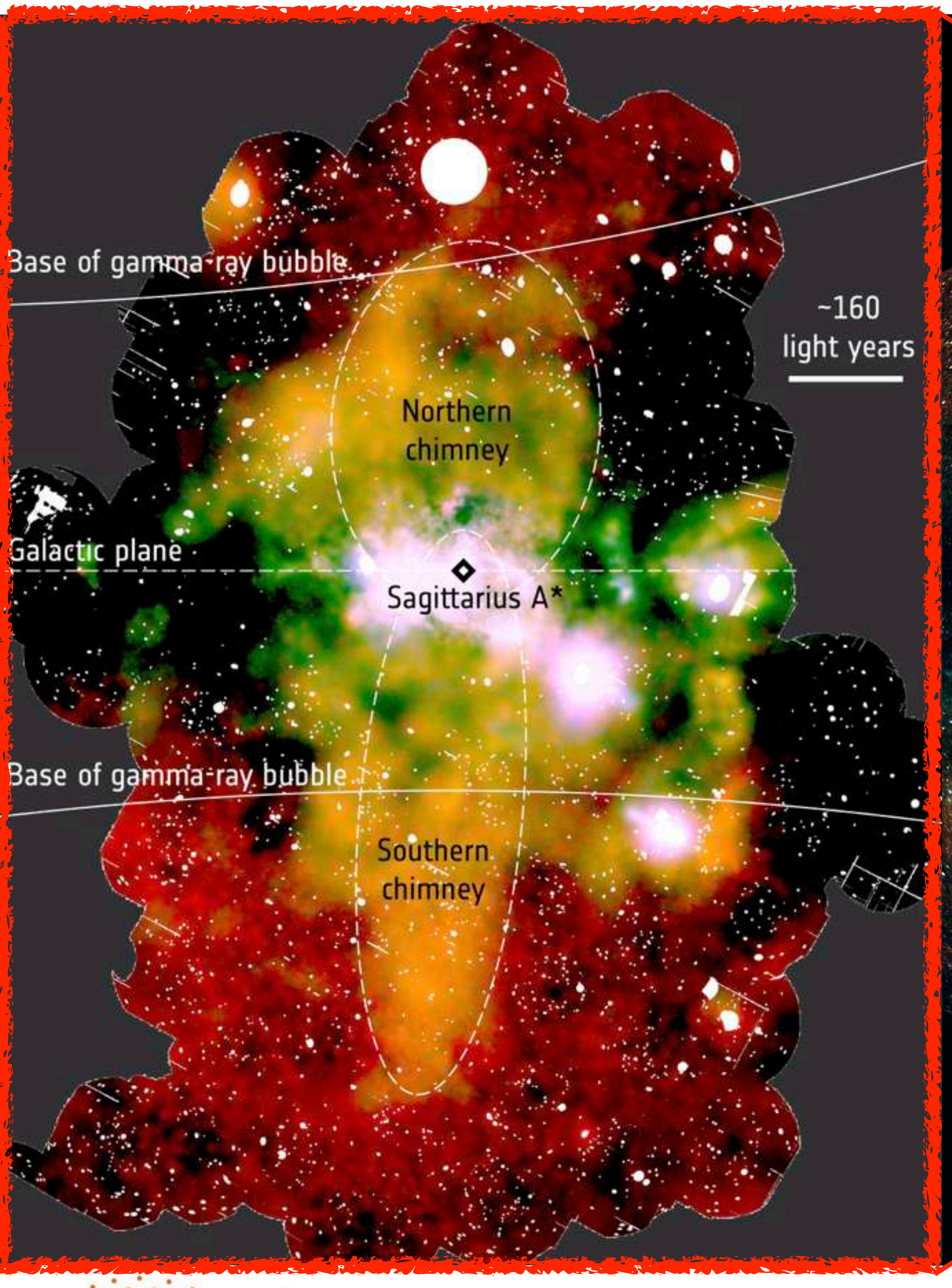
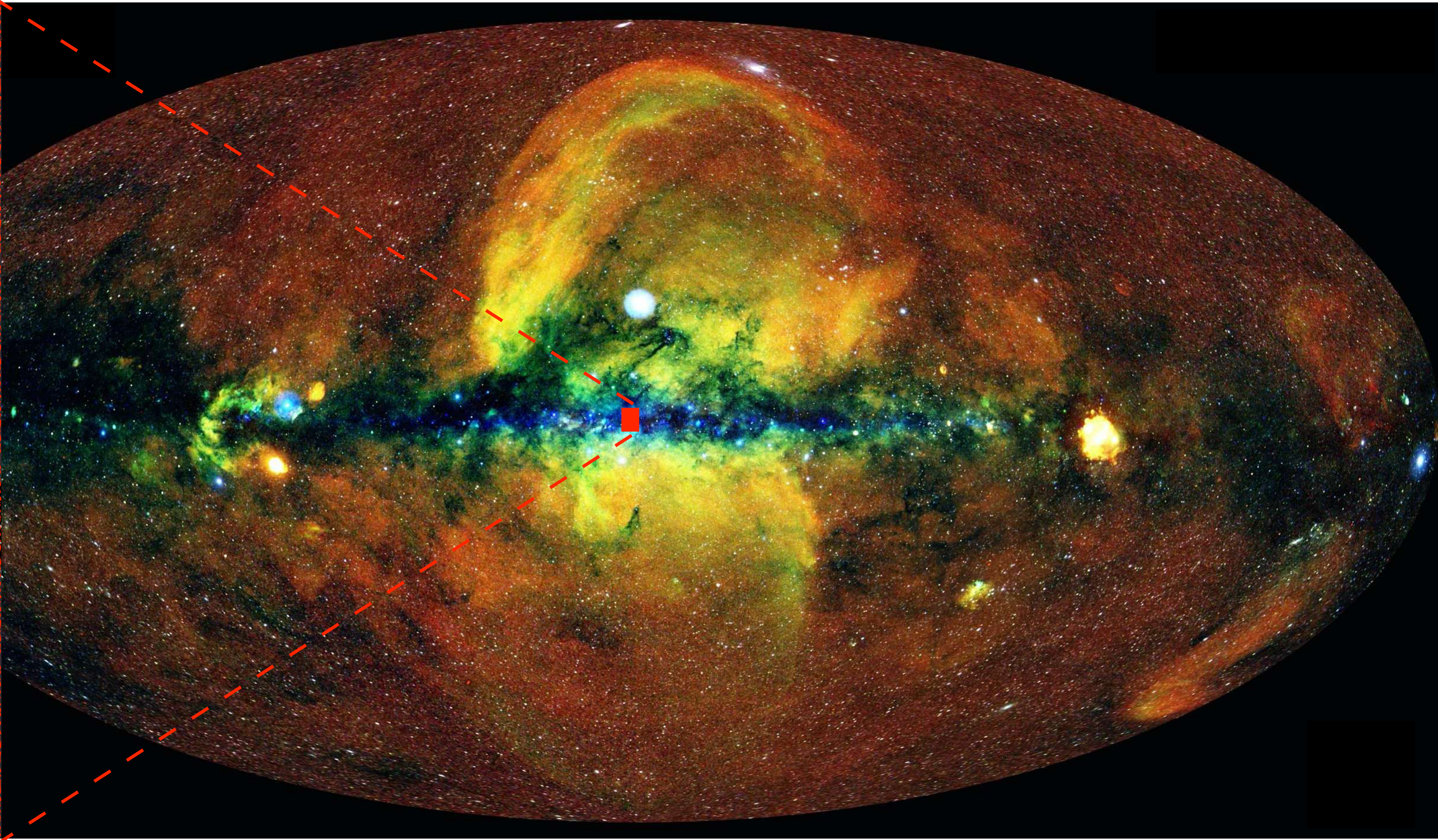
The base of the multi-phase Galactic outflow





European
Research
Council

Gabriele Ponti
INAF OA Brera - MPE

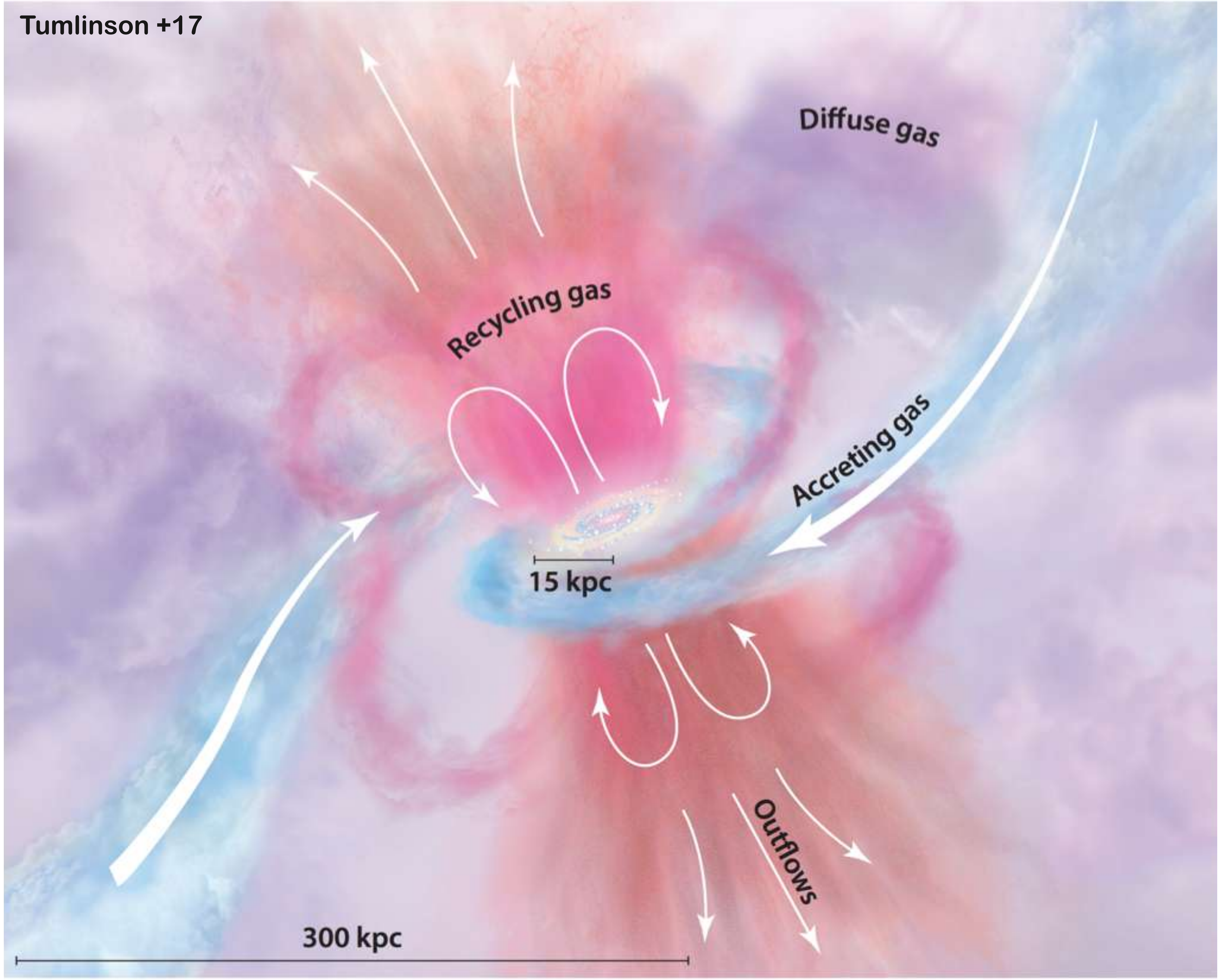
OSSERVATORIO ASTRONOMICO DI BRERA

eROSITA

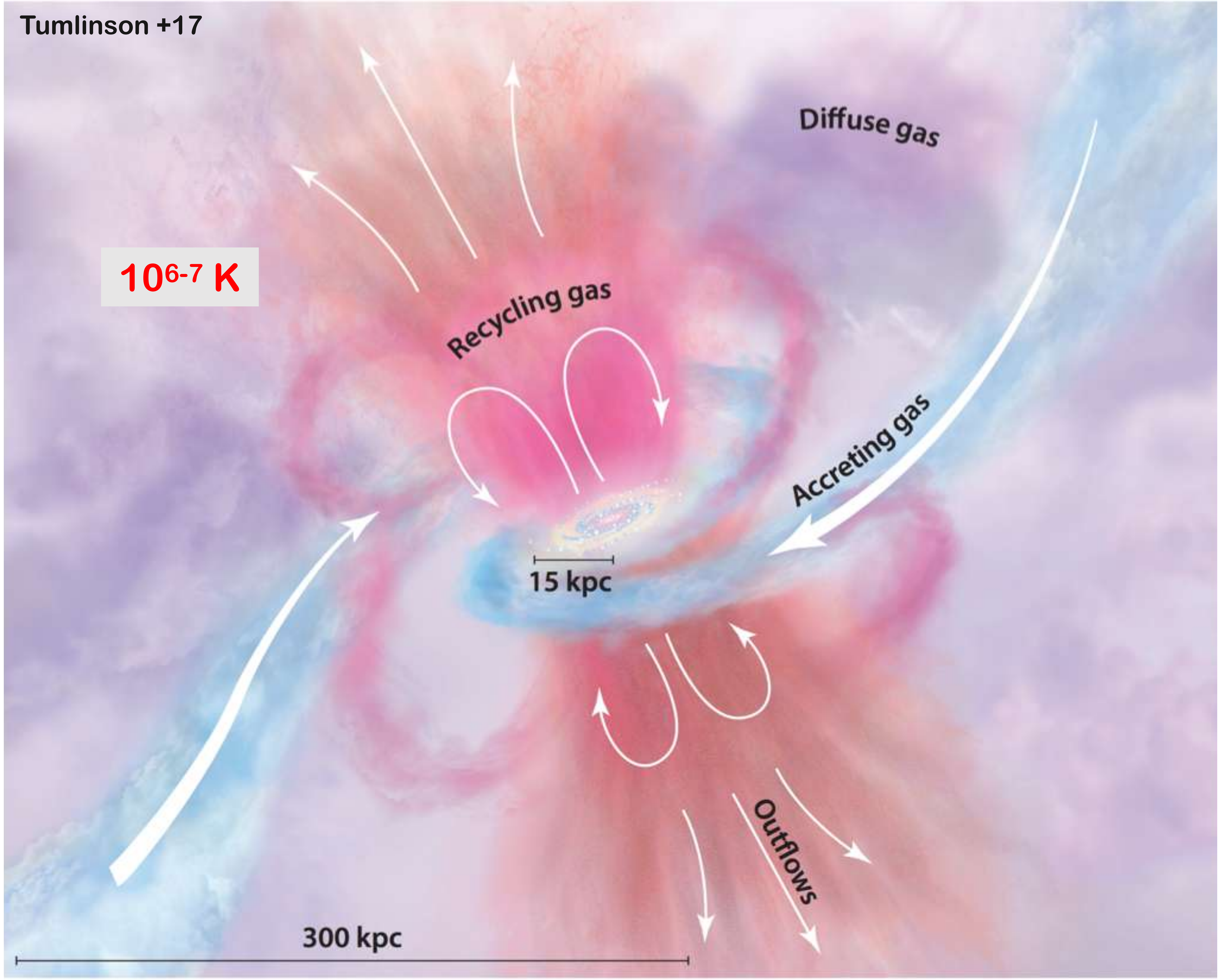
How do galaxies evolve?

NGC 7331 Hubble

The Baryon cycle



The Baryon cycle



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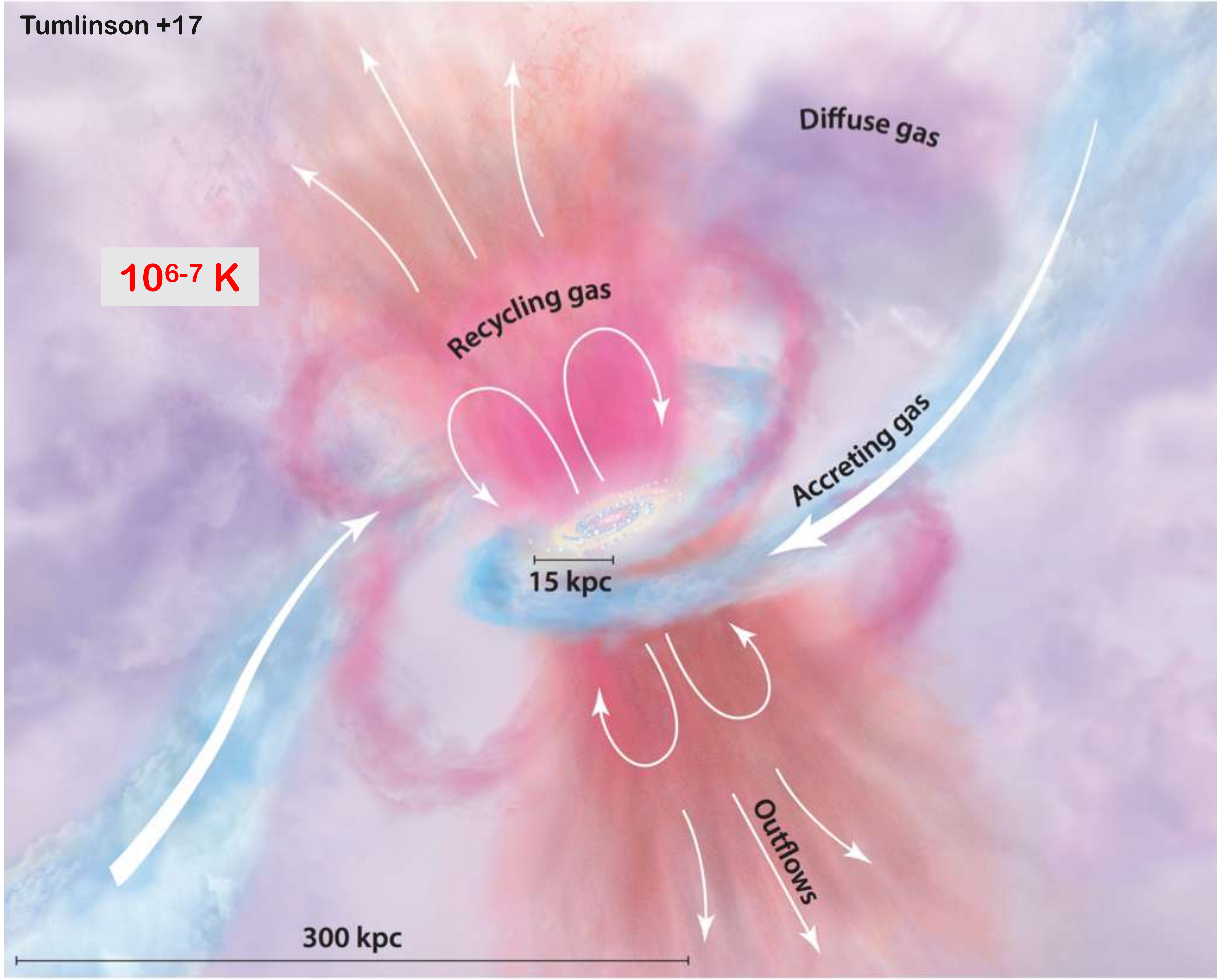


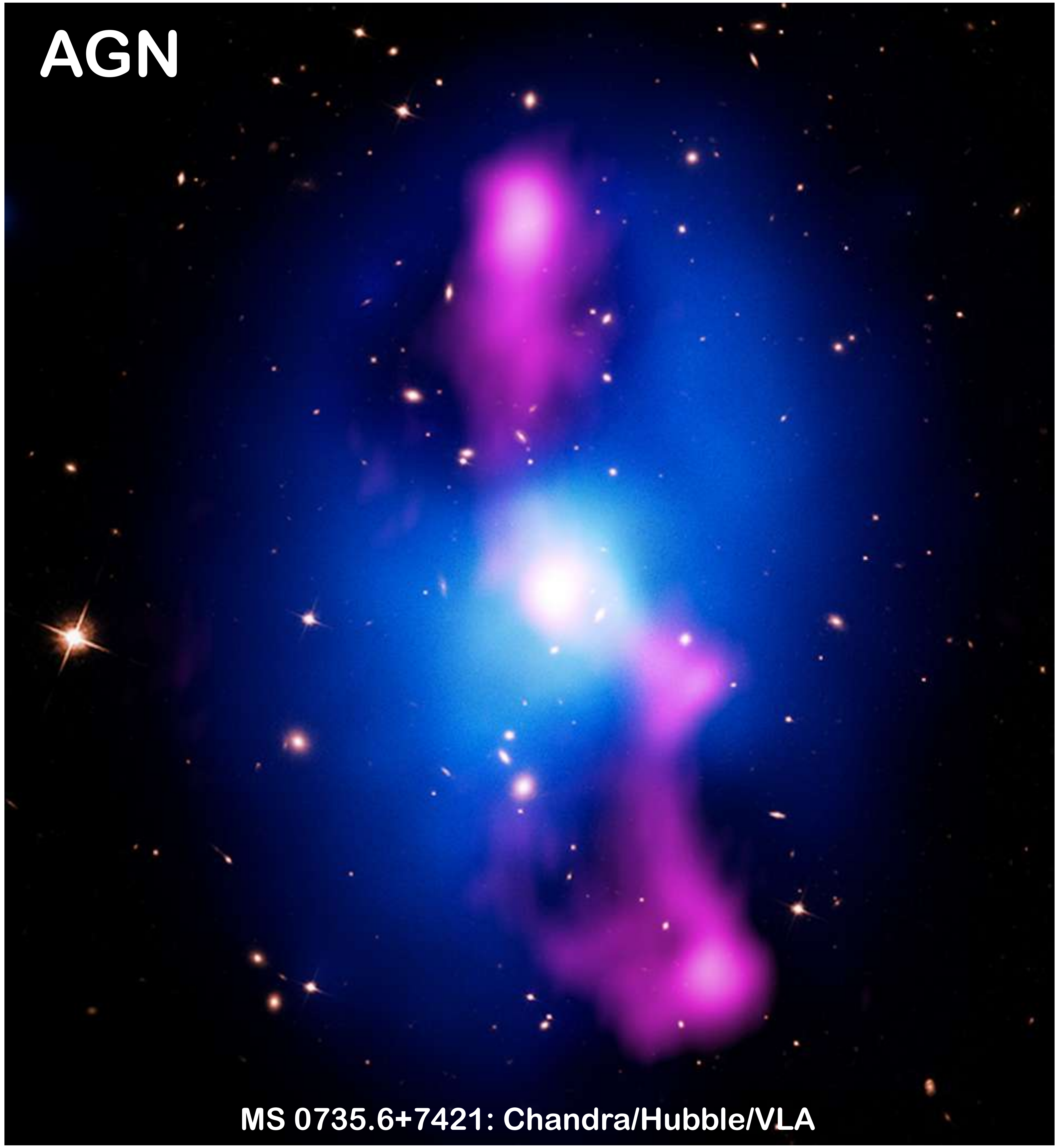
Hot Baryons:

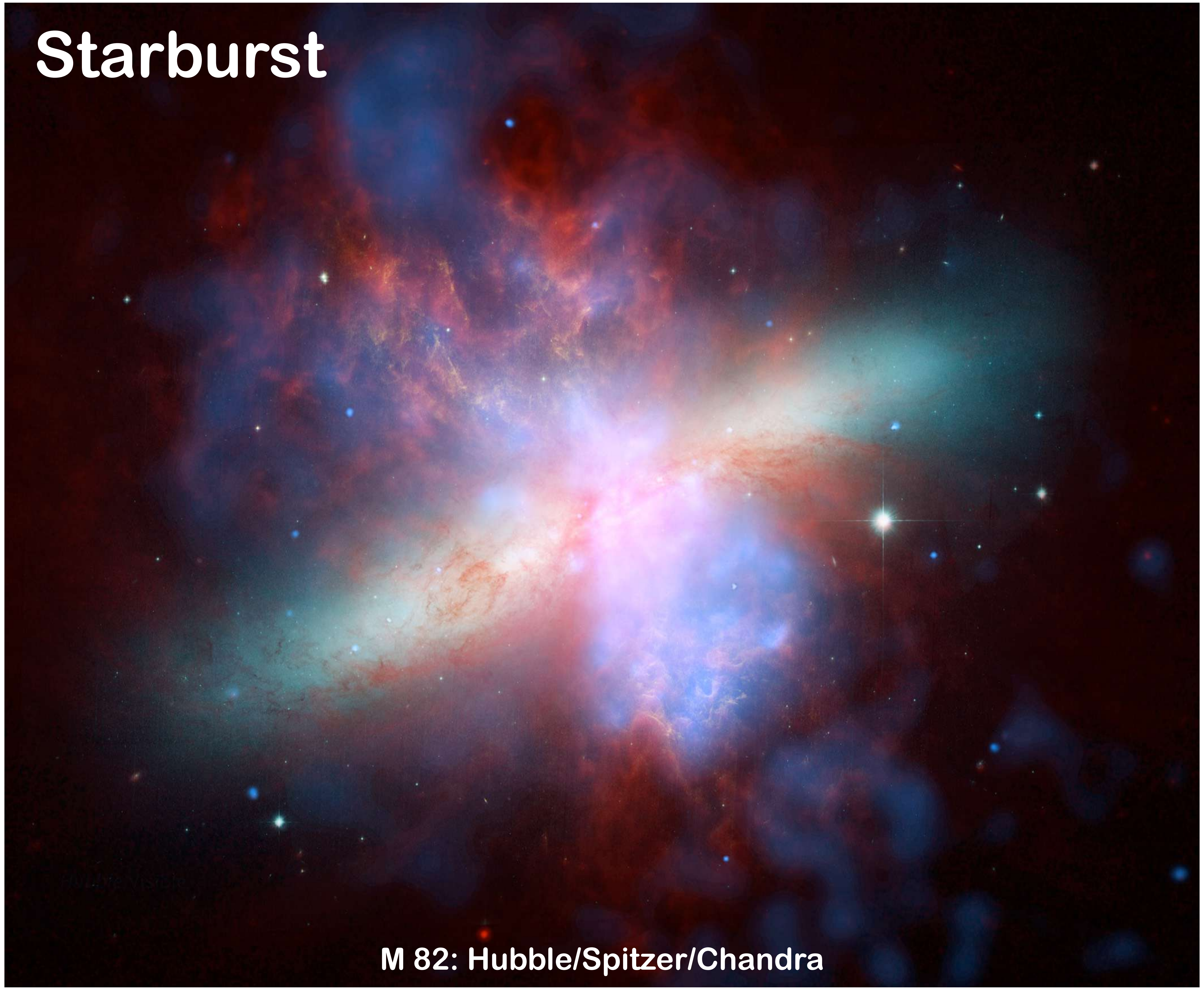
Bulk of Baryons

Re-condensation

Driver outflows

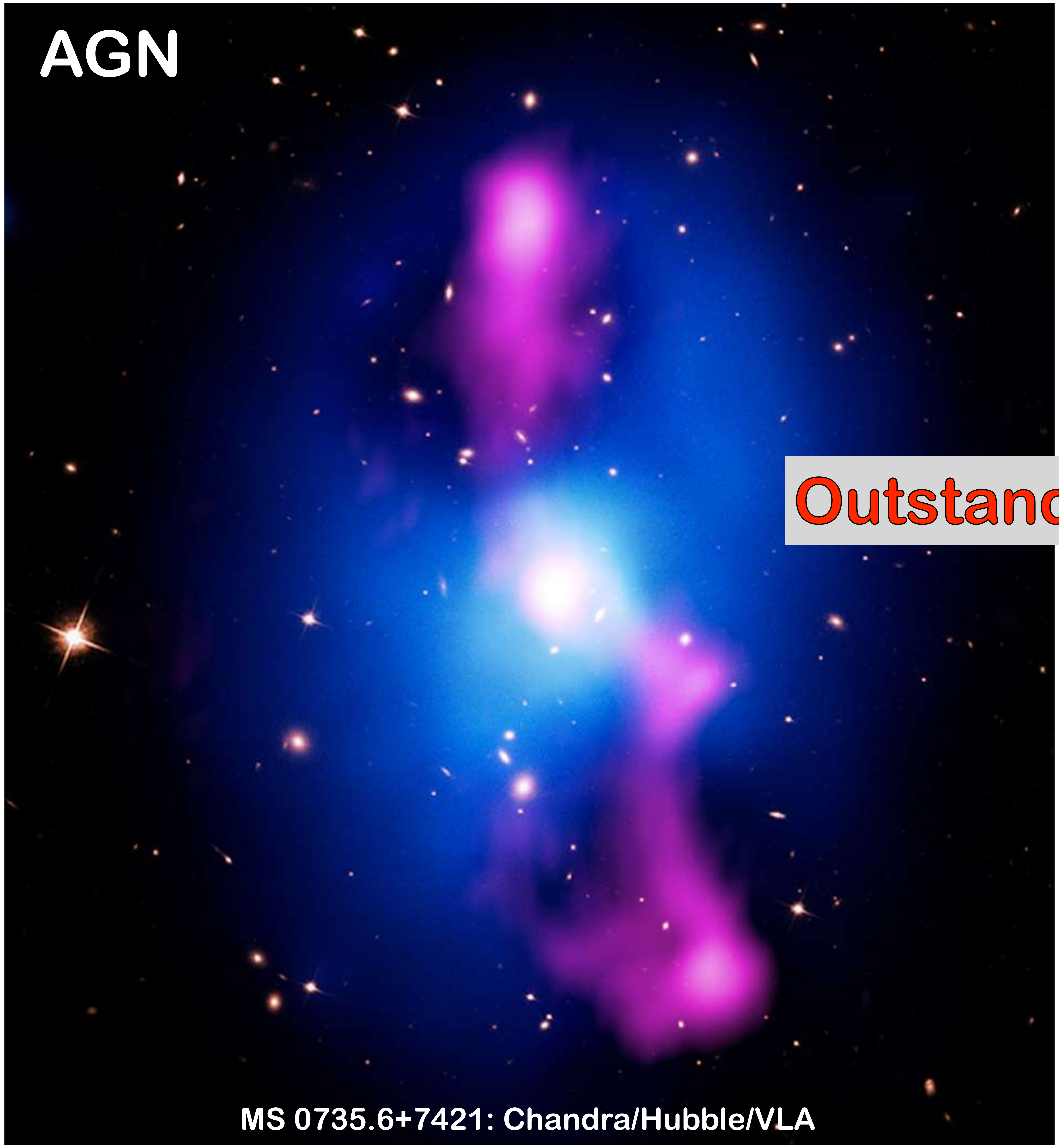
AGN and Starbursts influence CGM

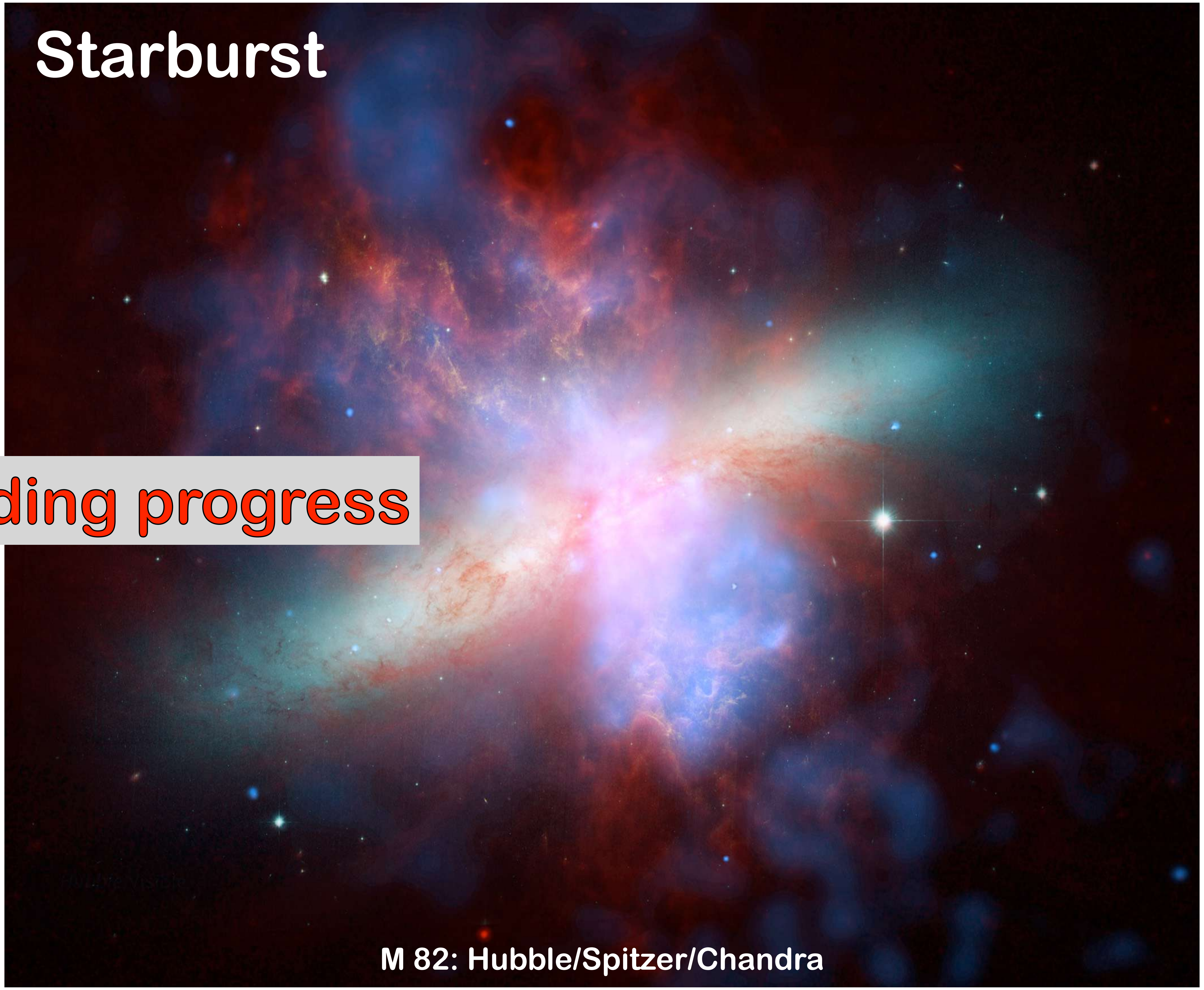




➜ Understand feedback between nucleus and CGM

AGN and Starbursts influence CGM





Outstanding progress

➜ Understand feedback between nucleus and CGM

Do normal galaxies influence their CGM?

M83: Subaru/ESO/Hubble

Do normal galaxies influence their CGM?

Does the nuclear activity of quiescent galaxies influence their CGM?

M83: Subaru/ESO/Hubble

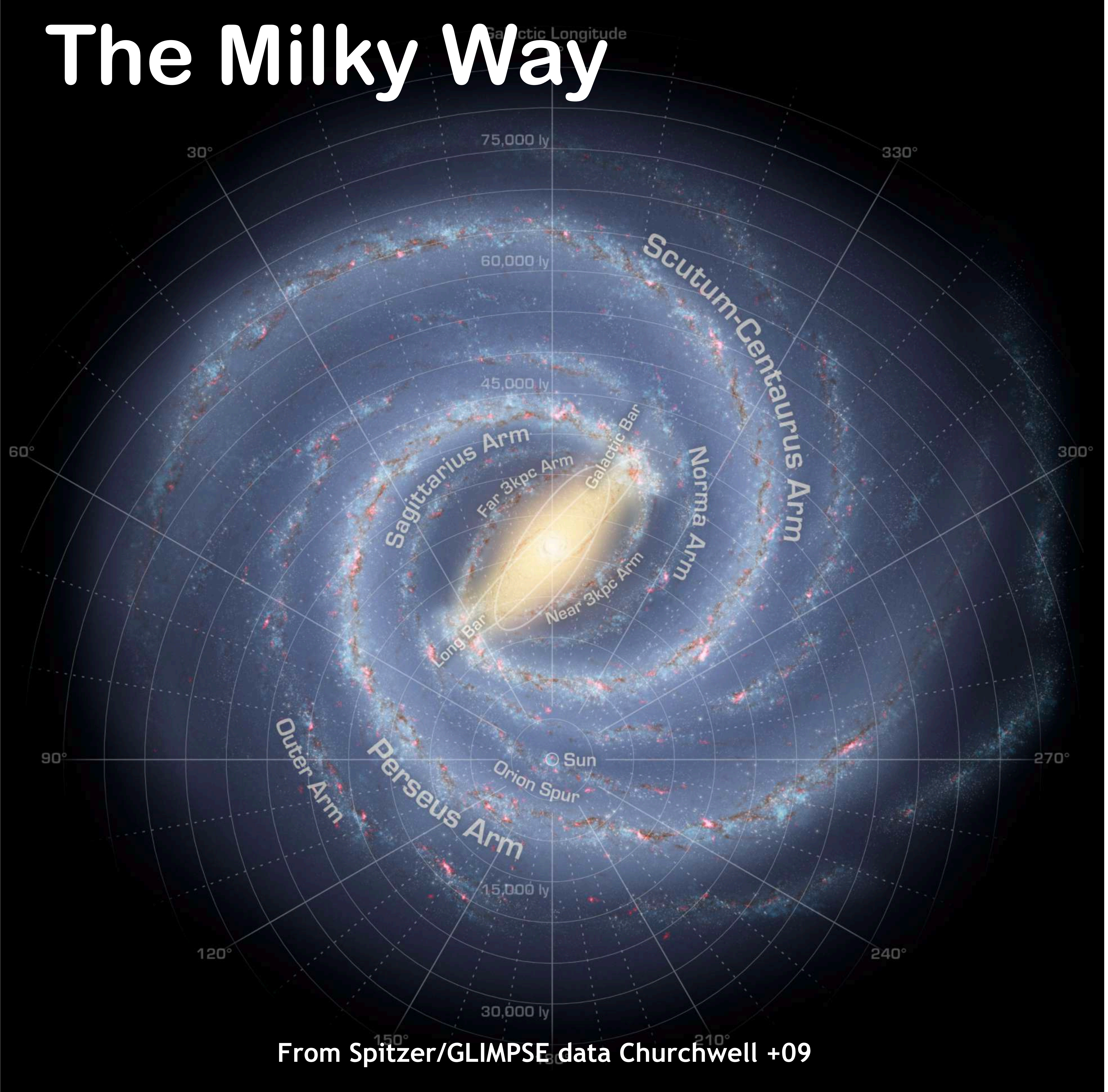
Do normal galaxies influence their CGM?

Does the nuclear activity of quiescent galaxies influence their CGM?

➜ Let's look to the Milky Way

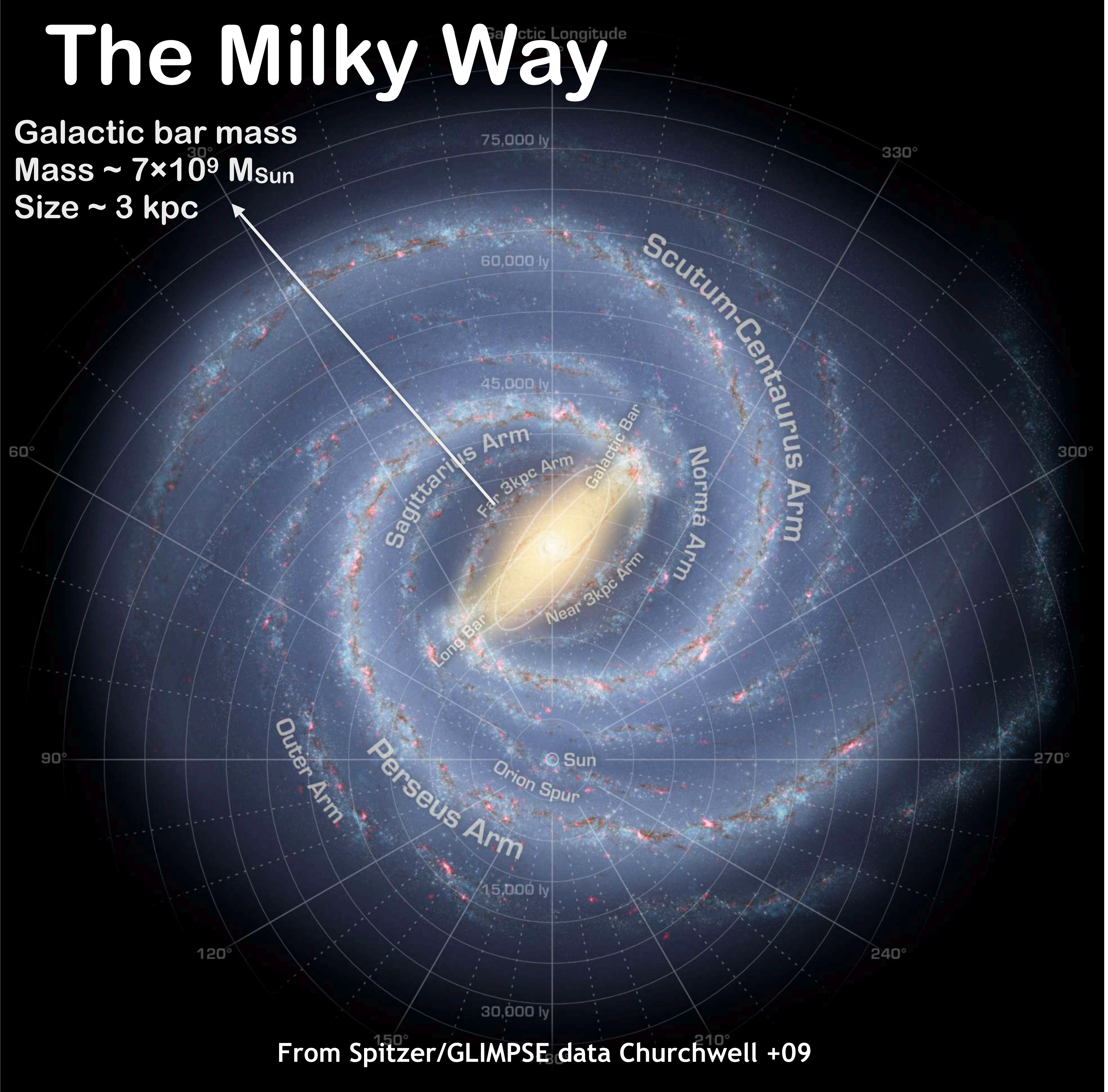
M83: Subaru/ESO/Hubble

The Milky Way



From Spitzer/GLIMPSE data Churchwell +09

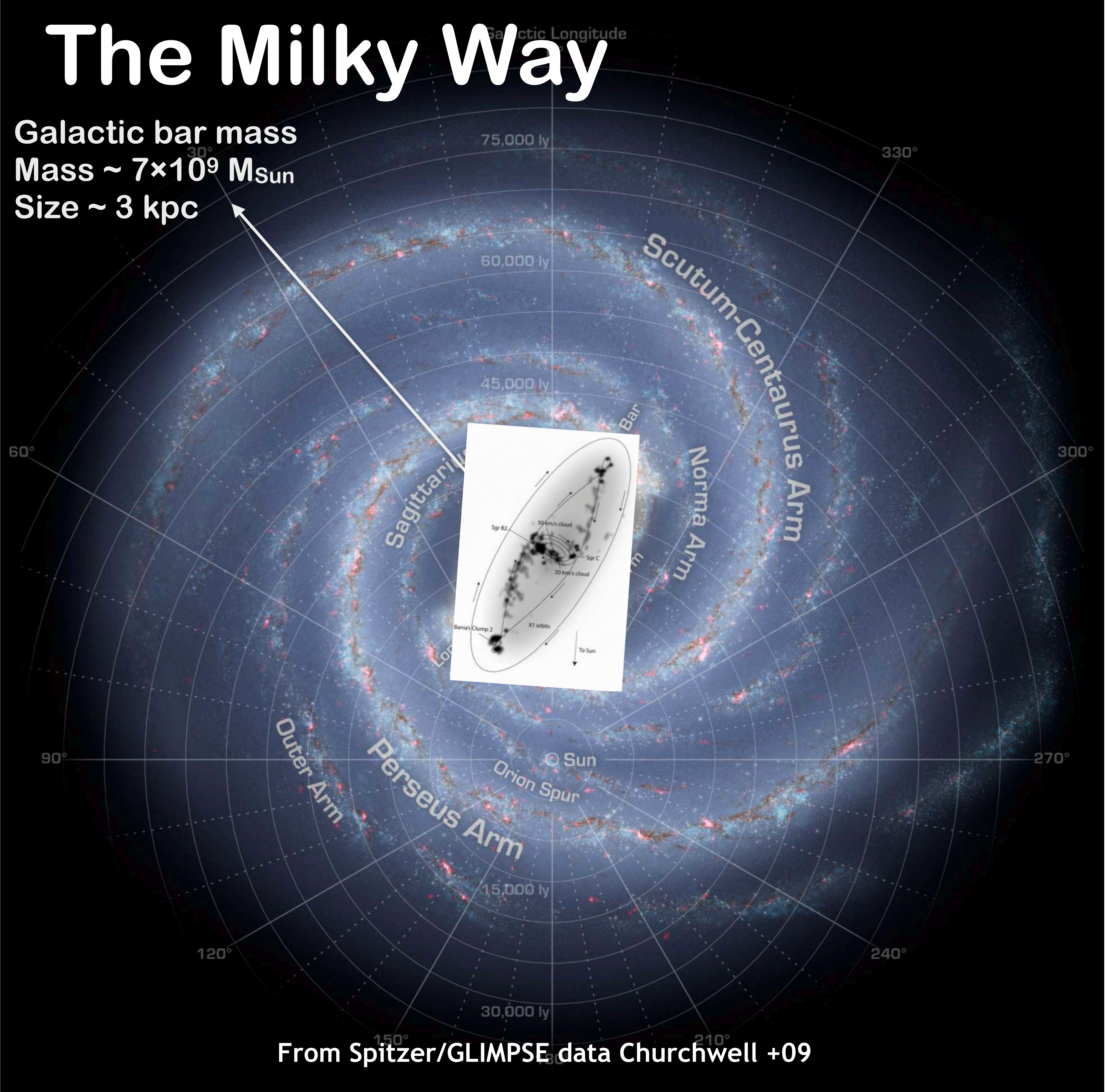
The Milky Way



From Spitzer/GLIMPSE data Churchwell +09

The Milky Way

Galactic bar mass
Mass ~ $7 \times 10^9\ M_{Sun}$
Size ~ 3 kpc



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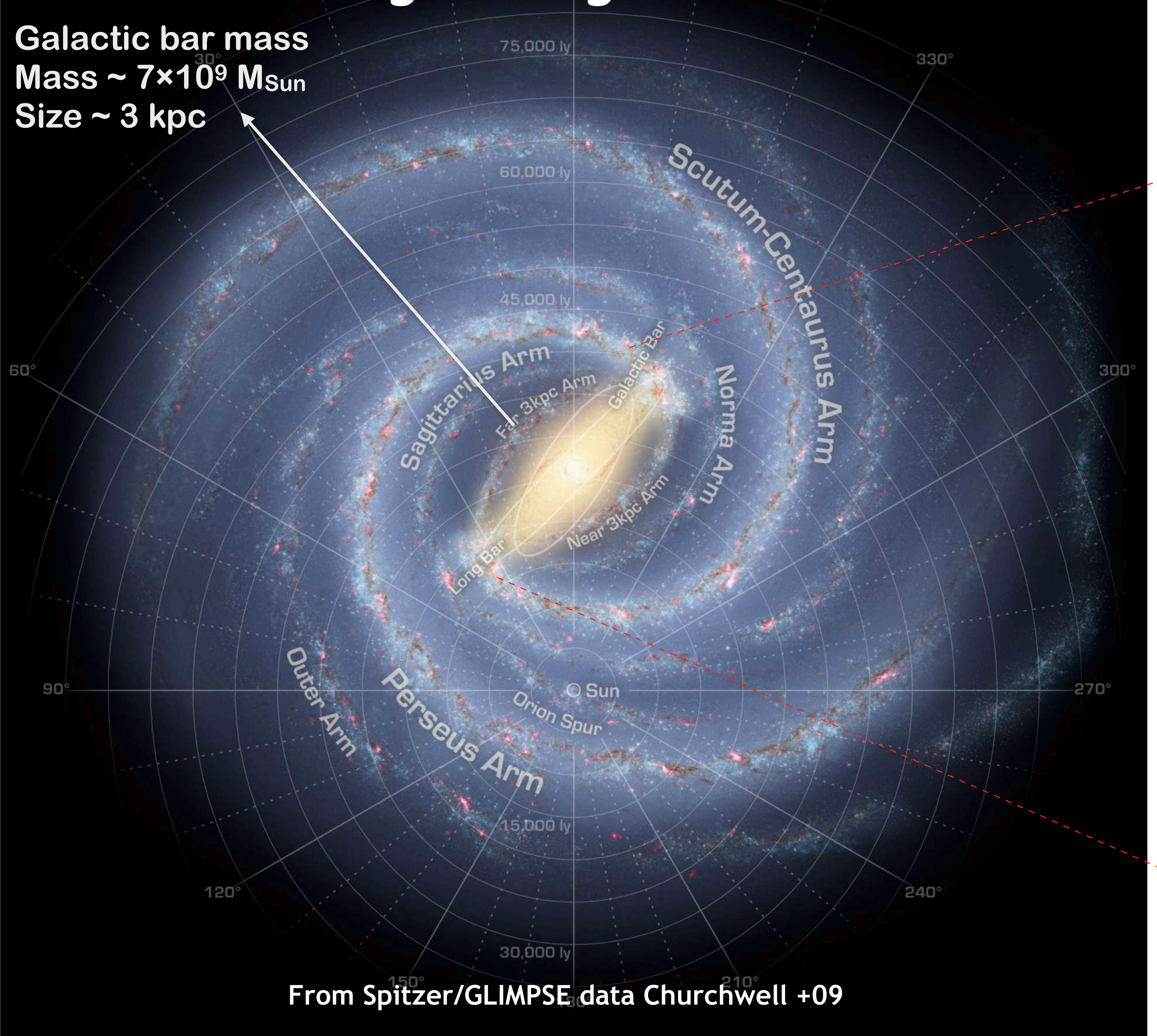

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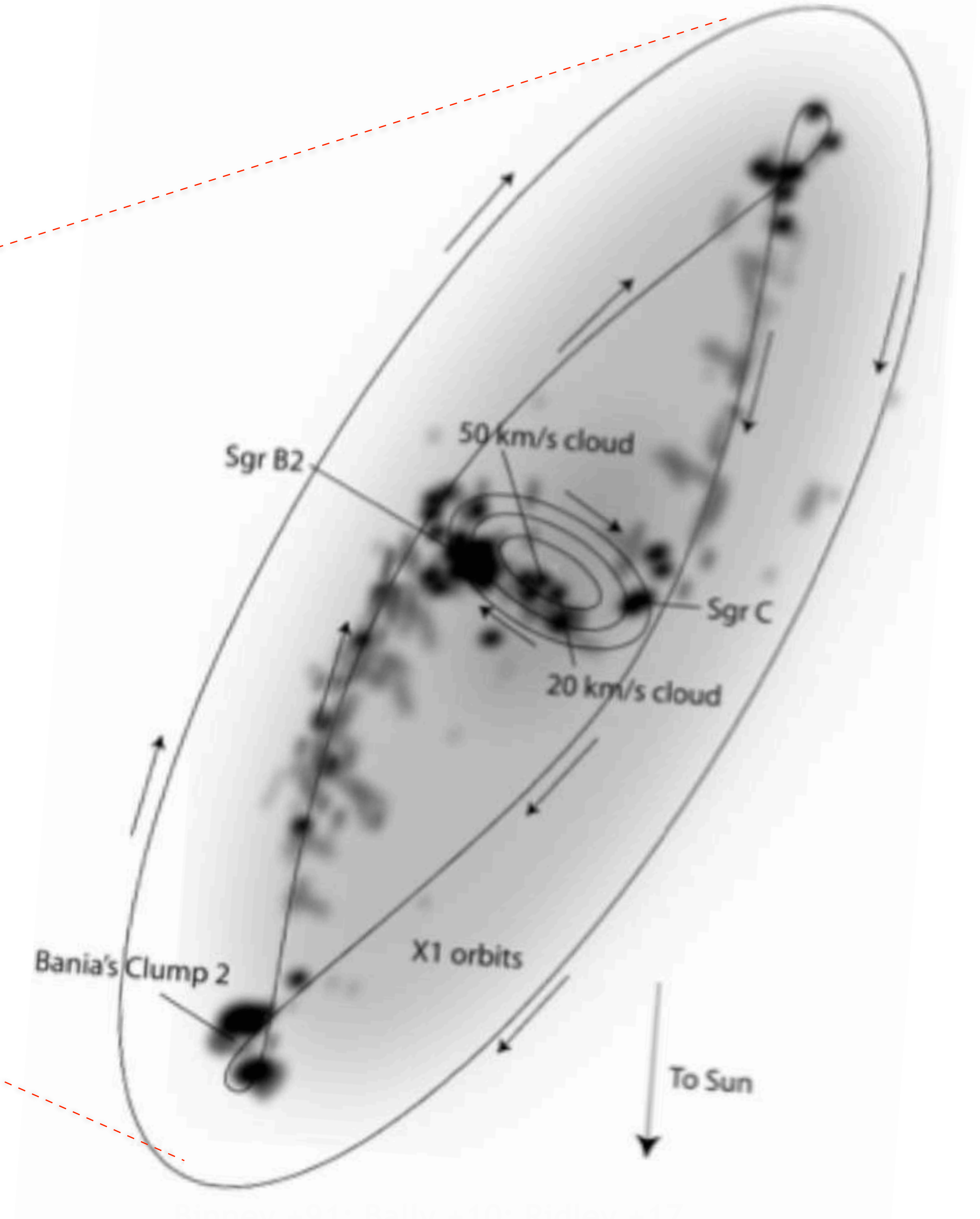

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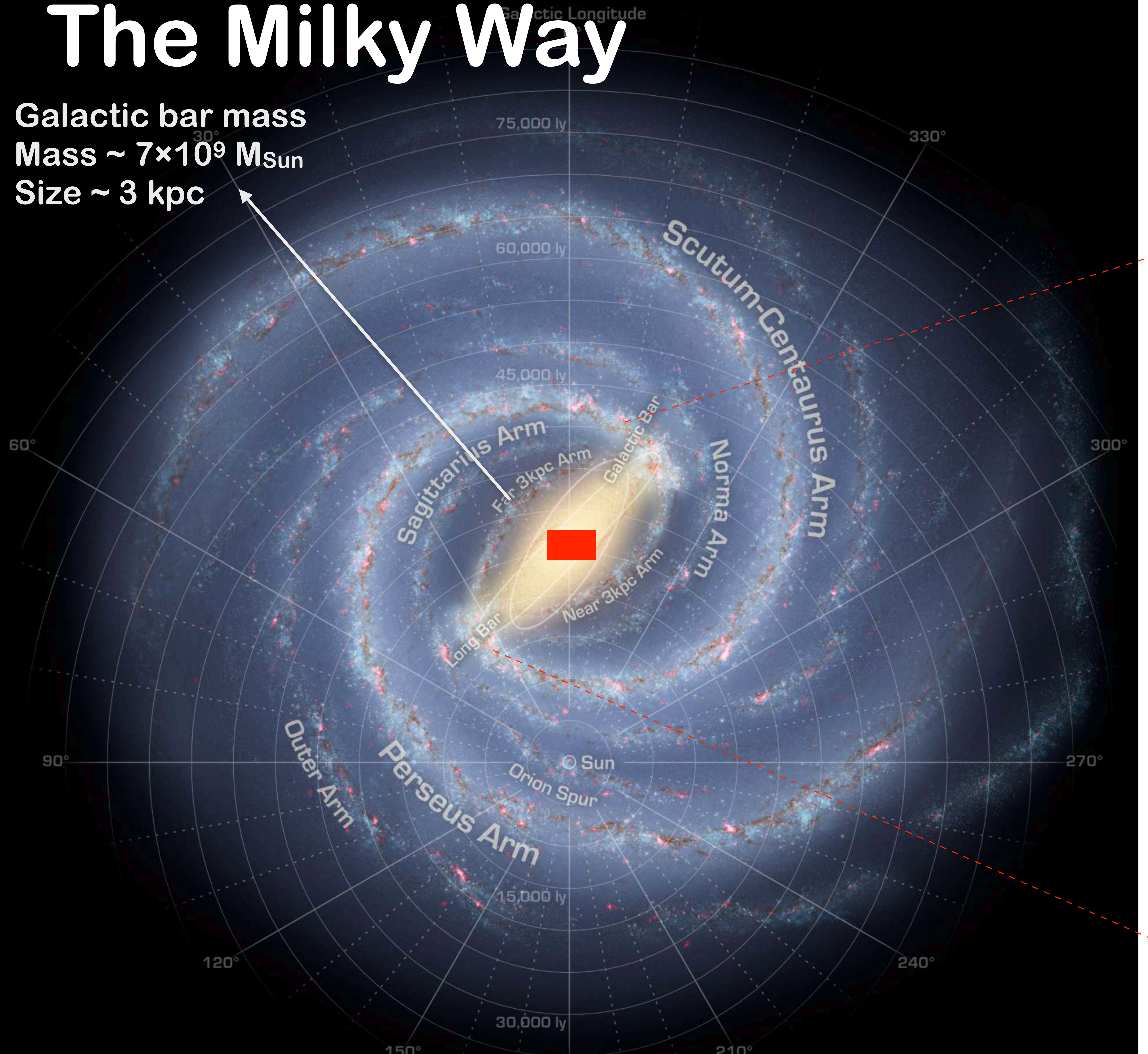

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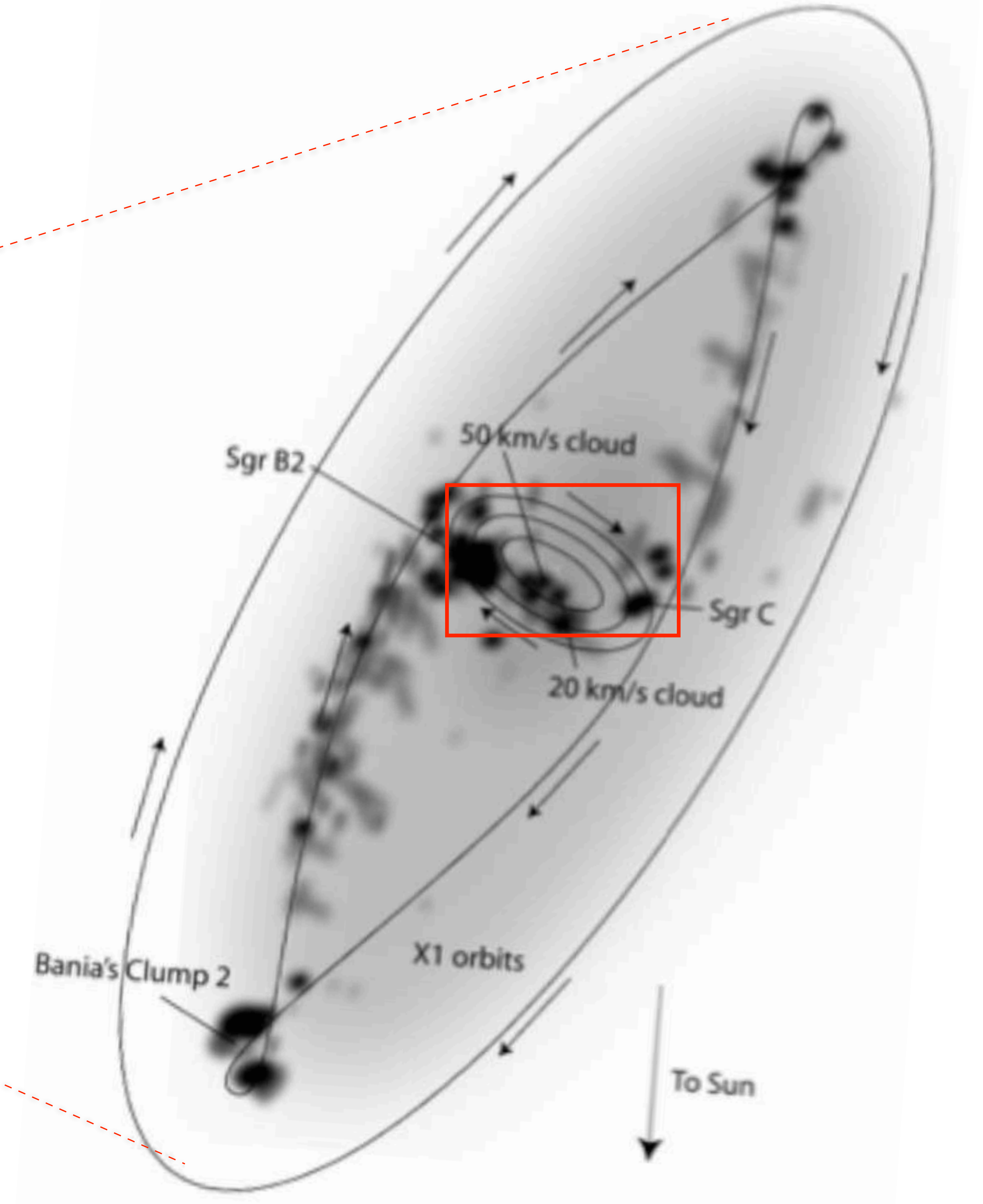
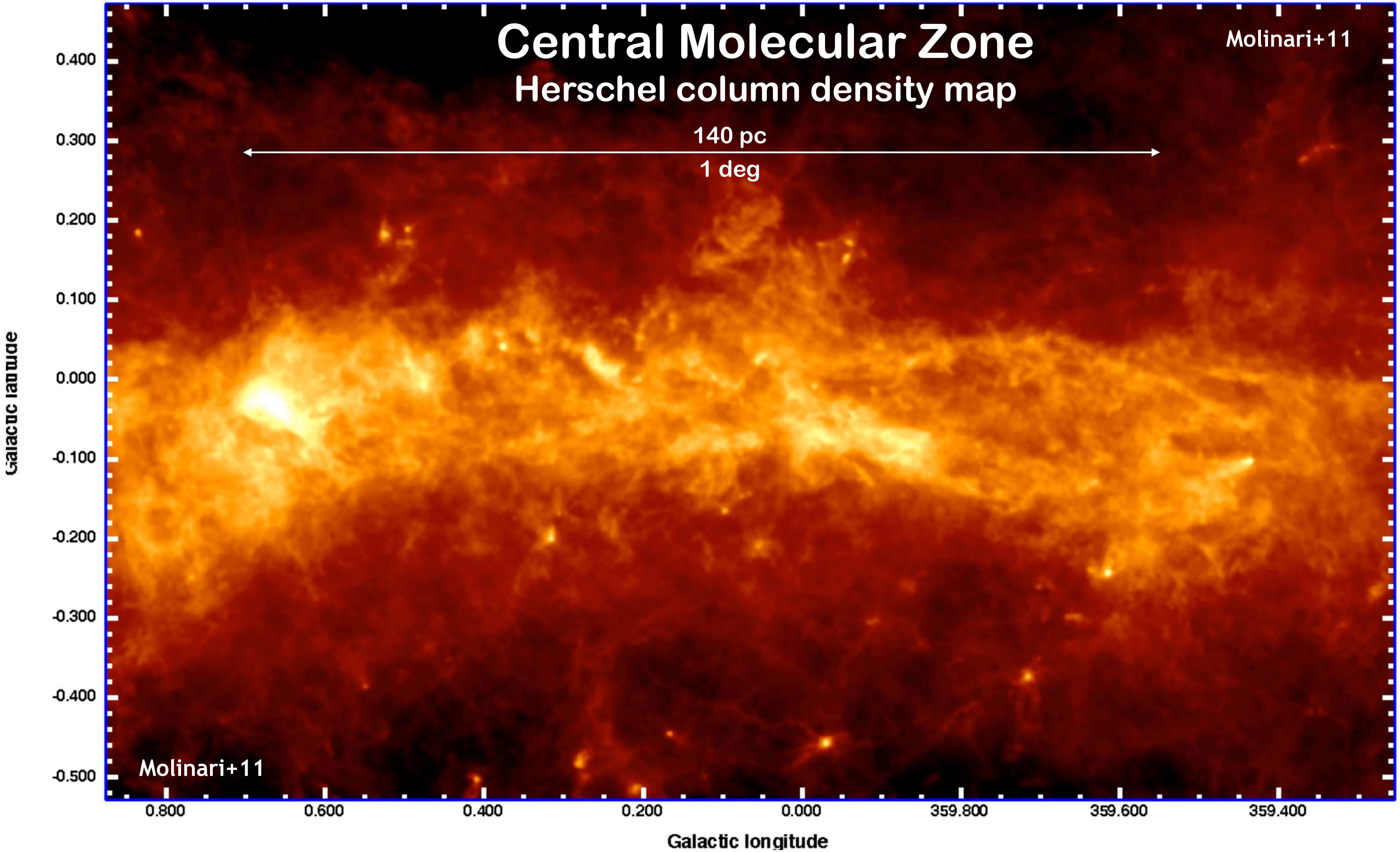
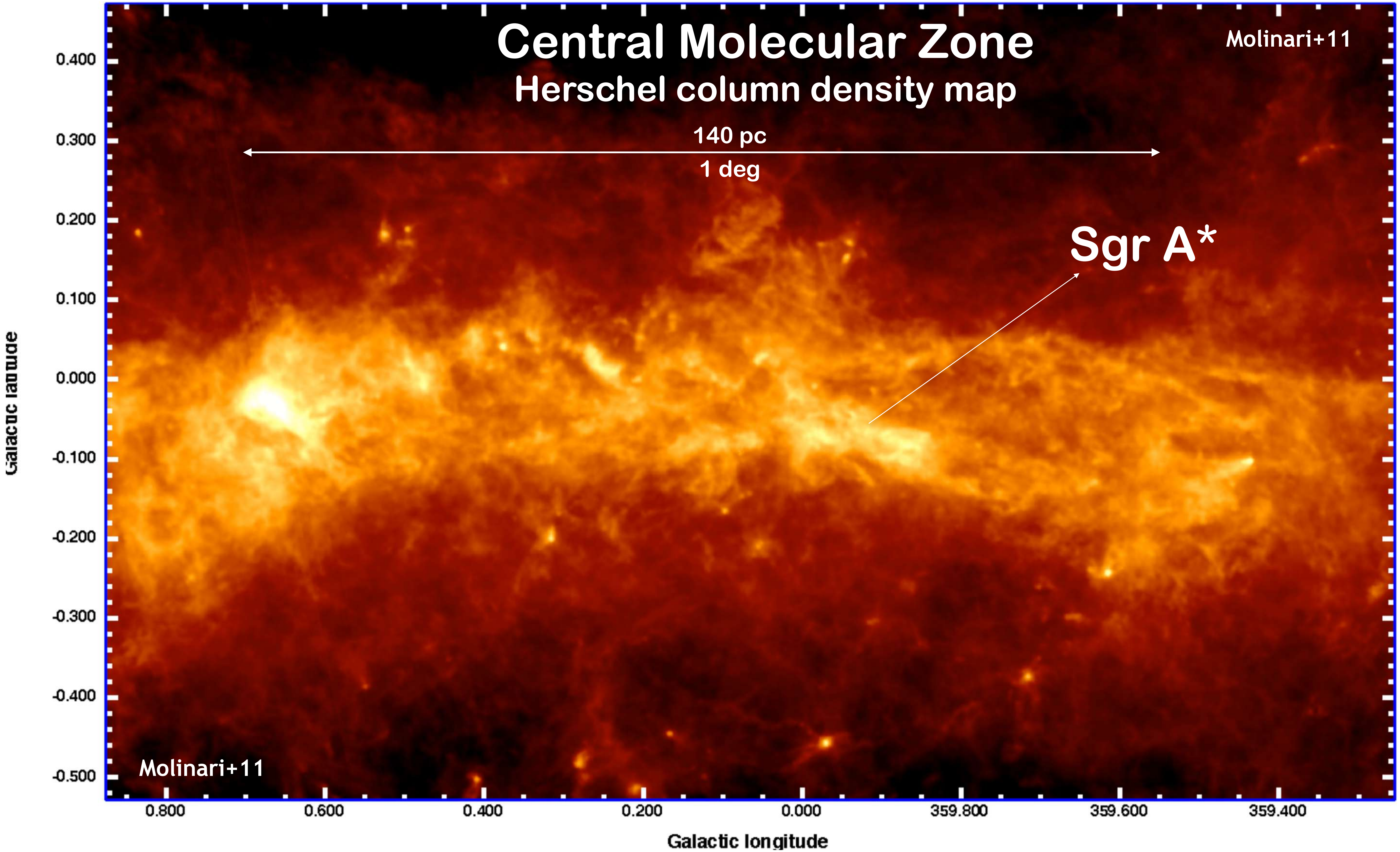


The central degrees of the Milky Way



The central degrees of the Milky Way



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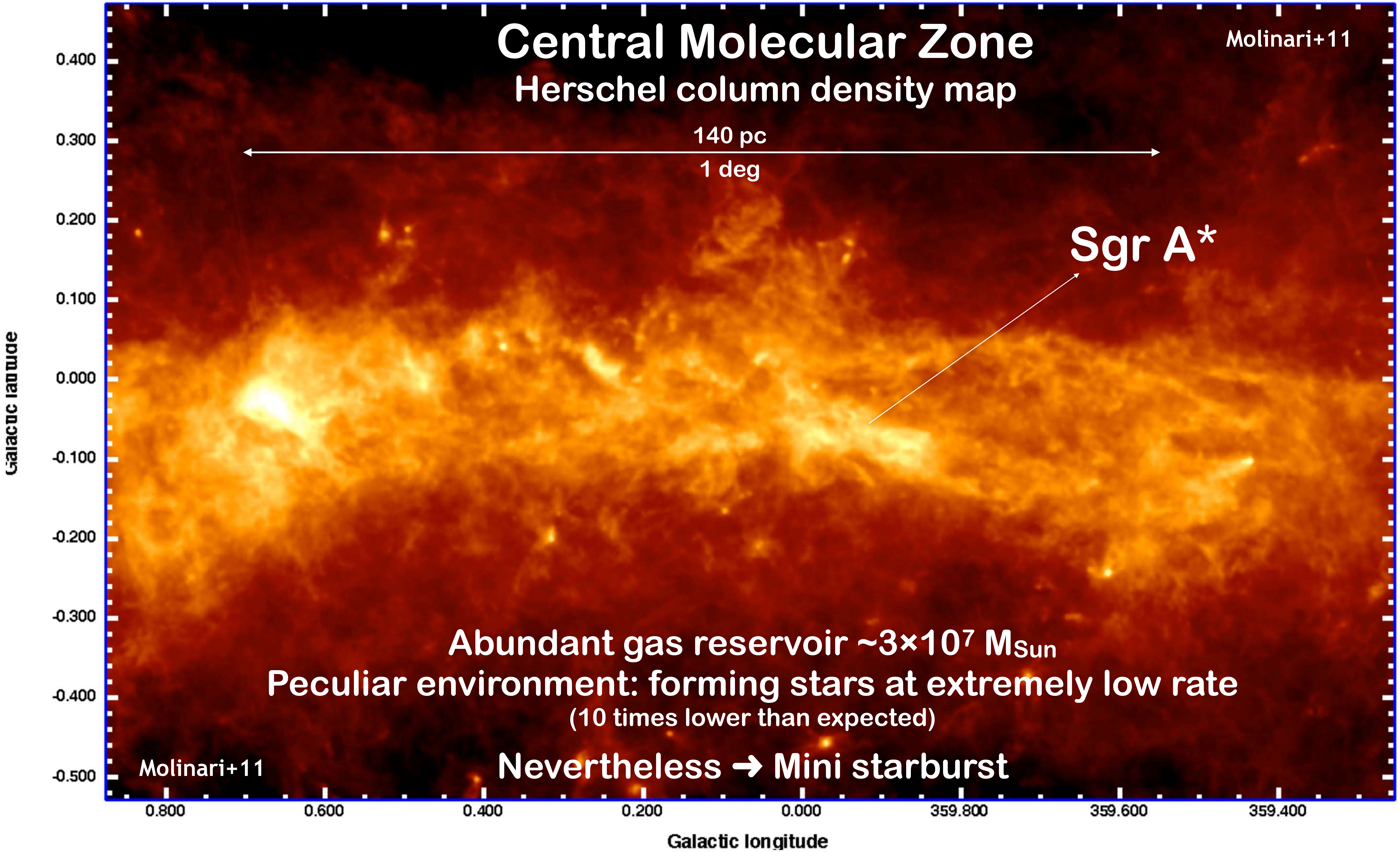

The Central Molecular Zone in X-rays

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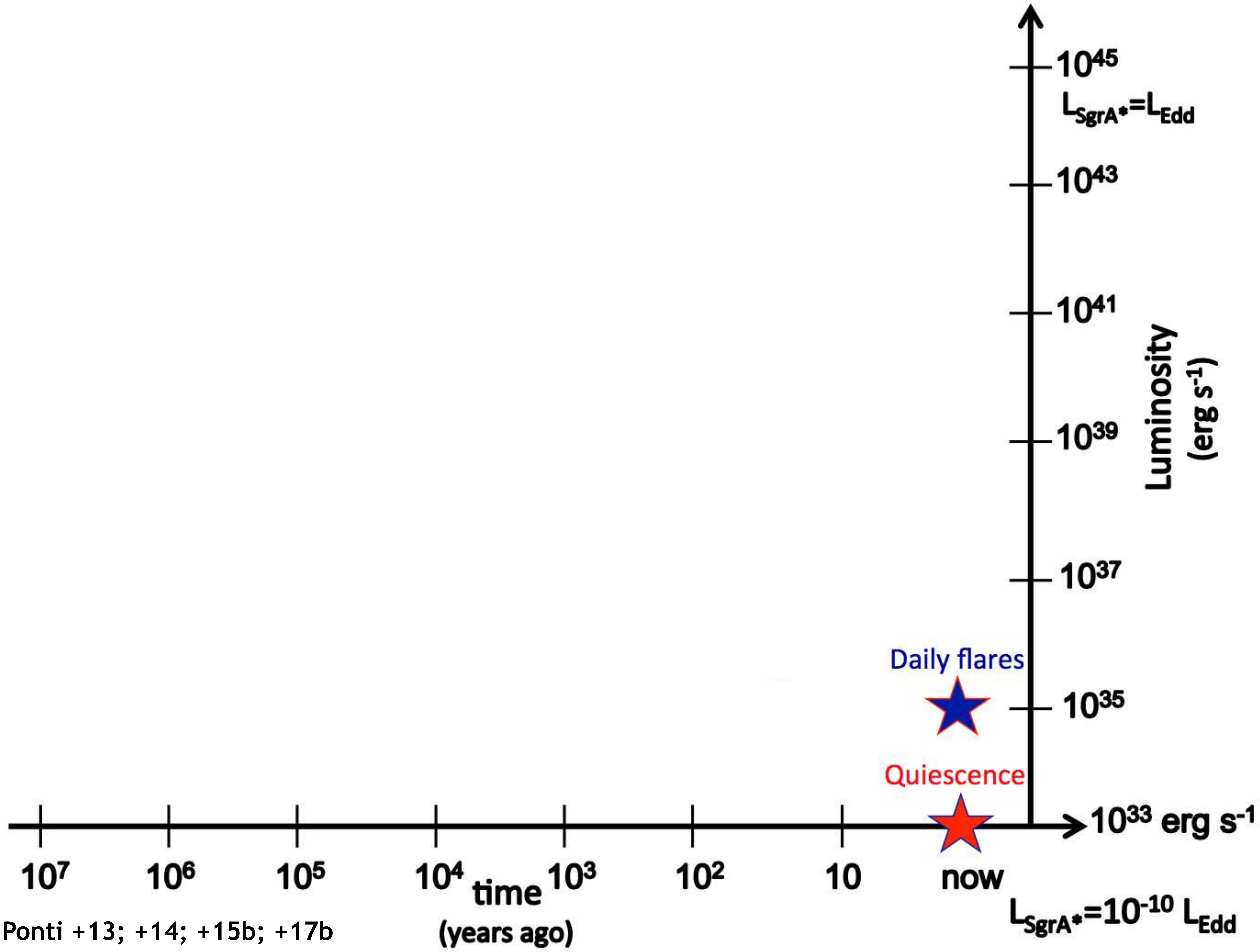
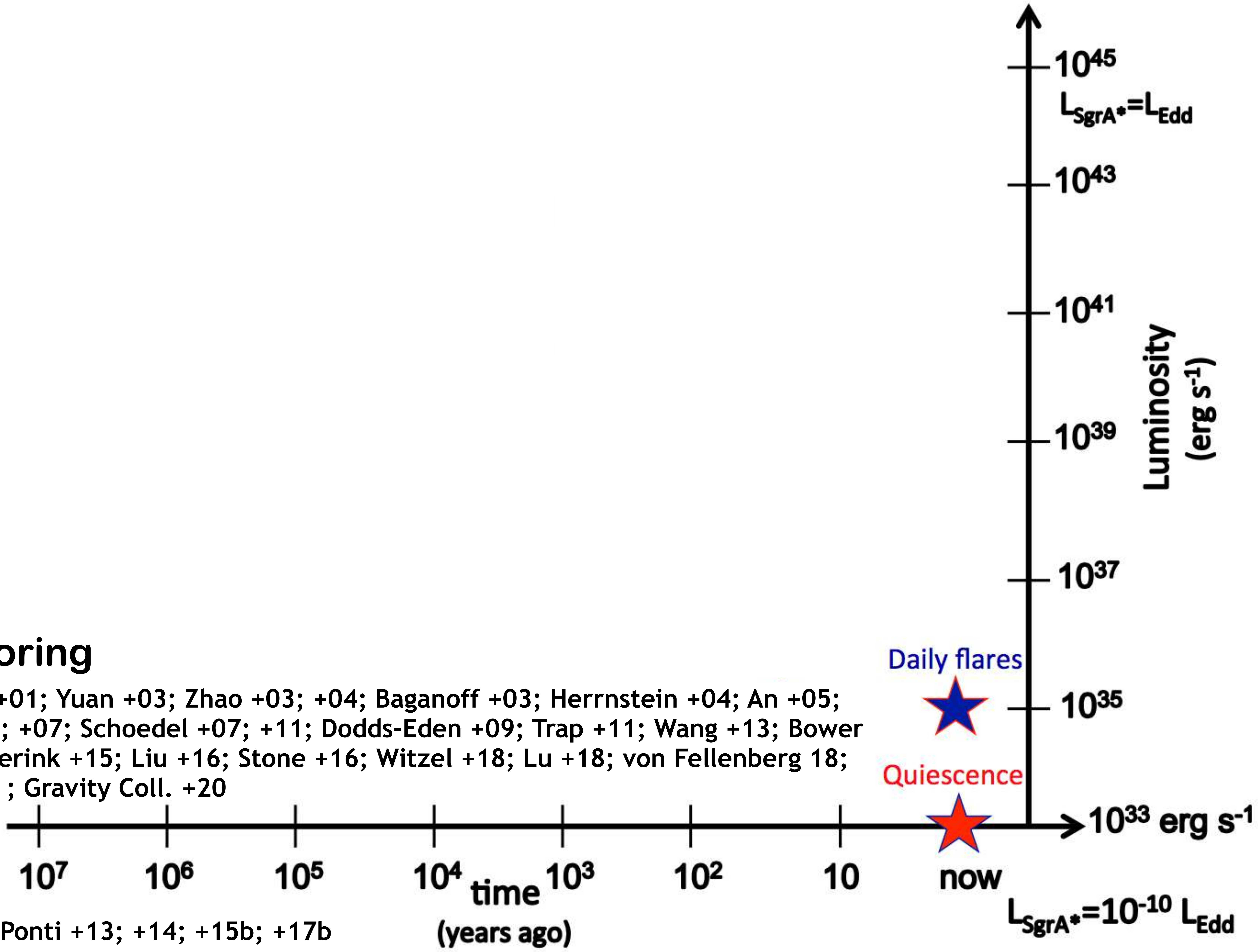
The Central Molecular Zone in X-rays

Sgr A* current emission



Ponti +13; +14; +15b; +17b

Sgr A* current emission



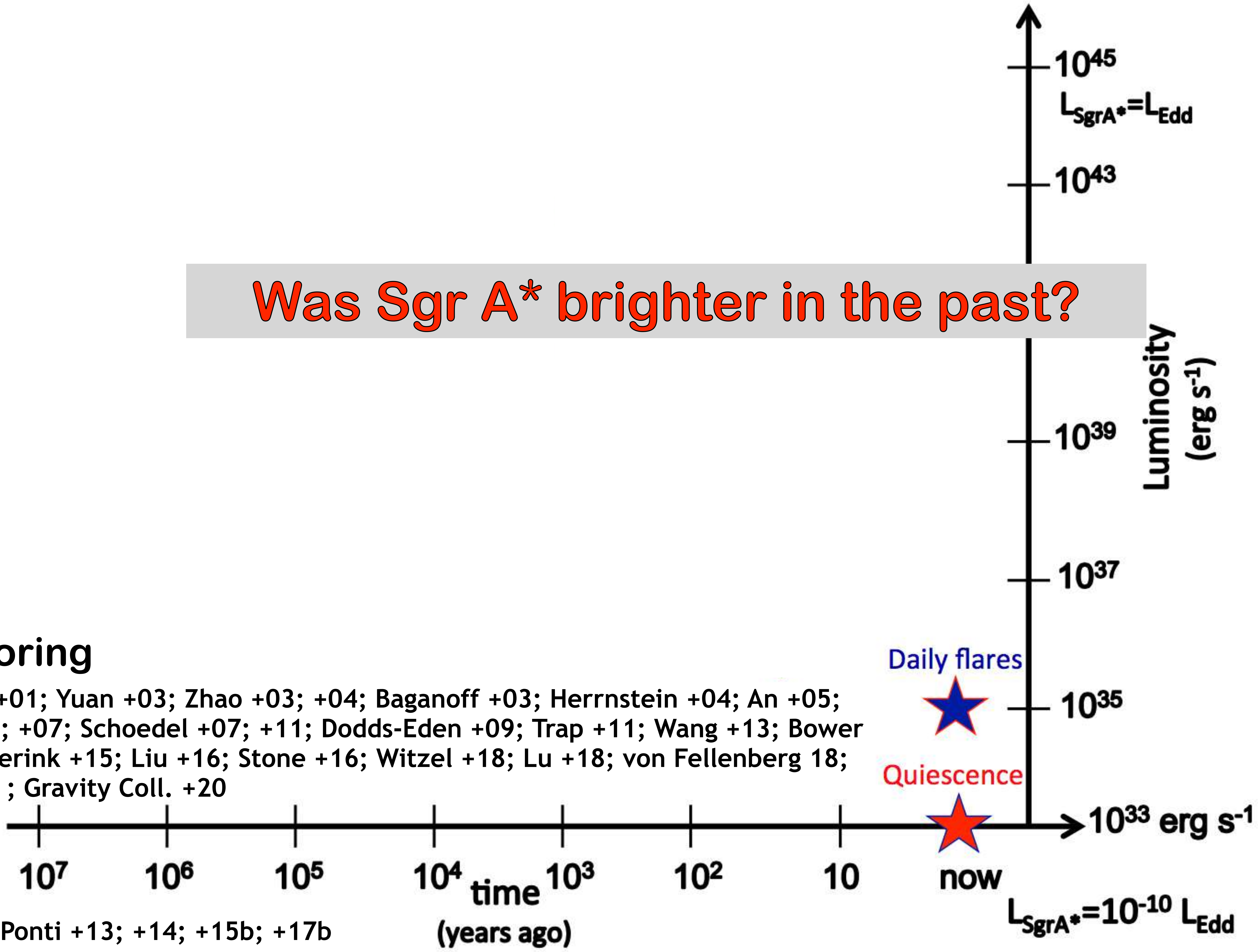
Sgr A* monitoring

Falcke +98; Markoff +01; Yuan +03; Zhao +03; +04; Baganoff +03; Herrnstein +04; An +05; Xu +06; Marrone +06; +07; Schoedel +07; +11; Dodds-Eden +09; Trap +11; Wang +13; Bower +15; +18; +19; Brinkerink +15; Liu +16; Stone +16; Witzel +18; Lu +18; von Fellenberg 18; Fazio +18; Iwata +20 ; Gravity Coll. +20

Ponti +13; +14; +15b; +17b

Sgr A* current emission

Was Sgr A* brighter in the past?



Sgr A* monitoring

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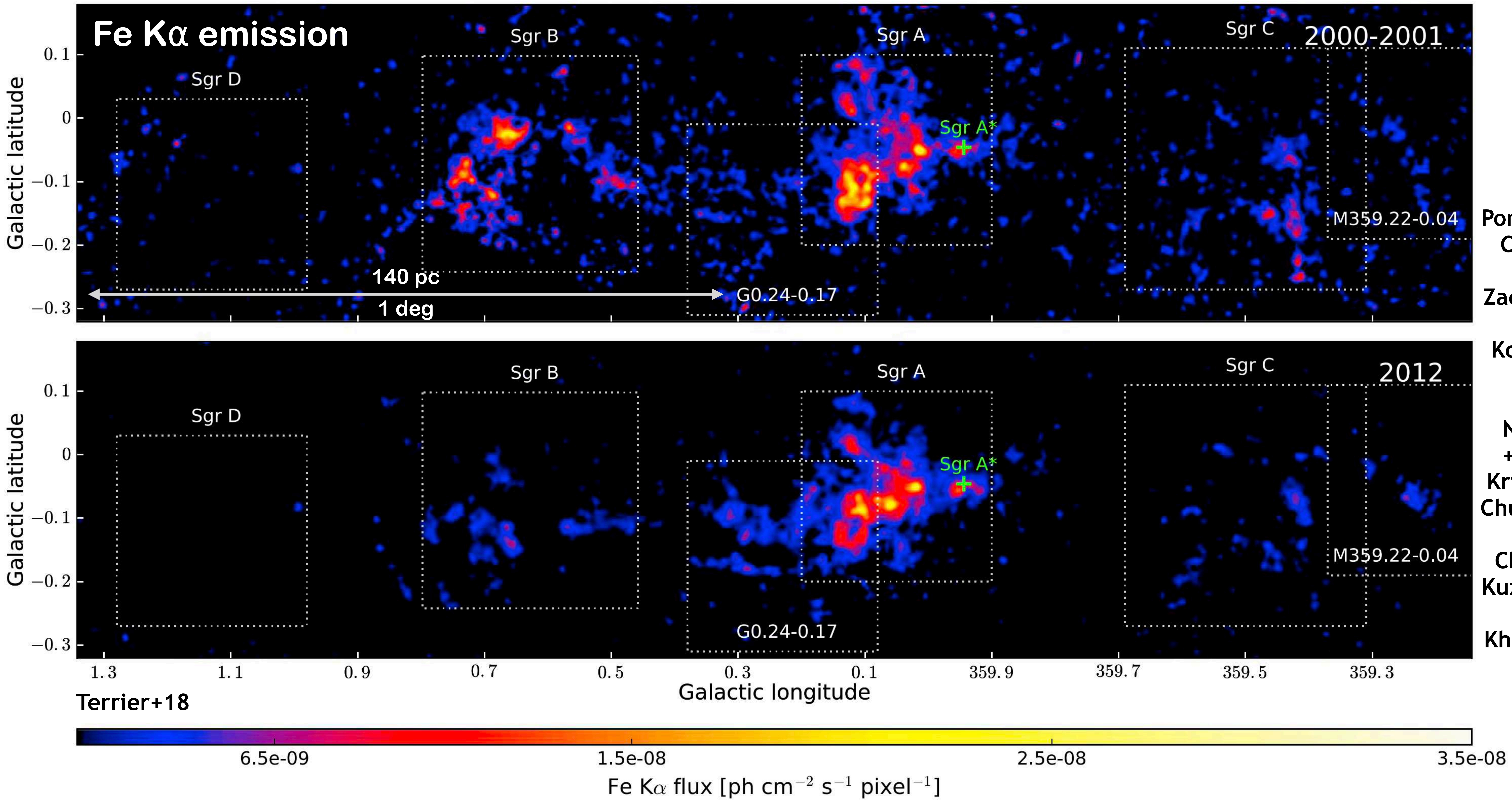
Ponti +13; +14; +15b; +17b

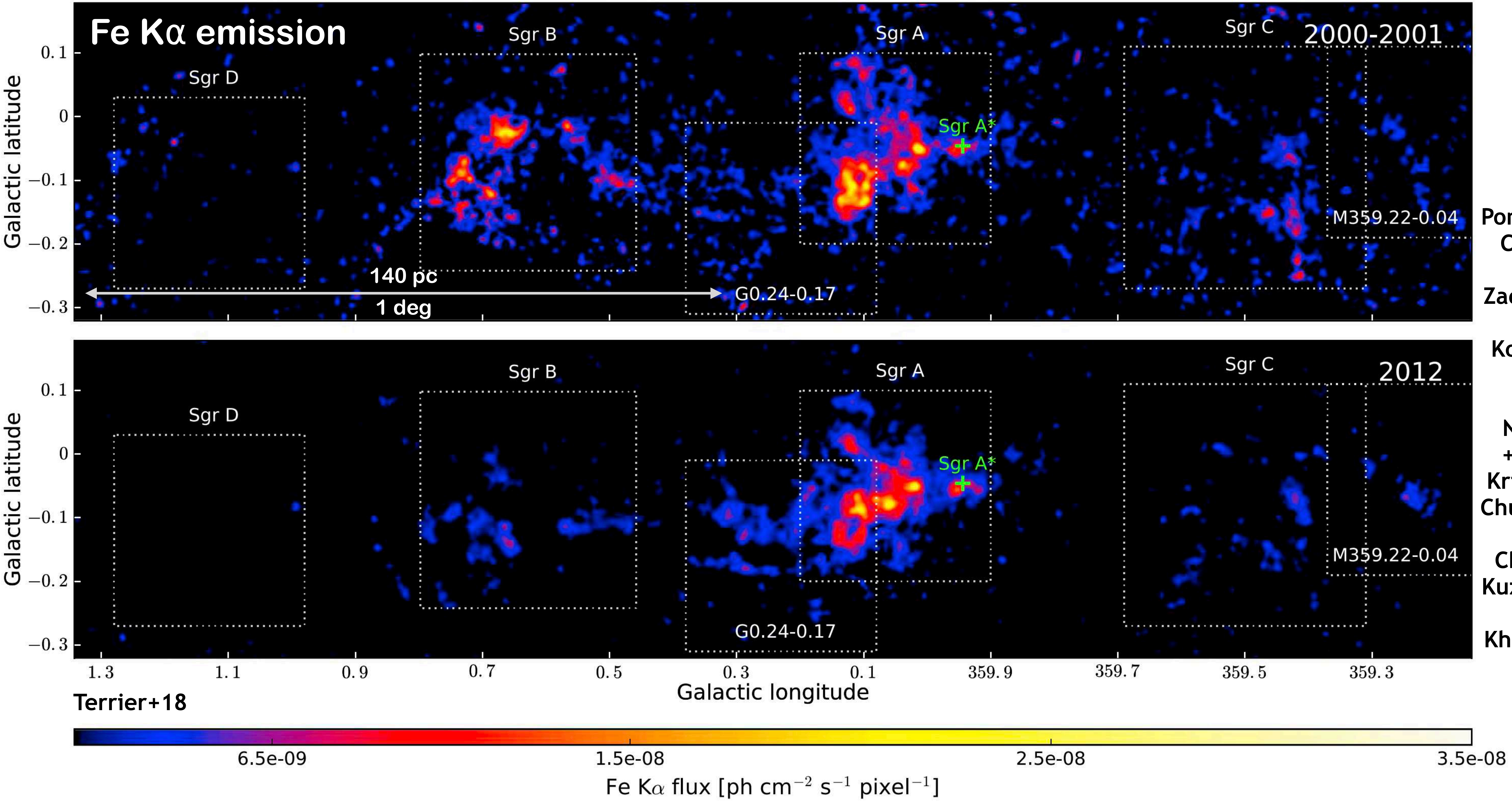
Reflection of a past bright flash



Terrier+18

See also Ponti+10;+13;+14; Clavel+13;+14; Yusef-Zadeh+13a,b;+19; Marin+14; Koyama+14;+18; Zhang+15; Mori+15; Nobukawa+15; +16; Walls+16; Krivonos+14;+17; Churazov+17a,b,c; Chuard+18; Chernyshov+18; Kuznetsova+19; Di Gesu+20; Khabibullin+20a,b

Reflection of a past bright flash

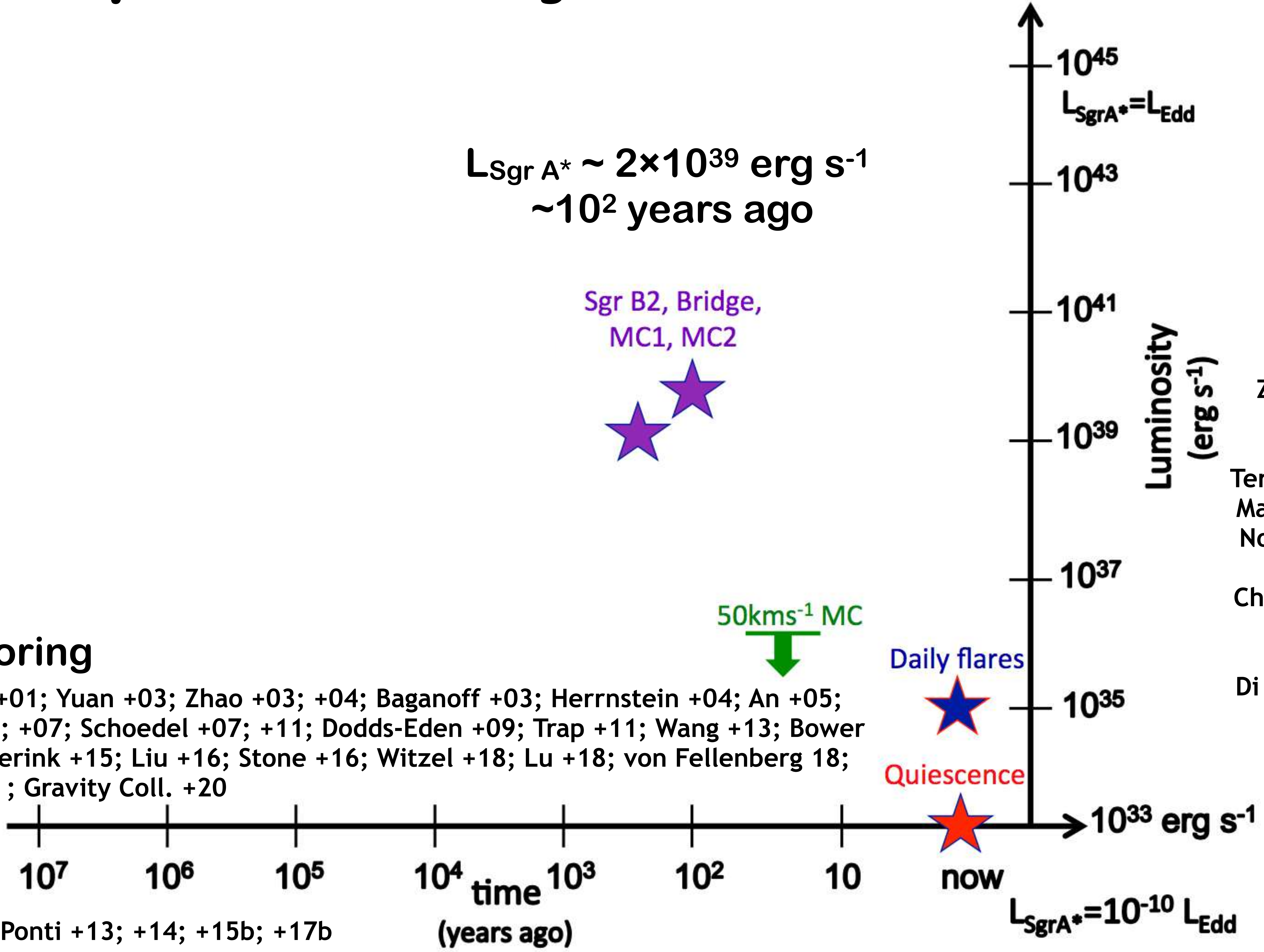


Terrier+18

See also Ponti+10;+13;+14; Clavel+13;+14; Yusef-Zadeh+13a,b;+19; Marin+14; Koyama+14;+18; Zhang+15; Mori+15; Nobukawa+15; +16; Walls+16; Krivonos+14;+17; Churazov+17a,b,c; Chuard+18; Chernyshov+18; Kuznetsova+19; Di Gesu+20; Khabibullin+20a,b

All bright Fe Kα clumps are variable ➜ Reflection by bright flash in the center

Sgr A*'s past activity



Sgr A* monitoring

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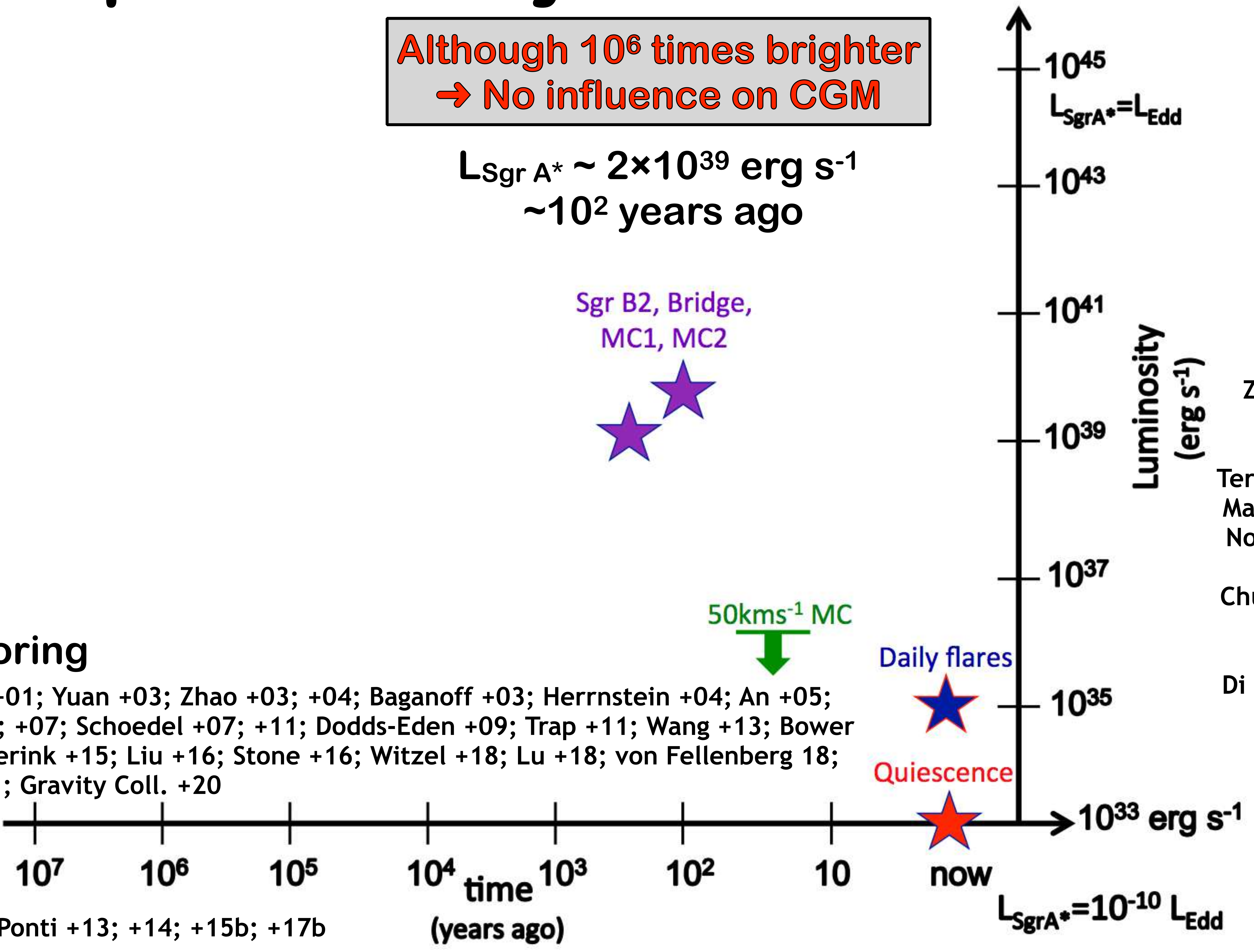
Ponti +13; +14; +15b; +17b

Sunyaev+93;+98; Koyama+97;+14;+18; Murakami+01; Yusef-Zadeh+02;+07;+13a,b;+19; Nakajima +09; Inui+09; Ponti+10;+13;+14; Terrier+10;+18; Clavel+13;+14; Marin+14; Zhang+15; Mori+15; Nobukawa+15; +16; Walls+16; Krivonos+14;+17; Churazov+17a,b,c; Chuard+18; Chernyshov+18; Kuznetsova+19; Di Gesu+20; Khabibullin+20a,b

Sgr A*'s past activity

Although 10^6 times brighter
➜ No influence on CGM

$L_{Sgr\ A^*} \sim 2\times10^{39}$ erg s^{-1}
~10^2 years ago



Sunyaev+93;+98; Koyama+97;+14;+18; Murakami+01; Yusef-Zadeh+02;+07;+13a,b;+19; Nakajima +09; Inui+09; Ponti+10;+13;+14; Terrier+10;+18; Clavel+13;+14; Marin+14; Zhang+15; Mori+15; Nobukawa+15; +16; Walls+16; Krivonos+14;+17; Churazov+17a,b,c; Chuard+18; Chernyshov+18; Kuznetsova+19; Di Gesu+20; Khabibullin+20a,b

Sgr A* monitoring

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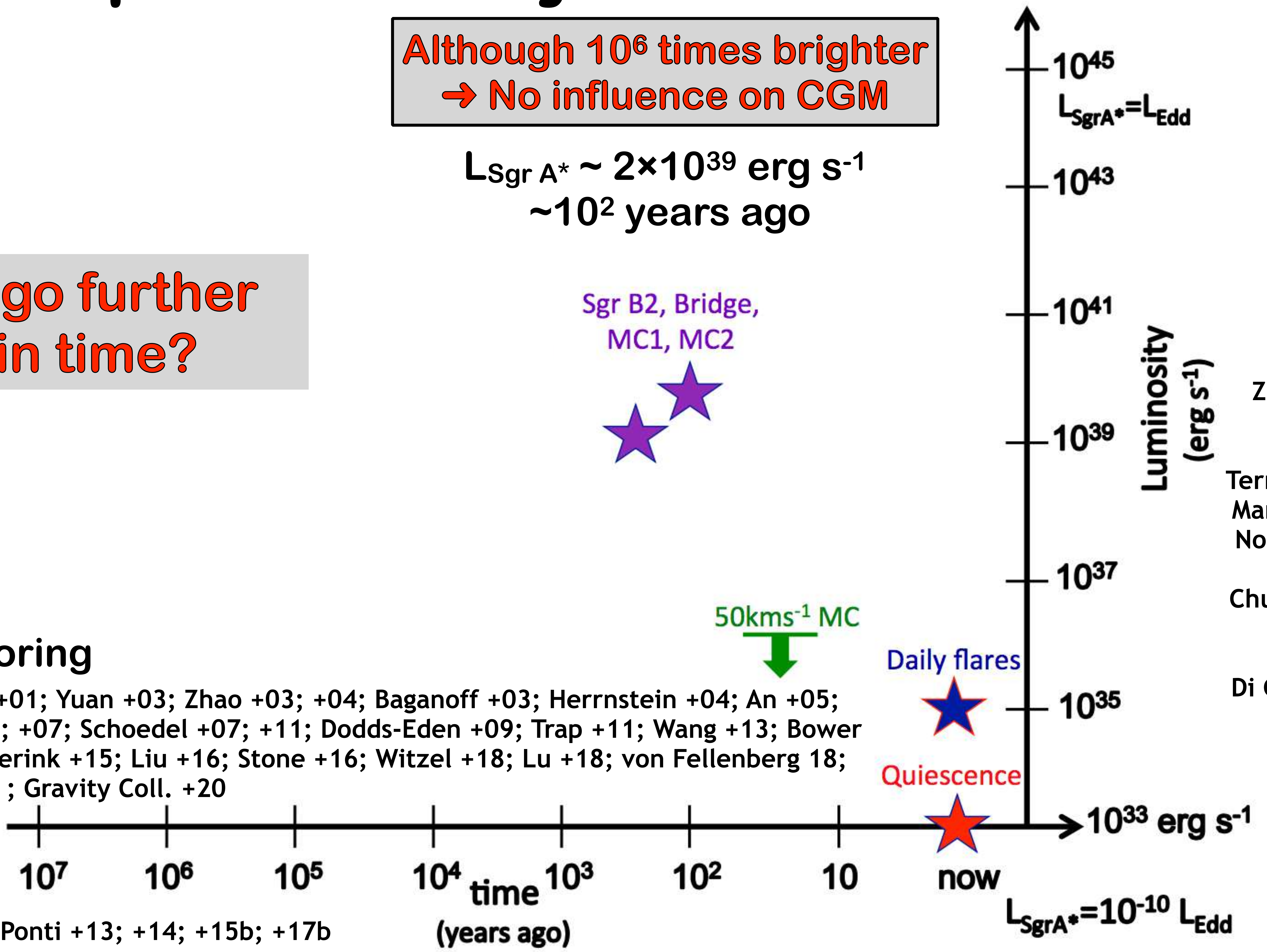
Sgr A*'s past activity

Although 10^6 times brighter
➜ No influence on CGM

$L_{Sgr\,A^*} \sim 2\times10^{39}$ erg s^{-1}
$\sim10^2$ years ago

Can we go further back in time?



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Ponti +13; +14; +15b; +17b

Hot plasma to trace past activity

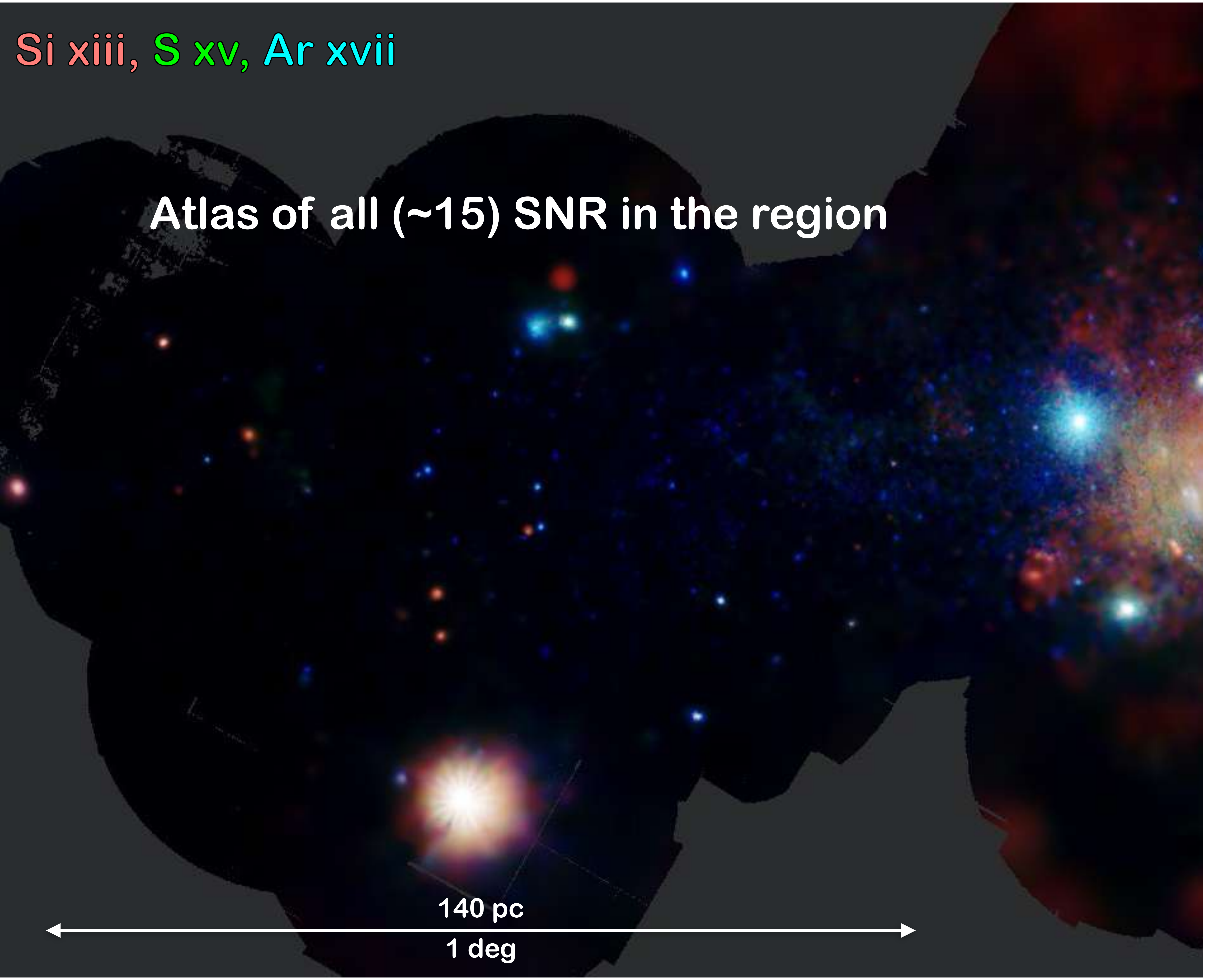
Patchy distribution with small and large structures

Total luminosity of soft plasma: $L_X \sim 3.4\times10^{36}$ erg s^{-1}

Hot plasma to trace past activity

Patchy distribution with small and large structures
Total luminosity of soft plasma: $L_X \sim 3.4\times10^{36}$ erg s^{-1}

Hot plasma to trace past activity



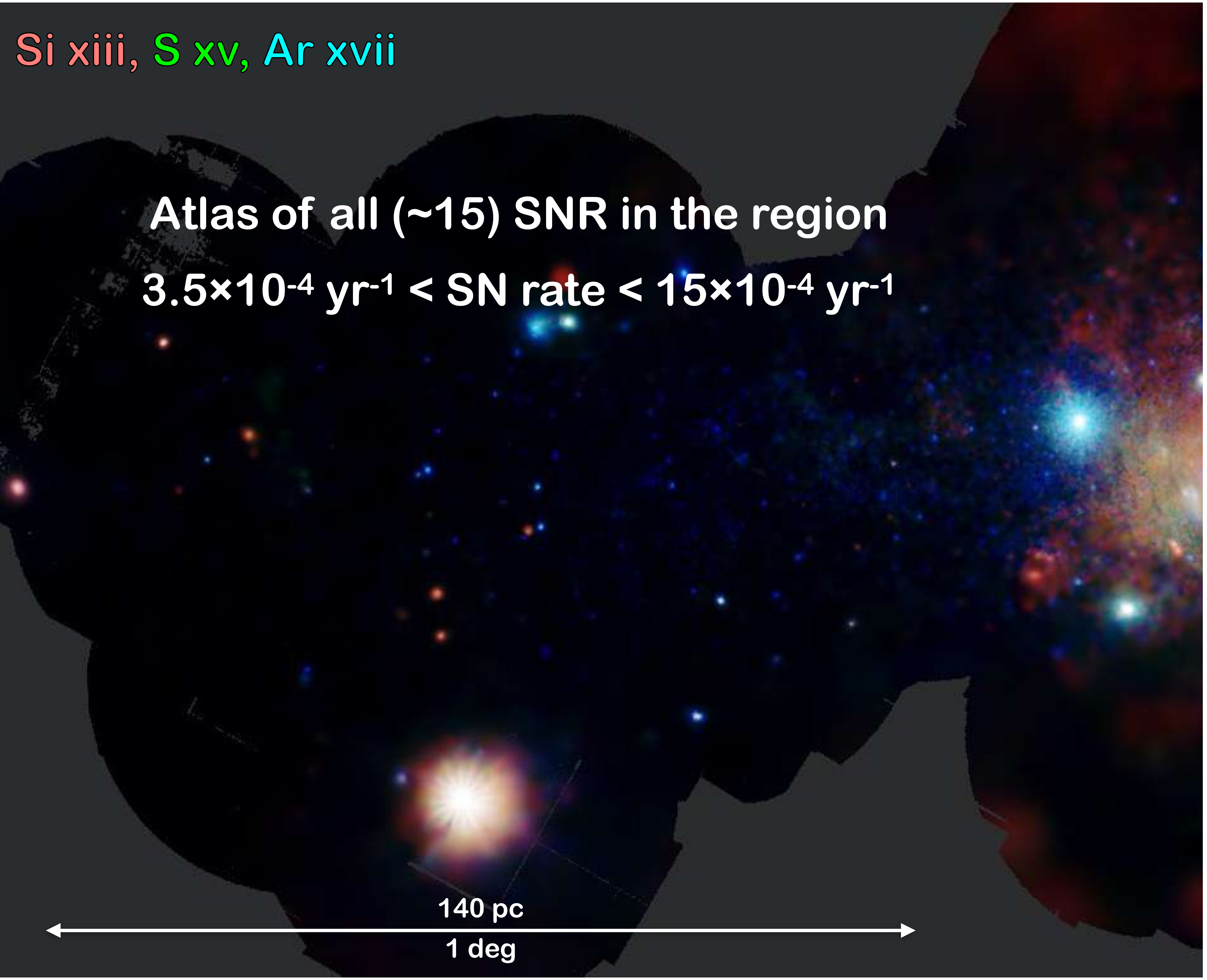
Ponti +15

ATLAS OF DIFFUSE X-RAY EMITTING FEATURES

Name	Other name	Coordinates (l, b)	Size arcsec	References
STAR CLUSTERS:				
Central star cluster		359.9442, -0.046	0.33	45,116,117,118
Quintuplet		0.1604, -0.0591	0.5	1,63,11
Arches	G0.12+0.02	0.1217, 0.0188	0.7	1,2,3,4,5,6,7,8,9,39,40,11
Sh2-10	DB00-6	0.3072,-0.2000	1.92	10,11,12,63,11
Sh2-17	DB00-58	0.0013, 0.1588	1.65	13,63,11
DB00-05	G0.33-0.18	0.31 -0.19	0.4	22,63,11
SNR - BUBBLES - SUPER-BUBBLES:				
G359.0-0.9	G358.5-0.9 - G359.1-0.9	359.03,-0.96	26 × 20	X-R 48,51,75,76,81,119,120
G359.07-0.02	G359.0-0.0	359.07,-0.02	22 × 10	R 14,48,51,66
	G359.12-0.05	359.12,-0.05	24 × 16	X 66
G359.10-0.5		359.10,-0.51	22 × 22	X-R 37,48,51,56,74,75,81,120,121
G359.41-0.12		359.41,-0.12	3.5 × 5.0	X 14
Chimney		359.46,+0.04	6.8 × 2.3	X 14
G359.73-0.35‡		359.73,-0.35	4	X 58
G359.77-0.09	Superbubble	359.84,-0.14	20 × 16	X 15,16,17,58
	G359.79-026♮	359.79,-0.26	8 × 5.2	X 15,16,17,58
	G0.0-0.16††	0.00,-0.16		X This work
G359.87+0.44	Cane	359.87,+0.44	11 × 5	R 48
	G359.85+0.39			
20pc Sgr A*'s lobes		359.94, -0.04	5.88	R 32,33,34,17
G359.92-0.09‡	Parachute - G359.93-0.07	359.93,-0.09	1	R 35,38,43,47,58,60,61
Sgr A East	G0.0+0.0	359.963, -0.053	3.2 × 2.5	X-R 5,18,19,20,48,75,81
G0.1-0.1	Arc Bubble	0.109,-0.108	13.6 × 11	X This work
	G0.13,-0.12♭	0.13,-0.12	3 × 3	X 17
G0.224-0.032		0.224,-0.032	2.3 × 4.6	X This work
G0.30+0.04	G0.3+0.0	0.34,+0.045	14 × 8.8	R 21,48,51,81,82
	G0.34+0.05			
	G0.33+0.04			
G0.40-0.02	Suzaku J1746.4-2835.4	0.40,-0.02	4.7 × 7.4	X 22
	G0.42-0.04			
G0.52-0.046		0.519,-0.046⋄	2.4 × 5.1	This work
G0.57-0.001		0.57,-0.001	1.5 × 2.9	This work
G0.57-0.018†	CXO J174702.6-282733	0.570,-0.018	0.2	X 23,24,58,59,68,80
G0.61+0.01†	Suzaku J1747.0-2824.5	0.61,+0.01	2.2 × 4.8	X 22,65,79
G0.9+01♡	SNR 0.9+0.1	0.867,+0.073	7.6 × 7.2	R 25,26,27,28,29,48,75,81,82
DS1	G1.2-0.0	1.17,+0.00	3.4 × 6.9	X 31
Sgr D SNR	G1.02-0.18	1.02,-0.17	10 × 8.0	R 30,31,48,51,75,77,81,82
	G1.05-0.15			
	G1.05-0.1			
	G1.0-0.1			
G1.4-0.1		1.4,-0.10	10 × 10	R 73,81,82

Ponti +15

Hot plasma to trace past activity



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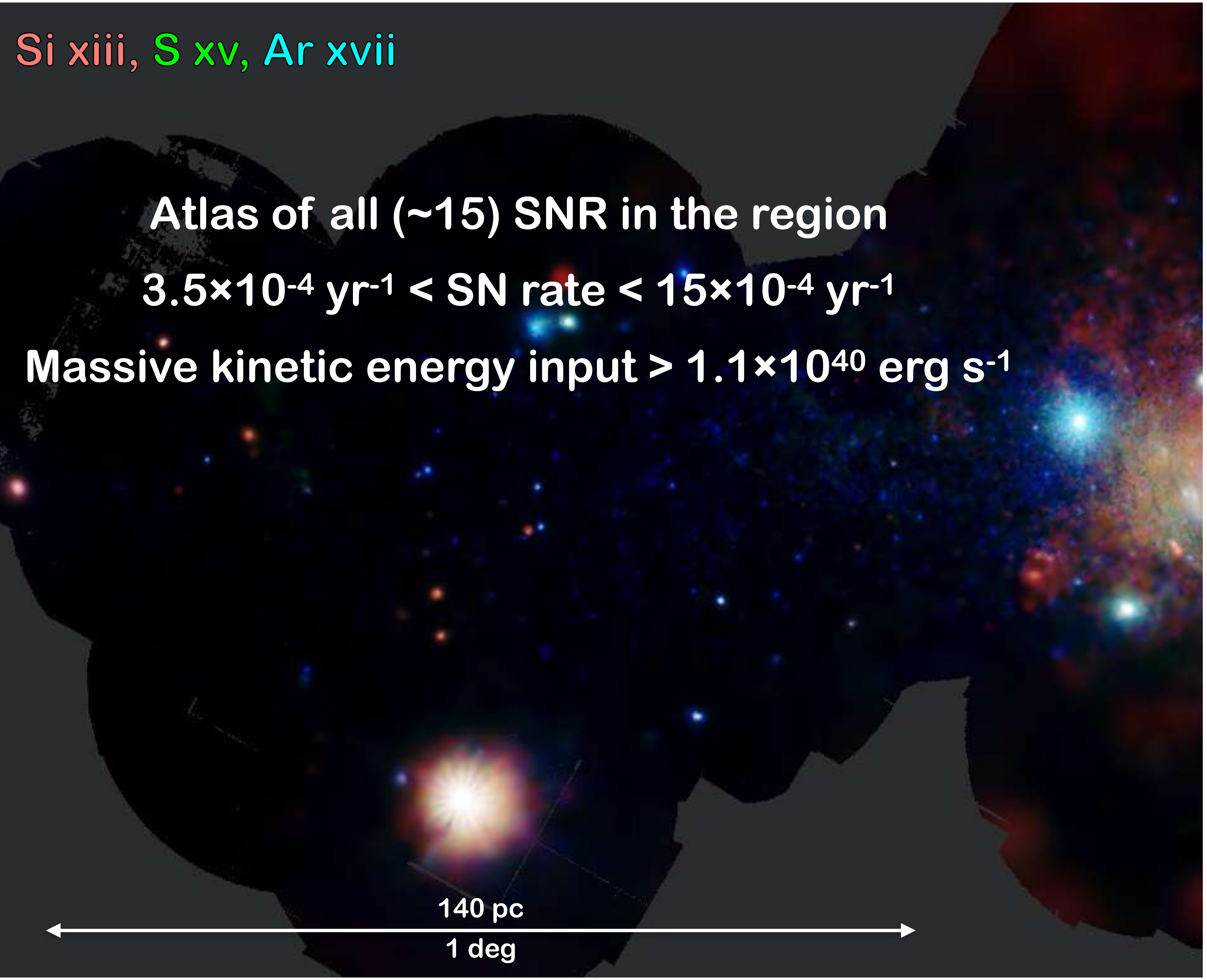
	G1.05-0.15			
	G1.05-0.1			
	G1.0-0.1			
G1.4-0.1		1.4,-0.10	10 × 10	R 73,81,82

Ponti +15

Hot plasma to trace past activity



Ponti +15

ATLAS OF DIFFUSE X-RAY EMITTING FEATURES

Name	Other name	Coordinates (l, b)	Size arcsec	References
STAR CLUSTERS:				
Central star cluster		359.9442, -0.046	0.33	45,116,117,118
Quintuplet		0.1604, -0.0591	0.5	1,63,11
Arches	G0.12+0.02	0.1217, 0.0188	0.7	1,2,3,4,5,6,7,8,9,39,40,11
Sh2-10	DB00-6	0.3072,-0.2000	1.92	10,11,12,63,11
Sh2-17	DB00-58	0.0013, 0.1588	1.65	13,63,11
DB00-05	G0.33-0.18	0.31 -0.19	0.4	22,63,11
SNR - BUBBLES - SUPER-BUBBLES:				
G359.0-0.9	G358.5-0.9 - G359.1-0.9	359.03,-0.96	26 × 20	X-R 48,51,75,76,81,119,120
G359.07-0.02	G359.0-0.0	359.07,-0.02	22 × 10	R 14,48,51,66
	G359.12-0.05	359.12,-0.05	24 × 16	X 66
G359.10-0.5		359.10,-0.51	22 × 22	X-R 37,48,51,56,74,75,81,120,121
G359.41-0.12		359.41,-0.12	3.5 × 5.0	X 14
Chimney		359.46,+0.04	6.8 × 2.3	X 14
G359.73-0.35‡		359.73,-0.35	4	X 58
G359.77-0.09	Superbubble	359.84,-0.14	20 × 16	X 15,16,17,58
	G359.79-026♮	359.79,-0.26	8 × 5.2	X 15,16,17,58
	G0.0-0.16††	0.00,-0.16		X This work
G359.87+0.44	Cane	359.87,+0.44	11 × 5	R 48
	G359.85+0.39			
20pc Sgr A⋆'s lobes		359.94, -0.04	5.88	R 32,33,34,17
G359.92-0.09‡	Parachute - G359.93-0.07	359.93,-0.09	1	R 35,38,43,47,58,60,61
Sgr A East	G0.0+0.0	359.963, -0.053	3.2 × 2.5	X-R 5,18,19,20,48,75,81
G0.1-0.1	Arc Bubble	0.109,-0.108	13.6 × 11	X This work
	G0.13,-0.12♭	0.13,-0.12	3 × 3	X 17
G0.224-0.032		0.224,-0.032	2.3 × 4.6	X This work
G0.30+0.04	G0.3+0.0	0.34,+0.045	14 × 8.8	R 21,48,51,81,82
	G0.34+0.05			
	G0.33+0.04			
G0.40-0.02	Suzaku J1746.4-2835.4	0.40,-0.02	4.7 × 7.4	X 22
	G0.42-0.04			
G0.52-0.046		0.519,-0.046⋄	2.4 × 5.1	This work
G0.57-0.001		0.57,-0.001	1.5 × 2.9	This work
G0.57-0.018†	CXO J174702.6-282733	0.570,-0.018	0.2	X 23,24,58,59,68,80
G0.61+0.01†	Suzaku J1747.0-2824.5	0.61,+0.01	2.2 × 4.8	X 22,65,79
G0.9+01♡	SNR 0.9+0.1	0.867,+0.073	7.6 × 7.2	R 25,26,27,28,29,48,75,81,82
DS1	G1.2-0.0	1.17,+0.00	3.4 × 6.9	X 31
Sgr D SNR	G1.02-0.18	1.02,-0.17	10 × 8.0	R 30,31,48,51,75,77,81,82
	G1.05-0.15			
	G1.05-0.1			
	G1.0-0.1			
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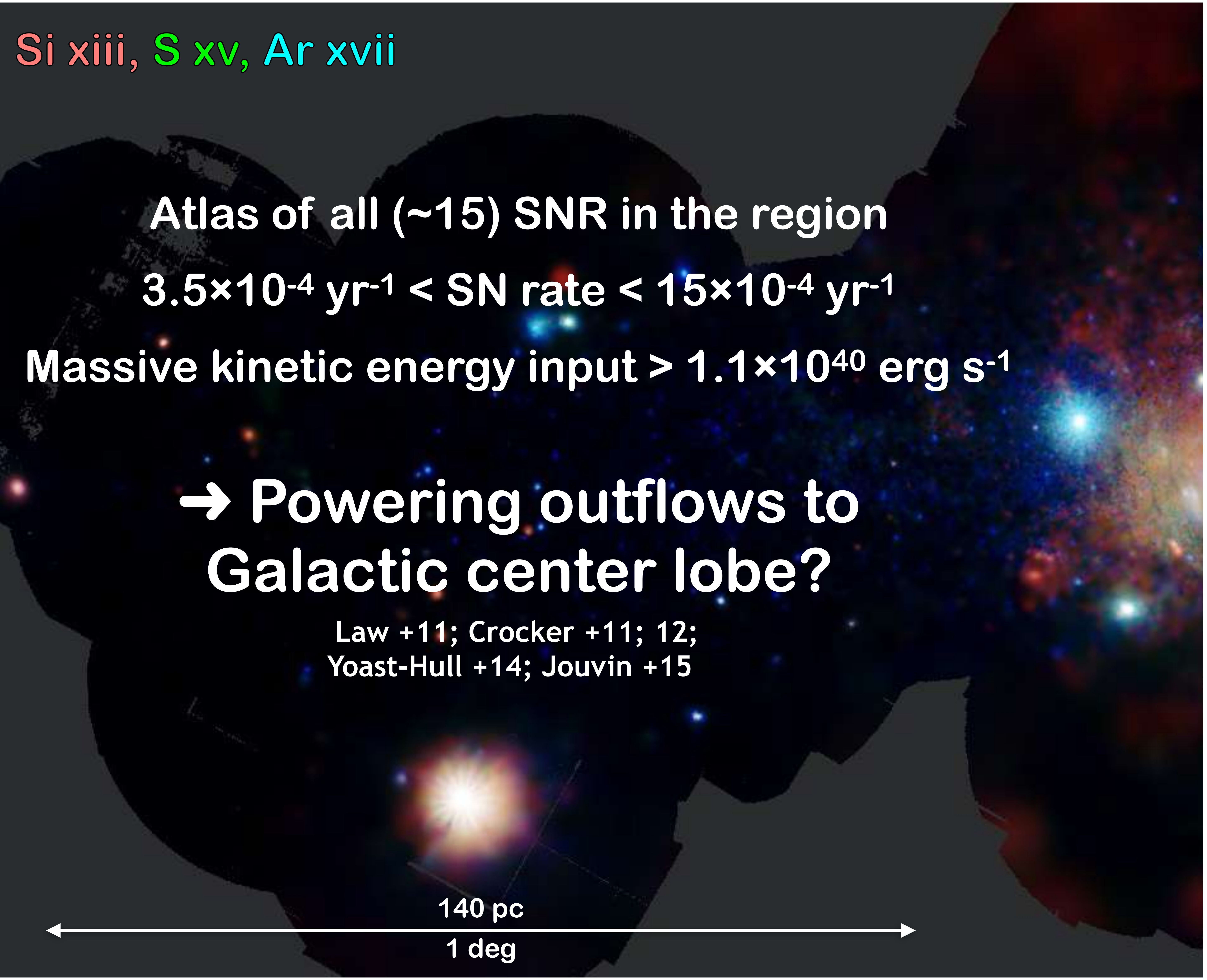
Hot plasma to trace past activity



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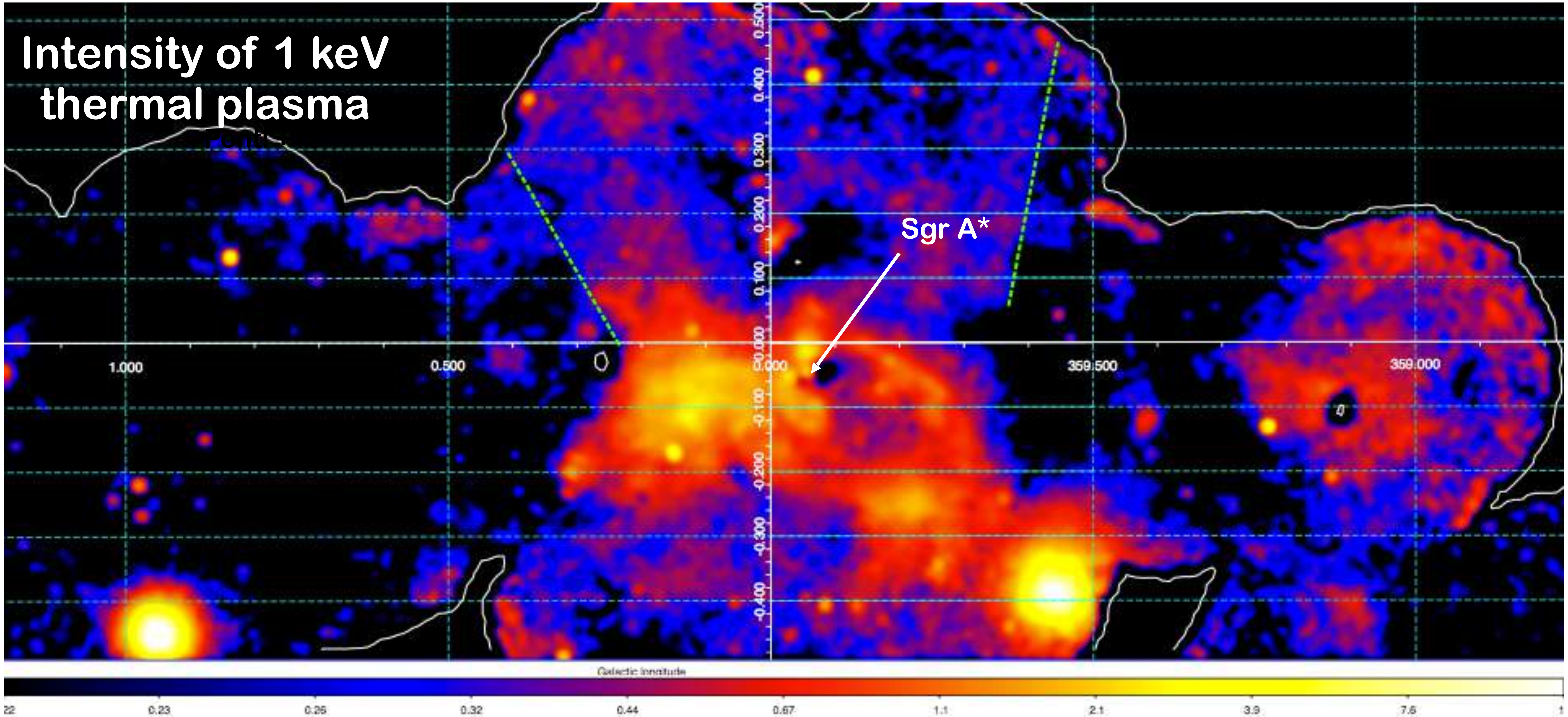
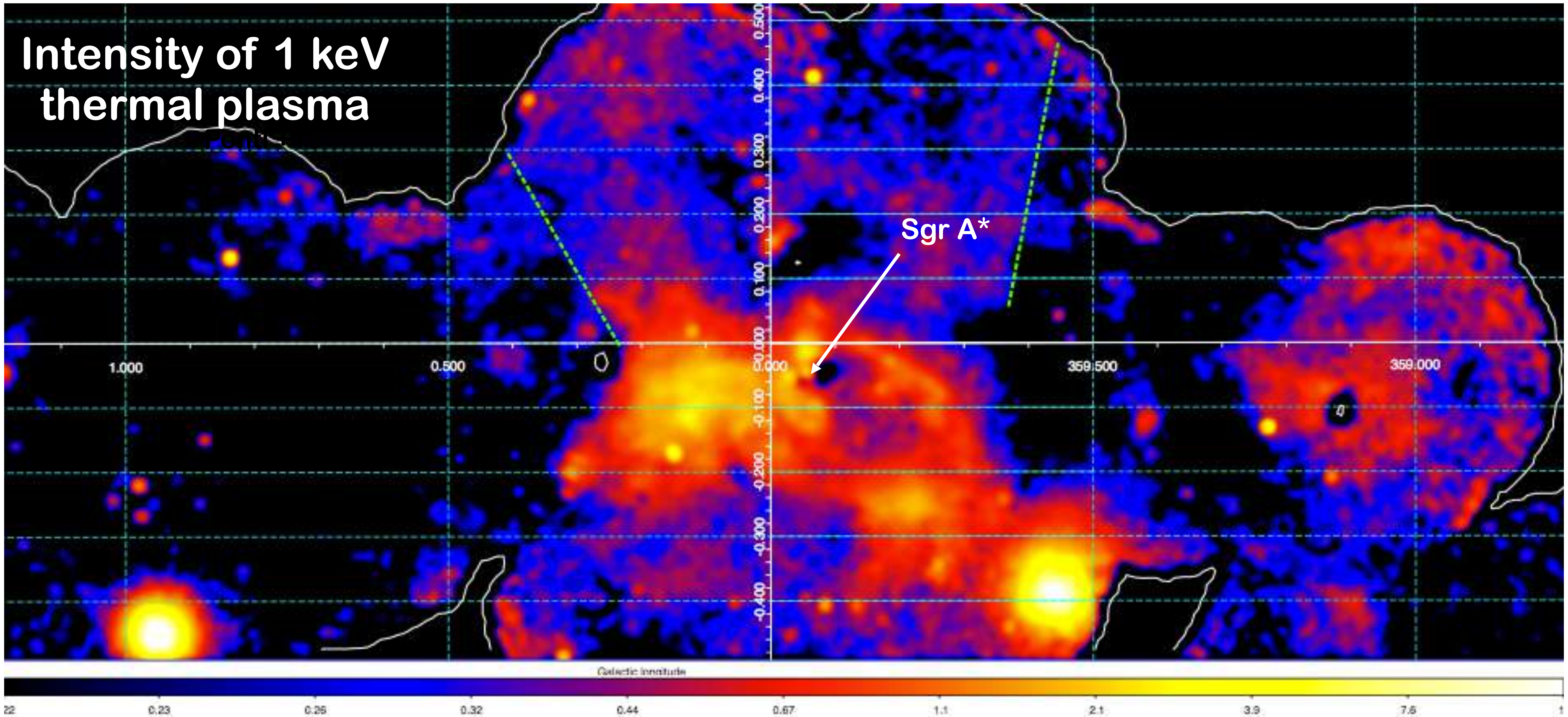
Ponti +15

Discovery of high latitude hot plasma



Discovery of high latitude hot plasma

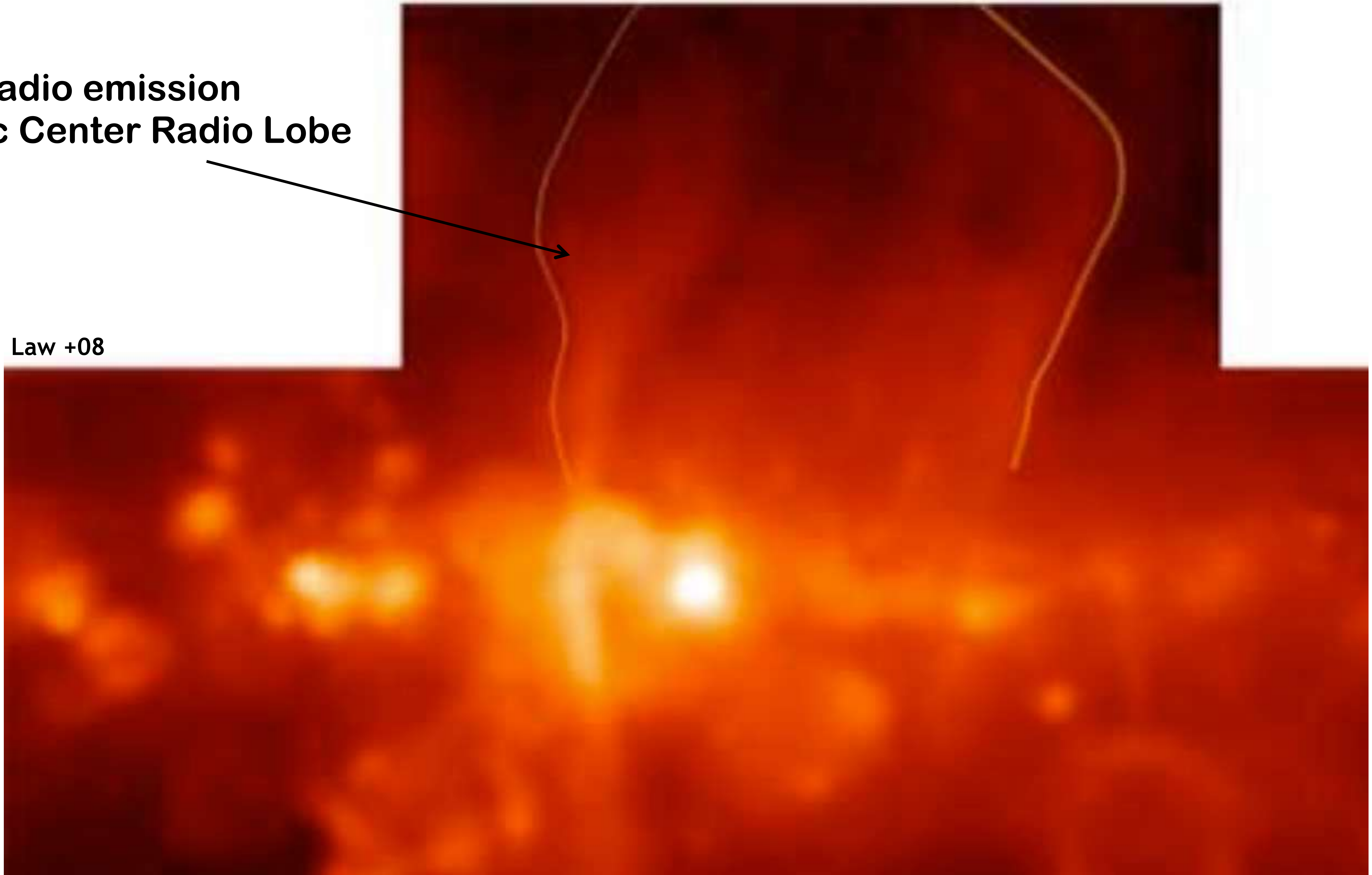
What is this?



Galactic center radio lobe

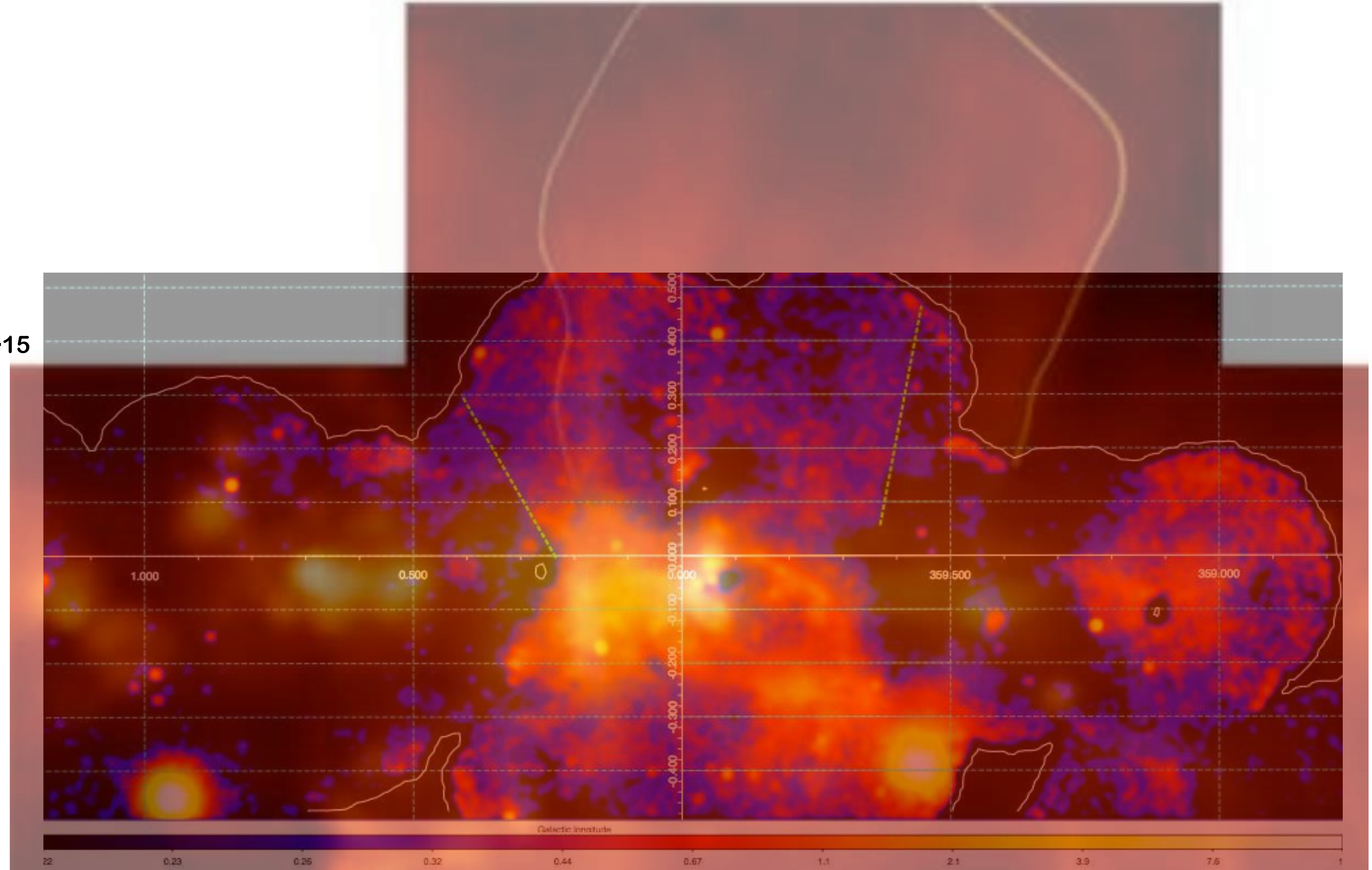
Radio emission
Galactic Center Radio Lobe

Law +08



What is the origin of this hot plasma?

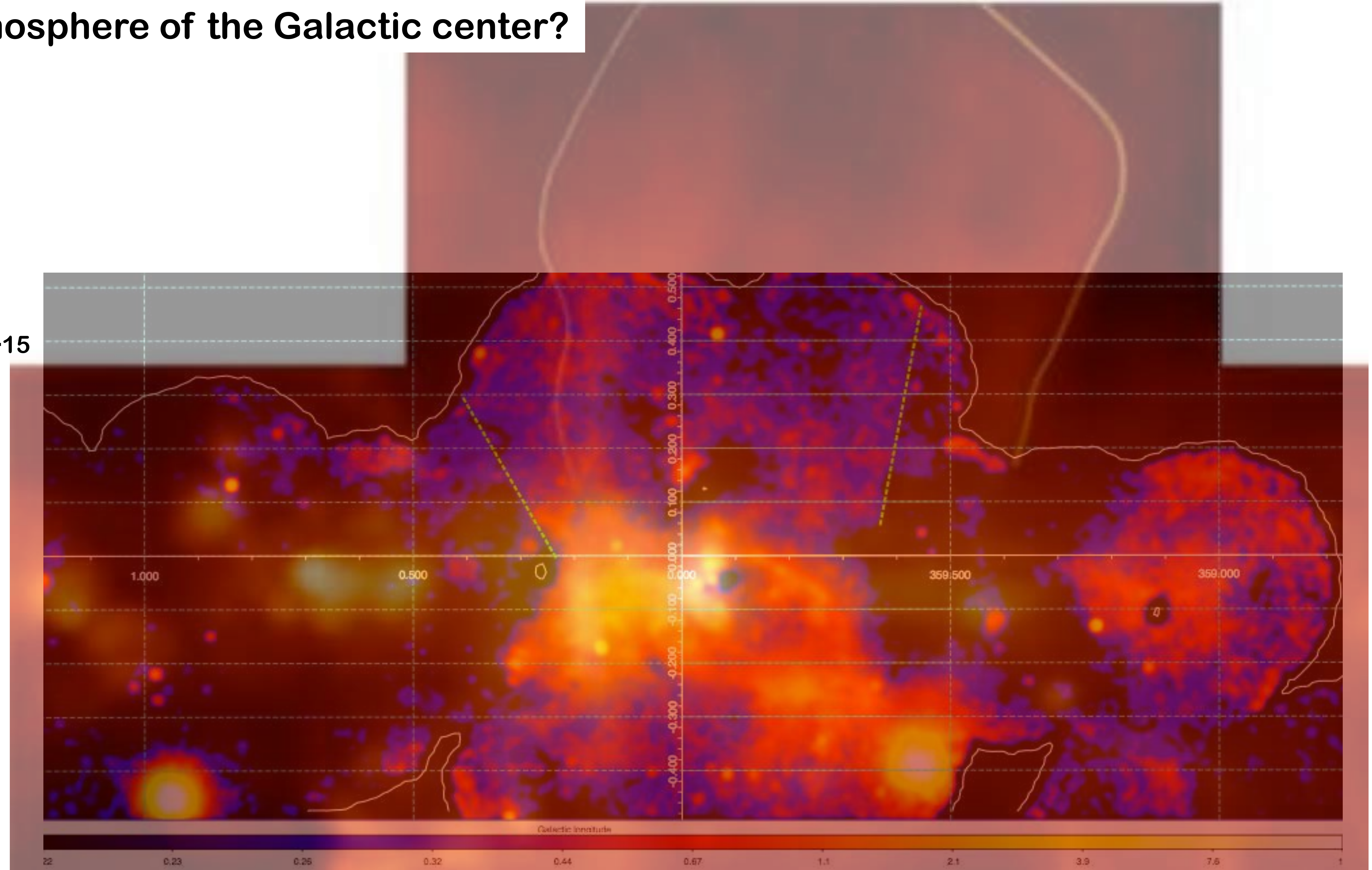
Ponti +15



What is the origin of this hot plasma?

Hot atmosphere of the Galactic center?

Ponti +15



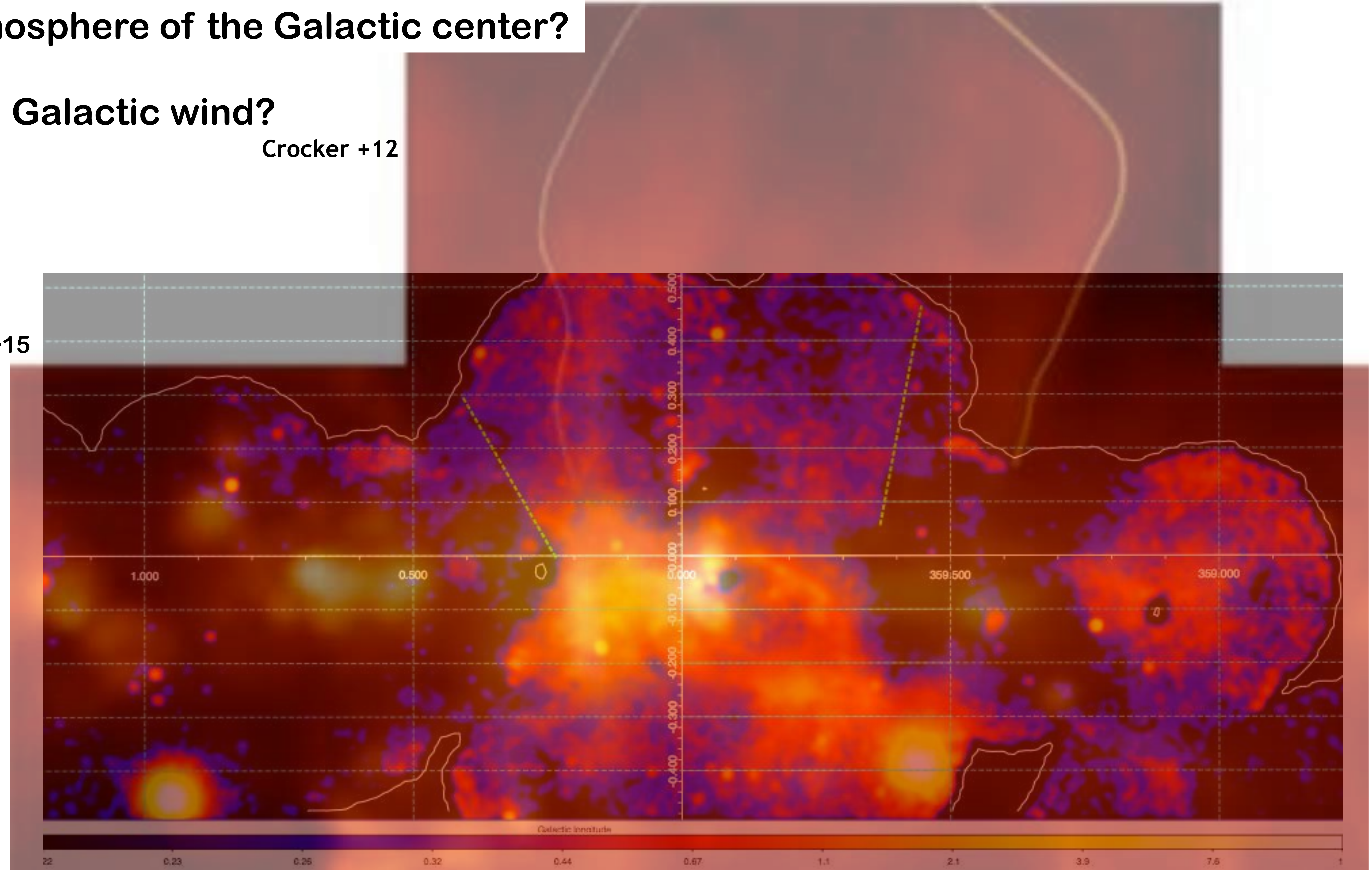
What is the origin of this hot plasma?

Hot atmosphere of the Galactic center?

Base of Galactic wind?

Crocker +12

Ponti +15



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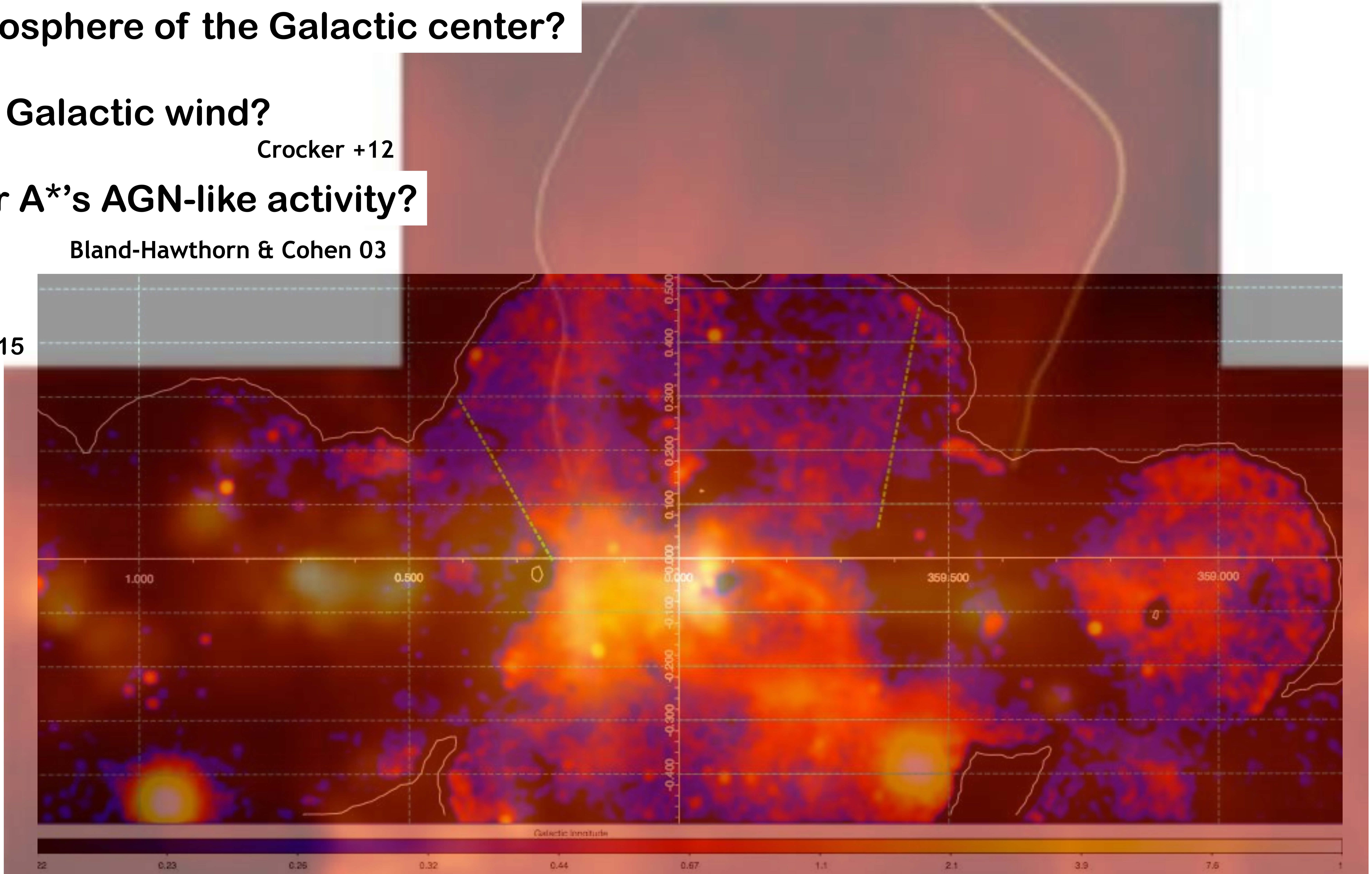
Crocker +12

Past Sgr A*'s AGN-like activity?

Bland-Hawthorn & Cohen 03

Ponti +15



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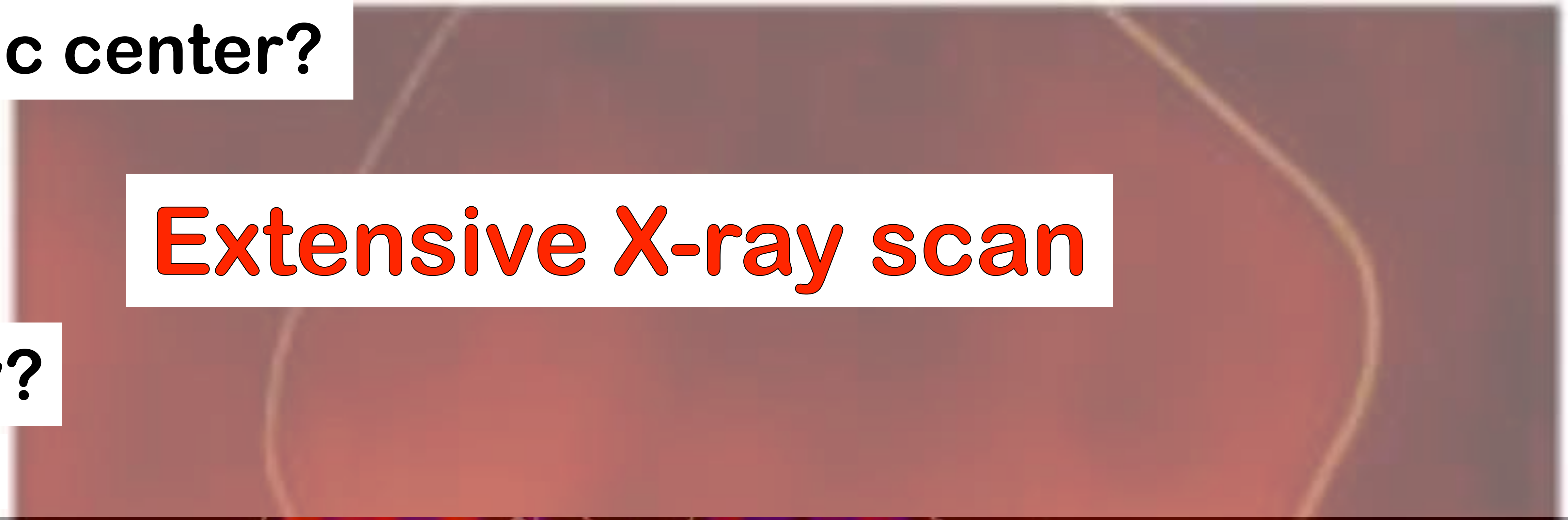
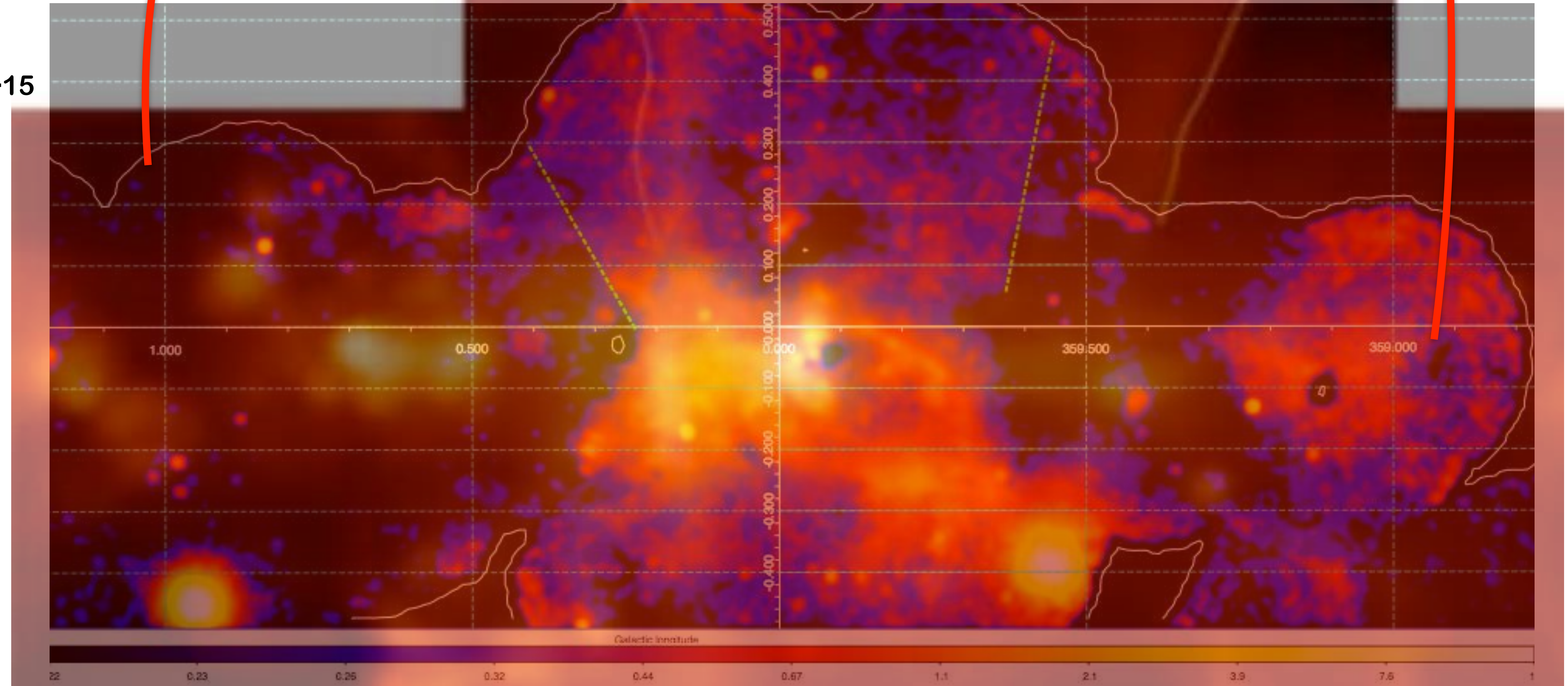


Ponti +15

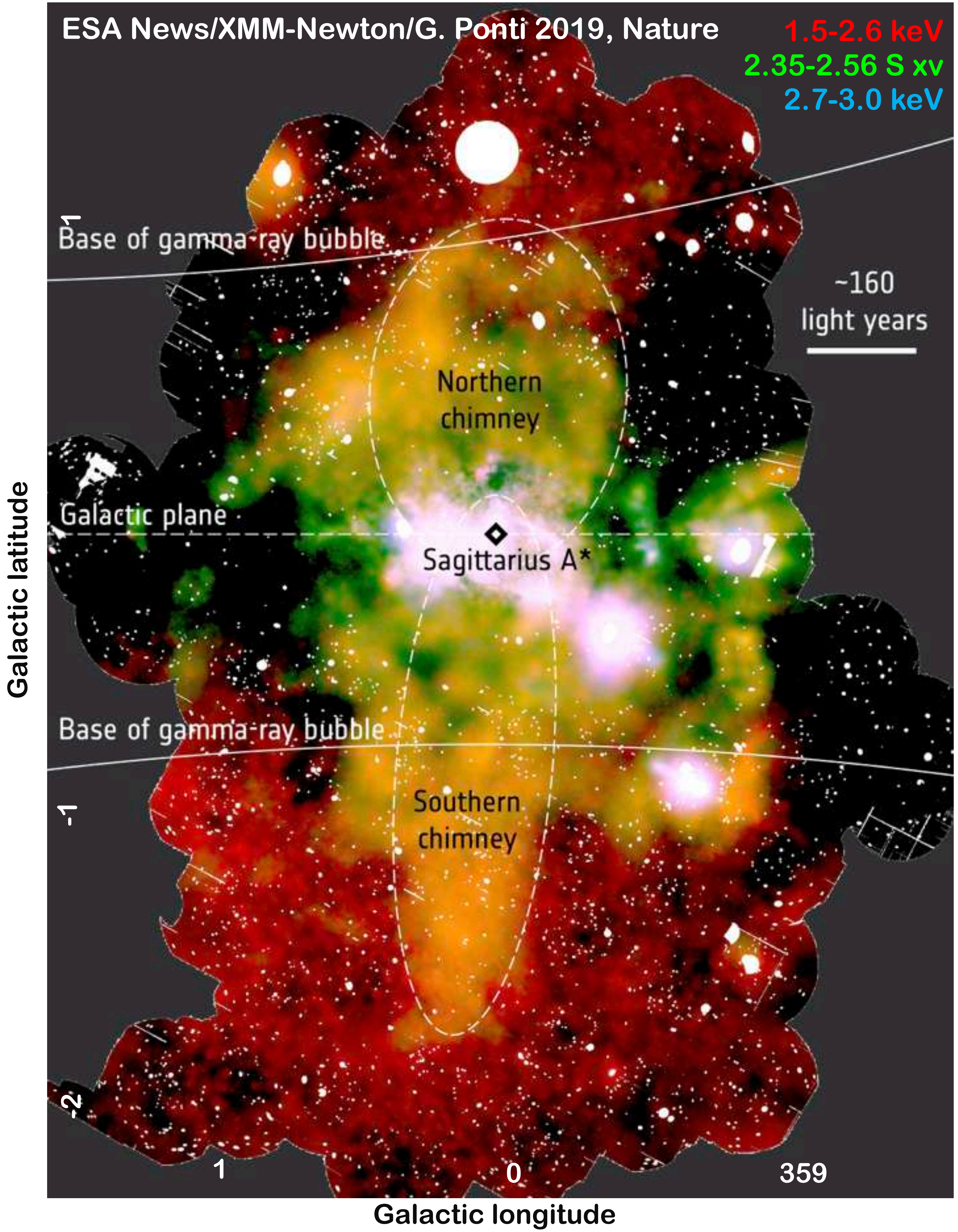


Suspense….

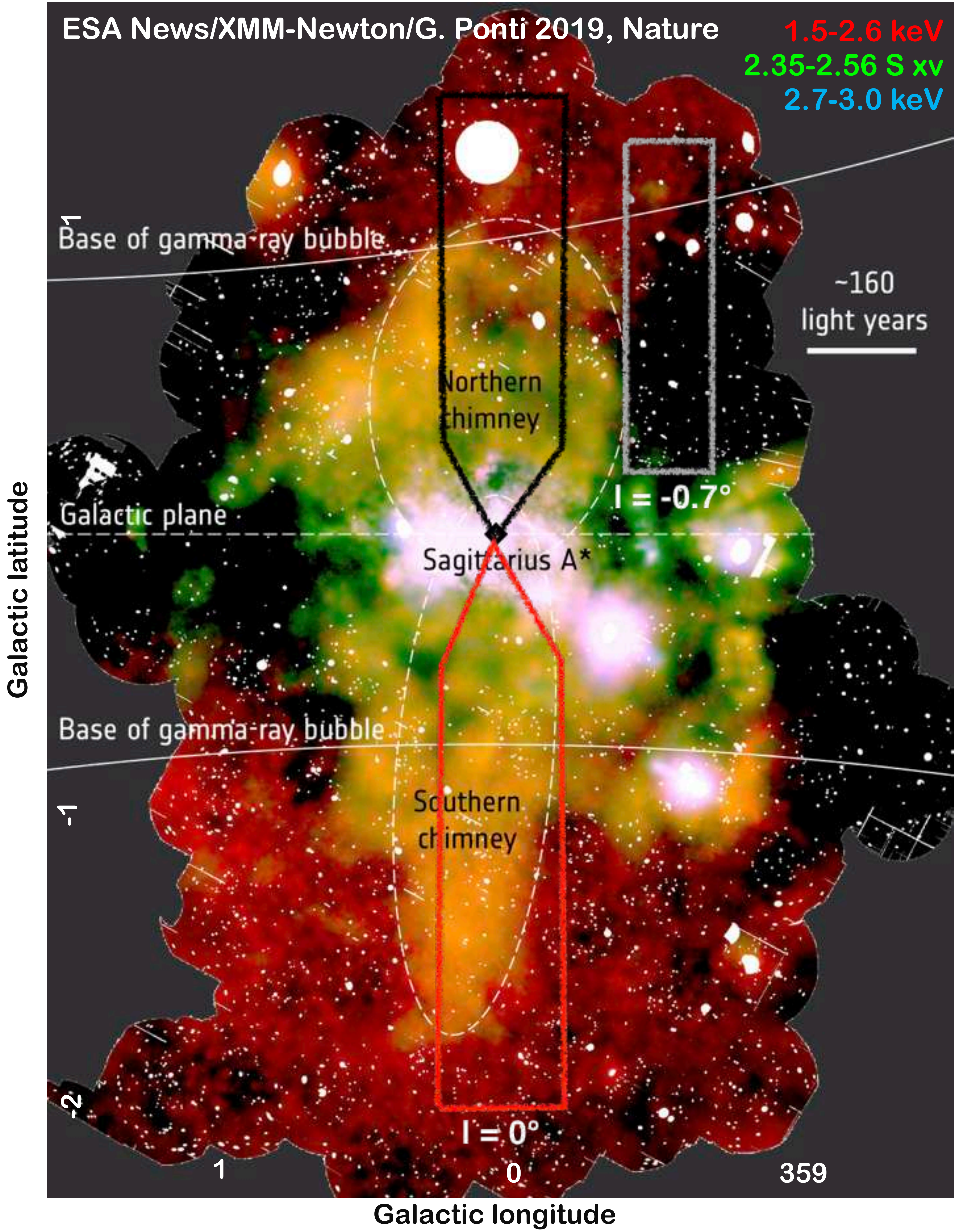

ESA News/XMM-Newton/G. Ponti
2019, Nature
Base of gamma-ray bubble
1.5-2.6 keV
2.35-2.56 S xv
2.7-3.0 keV
~160
light years
Northern
chimney
Galactic plane
Sagittarius A*


ESA News/XMM-Newton/G. Ponti
2019, Nature
Base of gamma-ray bubble
1.5-2.6 keV
2.35-2.56 S xv
2.7-3.0 keV
~160
light years
Hot outflow
Northern
chimney
Galactic plane
Flow molecular matter
Sagittarius A*

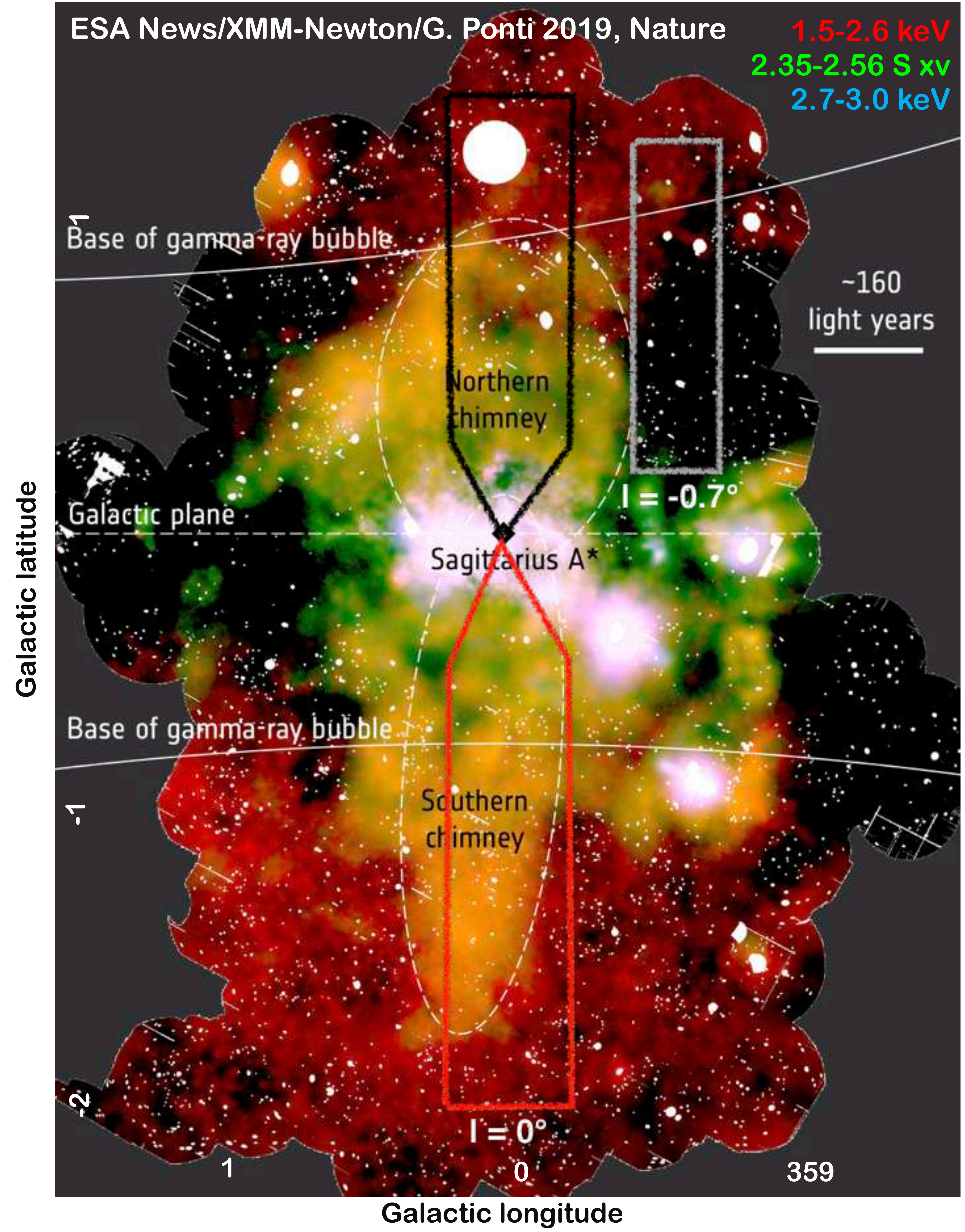
The Galactic center Chimneys

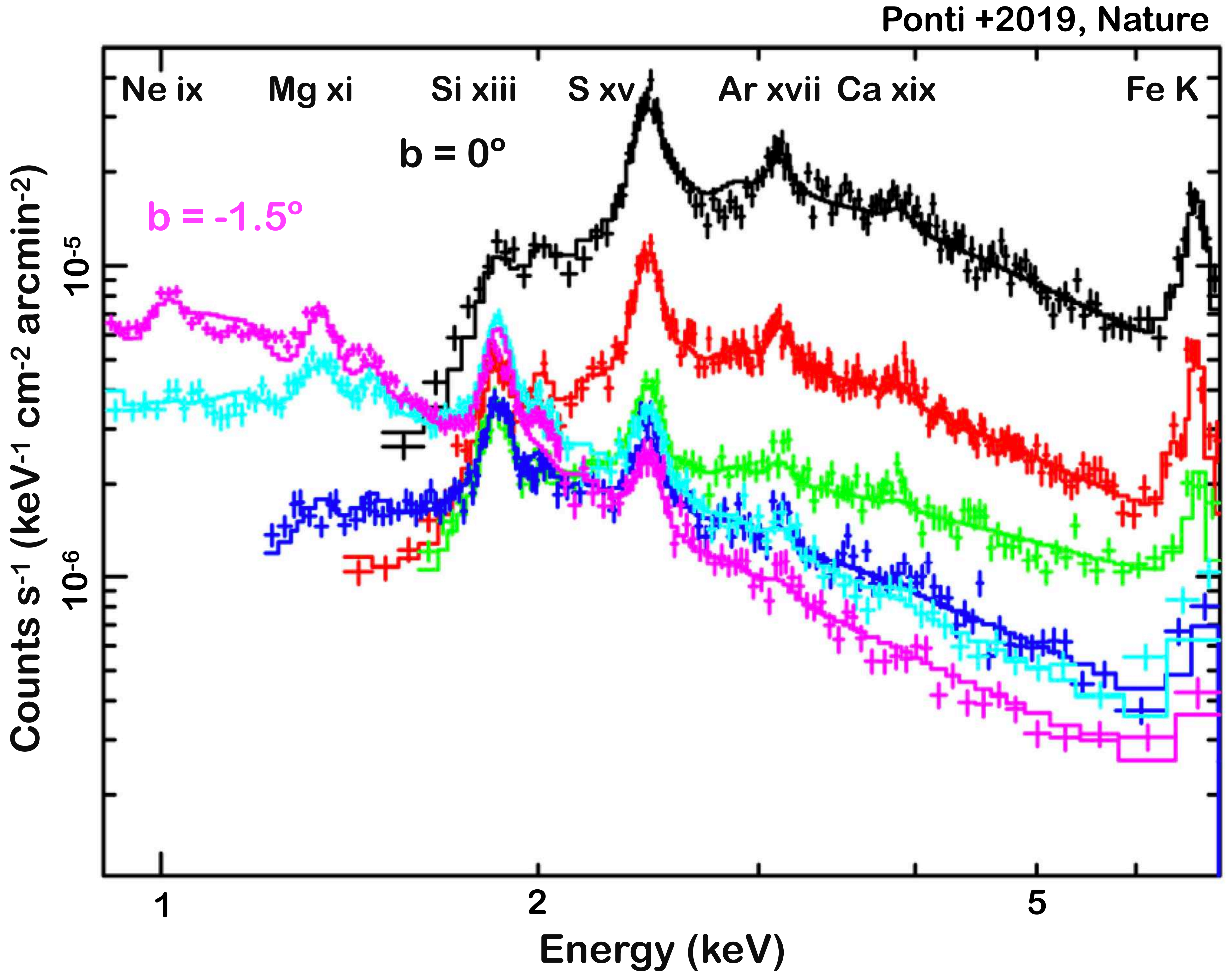


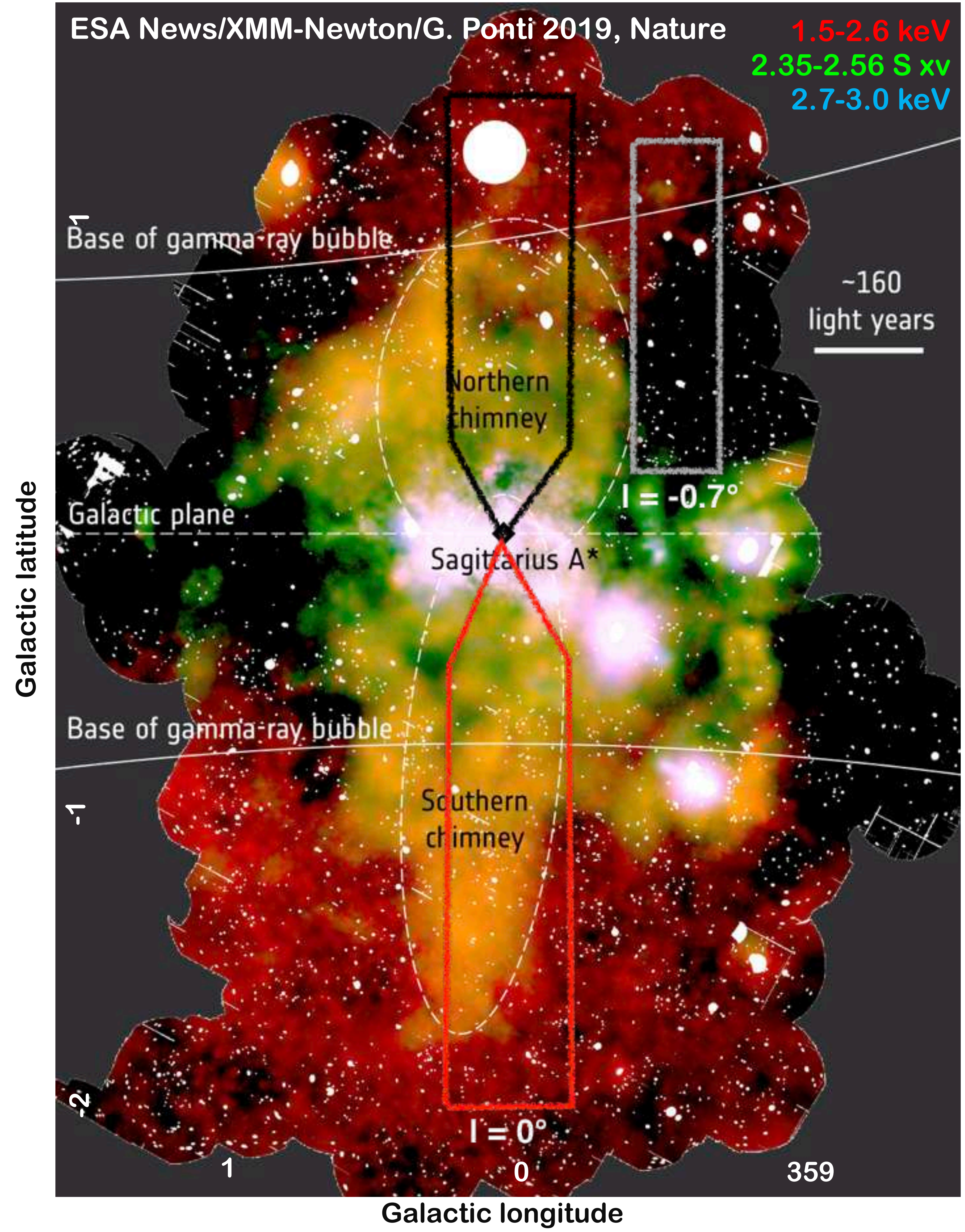
The Galactic center Chimneys



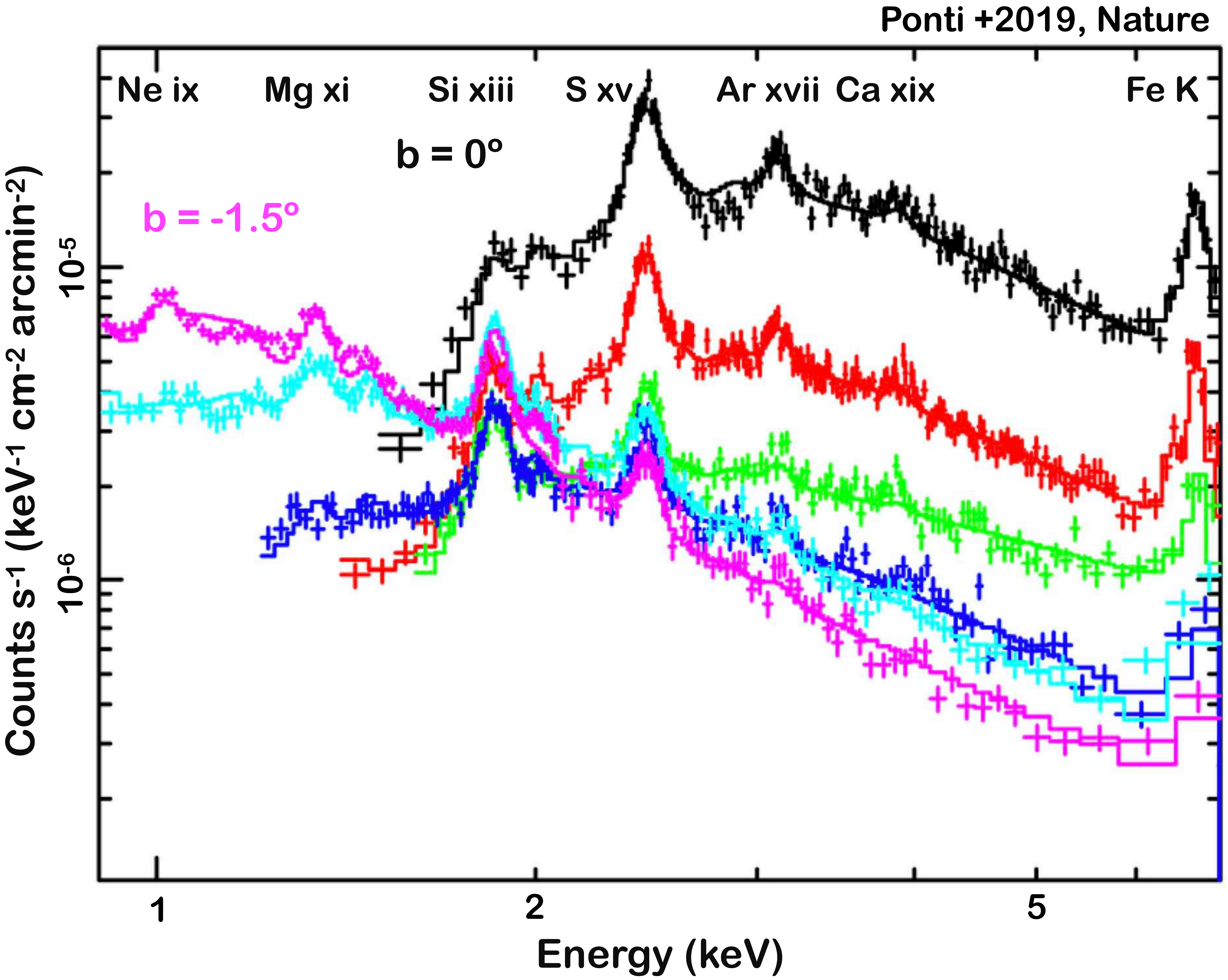
The Galactic center Chimneys



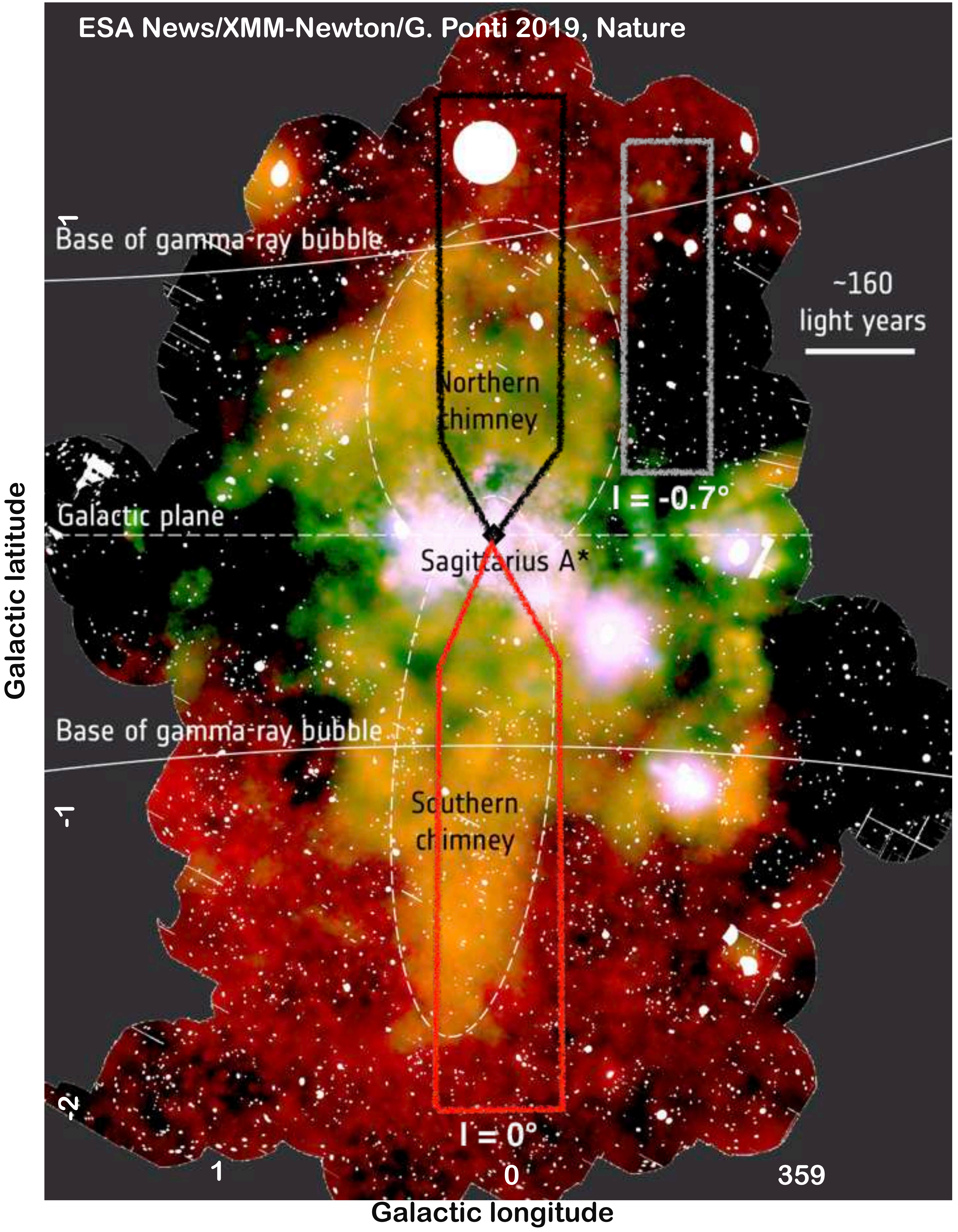




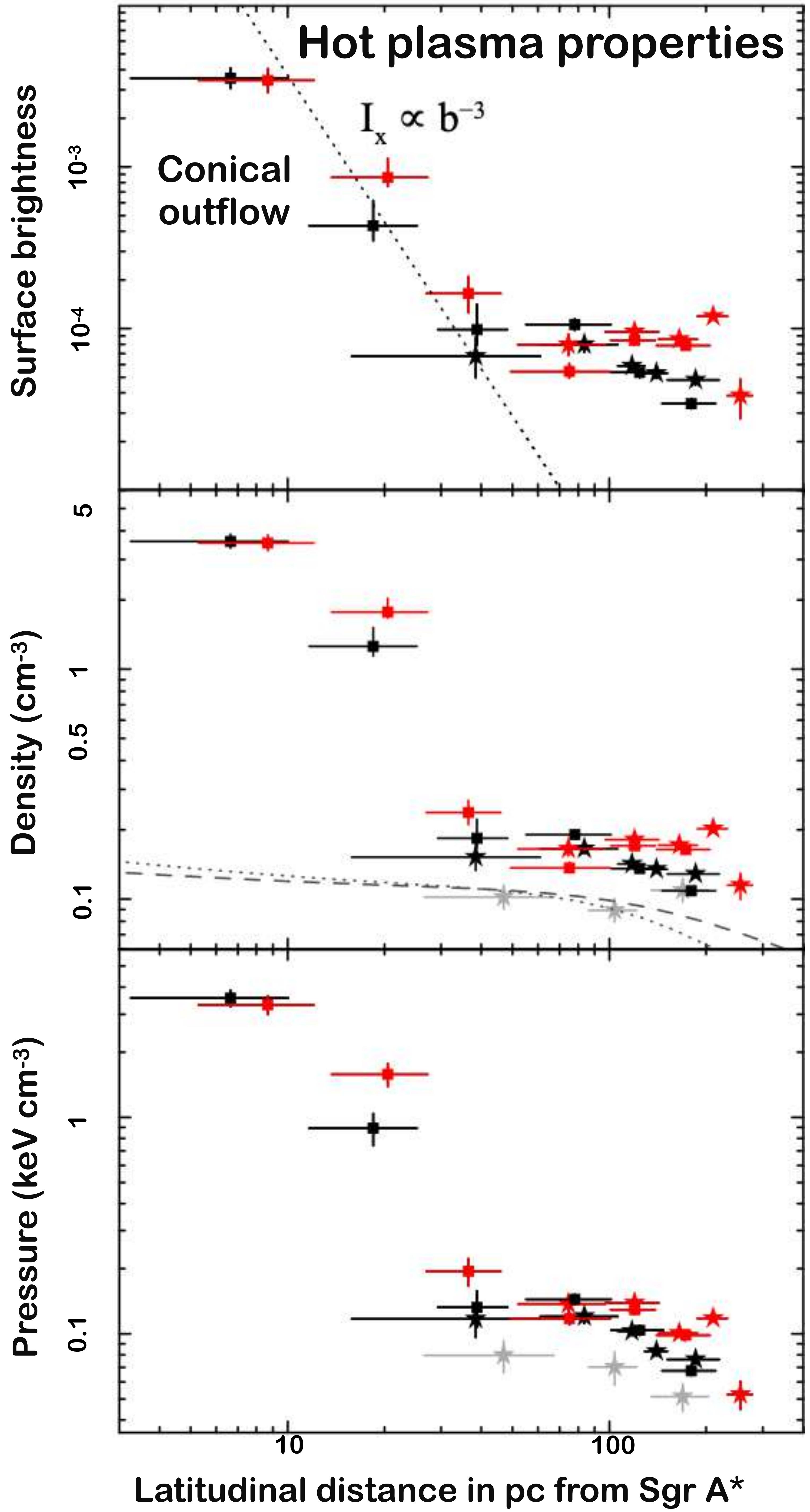
The Galactic center Chimneys



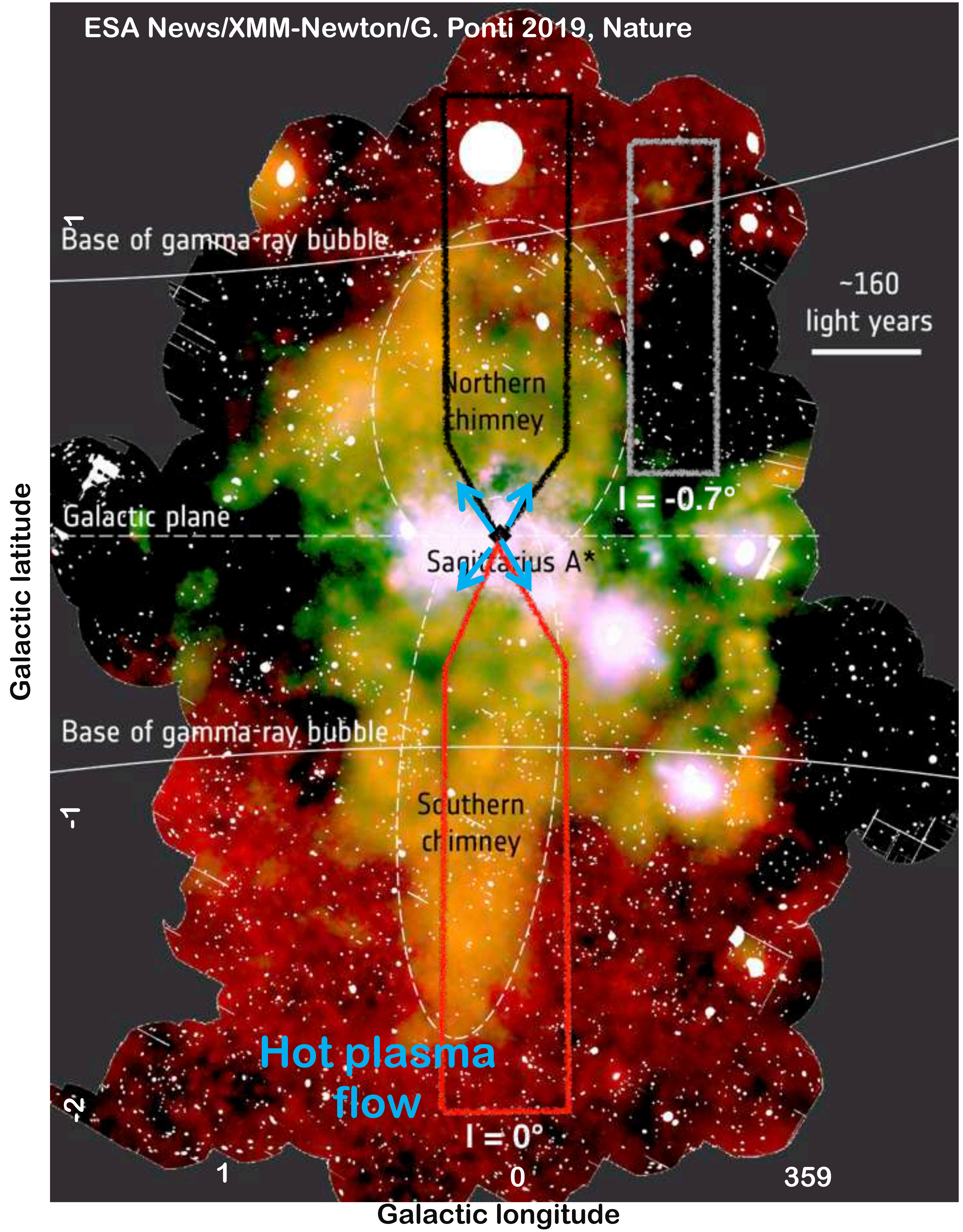
➜ **Measure kT, n, p, abundances of hot plasma**



ESA News/XMM-Newton/G. Ponti 2019, Nature
Base of gamma-ray bubble
~160
light years
Northern
chimney
l = -0.7°
Galactic plane
Sagittarius A*
Base of gamma-ray bubble
Southern
chimney
l = 0°
-1
-2
1
0
359
Galactic latitude
Galactic longitude



Hot plasma properties
$I_x \propto b^{-3}$
Conical
outflow
Surface brightness
10^{-3}
10^{-4}
Density (cm^{-3})
5
1
0.5
0.1
Pressure (keV cm^{-3})
1
0.1
10
100
Latitudinal distance in pc from Sgr A*



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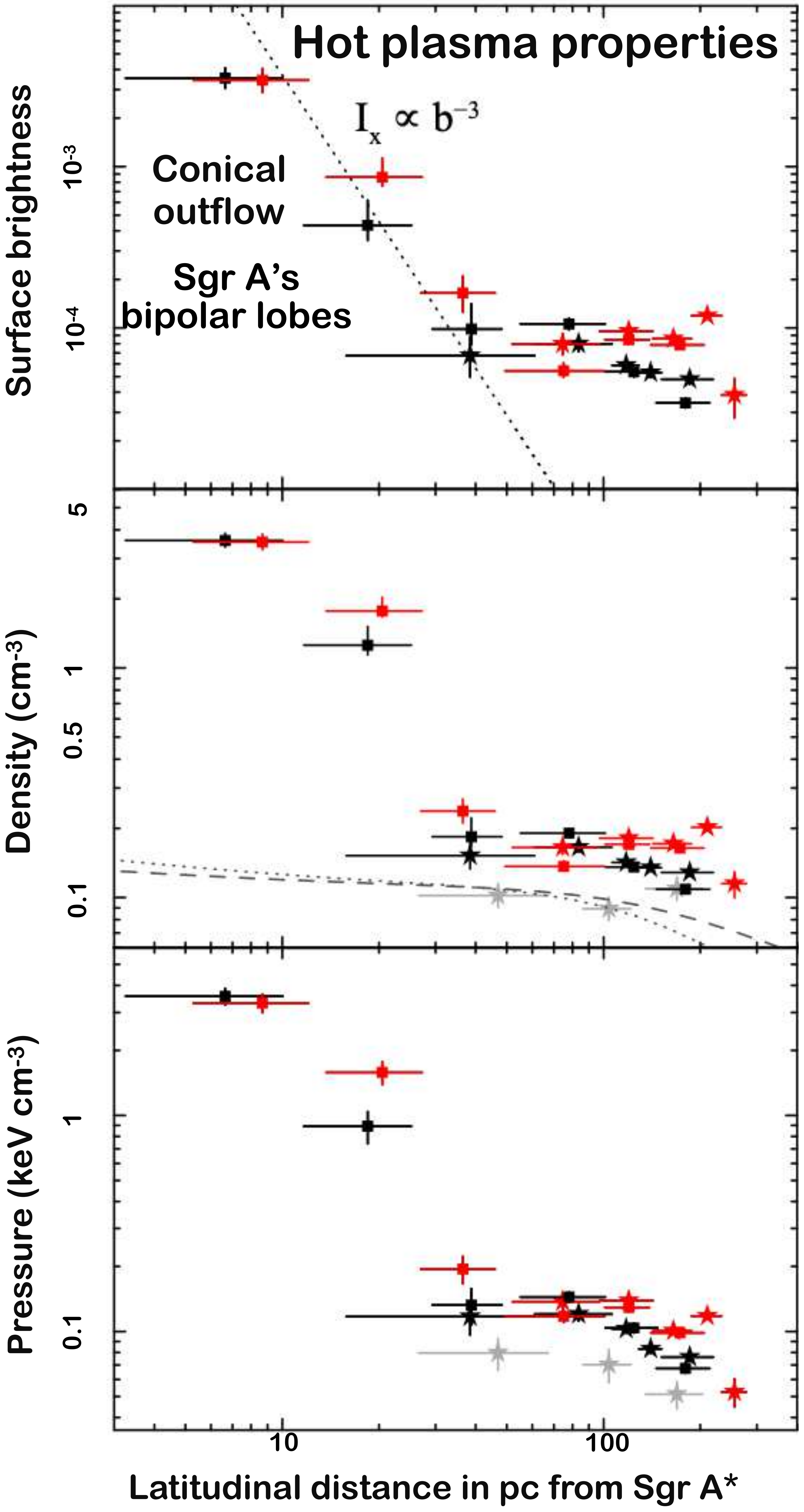
Galactic longitude



Hot plasma properties
$I_x \propto b^{-3}$
Conical
outflow
Sgr A's
bipolar lobes
Surface brightness
10^{-3}
10^{-4}
Density (cm^{-3})
5
1
0.5
0.1
Pressure (keV cm^{-3})
1
0.1
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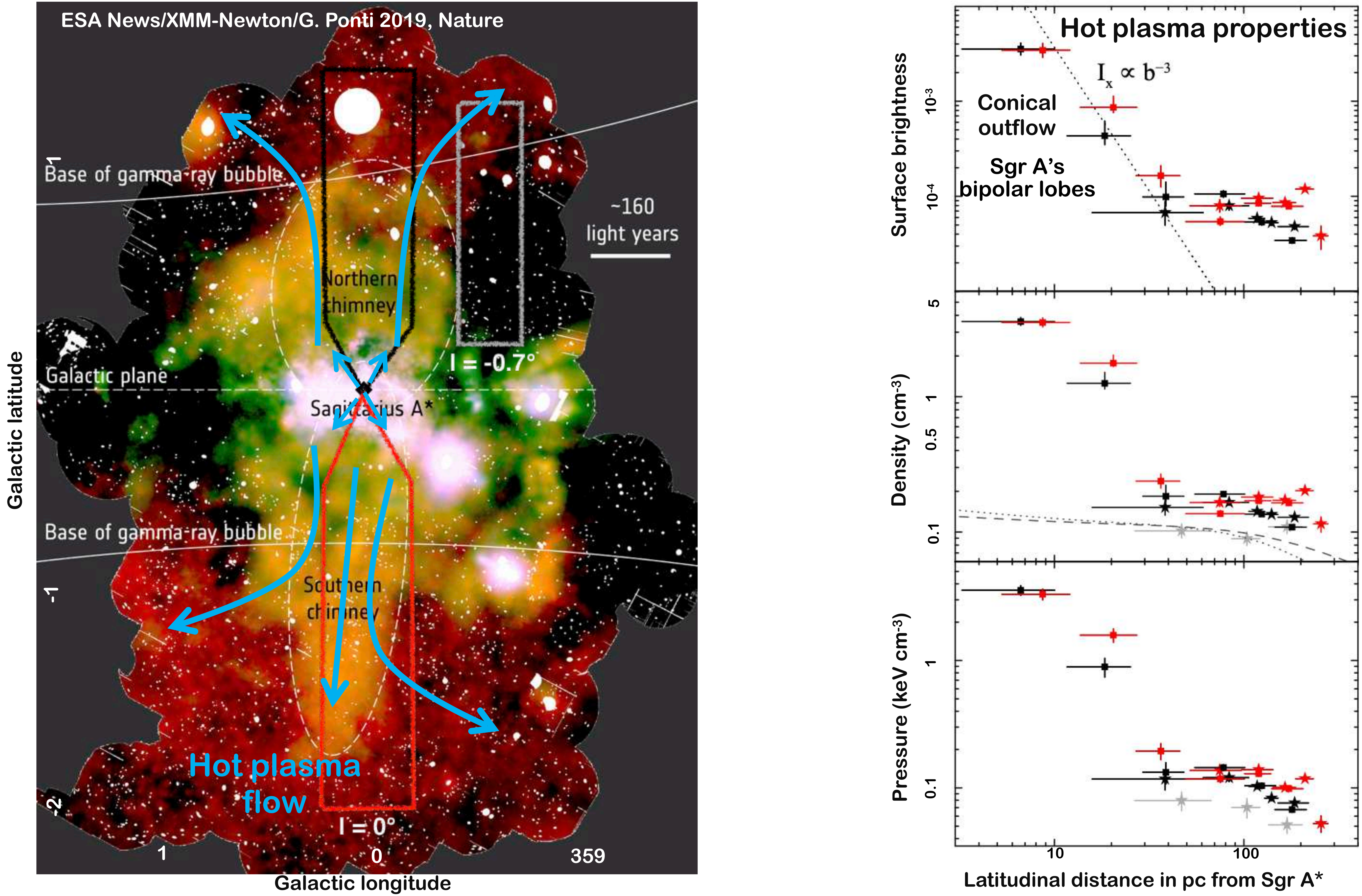
100
Latitudinal distance in pc from Sgr A*



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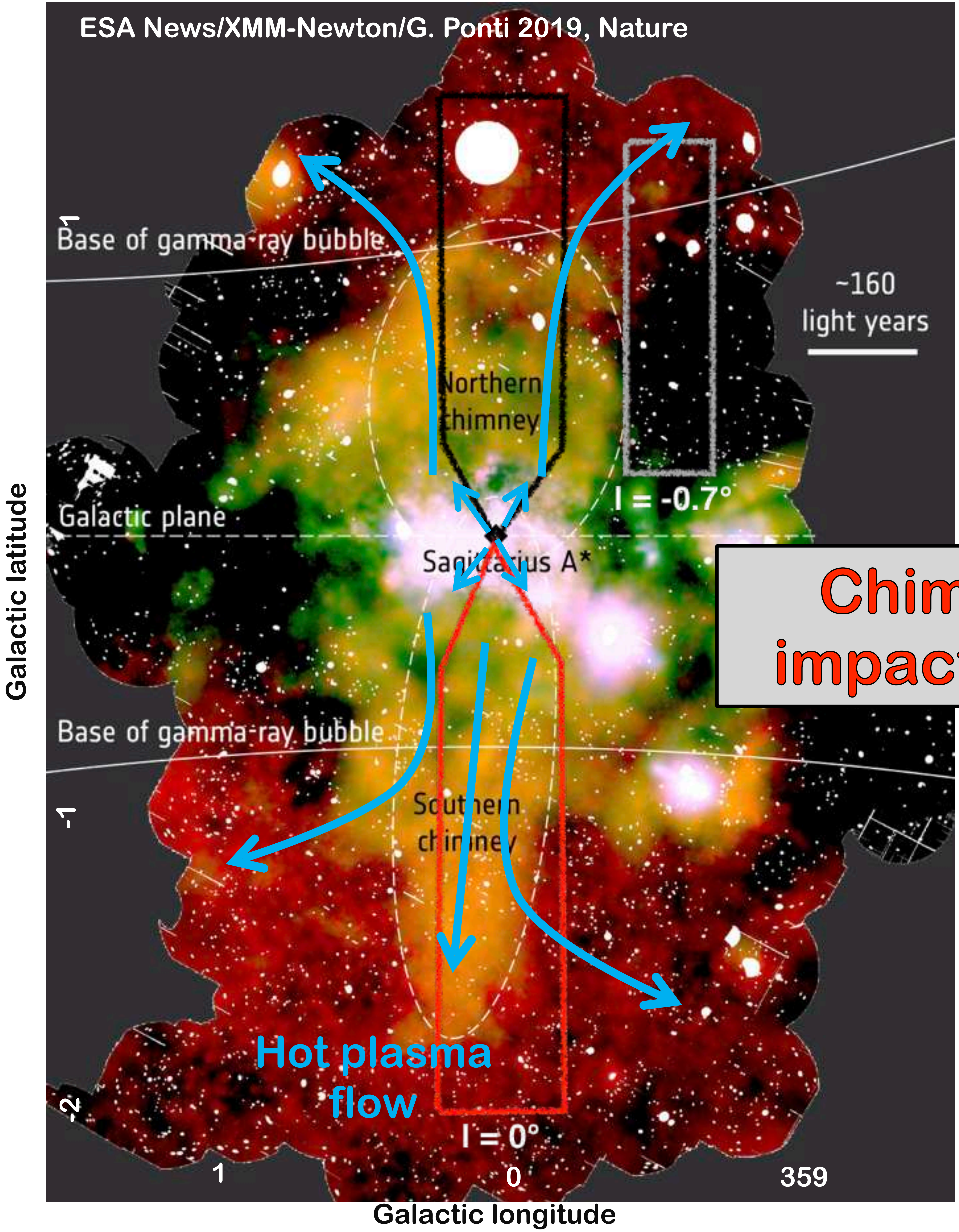
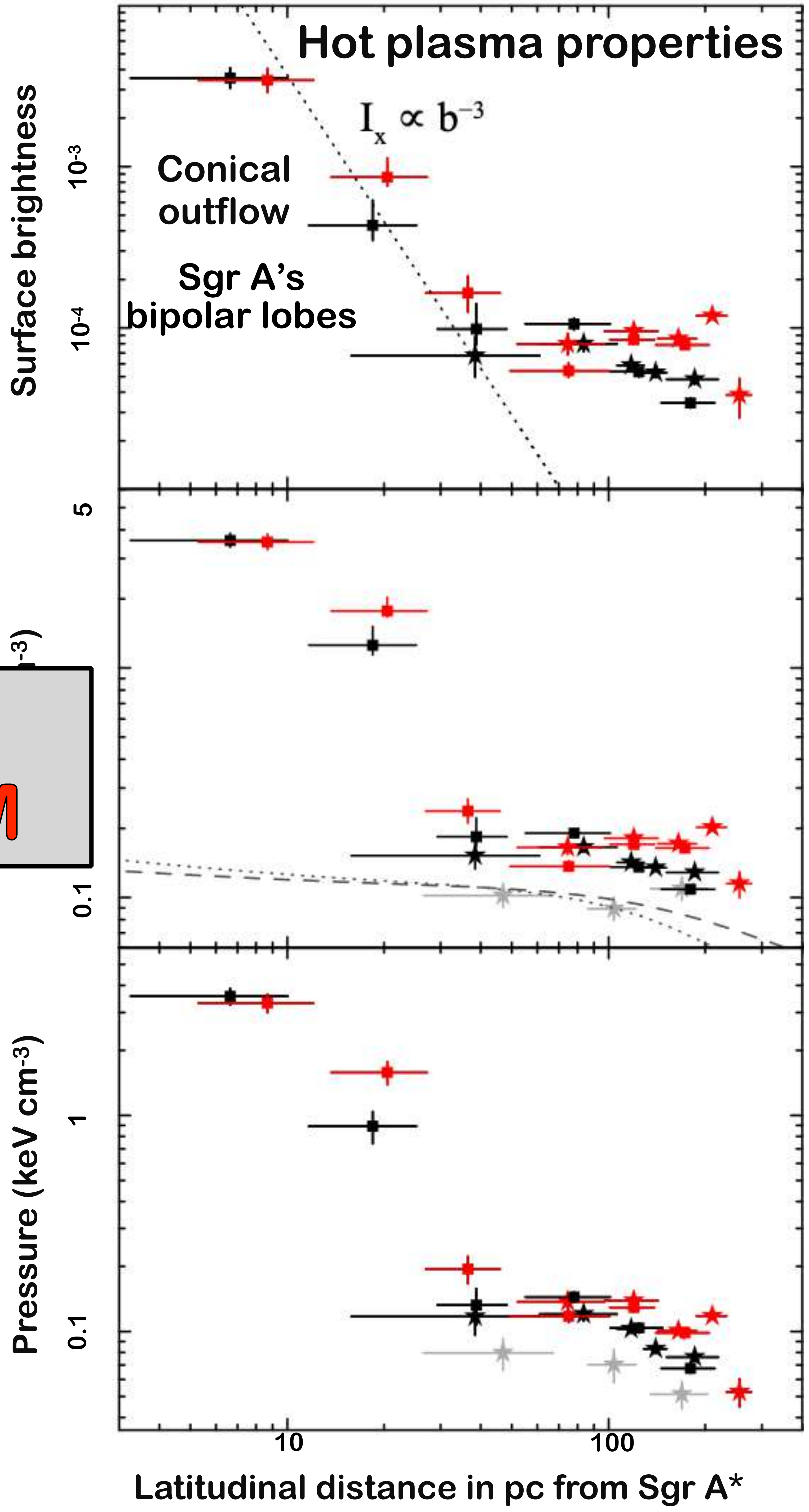
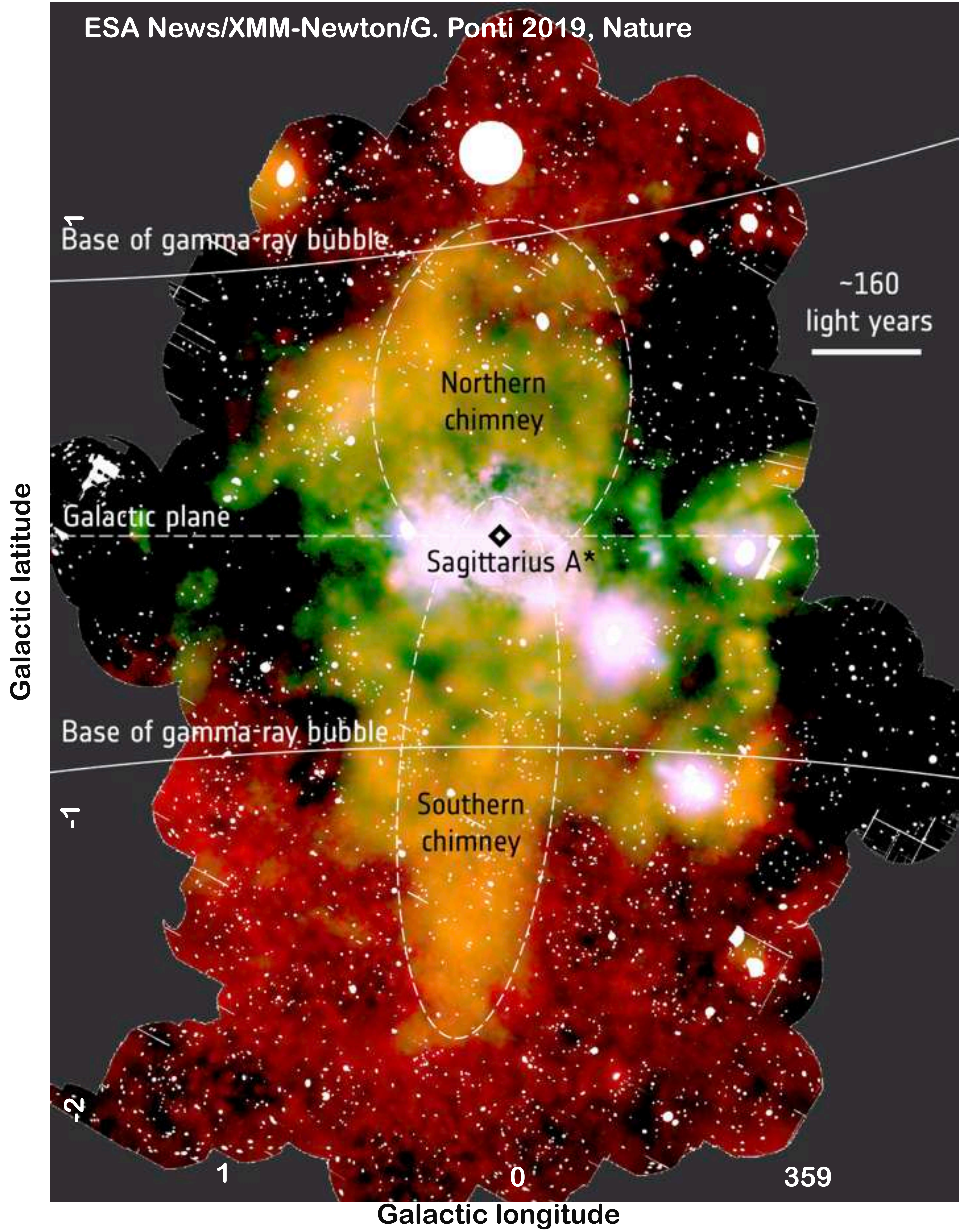
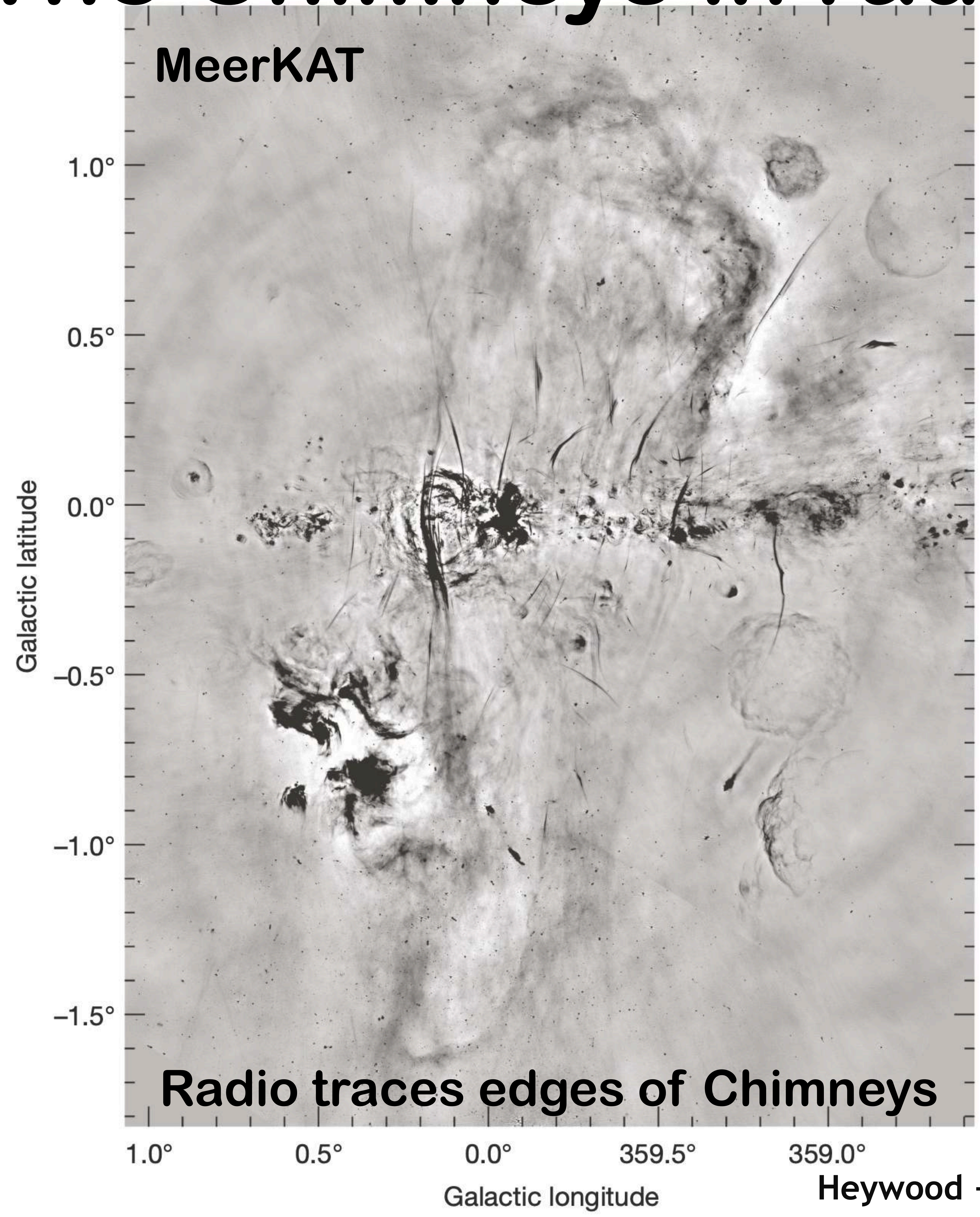


Chimneys → impact on CGM



The Chimneys in radio

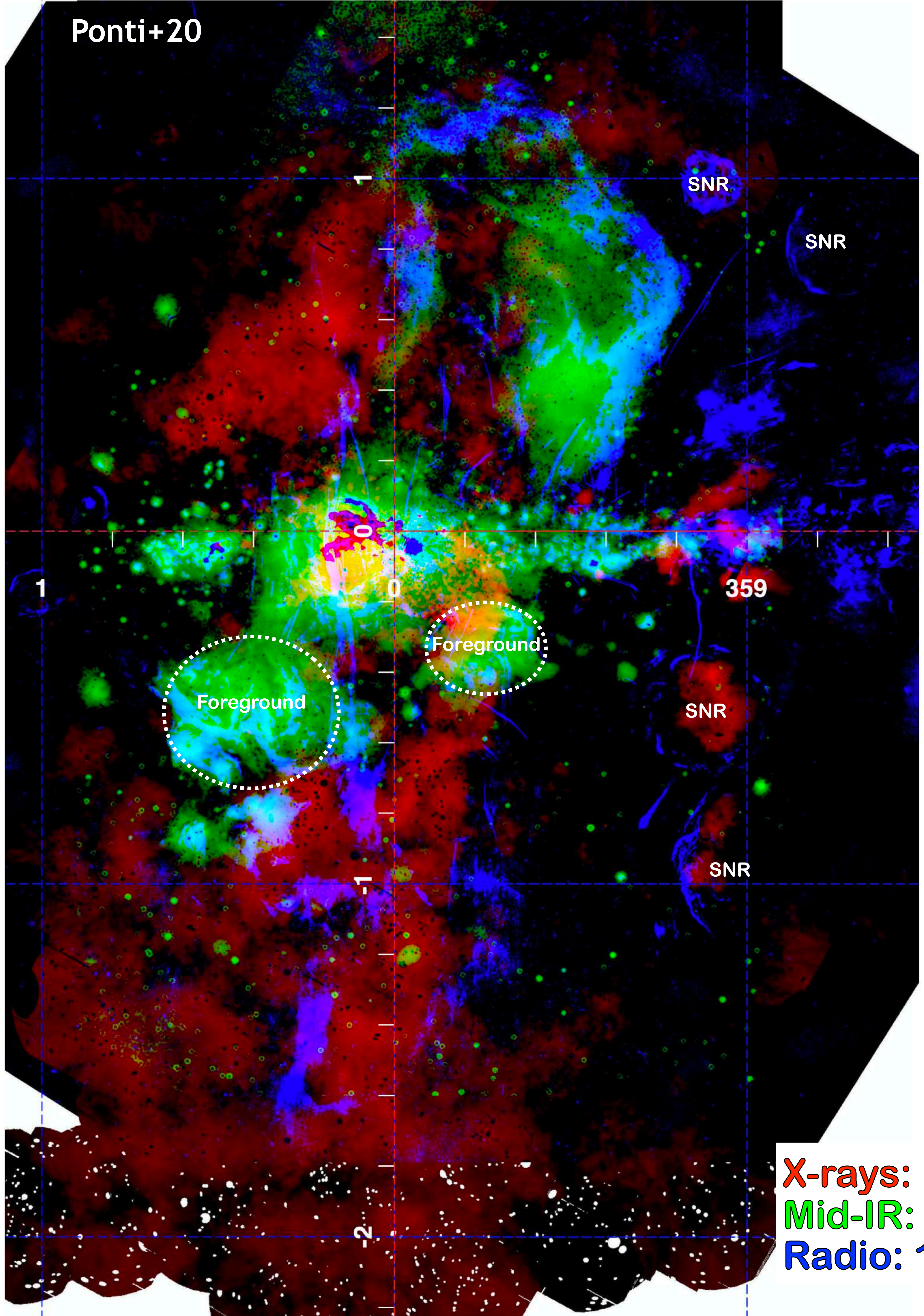




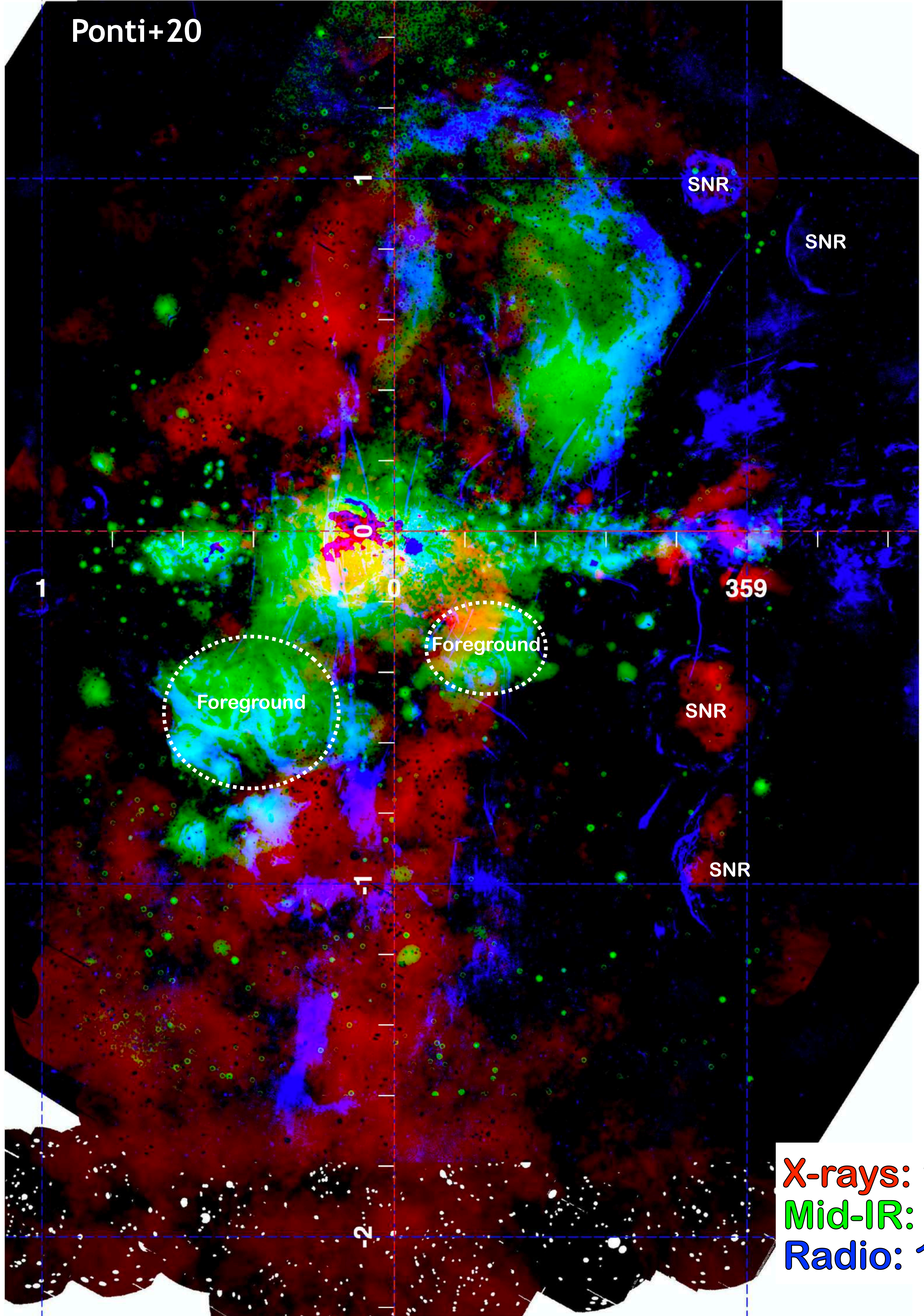
Heywood +19, Nature

Outflow has radio counterpart

Multi-phase multi-epoch Galactic outflow



X-rays: 1.5-2.6 keV
Mid-IR: 22.2/12.08 μm
Radio: 1.284 GHz



Multi-phase multi-epoch Galactic outflow

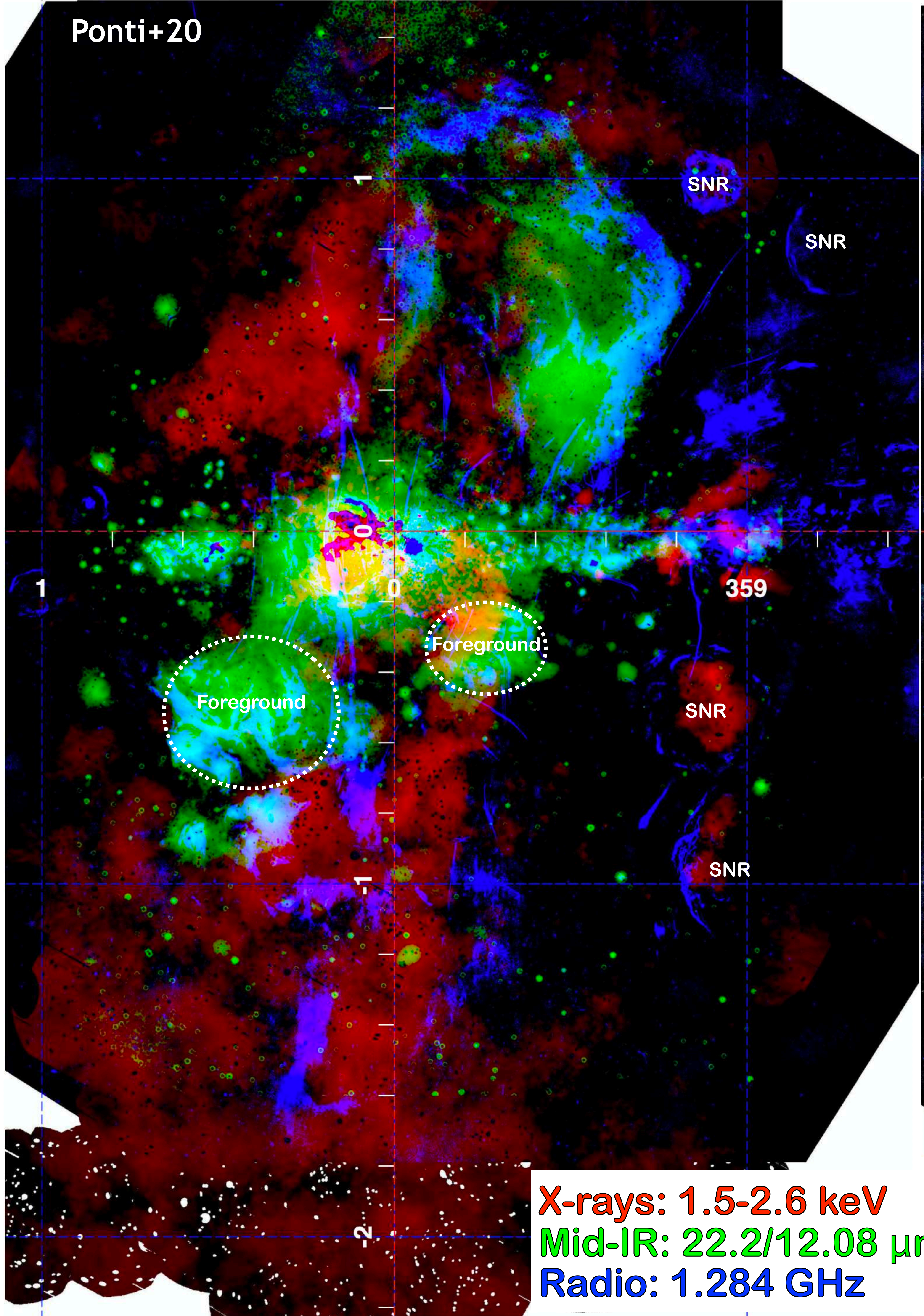
Hot plasma (X-rays)
warm dust (mid-IR)
shocks (radio)

➜ Coherent features on > 10^2 pc scales

➜ Deeply interconnected and linked to the Galactic outflow

X-rays: 1.5-2.6 keV
Mid-IR: 22.2/12.08 μm
Radio: 1.284 GHz

Radio emission



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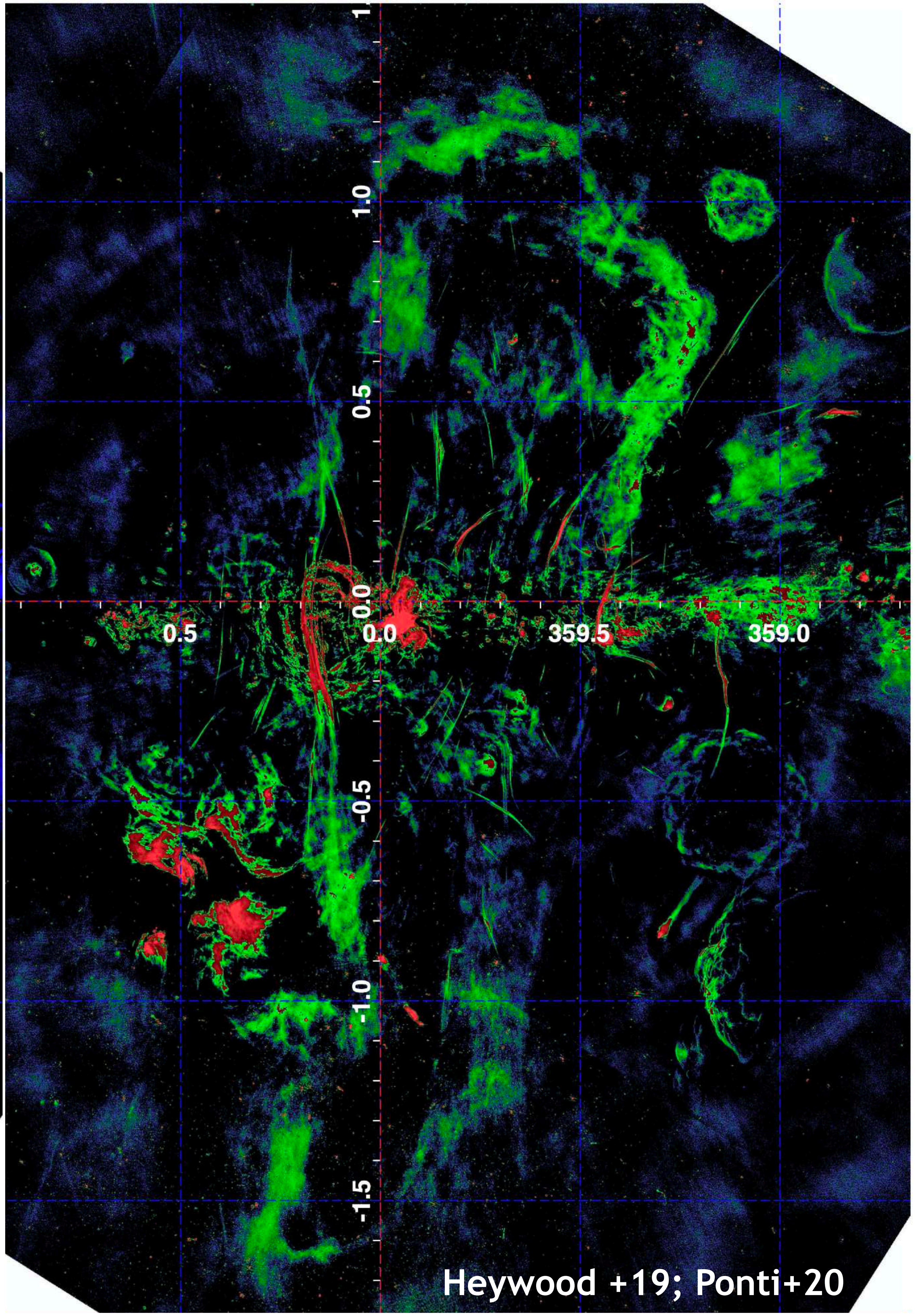


MeerKAT: 1.284 GHz

➜ What is the origin of the non-thermal radio filaments?

Nonthermal radio filaments

Nonthermal radio filaments

➜ Only in the GC

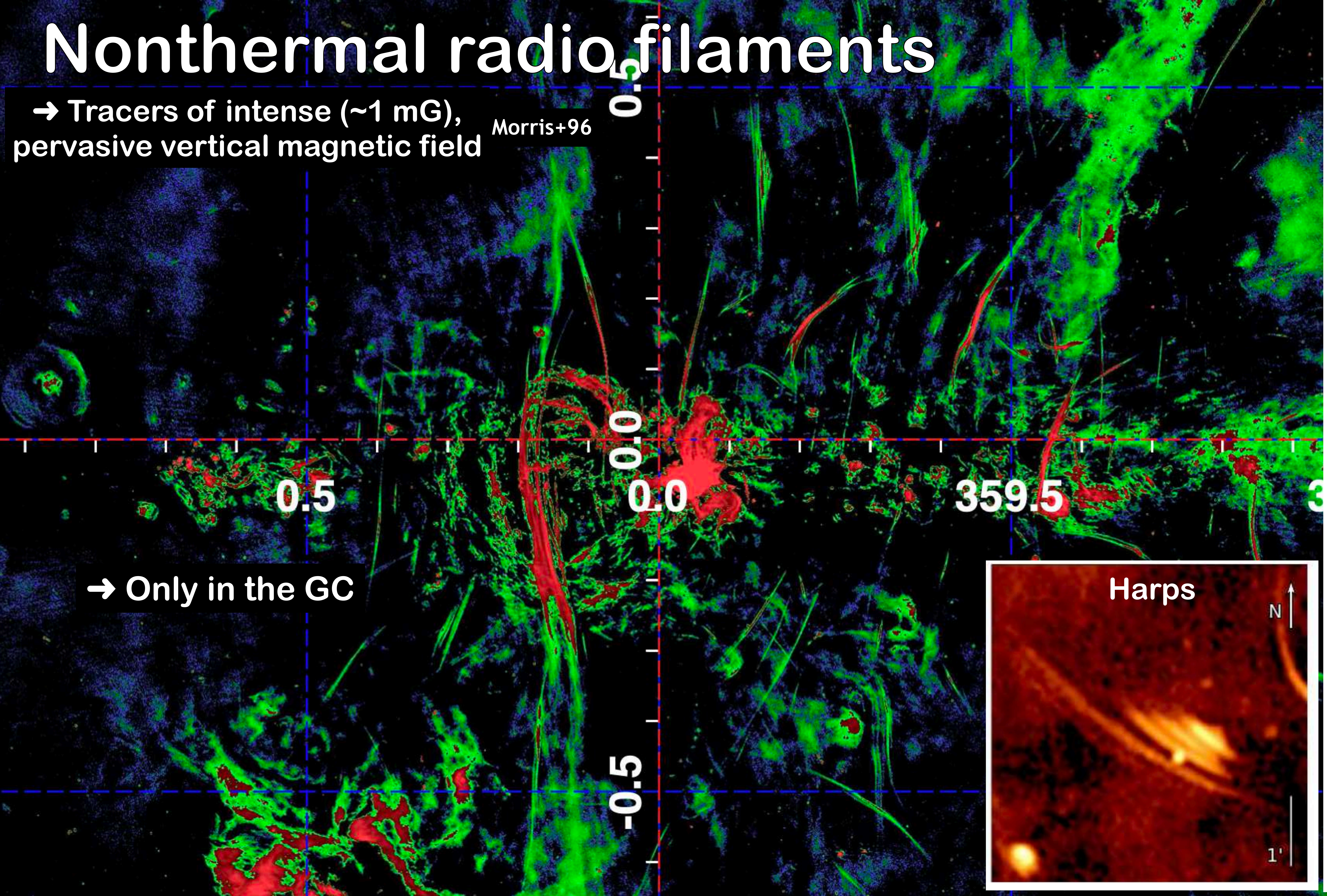
Nonthermal radio filaments

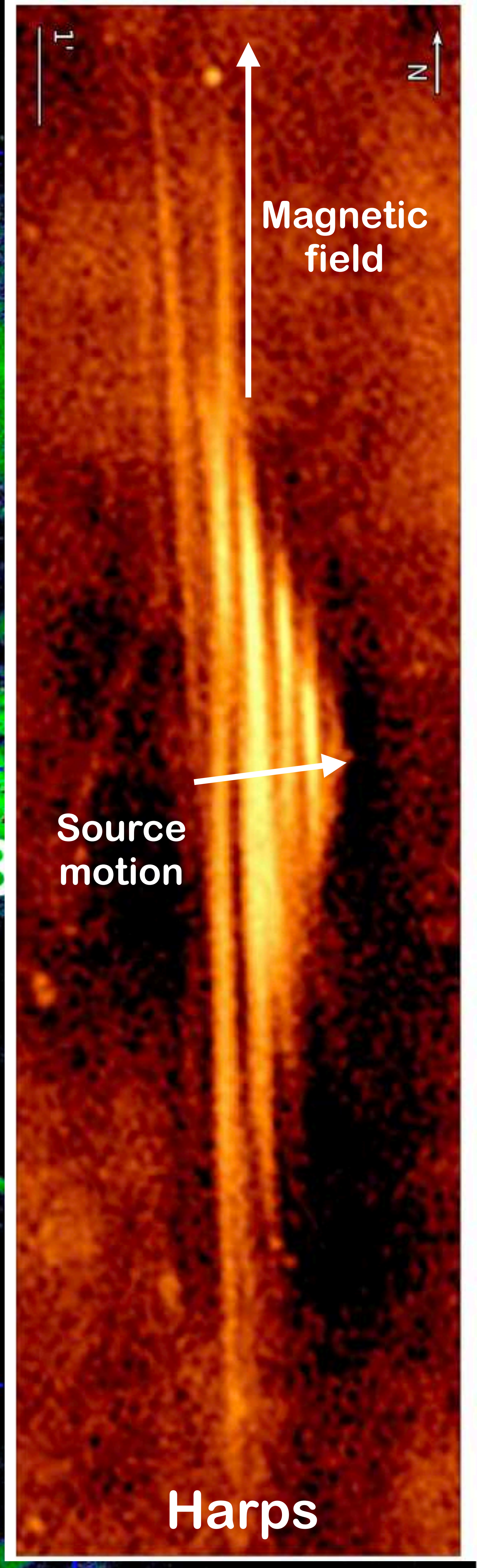
Nonthermal radio filaments

➜ Tracers of intense (~1 mG), pervasive vertical magnetic field

Morris+96

➜ Only in the GC



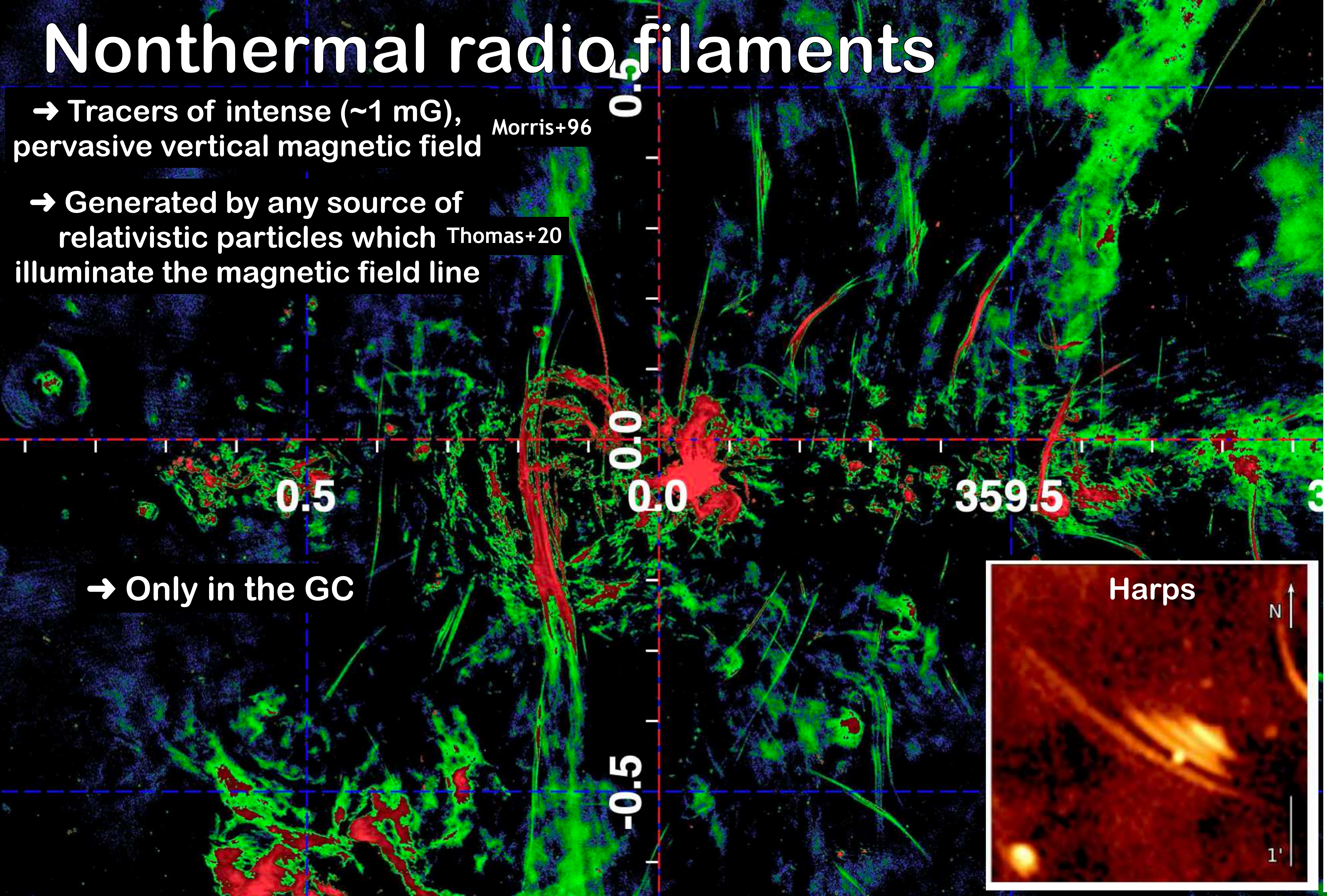


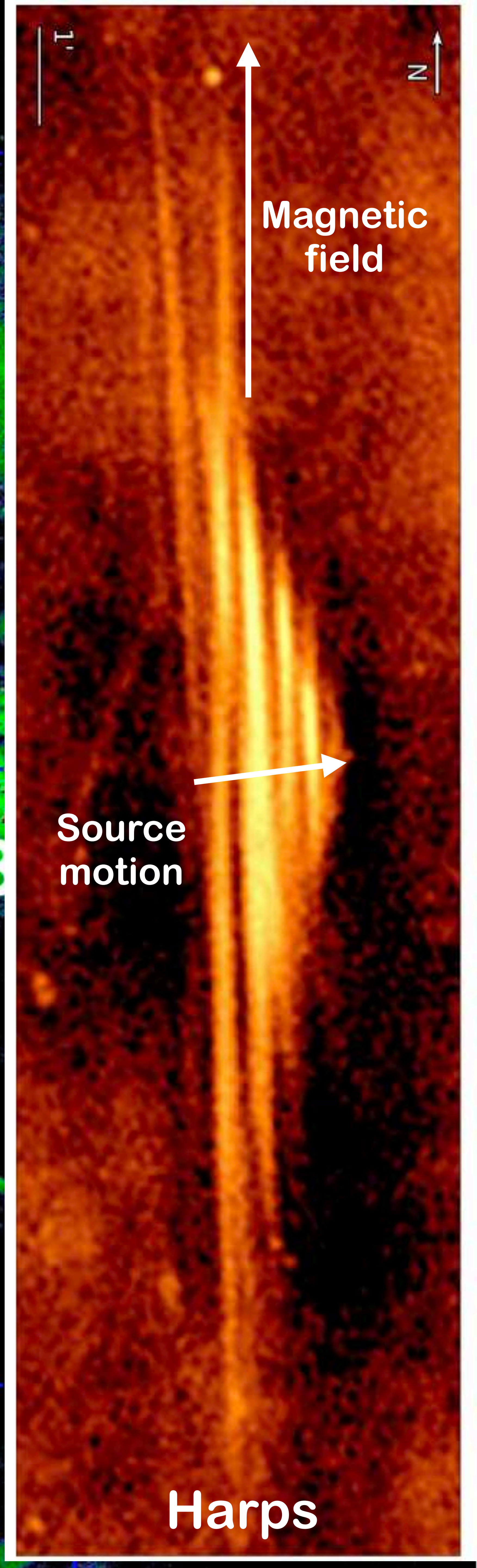
Nonthermal radio filaments

➜ Tracers of intense (~1 mG), pervasive vertical magnetic field Morris+96

➜ Generated by any source of relativistic particles which illuminate the magnetic field line Thomas+20

➜ Only in the GC





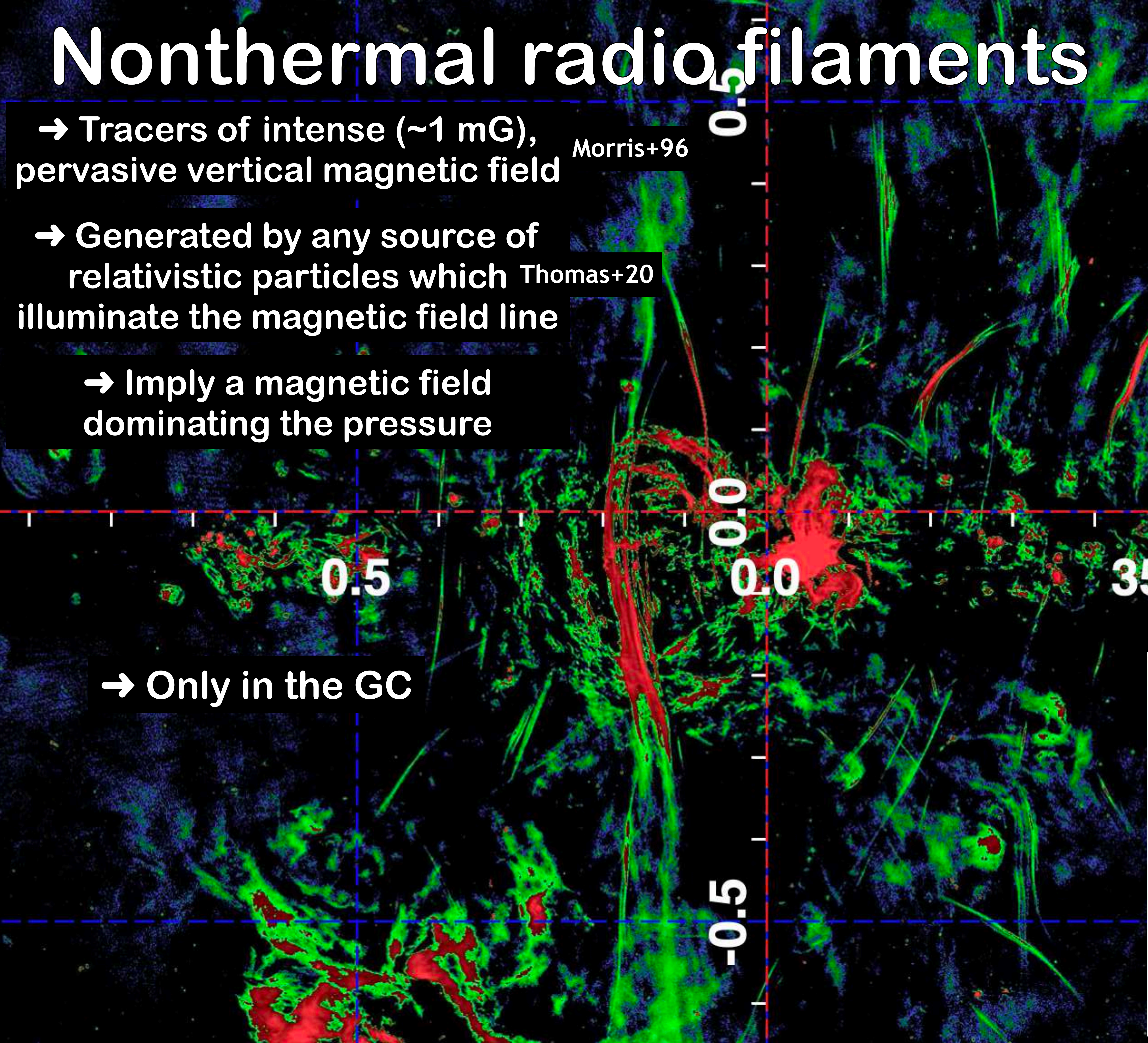
Nonthermal radio filaments

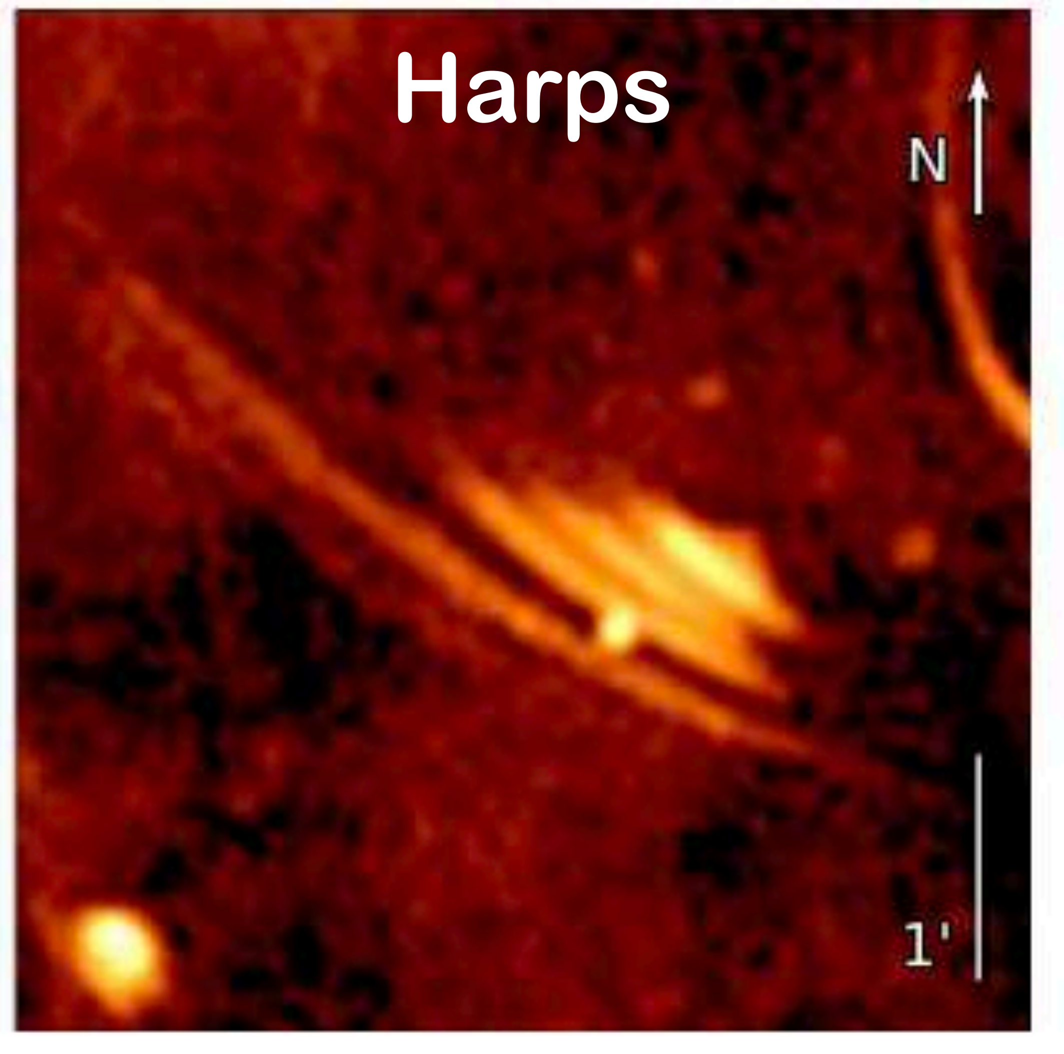
➜ Tracers of intense (~1 mG), pervasive vertical magnetic field Morris+96

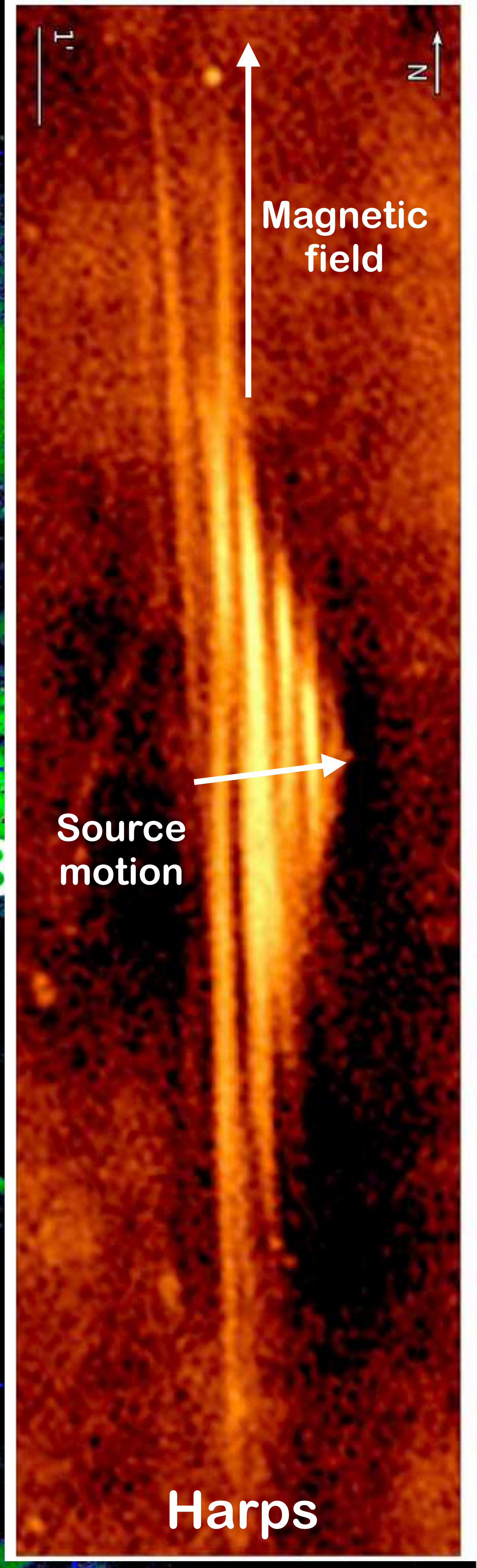
➜ Generated by any source of relativistic particles which illuminate the magnetic field line Thomas+20

➜ Imply a magnetic field dominating the pressure

➜ Only in the GC







Nonthermal radio filaments

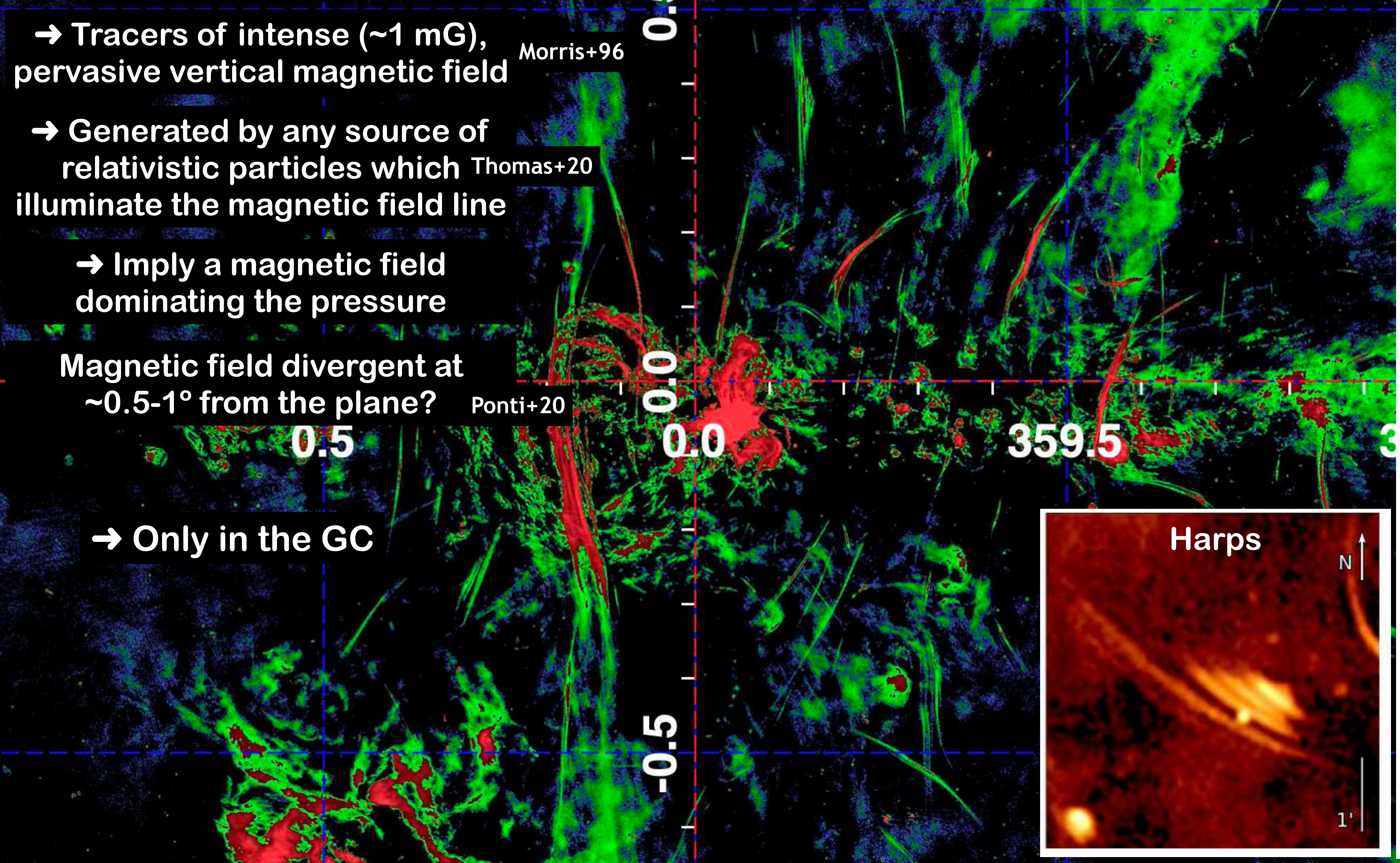
➜ Tracers of intense (~1 mG), pervasive vertical magnetic field Morris+96

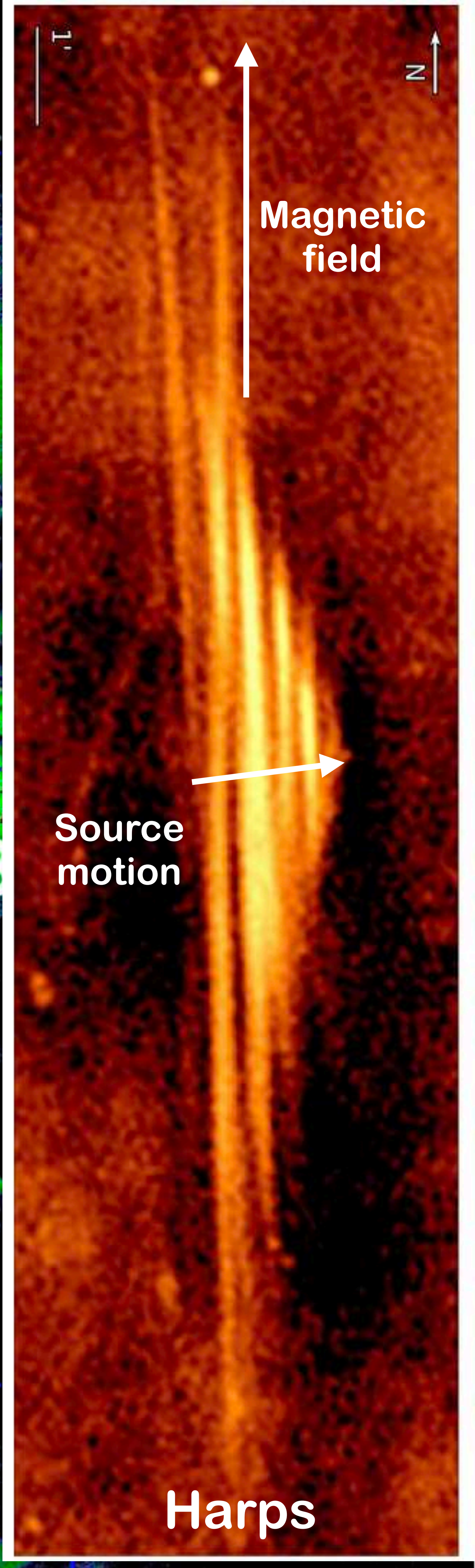
➜ Generated by any source of relativistic particles which illuminate the magnetic field line Thomas+20

➜ Imply a magnetic field dominating the pressure

Magnetic field divergent at ~0.5-1° from the plane? Ponti+20

➜ Only in the GC





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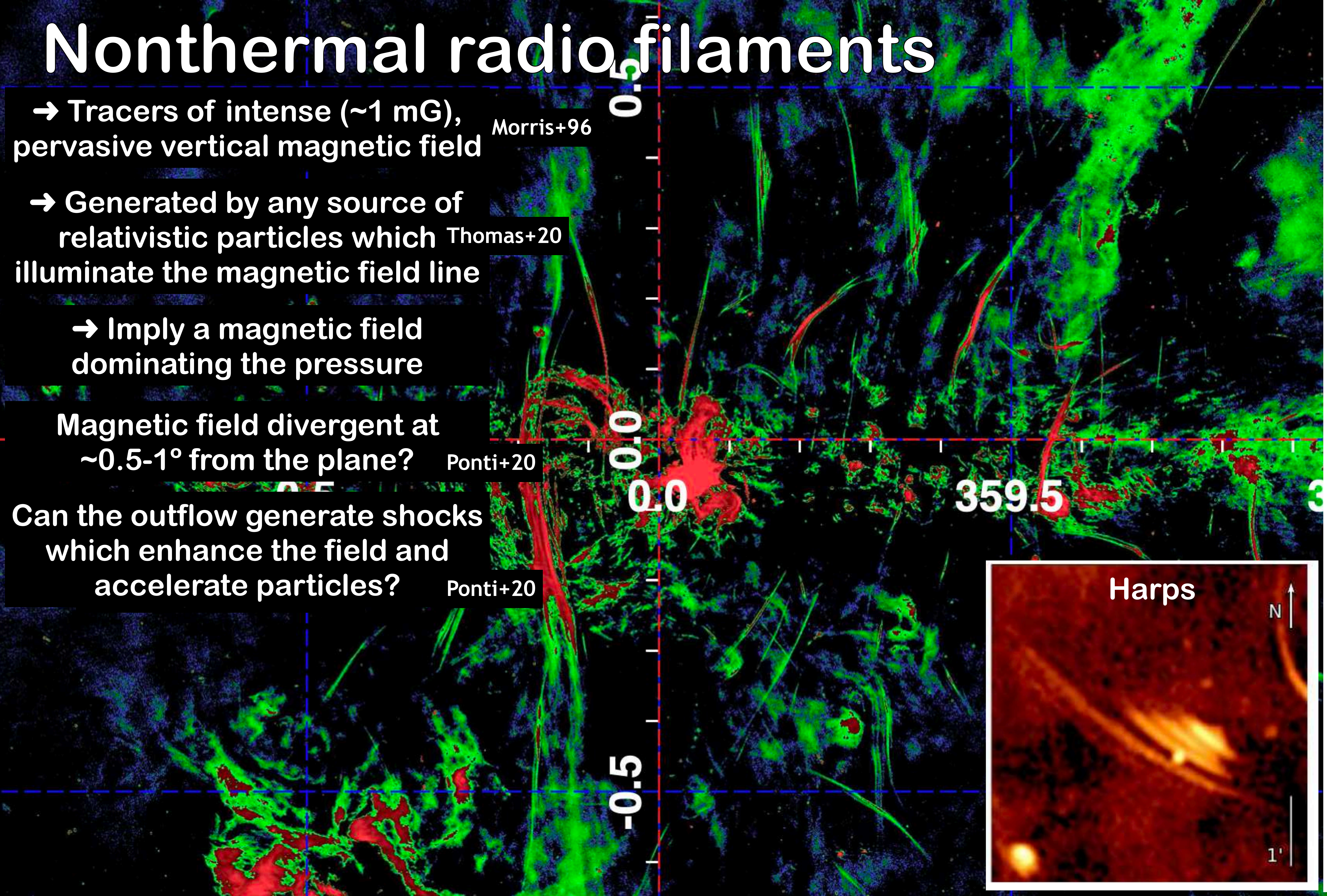

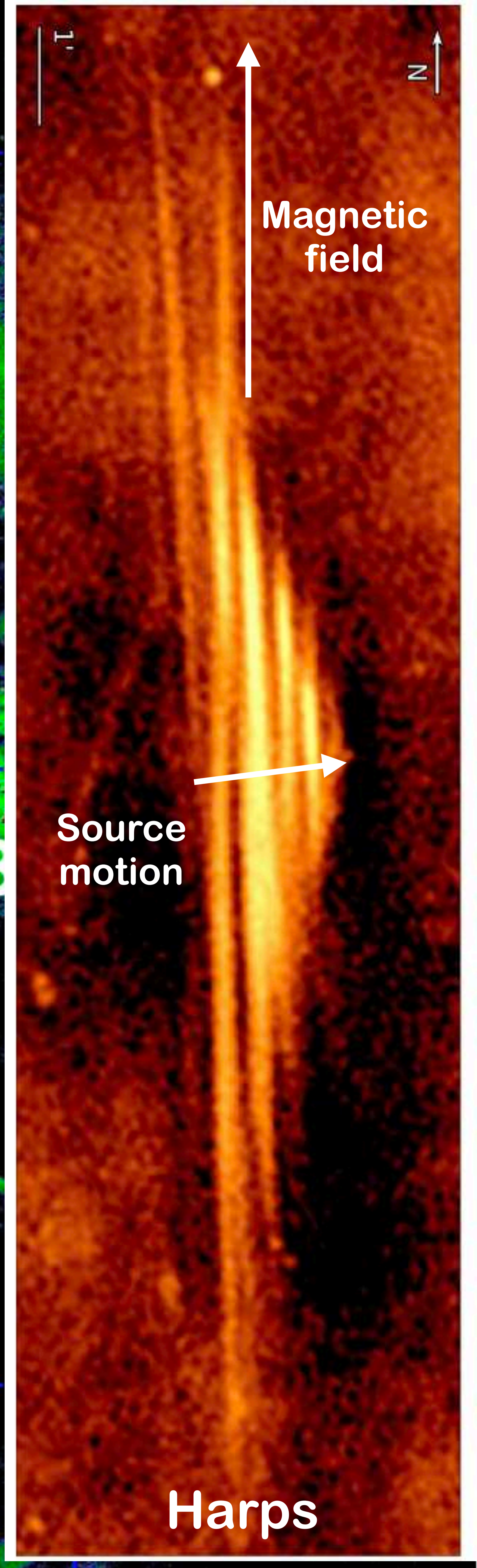

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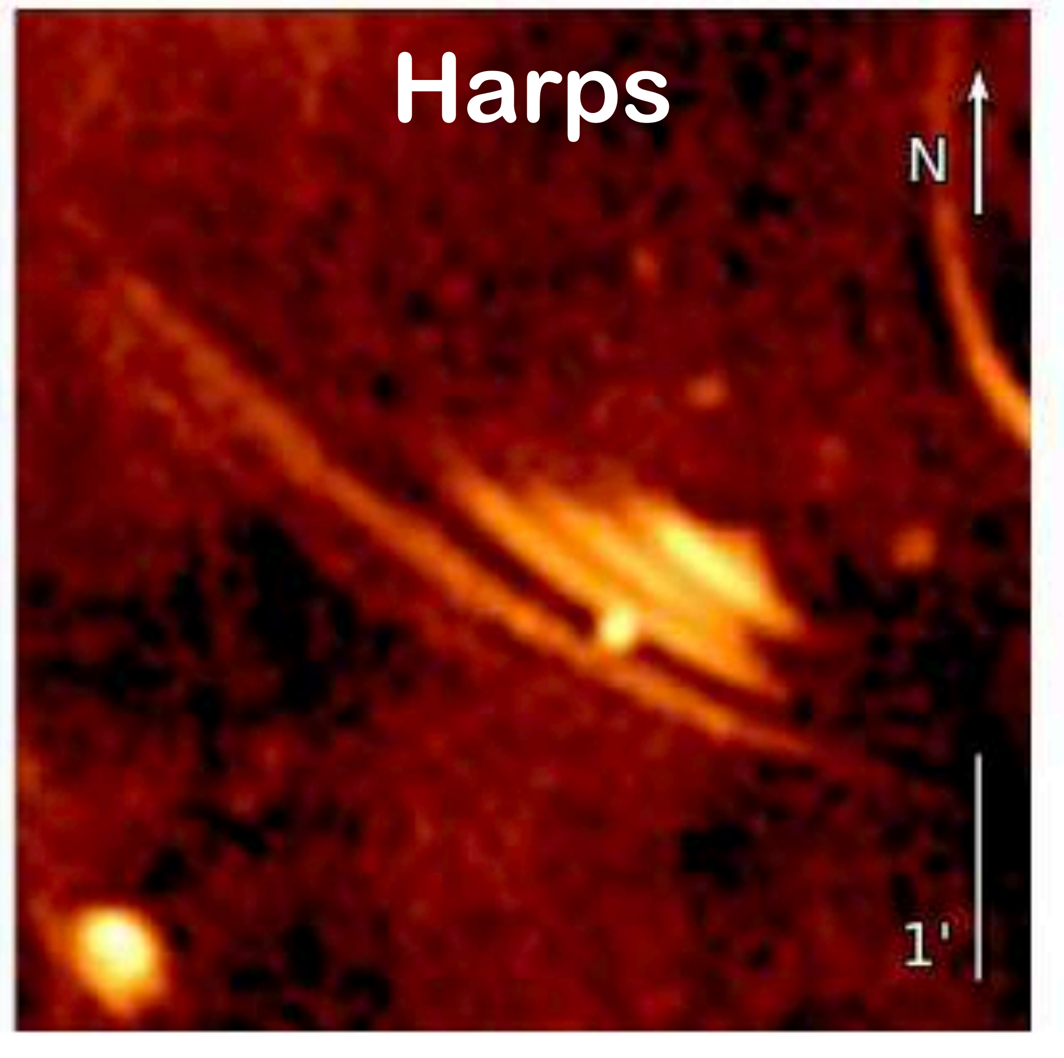
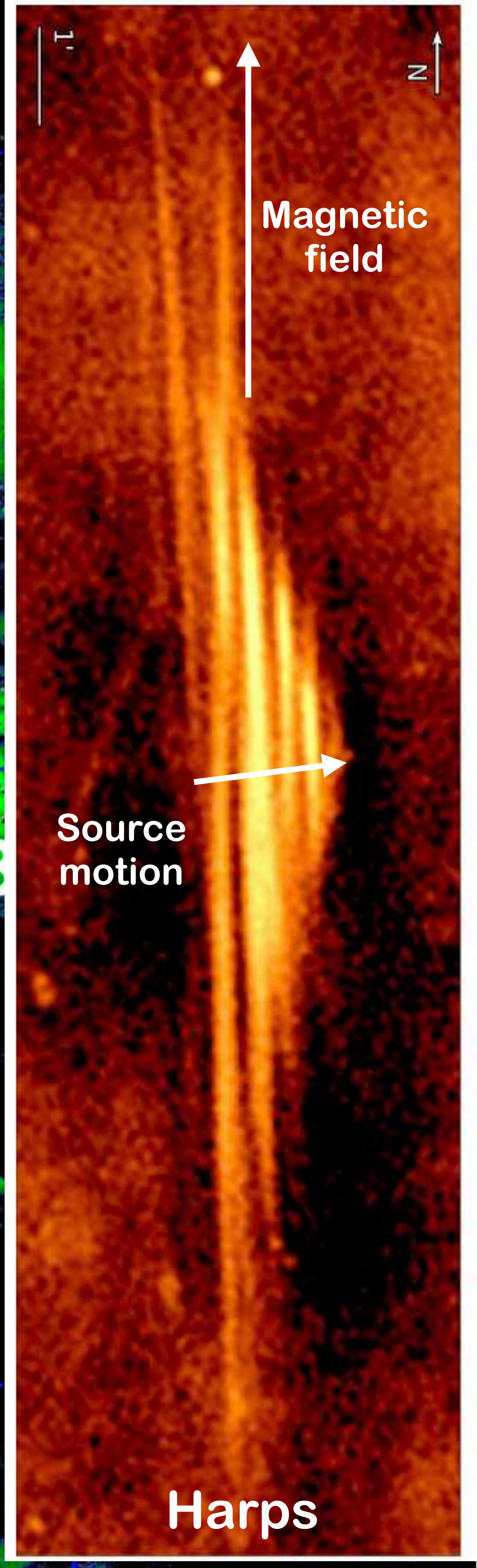
Alternatives:
Magnetic reconnection; Pulsar wind nebulae; Alfven waves; Magnetised wakes of molecular clouds; Stellar winds; Acceleration in young star clusters

Lesch+92; Serbin+94; Rosner +96; Shore +99; Bicknell +01; Yusef-Zadeh +03; 19; Bykov +17; Sofie +20





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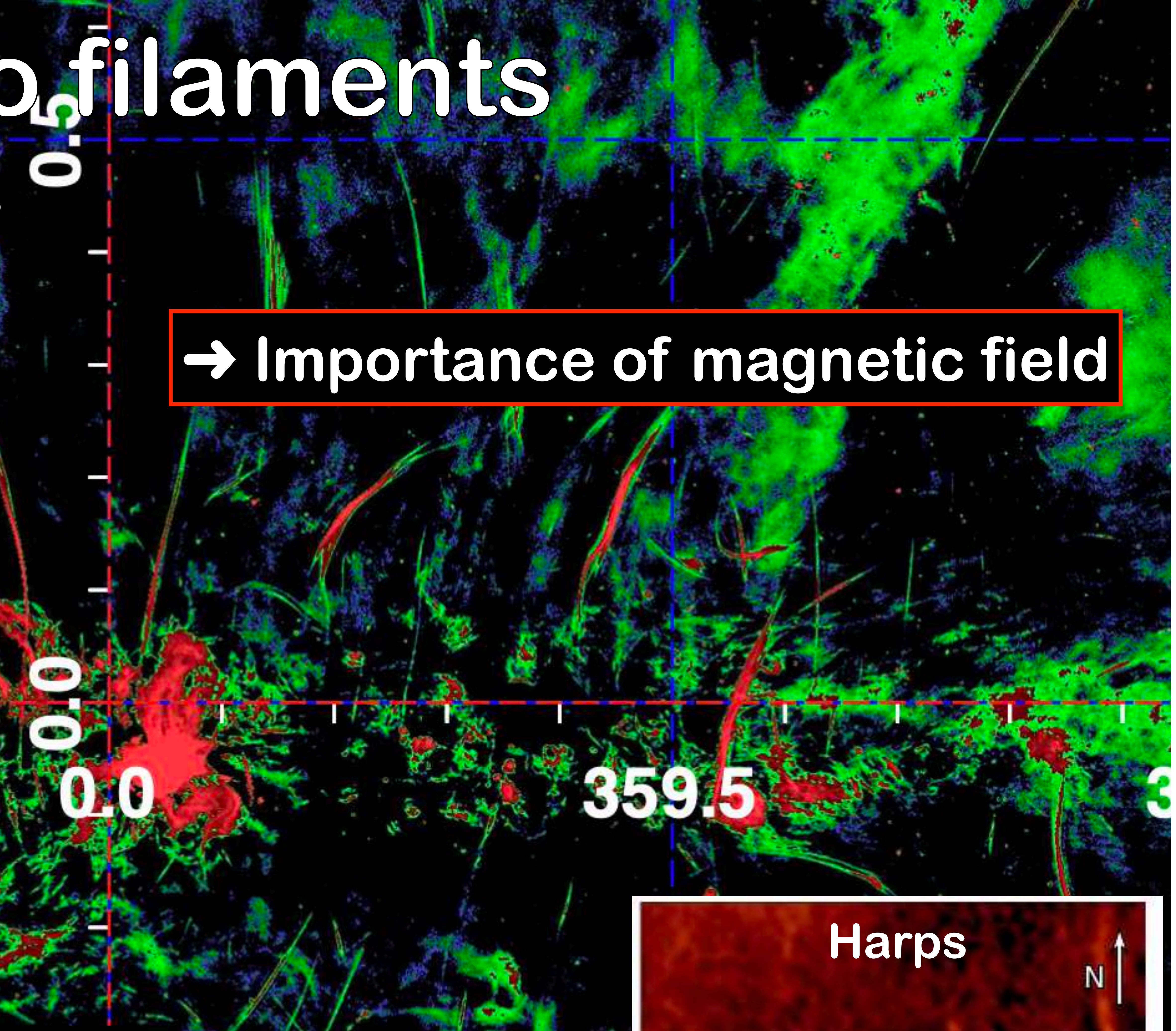
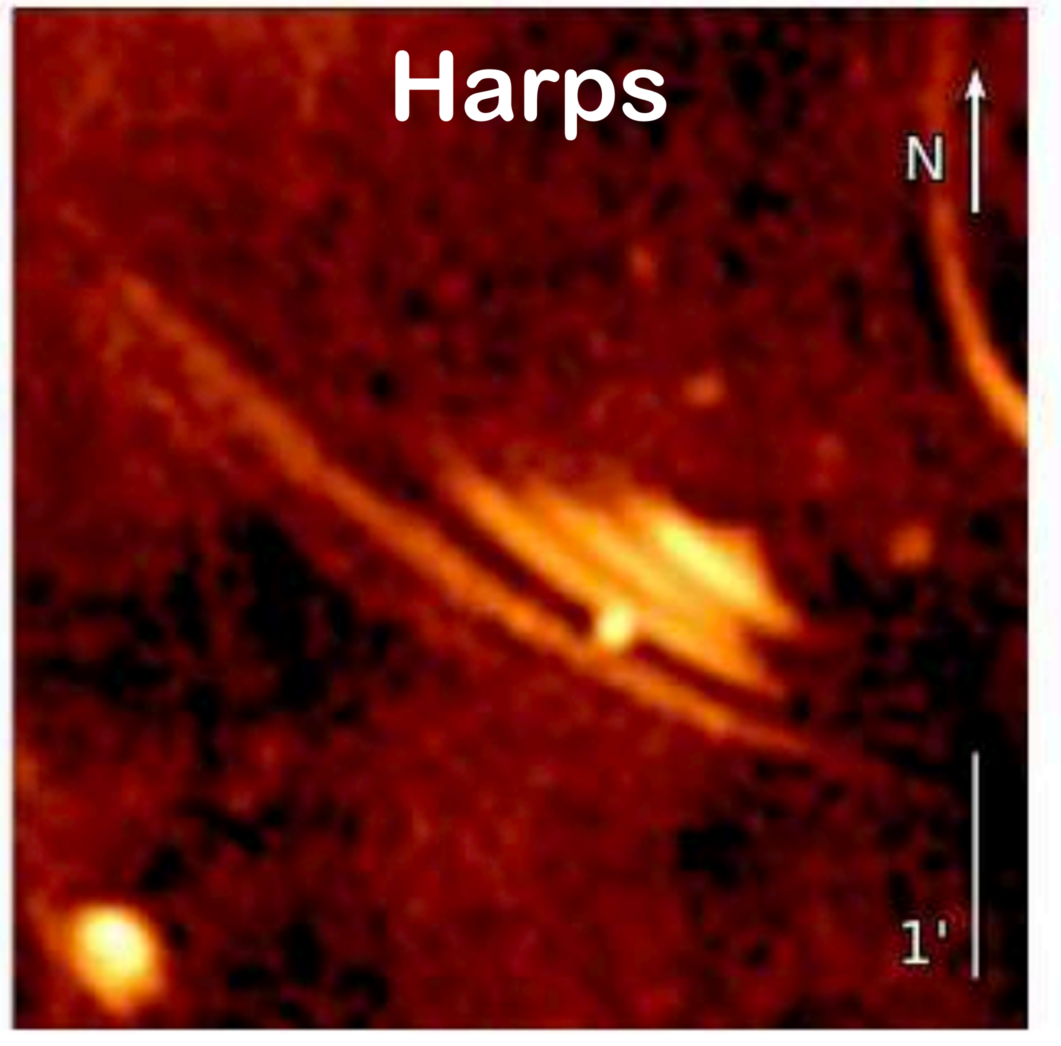
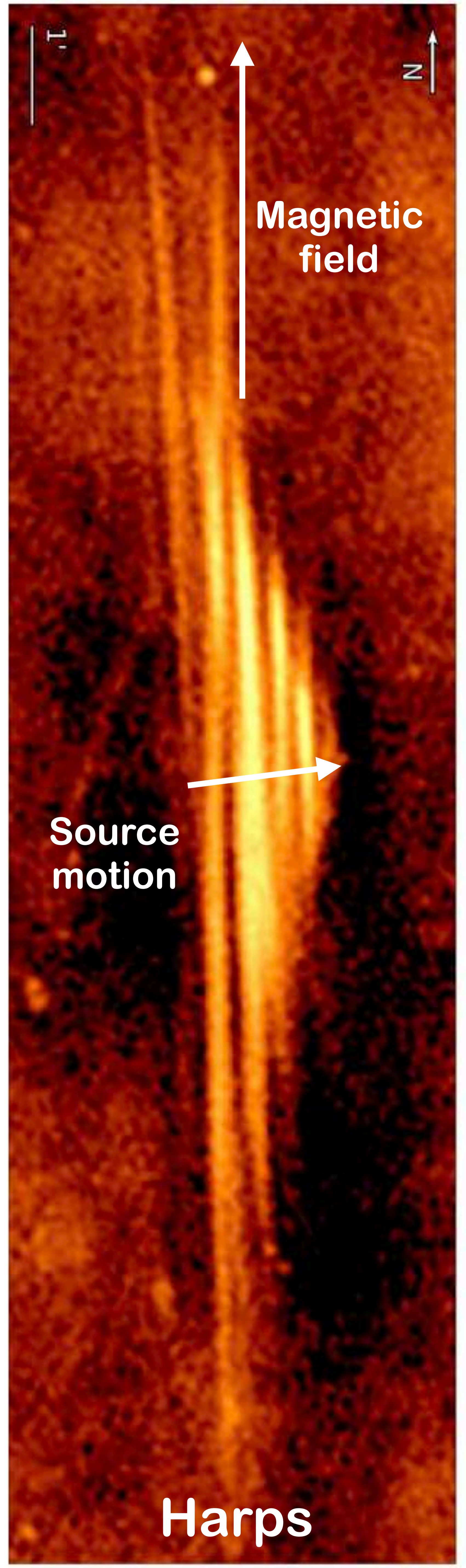
➜ Importance of magnetic field







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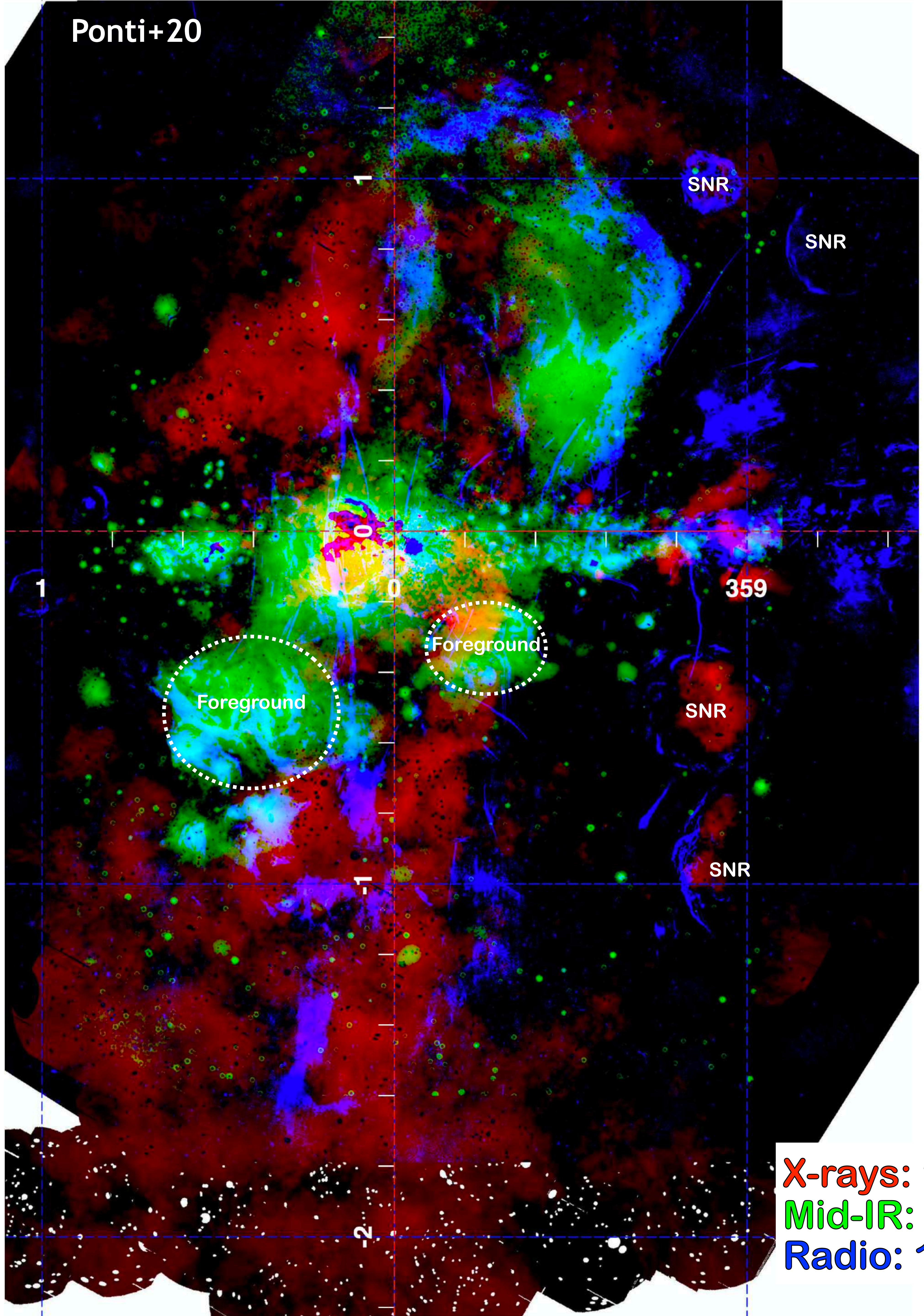


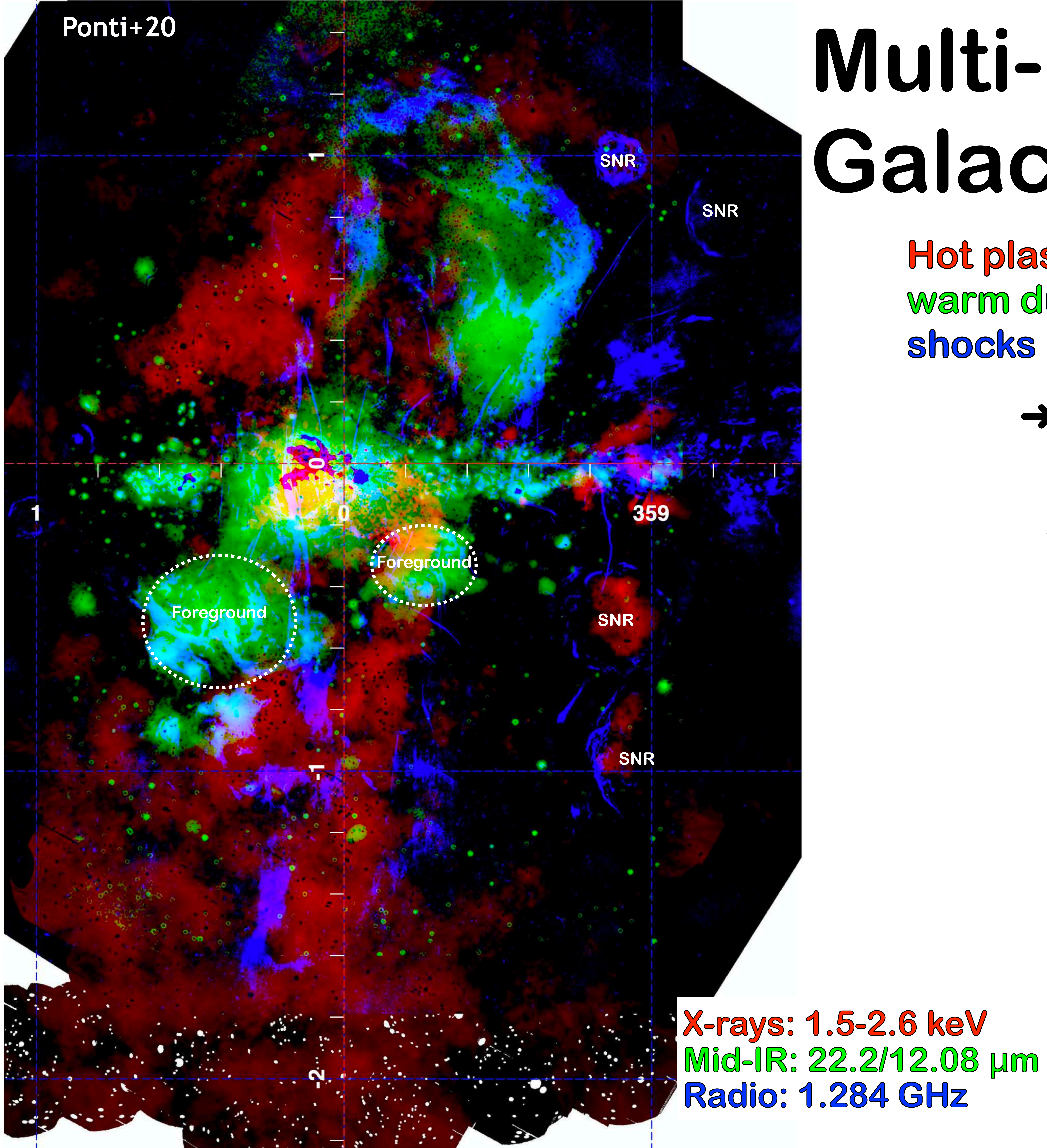
Multi-phase multi-epoch Galactic outflow

Hot plasma (X-rays)
warm dust (mid-IR)
shocks (radio)

➜ Coherent features on > 10^2 pc scales

➜ Deeply interconnected and linked to the Galactic outflow

X-rays: 1.5-2.6 keV
Mid-IR: 22.2/12.08 μm
Radio: 1.284 GHz



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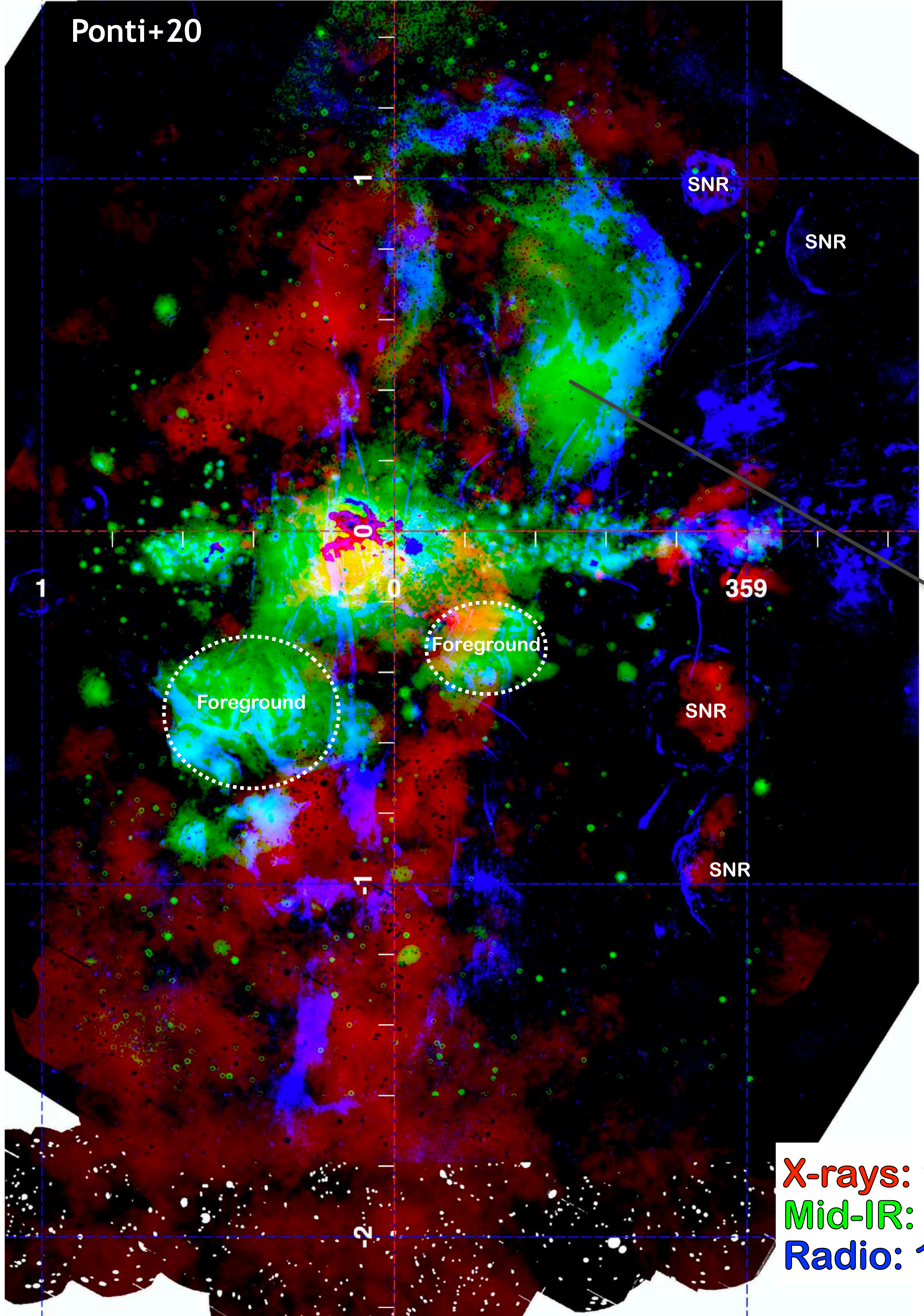

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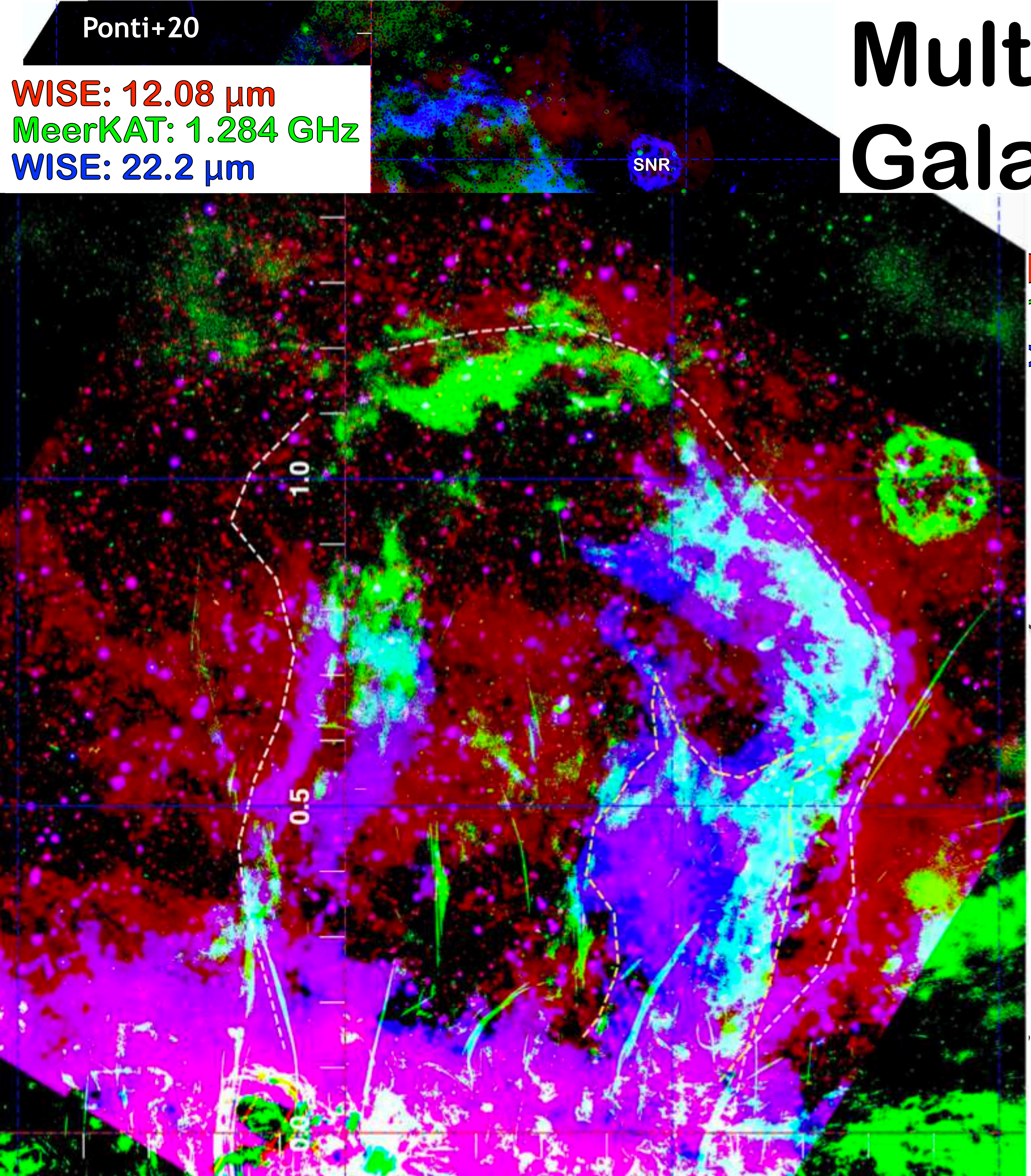

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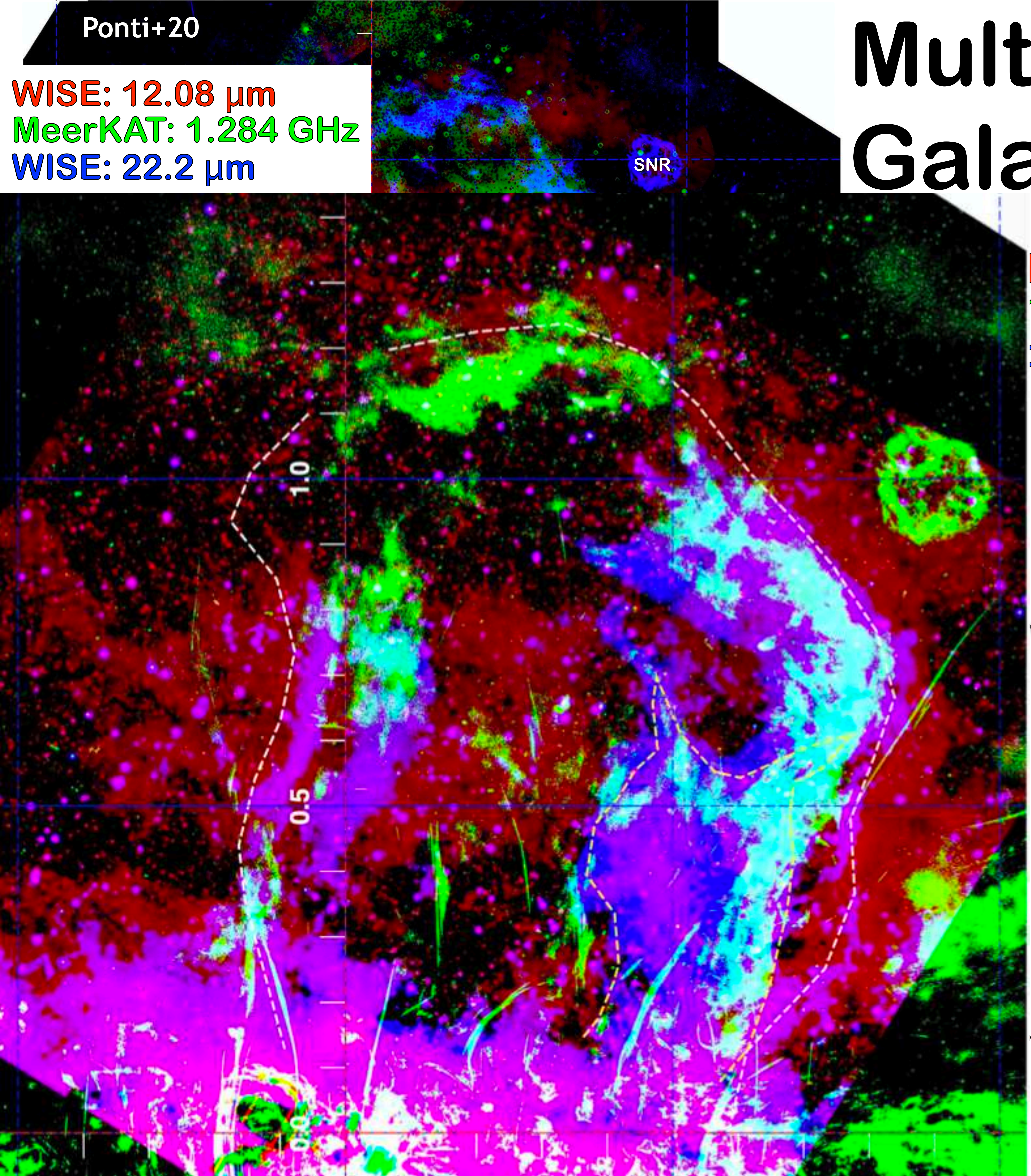

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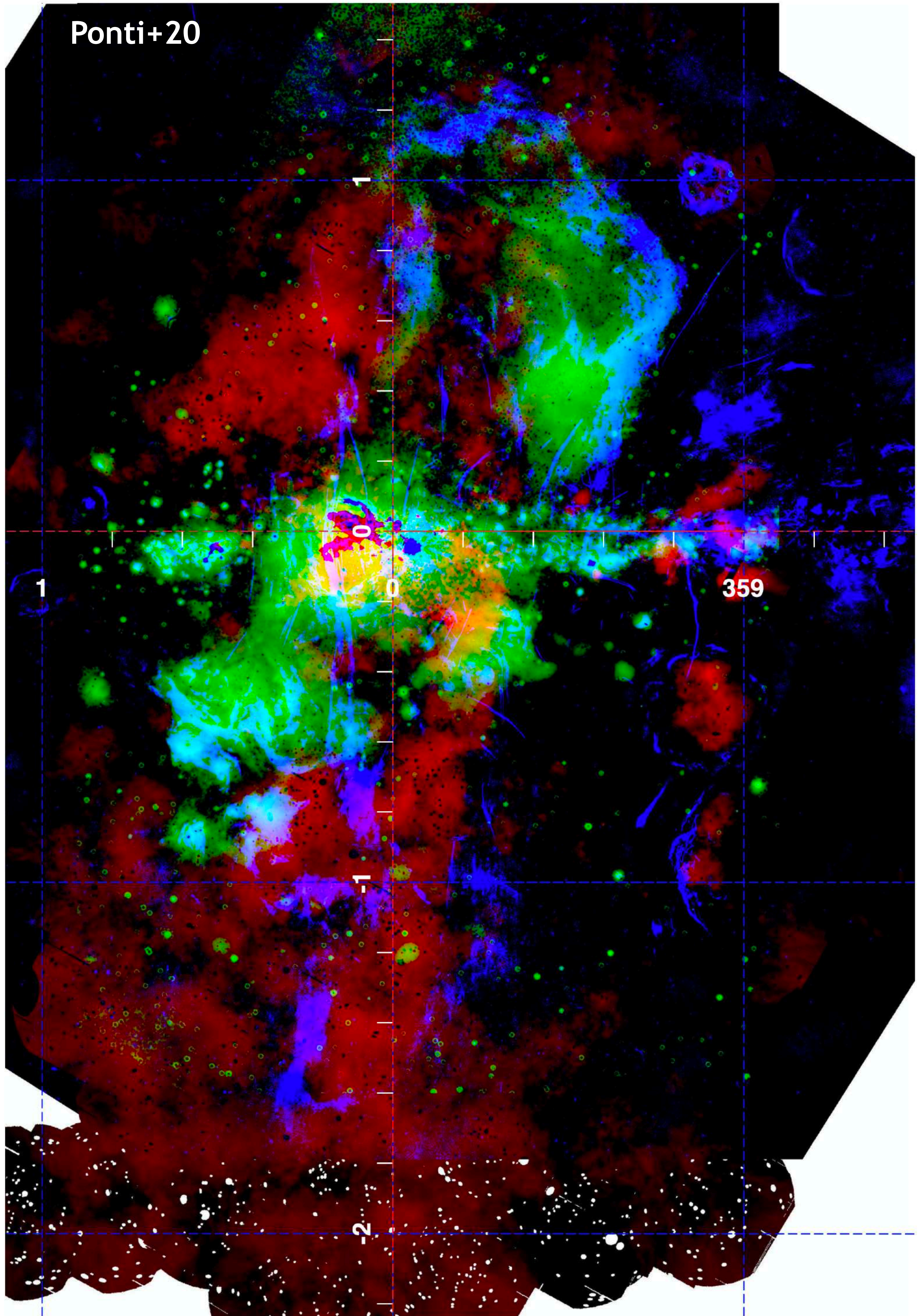
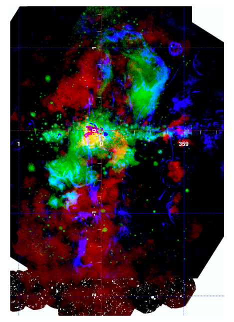
µm

Large scale cold Galactic outflow



Large scale cold Galactic outflow

Base Fermi bubbles



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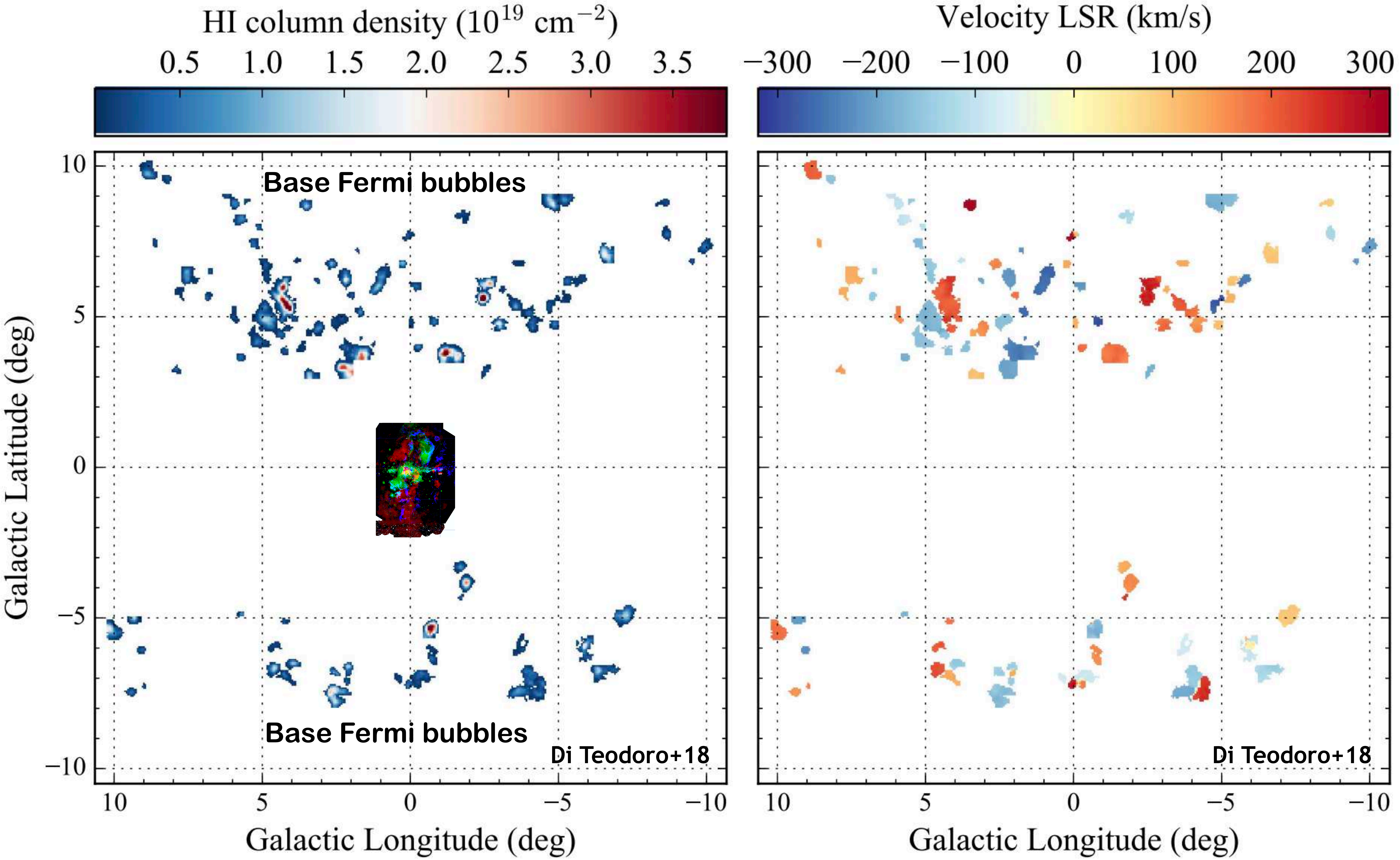

McClure-Griffith+13; Di Teodoro+18;+20; Lockman+20

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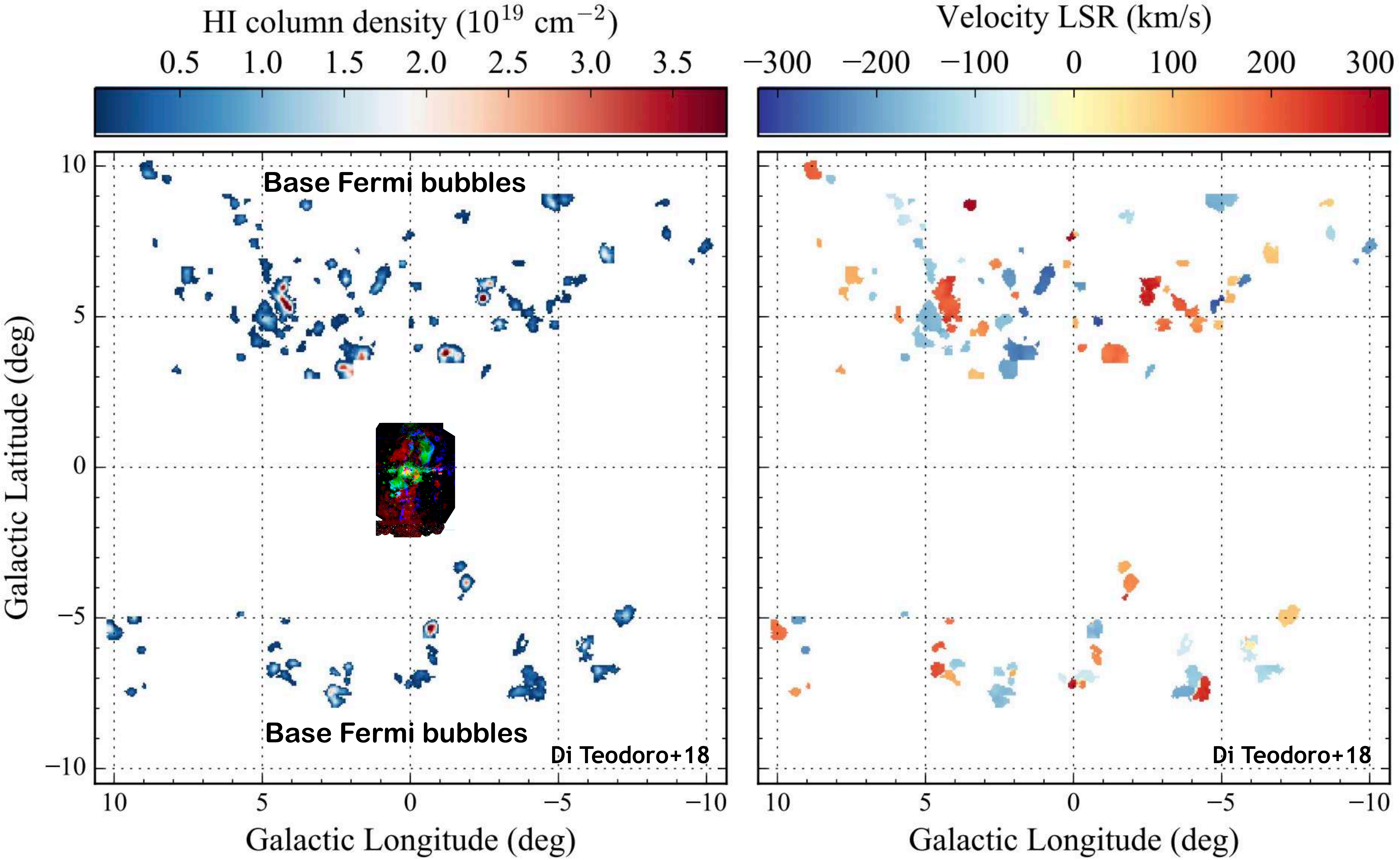

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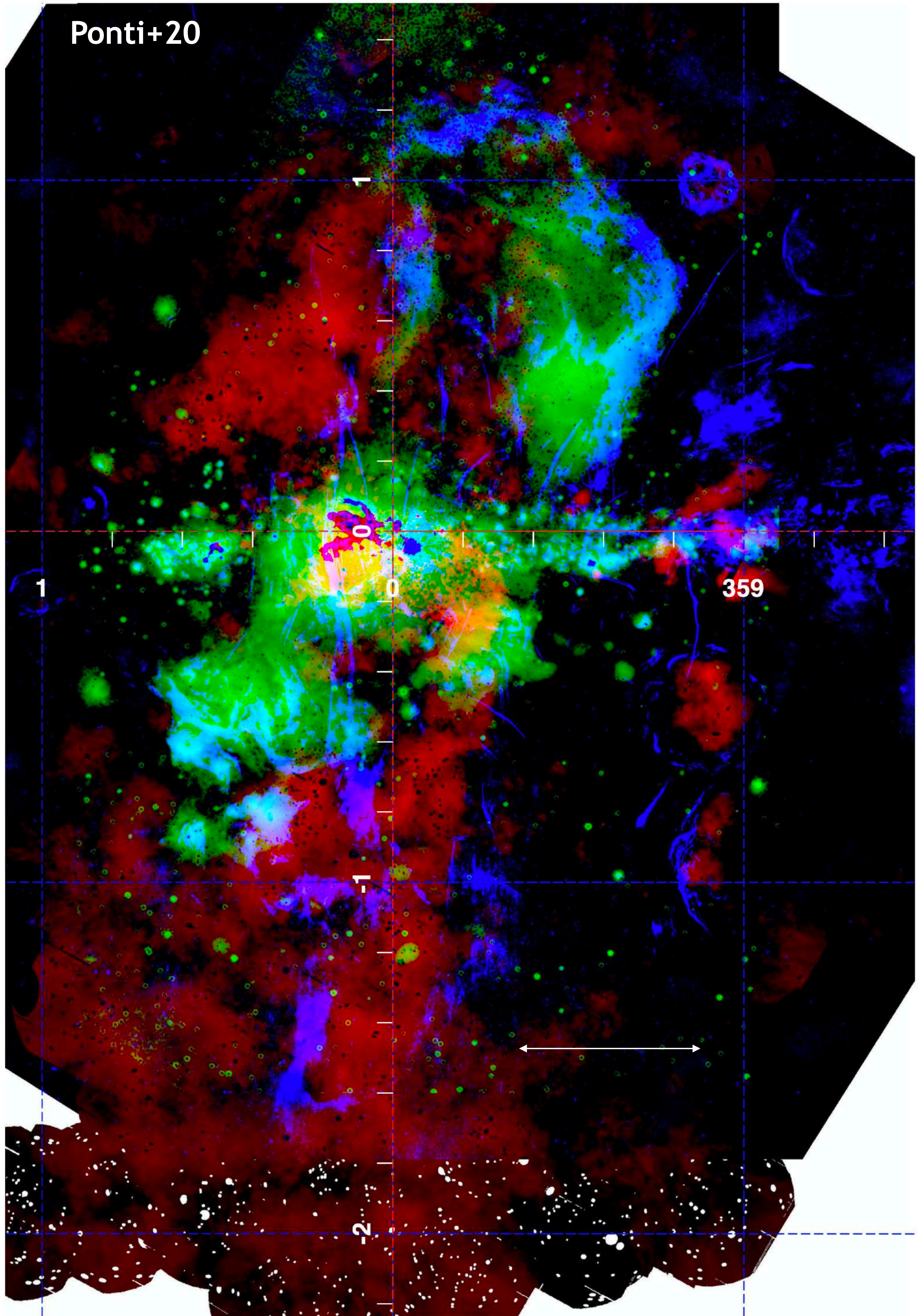
AFGL 5376 similar to clouds at the base of the Fermi bubbles

Small scale molecular Galactic outflow



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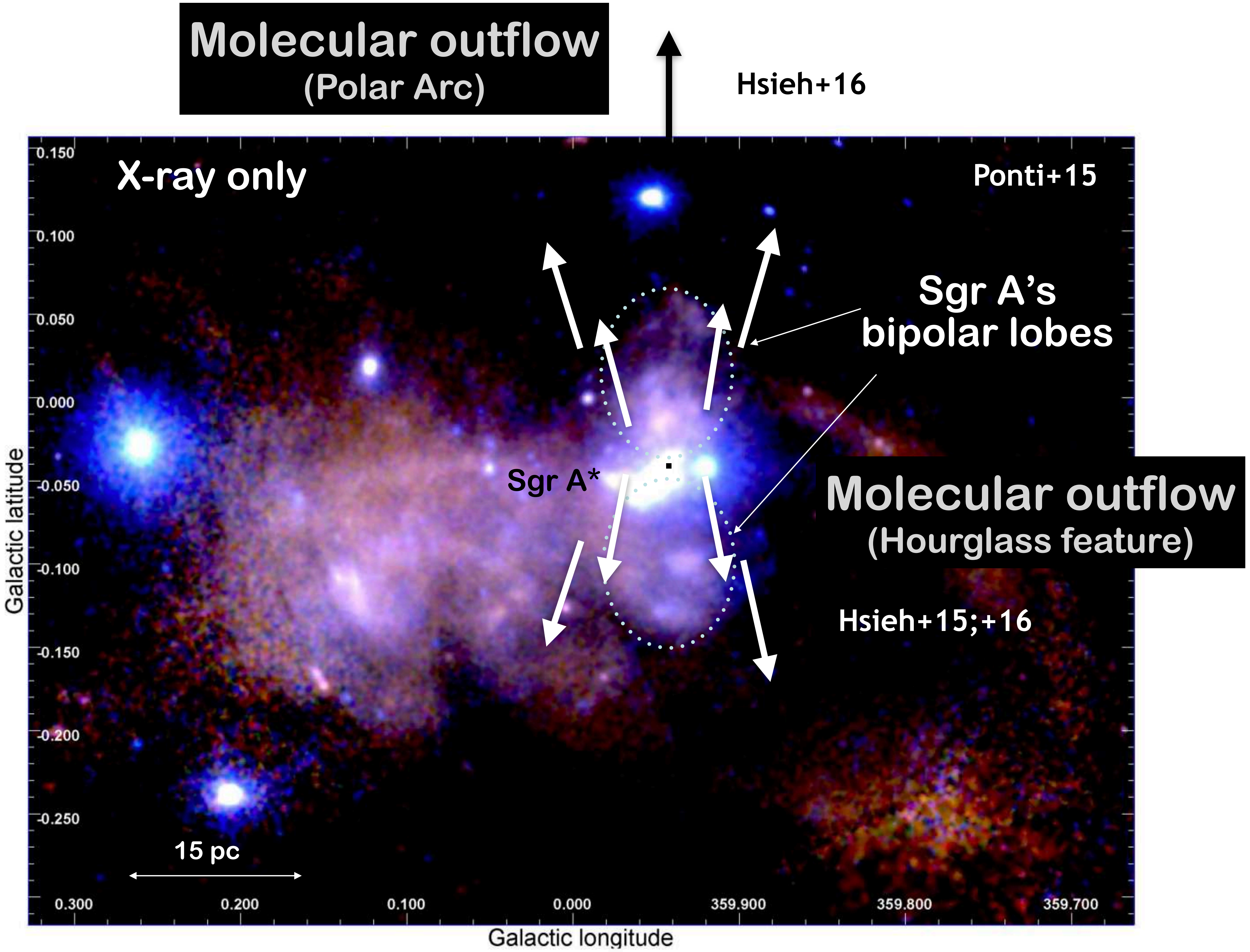

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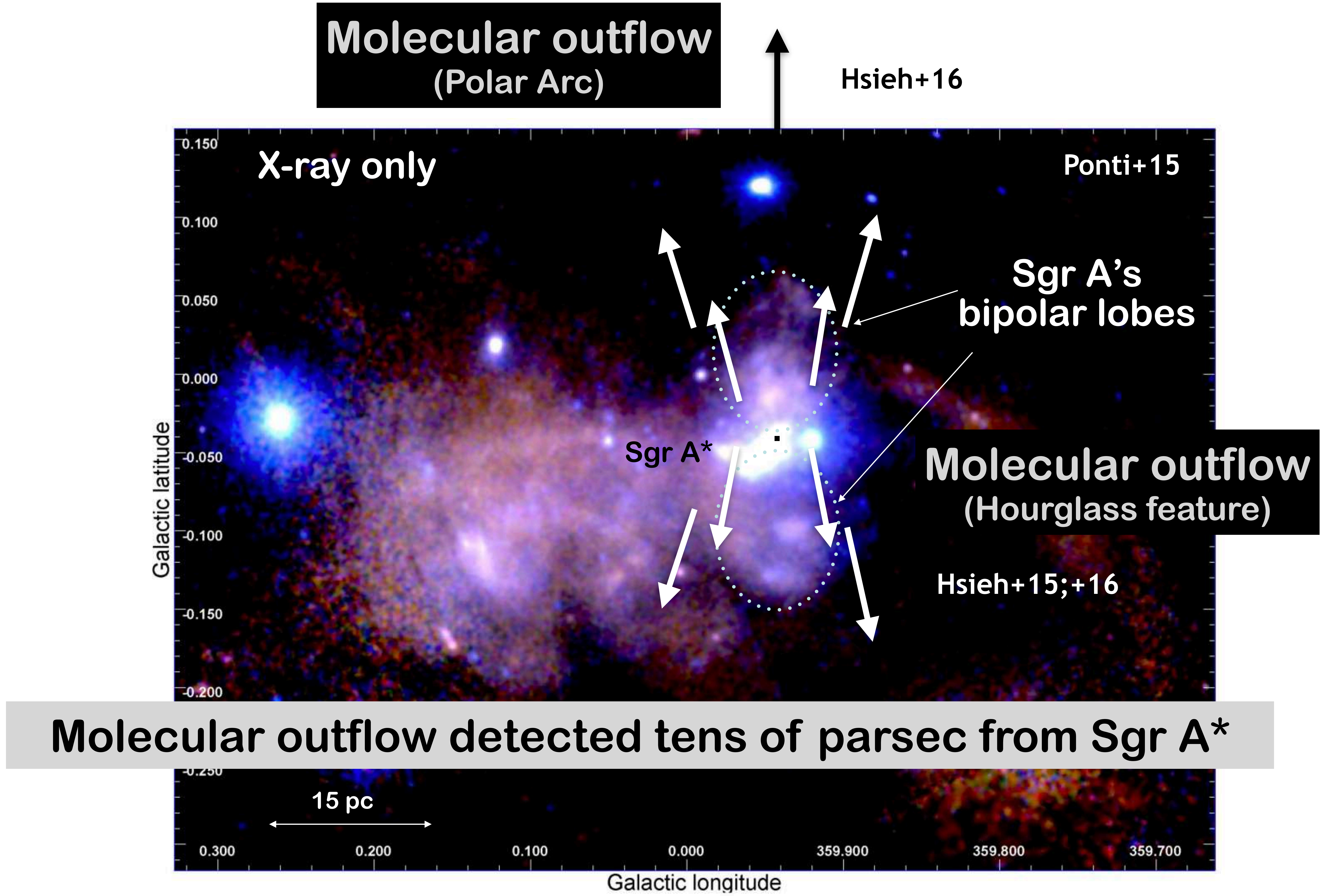
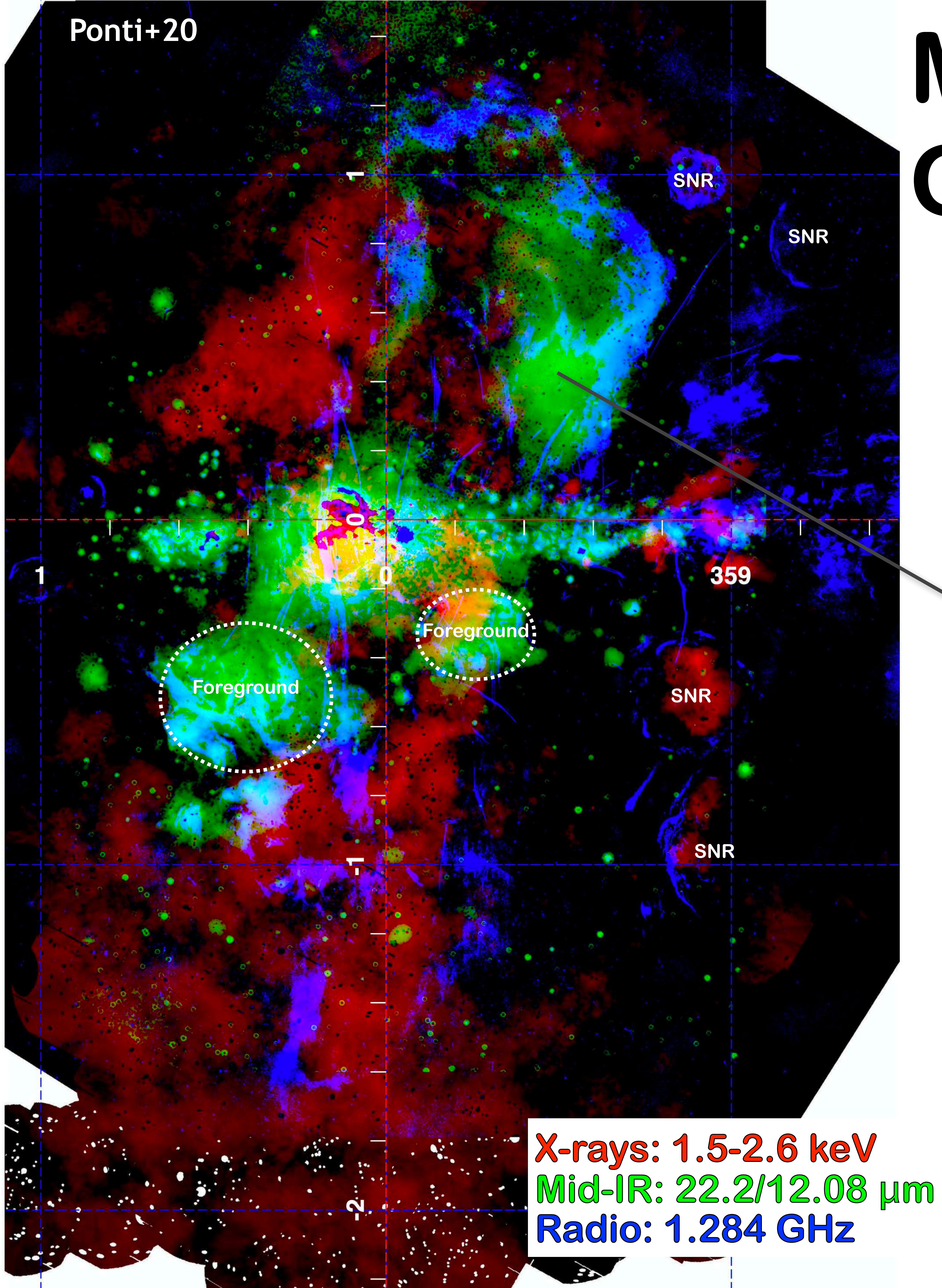


Molecular outflow detected tens of parsec from Sgr A*



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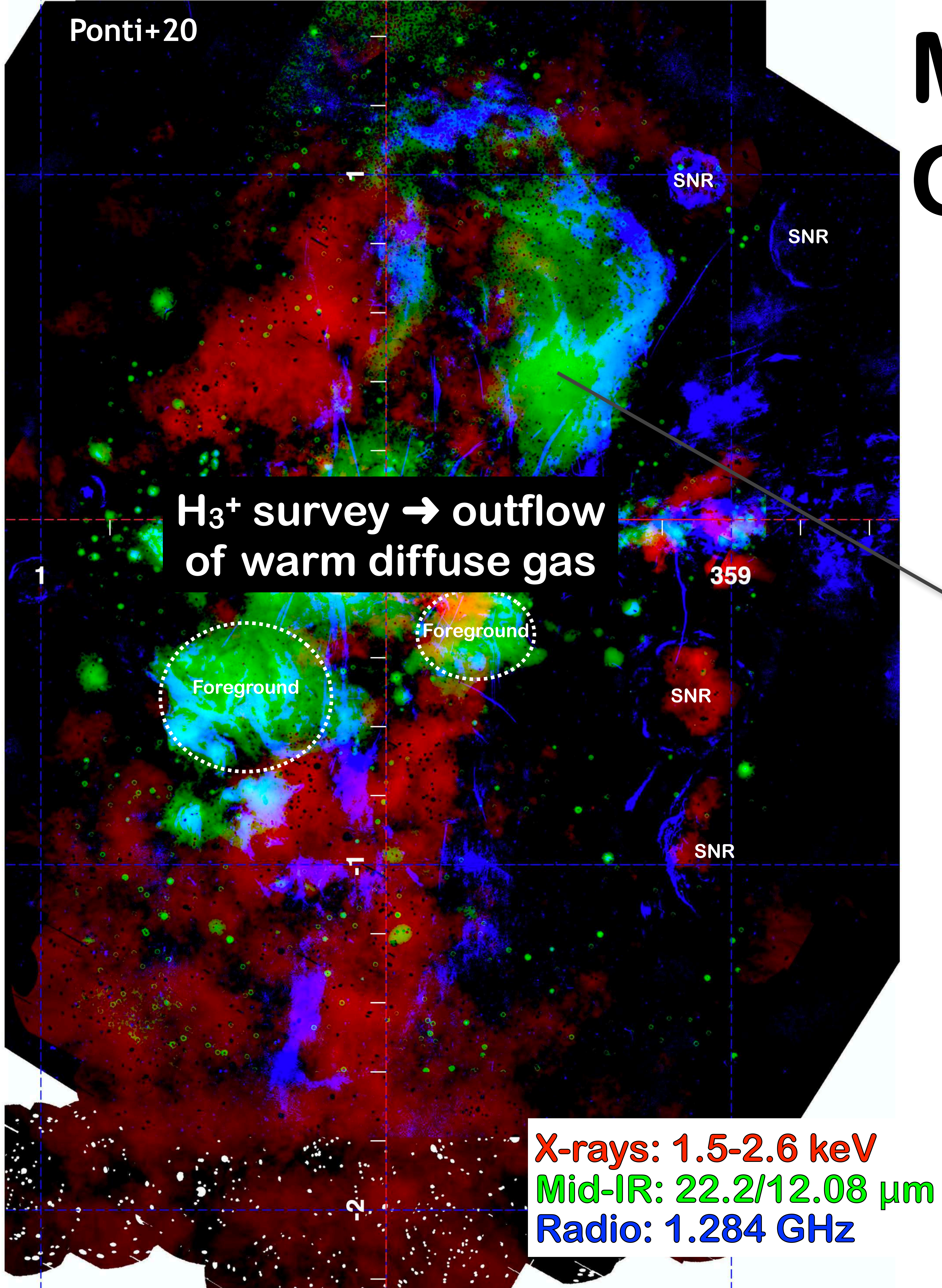

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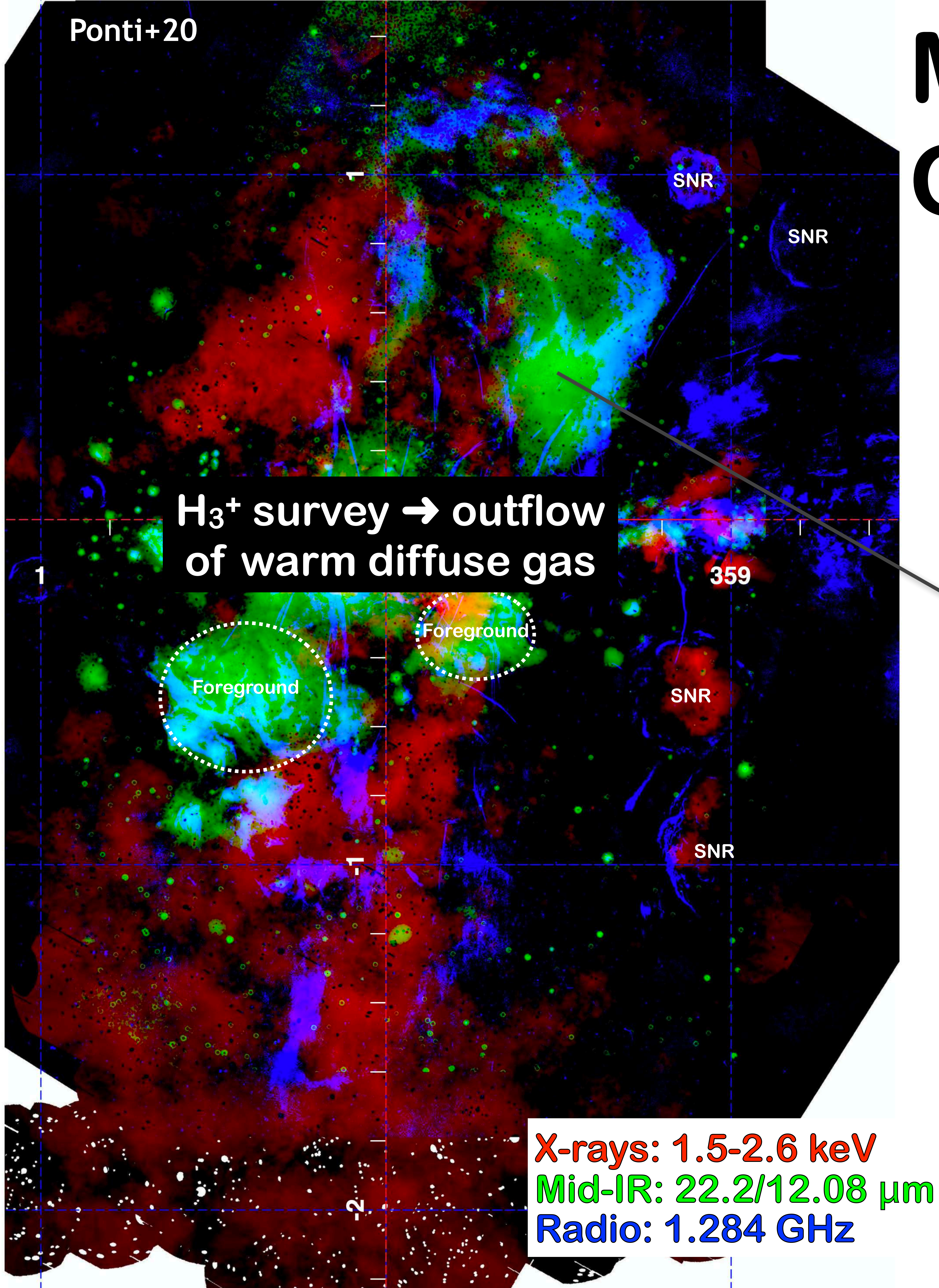

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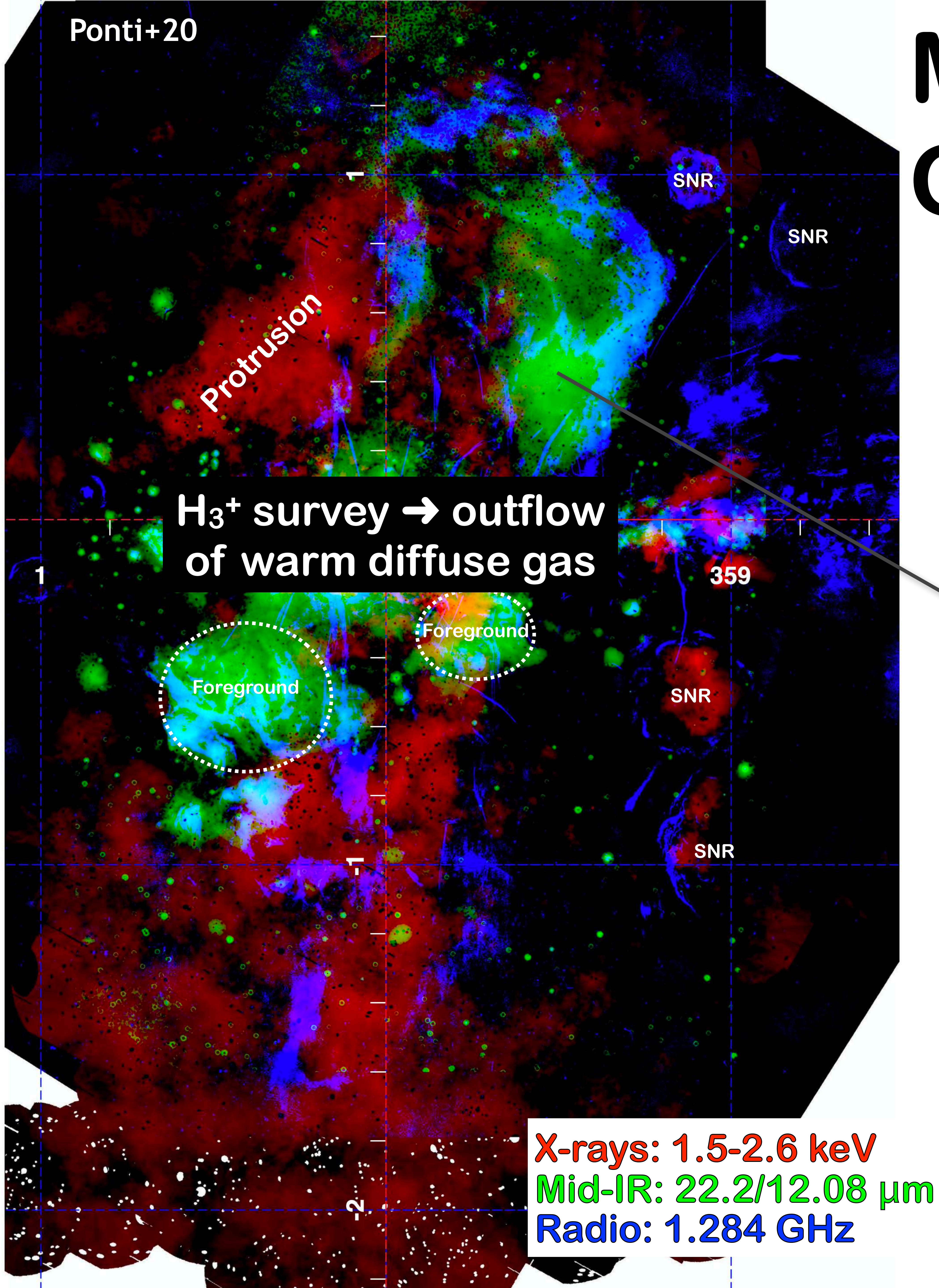
Multi-phase multi-epoch Galactic outflow



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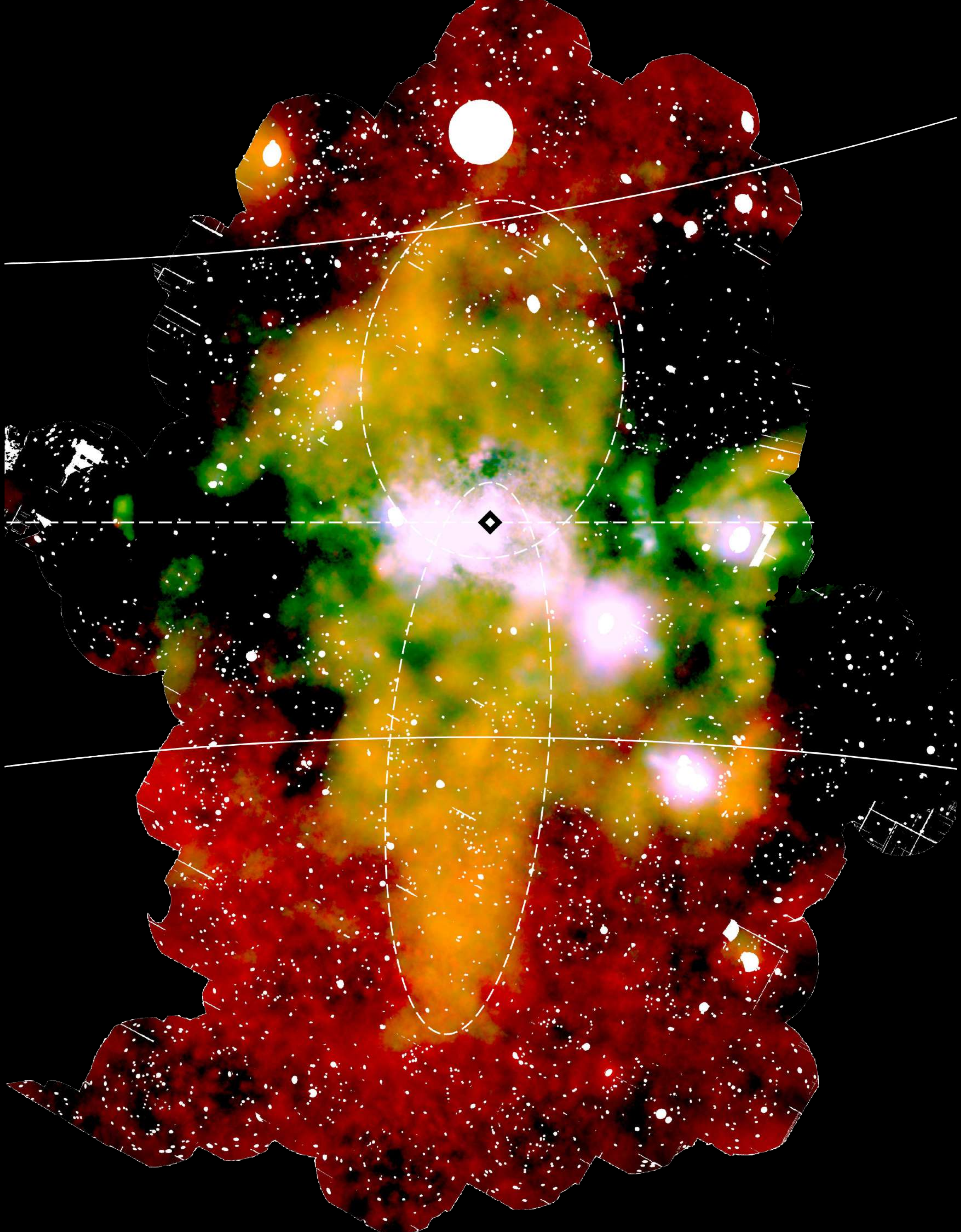
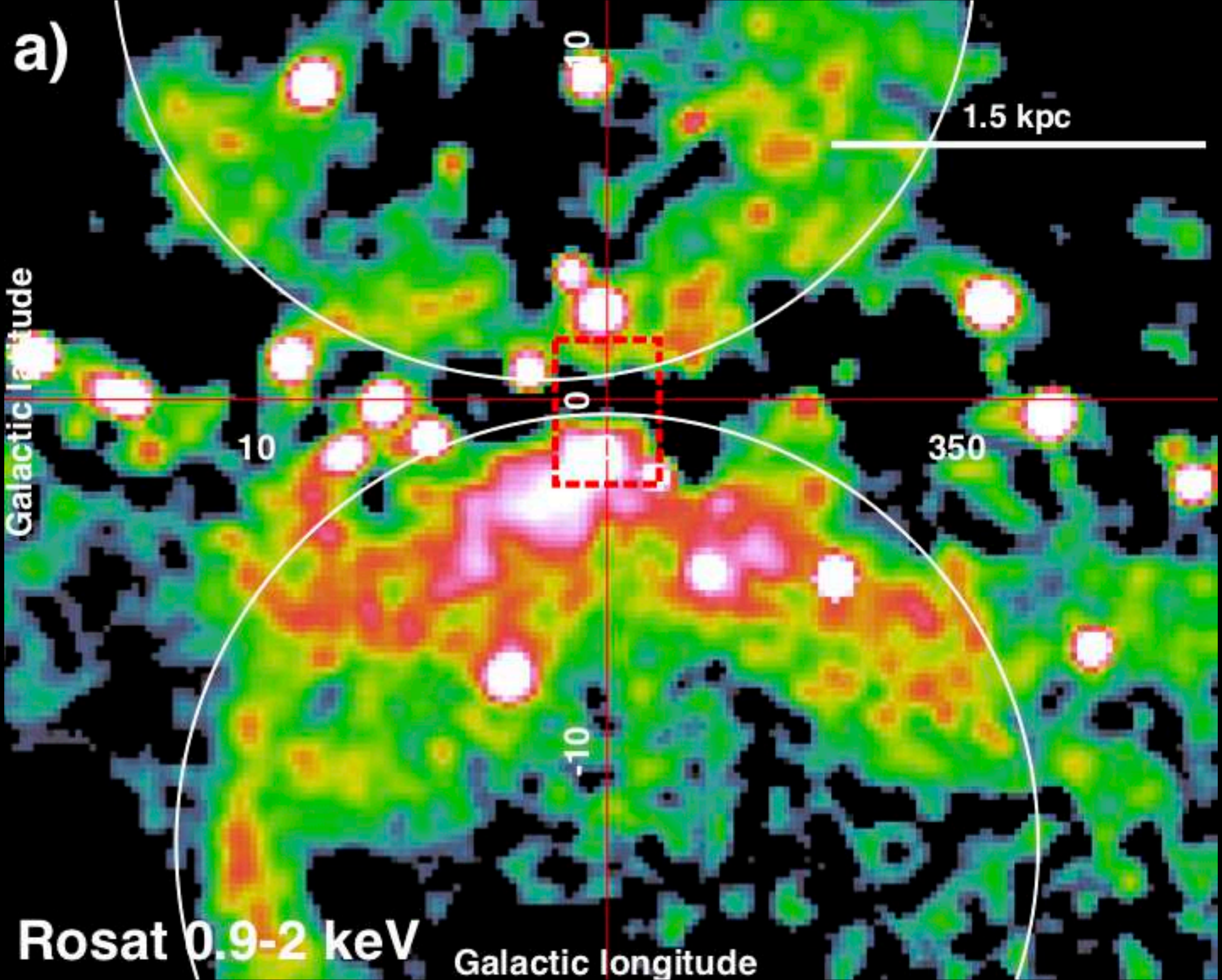
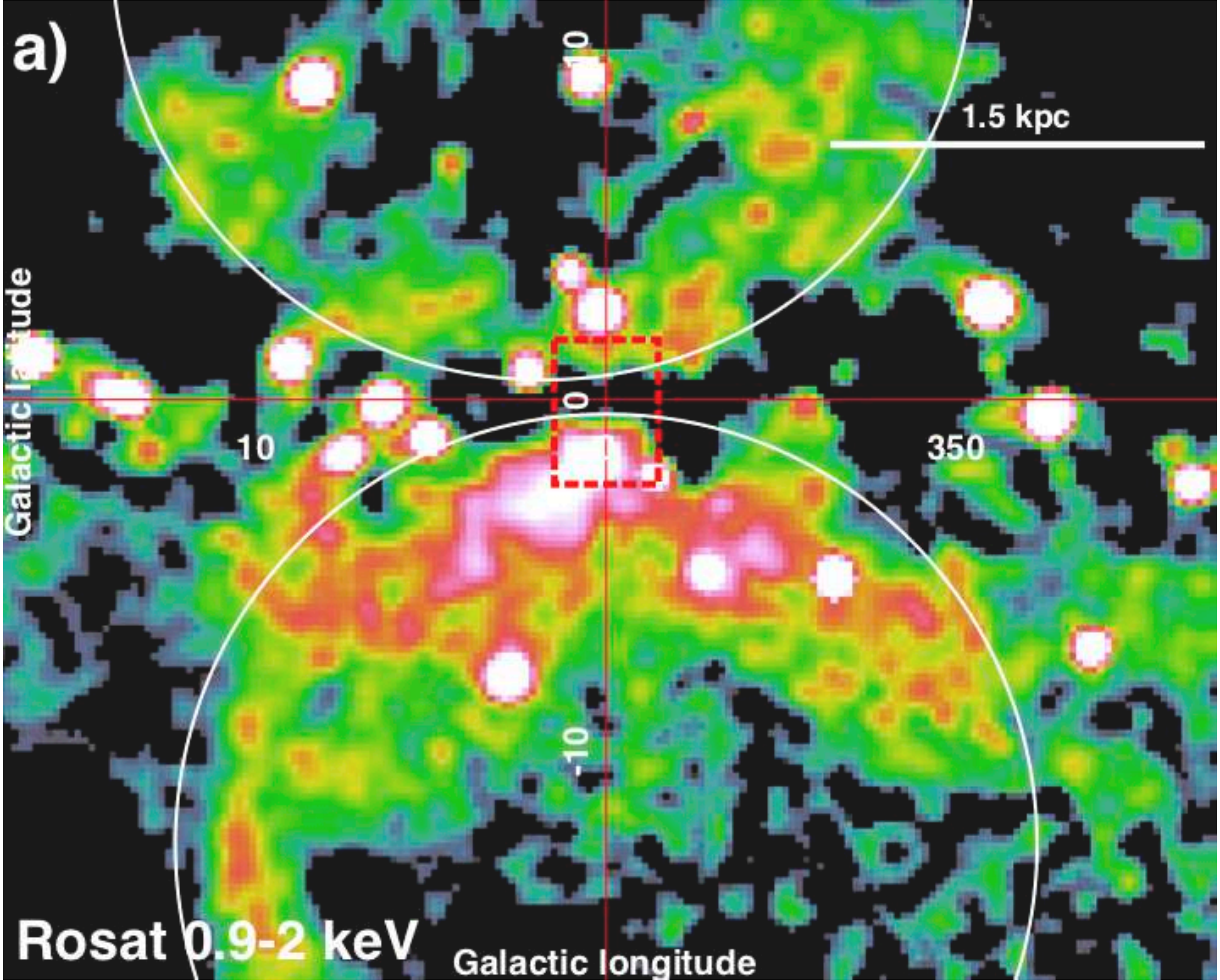
What we do not understand:

Projection effects?
Origin of protrusion?
Hot plasma has small pressure ➜ Relic outflow? Different driver?
(Cosmic rays? Alfven MHD waves? Fast&Cold outflow? Very hot plasma?)
AGN driven? Starburst?





a)
1.5 kpc
10
0
-10
10
350
Galactic latitude
Galactic longitude
Rosat 0.9-2 keV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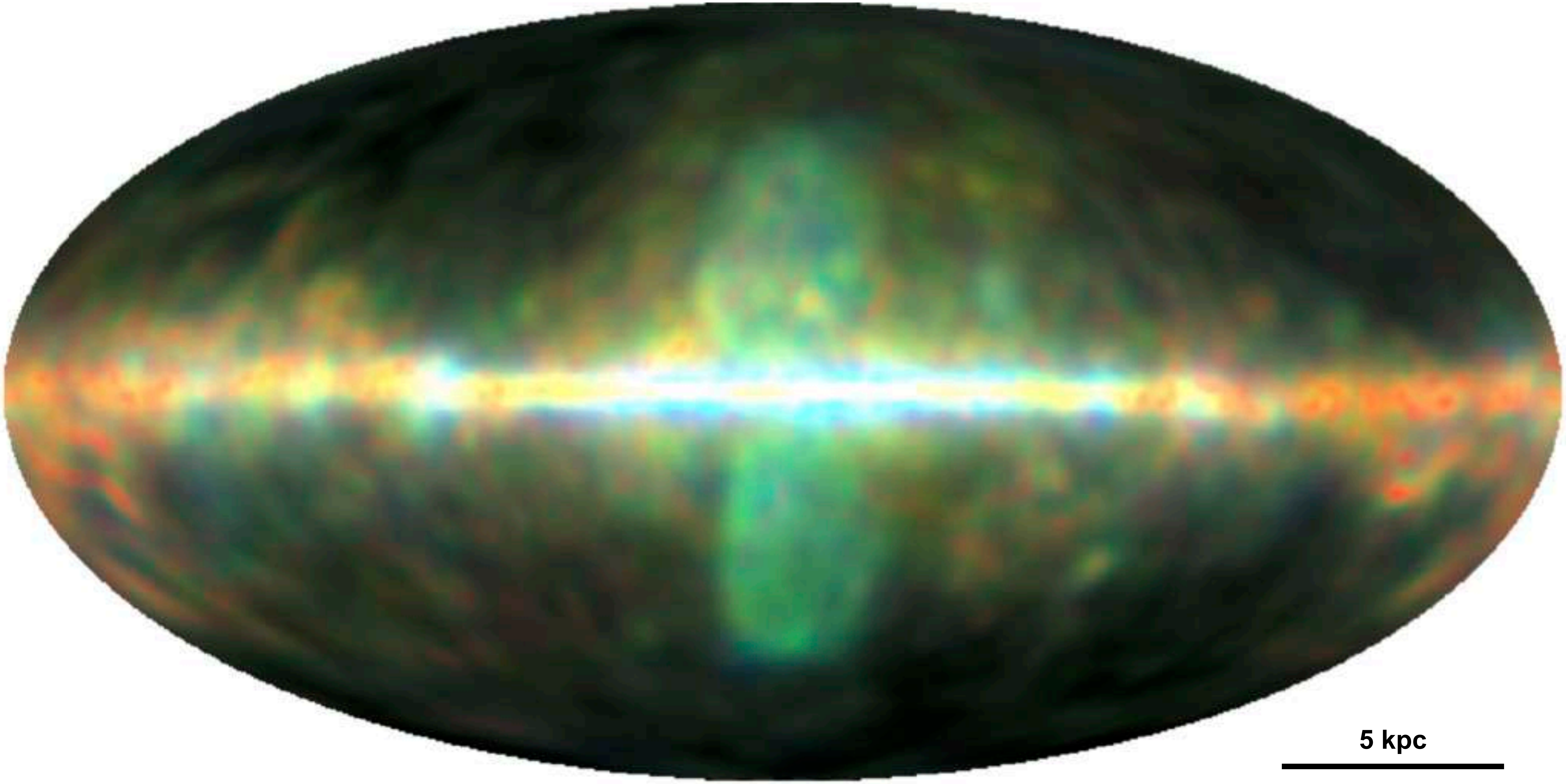
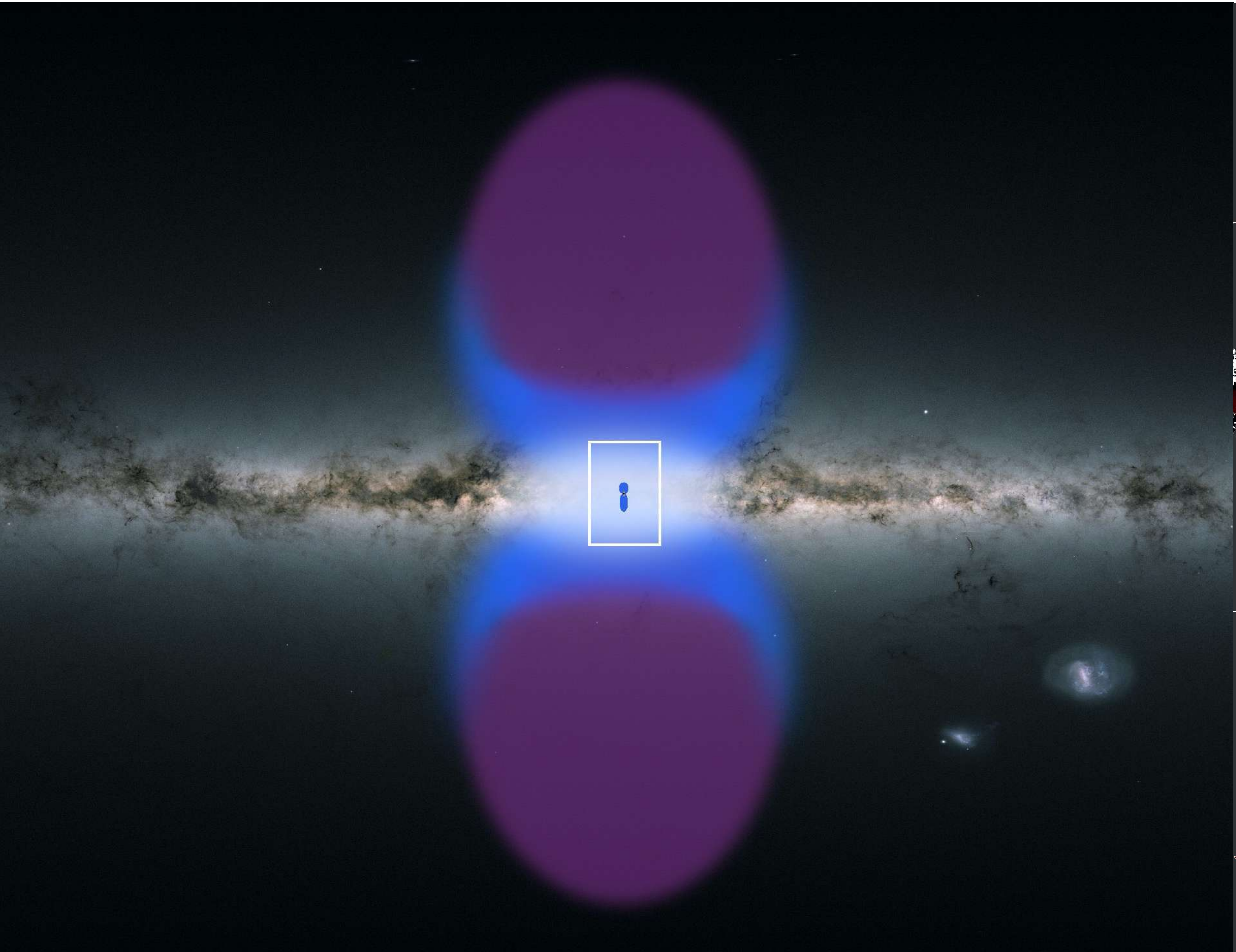
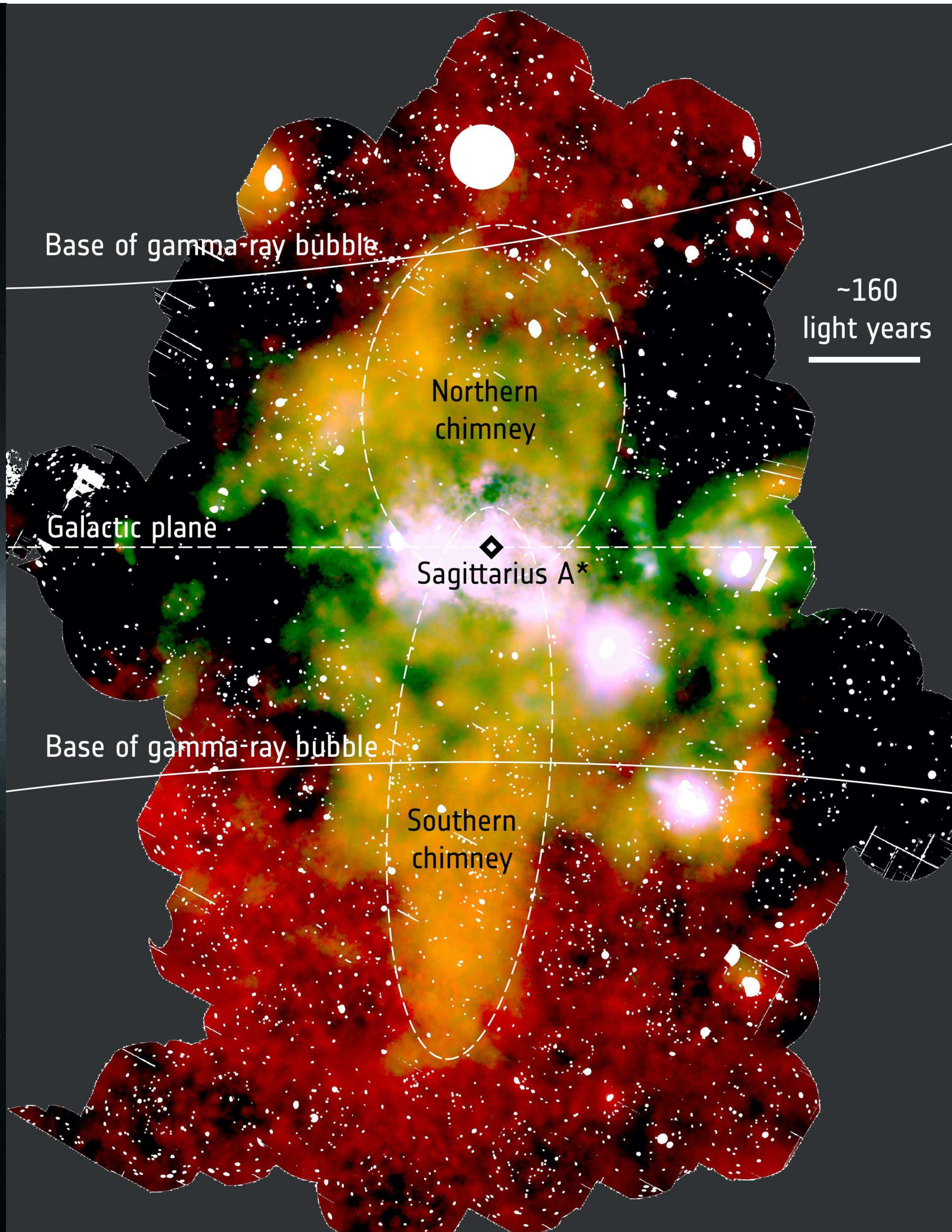


Fermi RGB image Selig +15

The channel feeding the Fermi bubbles



ESA News/XMM-Newton/G. Ponti et al. 2019, Nature



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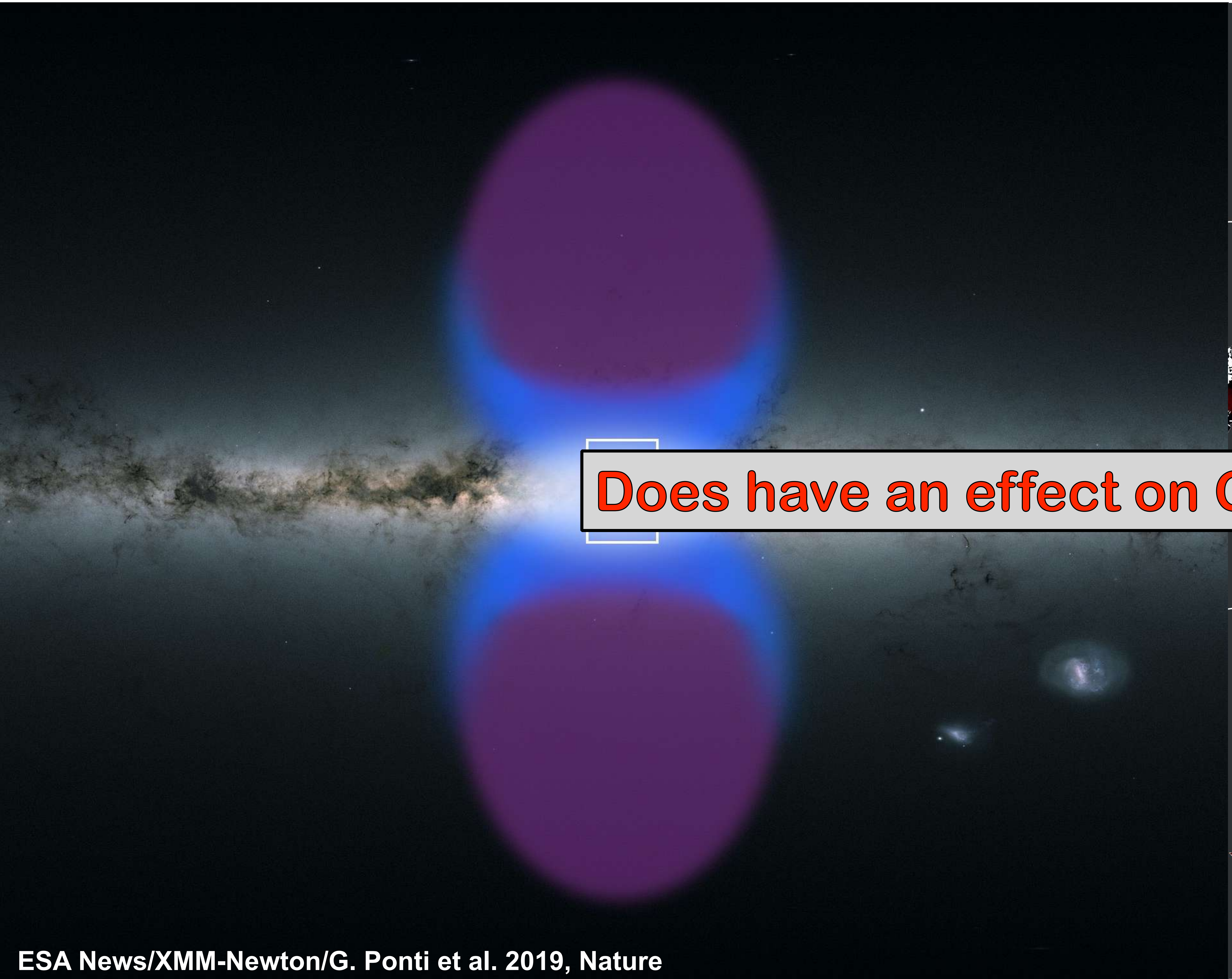

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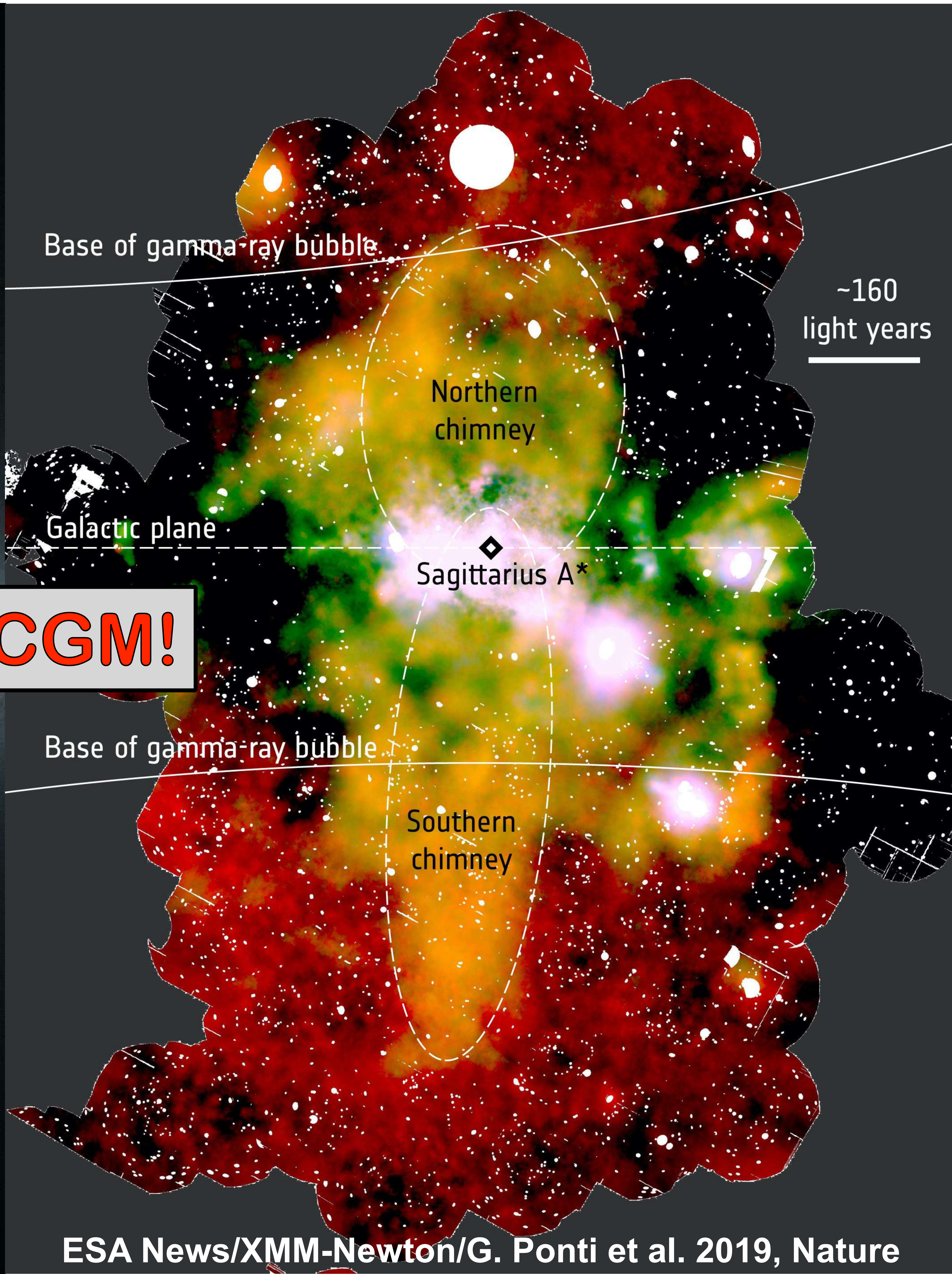

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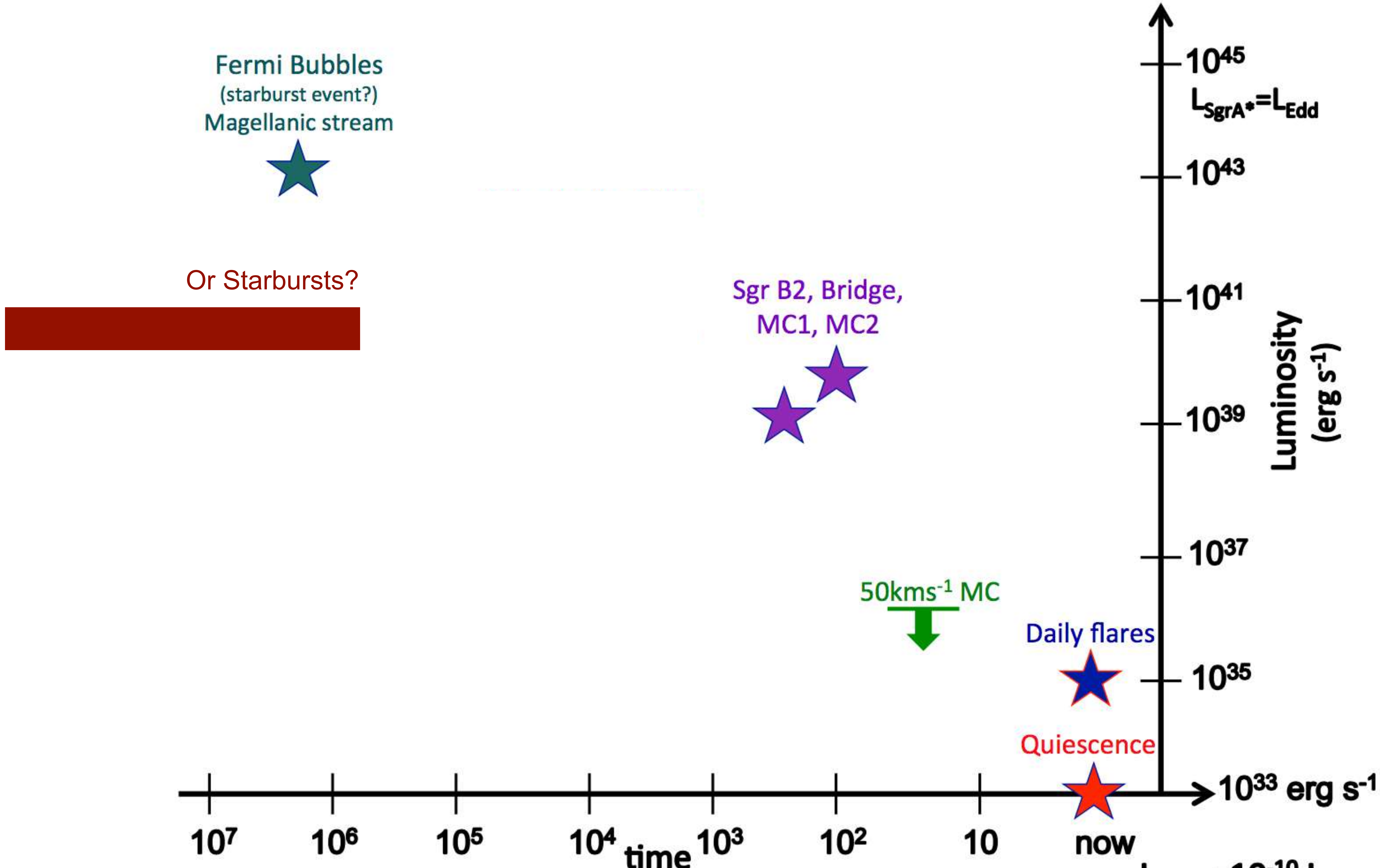
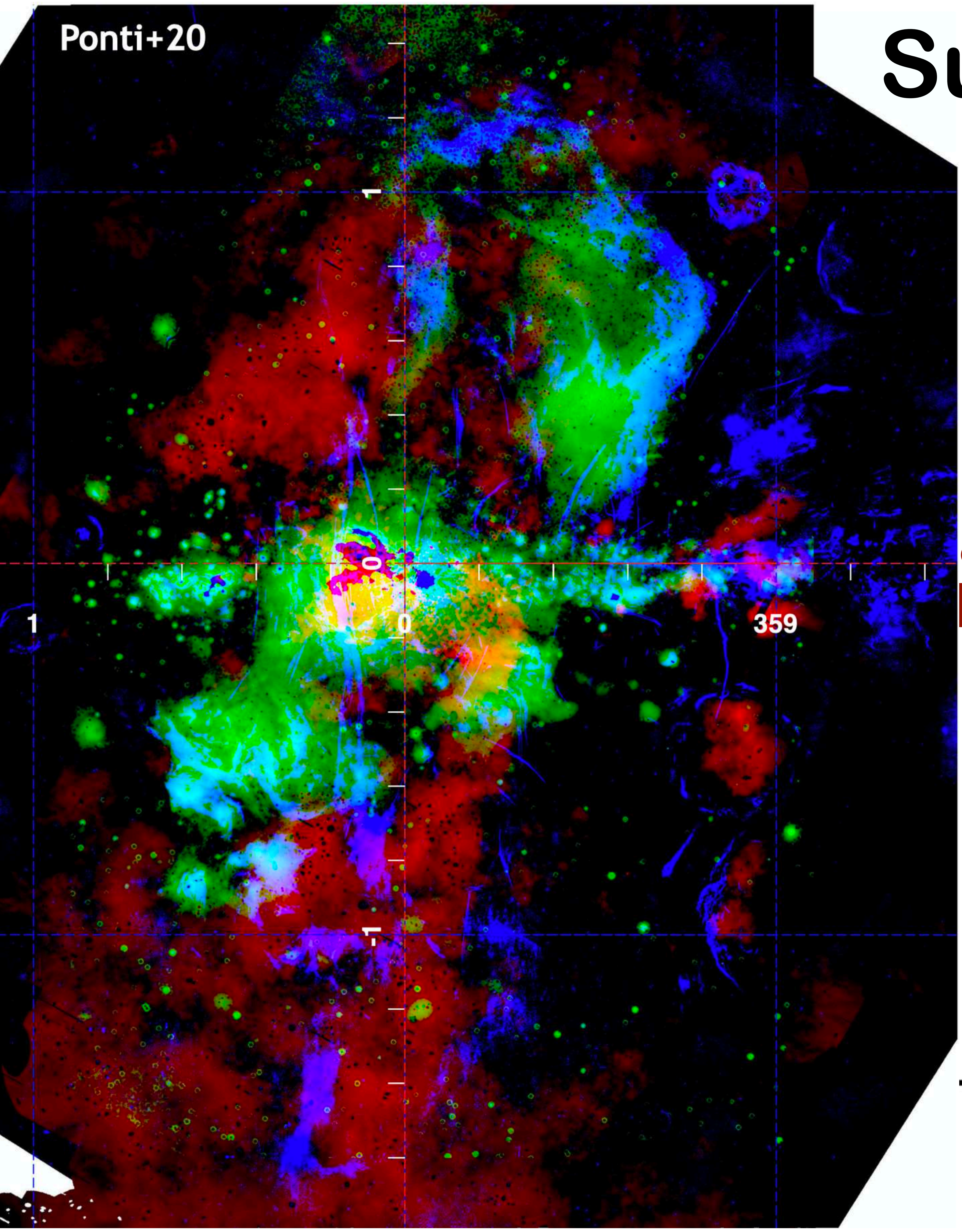
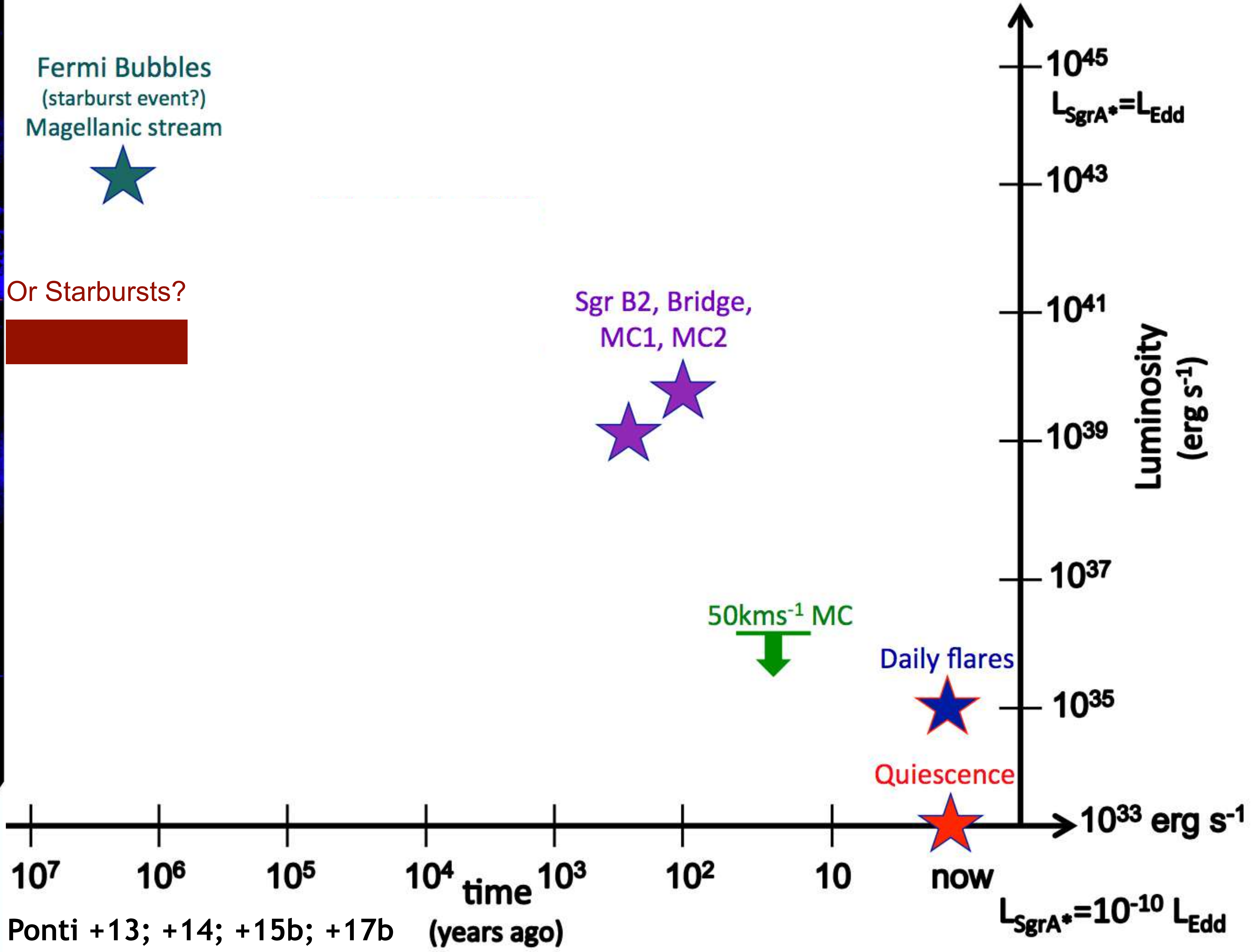
Summary



Ponti +13; +14; +15b; +17b

Summary





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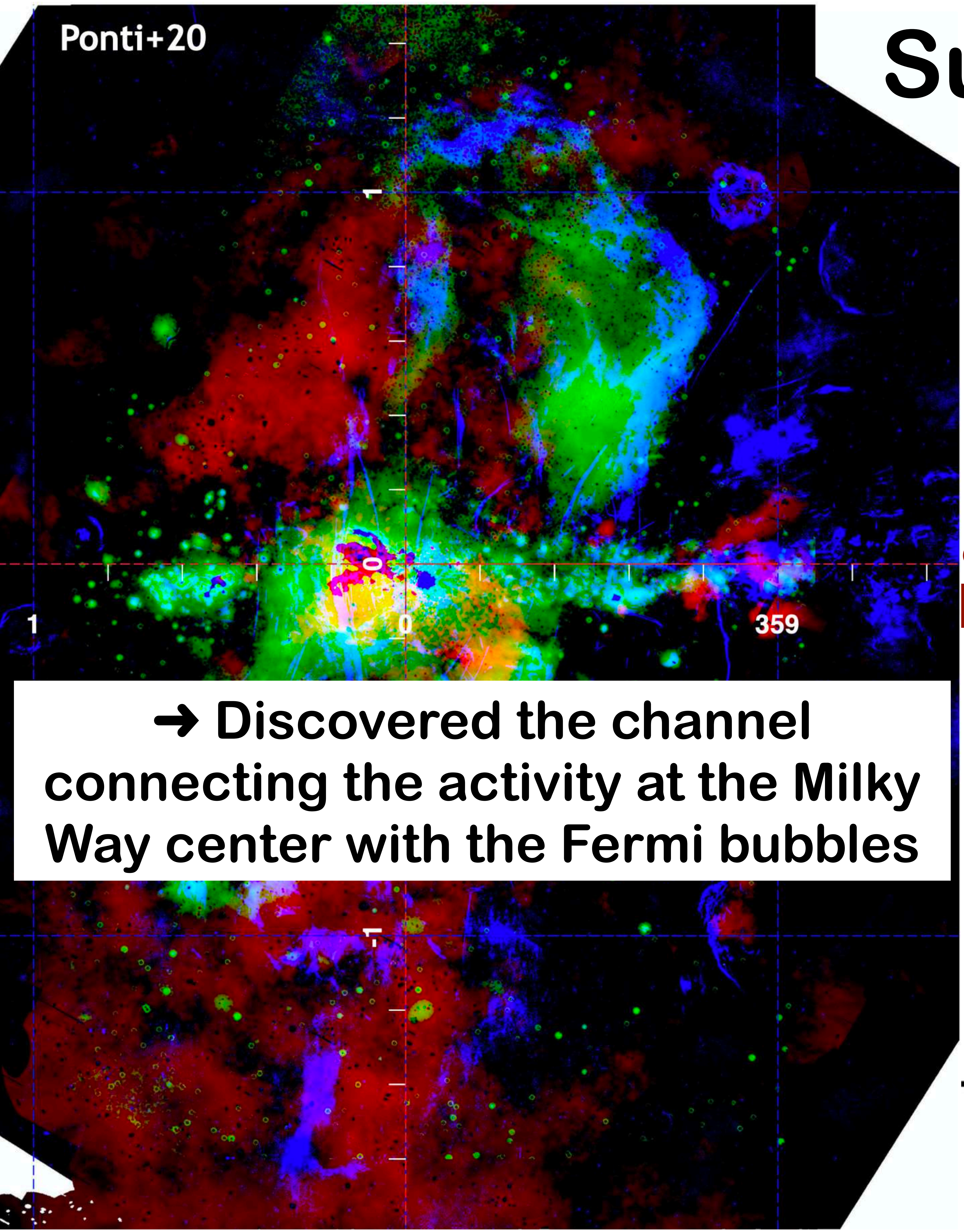
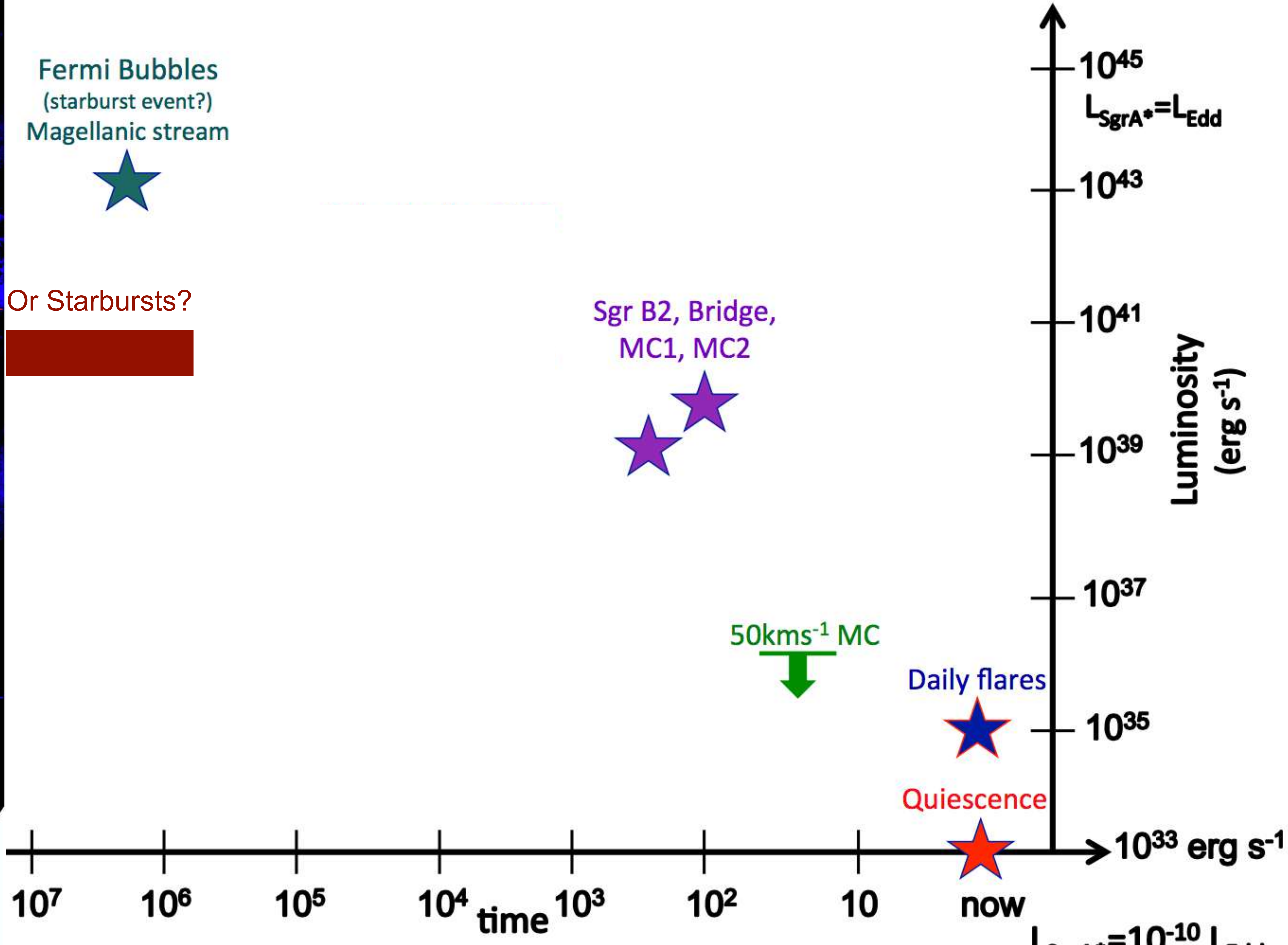


➜ Discovered the channel connecting the activity at the Milky Way center with the Fermi bubbles



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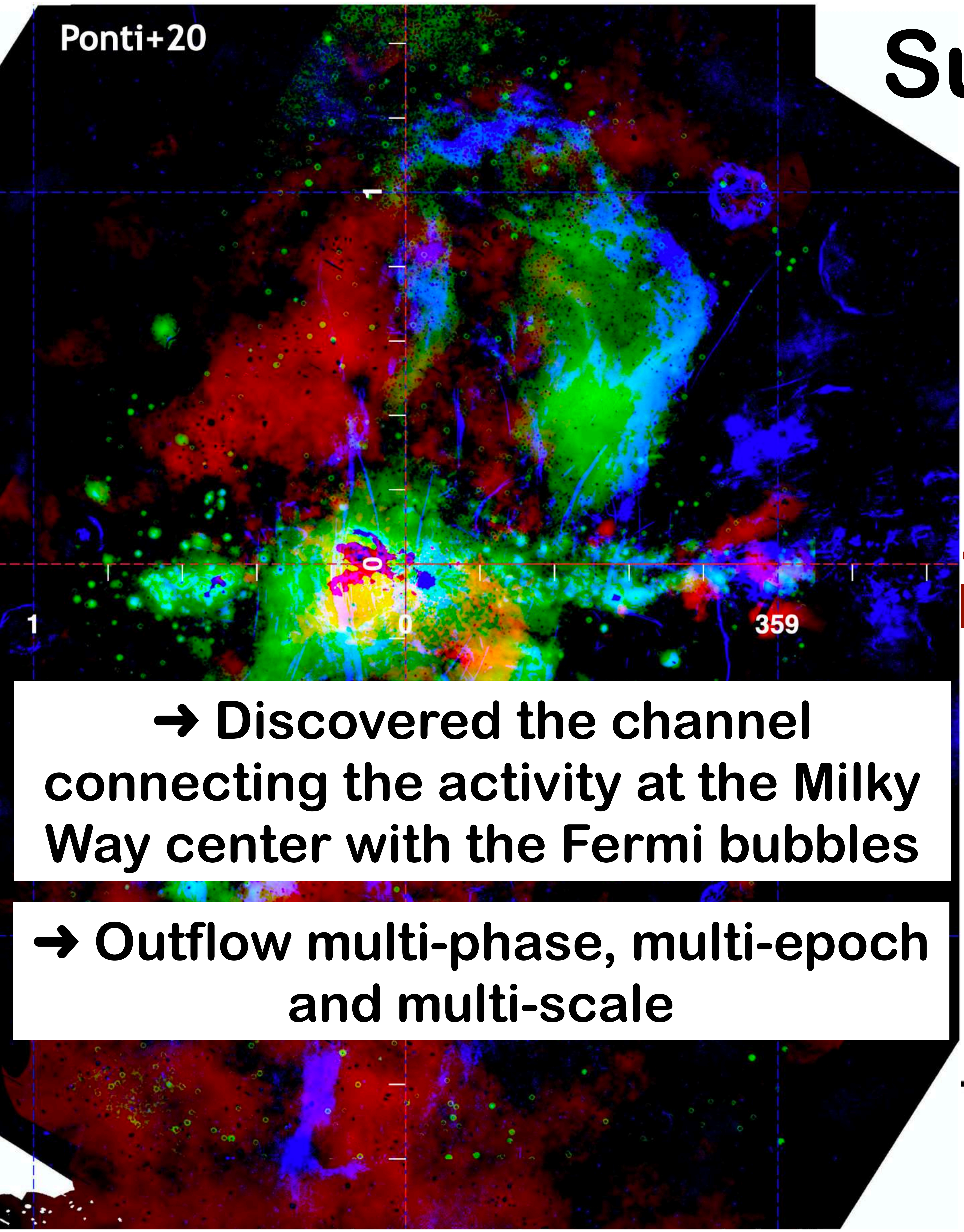

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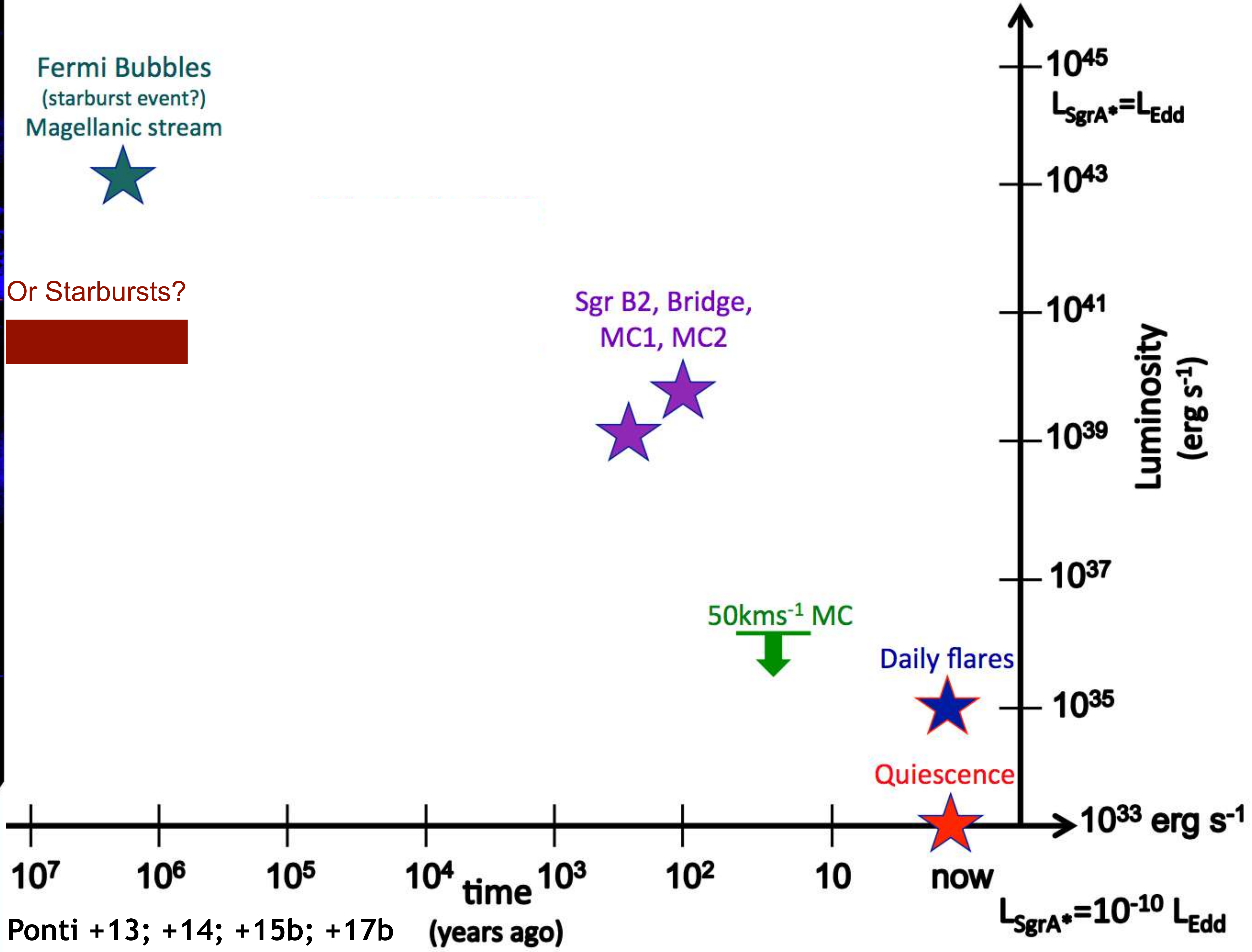

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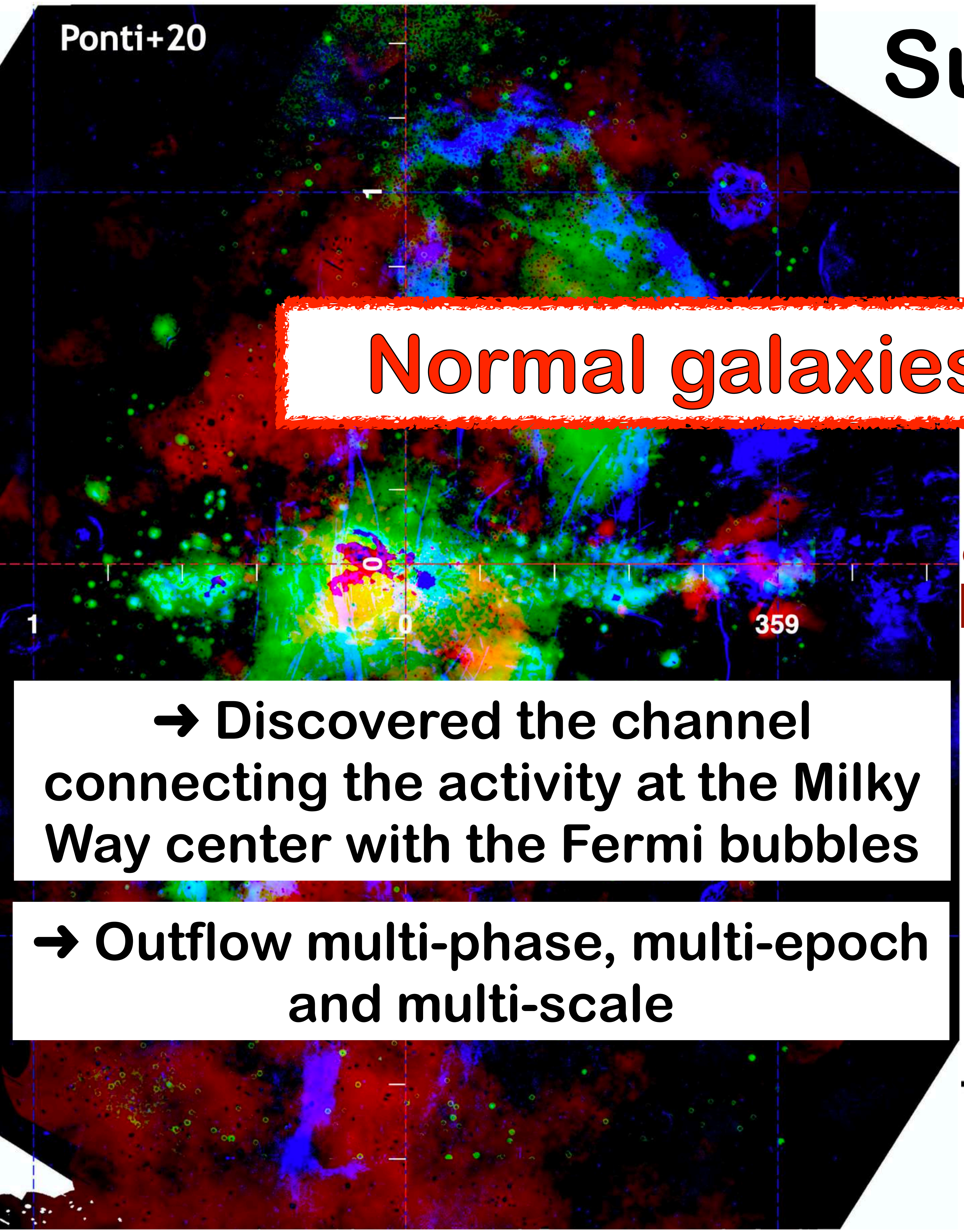

Normal galaxies hold outflows to CGM

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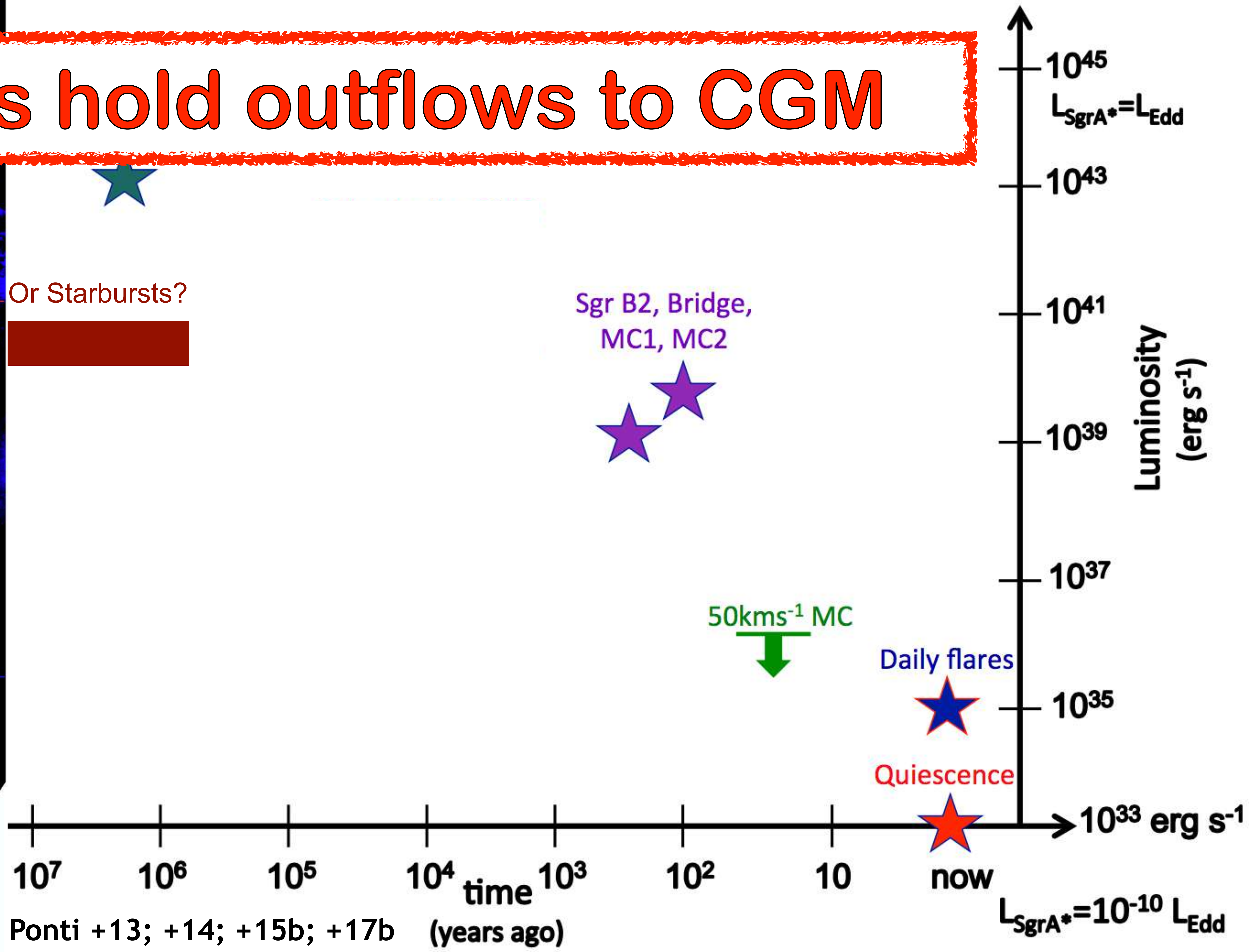

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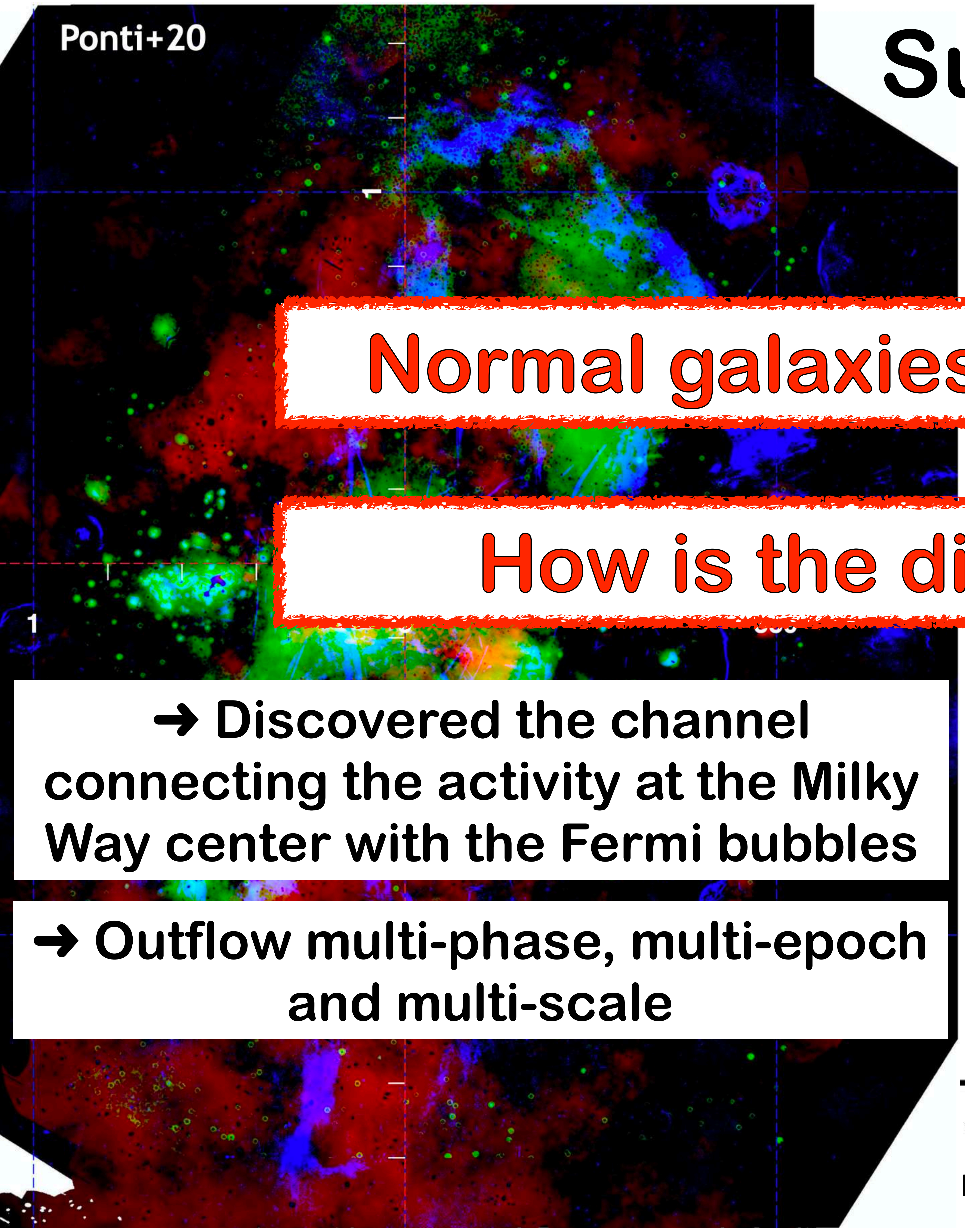

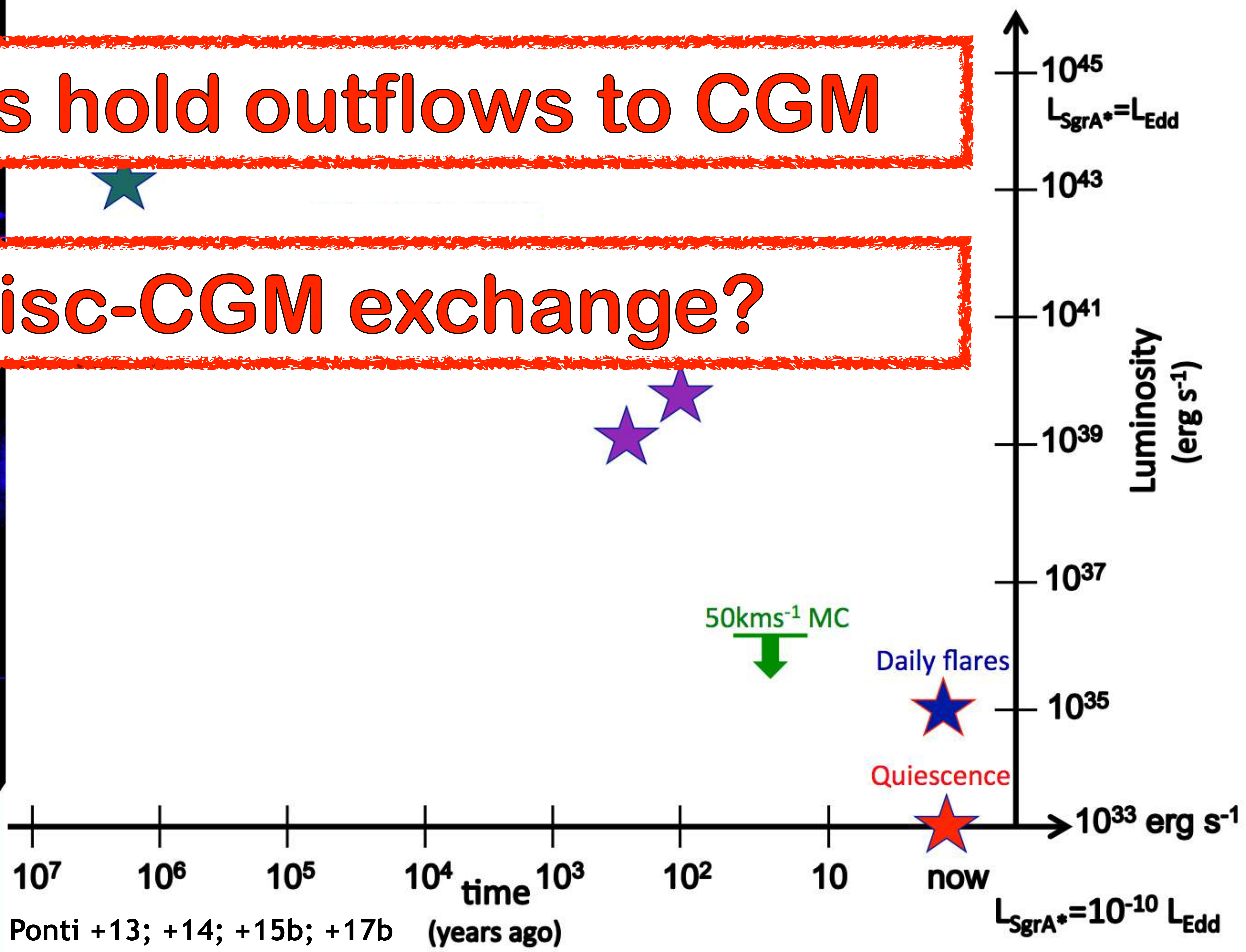

Normal galaxies hold outflows to CGM

How is the disc-CGM exchange?

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eROSITA (Spektr-RG)'s launch

Baikonur, July 13th, 2019

Source: Roscosmos

Map the flows of hot Galactic Baryons

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How is the disc-CGM exchange?

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European Research Council

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Discovery of the eROSITA bubbles!

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X-rays: eROSITA
γ-rays: Fermi

Discovery of the eROSITA bubbles!

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Discovery of the eROSITA bubbles!

Discovery of the eROSITA bubbles!

Discovery of the eROSITA bubbles!

North polar spur appears part of a bubble

➜ Origin at the Galactic center

Such bubble has a Southern counterpart

Energy = 10^{56} erg (Fermi × 10)

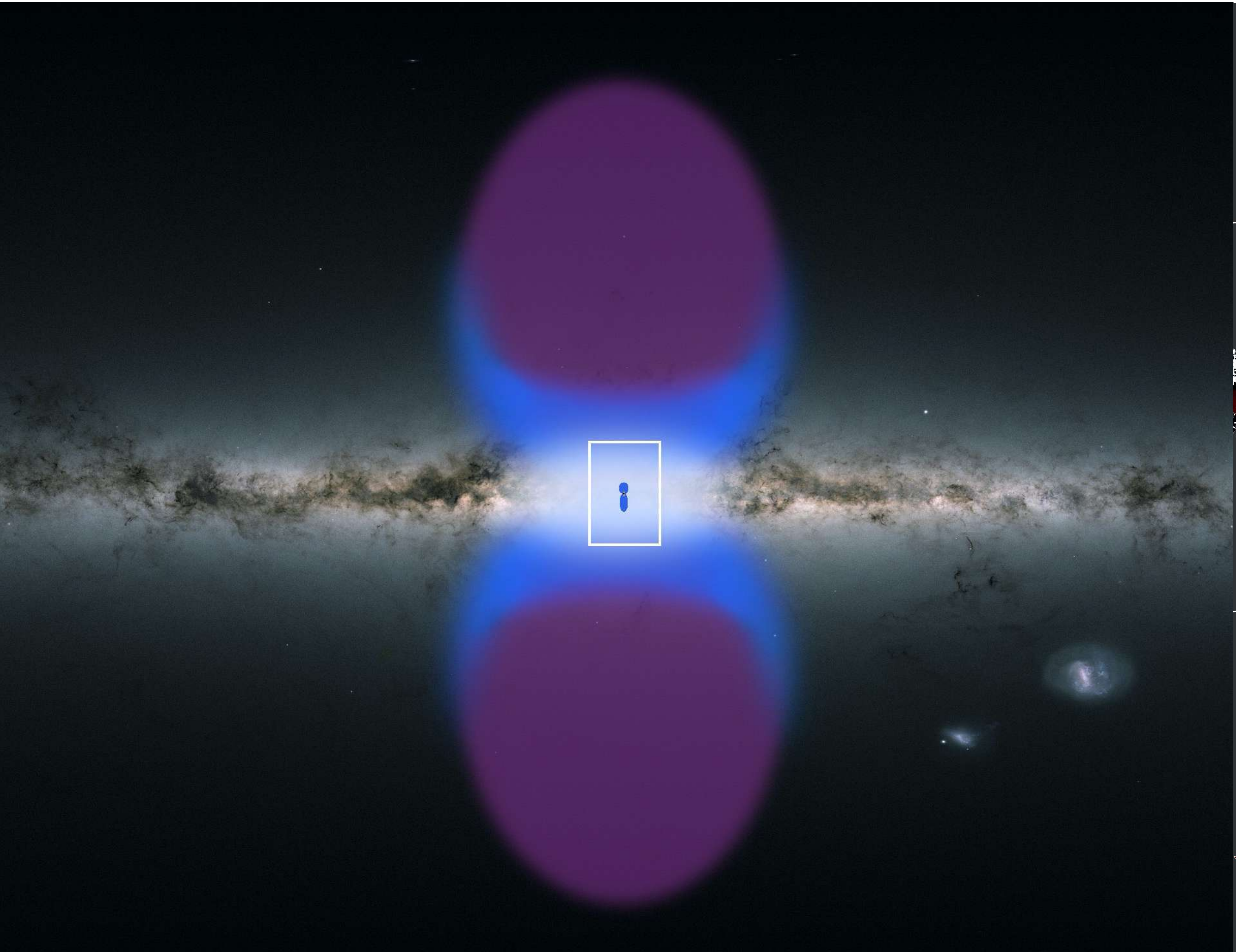
X-rays: eROSITA

γ-rays: Fermi

Discovery of the eROSITA bubbles!

X-rays: eROSITA
γ-rays: Fermi

Chimneys: The base of the Galactic outflow



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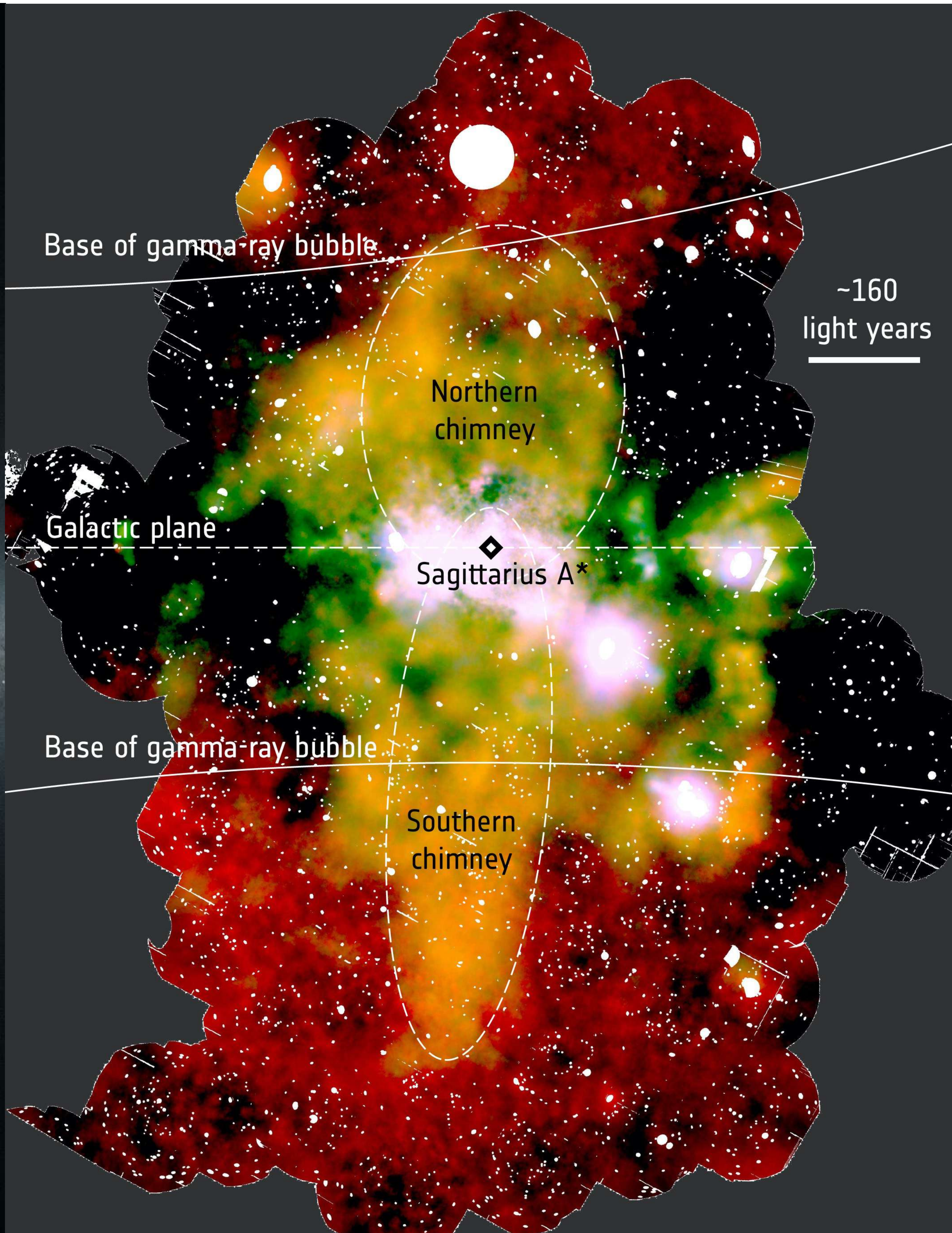

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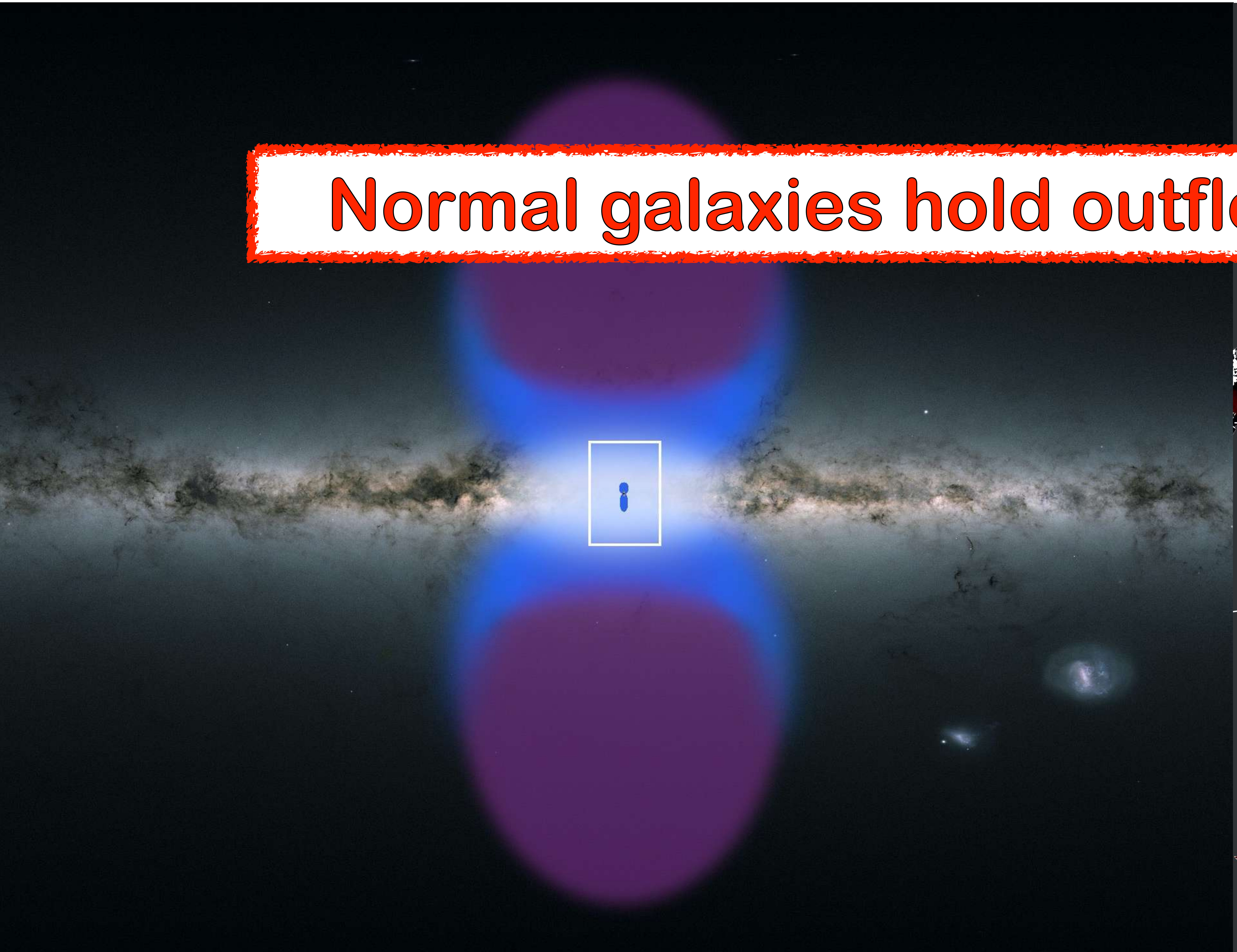

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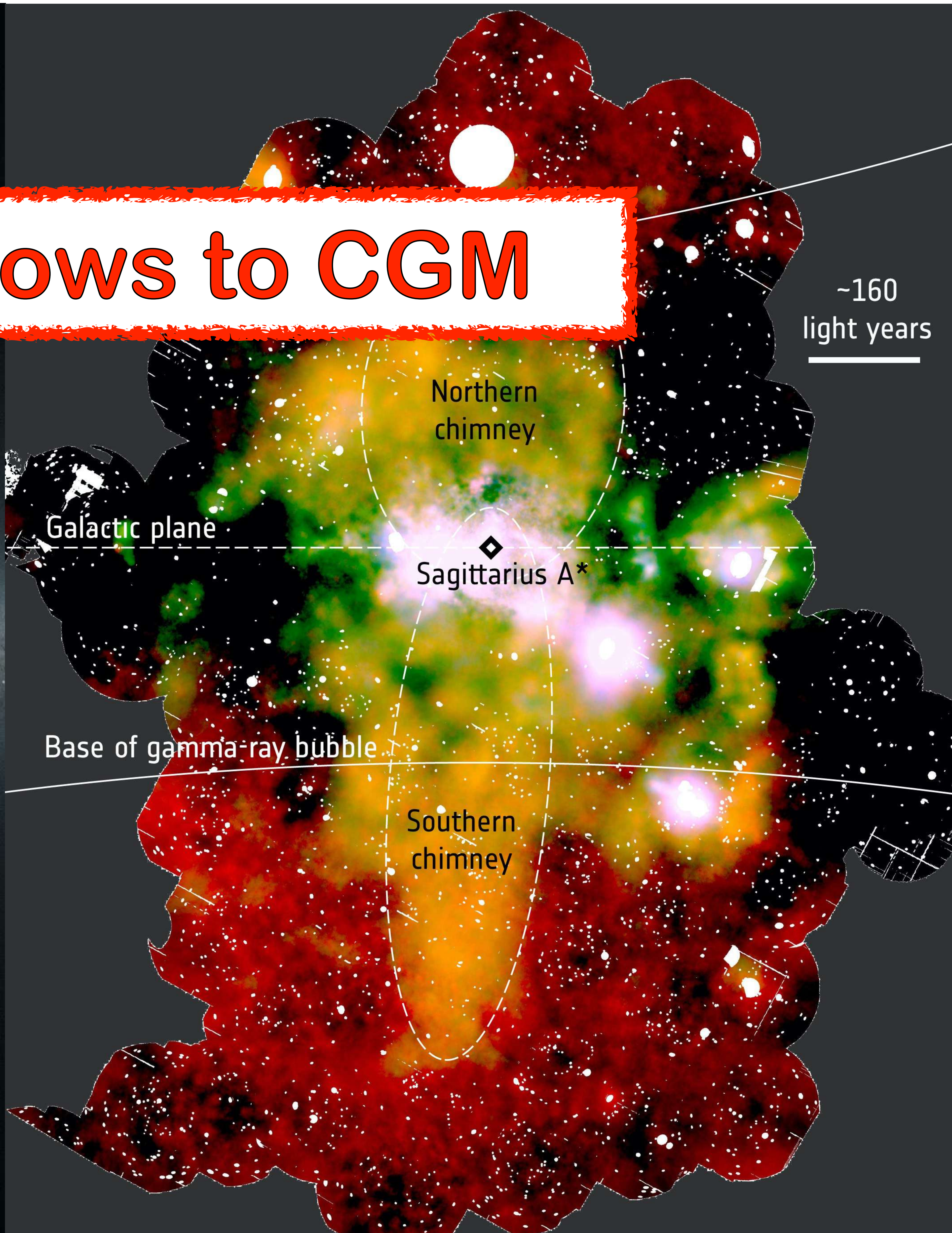
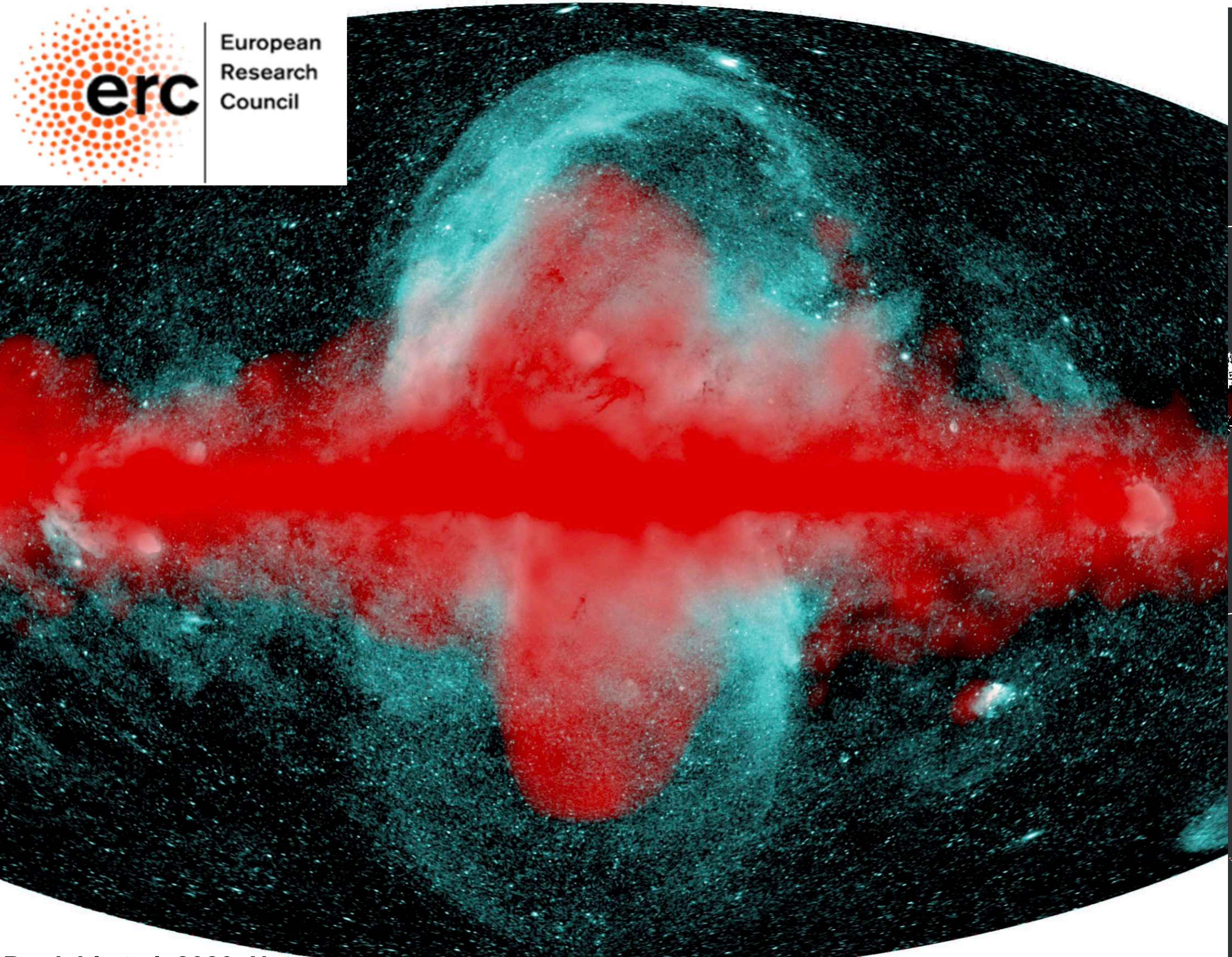


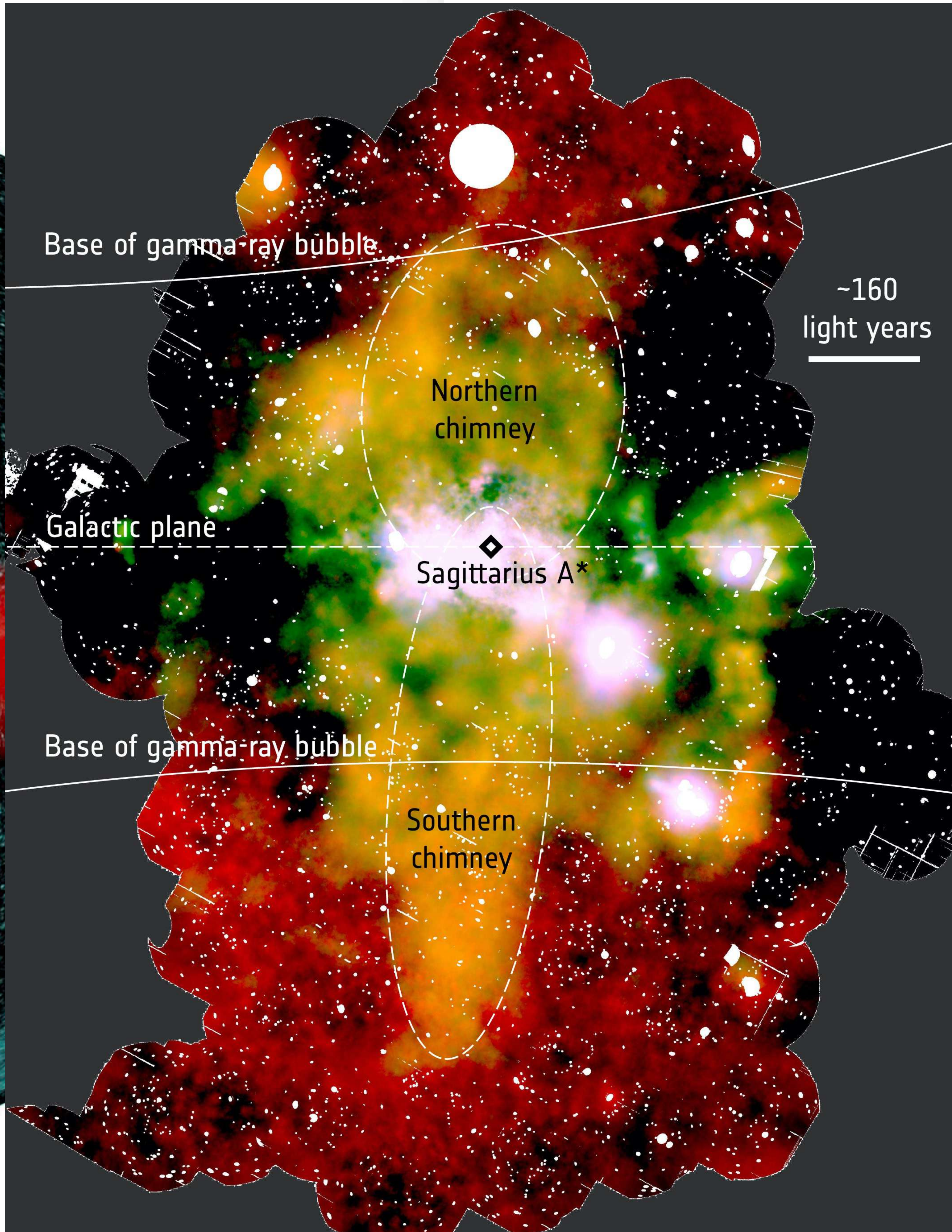
ESA News/XMM-Newton/G. Ponti et al. 2019, Nature

eROSITA has the power to constrain the CGM

European Research Council



Predehl et al. 2020, Nature



ESA News/XMM-Newton/G. Ponti et al. 2019, Nature

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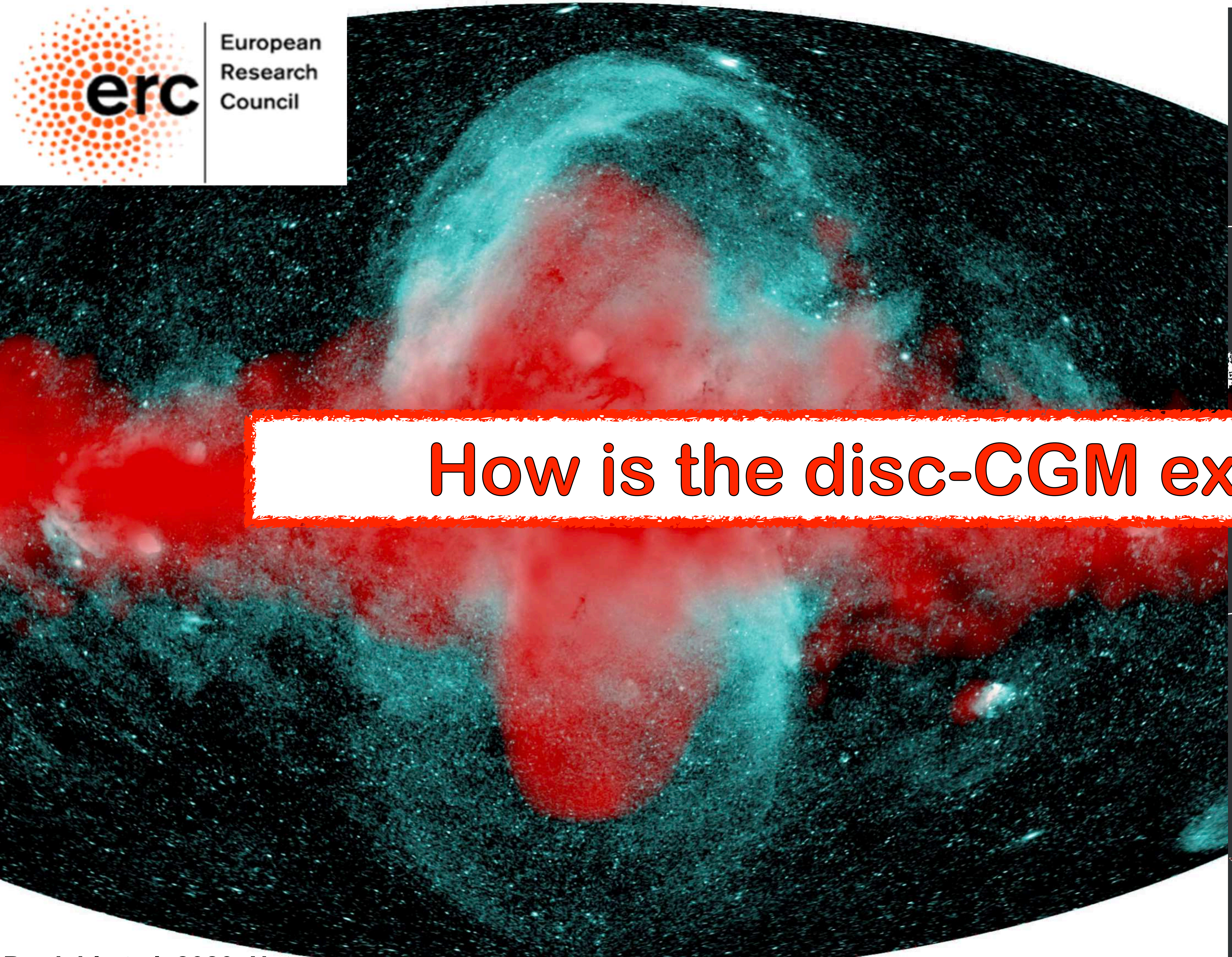
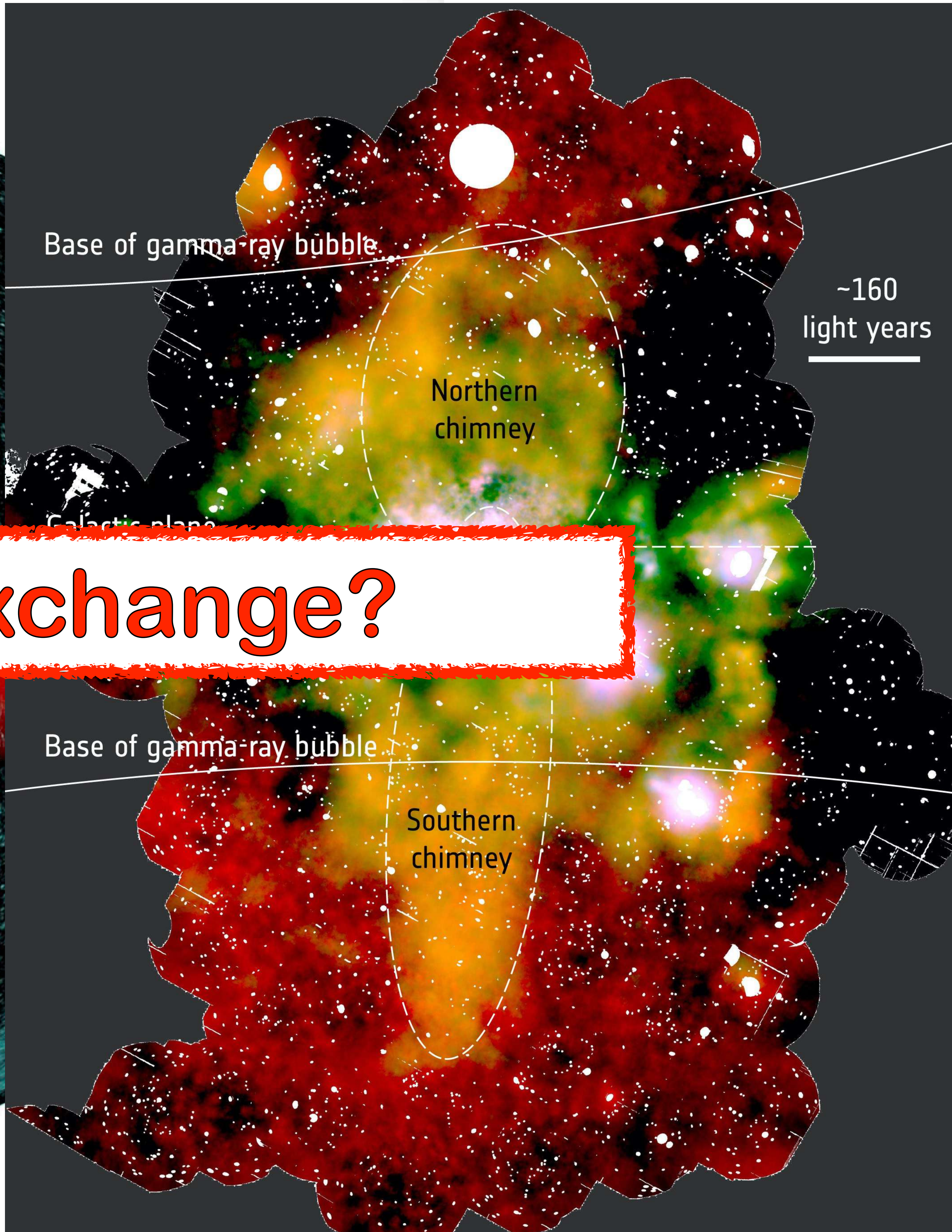


Predehl et al. 2020, Nature



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How is the disc-CGM exchange?