Constraining the mass and radius of neutron star by future observations

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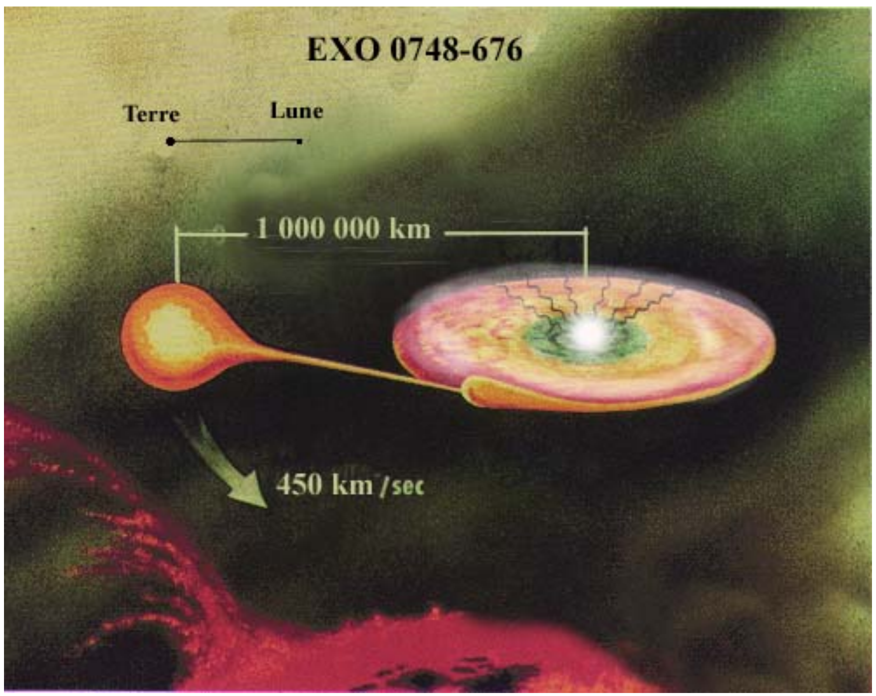
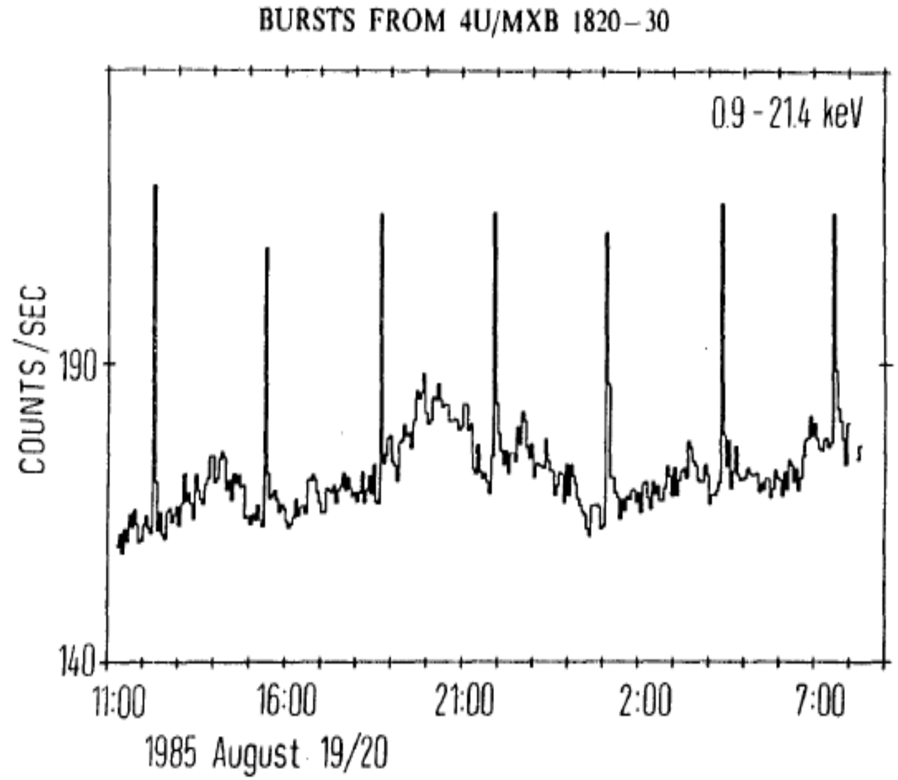
Outline

- Simultaneously estimating mass and radius of neutron star (NS)
  - Photospheric radius expansion (PRE) in X-ray bursts (XRBs)
  - Opacity determined by companion star
- Future observations to constrain the mass and radius of NS further
  - Constraints on the opacity by identifying companion stars
  - Example: XRBs in globular clusters (GCs)

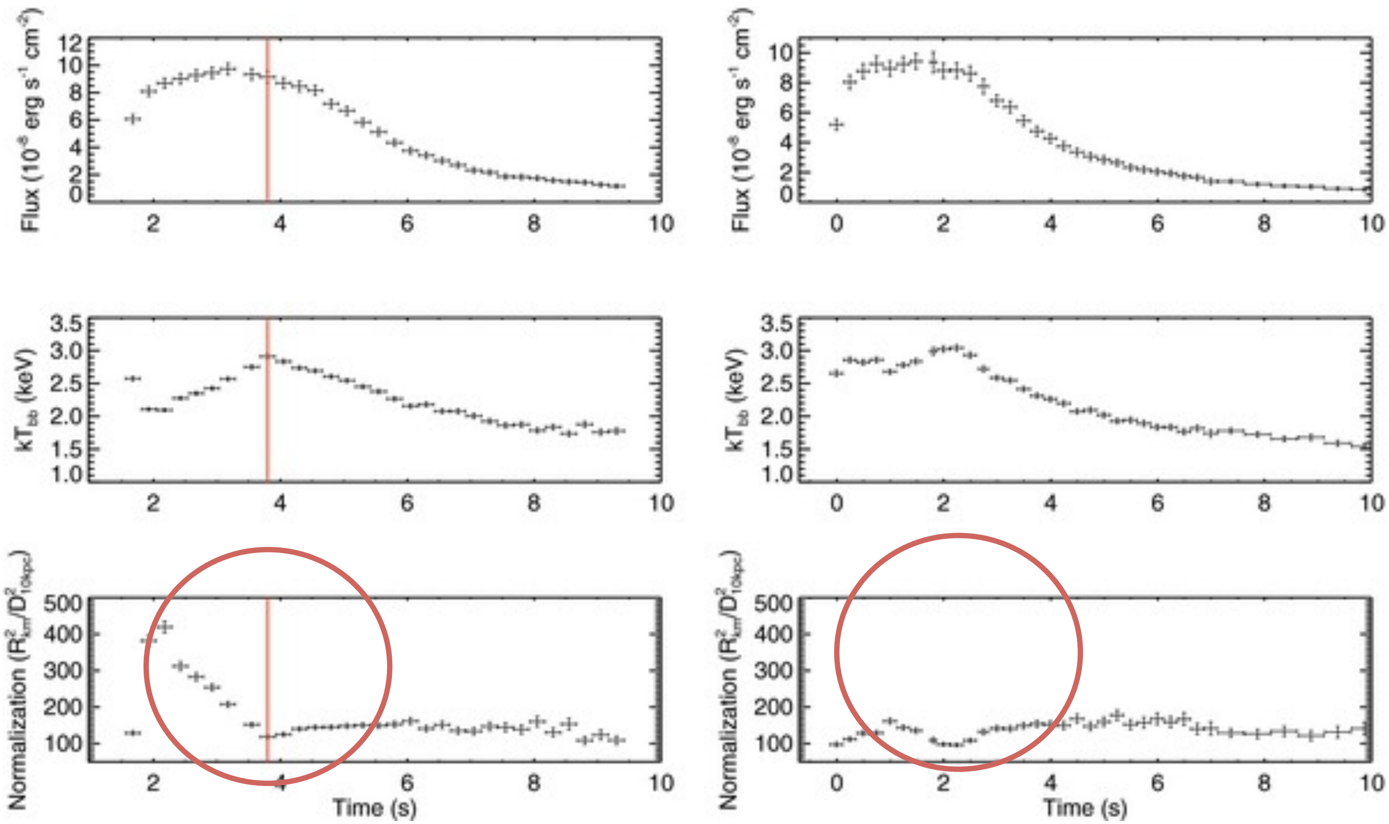
X-ray Bursts (XRBs)
in Low Mass X-ray Binary (LMXB)





Photospheric Radius Expansion (PRE) in XRBs I

PRE or non PRE X-ray burst in 4U 1728-34



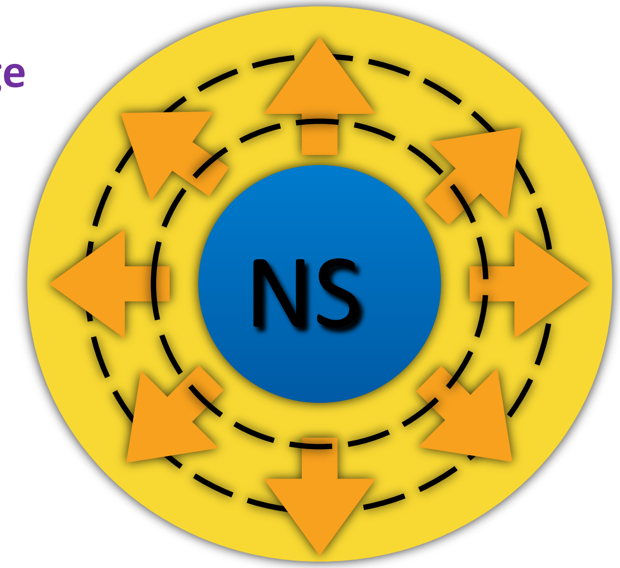
PRE (burst ID:86)

non-PRE (burst ID:104)

Guver et al, 2012

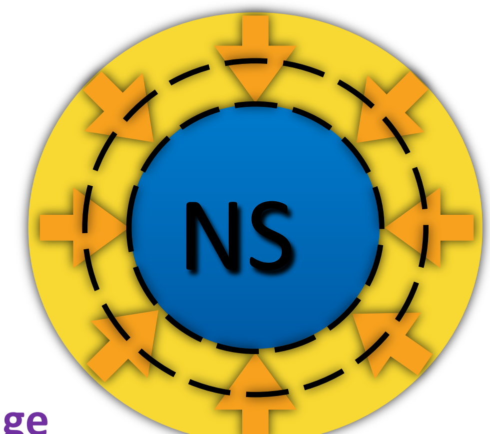
Photospheric Radial Expansion (PRE) in XRBs II

Expansion stage



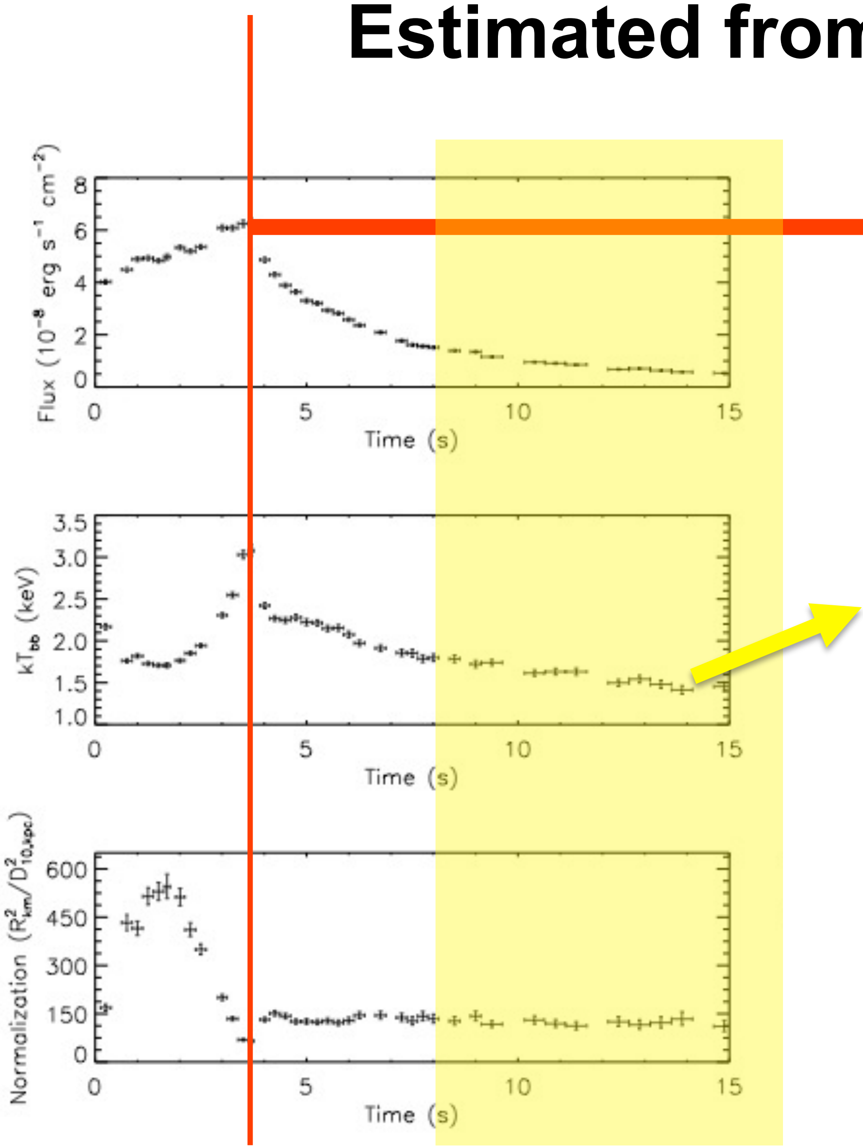
- In bright bursts, luminosity *L* can reach the Eddington limit L_{edd} *when* $P_{radiation} >> P_{gravitation}$. *Then, photospheric layers are lifted off.*
- During PRE, the luminosity is nearly constant (near L_{Edd}).
- About 20% shows the evidence of PRE bursts (Galloway et al. 2008).

Photosphere



‘touchdown’ stage

Mass and Radius of NS Simultaneously Estimated from PRE XRBs



Ozel et al. 2009

$$F_{\mathrm{TD},\infty} = \frac{GMc}{\kappa D^2}\left(1 - \frac{2GM}{Rc^2}\right)^{1/2}$$

$$\kappa = 0.2(1 + X)\ \mathrm{cm}^2\ \mathrm{g}^{-1}$$

$$A \equiv \frac{F_\infty}{\sigma T^4_{\mathrm{bb},\infty}} = f_c^{-4}\frac{R^2}{D^2}\left(1 - \frac{2GM}{Rc^2}\right)^{-1}$$

Method to determine Mass and Radius II

Quantities	EXO 1756–248	4U 1608–522	4U 1820–30	4U 1746–37	EXO 0748-676
D	6.3 ± 0.6	5.8± 2.0	8.2± 0.7	11.05± 0.85	7.1± 1.2
A	1.17± 0.13	3.246± 0.024	0.9198± 0.0186	0.109± 0.044	1.14± 0.10
$F_{\mathrm{TD},\infty}$	6.25± 0.2	15.41± 0.65	5.39± 0.12	0.269± 0.057	2.25± 0.23

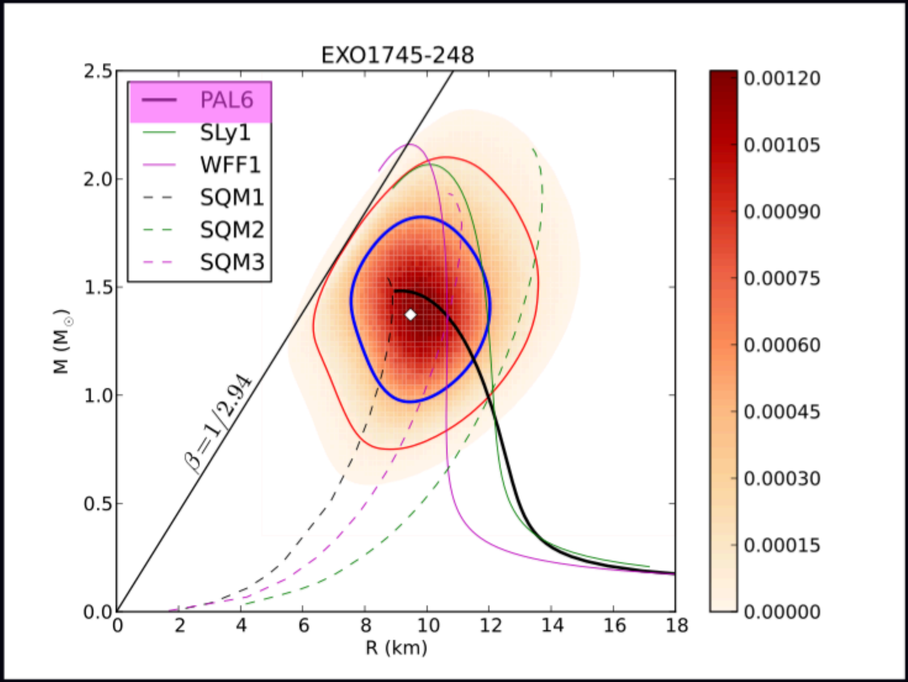
D (kpc): distance
A ($\mathrm{km}^2\ \mathrm{kpc}^{-2}$): normalised surface area
F_{TD} (10^{-8} erg $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$): touchdown flux

- Previous - Gaussian distribution of F_{TD}, A, and D (observation)
  uniform distribution of f_c and x *(theoritical)*
  $f_c(=T_{bb}/T_{eff})$: 1.3 -1.4,
  x : 0.0 - 0.7

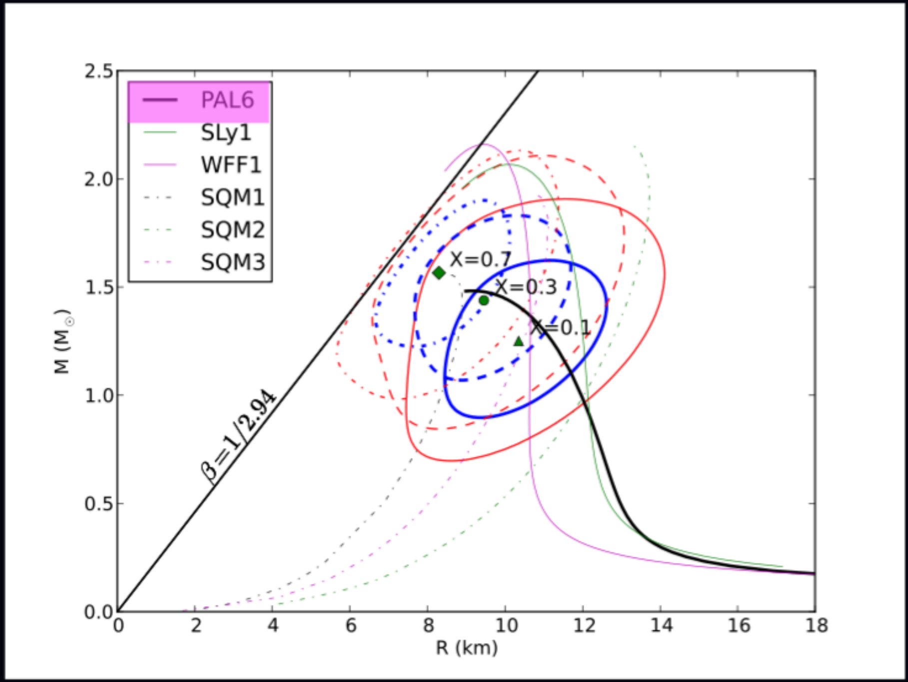
- Our work - x dependence (0.1, 0.3, 0.7)

M-R probability distribution I

uniform distribution



fixed distribution



- mass increases and radius decreases as x increases
- mass (M/M⊙) : 1.24 - 1.57
  radius (km) : 8.29 - 10.38

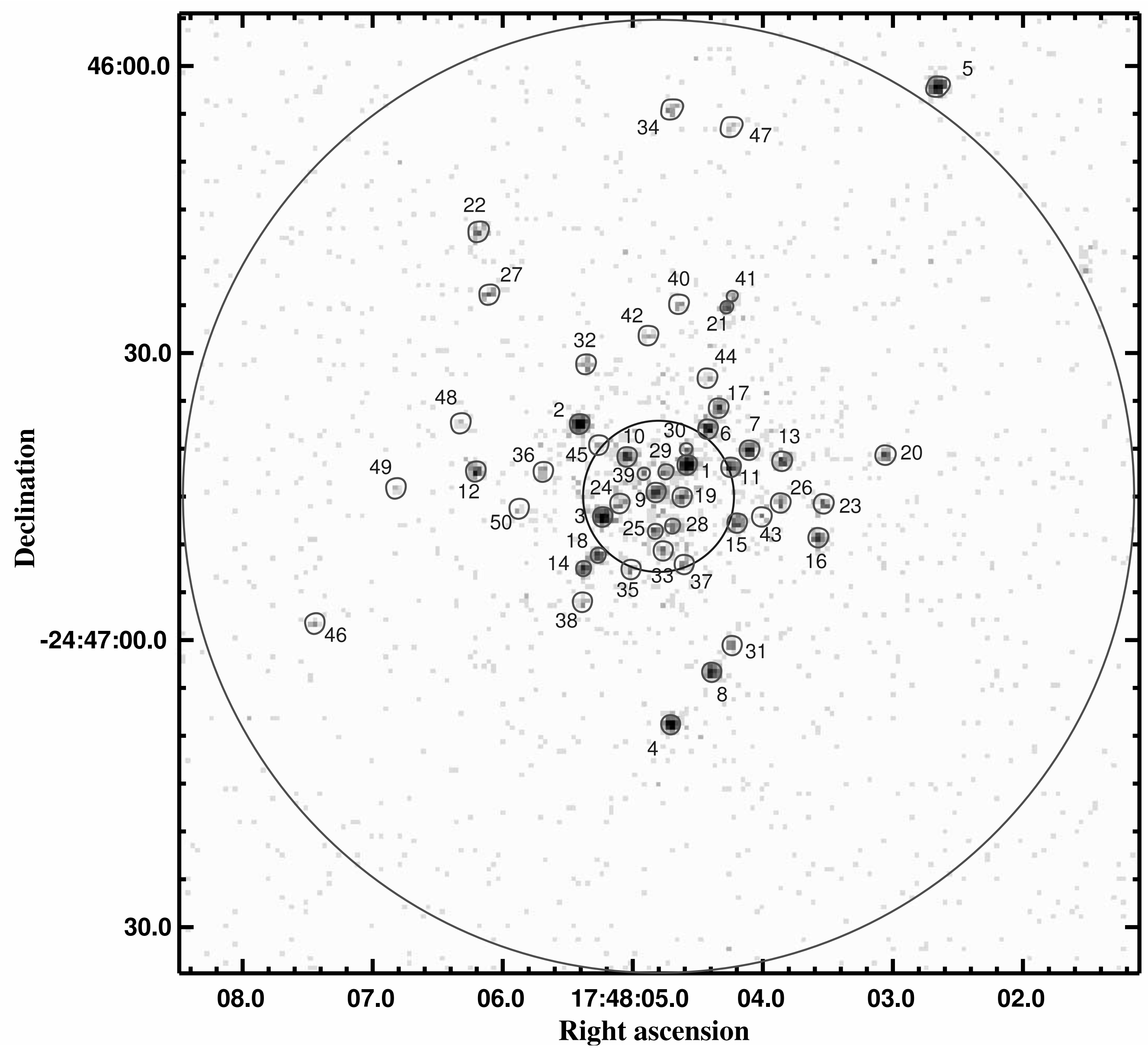
Searching for Companions

- Sources not in GC
  - 4U 1608-522: QX Nor (Variable star)
  - EXO 0748-676: UY Vol (Variable star)
  - Hard to measure distances
- Difficult for the sources in GC
  - Due to high stellar population
  - Methods available to measure distances to GCs

Individual Sources

- EXO 1745-248
  - Terzan 5 (**GC**, distance ~ 6.3 kpc)
  - Ter 5 is well studied, but little information on companion star
- 4U 1608-522
  - Not in GC
  - Optical counterpart QX Nor variable star
- 4U 1820-30
  - NGC 6624 (**GC**)
  - Ultracompact companion (He-WD) with kappa ~ 0
- 4U 1746-37
  - NGC 6441 (**GC**)
- EXO 0748-676
  - Not in GC
  - Claimed to have emission line in X-ray which could be used for gravitational redshift

Terzan 5 Hosting EXO 1745-248



Heinke + 2006 ApJ
Using Chandra

Inner circle = core of GC with a radius of 7.9”

Outer circle contains half mass of GC

50 sources with Lx > 3×10^{31} erg/s (1-6 keV)

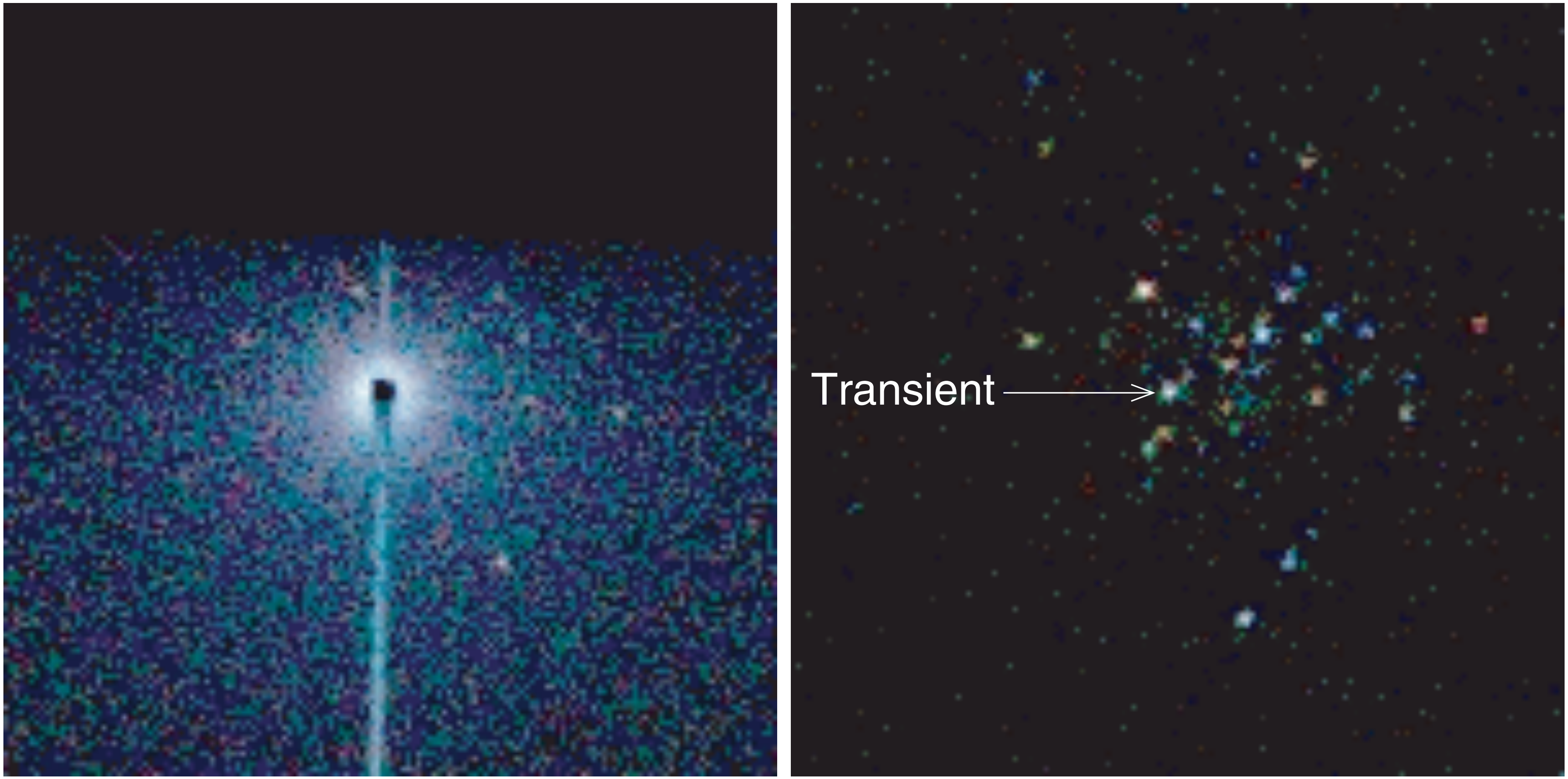
3 = EXO 1745-248

2 = qLMXB

qLMXB candidates = 9, 12, 14, 15 … (12 total)

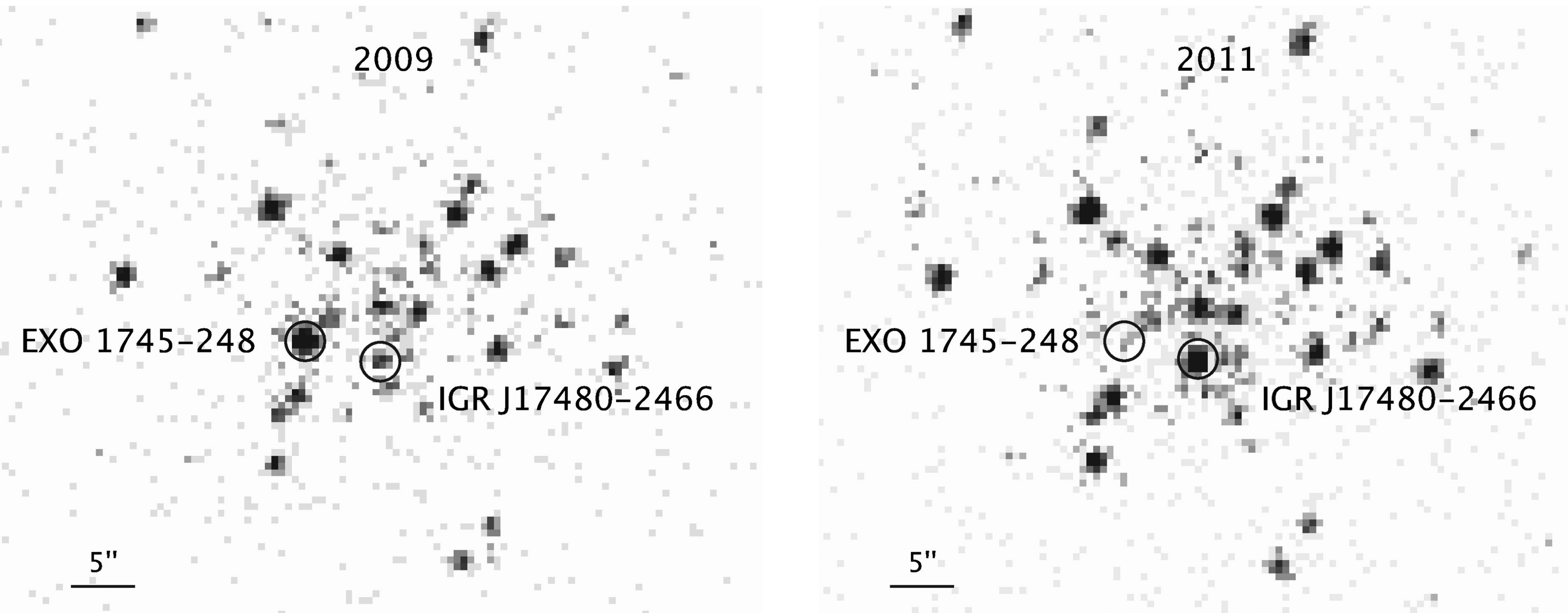
EXO 1745-248: Burst vs. Quiescent

73.8” x 73.8”



Burst on 2000 July 24 vs. Quiescent on 2003 July 13-14
Wijnands + 2005 ApJ using Chandra

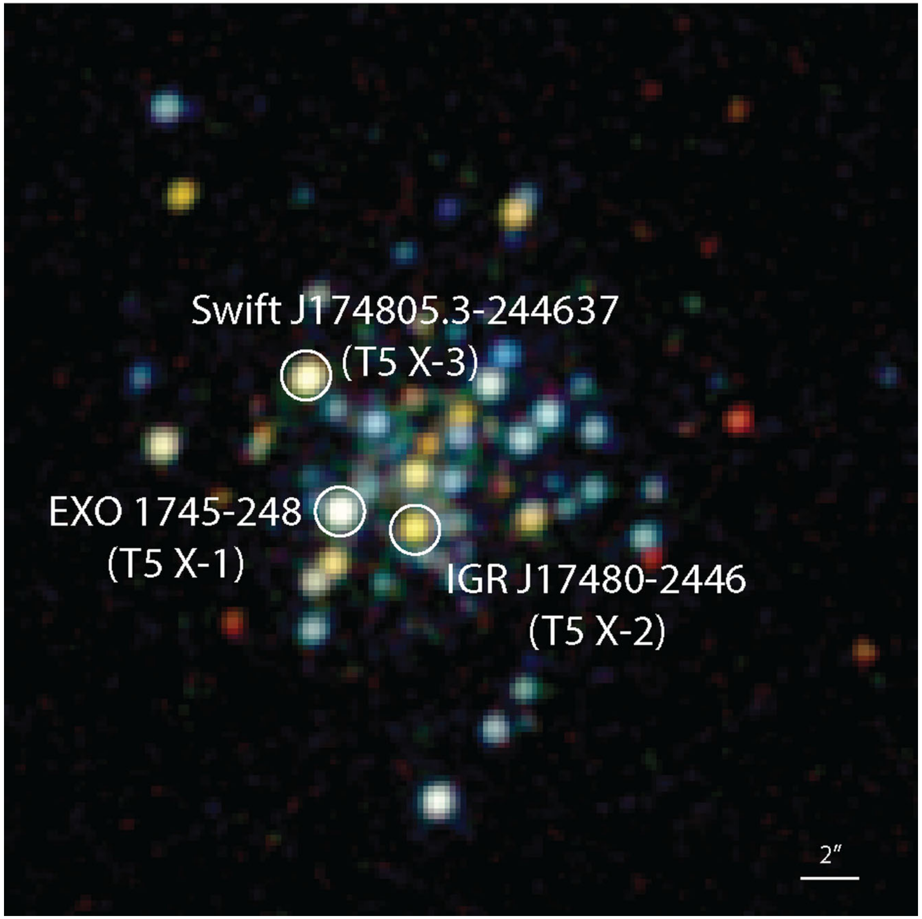
EXO 1745-248: Varying even during quiescent stage

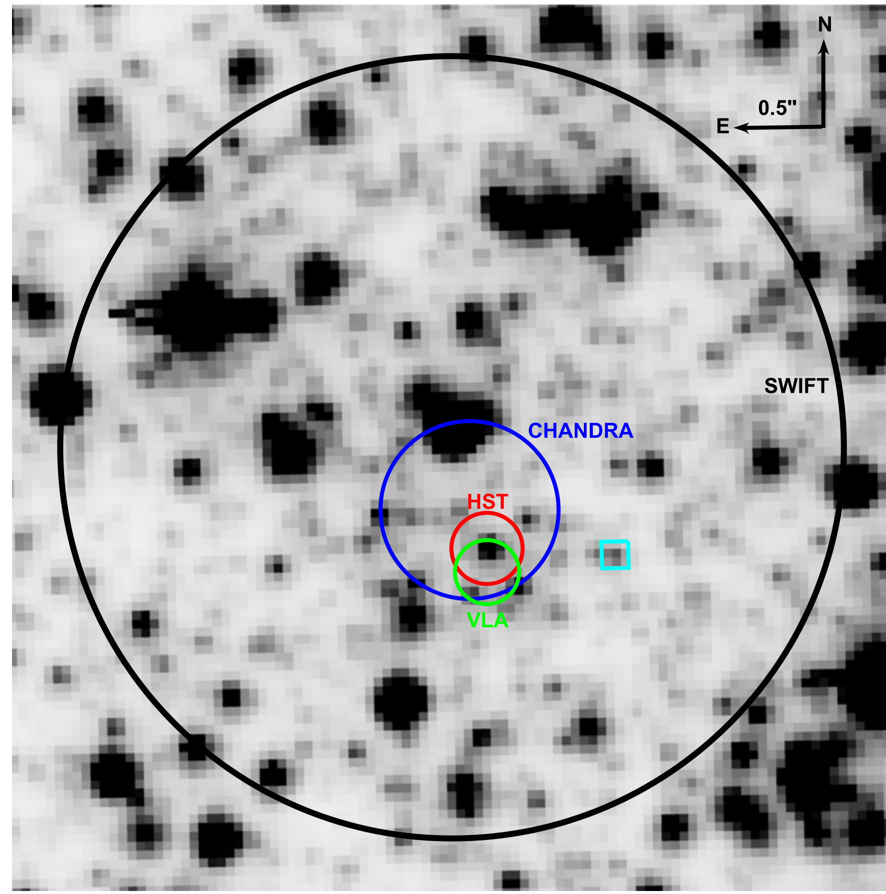


Degenaar & Wijnands 2012 MNRAS

EXO 1745-248 Observed with Different Spatial Resolution

Terzan 5



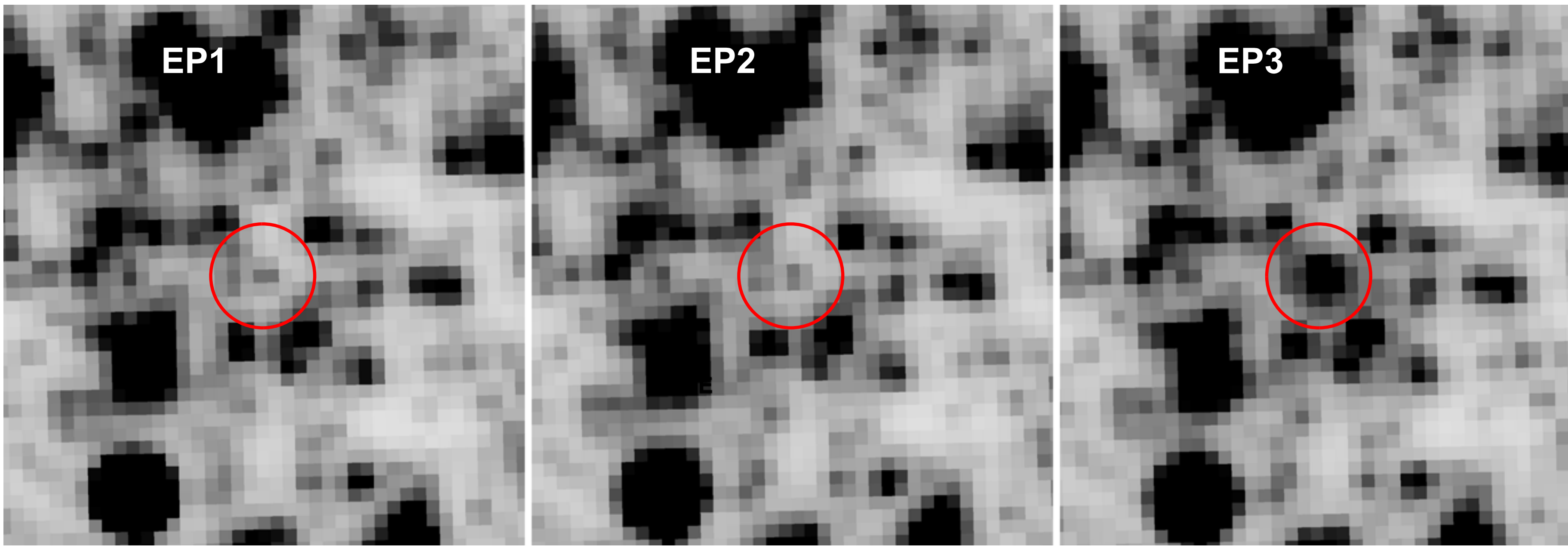


Degenaar + 2015 MNRAS
Accumulated Chandra/ACIS image
Three known transient LMXBs

Ferraro + 2015 ApJL
HST/ACS image after Swift detection of the EXO 1745-248 burst

Counterpart of EXO 1745-248 Burst I

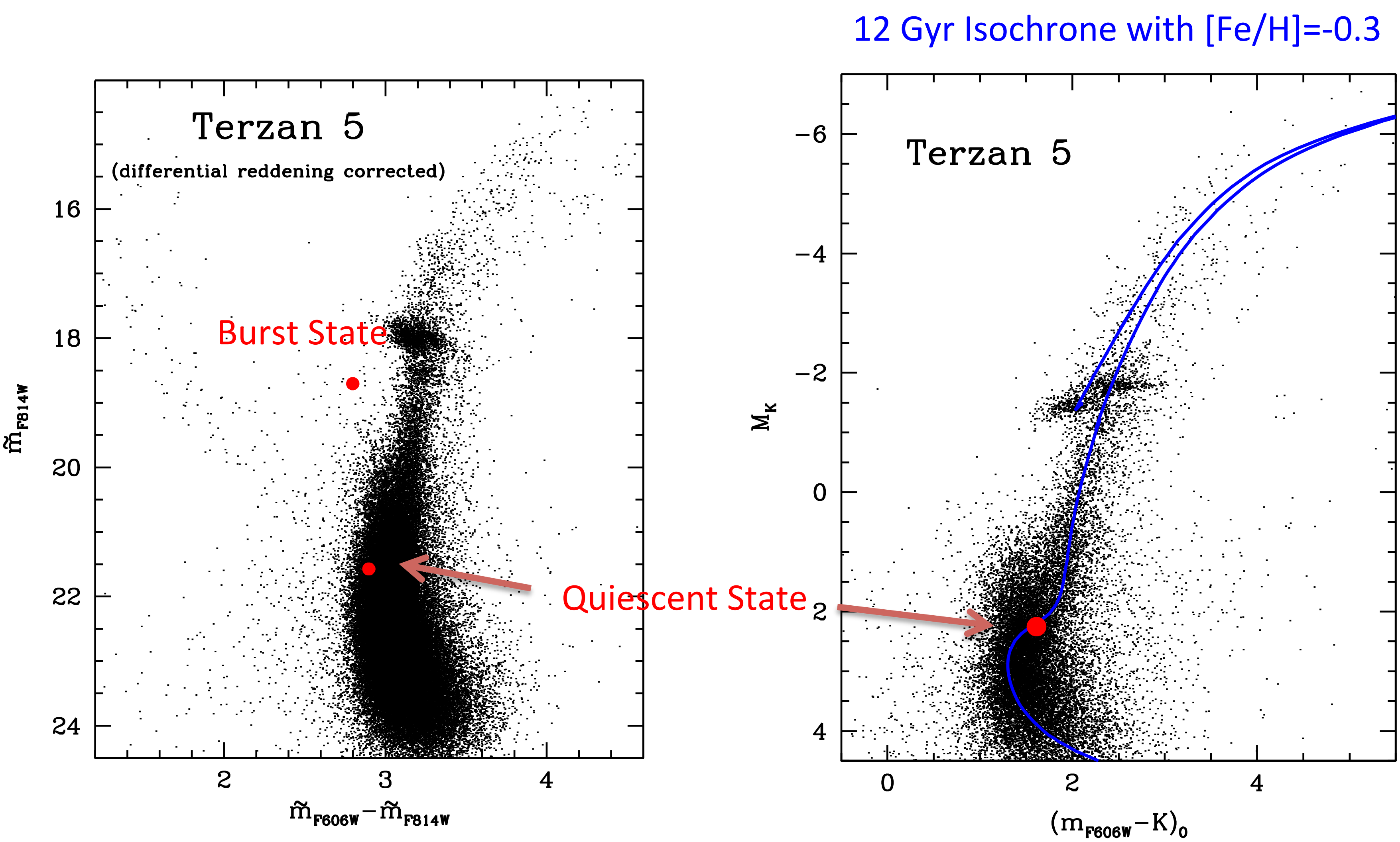
2” x 2”



Quiescent

Burst

Counterpart of EXO 1745-248 Burst II



Current High-Resolution Observatories I

- Chandra ACIS
  - physical size of the CCD pixels ~ 0.492 arcsec
  - High Resolution Camera (HRC): spatial resolution, FWHM ~ 0.4 arcsec
- HST
  - STIS (Space Telescope Imaging Spectrograph)
    - visible plate scale ~ 0.05071 arcsec per pixel
    - ultraviolet plate scale ~ 0.0246 arcsec per pixel

Current High-Resolution Observatories II

- HST
  - COS (Cosmic Origin Spectrograph)
    - ~ 0.07 arcsec for G185M and G230L
    - ~ 0.06 arcsec for G225M and G285M
  - NICMOS
    - f/80 11"x11 43 mas/pix
    - f/45 19”x19” 76 mas/pix
    - f/17 52"x52” 200 mas/pix
  - ACS (Advanced Camera for Survey)
    - ~ 0.05 arcsec/pix (WFC)
    - ~ 0.028 x 0.025 arcsec/pix (HRC)
    - ~ 0.034 x 0.030 arcsec/pix (SBC)

Current High-Resolution Observatories III

- HST
  - Wide Field Camera 3 (WFC 3)
    - ~ 0.04 arcsec/pix (UVIS)
    - ~ 0.13 arcsec/pix (IR)
- Very Large Telescope (VLT)
  - Four 8.2m telescopes
    - ~ 0.05 arcsec for individual telescope
    - ~ 0.001 arcsec (= 1 mas) with interferometry
  - VLT UT2
    - ~ 0.16 arcsec (blue) - 0.22 arcsec (red) per pixel

Spatial Resolution of Future Observatories

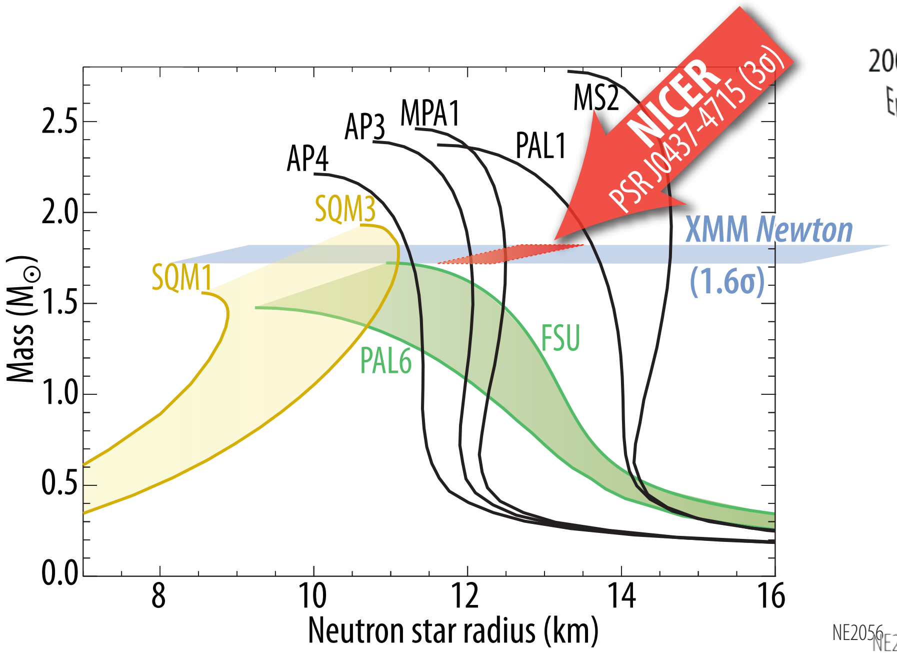
- Giant Magellan Telescope (GMT)
  - Integral-Field Spectrograph
    - ~ 5 mas/pix, 20.4 x 20.4 arcsec field of view at 1 micron
    - ~ 13 mas at J, ~ 16 mas at H, ~ 22 mas at K
  - Facility Fiber Optics Positioned − MANIFEST
    - Positioning accuracy ~ 0.02 arcsec
- Thirty Meter Telescope (TMT)
  - Infrared Imager and Spectrometer (IRIS)
    - ~ 0.004, 0.010, 0.025, 0.050 arcsec/pix for IFU (at different wavelength of IR)
    - ~ 7 mas at 1 micron
  - High-Resolution Optical Spectrometer (HROS)
    - spatial sampling: < 0.2 arcsec/pix

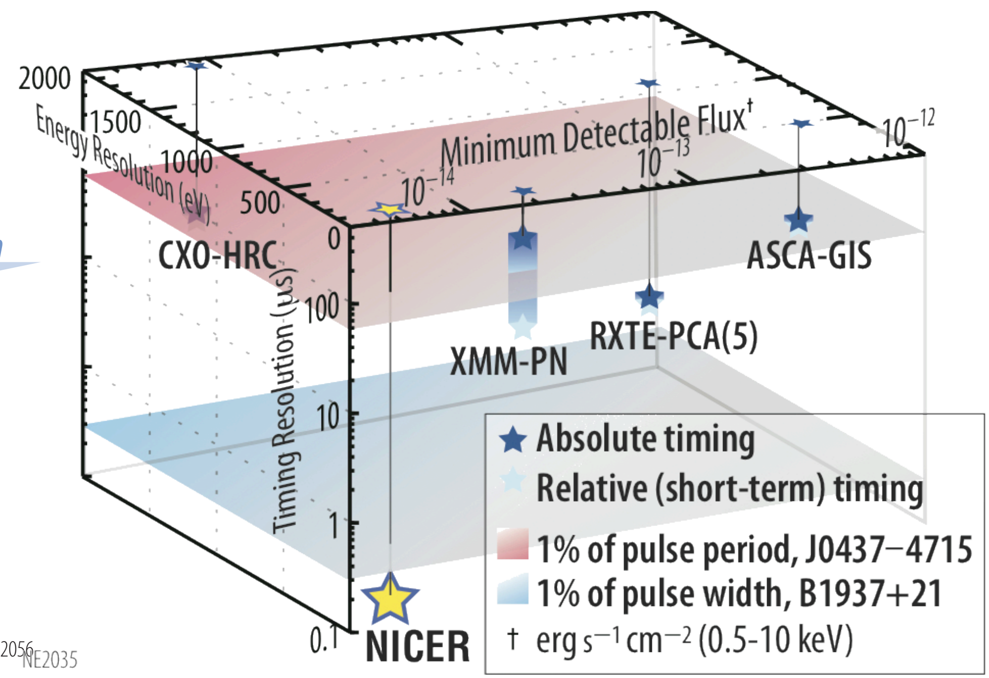
Spatial Resolution of Future Observatories

- JWST
  - ~ 0.1 arcsec at 2 microns
  - Near-Infrared Camera (NIRCam)
    - ~ 0.032 arcsec/pix at 2.0 microns
    - ~ 0.065 arcsec/pix at 4.0 microns
  - Mid-Infrared Instrument (MIRI)
    - ~ 0.18 arcsec at 5 microns
    - full width at half maximum ~ 0.035 x Lambda (in microns) arcsec at Lambda

NICER (Neutron star Interior Composition Explorer)

- Operating now after installed at ISS on June 12-13, 2017





Gendreau + 2012

Discussion

- Past and current X-ray observatories
  - Low spatial resolution with high time resolution: RXTE found XRBs in LMXBs
  - High spatial resolution with low time resolution: Chandra, XMM-Newton, and Suzaku are not optimized for detecting XRB signals
- Past and current optical and IR observatories
  - Higher spatial resolution than X-ray observatories
- Best combination of multi-band observations to pin down companions
  - High resolution in all bands
  - Currently lacking: UV and X-ray

Possibilities with Limitations

- Continue to search variable objects with high resolution UV, optical, and IR observations within the error circles of X-ray observation
- Statistically constrain the opacity
  - Count different stellar types within the error circle
  - Stars with hydrogen envelope or not

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Center for High Energy Astrophysics (CHEA)

❑ 센터소개

고에너지 천체물리학은 열적(thermal)·비열적(nonthermal) 고에너지 입자들이 방출하는 전파, X-선, 감마선 등 전자기파와 중성미자, 중력파 등의 관측에 기반을 두어, 이와 관련된 천문학 현상의 물리 기작을 연구하는 분야이다. 본 센터에는 이론·시뮬레이션을 중심으로 하는 천체물리를 천문 관측 및 실험 천체물리(laboratory astrophysics)와 결합하여, 은하단(clusters of galaxies)과 밀집천체(compact objects)에서 고에너지 천체물리 현상에 대한 연구를 수행한다. 이를 통해 고에너지 천체물리 연구의 국내 거점을 마련하고, 세계 선도 연구 그룹으로 발전할 기반을 구축하는 한편, 이 분야에서 세계적 수준의 미래 핵심 인력을 양성한다.

❑ 센터목표

PAL-XFEL: 4세대 방사광 가속기
RAON: 한국형 중이온 가속기

주관: 울산과학기술원 (UNIST)

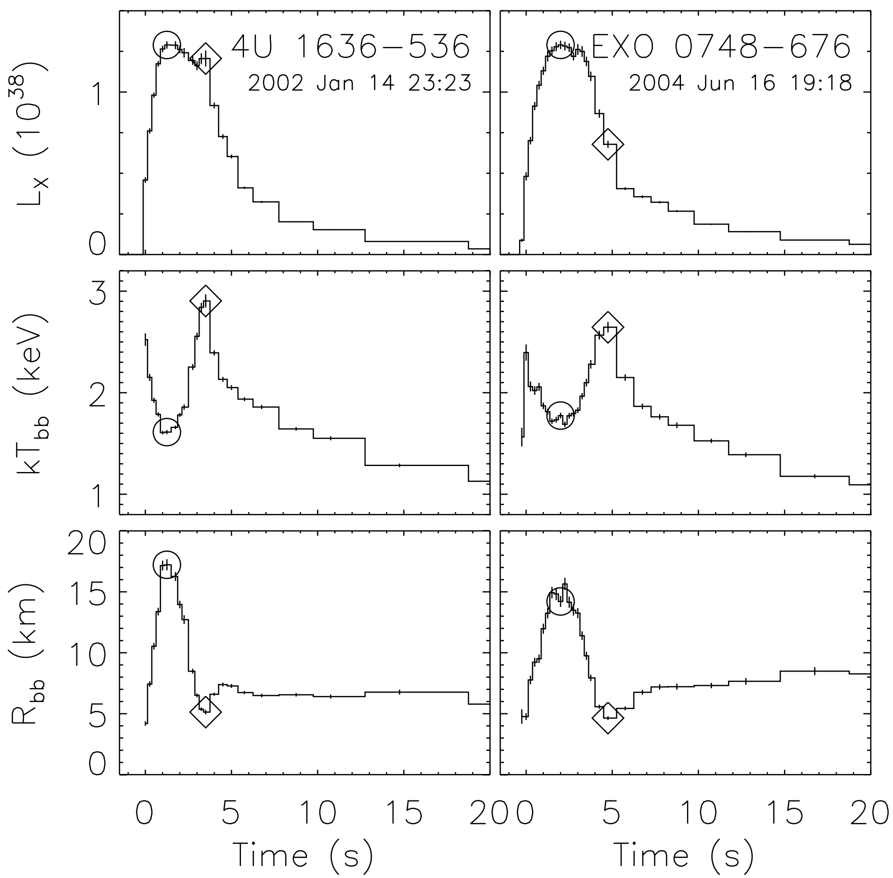
연구책임자: 류동수

Thank you!

Search More

- X-ray observations
  - High spectral resolution observatory like Hitomi
- Importance of Future UV observatories
  - Spatial resolution toward GCs near the Galactic center is hindered via extinction

PRE XRBs at high inclination angle



Galloway + 2008 MNRAS