

全天X線監視装置 MAXI による ブラックホール探査

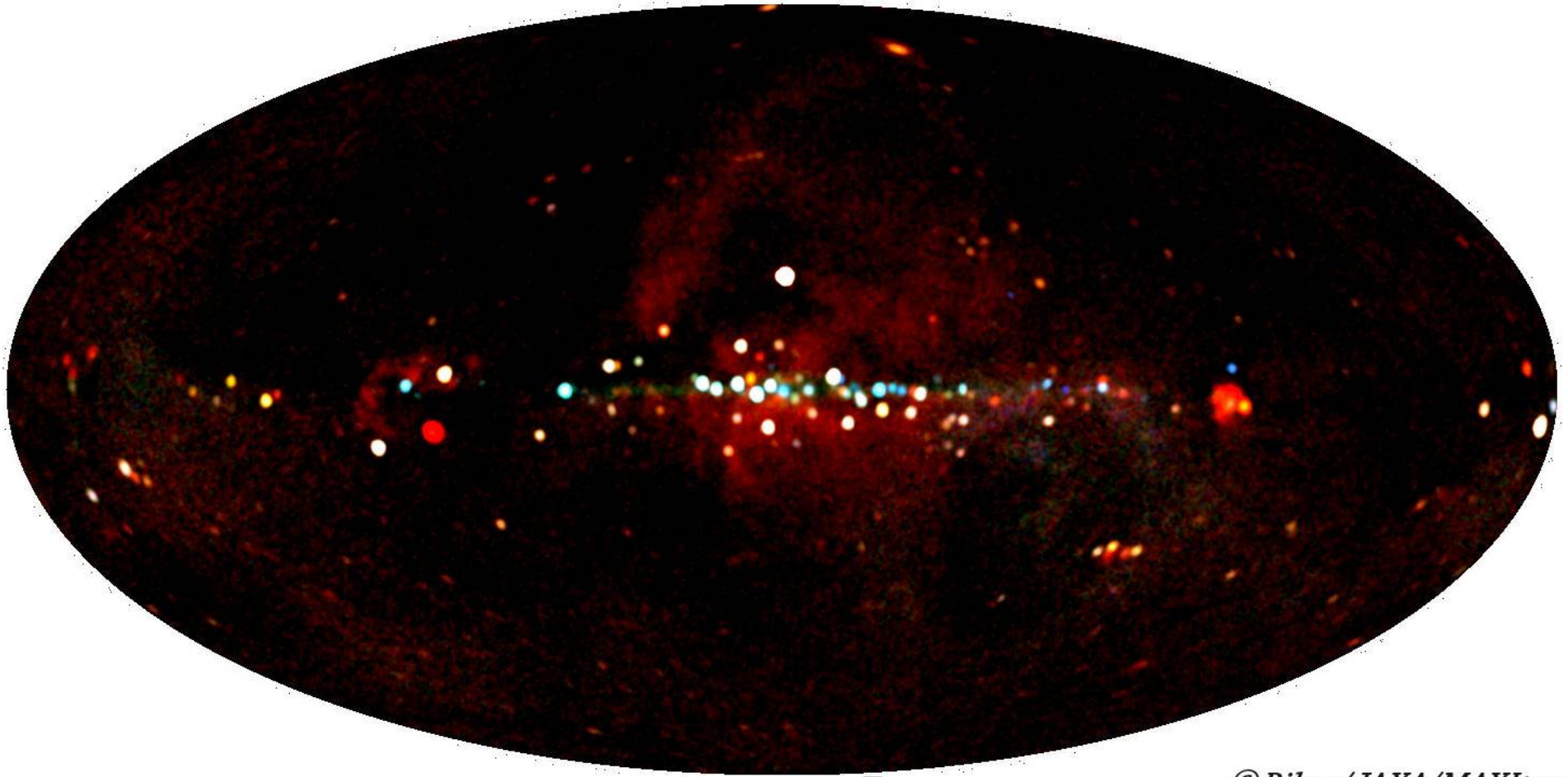
根來 均 (日大理工)



- 0) MAXI について
- 1) ブラックホール候補天体の特徴と探査
- 2) MAXI が見つけたブラックホール候補天体
- 3) 観測される様々な「状態」と降着円盤
- 4) 各状態が示すブラックホール(存在)の証拠!?
- 5) 各状態と状態遷移での未解決問題

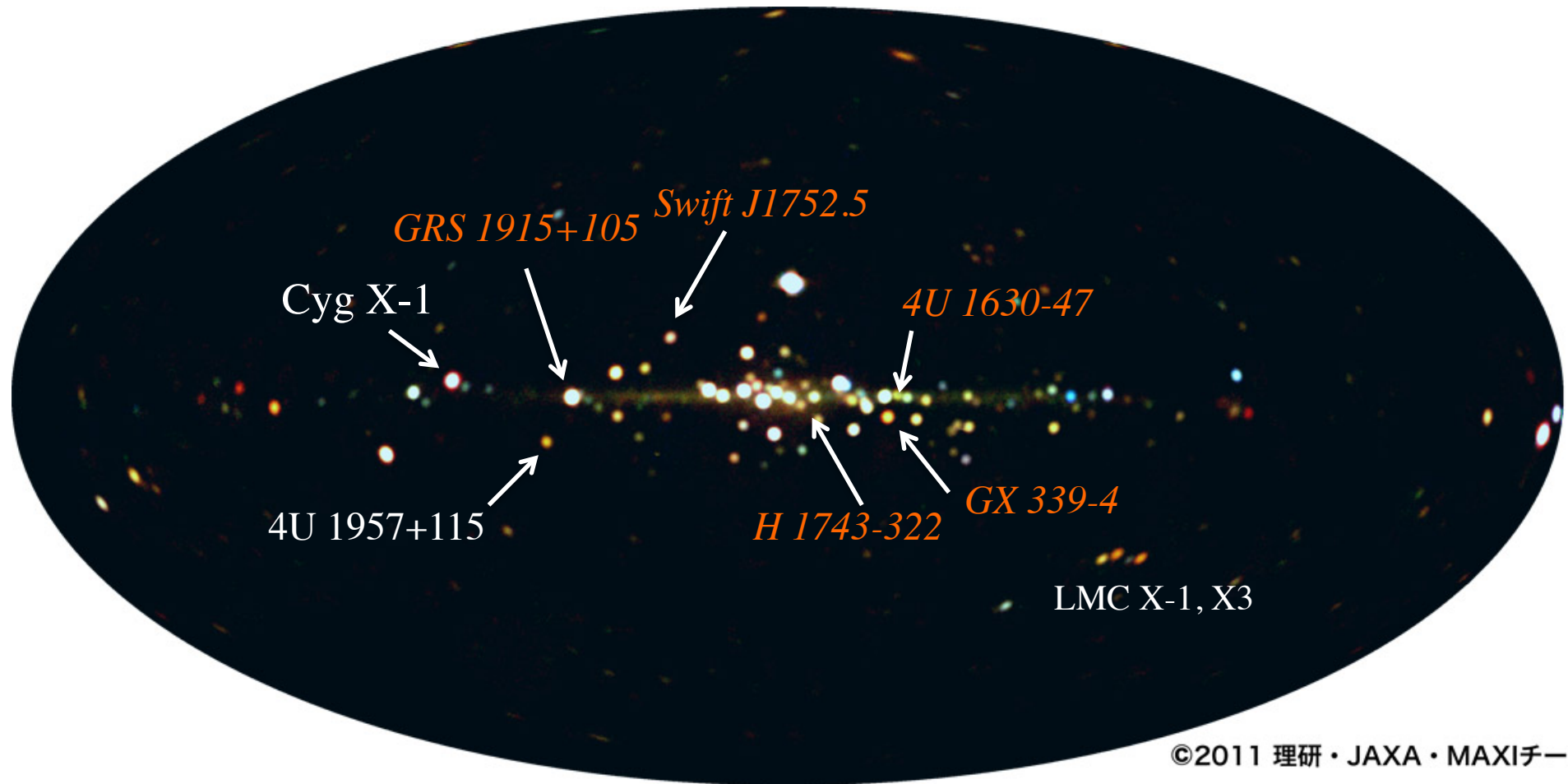
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MAXI GSC & SSC All-sky Map



©Riken/JAXA/MAXIteam

Known Black Hole Candidates



Orange: Transient, not persistent. (Renewed Activities are detected.)

なぜブラックホールは
観測されない(少ない)のか？



NASA/GSFC

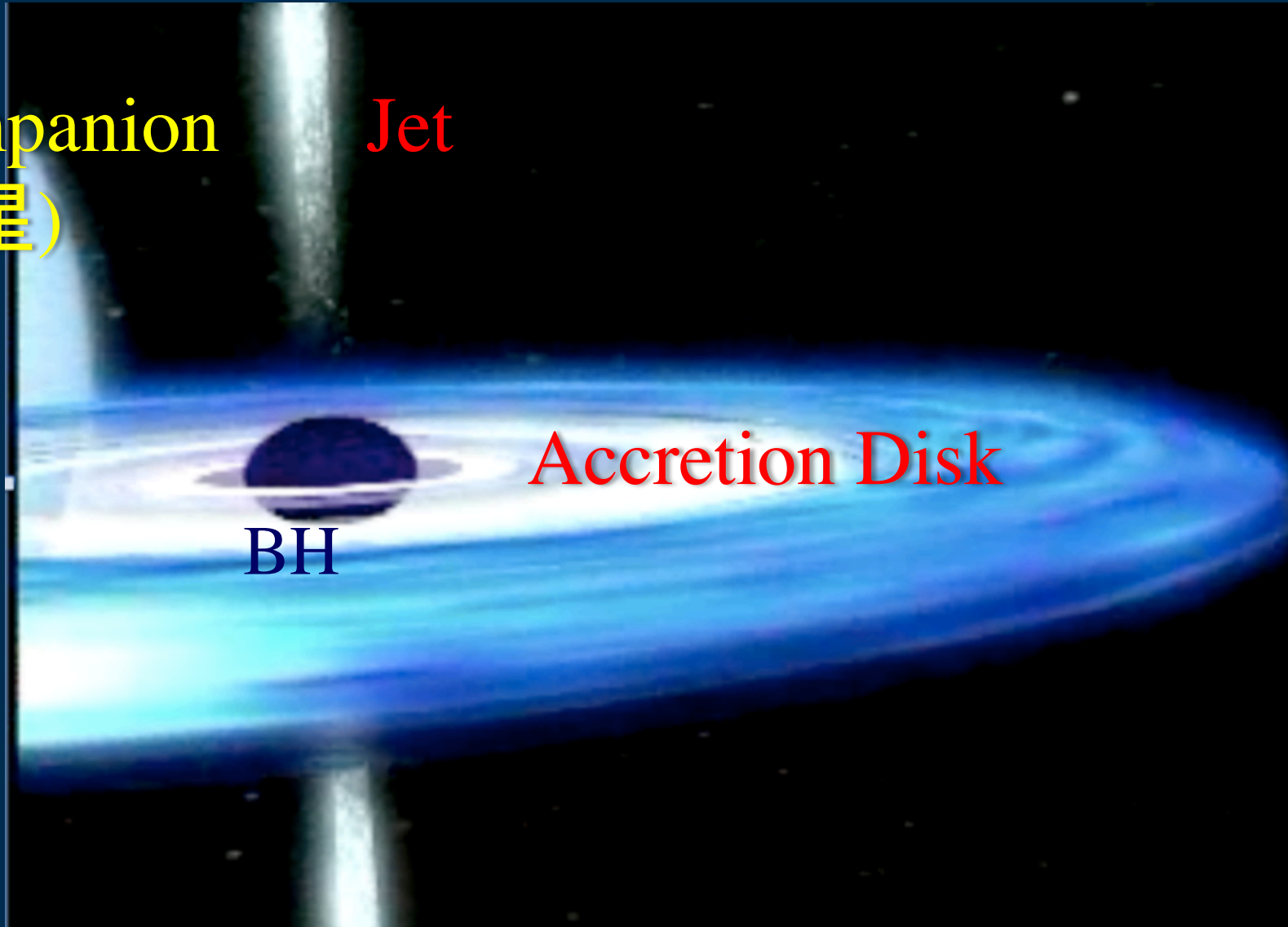
Accretion Disk (降着円盤)

Companion
(伴星)

Jet

Accretion Disk

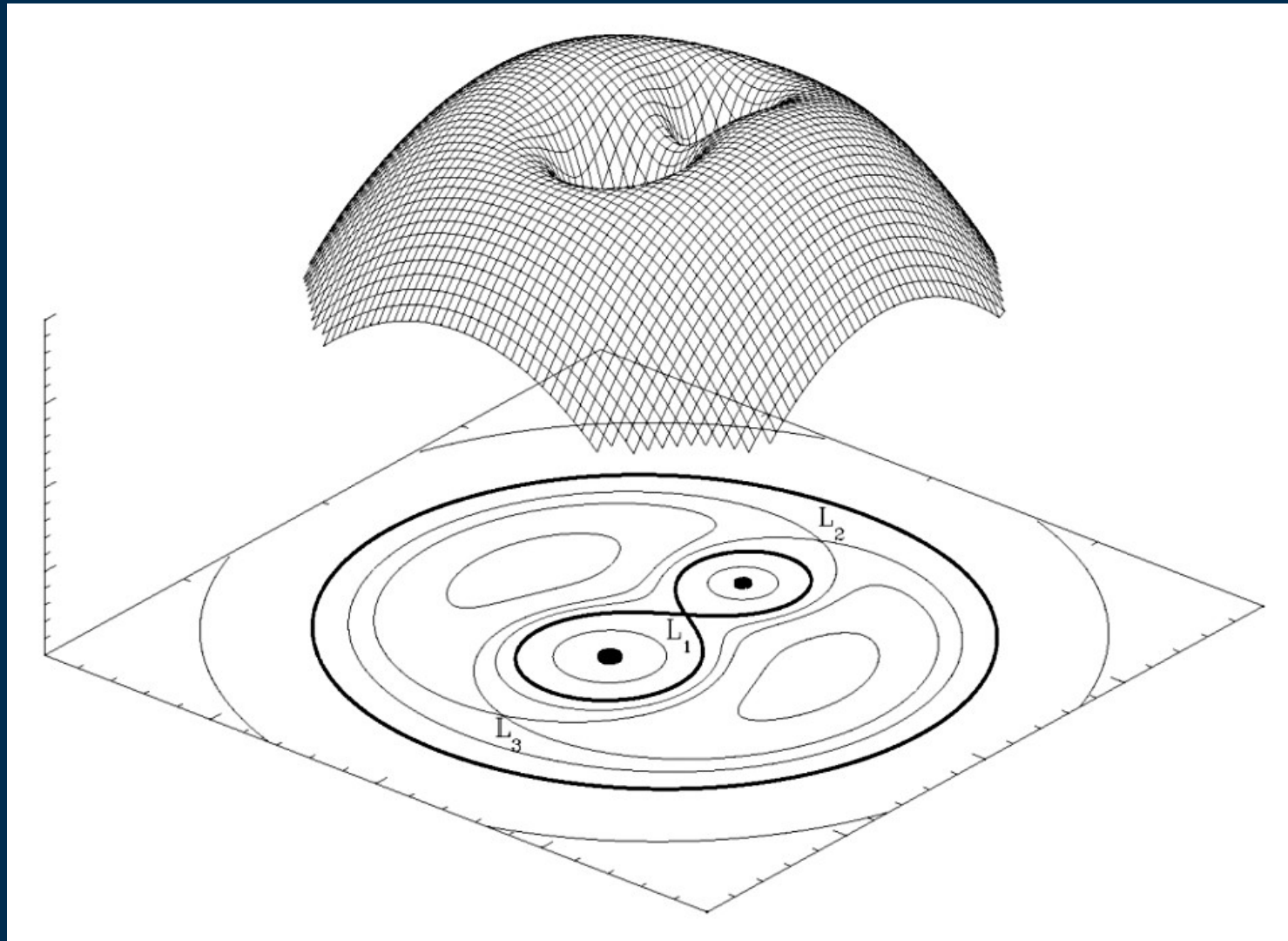
BH



Roche Potential

Roche-Lobe Overflow

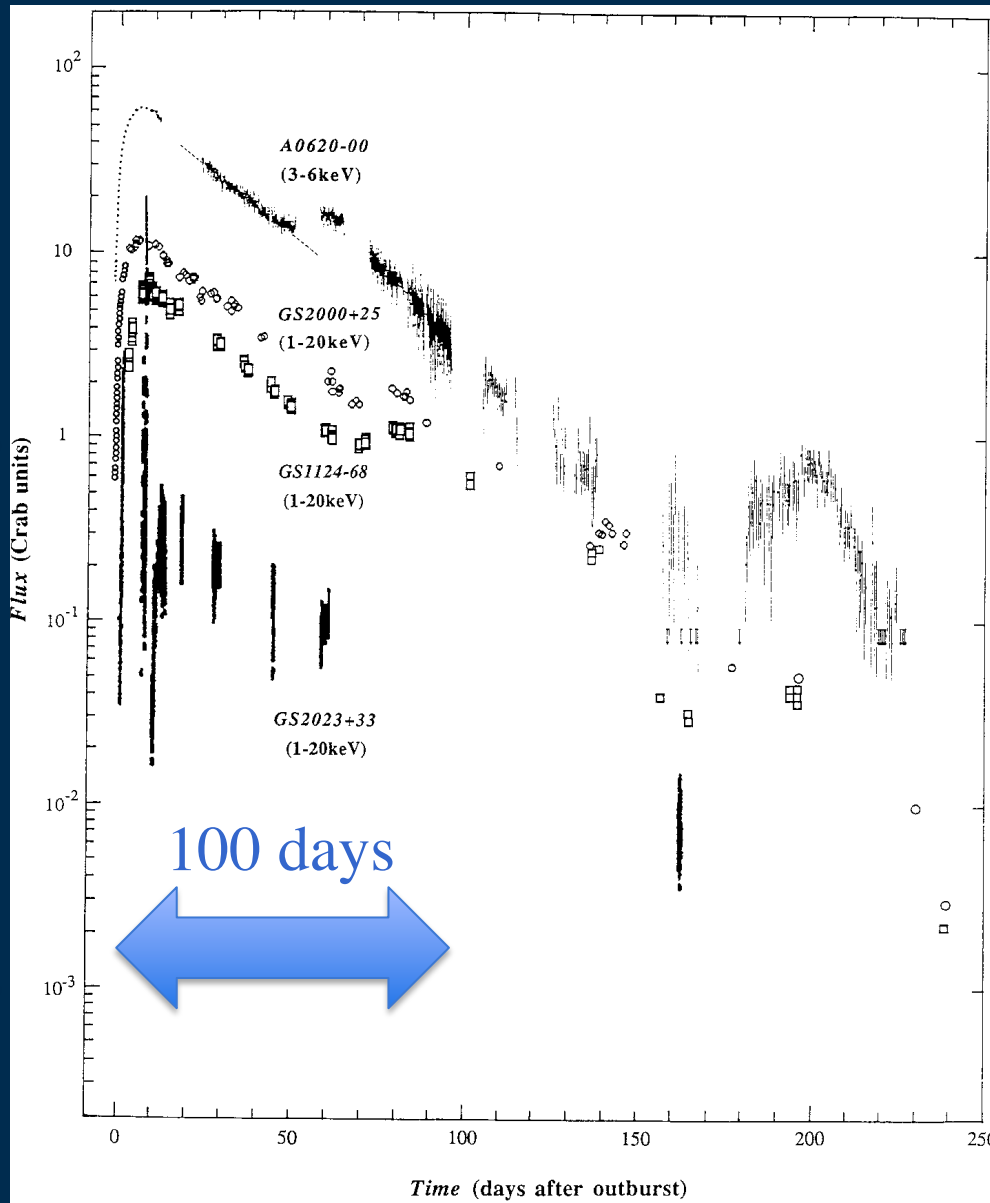
Wikipedia



X-ray Nova (X線新星), Outburst

Flux
1 Crab \rightarrow
(= 2.4×10^{-8} erg/s
2-10 keV)

1 mCrab \rightarrow

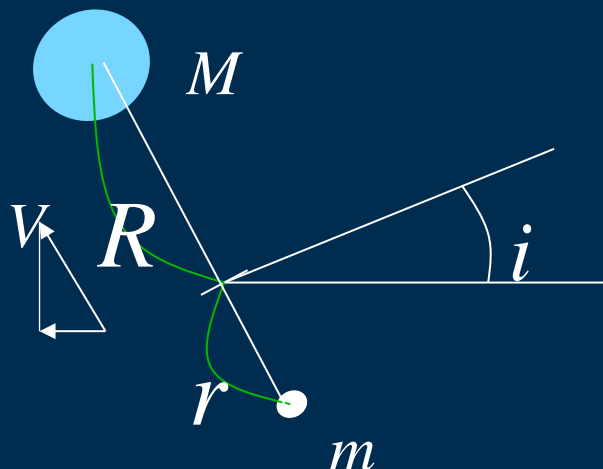


*Tanaka &
Shibasaki 96*

ブラックホール観測 の基礎

観測的ブラックホール論の基礎 1

- 観測されるのは BH ではなく、降着円盤
- BH の条件
 - 伴星の質量と軌道パラメータから見積もられた質量が中性子星の理論上の上限である $3 M_{\odot}$ 以上。(系内に $20 \text{ 弱} \ll 1e8$)
 - 上記の天体とよく似たX線での性質を示す。(40 ほど)
 - BH の直接証拠はまだないので、BH Candidate (BH 候補星) と呼ばれる。BHC は、上記の「よく似た」方だけを示すこともある。
- これまで見つかった BH の **9 割以上がX線新星**



$$\frac{GMm}{(R+r)^2} = M \frac{V^2}{R}$$
$$MR = mr$$

Mass Function

$$\frac{Gm^3}{(m+M)^2} = \frac{T}{2\pi} V^3$$

観測的ブラックホール論の基礎 2

- 相対論に直接関係する重要な半径
 - 重力半径 r_g (Schwarzschild 半径 $r_s = 2GM/c^2$)
 - 降着円盤の最内縁安定半径 $r_{in} = f(M, a)$ a : spin parameter
 - isco : innermost stable circular orbit
 - Schwarzschild Hole (回転していないBH) では $r_{in} = 3r_s$
- 降着円盤で解放されるエネルギー

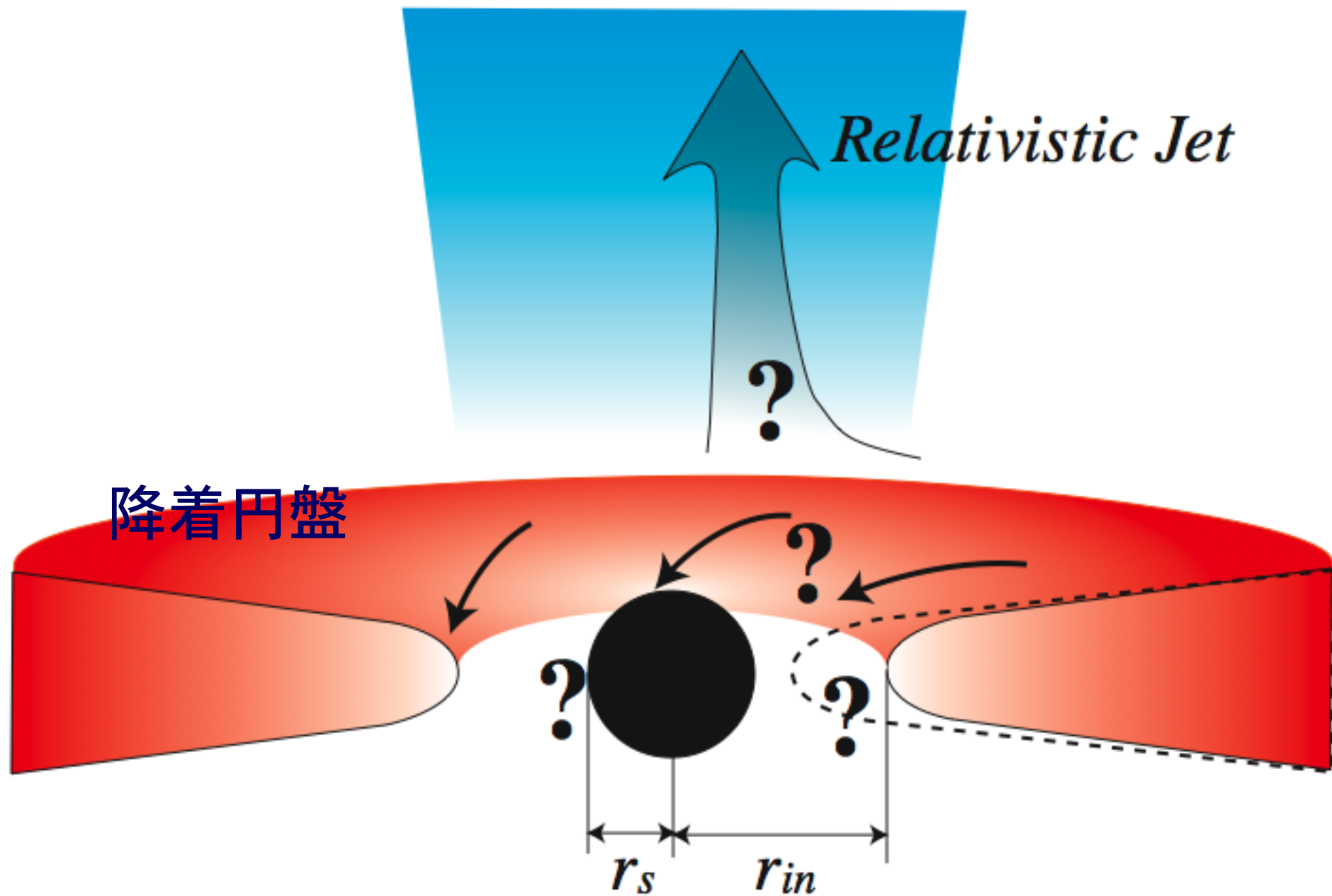
$$E_{grav} = \frac{1}{2} \frac{GMm_p}{3r_s} = \frac{GMm_p}{6(2GM/c^2)} = \frac{1}{12} m_p c^2 \gg E_{nuclear}$$

- 厳密には.. Schwarzschild Hole で静止エネルギーの 5.72 %, Kerr Hole (回転しているBH)で最大 42.3 % !!

佐藤文隆「相対論と宇宙論」

Landau & Lifshitz「場の古典論」

Shapiro & Teukolsky “Black Holes, White Dwarfs, and Neutron Stars”



ブラックホール観測 (X線新星)の歴史

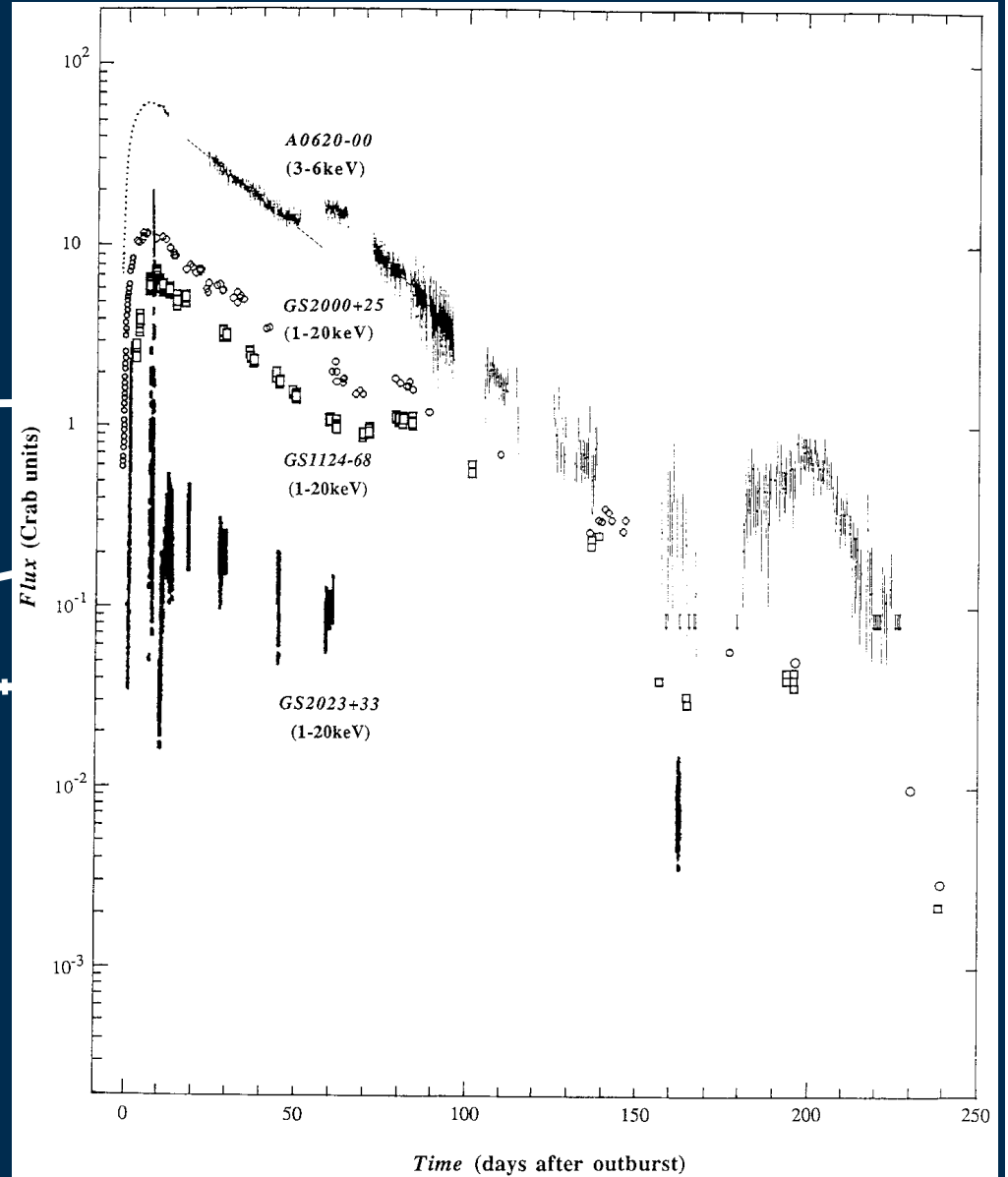
State Transition & Canonicals

A 0620-00 (75)
4U 1543-47 (87)

X1354-644
GS2000+251
GS2023+338
GS1124-684

1990

2000

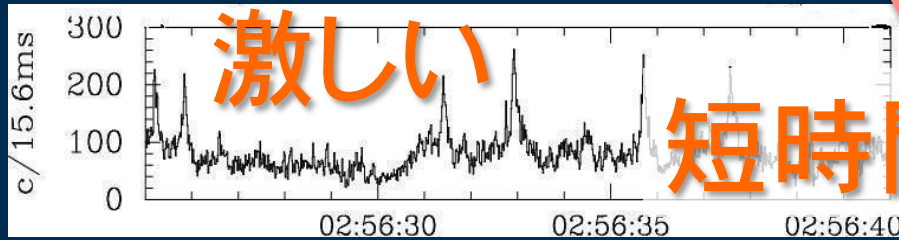


Tanaka & Shibasaki 1996

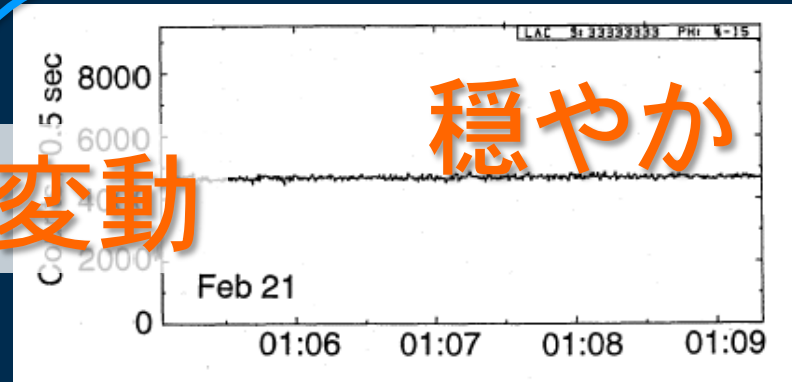
State (状態)

Low/Hard State

High/Soft State



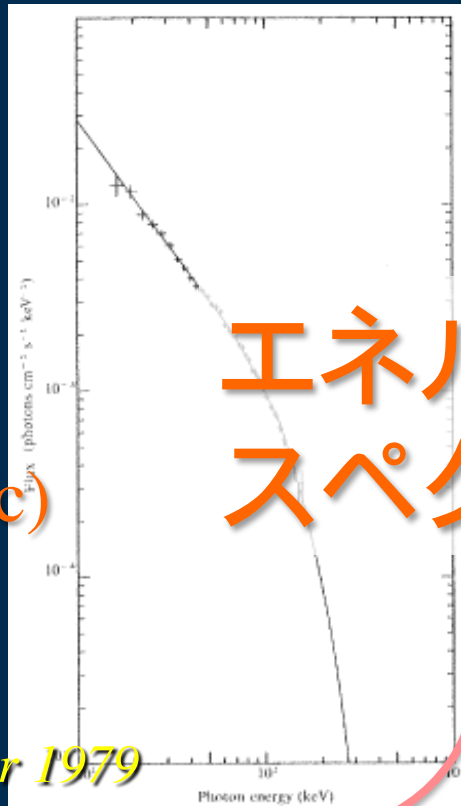
Cyg X-1:
Negoro 1995



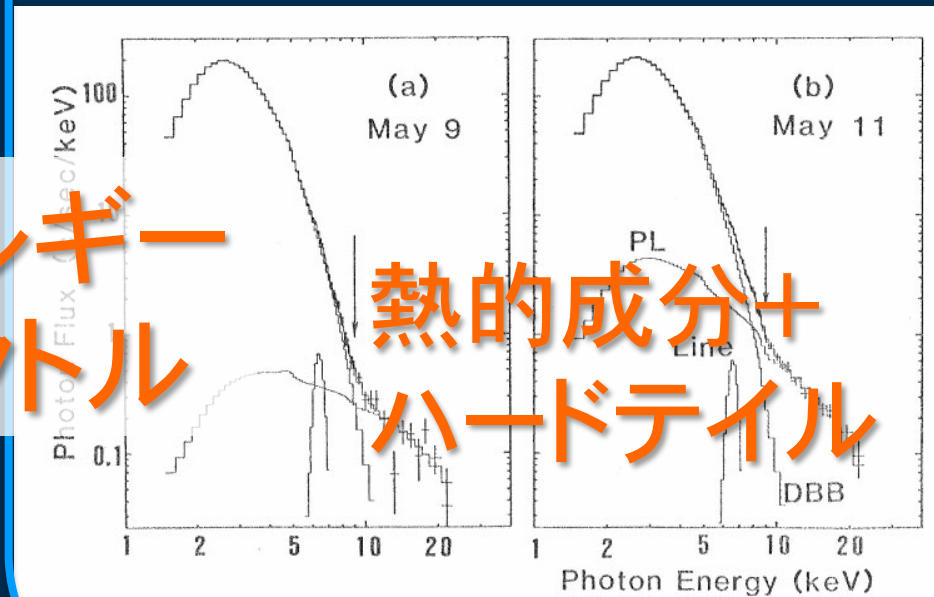
GS 1124-68: Ebisawa et al. 1994

べき状

$$E^{-\alpha} \exp(-E/E_c)$$

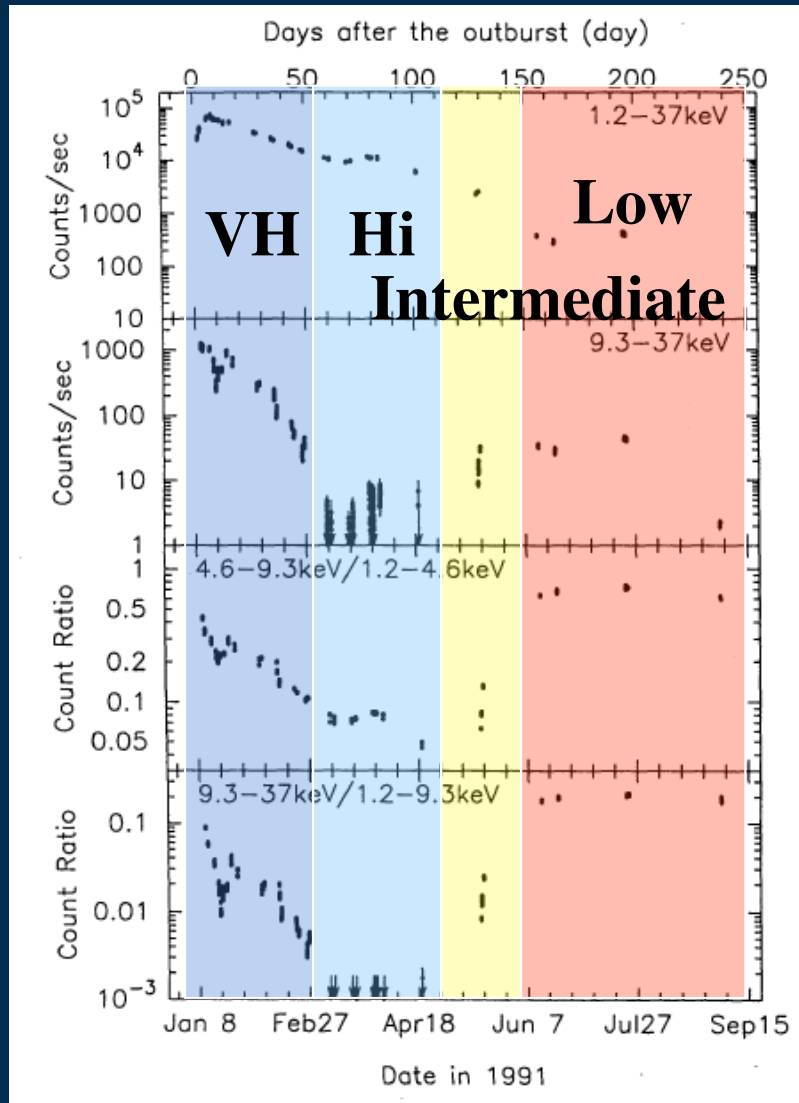


Cyg X-1:
Sunyaev & Trumper 1979

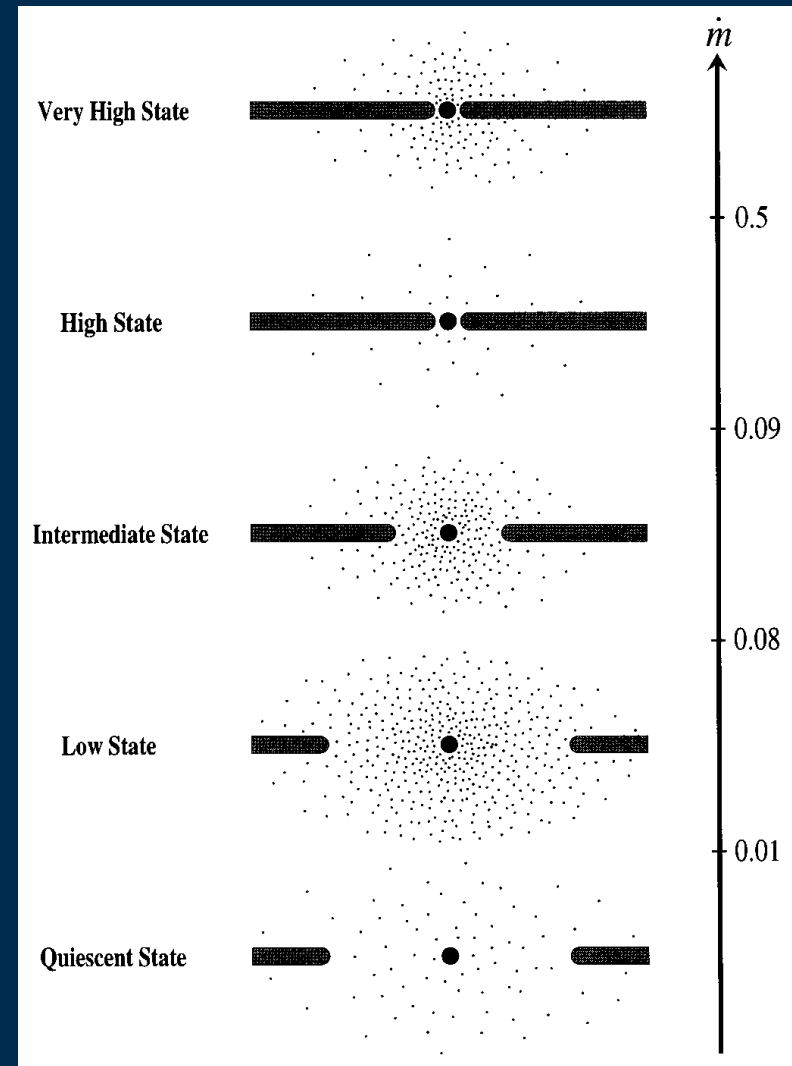


GX339-4: Makishima et al. 1986

State Transition (状態遷移)



GS1124-68: *Ebisawa et al. 1994*



Esin et al. 1997, 1998

降着円盤の物理

Shapiro & Teukolsky 1983

Kato, Fukue, Mineshige 1998

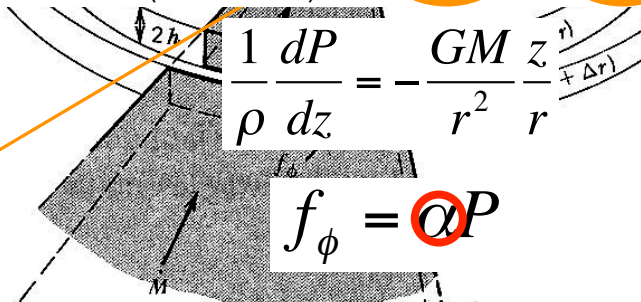
- 質量保存 (連続の式)
- 角運動量保存
- エネルギー保存
- 圧力平衡 (鉛直方向)
- 粘性
- 圧力

$$\Sigma \approx 2h\rho$$

$$\dot{M} = 2\pi r \Sigma v_r = \text{constant}$$

$$f_\phi \times 2\pi r \cdot 2h \times r = \dot{M} \sqrt{GMr} - \dot{M} \sqrt{GMr_{in}}$$

$$\frac{3\dot{m}}{8\pi r^2} \frac{GM}{r} \left(1 - \sqrt{\frac{r_{in}}{r}}\right) = \left(\frac{acT^4}{k\Sigma}\right) \left(\eta \Lambda(\rho, T)\right) + Q_{adv}^-$$



$$\frac{1}{\rho} \frac{dP}{dz} = -\frac{GM}{r^2} \frac{z}{r}$$

$$f_\phi = \alpha P$$

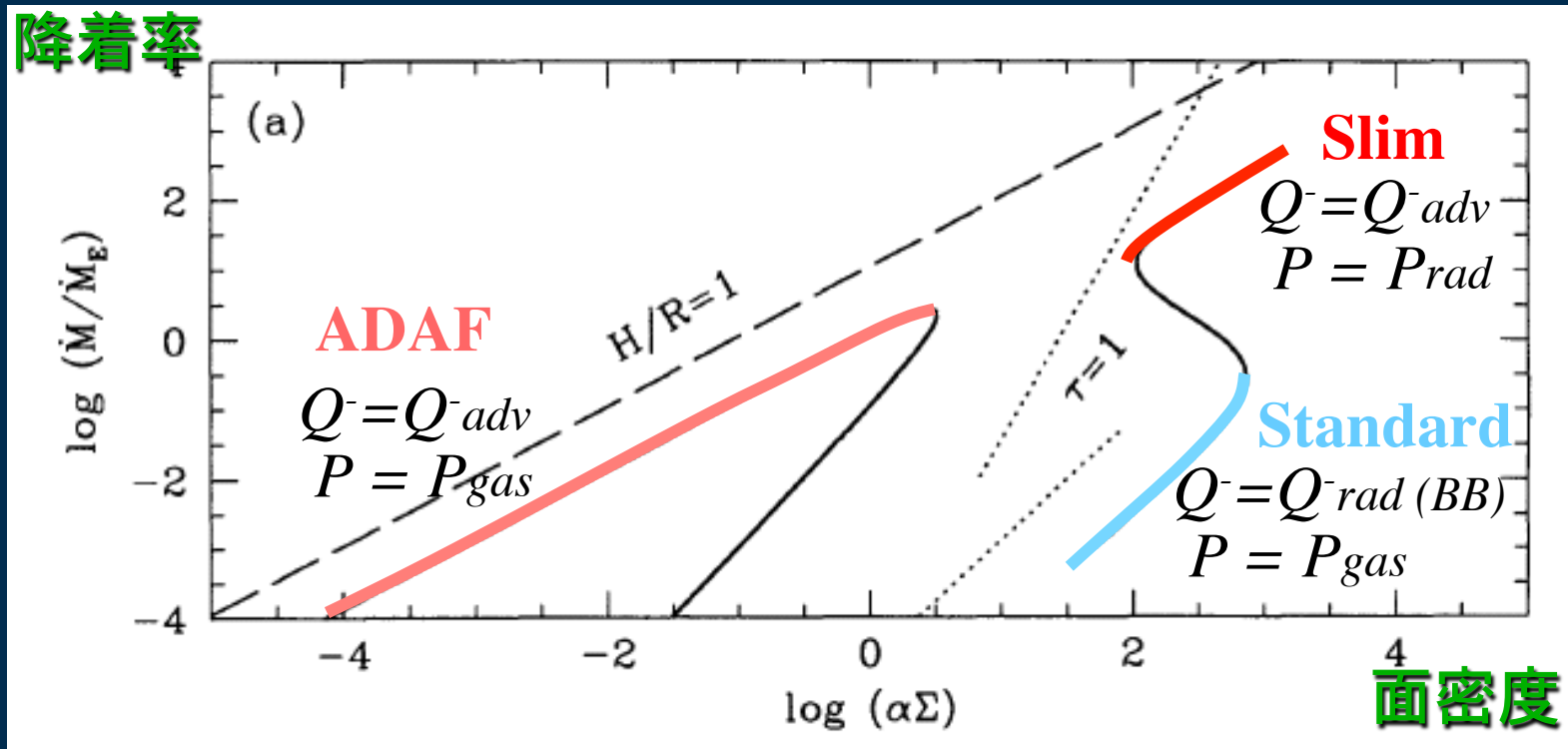
$$P = \frac{2\rho kT}{m_p} + \frac{1}{3} aT^4$$

$$r_{in} = 3r_s : mc^2/2 = GMm/r_s : r_s = 2GM/c^2$$

降着円盤方程式の解

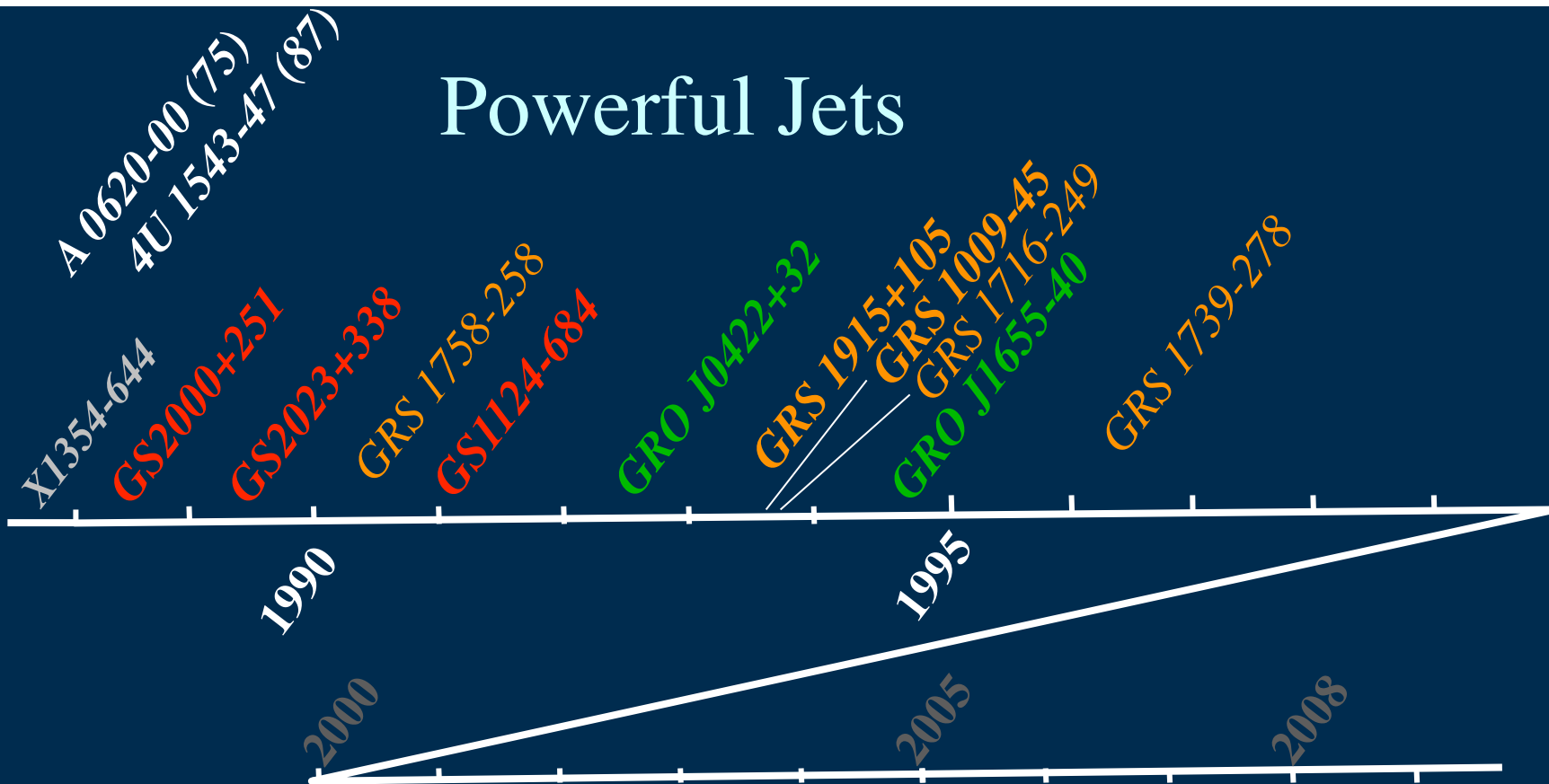
$$M = 10M_{\odot}, r = 5, \alpha = 0.1$$

Abramowicz et al. 1995



薄い ← 光学的に → 厚い

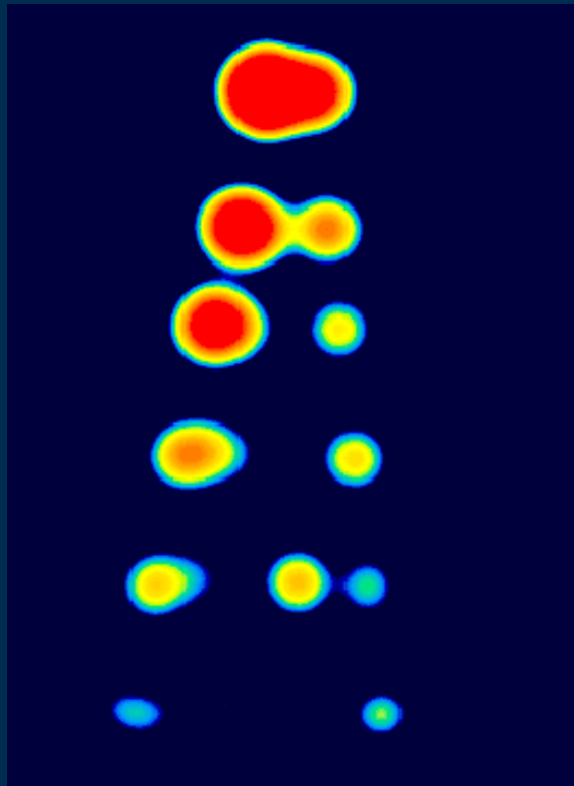
Powerful Jets



未解決問題

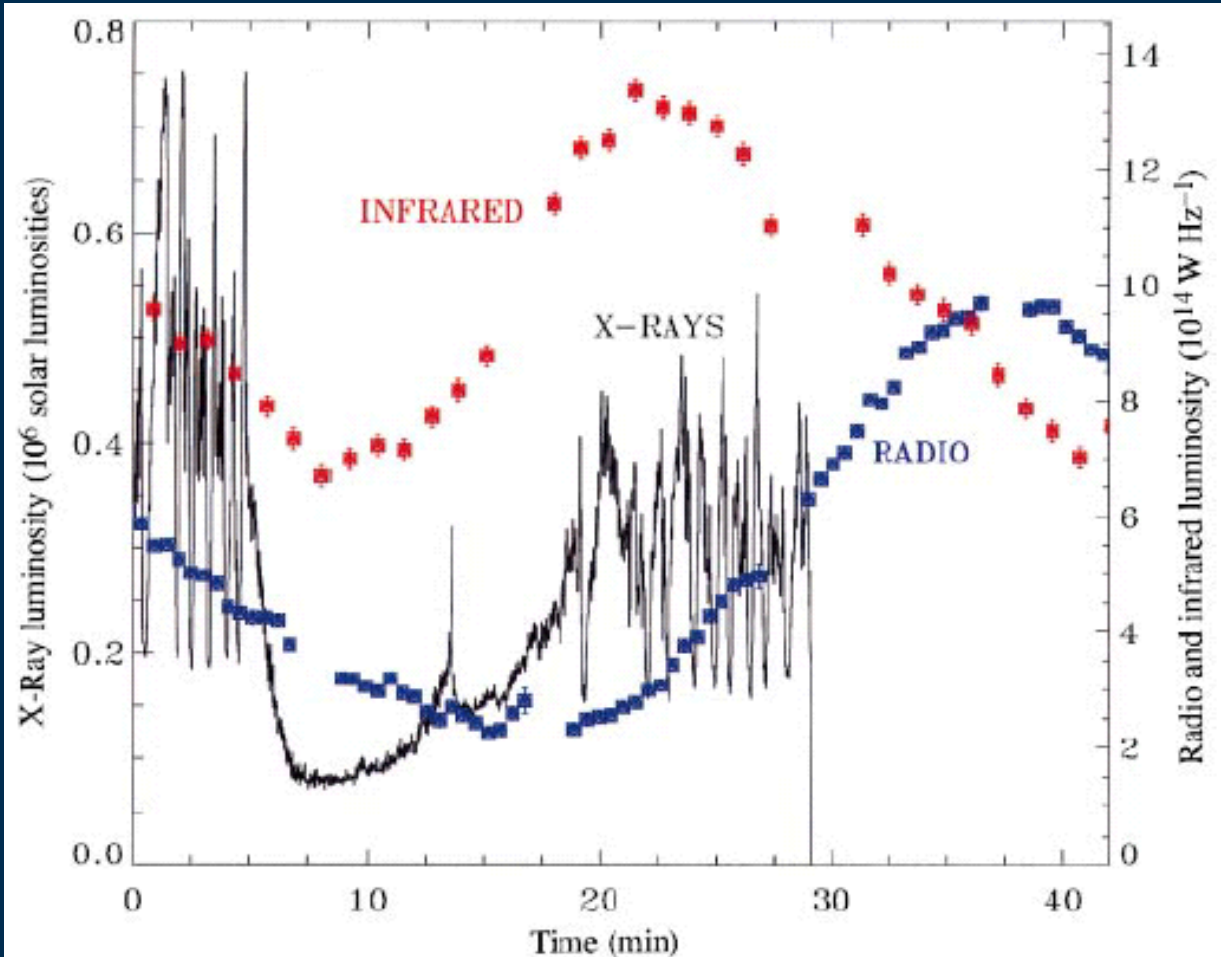
Super Luminal Jet Sources Micro-Quasar

GRS 1915+105:
Mirabel et al. 1994

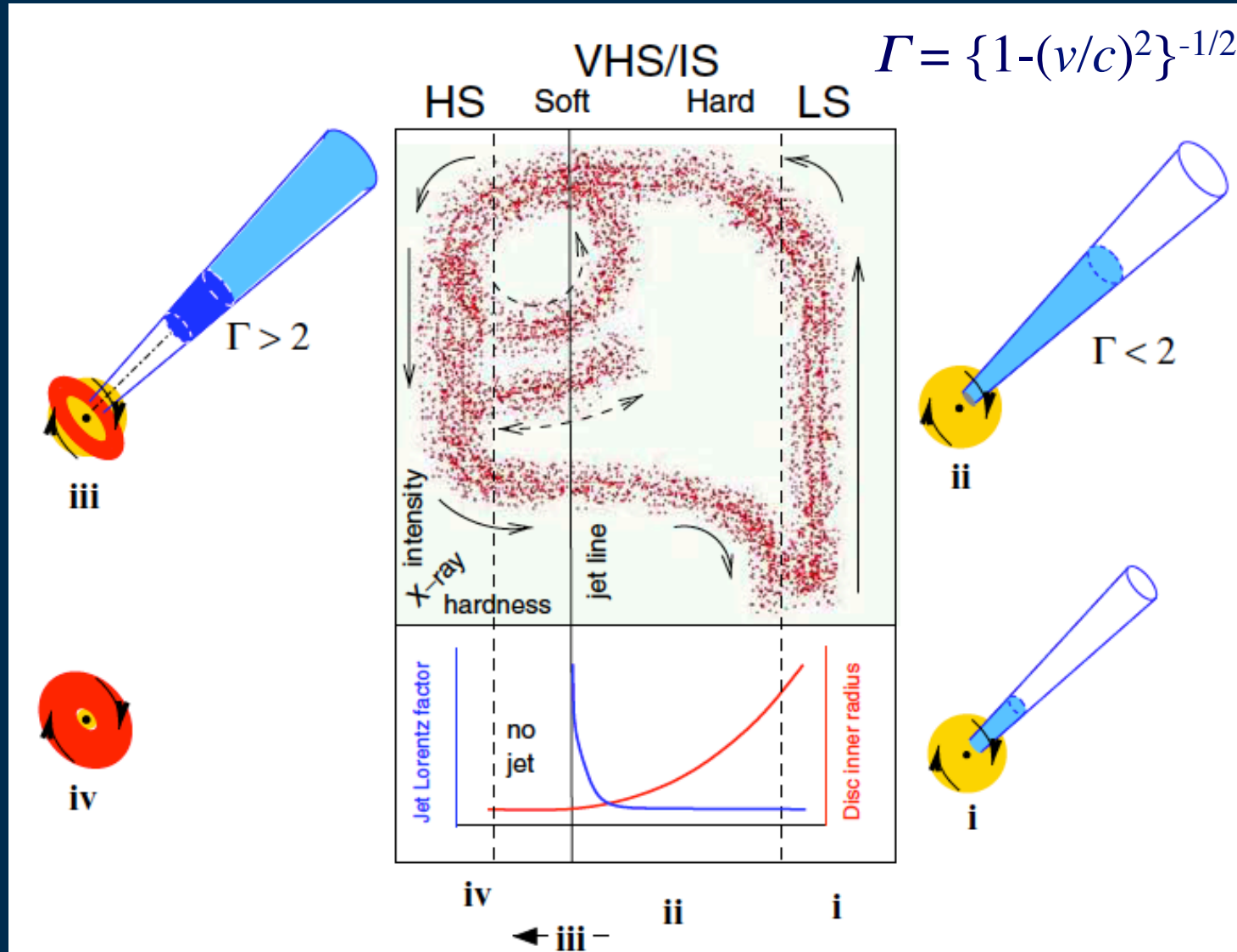


$v \sim 0.92 c$

GRS 1915+105/RXTE: *Mirabel & Rodriguez 1998*



Jet & State

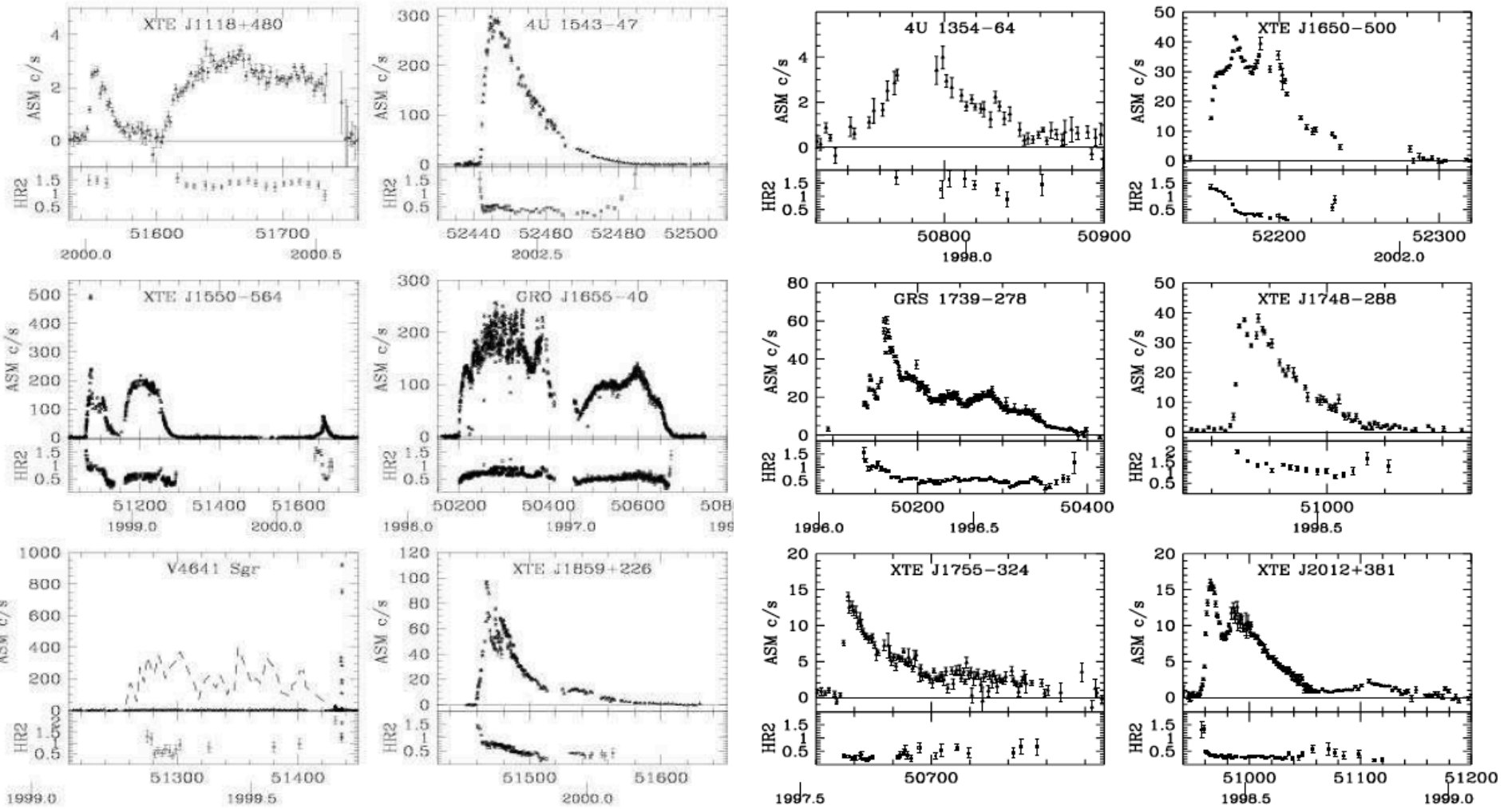


Various Novae

1620-00 (75)
1543-47 (87)

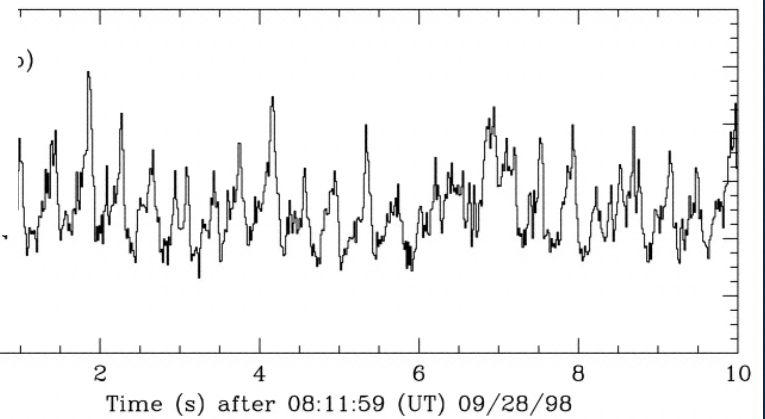
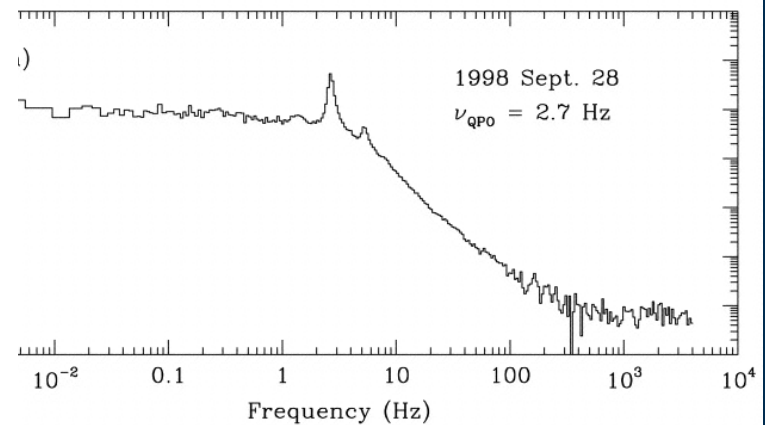
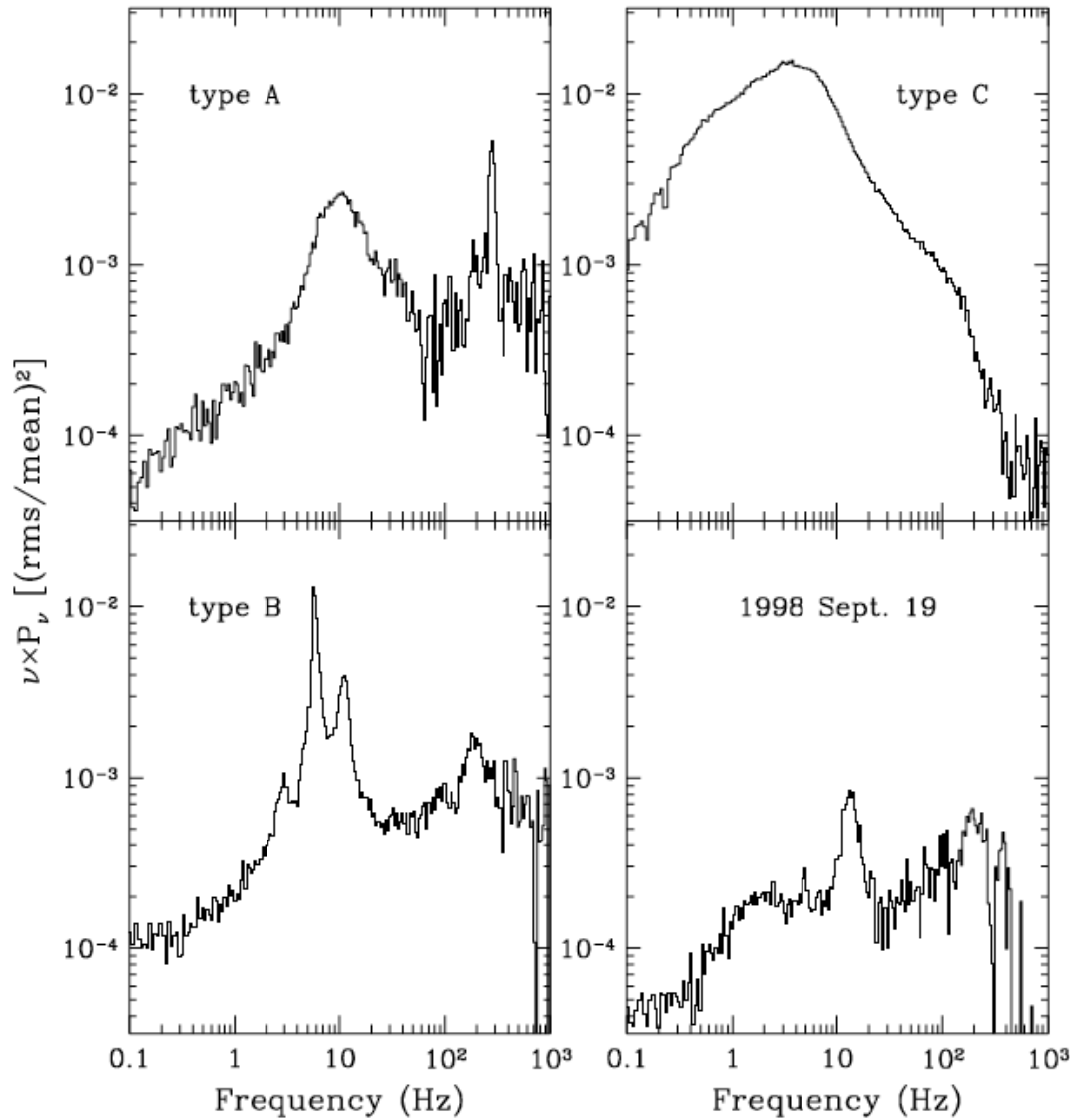
1345
1349

13324
12+381
288



Various LF QPOs

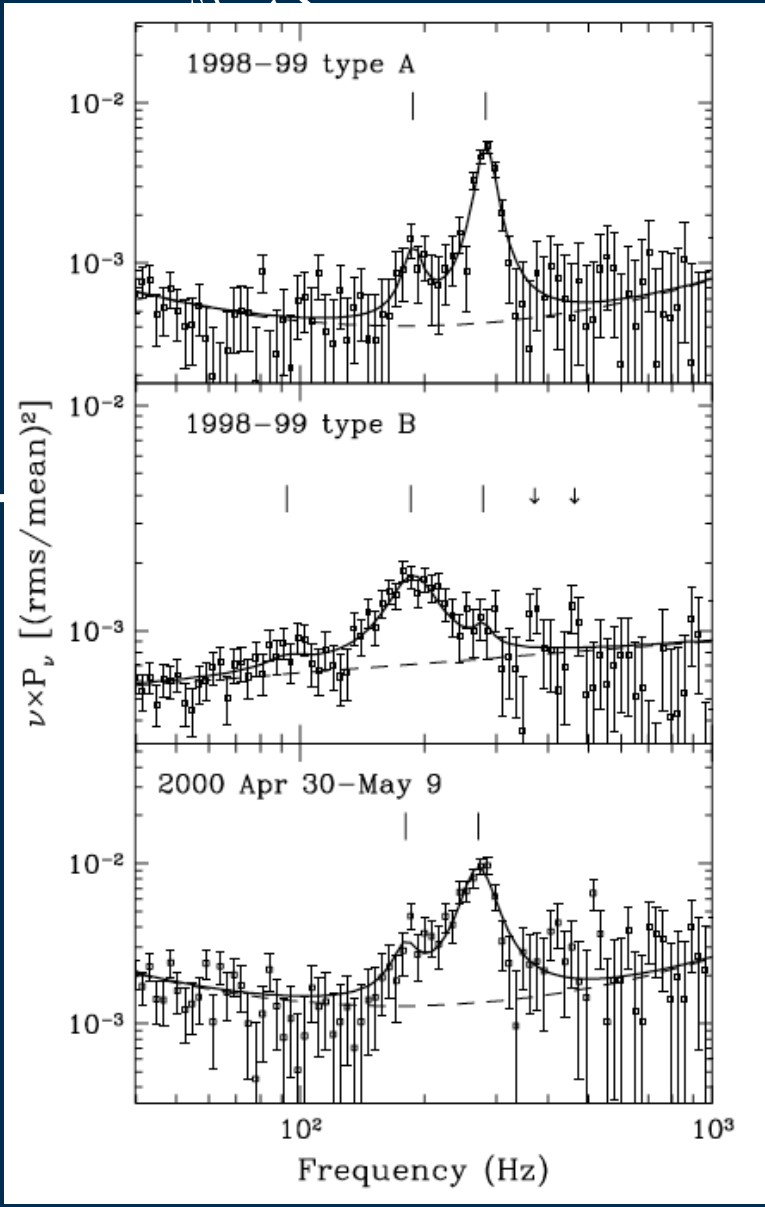
PS 1739-278
 XTE J1856+053
 XTE J1755-324
 XTE J2012+361
 XTE J1748+288
 XTE J1550+564
 Sgr
 XTE J1859+226



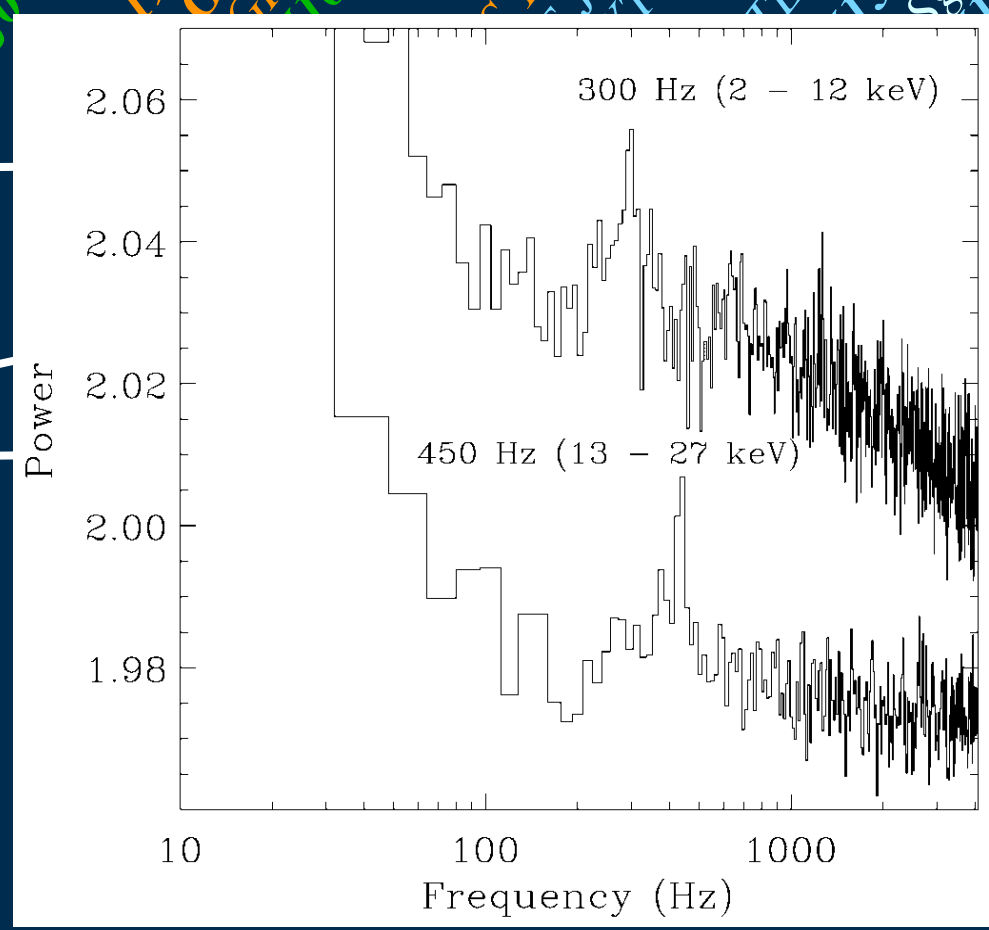
XTE J1550-564
Remillard et al. 02

XTE J1550-564 Sobcrak et al. 2002

HF QPOs



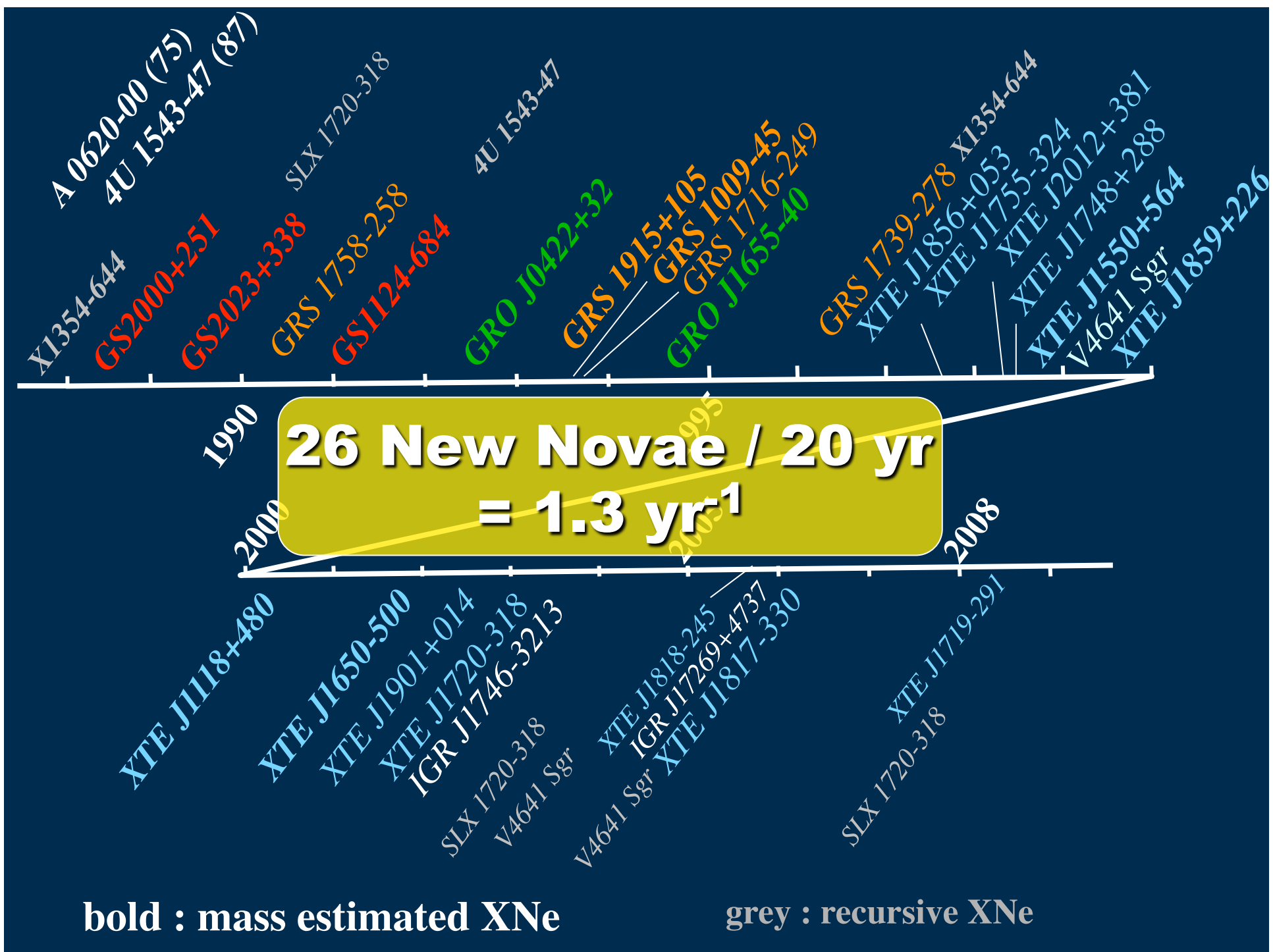
XTE J1550-564
Remillard et al. 02



GRO J1655-40 Strohmayer. 01

(75) (87)

0422+32
 1915+105
 GRS 1009-45
 GRS 1716-249
 1655-40
 1739-278
 J1856+053
 XTE J1755-324
 XTE J2012+381
 XTE J1748+288
 1550+564
 Sgr
 1859+226



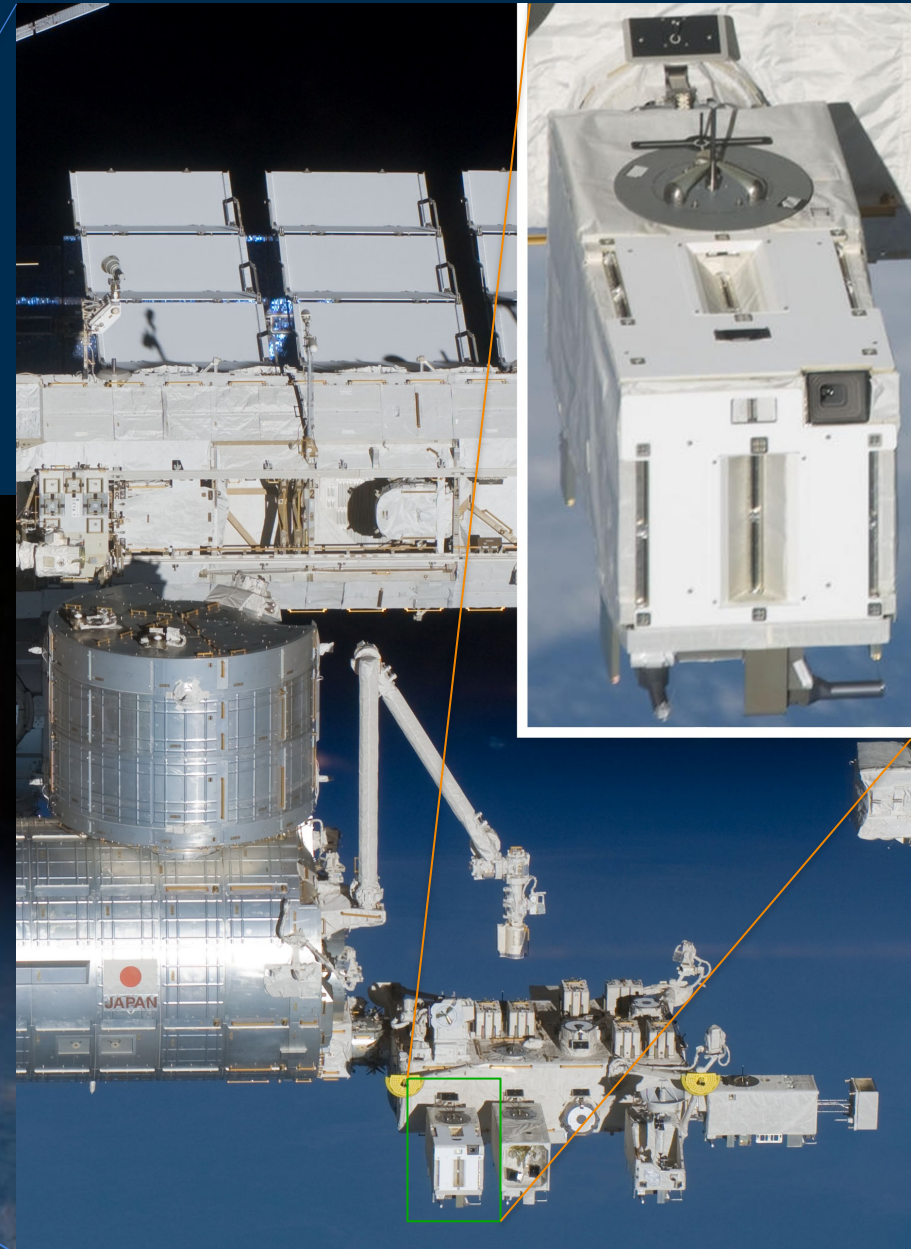
MAXI

Monitor of All-sky X-ray Image

MAXI の歴史

- 構想 10 年
 - 1997/4 に ISS の暴露部の最初のミッションとして採択
 - PI 松岡 勝 (理研 宇宙放射線研究室 + 阪大 常深研)
 - 目的
 - 突発天体の発見 (cf. HETE2)
 - X線天体の長期モニター
 - 全天マップ／カタログ
 - 当初は 2003 年に H-II A で打ち上げ予定だった。。
 - 妄想 3 年
- 2009 年 8 月 15 日から ISS 「きぼう」実験棟で観測開始
- JAXA, 理研, 阪大, 東工大, 青学, 日大, 京大, 中央大, 宮崎大 により 24 時間 365 日運用

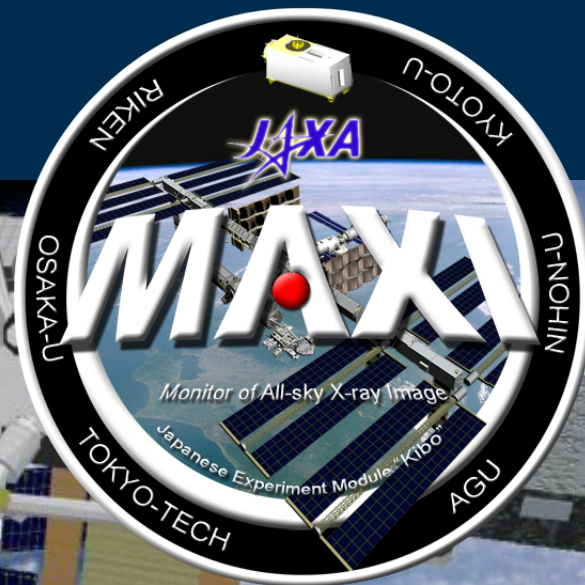
Monitor of All-sky X-ray Image MAXI



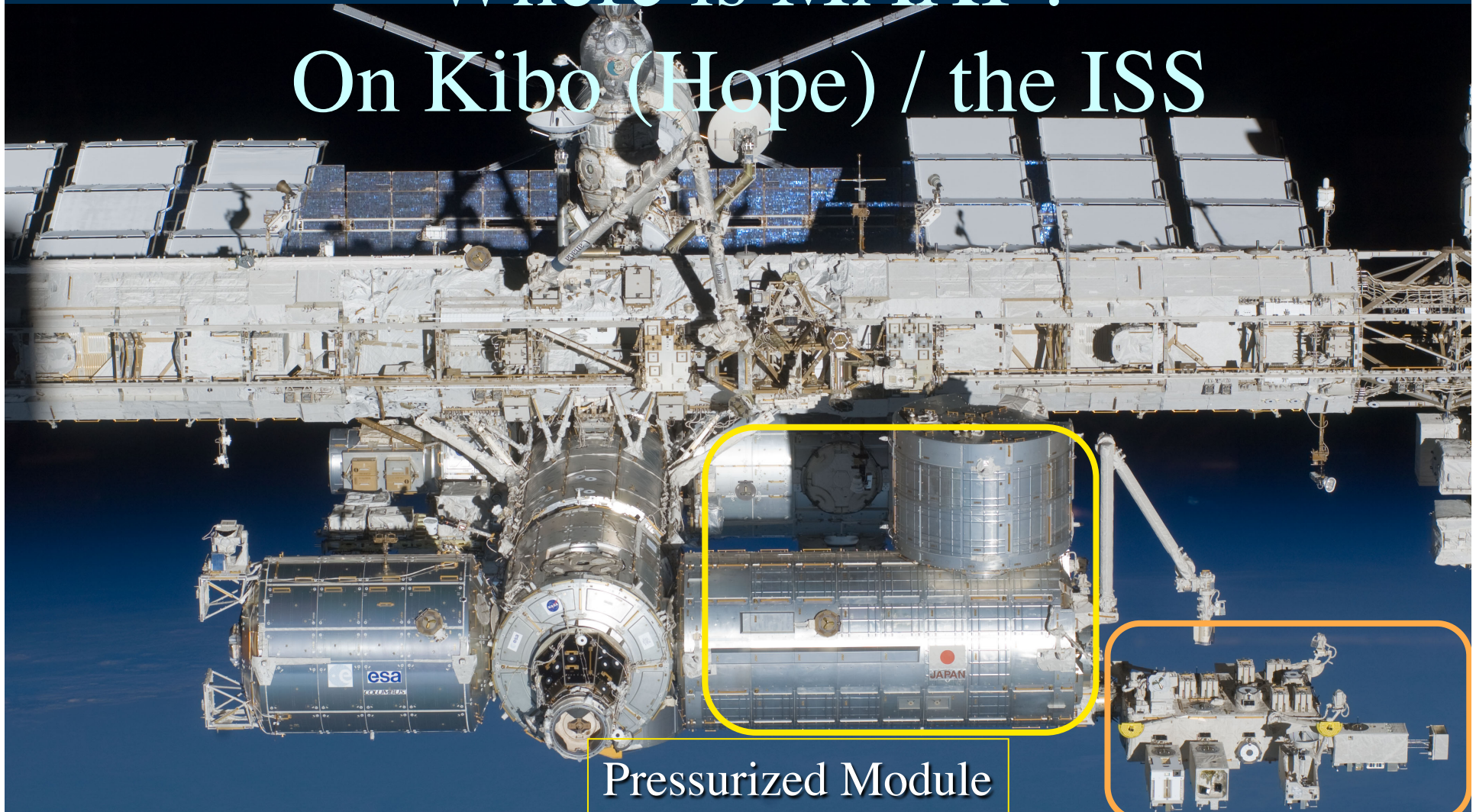
Matsuoka et al. 2009

全天X線監視装置 MAXI

09/07/16 打ち上げ
およそ90分で
全天を観測



Where is MAXI ? On Kibō (Hope) / the ISS

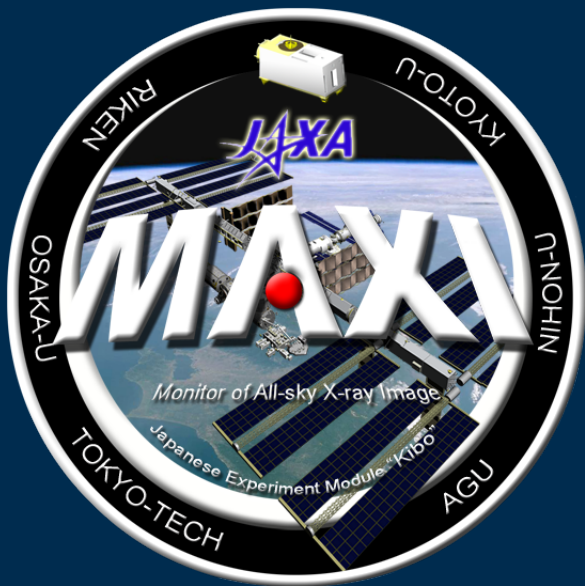
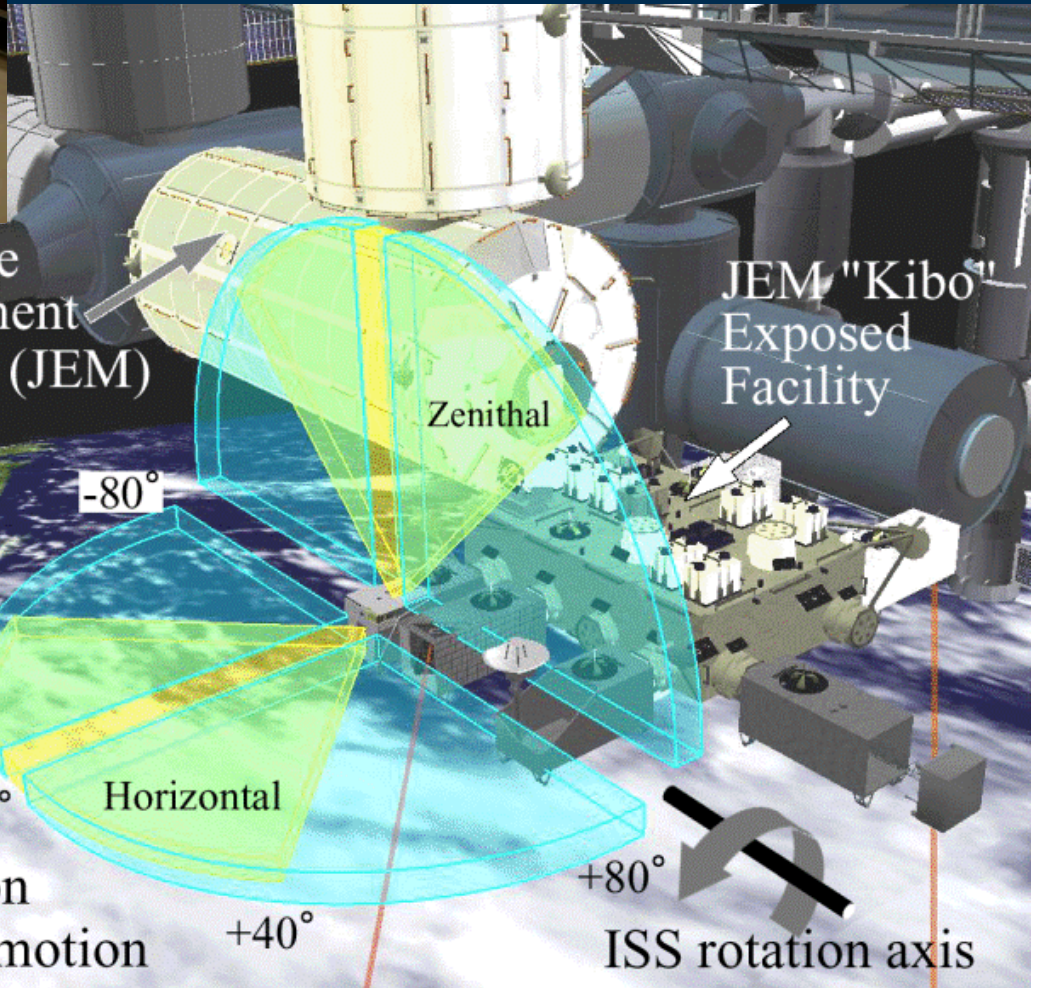
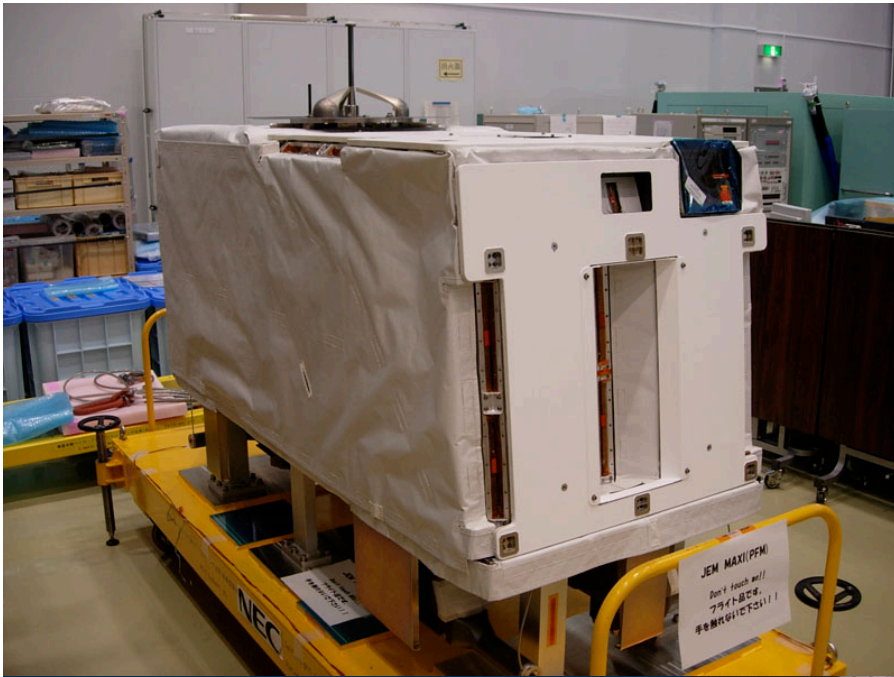


Pressurized Module
2008/06 Attached

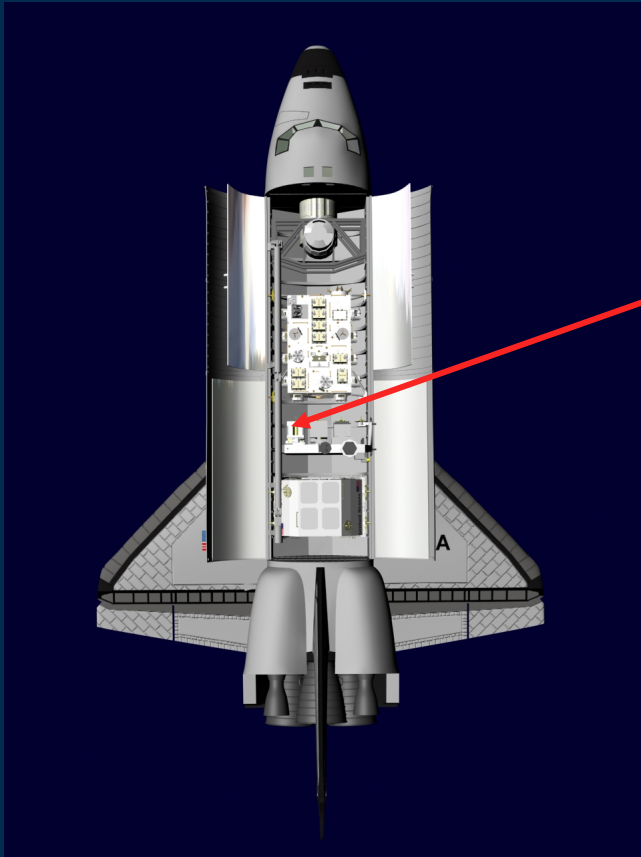
JEM Exposed Facility
2009/07/16 Launched
07/19 Attached

MAXI

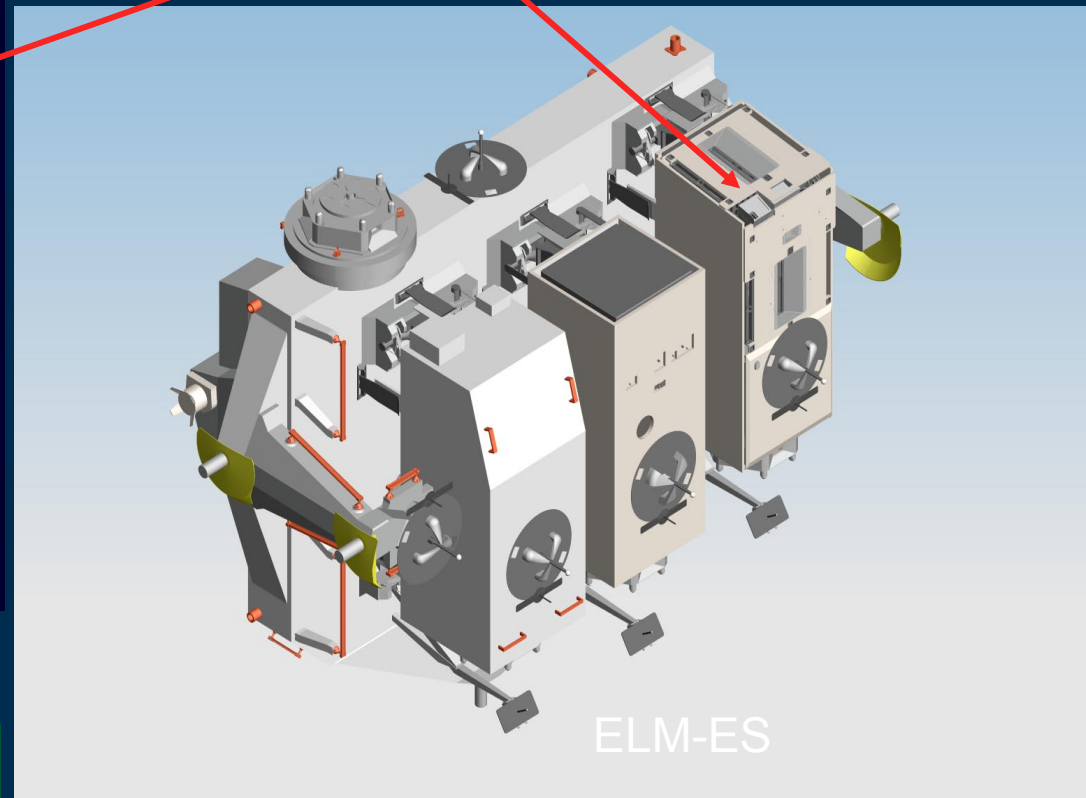
Monitor of All-sky X-ray Image



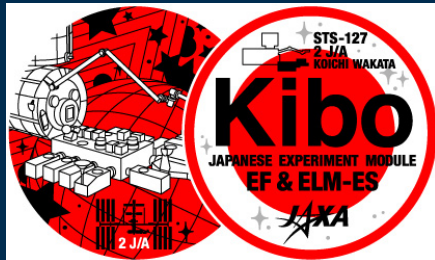
打上げコンフィギュレーション



MAXI
(PAM#3)

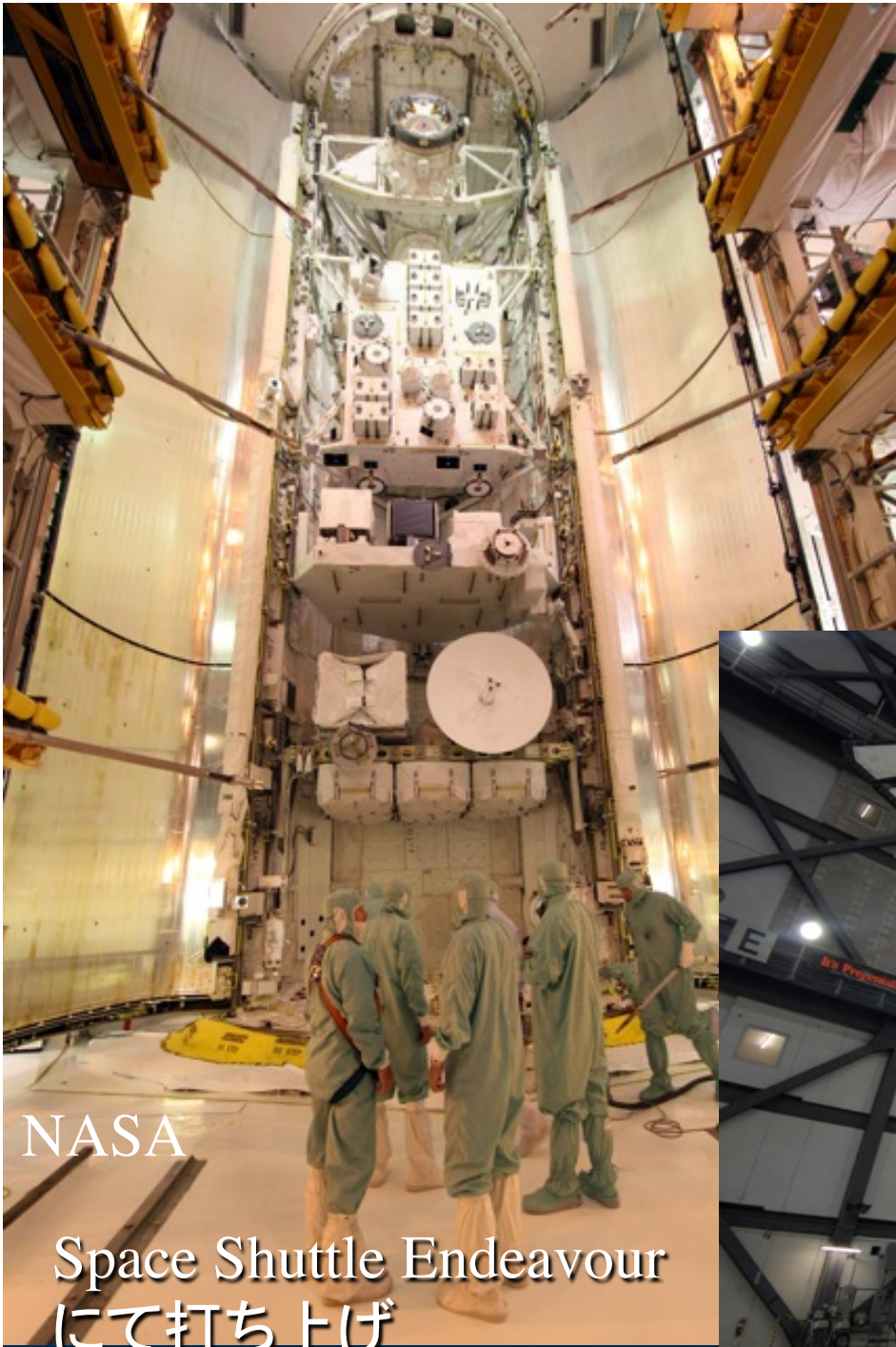


ELM-ES



Flight 2J/A
Launch

STS-127



NASA

Space Shuttle Endeavour
にて打ち上げ



NASA

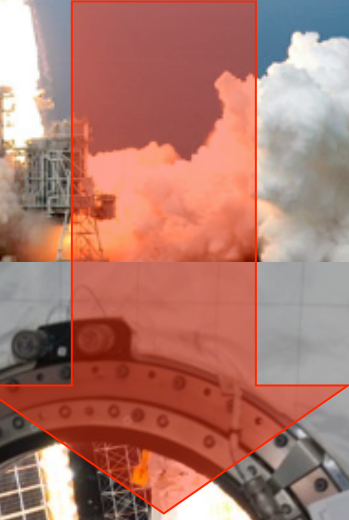


NASA

S127E008112



NASA

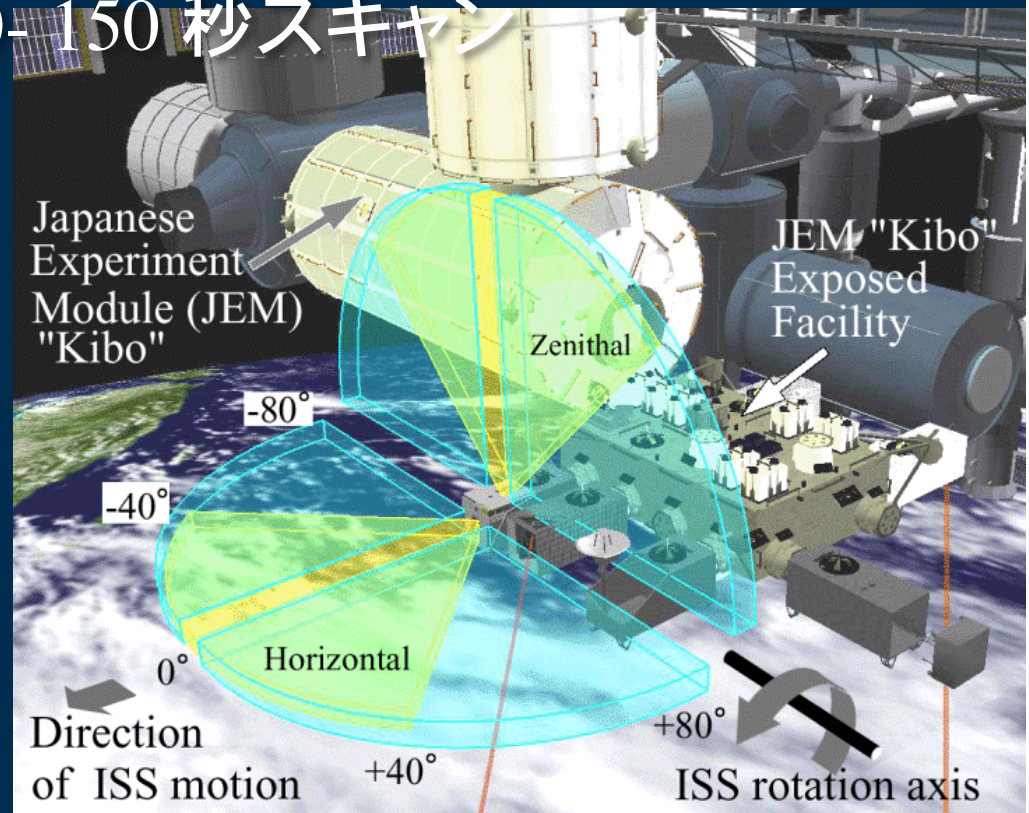
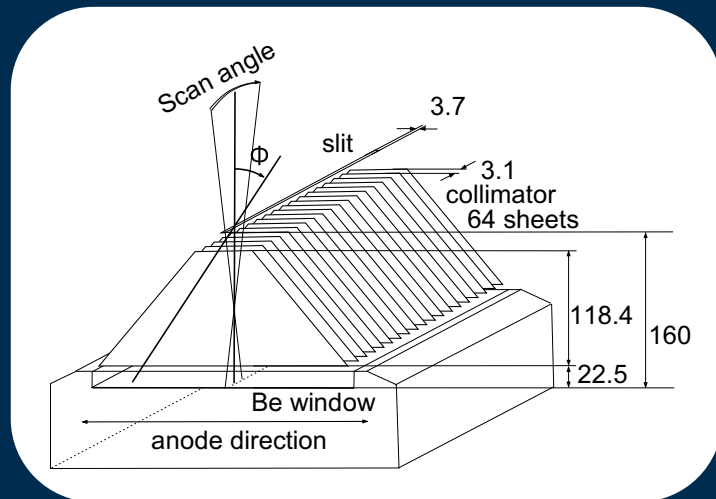


NASA

S127E008135

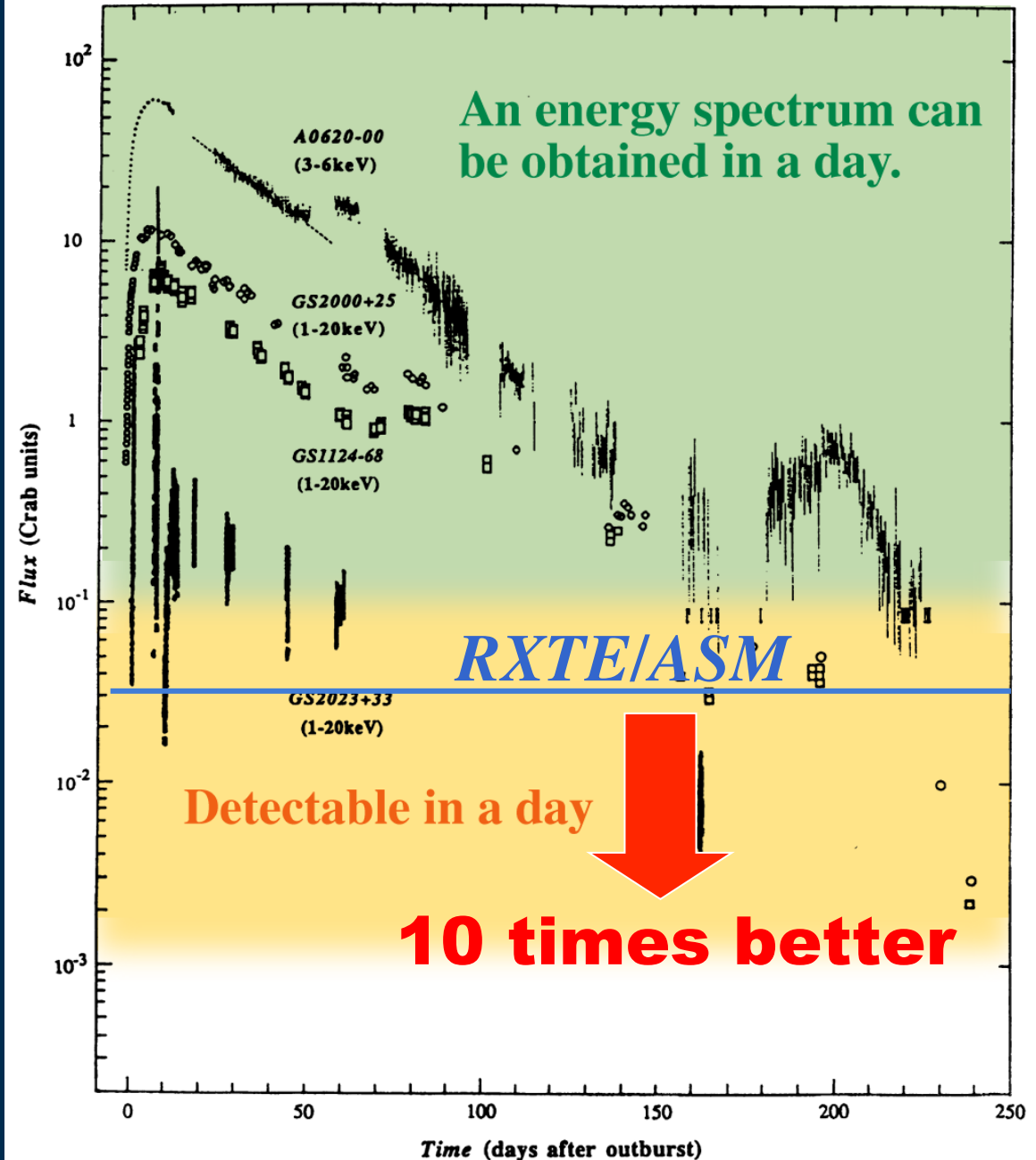
Instruments and Observation

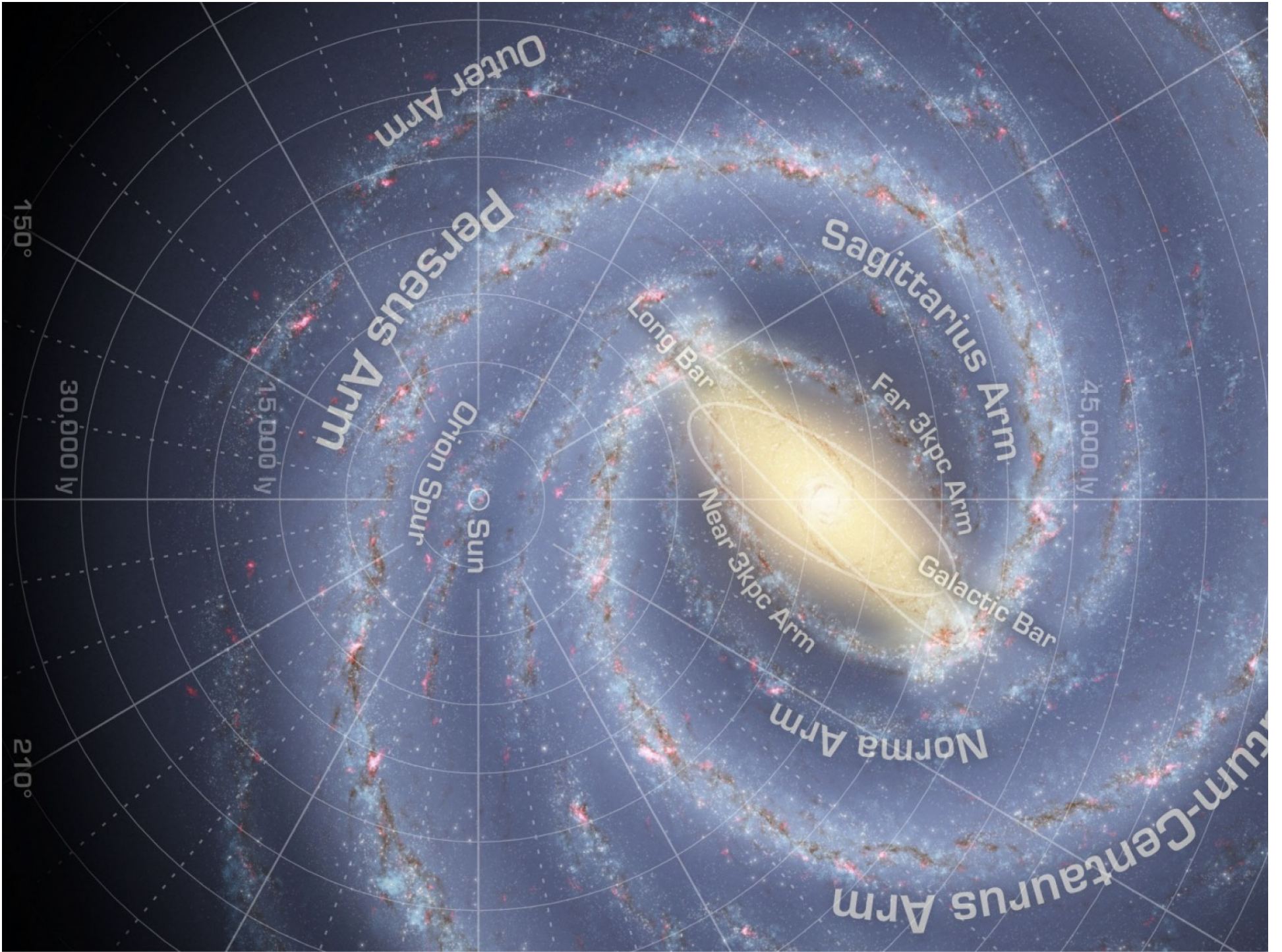
- 検出器
 - GSC (比例計数管): 3-20 keV
 - SSC (CCD カメラ): 0.7-12 keV
 - PSF \sim 1.5 deg (FWHM), 位置決定精度 \leq 0.2 deg
- 92 分で 1 または 2 回 40-150 秒スキャン

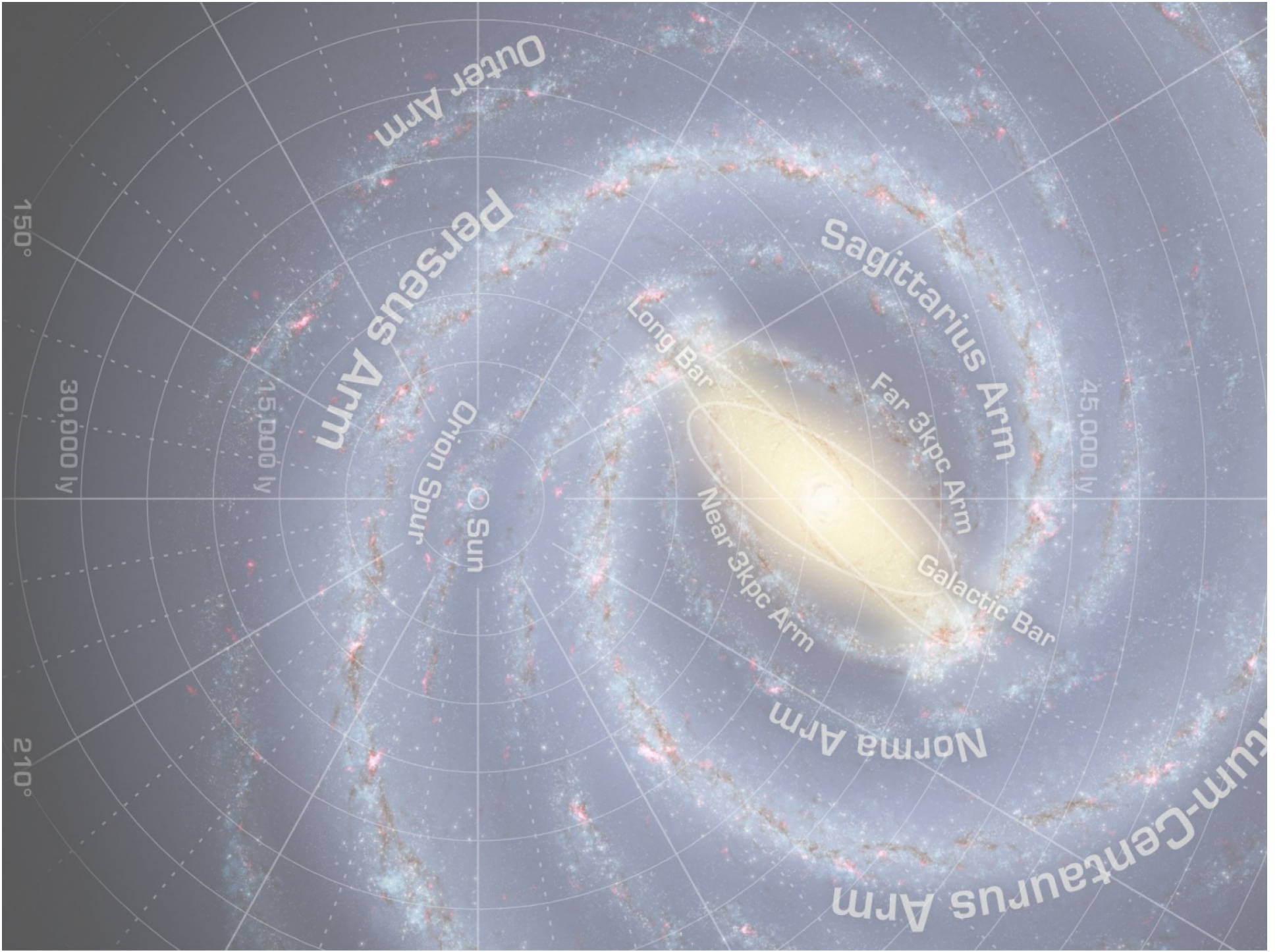


X線新星における 全天X線監視装置 MAXI の能力

- 桁高い感度
- 幅広いエネルギーバンド
- 高い時間分解能

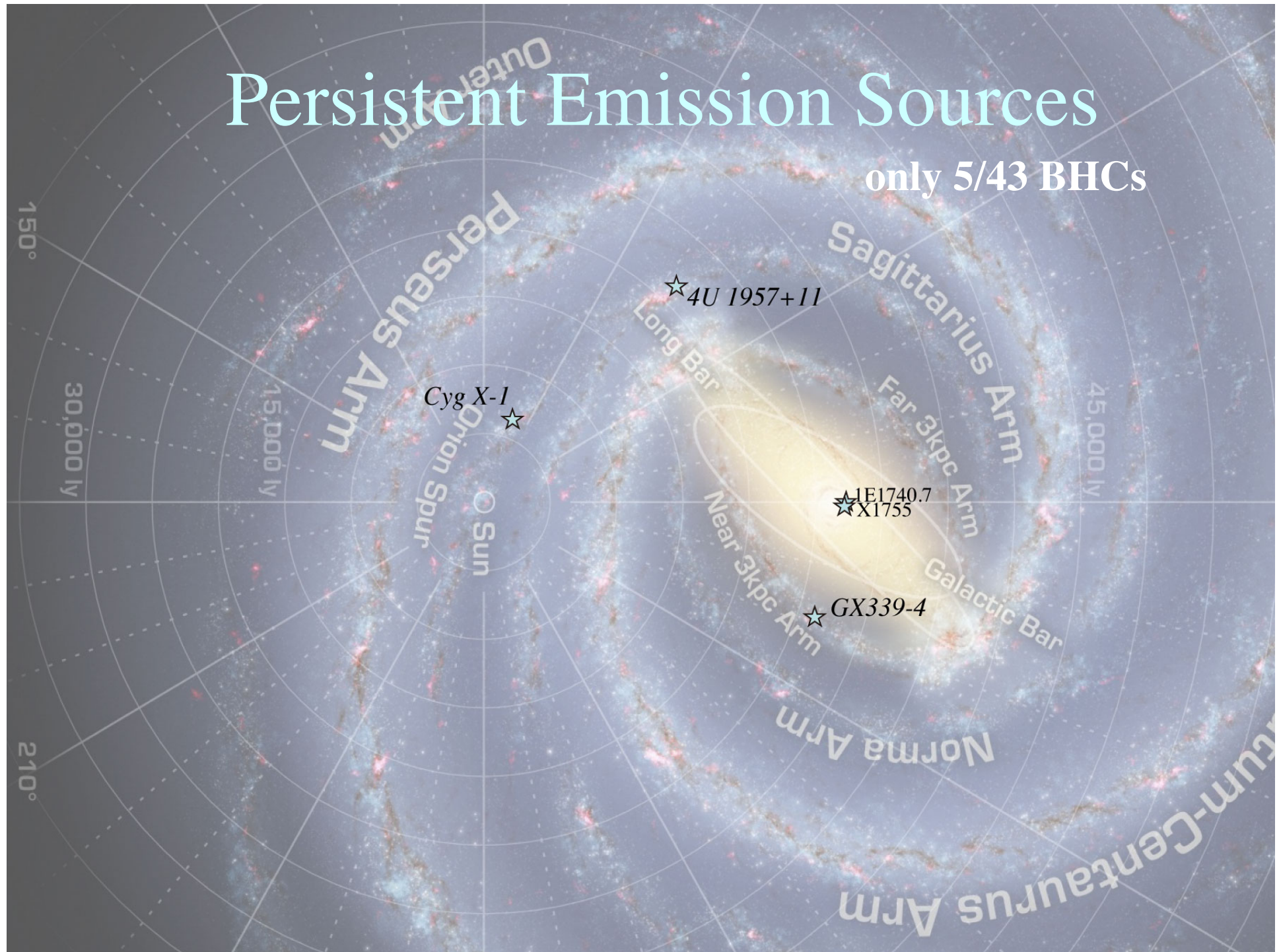




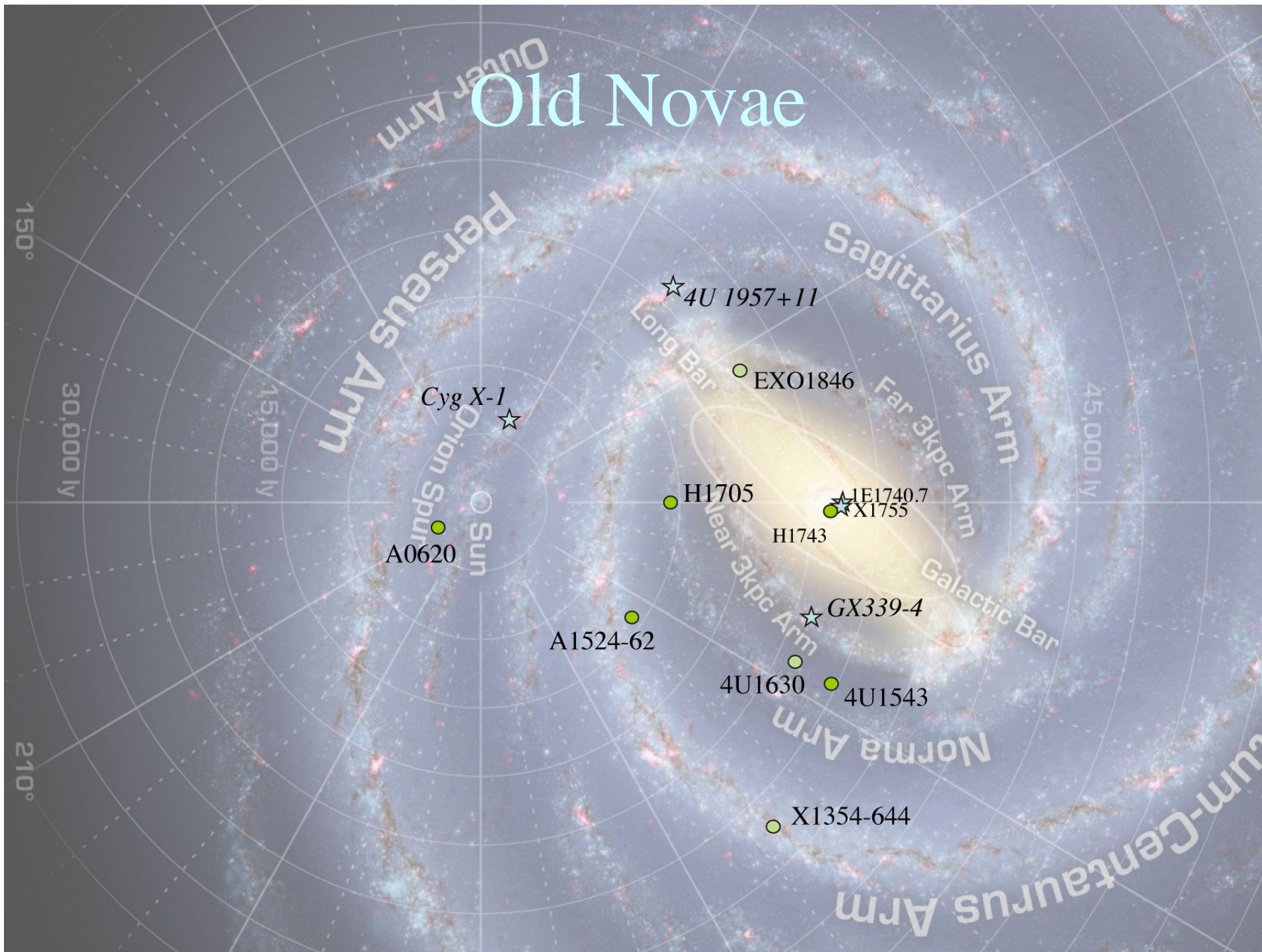


Persistent Emission Sources

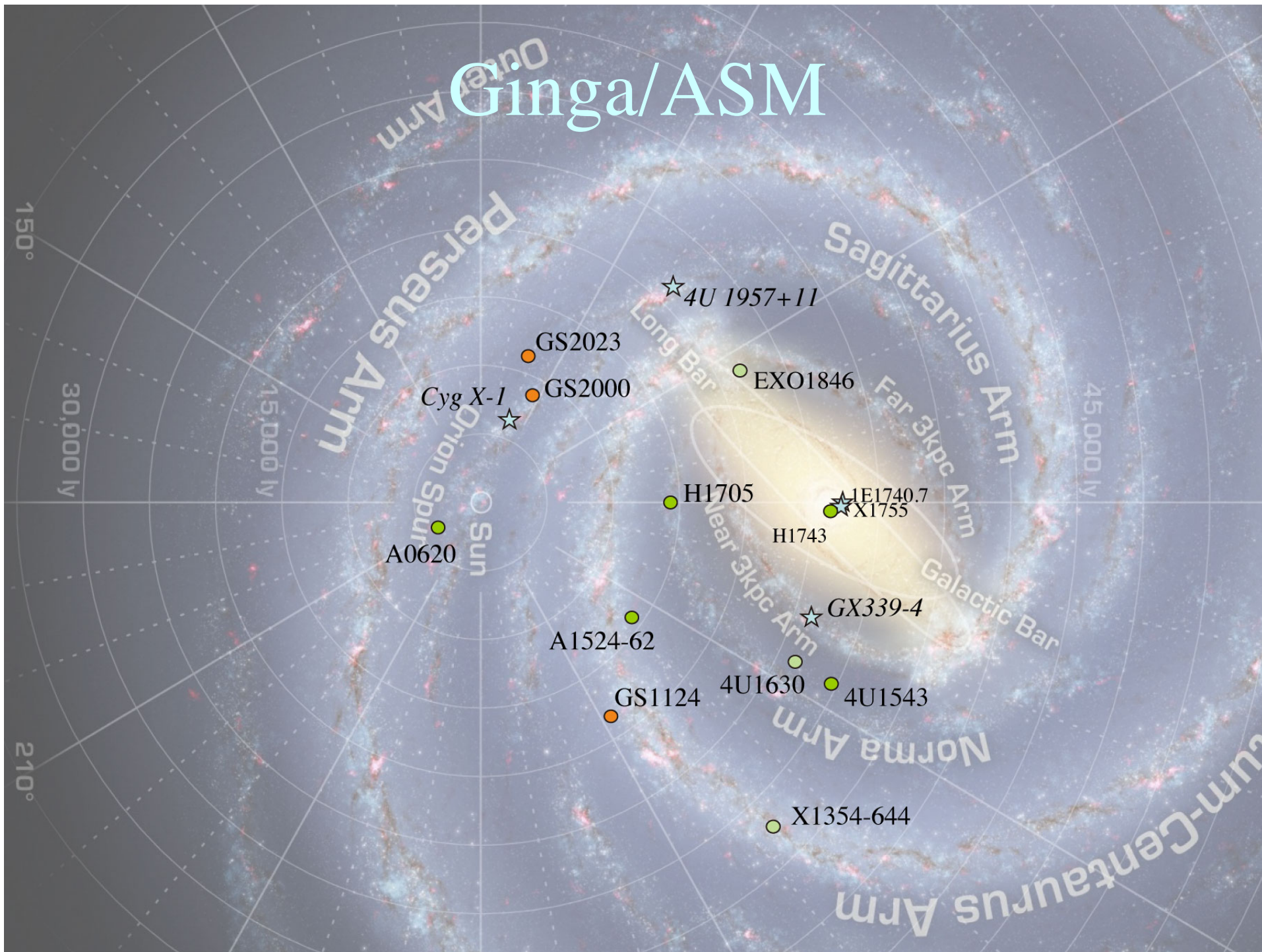
only 5/43 BHCs



Old Novae

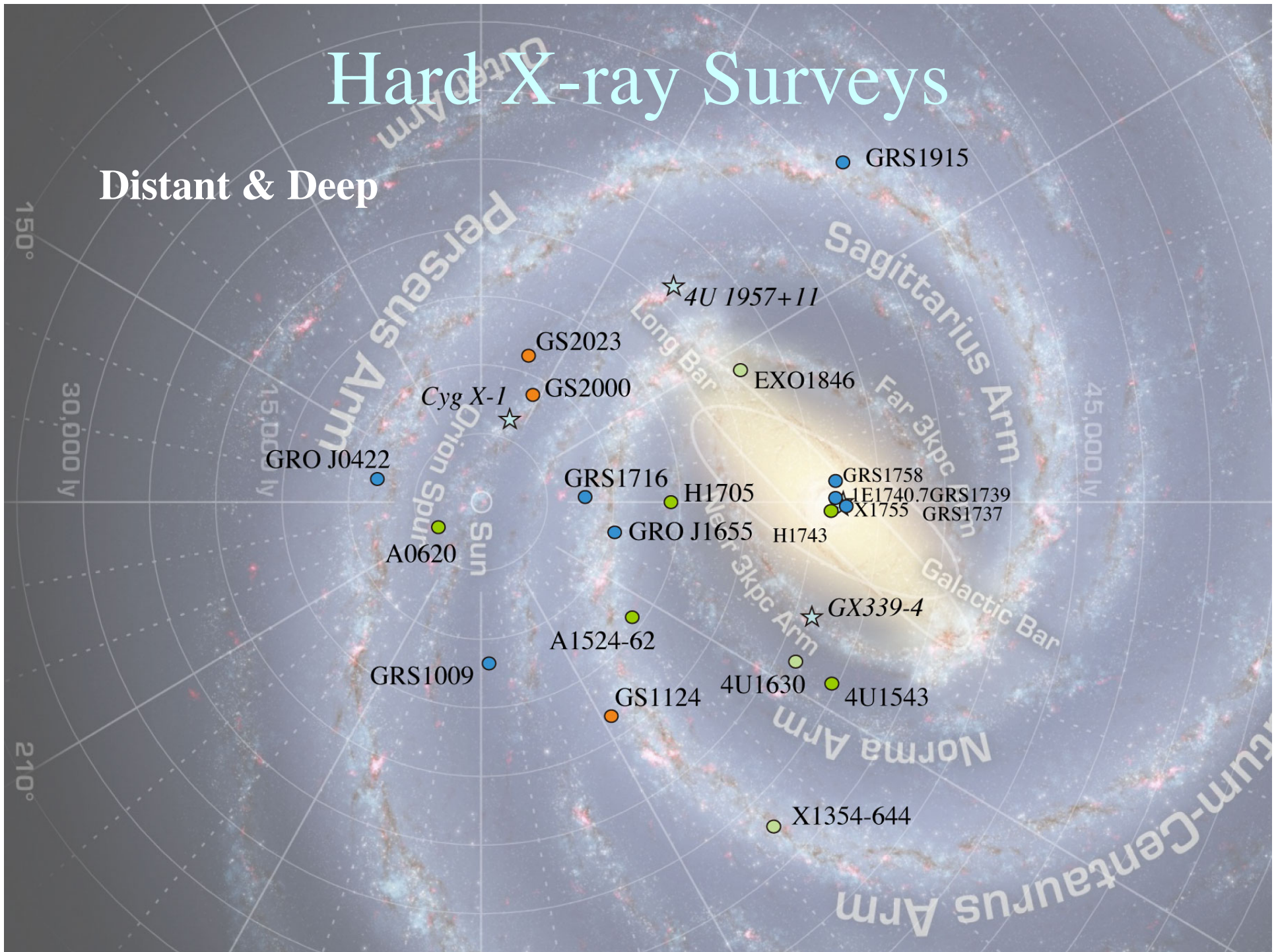


Ginga/ASM

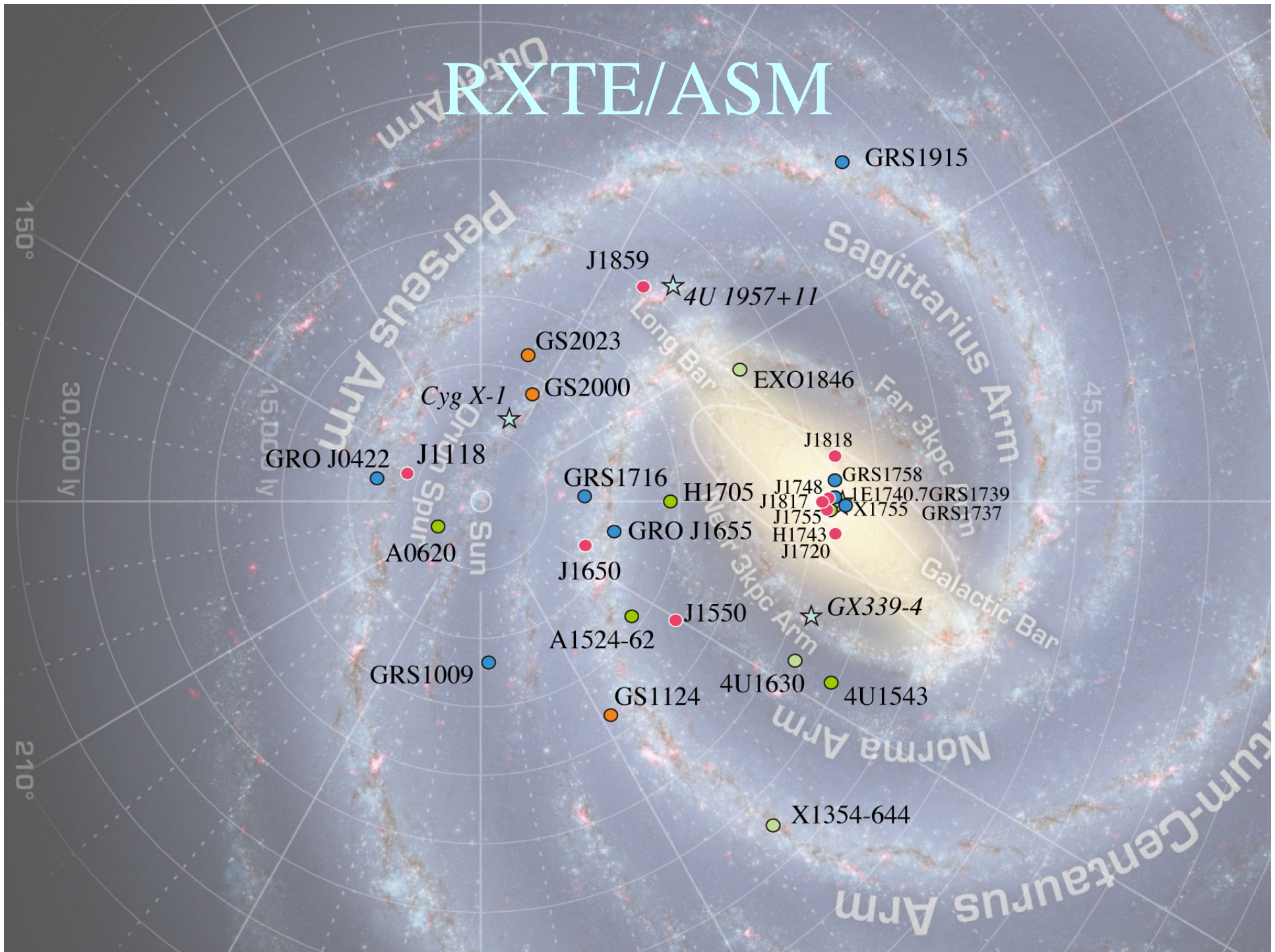


Hard X-ray Surveys

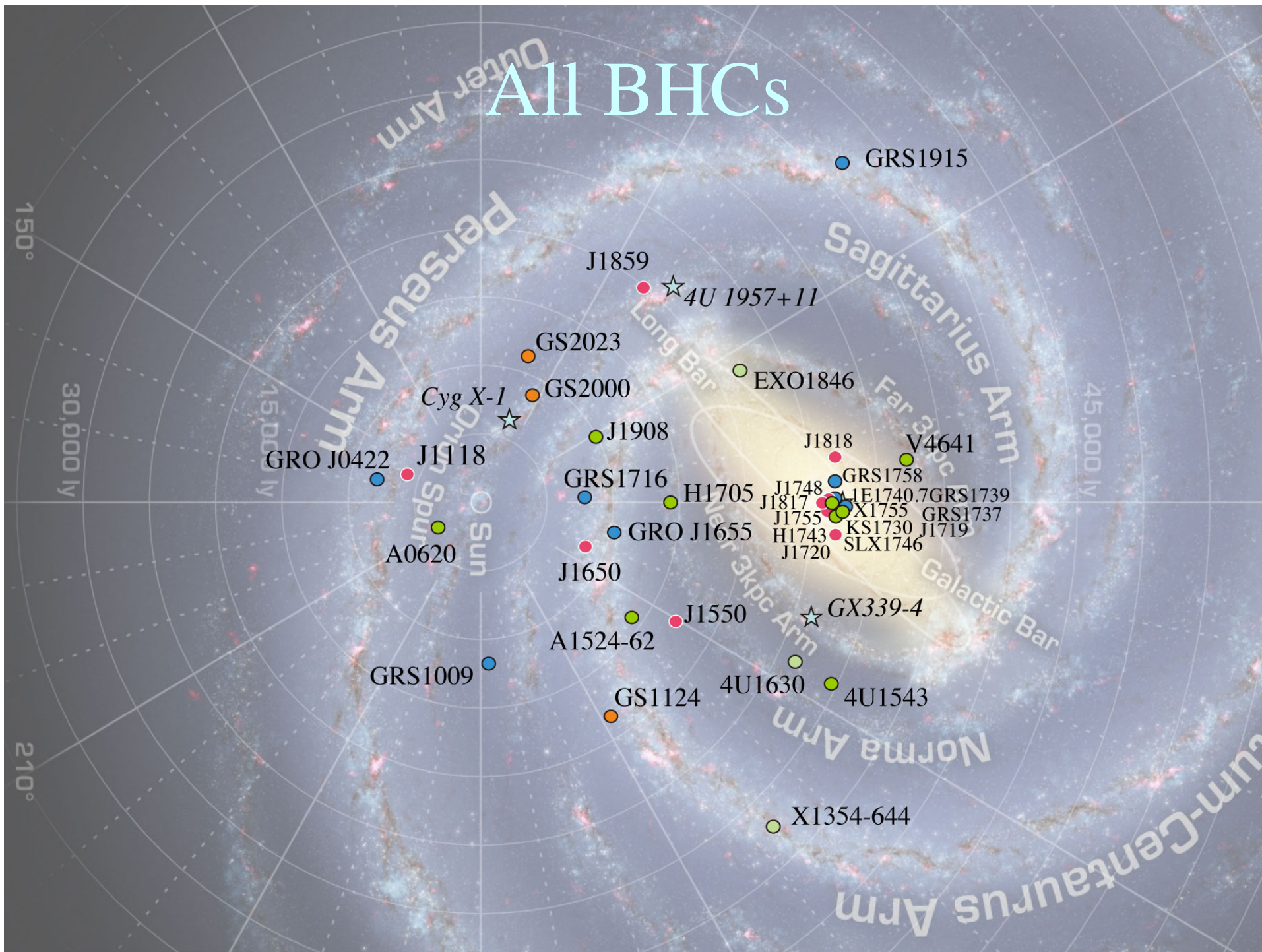
Distant & Deep

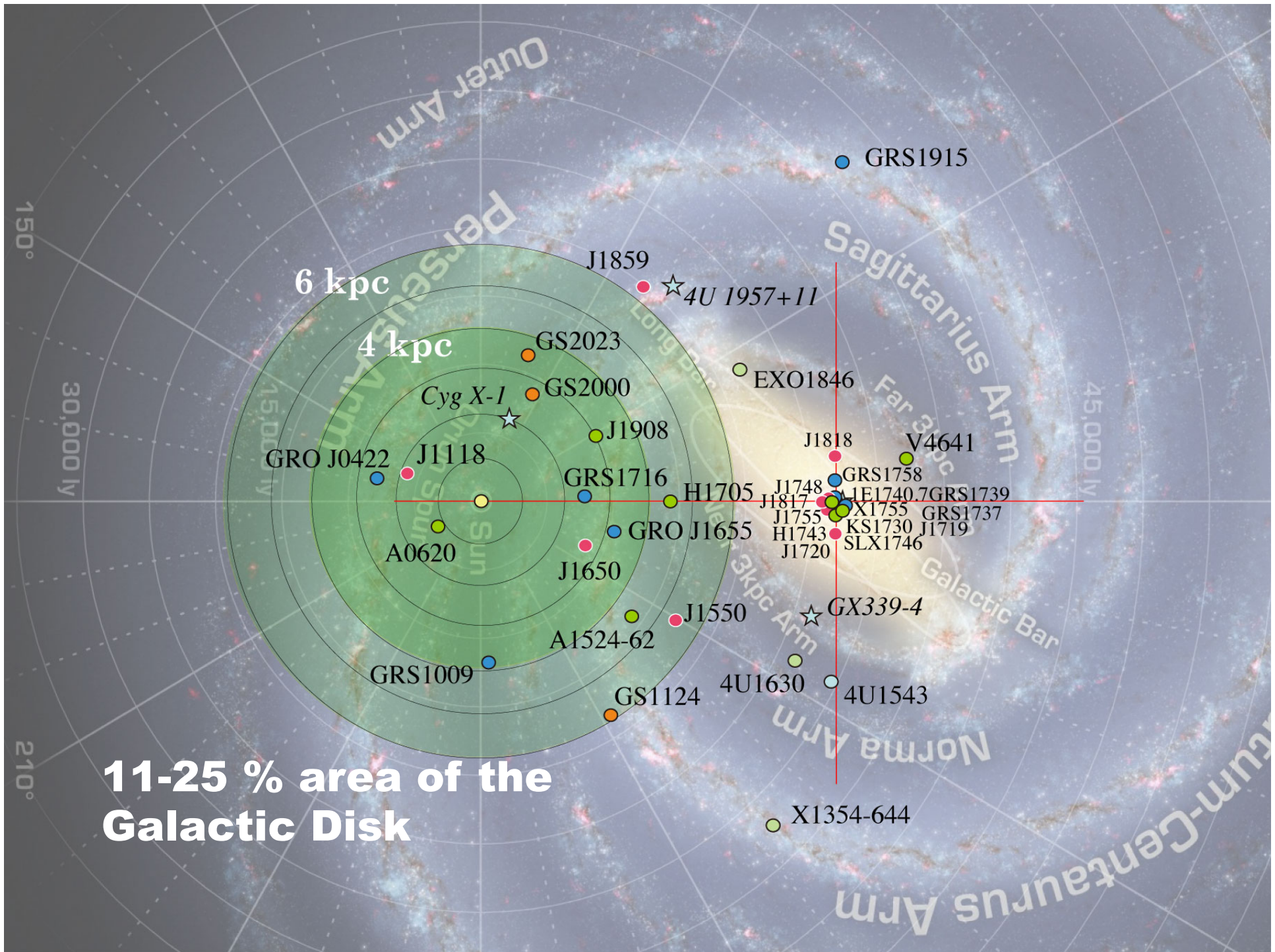


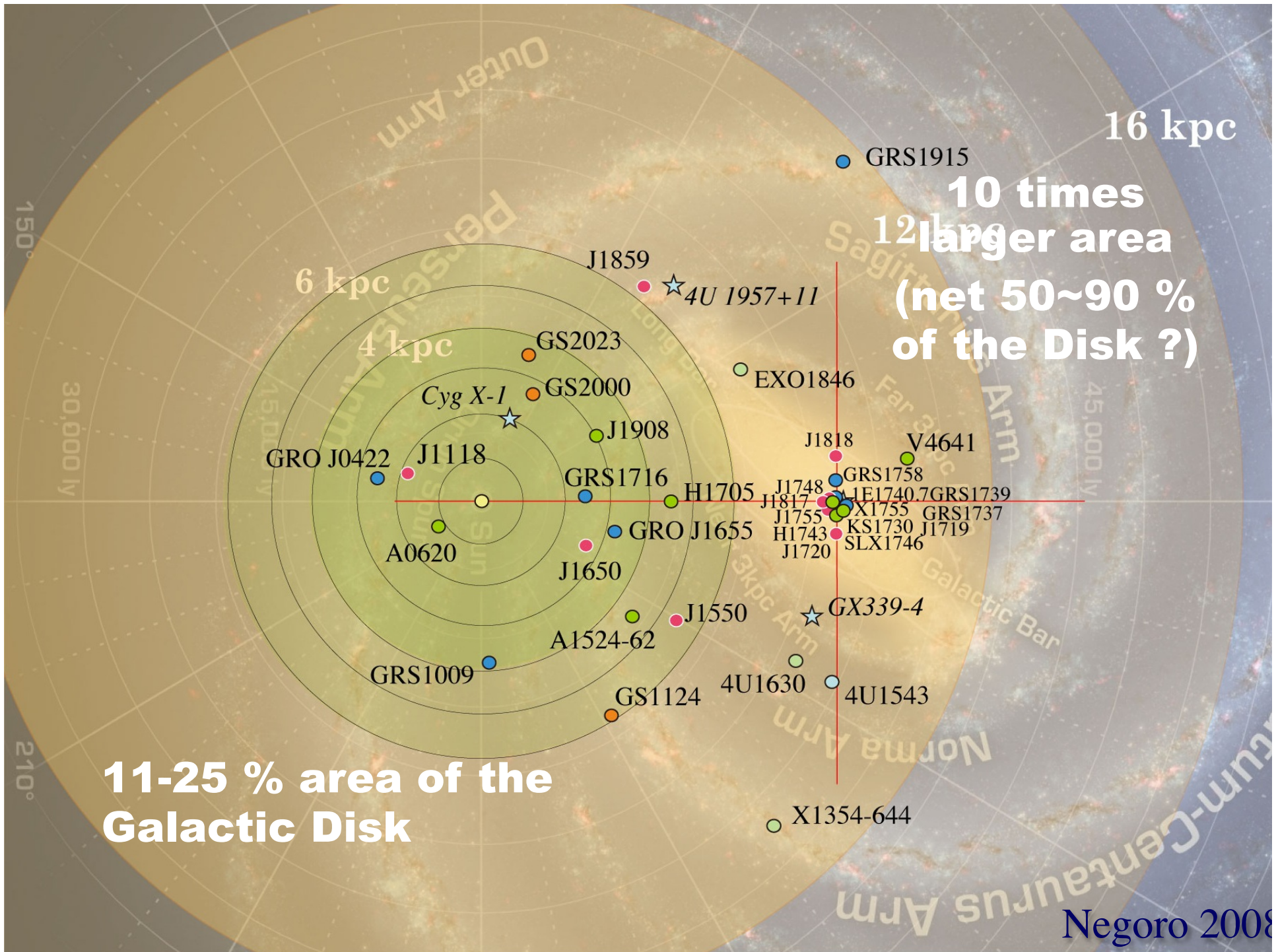
RXTE/ASM

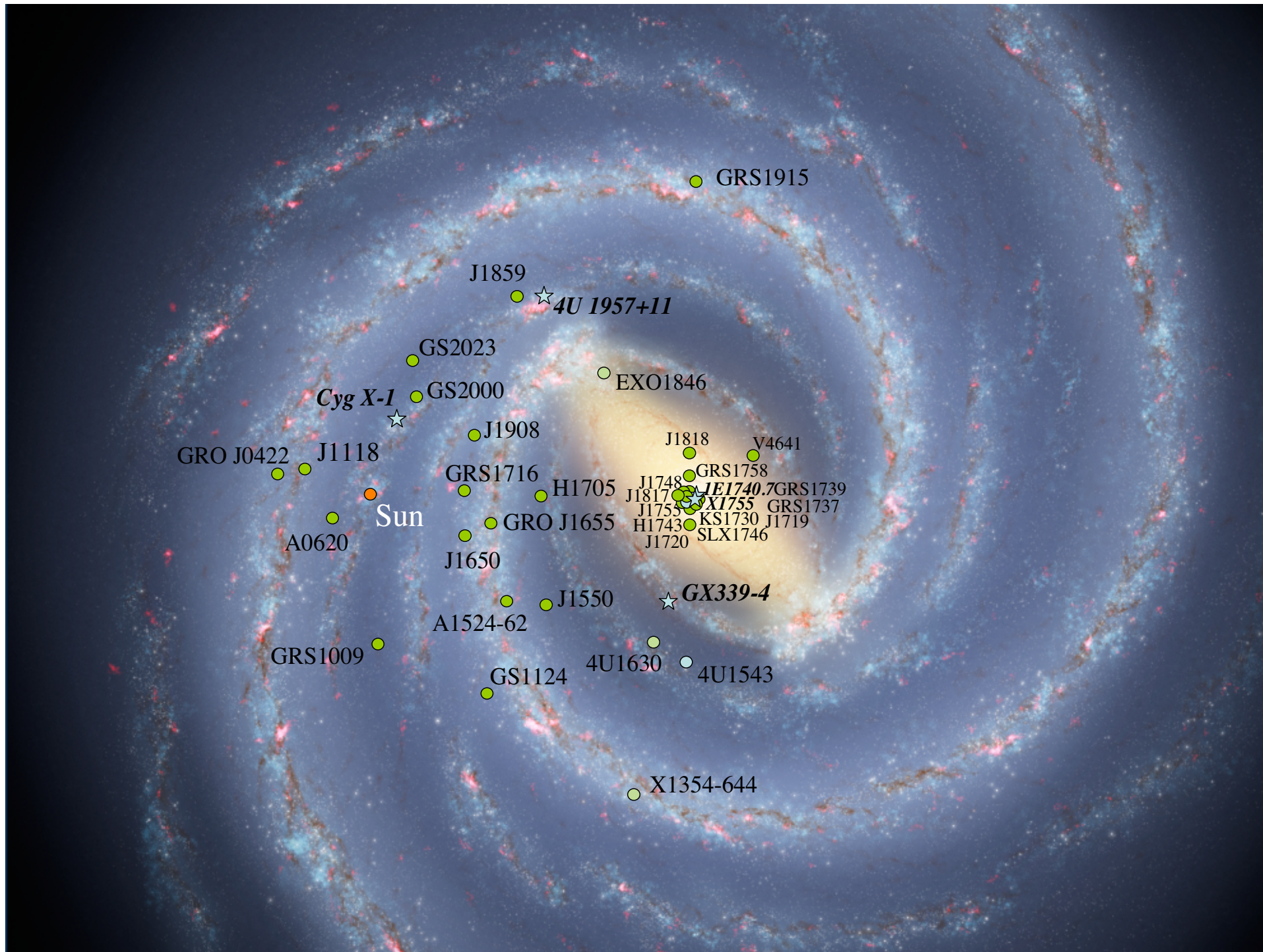


All BHCs







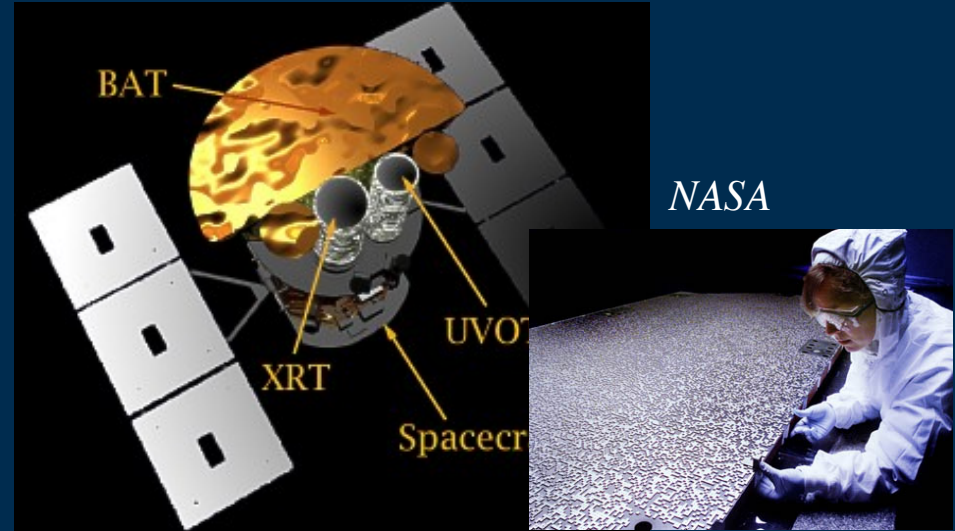


Competition and/or Collaboration



NASA

RXTE/ASM (2-10 keV)



NASA

Swift/BAT (15-150 keV)



ESA

INTEGRAL/IBIS (15 keV – 1 MeV)



Fermi
BGM
(150 keV – 30 MeV)
LAT
(30 MeV – 300 GeV)

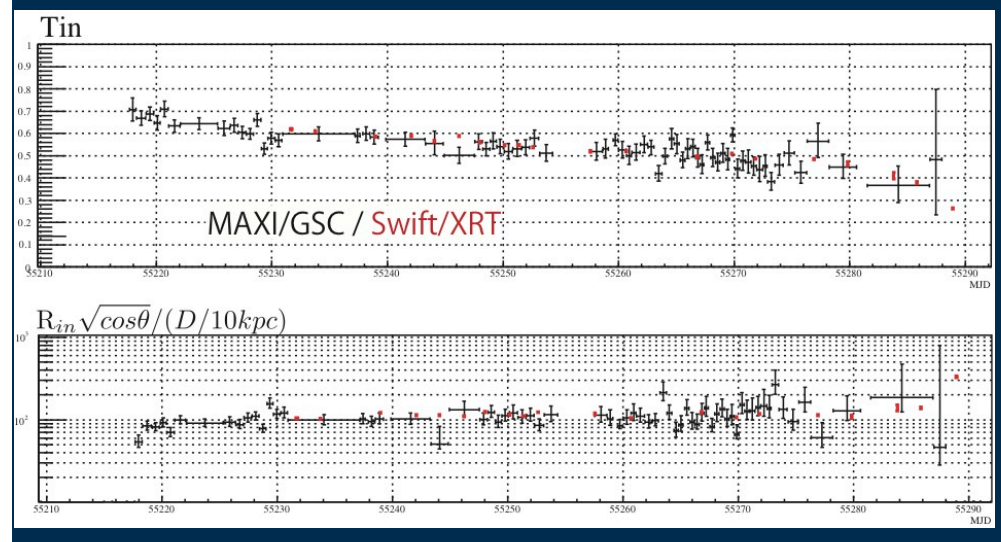
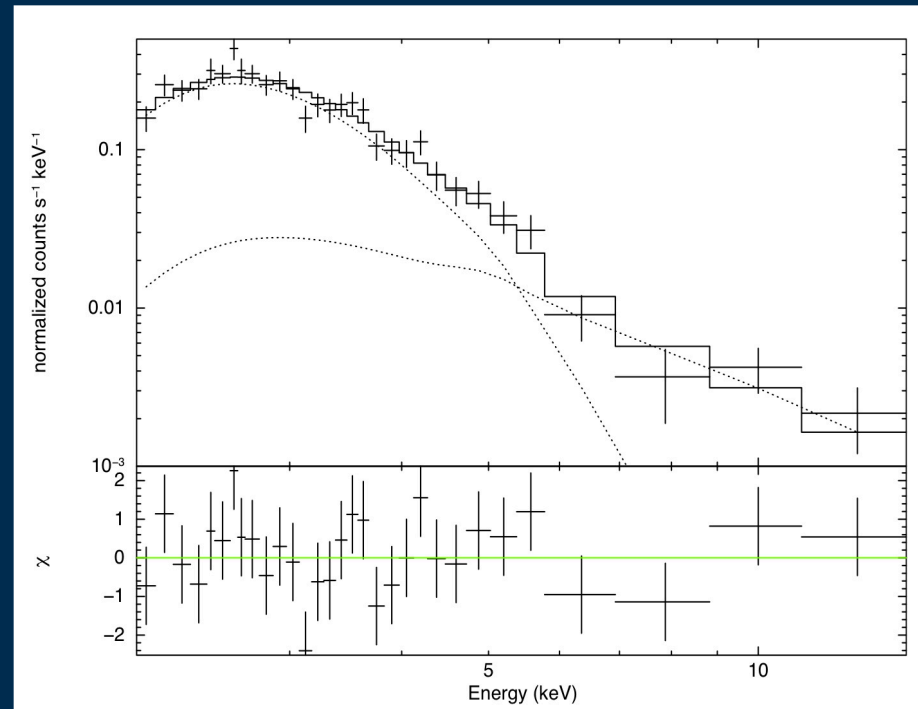
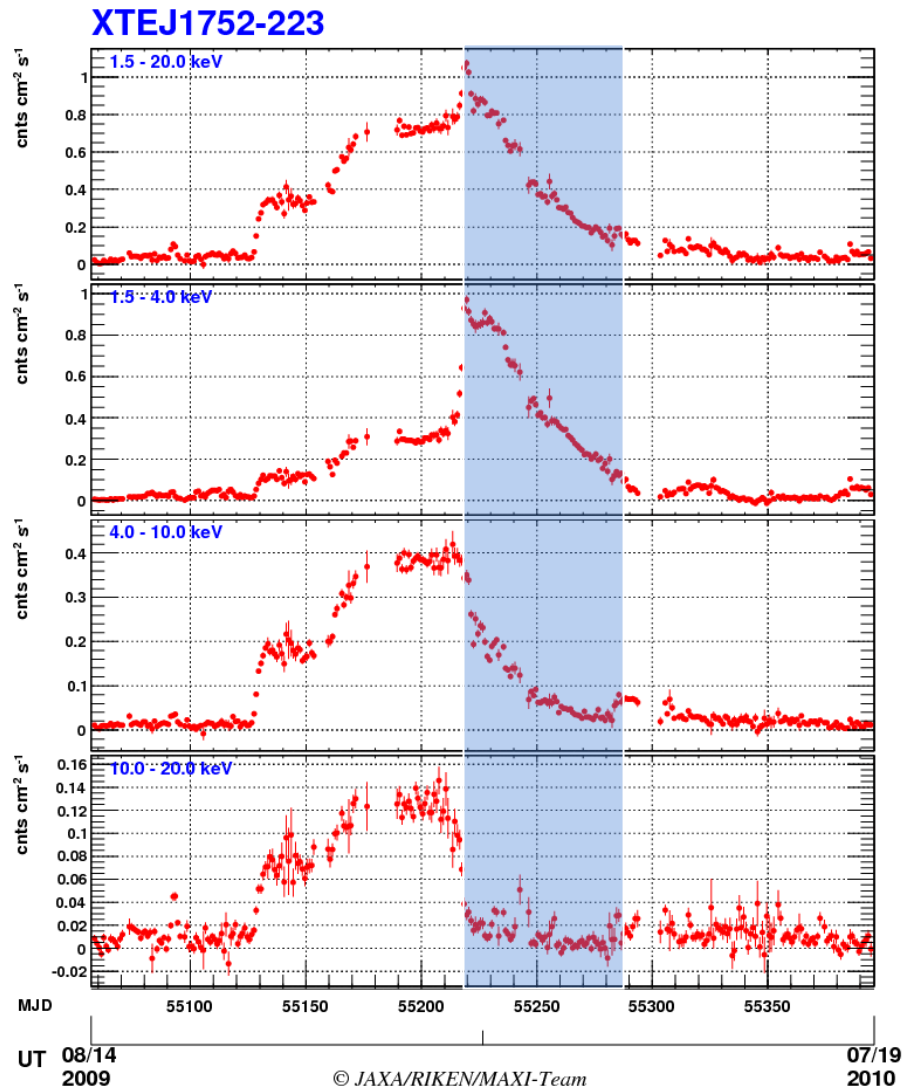
NASA

Continuous Monitoring

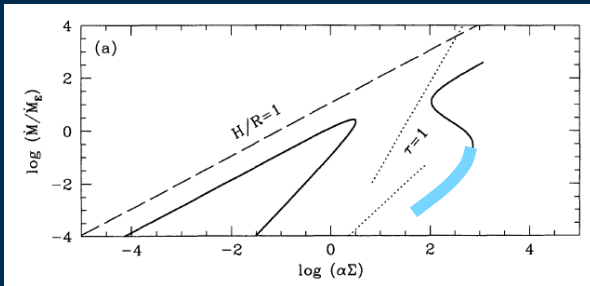
<http://maxi.riken.jp>

Continuous Spectral Changes XTE J1752-223

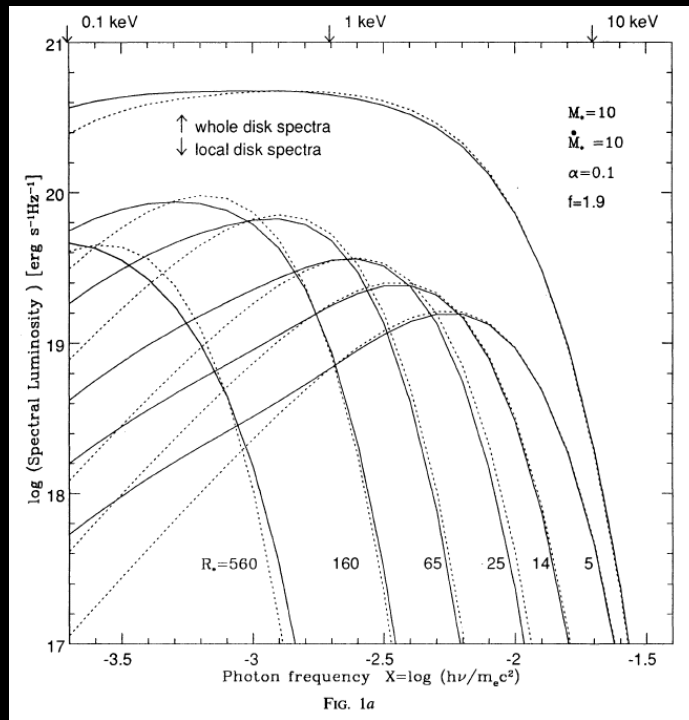
Nakahira+ 2010, PASJ



MCD - *Standard Disk*

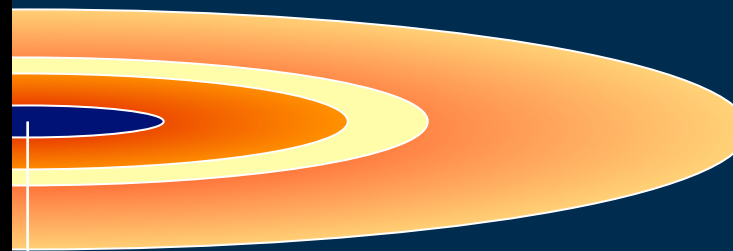


Shimura & Takahara 1995



) model

Mitsuda et al. 1984

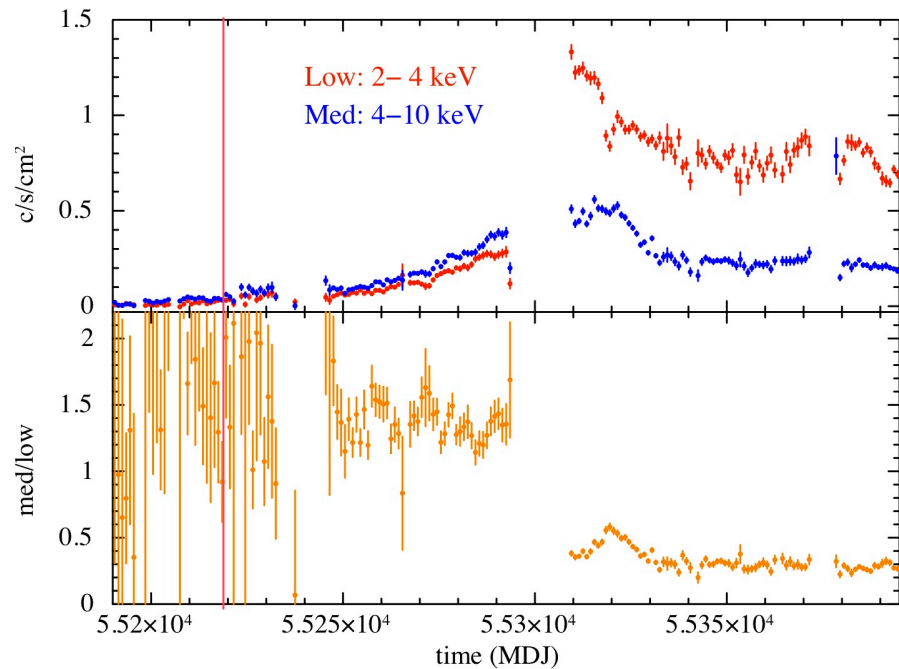


$$T(r) = \left(\frac{3GM\dot{m}}{8\pi\sigma r^3} \right) \left(1 - \sqrt{\frac{r_{in}}{r}} \right)^{1/4}$$

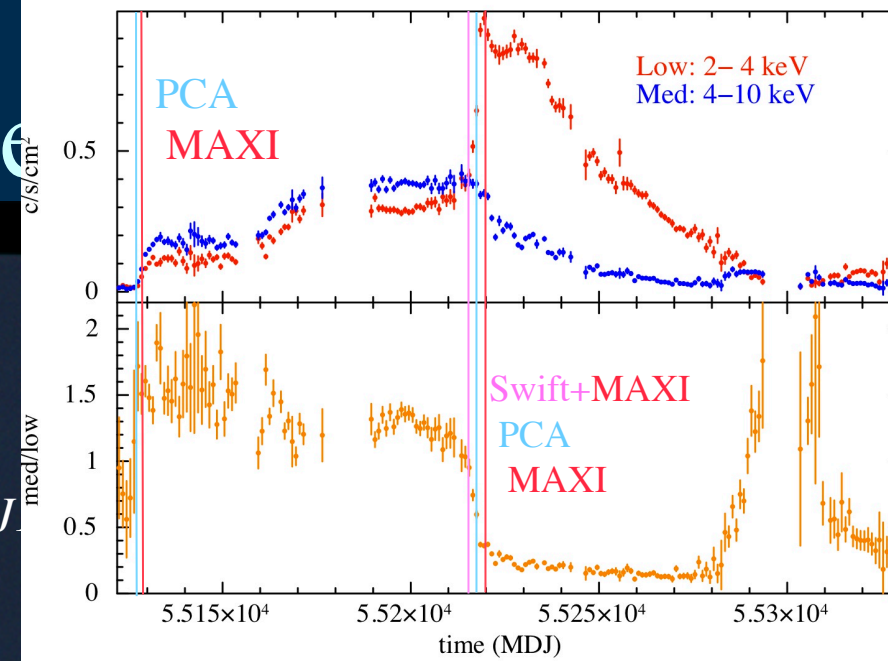
$$T(r) = \left(\frac{GM\dot{m}}{8\pi\sigma r^3} \right)^{1/4} = T_{in} \cdot \left(\frac{r}{r_{in}} \right)^{-3/4}$$

$$f(E) = \frac{\cos i}{d^2} \int_{r_{in}}^{r_{out}} 2\pi r B(E, T(r)) dr = \frac{8\pi r_{in}^2 \cos i}{3d^2} \int_{T_{out}}^{T_{in}} \left(\frac{T}{T_{in}} \right)^{-11/3} B(E, T) \frac{dT}{T_{in}}$$

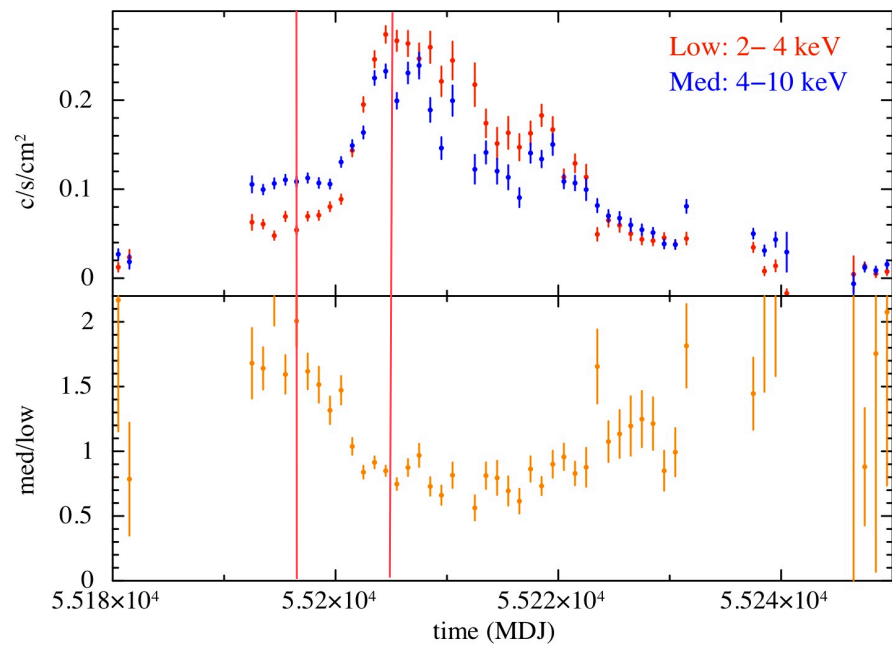
GX 339-4



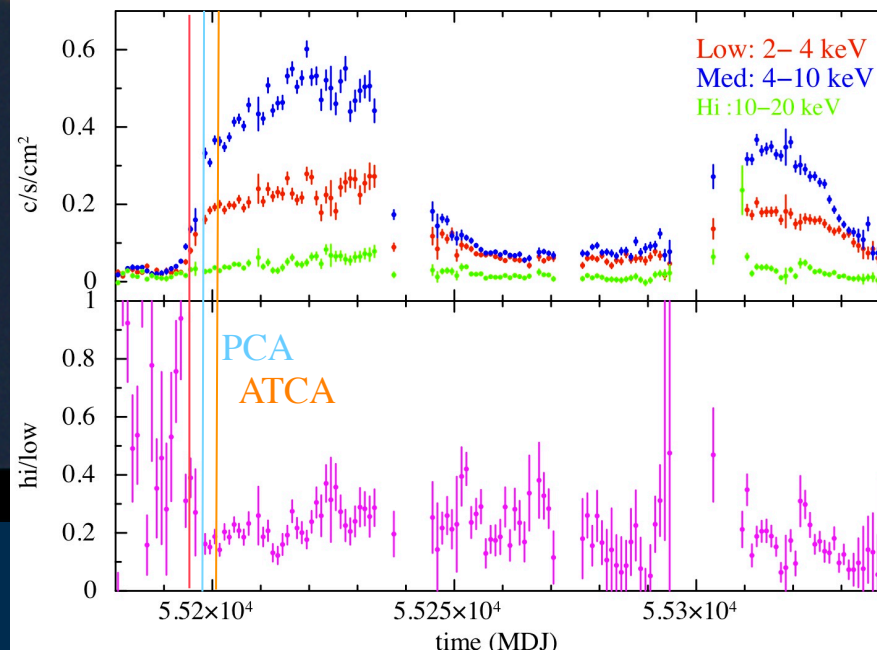
XTE J1752-223



H1743-322



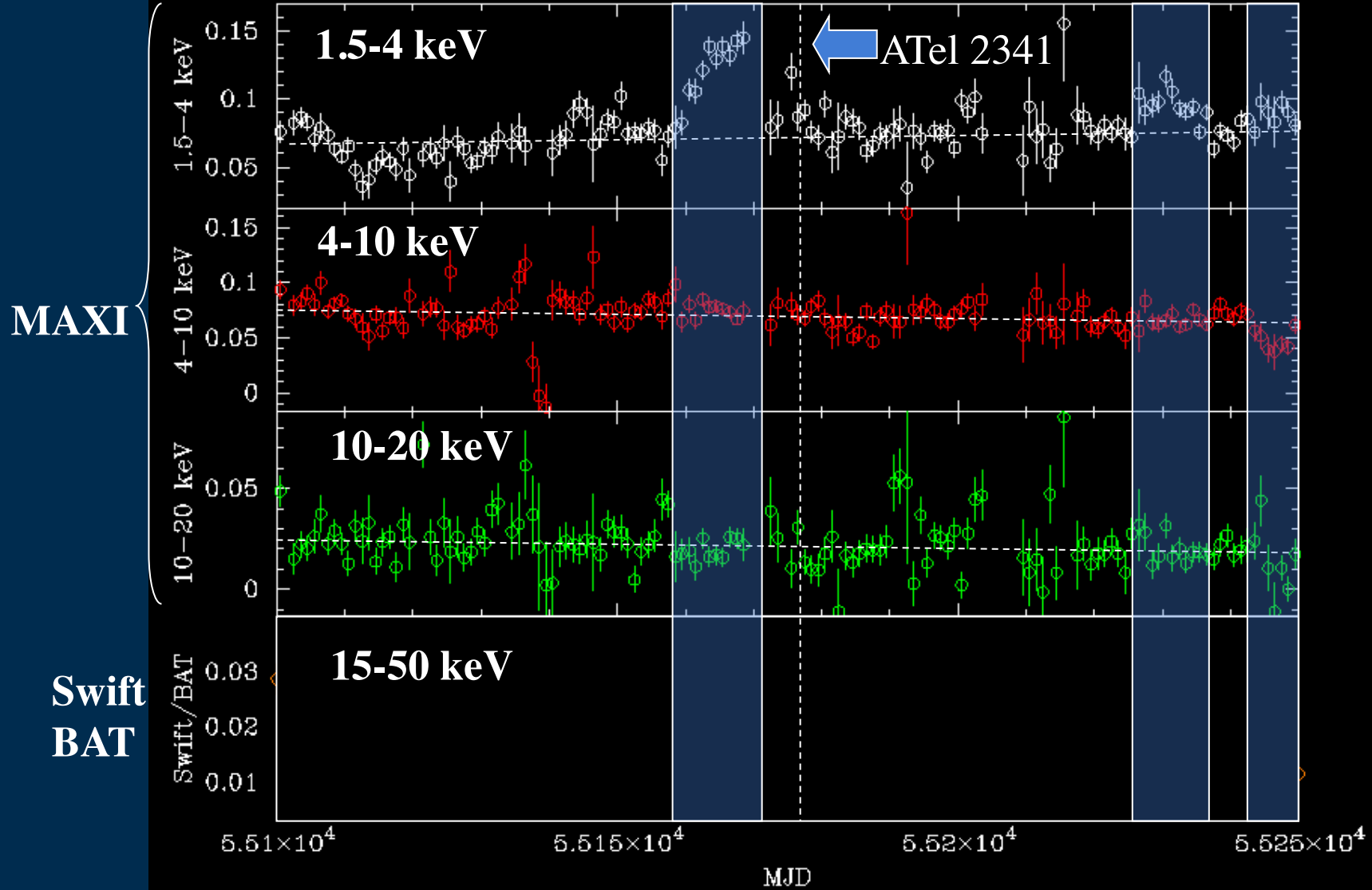
4U 1630-47



XTE J

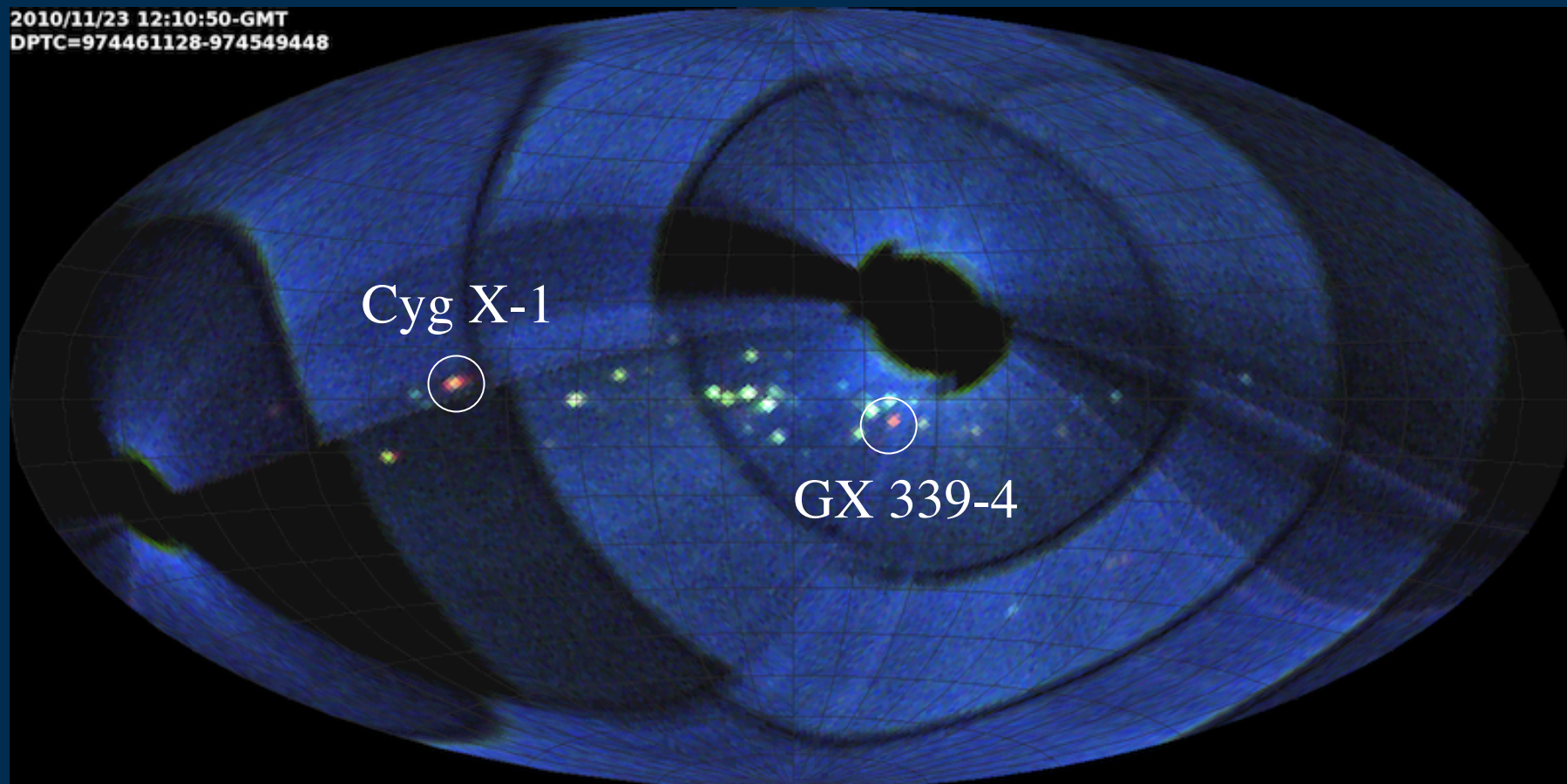


Swift J1753.5-0127: Possible State Transition on Nov 25-, 2009



Cyg X-1 and GX 339-4 both in the soft state ?

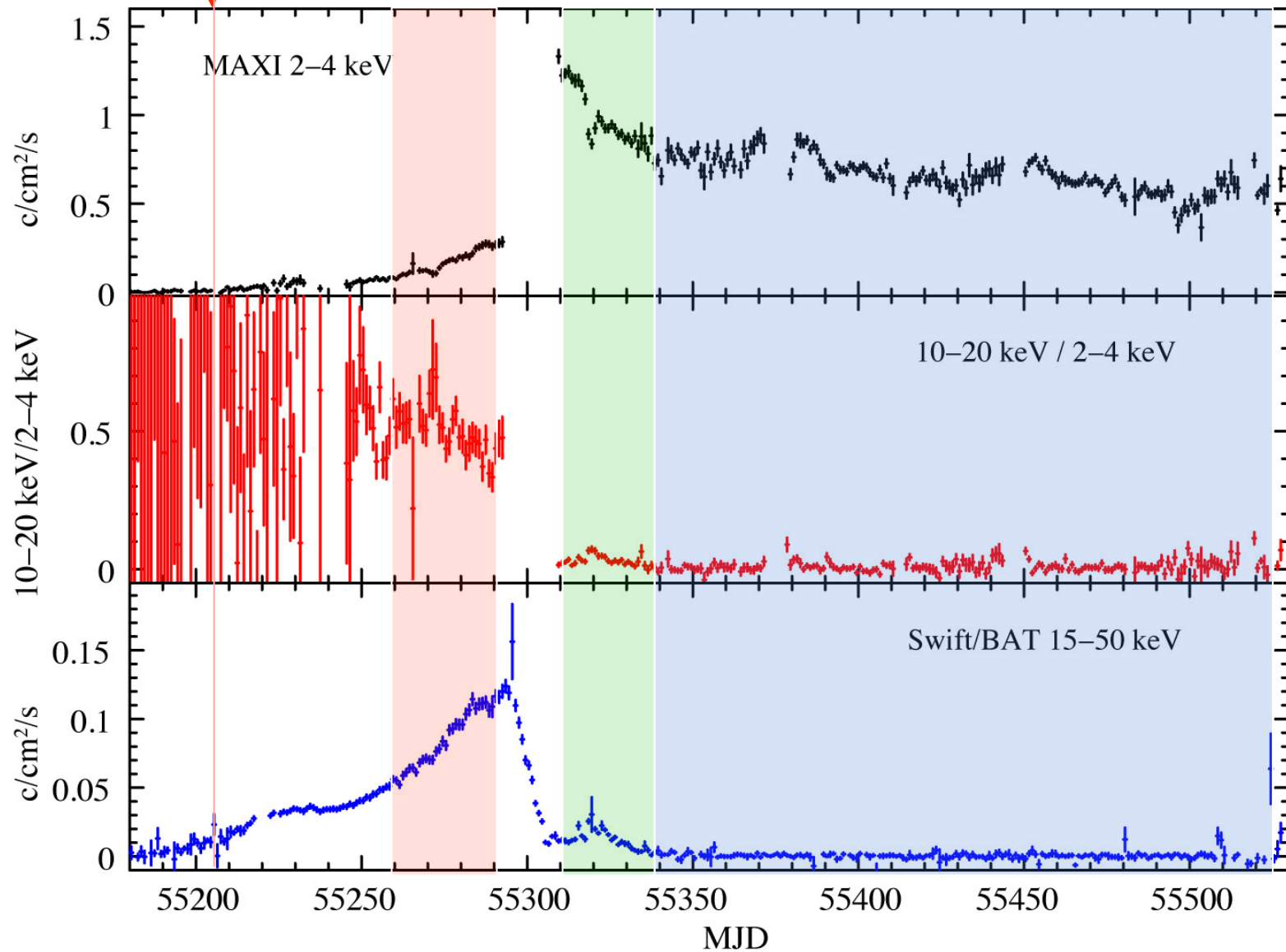
2010/11/23 12:10:50-GMT
DPTC=974461128-974549448



Soft State Transition in GX 339-4

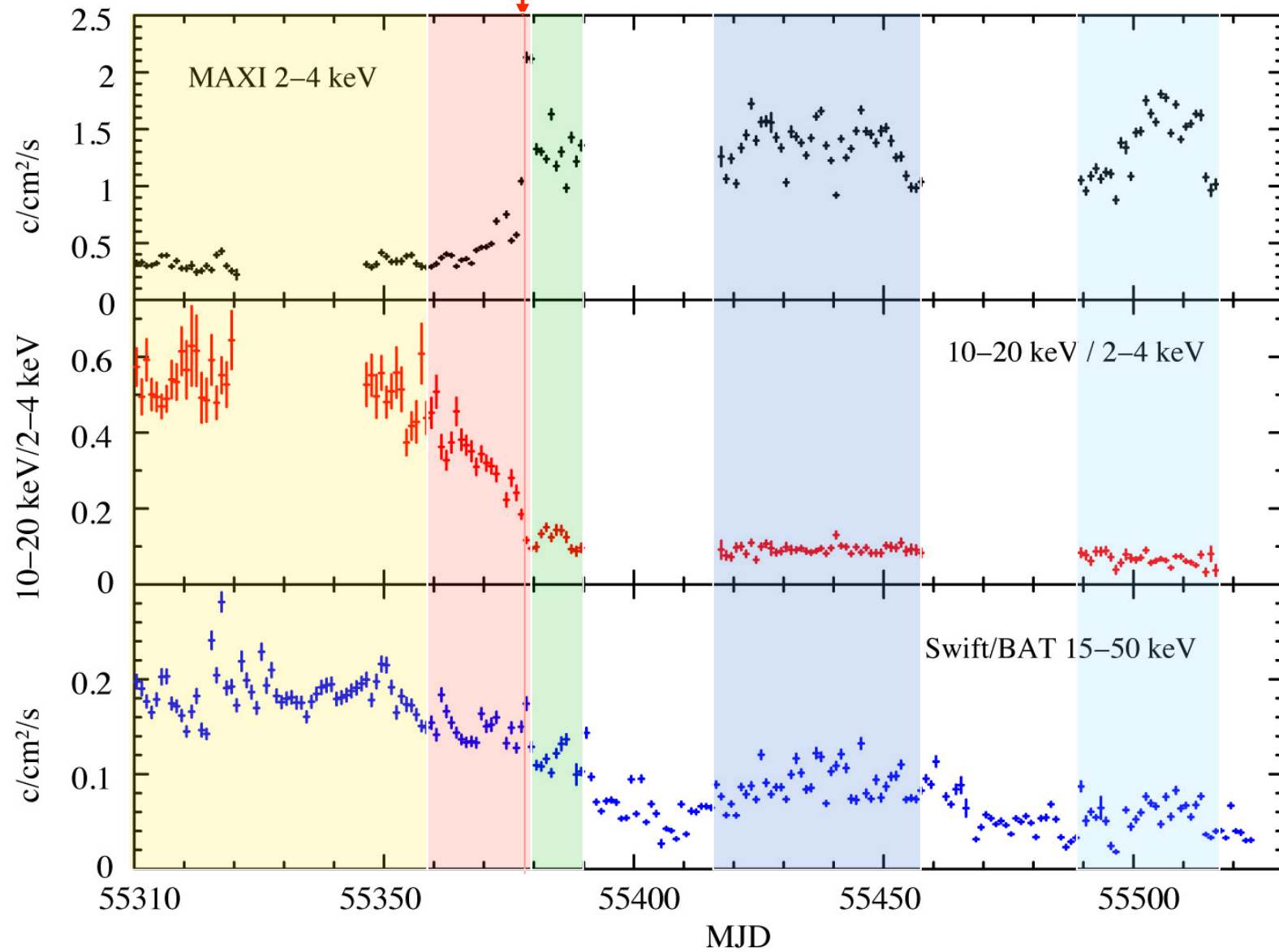
Yamaoka+ ATEL 2380

Shidatsu+ 2011



Soft? State Transition in Cygnus X-1

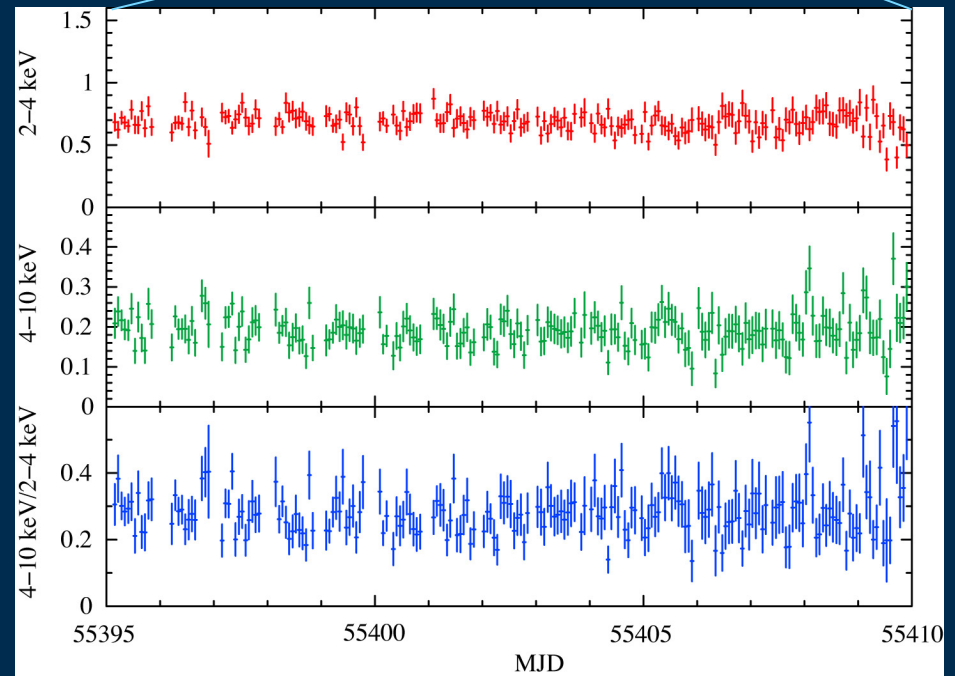
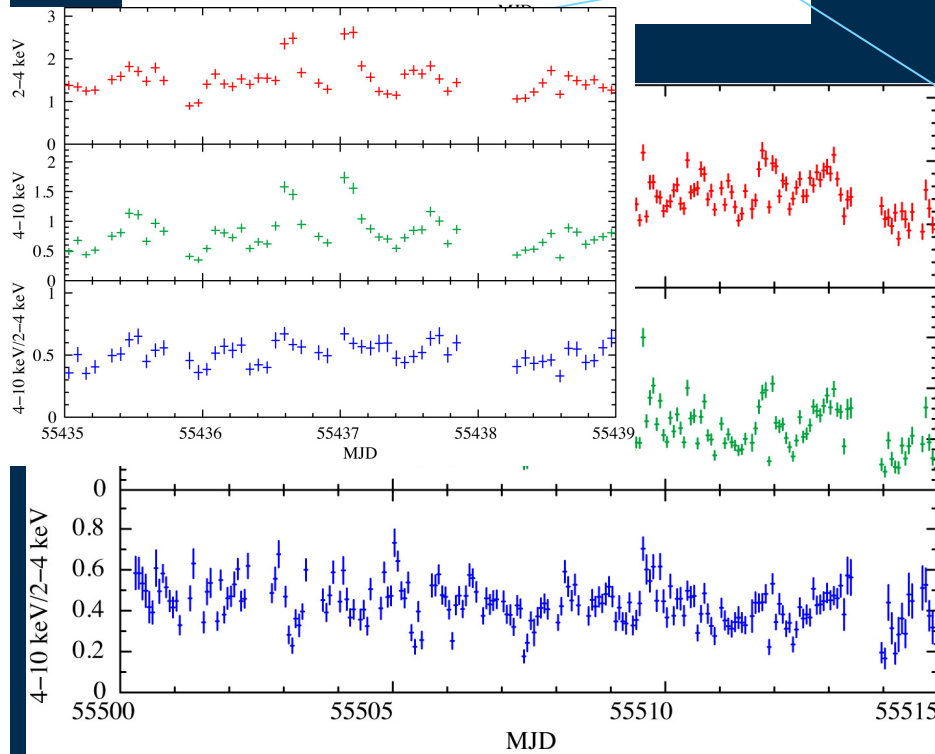
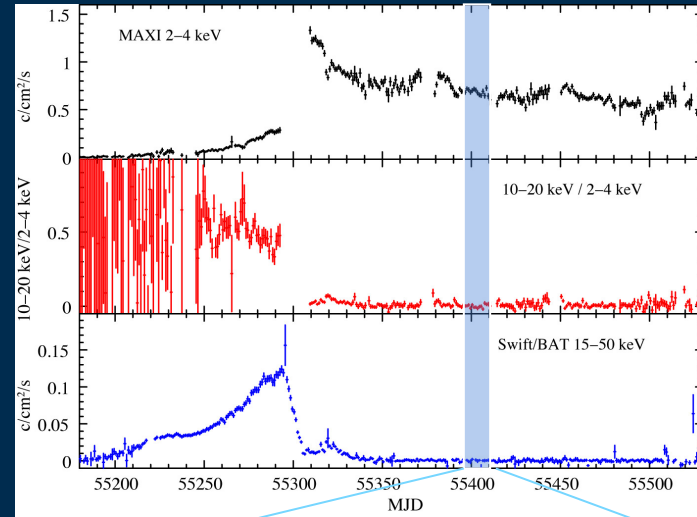
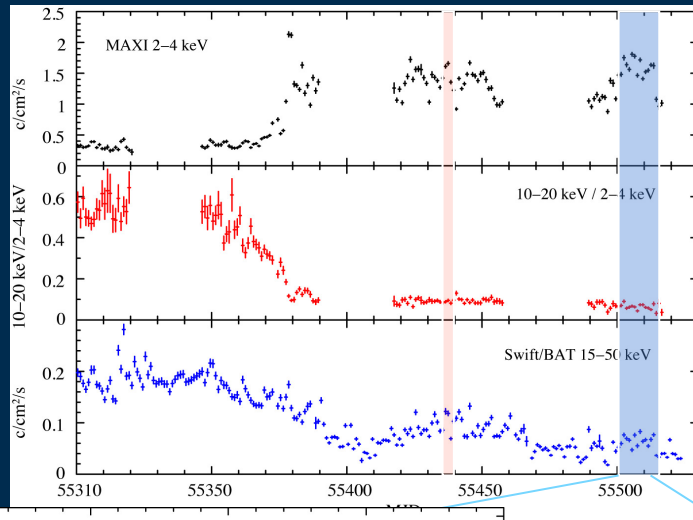
Negoro+ ATel 2711



Cyg X-1

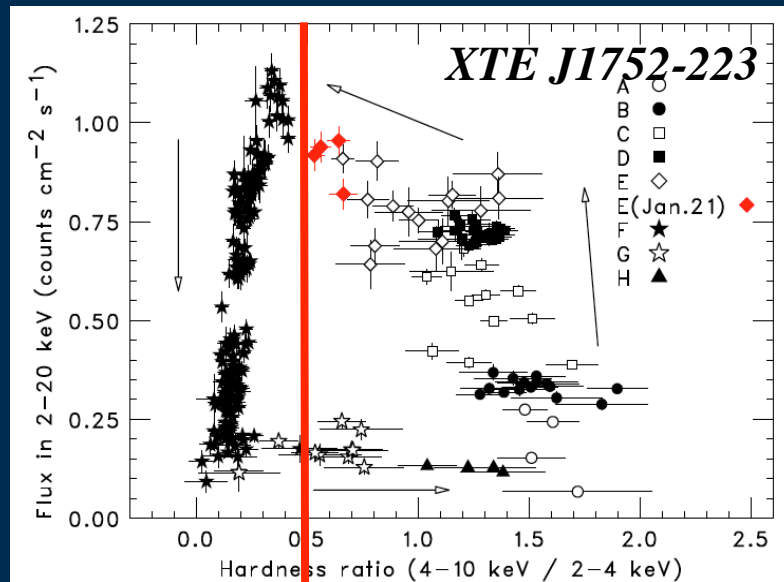
Short-term Variability

GX 339-4

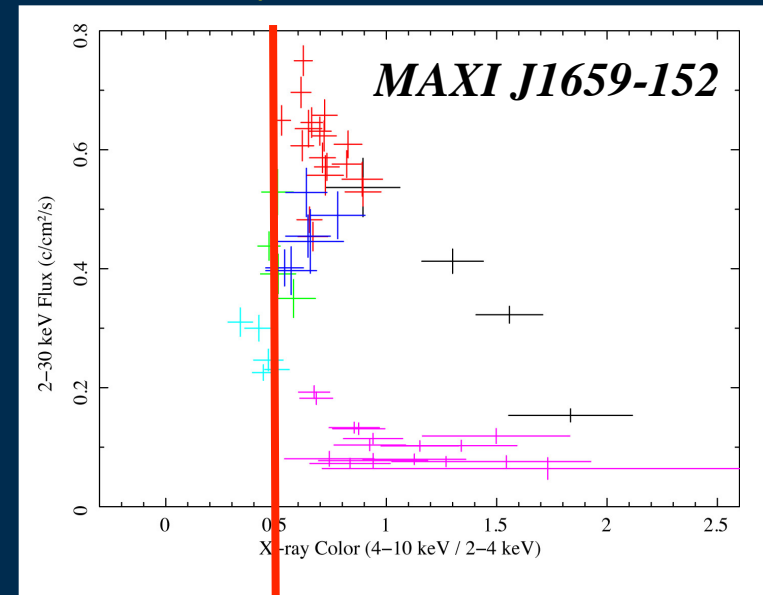


Soft-State Source or Intermediate-State Source ?

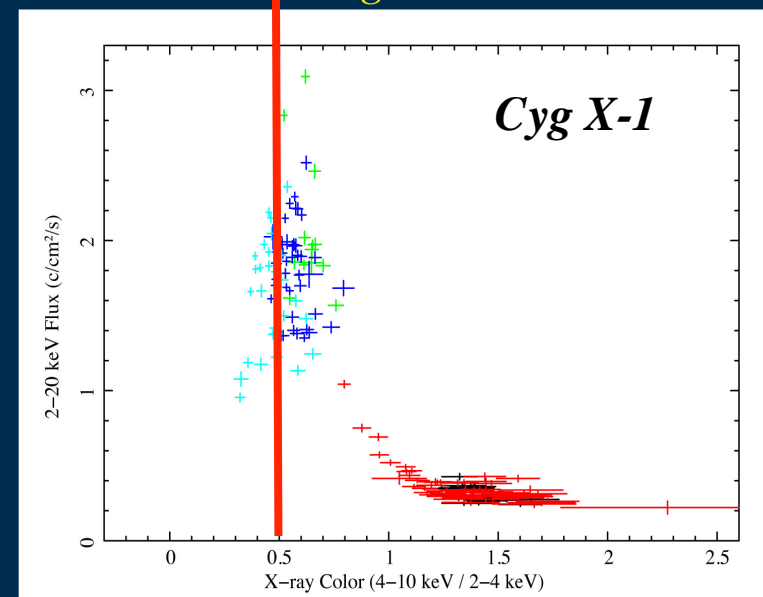
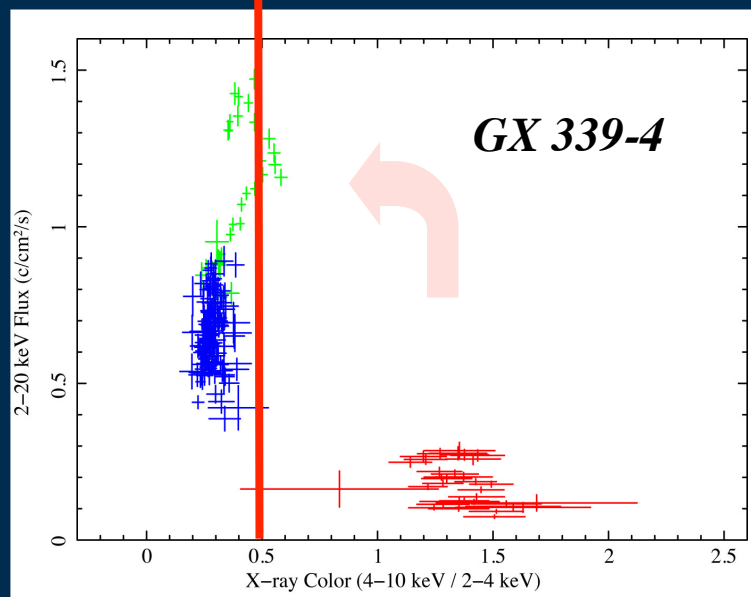
cf. Gierlinski & Newton 2006



Dark and Fast? Transition

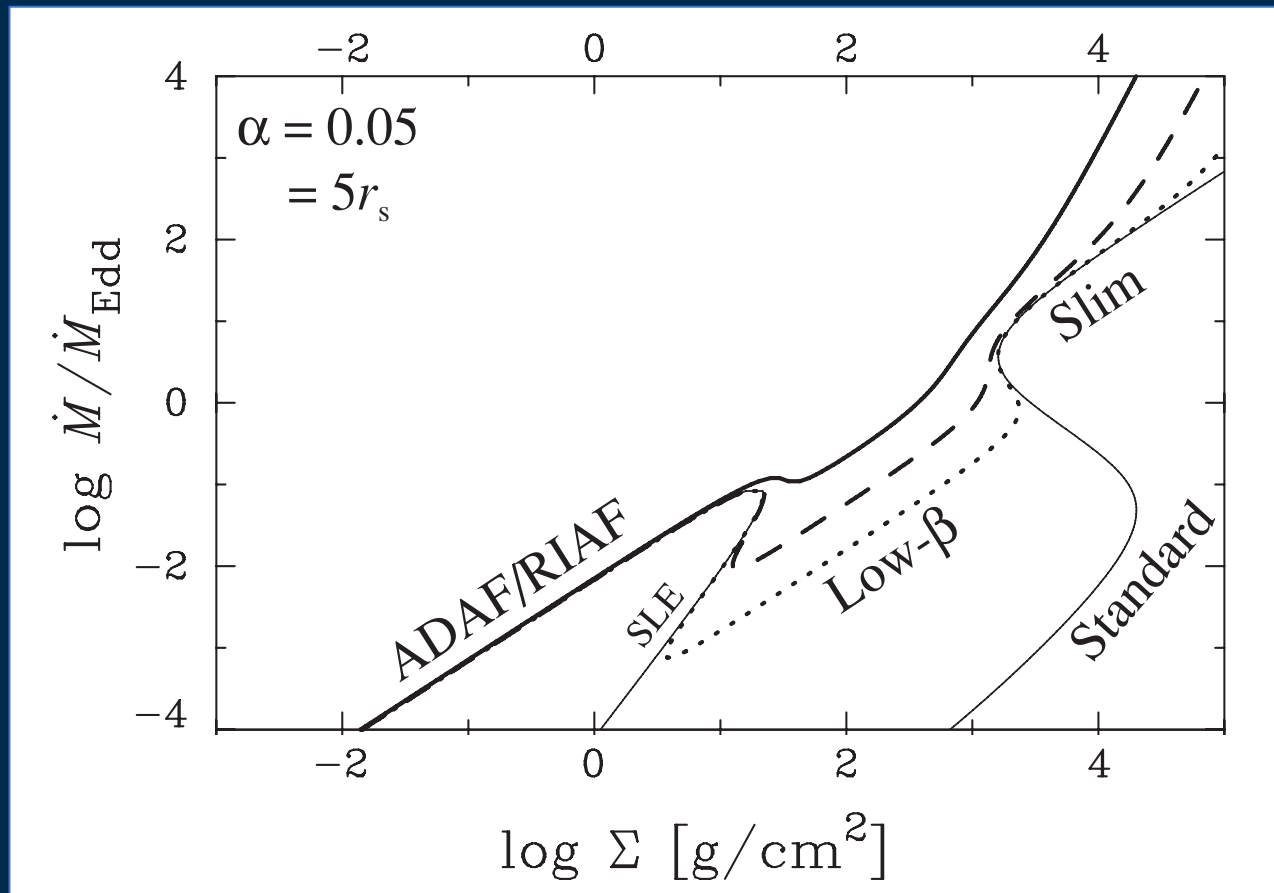


Bright and Slow? Transition



6th State ?

Optically Thin, Magnetically Supported Disk



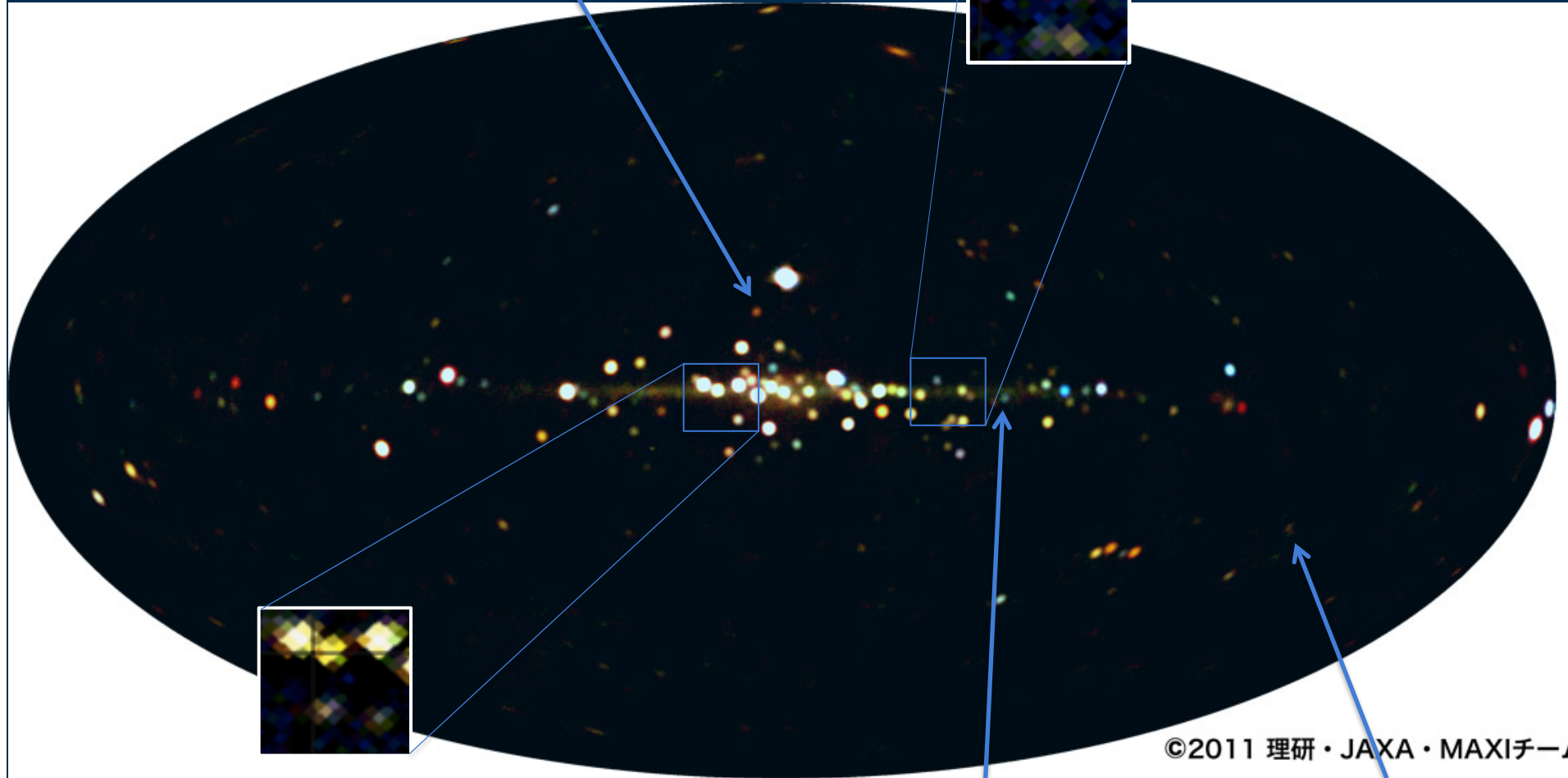
Oda et al. 2009

Discoveries & Alert

<http://maxi.riken.jp/mailman/listinfo>

2010/09/25
MAXI J1659-152

2011/05/08
MAXI J1543-564

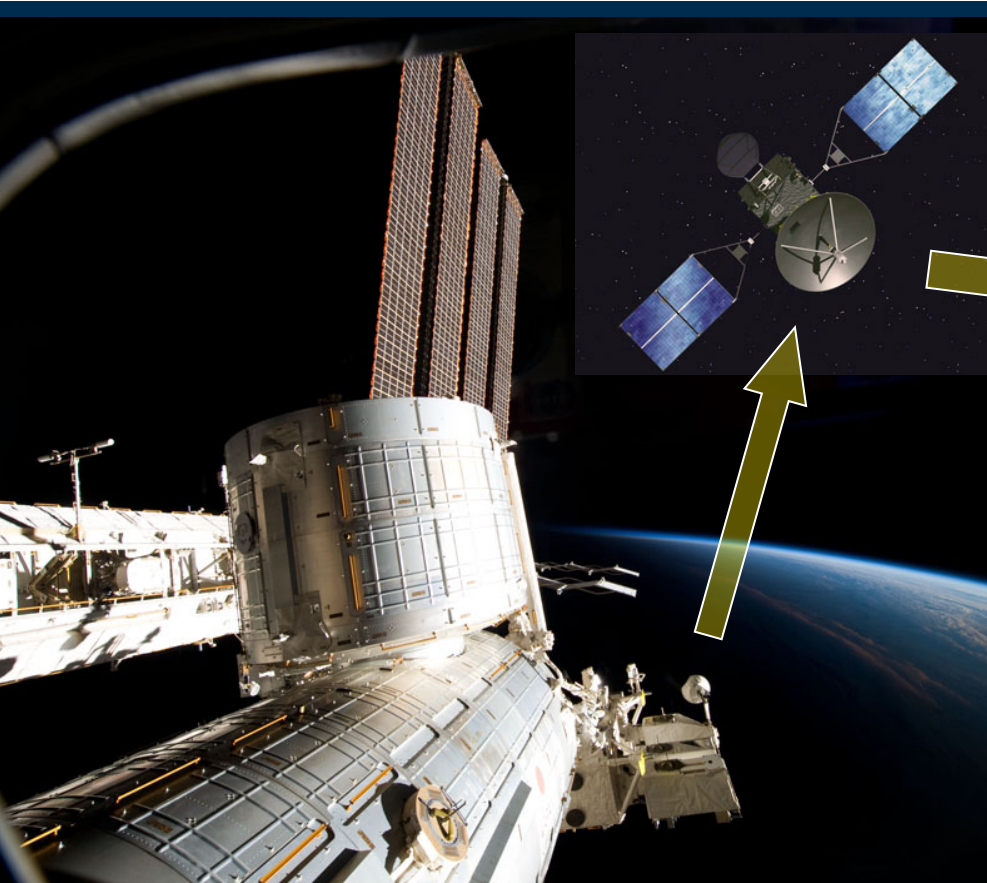


©2011 理研・JAXA・MAXIチーム

2011/08/30
MAXI J1836-194

2010/10/20
MAXI J1409-619

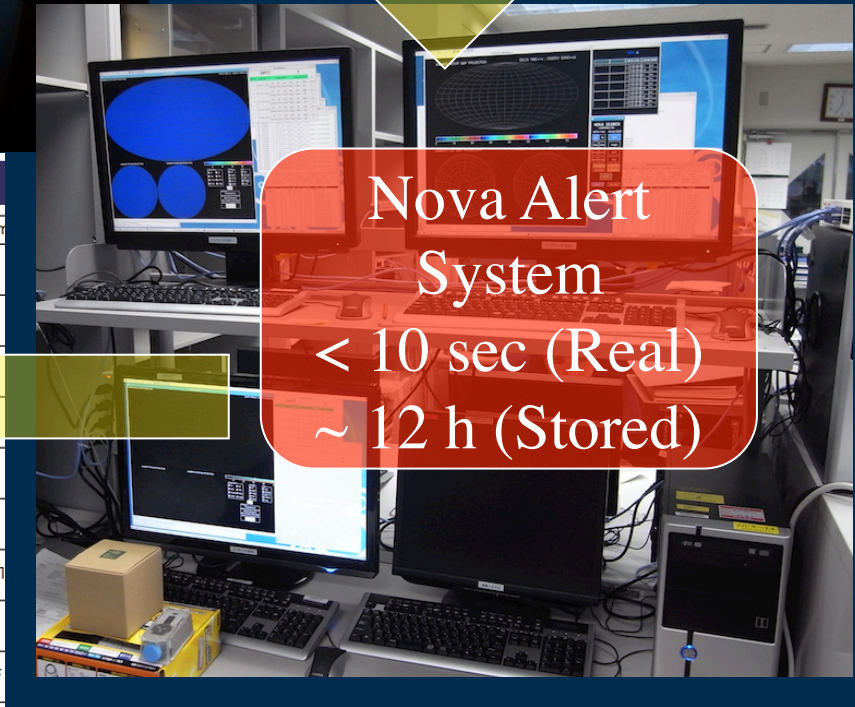
2011/01/21
MAXI J0556-3



RIKEN
&
MAXI
MLs
(& ATeI/GCN)

Novae -- list --

ID	Image	Date	RA, Dec	com
5337375271 958473409 (Warning)		2010-05-21T10:36:34	(308.764, 37.464)	EXO 2030+375
5352037956 959732429 (Alert)		2010-06-05T00:20:14	(82.544, -66.334)	LMC X-4
5360024421 960424195 (Warning)		2010-06-13T00:29:40	(230.060, -57.227)	Cir X-1
5360277271 960453730 (Alert)		2010-06-13T08:41:55	(277.330, -24.044)	GS 1826-238
5360774677 960506625 (Alert)		2010-06-13T23:23:30	(230.037, -57.016)	Cir X-1
5363094768 960687741 (Warning)		2010-06-16T01:42:06	(52.055, -40.713)	Transient event
5365027798 960859712 (Alert)		2010-06-18T01:28:17	(289.188, -5.447)	X-ray burst of 4U
5374275857 961659391 (Warning)		2010-06-27T07:36:16	(84.738, 26.065)	A 0535+262
5378212885 962002493 (Warning)		2010-07-01T06:54:38	(189.997, -34.181)	likely to be an XRF



Nova Alert
System
< 10 sec (Real)
~ 12 h (Stored)

TKSC/JAXA

Nova-Alert System (Auto-Detection)

The interface displays a large map of the sky in HAMMER-AITOFF MAP PROJECTION. Below it are two smaller maps in LAMBERT-TOP and LAMBERT-DOWN MAP PROJECTIONS. A control panel on the right allows users to adjust Delta-Time, Energy, and other parameters. A data table on the right shows detected events, with the first event highlighted in red.

DELTA TIME=1scan : ENERGY BAND=L+M

LAMBERT-TOP MAP PROJECTION LAMBERT-DOWN MAP PROJECTION

Delta-Time: 1s, 3s, 10s, 30s, 1scan, 1orb, 4orb, 1day

Energy: L+M, high, med, low

Gal: Gal, RA,Dec, Scale, Linear, Log

draw mode: Normal, All, Latest

Settings: Threshold=50, poisson-level=1.00e-06, latest backup=0, detx range=(700,5700), alpha=1.10 beta=2.00

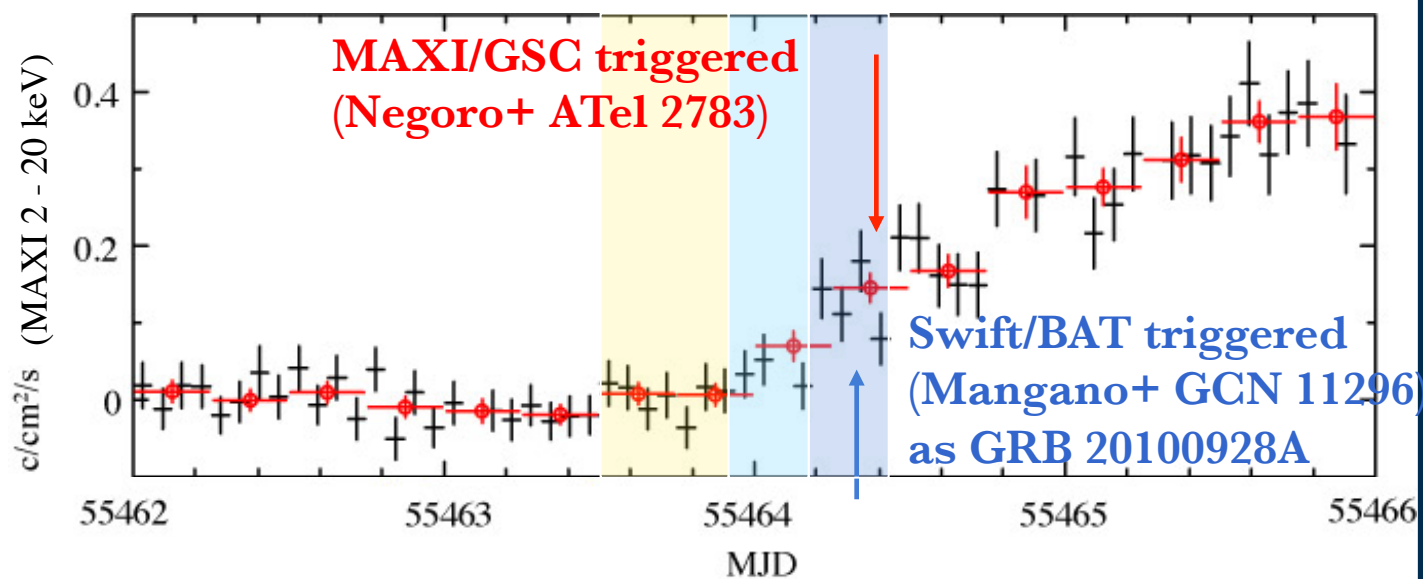
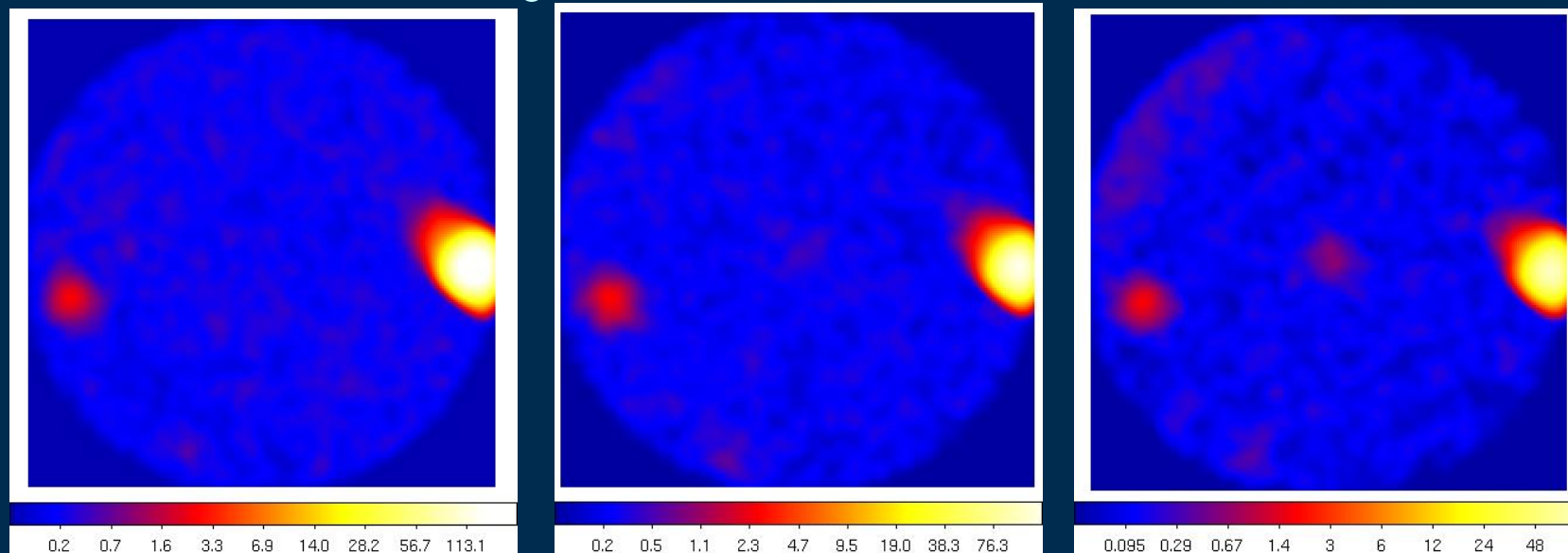
DPTC	(GL,GB)	Delta-Time				Energy-Band		All
938015421	(349.45,2.39)	1s	3s	10s	30s	L+M	high	Check
		1scan	1orb	4orb	1day	med	low	LC
0	(0.00,0.00)	1s	3s	10s	30s	L+M	high	Check
		1scan	1orb	4orb	1day	med	low	LC
0	(0.00,0.00)	1s	3s	10s	30s	L+M	high	Check
		1scan	1orb	4orb	1day	med	low	LC
0	(0.00,0.00)	1s	3s	10s	30s	L+M	high	Check
		1scan	1orb	4orb	1day	med	low	LC

CLOSE UP : (r=15.00)
(Gl,Gb) = (77.48,-3.25)
dt=1scan,erg=L+M

Cyg X-2, Cyg X-3, Cyg X-1, EXO 2030+375

If a statistically significant event is detected, auto-pipeline process starts.

Discovery of MAXI J1659-152



Nova Alert
System:
Ozawa+
Suwa+

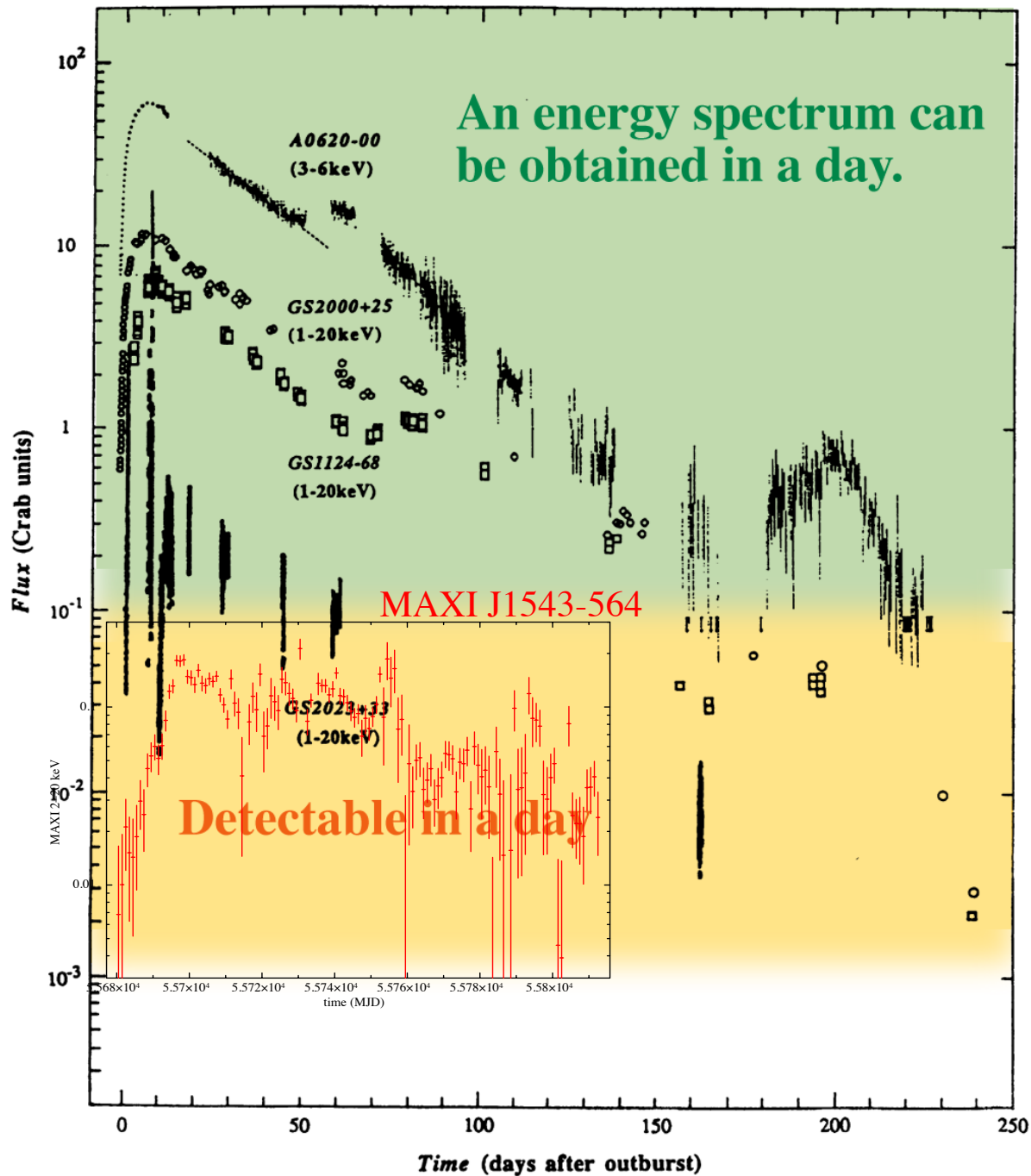
発見から速報まで

MAXI J1659-152

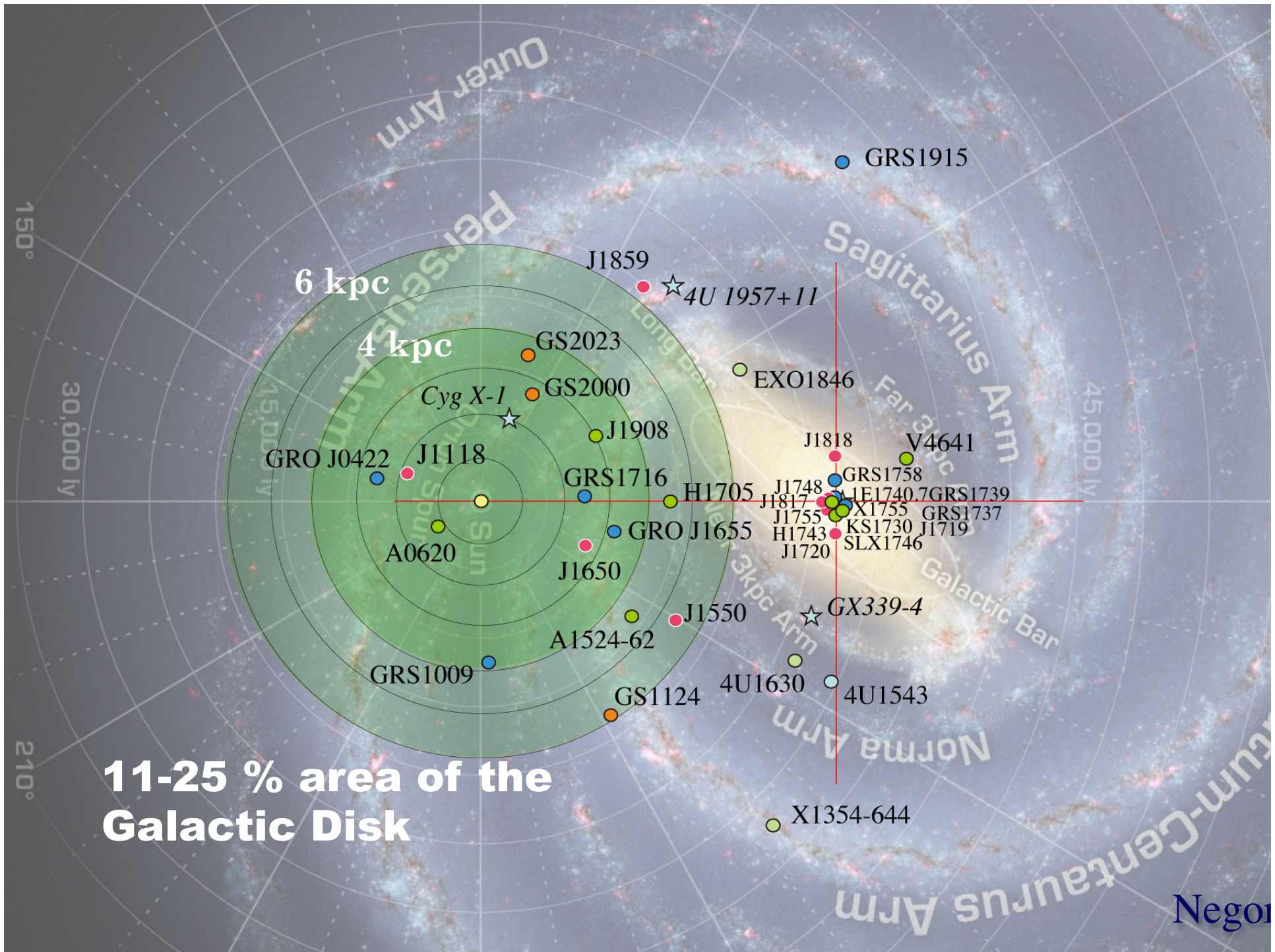


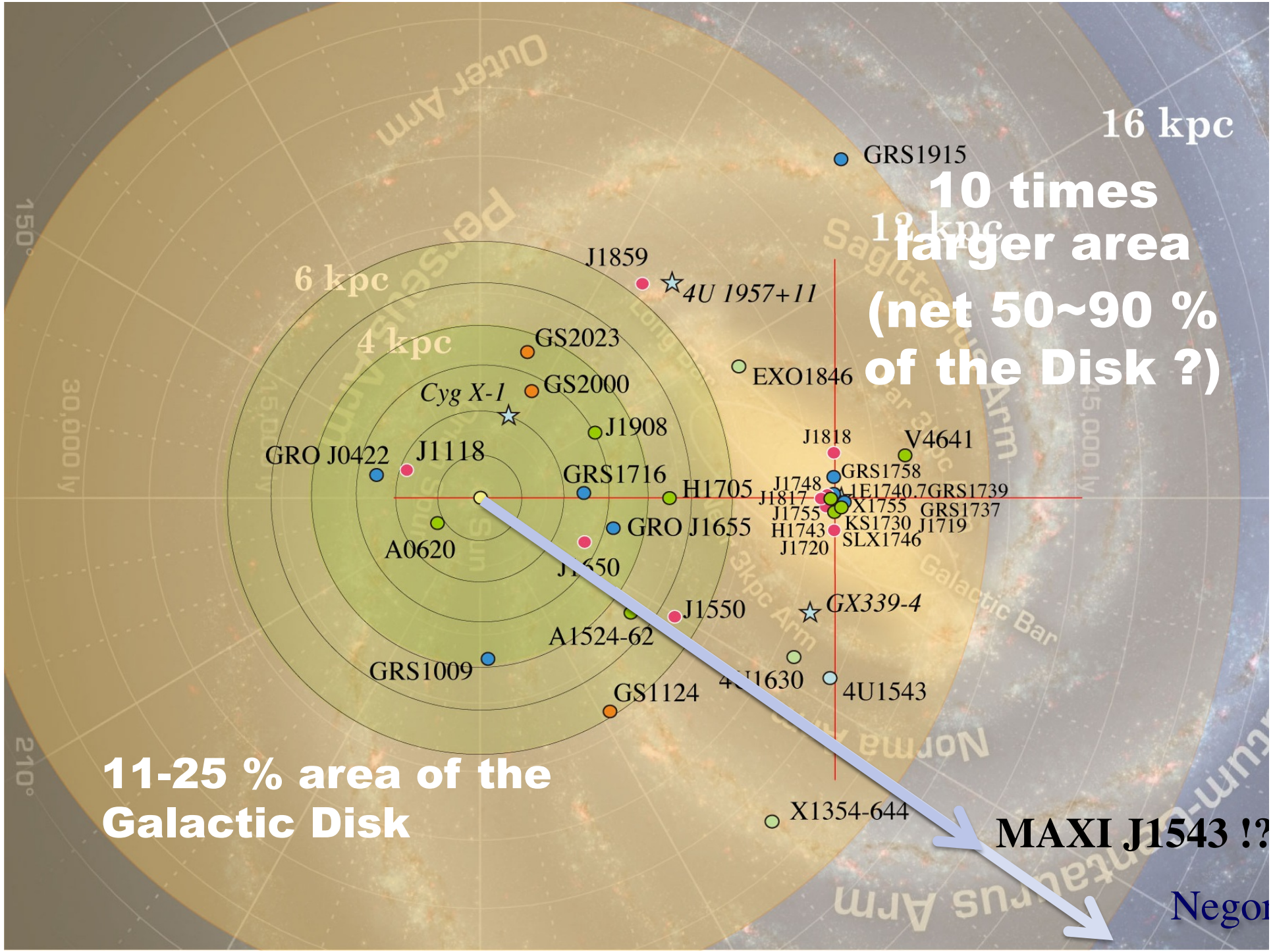
MAXI J1543-564

MAXI ML: <http://maxi.riken.jp>



Tanaka &
Shibazaki 1996





16 kpc
 12 kpc
10 times larger area (net 50~90 % of the Disk ?)

11-25 % area of the Galactic Disk

MAXI J1543 !?

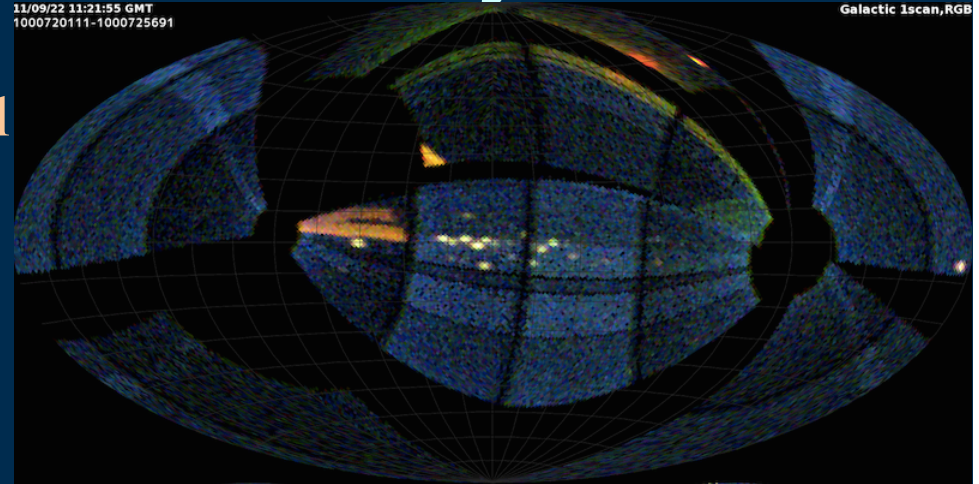
Negor

MAXI運用後の ブラックホール天体の発見競争

発見日 (年/月/日)	Astronomer's Telegram		名前	コメント
	投稿番号	引用回数		
09/10/23	2258	16	XTE J1752-223	
09/11/13	2300	0	Swift J1713.4-4219	情報少ない
10/09/25	2873	24	MAXI J1659-152	Swift とほぼ同時発見
11/01/28	3138	6	Swift J1357.2-0933	中性子星の可能性もあり
11/03/15	3223	6	IGR J17177-3656	BH 以外の可能性もあり
<i>11/03/28</i>	<i>3242</i>	<i>4</i>	<i>Swift J164449.3+573451</i>	<i>(別銀河の超巨大BH) MAXI でも検出</i>
11/05/08	3330	10	MAXI J1543-564	
11/08/30	3611	7	MAXI J1836-194	
12/04/10	4024	7	MAXI J1305-704	中性子星の可能性もあり
12/06/01	4140	8	MAXI J1910-057	Swift J1910.2-0546

Transient Objects Observed by MAXI

- Star
 - Sun, dMe, RSCVn, YSOs, Algol
- White Dwarfs
 - CVs, Super Soft Source
 - MAXI J0158-744
- Neutron Stars
 - LMXB (Burst, Superburst, Outburst), Pulsars, Supergiant Fast X-ray Transients
 - MAXI J0556-332, MAXI J1409-619, MAXI J1647-227
- Black Holes
 - MAXI J1659-152, MAXI J1543-564, MAXI J1836-194, MAXI J1305-704, MAXI J1910-057 (Swift J1910.2-0546)
- GRB, XRF
 - About 1 GRB or XRF/month (GRB 120528B, 120528C)
- AGN
 - Mrk 421, M82, Cyg A, NGC 4151, Cen A, ..., Swift J1644+57



Swift J164449.3+573451



まとめ

- BH の観測的研究は大局的には理解されている。
- しかし、まだ説明できない観測事実や矛盾がある。
 - Jet, QPO, State Transition
- MAXI によりこれまでに5つのブラックホールが発見された
- 未解決問題の解決や新天体の正体を知るためにも、多波長観測がますます重要となってきている