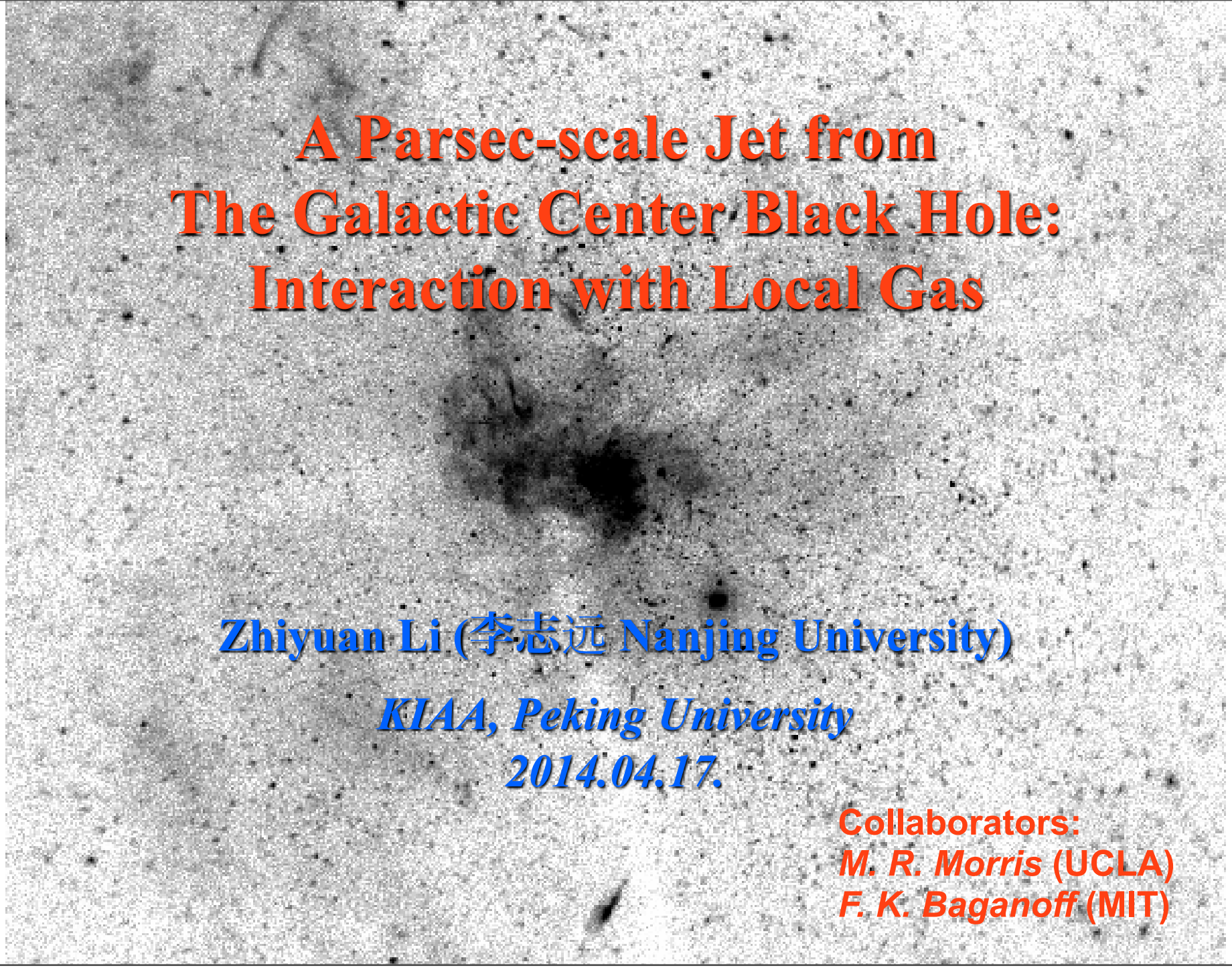


A Parsec-scale Jet from The Galactic Center Black Hole: Interaction with Local Gas

Zhiyuan Li (李志远 Nanjing University)

KIAA, Peking University

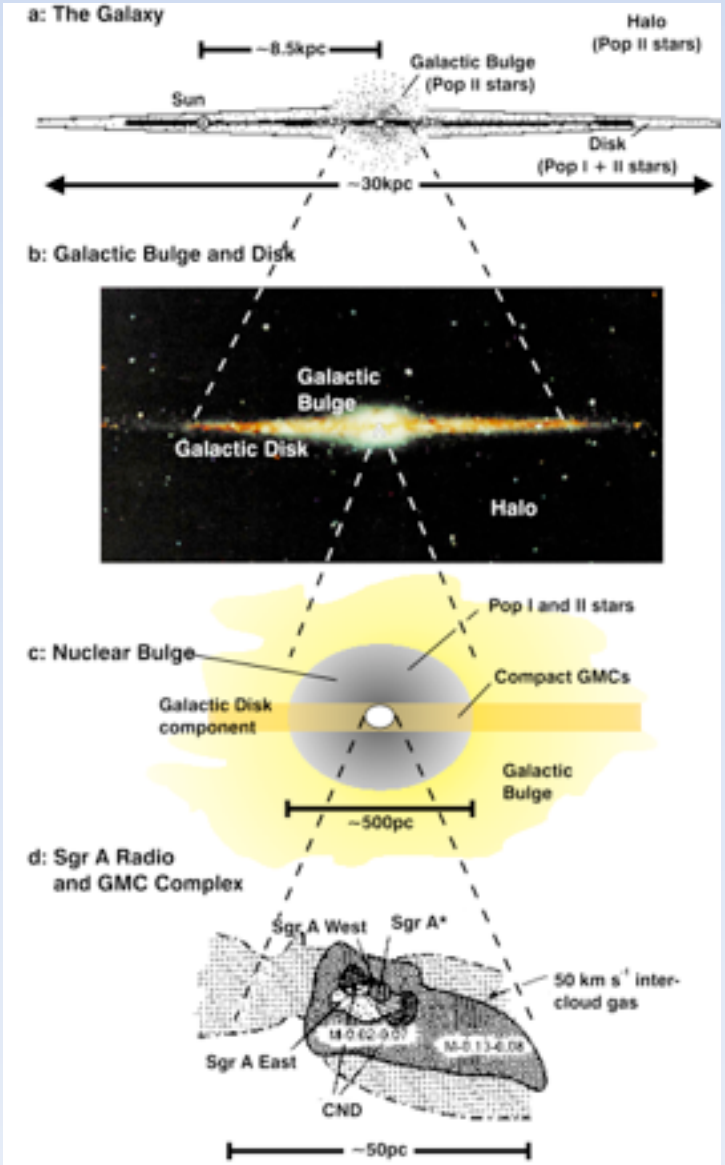
2014.04.17.

Collaborators:
***M. R. Morris* (UCLA)**
***F. K. Baganoff* (MIT)**

Outline

- Background: the Galactic center black hole and its environment
- A brief review of jet candidates
- Multi-wavelength evidence for a parsec-scale jet
- Summary and future perspectives

Our Galaxy

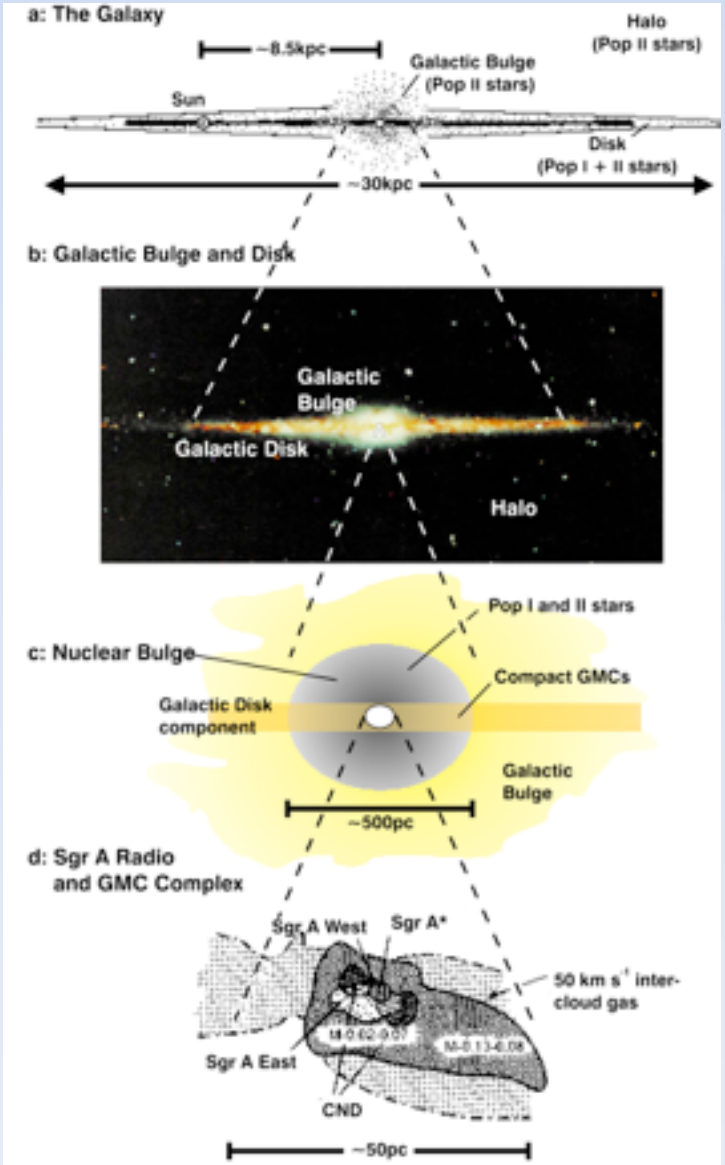


Component	*Nuclear Bulge*		*Galactic Bulge*		*Galactic Disk*		*Total*	*Halo*
R/kpc	≤ 0.3		0.3 - 3		3 - 14		< 14	> 1
$M_*/M_\odot$	$4\ 10^9$	[1]	$\sim 10^{10}$	[14]	$9\,10^{10}$	[10]	$1\ 10^{11}$	$\geq 1\,10^{11}$
$L_*/L_\odot$	$1.4\,10^9$	[2]	$3.5\,10^9$	[8]	$3.6\,10^{10}$	[11]	$4.0\ 10^{10}$	
$M_{\rm HI}/M_\odot$	$1\,10^7$	[3]	$3\,10^7$	[3]	10^9	[10]	10^9	
$M_{\rm H_2}/M_\odot$	$1\,10^8$	[3]	$\ll 1\,10^8$		$9\,10^8$	[10]	10^9	
$Z/Z_\odot$	2	[4]	4 - 0.1	[9]	3 - 1	[4]	–	
$L_{\rm IR}/L_\odot$	$1.3\,10^9$	[5]	–		$1.1\ 10^{10}$	[12]	$1.2\ 10^{10}$	
$\langle T_{\rm d}\rangle$ /K	28	[6]	–		22 - 15	[6]	–	
$N_{\rm Lyc}/{\rm s}^{-1}$	$2\ 10^{52}$	[7]	–		$2.0\ 10^{53}$	[10]	$2.2\ 10^{53}$	
$M_{\rm HII}({\rm ELD})/M_\odot$	$1.3\ 10^6$	[7]	–		$1.1\ 10^8$	[13]	$1.1\ 10^8$	
$\langle B\rangle$ GMC/mG	2	[15]	–		≤ 0.1	[3]	–	
$(L_{\rm IR}/M_{\rm H})/$ $(L_\odot/M_\odot)$	13		–		7.4		7.5	

Mezger et al. 1996

- The inner 200-pc region accounts for ~10% of the molecular gas and ~10% of current star formation in the Galaxy
- This *central molecular zone* (CMZ) is heavily obscured in the optical, UV and soft X-ray (<2 keV) bands -- radio, IR and hard X-ray observations are the most promising tools

Our Galaxy



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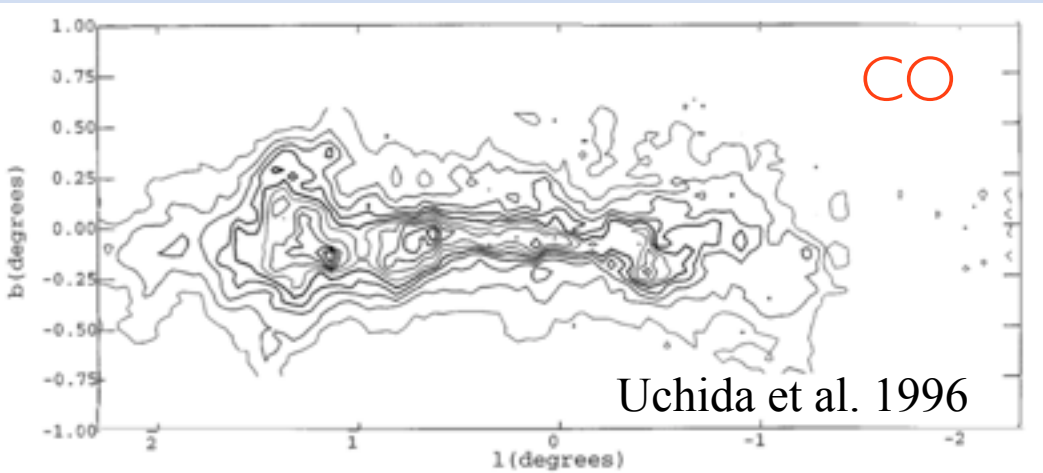
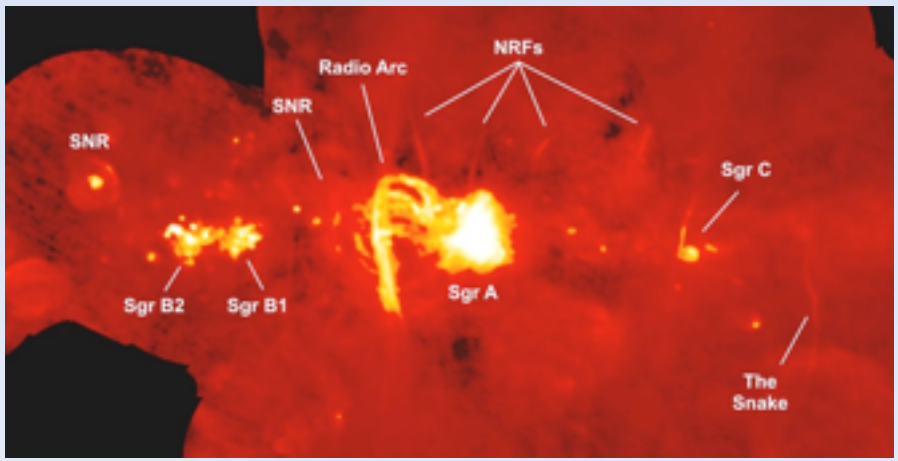
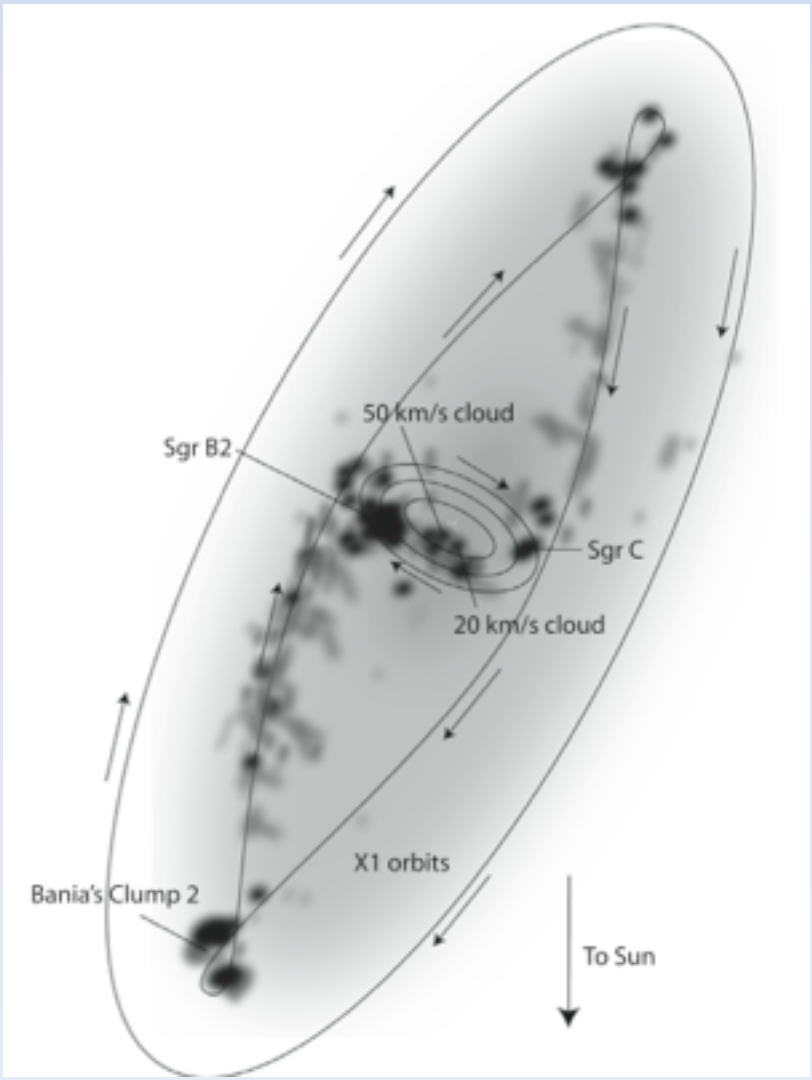
Central Molecular Zone (CMZ)



Uchida et al. 1996



Morris & Serabyn 1996



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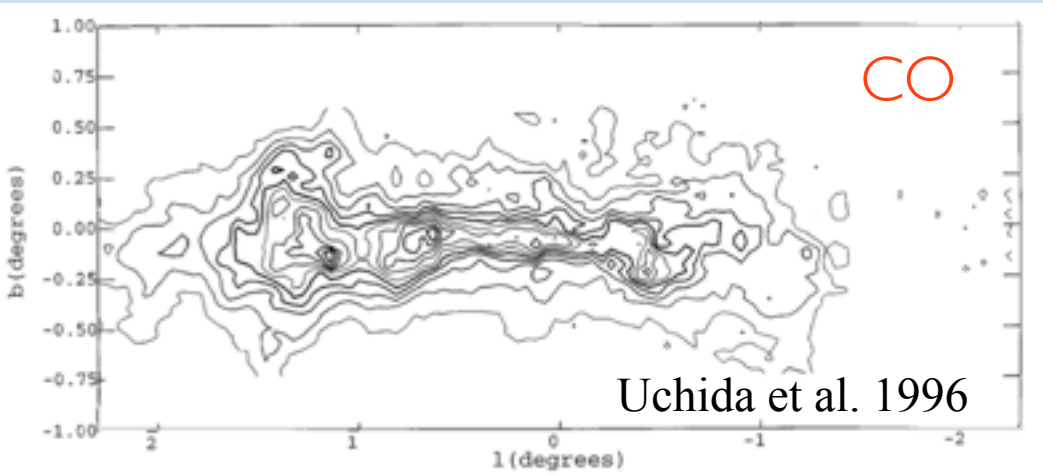

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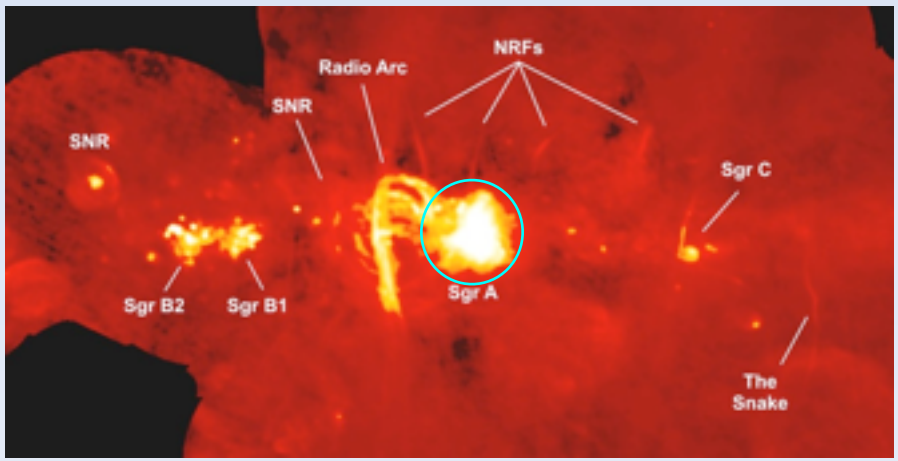

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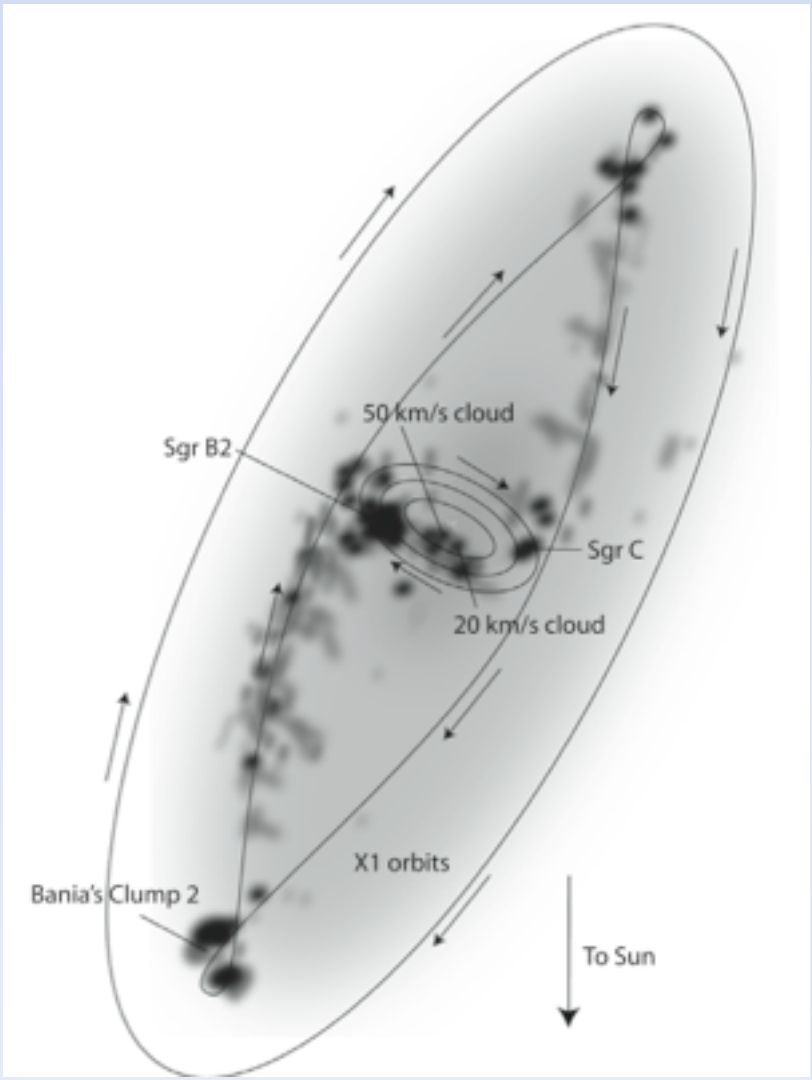

The innermost few parsecs of the GC

- The Circum-Nuclear Disk (CND) of molecular gas
- A hot gas corona/outflow
- The Sgr A West HII region (a.k.a. the *mini-spiral*)
- The central star cluster
- The SMBH

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1” $\equiv$ 0.04 pc at the GC (d = 8 kpc)

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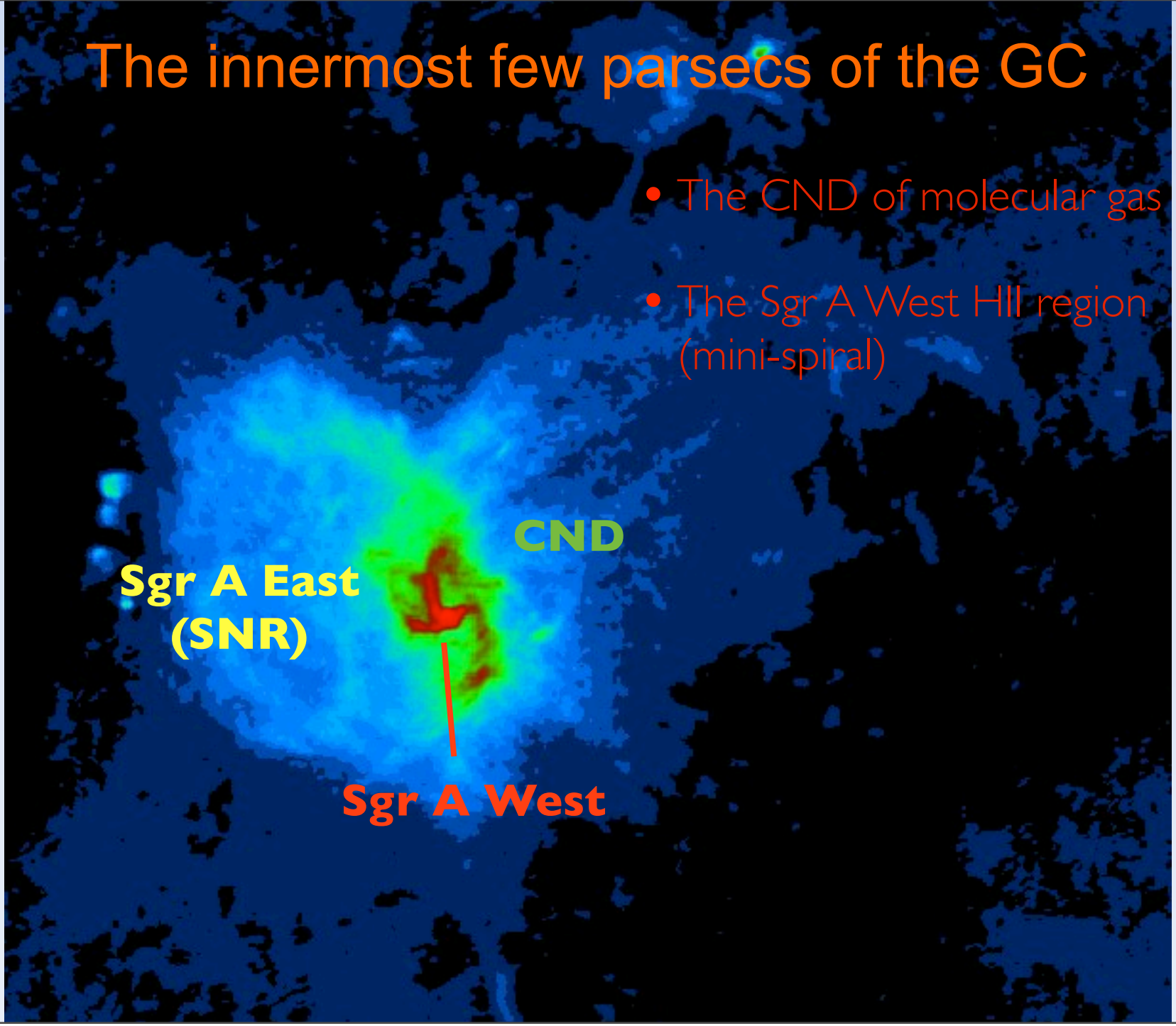

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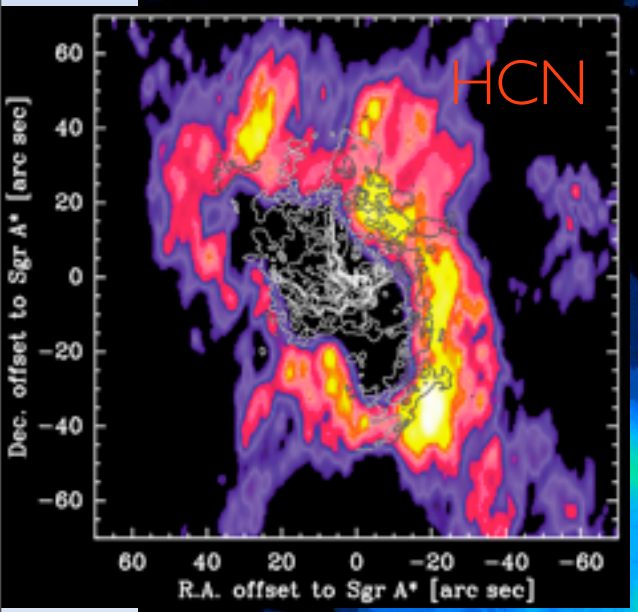

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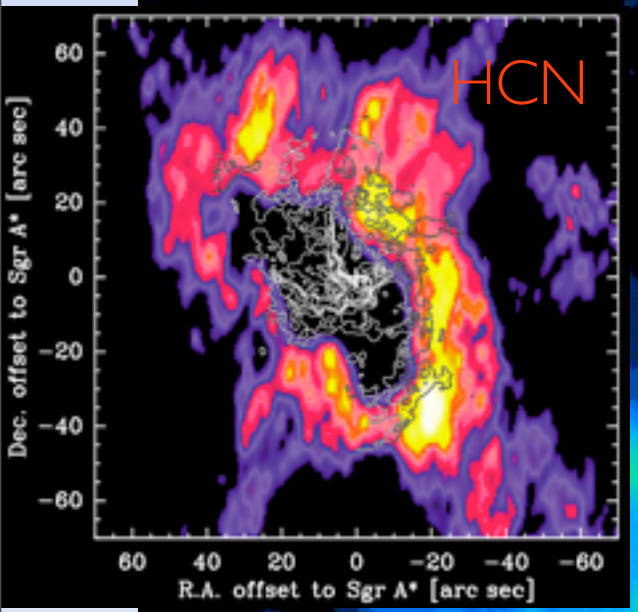
CND

Sgr A East (SNR)

Sgr A West

The innermost few parsecs of the GC



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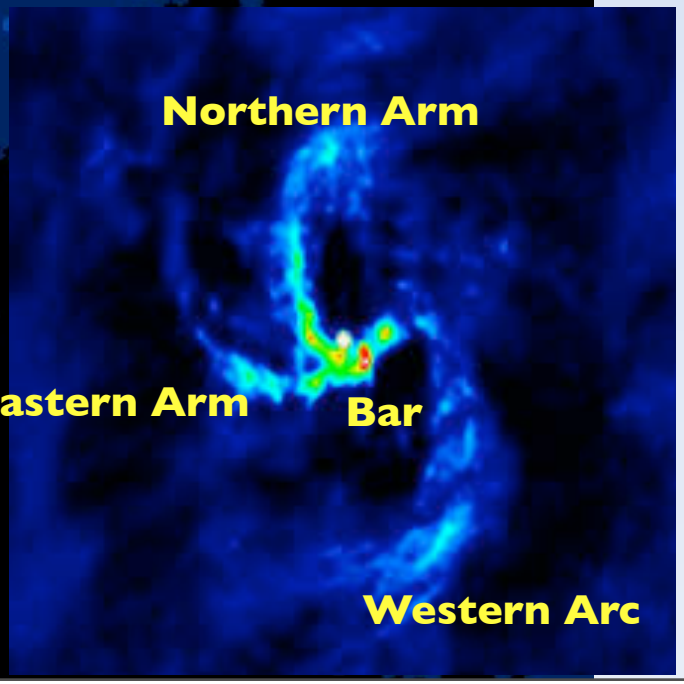

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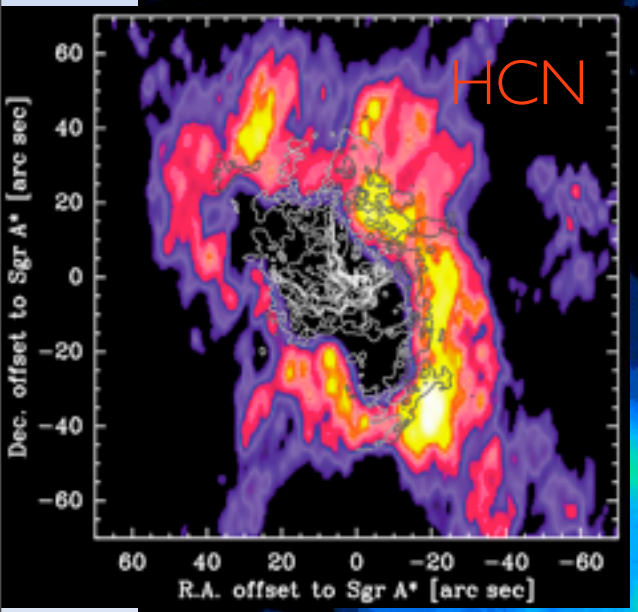

- The CND of molecular gas
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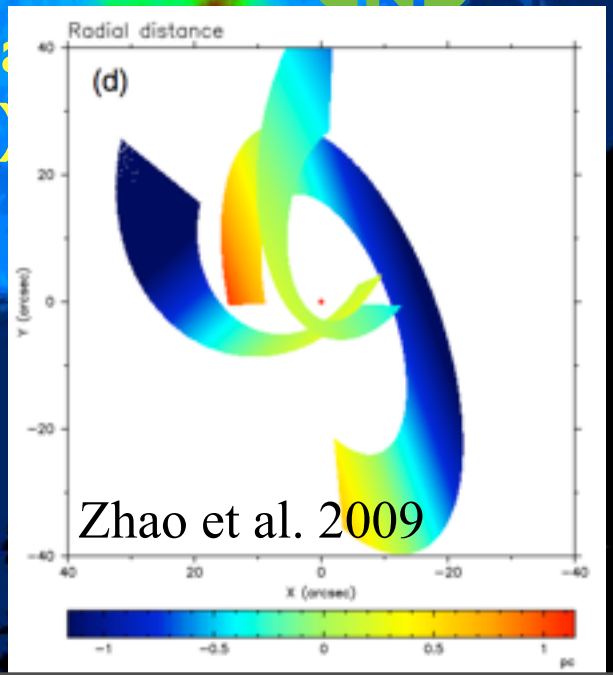
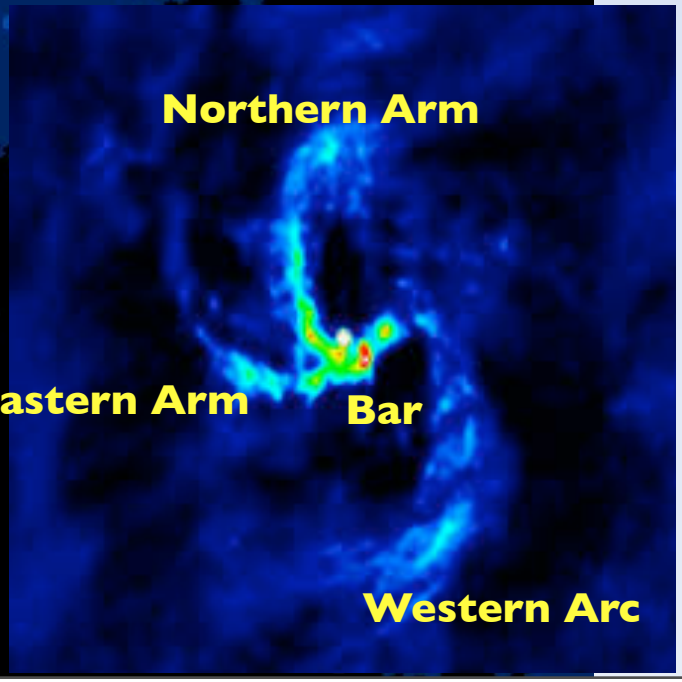
The ionized gas streamers follow quasi-Keplerian motions

CND

Sgr A E
(SNR)





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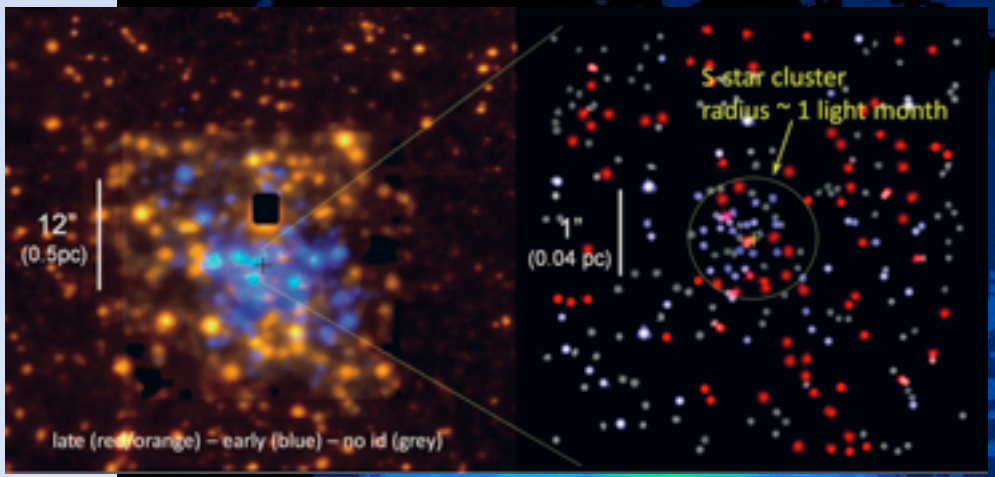

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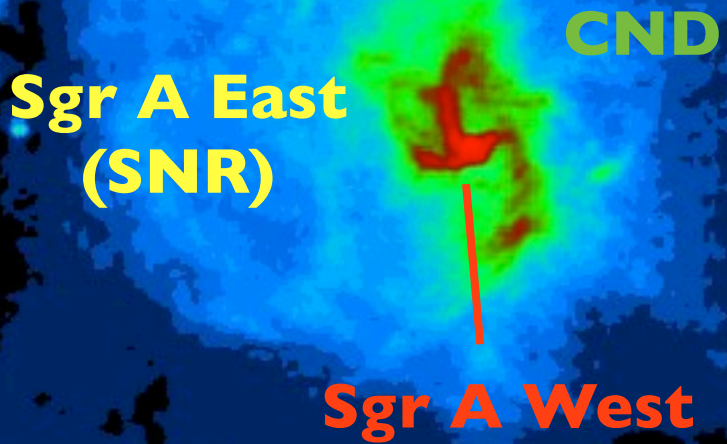

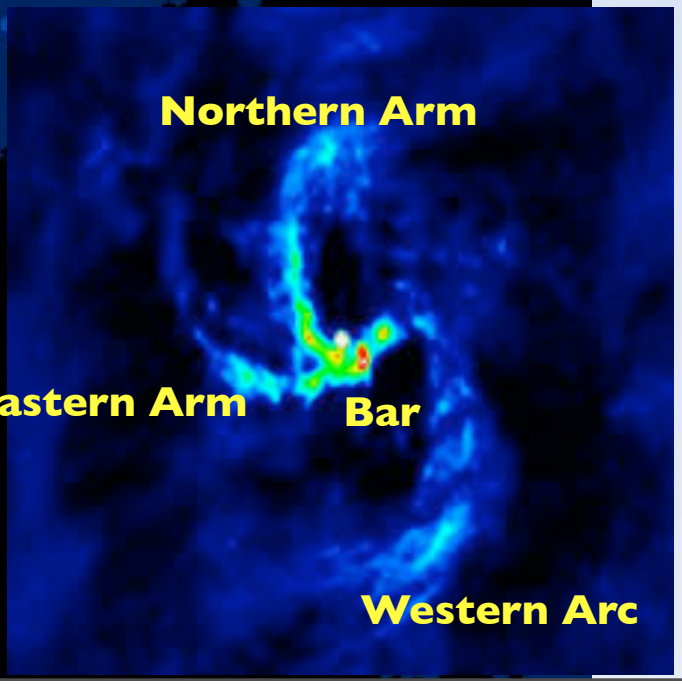

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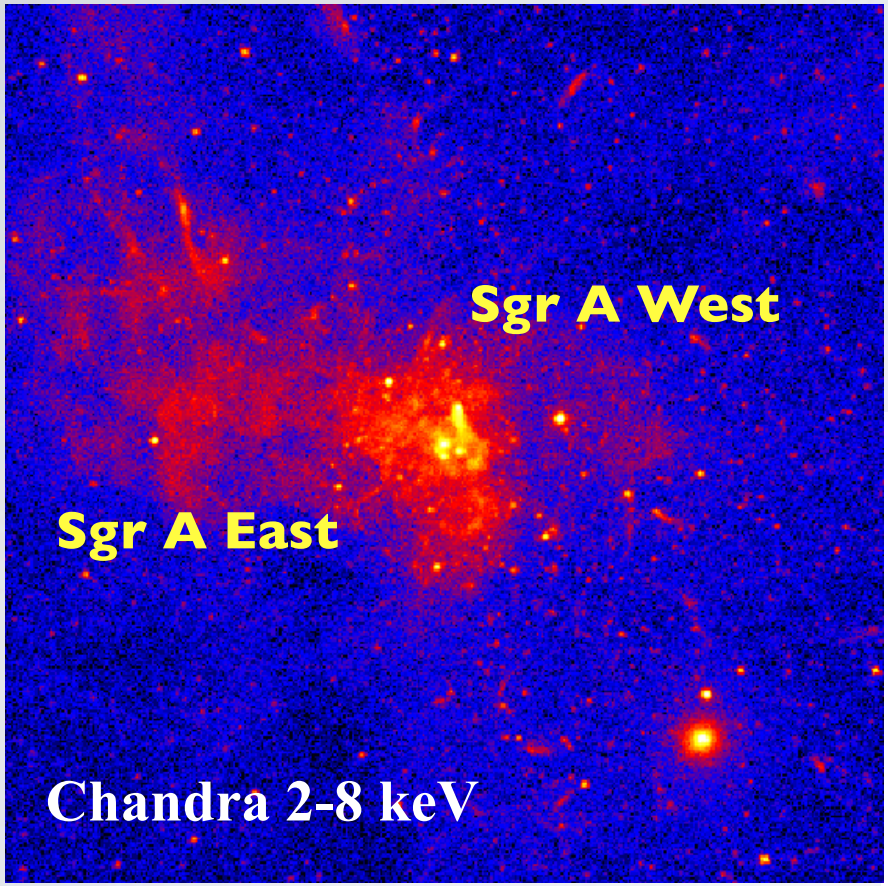
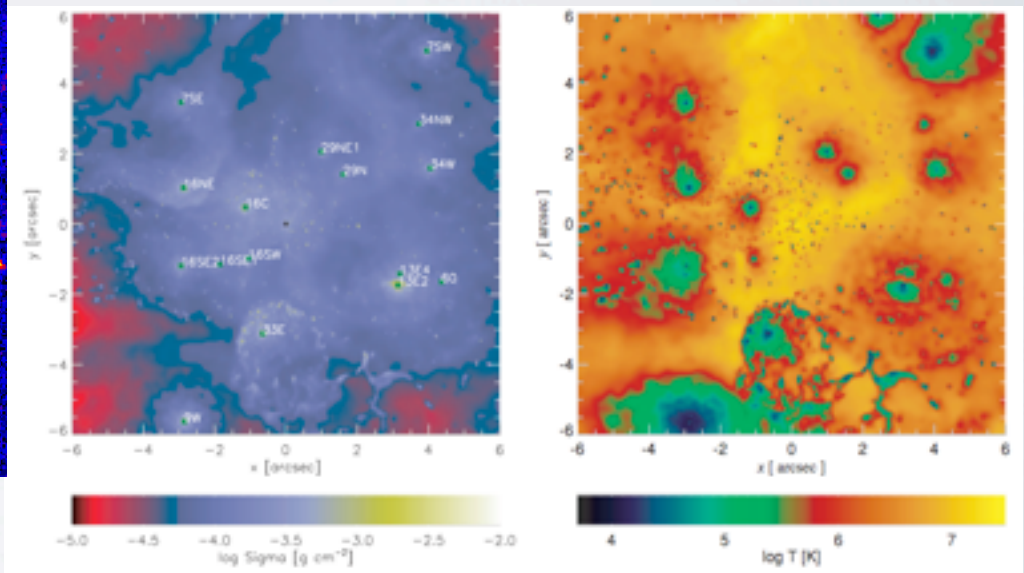


- Diffuse X-ray emission produced by colliding stellar winds: a corona/ outflow of hot gas (~ 1 keV)



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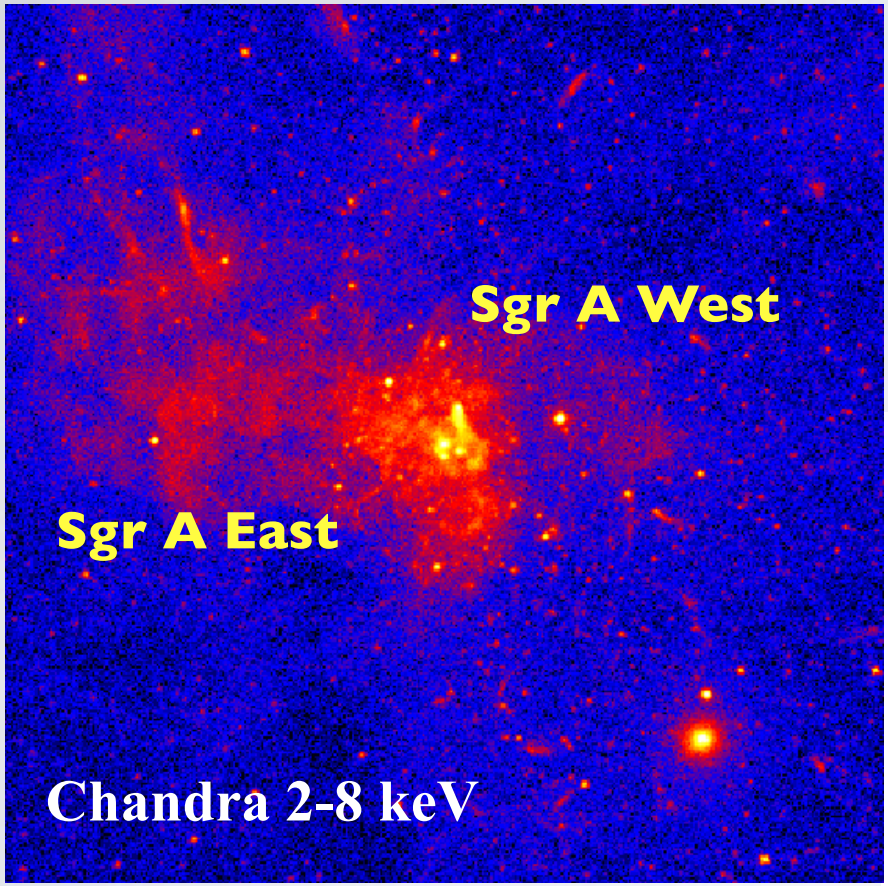

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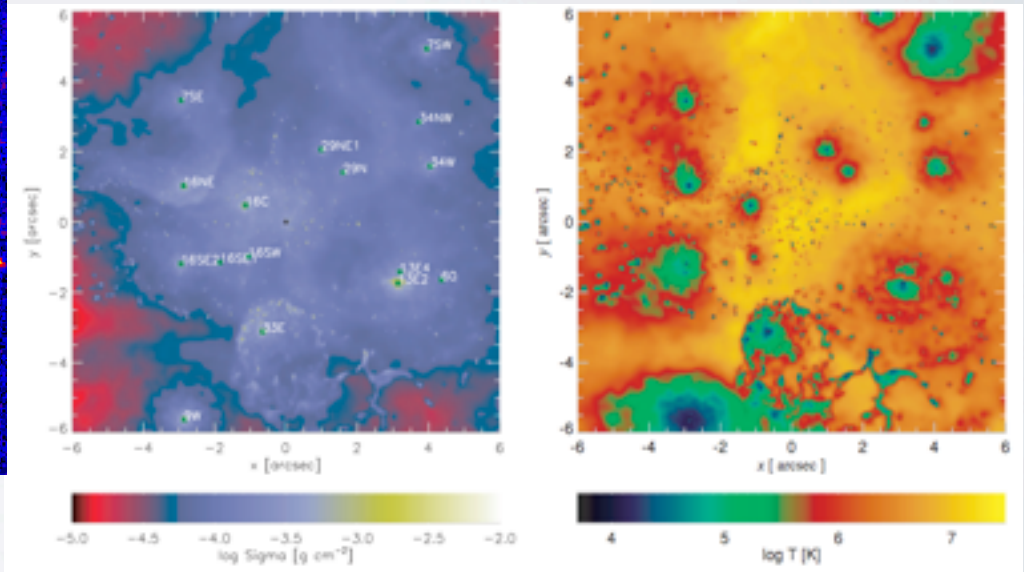


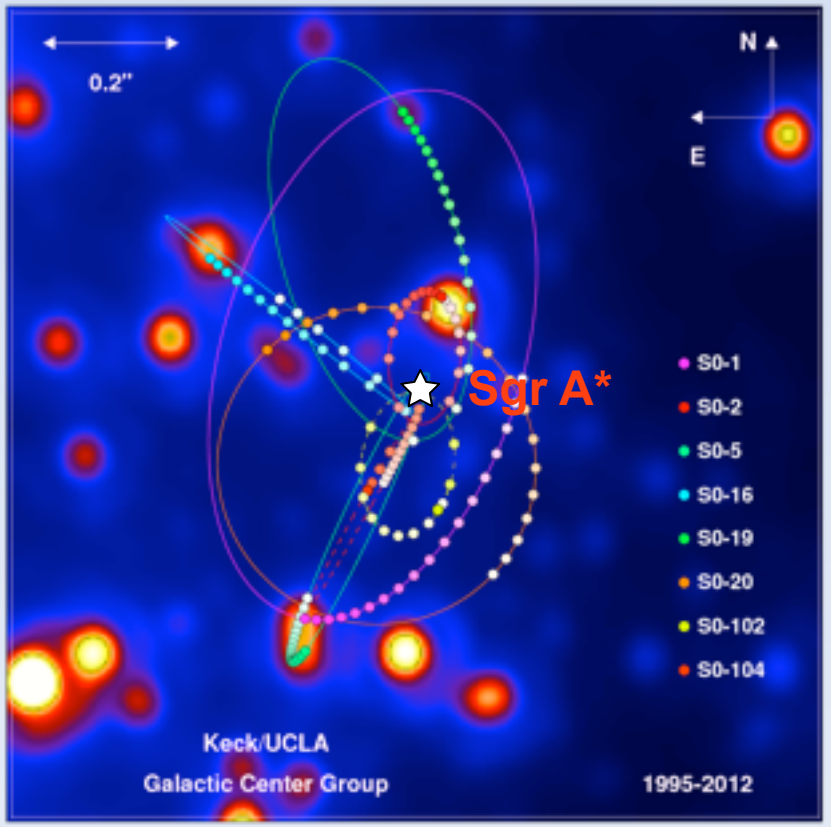
Cuadra et al. 2008

The Galactic center black hole

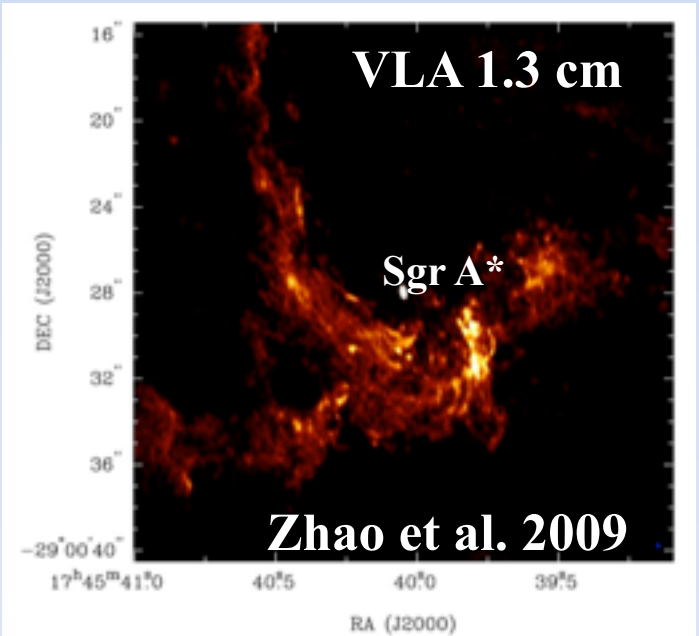
- Lynden-Bell & Rees (1971) speculated the existence of a massive black hole in the nucleus of our Galaxy
- Balick & Brown (1974) discovered a compact nuclear radio source with the NRAO interferometer; named Sagittarius A* (Sgr A*) by Brown (1982)
- Backer & Sramek (1982) found the proper motion of Sgr A* consistent with a source at rest in the Galactic center

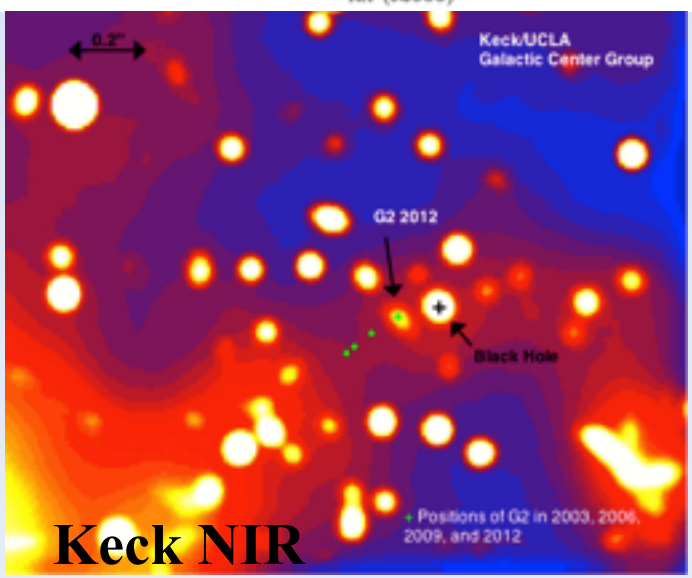
The Galactic center black hole

- Stellar proper motions (Keplerian orbits) indicate a dark mass of $4 \times 10^6 \, M_\odot$ within ~100 AU: the most compelling evidence for a SMBH
- Sgr A* is coincident with the position of the dynamical center

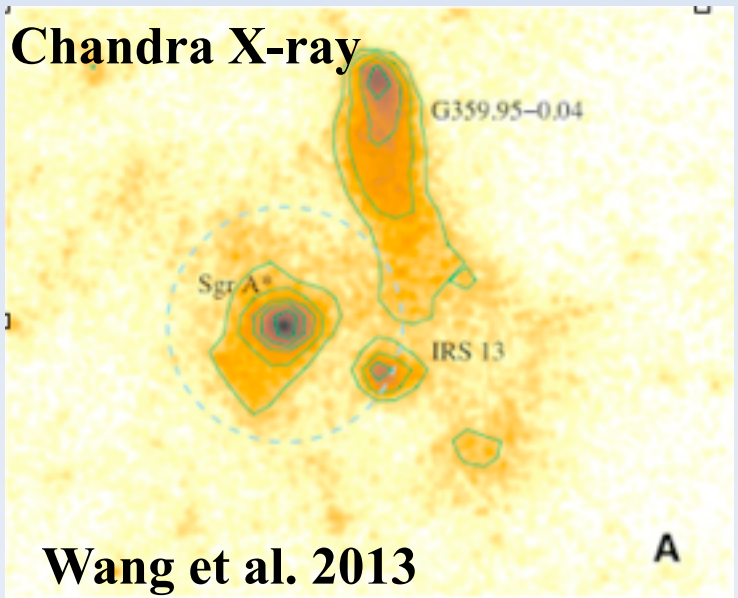


Radiation from Sgr A*



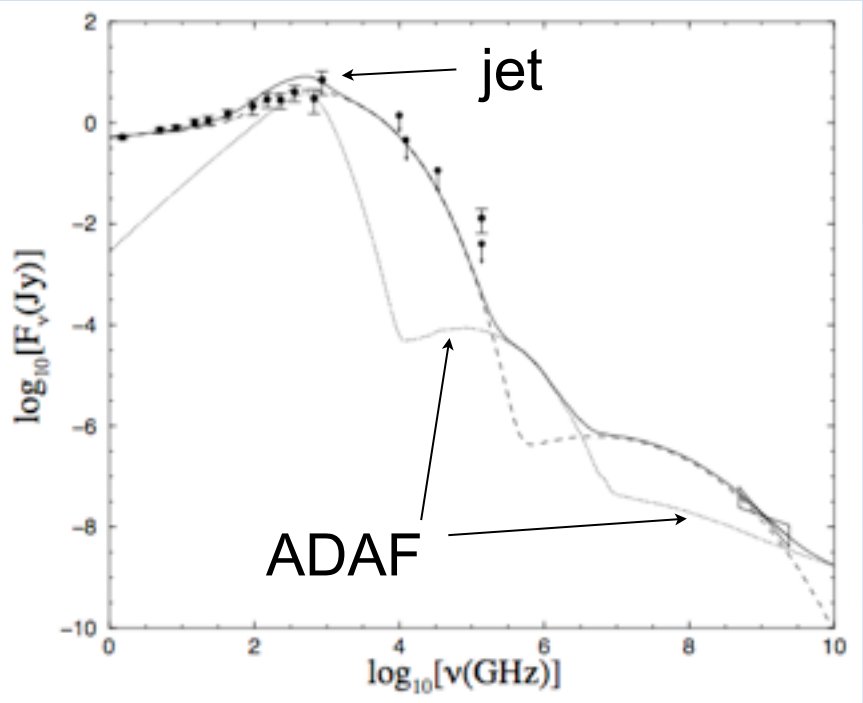


- Detected in radio, NIR and X-rays
- Exhibit flares at all wavelengths; origin unknown



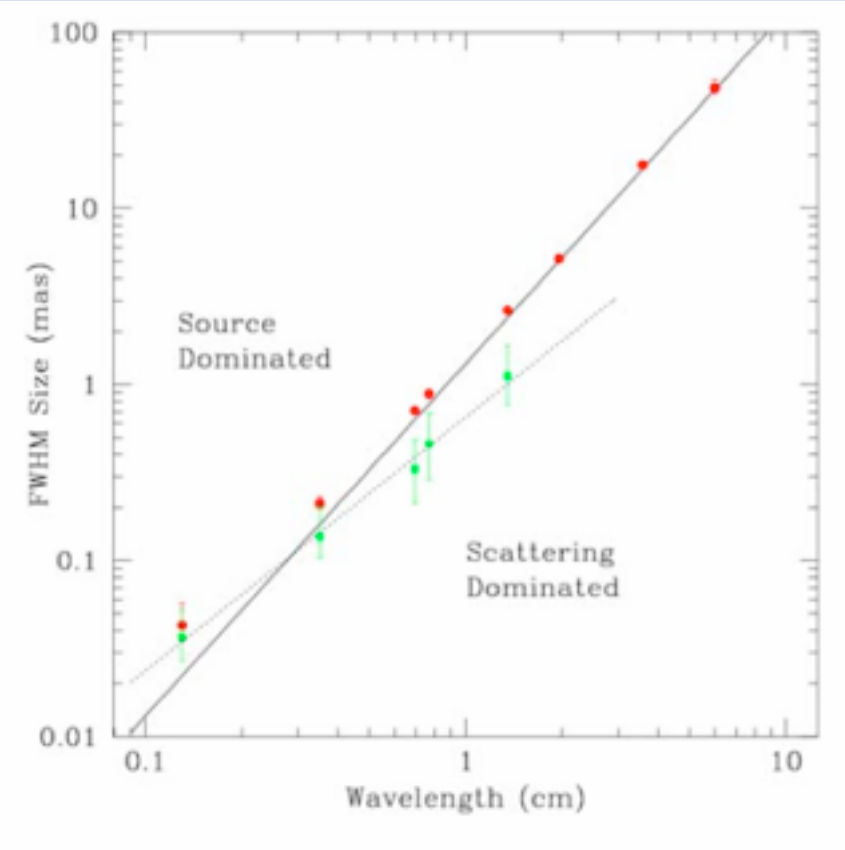
Nature of the emission from Sgr A*

- Sgr A* is the least luminous "AGN" known: $L_{bol} \lesssim 10^{-8} L_{Edd}$; accretion rate ~ $10^{-6} M_{\odot}$/yr (fed by stellar winds)
- A jet-ADAF model (e.g., Yuan et al. 2002) can satisfactorily explain the broad-band SED of Sgr A*: the jet accounts for the radio synchrotron
- The flares may be due to episodic jets (Yuan et al. 2009)



The jet scenario for Sgr A*

- Belief: jets are the *standard* explanation for radio emission from low-luminosity AGNs; jet-like structures are sometimes resolved (e.g, M81*)
- Doubt: jet-like structures not seen by VLBI observations -- diameter of Sgr A* $\lesssim$ 4 Rs (Doeleman et al. 2008)

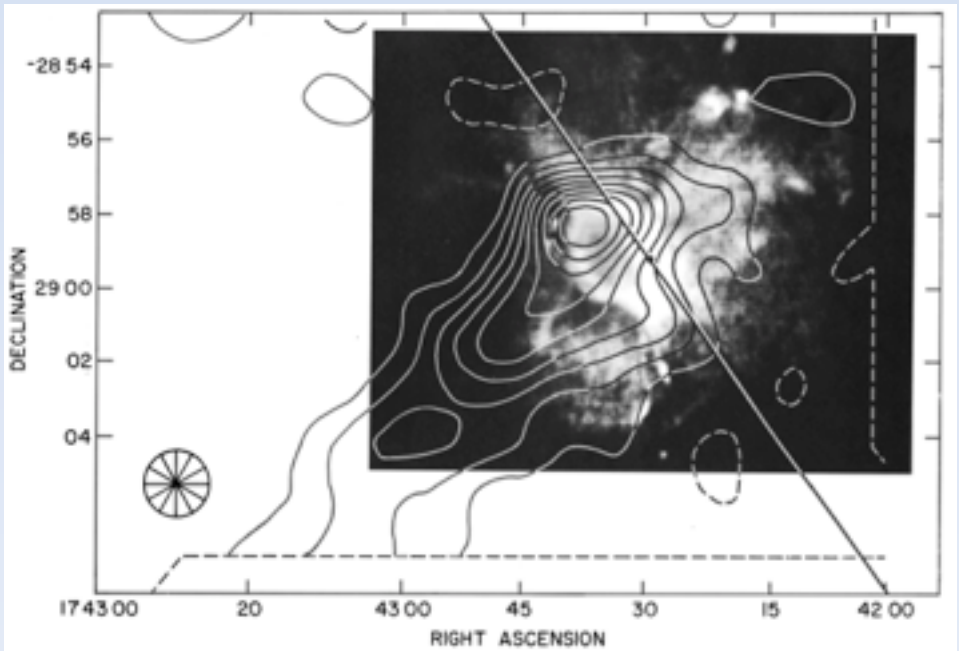


Searching for the Sgr A* jet

- The putative jet should escape the SMBH and interact with the ISM
- A much higher accretion rate (hence the jet power) probably operated in the recent past
- Jet manifestations have been suggested on various wavelengths (radio, X-ray, gamma-ray) and various physical scales (pc to kpc)

Searching for the Sgr A* jet

A 30-pc long “radio ridge” (160 MHz)
Yusef-Zadeh et al. (1986)



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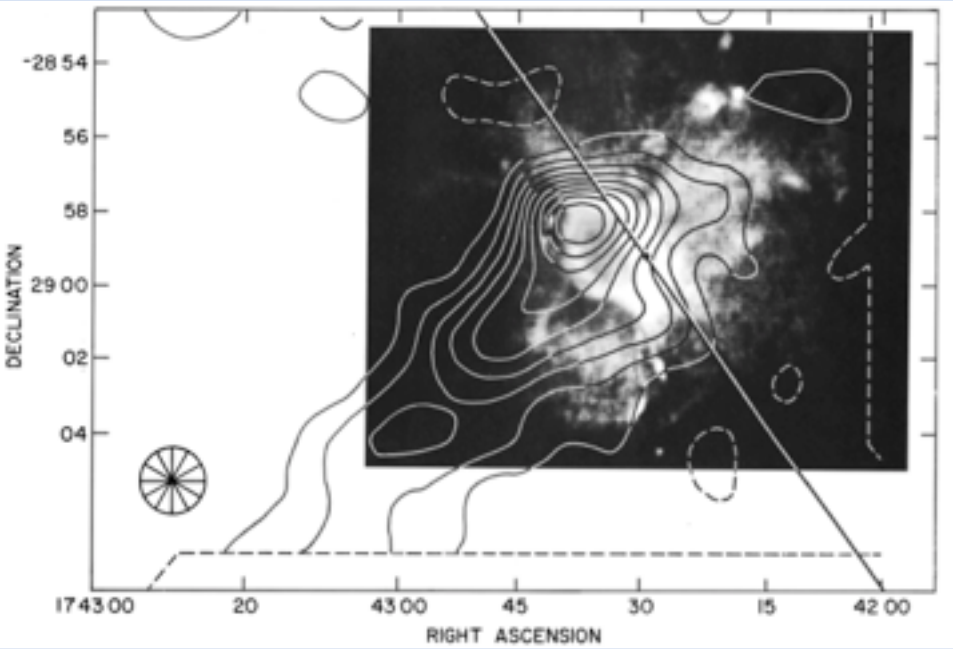
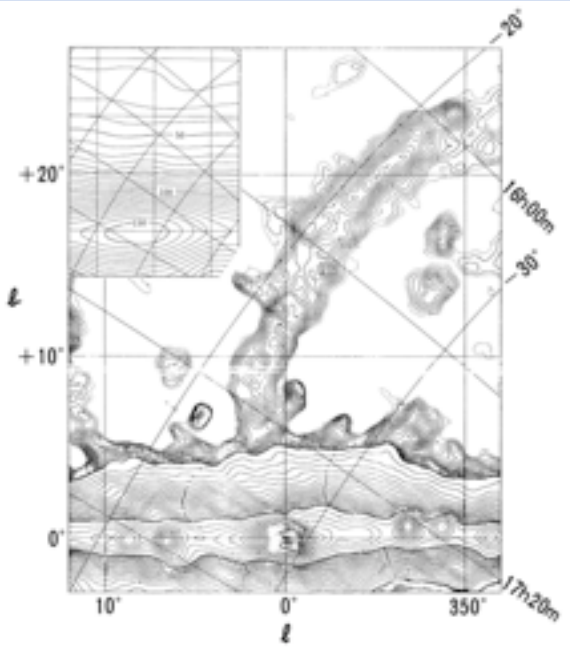
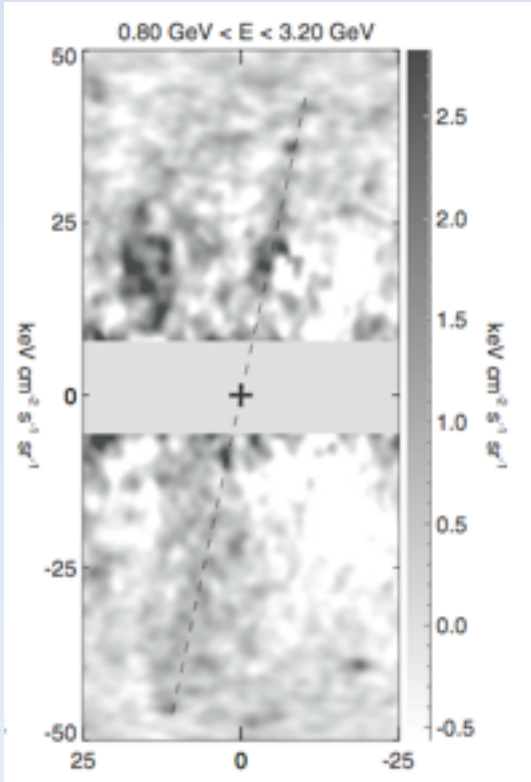




“Galactic center spur” (408 MHz)
Sofue et al. (1989)

Searching for the Sgr A* jet

Femi Gamma-ray "jets" (kpc-scale), partially coincident with the GCS; may be related to the *Fermi bubbles*
Su & Feinbeiner (2012)



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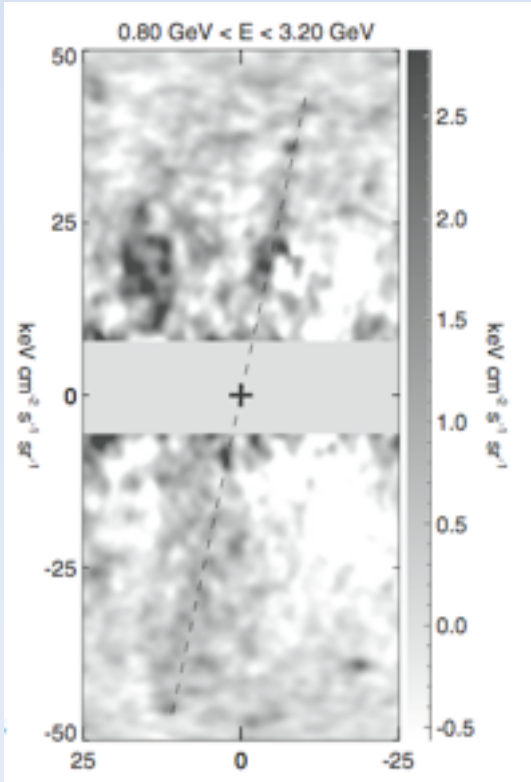
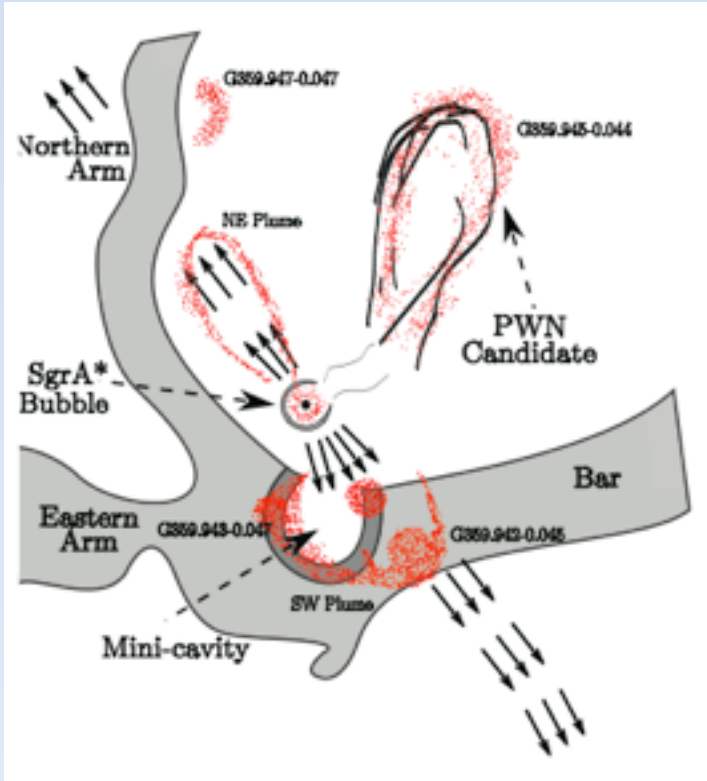


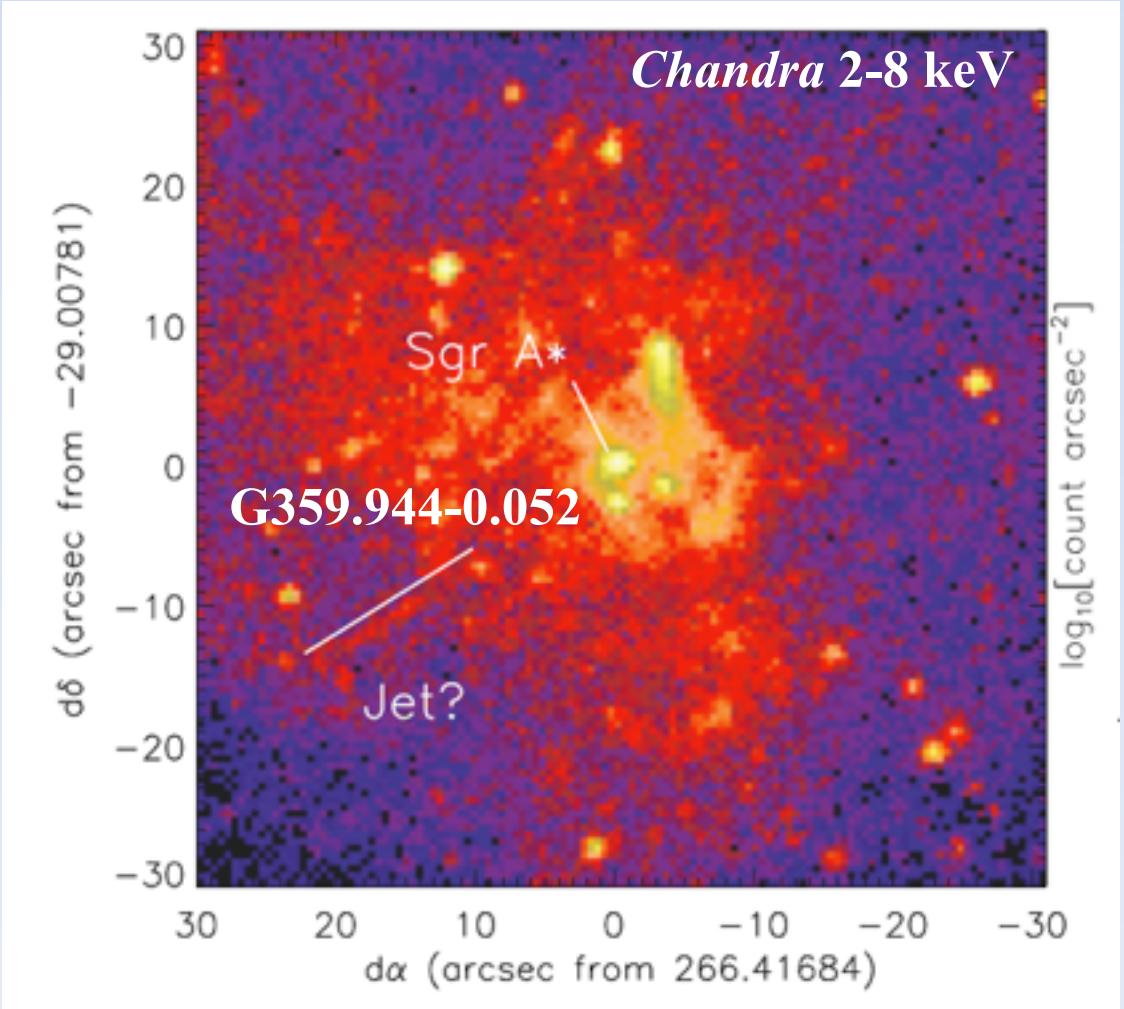


A radio jet/outflow in the inner 3-pc, roughly following the Galactic plane
Yusef-Zadeh et al. (2012)

Searching for the Sgr A* jet

- The putative jet should escape the SMBH and interact with the ISM
- A much higher accretion rate (hence the jet power) probably operated in the recent past
- Jet manifestations have been suggested on various wavelengths (radio, X-ray, gamma-ray) and various physical scales (pc to kpc)
- None has been fully accepted; most cases can also be explained by outflows driven by the central cluster or past nuclear starbursts

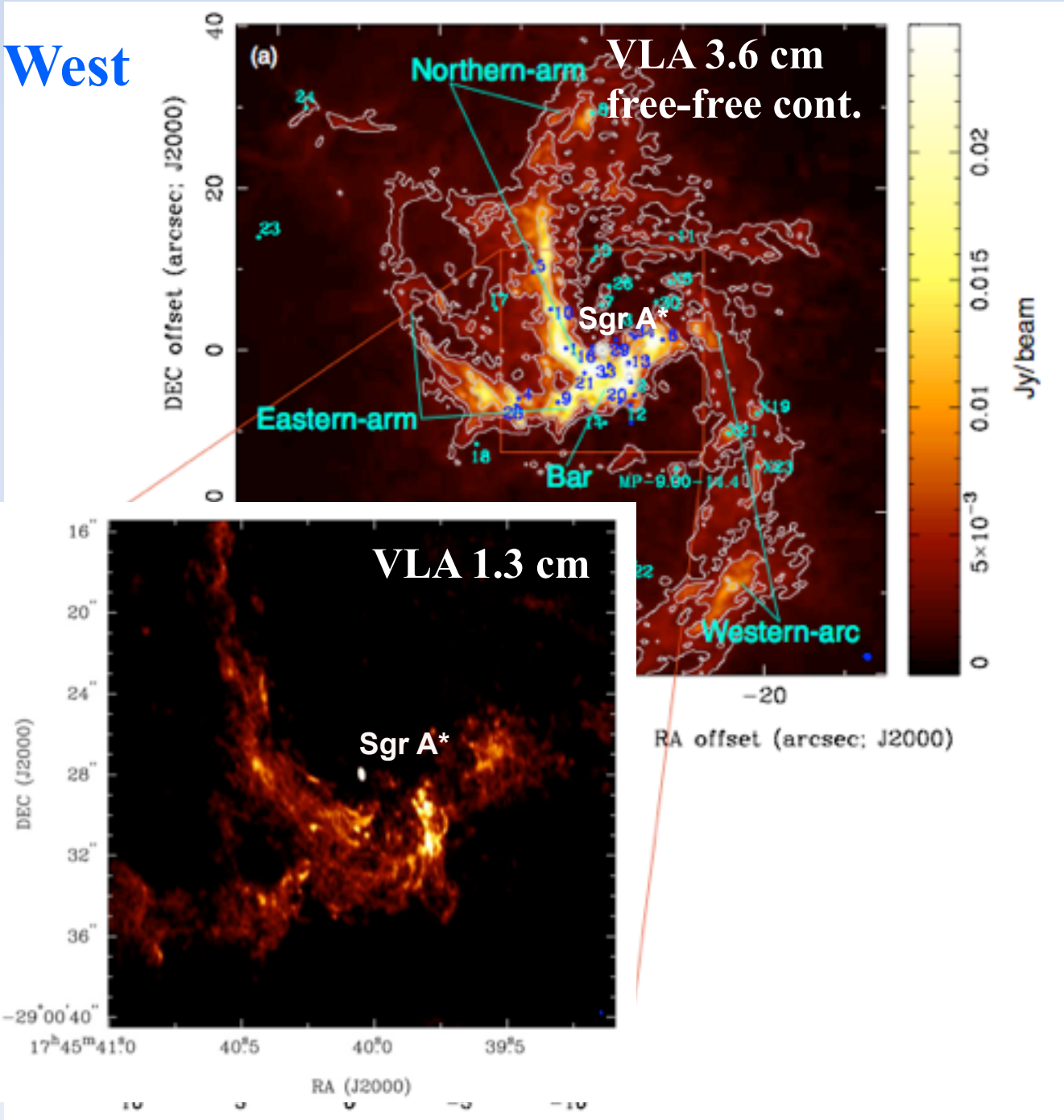
- An X-ray filament in the central pc, pointing to the position of Sgr A* (Muno et al. 2008)
- Very unlikely a pulsar wind nebula
- Can it trace the Sgr A* jet?



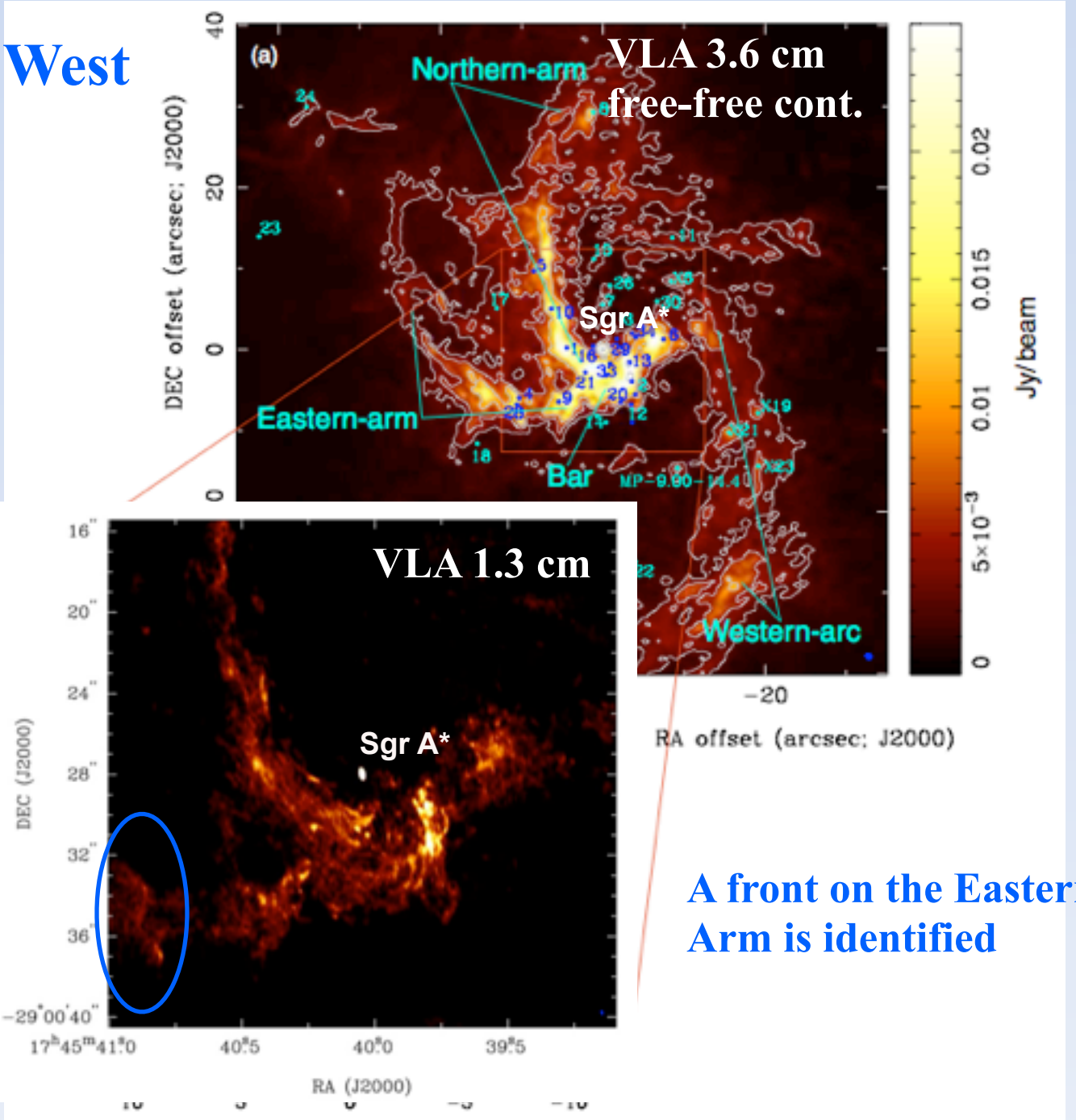
Multi-wavelength Observations

- High-resolution (FWHM ~ 0.1”) VLA 1.3 cm image of Sgr A West (Zhao et al. 2009)
- Ultra-deep (1.5 Ms) *Chandra*/ACIS imaging-spectroscopic observations of the GC, spanning ~10 yrs
- Infrared Telescope Facility/TEXES [Ne II]12.8 μm data cube of Sgr A West (Irons et al. 2012)

Sgr A West

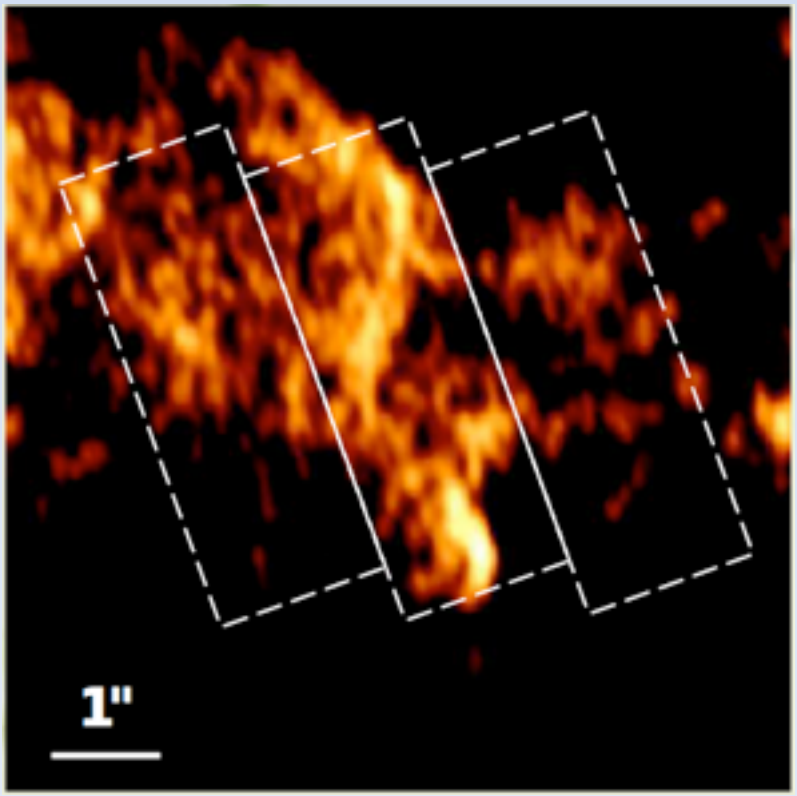

(a)
Northern-arm
VLA 3.6 cm
free-free cont.
Sgr A*
Eastern-arm
Bar
Western-arc
DEC offset (arcsec; J2000)
RA offset (arcsec; J2000)
Jy/beam
VLA 1.3 cm
Sgr A*
DEC (J2000)
RA (J2000)

Sgr A West



A front on the Eastern Arm is identified

Nature of the radio front



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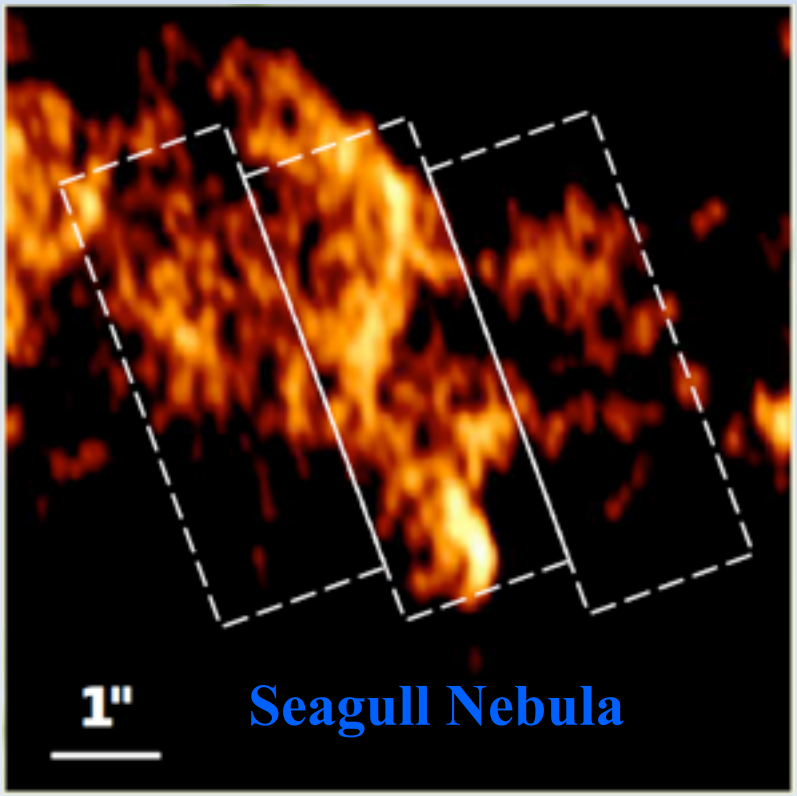

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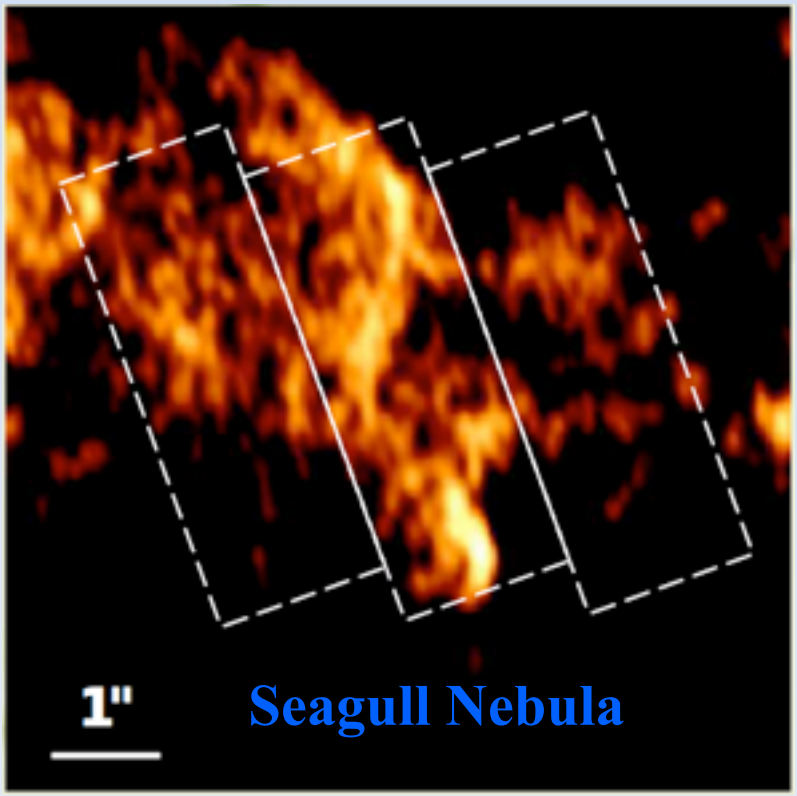

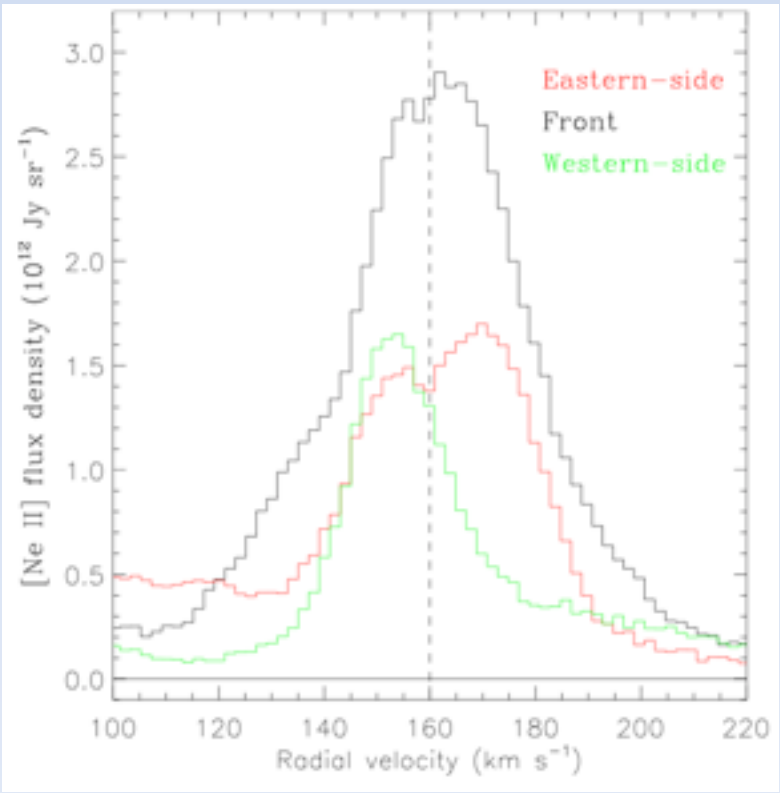

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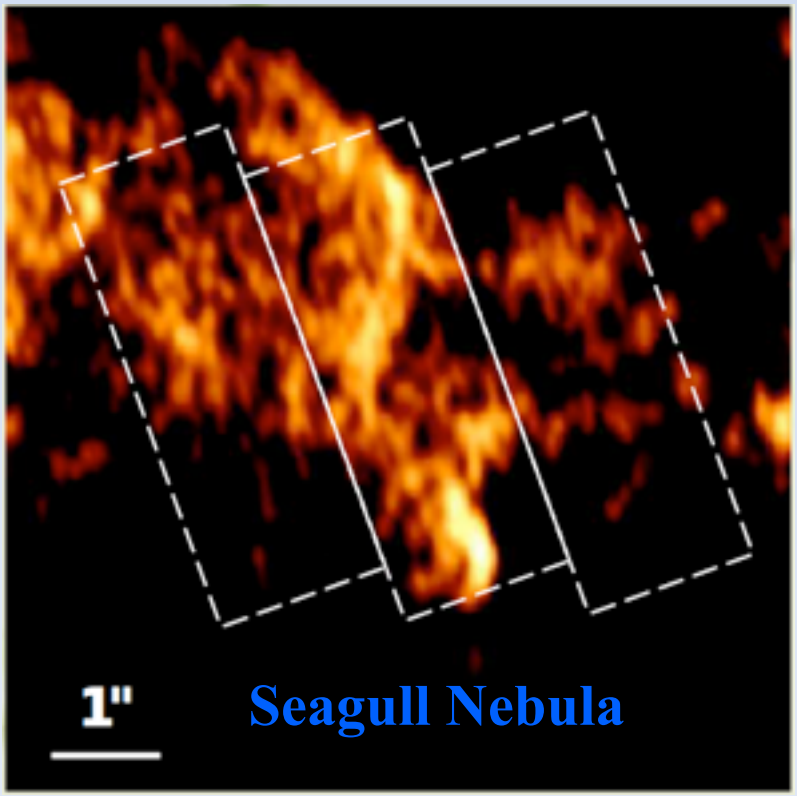
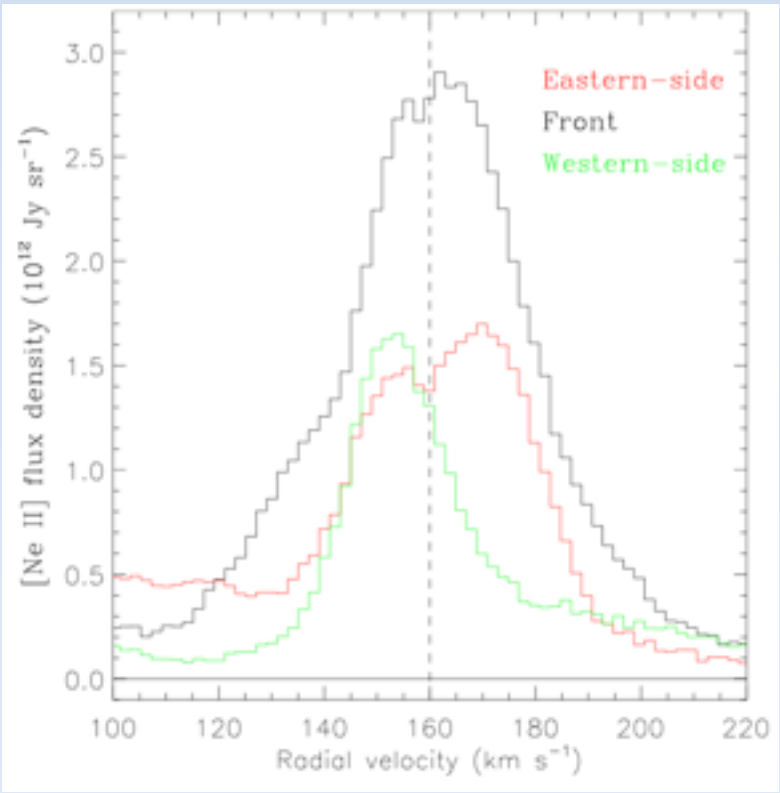
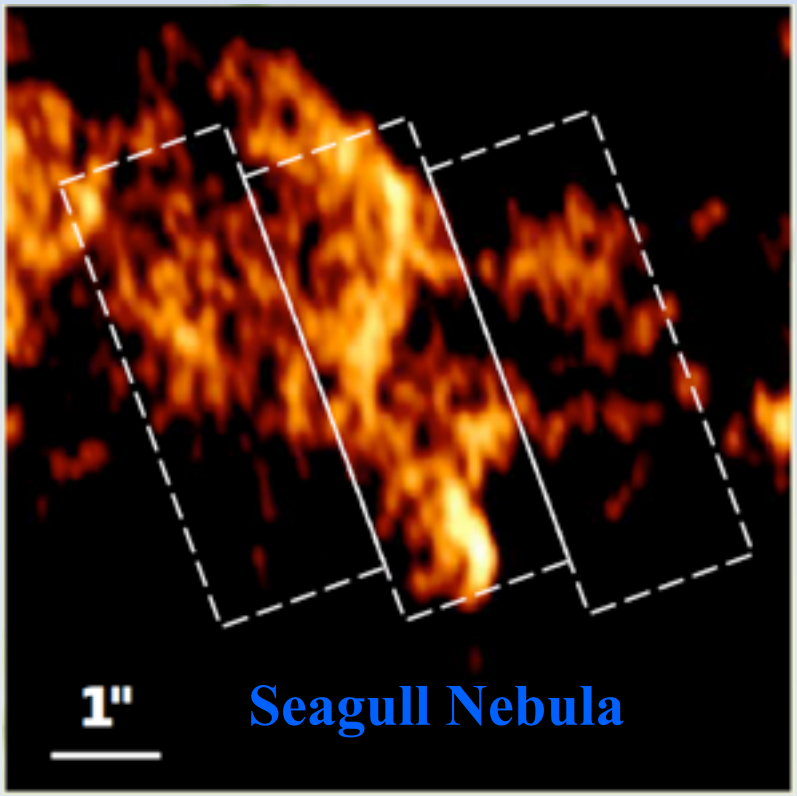
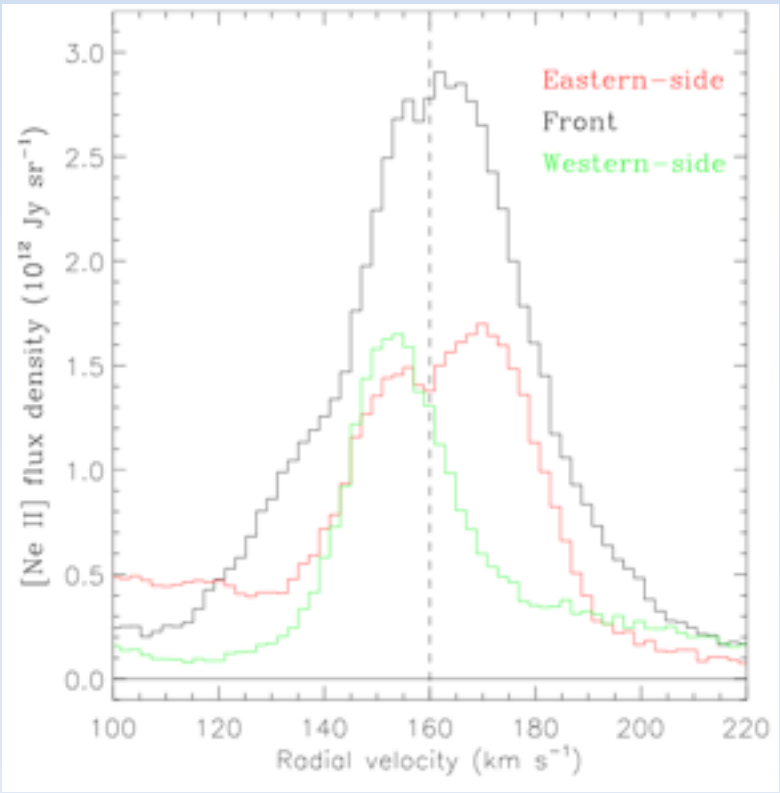




- Depletion of gas downstream (eastern side) of the front
  -- an external momentum (i.e., a shock) arriving from the west

Nature of the radio front





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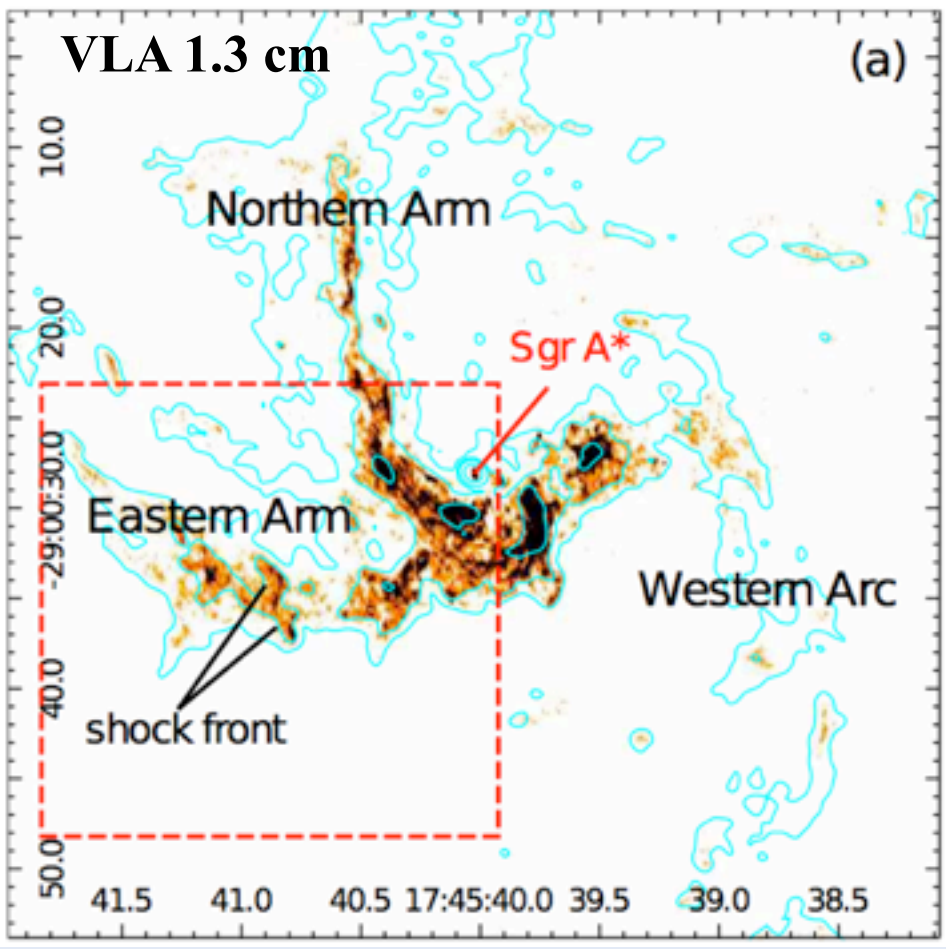
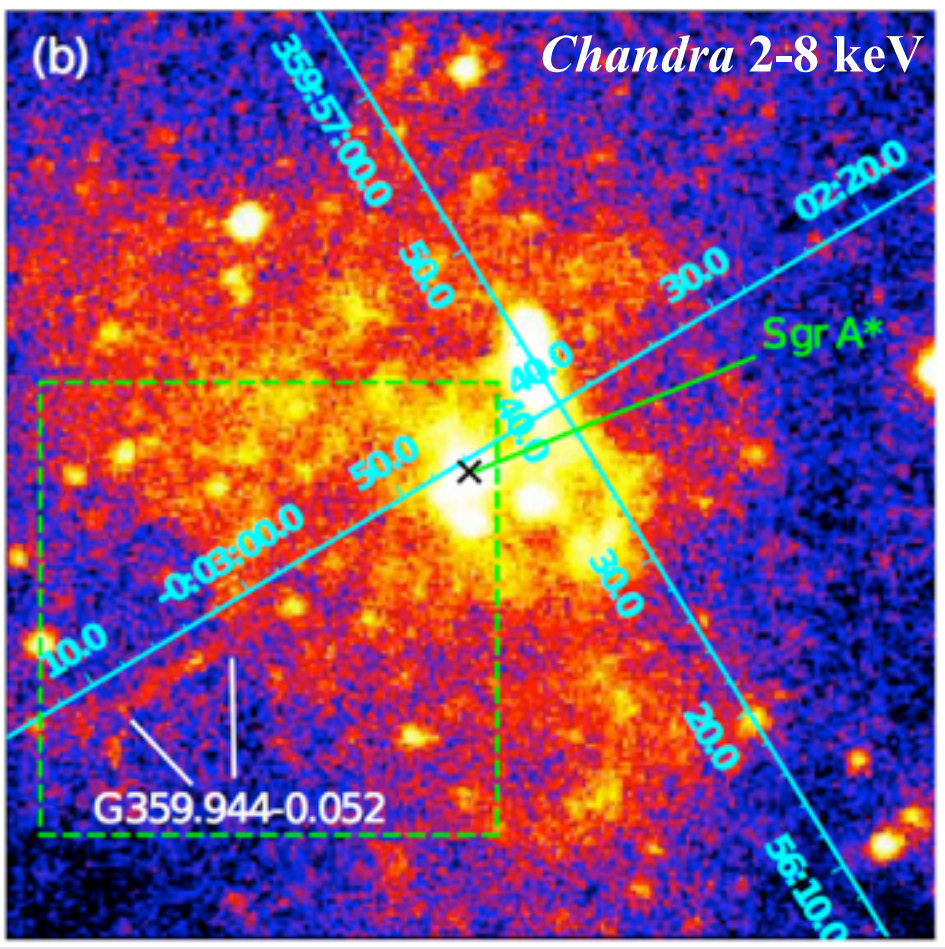
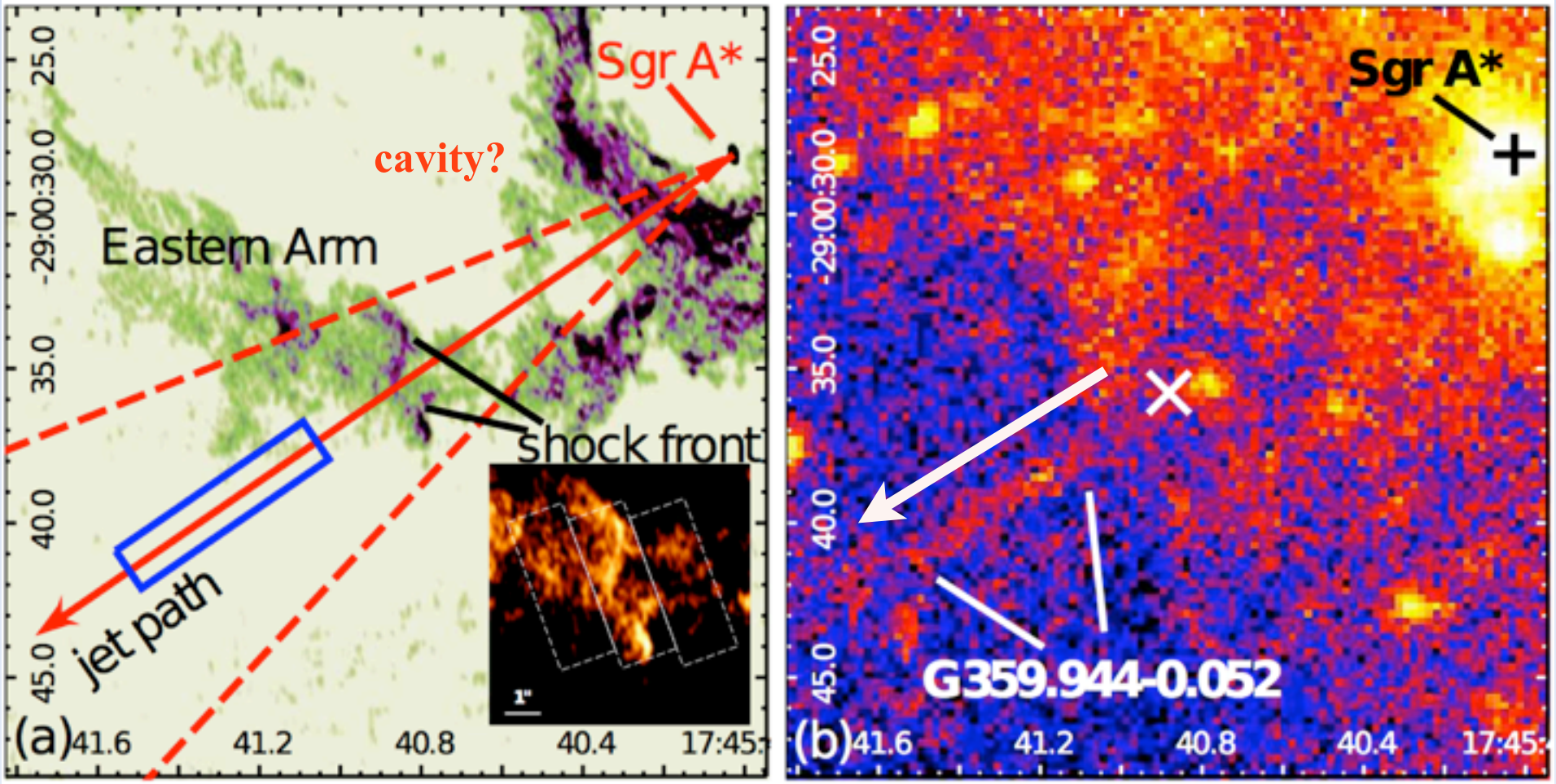
The origin of the shock?

2 parsec


VLA 1.3 cm
(a)
Northern Arm
Sgr A*
Eastern Arm
Western Arc
shock front
10.0
20.0
-29:00:30.0
40.0
50.0
41.5
41.0
40.5
17:45:40.0
39.5
39.0
38.5


(b)
Chandra 2-8 keV
359:57:00.0
50.0
02:20.0
30.0
Sgr A*
40.0
40.0
50.0
-0:03:00.0
10.0
30.0
20.0
G359.944-0.052
56:10.0

A striking geometric relation among Sgr A*, the shock front and G359.944-0.052



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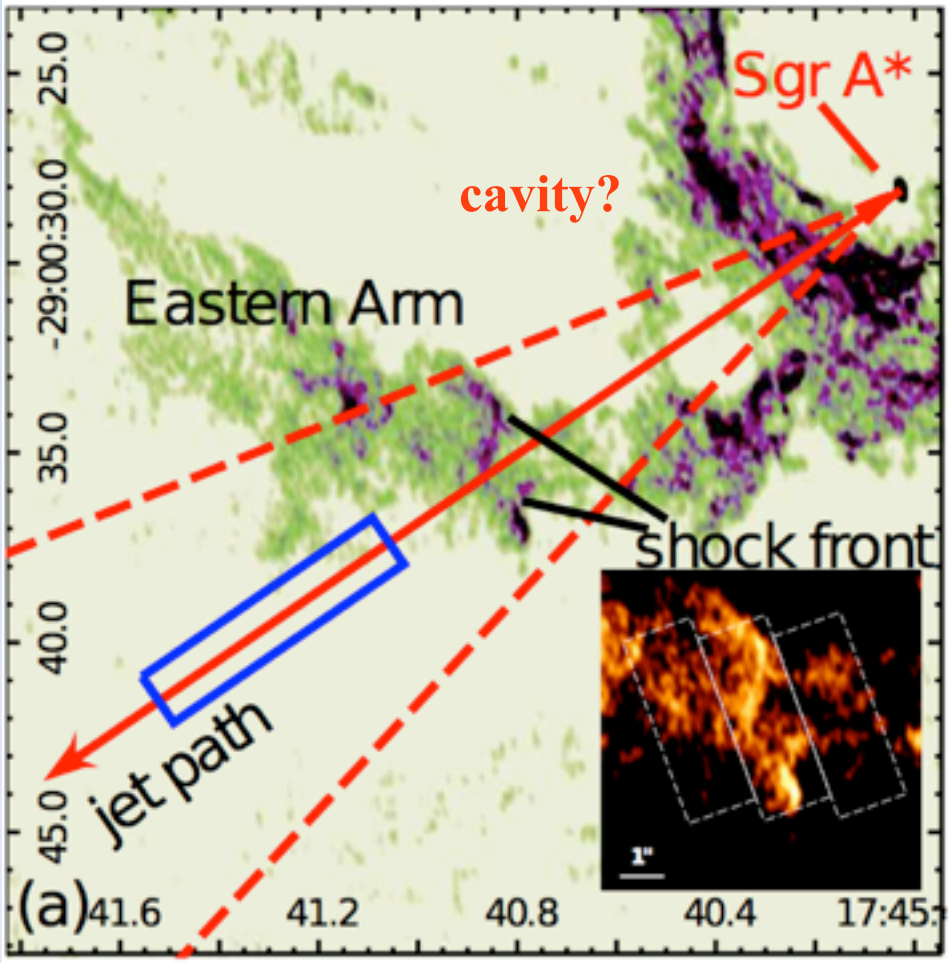
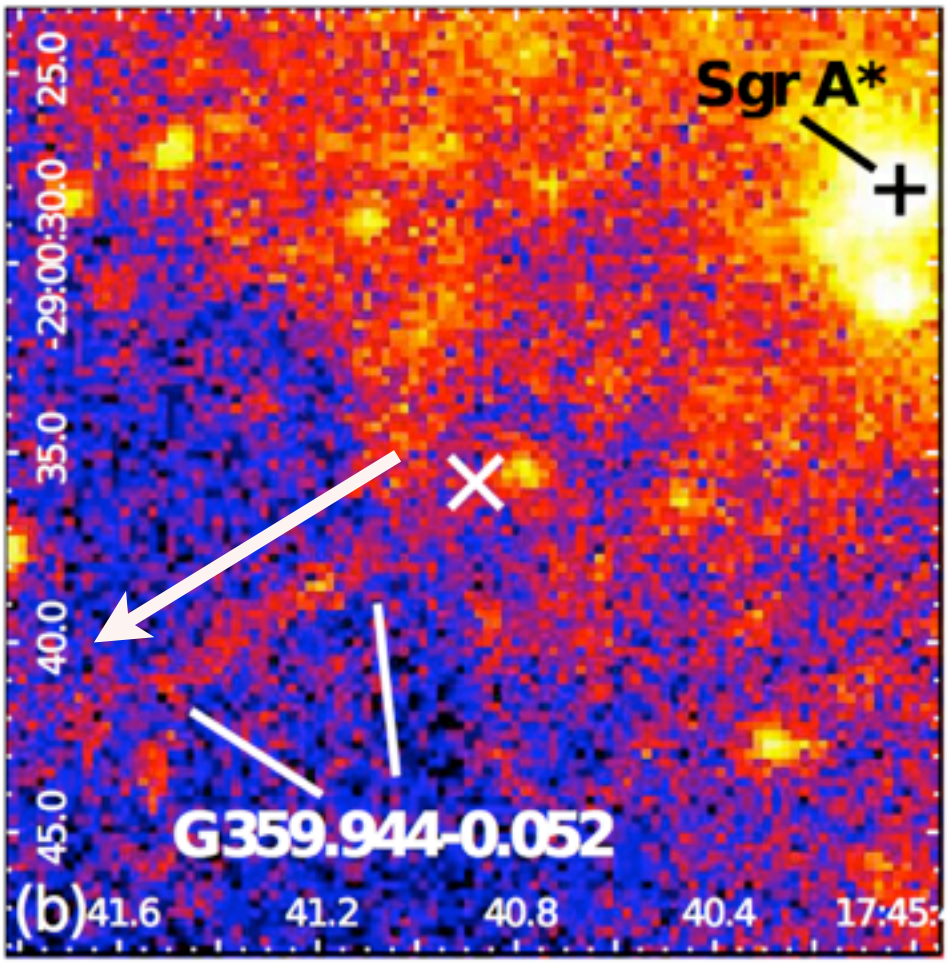
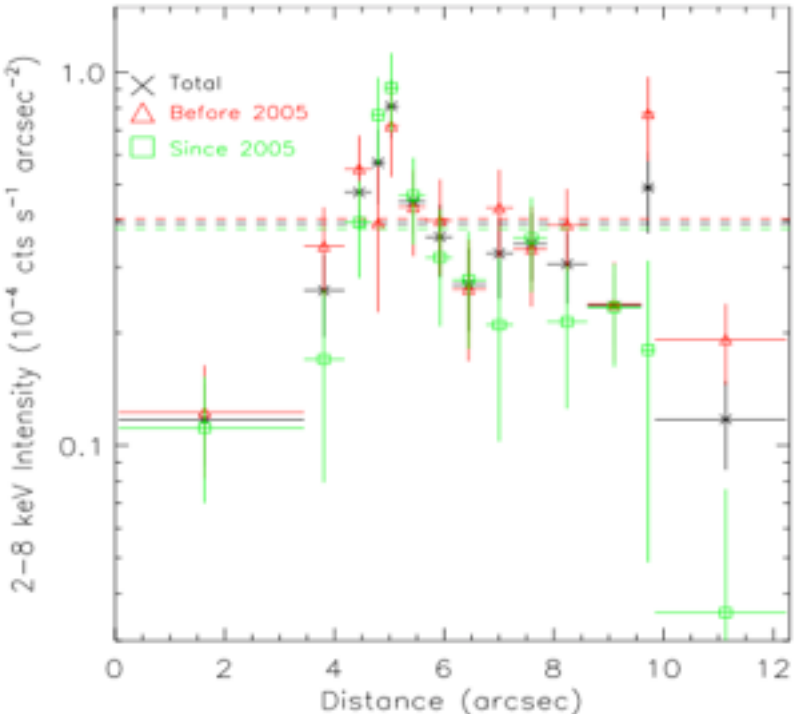
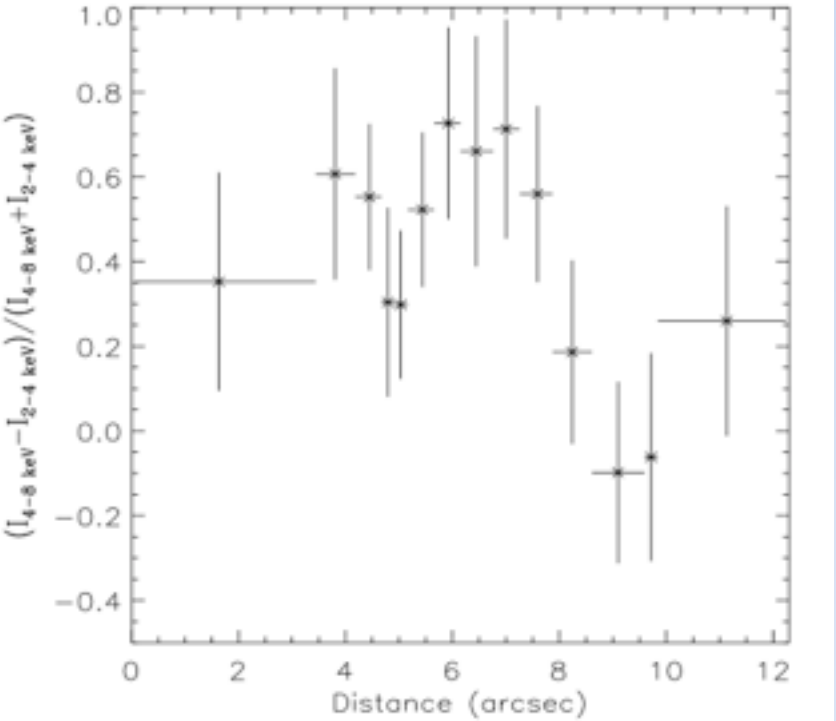
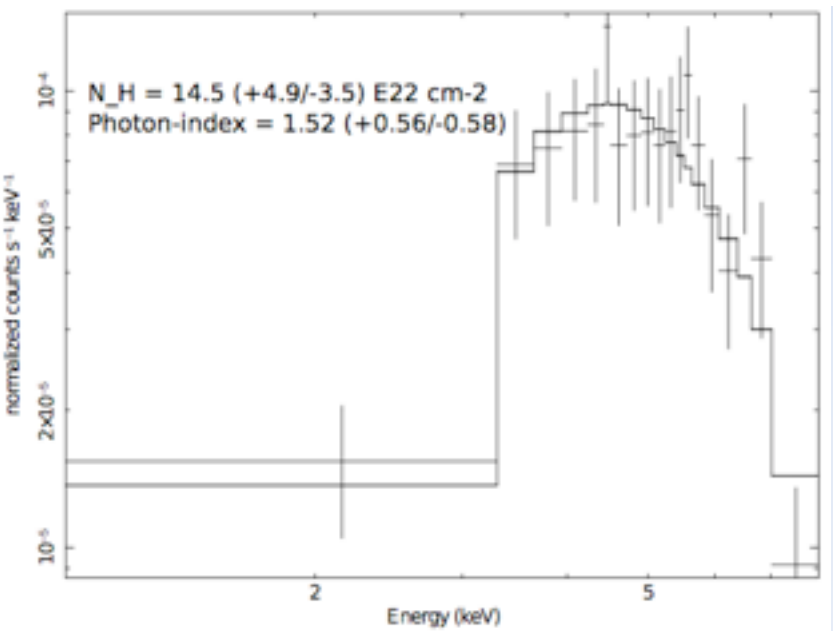




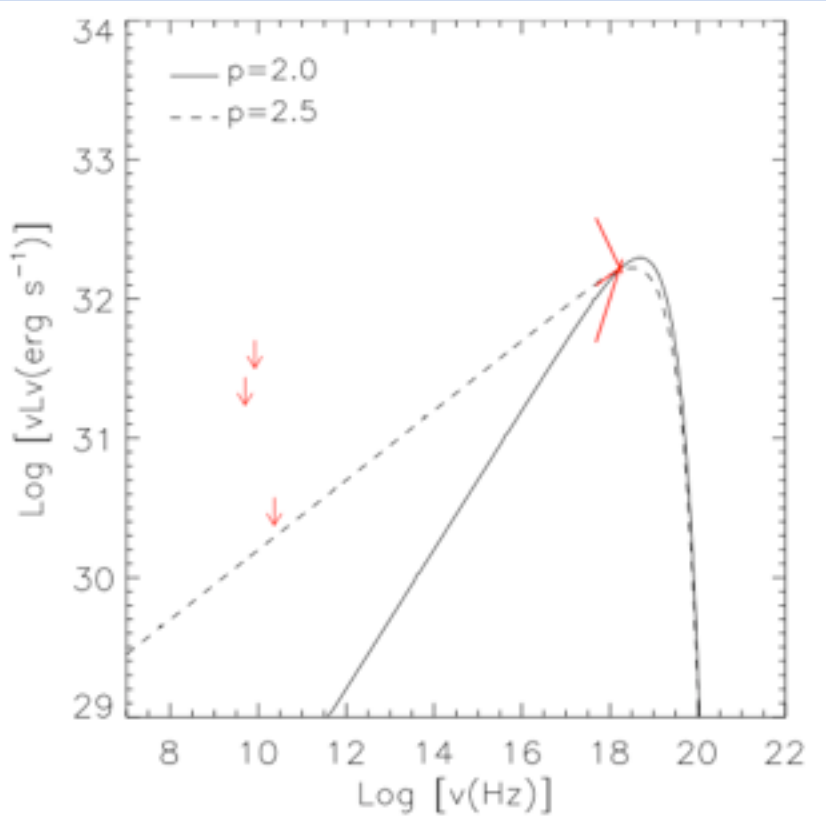
A jet from Sgr A* interacting with the local gas!



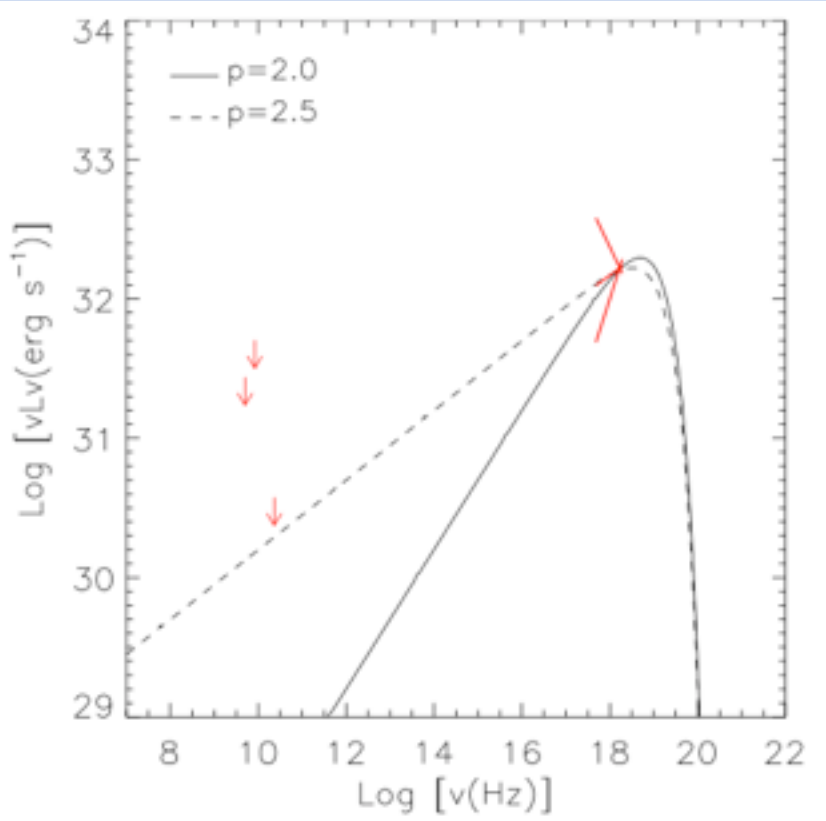




- A 14-sigma detection (~500 net counts)
- A full length of ~0.3 pc (but one-sided)
- No temporal variation on 10-yr scale
- A spectral softening at the far-side
- A power-law model fits the overall spectrum: non-thermal emission
- $L_{2\text{-}10\ keV}$ ~ 2E32 erg/s vs. available accretion power of ~1E41 erg/s



- A simple one-zone *synchrotron* model can explain the X-ray PL spectrum
- Cooling timescale consistent with the length of G359.944-0.052
- Inverse Compton models are strongly ruled out due to the lack of radio/IR counterparts



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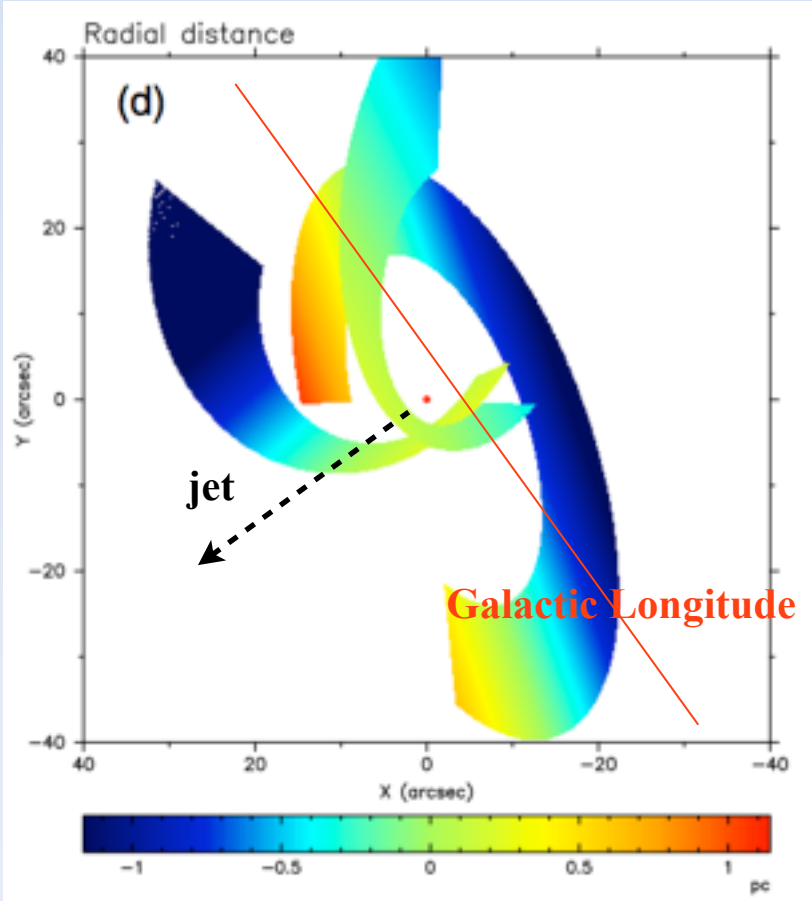

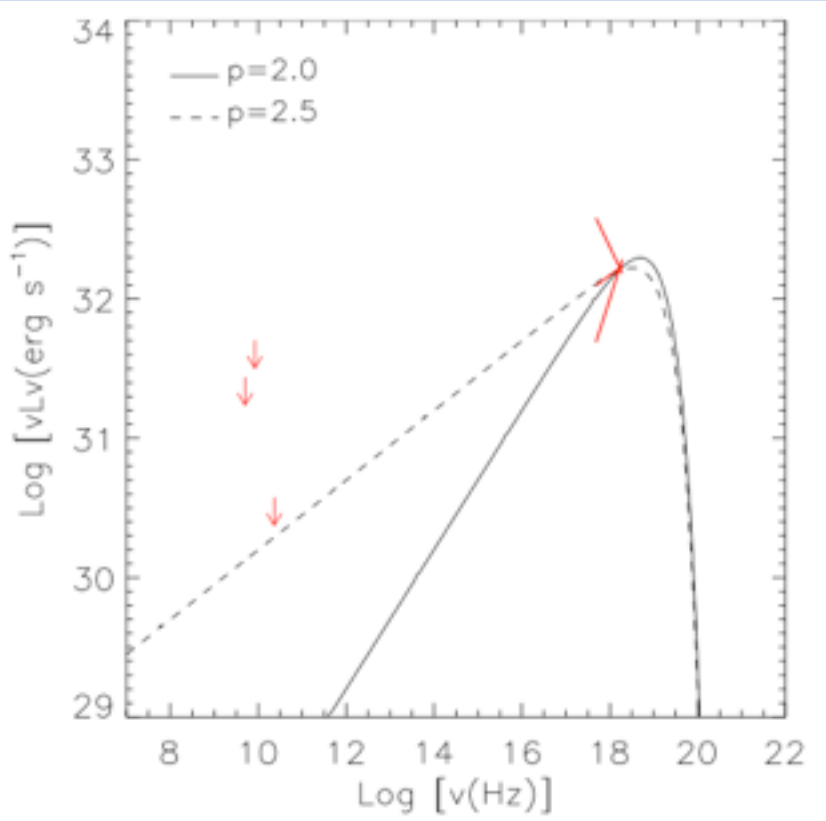

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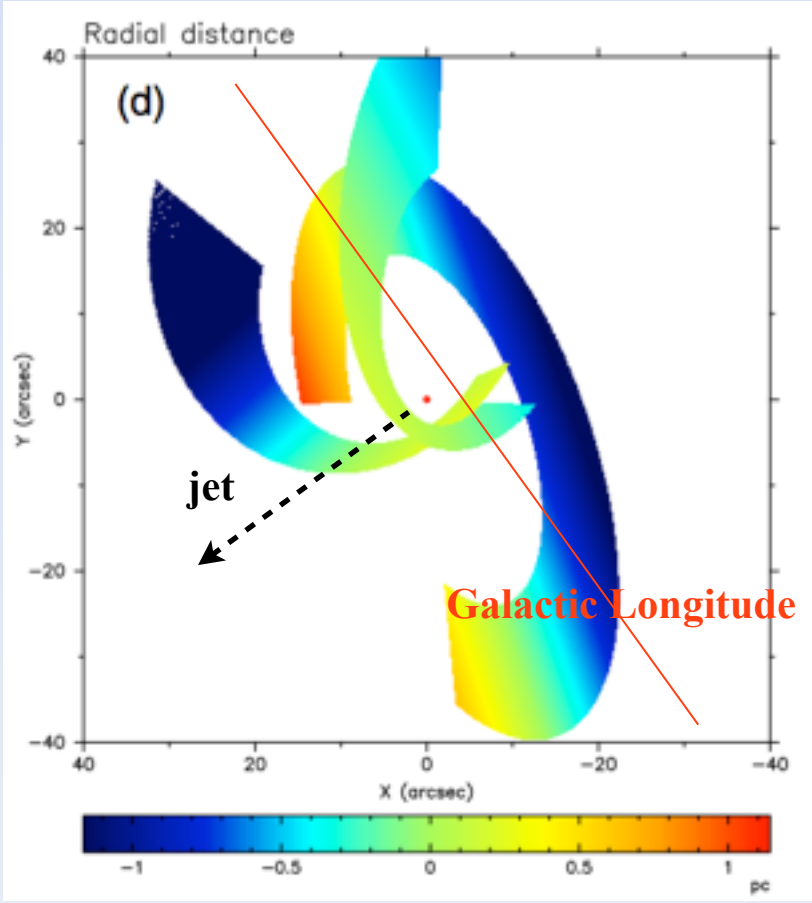
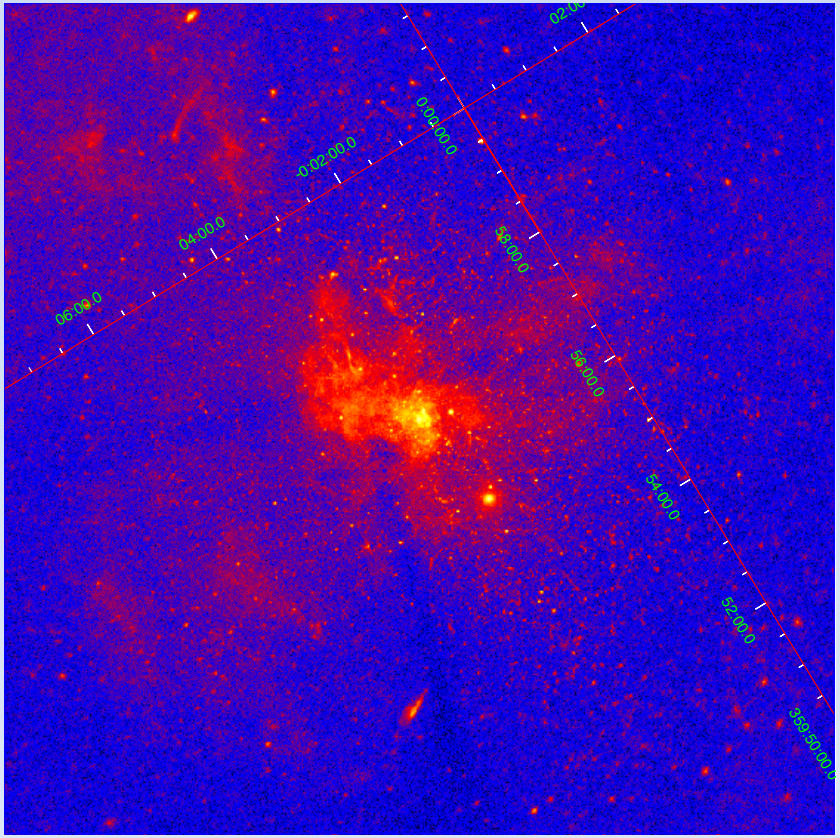


Implications:

- The jet is aligned with the Galaxy's rotation axis -- coupling between the BH spin and the Galaxy's angular momentum

- Only a small fraction of the putative jet power (10^{36}-10^{38} erg/s) is dissipated into radiation



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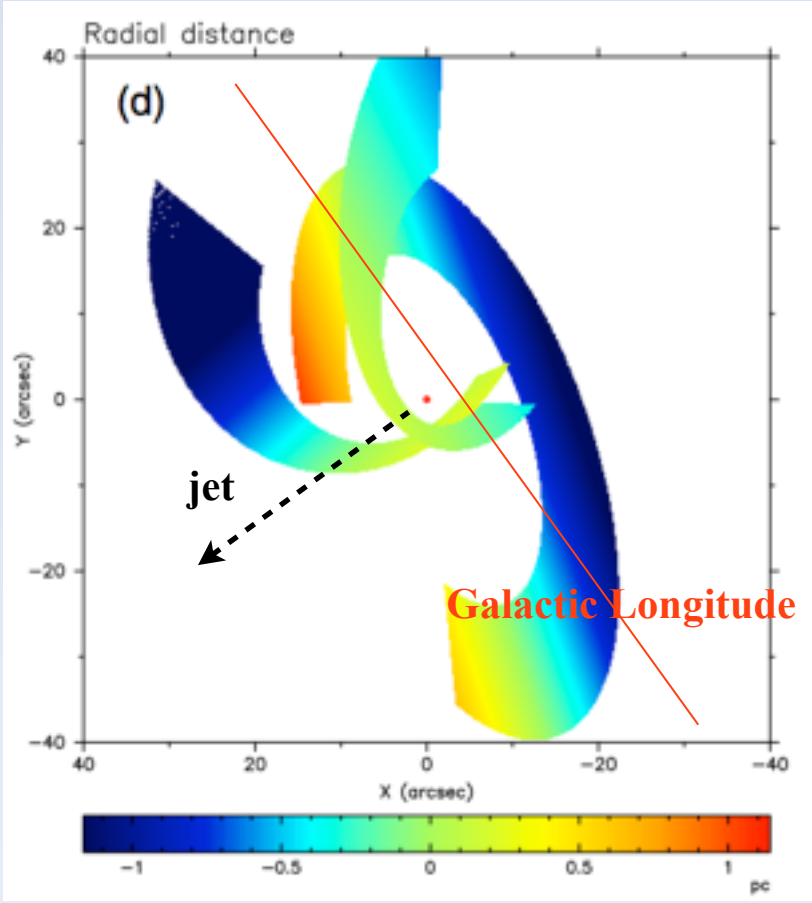

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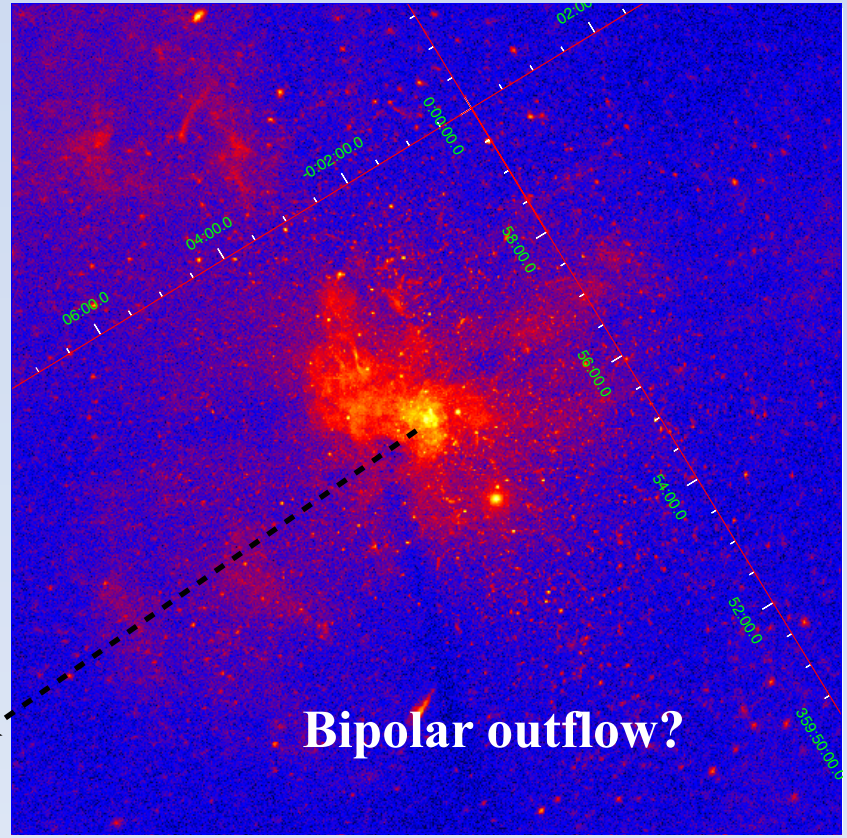

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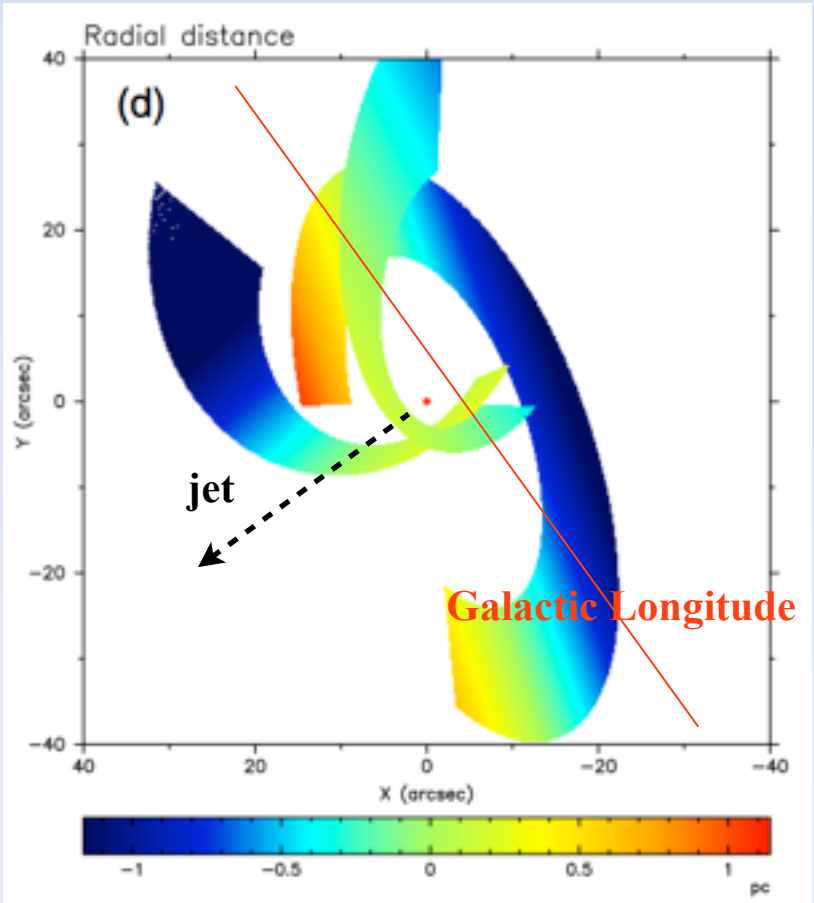

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Summary

- We have used recent Chandra/VLA observations to reveal an intriguing spatial relation among Sgr A*, G359.944-0.052, and a radio front on the Eastern Arm

- As evidence of a jet emanating from Sgr A*: a shock is created when the jet collides with the Eastern Arm, producing a population of ultra-relativistic electrons; these electrons are responsible for the X-ray synchrotron emission from downstream along the jet path

- The jet appears to be aligned with the Galaxy's rotation axis, indicating a coupling between the SMBH and the Galactic disk

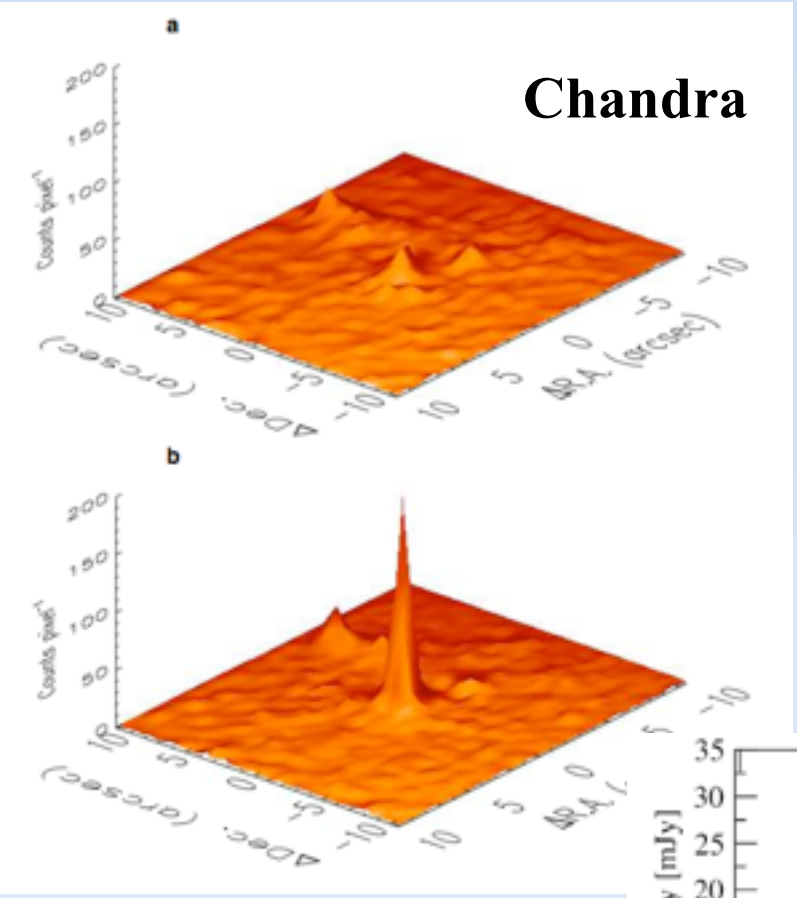
Future perspectives

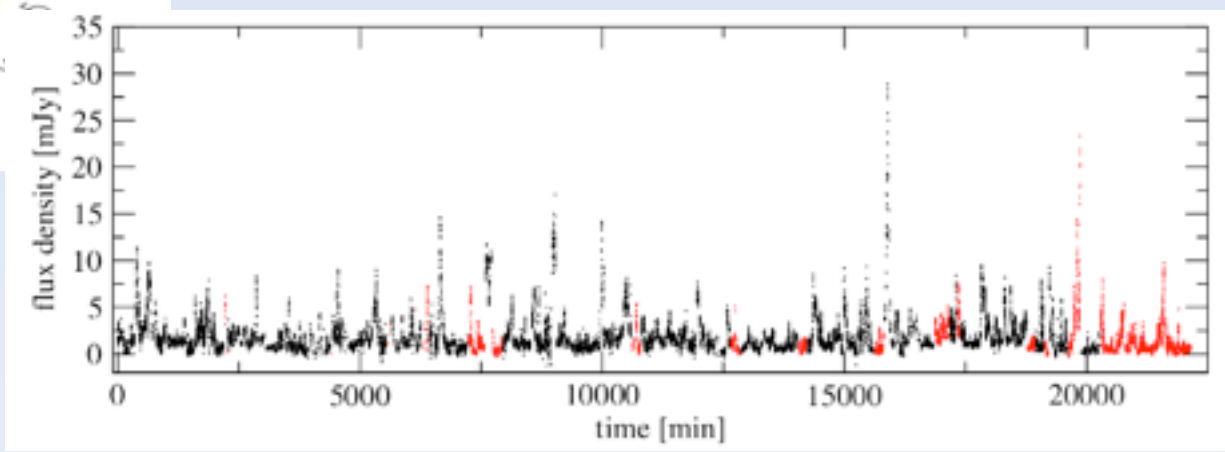
- Open questions: Is the jet intrinsically one-sided? Continuous or episodic?
- Probe the low-frequency (polarized) counterpart of G359.944-0.052 with ALMA and VLA
- Map the gas velocity field across the shock front using high-resolution IR spectra (with upcoming Gemini/TEXES observations)
- Hydrodynamic simulations of jet-Eastern Arm interaction
- Confirmation of the jet axis with future VLBI observations toward the immediate vicinity of Sgr A*

Welcome to our PhD Forum


Thank you!

Radiation from Sgr A*: flares





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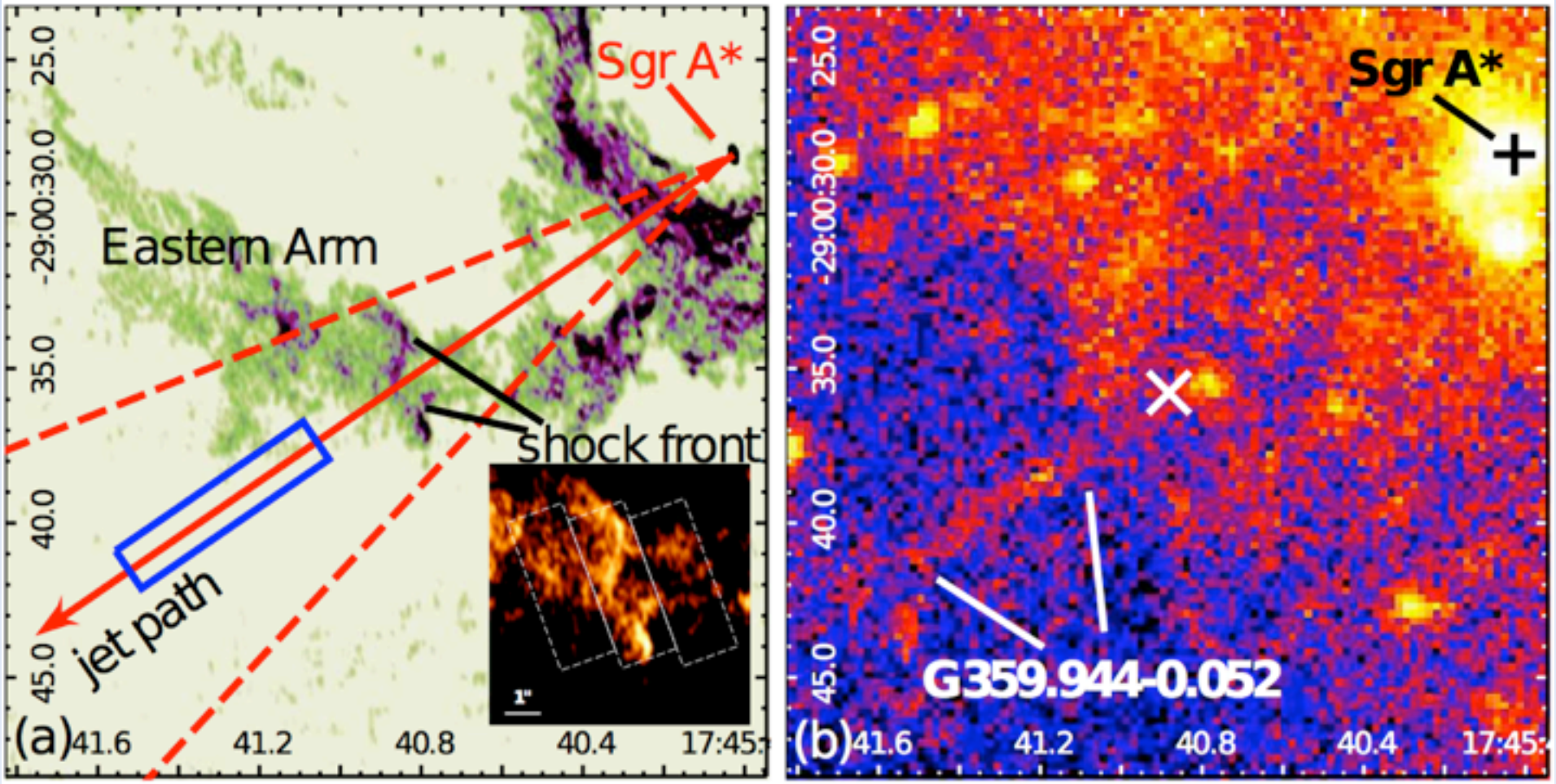

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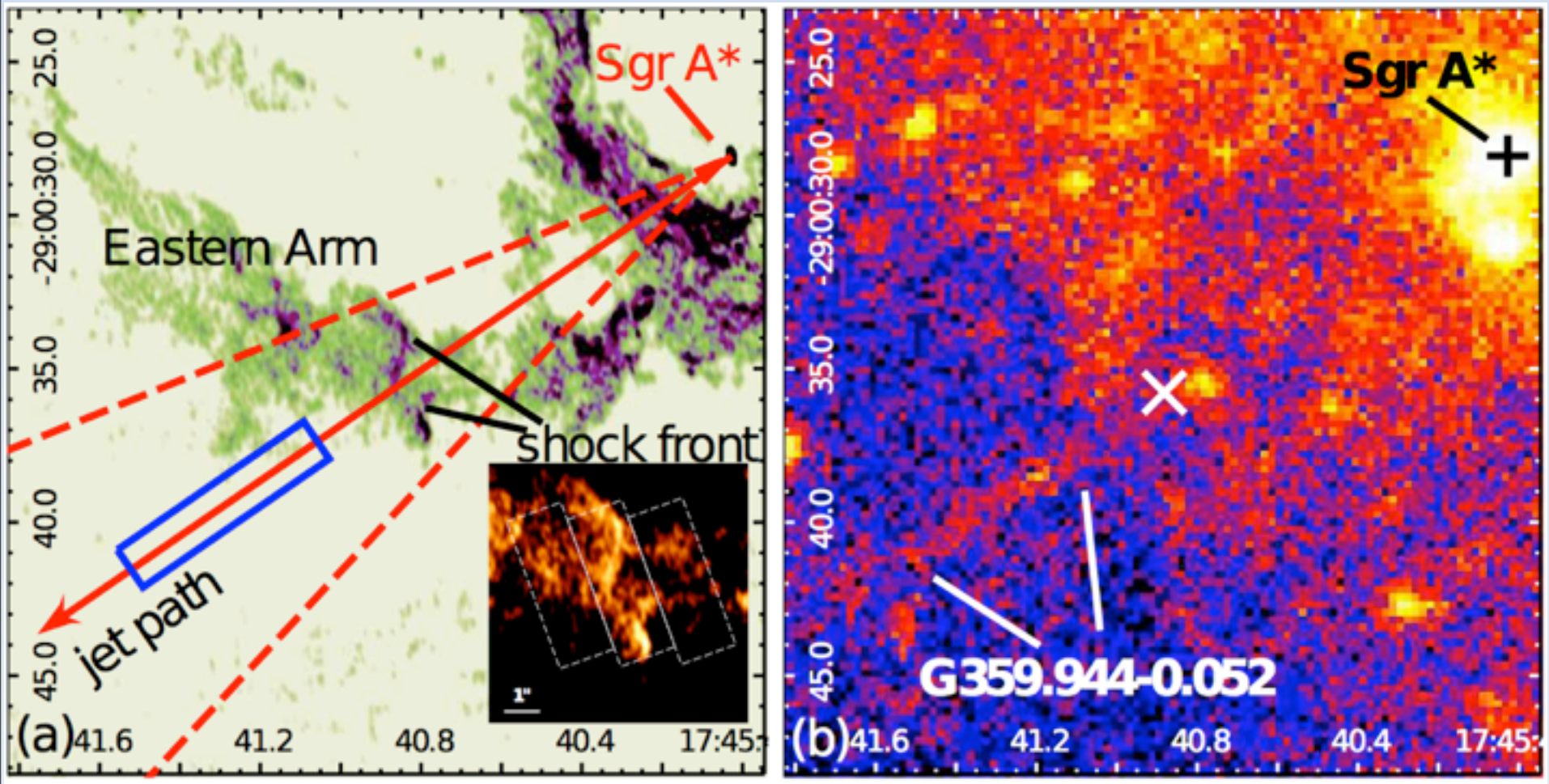

A jet from Sgr A* interacting with the local gas!

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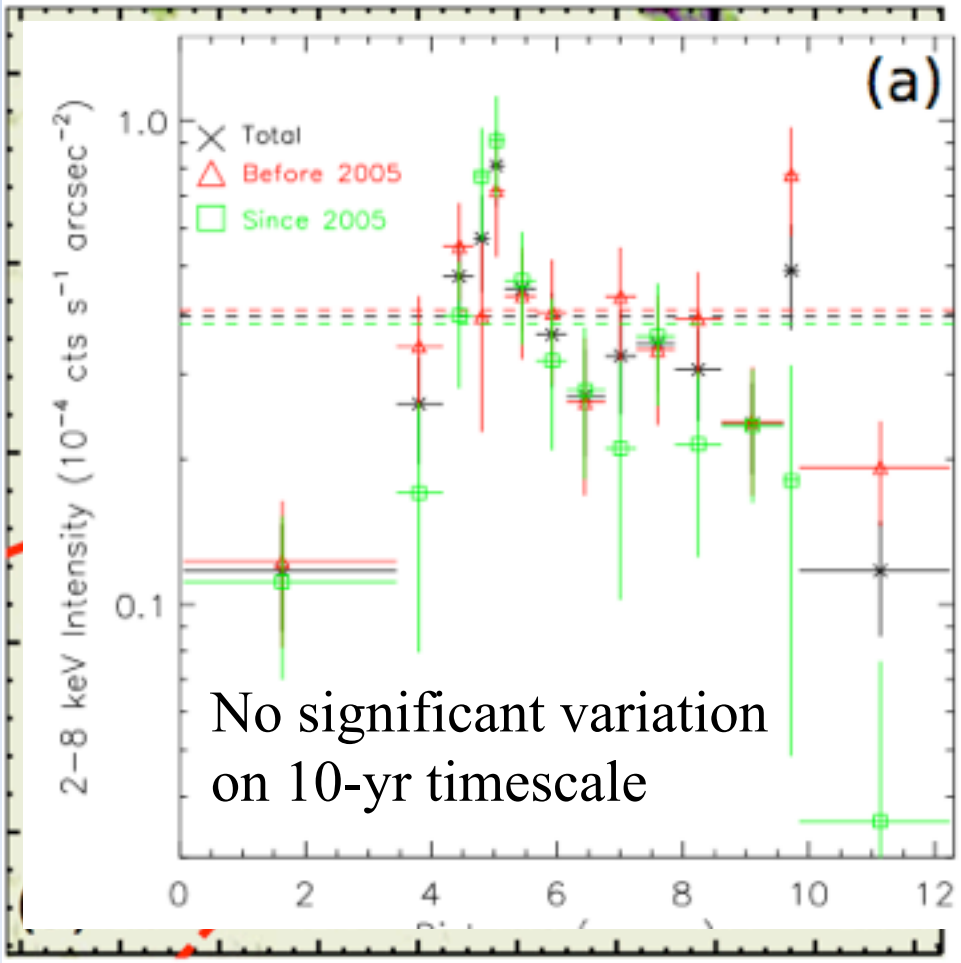

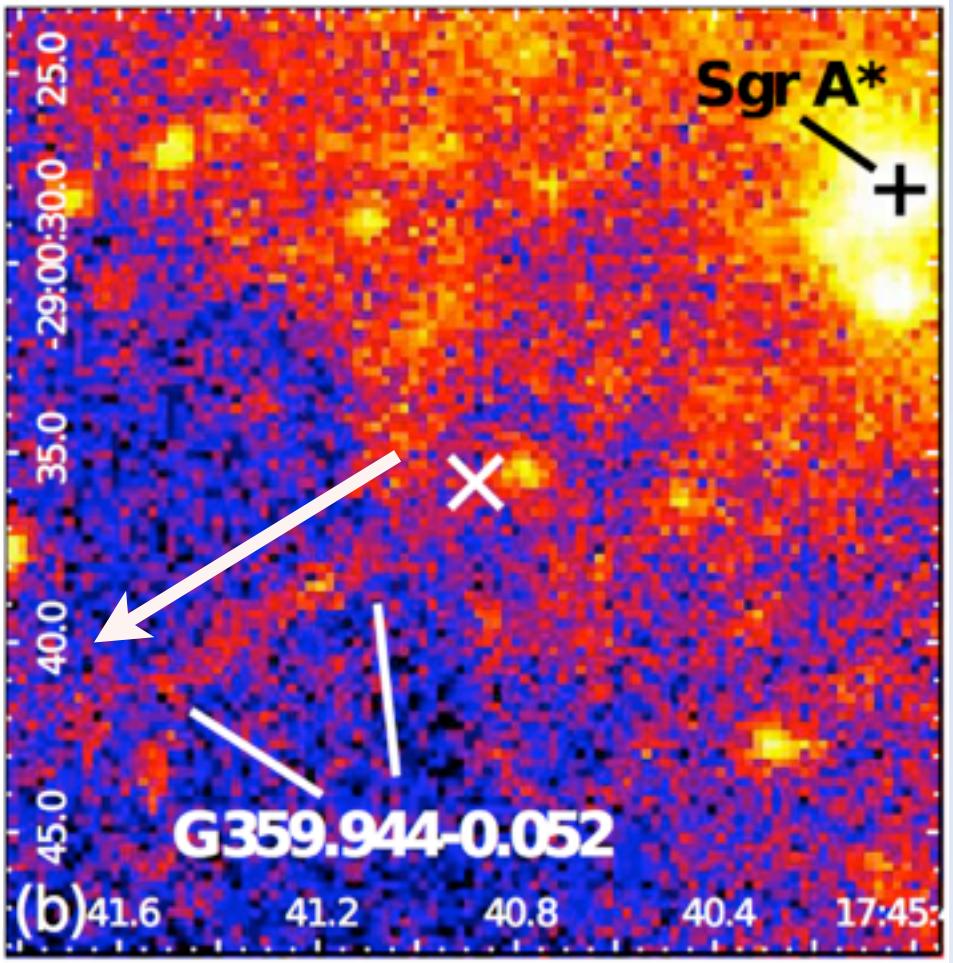

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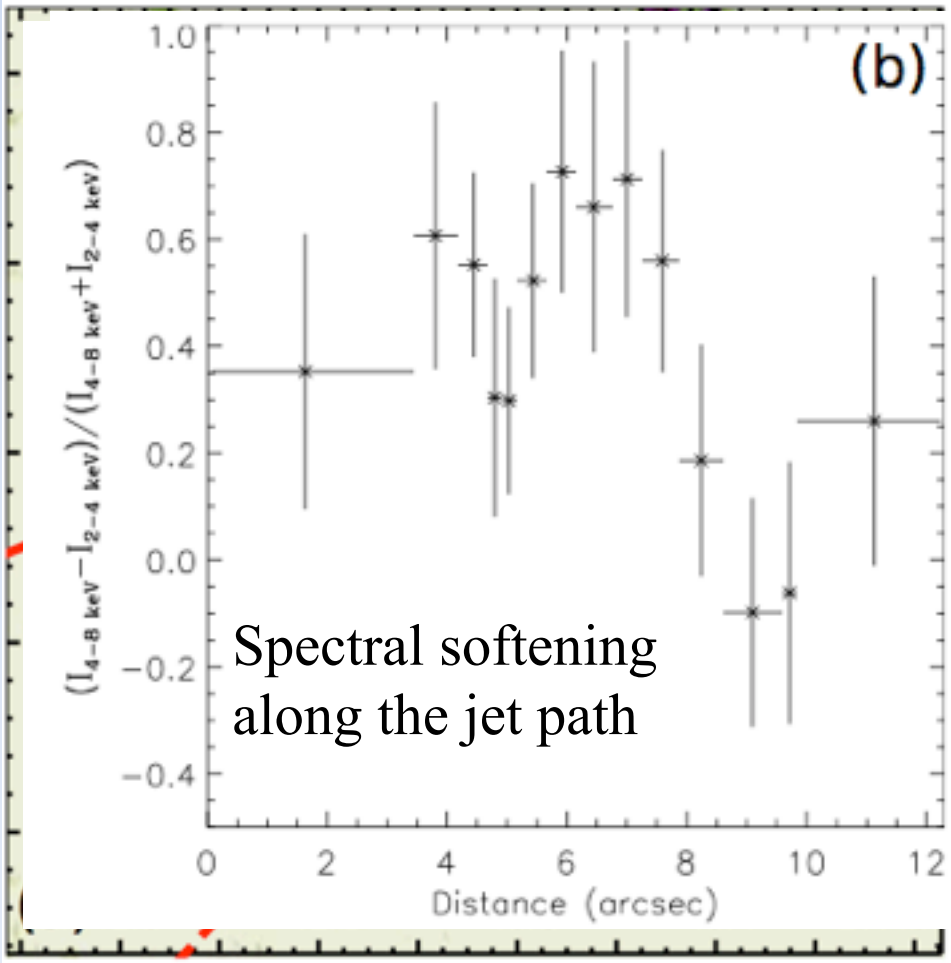

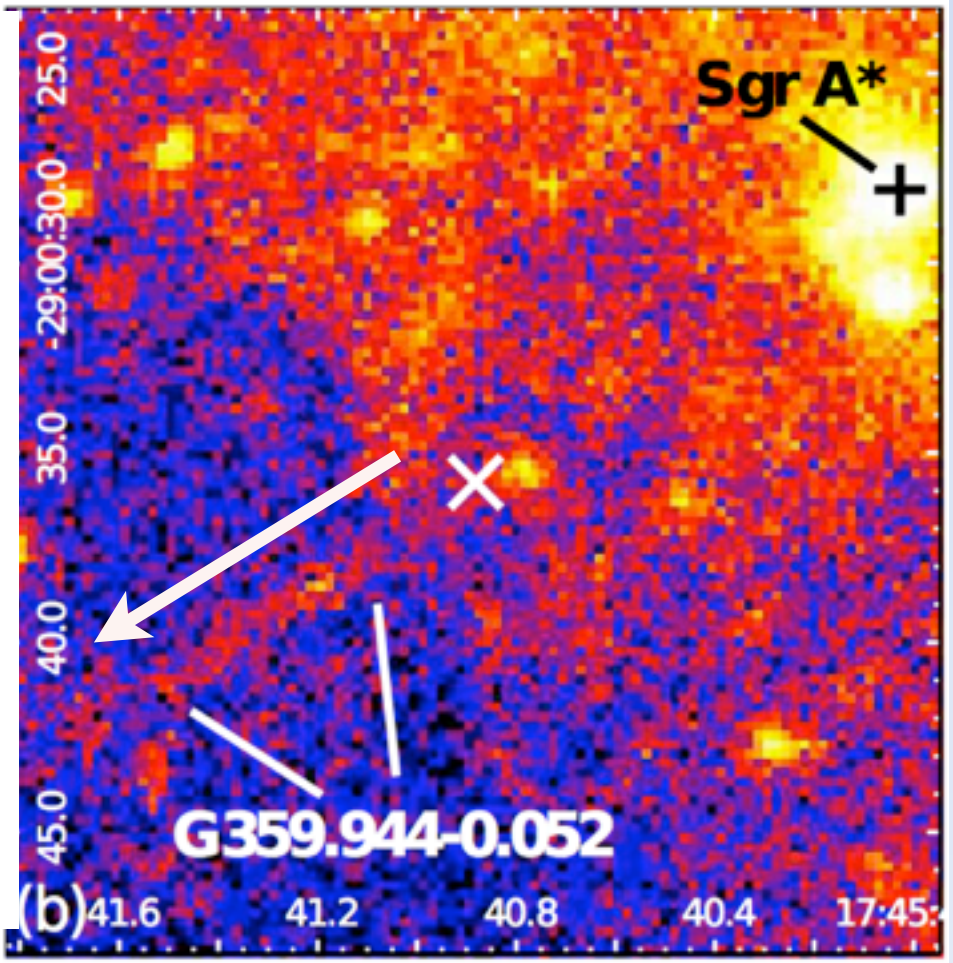

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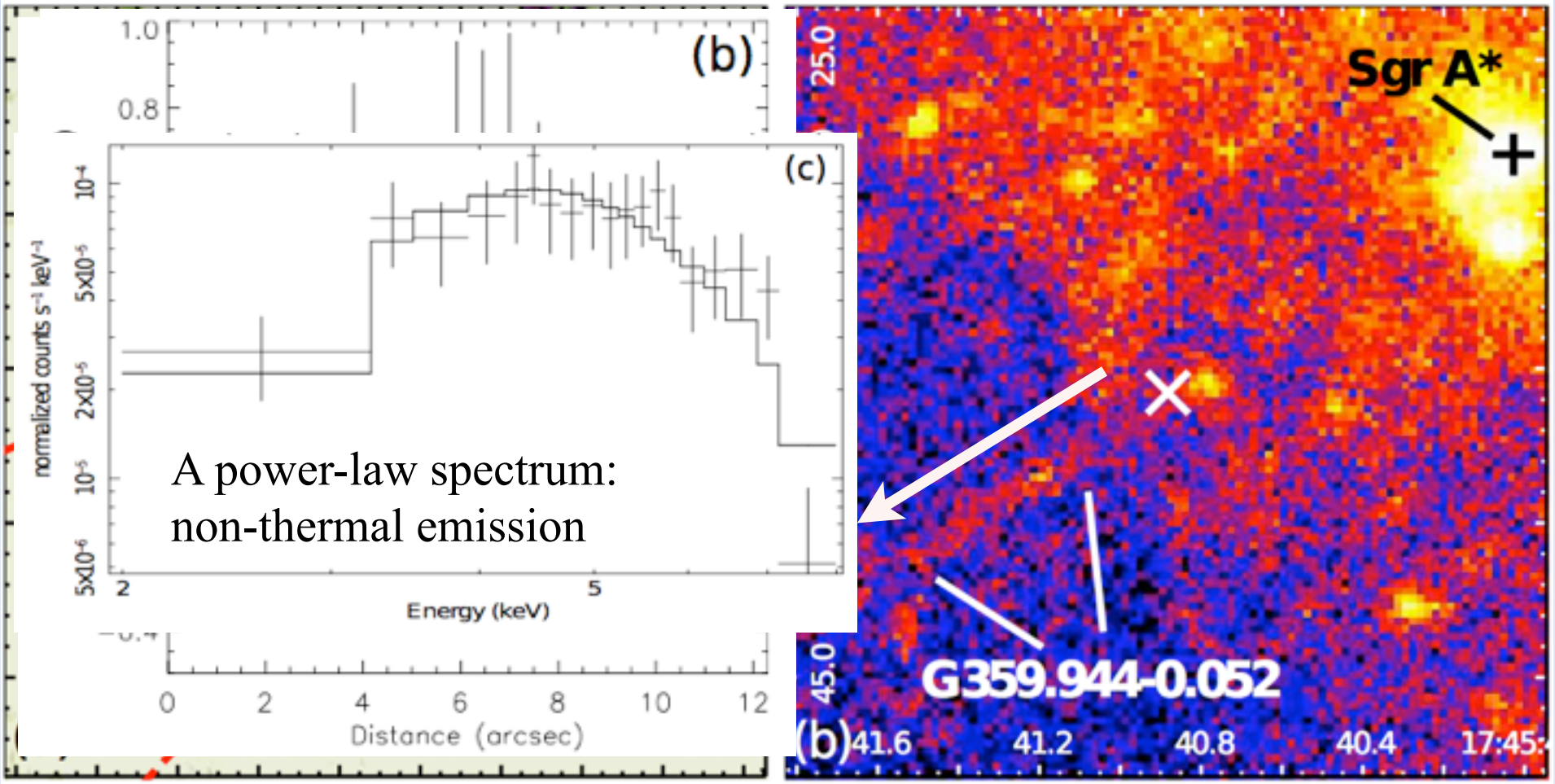

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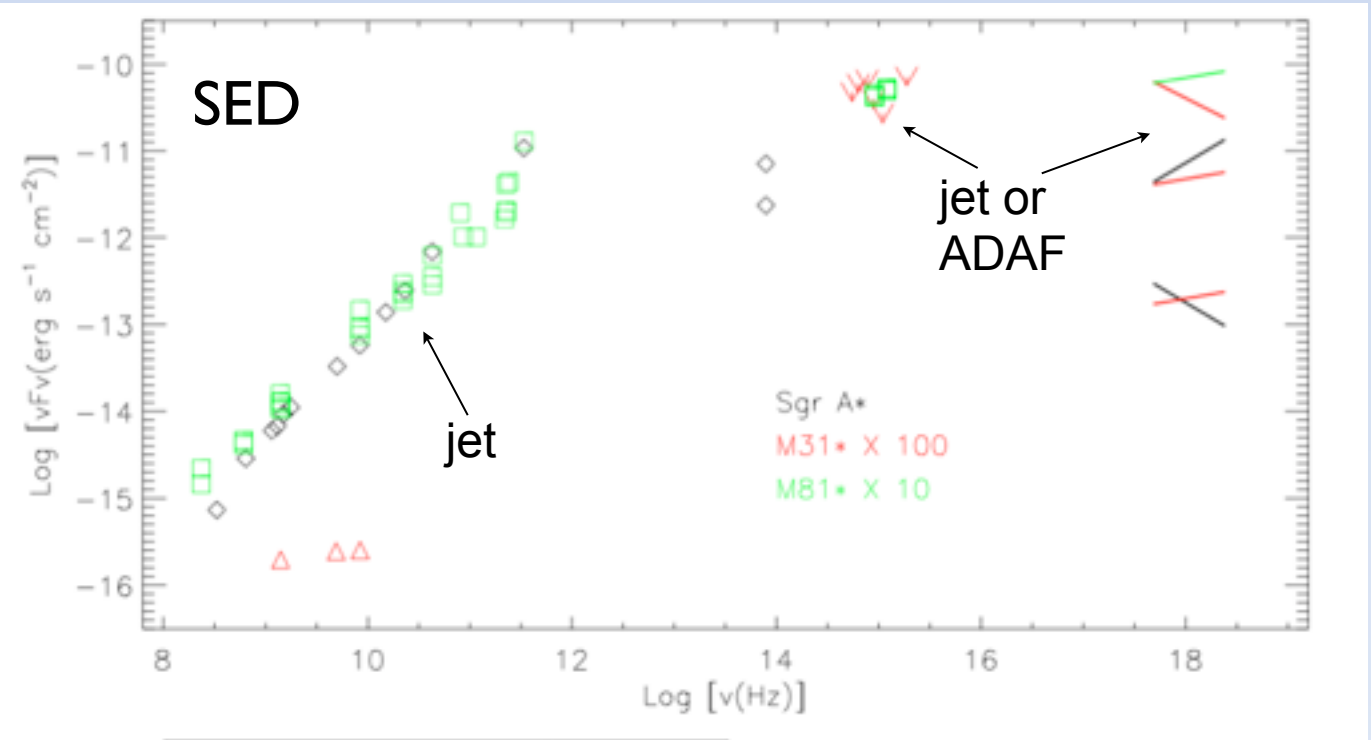

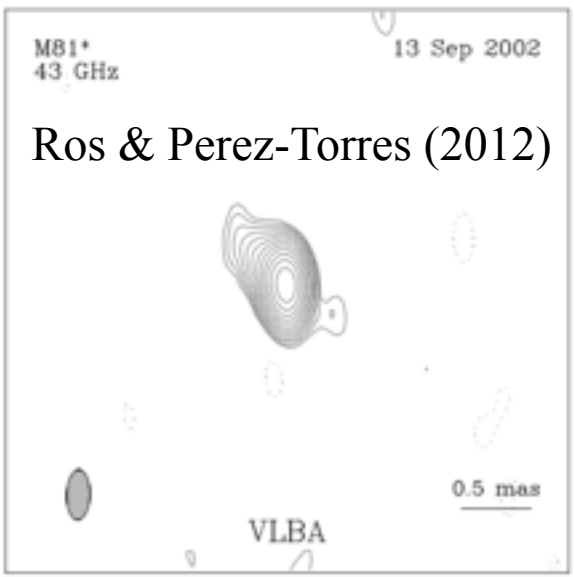

- VLBI resolves a one-sided jet from M81*, whose radio SED is highly similar to that of Sgr A*