

Large-scale radio bubbles around the black hole transient V4641 Sgr

Microquasar Workshop XI (2025)

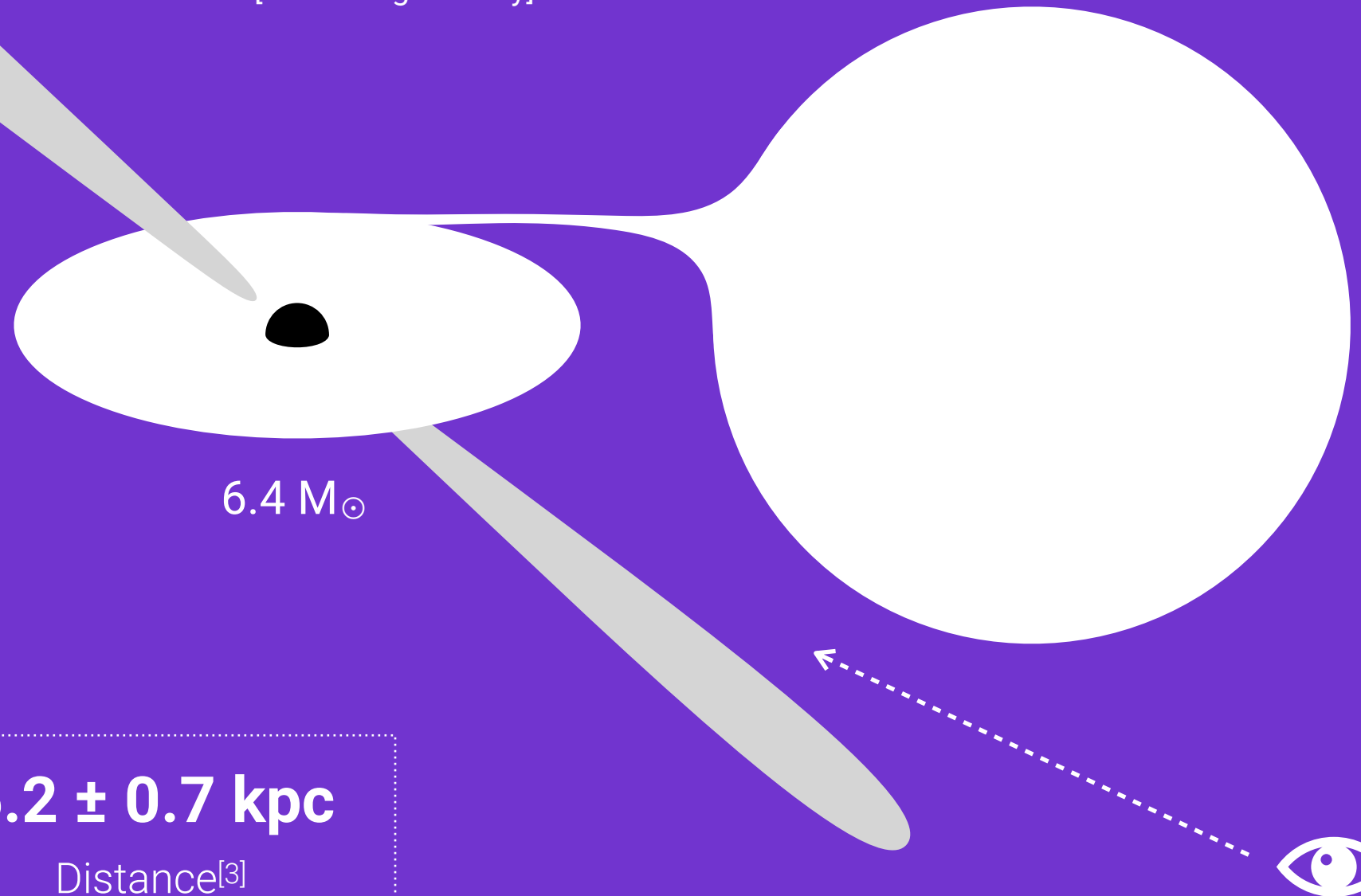
Noa Grollimund (PhD student at CEA Saclay/Univ. Paris Cité, France)

with Stéphane Corbel (PhD advisor), Rob Fender, James Matthews, Ian Heywood, Fraser Cowie, Andrew Hughes, Francesco Carotenuto, Sara Motta and Patrick Woudt
as part of the *ThunderKAT* and *X-KAT* collaborations

V4641 Sgr

[Possible geometry]

B9III star / $2.9 M_{\odot}$



1999

Discovery^[1]

Superluminal

radio jets in 1999^[2]

6.2 ± 0.7 kpc

Distance^[3]

$\sim 1-3$ years

Outburst recurrence time

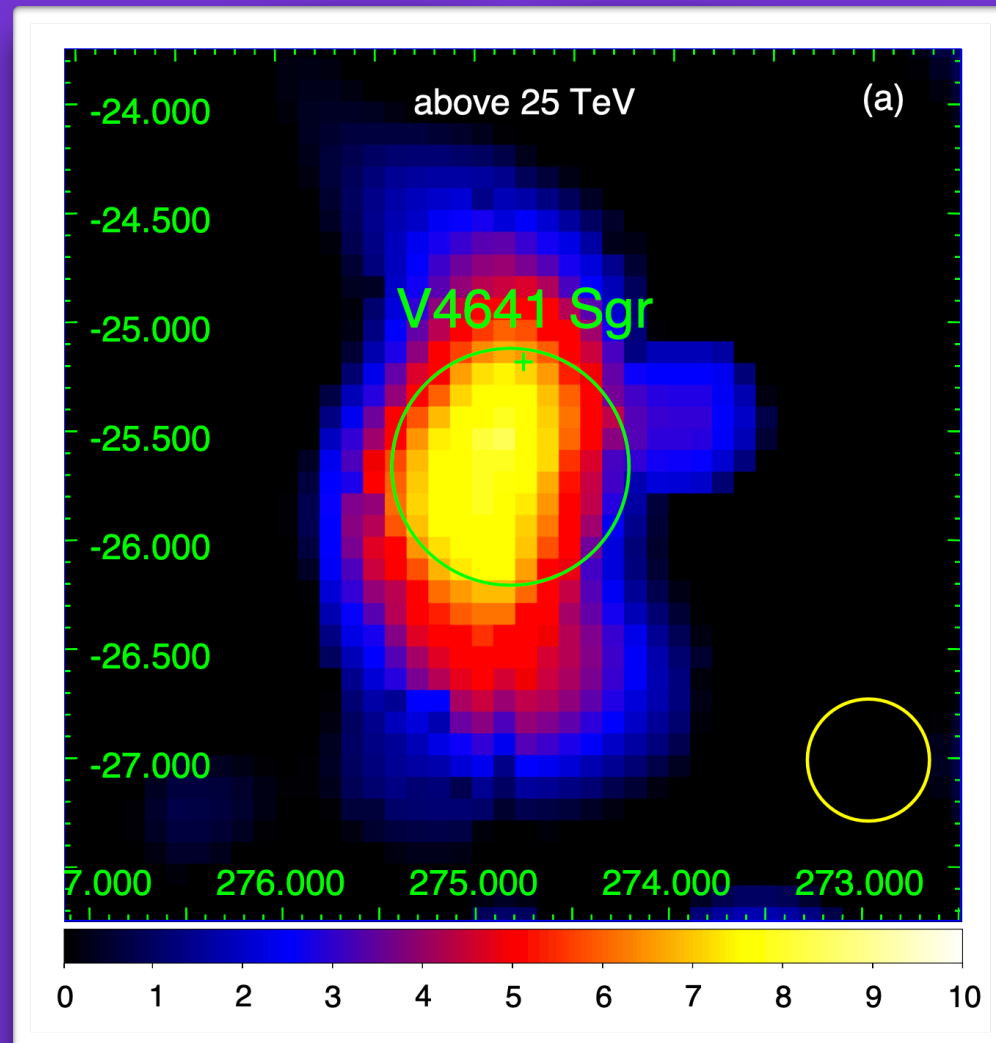
Strong spin-orbit misalignment

High orbital
inclination
($72.3 \pm 4.1^{\circ}$)^[4]

vs

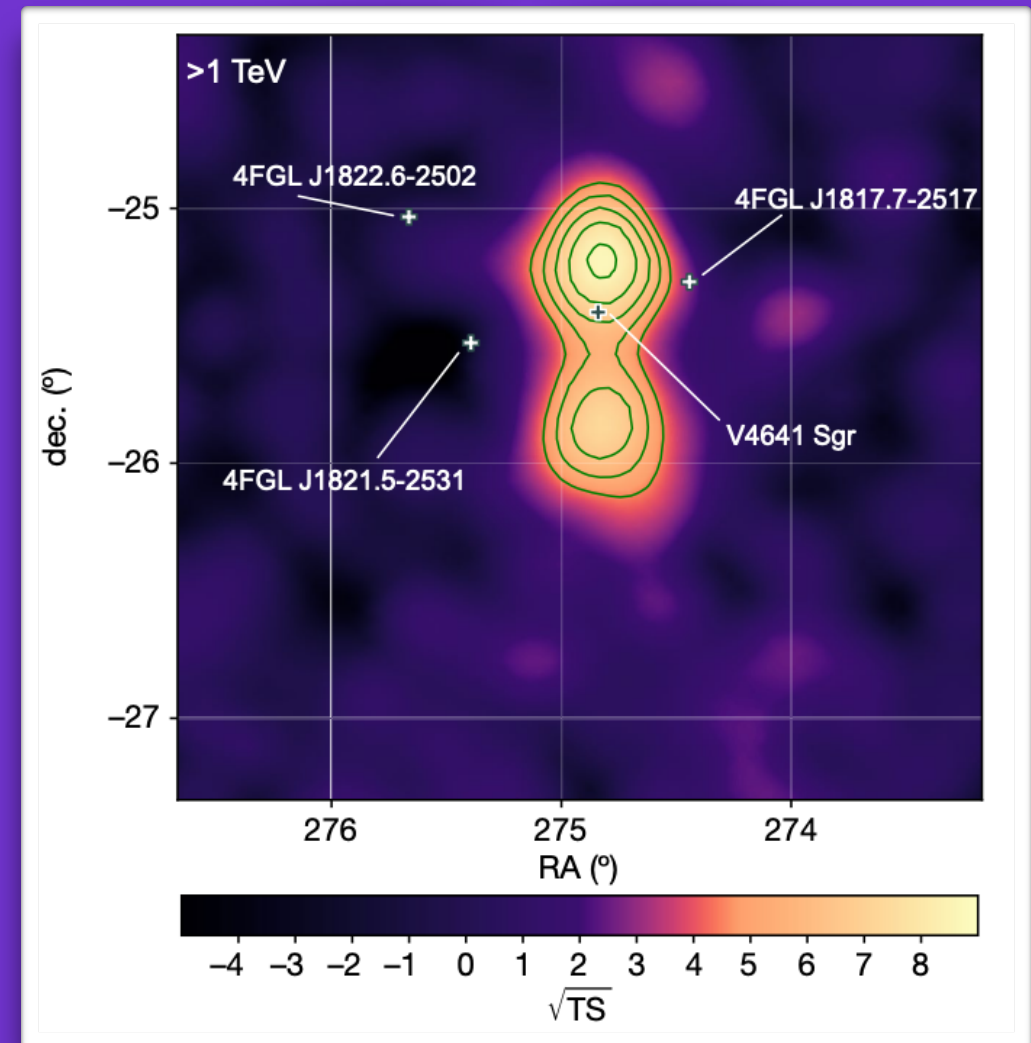
Low jet
inclination
($< 16^{\circ}$)^[2,5]

Very-high-energy gamma-ray bubbles



LHAASO Collaboration 2024

LHAASO



Alfaro+2024

HAWC

→ **Microquasars** as promising **PeVatron** candidates

MeerKAT deep observations

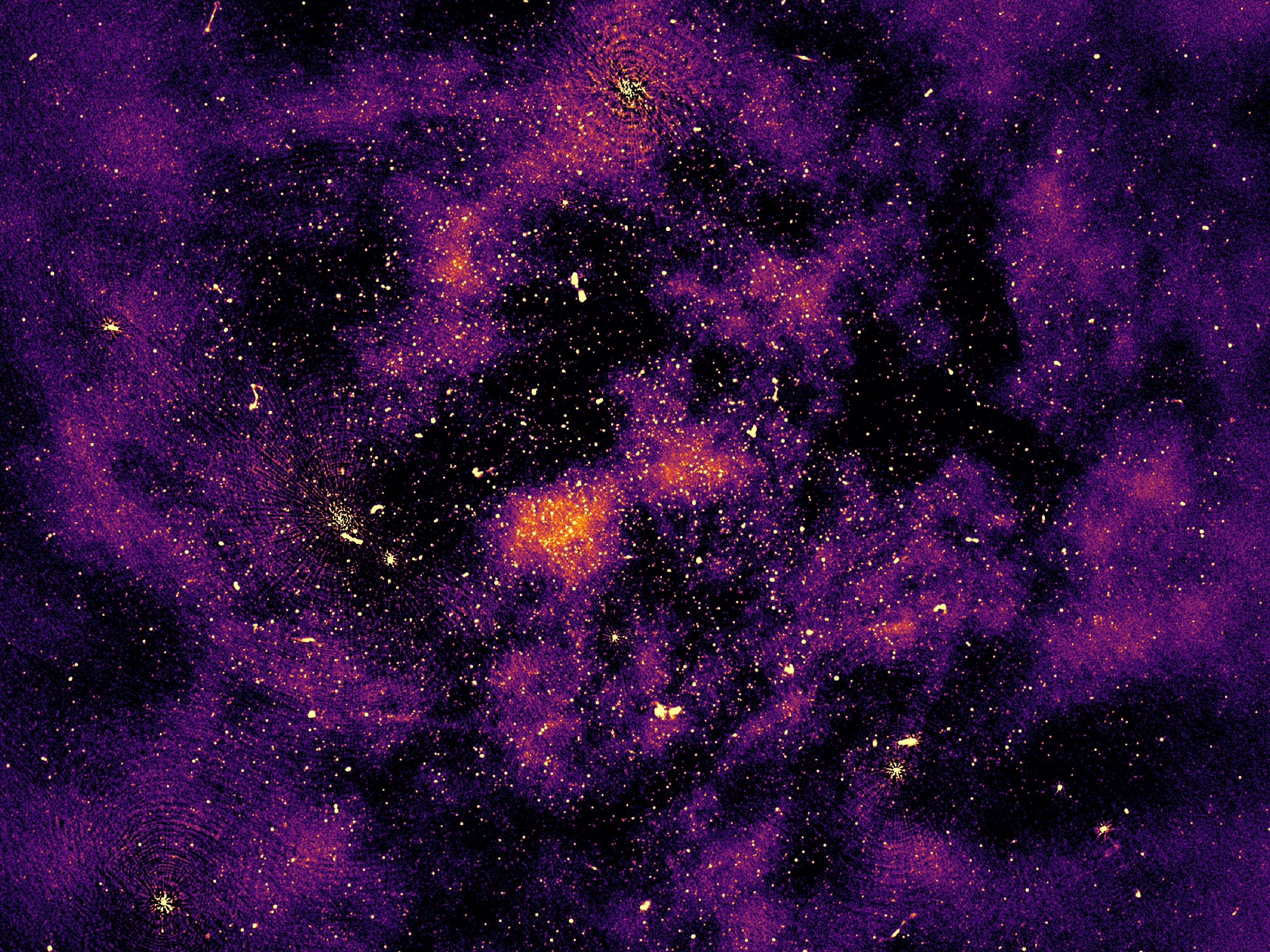


- Archival (2021-2022) & new (2024-2025) observations as part of the **ThunderKAT** & **X-KAT** programs
- L-band (**1.2 GHz**) / UHF-band (**0.8 GHz**)
- Total exposure time of **11h** / **1h**



- Reduced and imaged using **high dynamic range** techniques
→ RMS noise level of **$\sim 4 \mu\text{Jy/bm}$** at L-band



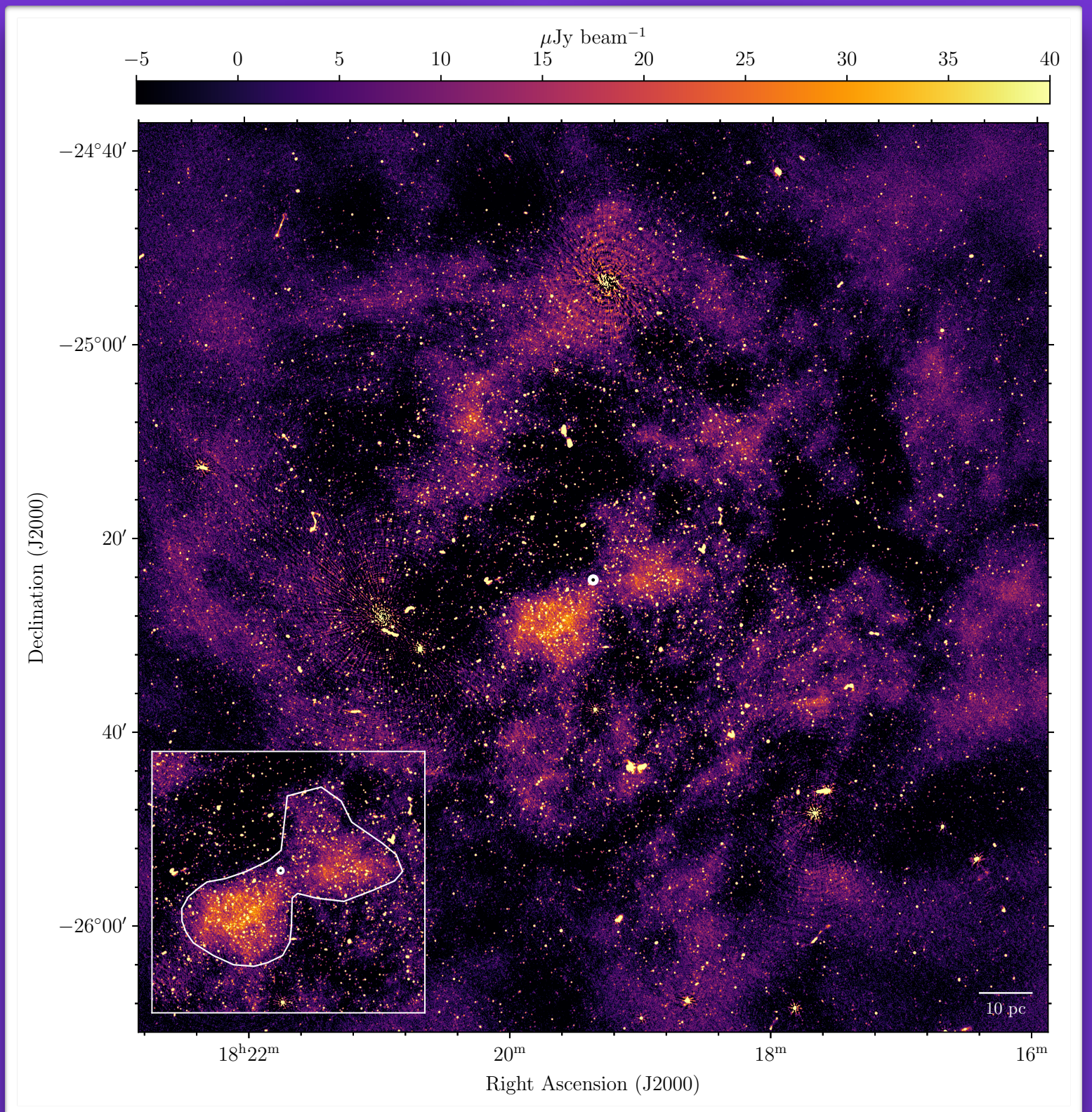


The 'bow-tie'

'Bow-tie' shaped diffuse structure

- **Large-scale** [20' $\leftrightarrow$ 35 pc]
- **Faint** [$< 50 \mu\text{Jy/bm}$]
- **Symmetric** w.r.t. V4641 Sgr
- Radio (UHF/L) **spectral index**
 $\alpha_r = 0.37 \pm 0.95$

Associated with V4641 Sgr?

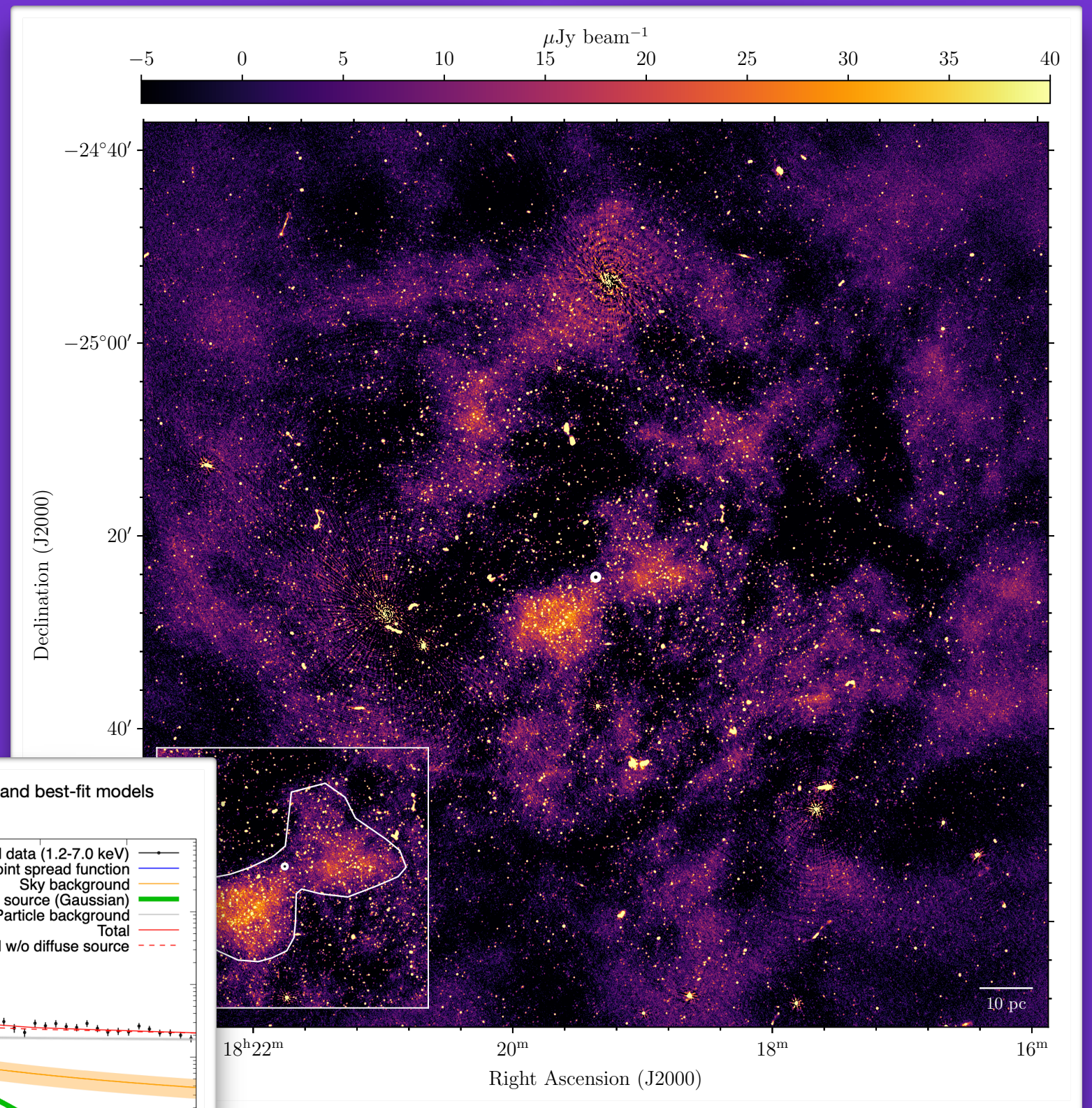


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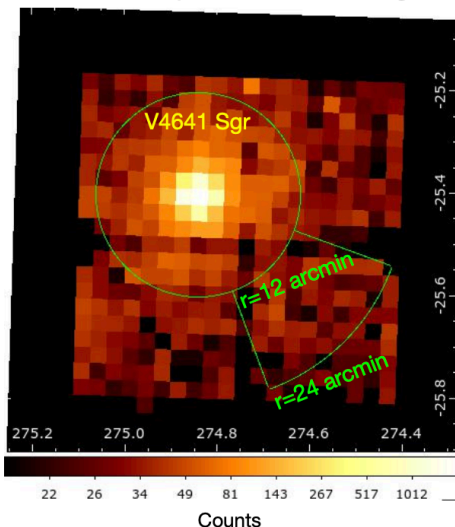
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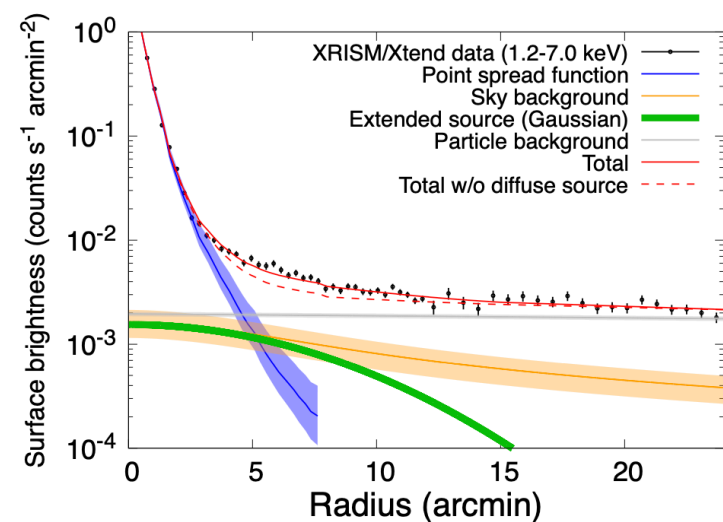
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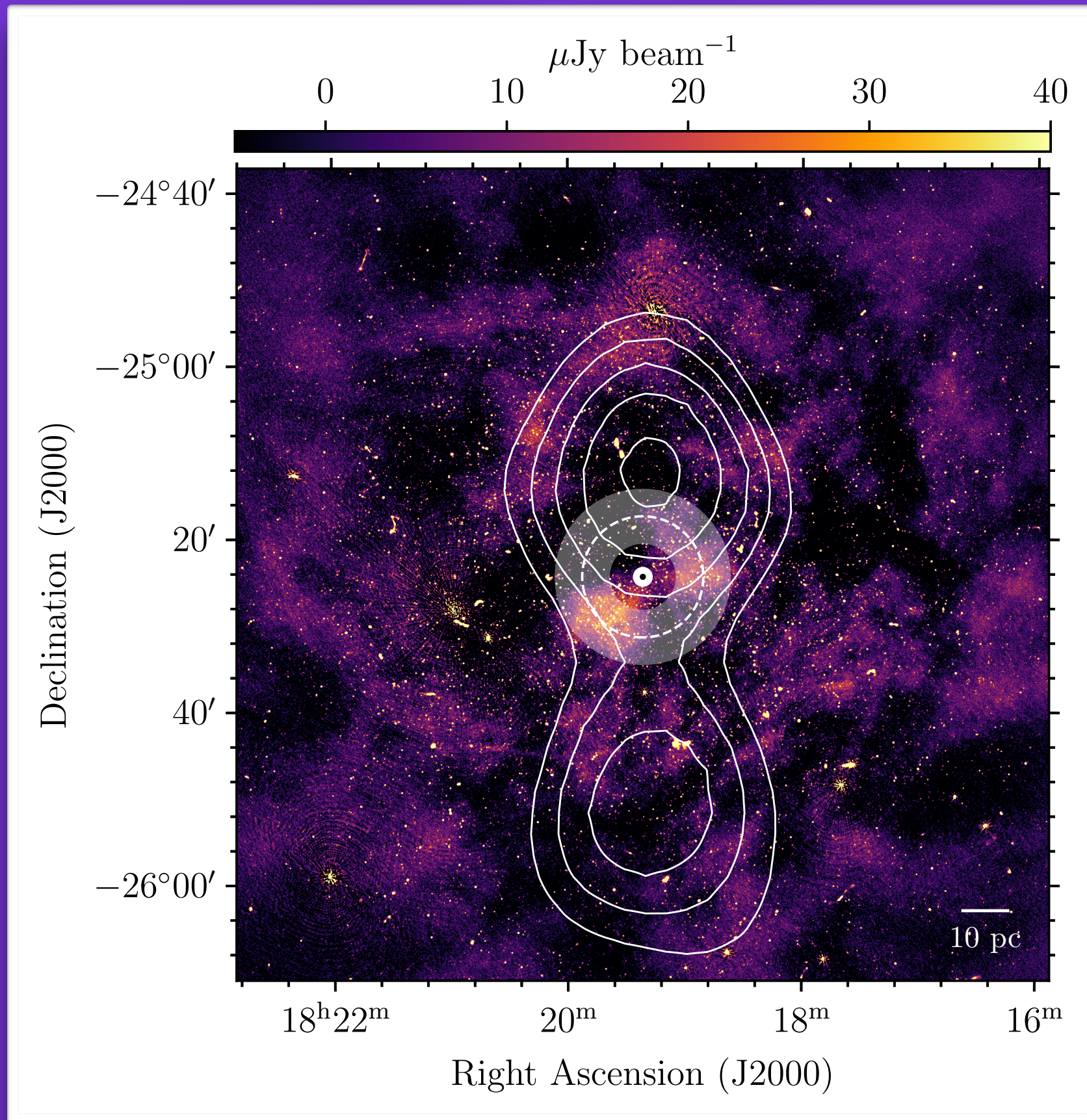
(a) XRISM/Xtend 1.2–7.0 keV image with radial-profile extraction region



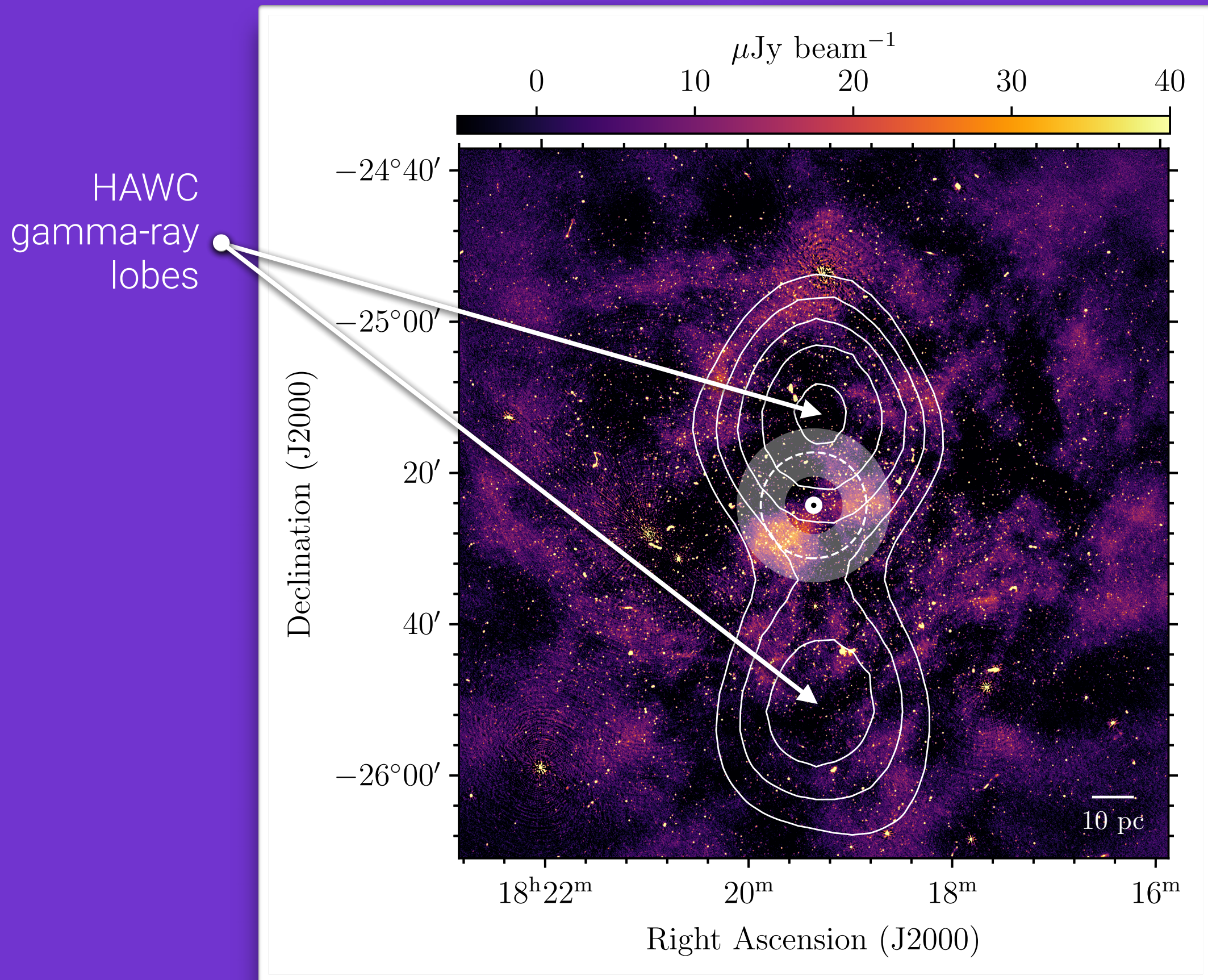
(b) 1.2–7.0 keV radial profile and best-fit models



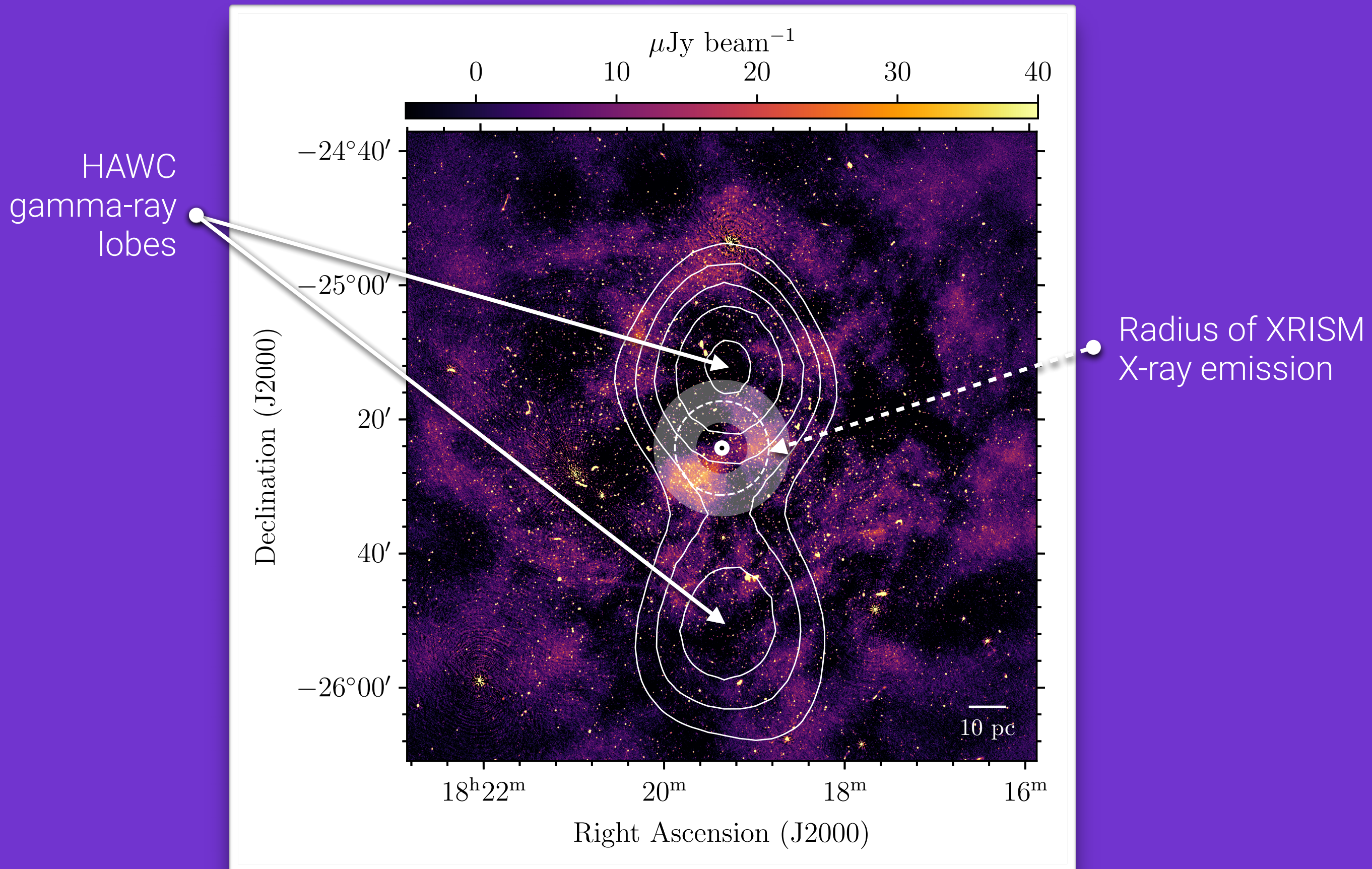
Counterparts?



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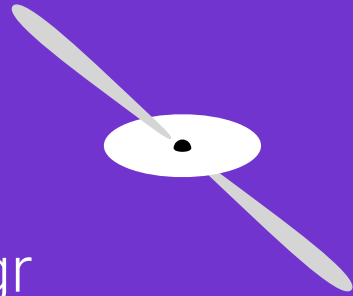
Counterparts?



The jet and wind scenarios

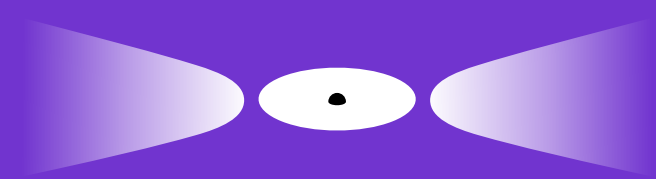
Jets

Long-term action of
large-scale jets from V4641 Sgr



Disk winds

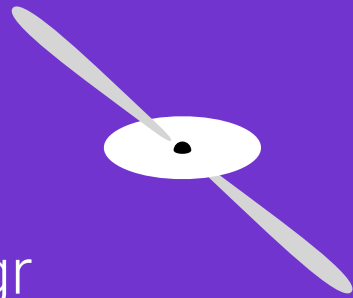
Wind-driven shocks
propagating through the ISM



The jet and wind scenarios

Jets

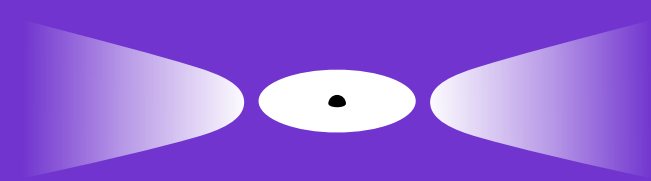
Long-term action of large-scale jets from V4641 Sgr



- **Low jet inclination**, or,
- **Precessing jets**

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Wind-driven shocks propagating through the ISM



Large apparent opening angle ($\sim 50^\circ$) vs typically **a few degrees**

- Winds are **not collimated**, large opening angle allowed.

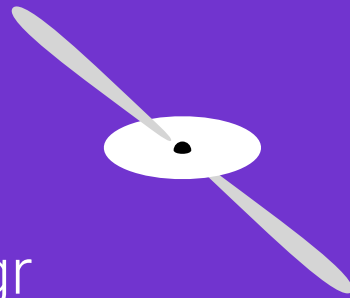
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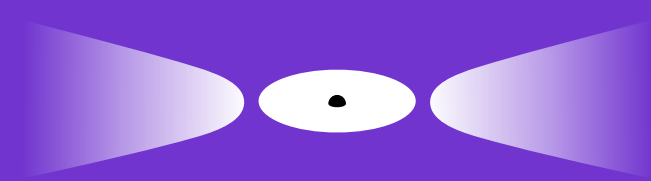
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- Collimated **jets** vs particles **streaming** along ordered **B field lines** [Neronov+2025]



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- Radio jets/'bow-tie' and VHE lobes have:
- different **orientations**

- Equatorial disk winds likely have different orientations than the jets.

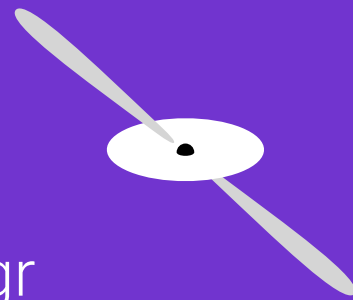
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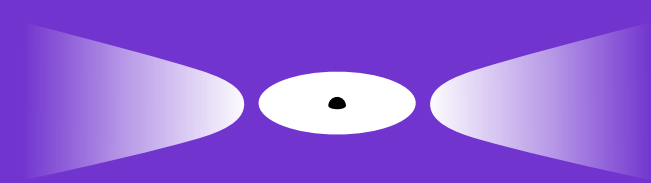
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- different **spatial extent** → electrons cool faster than protons

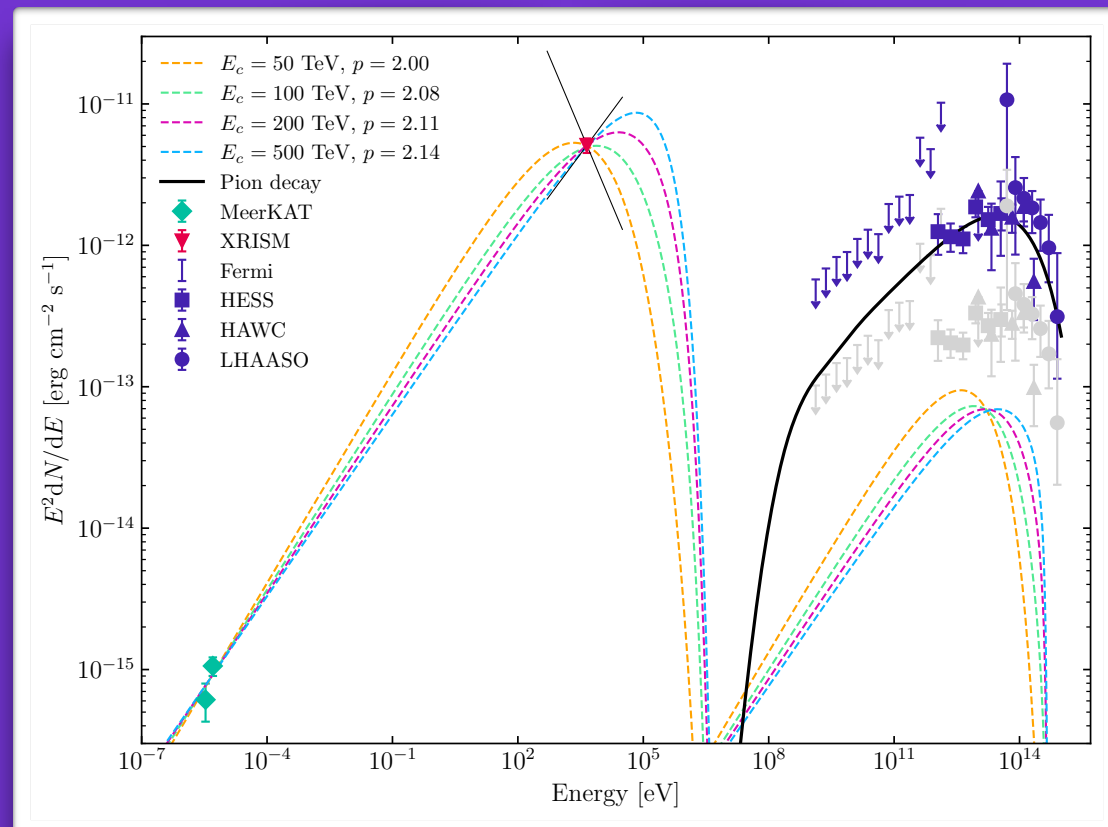
Emission mechanism

2 spatially distinct **emission regions**:

- **leptons/hadrons (?)** at **large distances**
- **leptons closer** to the black hole

Synchrotron

- **Persistent radio lobes** around GRS 1758-258 [Mirabel & Rodríguez 1999] or 1E 1740.7-2942 [Mirabel+1992]
- Radio + X-rays ($\alpha = -0.58 \pm 0.02$)



Thermal bremsstrahlung

- **Equatorial 'ruff'** around SS 433 [Paragi+1999] and Cir X-1 [Cowie+2025]
- Radio only ($\alpha_r = 0.37 \pm 0.95$)

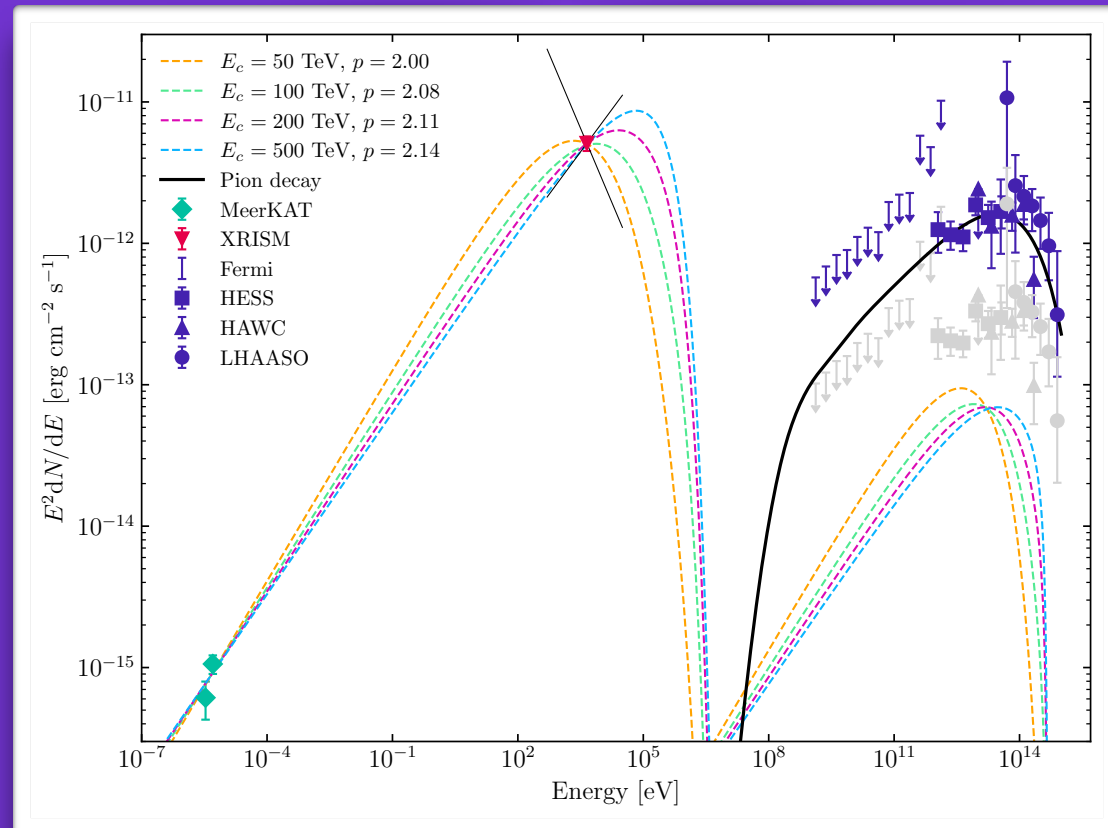
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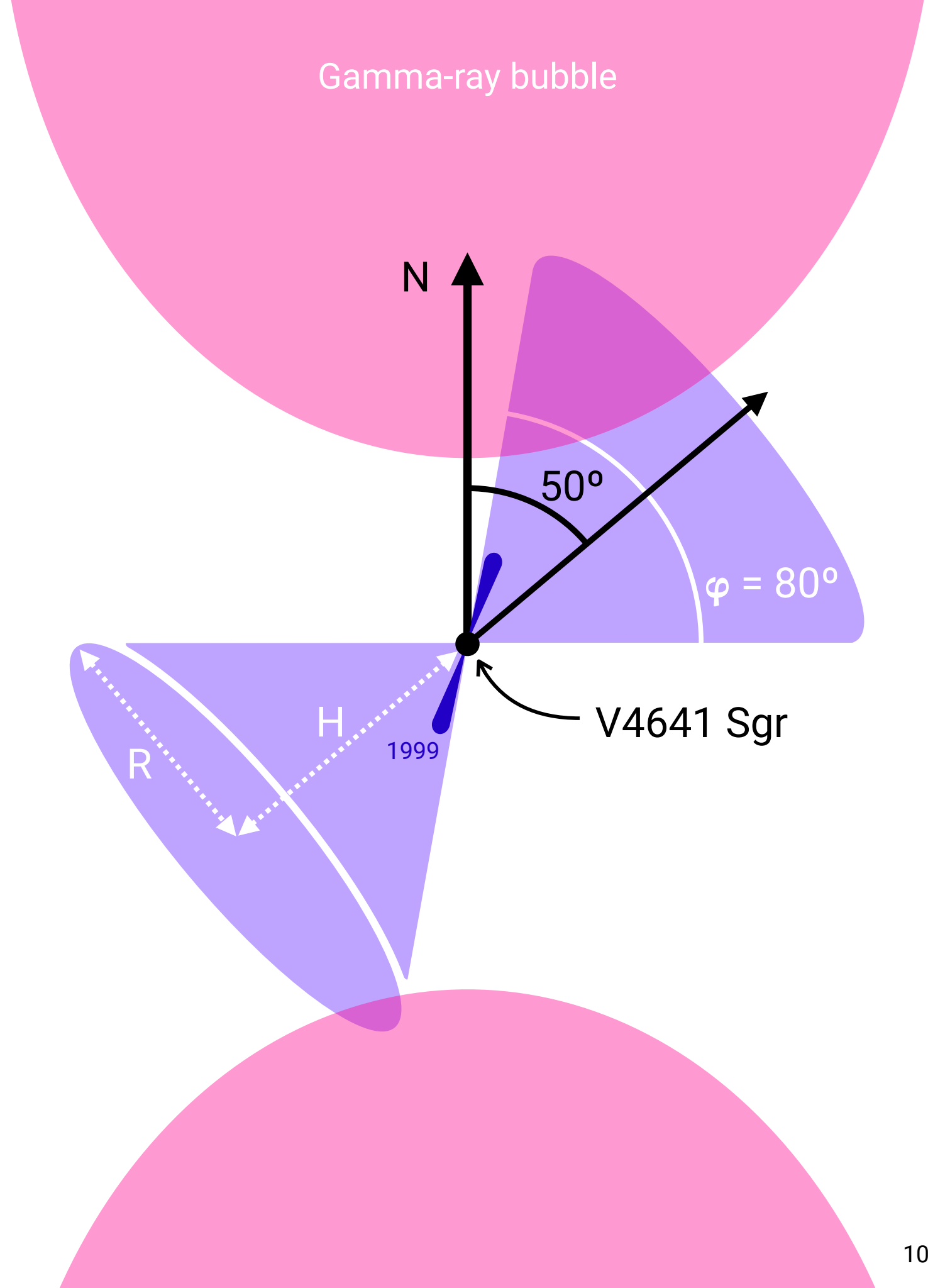
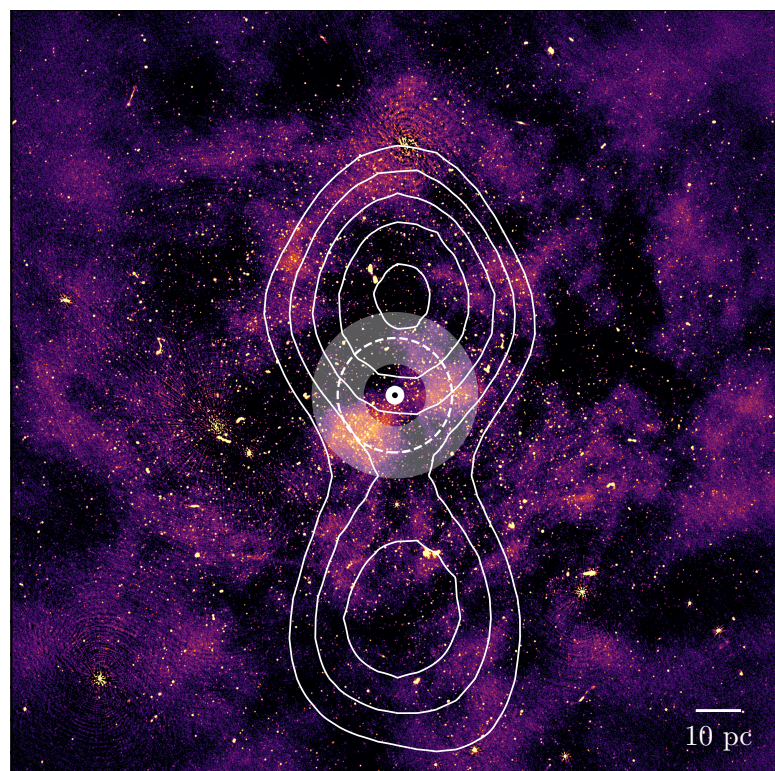
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→ Energetics / timescales?

Emission mechanism

Synchrotron



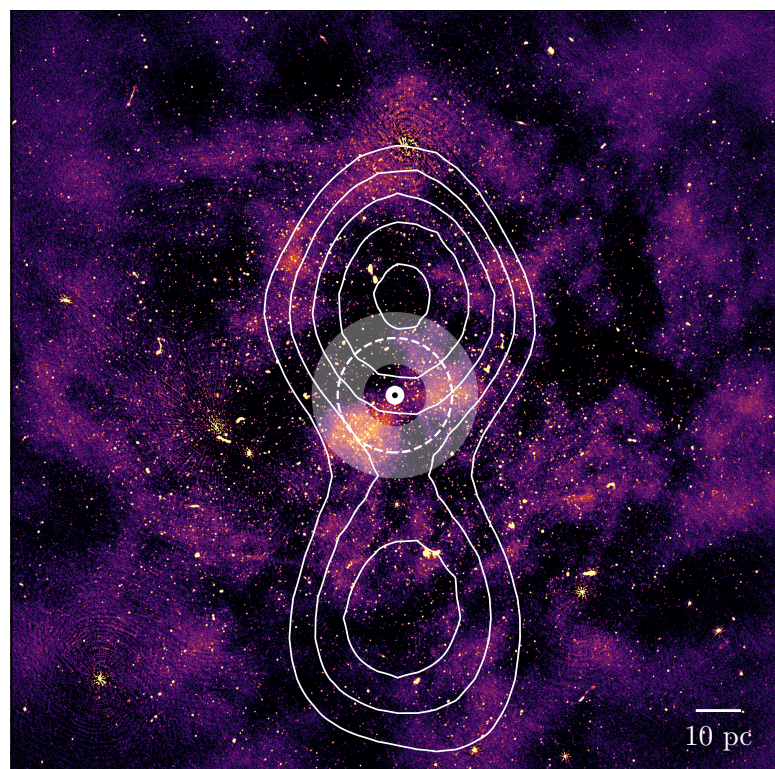
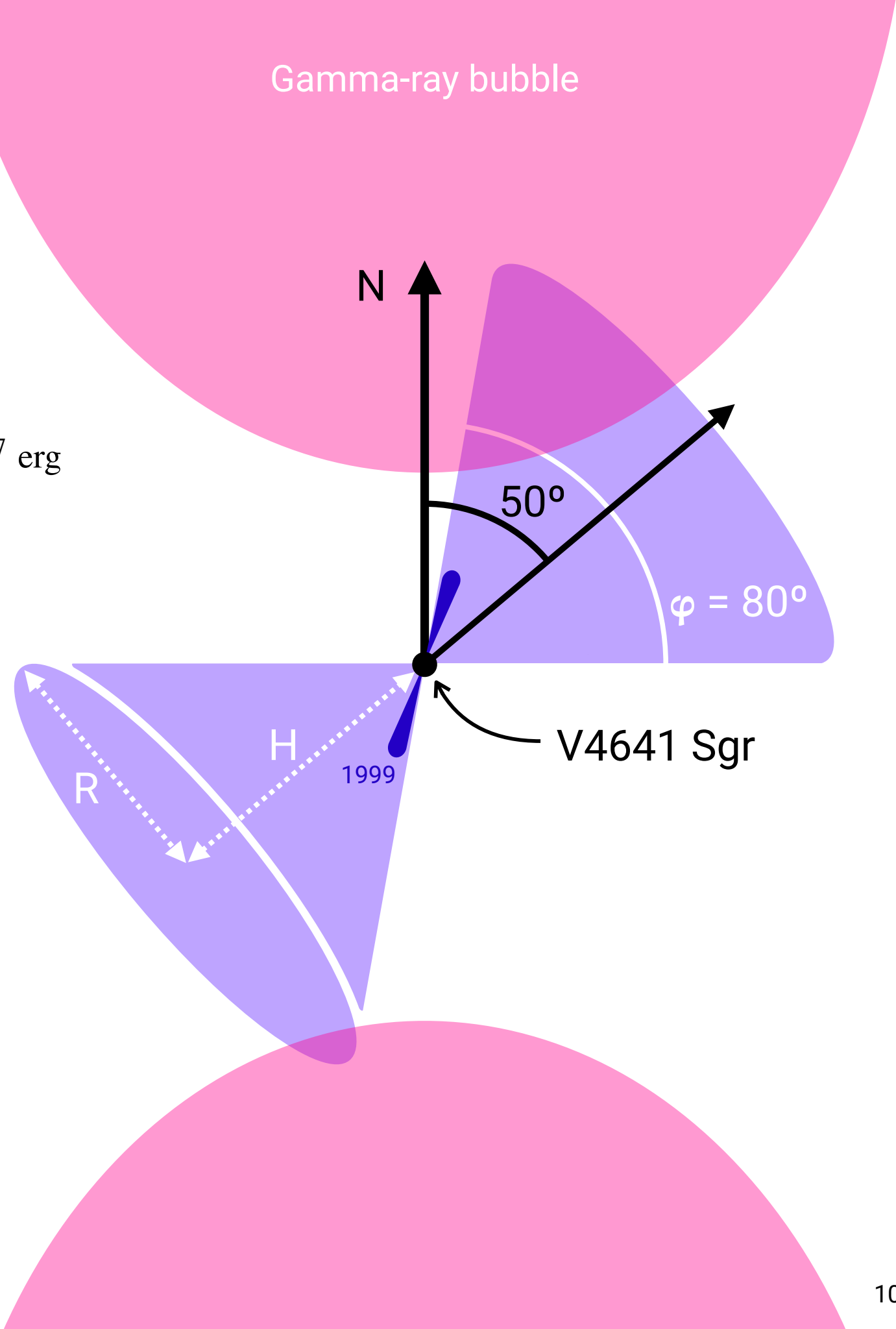
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Synchrotron

Minimum energy requirements
(volume **V** and bolometric luminosity **L**)

$$B_{\text{eq}} \propto \left(\frac{L}{V}\right)^{2/7} \sim 5.8 \mu\text{G} \quad E_{\text{min}} \propto LB_{\text{eq}}^{3/2} \sim 2.1 \times 10^{47} \text{ erg}$$

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Age of the structure (jet scenario)?

→ expansion time at 0.1c? **~590 yrs**

→ synchrotron cooling time? **~2.9 kyrs**

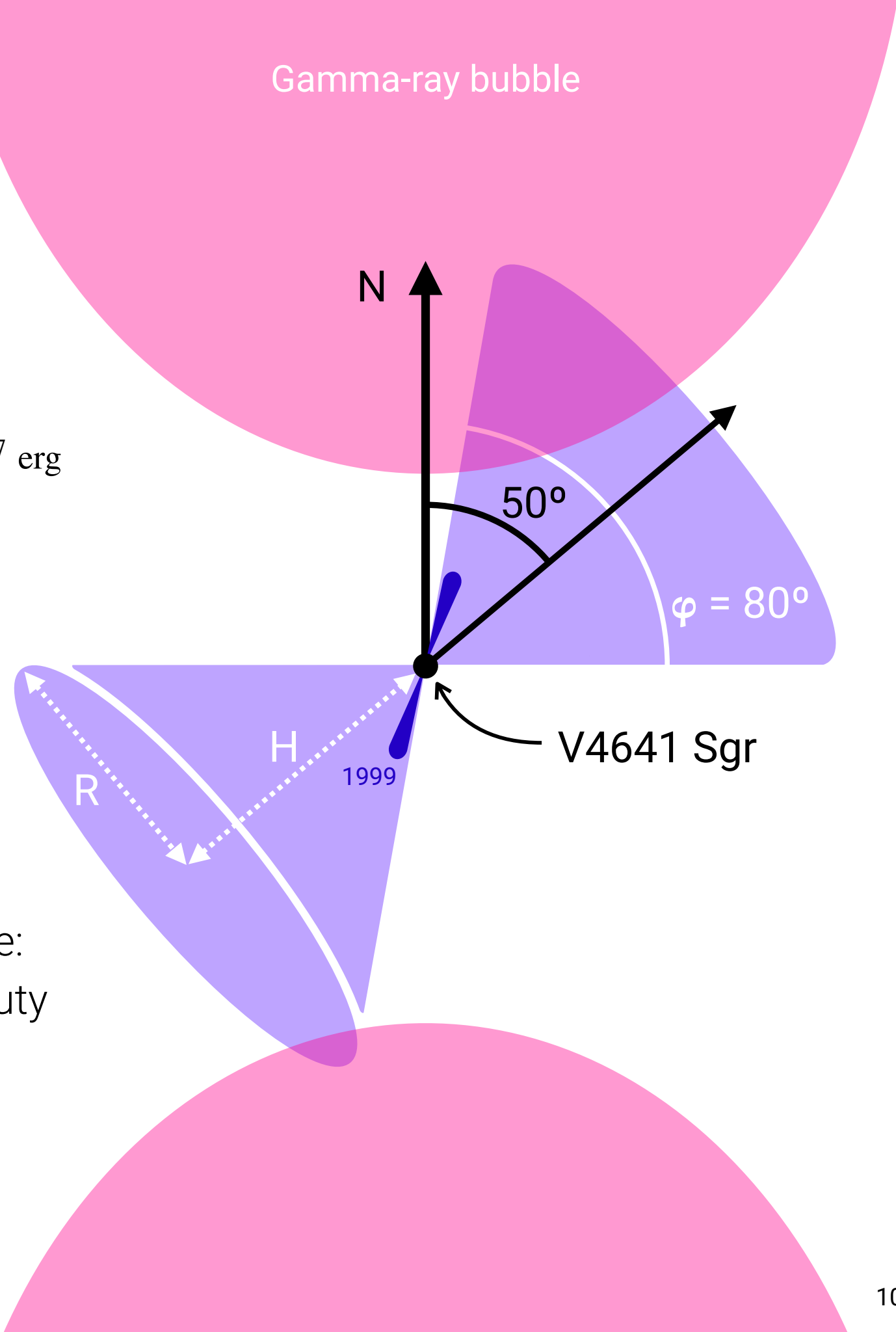
VS

Time to accumulate E_{min} at Eddington rate:

~8 yrs BUT **~600 yrs** when considering duty cycle 

Disk winds? Expansion time of **~5.9 kyrs**

→ less likely 



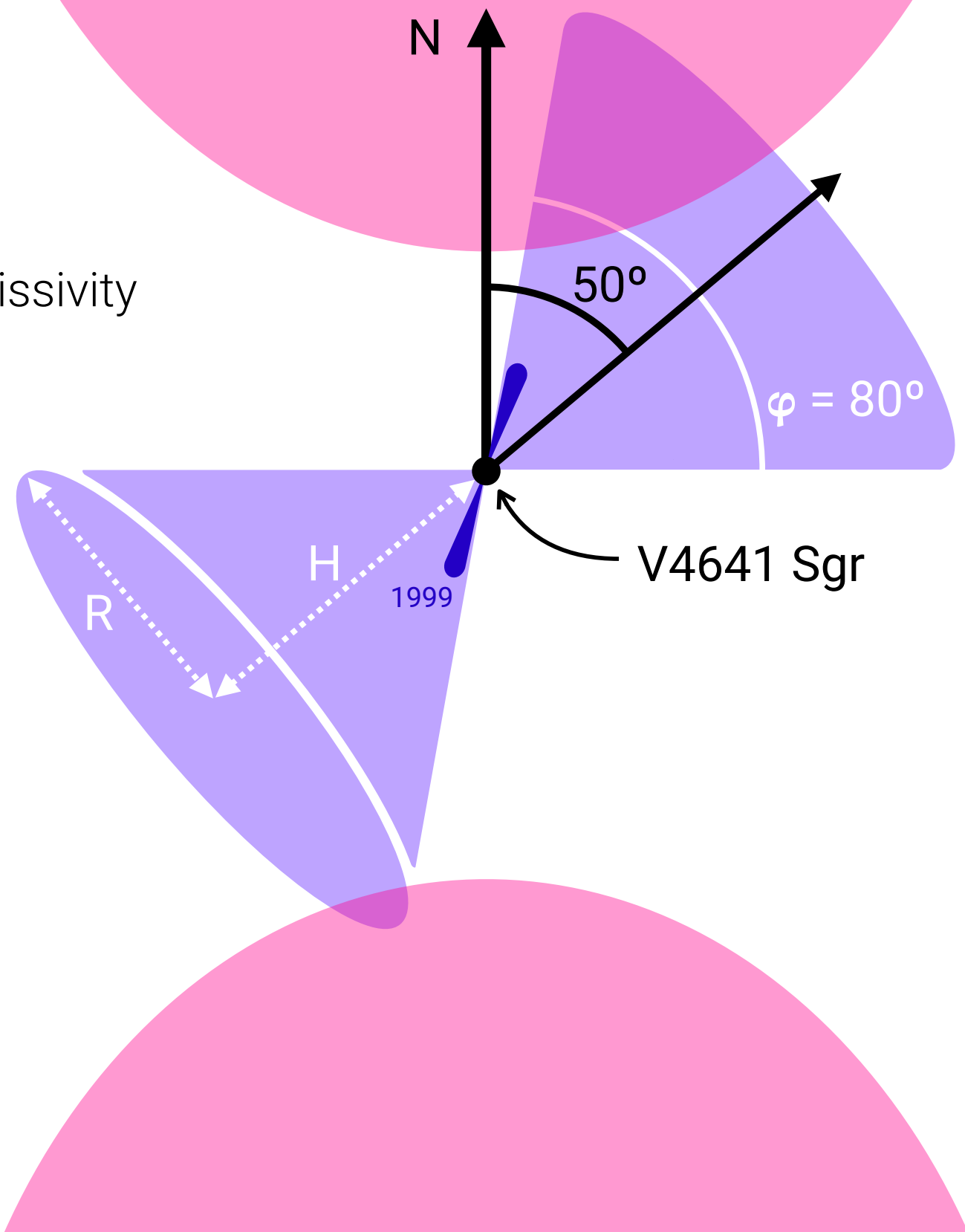
Emission mechanism

Thermal bremsstrahlung

Using the free-free **emissivity** ϵ_ν and assuming **T = 10⁴–10⁷ K**:

$$n_e \propto \epsilon_\nu^{1/2} T^{1/4} \sim 2 - 11 \text{ cm}^{-3}$$

→ free-free can produce the observed emissivity under **reasonable ambient conditions** ✓



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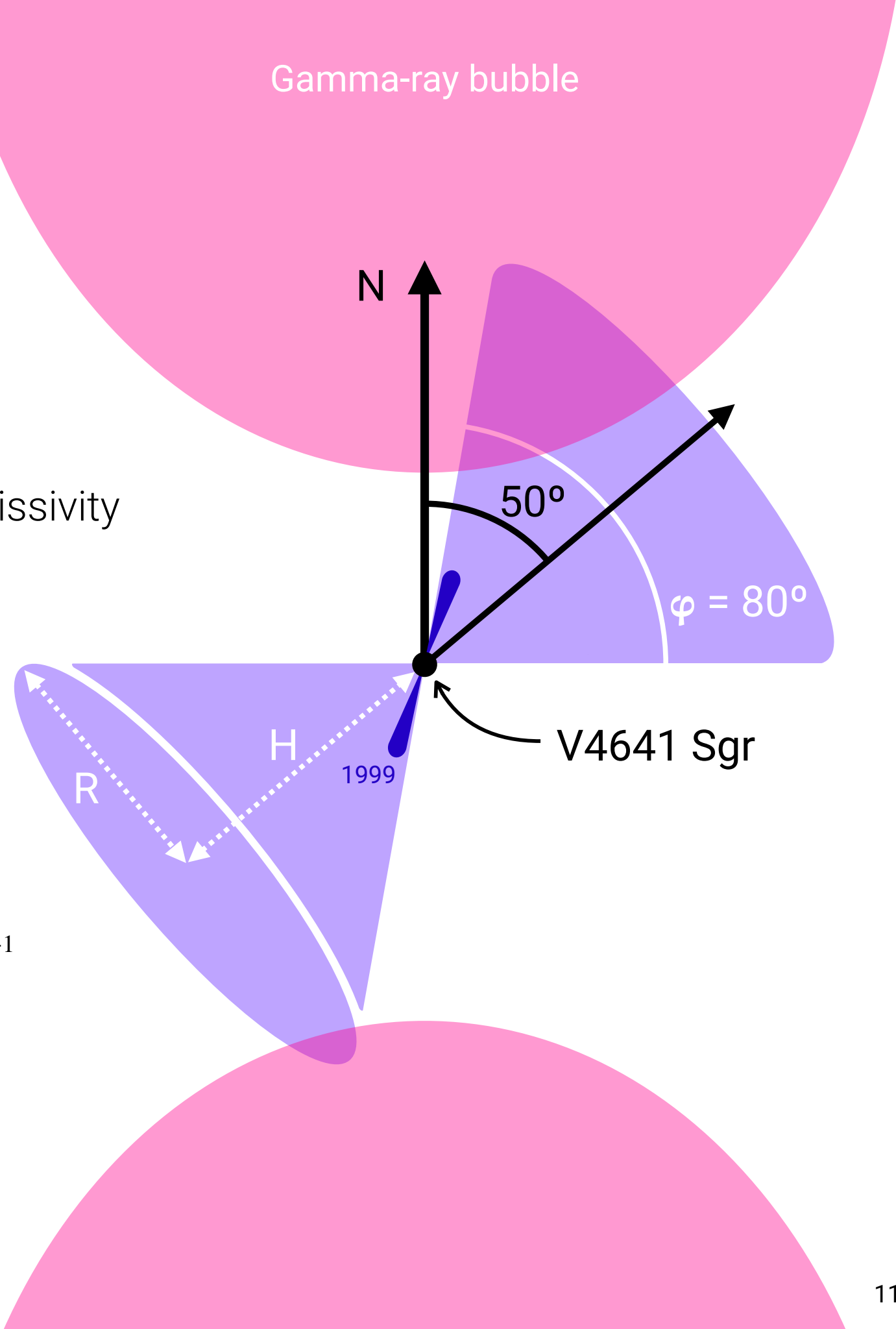
Wind model in radio-quiet quasars

[Blundell & Kuncic 2007]:

$$L_\nu \propto \left(\frac{\dot{m}_w}{v_w} \right)^{4/3} \sim (2.3 - 3.4) \times 10^{15} \text{ erg s}^{-1} \text{ Hz}^{-1}$$

Our measurement: $L_\nu \sim 4.0 \times 10^{21} \text{ erg s}^{-1} \text{ Hz}^{-1}$

→ **6 orders of magnitude brighter** 🚫



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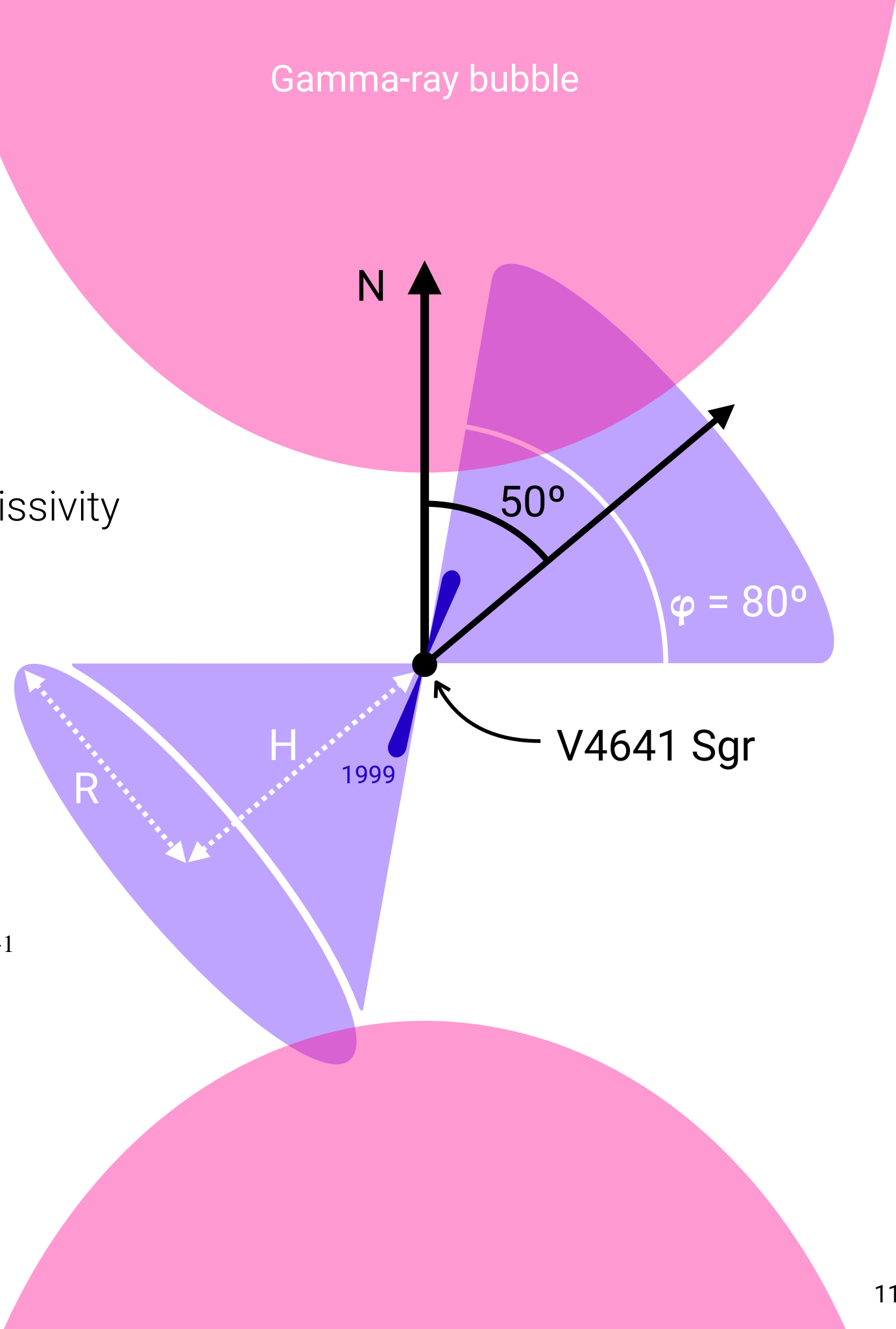
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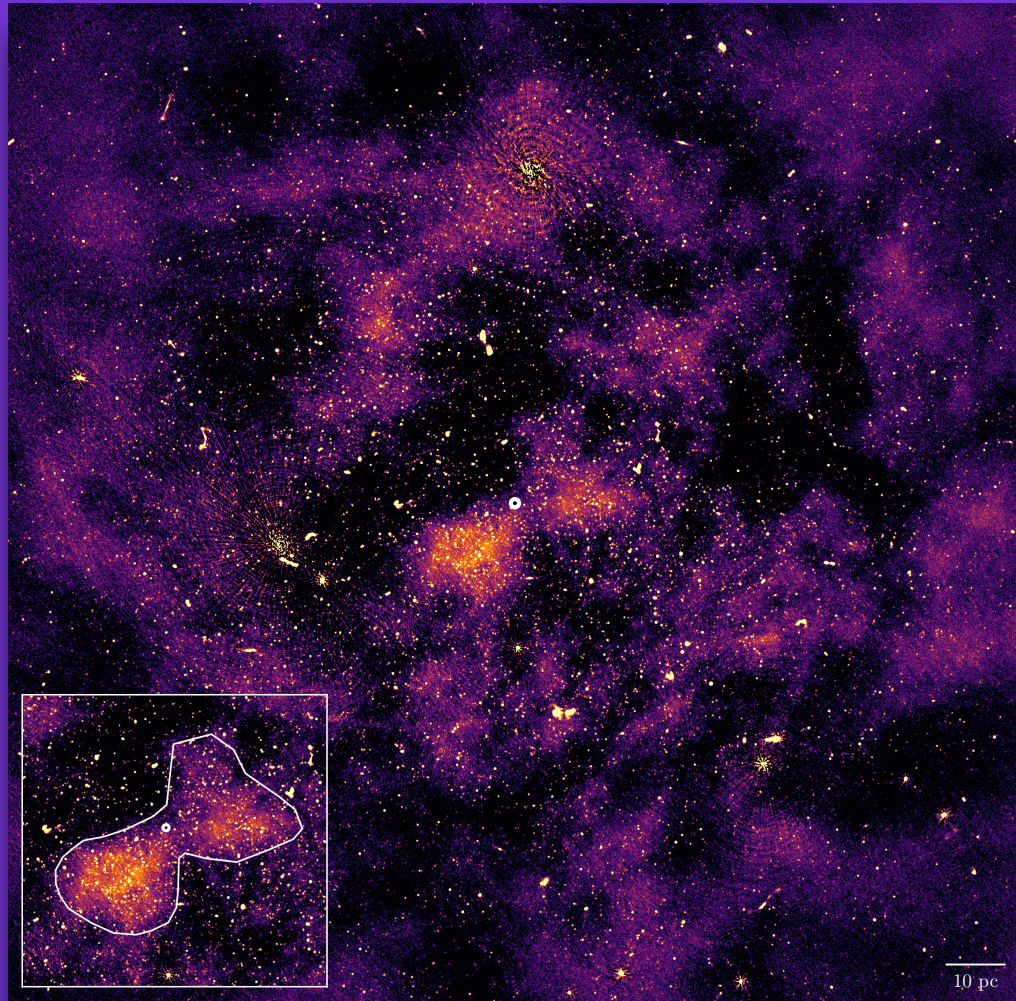
Enthalpy of the region:

$$H = 1.2 \times 10^{48} - 4.9 \times 10^{51} \text{ erg}$$

Accumulated in **~3.4 kyrs–14 Myr** ⚠️



Conclusions



- Discovery of a **large-scale** (~ 35 pc), **symmetric structure** around V4641 Sgr in deep MeerKAT radio observations
- No clear counterpart to the VHE bubbles but the **'bow-tie'** is likely related to the XRISM **X-ray extended emission**
- **Jet and wind scenario** explored, **synchrotron** emission favored on energetic grounds

→ Paper submitted to A&A!

Thank you!