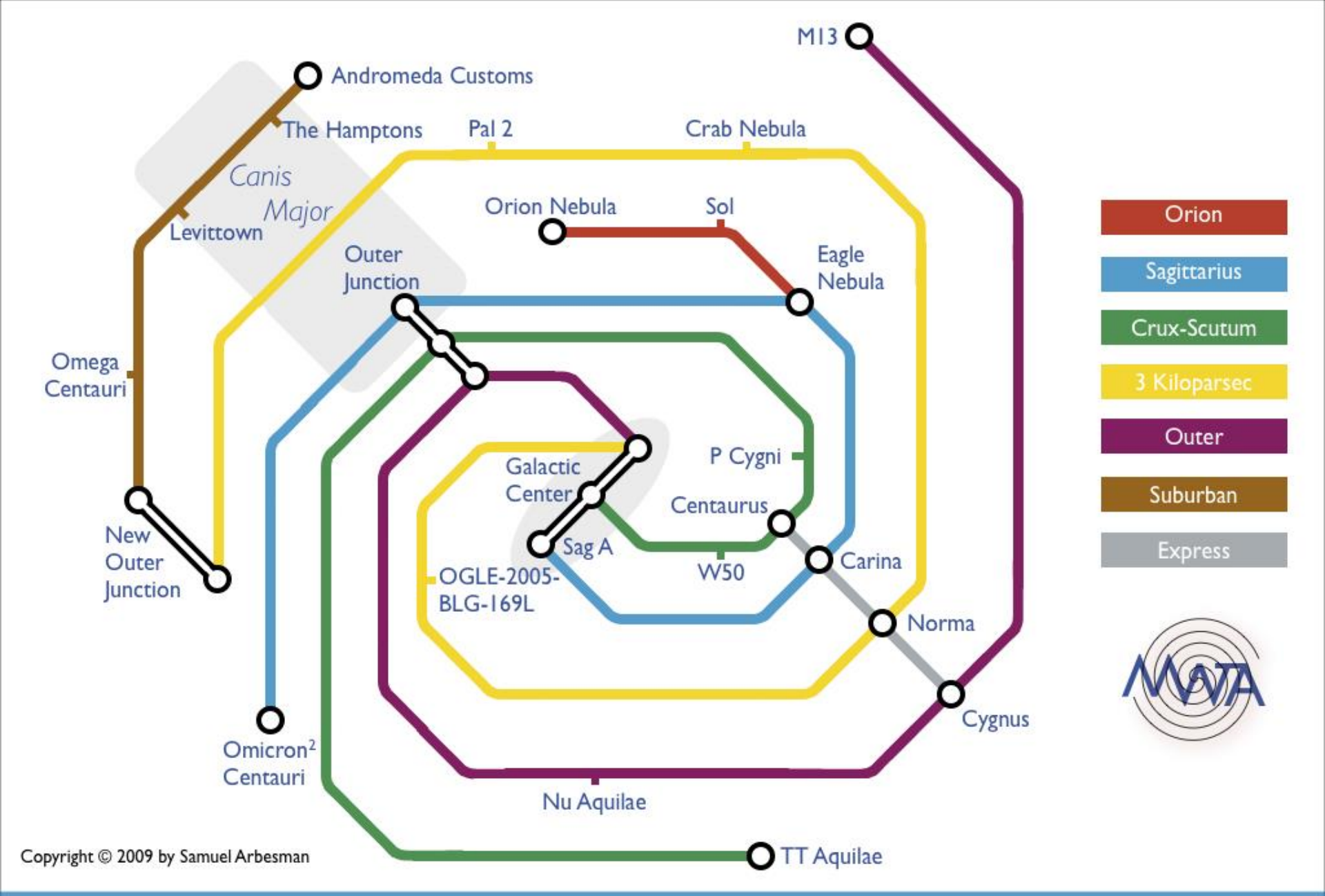
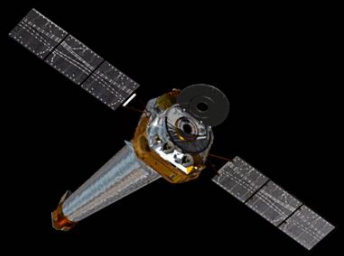


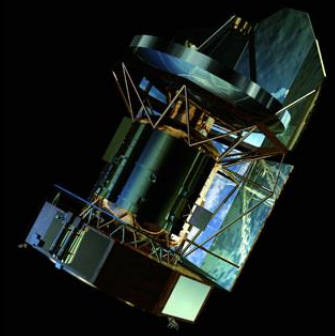
The cycle of star formation and ISM transport in the CMZ

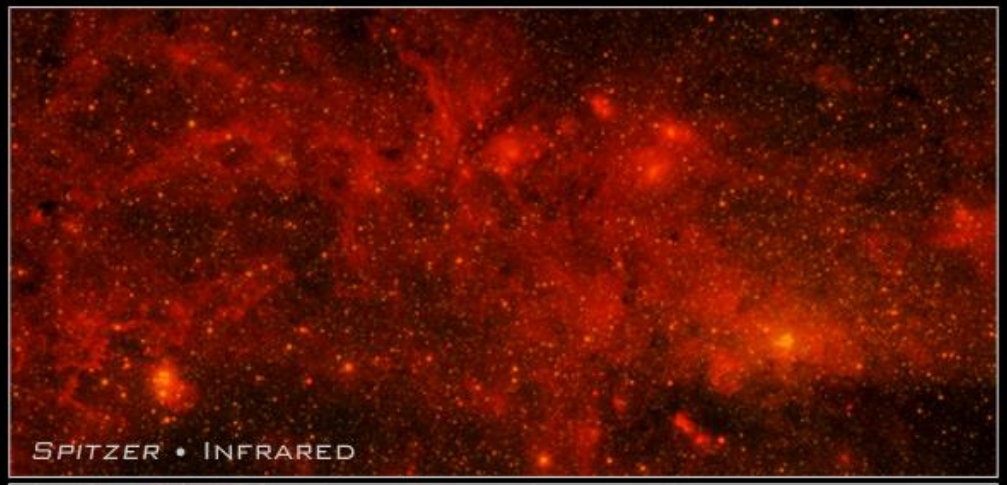
Aaron Bryant
Universität Stuttgart

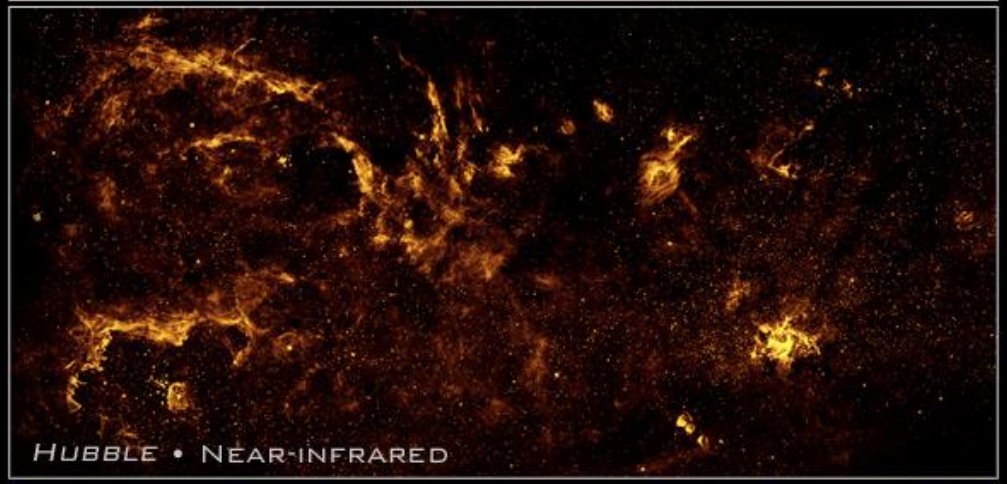


Milky Way Transit Authority



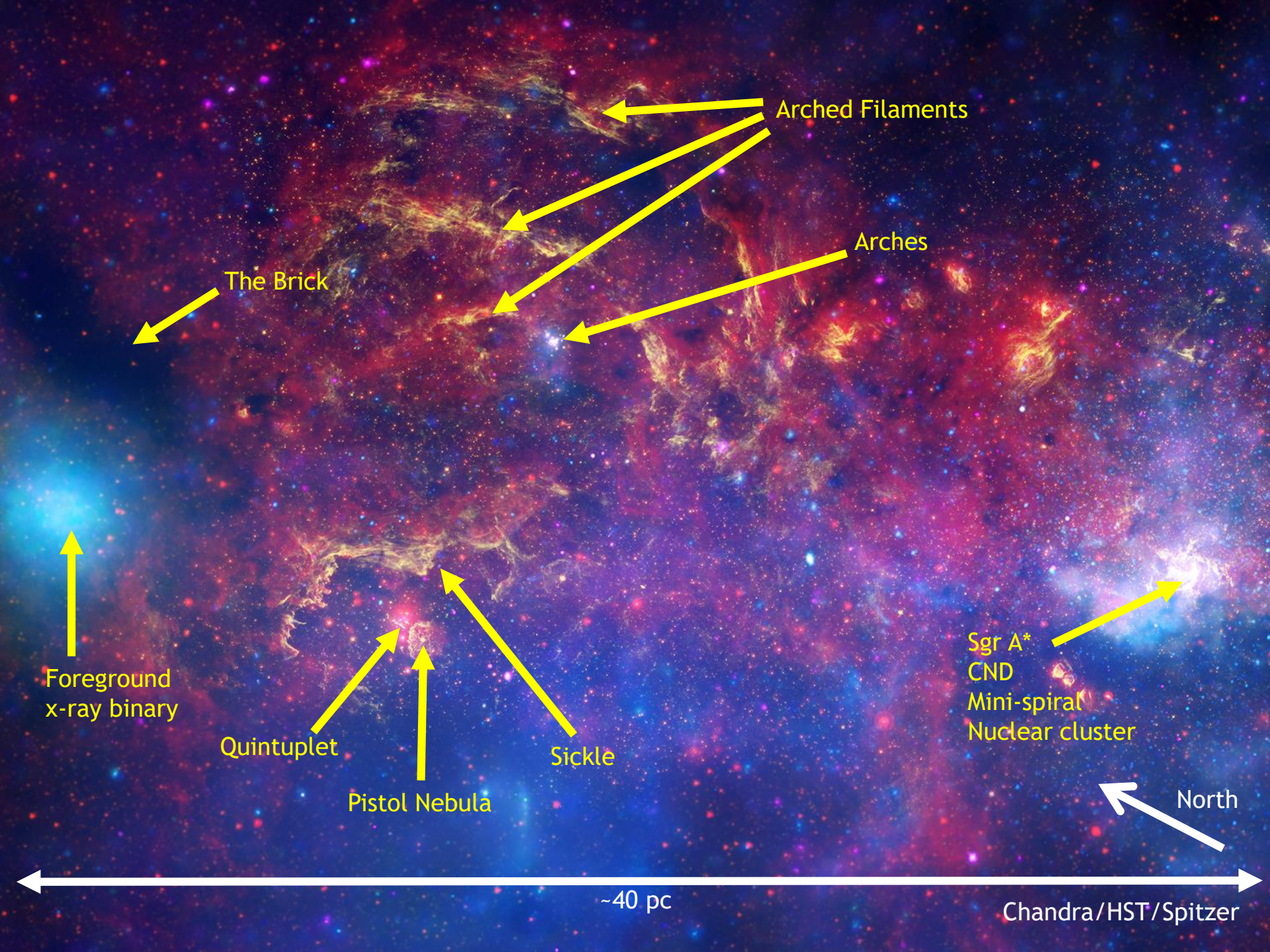



Spitzer • Infrared

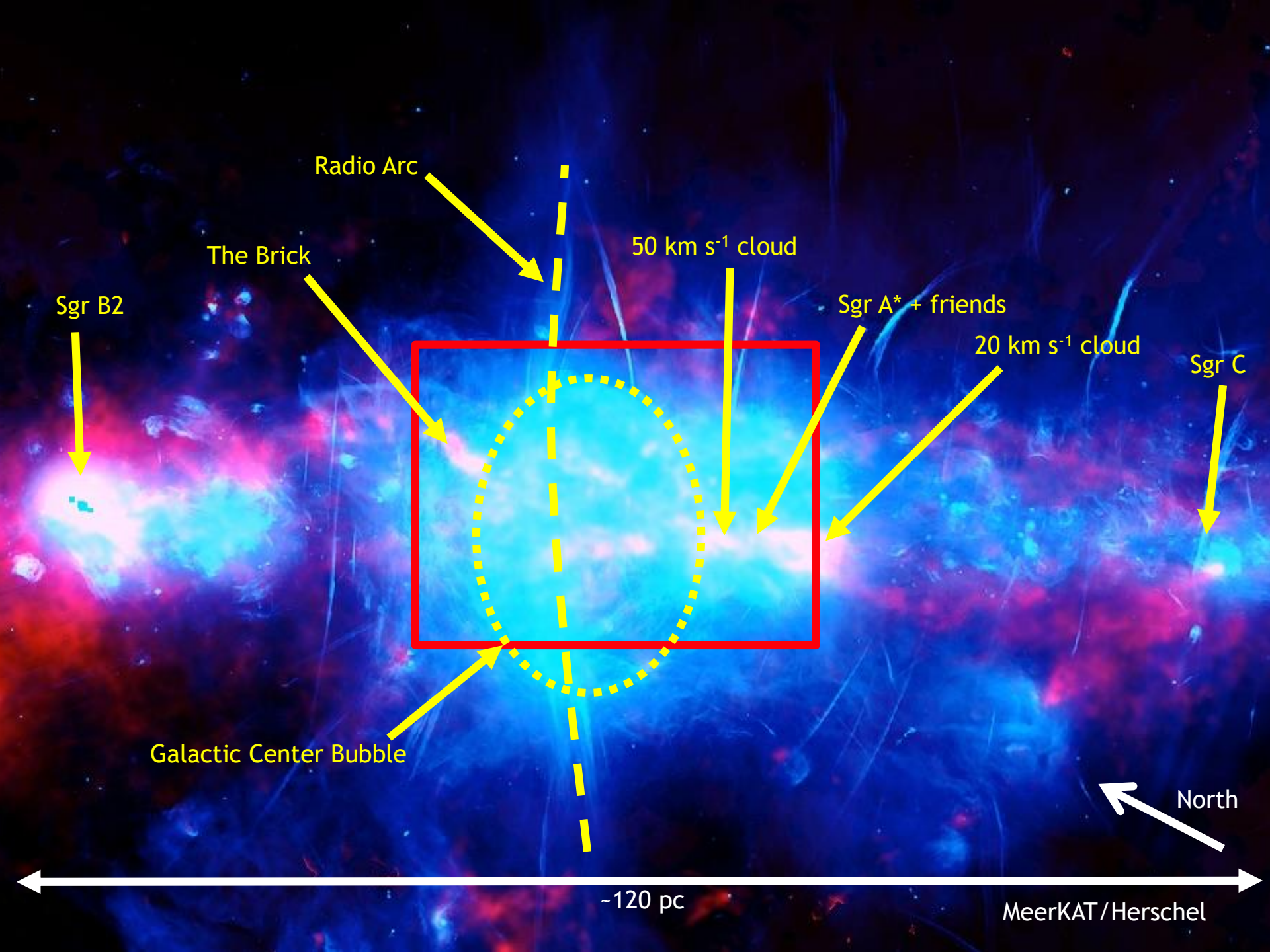

Hubble • Near-infrared


Chandra • X-ray


North
Chandra/HST/Spitzer


Arched Filaments
Arches
The Brick
Foreground
x-ray binary
Quintuplet
Pistol Nebula
Sickle
Sgr A*
CND
Mini-spiral
Nuclear cluster
North
~40 pc
Chandra/HST/Spitzer


North
MeerKAT/Herschel


Radio Arc
The Brick
50 km s-1 cloud
Sgr B2
Sgr A* + friends
20 km s-1 cloud
Sgr C
Galactic Center Bubble
North
~120 pc
MeerKAT/Herschel

Exotic laboratory on our doorstep

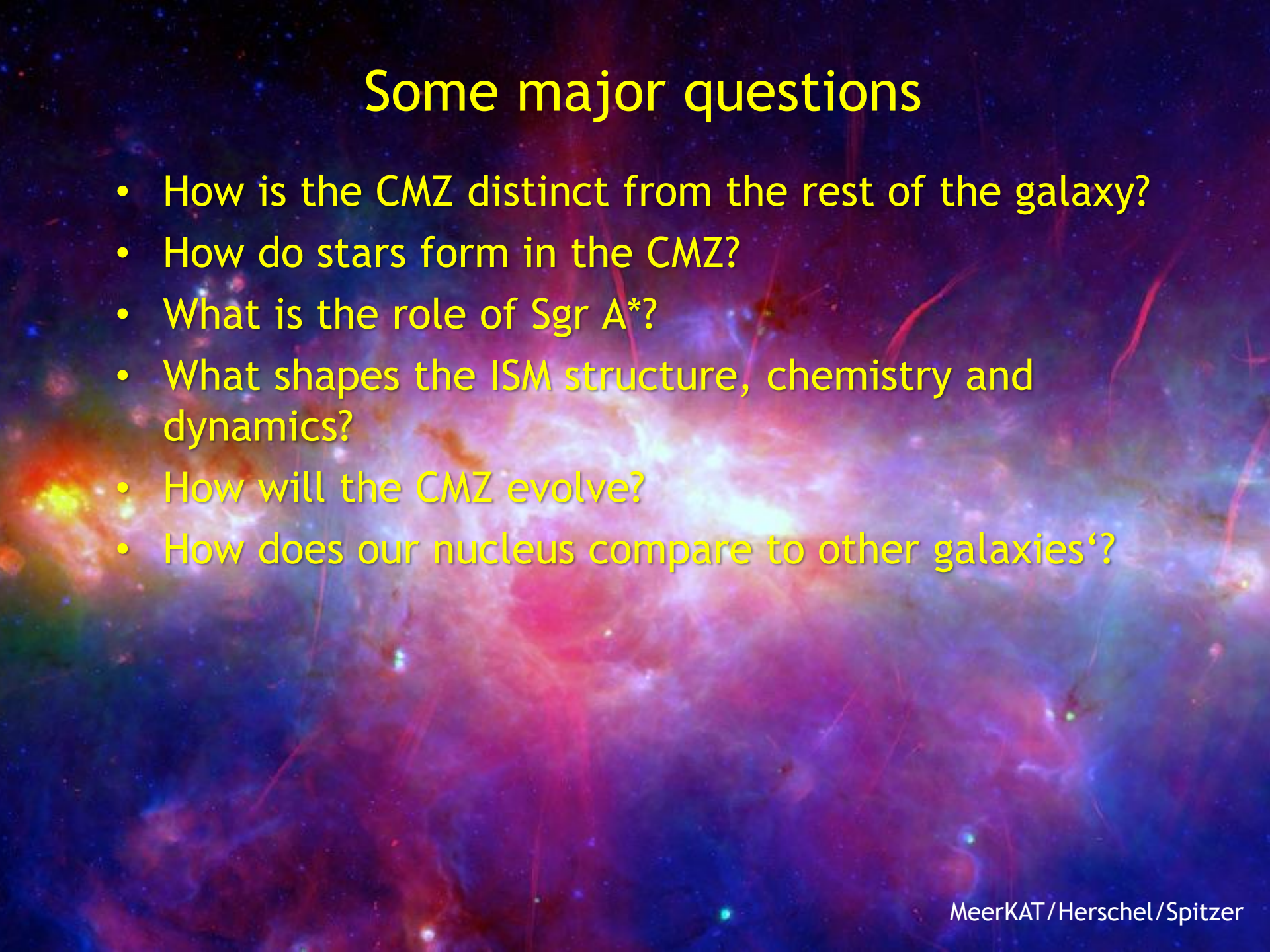
- Closest observable nucleus – $R_0 \approx 7.86 \pm 0.14$ kpc
- 4 x 10^6 $M_\odot$ supermassive black hole
- 10% Milky Way's gas mass in central 400 pc
- Three >10^4 $M_\odot$ star clusters

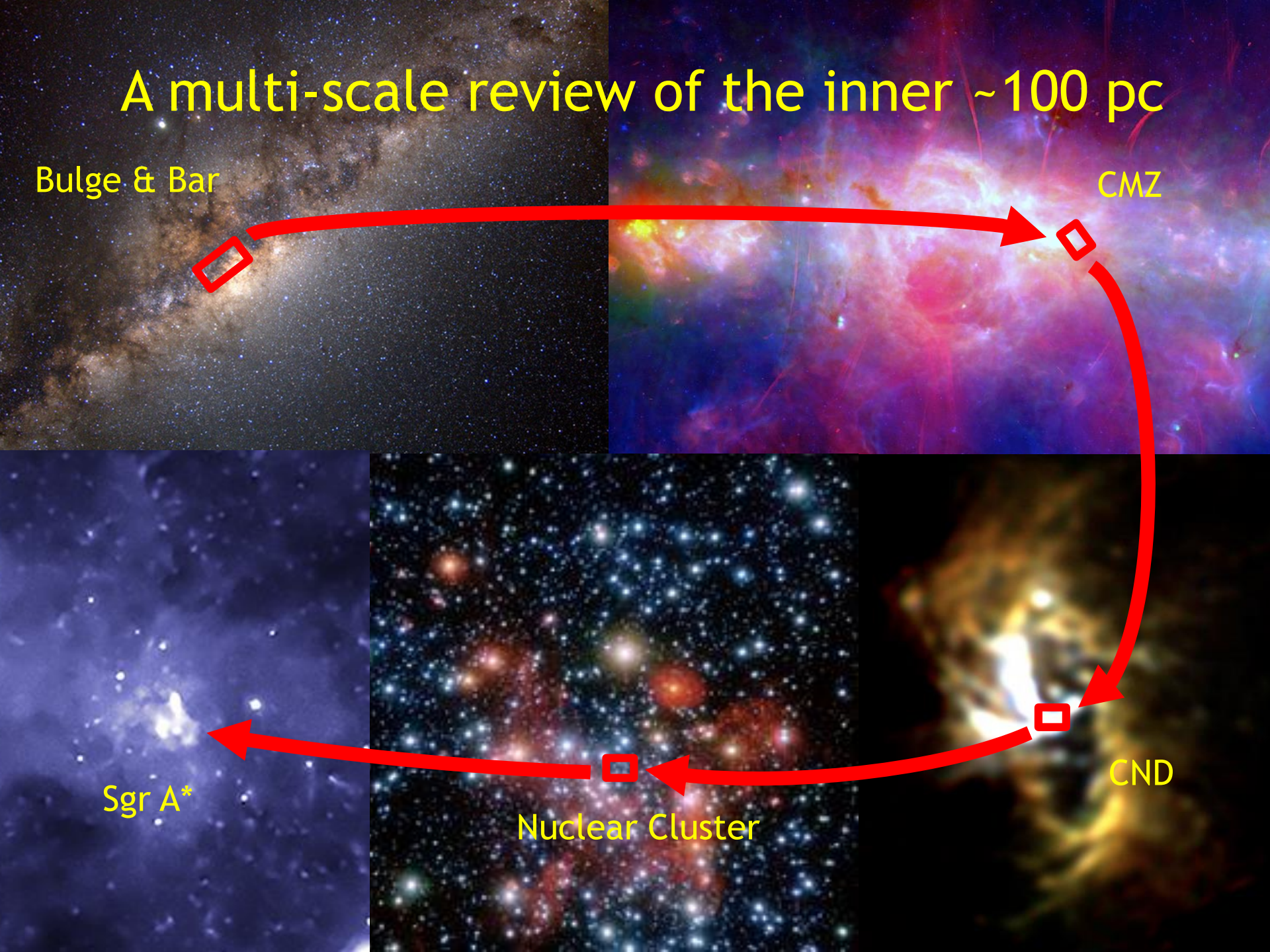
- Complex gas and dust structures
- Extreme environment:
  - Magnetic fields, tidal shear, in- and outflow, feedback, shocks, ionising fields, photo-dissociation, supernova remnants, etc…

MeerKAT/Herschel

Some major questions

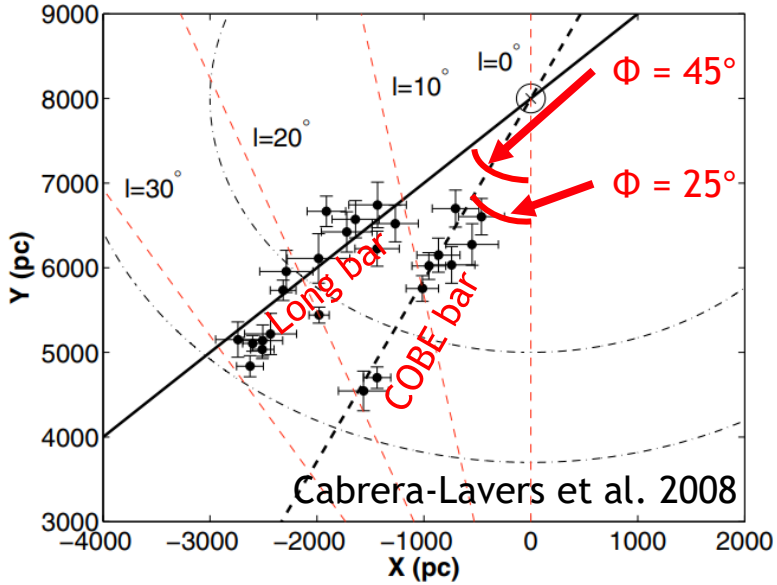
- How is the CMZ distinct from the rest of the galaxy?
- How do stars form in the CMZ?
- What is the role of Sgr A*?
- What shapes the ISM structure, chemistry and dynamics?
- How will the CMZ evolve?
- How does our nucleus compare to other galaxies‘?

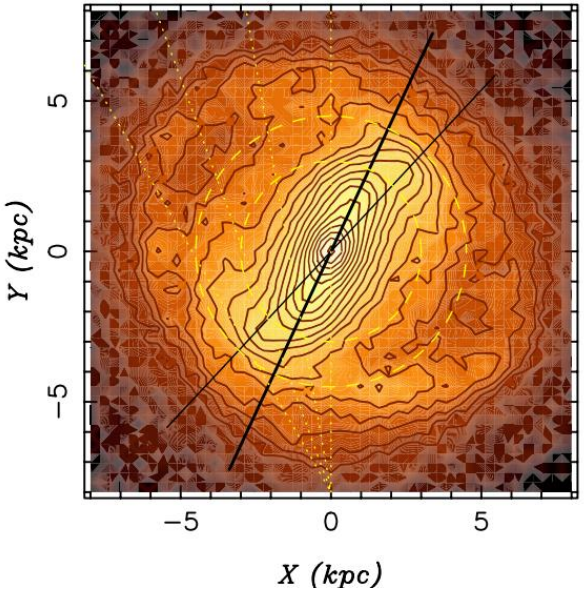



A multi-scale review of the inner ~100 pc
Bulge & Bar
CMZ
CND
Nuclear Cluster
Sgr A*

Galactic Bulge & Bar

- Old red star population
- Not well defined:
  - R ~ 2 – 3.5 kpc
  - Φ ~ 10 - 40°
  - a:b:c ~ 10:7:4 – 10:3:3
- At least two components
  - Triaxial boxy peanut-shaped “COBE bar”
  - Thin Φ > 40° “Long bar” from NIR star counts
  - Reconciled in models

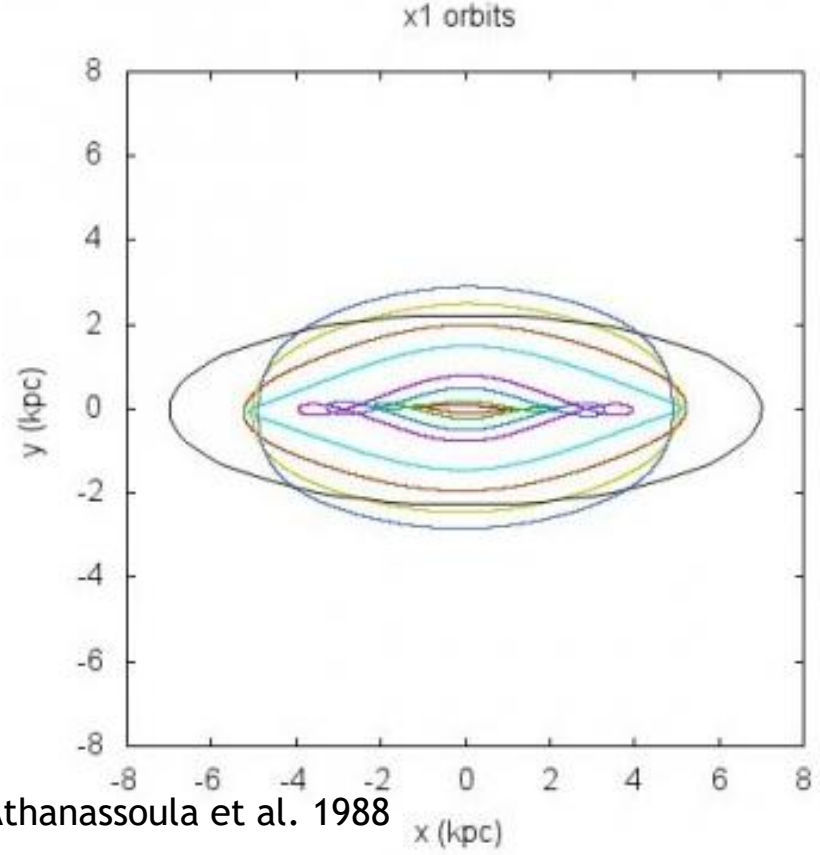




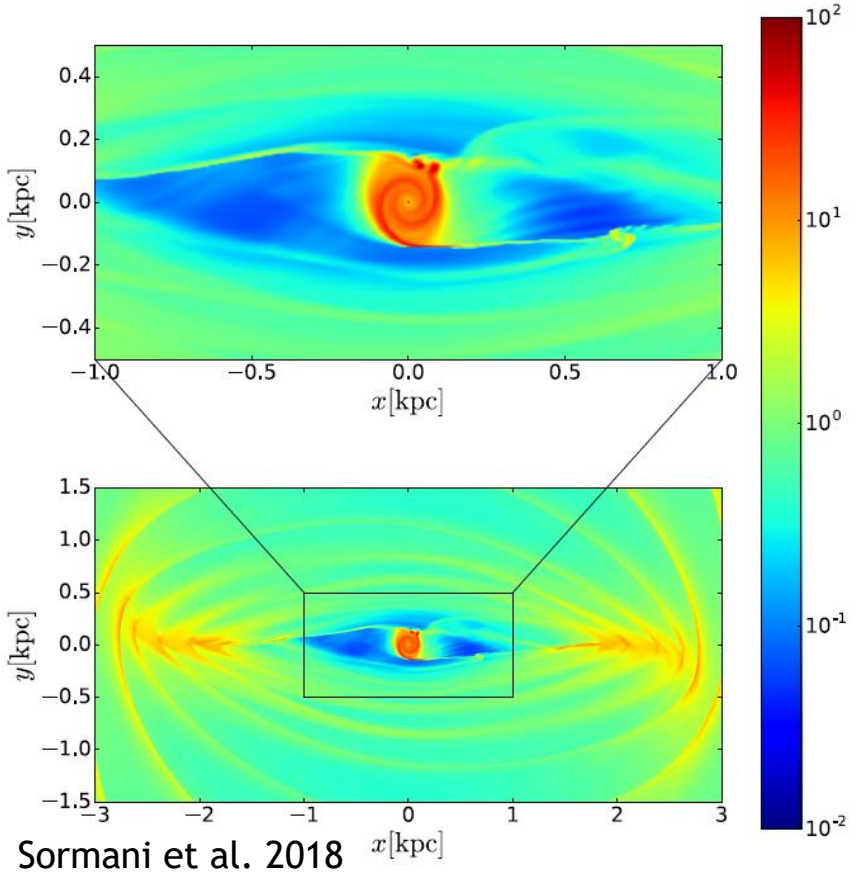
Martinez-Valpuesta, Gerhard 2011

Bar motions

- Bar dominates gravitational potential inward of ~3 kpc until close to Sgr A*
- Barred potential results in family of stable orbits
- Gas flow from disk ~ 1 kpc Gyr^{-1}
- Thermal & shock instabilities form quickly



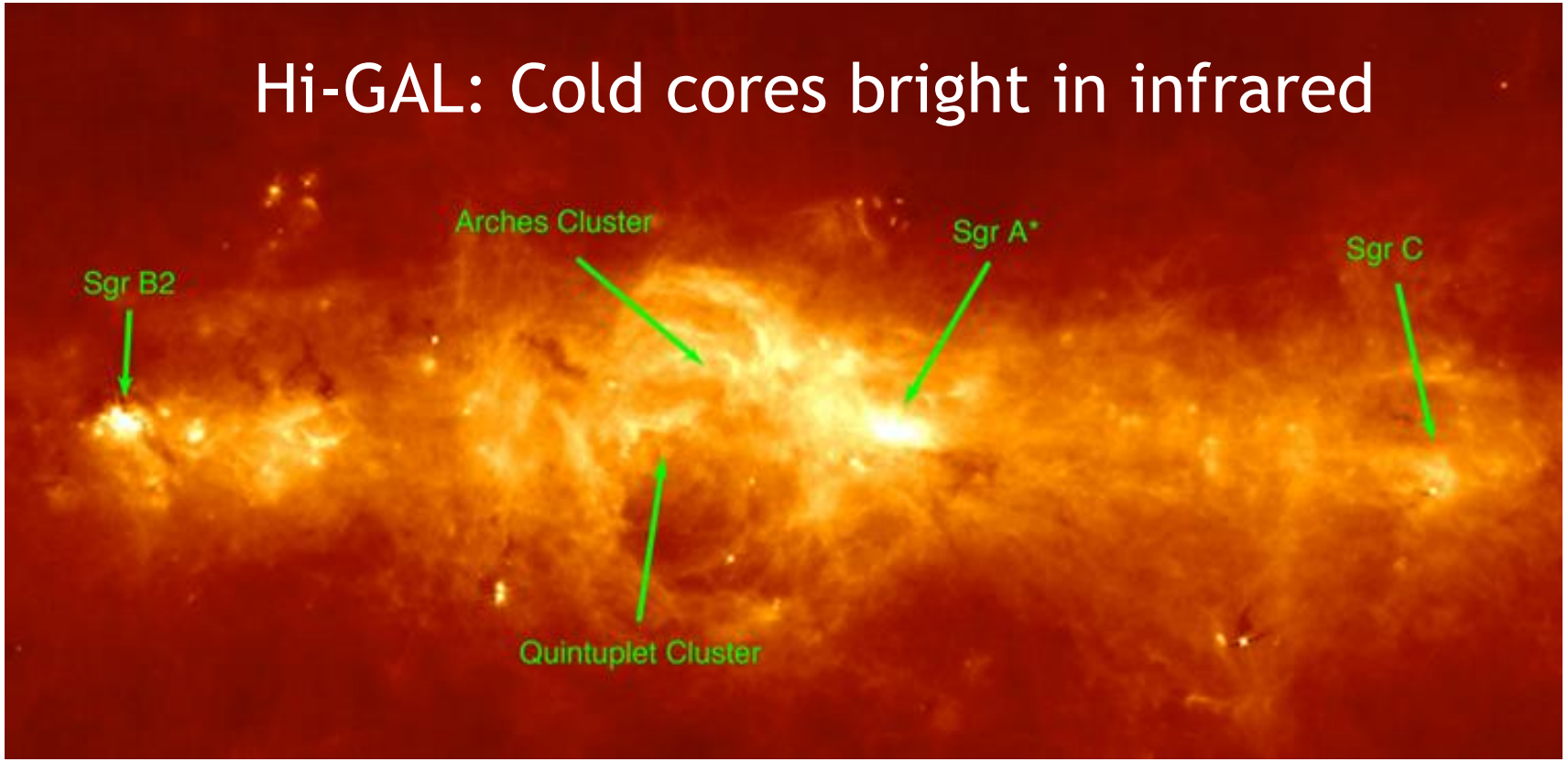
Athanassoula et al. 1988



Sormani et al. 2018

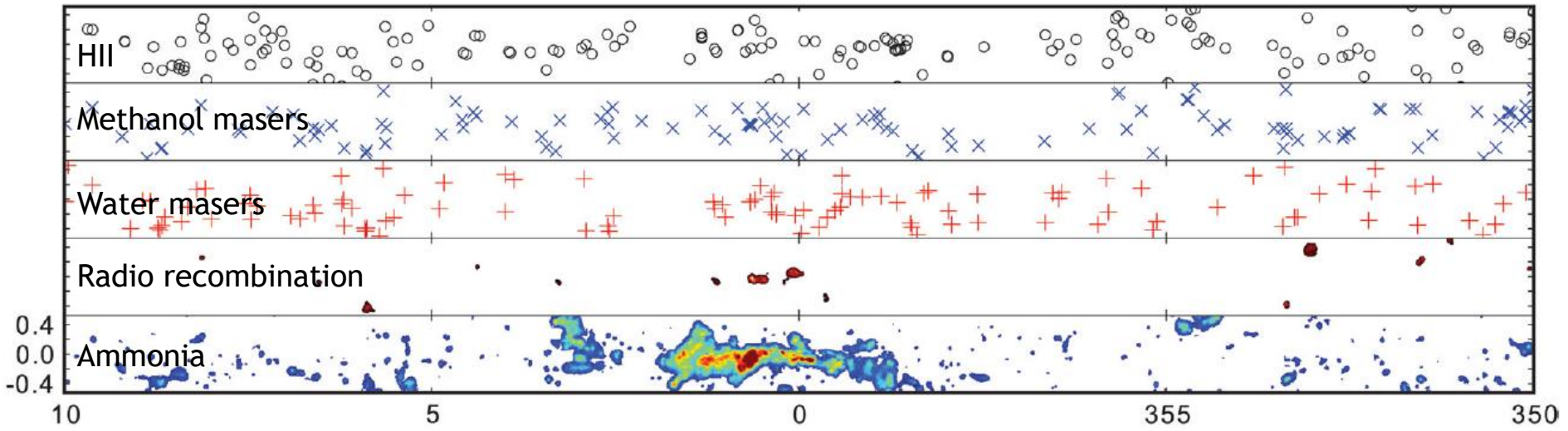
Central Molecular Zone (CMZ)

- Central ~100 pc, $-1 < l < +1.5$
- $n_{gas} \approx 10^4$ cm^{-3}, $M_{gas} \approx 3\text{-}5 \times 10^7 M_\odot \rightarrow$ 5-10% of M_{MW}!
- Raised temperatures, pressures, turbulence



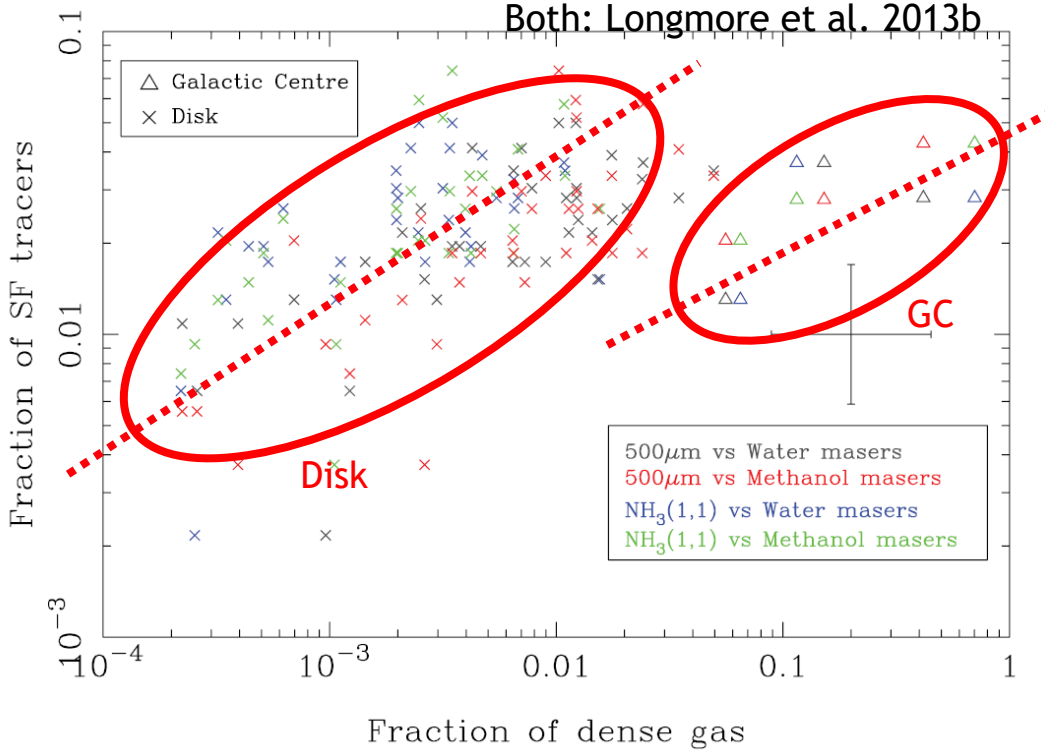
Molinari et al. 2011

Star formation in the CMZ is deficient!



- 0.01 – 0.02 $M_\odot$ yr^{-1}
- Based on universal relation, lower than 2 orders of magnitude
- How is the ISM different?

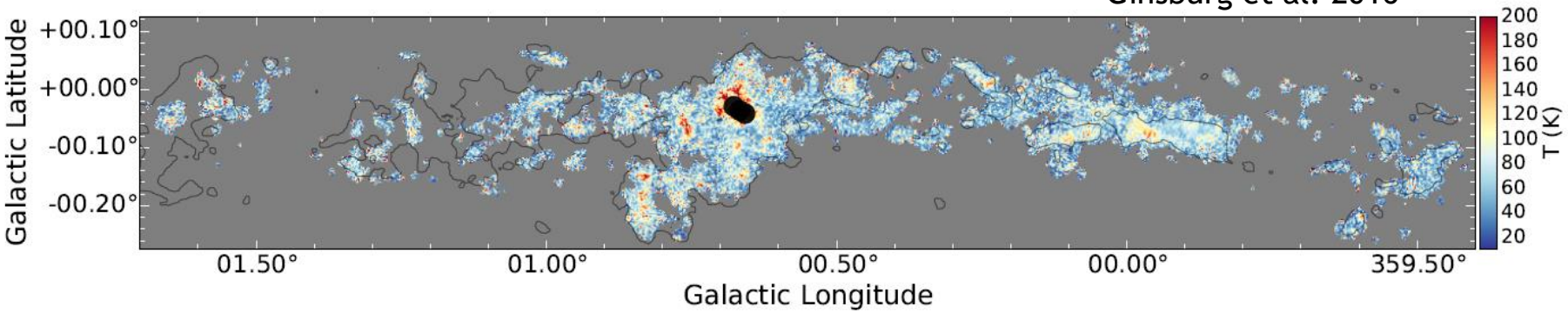
Both: Longmore et al. 2013b



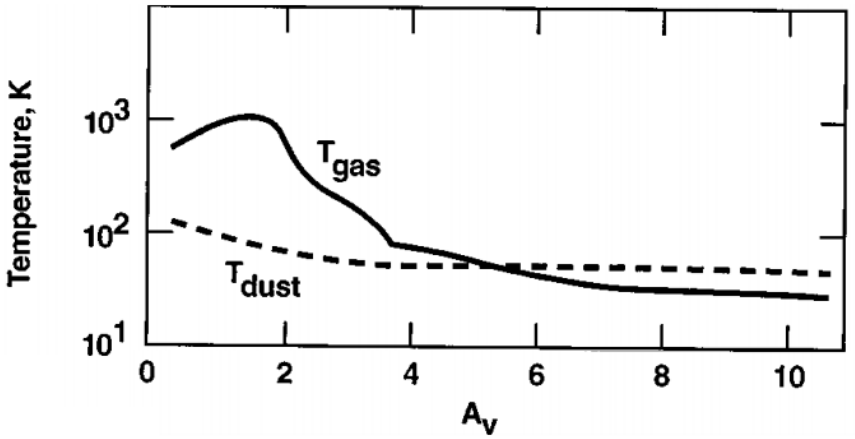
Dust-gas temperature discrepancies

- T_{dust} & T_{dust} do not match well in the CMZ
- Dense, 60-150 K gas pervades the inner degrees

Ginsburg et al. 2016



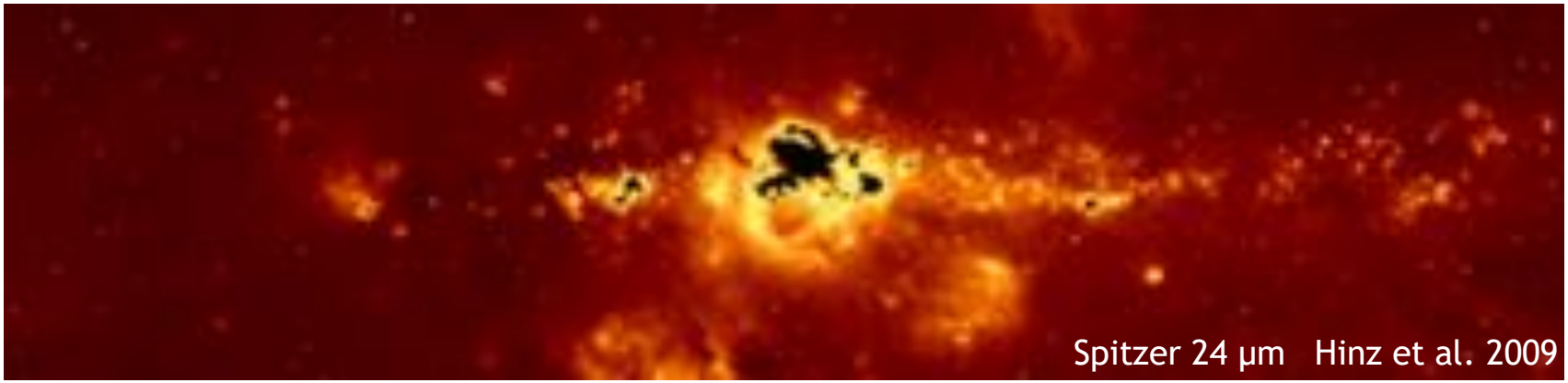
- Dust continuum cannot be used as gas temp proxy
- Dust is a major coolant
- Predominant gas heating mechanism on large and small scales is still unclear

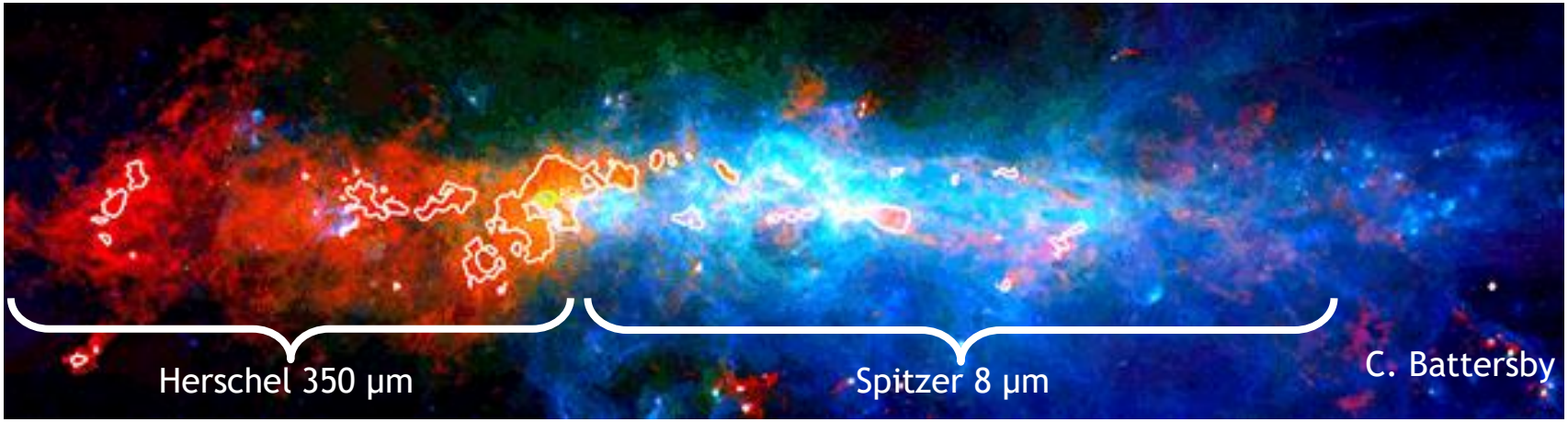


Hollenbach & Tielens 1999

CMZ large scale features

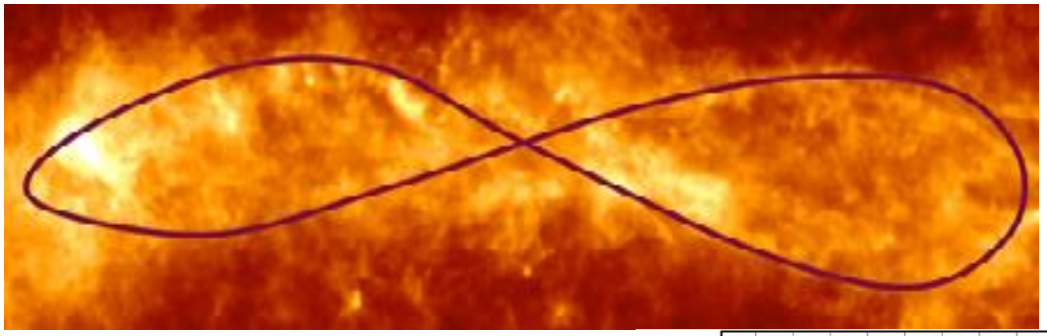
- Far/Mid infrared asymmetry
- ~3/4s of dense molecular ISM (SF ingredients) is at positive l





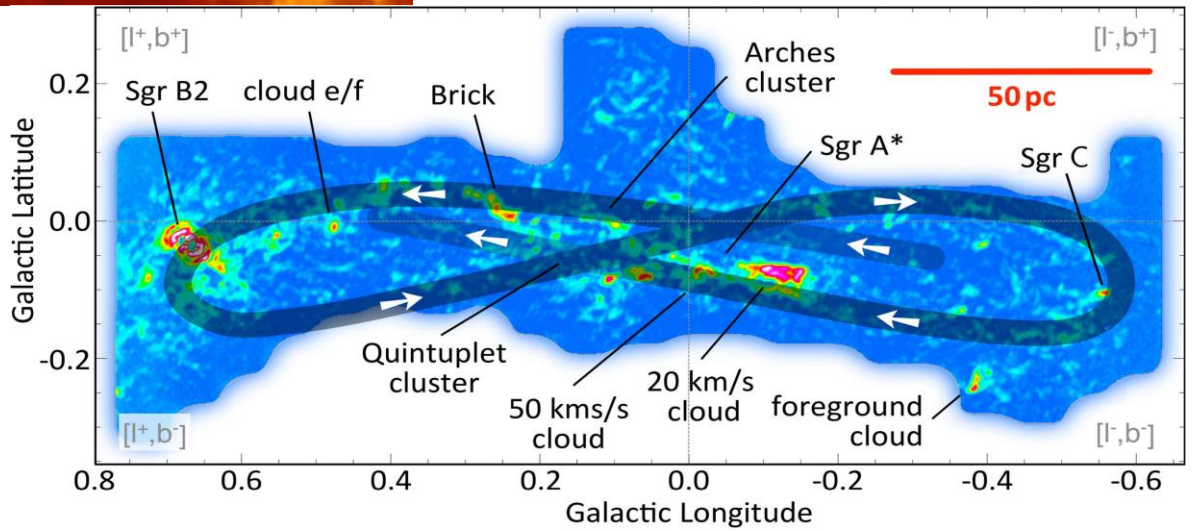
The 100 pc scale Ring

- Arcs visible in FIR and sub-mm
- Follows theoretical stable x_2 orbit
- Sgr B2 and C located at extreme ends
- “The Brick” and “dust-ridge” clouds lie in between



Molinari et al. 2011

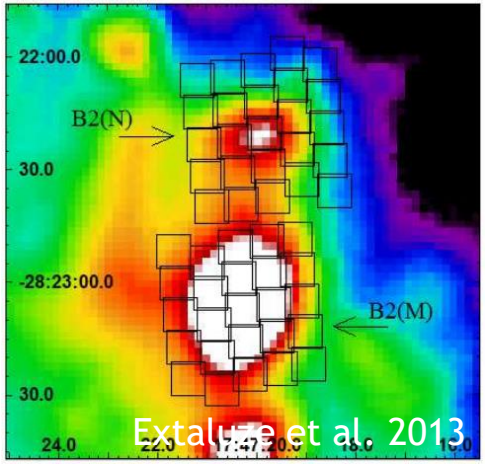
Krieger et al. 2017



Diverse structures along the 100 pc Ring

Sgr B2

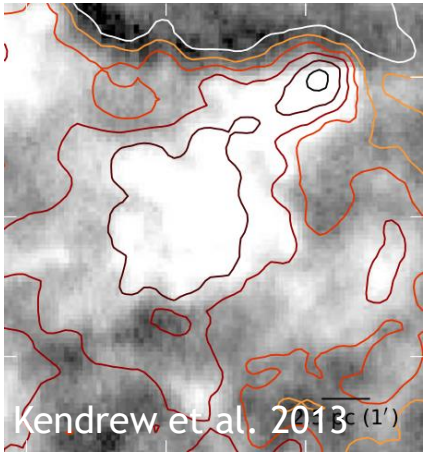
- ~10% of CMZ gas
- >49 HII sources
- Intense starburst



Extalude et al. 2013

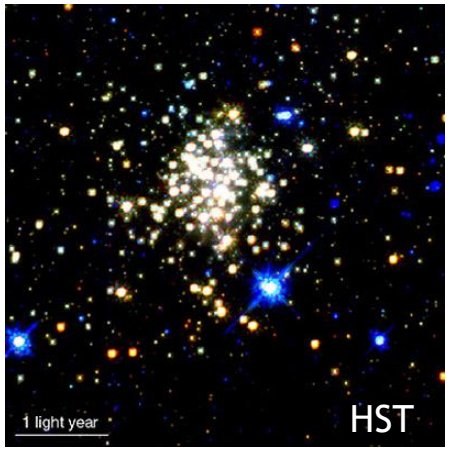
Sgr C

- Lower mass than B2
- Only major SF site in western CMZ


Kendrew et al. 2013

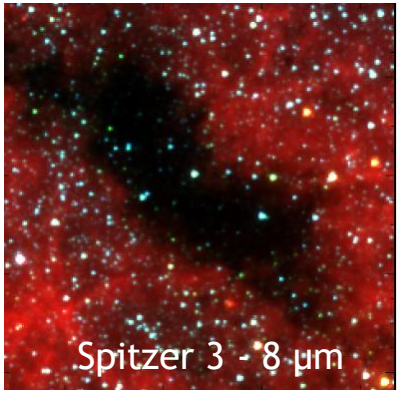
Arches cluster

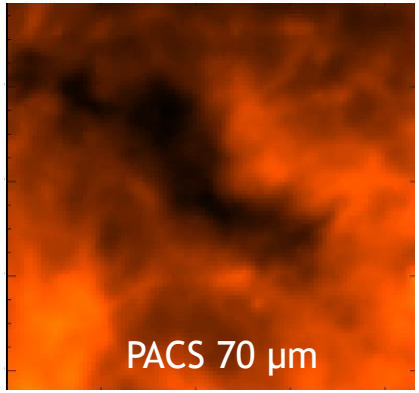
- $\rho_{stars} \approx 10^{5.6}\ M_\odot\ pc^{-3}$
- Luminous evolved WN stars



G0.253+0.016 "The Brick"

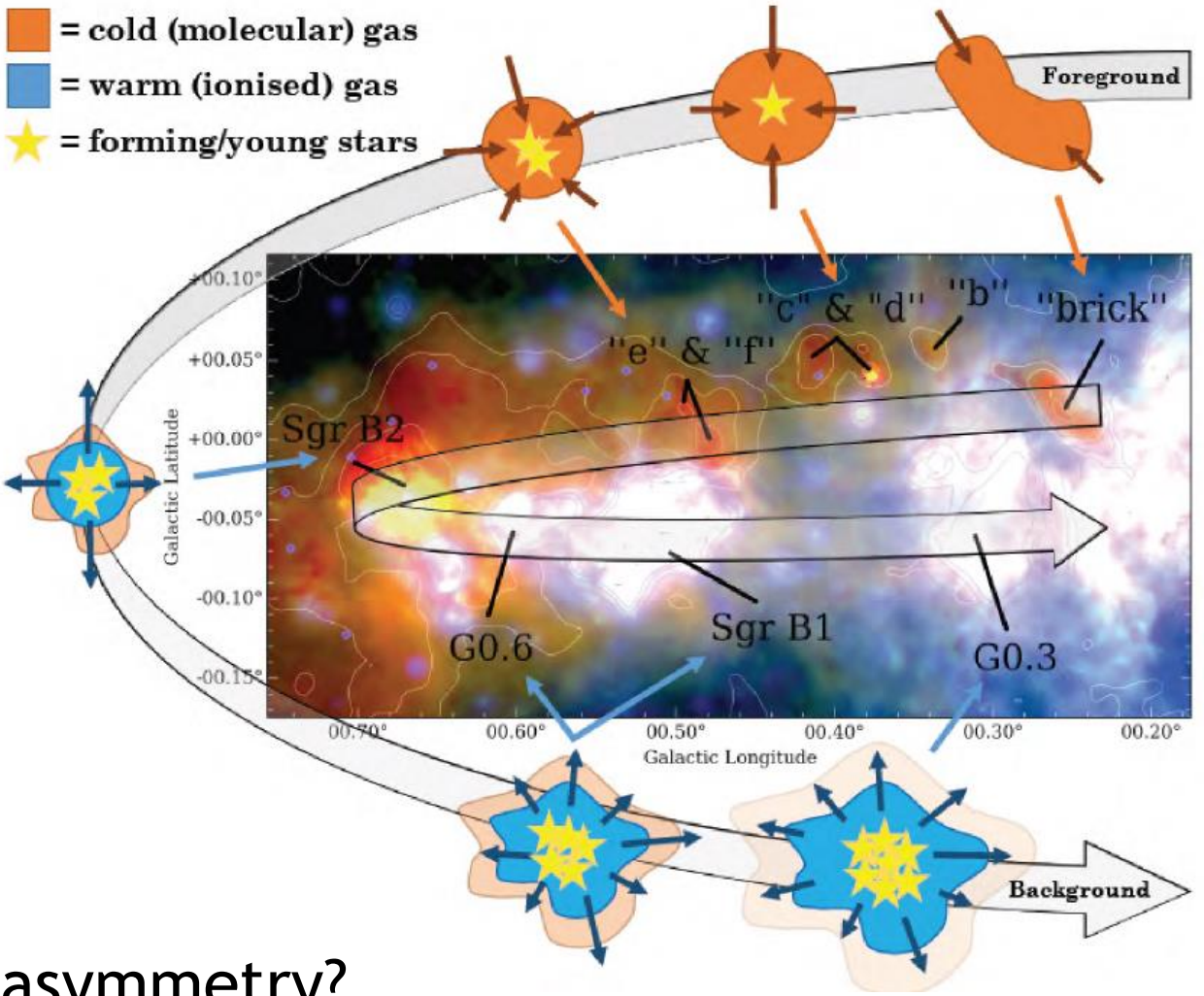
- Infrared Dark Cloud (IRDC)
- High density $n(H_2) = 2 \times 10^5\ cm^{-3}$
- Devoid of star formation
- Primordial stellar cluster?



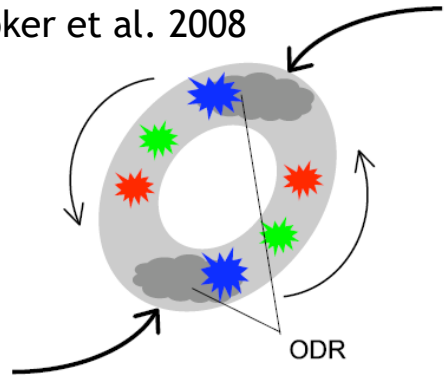


„Pearls on a string“

- Time evolution of collapsing clouds and SF



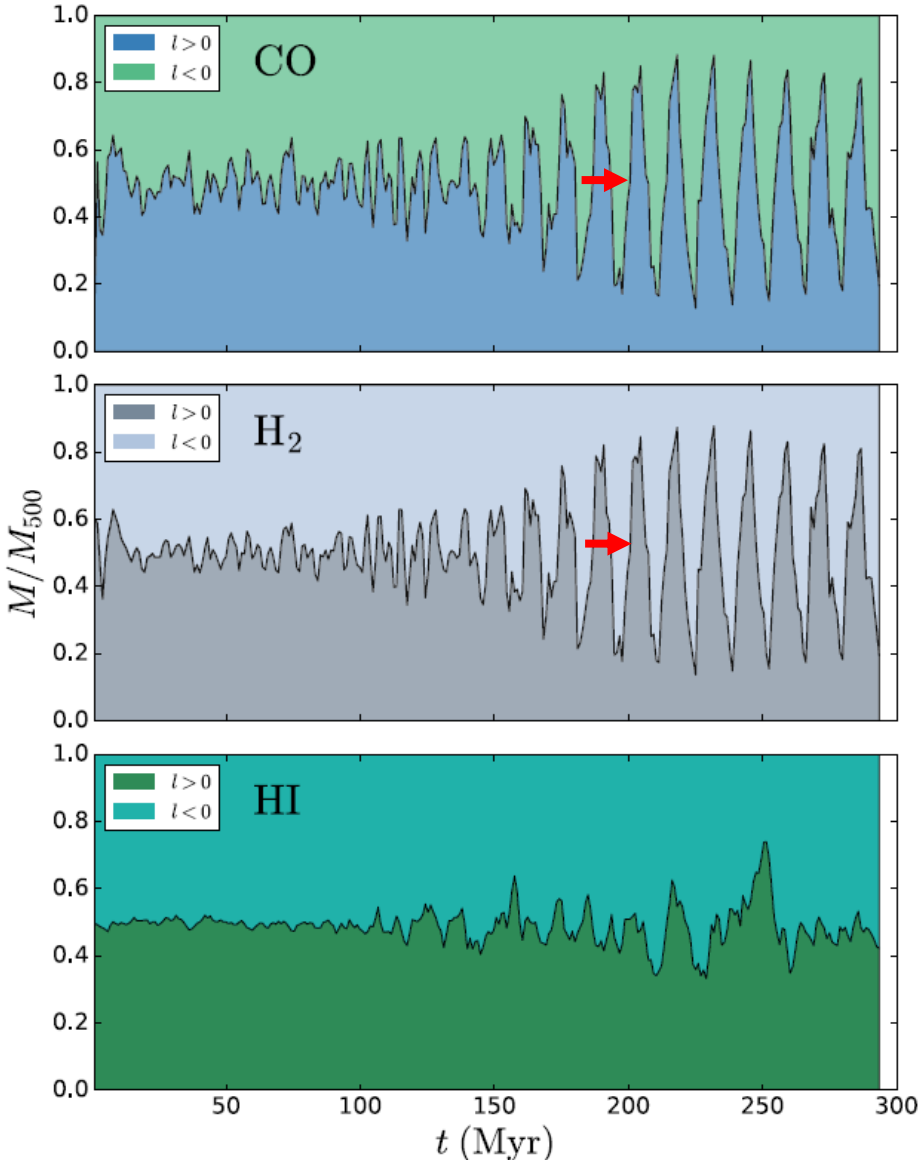
Böker et al. 2008



- Drives CMZ asymmetry?...

Longmore et al. 2013a

…or just a coincidential snapshot?

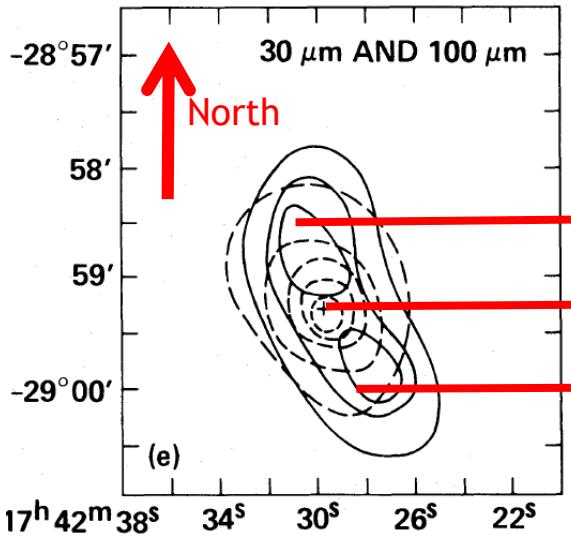


- Simulating gas asymmetry in central 500 pc
- Even with perfectly symmetric initial conditions, asymmetry develops in ~50 Myr
- Induced by thermal and shock instabilities
- ~10 Myr period

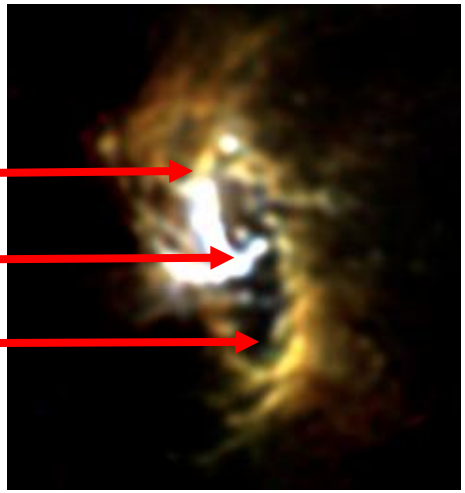
Sormani et al. 2018

Circumnuclear Disk (CND)

- Double lobed ring/disk of dense gas, R_{inner} ~1.5 pc nearly centred on Sgr A*
- Clumpy morphology, multiple streamers



KAO: Becklin et al. 1982

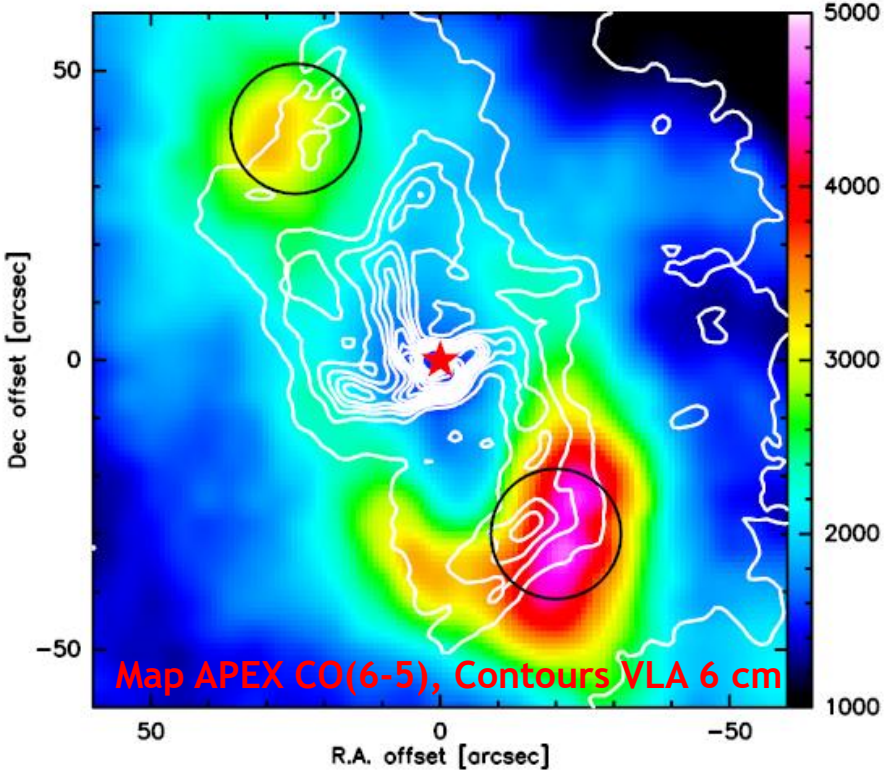


SOFIA-FORCAST: Lau et al. 2012

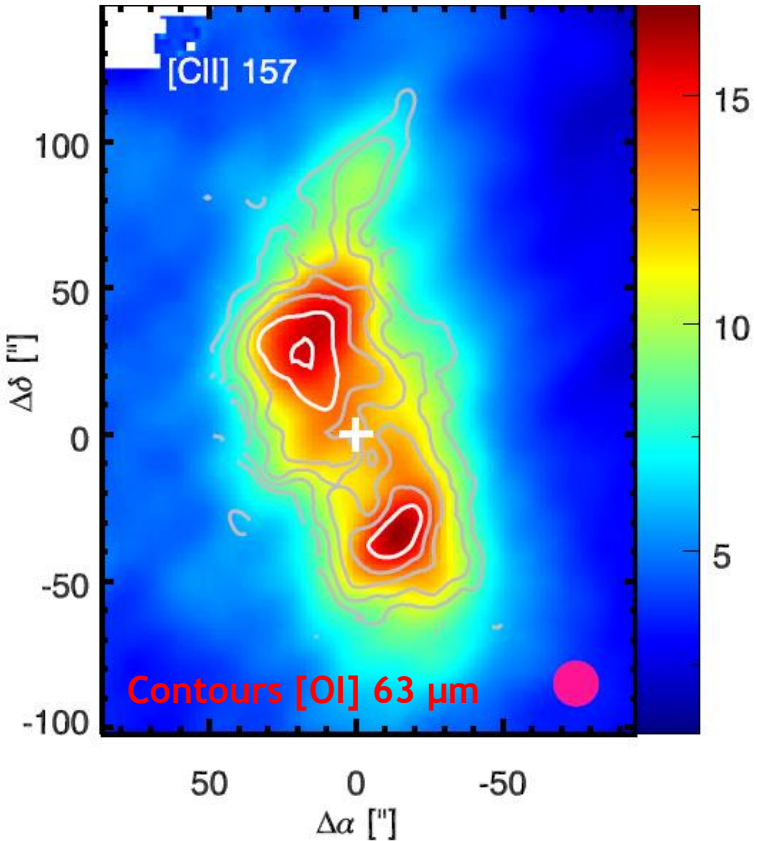
State of the CND neutral gas

- Low density ($10^{4\text{-}6}$ cm^{-3}) clumps
  - Assumption of virialisation
- Herschel found multiple molecular temperature phases
  - UV field cannot be only excitation source (Goicoechea et al. 2013)

SOFIA-GREAT: CO excitation ladder
Requena-Torres et al. 2012

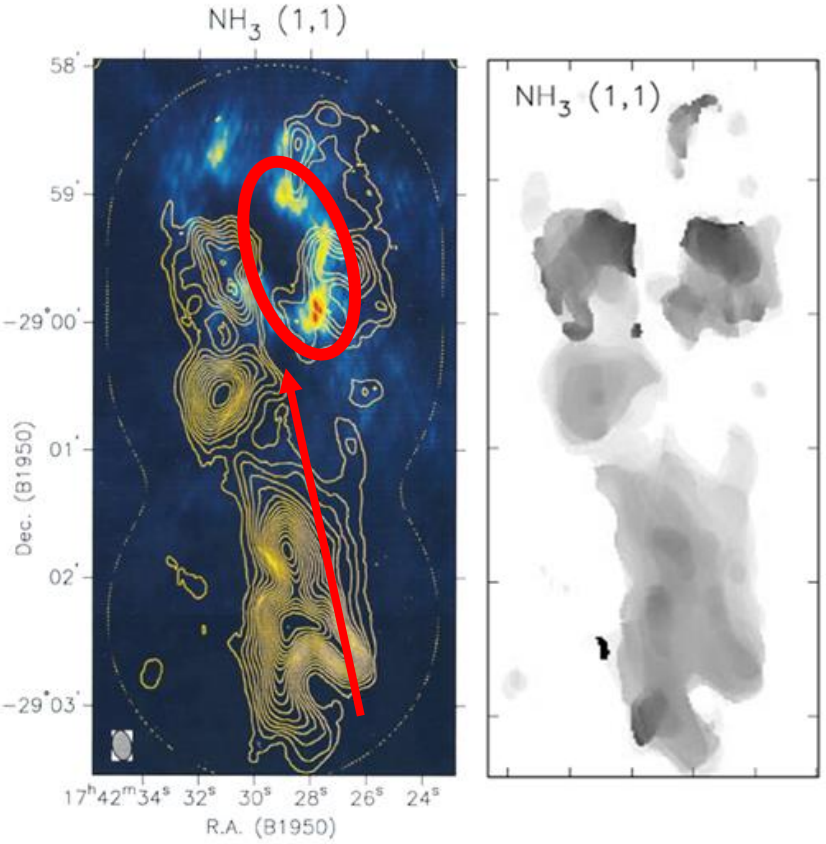


SOFIA FIFI-LS: Dense PDR
analysis Iserlohe et al. in press



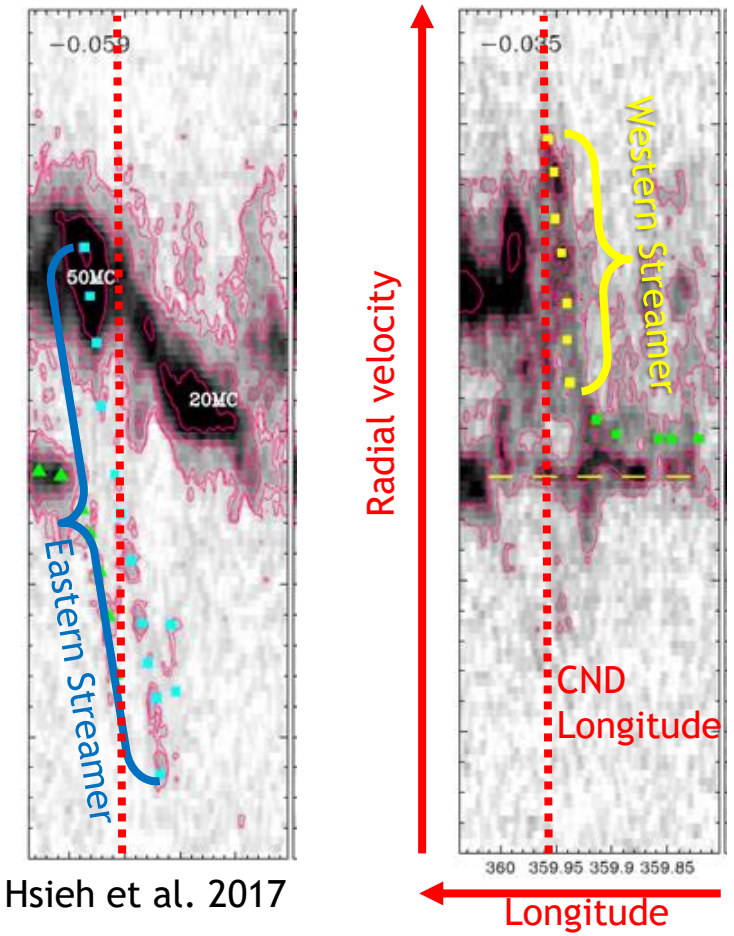
Neutral matter infall to the CND

Southern streamer



Coil & Ho 1999

Eastern & Western streamers

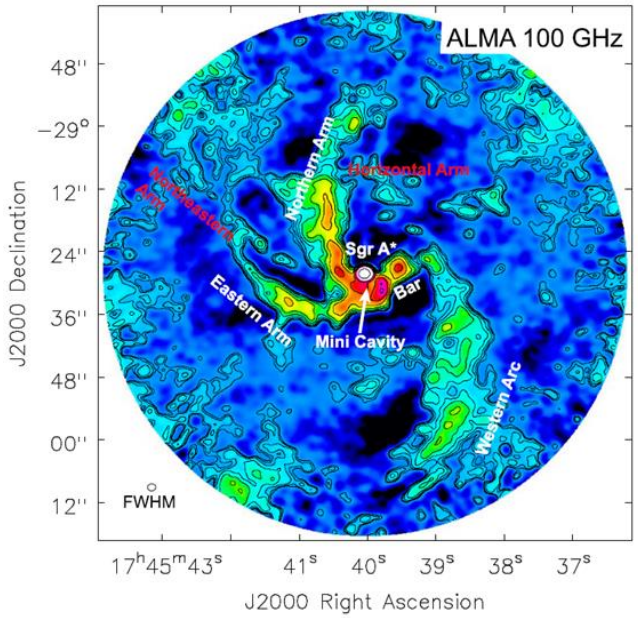


Hsieh et al. 2017

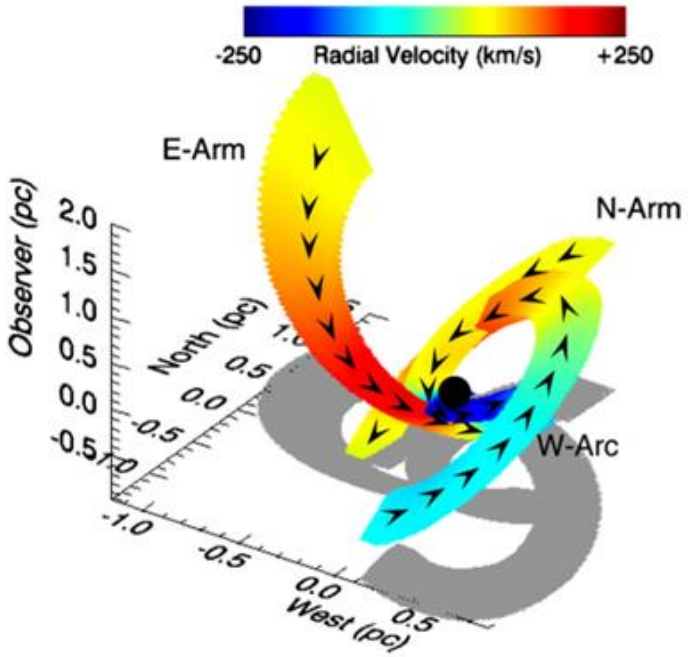
- Need for velocity resolved distinctions between streamers and CND

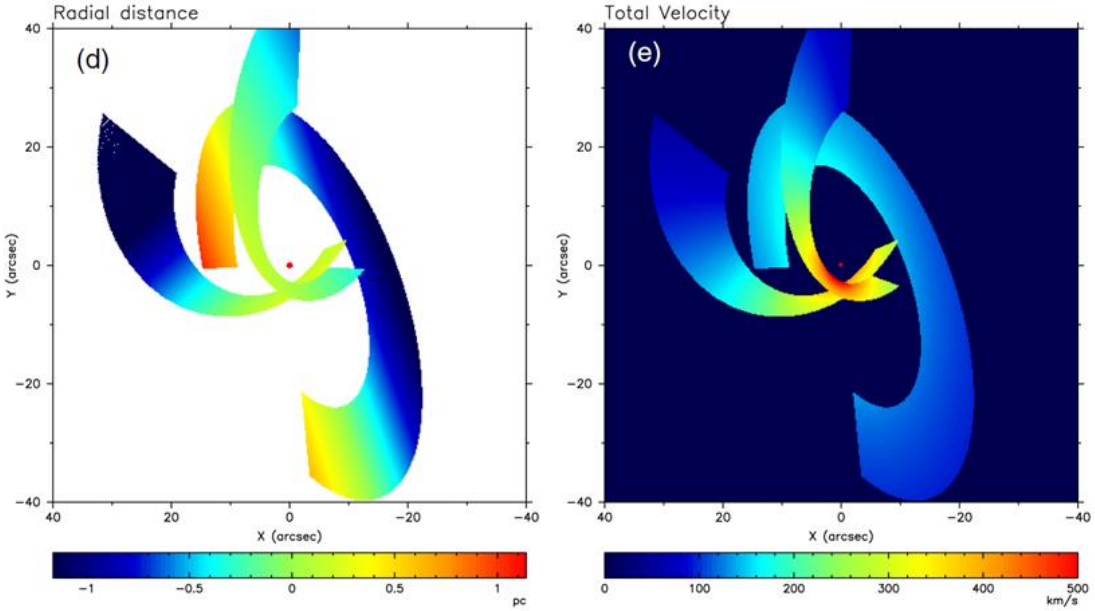
Ionised matter infall to Sgr A*

- Multi-epoch VLA observations of mini spiral
- Mini spiral arms orbitally associated with Sgr A*
- Non-Keplerian components exist → cloud-cloud interactions, mag fields, stellar winds



Tsuboi et al. 2016a

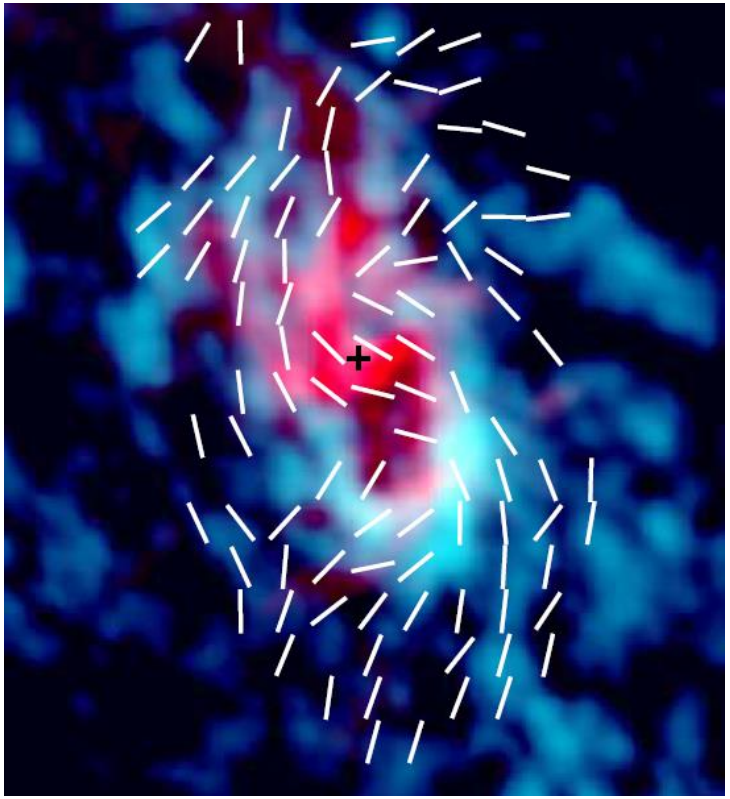




Zhao et al. 2009

B-fields in the inner parsecs

- Single B-field links gaseous disk, mini-spiral and streamers
- Varying field configuration in streamers suggests different stages of streamer accretion
- B-fields may sustain CND‘s inner edge radius (Blank et al. 2016)
- SOFIA-HAWC+ pol maps to come – fields can channel the gas inwards

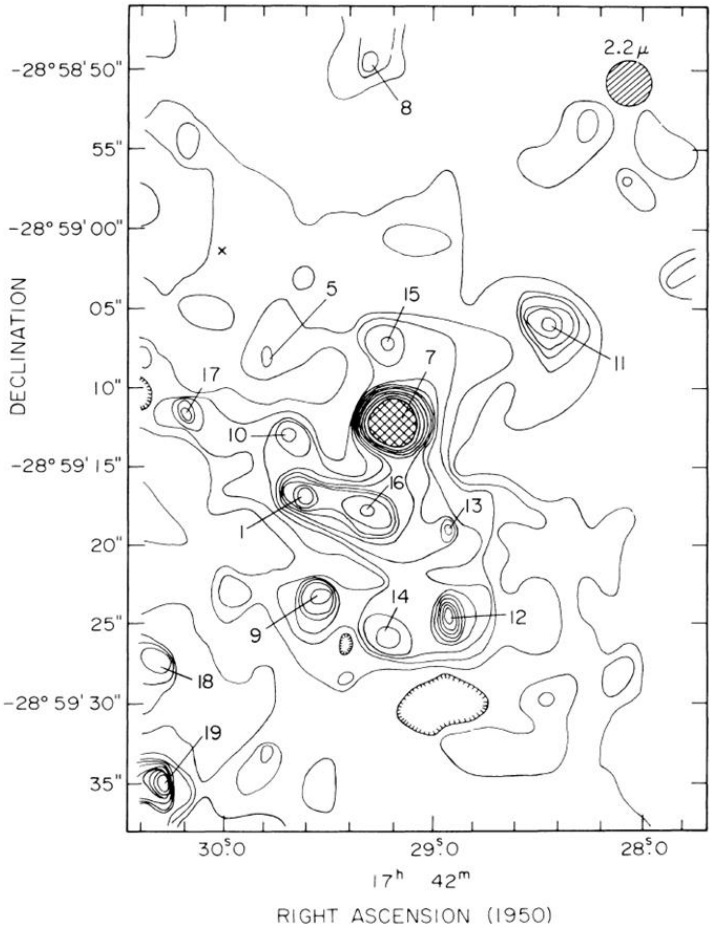


JCMT-SCUPOL 850 µm - Hsieh et al. 2018

SOFIA-HAWC+ 53 µm - D. Dowell, HAWC+ team

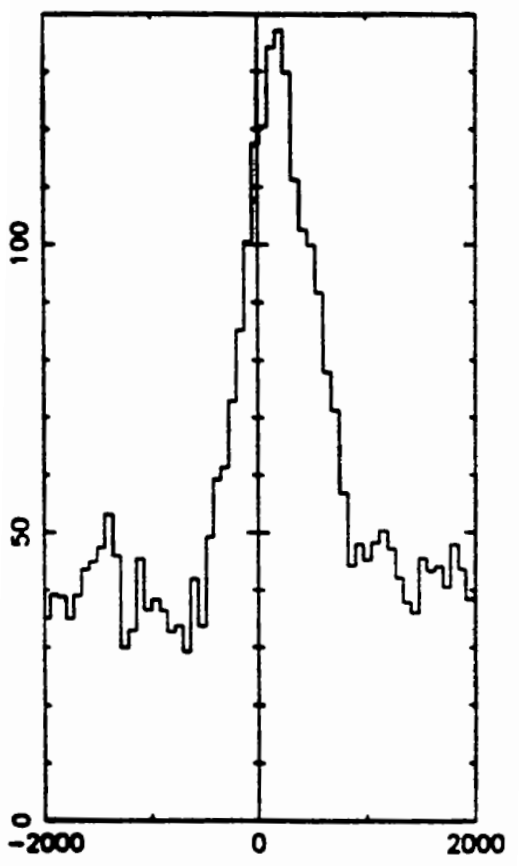
Massive star formation around Sgr A*

IRS 1-19 @ 2.2 and 10 μm
central 1.2 pc

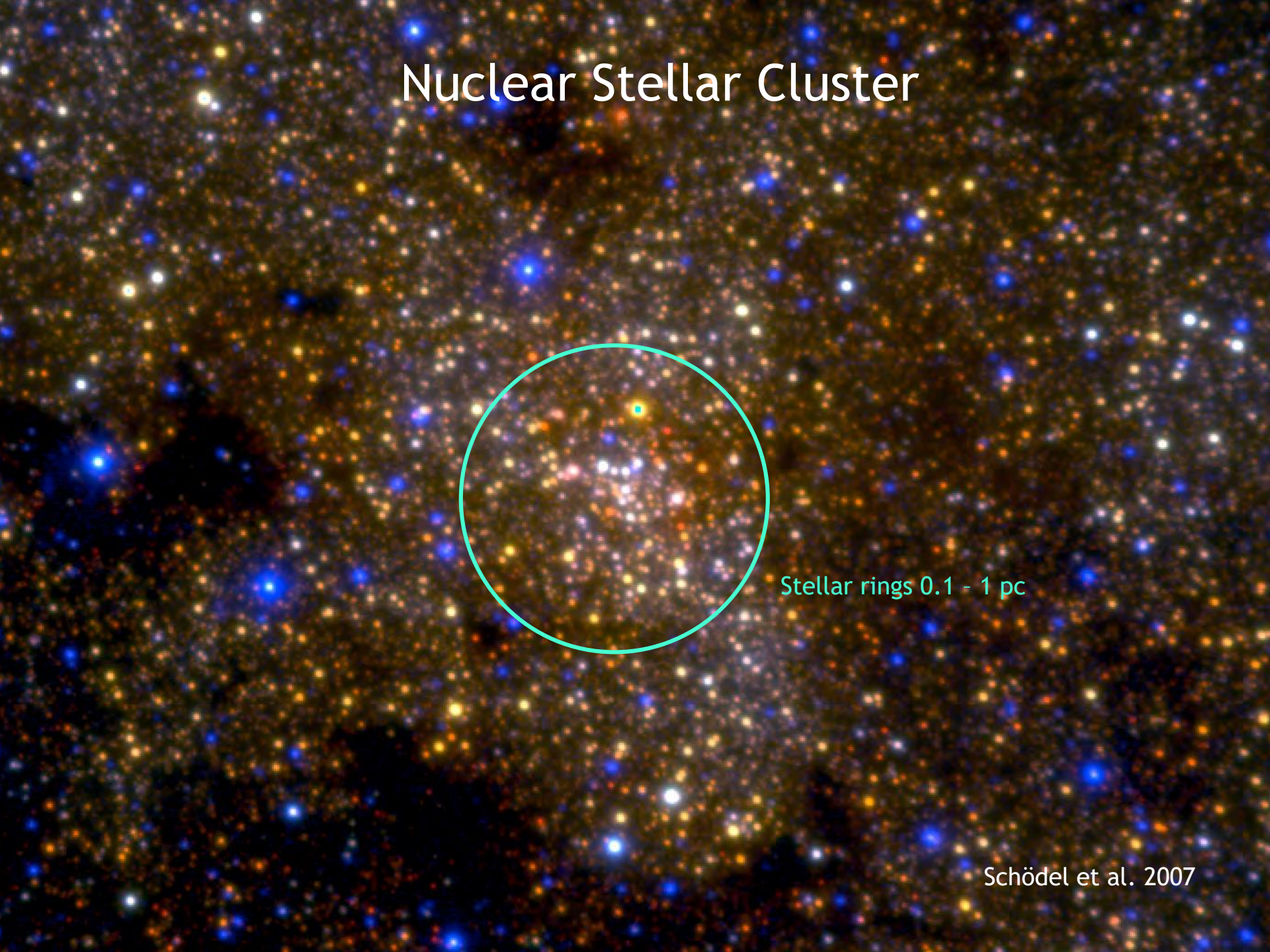


Becklin & Neugebauer 1975

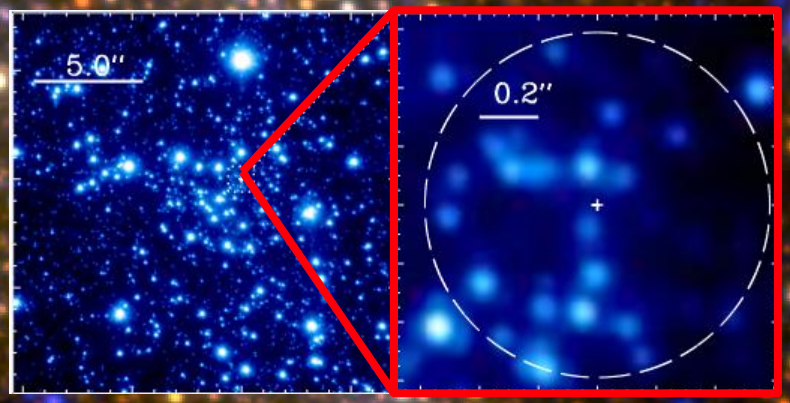
AF star @ He I 2.058 μm
Young WN9/Opfe type



Forrest et al. 1987
Allen et al. 1990


Nuclear Stellar Cluster
Stellar rings 0.1 - 1 pc
Schödel et al. 2007

Nuclear Stellar Cluster

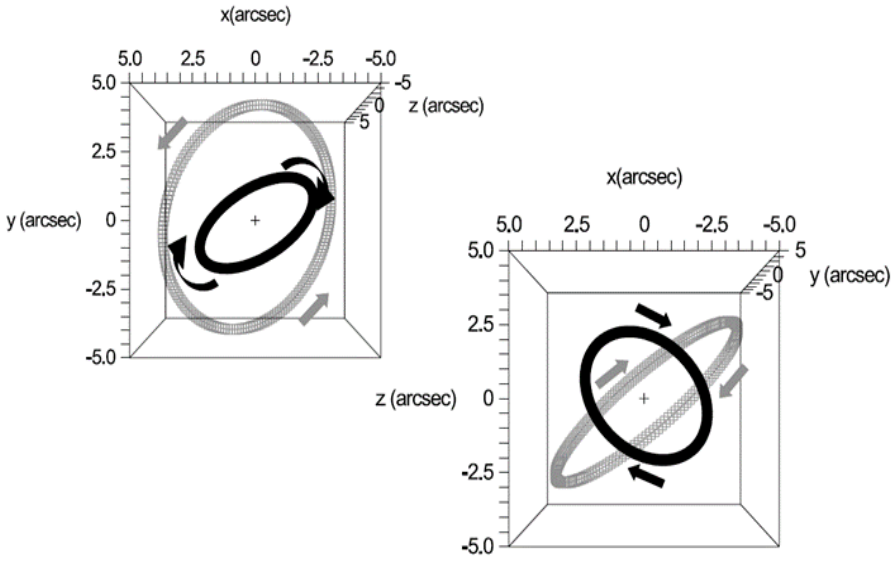


S-star cluster < 0.1 pc
Sabha et al. 2013

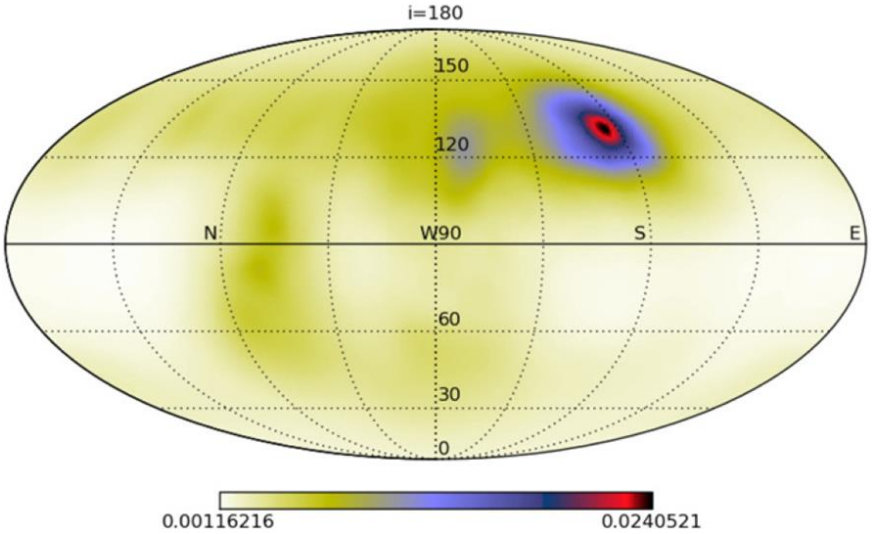
Schödel et al. 2007

Nuclear Stellar Cluster

- Many early type WR, O & B stars
- Distributed in 2 disks 0.1 – 1 pc from Sgr A*
- CW disk strong evidence, CCW less so



Genzel et al. 2003



Yelda et al. 2014

- Also central cusp “S-star cluster” < 0.1 pc from Sgr A*

The paradox of youth

- Sgr A* creates tidal force to inhibit star formation
- Roche limit for gravitational collapse of cloud

$$n_{Roche}(R) \sim 6 \times 10^{10} \left(\frac{R}{0.1\ \mathrm{pc}} \right)^{-3} \ \mathrm{cm}^{-3}$$

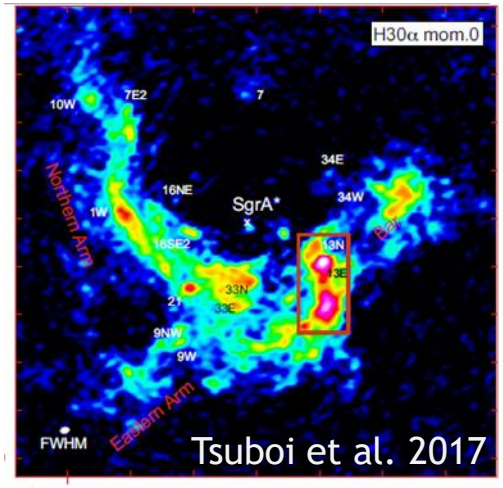
- 3-5 x 10^7 cm^{-3} at 1 pc
- Many CMZ clouds are much lower

- How did the stellar cluster form in these conditions?

The paradox of youth

Infalling stellar cluster

- Nuclear star cluster forms further out
- Falls towards Sgr A*
- Friction forms IMBH
- Stars deposited in disk ~0.1 pc from centre

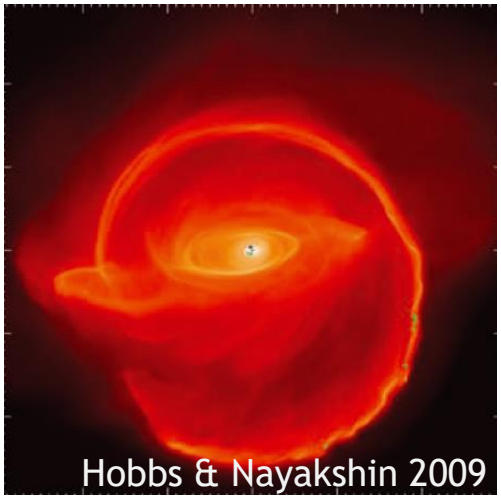


But…

- Inconsistent with observed disk profile

In-situ formation

- Stars formed close to their current position
- Self-gravitating disk fed by accretion
- Two colliding molecular clouds



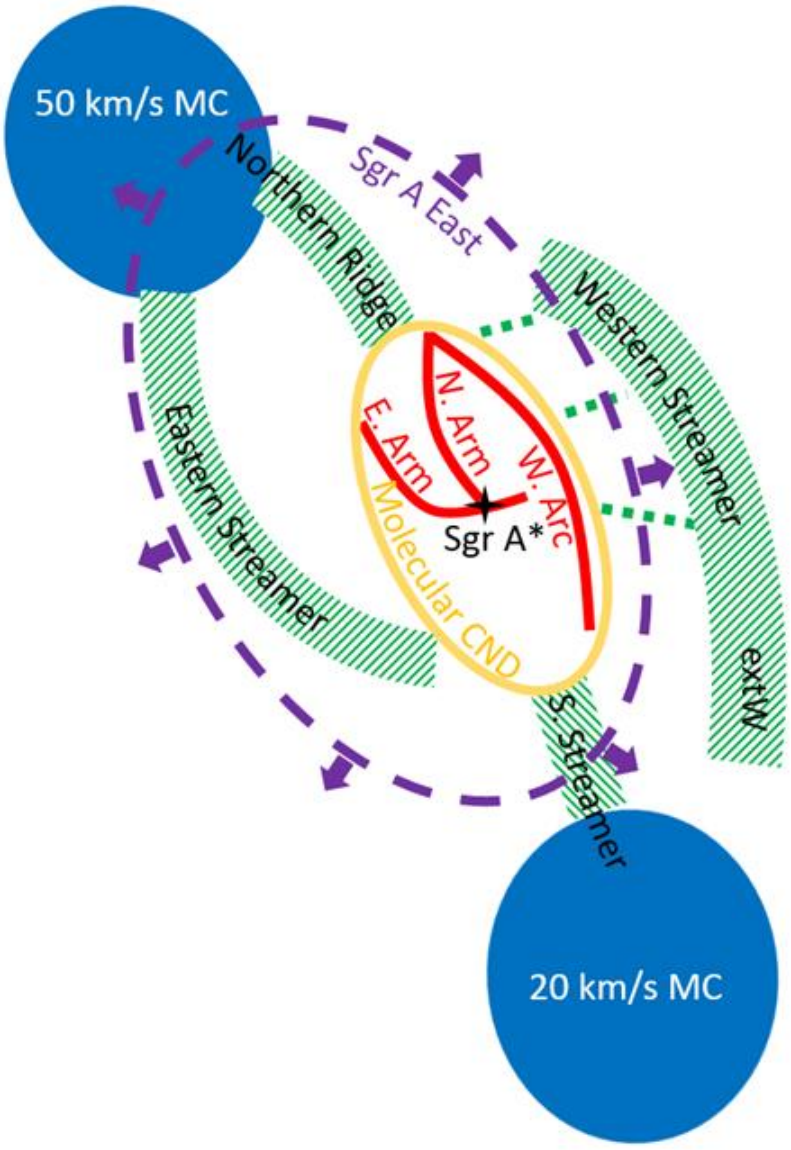
- Plenty of quiescent clouds within 20 pc
- CND
- 20 & 50 kms clouds

Difficult to replicate?

Need stable gas reservoir

The central few parsecs in a nutshell

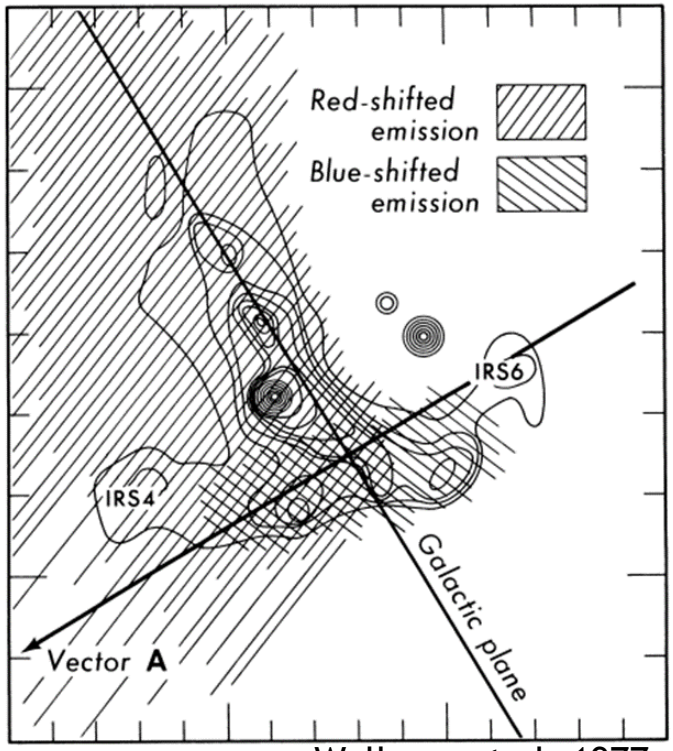
- Complex morphology and kinematics
- Infall from outer GMCs onto CND possible
- Infall along Keplerian orbits of the mini spiral
- CND might be the “pit stop” for matter falling onto Sgr A*
- Is this a reliable reservoir for the formation of the stellar cluster?
- → Transient or not?!



Sgr A*

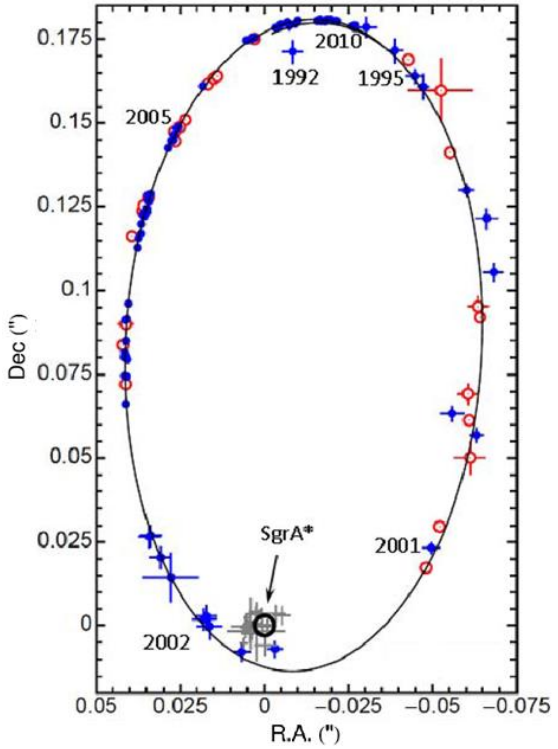
- Wealth of evidence for super massive black hole

ISM dynamics



Wollman et al. 1977

Stellar orbital solutions

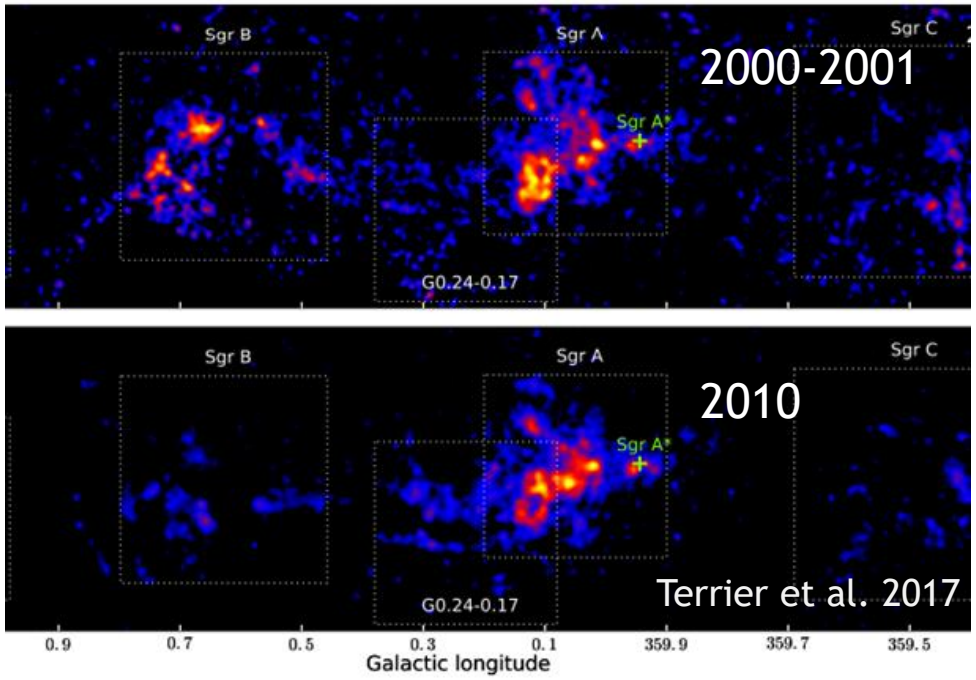


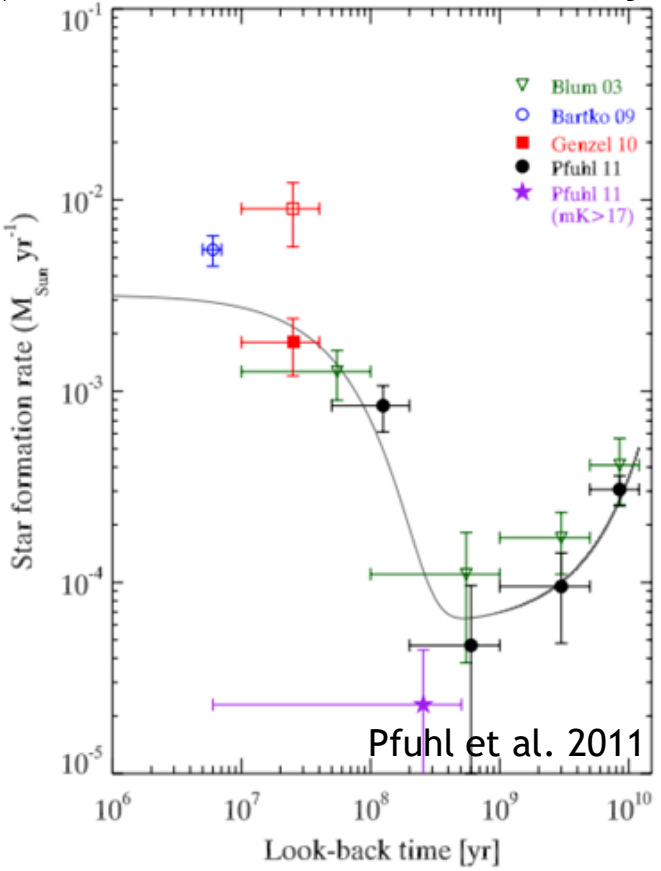
Genzel et al. 2010b

- ~ 3 x 10^6 $M_\odot$
- ~ 7.8 kpc distant
- EHT accretion disk imaging?

Sgr A* activity

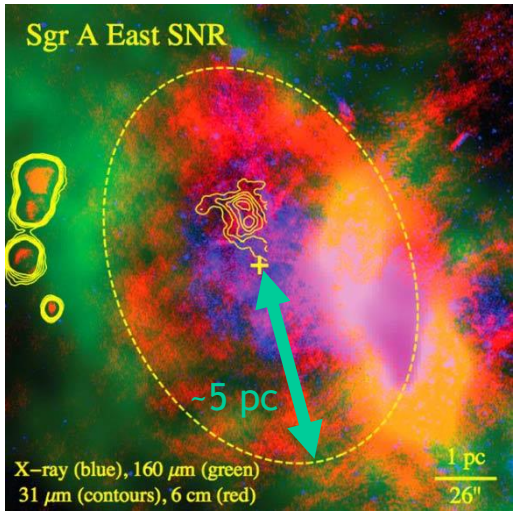
- Sgr A* dim by AGN standards, rapid variability observed (e.g. Nowak et al. 2012)
- Variable X-ray “echo” seen in CMZ, required luminosity ~100000x higher than today
- Nuclear cluster (not early-type) SFR maximum ~5 Gyr ago, later a deep minimum



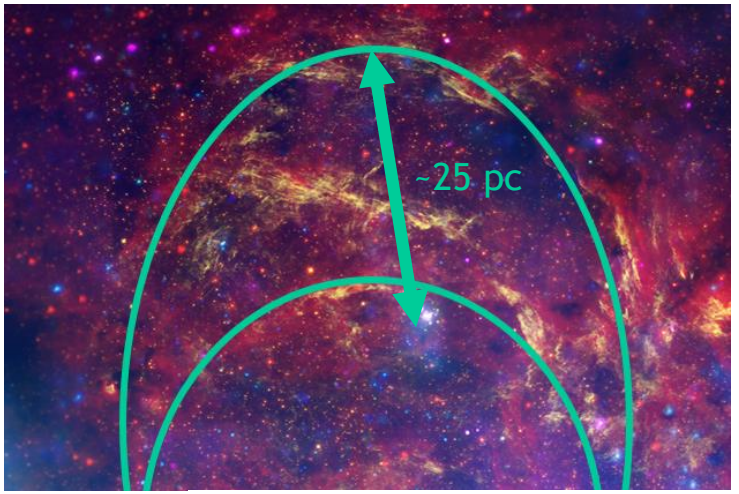


Episodic star formation

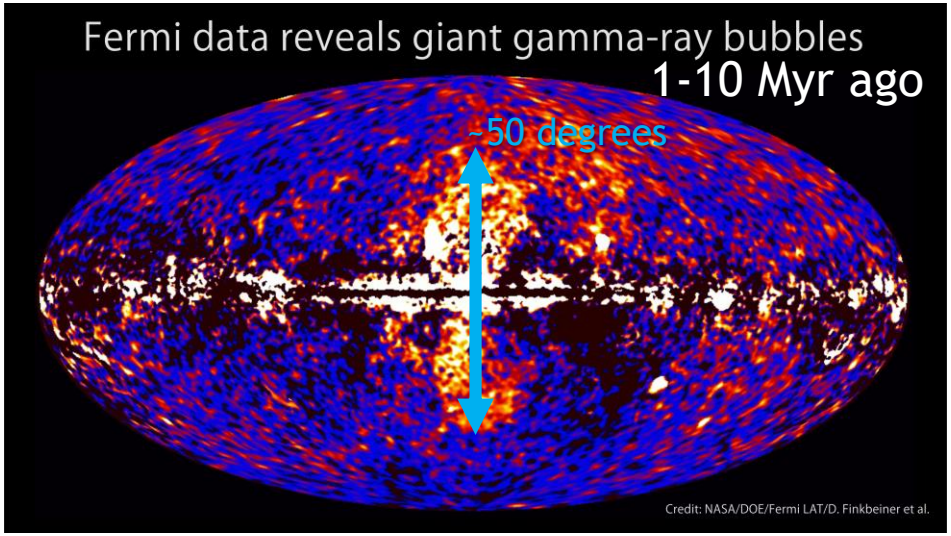
- Stellar cluster WR/O/B stars, lifespan ~1-10 Myr
- Nested concentric “bubbles” in CMZ, echoes of past starbursts?



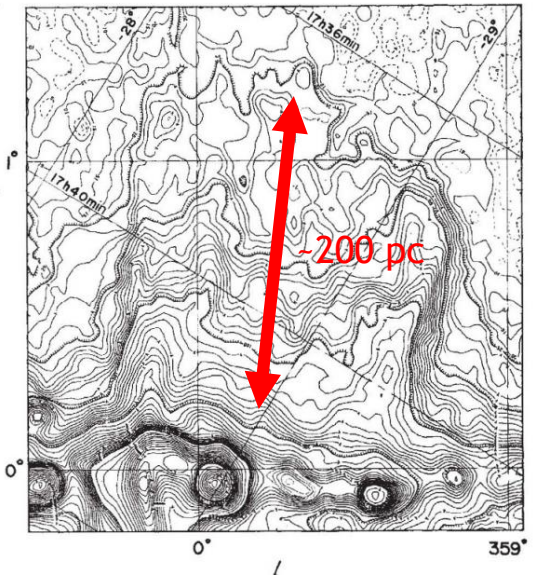
Lau et al. 2015



Chandra/HST/Spitzer



NASA/Fermi-LAT/Finkbeiner



Sofue & Handa, 1984

Timescales of matter transport and SF

Process	Timescale [Myr]
Time since GC star formation minimum	1000
Time since increase in NSC star formation from minimum	200-300
Gas accumulation along 100 pc ring before acoustic instability	10
Gas accumulation at outer edge of galactic bar	100
Matter feeding duration for global CMZ starburst	300
CMZ starburst duration	10
Fading of CMZ starburst stellar winds	10
CND rotation period (pure circular)	0.1
Infall of current GCMS mass towards Sgr A*	0.03
Accumulation of 10^4 $M_\odot$ onto NSC via GCMS	0.7
High density CND lifetime	10
Low density CND lifetime	0.01-0.1
Accumulation of 200 $M_\odot$ onto CND via Eastern Streamer	0.1
Maintenance of CND/cavity inner edge	> 1
Time since Sgr A East SNR	0.01
Time since Fermi-LAT bubble episode	1-10
Time since early type NSC formation	5

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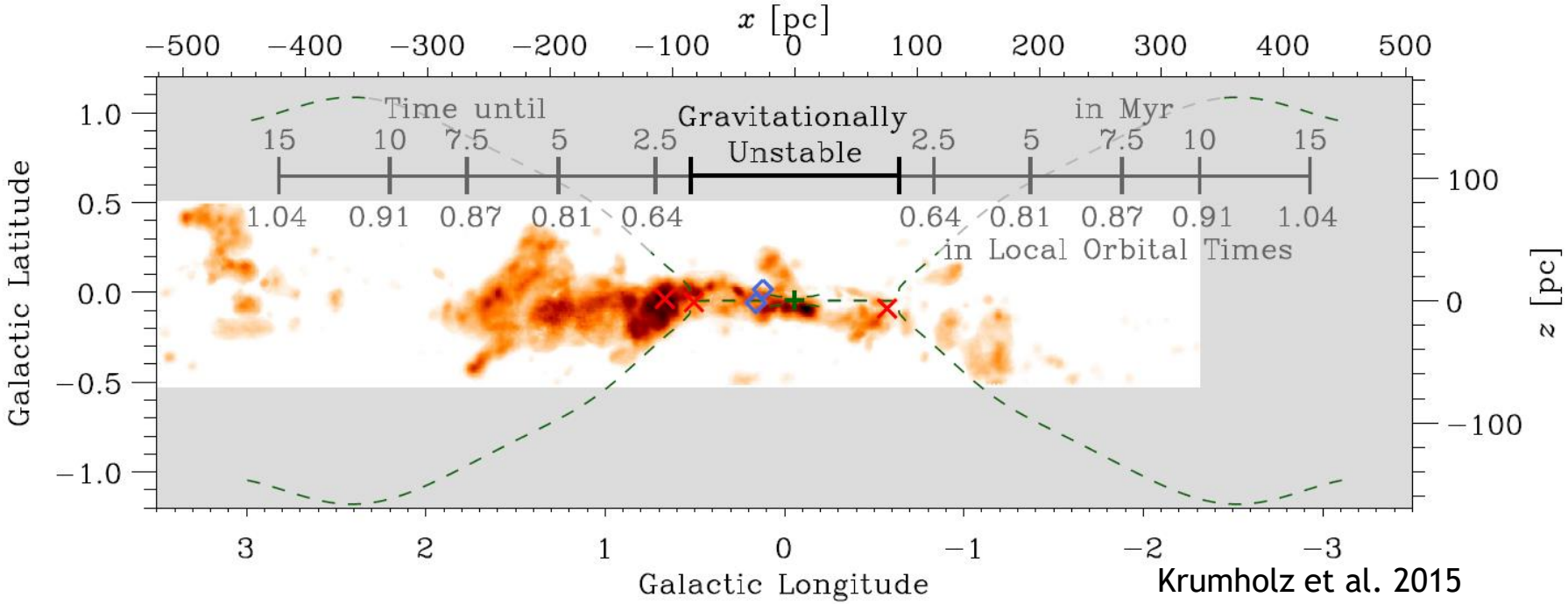
~10 Myr cycle

Fitting it all together

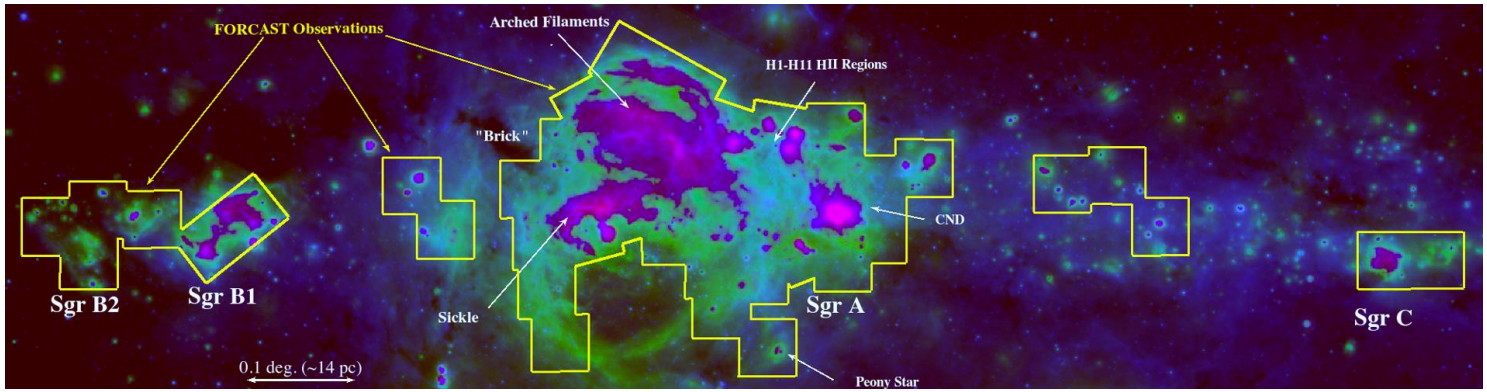
- Bars provide routes for matter to accumulate from disk
- 100 pc ring shows evolutionary chain of GMCs/clusters
- CMZ clouds can feed matter onto central parsecs
- Nuclear cluster forms stars on a ~10 Myr cycle
- Cluster feedback resets the cycle, sets CND radius



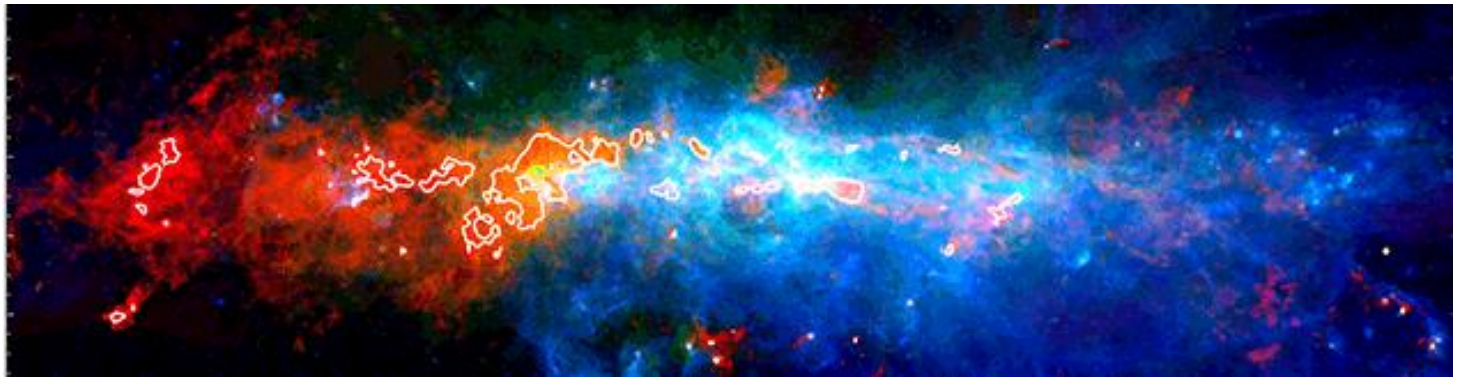
Krumholz et al. 2015

Still to come

- SOFIA-FORCAST 25/37 μm point source catalog
  - Matt Hankins Caltech, Cycle 7 Legacy Program



- CMZoom, SMA (+APEX+CSO) 230 GHz cont, dense gas lines
  - Cara Battersby U.Conn



- SOFIA-GREAT CMZ map in FIR lines (D. Riquelme)

In conclusion

- Galactic centre is diverse and complex laboratory
  - Chance to apply our knowledge to extragalactic cores
- SF deficient at large scale, but local regions of intense activity

- Multiple timescales of episodic SF and matter transport
  - Sgr A* likely plays a role in the longer scale cycles
- Important to look at ISM dynamics, stellar history, echoes of past activity, large scale motions
- Still many unknowns – Mag fields, non-thermal processes, many entangled gas phases
- SOFIA has already revealed much, plus more to come


Thank you