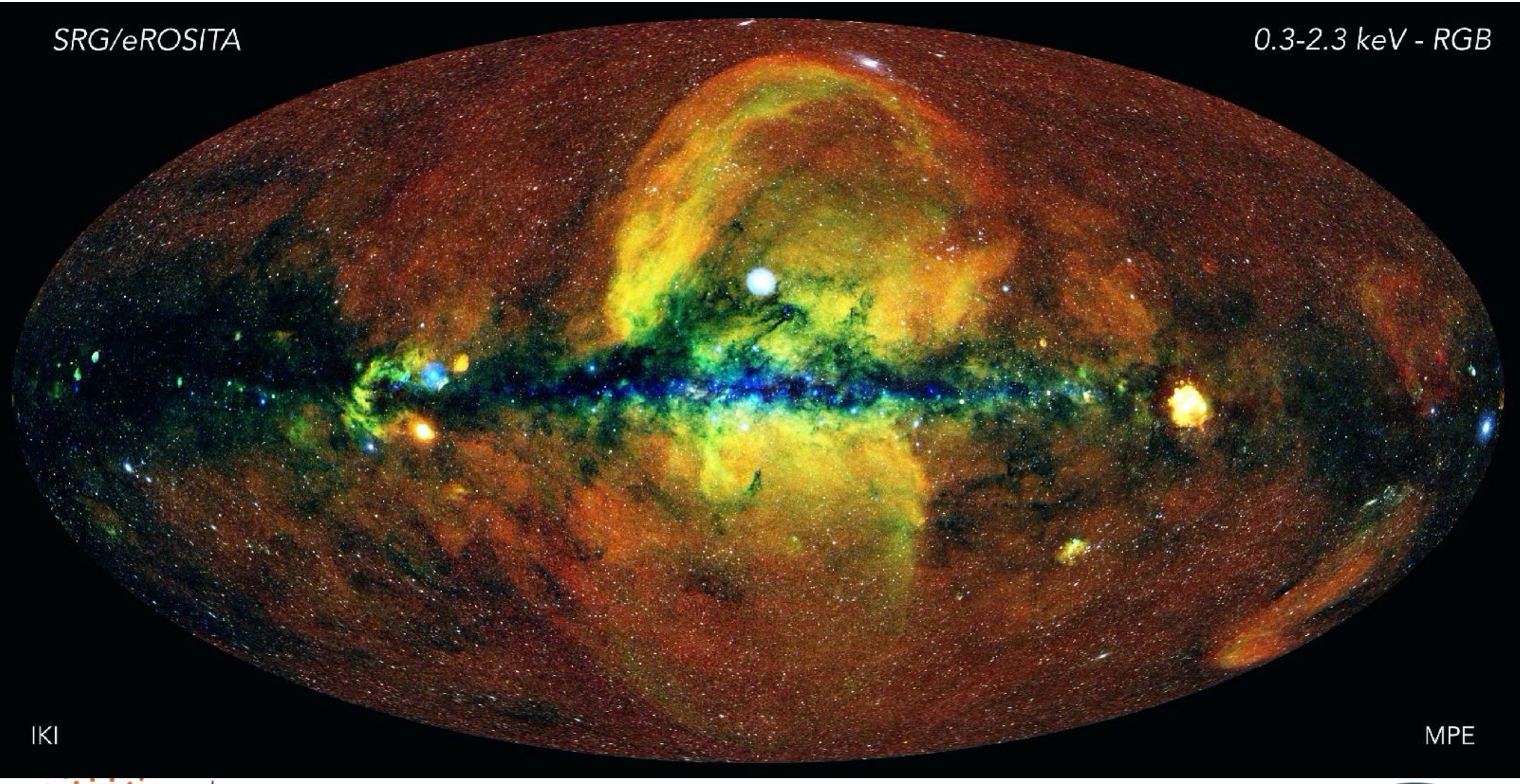
Present and past activity at the Galactic center



European Research Council

Gabriele Ponti

INAF OA Brera - MPE

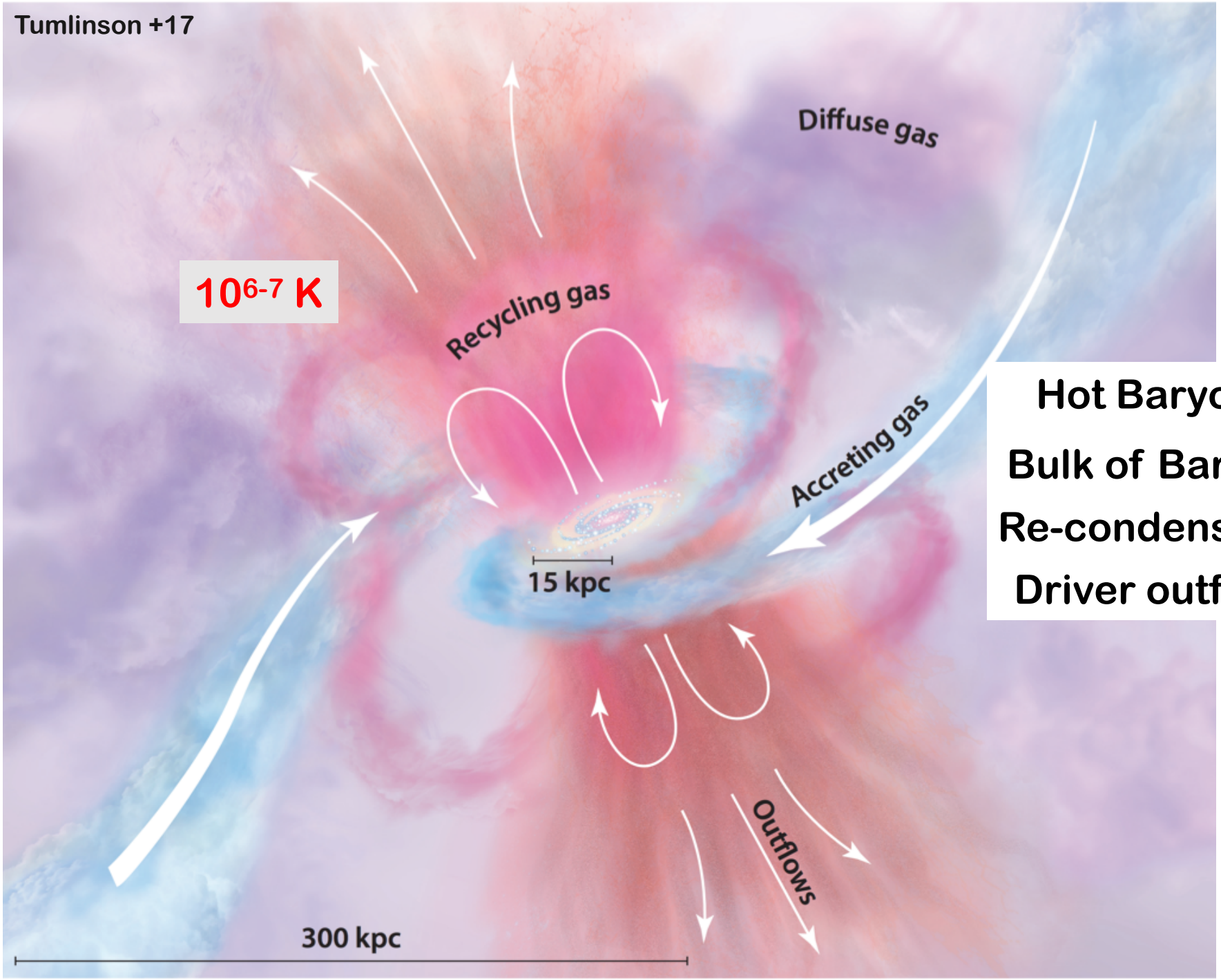
OSSERVATORIO ASTRONOMICO DI BRERA

eROSITA

How do galaxies evolve?

NGC 7331 Hubble

The Baryon cycle



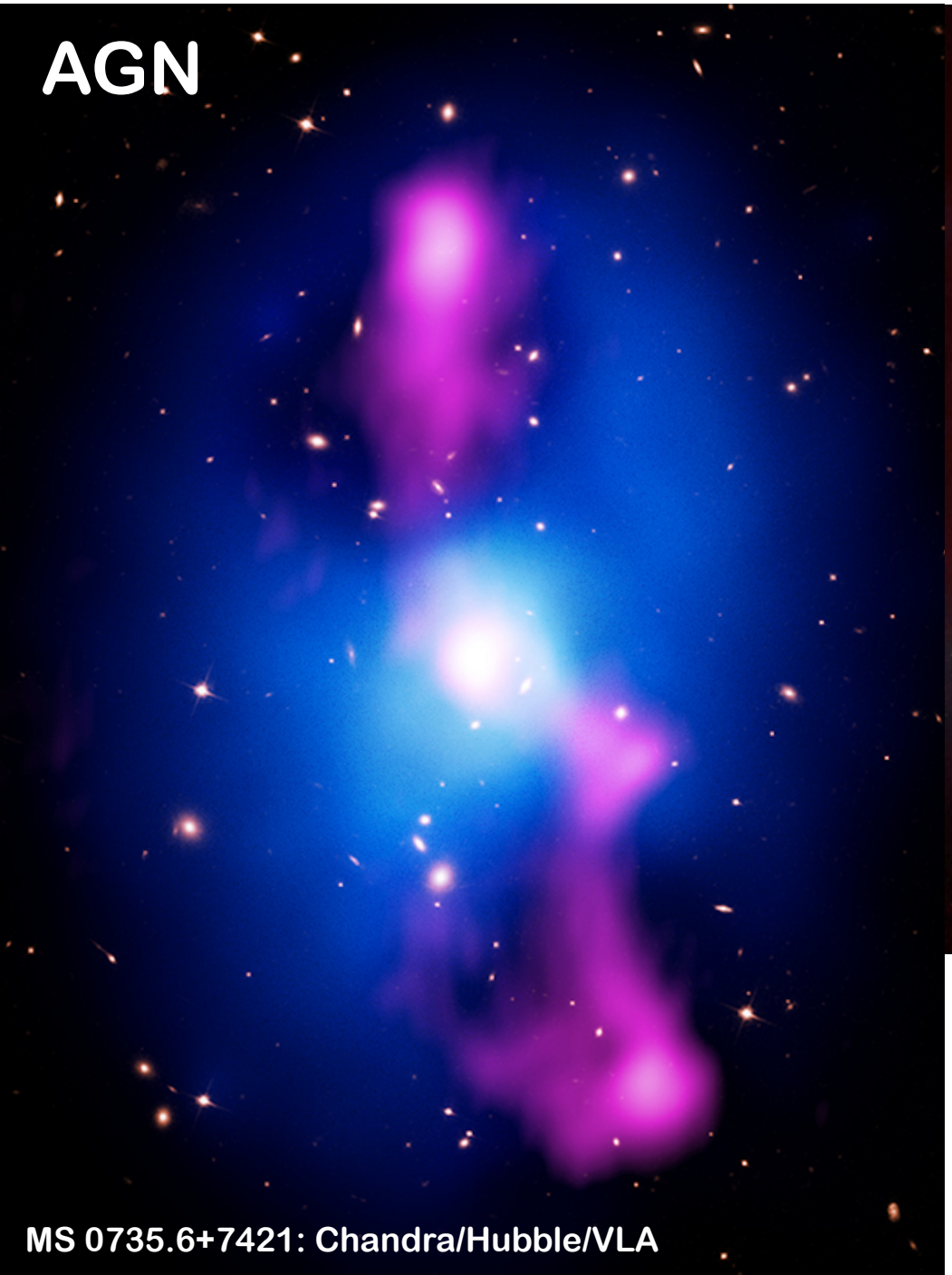
Hot Baryons:

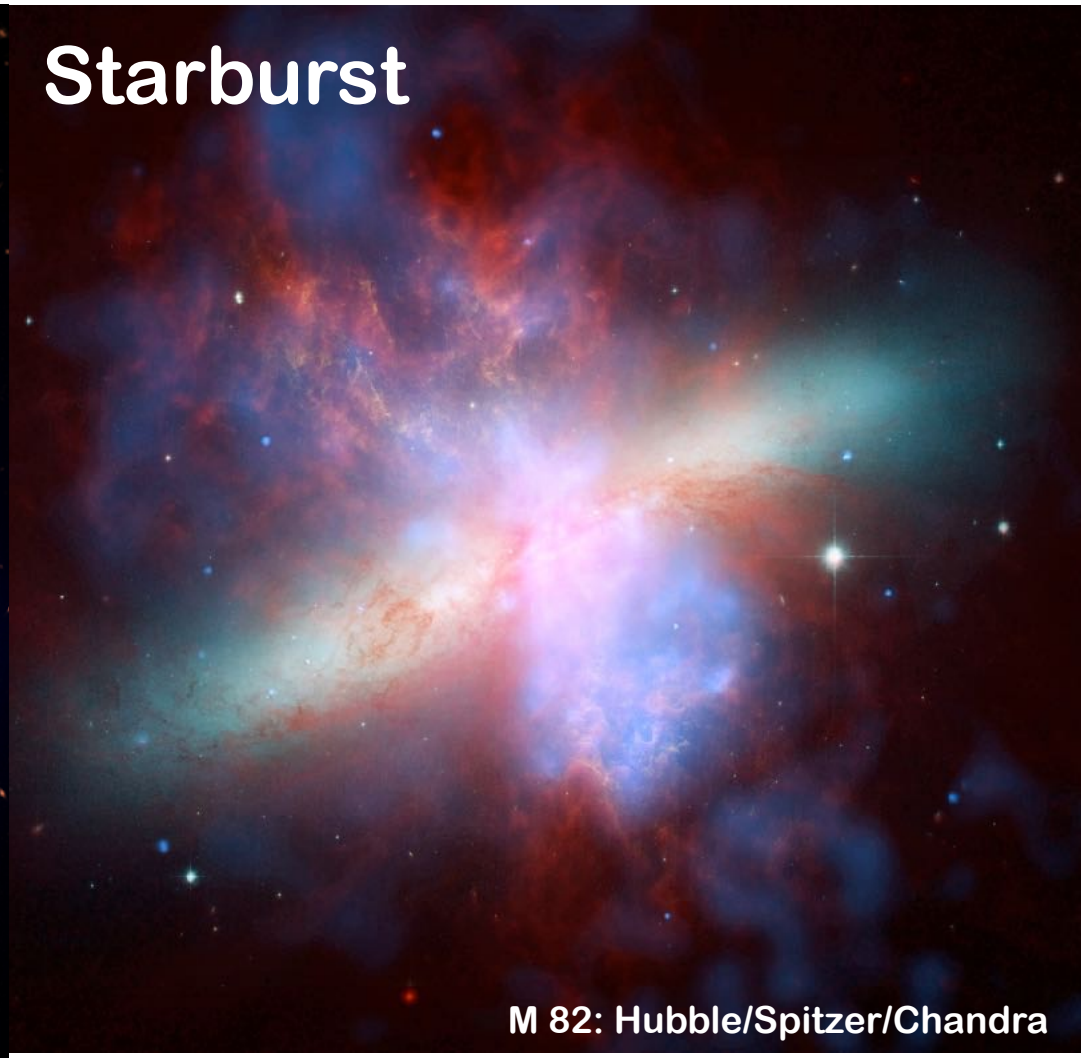
Bulk of Baryons

Re-condensation

Driver outflows

AGN - Starbursts influence CGM

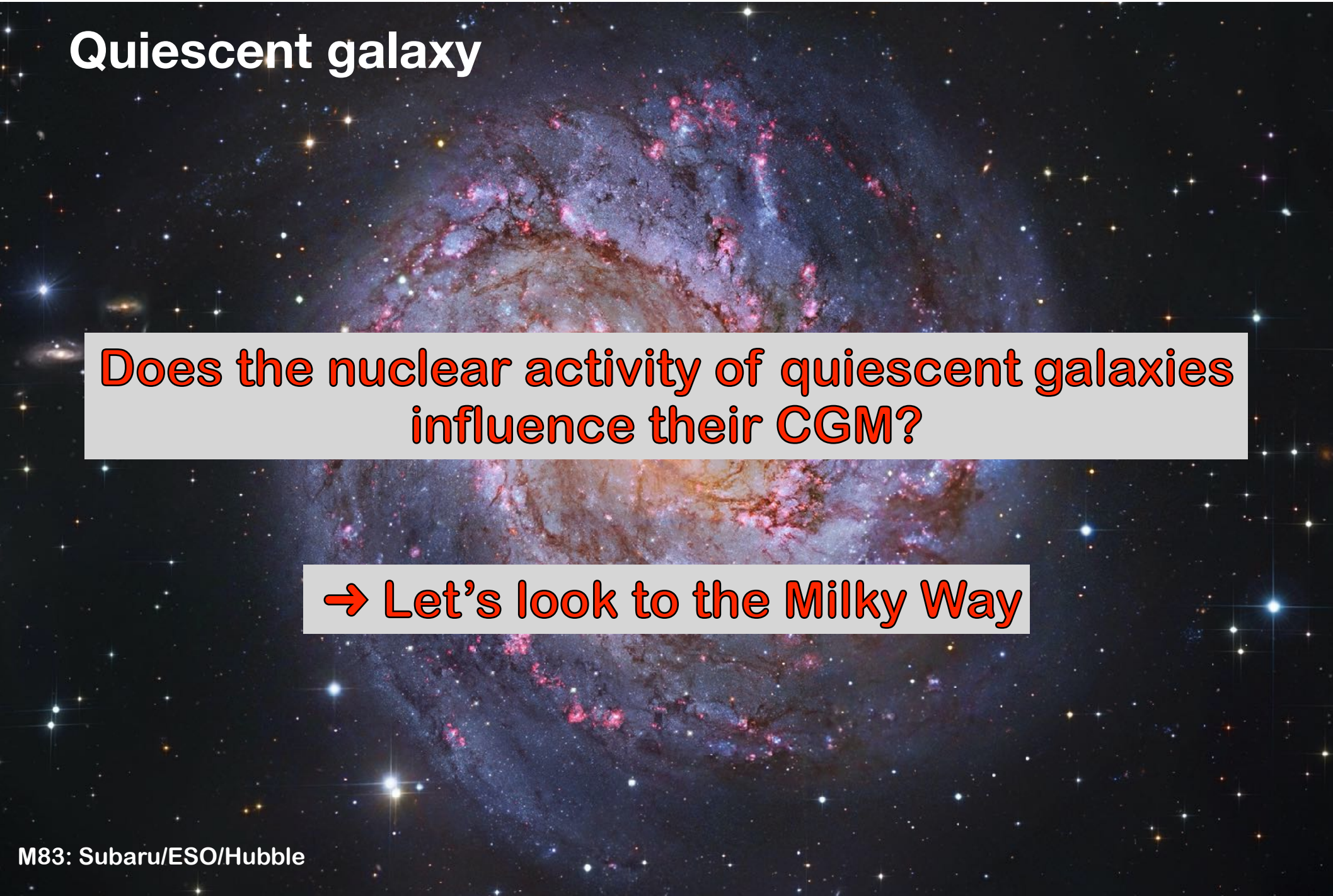




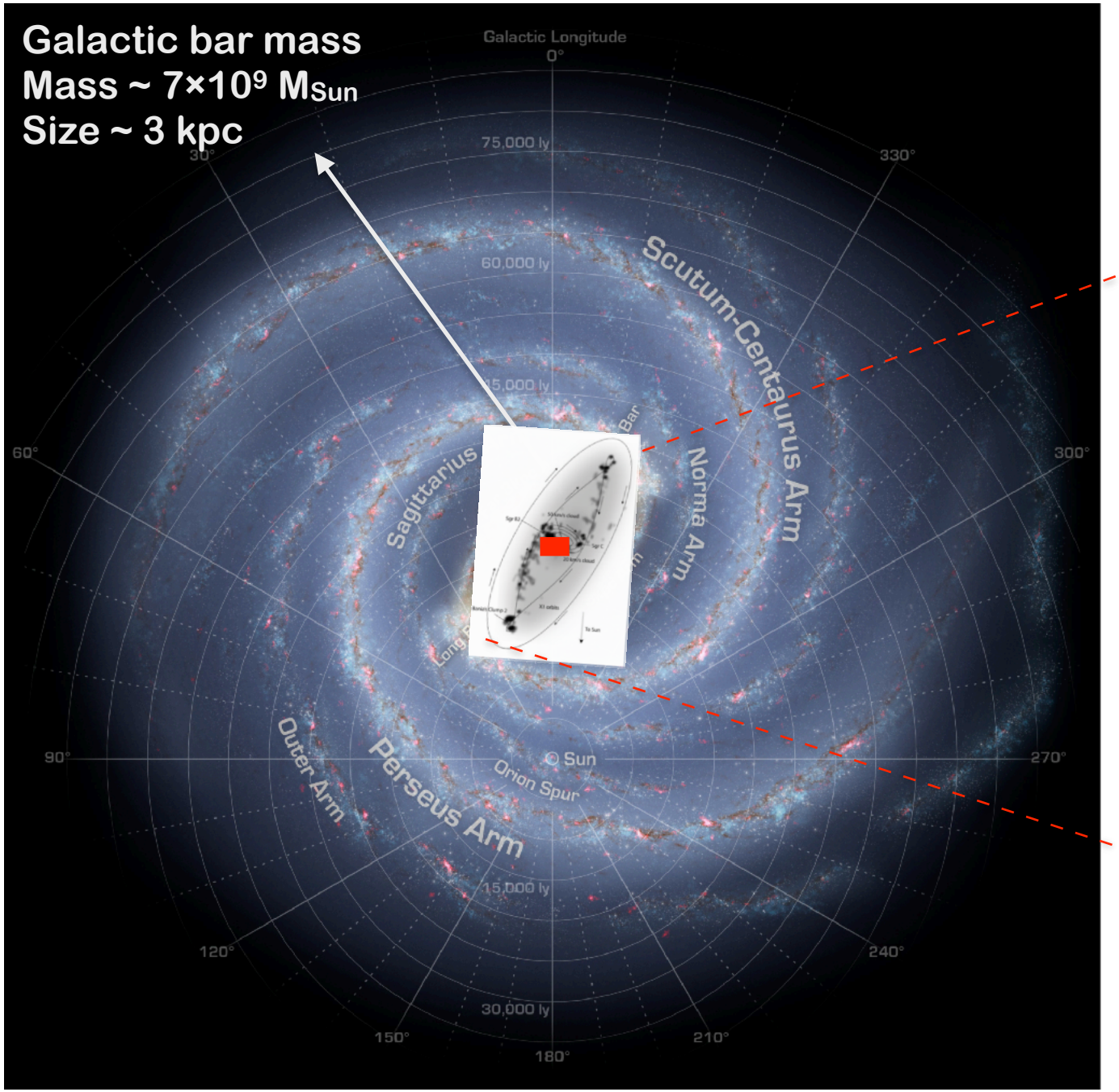
Outstanding progress

➜ Understand feedback between nuclear activity and CGM

Do galaxies influence their CGM?



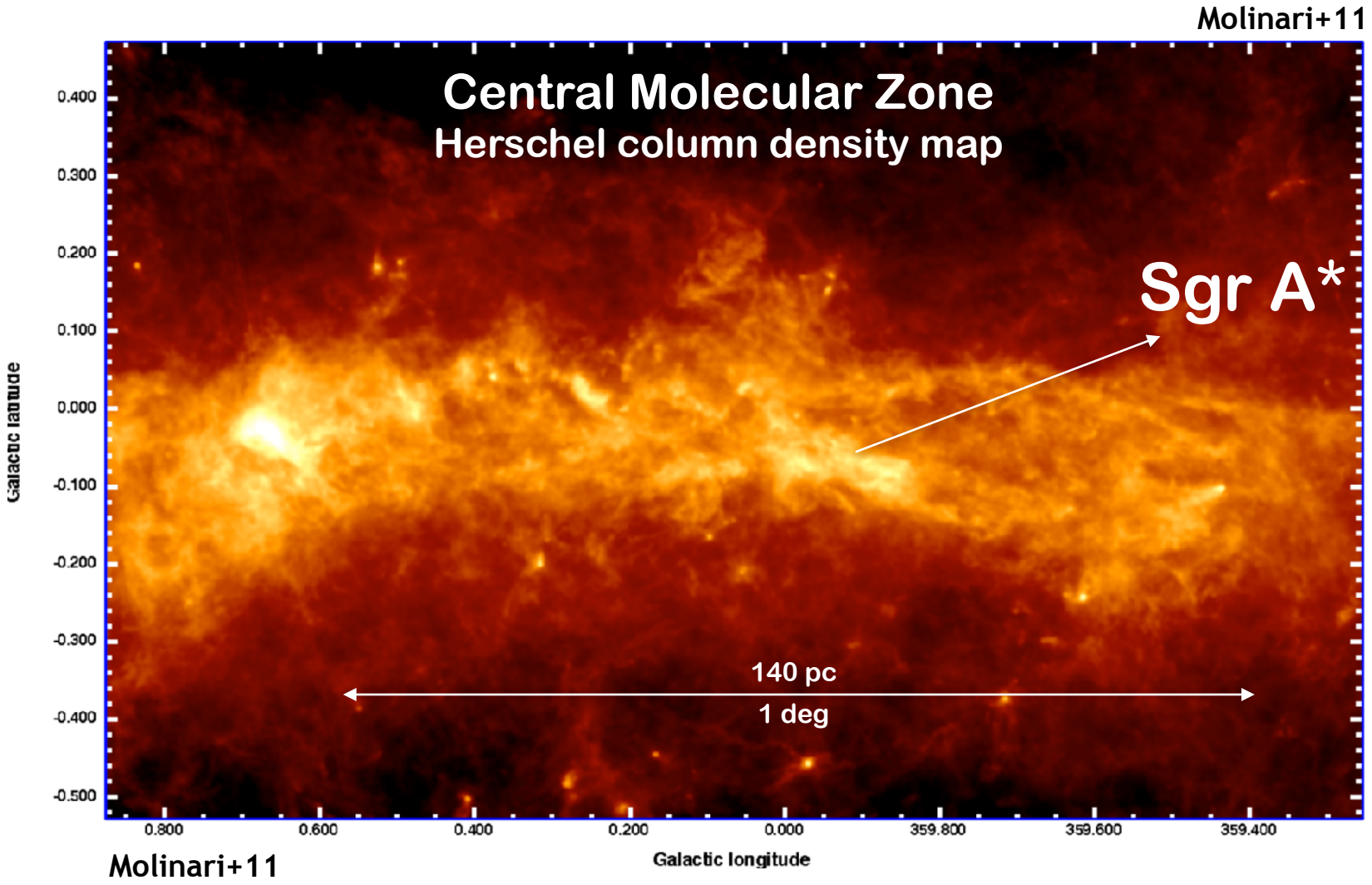
The structure of the Milky Way



From Spitzer/GLIMPSE data Churchwell +09

Binney +91; Bally +10; Ridley +17

The central degrees of the Milky Way



Abundant gas reservoir ~3×10^7 M_{Sun}

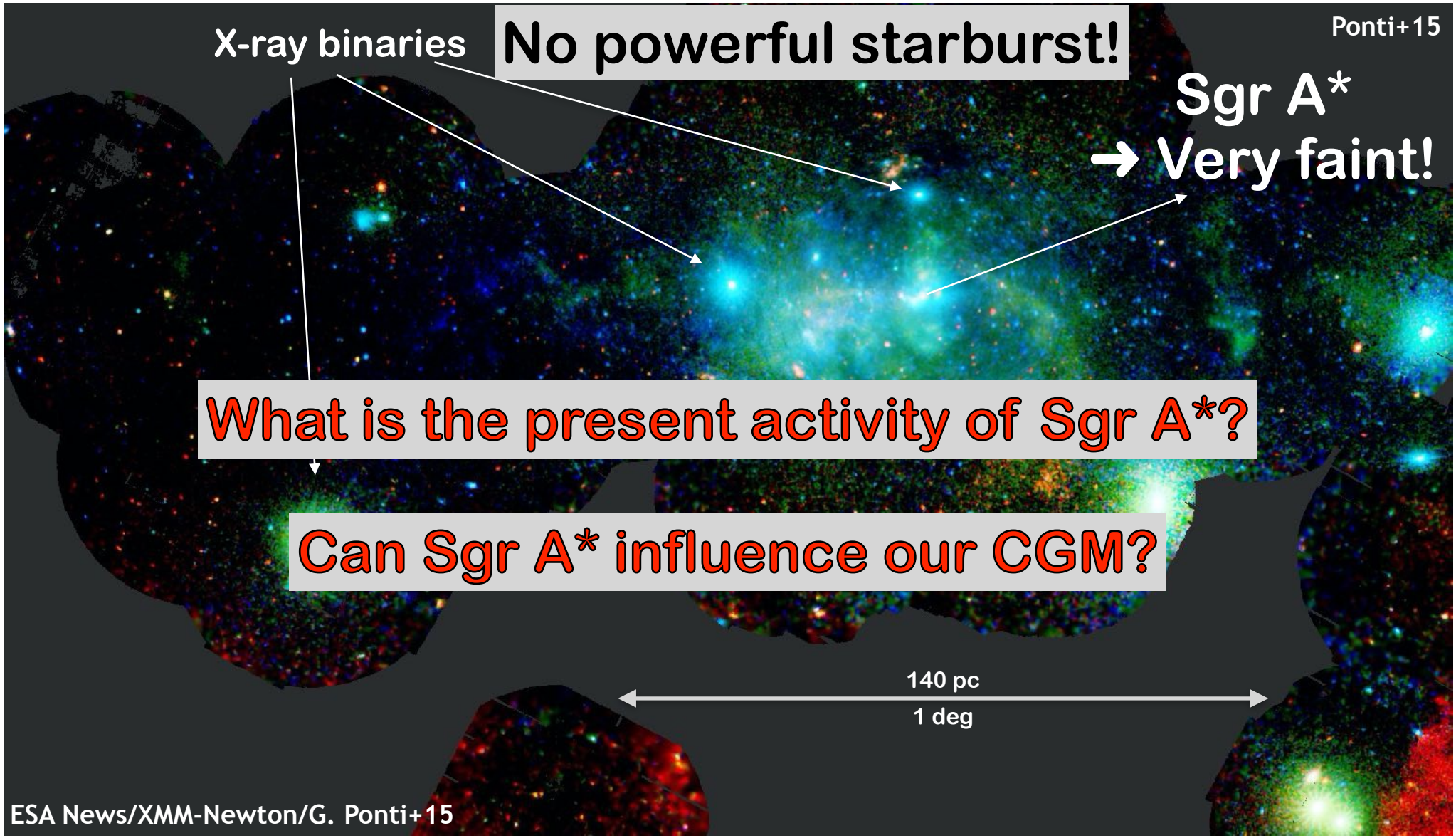
Peculiar environment: forming stars at extremely low rate (10 times lower than expected)

Nevertheless ➜ Mini starburst

The Central Molecular Zone in X-rays

More than 100 EPIC observations

Exposure > 1.5 Ms (central 15')
> 200 ks in the plane



The Central Molecular Zone in X-rays

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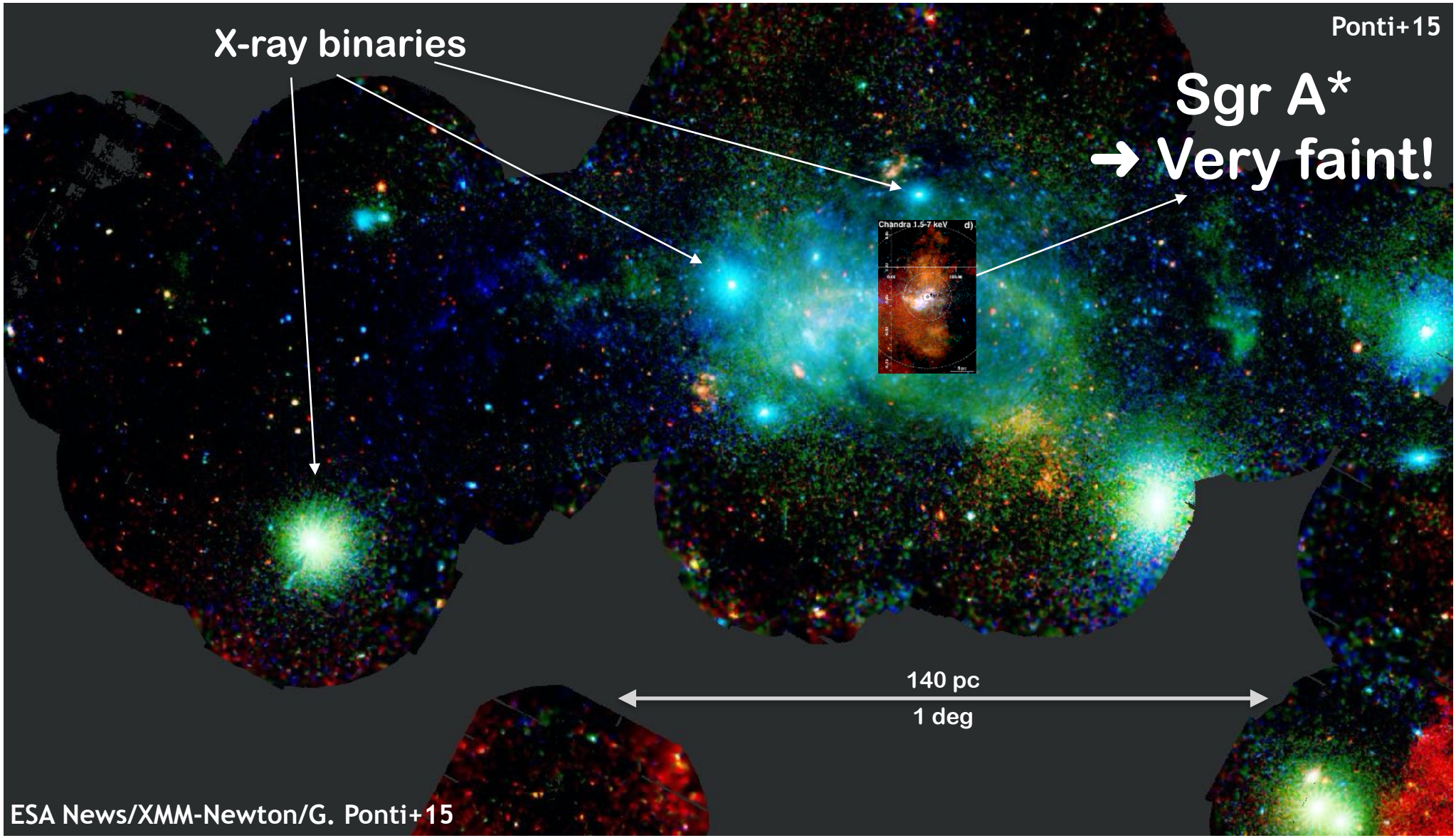
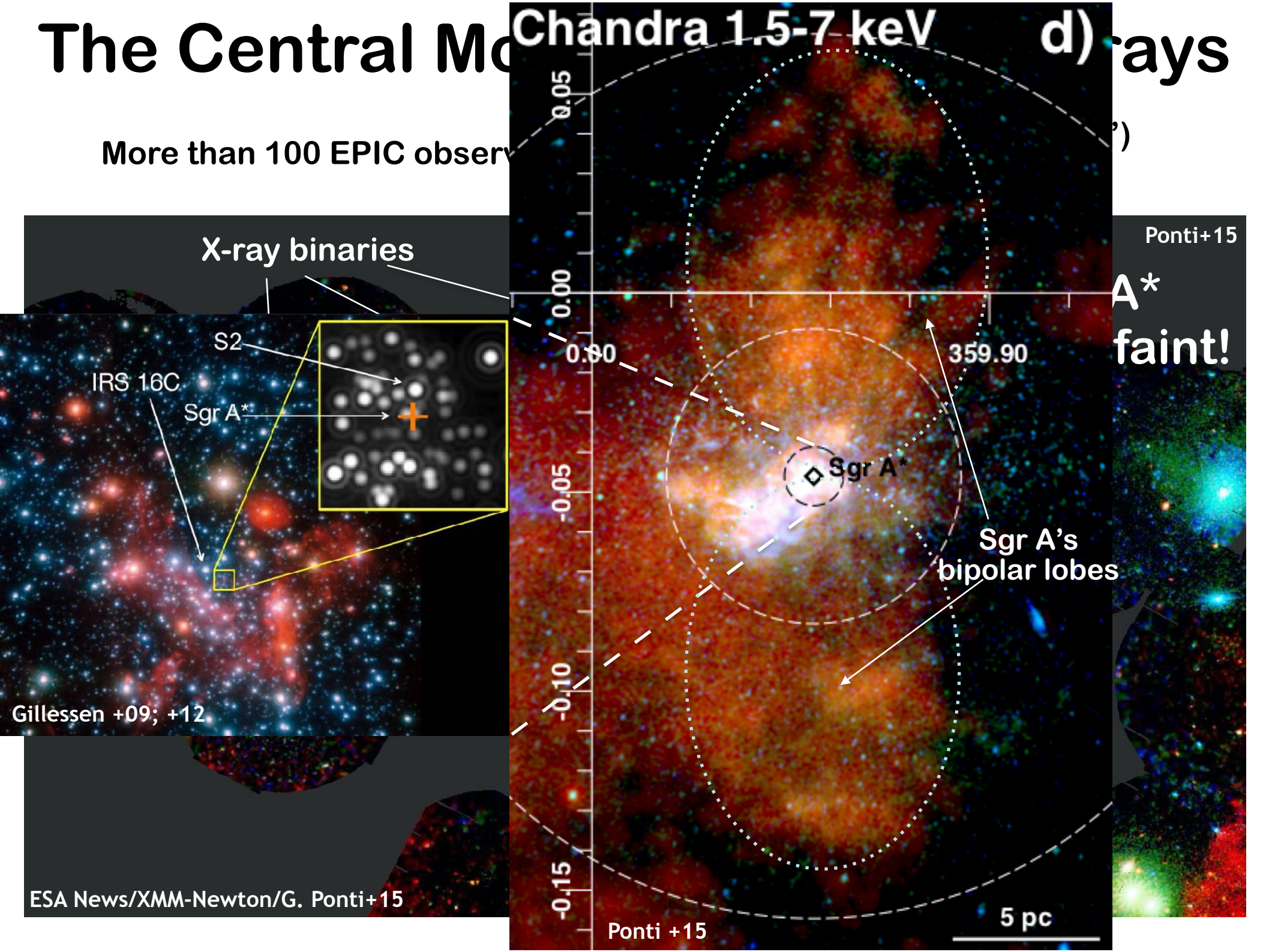


The Central Mo rays

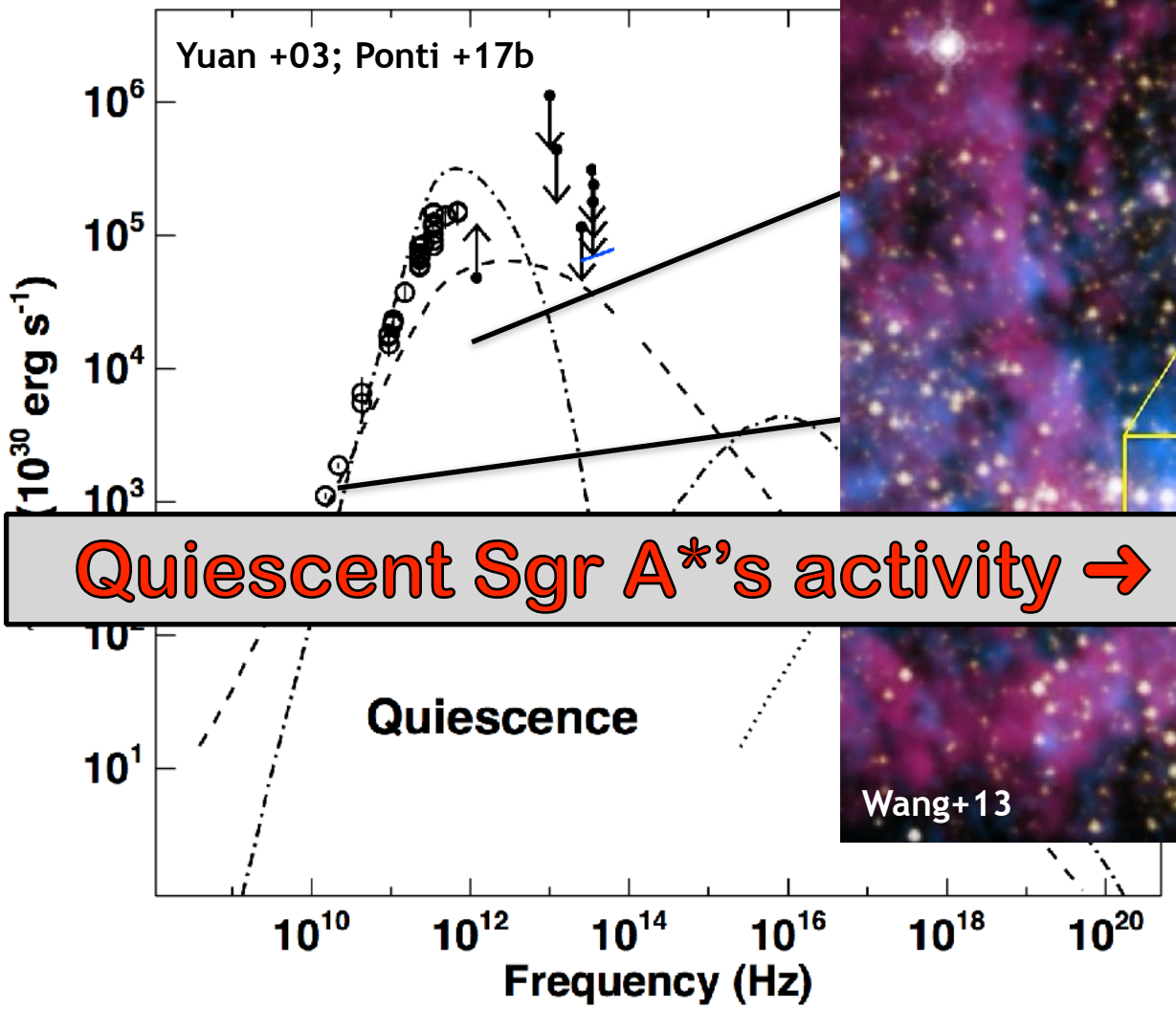
More than 100 EPIC obser ')

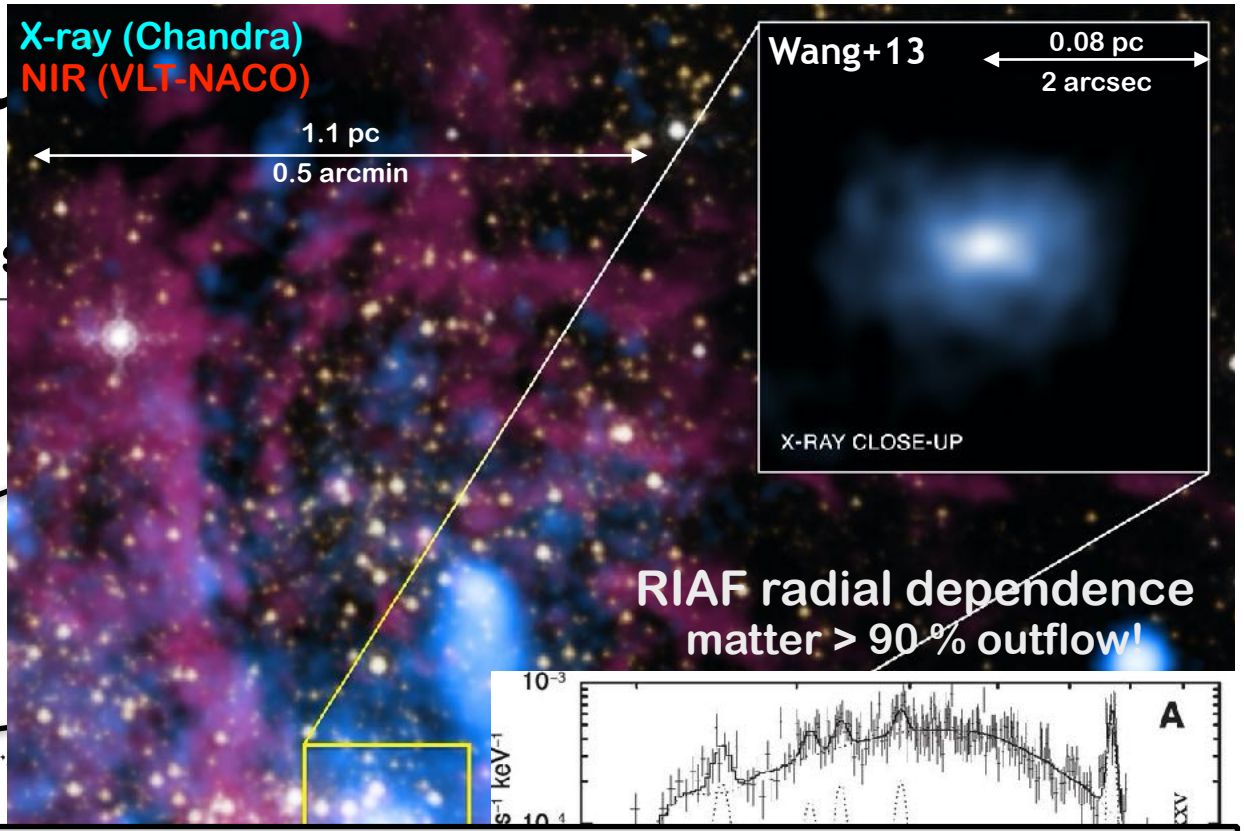


Sgr A*'s qu

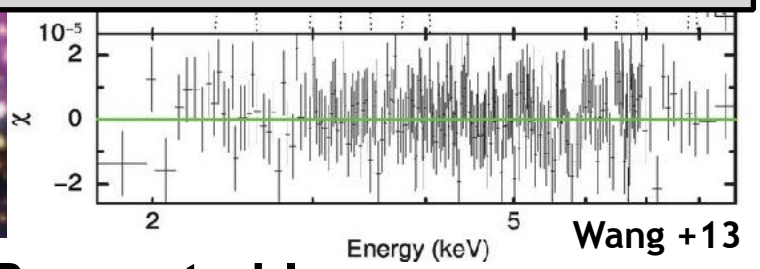
$L_{Sgr\ A^*} \sim 10^{-9}\ L_{Edd}$

Best target to study low luminos





Quiescent Sgr A*'s activity → No influence on CGM



Wang +13

Bremsstrahlung

r ~ 10^5 R_S

extended (~1") accretion from stars wind

kT_e ~ 7×10^7 K

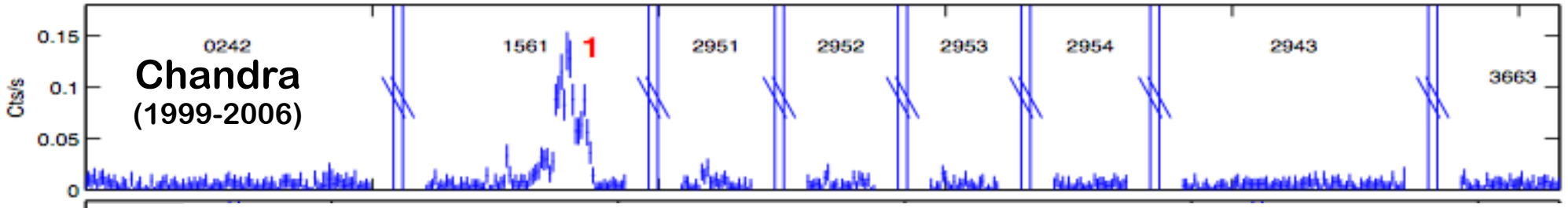
n_e ~ 100 cm^{-3}

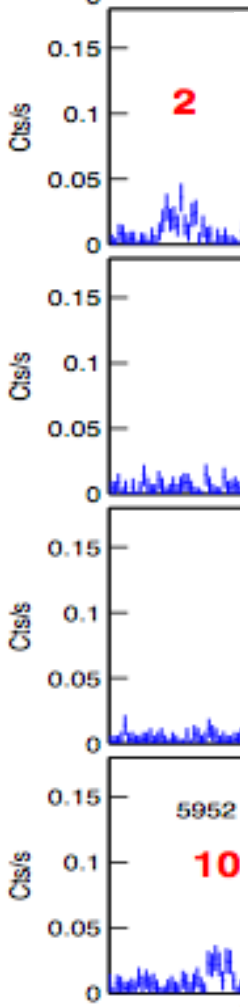
Melia +92; Quataert 02; Baganoff +03; Cuadra +05; Xu +06; Wang +13

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

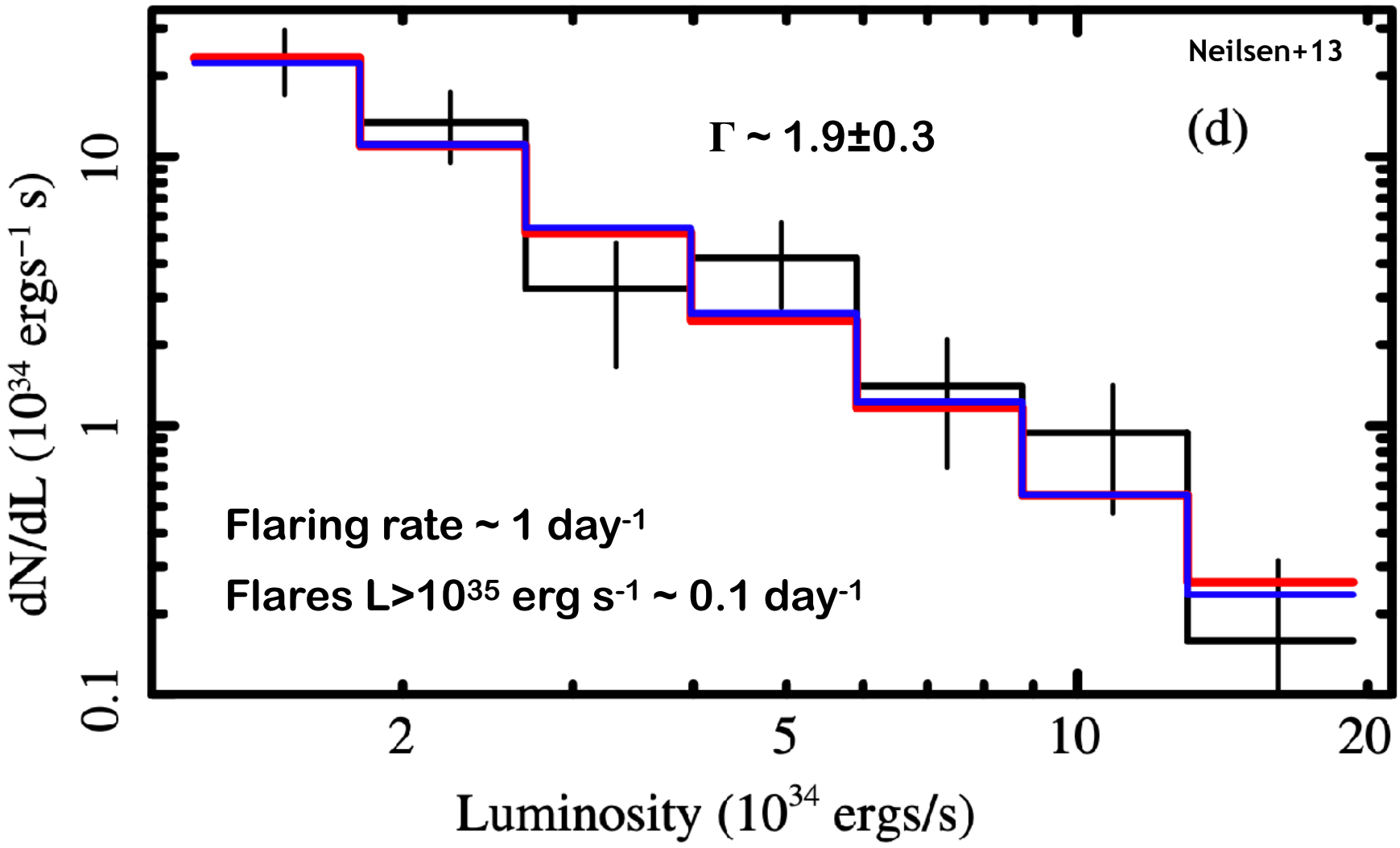
X-ray flares of Sgr A*

Ponti +15b





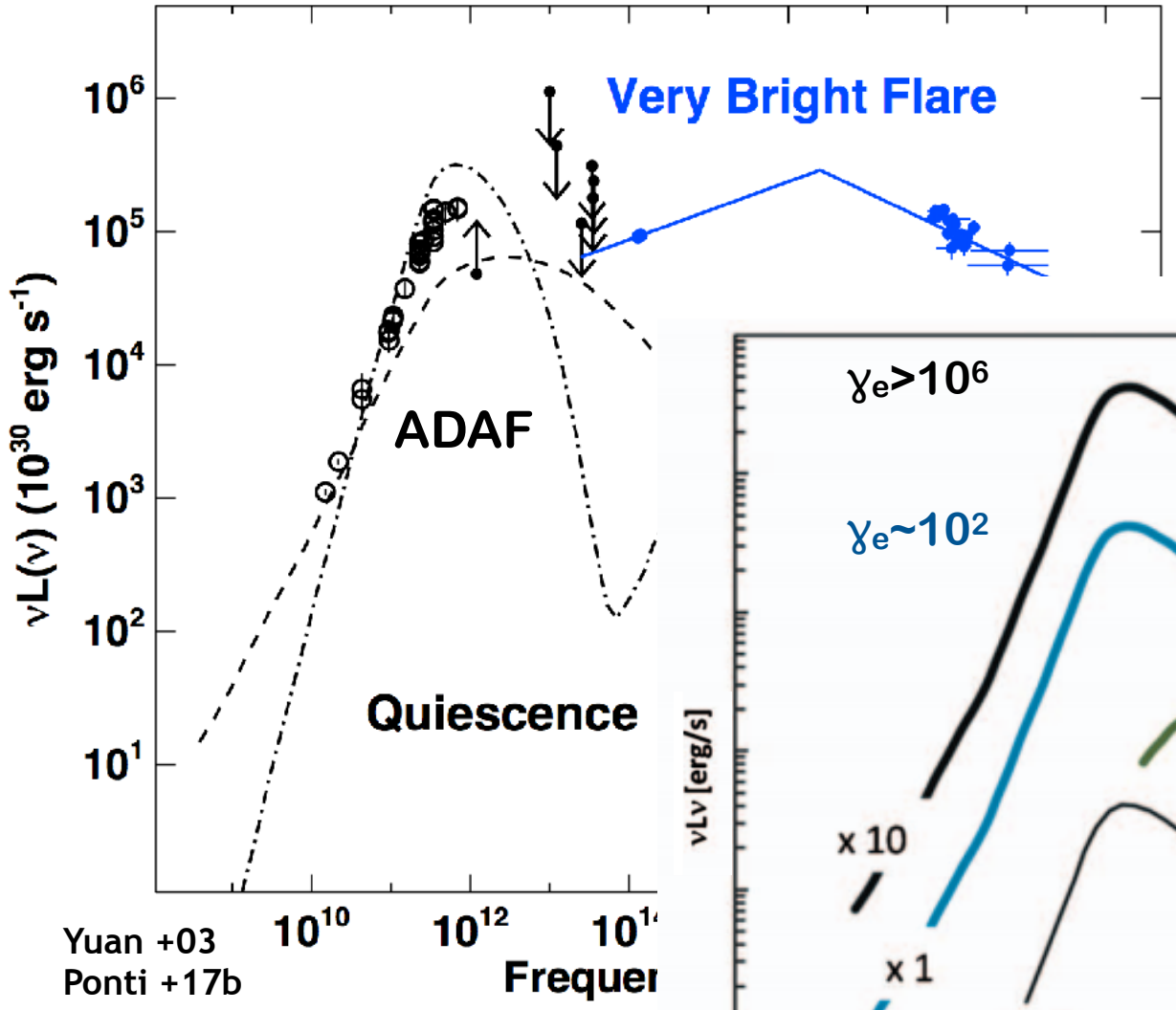
Sgr A*'s flare distribution



Baganoff+01; G
Ponti+15; Mo
Boyce+19;

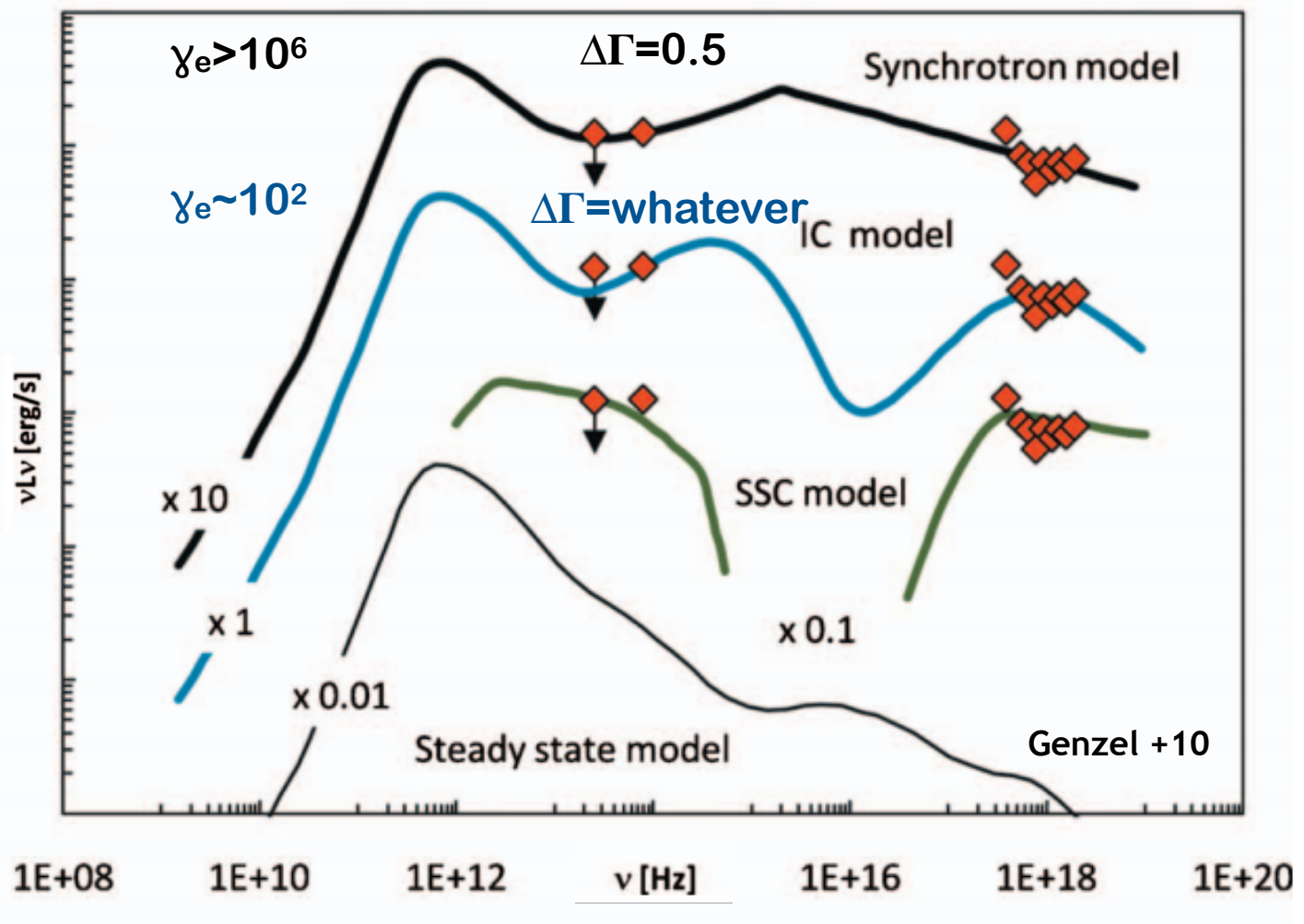
Sgr A*'s emission during X-ray flares?

Best target to study low luminosity accretion



Yuan +03
Ponti +17b

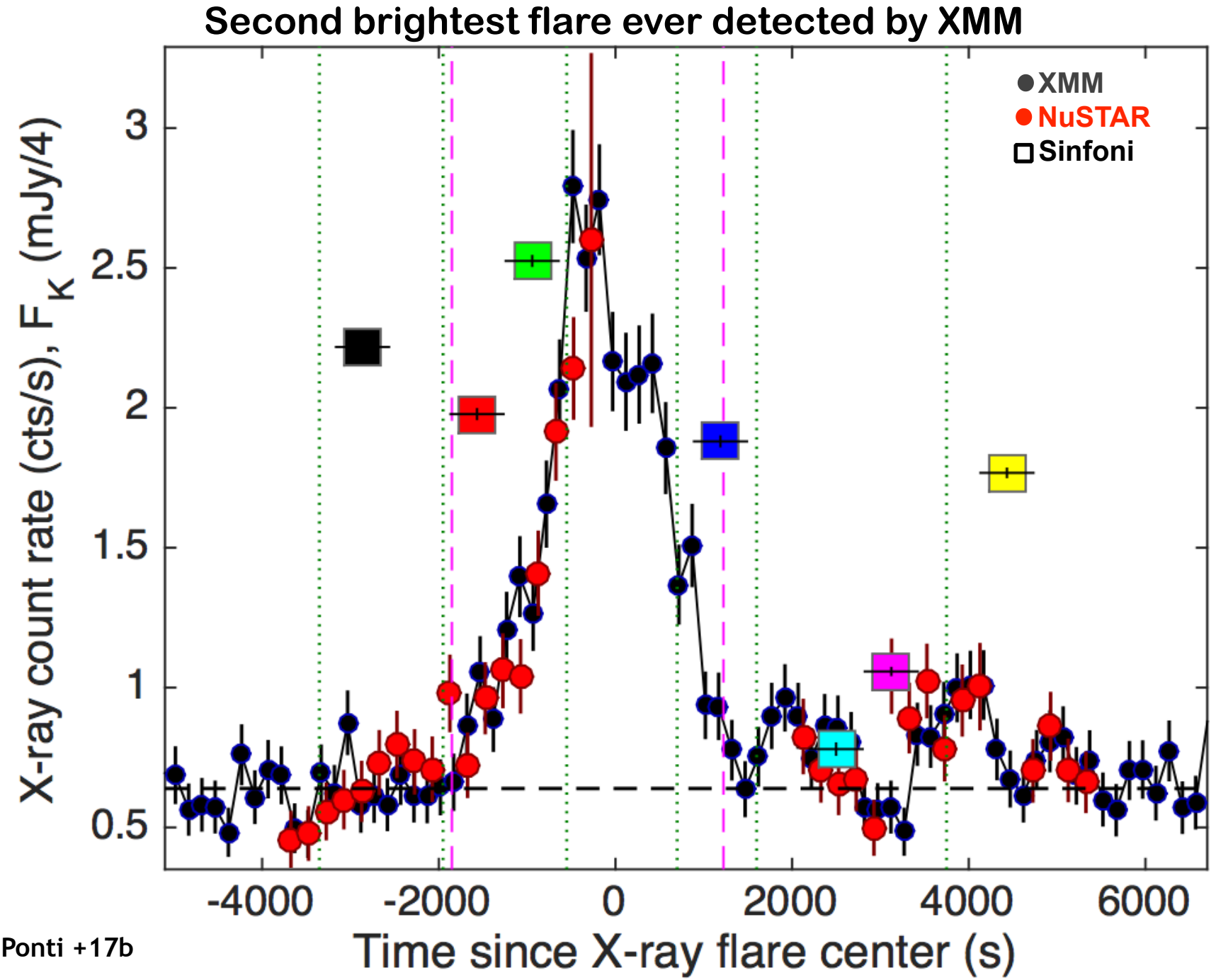
During flares → $\Gamma_{IR} \sim 1.6$
IR polarised → Synchrotron



For 15 years we wondered…

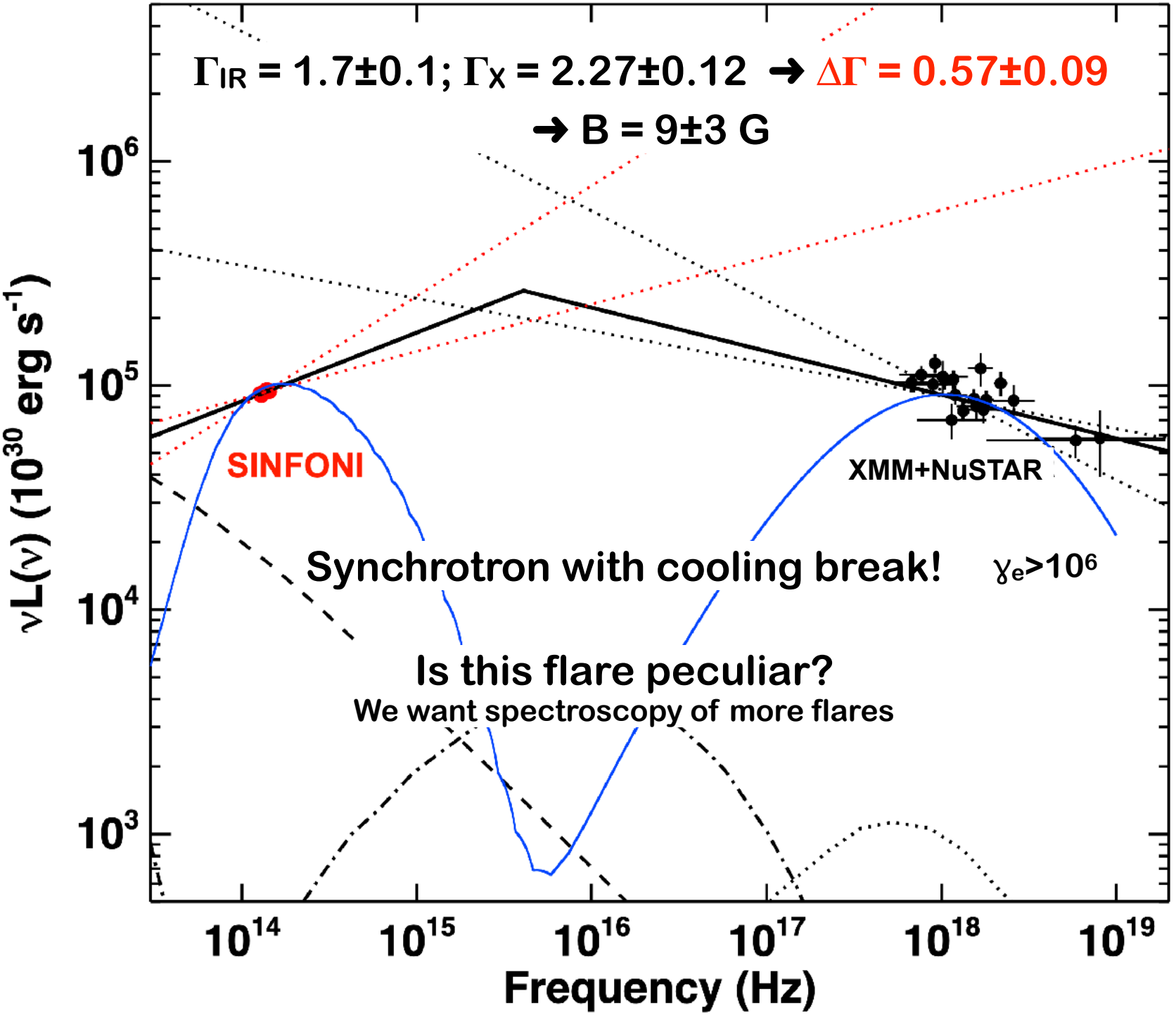
What is the radiative process in X-ray?

First NIR and X-ray spectrum of a flare



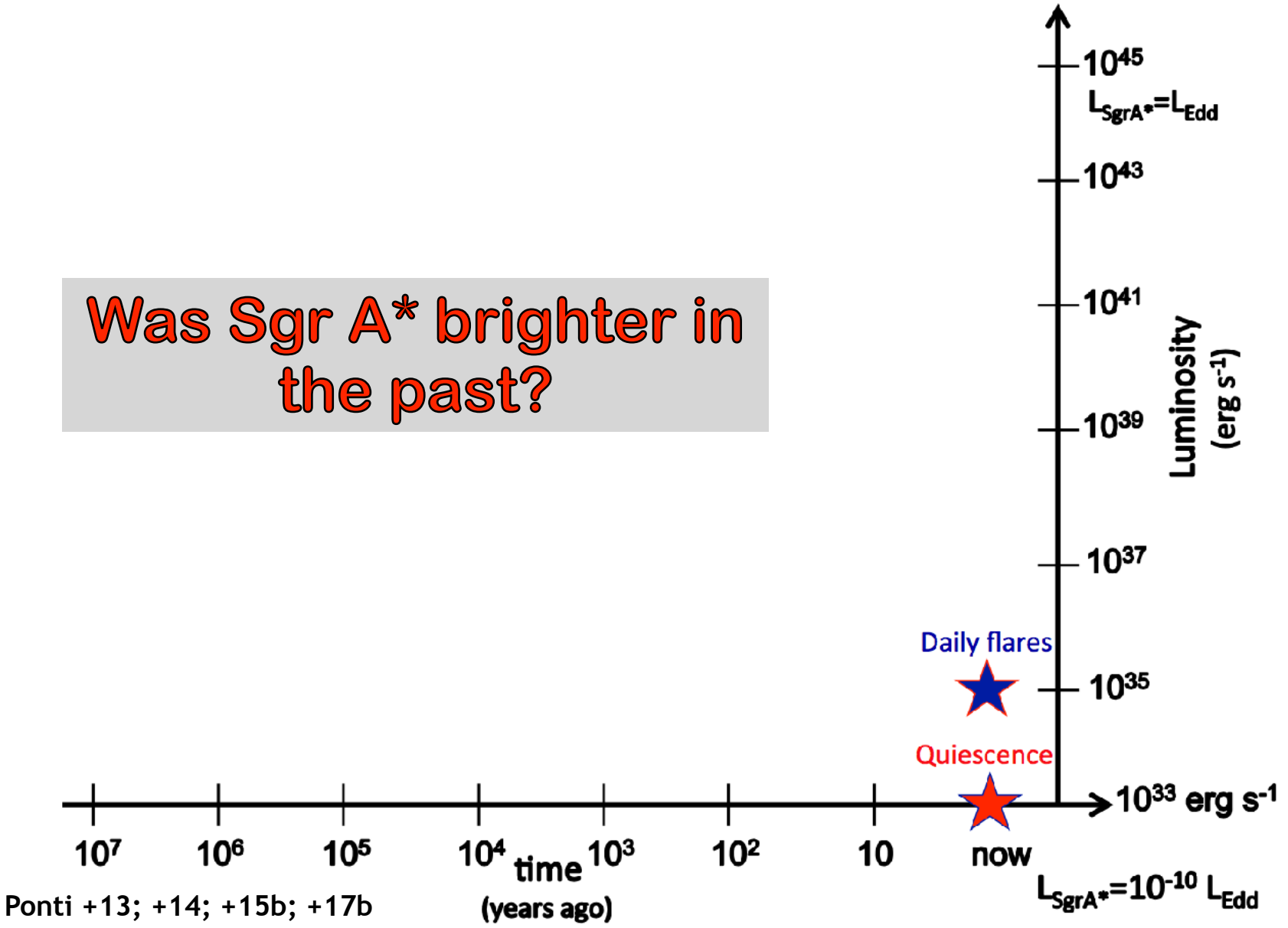
Ponti +17b

First NIR and X-ray spectrum of a flare



Sgr A*'s present activity

Was Sgr A* brighter in the past?



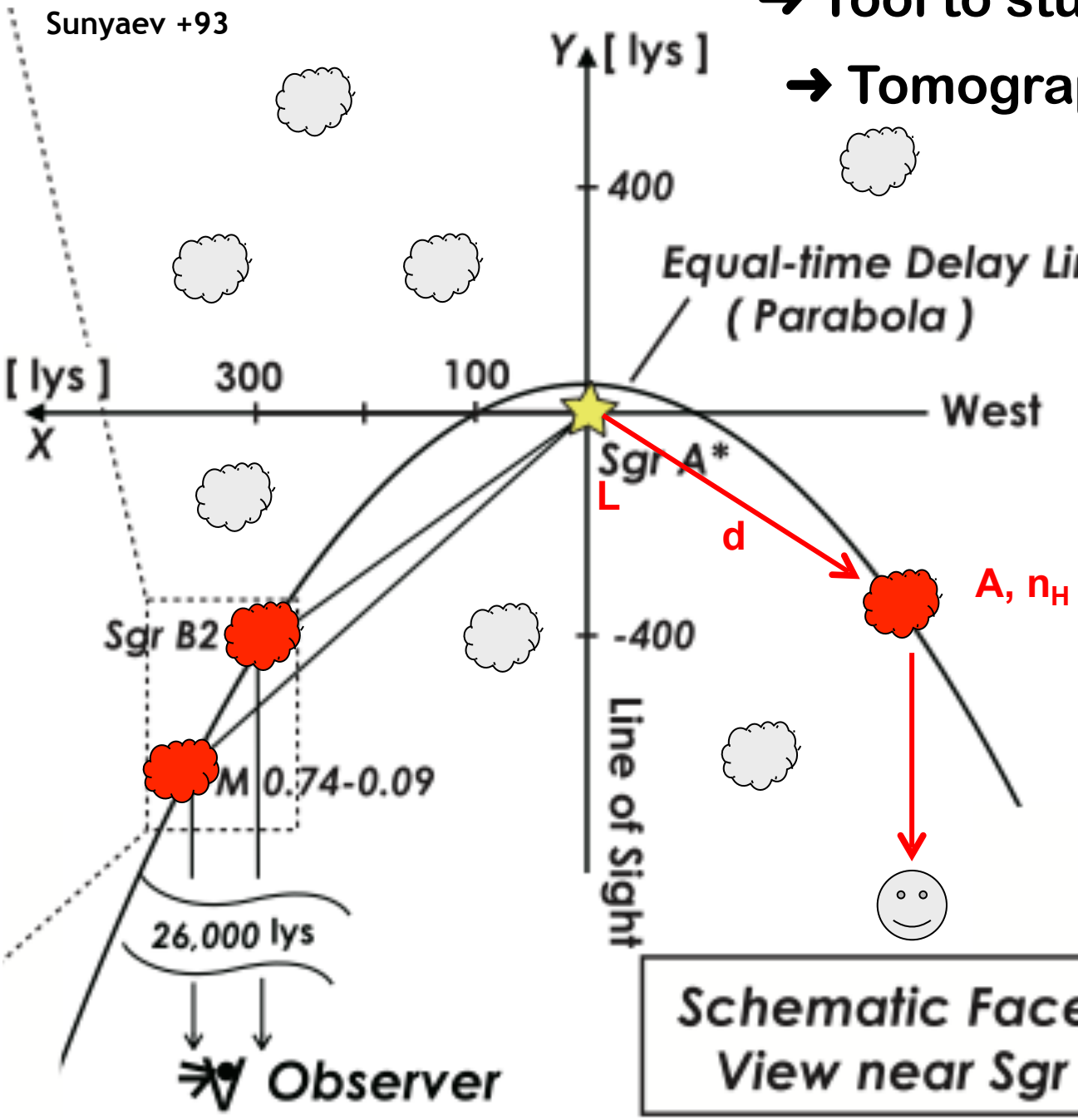
Ponti +13; +14; +15b; +17b

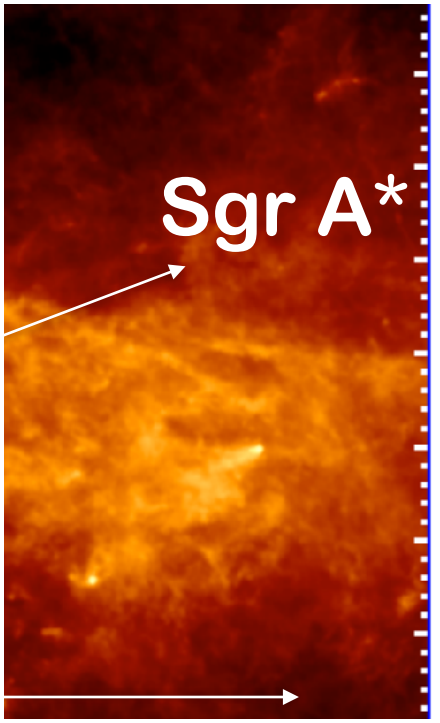
Current activity → No influence on CGM

Clouds: mirrors of past activity

➜ Tool to study Sgr A*'s past activity

➜ Tomography of cloud distribution

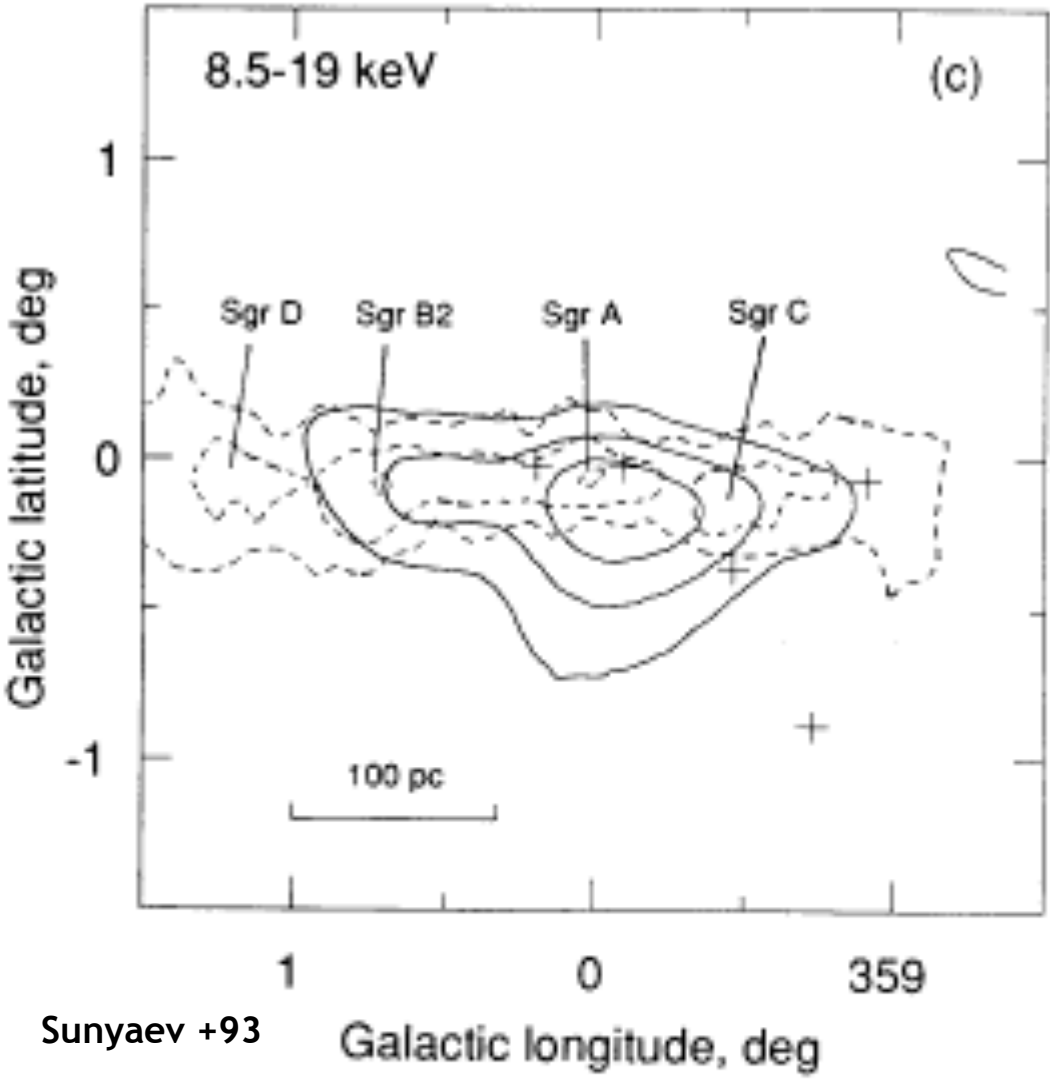




$$L_{SgrA*} \propto \frac{n_H \times A \times I_{\mathrm{FeK}}}{d^2}$$

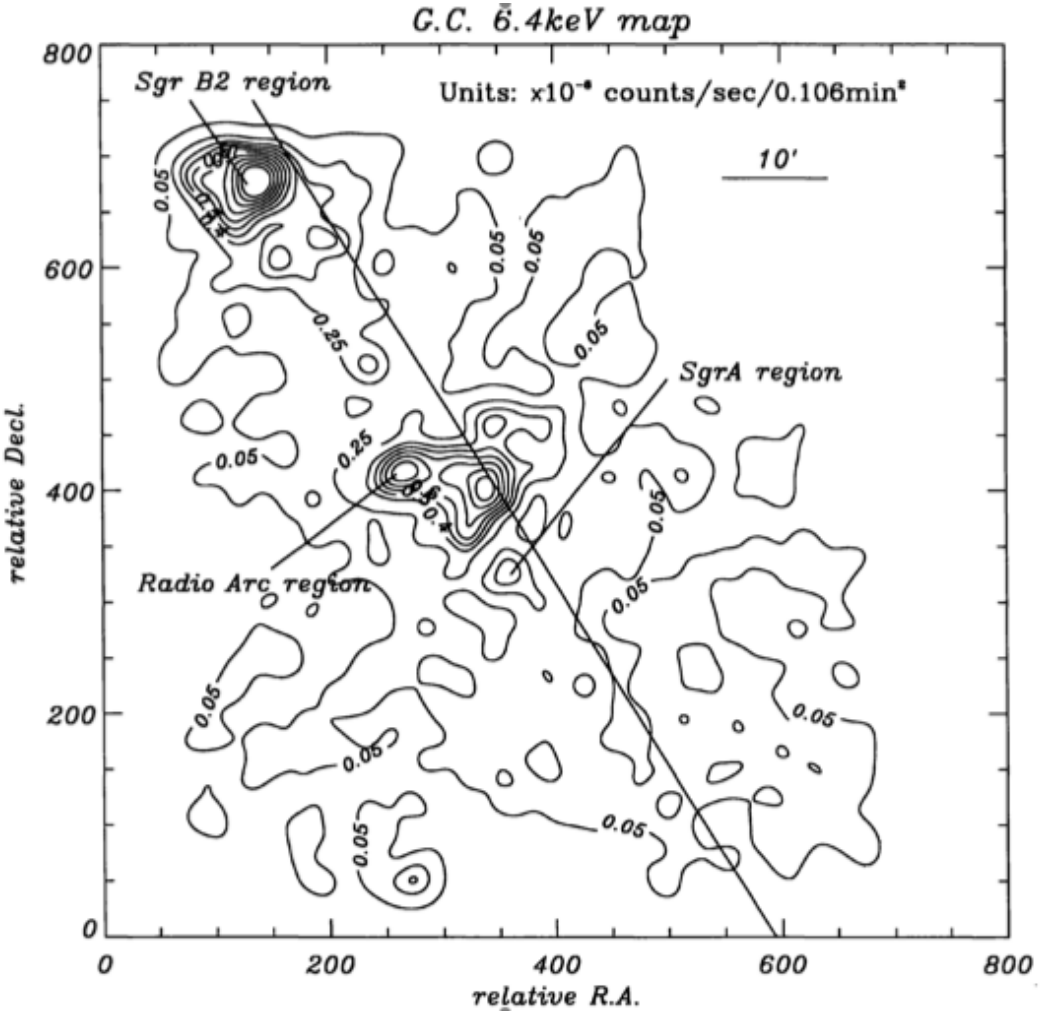
Clouds as X-ray mirrors

GRANAT: Hard X-ray/MC



Sunyaev +93

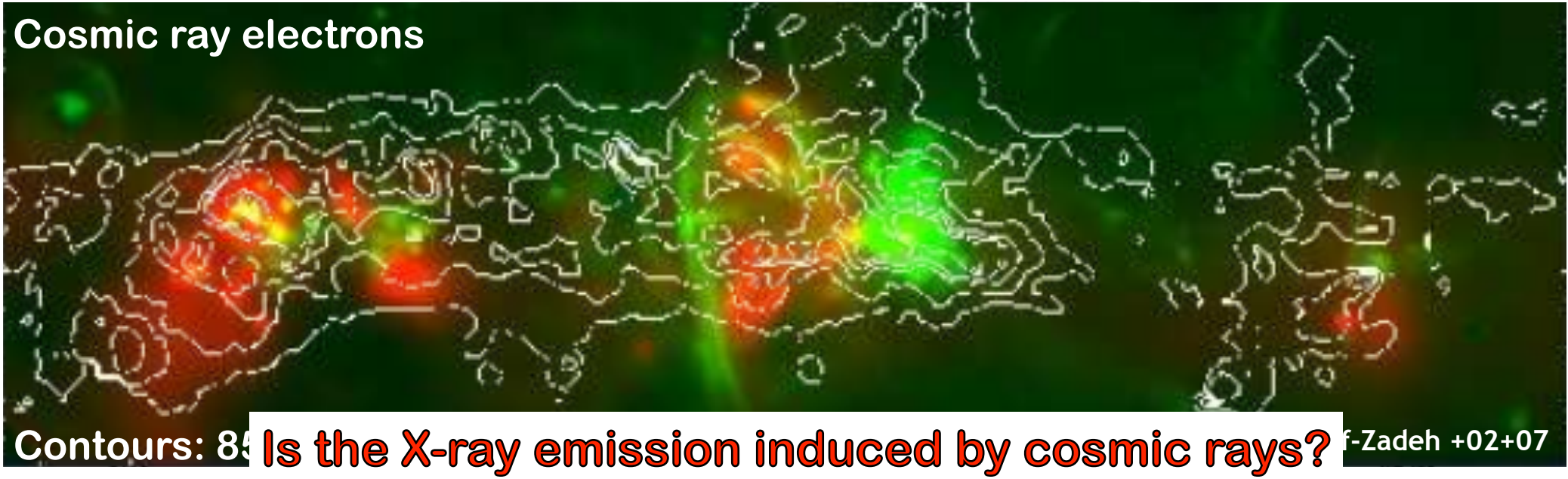
ASCA: Fe Kα from some MC



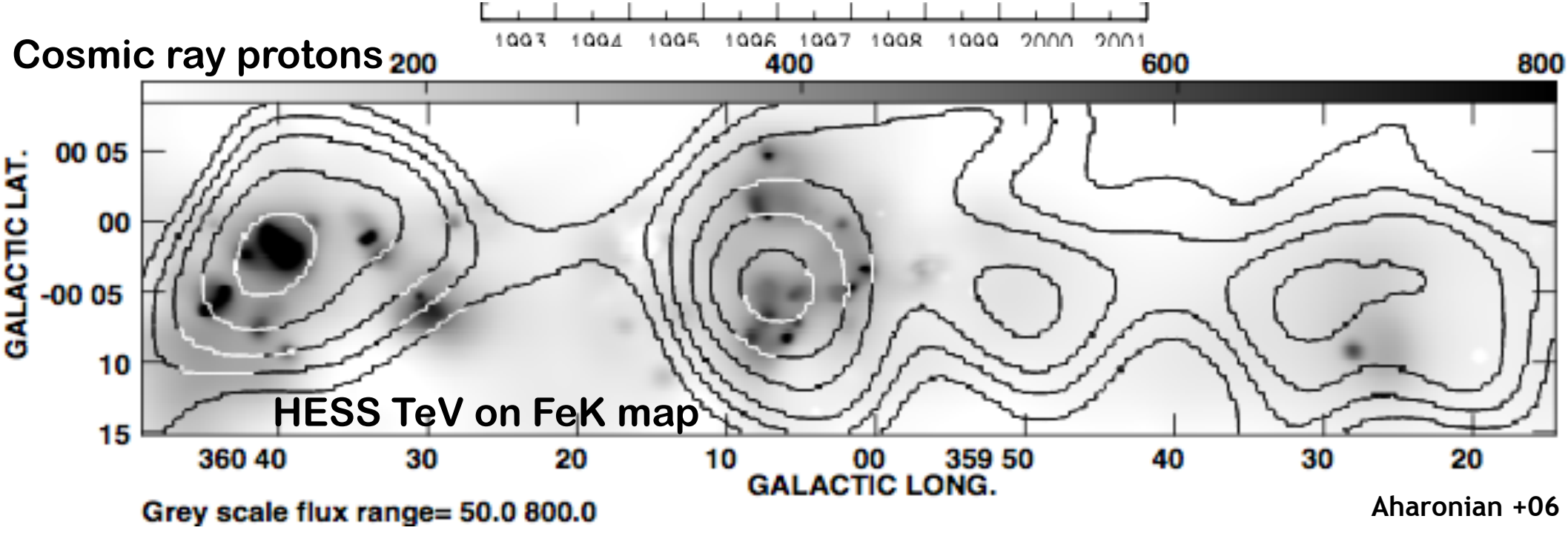
Koyama +96

Are clouds reflecting Sgr A* radiation?

Puzzling result: constant FeKα emission

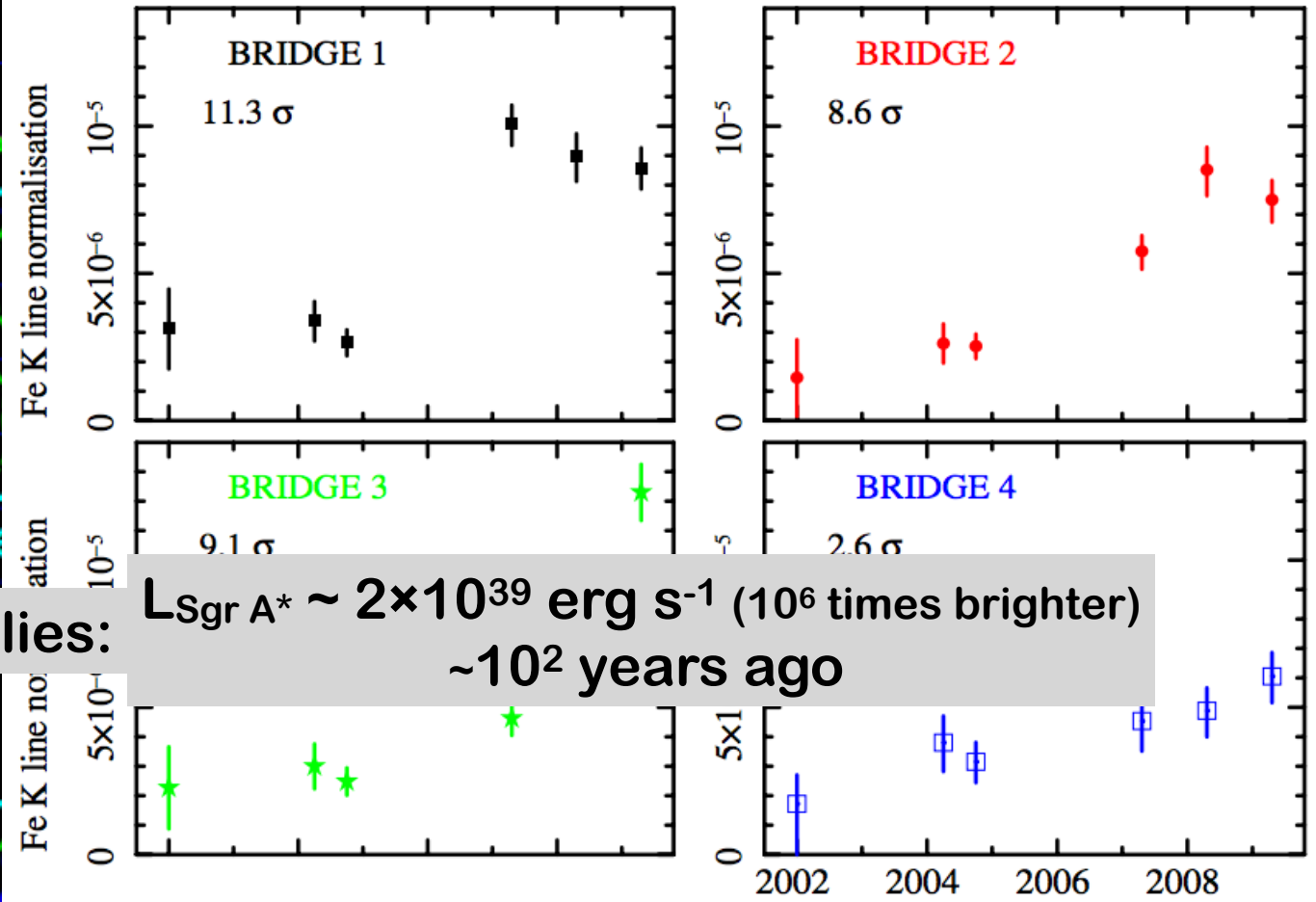


Is the X-ray emission induced by cosmic rays?



Super-luminal echo ➜ clouds as mirrors

XMM: Fe Kα emission

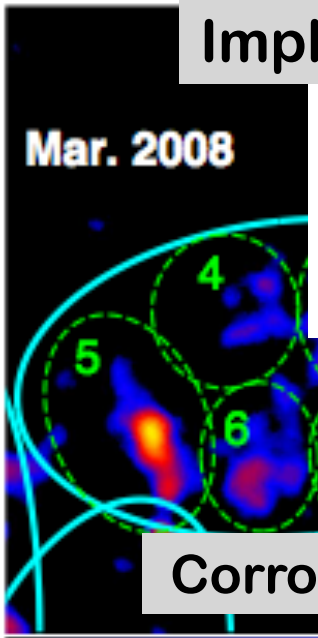


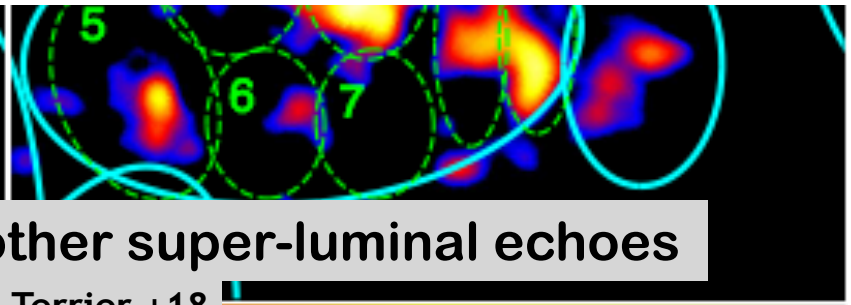
Ponti +10

Significant variation of the Fe Kα emission

Super-luminal Fe Kα propagation

Implies: $L_{Sgr\ A^*} \sim 2\times10^{39}$ erg s^{-1} (10^6 times brighter) ~10^2 years ago





➜ Rule out cosmic rays

➜ Clouds are mirrors of past activity

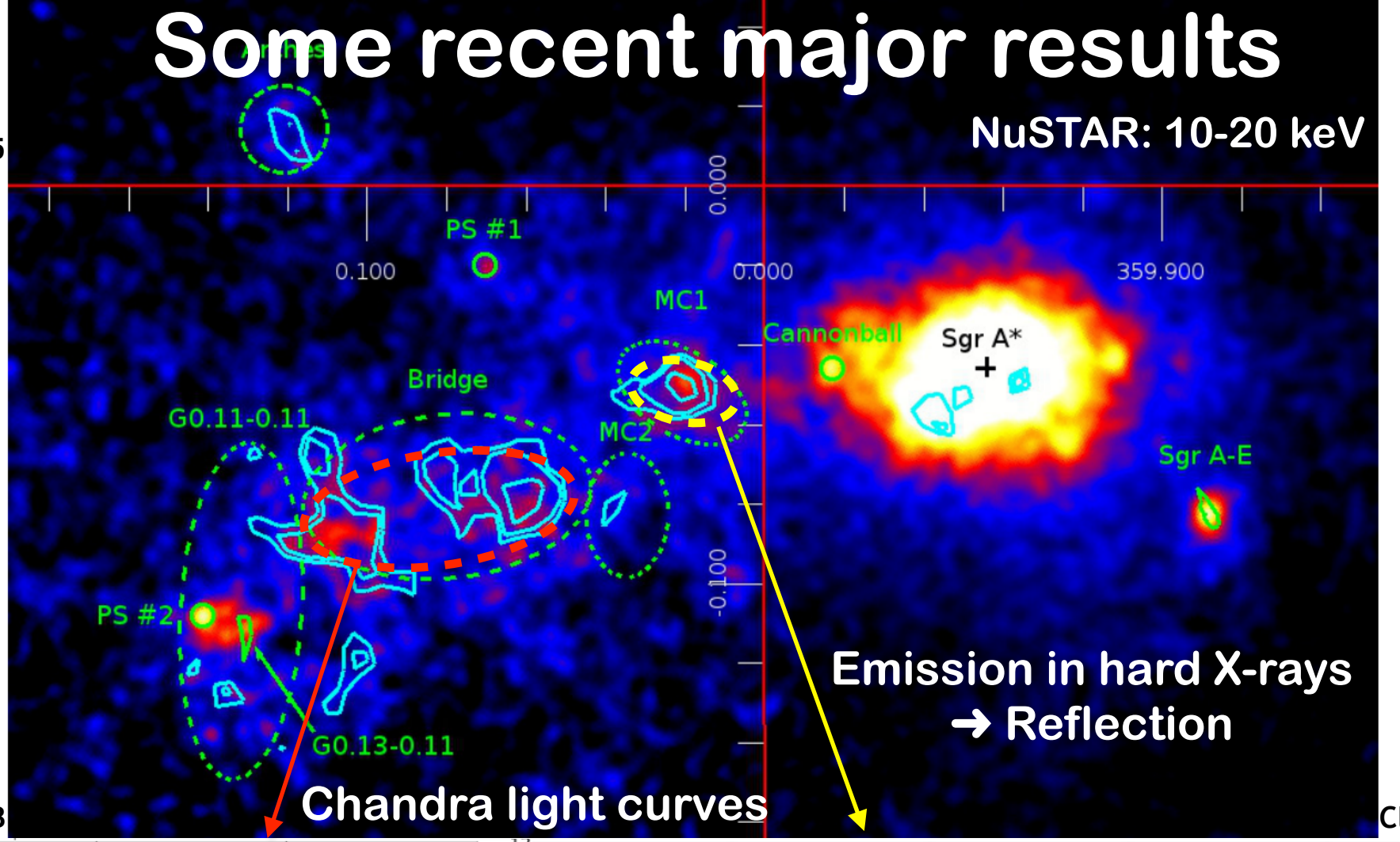
Corroborated by several other super-luminal echoes

Clavel +13; Terrier +18

e.g. Ponti +10;+13

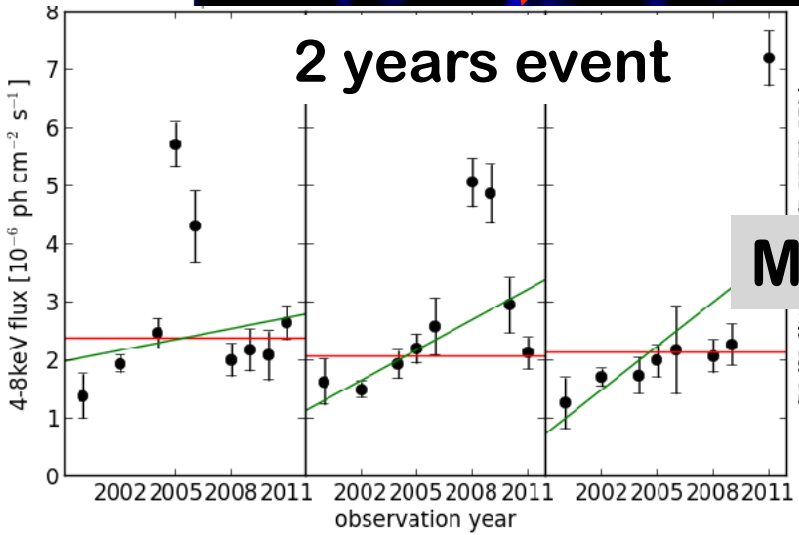
Some recent major results

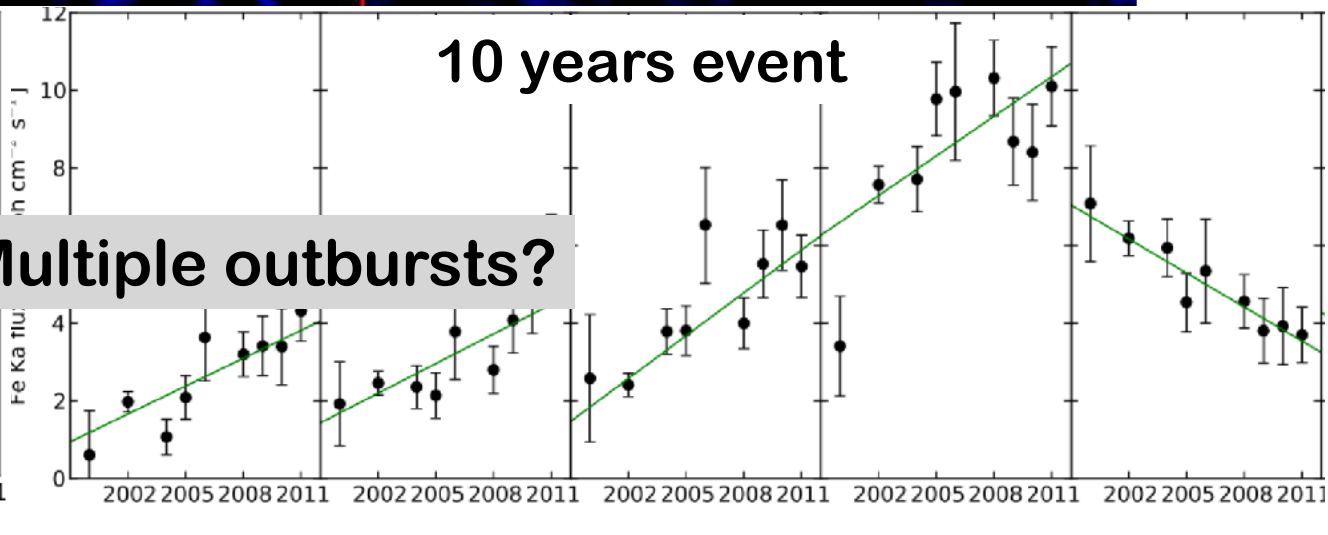
Mori +15;
Zhang +15



Clavel +13

Clavel +13

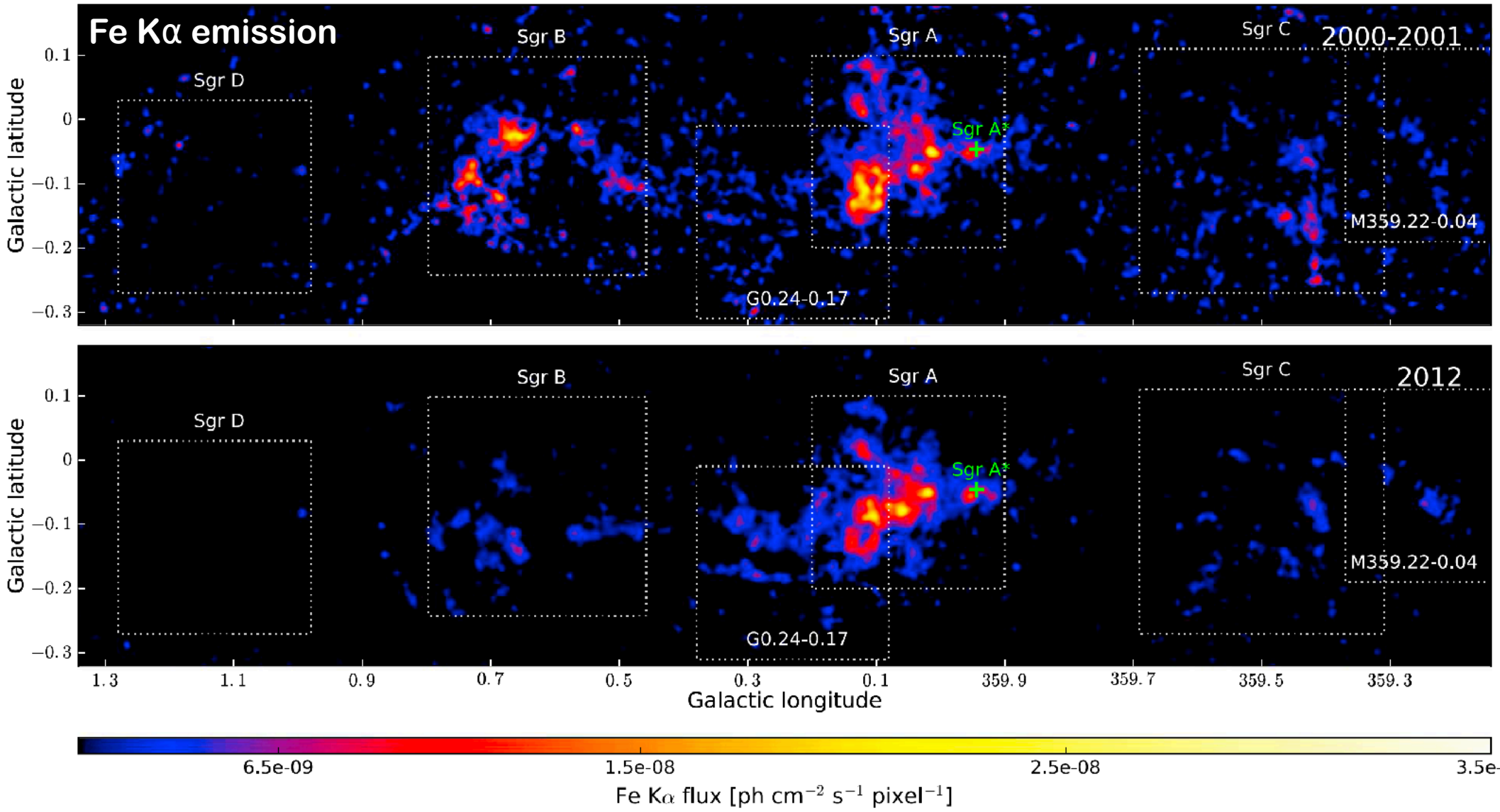




Multiple outbursts?

Some recent major results

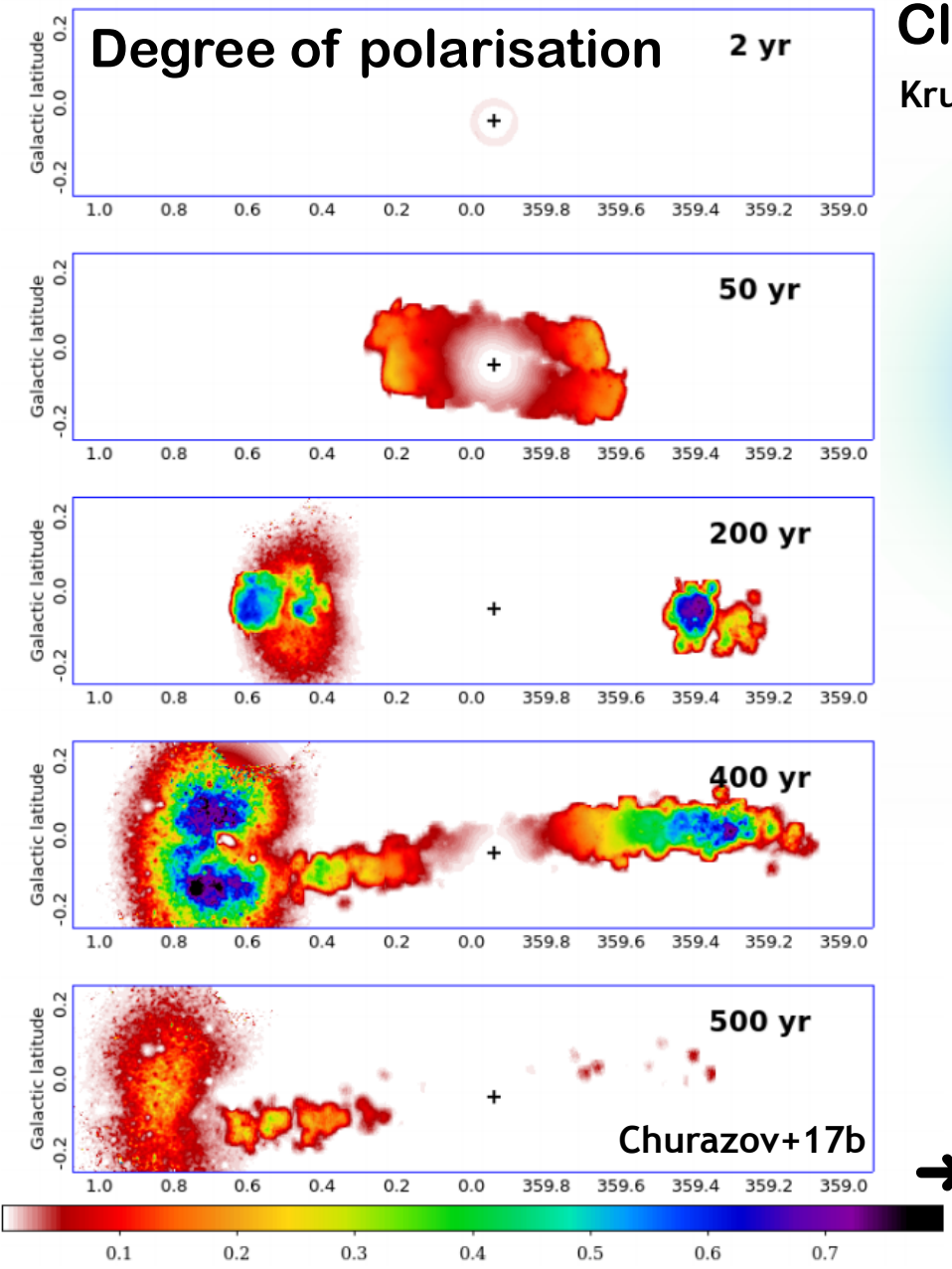
Terrier+18



All Fe Kα bright regions are variable

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

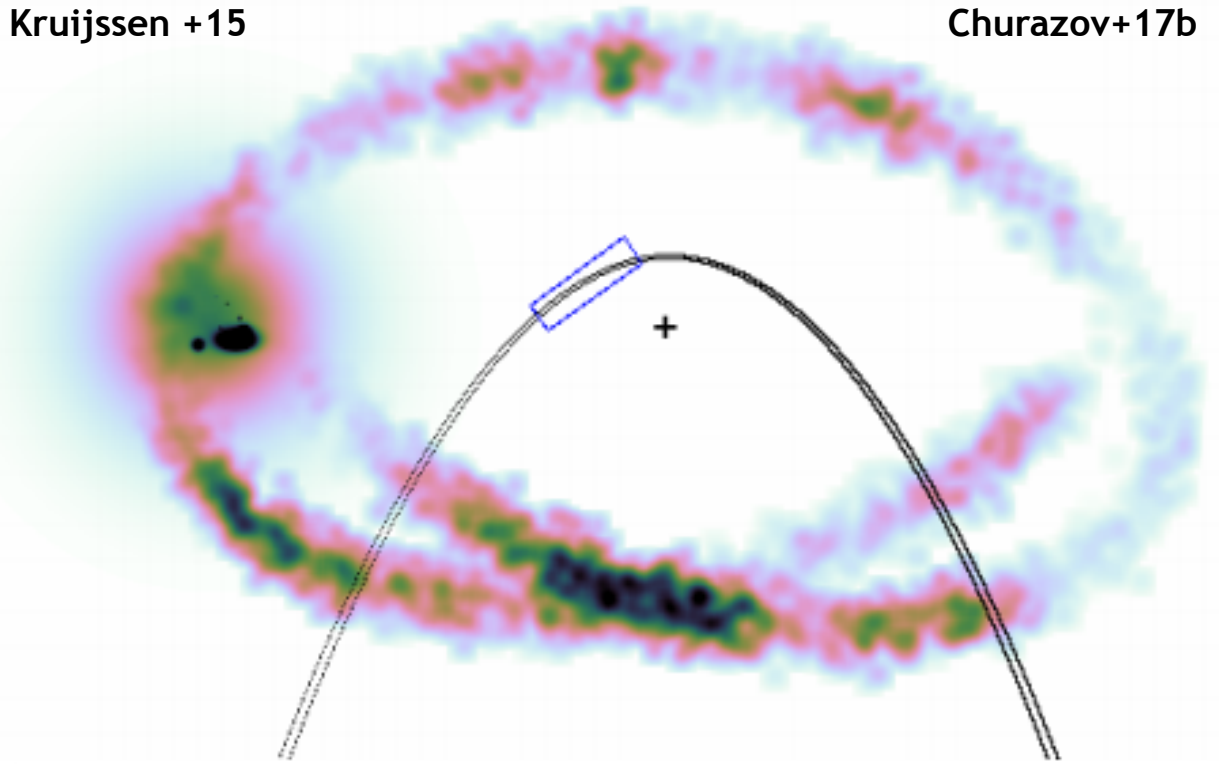
Future prospects: X-ray polarisation!



Cloud distribution in central molecular zone

Kruijssen +15

Churazov+17b



Angle and degree of polarisation

Achievable with IXPE (2021) EXTP (2027)

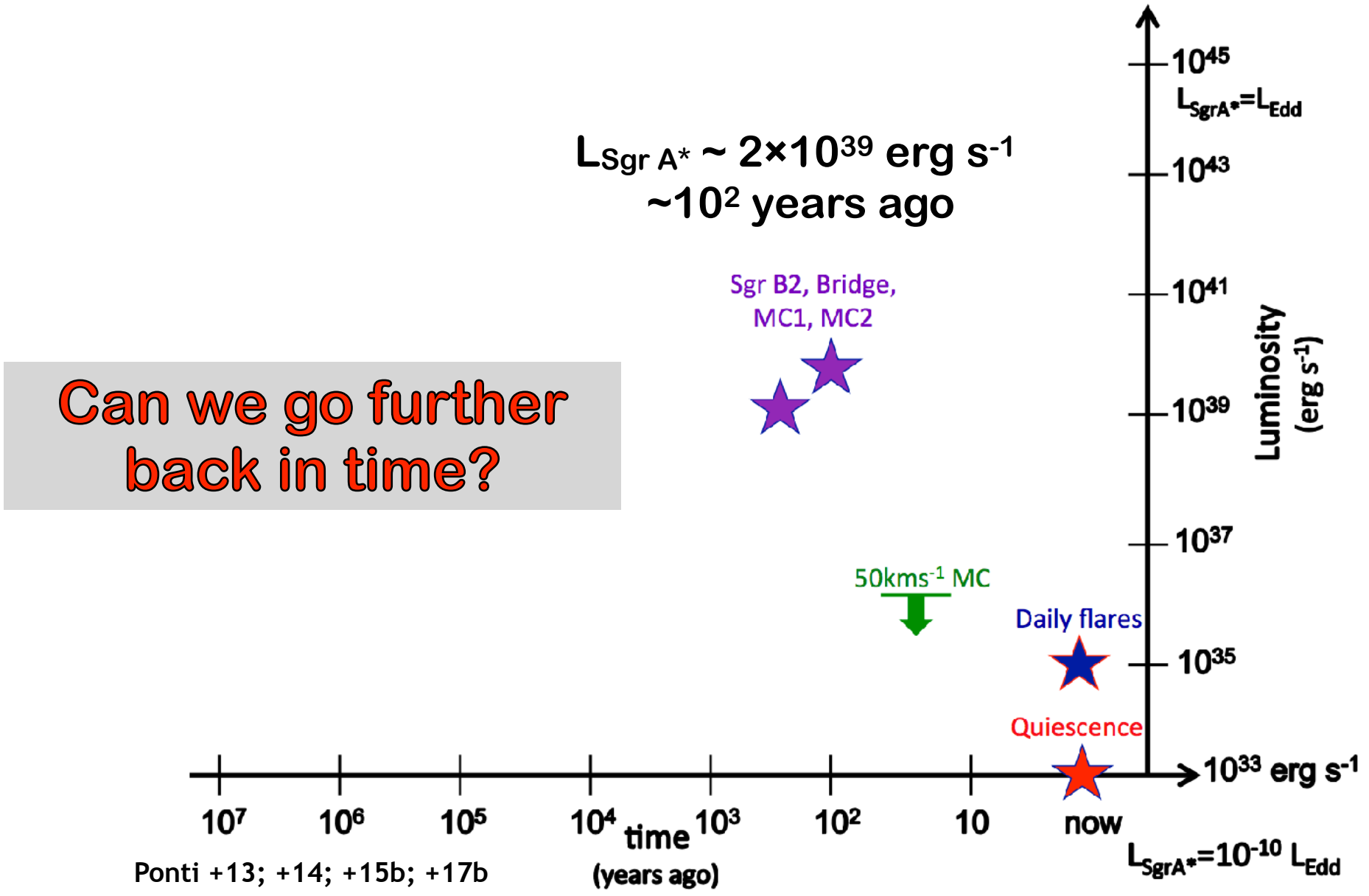
Churazov+02+17b; Di Gesu+20; Khabibullin+20b

➜ Derive Sgr A*'s light curve

➜ Reconstruct 3-d distribution of clouds

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

Sgr A*'s present and past activity

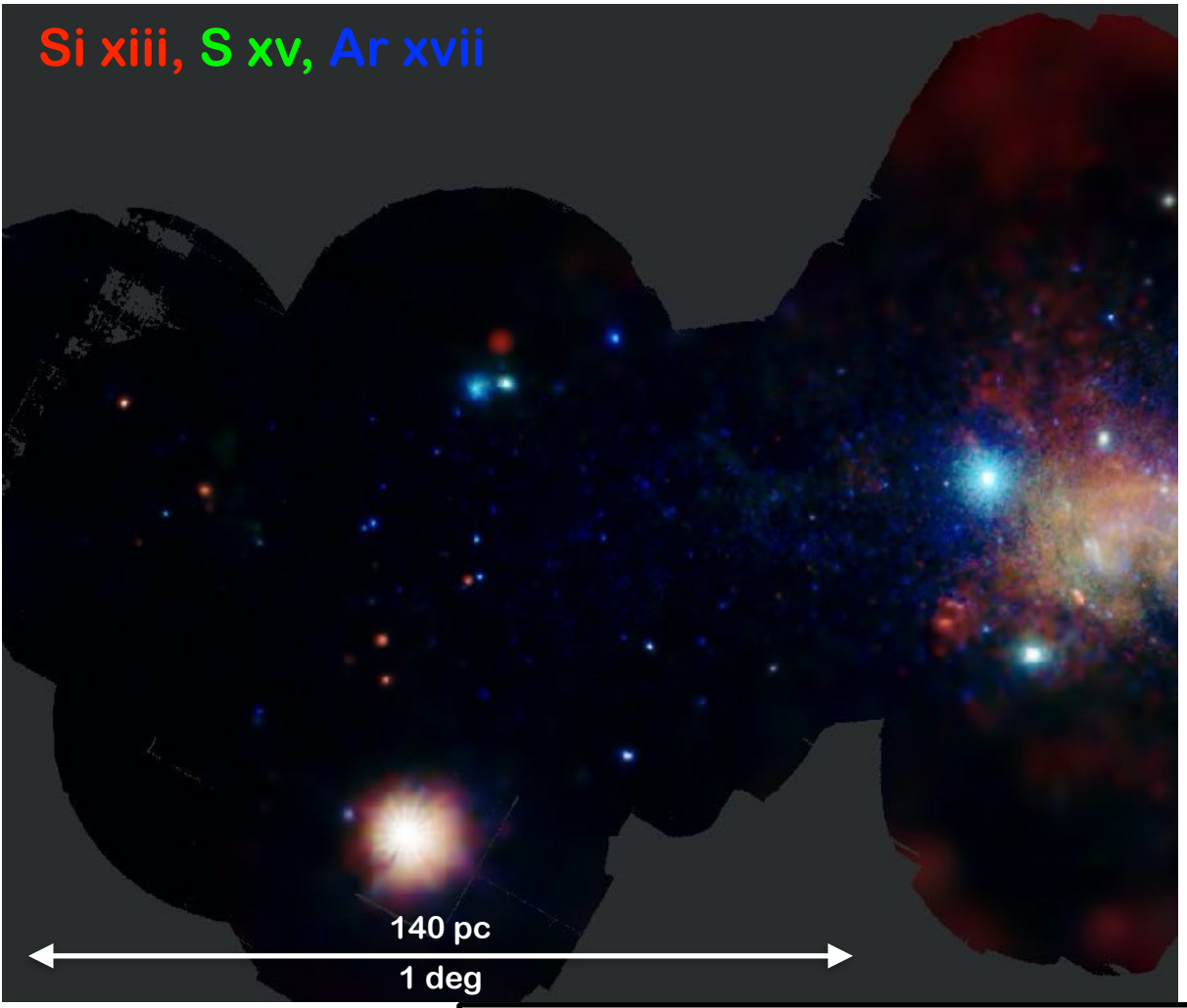


Can we go further back in time?

Although 10^6 times brighter → No influence on CGM

Distribution of remnants and outflows

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			
		10	10 × 10	R 73,81,82

Atlas of all

Possible influence on CGM?

3.5×10^{-4} yr^{-1} < SN rate < 15×10^{-4} yr^{-1}

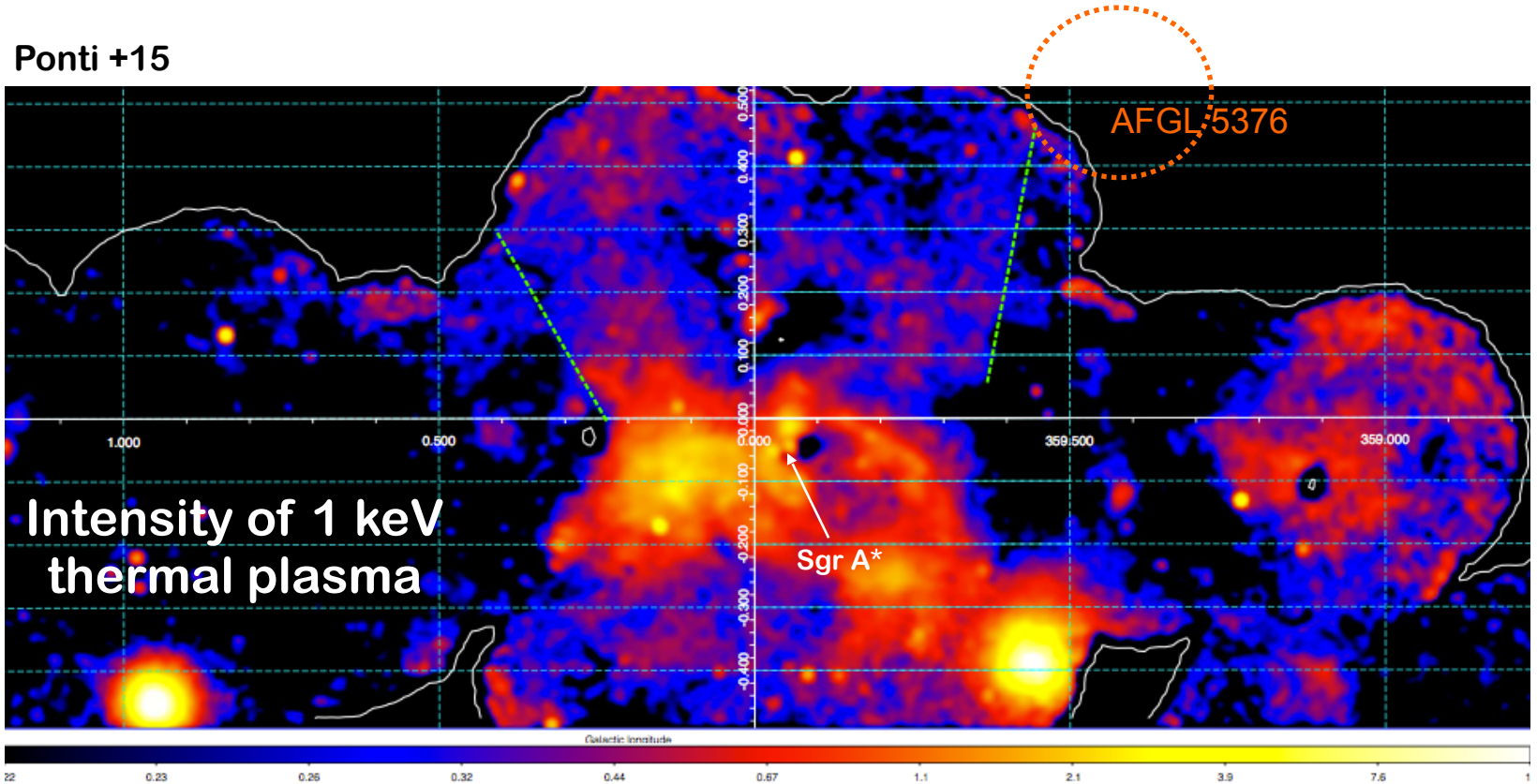
Massive kinetic energy input > 1.1×10^{40} erg s^{-1}

➜ Powering outflows to Galactic center lobe?

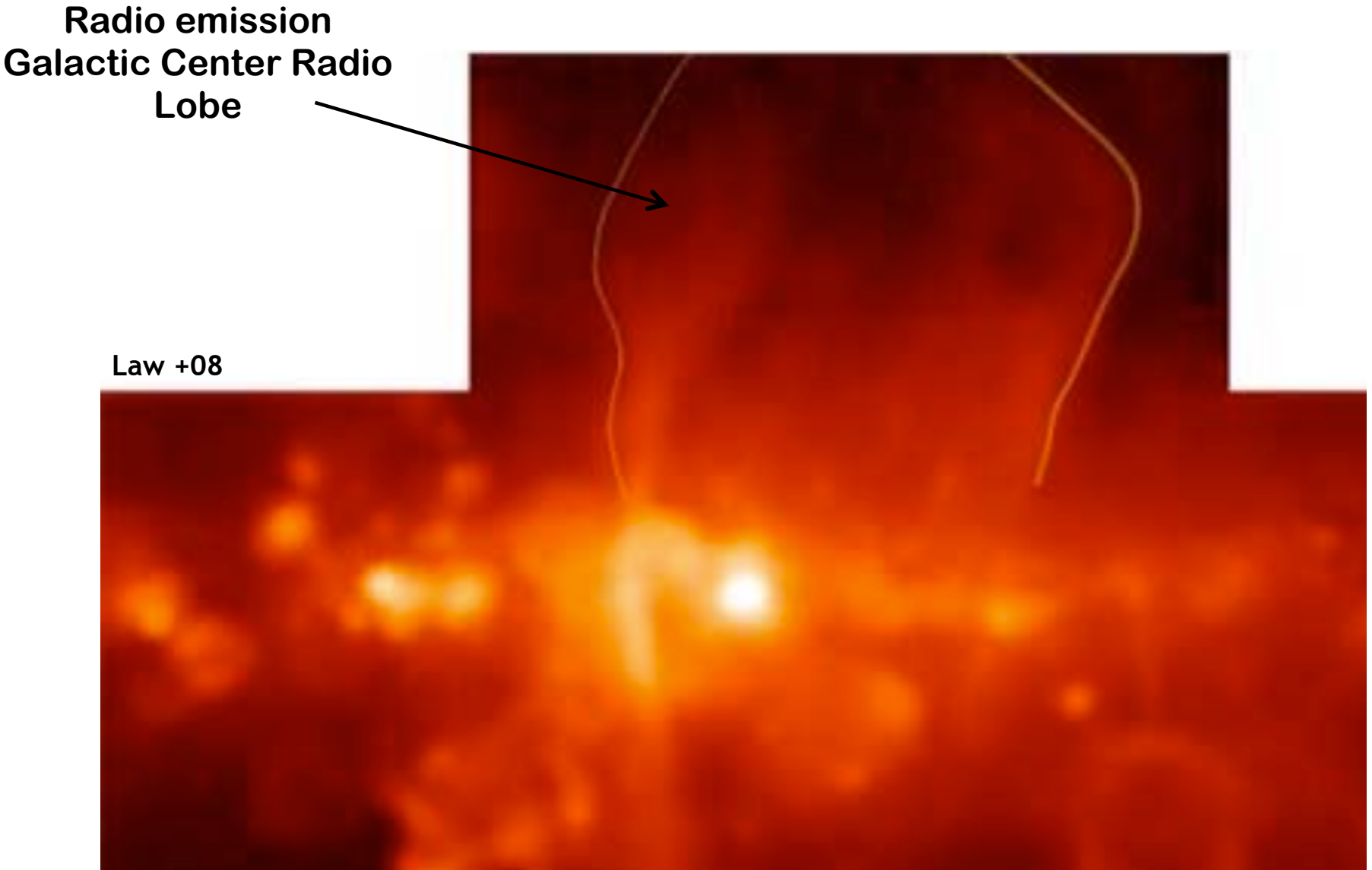
Law +11; Crocker +11; 12; Yoast-Hull +14; Jouvin +15

Discovery of high latitude hot plasma

What is this?



Galactic center radio lobe

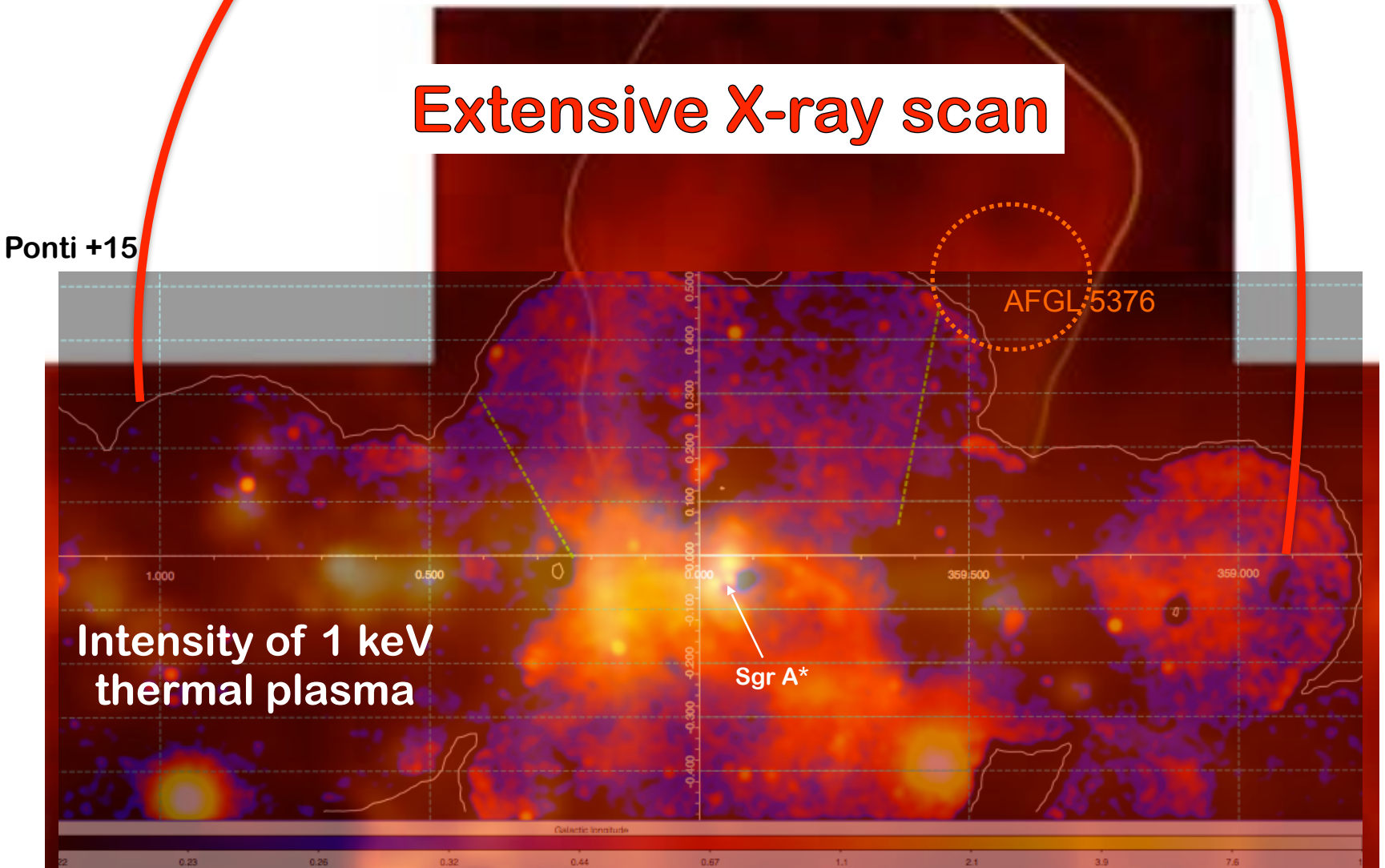


What is the origin of this hot plasma?

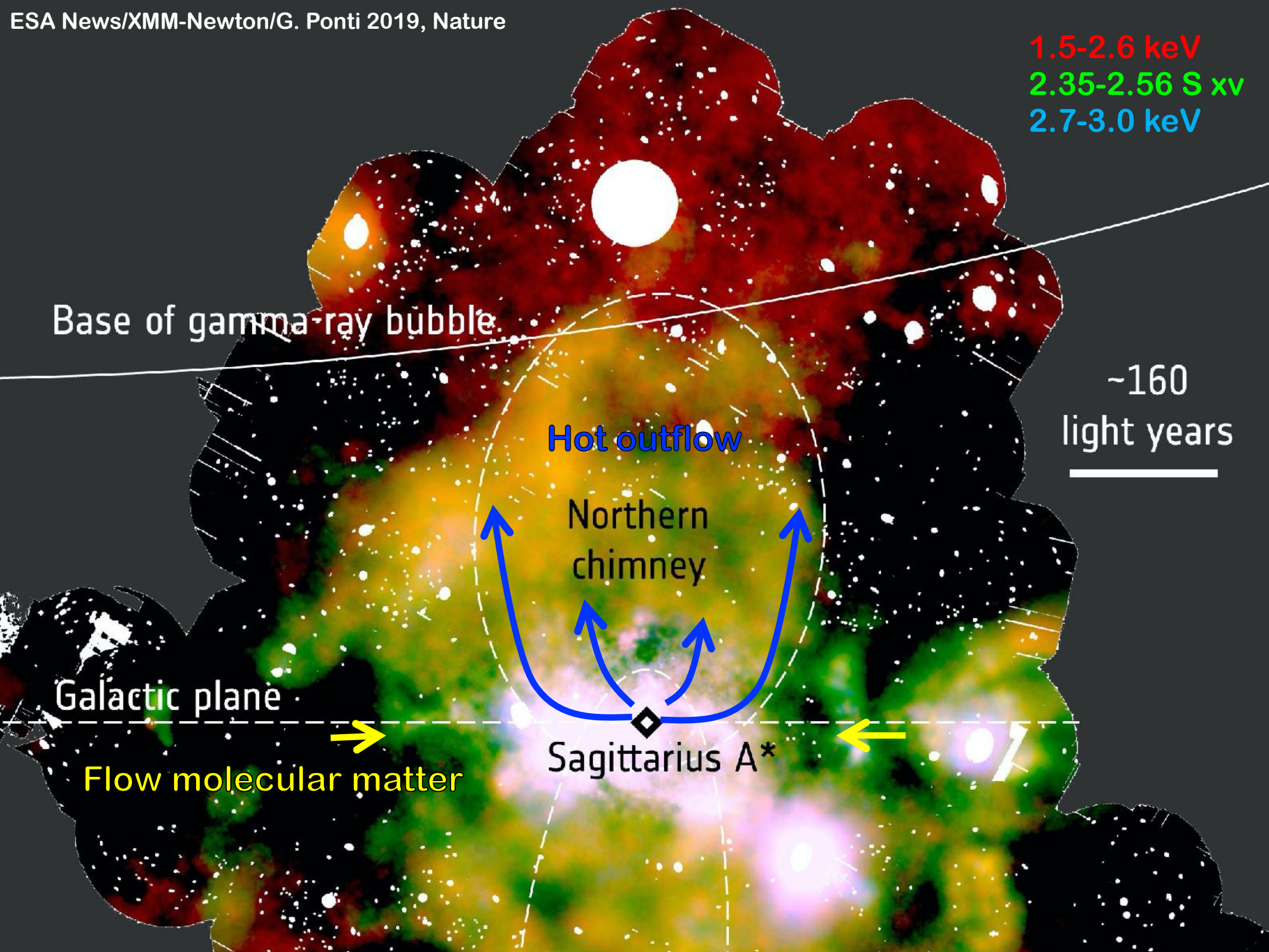
Hot atmosphere of the Galactic center?

Base of Galactic wind? Crocker +12

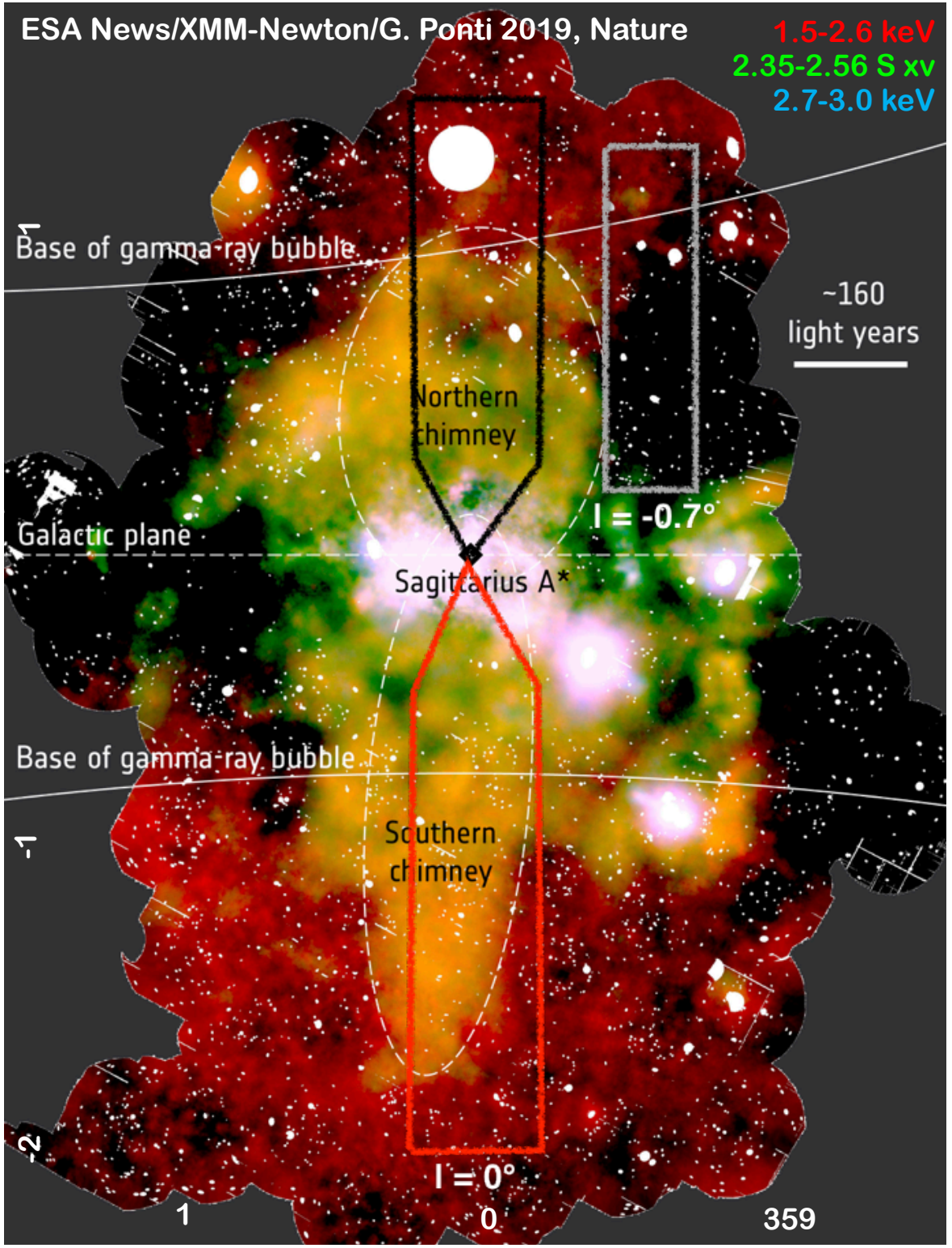
Past Sgr A*'s AGN-like activity? Bland-Hawthorn & Cohen 03

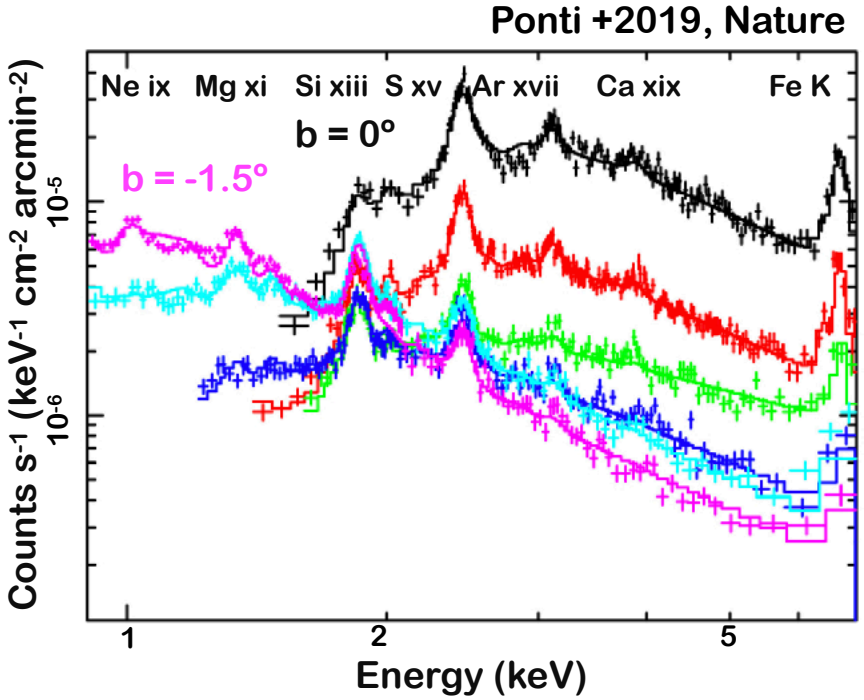


Suspense....

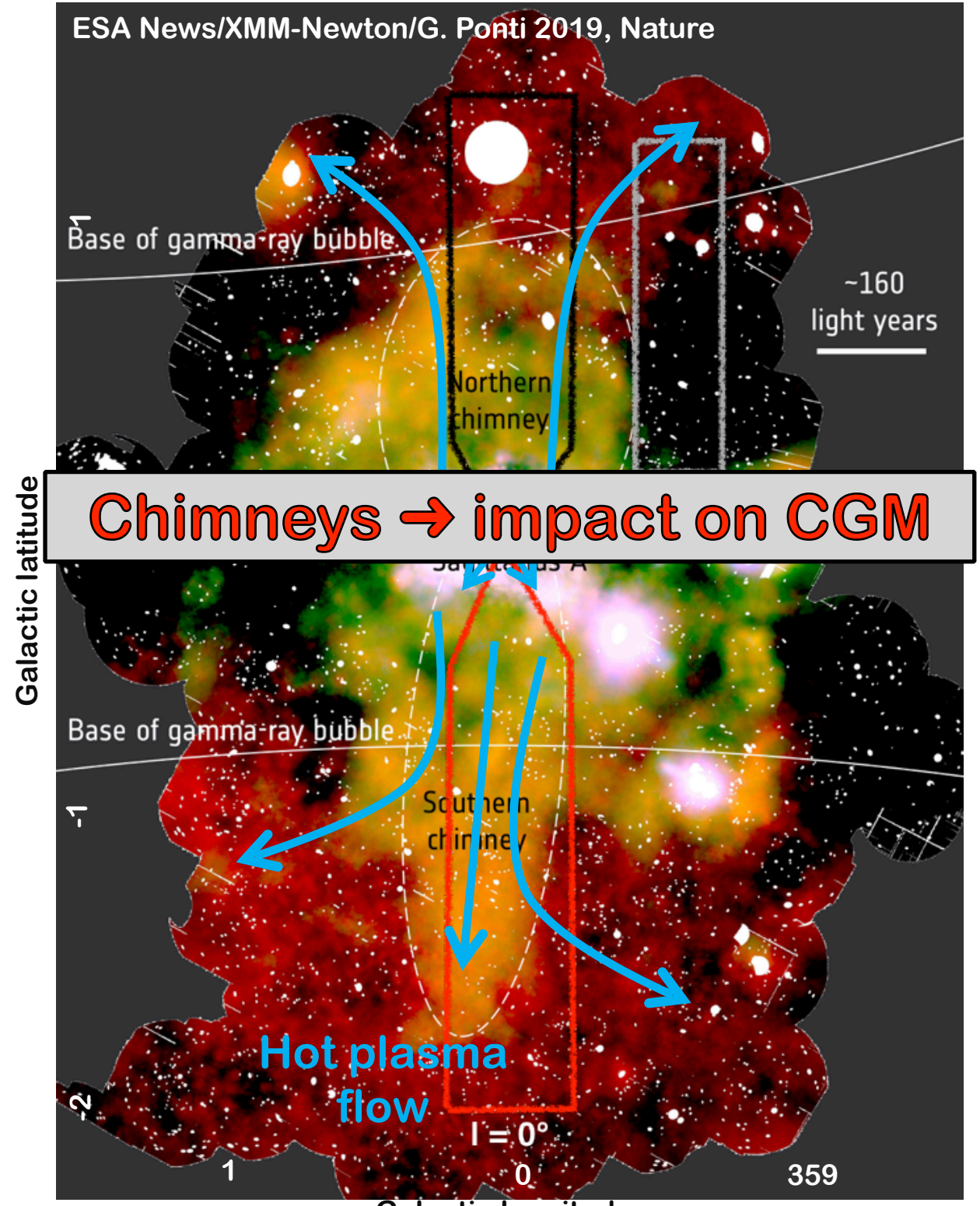

ESA News/XMM-Newton/G. Ponti 2019, Nature
1.5-2.6 keV
2.35-2.56 S xv
2.7-3.0 keV
Base of gamma-ray bubble
~160
light years
Hot outflow
Northern
chimney
Galactic plane
Sagittarius A*
Flow molecular matter

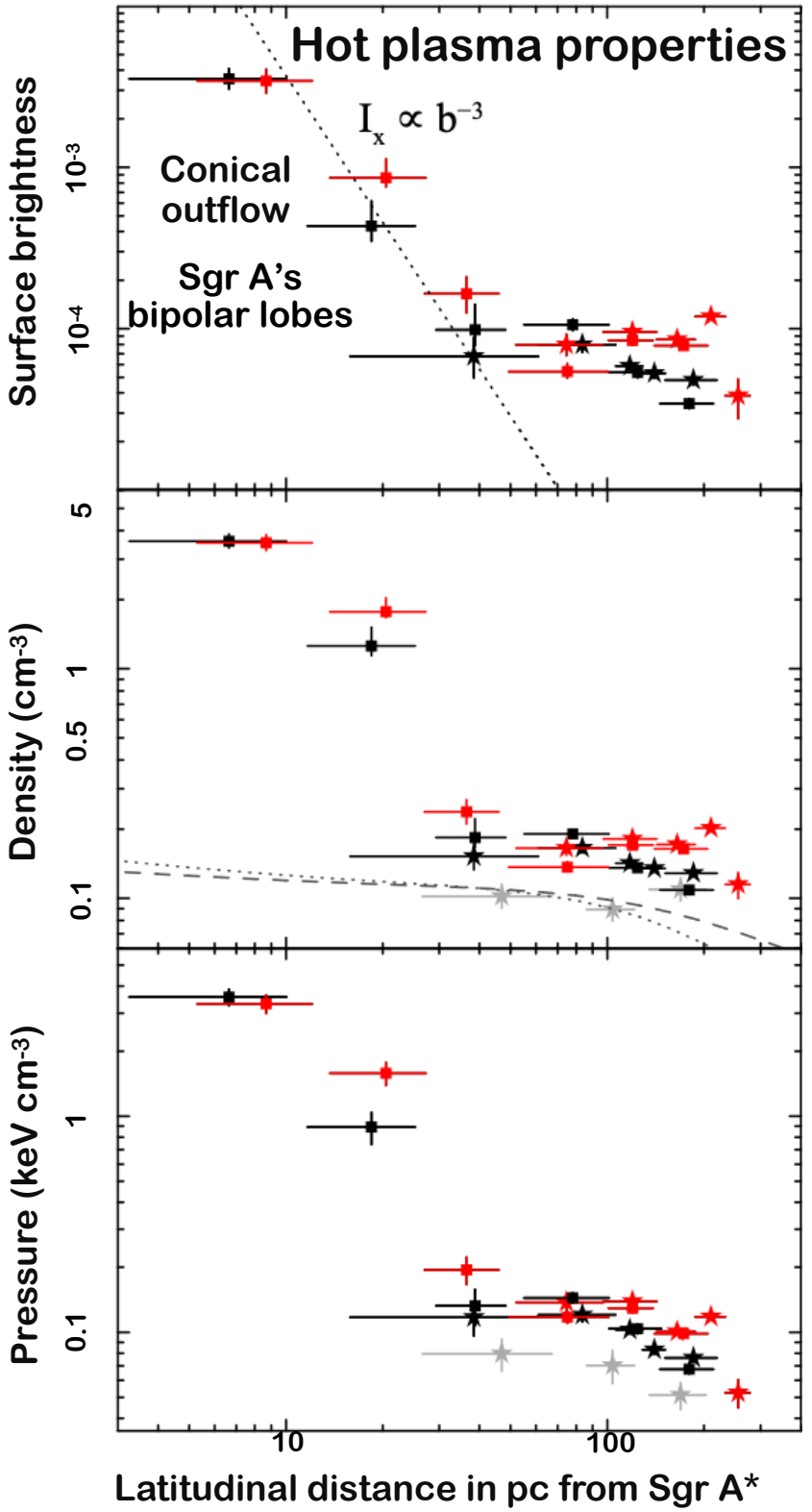
The Galactic center Chimneys



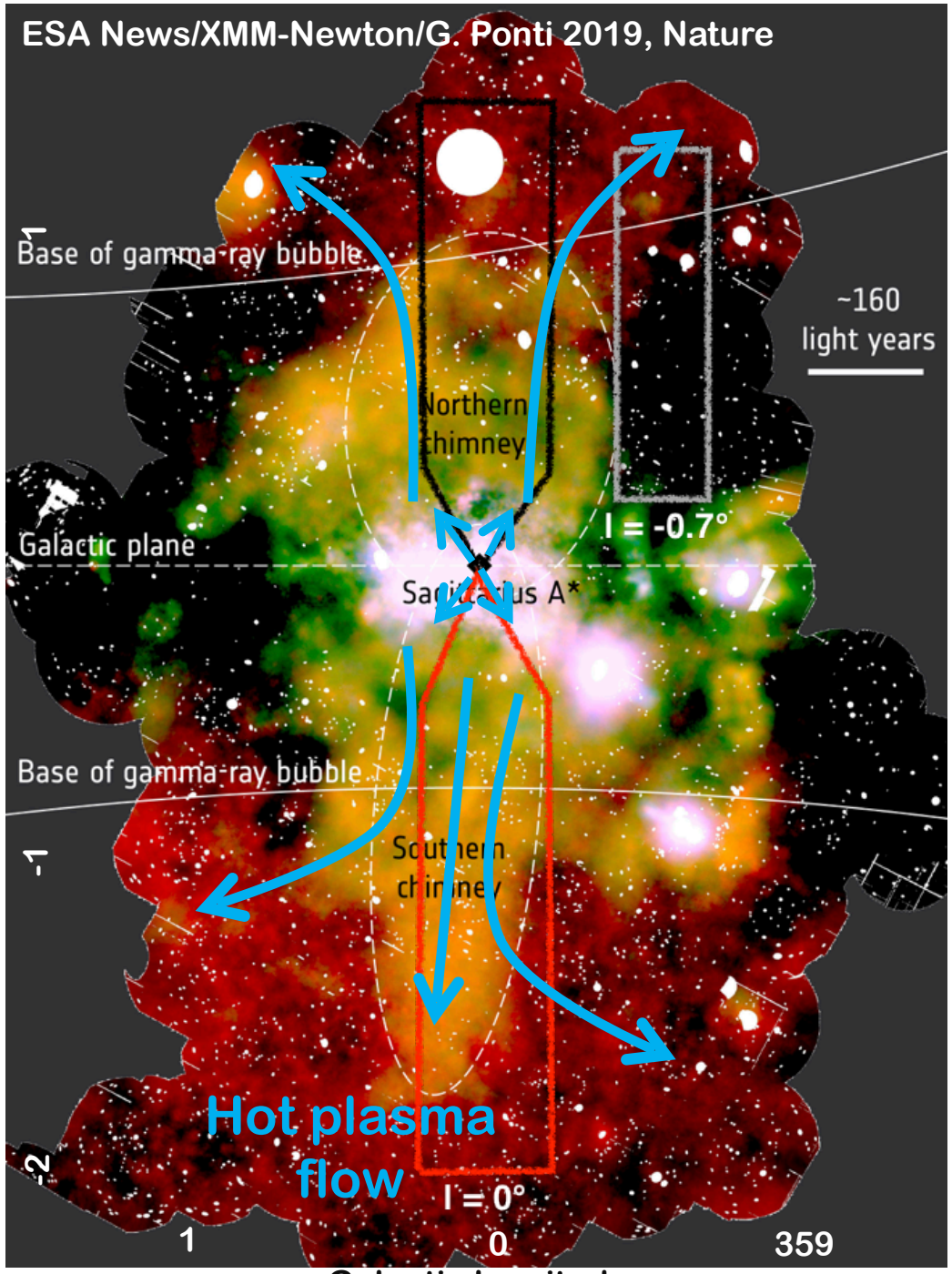


➜ Measure kT, n, p, abundances of hot plasma

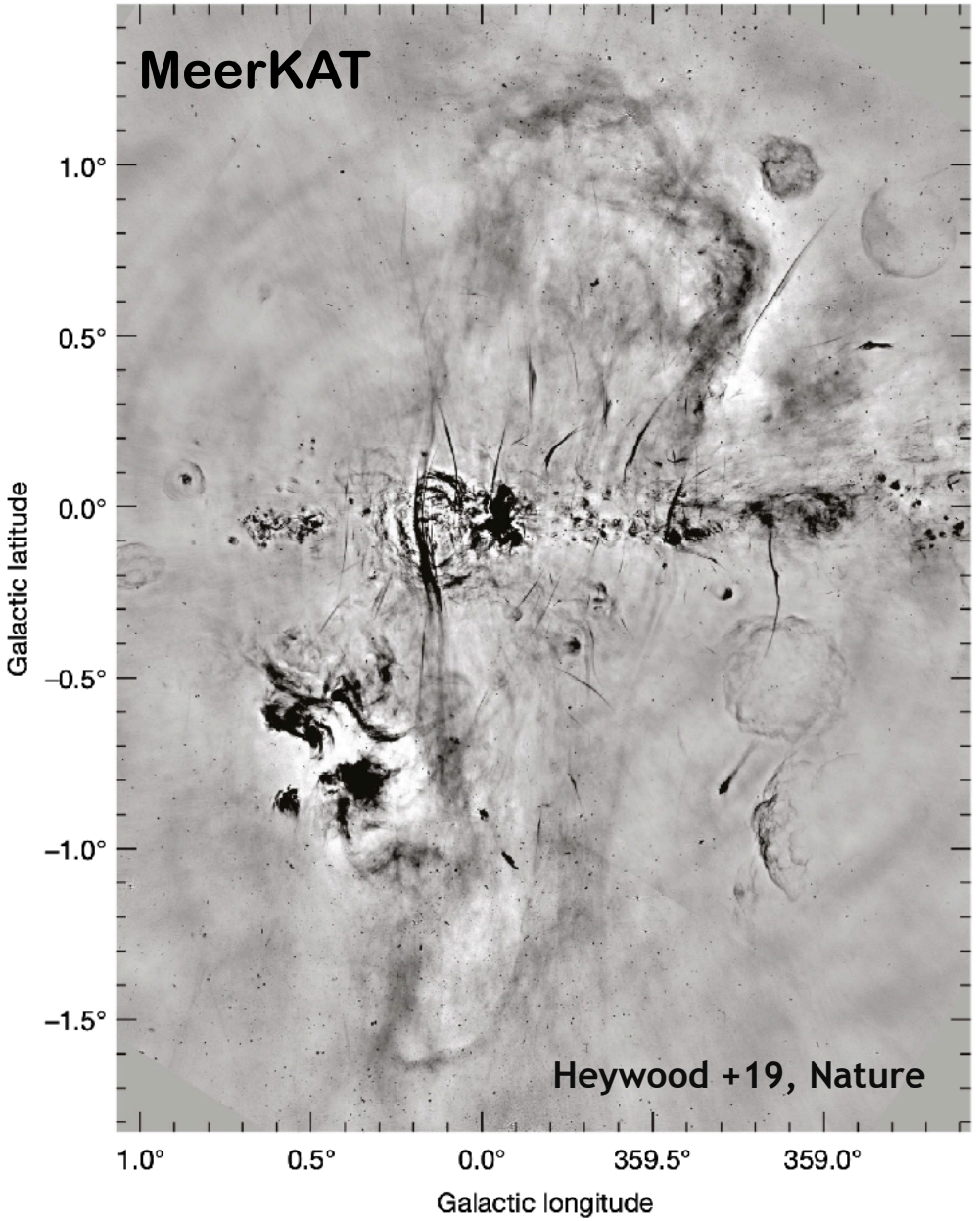

ESA News/XMM-Newton/G. Ponti 2019, Nature
Base of gamma-ray bubble
~160
light years
Northern
chimney
Chimneys → impact on CGM
Base of gamma-ray bubble
Southern
chimney
Hot plasma
flow
l = 0°
Galactic latitude
Galactic longitude
1
-1
-2
1
0
359


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
10
100
Latitudinal distance in pc from Sgr A*

The radio view of the Chimneys

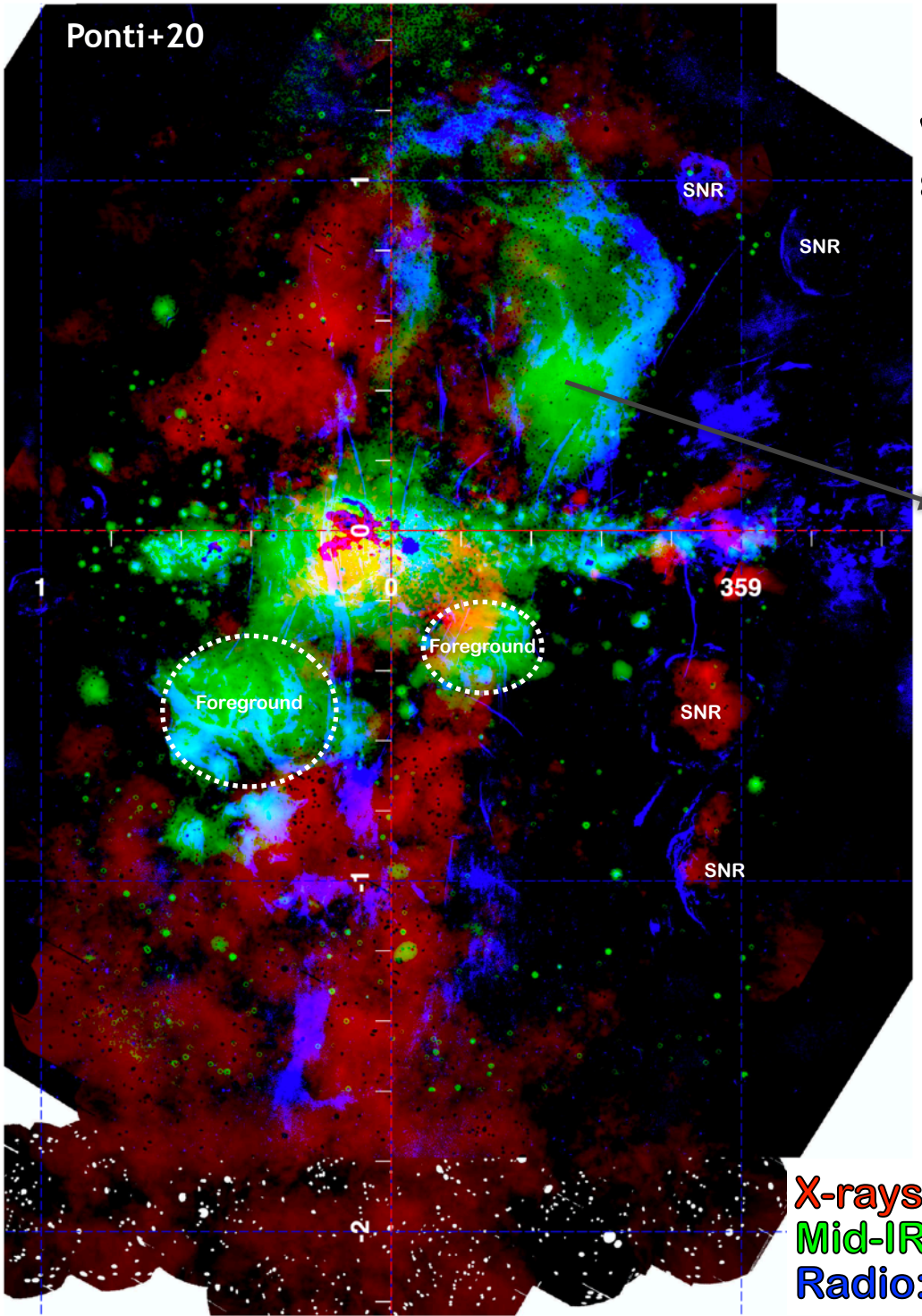


Radio traces edges of Chimneys



Outflow has radio counterpart

Multi-phase multi-epoch Galactic outflow



Hot plasma (X-rays)
warm dust (mid-IR)
shocks (radio) ➜ Coherent features on > 10^2 pc scales

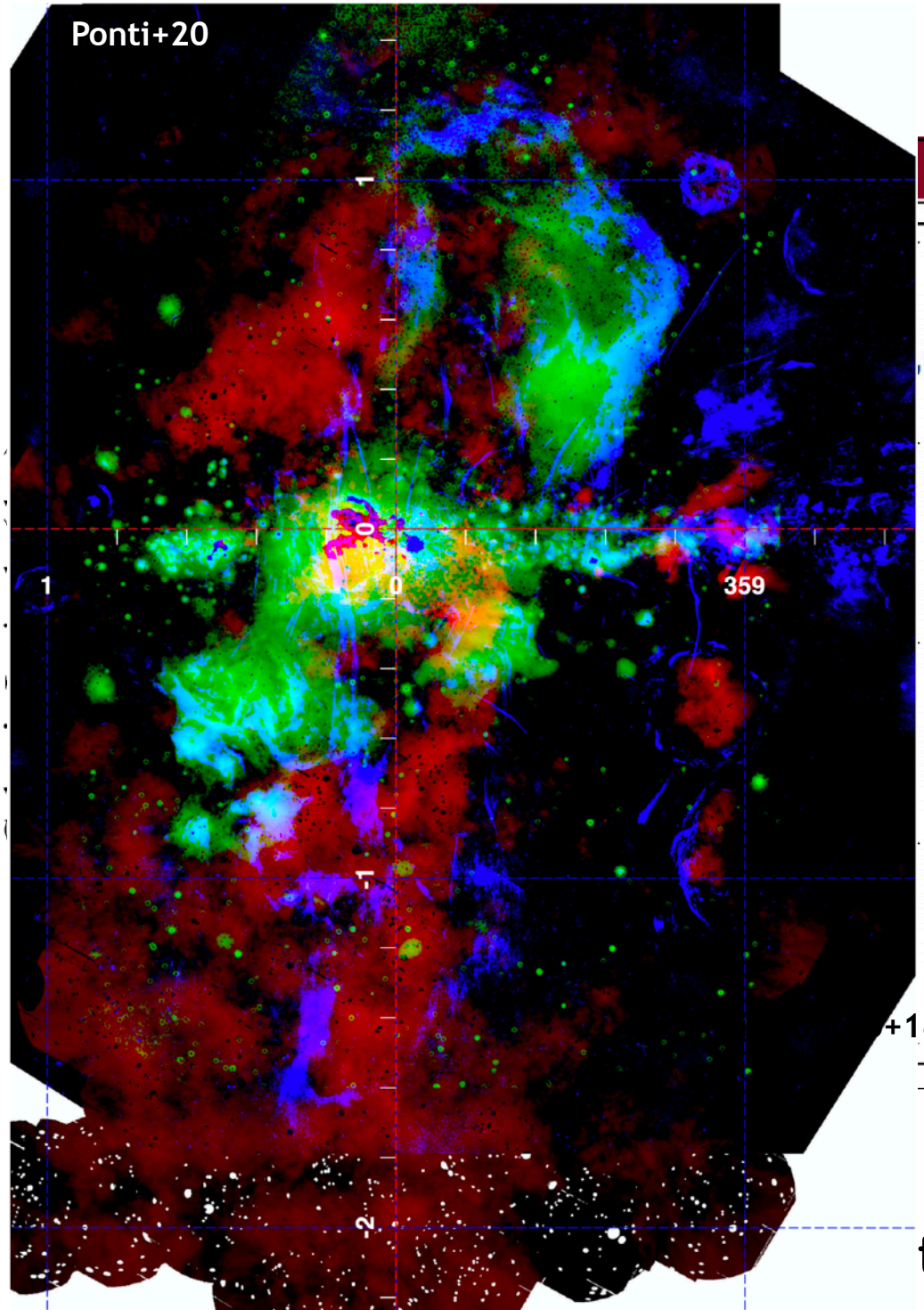
➜ Deeply interconnected and linked to the Galactic outflow

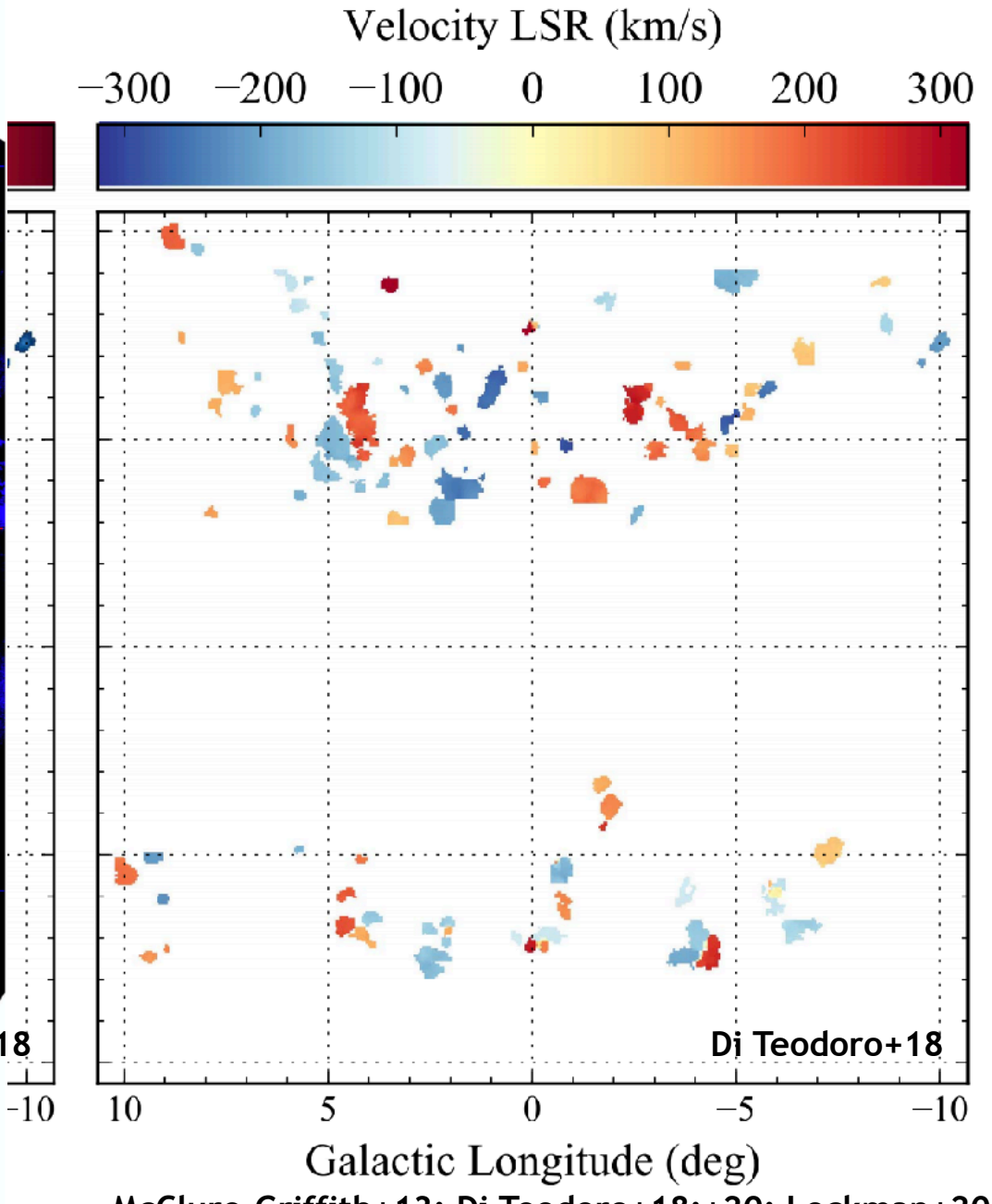
➜ Strong shocks at the chimney-ISM interface (radio + shorter-lived dust emission)

➜ AFGL 5376 > 0.1 kpc molecular shock
Uchida+94

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

Large scale cold Galactic outflow

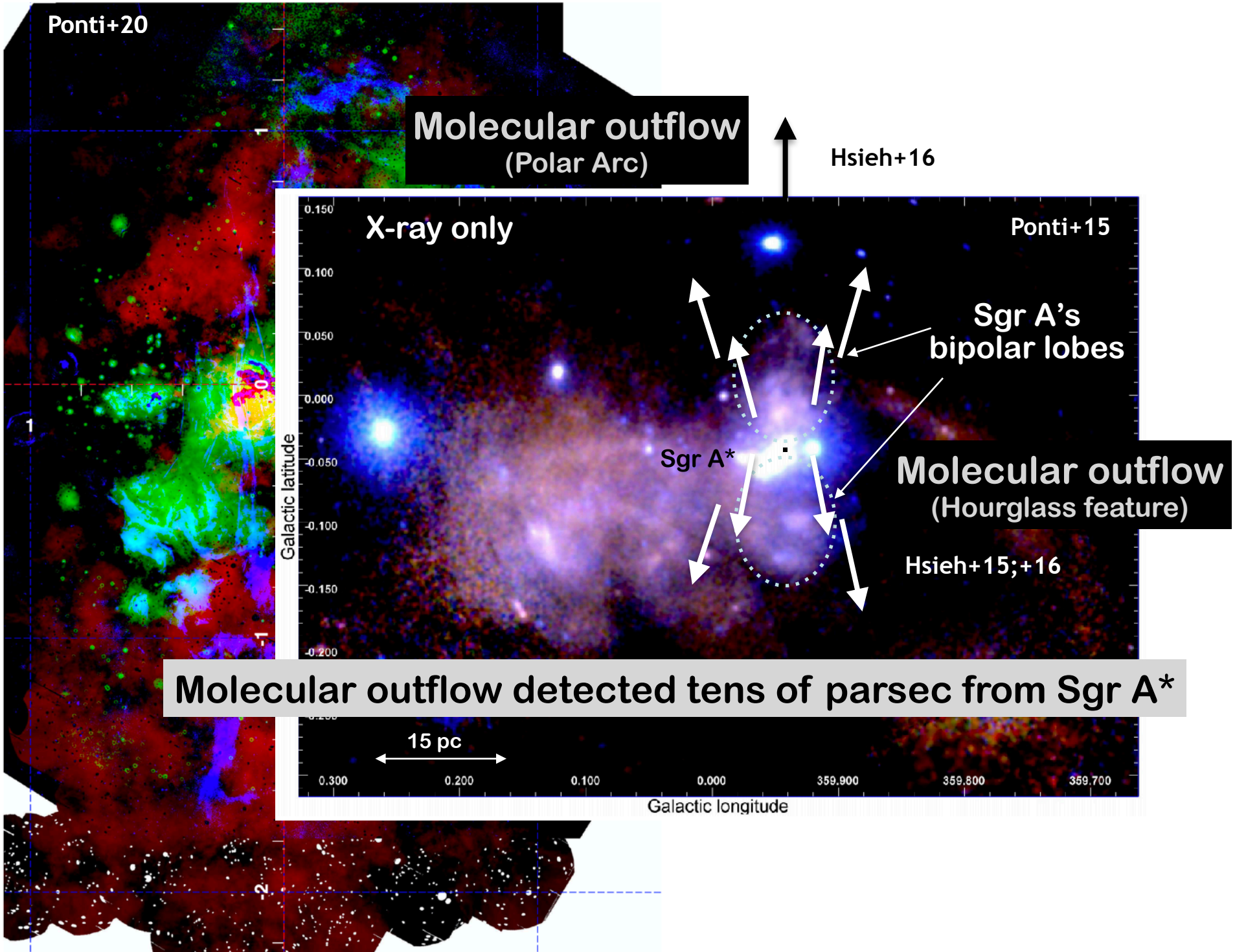




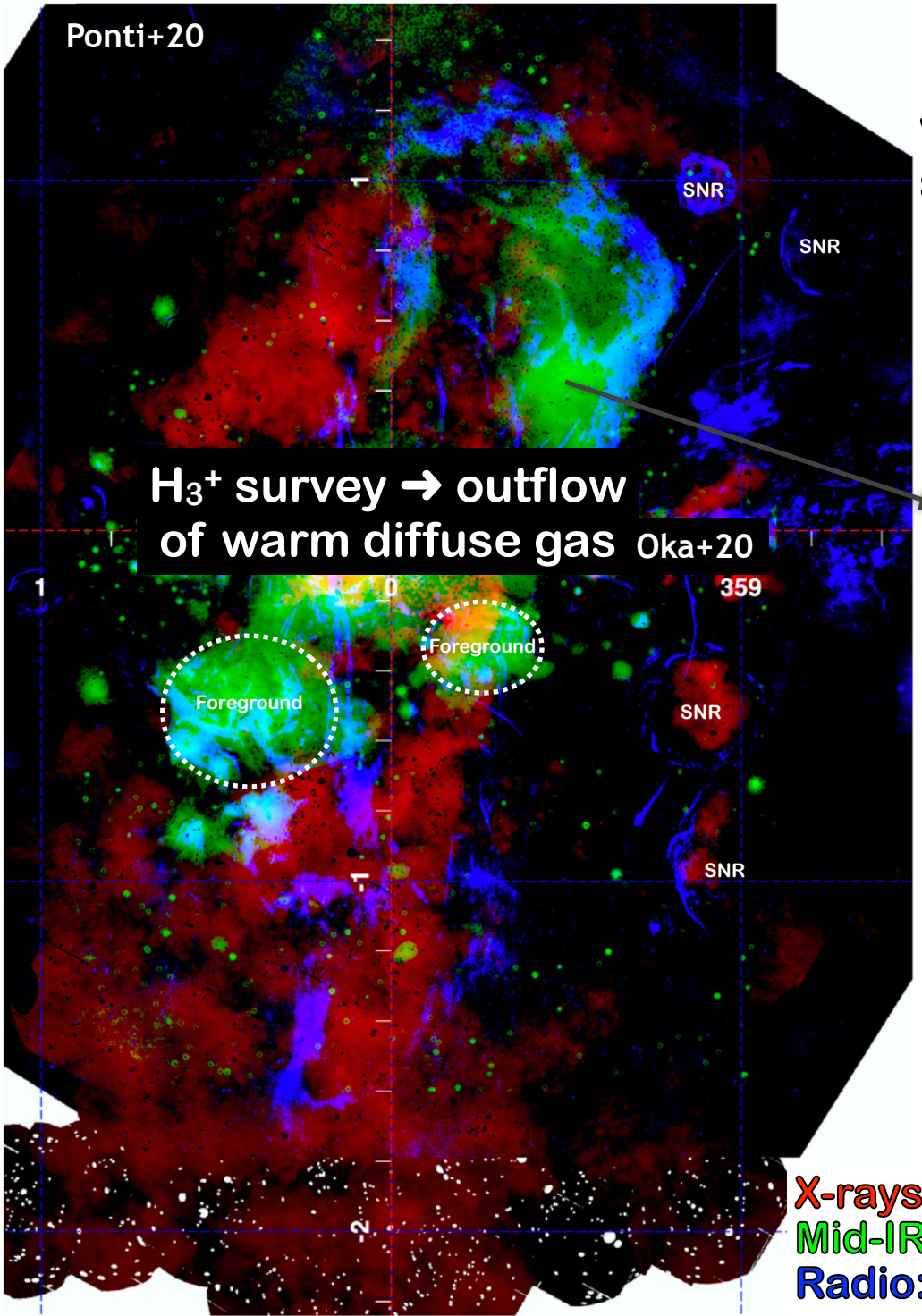
McClure-Griffith+13; Di Teodoro+18;+20; Lockman+20

t the base of the Fermi bubbles

Small scale molecular Galactic outflow



Multi-phase multi-epoch Galactic outflow



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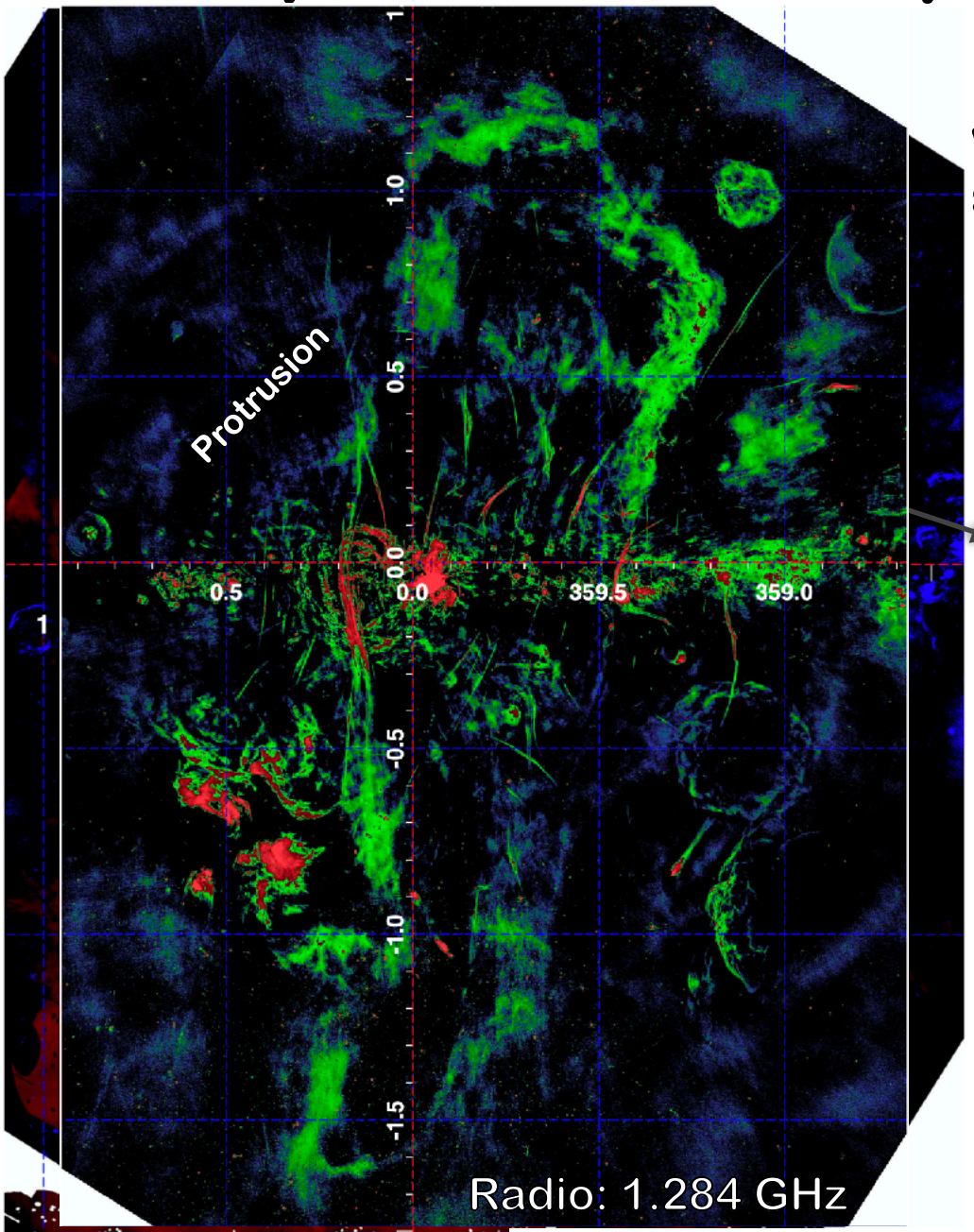
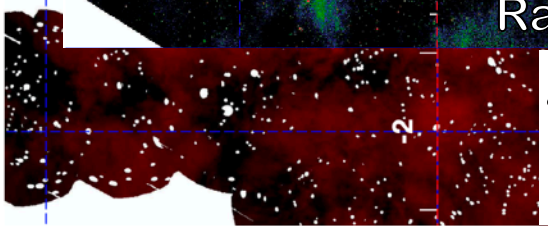
Multi-phase multi-epoch Galactic outflow





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→ Multi-phase (hot, molecular, warm-diffuse)

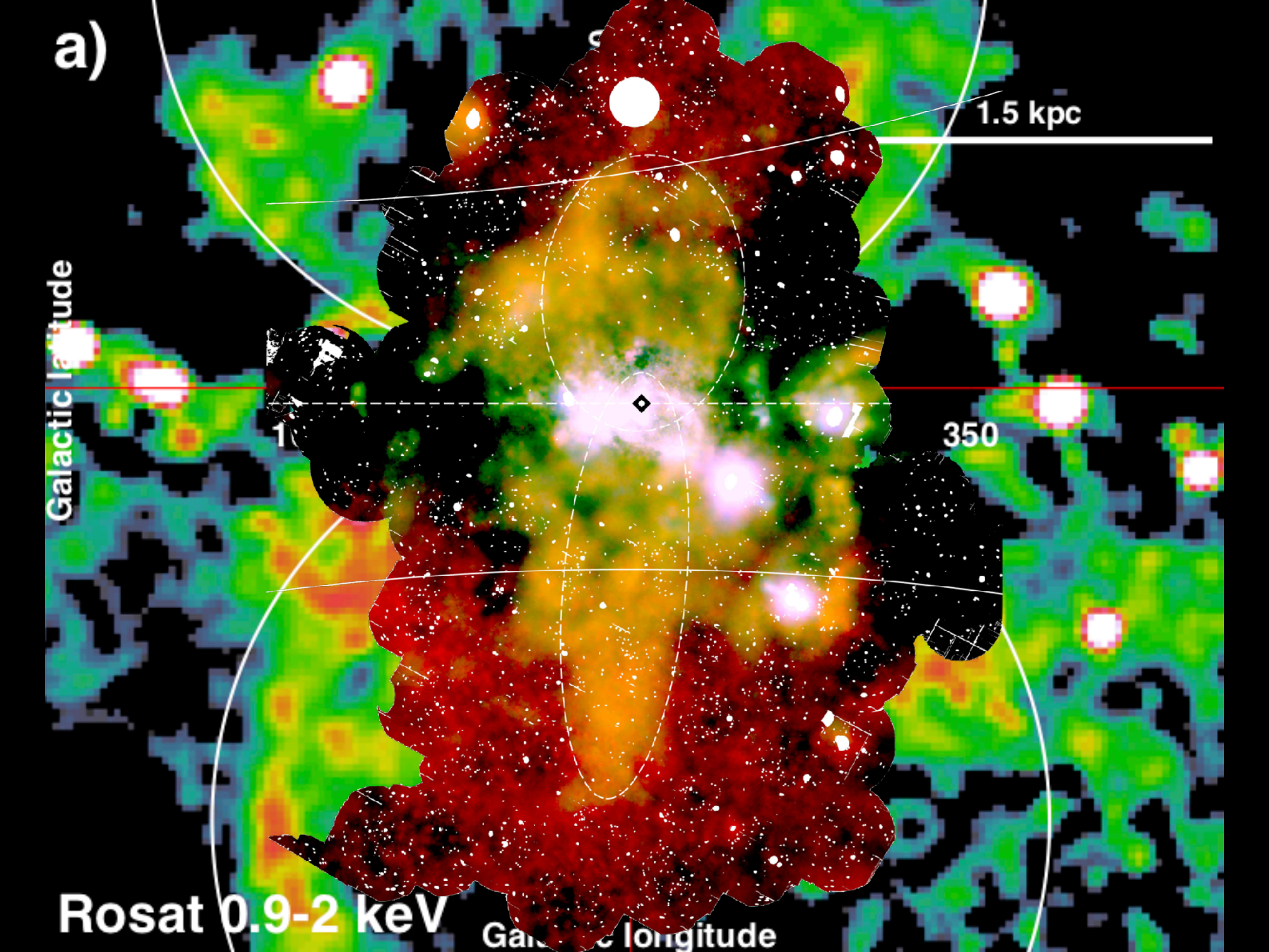
→ Multi-scale and multi-epoch outflow

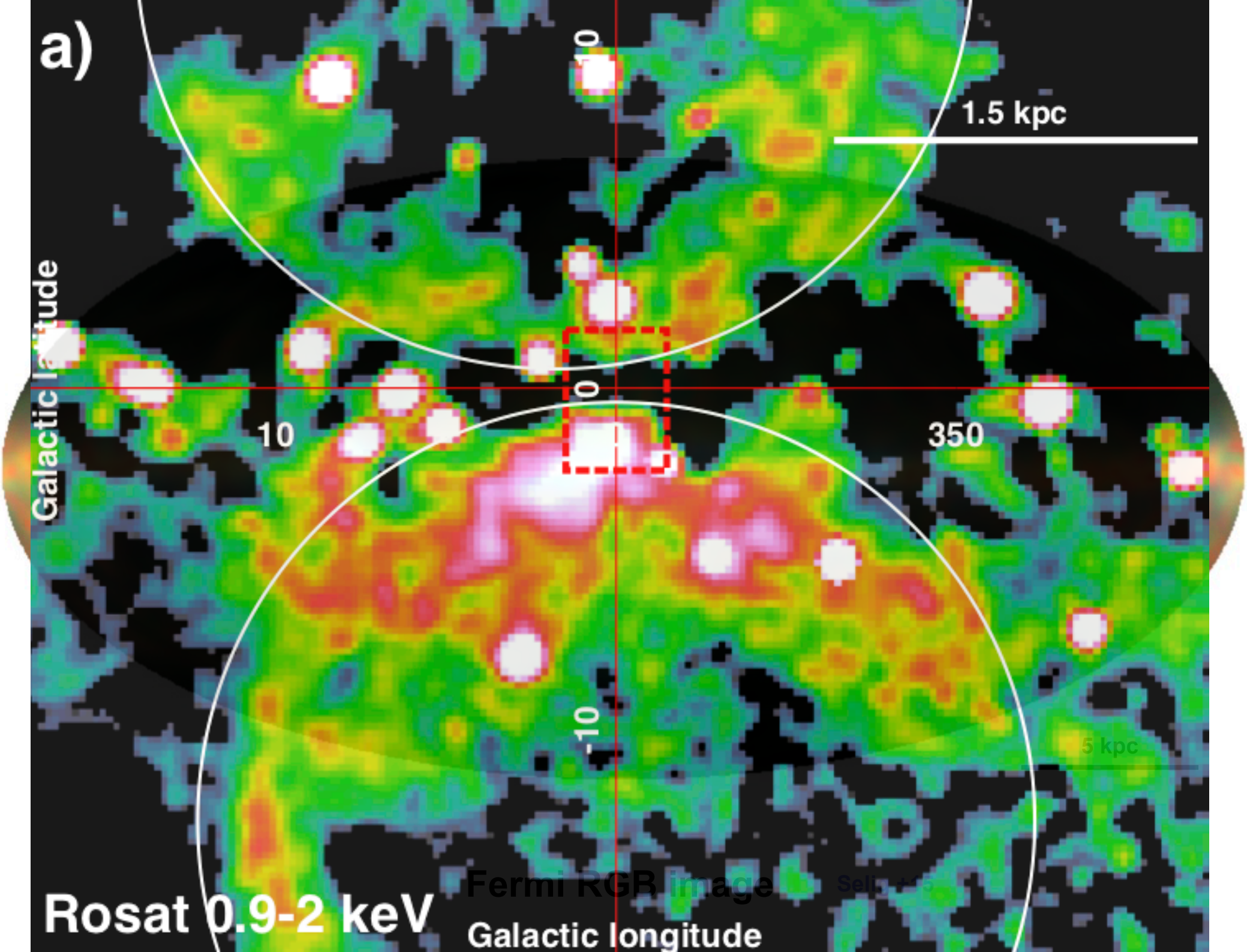
→ Vertical (dominant? B~0.1-1 mG) magnetic field diverging beyond |b|~0.5°

→ Hot (X-ray) plasma cannot drive outflow
Relic? Dark? outflow

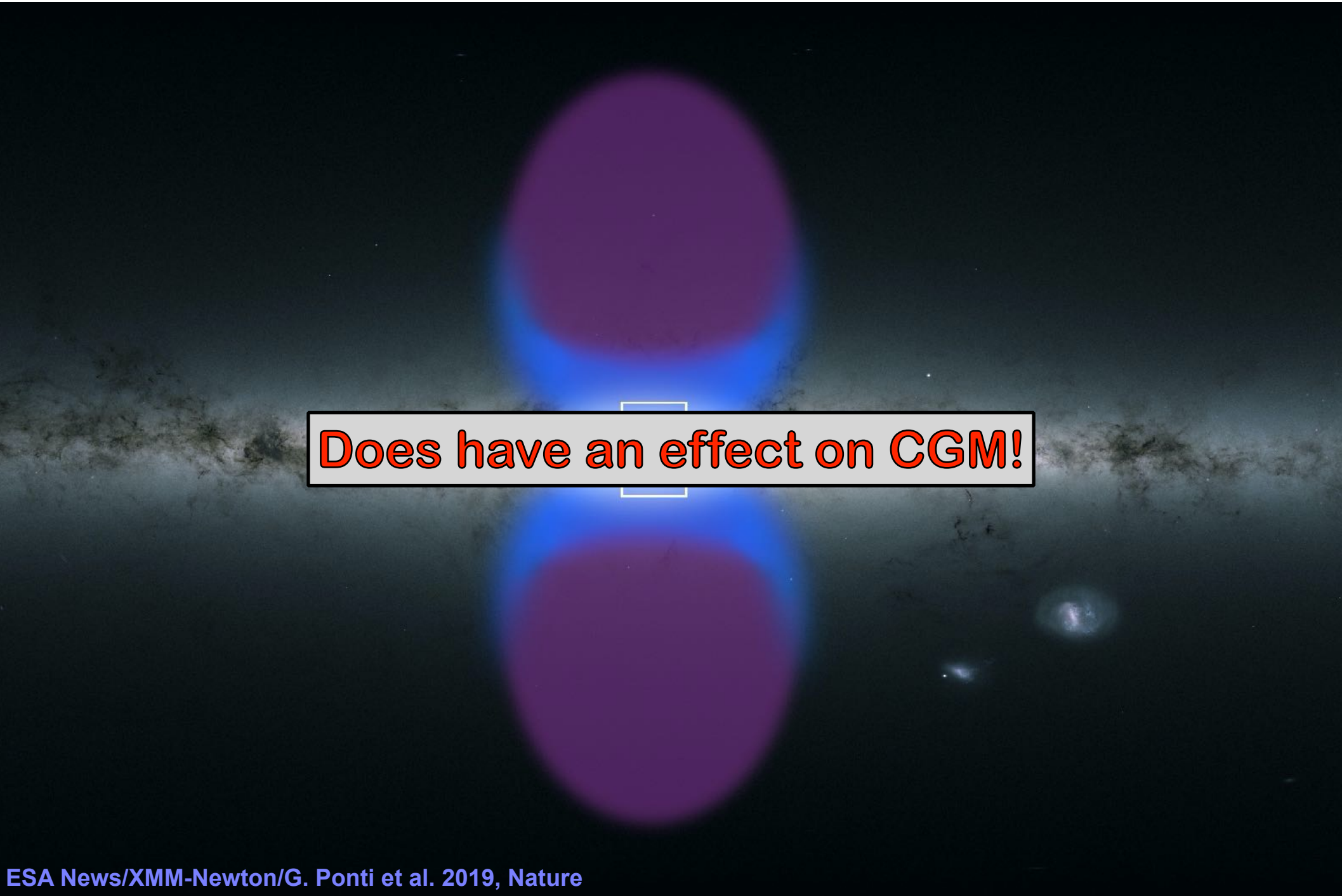
What we do not understand:

Origin of protrusion?
Why not perfectly symmetric?
Relic outflow? Dark outflow?
AGN driven? Starburst?


a)
1.5 kpc
Galactic latitude
1
350
Rosat 0.9-2 keV
Gal c longitude


a)
10
1.5 kpc
Galactic latitude
0
10
350
-10
5 kpc
Rosat 0.9-2 keV
Fermi RGB image
Galactic longitude

The channel feeding the Fermi bubbles



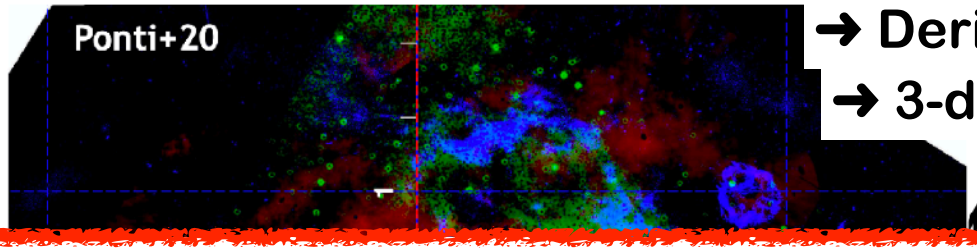
ESA News/XMM-Newton/G. Ponti et al. 2019, Nature

Summary

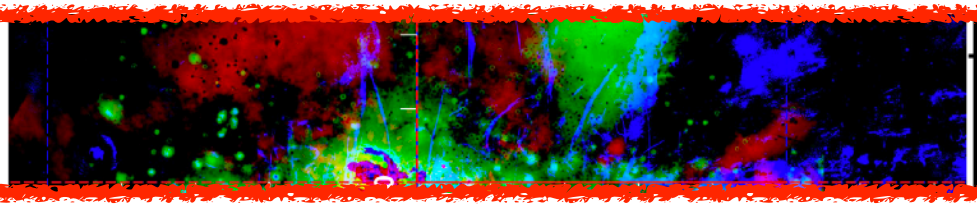
X-ray polarisation

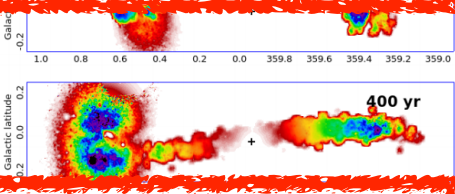
➜ Derive Sgr A*'s light curve

➜ 3-d distribution of clouds

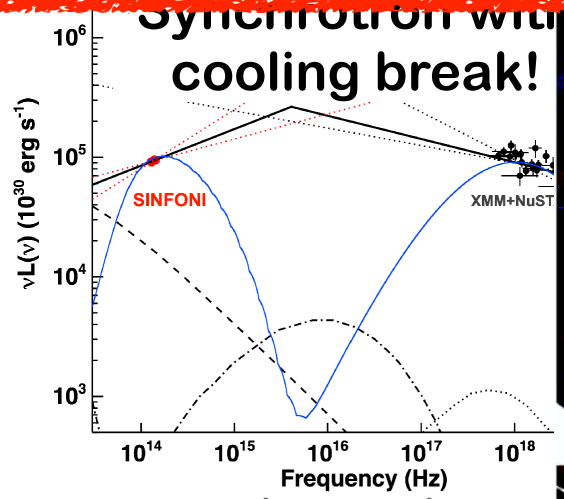


Normal galaxies hold outflows to CGM



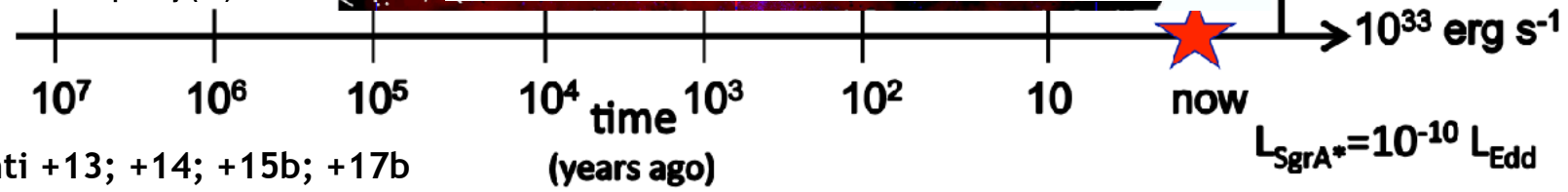


How is the disc-CGM exchange?



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

➜ Outflow multi-phase, multi-epoch and multi-scale



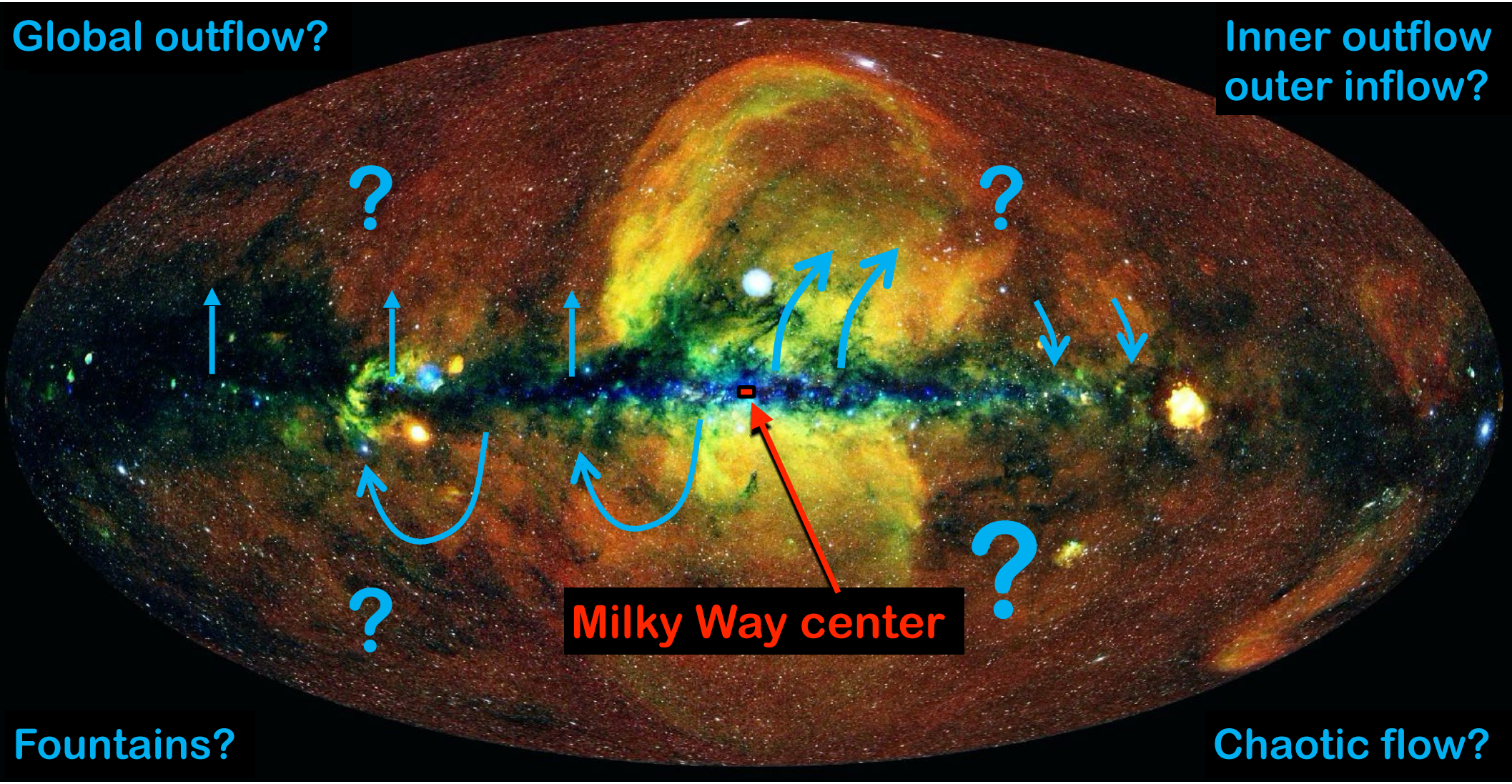
Ponti +13; +14; +15b; +17b

eROSITA (Spektr-RG)'s launch

Baikonur, July 13th, 2019

Source: Roscosmos

Map the flows of hot Galactic Baryons

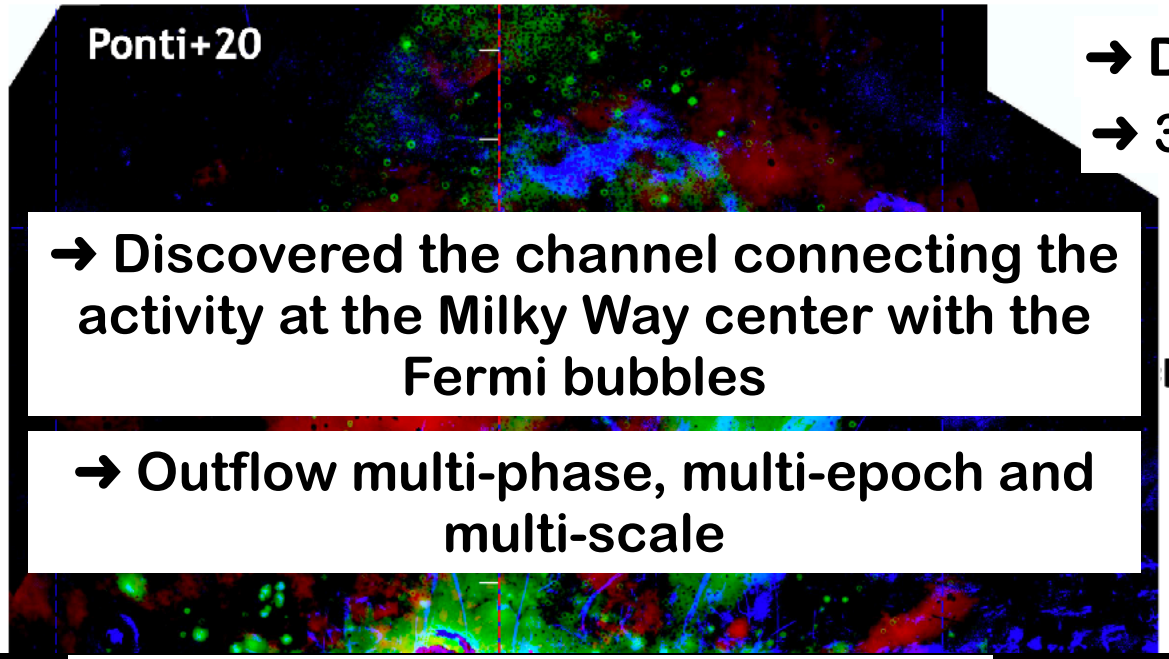


Conclusions

X-ray polarisation

➜ Derive Sgr A*'s light curve

➜ 3-d distribution of clouds



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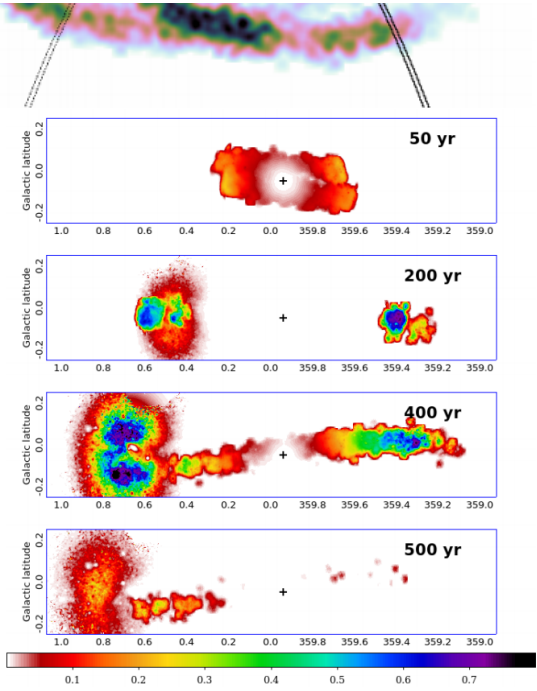
Fermi Bubbles
(starburst event?)
Magellanic stream

Starbursts?

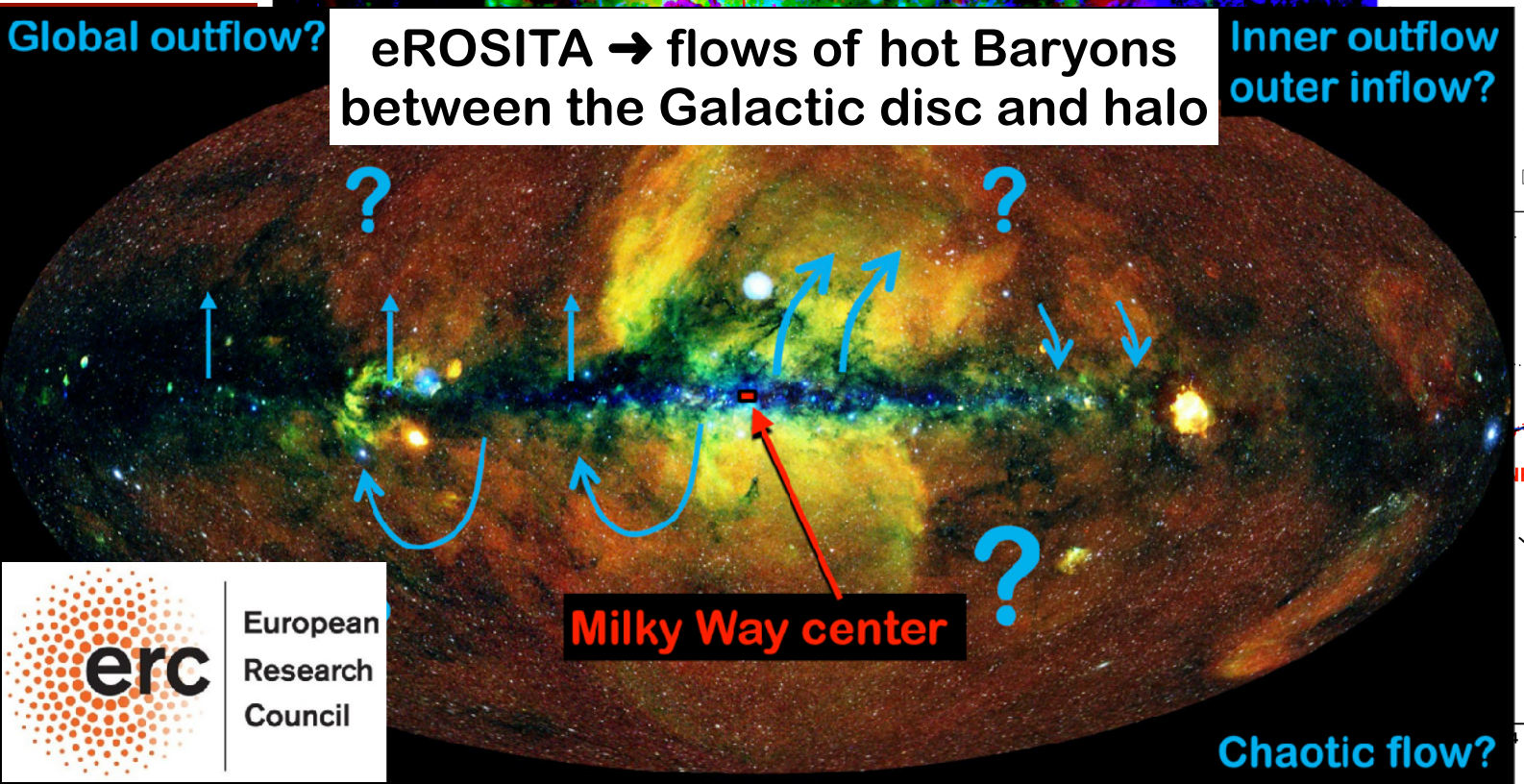
L_{Edd}



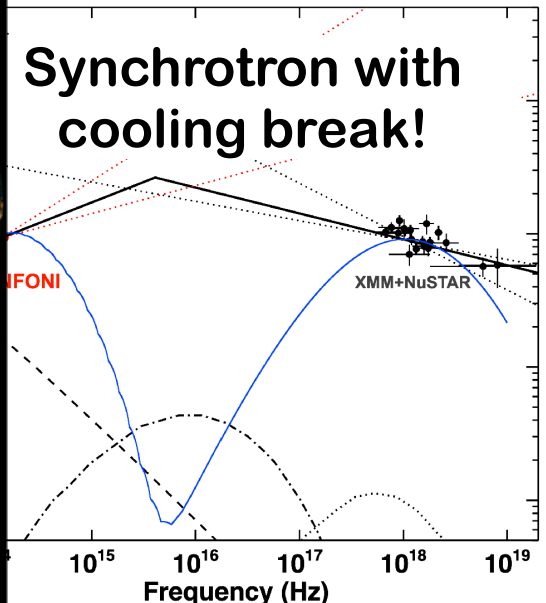
Global outflow?

eROSITA ➜ flows of hot Baryons between the Galactic disc and halo

Inner outflow
outer inflow?

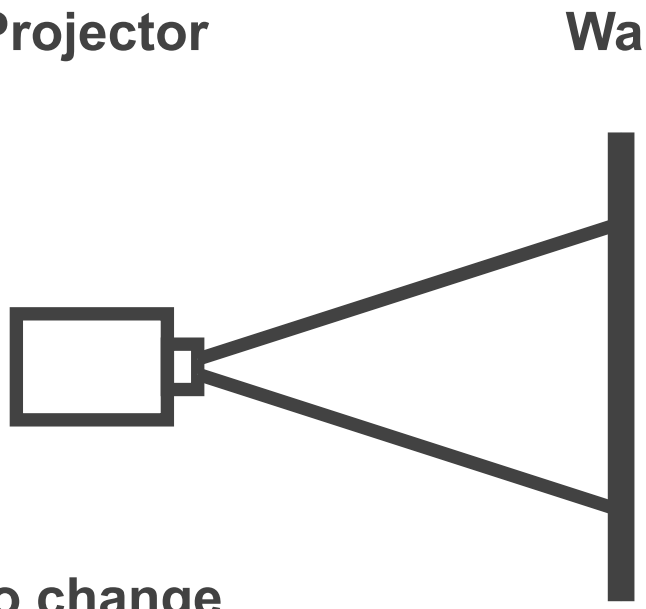


Chaotic flow?



erc European Research Council

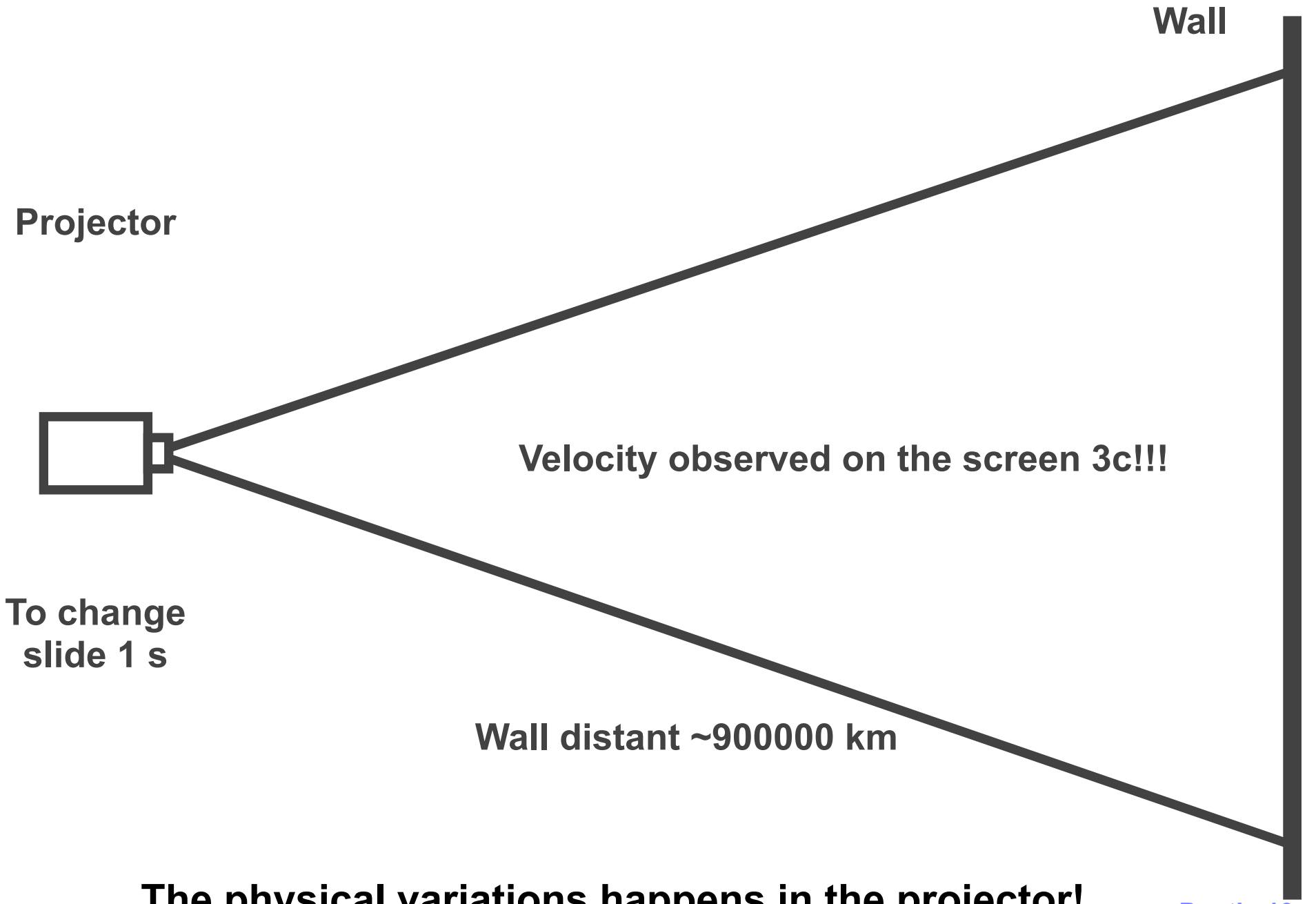
How can a super-luminal echo happen?



Velocity observed on the screen 1m/1s

e.g. Ponti +10;+13

How can a super-luminal echo happen?



The physical variations happens in the projector!

e.g. Ponti +10;+13

Conclusions

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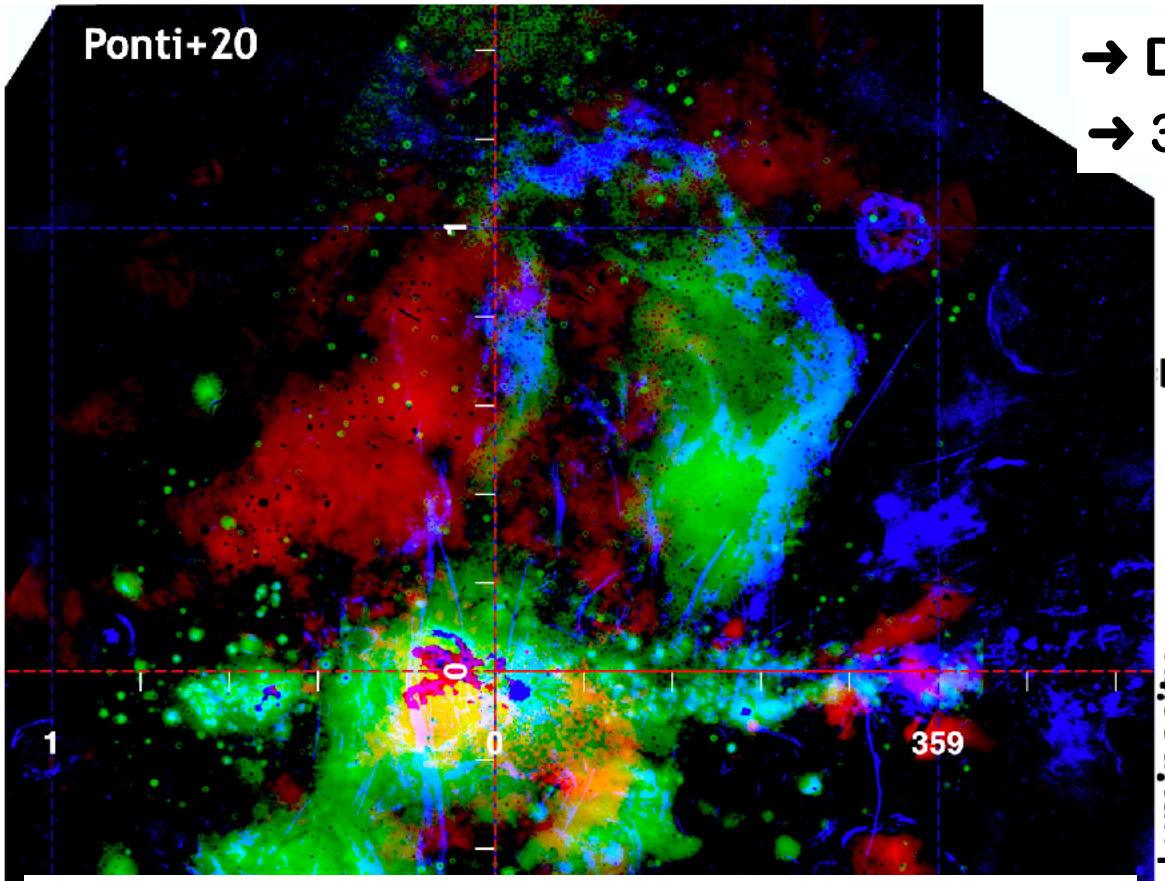

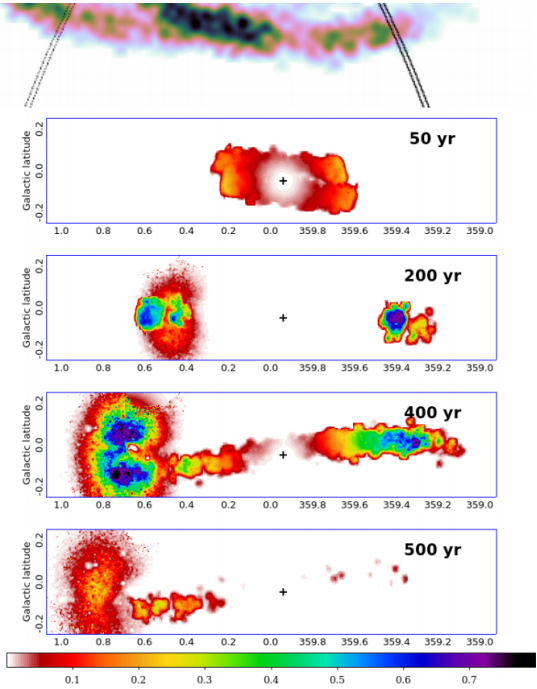

L_{Edd}

Luminosity (erg s^{-1})

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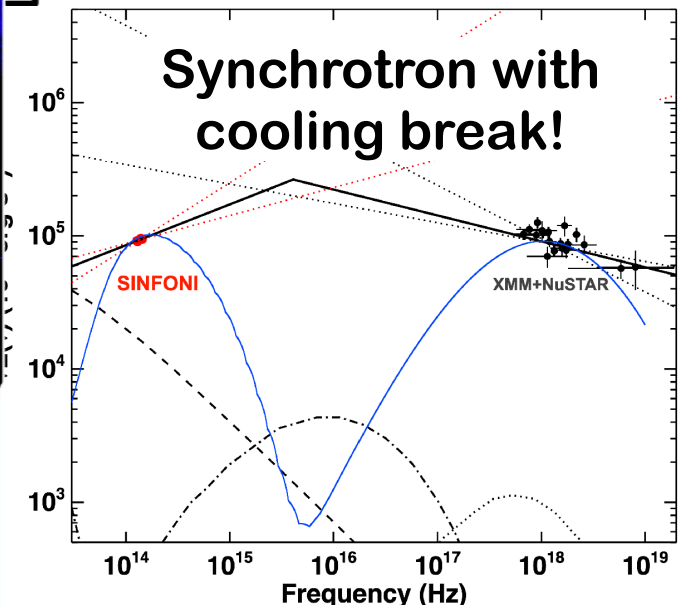

10^7 10^6

Ponti +13; +14;