Phenomena Unique to the Galaxy's Central Parsec:
Outstanding Questions

10 GHz JVLA image: credit Jun-Hui Zhao

Mark Morris
University of California, Los Angeles,

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IAU Symposia

405 – 136 = 269

2026 Brno

1988 UCLA

IAU Symposia in 38 years

Including:

IAUS 184 (1998, Kyoto)
IAUS 303 (2014, Santa Fe)
IAUS 322 (2016, Queensland)

Presently Open Questions:

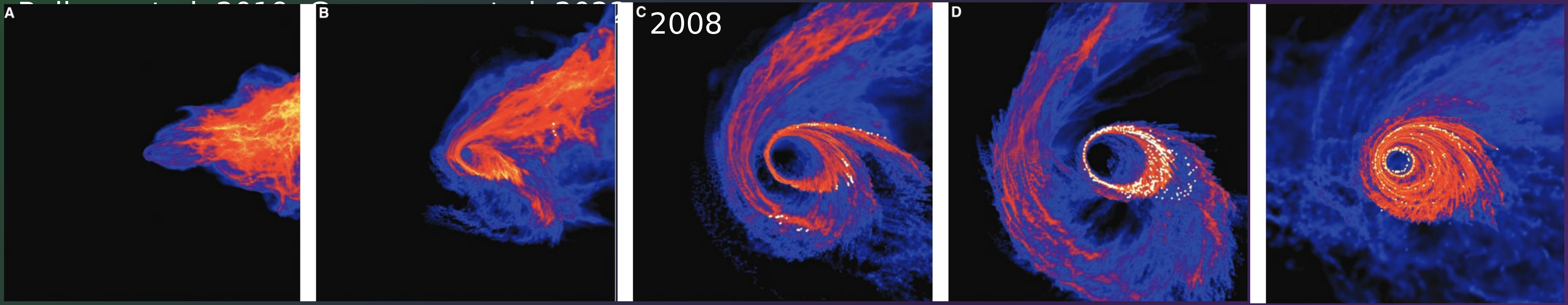
1. What prior history of the central parsec led to the formation of the young nuclear star cluster?
2. Is there current and ongoing star formation in the hostile environment of the central parsec?
3. What are the observable manifestations of the inevitable ***outflows*** generated by the accretion flow onto Sgr A*?
4. How often do stellar collisions take place in the central parsec, and have we already observed the aftermath of such collisions?
5. How can we best investigate the expected presence of a concentration of stellar remnants, and in particular, stellar-mass black holes, in the entourage of Sgr A*?
6. Where are the neutron stars?
7. We know that magnetic fields are strong and important throughout the CMZ, but what role do they play in the central parsec?

What prior history of the central parsec led to the formation of the young nuclear star cluster?

Popular paradigm: encounter of a molecular cloud with Sgr A*:

Sanders 1998; Bradford et al. 2005; Bonnell & Rice 2008; Wardle & YusefZadeh 2008; Hobbs & Nayakshin 2009;
Alig et al. 2011; Oka et al. 2011; Mapelli et al. 2012; Mapelli & Trani 2016; Goicoechea et al. 2018; Trani et al. 2018;

Bonnell & Rice 2008



Quasi-radial infall → circularization → accretion disk → star formation

Star formation in disk as modelled by Nayakshin, Cuadra, & Springel 2007

The Problem: this model calls upon a cloud with near-zero angular momentum.

Generozov et al. (2022) invoke “a cloud on a rather radial orbit, so that different sides of the
cloud pass the SMBH on opposite sides, collide behind it, and then get bound to the central pc.”

→ Their model: 8-pc radius cloud starting at R = 10 pc, with initial pericenter radius of 0.21 pc

How would nature arrange that?

- Cloud orbits generally conform to the sense of Galactic rotation (e.g., Henshaw et al. 2016)
- Radially infalling clouds would require *very* unusual conditions

- massive perturber? → no candidates

- collisions with retrograde clouds (Hobbs & Nayakshin 2009; Tartėnas & Zubovas 2020) → none known

- supernovae? → can’t move massive clouds

→ can redistribute matter, but can’t bring orbiting clouds to a halt

What is the alternative?

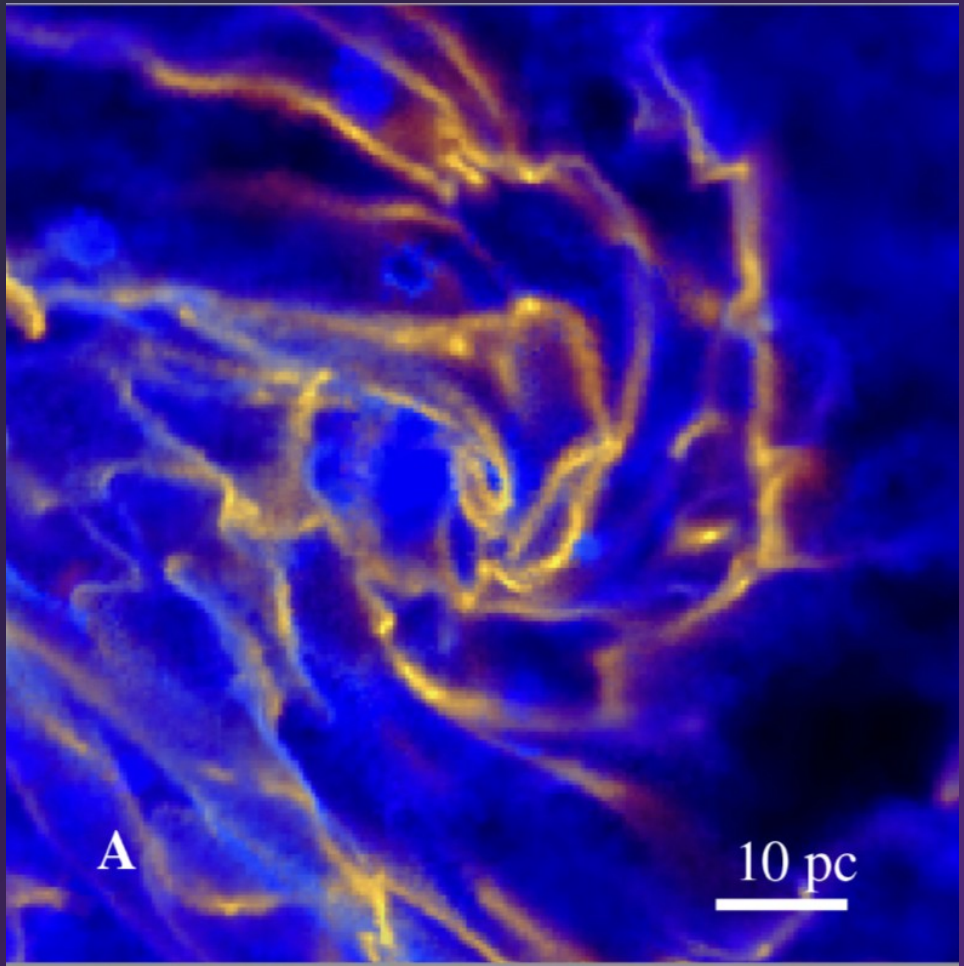
→ Viscous evolution of the CND, causing its inner edge to migrate inward, coupled with persistent feeding from the external CMZ

- This begs the question: is the CND transient or an enduring structure?

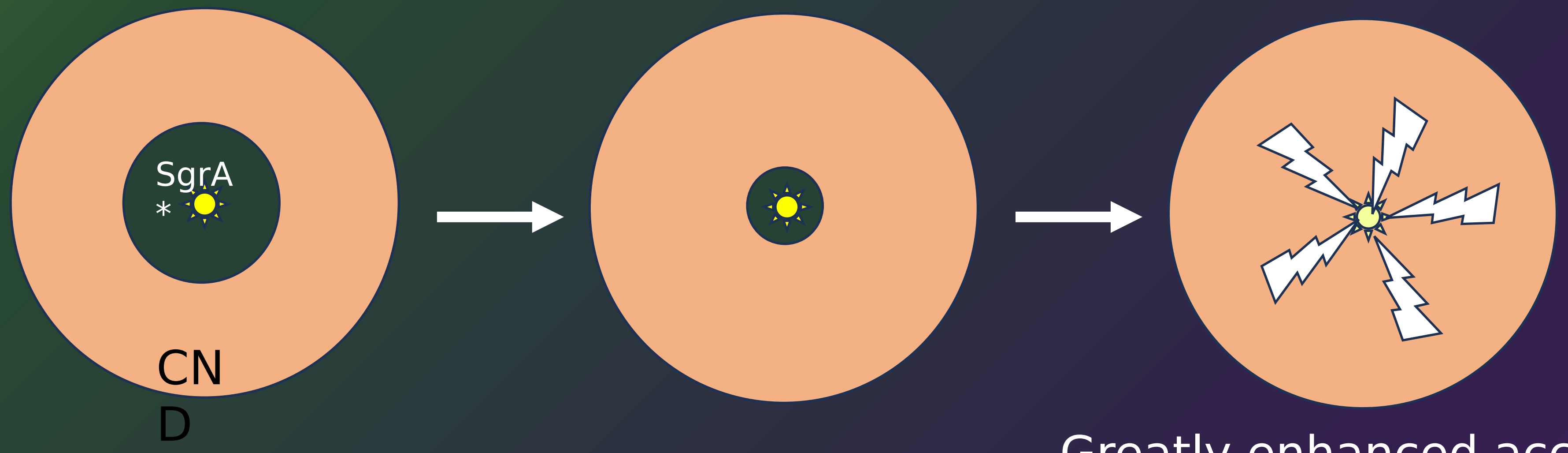
- Dinh et al. (2021): "CND fed piecemeal and relatively slowly and quasi-continuously by tidal streams from CMZ clouds already orbiting in its vicinity"
  (Ho et al. 1991; Wright et al. 2001; Liu et al. 2012; Hsieh et al. 2017; Tsuboi et al. 2018)

- Recent papers by Tress et al. (2020) → and Kobayashi et al. (2026) show how gas can intermittently migrate inward from the 100-pc ring

+ see Thursday talk by Zixuan Feng, poster by David Komanek & Richard Wunsch



Viscous evolution → inward migration of inner CND edge



Greatly enhanced accretion possibly approaching the Eddington rate

→ Does the rapid onset of accretion energy in this scenario play a role in provoking the otherwise tidally inhibited star formation by providing strong shocks and an coronal overpressure above the disk?

→ ***In any case, strong accretion onto Sgr A* must have accompanied the formation of the young nuclear cluster***

→ ***And both models are consistent with star formation in a disk***

Is there current and ongoing star formation in the hostile environment of the central parsec?

Robert Sanders (1992) →
if star formation is taking place in the central pc, then there must not be a supermassive black hole there because the tidal force would prevent cloud collapse to form stars.

The spirit of this argument is still valid… what happened 3 – 6 million years ago to form the young nuclear cluster was a very special circumstance involving the black hole.

But some have argued for ongoing or recent star formation, suggesting that YSOs or protostars might be present (e.g., Eckart et al. 2013; Yusef-Zadeh et al. 2015) based on various criteria:

- presence of H_2O masers
- bow shocks resembling those from proplyds [see Wednesday talk by Nadeen Sabha]
- shock diagnostics – SiO line emission
- velocity structures interpreted as bipolar protostellar jets
- an apparent cluster of embedded stars interpreted as protostars

Whether stars are still forming in the central parsec is still an open question worth further investigation …

- Can the water masers be explained by the high densities and temperatures found in the circumnuclear disk, conditions comparable to those in protostellar environments ?

- Similarly, are the chemical shock diagnostics a result of the extreme conditions in the gas occupying the central parsec? [see poster by Pierre Vermot]

- Are the bipolar outflows interpreted as arising in protostars really a result of stellar mergers?

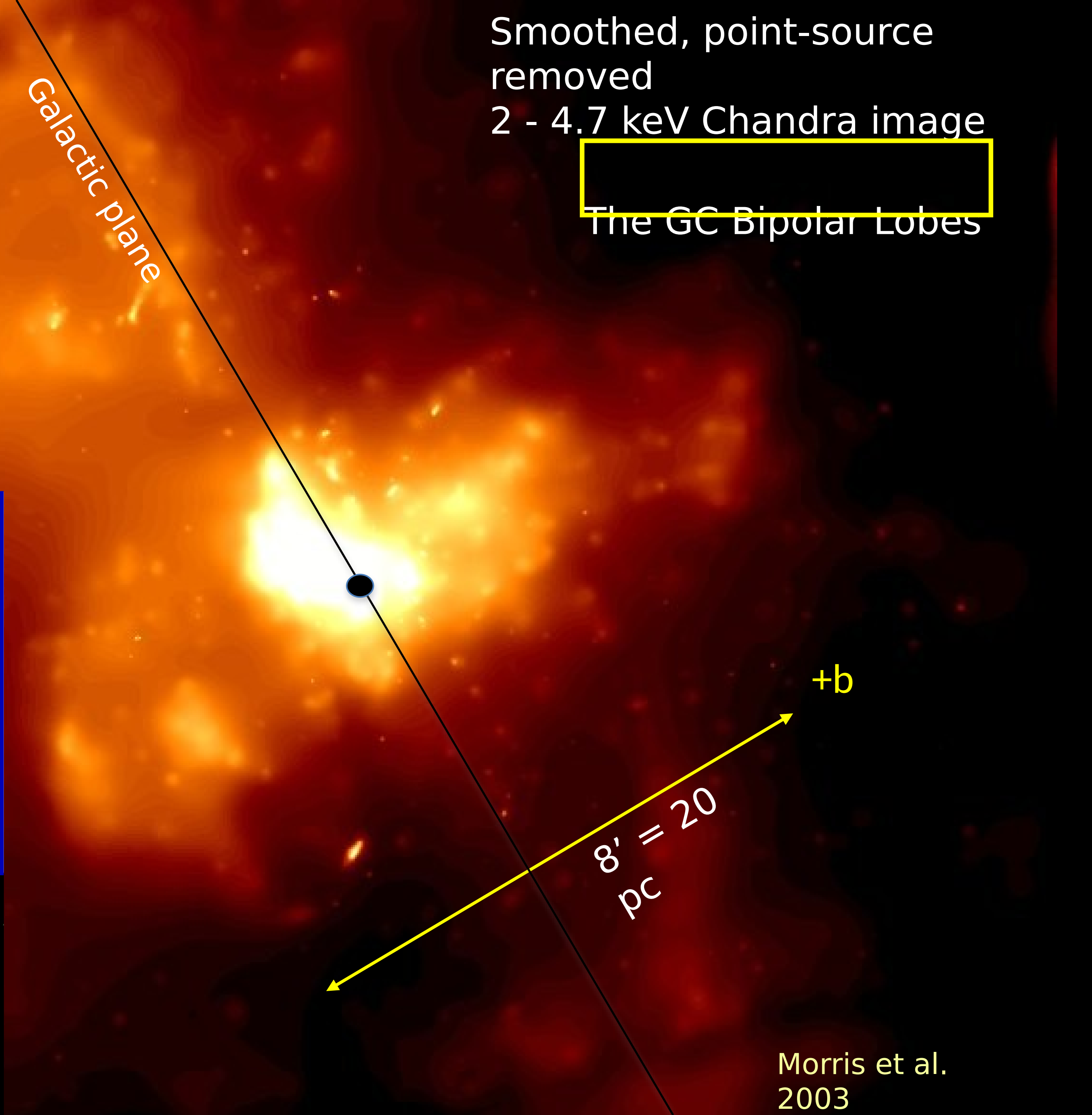
What are the observable manifestations of the inevitable outflows generated by the accretion flow onto Sgr A*?

- The focus has been on accretion flow, especially the strongly emitting material within a few Schwarzchild radii of Sgr A*, but theory tells us that the vast majority of material that enters the accretion flow out at the Bondi radius is blown out in a powerful wind, carrying out energy angular momentum and most of the mass (e.g., Melia & Falcke 2002; Yuan et al. 2012; Morris 2022)

- Possible manifestations of outflows:
  - a bipolar outflow, with bowshocks
  - the plasma chimneys
  - Fermi Bubbles
  - a jet, or a highly collimated outflow
  - the aftermath of a tidal disruption event

However, inconclusive →

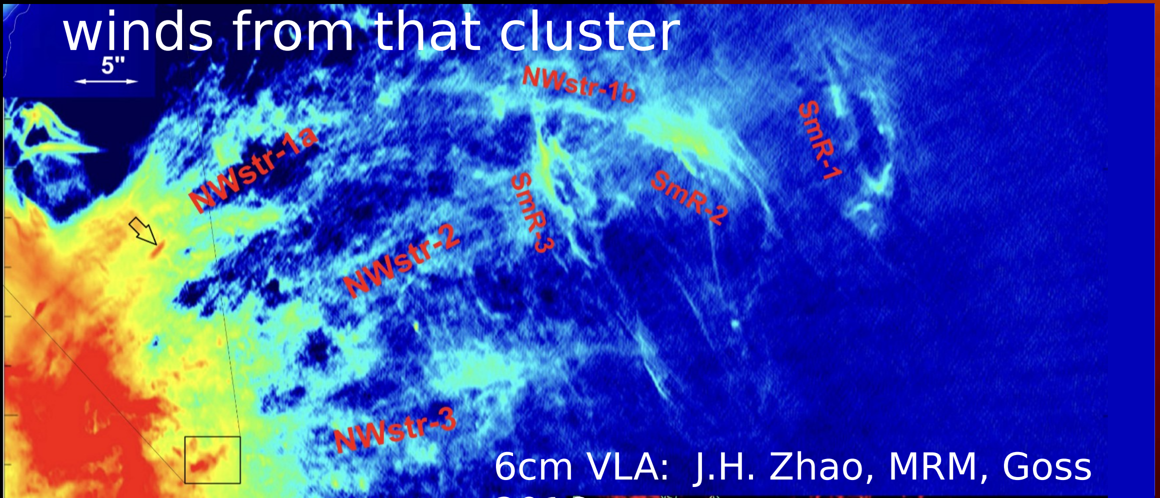
Could be attributed easily to supernovae within the young nuclear cluster and to the collective winds from that cluster



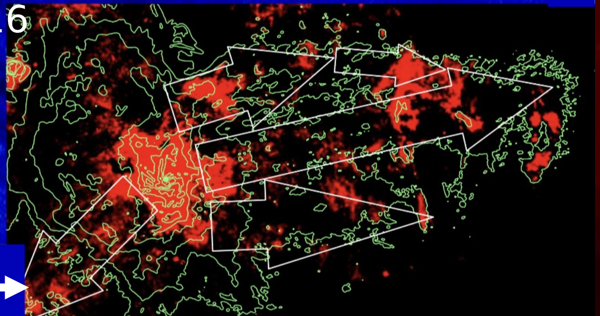
Smoothed, point-source removed
2 - 4.7 keV Chandra image

The GC Bipolar Lobes

Morris et al. 2003



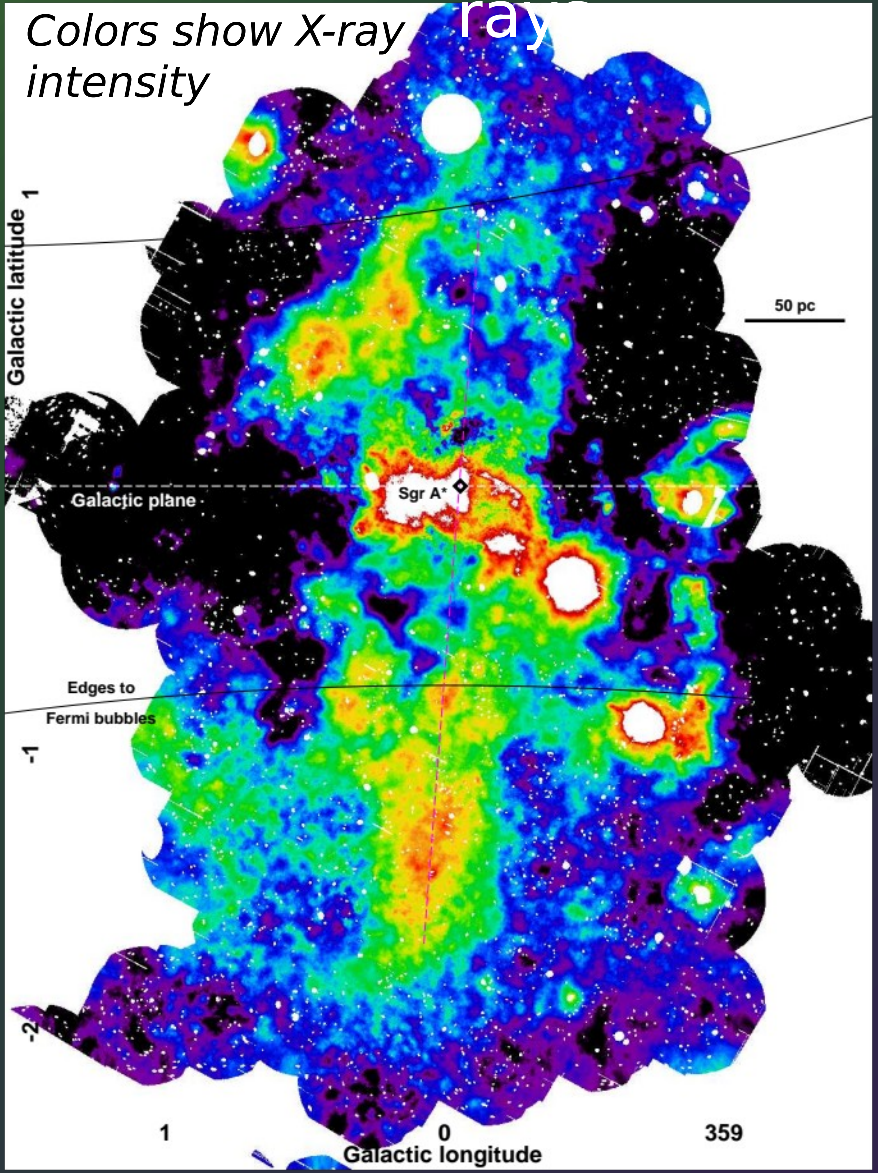
6cm VLA: J.H. Zhao, MRM, Goss 2016

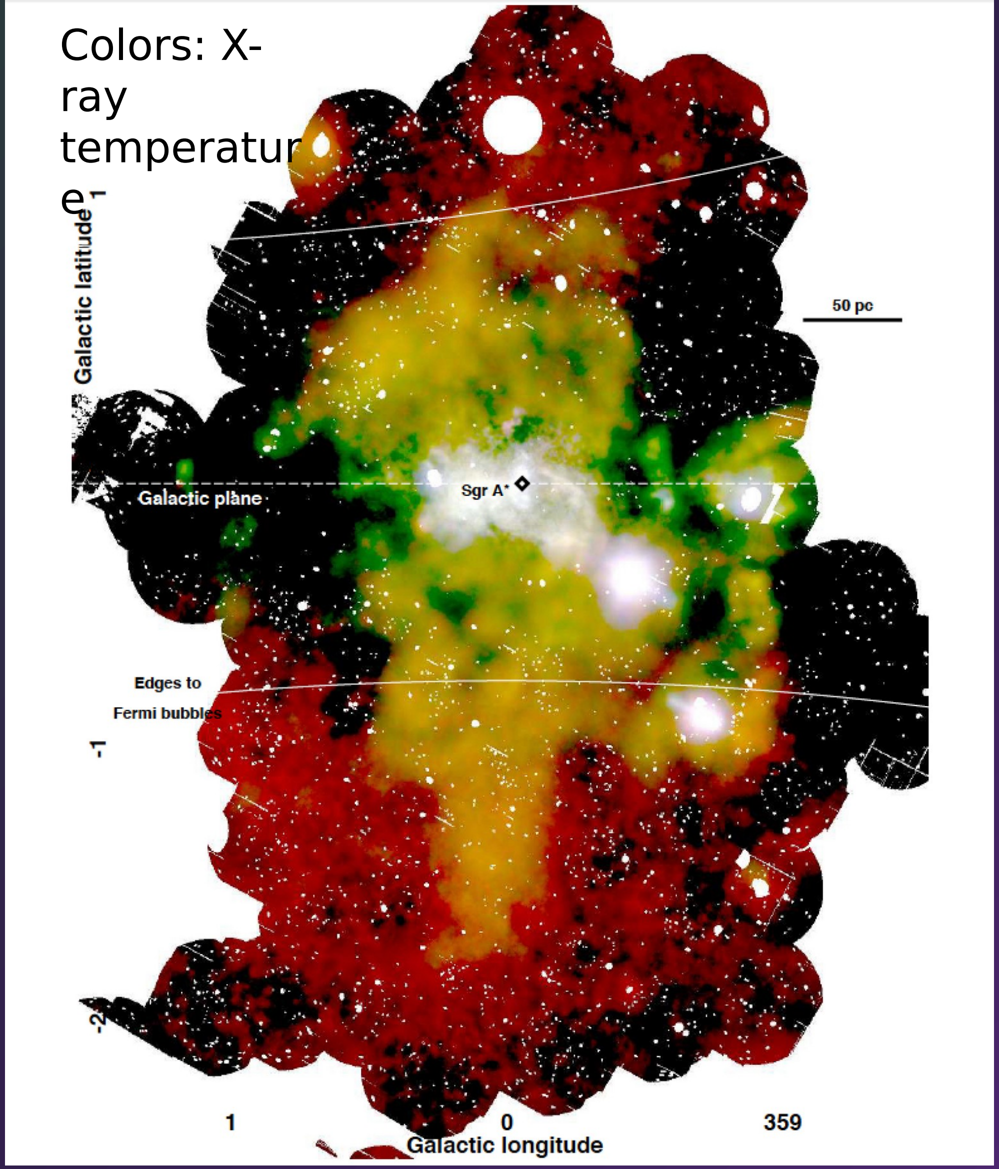


Radio contours on

The Galactic Center Chimney, X-ray

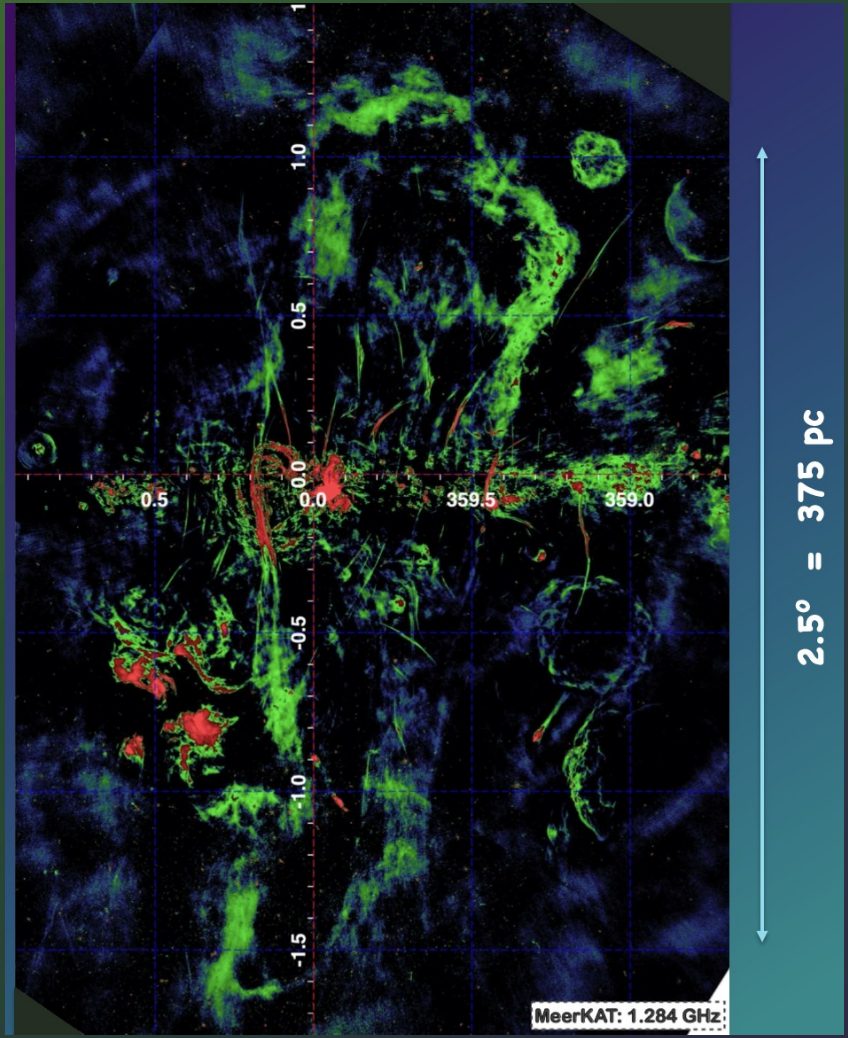
500 parsecs





Ponti et al. 2019, using the XMM-Newton Observatory

White spots → removed point sources



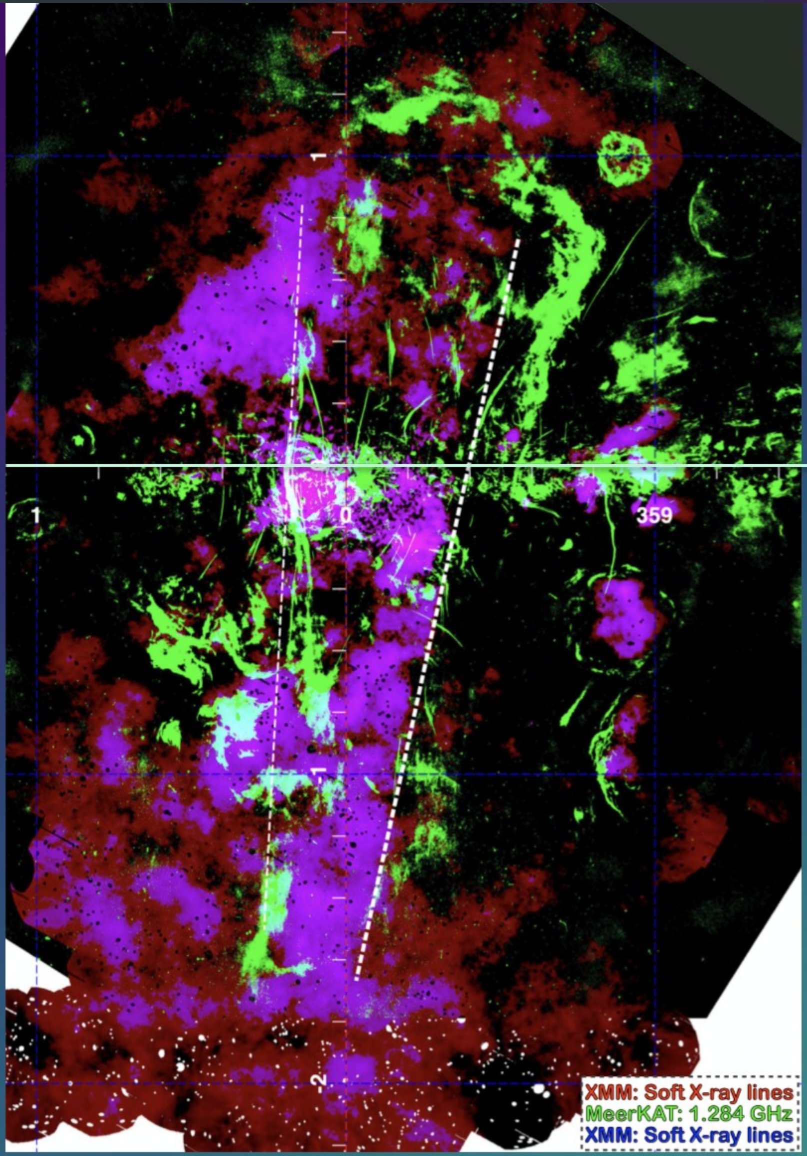
Heywood et al. 2019

Superposition of soft X-rays and radio

Radio ●

X-rays ●

- The X-ray chimney extends beyond the radio bubble
- Radio is more limb-brightened, forming a shell around the X-ray plasma



Galactic plane

Ponti et al. 2021

While the chimney could be at least partially powered by outflows from Sgr A*, it could also be powered by supernovae throughout the Central Molecular Zone

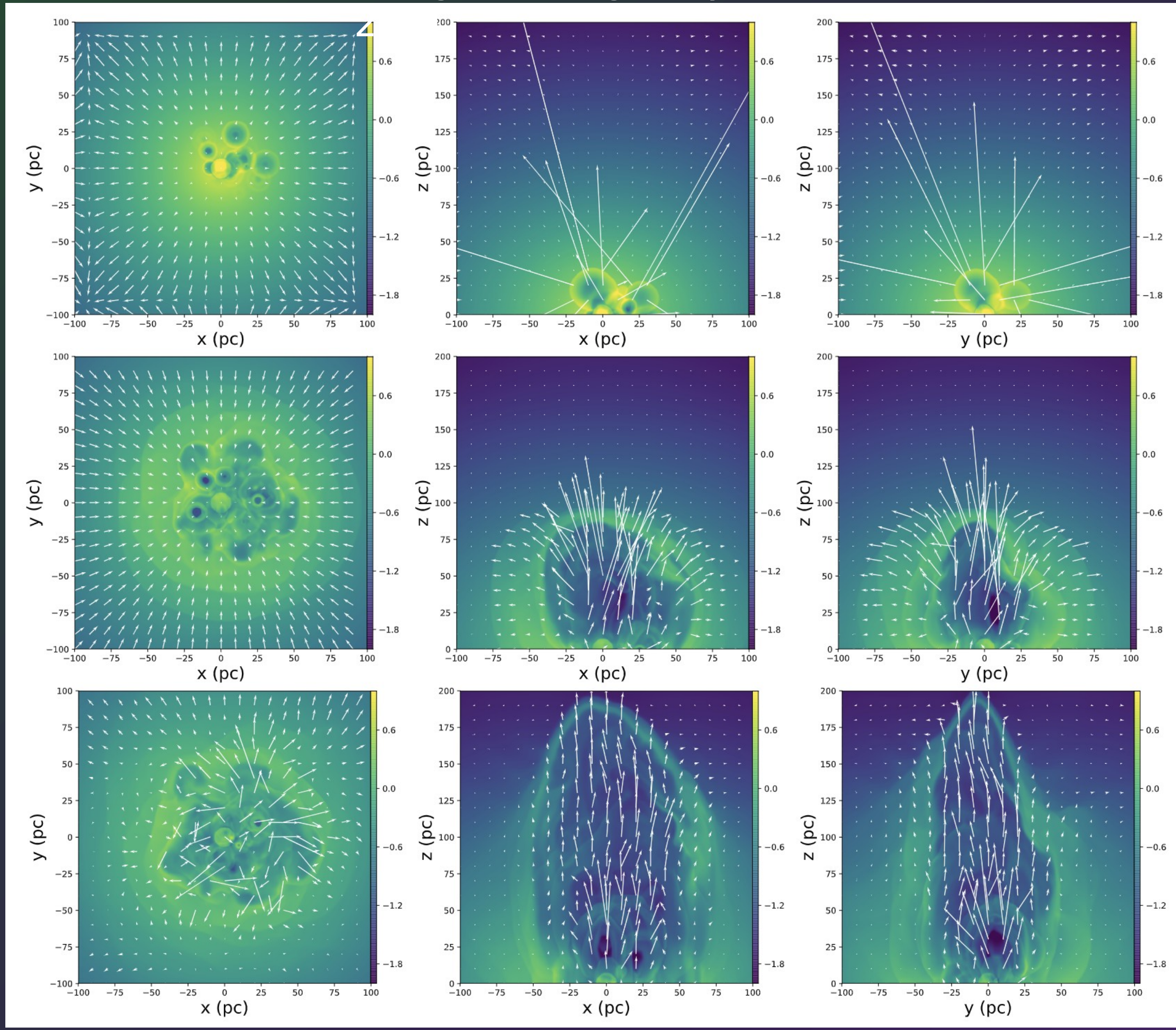
Views along all three axes, after ...

30 kyr

180 kyr

330 kyr

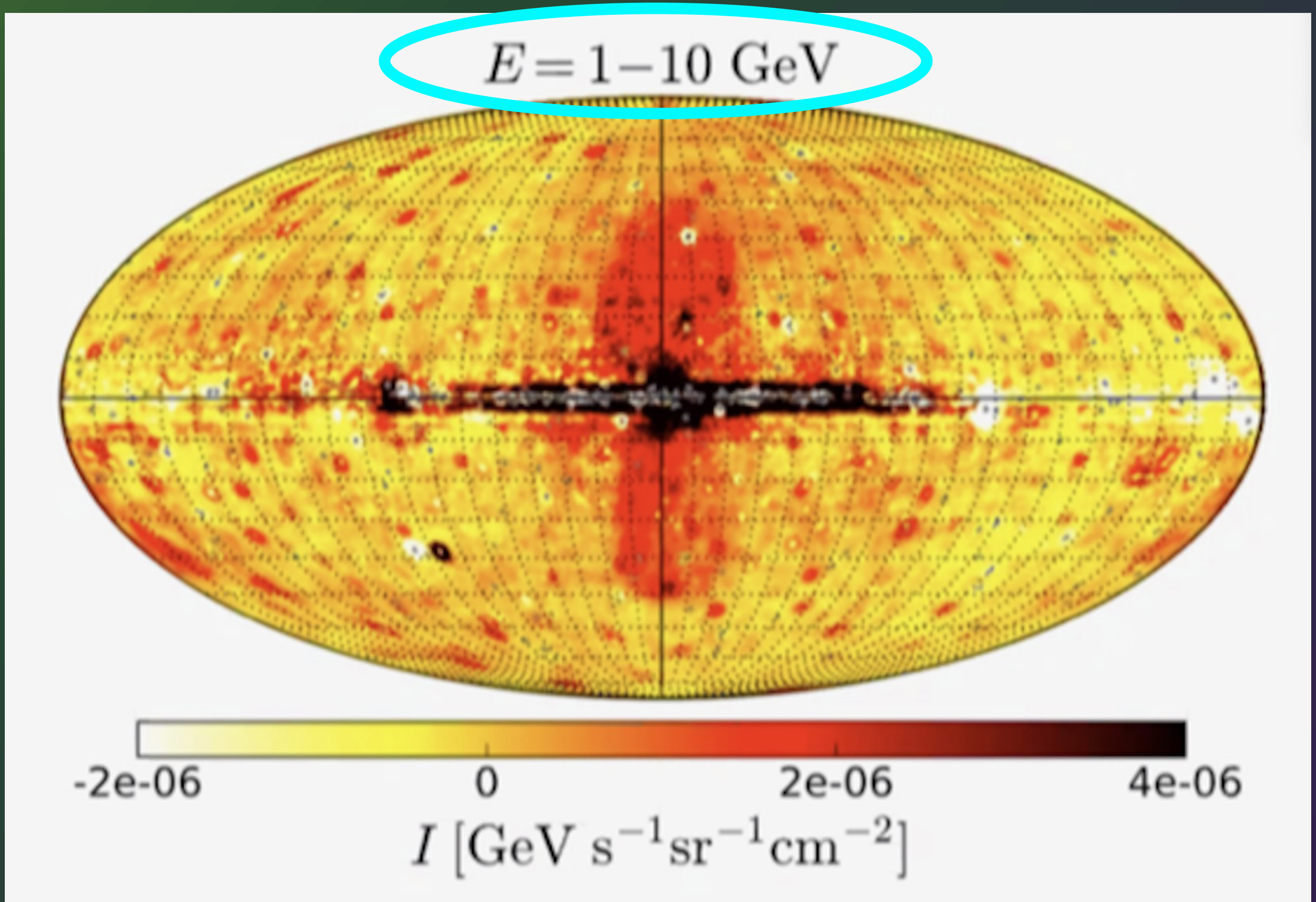
Mengfei Zhang, Zhiyuan Li, MRM



here: 1 SN/kyr

vertical B = 80 μG

The Fermi Bubbles



Cosmic rays generated by star formation in the CMZ ?

Crocker & Aharonian 2011, Crocker 2012, Lacki 2014
Crocker et al. 2015

Or channeled outflows from Sgr A* ?

Su et al. 2010, Zubovas, King & Nayakshin 2011
Zubovas & Nayakshin 2012
Guo & Mathews 2012, Yang et al. 2018, 2022

A Jet ?

- Considerable historical literature on how a highly collimated jet could account for the variable
radio emission from Sgr A* -- Falcke et al. 1993; Falcke & Markoff 2000; Markoff et al. 2001; Yuan, Markoff & Falcke 2002; Markoff, Bower & Falcke 2007; Falcke, Markoff & Bower 2009; Moscibrodzka & Falcke 2013)

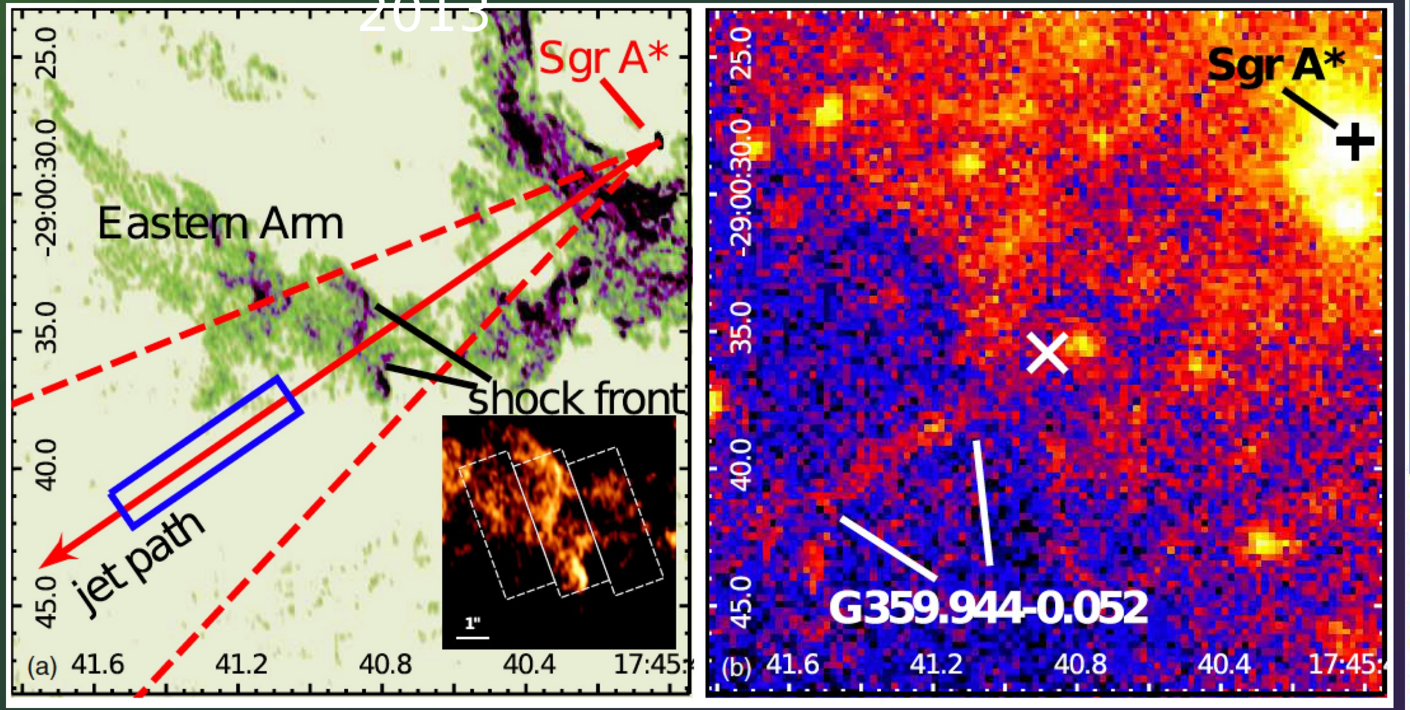
- But no obvious *radio* jet has been observed, and the recent focus has been on observing tl radio & submillimeter emission from the accretion flow within the inner few Schwarzchild radii, especially with the EHT Collaboration

- Various claims have been made for observable morphological manifestations of a jet, or a collimated outflow from Sgr A*, but none are yet widely accepted
Yusef-Zadeh et al. 1986; 2012, 2016, 2020; Sofue et al. 1989; Su & Finkbeiner 2012; Li et al. 2013, Gorski & Murchikova 2026, Cecil+2021
→ yesterday’s talk by Mark Gorski !

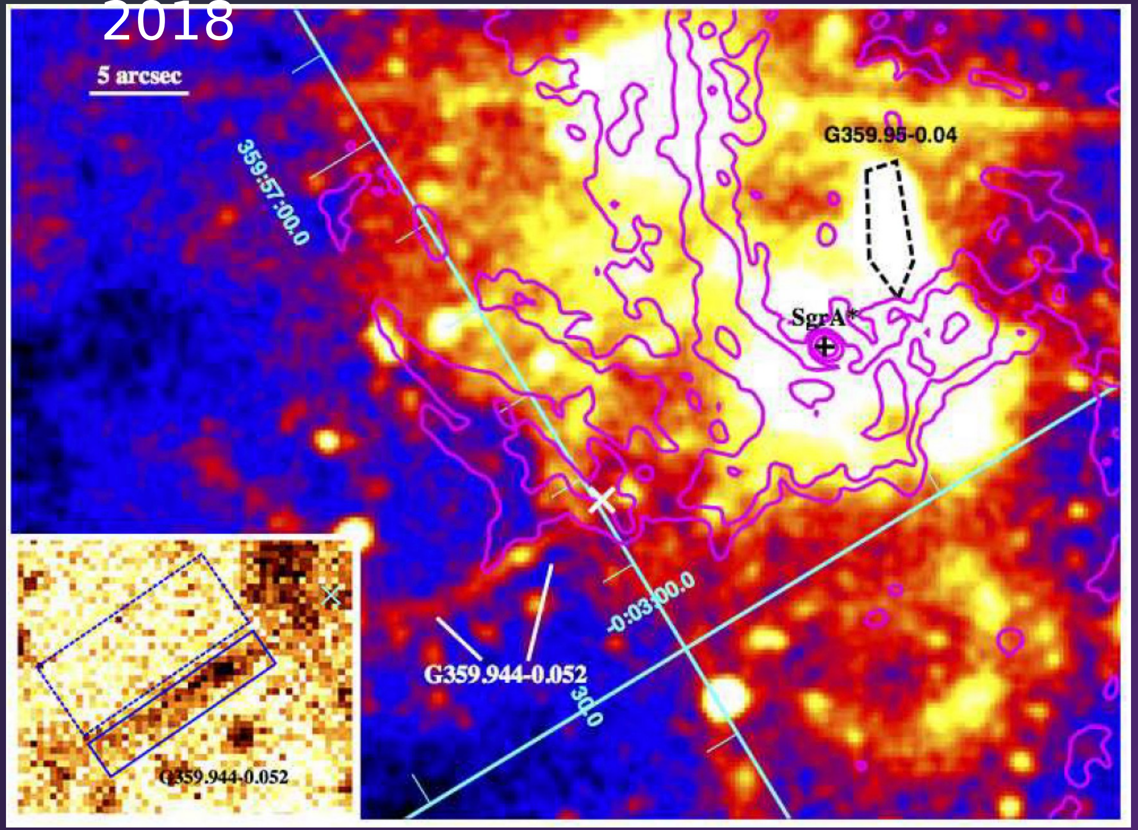
- However, there is a strong candidate for an X-ray jet well aligned with Sgr A*, but without a detected radio counterpart

Evidence for an X-ray emitting jet from Sgr A*

Zhiyuan Li et al. 2013

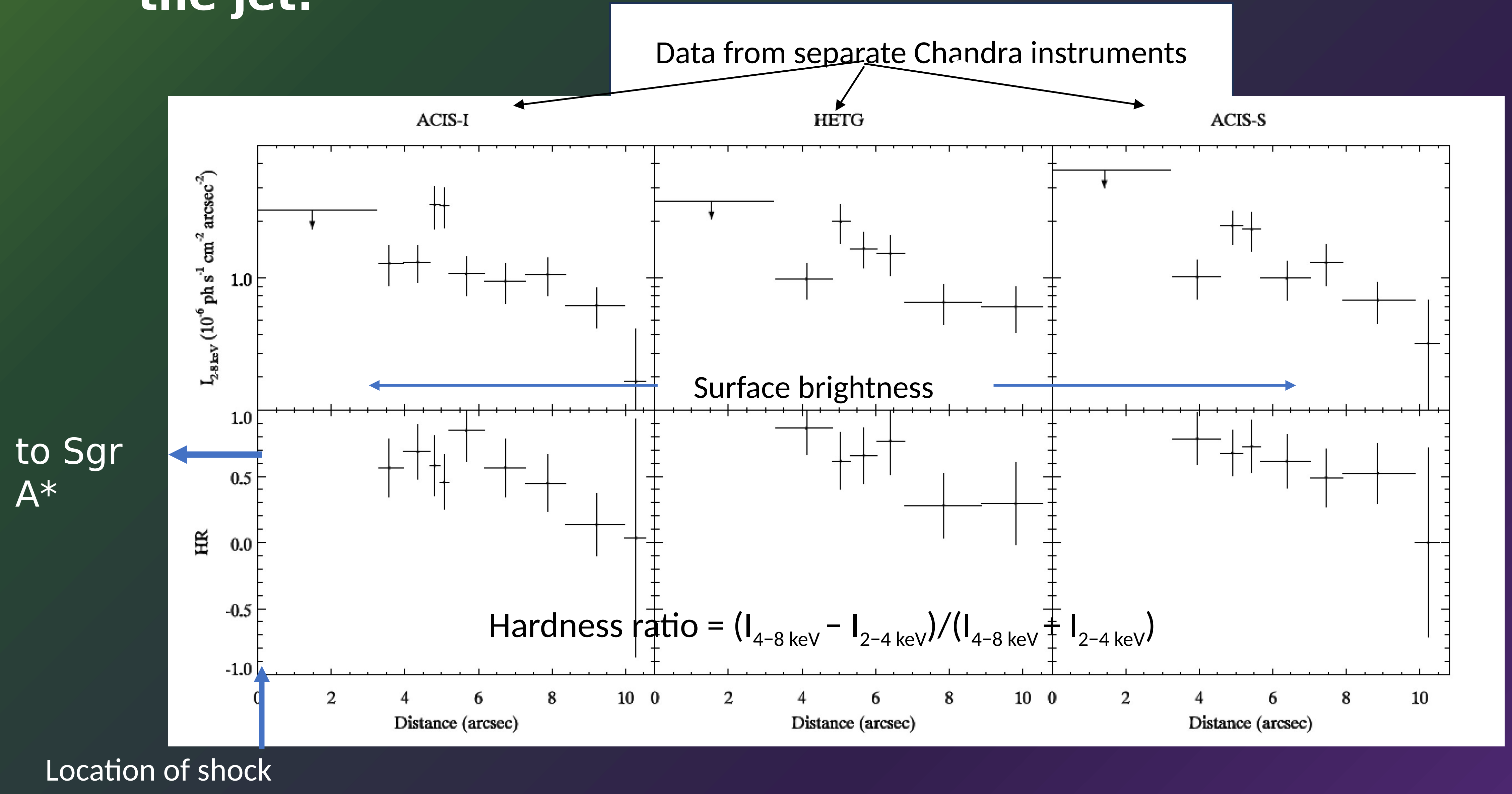


Zhenlin Zhu et al. 2018



This hypothetical jet is detectable starting at a shock in the Eastern Arm of Sgr A West

A key observation: spectral steepening along the jet:



How often do stellar collisions take place in the central parsec, and have
we already observed the aftermath of such collisions?

Modalities of stellar collisions:

- Collisions of independent stars or remnants → mostly grazing collisions at high velocities
- Binary stars undergoing extreme eccentricity oscillations driven by the Eccentric Kozai-Lidov (EKL) effect of a third massive body (Kozai 1962; Lidov 1962; Naoz 2016)
    - 3rd body is the supermassive black hole → most commonly invoked
    - Perturber is an asymmetric mass distribution (e.g., a non-axisymmetric cluster, Haas & Subr 2021)

Potential Evidence

- Depletion of red giants within ~ 0.3 pc of Sgr A*
- Existence of G objects – see several later talks
- The gas feature X7

- It has long been noted that red giants are underrepresented in the central 0.3 pc.
- Collisional removal of their atmospheres
  is one possible way to account for that

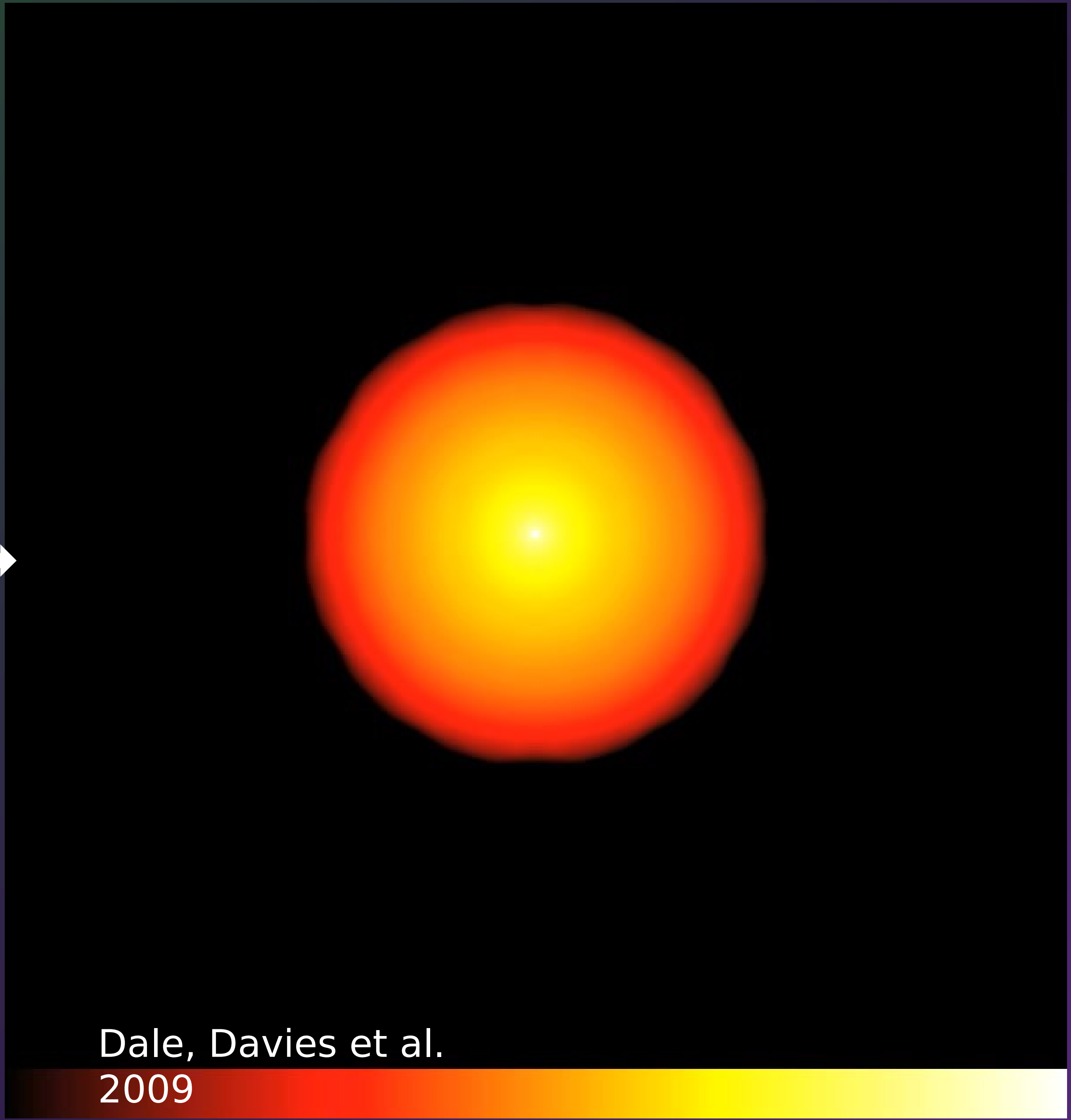
  Genzel+1996; Alexander 1999; Bailey & Davies 1999;
  Dale, Davies+2009; Davies+2011; Gallego-Cano+2018;
  Schödel+2018; Baumgardt+2018; Rose+2023,
  Kim & Goodman 2026

- In a cluster of stellar-mass black holes, red giants are big targets

Black hole – red giant collision

In this case, the expelled mass is widely distributed

But to account for the central dearth of red giants, the number density of black holes would have to be larger than some current limits on the extended dark mass

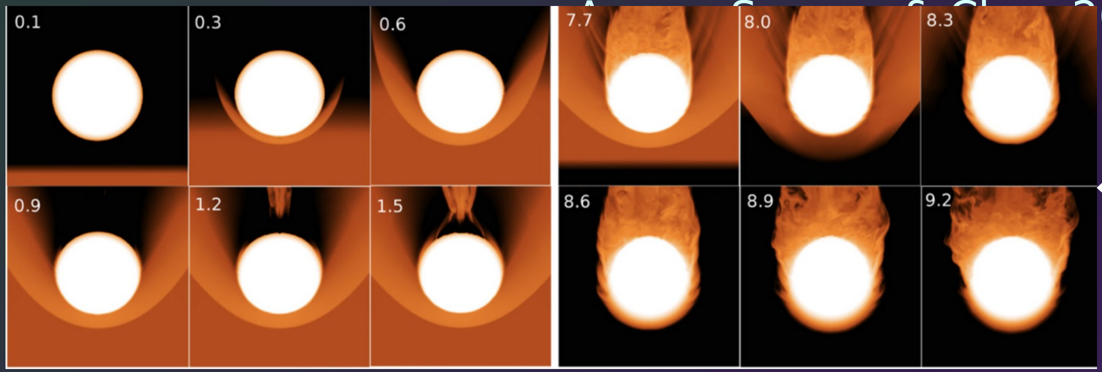


There are other mechanisms for removing red giant atmosphere, so we should hesitate to use the depletion of red giants as evidence for stellar collisions

1. The massive black hole has clearly had a massive star-forming accretion disk around it in the recent past, and red giants passing through such a disk in their orbits will have a portion of their atmosphere stripped in each passage. That would occur many times for every star near Sgr A* during the lifetime of such a disk.

014; Kieffer & Bogdanovic 2016

Red giant entering and leaving accretion disk



2. Strong outflows during Sgr A*’s active phases: jets can strip red giant atmospheres

Zajacek et al. 2020 see today’s talk by Petr Kurfürst

Most stellar collisions in the Galactic center would be expected to be high-speed grazing collisions that eject material in a preferred direction

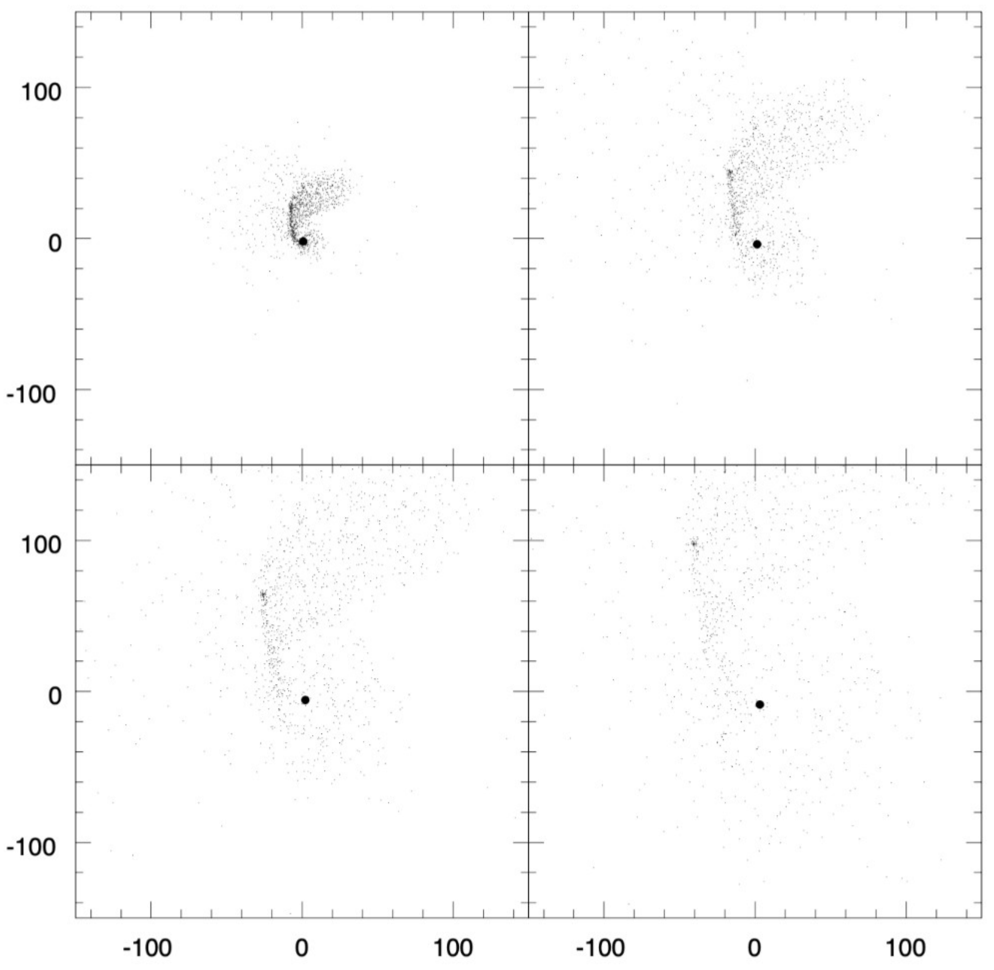
- Collision of a 10 M_8 black hole with a 1 M_8 main-sequence star

- The ejected material in high-speed collisions would be sent along an axis close to the direction of their relative velocity vector

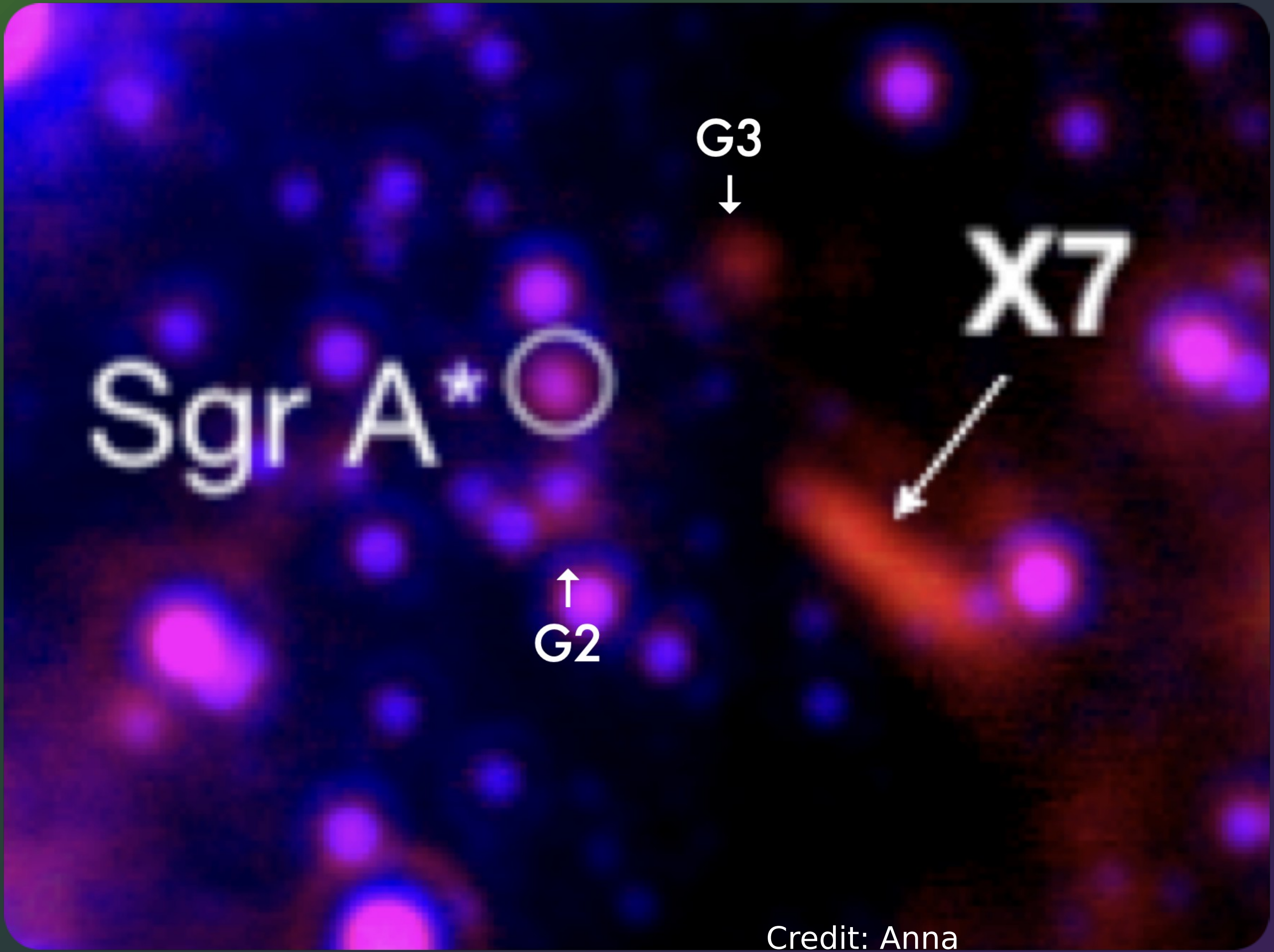
- Such a collision could be between two unrelated stars, or between the members of a binary whose eccentricity has approached unity as a result of the EKL effect

- An attractive candidate: X7

Davies, Church, Malmberg, Nzoke, Dale and Freitag 2011



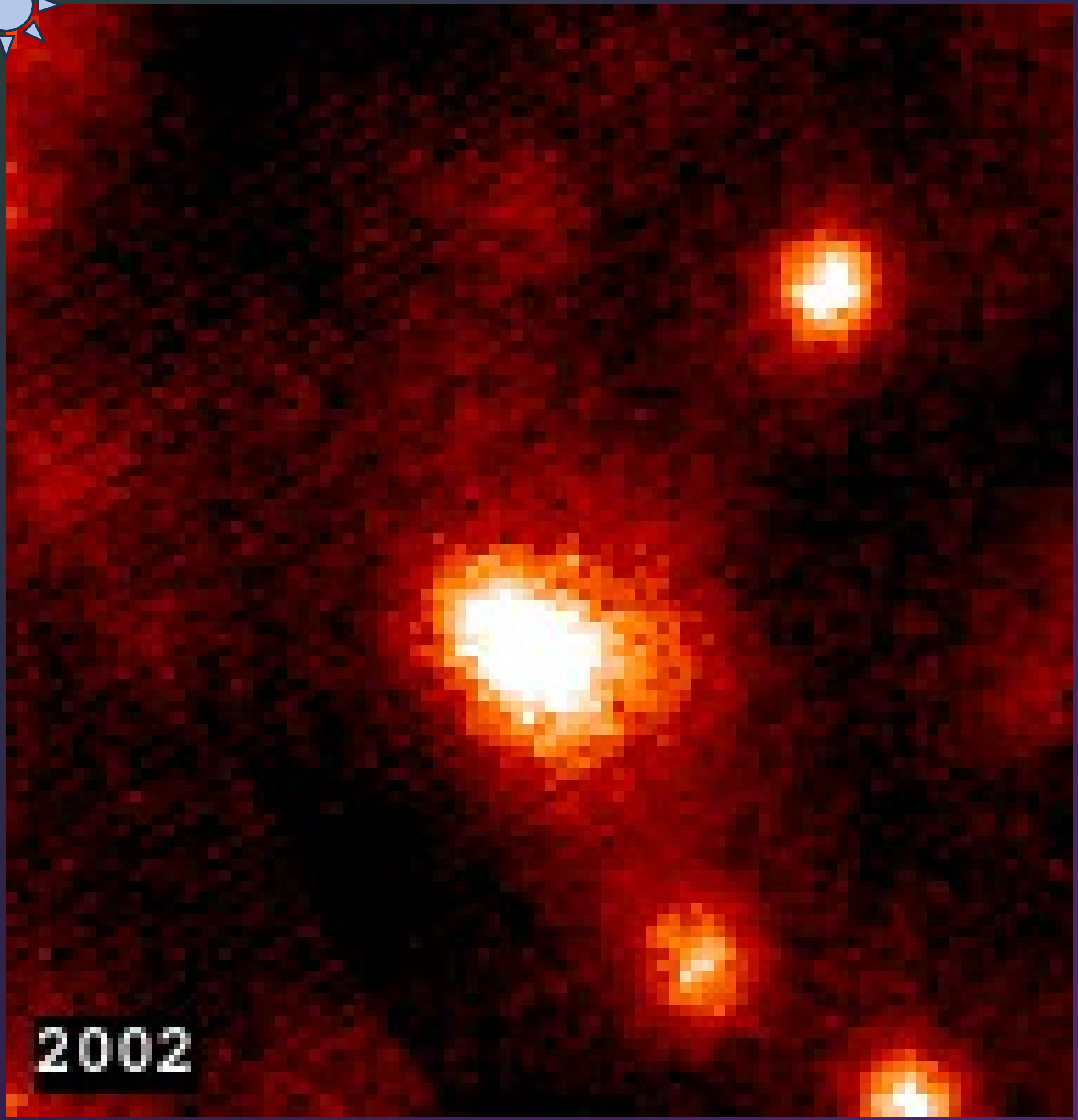
A candidate ejecta feature resulting from a stellar collision: the gas/dust cloud X7



Credit: Anna Ciurlo

Keck NIRC2 imaging (M/L/K)

Sgr A*



X7 through time, 2003 – 2021

3.8 µm imaging with NIRC2 on the Keck 2 telescope

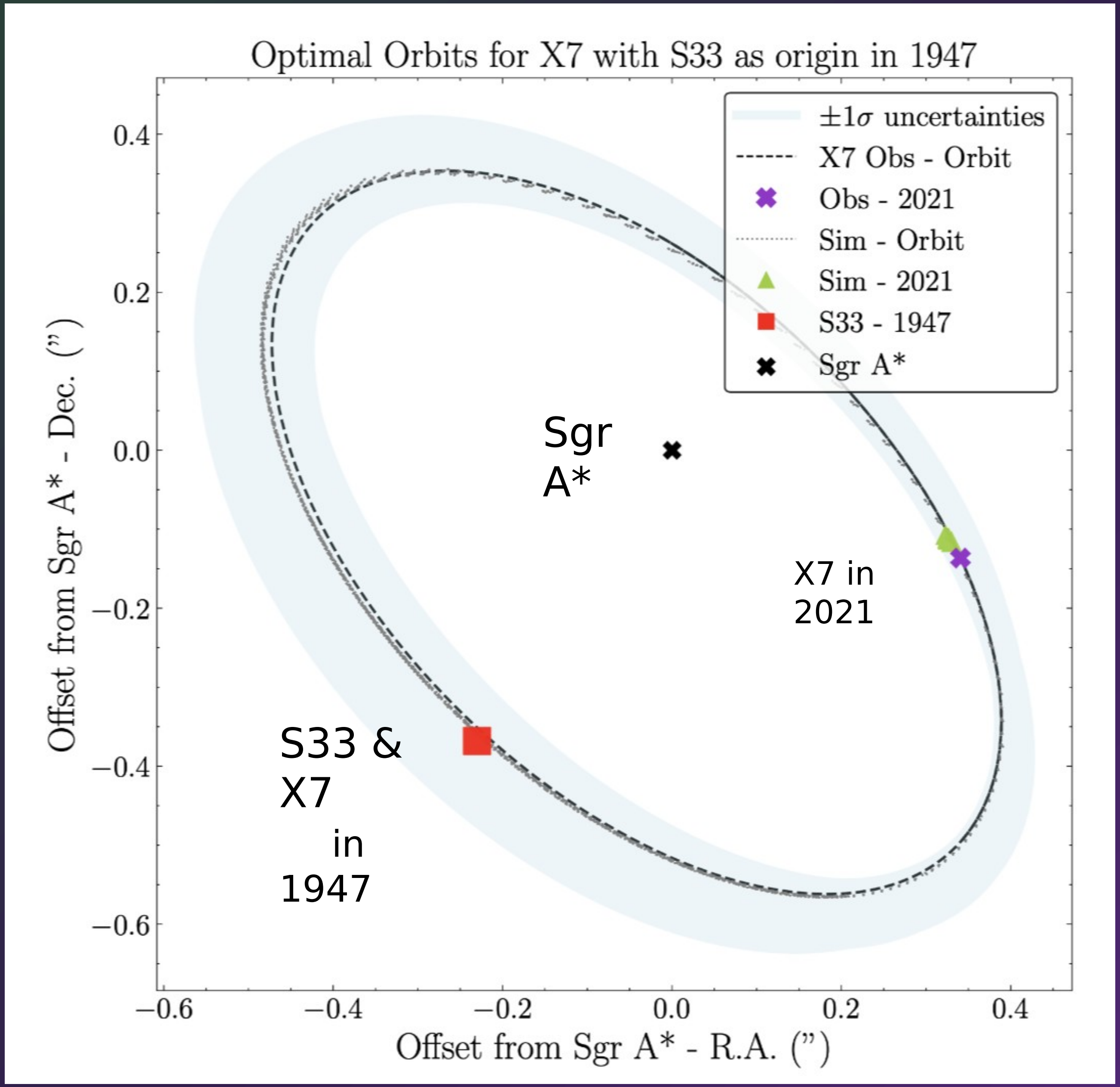
Is this 50 earth-mass gas/dust feature
the result of a stellar collision?

This question was investigated by Wasif Shaqil et al. 2025, who found
an excellent candidate:
the star S33/S0-30

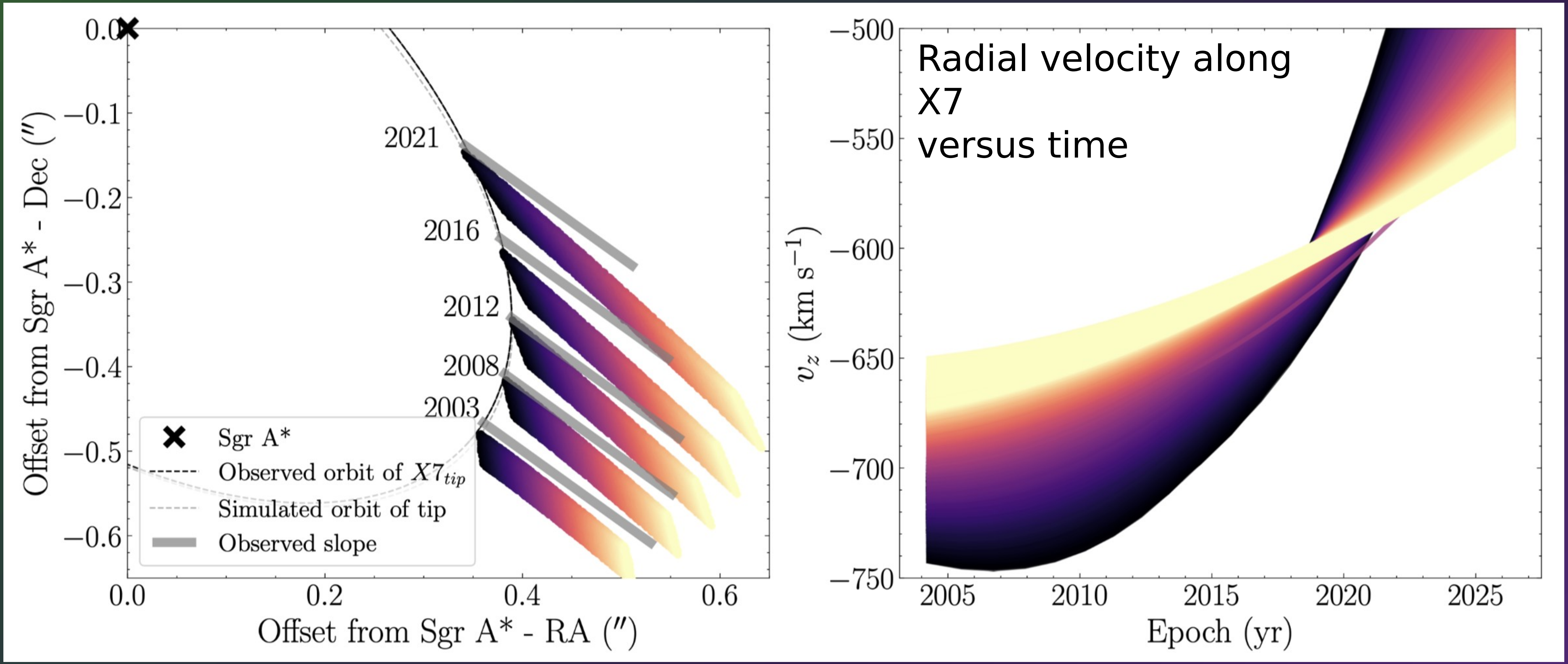
Based on the orbit of S33*, and the
orbit determined for the tip of X7,
the minimum distance between them
was ~ 610 AU ± 1000 AU and their
relative velocity was ~ 500 km s^{-1} in
the year ~1947.

*von Fellenberg et al. 2022

collision partner?



With the choice of initial ejection speed of 600 km/s the morphology and velocity structure
of Shaqil et al. (2025) agree well with the measurements of Ciurlo et al. (2024)



How can we best investigate the expected presence of a concentration of
stellar remnants, and in particular, stellar-mass black holes, in the
entourage of Sgr A*?

Mass segregation:

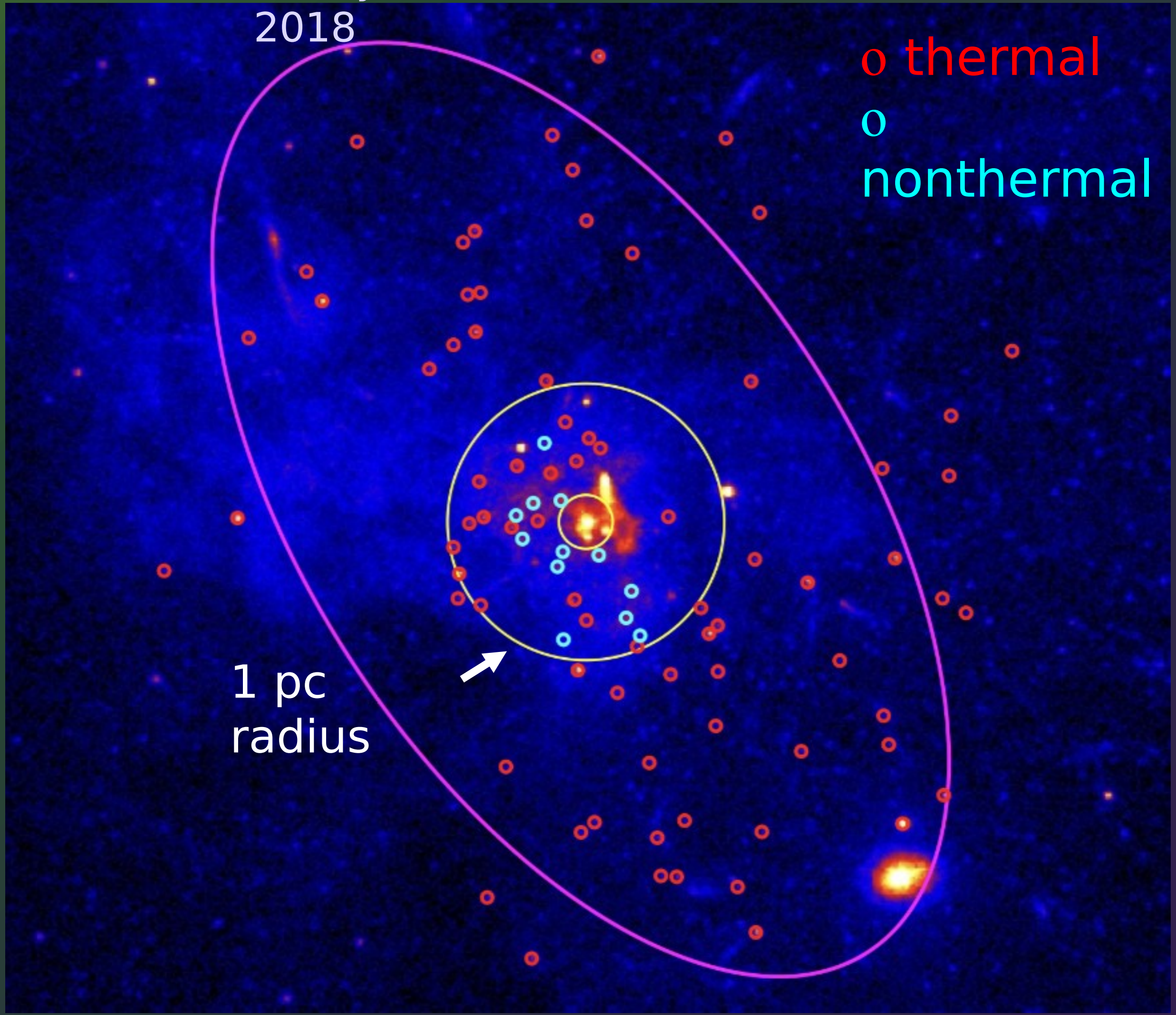
Morris, M. 1993, ApJ 408, 496
Miralda-Escudé, J. & Gould, A. 2000, ApJ 545, 847
Freitag M., Amaro-Seoane P., Kalogera V. 2006, ApJ 649, 91
O'Leary R. M., Kocsis B., Loeb A. 2009, MNRAS, 395, 2127
Merritt D. 2010, ApJ, 718, 739

Early universe merging of massive stellar clusters:

Antonini 2014 -- creating a central cusp of BHs. 1000 BHs in dynamical equilibrium with
S-star cluster accounts for their quasi-thermal distribution of eccentricities

Chandra 2–8-keV image of the Galactic Centre with X-ray point sources

Hailey et al. 2018



Hailey et al. interpret these 12 “soft” nonthermal sources as low-mass X-ray binaries containing a black hole.

They rule out neutron-star LMXBs because
They would have short recurrence times
of ~ 5–10 years between their large X-ray
outbursts

Note their central concentration

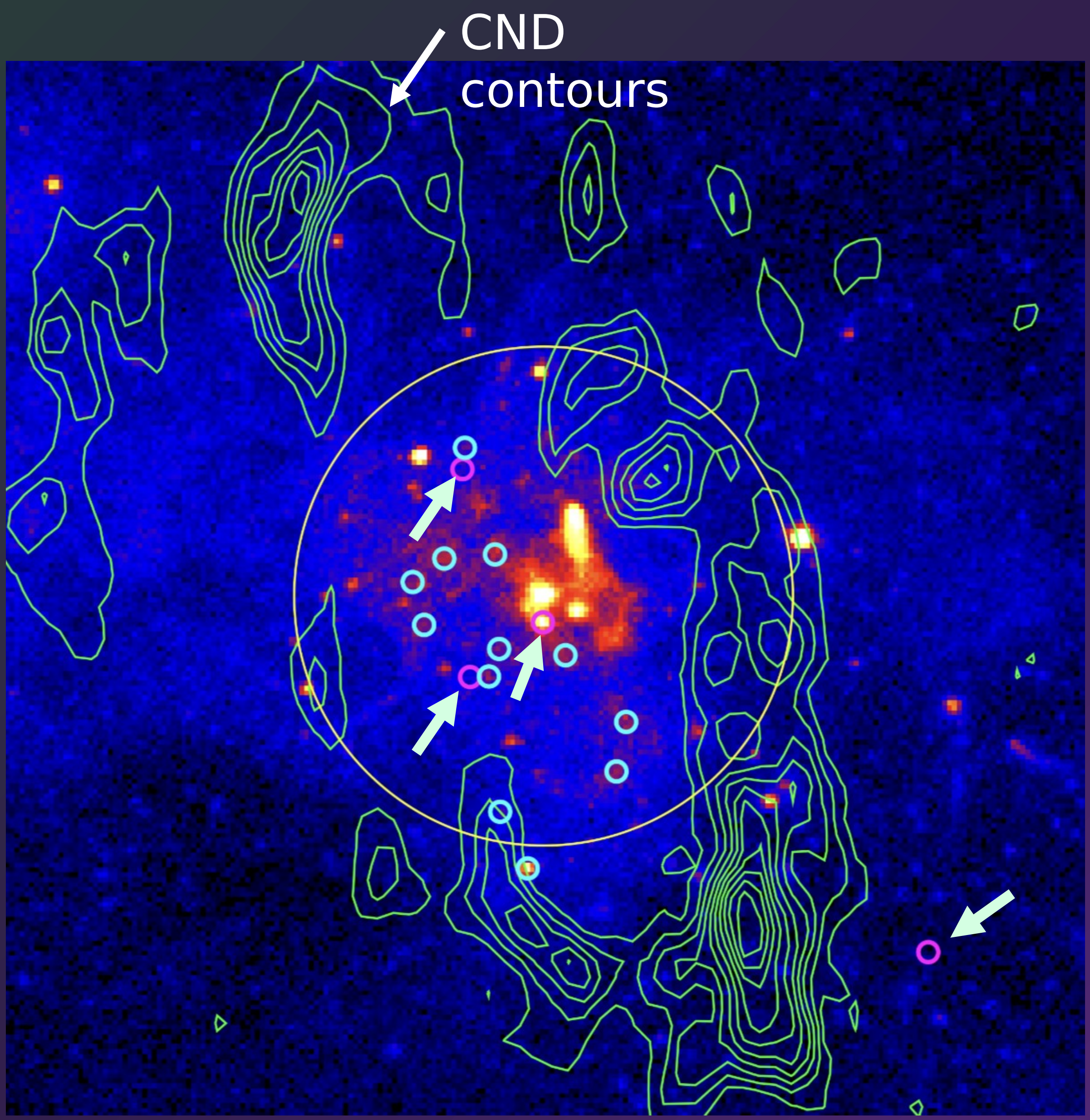
BHXRB formation:
Generozov et al. 2018: Of the ~1–4 × 10^4 BH that accumulate in the central parsec over the age of the Galaxy, predict ~60–200 currently exist as BH-XRBs formed from tidal capture, consistent withthe po pulation seen by Hailey

Krivonos et al. 2021:

- Long-term variability found in 9 of the 12 non-thermal sources (blue circles), indicating that most of them are quiescent XRBs rather than rotation-powered millisecond pulsars

- X-ray single outburst transients (cyan circles)
  2 of these are interpreted as BH-LMXRBs by Mori et al. 2019 using NuSTAR observations

- von Fellenberg, Labaj & Ressler: Possibilities for vastly increasing the known population of compact objects in central parsec binaries, particularly black holes using MICADO on the VLT



Where are the neutron stars?

- The “missing pulsar problem” is well-known and well documented. Given all the massive
stars in the Galactic center, past and present, there are almost no pulsars to be found,
not only in the central parsec, but throughout the CMZ

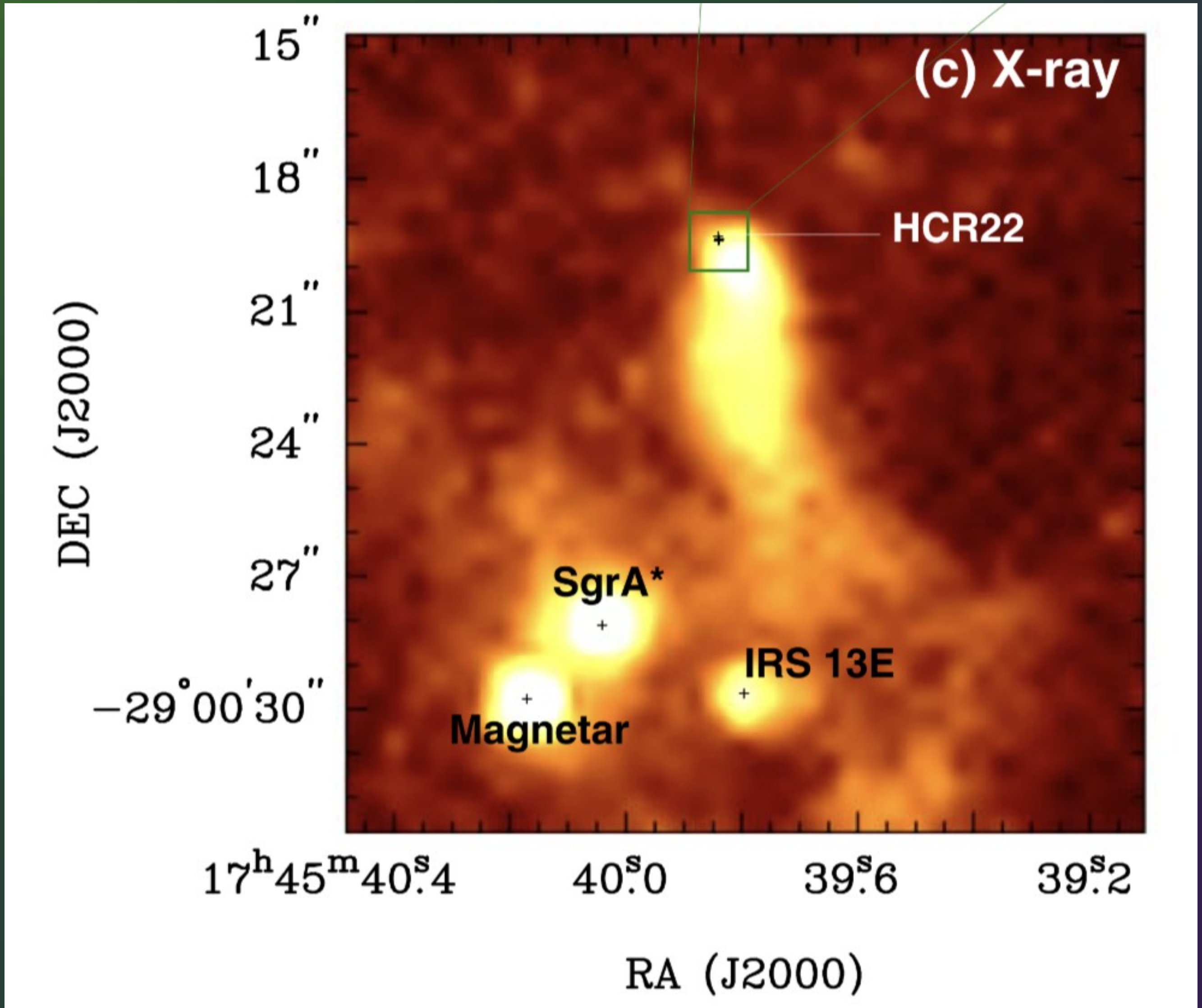
- ~10% of all high-mass stars in the Galaxy reside within ~200 pc of the GC

  e.g., Figer et al. 2004; Lorimer & Kramer 2004; Deneva et al. 2009; Mauerhan et al. 2010

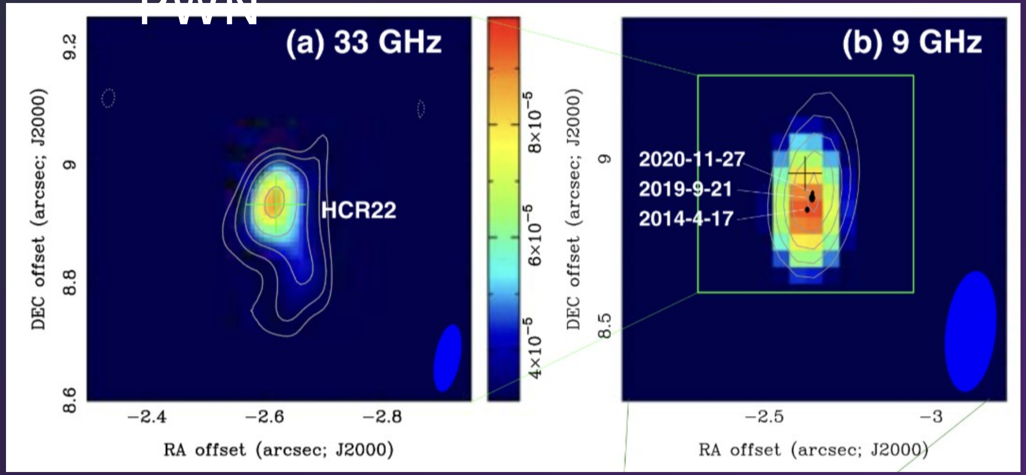
- Constant star formation and recent starburst models predict 10^2 – 10^8 NSs in the GC,
with 10–10^5 likely to be active pulsars Cordes & Lazio 1997; Nogueras-Lara et al. 2019, Perez et al. 2026

- Only 1 in the central parsec… the magnetar SGR J1745-2900, 2.4” away from Sgr A*

See later talk by Joanna Berteaud



Rado observations of the PWN



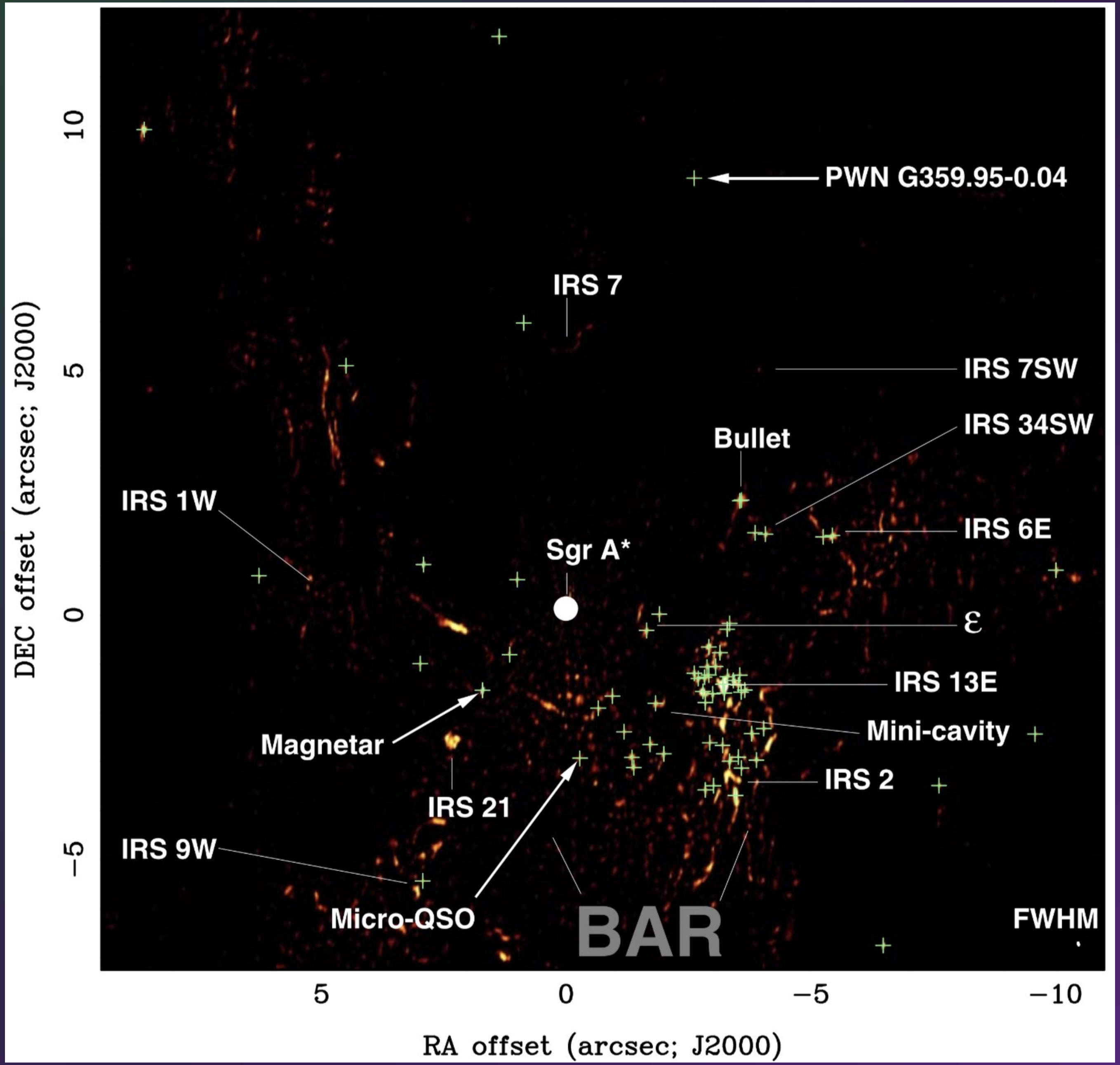
Zhao et al. 2023

Hypercompact Radio Sources in the
Central Parsec

Jun-Hui Zhao, MRM, W.M. Goss

33 GHz VLA observations with
0.08” x 0.03” resolution →

A sizeable population of relatively
high-frequency radio sources



The magnetar gives a potential clue ! Dexter & O'Leary 2014 →

The gas in the Central Molecular Zone is rather strongly magnetized, so are the stars
that formed there also strongly magnetized, and destined to leave behind highly magnetized
stellar remnants, i.e., magnetars?

Why might that help?

→ magnetar lifetimes as detectable pulsars are short (10^4 years) because of strong
magnetic braking, compared to normal pulsars (~few 10^6 yrs)

→ So the neutron stars in the GC might largely be "retired" as pulsars

→ So how could we find them if they are not newly formed?

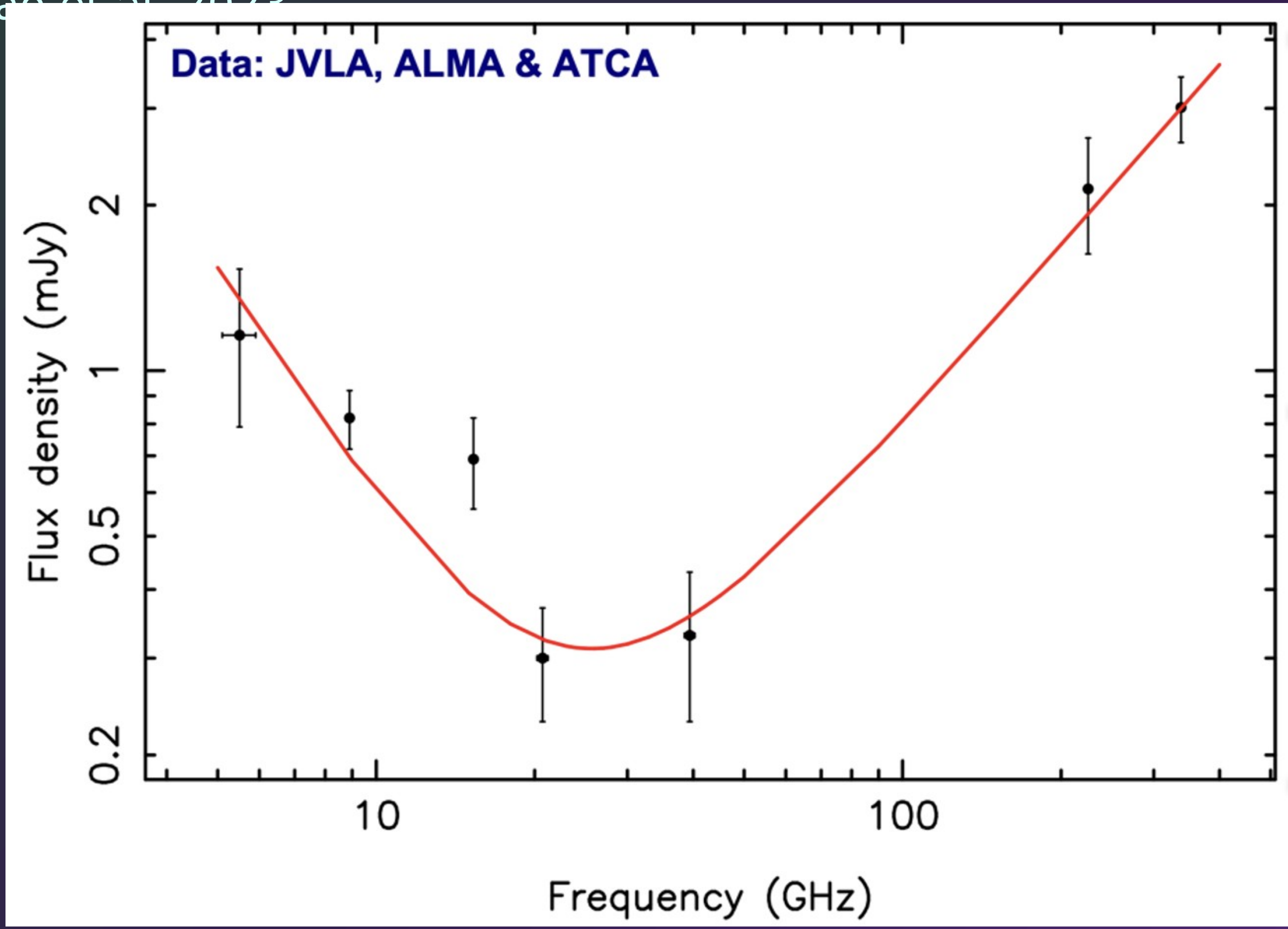
Pulsars usually have steeply falling spectra, but the magnetar has an inverted spectrum

Torne et al. 2017, Tsuboi et al. 2017, Zhao et al. 2023

Is this a common characteristic of magnetars?

If so, some of the hypercompact radio sources might be “dead” pulsars

→ Open question TBD



There are many more open questions.....

Let’s keep working