Is SS 433 a misaligned ultra-luminous X-ray source ?

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Ultra-luminous X-ray sources (ULXs)

=

extragalactic

off-nuclear

pointlike X-ray sources

with luminosity

above the Eddington limit

for a 10 M_{Sun} black hole

Super-critically accreting stellar-mass black holes with moderate collimation

King et al. 2001, Rappaport et al. 2005, Begelman et al. 2006, Poutanen et al. 2007

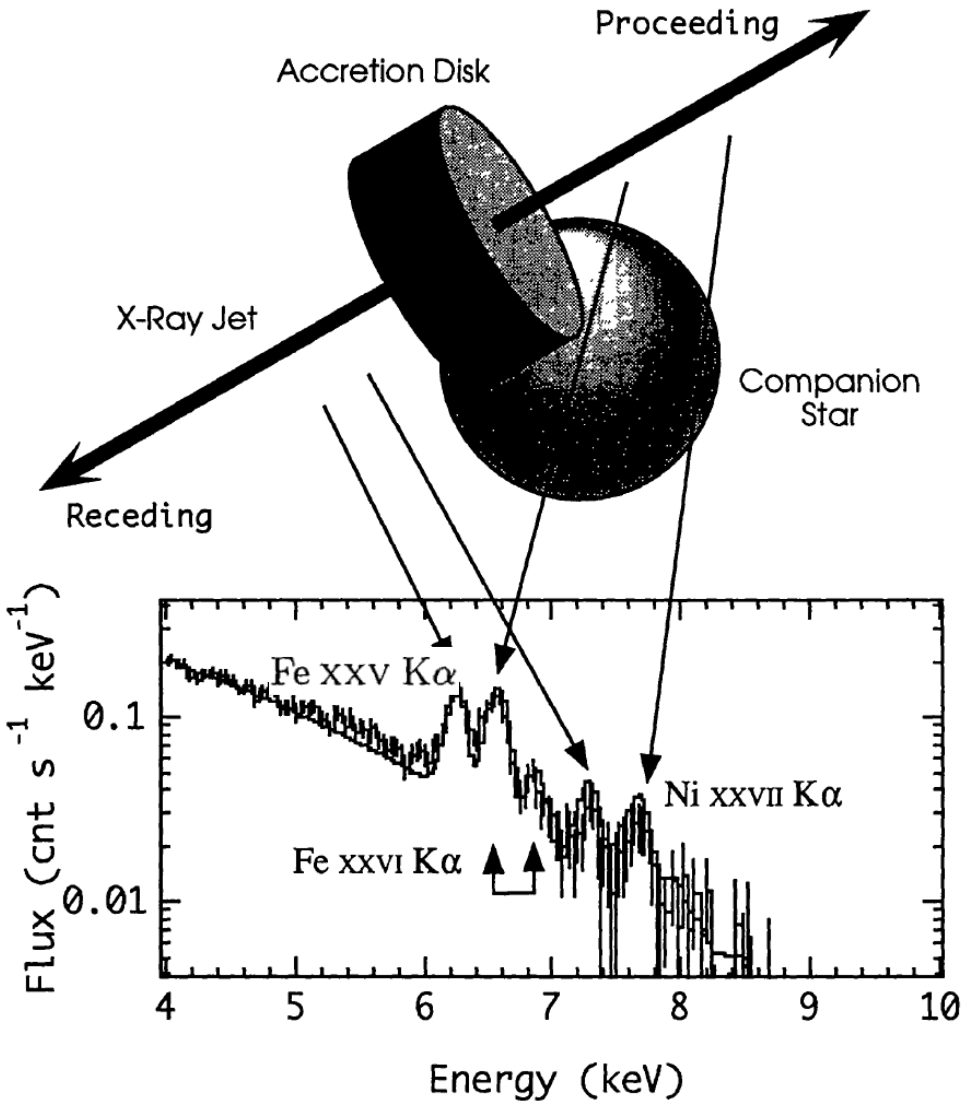
Super-critically accreting neutron stars

Bachetti et al. 2014; Israel et al. 2016, Fuerst et al. 2016

Intermediate-mass (100-10^4 M_{Sun}) black holes

Kaaret et al. 2001, Miller et al. 2003

Galactic super-accretor SS 433



Kotani et al. 1997

Powerful winds

$dM_w/dt \sim 400\ M_{cr}$

van den Heuvel et al. 1981, Fabrika 2004

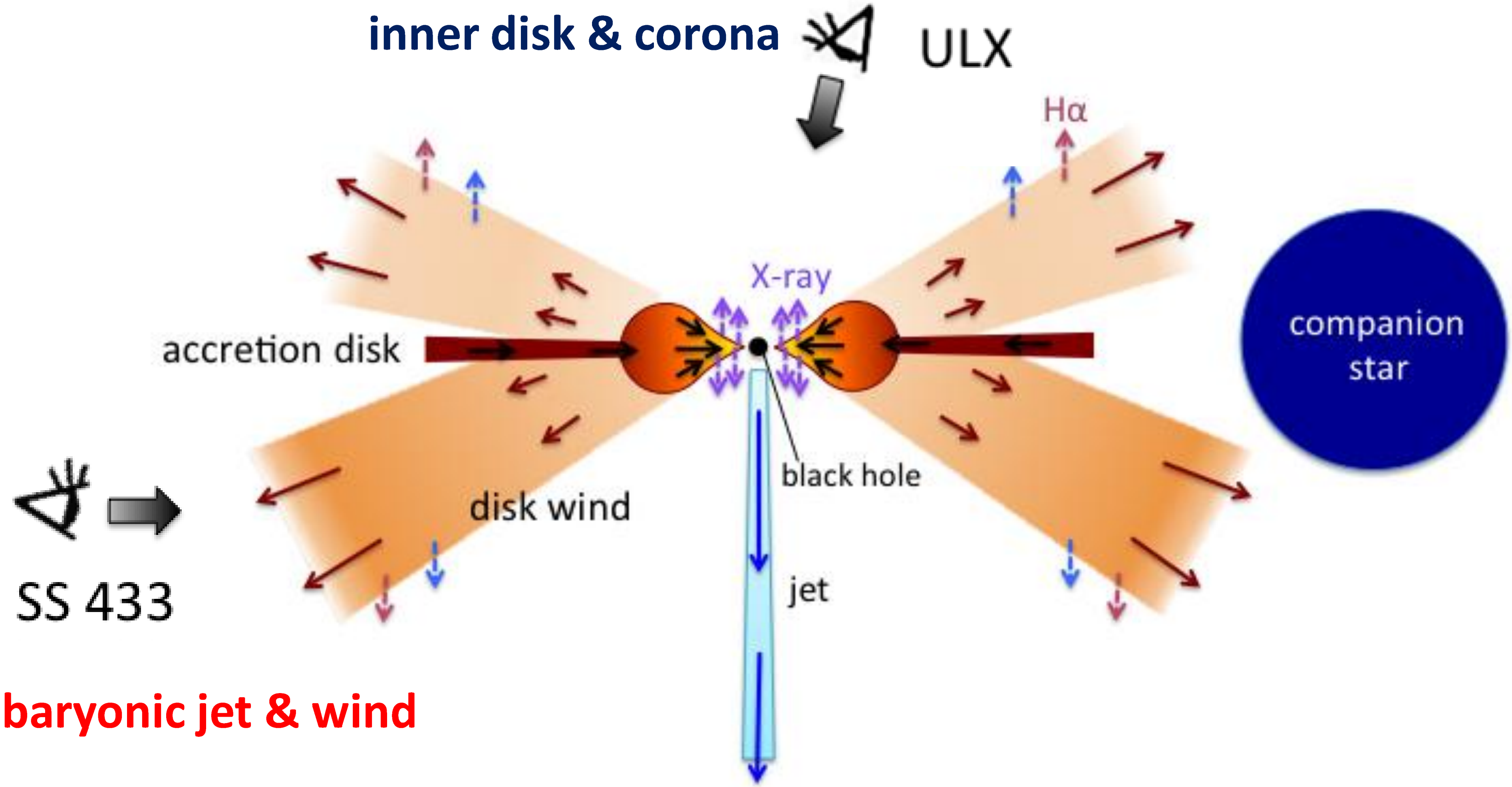
X-ray emission from <u>baryonic jets</u>

$L_X \sim 10^{36}$ erg/s

$L_k \sim 10^{39}$ erg/s

Kotani et al. 1997, Marshall et al. 2002, Medvedev & Fabrika 2010, Khabibullin et al. 2016

Are ULXs on-axis SS 433s?



Is SS 433 an off-axis ULX?

Image credit:
Kyoto University

Is SS 433 a misaligned ULX ?

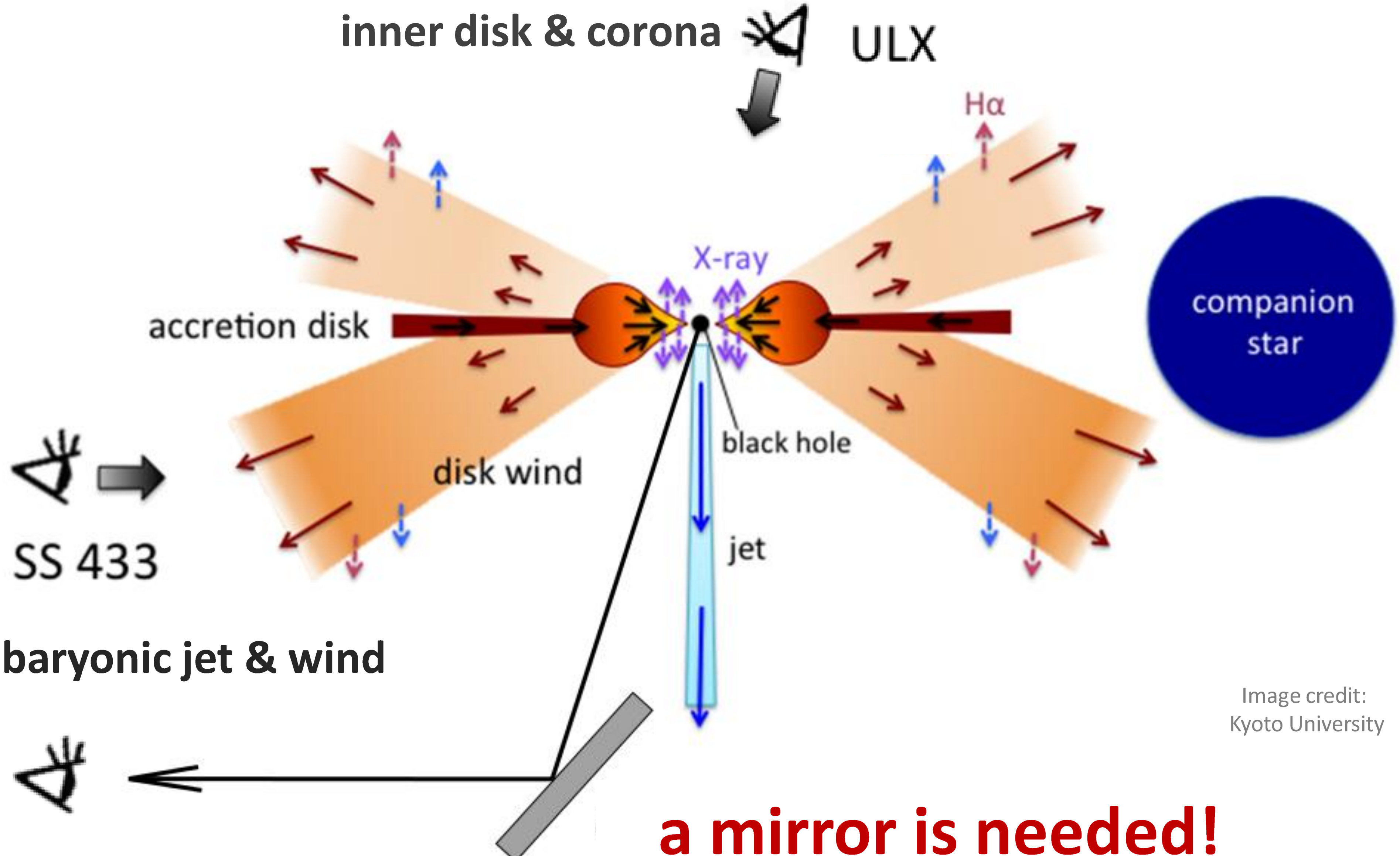


Image credit: Kyoto University

a mirror is needed!

What if we have no mirror?

Holmes was sitting with his back to me,
and I had given him no sign of my occupation.

"How did you know what I was doing?
I believe you have eyes in the back of your head."

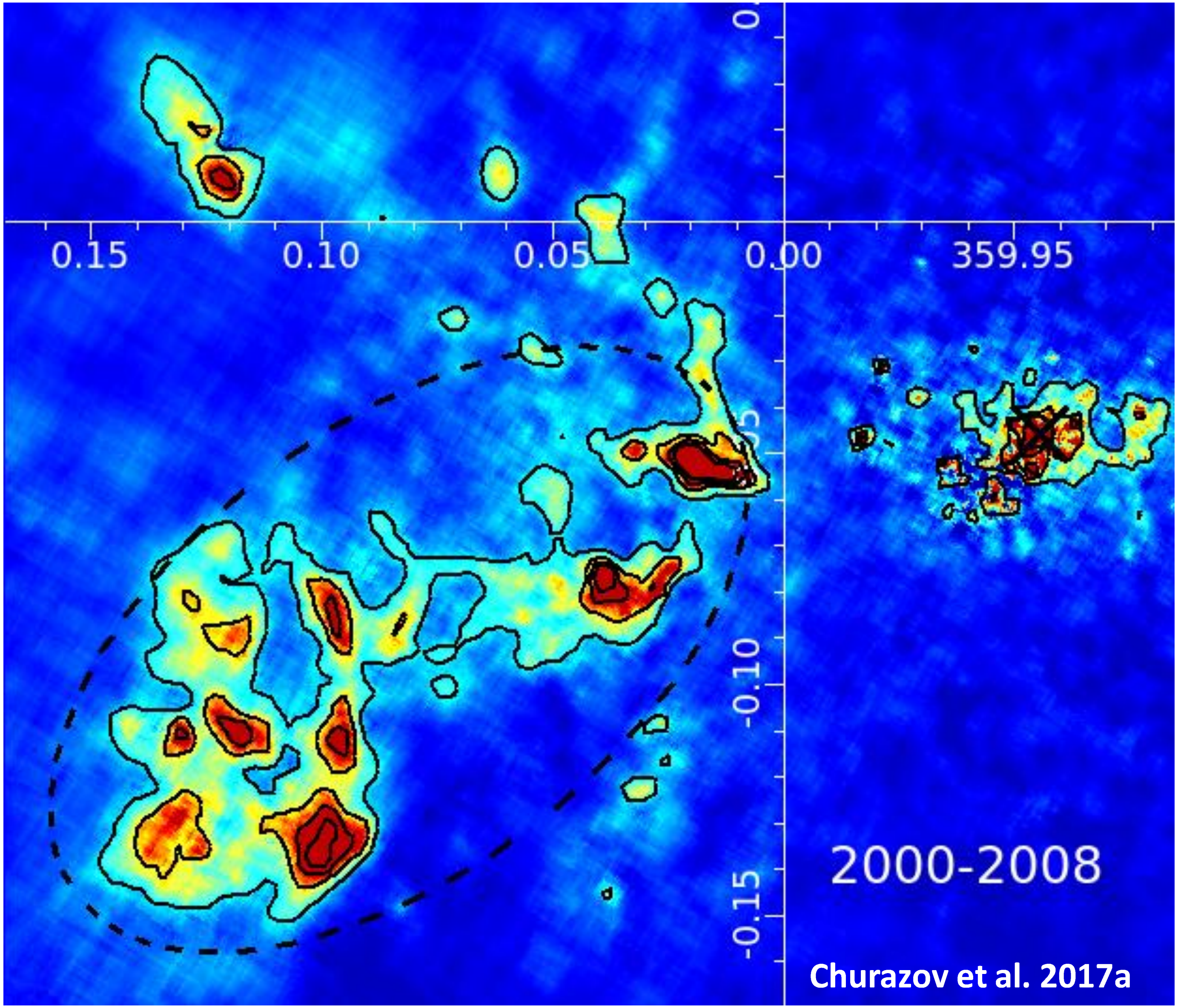
"I have, at least, a well-polished,
silver-plated coffee-pot in front of me."

A. Conan Doyle, The Hound of the Baskervilles

We have atomic and molecular gas!

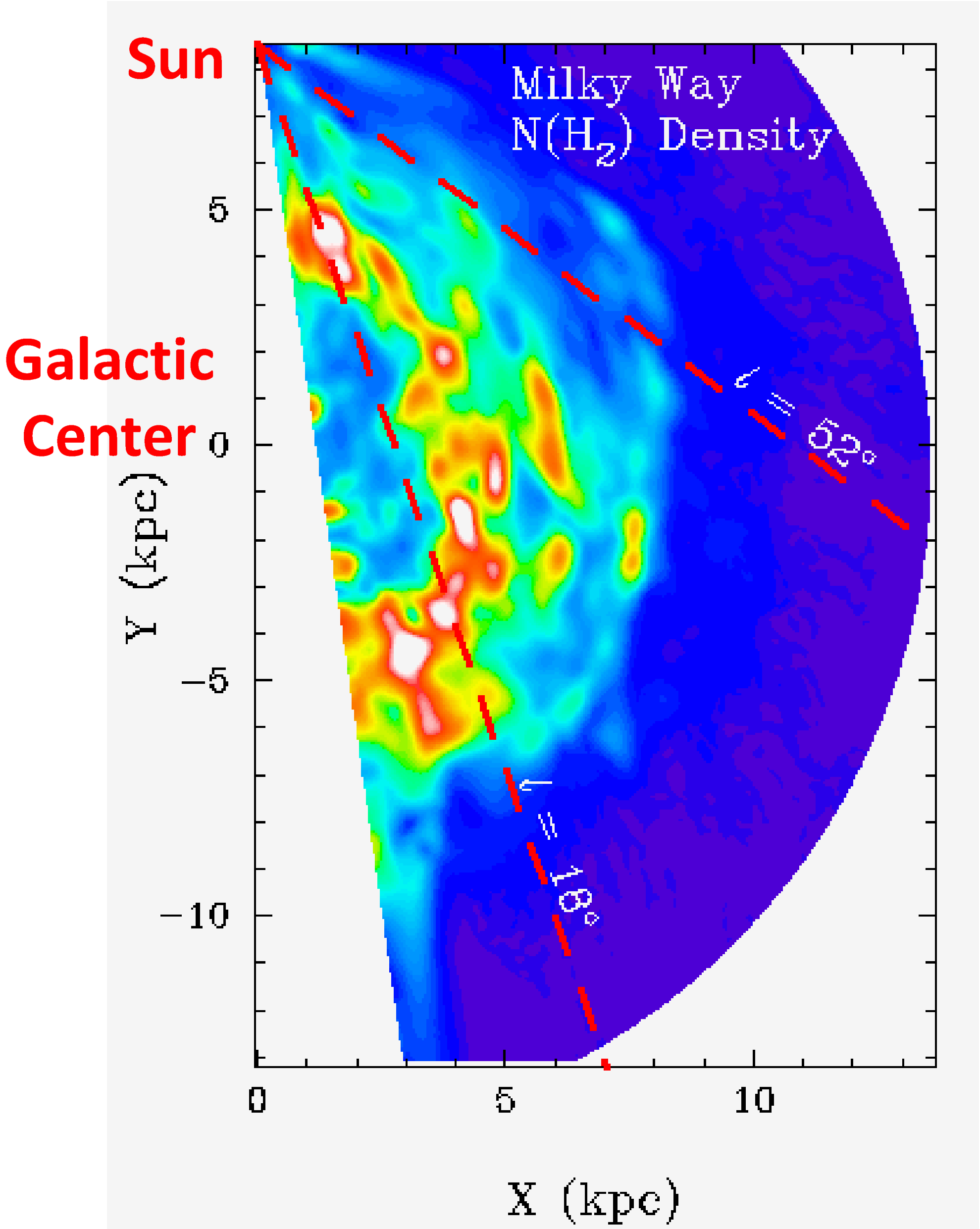
NASA and ESA • *Hubble Space Telescope* • WFC3/UVIS • STScI–PRC15–01b

Sgr A* X-ray echoes



Sunyaev et al. 1993, Koyama et al. 1996, Ponti et al. 2010

Molecular gas density



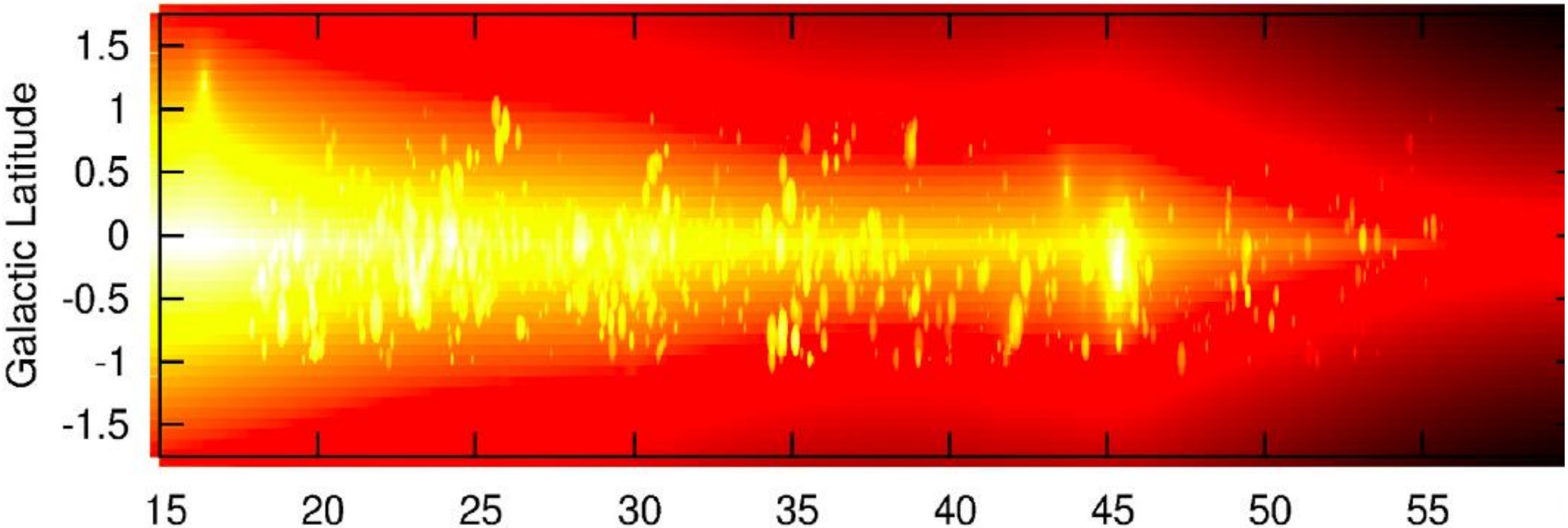
BU-FCRAO
Galactic Ring Survey

high-sensitivity 46''-resolution molecular gas density maps based on 13CO emission and HI self-absorption

Jackson et al. 2006,
Roman-Duval et al. 2010

Reflection in the Galactic plane

Molaro, Khatri & Sunyaev 2014

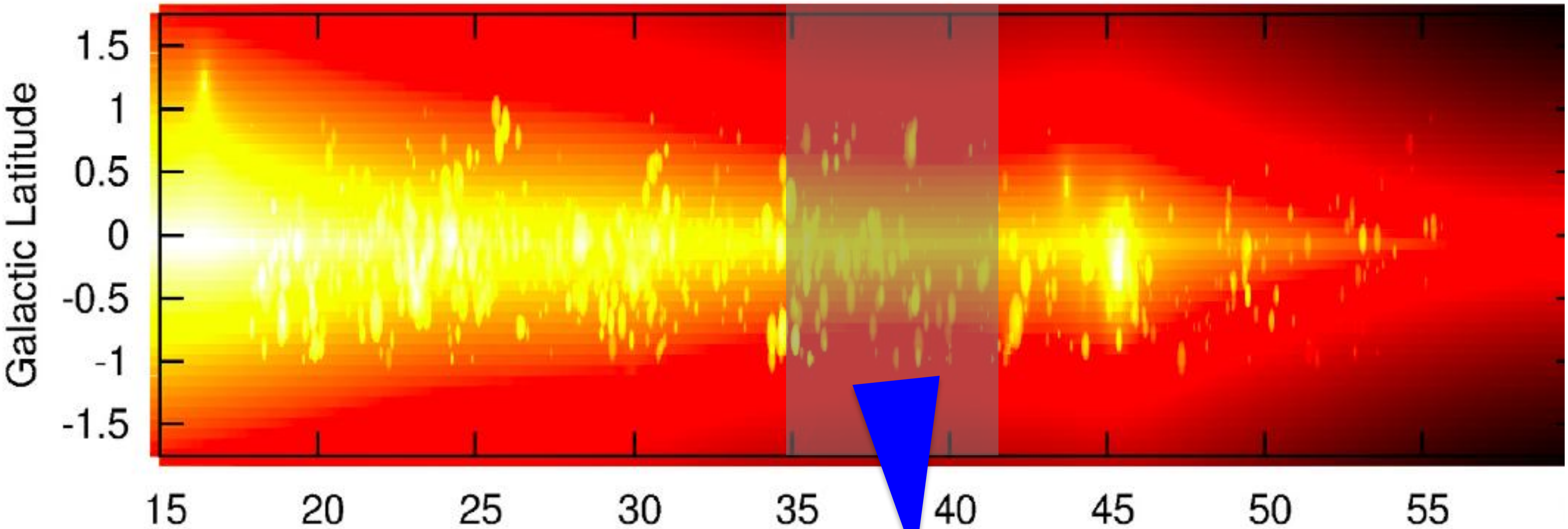


Reflection from the population of Galactic X-ray binaries

Radiation isotropy was a crucial assumption

Reflection in the Galactic plane

Molaro, Khatri & Sunyaev 2014



Isotropy assumption

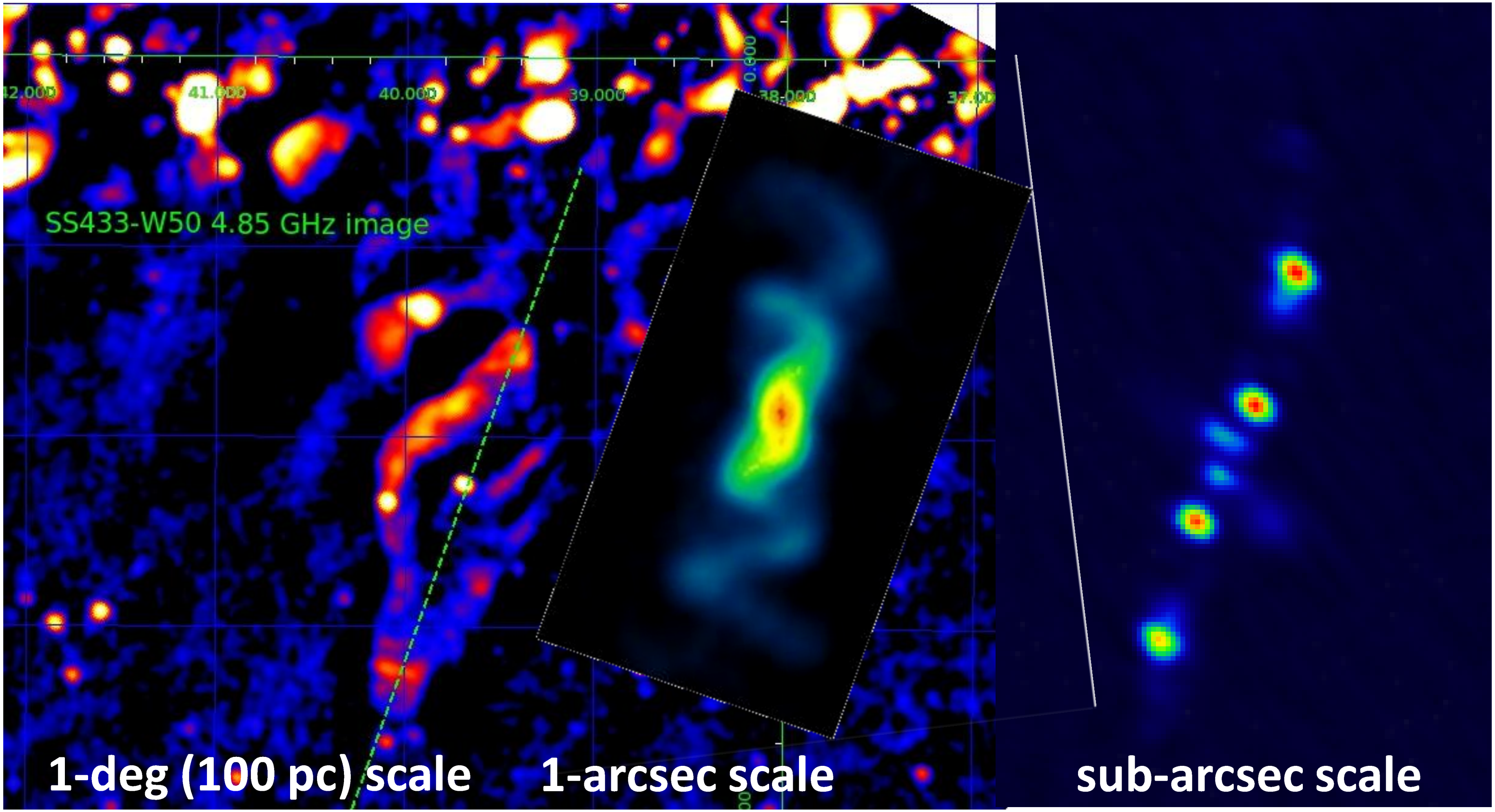
SS 433

l=39.69°, b=-2.24°

Potential reflection signal from SS 433 is missed

Galactic super-accretor SS 433

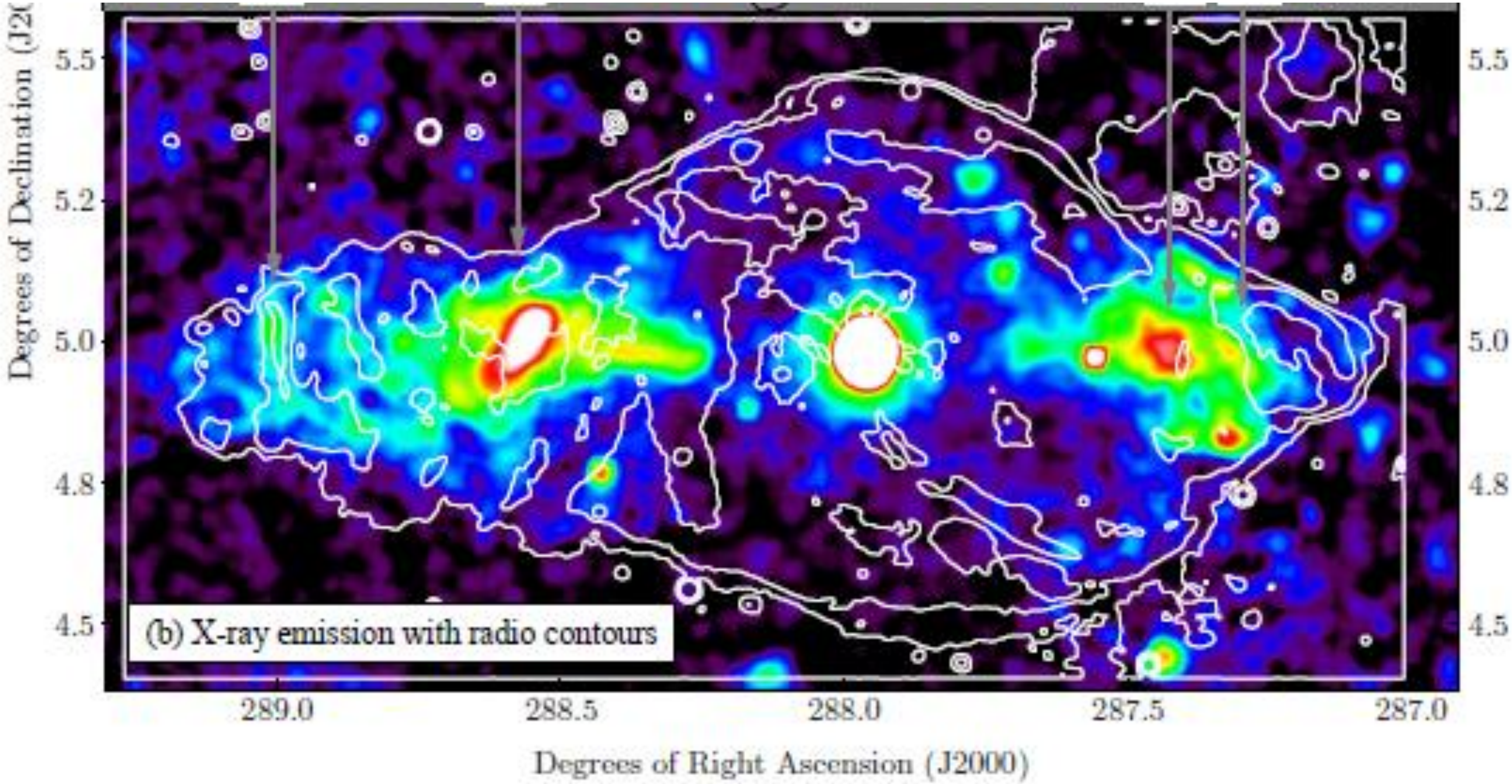
Credit: Blundell &Bowler



3D direction of the jets is known with high accuracy

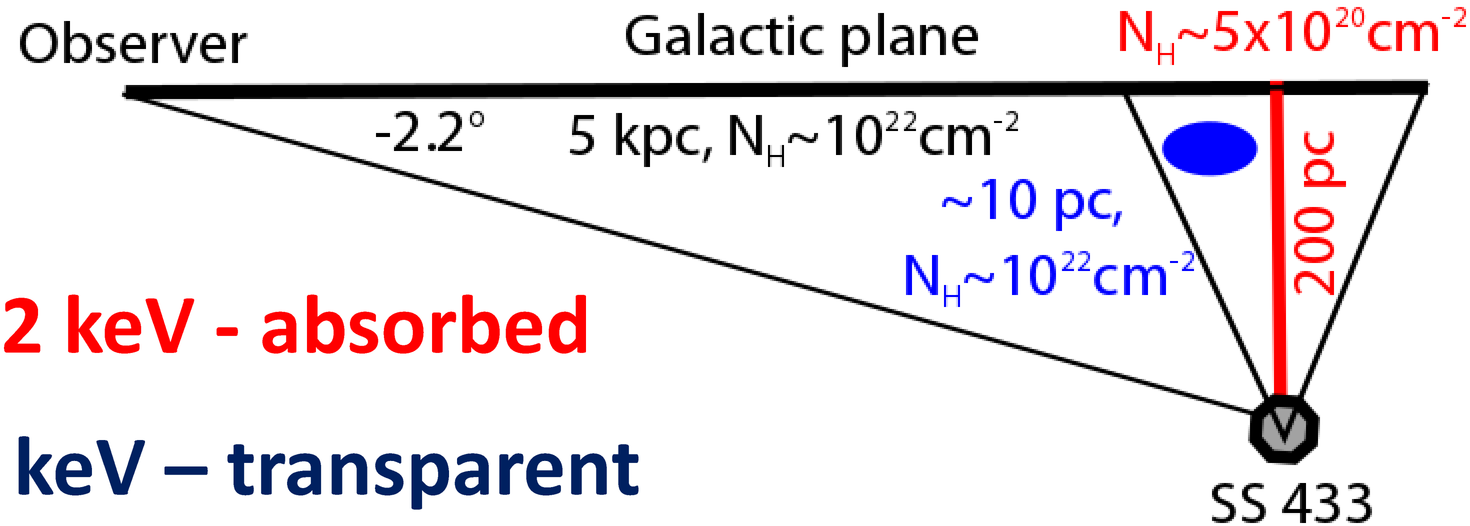
Galactic super-accretor SS 433

Gooodall et al



W50 provides an activity record for hundreds of years

Reflection in the Galactic plane



E< 2 keV - absorbed

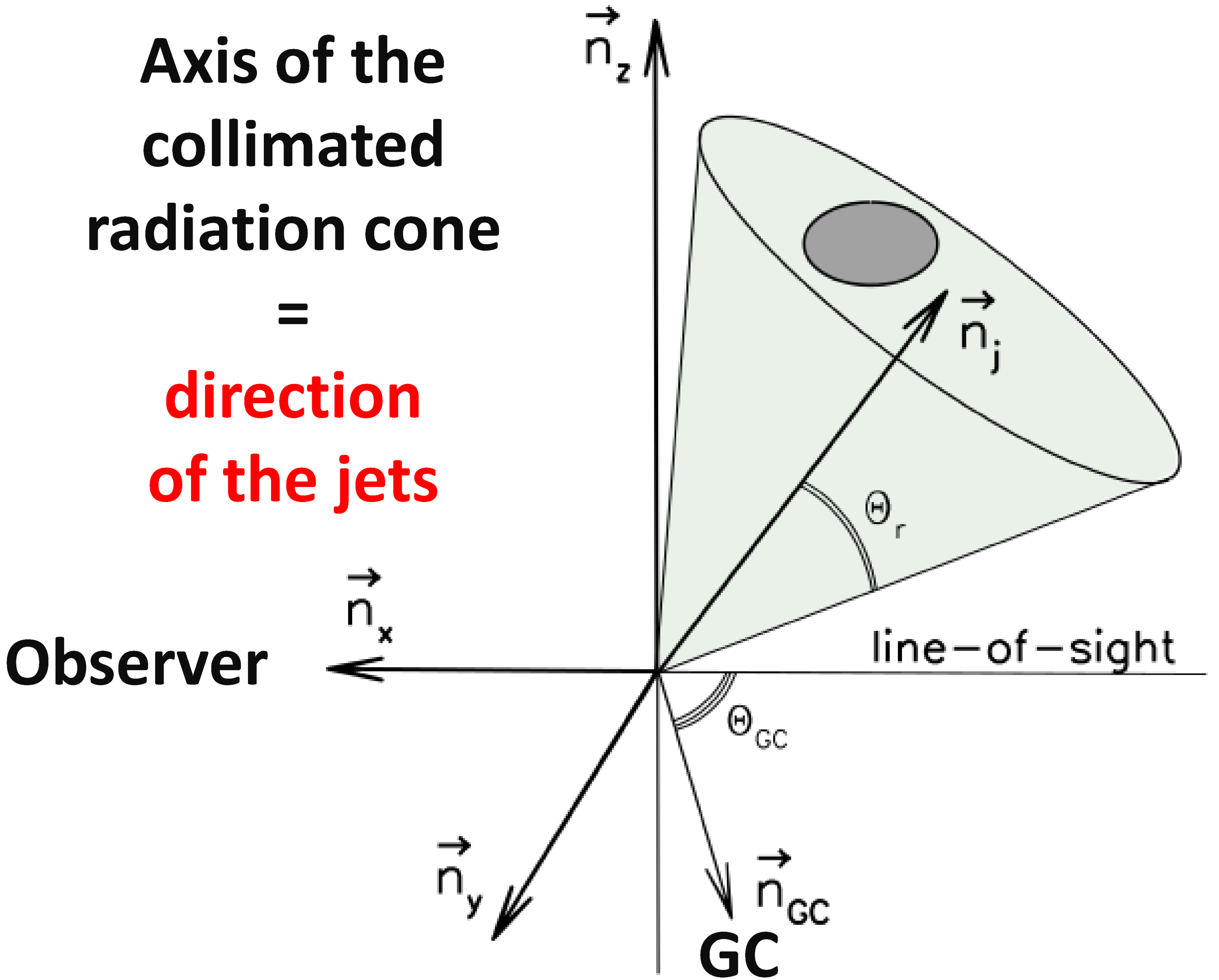
E> 4 keV – transparent – optically thin regime

$$\xi = \frac{L_{>4}}{nR^2} \sim \frac{1}{400}\frac{L_{39}}{nR^2_{200}}$$ **<< 1 – 'linear' regime**

Purely geometrical problem

Geometry of the problem

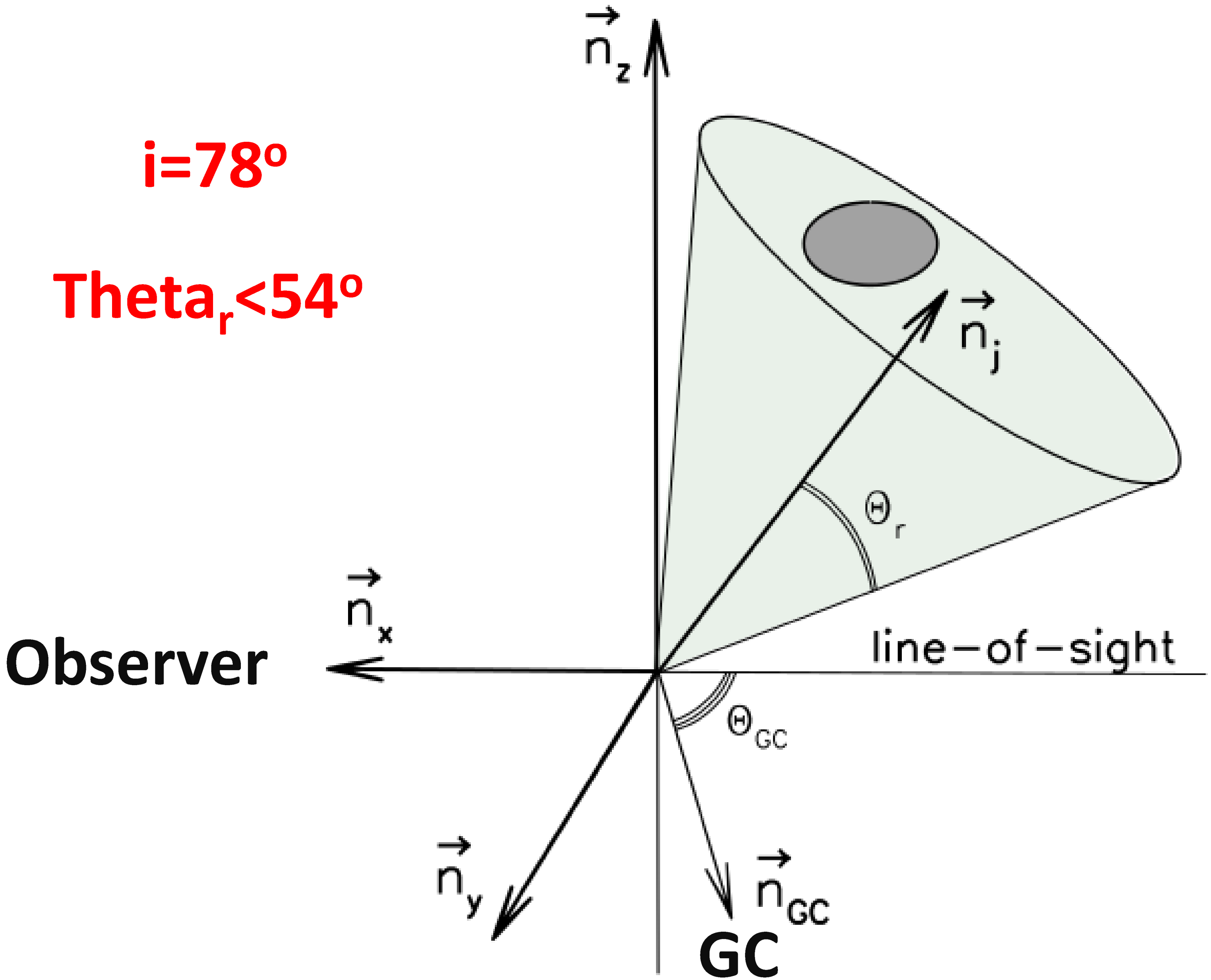
Axis of the collimated radiation cone = direction of the jets



Geometry of the problem

$i = 78^o$

$Theta_r < 54^o$

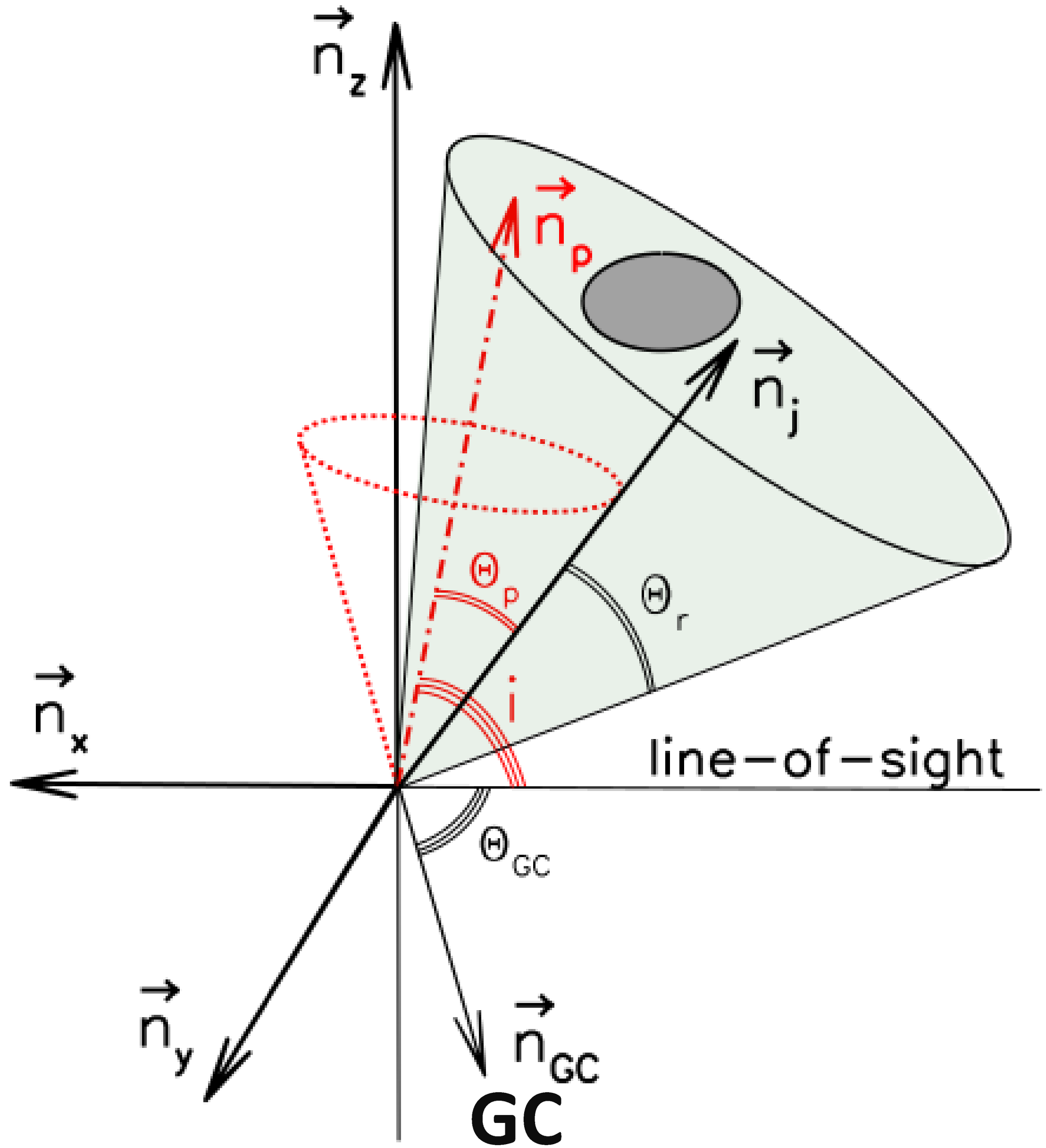


Precession of the radiation cone

$Theta_p$<21°

P_p=162 days

z_p=0.14 pc



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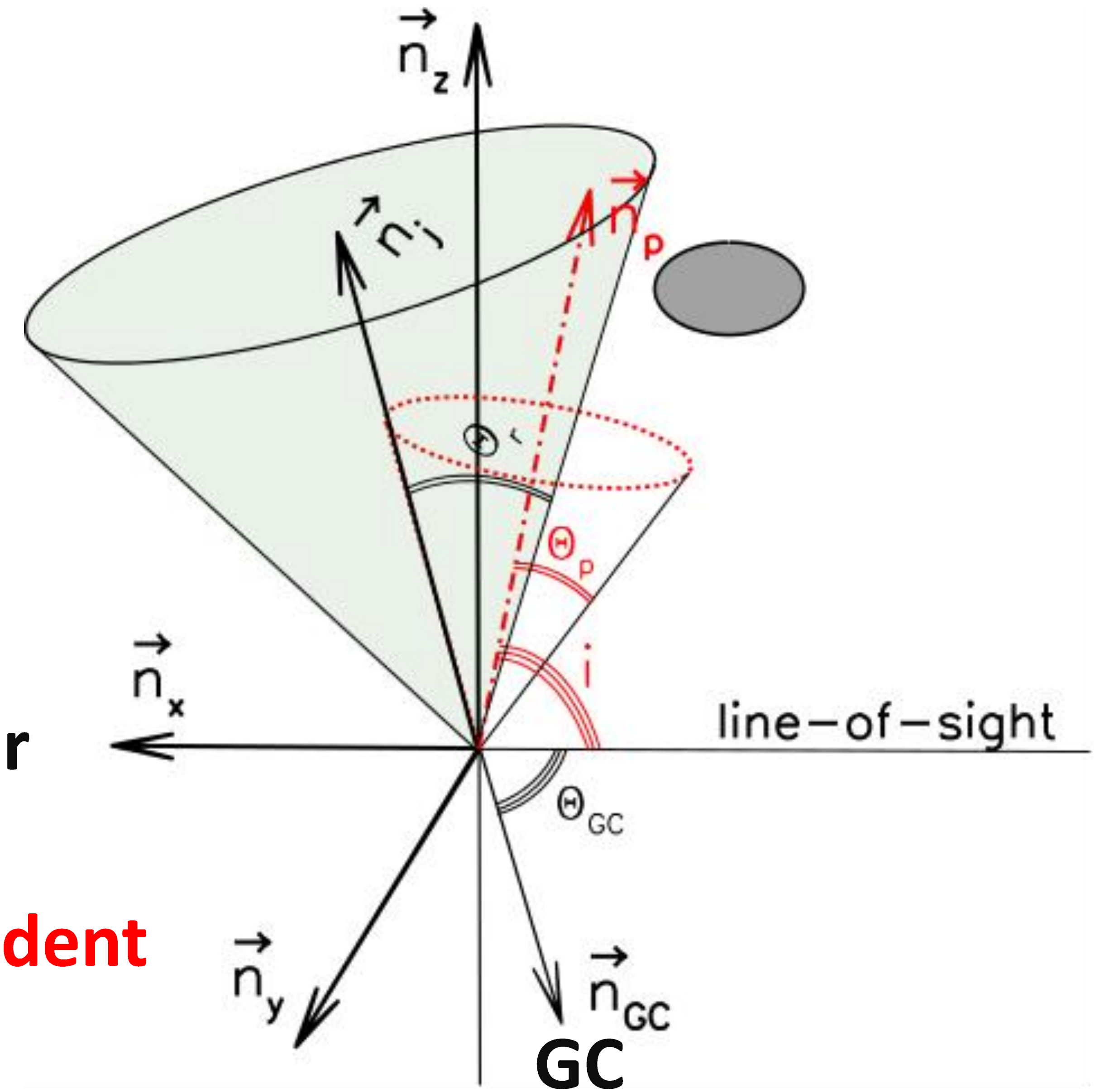
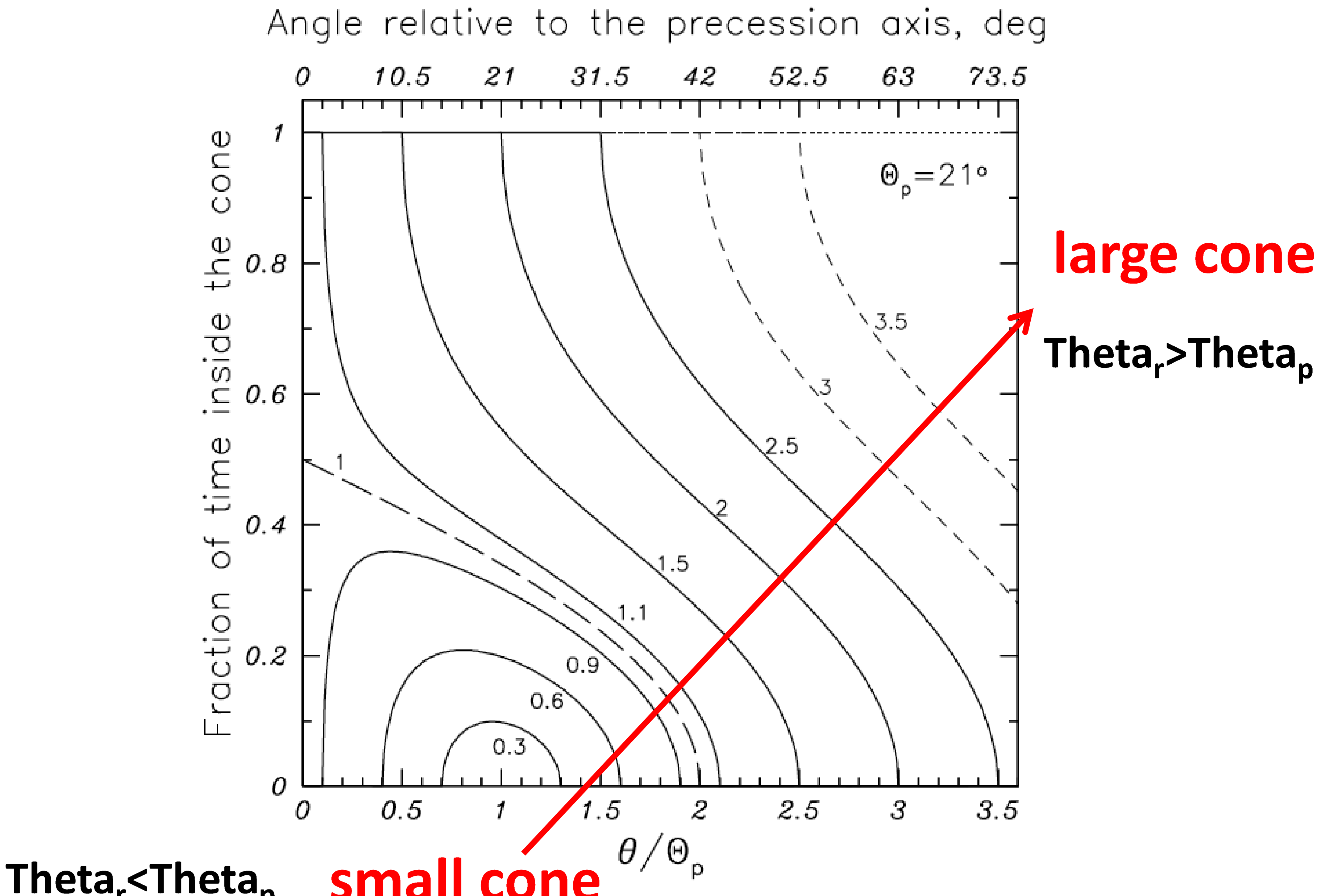
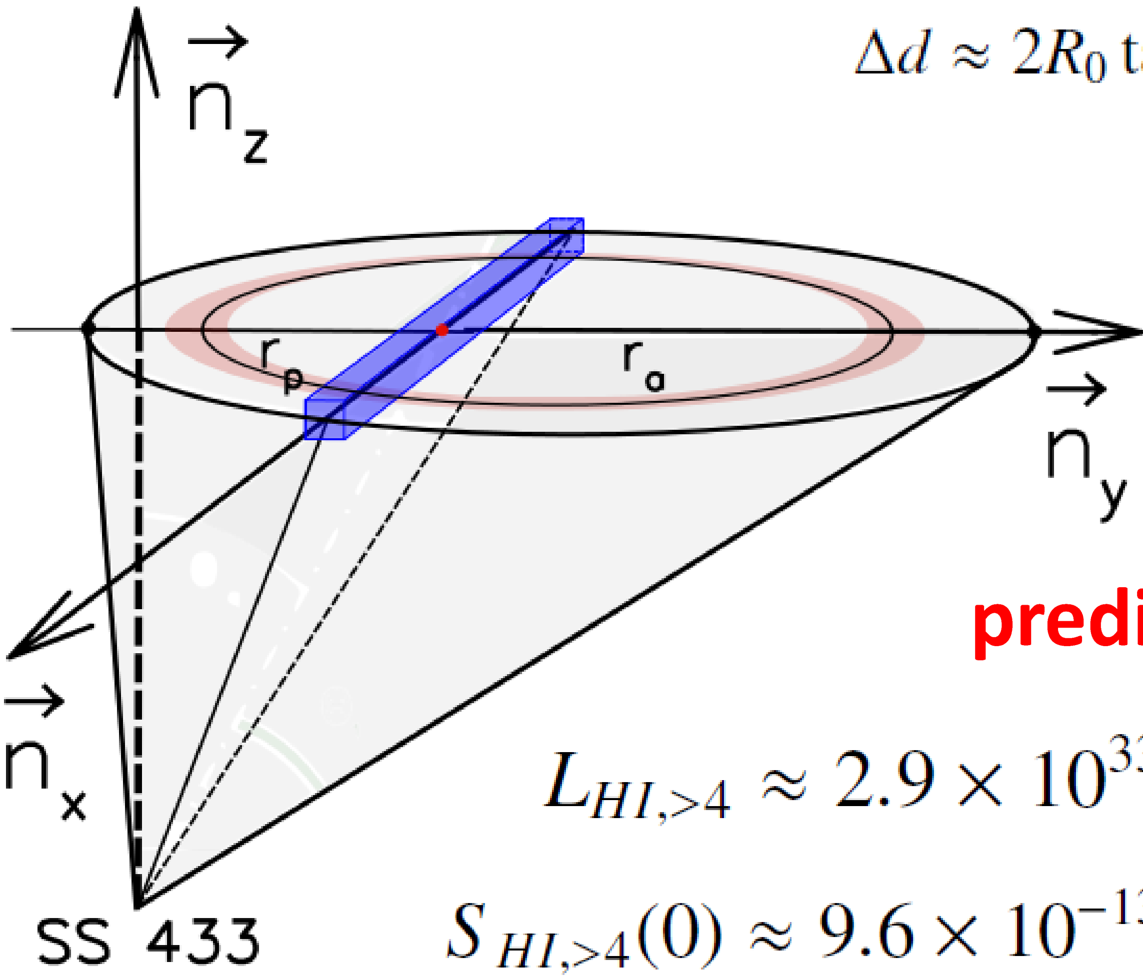


Time(space)-dependent illumination

Duty-cycle of the illumination



Reflection from uniform medium



Illuminated column:

$$\Delta d \approx 2R_0 \tan\Delta\Theta \approx 170 \frac{\tan\Delta\Theta}{\tan\Theta_p} \text{ pc}$$

$$k = \frac{\tan\Delta\Theta}{\tan\Theta_p}$$

predicted signal for HI:

$$L_{HI,>4} \approx 2.9\times10^{33}\ kL_{39}\ d_5 \text{ erg/s/deg}^2$$

$$S_{HI,>4}(0) \approx 9.6\times10^{-13} k\frac{L_{39}}{d_5} \text{ erg/s/cm}^2\text{/deg}^2$$

Reflection from atomic gas

Dependence on the Galactic latitude:

$$S_{HI,>4}(b) = \frac{\exp(-|b|/b_d)}{|b/b_{\rm SS433} - 1|} S_{HI,>4}(0),$$

Averaged signal:

$$< S_{HI,>4}(\Delta b) >= S_{HI,>4}(0)(1 - \exp^{-\Delta b/b_d})\frac{b_d}{\Delta b}$$

$$< S_{HI,>4} >_{0.5} \approx 0.6\, S_{HI,>4}(0) \approx$$

$$\approx 5.8 \times 10^{-13}\, k \frac{L_{39}}{d_5}\ {\rm erg/s/cm^2/deg^2}$$

Reflection from molecular clouds

$$f_{H_2,>4} = 3.5 \times 10^{-13} \frac{L_{39}}{d_5^2 R_{200}^2} M_4 \ \mathrm{erg/s/cm^2}$$

$$S_{H_2,>4} = \frac{f_{H_2,>4}}{\pi \delta \mathrm{l} \delta \mathrm{b}} \approx 1.1 \times 10^{-13} \frac{L_{39}}{d_5^2 R_{200}^2} \frac{M_4}{\delta \mathrm{l} \delta \mathrm{b}} \ \mathrm{erg/s/cm^2/deg^2}$$

1) Distance to the reflector is uncertain

2) Correction for the duty-cycle needed!

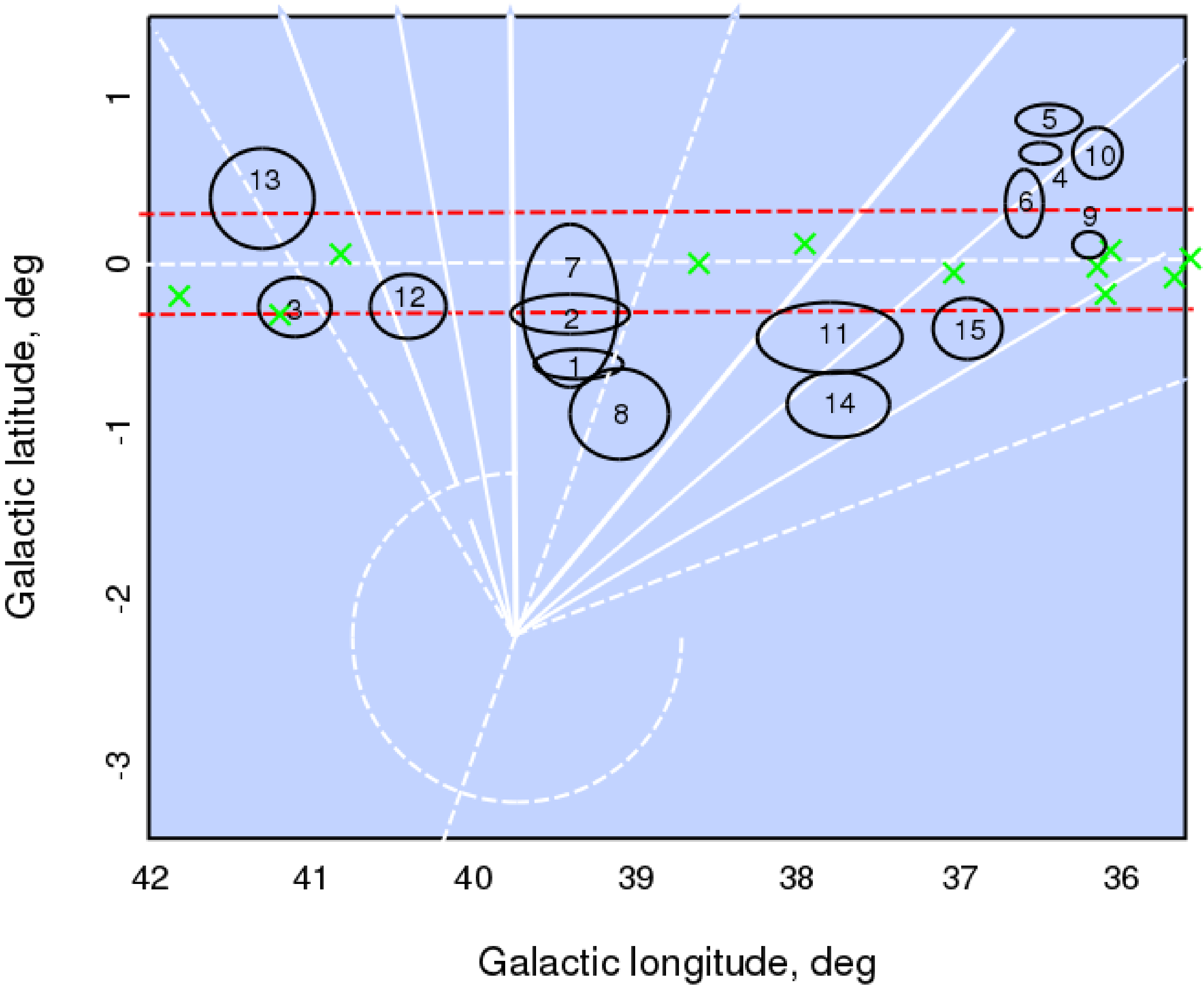
Candidates for the illumination

	GRS name	l deg	δl deg	b deg	δb deg	V_{LSR} km/s	δV_{LSR} km/s	d_{MC} kpc	Δd_{MC} kpc
1	G039.29-00.61	39.29	0.27	-0.61	0.09	64.5	3.5	4.4	0.2
2	★G039.34-00.31	39.34	0.36	-0.31	0.12	65.8	2.9	4.55	0.2
3	★G041.04-00.26	41.04	0.22	-0.26	0.18	65.8	5.2	4.7	0.4
4	G036.44+00.64	36.44	0.12	0.64	0.065	71.8	3.5	4.8	0.2
5	G036.39+00.84	36.39	0.20	0.84	0.095	71.3	2.6	4.8	0.1
6	G036.54+00.34	36.54	0.12	0.34	0.20	71.8	2.3	4.85	0.1
7	★G039.34-00.26	39.34	0.29	-0.26	0.49	69.7	6.2	4.9	0.5
8	★G039.04-00.91	39.04	0.30	-0.91	0.28	71.8	5.2	5.1	0.4
9	G036.14+00.09	36.14	0.10	0.09	0.08	75.6	3.9	5.15	0.2
10	G036.09+00.64	36.09	0.15	0.64	0.15	76.5	4.1	5.2	0.3
11	G037.74-00.46	37.74	0.44	-0.46	0.21	74.8	4.3	5.25	0.3
12	★G040.34-00.26	40.34	0.23	-0.26	0.20	72.2	5.7	5.4	0.7
13	★G041.24+00.39	41.24	0.31	0.39	0.30	71.3	2.2	5.5	0.4
14	G037.69-00.86	37.69	0.31	-0.86	0.20	77.7	2.8	5.6	0.3
15	★G036.89-00.41	36.89	0.21	-0.41	0.18	79.8	3.5	5.7	0.3

From the BU-FCRAO Galactic Ring Survey Catalogue

Roman-Duval et al. 2010

Candidates for the illumination

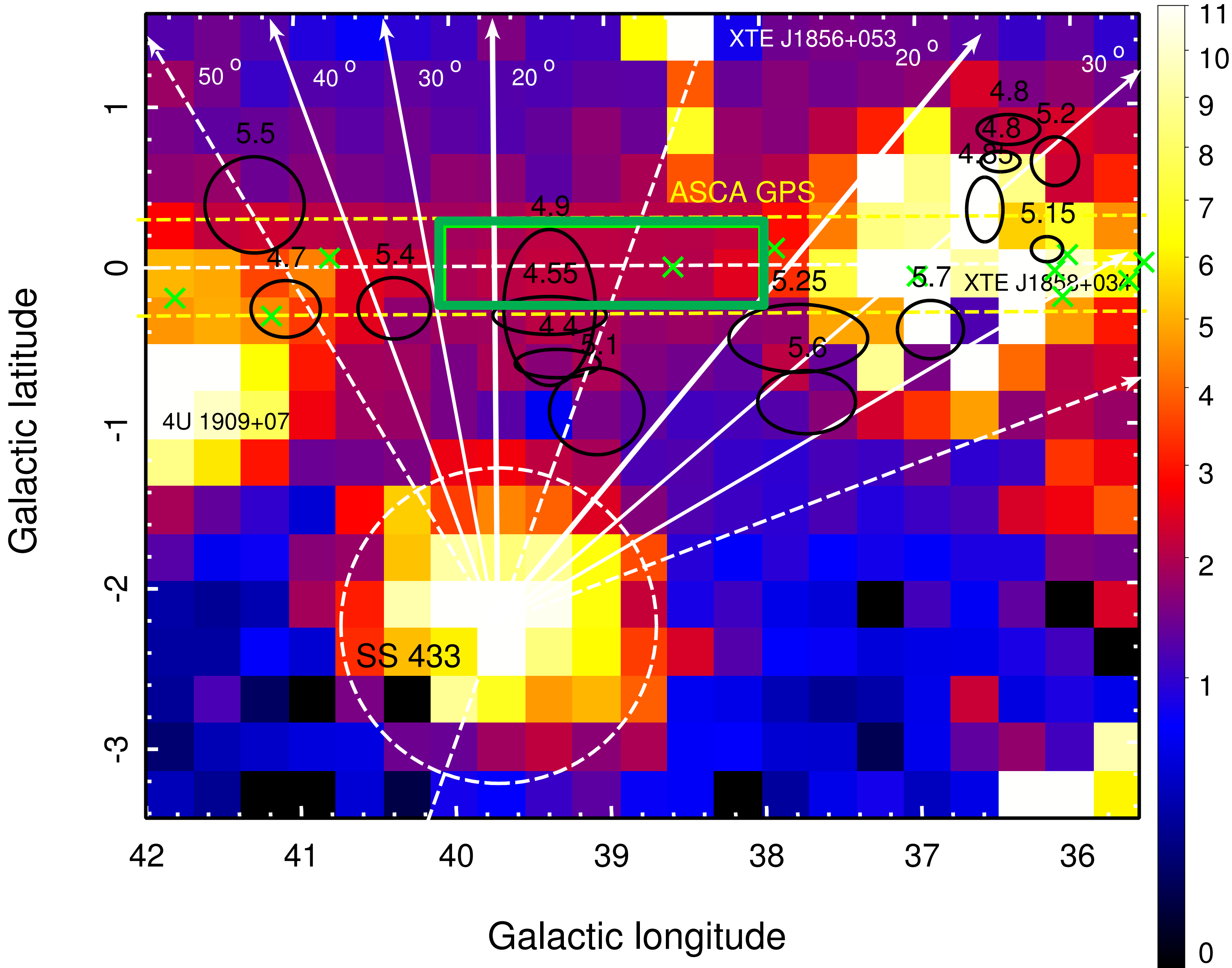


Predicted signal

	GRS name	R_{min} 200 pc	r pc	n_{H_2} cm^{-3}	Area deg^2	M $10^4 M_\odot$	δM $10^4 M_\odot$	$S_{sc,200}/10^{-11}$ $erg/s/cm^2/deg^2$	$f_{sc,200}/10^{-11}$ $erg/s/cm^2$
1	G039.29-00.61	0.65	6.7	194.2	0.076	1.6	0.6	0.7	0.05
2	★G039.34-00.31	0.78	7.7	200.9	0.14	2.5	1.0	0.6	0.08
3	★G041.04-00.26	0.98	25.6	94.6	0.12	44.0	7.0	12.0	1.5
4	G036.44+00.64	1.82	6.7	436.2	0.026	3.6	1.0	4.6	0.1
5	G036.39+00.84	1.89	5.0	351.0	0.06	1.2	0.4	0.67	0.04
6	G036.54+00.34	1.73	1.6	338.6	0.074	0.041	0.01	0.02	0.001
7	★G039.34-00.26	0.86	9.0	173.0	0.45	3.4	1.0	0.24	0.1
8	★G039.04-00.91	0.66	8.2	194.8	0.26	2.9	1.0	0.37	0.1
9	G036.14+00.09	1.91	2.8	288.8	0.025	0.17	0.07	0.23	0.006
10	G036.09+00.64	2.09	9.8	214.1	0.073	5.4	2.0	2.5	0.2
11	G037.74-00.46	1.21	8.8	95.3	0.3	1.8	0.7	0.2	0.06
12	★G040.34-00.26	0.98	10.5	160.6	0.14	5.1	1.0	1.2	0.2
13	★G041.24+00.39	1.47	3.6	221.3	0.3	0.28	0.1	0.03	0.009
14	G037.69-00.86	1.19	5.6	195.5	0.19	0.95	0.4	0.17	0.03
15	★G036.89-00.41	1.67	16.0	110.2	0.12	12.0	4.0	3.3	0.4

Predicted flux varies from 10^{-14} to 10^{-11} erg/s/cm^2

Comparison with the data



Reflection from the atomic gas

RXTE: $S_{3-20} \approx 2.6 \times 10^{-11}$ erg/s/cm^2/deg^2

ASCA: $S_{4-10} \approx 1.2 \times 10^{-11}$ erg/s/cm^2/deg^2

Sugizaki et al. 2001

Galactic Ridge:

$$S_{3-20} \approx 2.2 \times 10^{-11} \text{ erg/s/cm}^2/\text{deg}^2$$

$$S_{4-10} \approx 1.1 \times 10^{-11} \text{ erg/s/cm}^2/\text{deg}^2$$

with 20% systematic scatter allowed

Revnivtsev et al. 2006

Upper limits:

$$S_{4-10} \approx 4 \times 10^{-12} \text{ erg/s/cm}^2/\text{deg}^2$$

Constraints

Gamma=2, E_c=5 keV:

$$L_{2-10} < 1.4 \times 10^{40} \frac{d_5}{k} \text{ erg/s}$$

Apparent luminosity:

Narrow cone: $$L_{2-10} < 2.8 \times 10^{40} d_5 \left(\frac{\Theta_p}{\Theta_r}\right)^2 \text{ erg/s}$$

Wide cone: $$L_{2-10} < 5.5 \times 10^{39} \, d_5 (\tan \Theta_r)^{-1} \text{ erg/s}$$

Angular-integrated luminosity:

Narrow cone: $$L_{c,2-10} \approx 0.5 \Theta_r^2 L_{2-10} < 1.8 \times 10^{39} \, d_5 \text{ erg/s}$$

Wide cone: $$L_{c,2-10} < 1.65 \times 10^{39} \, d_5 \, [1 + 0.4(\Theta_r - \pi/4)] \text{ erg/s}$$

What does this all mean?

SS 433 is unlikely an archetypal bright ULX

(like NGC 1313 X-1, Ho IX X-1 or NGC 5048 X-1)

unless it is highly beamed

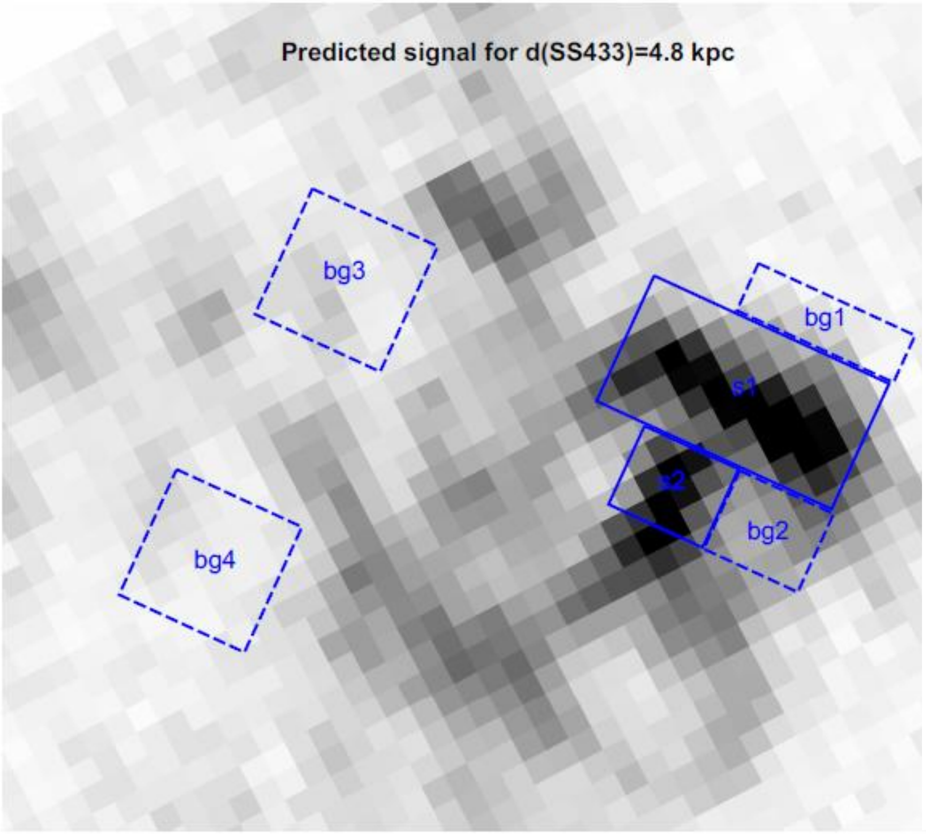
with $Theta_r << Theta_p$

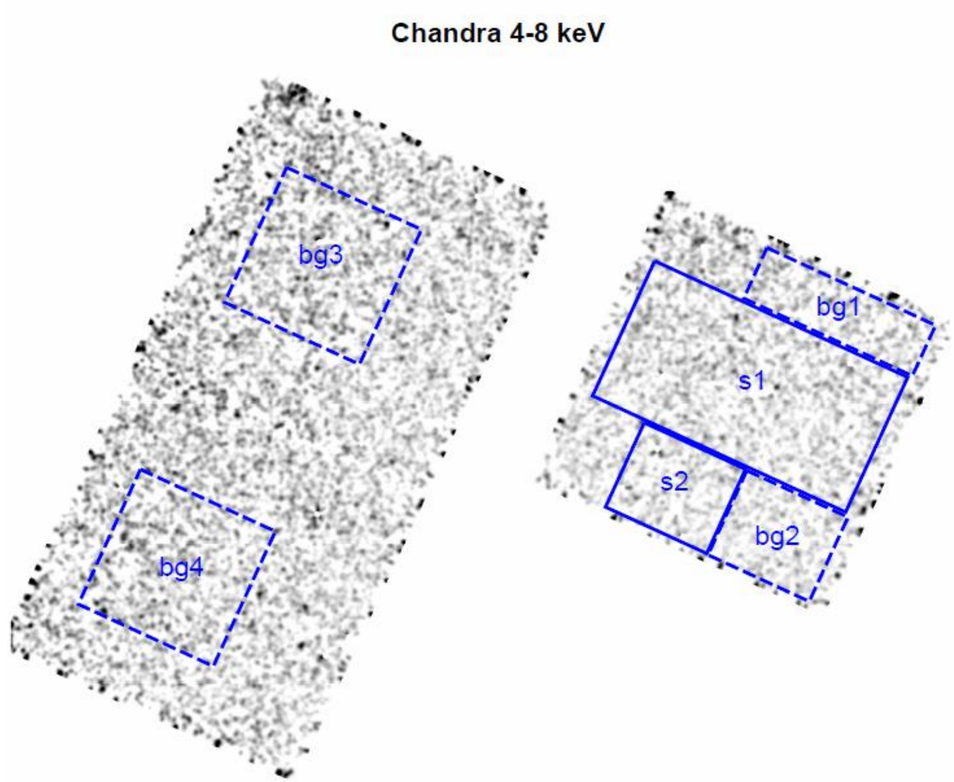
The total (angular-integrated) 2-10 keV luminosity does not exceed $2x10^{39}$ erg/s

With a complete X-ray survey of the candidate molecular clouds, significantly tighter constraints can be obtained

unless SS 433 is actually a ULS

Constraints from molecular clouds





Work in progress with Chandra and XMM-Newton

The End

Duty-cycle of the illumination

$$\xi_{\Theta_p,\Theta_r}(\theta) = \frac{\cos\Theta_r - \cos\theta\cos\Theta_p}{\sin\theta\sin\Theta_p}.$$

$$F(\theta) = \frac{1}{\pi}\cos^{-1}\left[\xi_{\Theta_p,\Theta_r}(\theta)\right], \quad \text{if} \quad |\xi_{\Theta_p,\Theta_r}(\theta)| \leqslant 1,$$

$$F(\theta) = 1, \quad \text{if} \ \xi_{\Theta_p,\Theta_r}(\theta) \leqslant -1 \ \text{and}$$

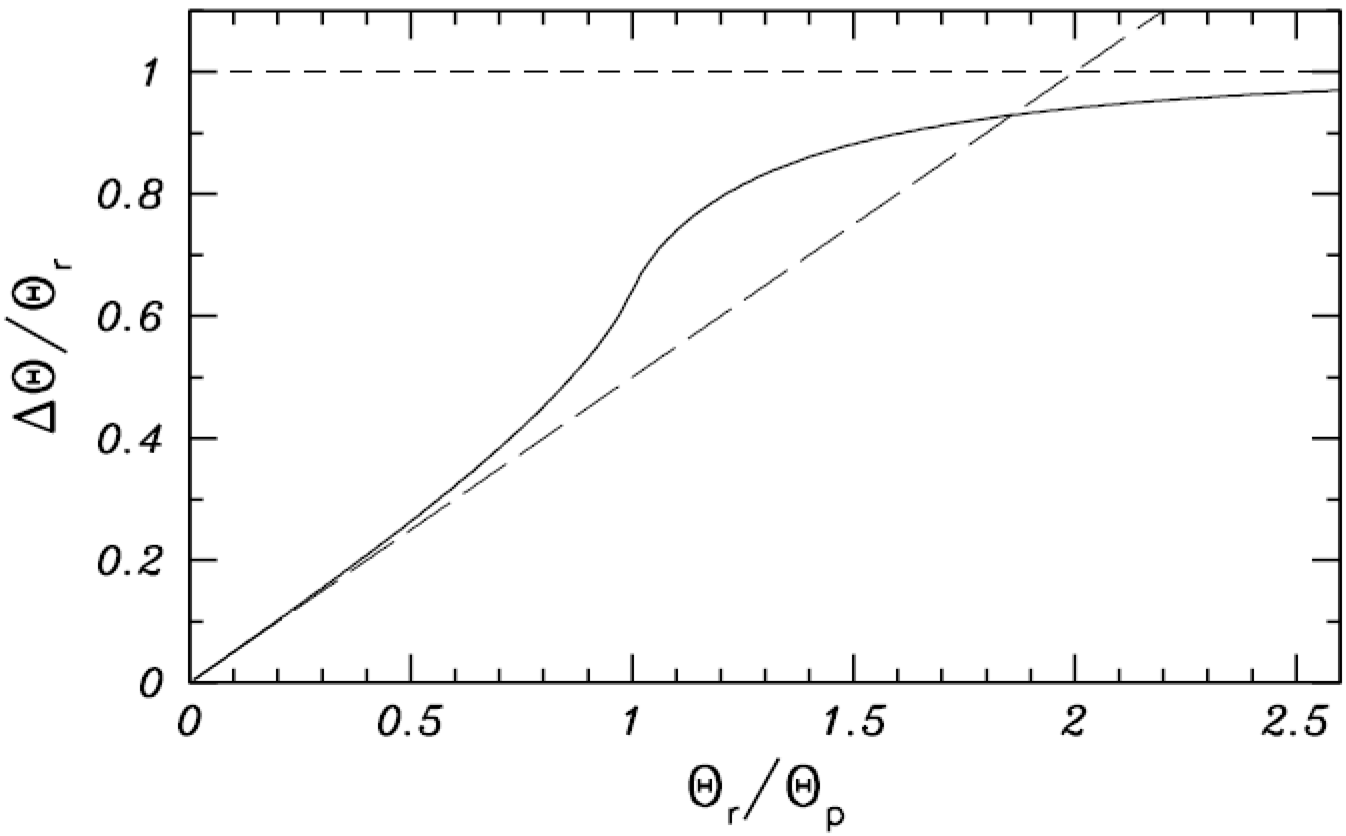
$$F(\theta) = 0, \quad \text{if} \quad \xi_{\Theta_p,\Theta_r}(\theta) \geqslant 1,$$

Small angles: $\eta = \Theta_r/\Theta_p$

$$\xi_{\Theta_p,\Theta_r}(\theta) \approx \xi_\eta(\theta) = \frac{1-\eta^2+(\theta/\Theta_p)^2}{2(\theta/\Theta_p)}$$

Illumination grasp

$$\Delta\Theta = \int_0^{\pi/2} F(\theta)d\theta$$



Small cone: $\Delta\Theta/\Theta_r = 0.5\eta$

Candidates for the illumination