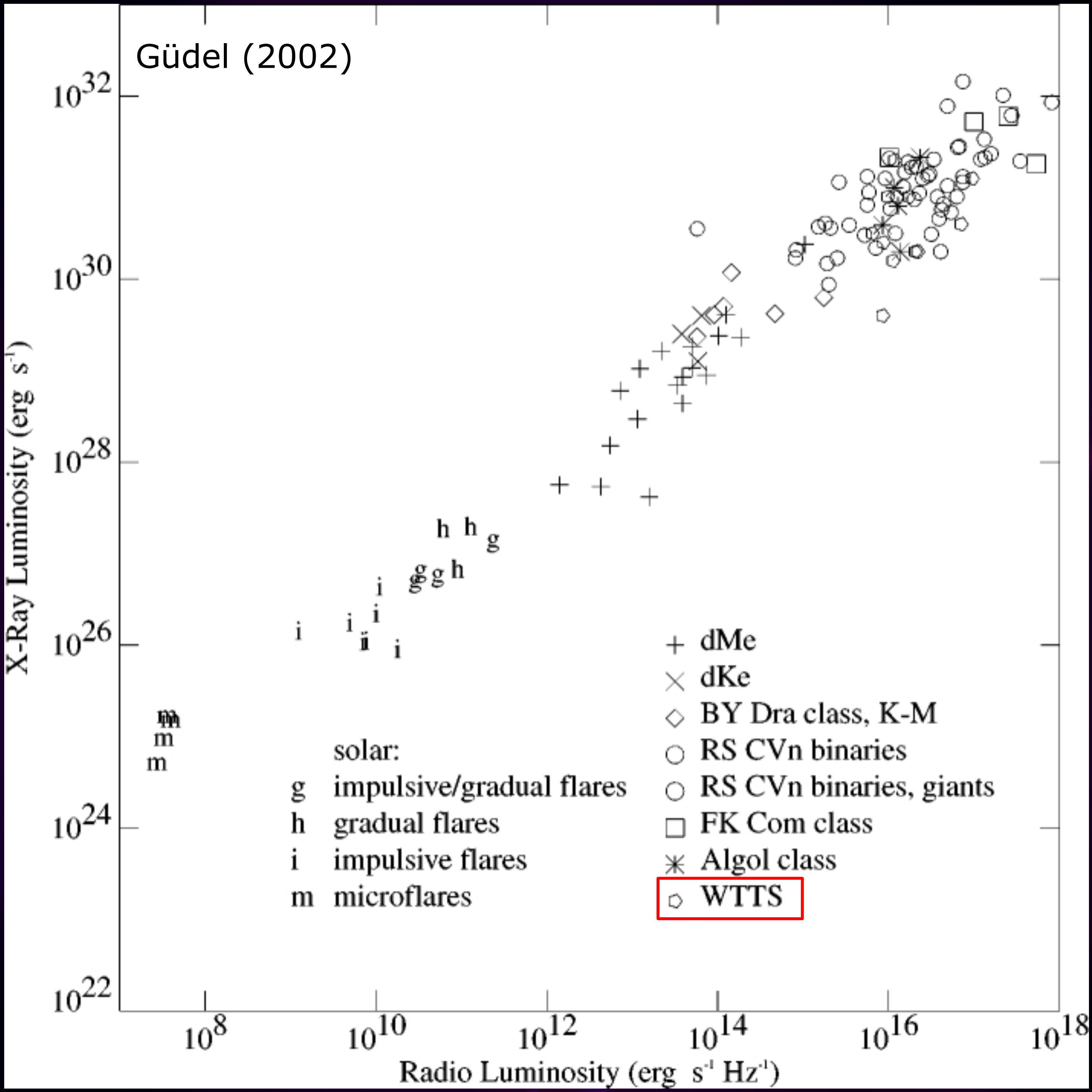
The Radio/X-ray Connection in Young Stellar Objects in the Orion Nebula Cluster

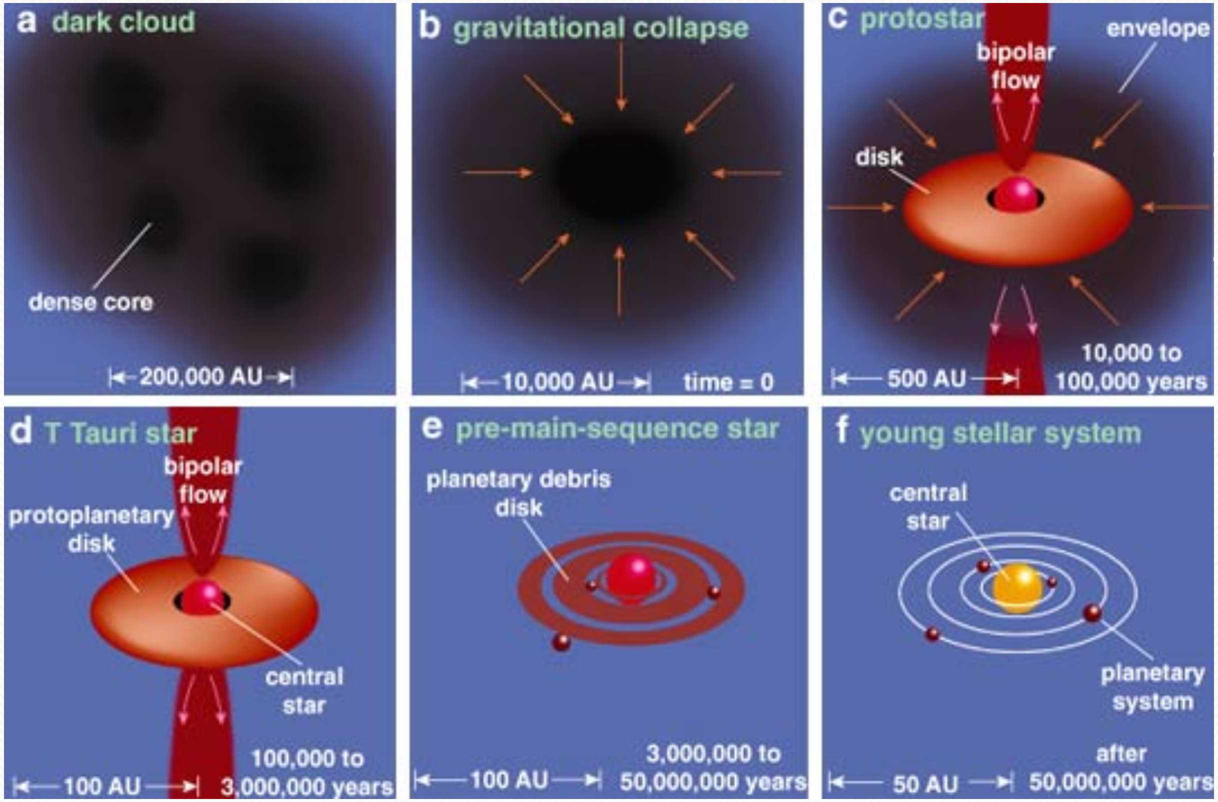
By Scott J. Wolk and Jan Forbrich



Güdel (2002)
X-Ray Luminosity (erg s-1)
Radio Luminosity (erg s-1 Hz-1)
solar:
g impulsive/gradual flares
h gradual flares
i impulsive flares
m microflares
dMe
dKe
BY Dra class, K-M
RS CVn binaries
RS CVn binaries, giants
FK Com class
Algol class
WTTS

Classes of Young Stellar Objects (YSOs)

"class 0" "class I"

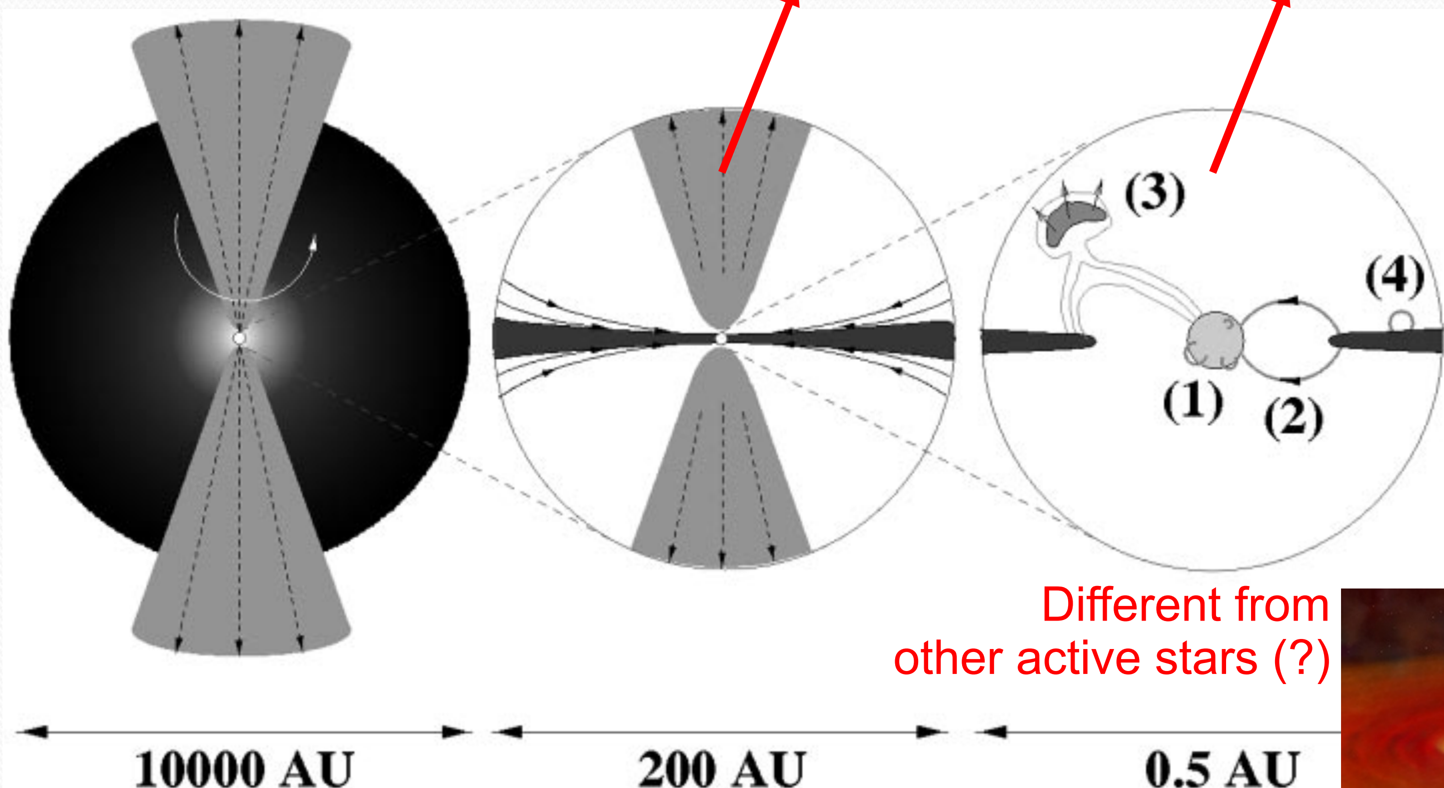


"class II" "class III"

Lada (1987)
André et al. (2000)

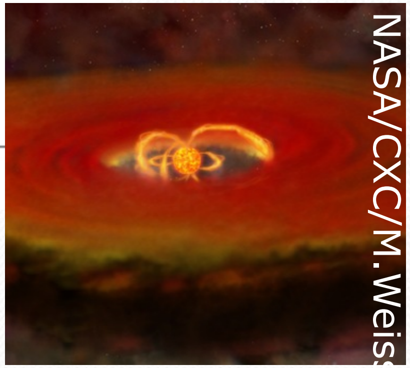
thermal radio

(thermal) X-rays,
***nonthermal* radio**



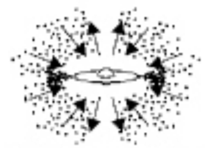
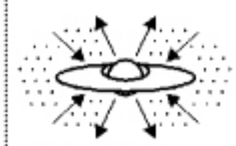
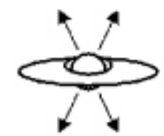
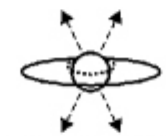
Feigelson & Montmerle (1999)

Different from
other active stars (?)

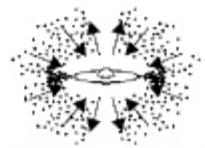
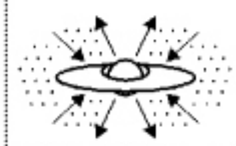
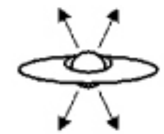
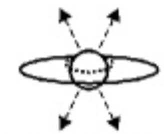


NASA/CXC/M.Weiss

X-rays *and* nonthermal radio emission probe the **innermost regions** of protostars, but currently only radio observations offer high angular resolution (VLBI).

PROPERTIES	*Infalling Protostar*	*Evolved Protostar*	*Classical T Tauri Star*	*Weak-lined T Tauri Star*	*Main Sequence Star*
SKETCH					
AGE (YEARS)	10^4	10^5	$10^6 - 10^7$	$10^6 - 10^7$	$> 10^7$
mm/INFRARED CLASS	Class 0	Class I	Class II	Class III	(Class III)
DISK	Yes	Thick	Thick	Thin or Non-existent	Possible Planetary System
X-RAY	?	Yes	Strong	Strong	Weak
Thermal radio (e.g., free-free emission)	Yes	Yes	Yes	No	No
Nonthermal radio (e.g., gyrosynchrotron emission)	No	Yes	No ?	Yes	Yes

Feigelson & Montmerle (1999)

Properties	*Infalling Protostar*	*Evolved Protostar*	*Classical T Tauri Star*	*Weak-lined T Tauri Star*	*Main Sequence Star*
Sketch					
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...only ~2 sources!

Feigelson & Montmerle (1999)

YSO Radio Emission

Process: Gyrosynchrotron/non-thermal radiation
or Thermal free-free

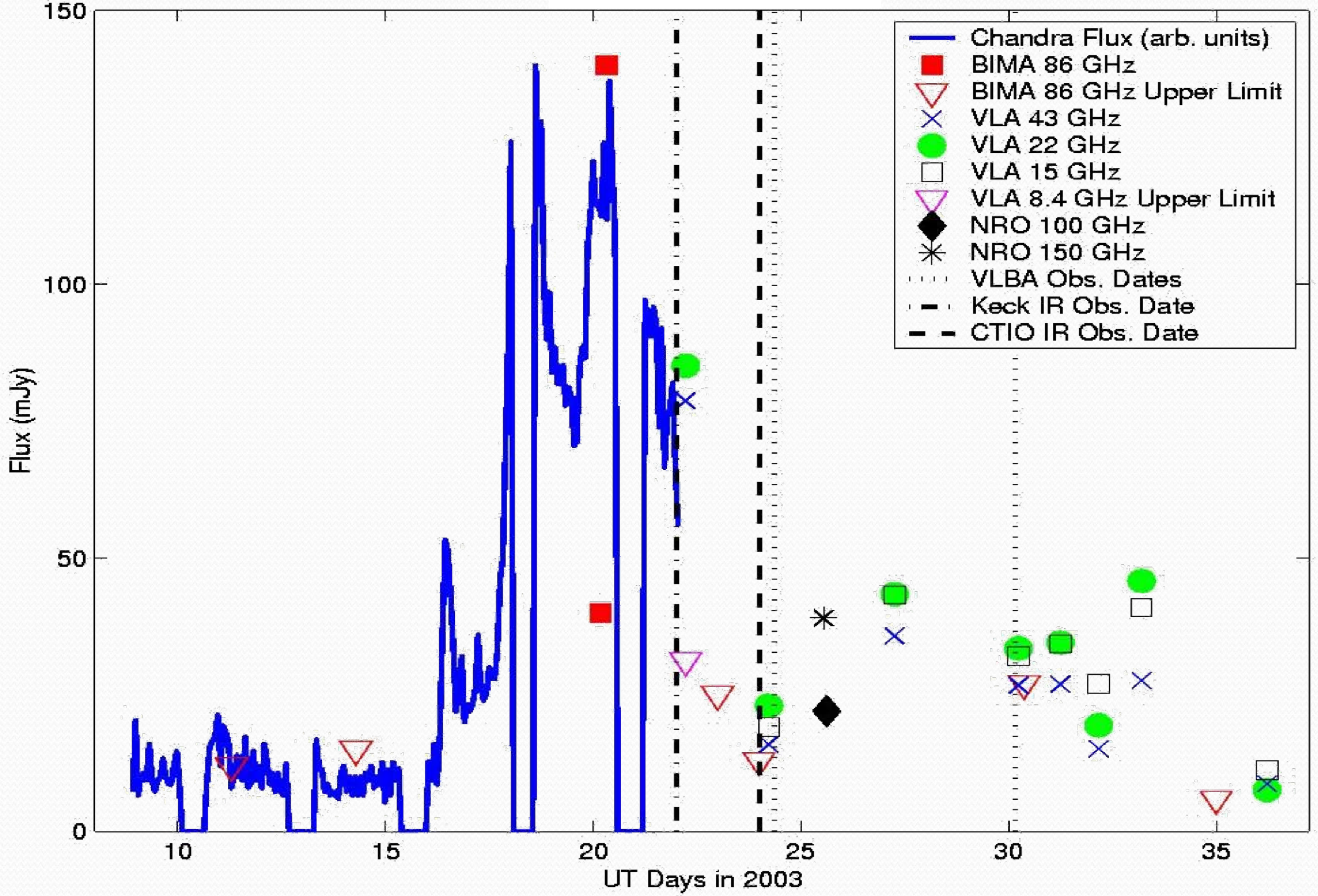
GS identified by: Polarization, spectral index, rapid variability, high brightness temperature

Problem (VLA): weak sources,
measurement at single frequency

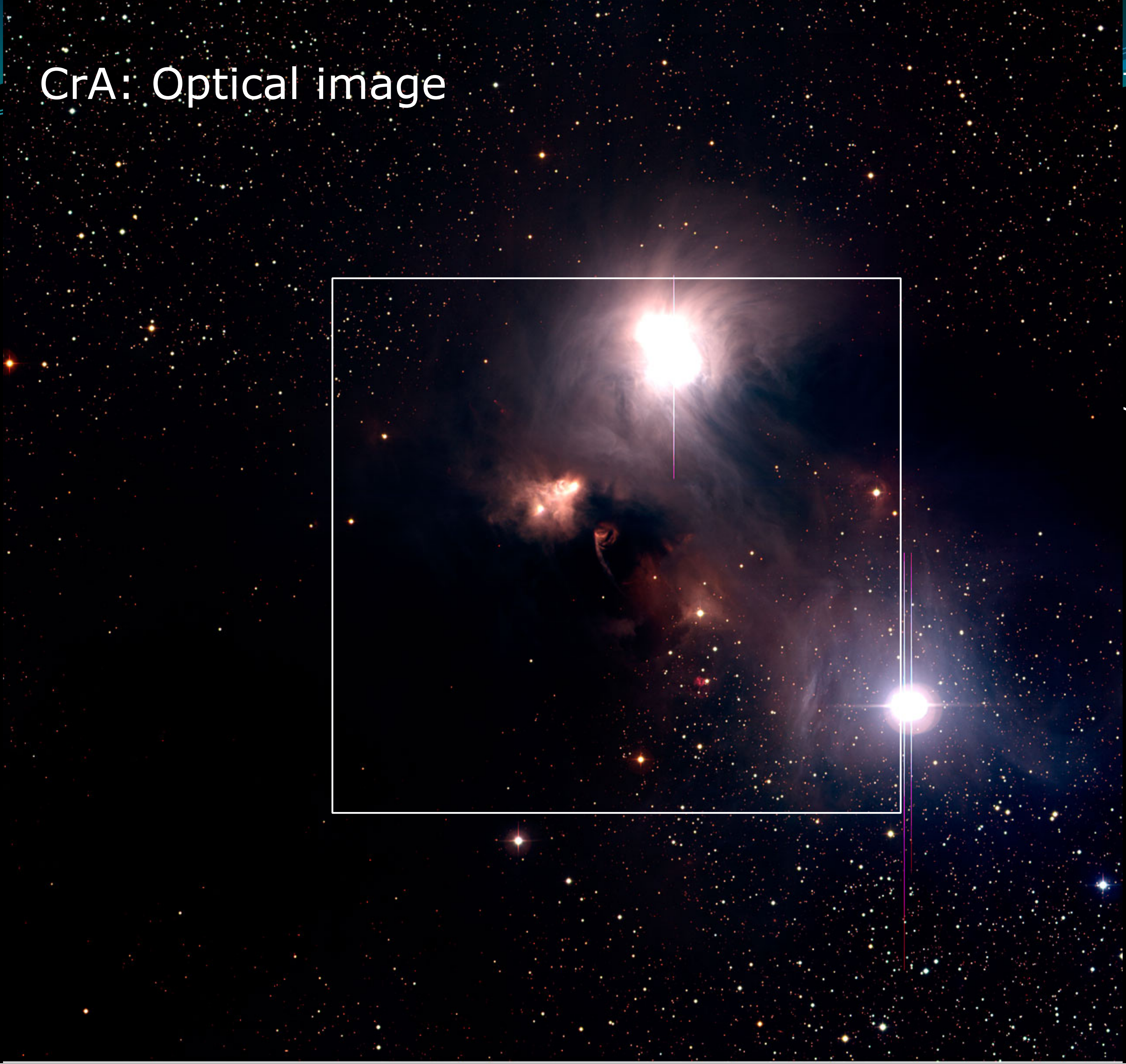
→ Best evidence for non-thermal radiation requires high S/N – often not the case.

→ Difficult to constrain the emission processes of many weak sources.

GMR A (Bower et al. 2003, Getman et al. 2003)

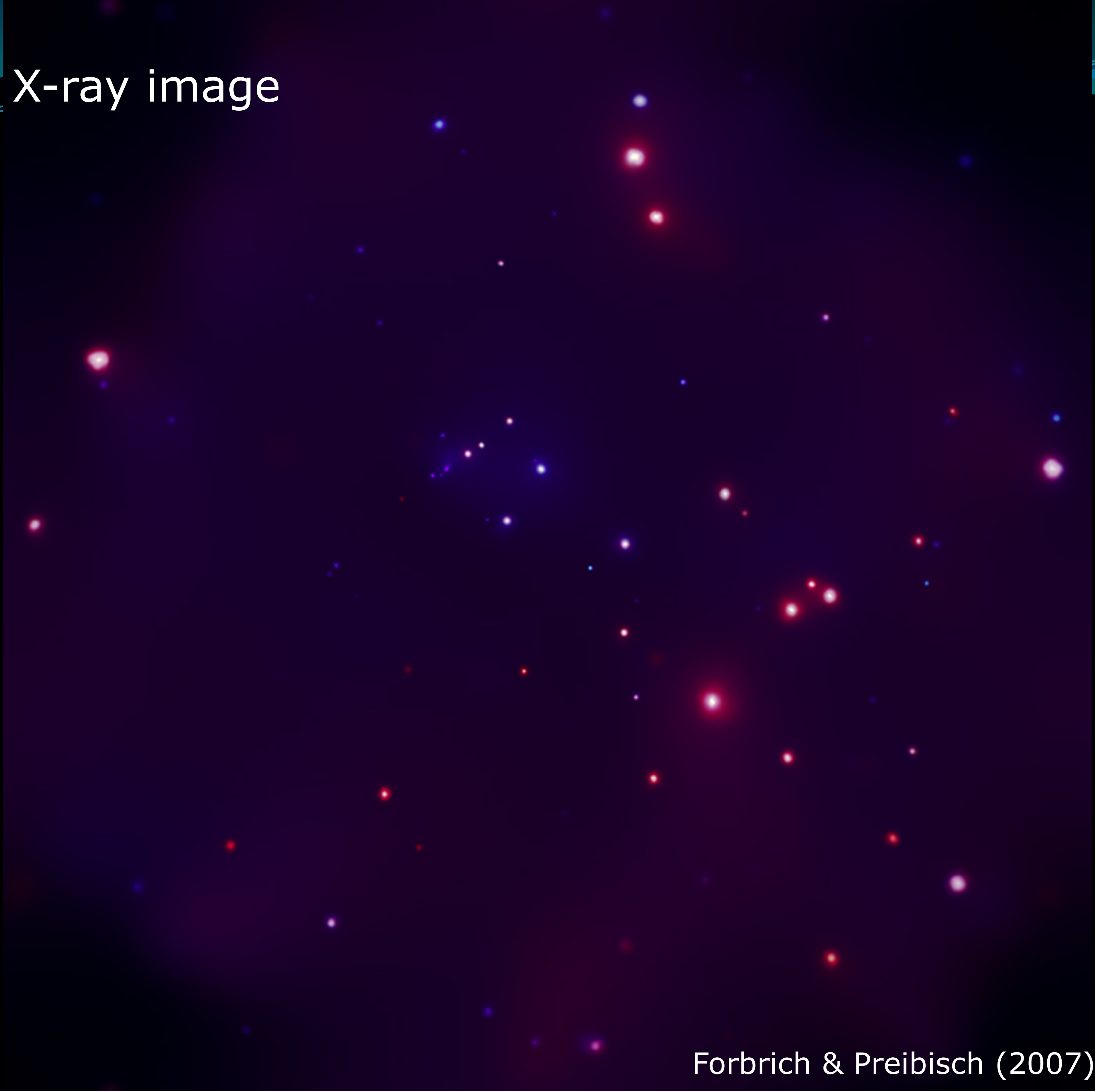


CrA: Optical image



European Southern Observatory

X-ray image



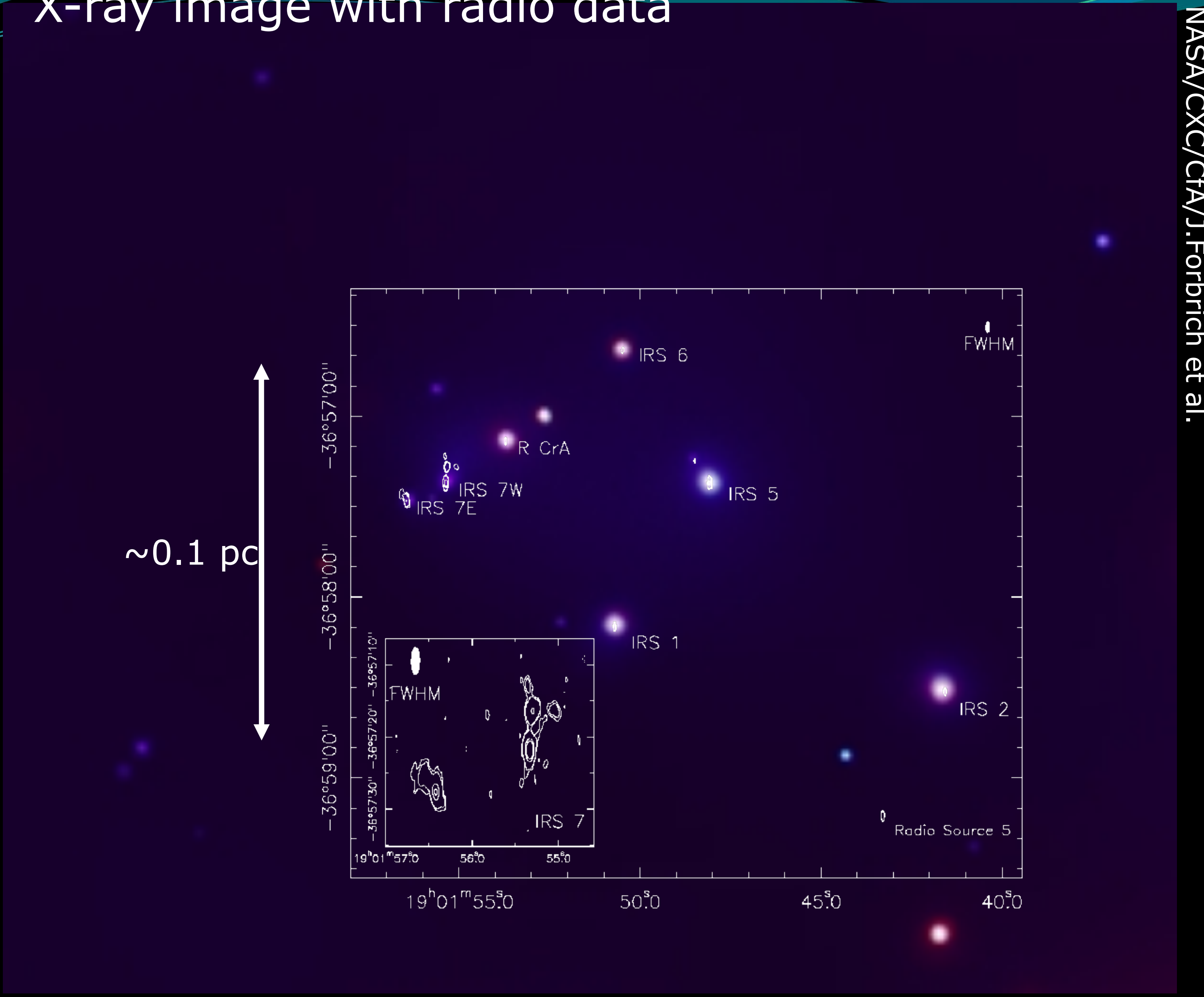
NASA/CXC/CfA/J.Forbrich et al.

Forbrich & Preibisch (2007)

X-ray image

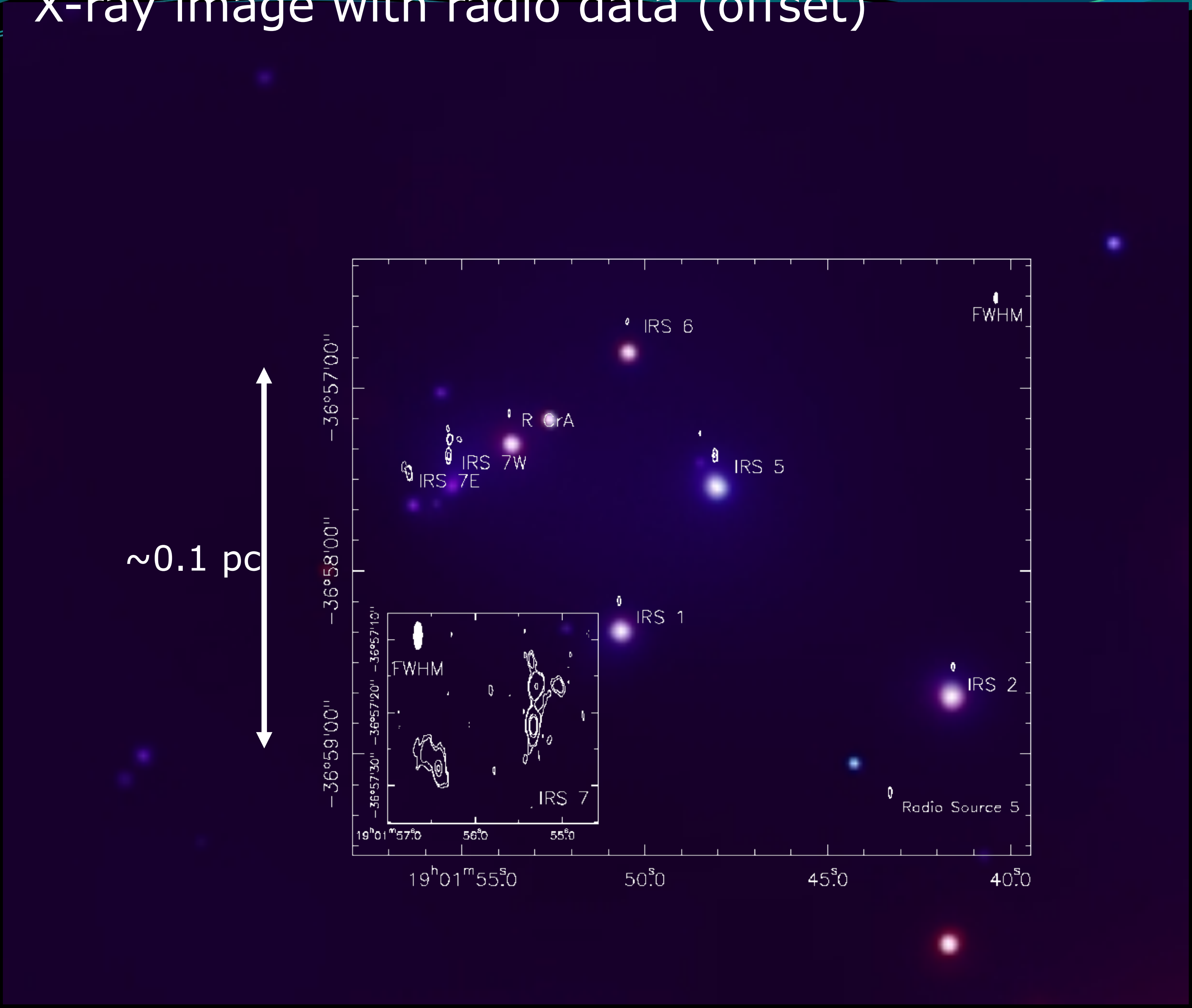
NASA/CXC/CfA/J.Forbrich et al.

X-ray image with radio data



Forbrich et al. (2006, 2007)

X-ray image with radio data (offset)

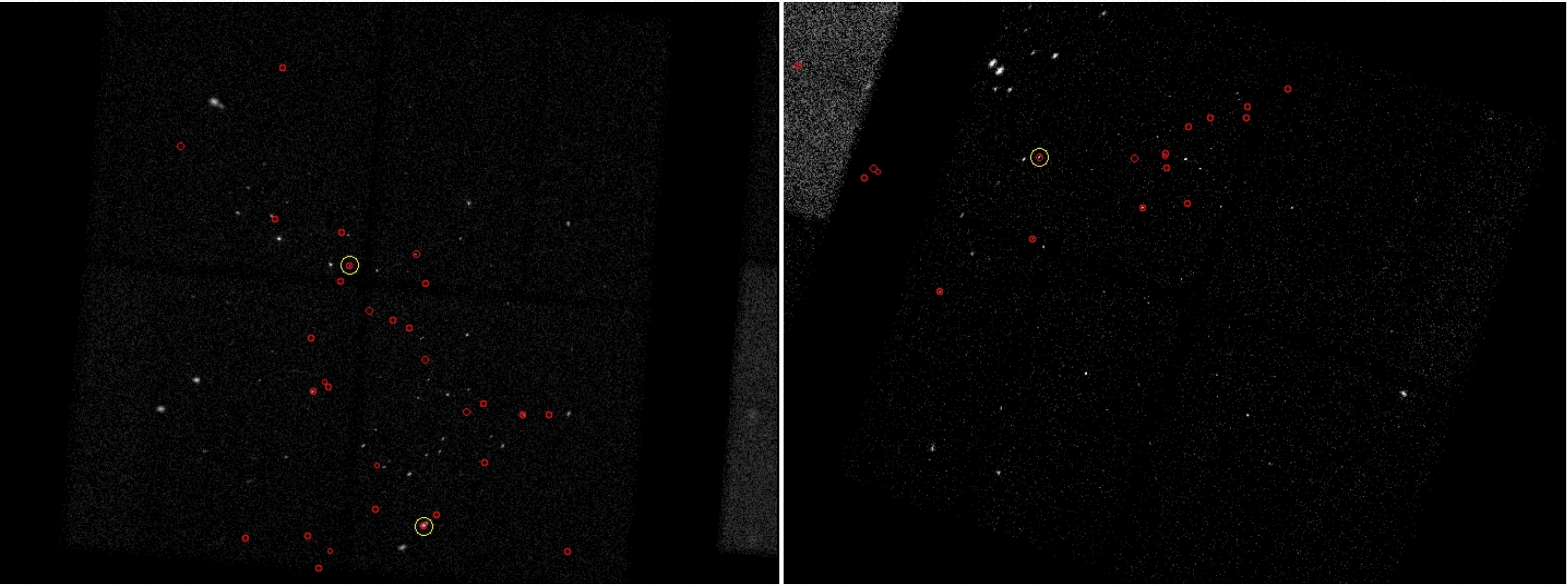


NASA/CXC/CfA/J.Forbrich et al.

Forbrich et al. (2006, 2007)

What about other clusters?

NGC 1333 & IC 348



Forbrich, Osten & Wolk 2011

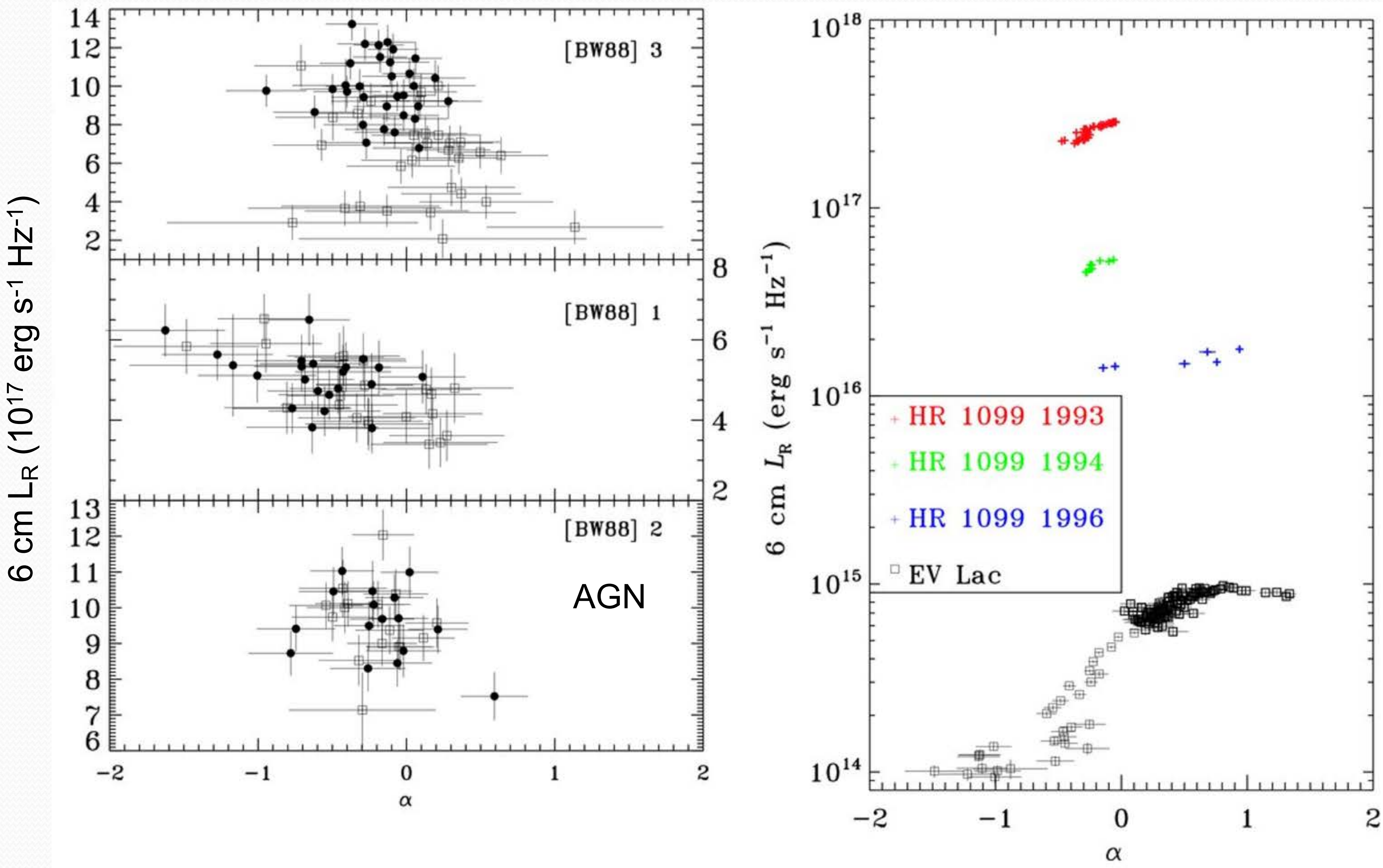
NGC 1333: 2x 40 ksec Chandra + 22h VLA (X & C in subarrays)
IC 348: 2x 40 ksec Chandra + 22h VLA (X & C in subarrays)

~5% of YSOs have Simultaneous X-ray & radio detections

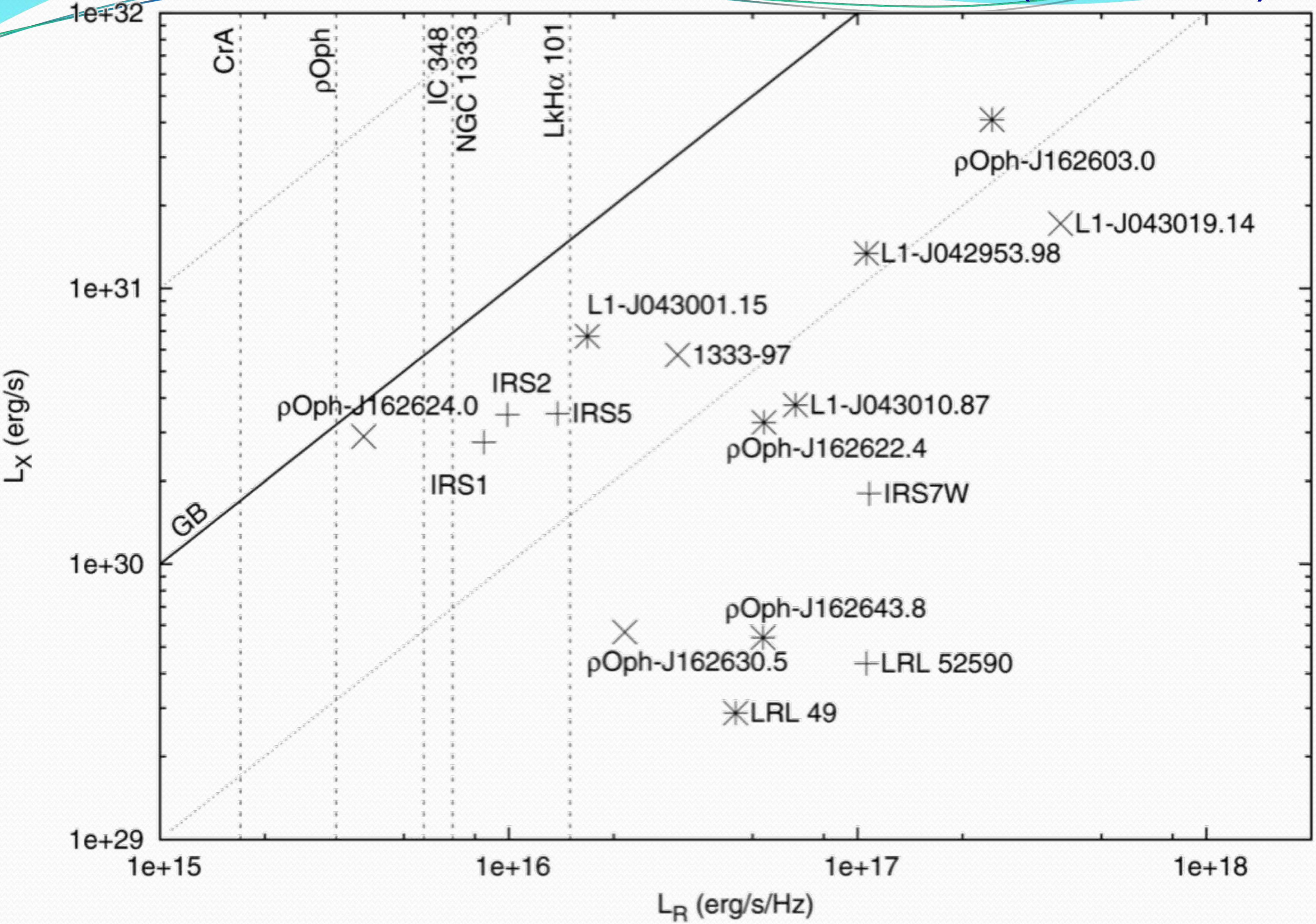
→ only three class I sources detected in X-rays *and* radio

What about other clusters?

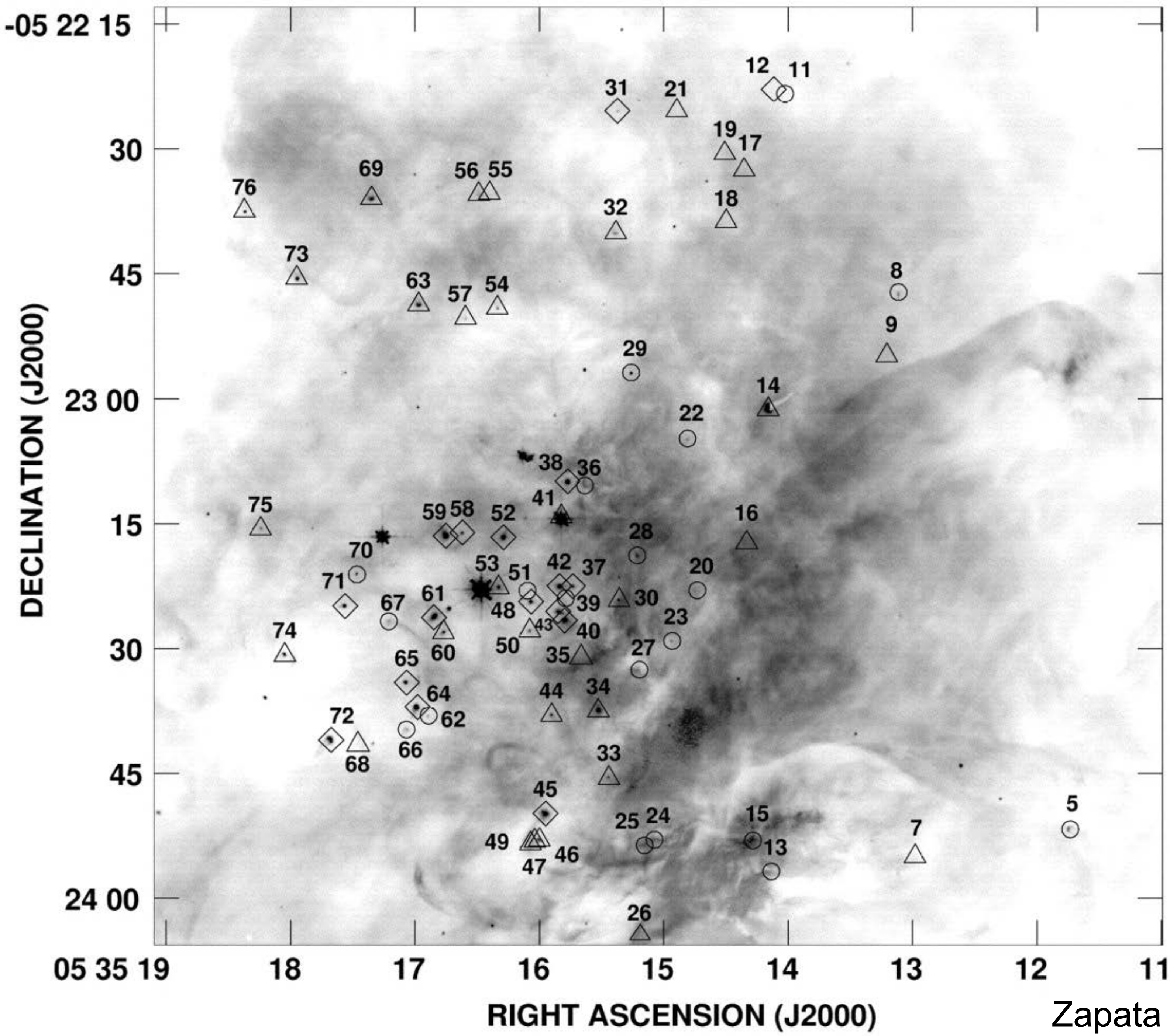
LkHα101 (Osten & Wolk 2009)



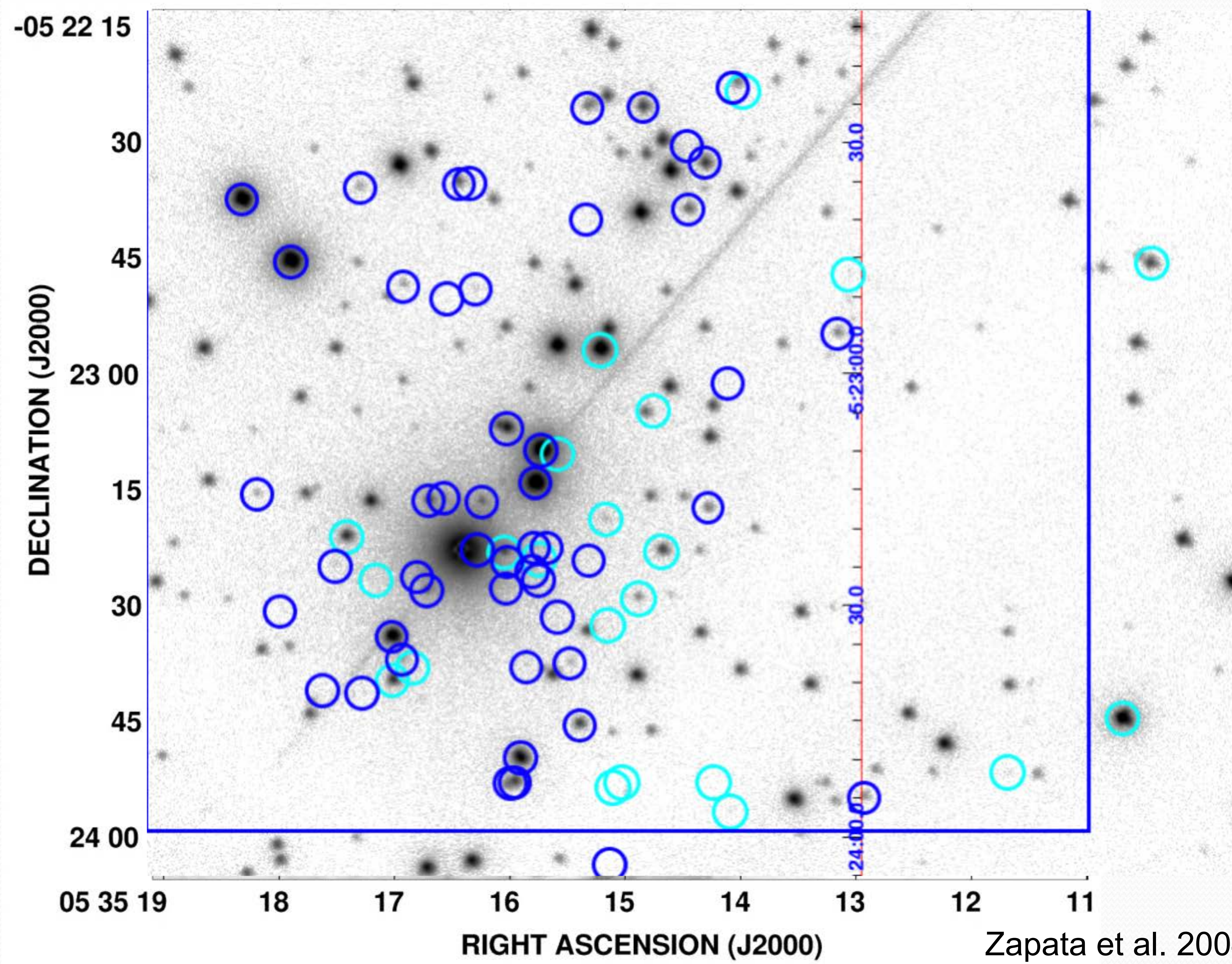
All YSOs with Chandra and VLA detections (5 clusters)



Forbrich, Osten & Wolk 2011



Zapata et al. 2004

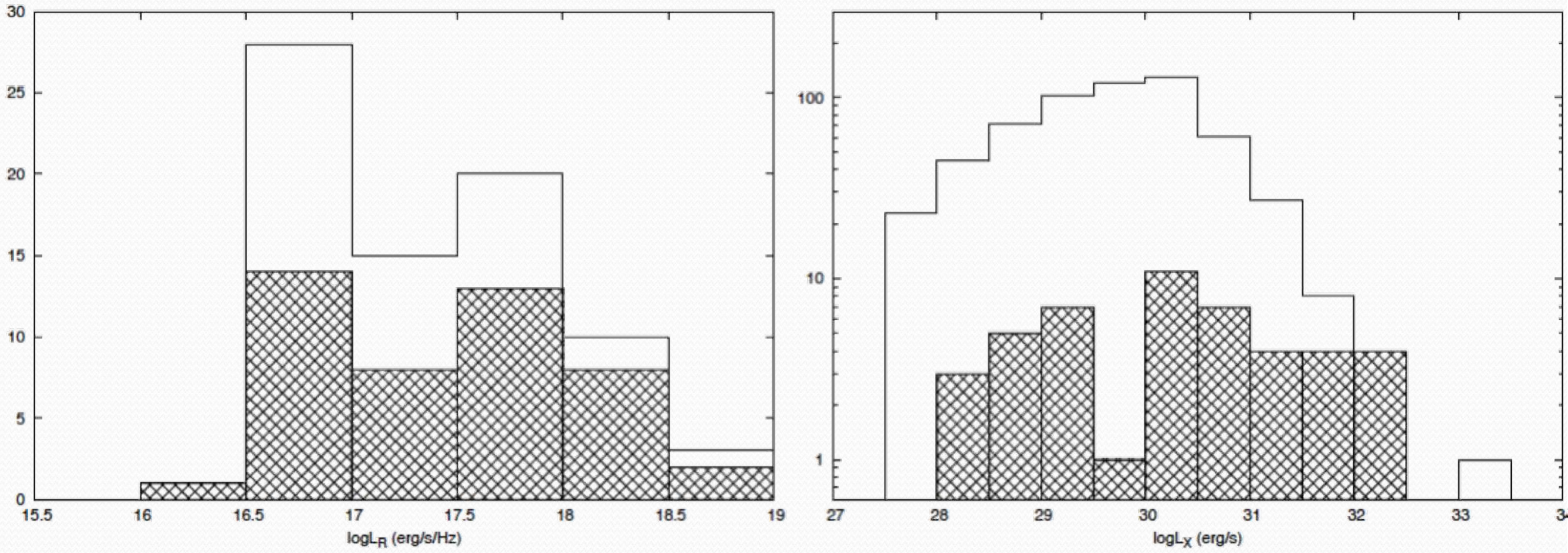


Zapata et al. 2004

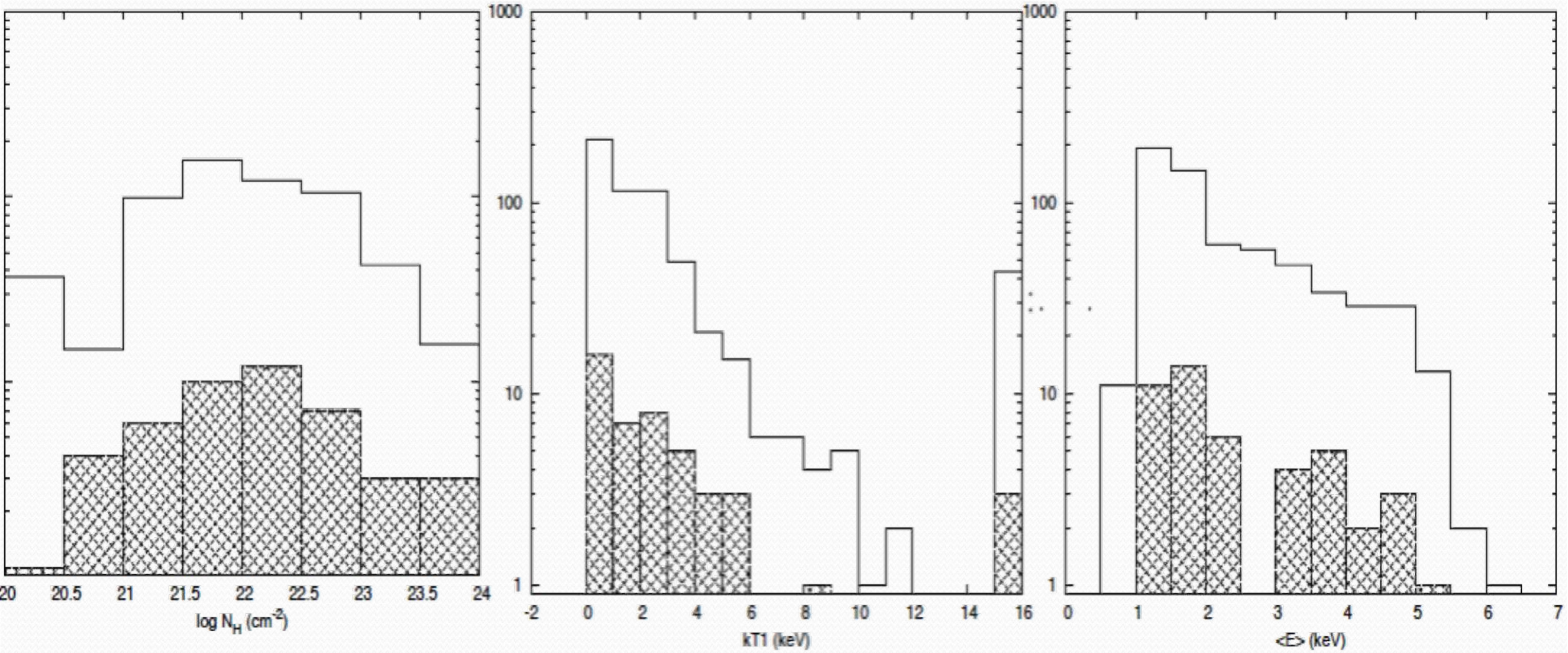
Results

- 70 radio sources were detected in the primary VLA field of the 3.6 cm observations
  - rms noise ~0.05 mJy → but high free-free background
  - 11 known class I/II YSOs
- 623 X-ray source in that field
  - 850 ks observation sensitive to log L_X~27
  - Note: L_X gives a rough estimate of stellar parameters
- Only 46 detected in both.
  - 5 Class II YSOs
  - 1 Class I

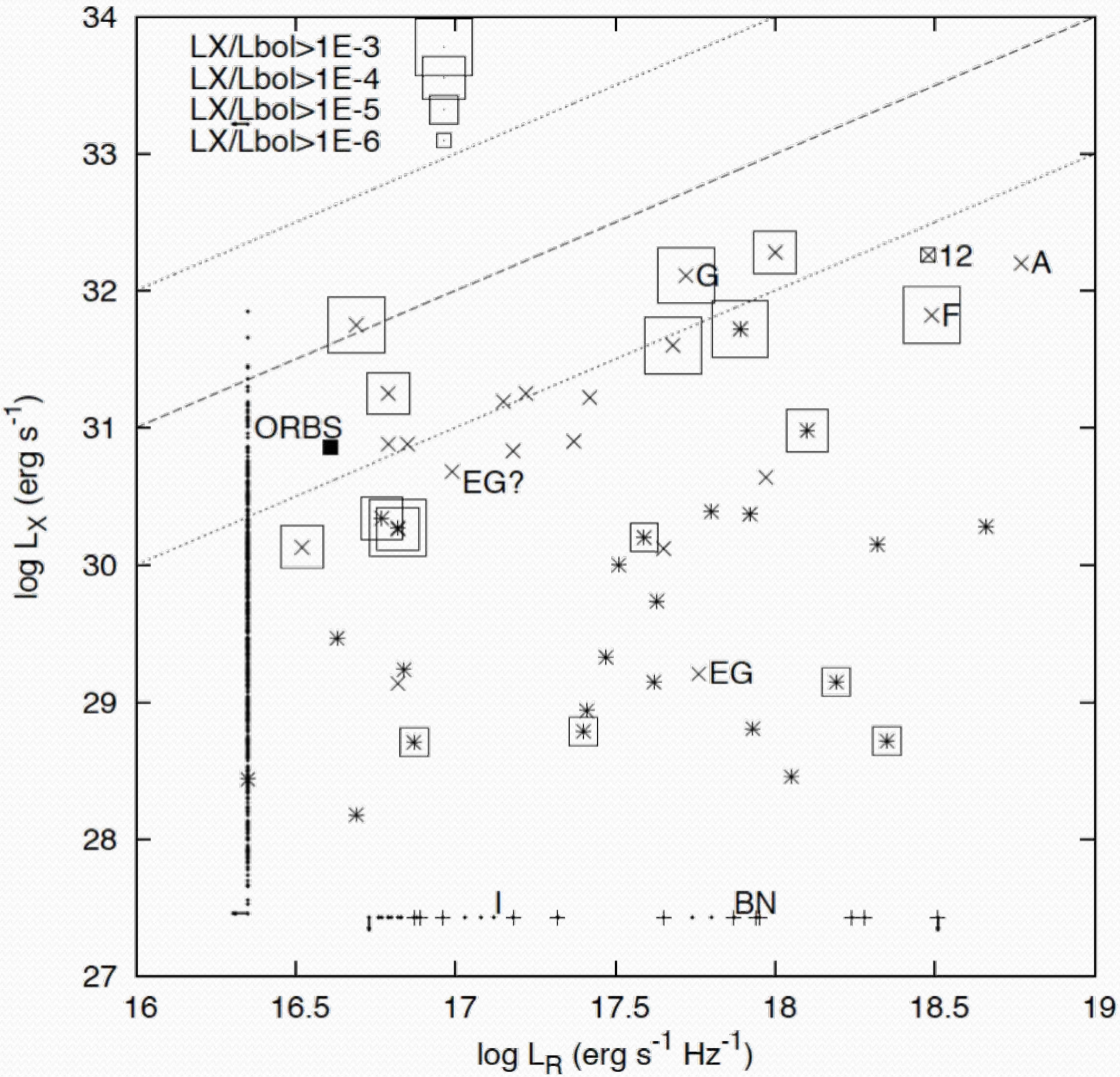
X-ray and Radio detection rates



(Lack of) Impact of X-ray parameters on radio detection



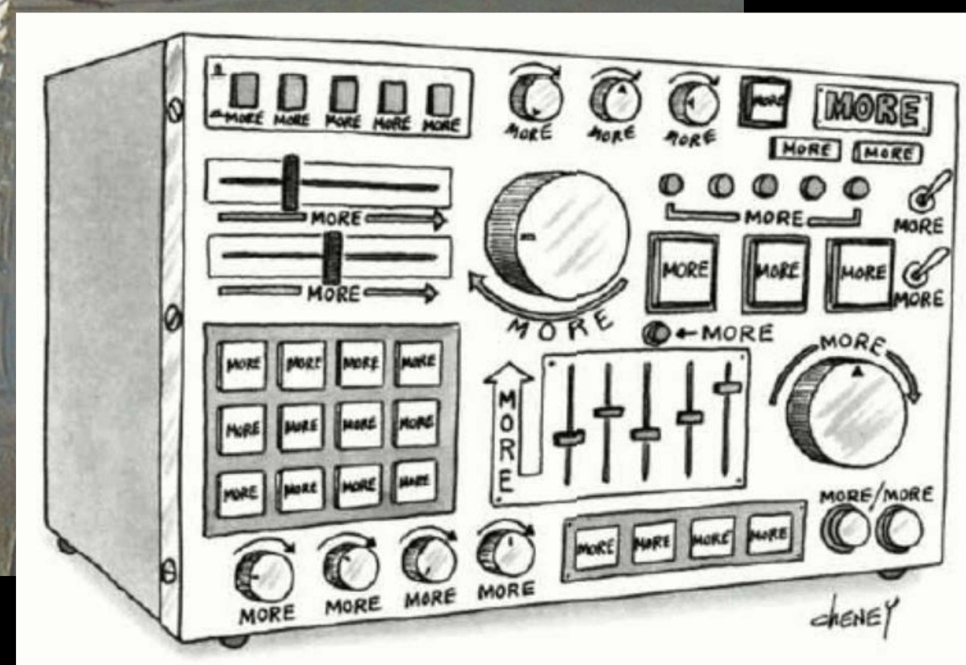
L_X vs. L_R diagram for the ONC



What do we know?

- We usually don't see YSOs in the radio, but when we do they are over bright
- We don't know:
  - Their YSO Class
  - Radio Spectrum
- The radio signal is sometimes gyrosynchrotron
  - GMR A, CRA IRS 5
  - Other sources could be too, **not enough S/N**
  - Optical depth could delay one of the signals
- Could be thermal free-free
  - Free-free should be bright.
  - 26/15 ARE proplyds
  - But most (109) proplyds are not detected and most radio sources are not proplyds.

VLA ⟶ JVLA

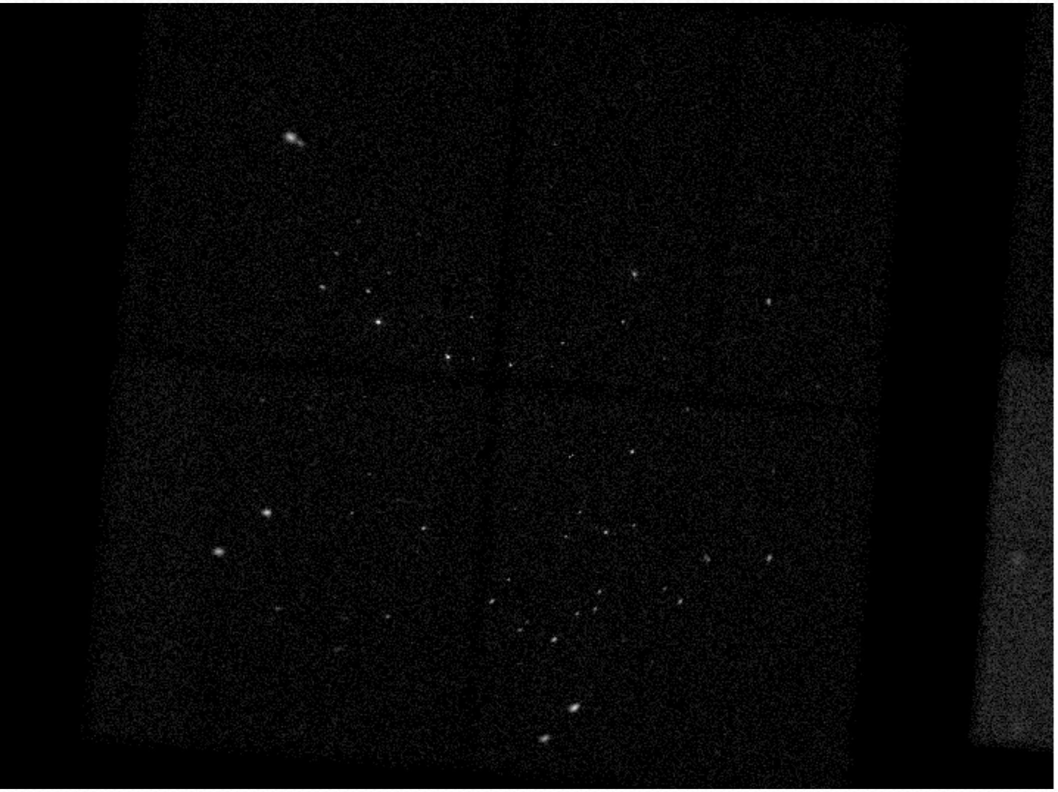


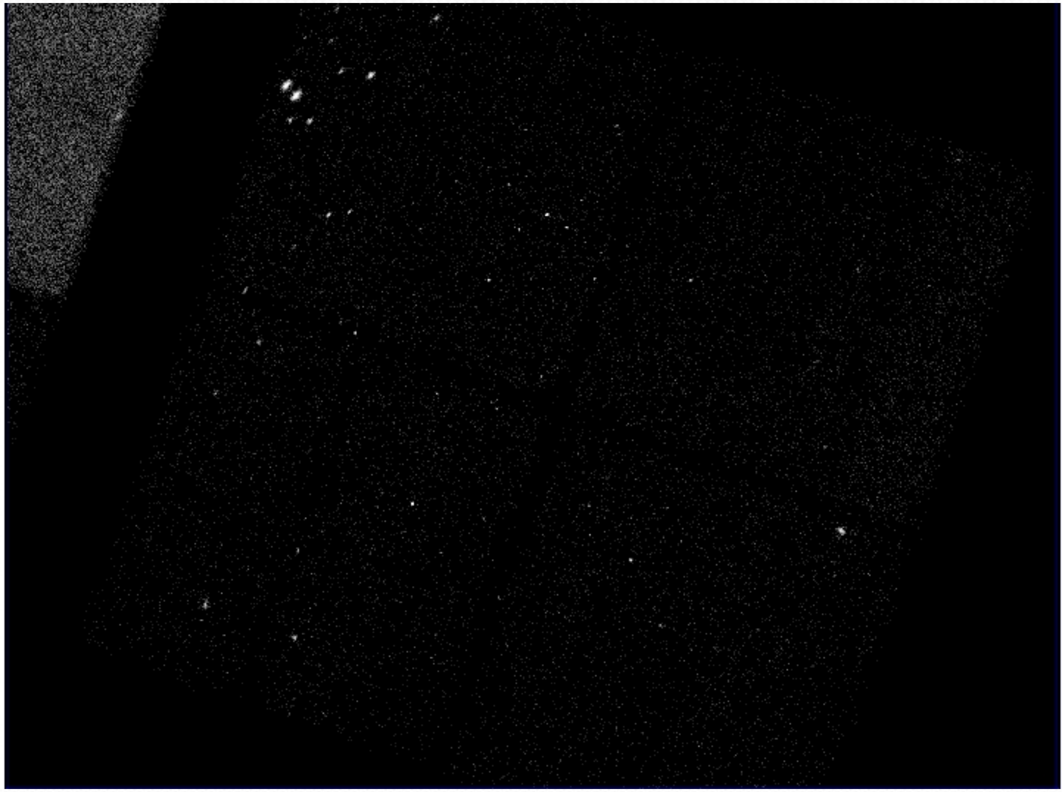
The New Yorker

Conclusions

1. With Chandra and XMM-*Newton*, the number of X-ray detected YSOs has gone through the roof. Yet, the number of radio-detected YSOs has barely changed.
2. Observations (simultaneous) of the ONC, (NGC 1333, Lk Hα101, CrA, ρ Oph and IC 348) are limited by the radio sensitivity; only a very low detection fraction of YSOs in both bands is found.
3. The NRAO Very Large Array is history – it is right now being transformed into the Jansky Very Large Array, a very different instrument (much better to prove the kind of emission!).

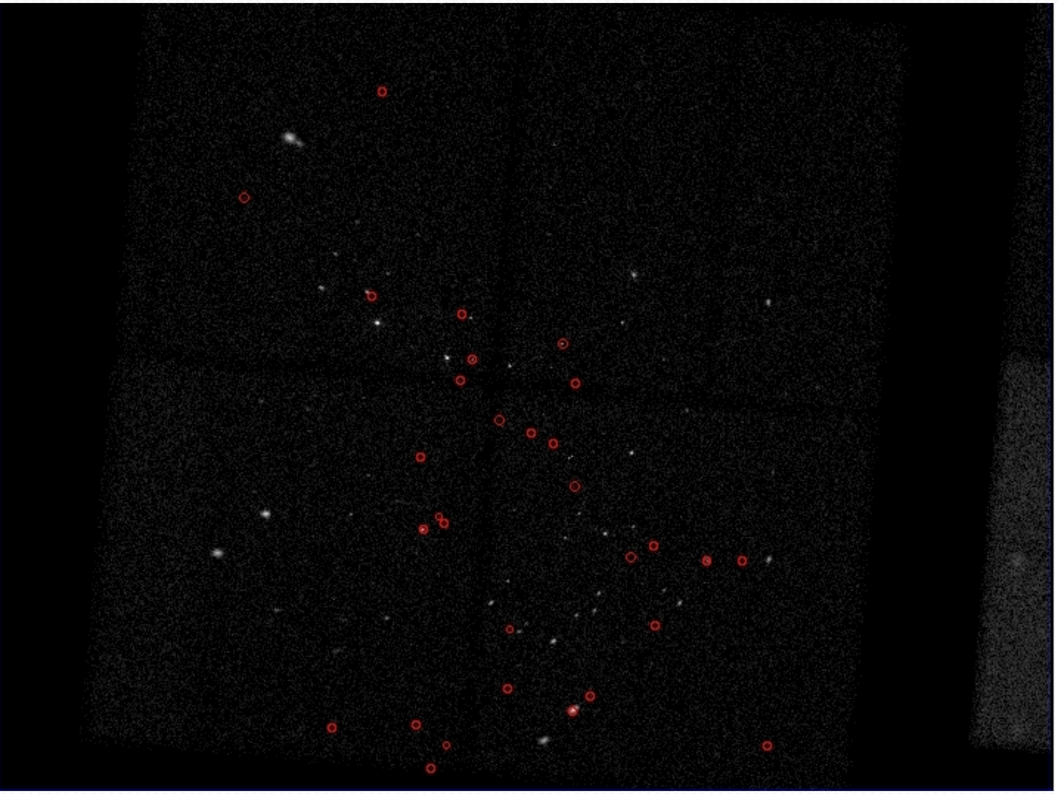
NGC 1333 & IC 348

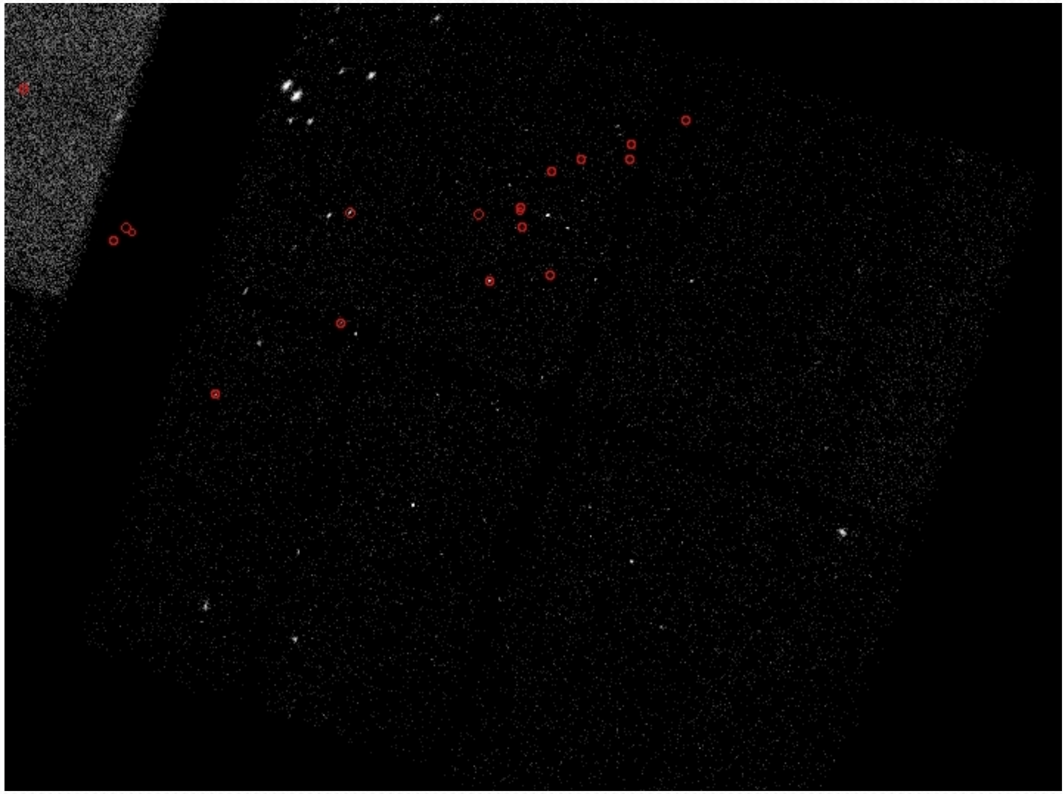




NGC 1333: 2x 40 ksec Chandra + 22h VLA (X & C in subarrays)
IC 348: 2x 40 ksec Chandra + 22h VLA (X & C in subarrays)

NGC 1333 & IC 348



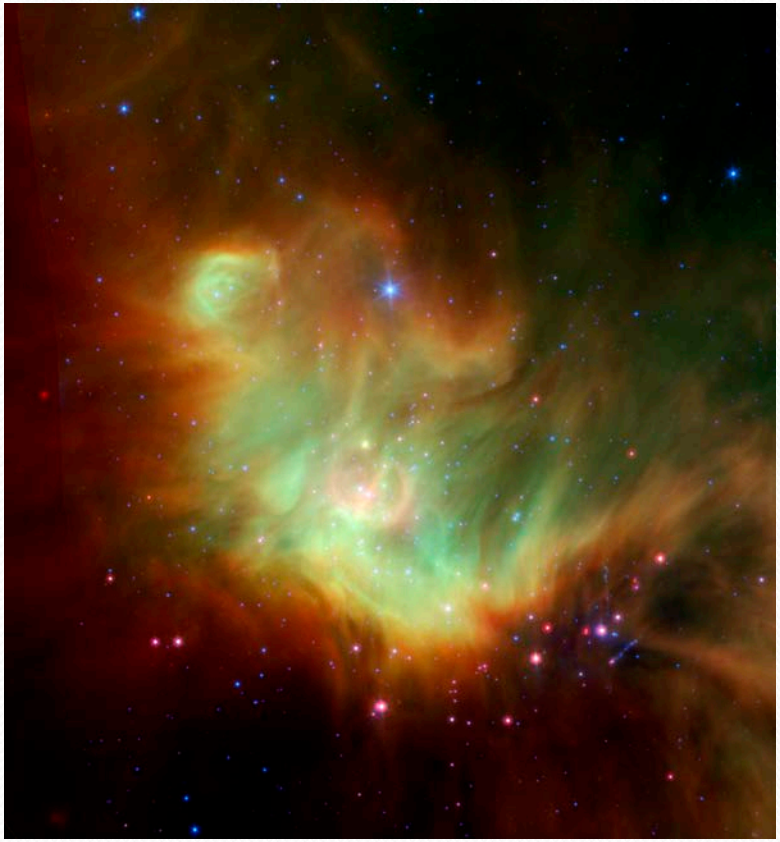


Class I sources (Gutermuth et al. 2008, Muench et al. 2007)

What about other clusters?

ρ Oph (Gagné et al. 2004), LkHα101 (Osten & Wolk 2009)

Class I protostars first detected in X-rays *and* radio in CrA.
→ try even more prominent (and compact) star-forming regions



IC 348

NGC 1333

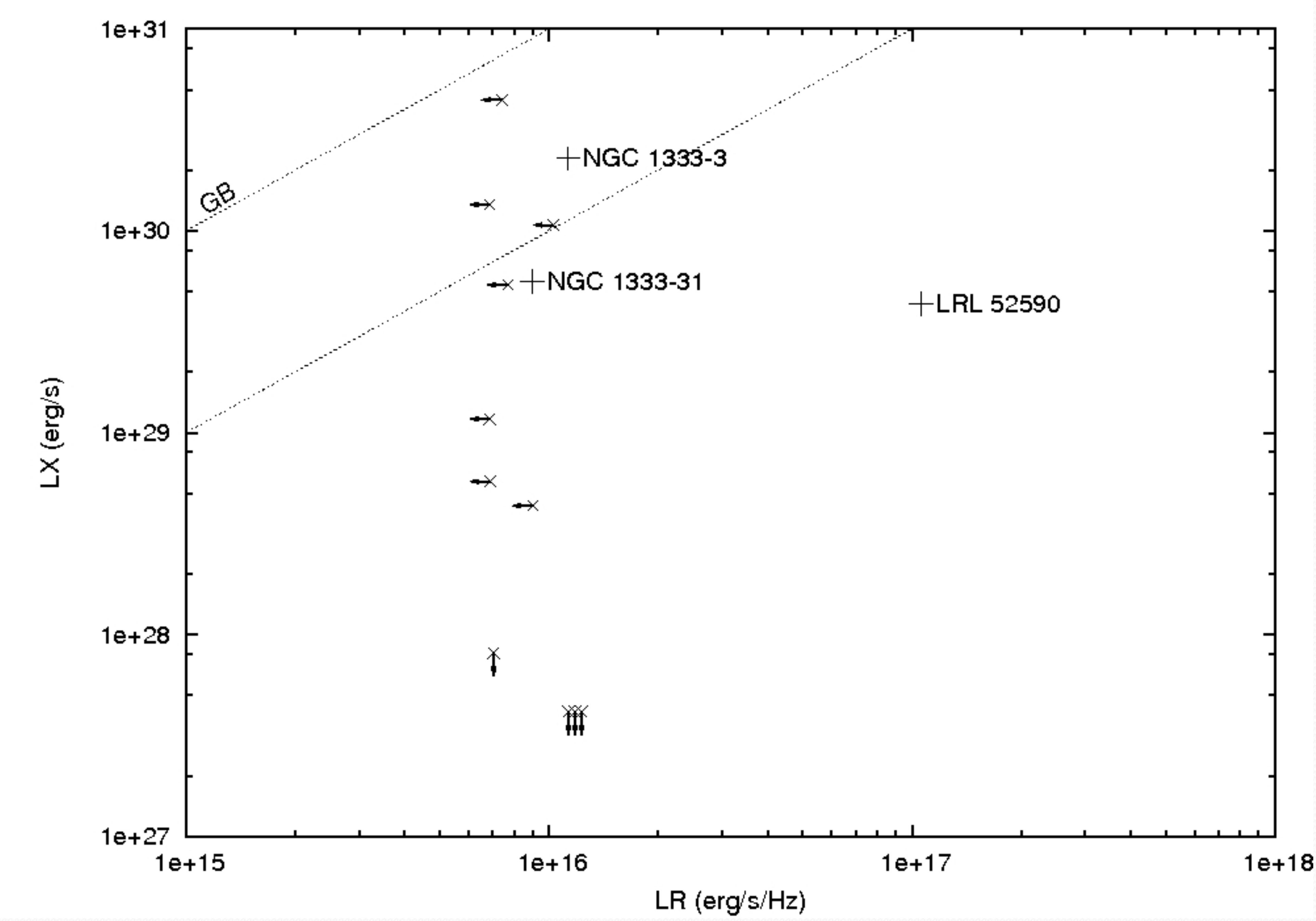
Developments since 1999

1) With Chandra and XMM-*Newton*, the number of X-ray detected YSOs has gone through the roof. Yet, the number of radio-detected YSOs has barely changed.

2) The (still growing) legacy of the Spitzer Space Telescope has provided us with a consistent roadmap to look for YSOs. We now Know much better where to look.

3) The NRAO Very Large Array is history – it is right now being transformed into the Expanded Very Large Array, a very different instrument.

All Class I sources in VLA FOV



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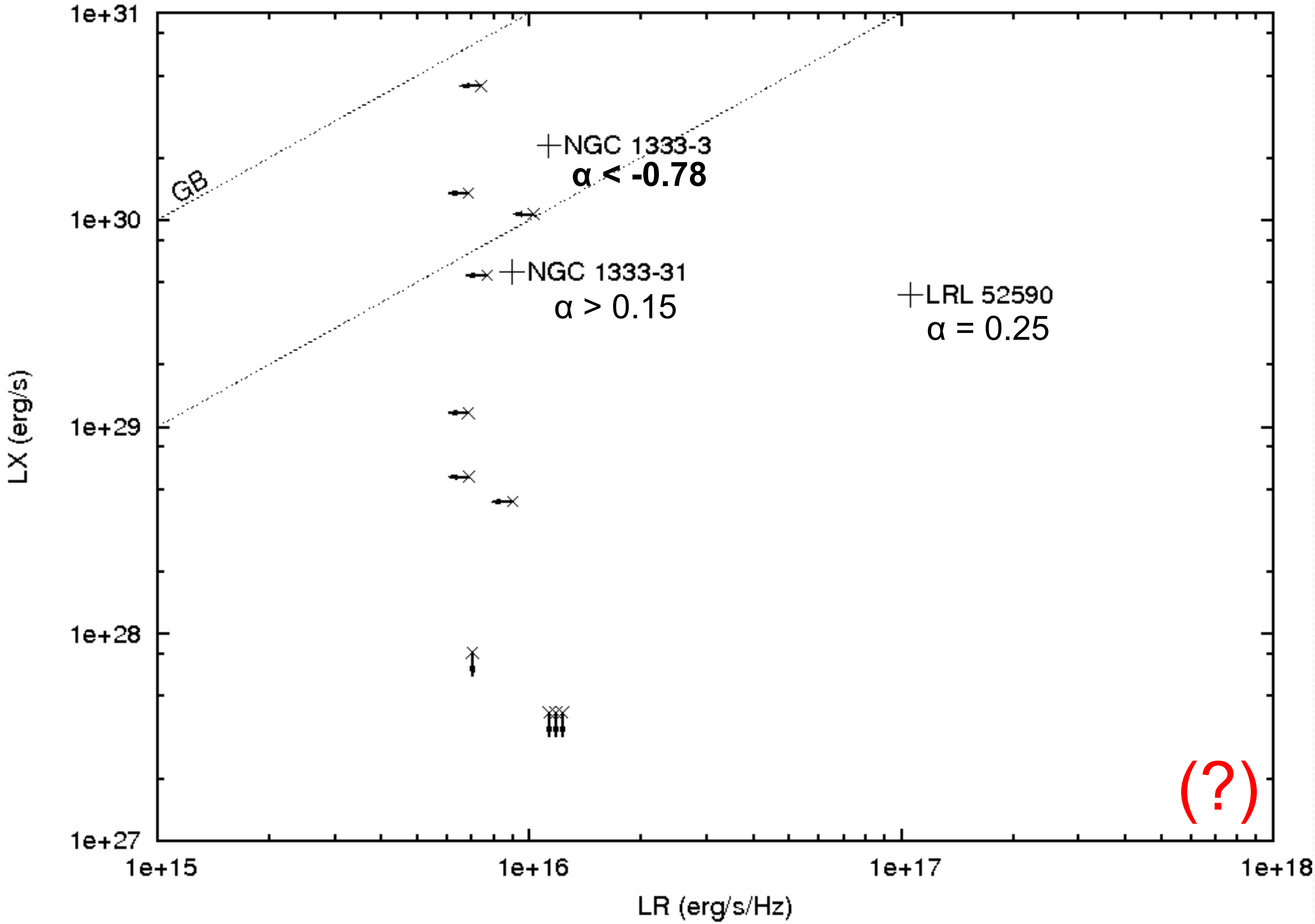
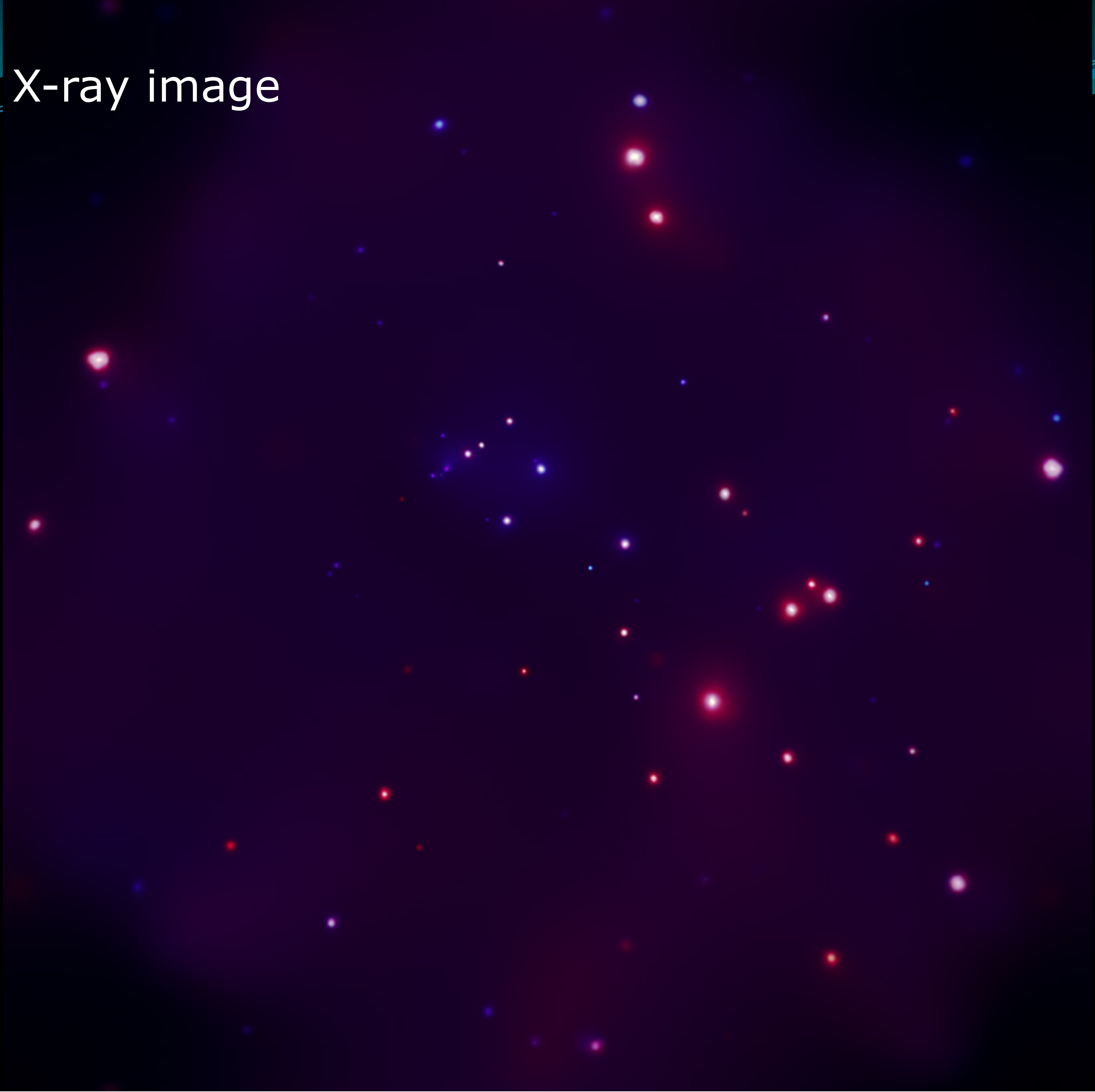


X-ray image



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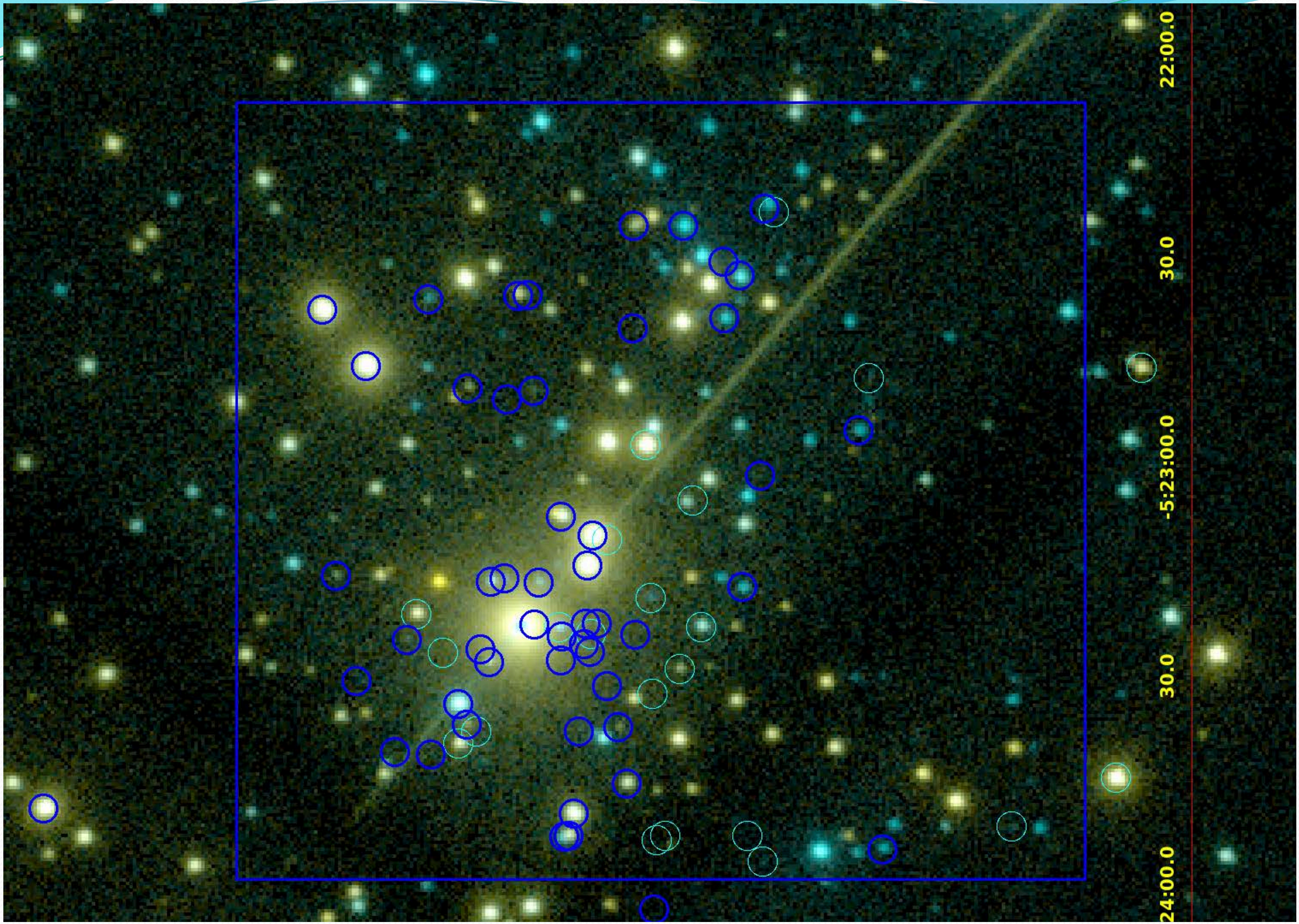
22:00.0
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-5:23:00.0
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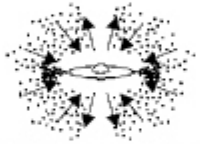
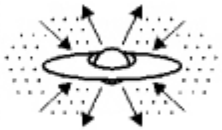
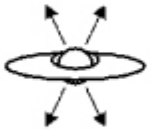
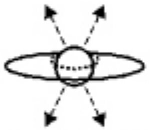
Properties	*Infalling Protostar*	*Evolved Protostar*	*Classical T Tauri Star*	*Weak-lined T Tauri Star*	*Main Sequence Star*
Sketch					
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Disk	Yes	Thick	Thick	Thin or Non-existent	Possible Planetary System
X-ray	?	Yes	Strong	Strong	Weak
Thermal Radio	Yes	Yes	Yes	No	No
Non-Thermal Radio	No	Yes	No ?	Yes	Yes

Feigelson & Montmerle (1999)

EVLA Observations

1) 2 Ghz vs. 100 MHz

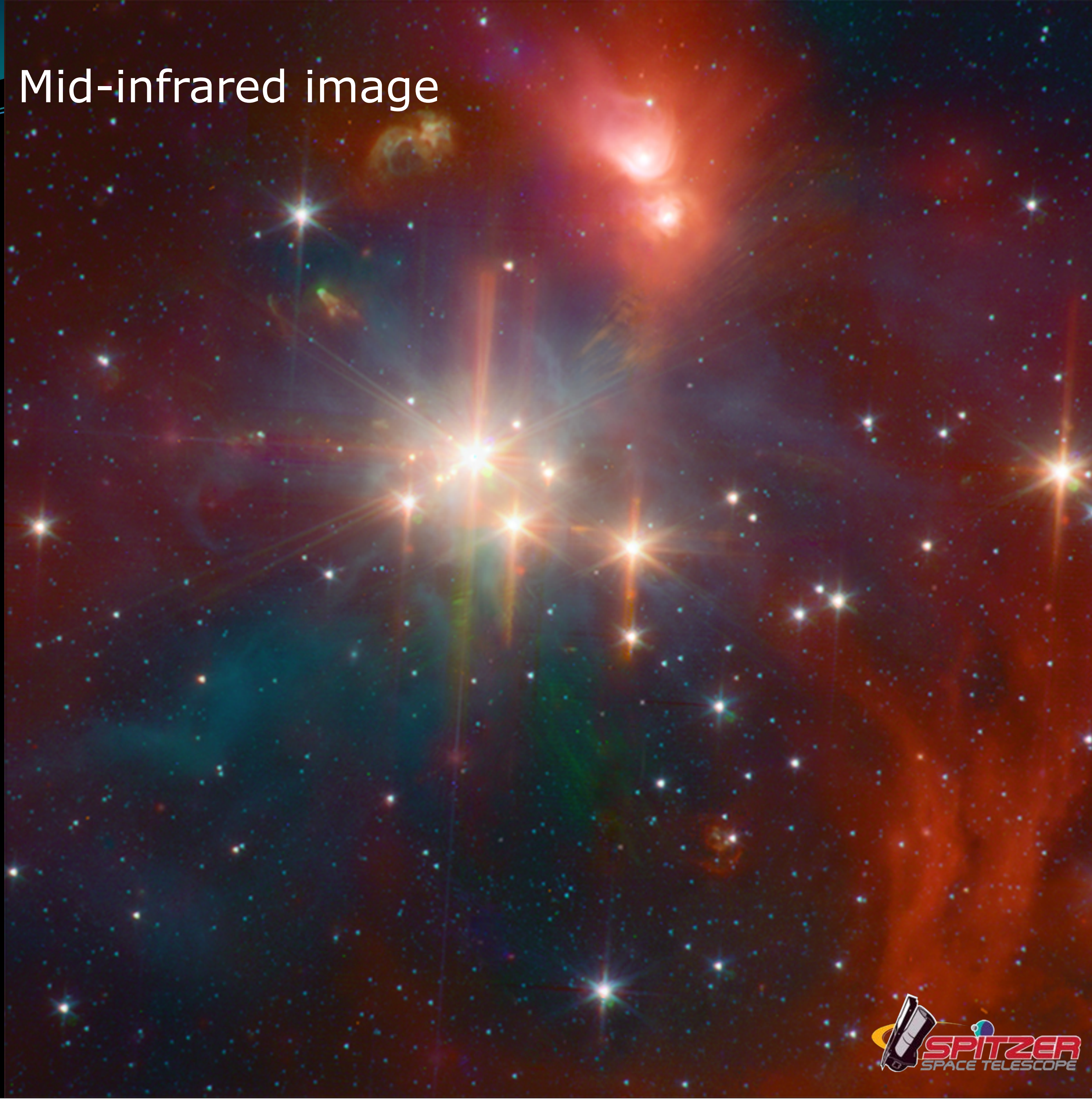
2) 24 hours within one week

3)

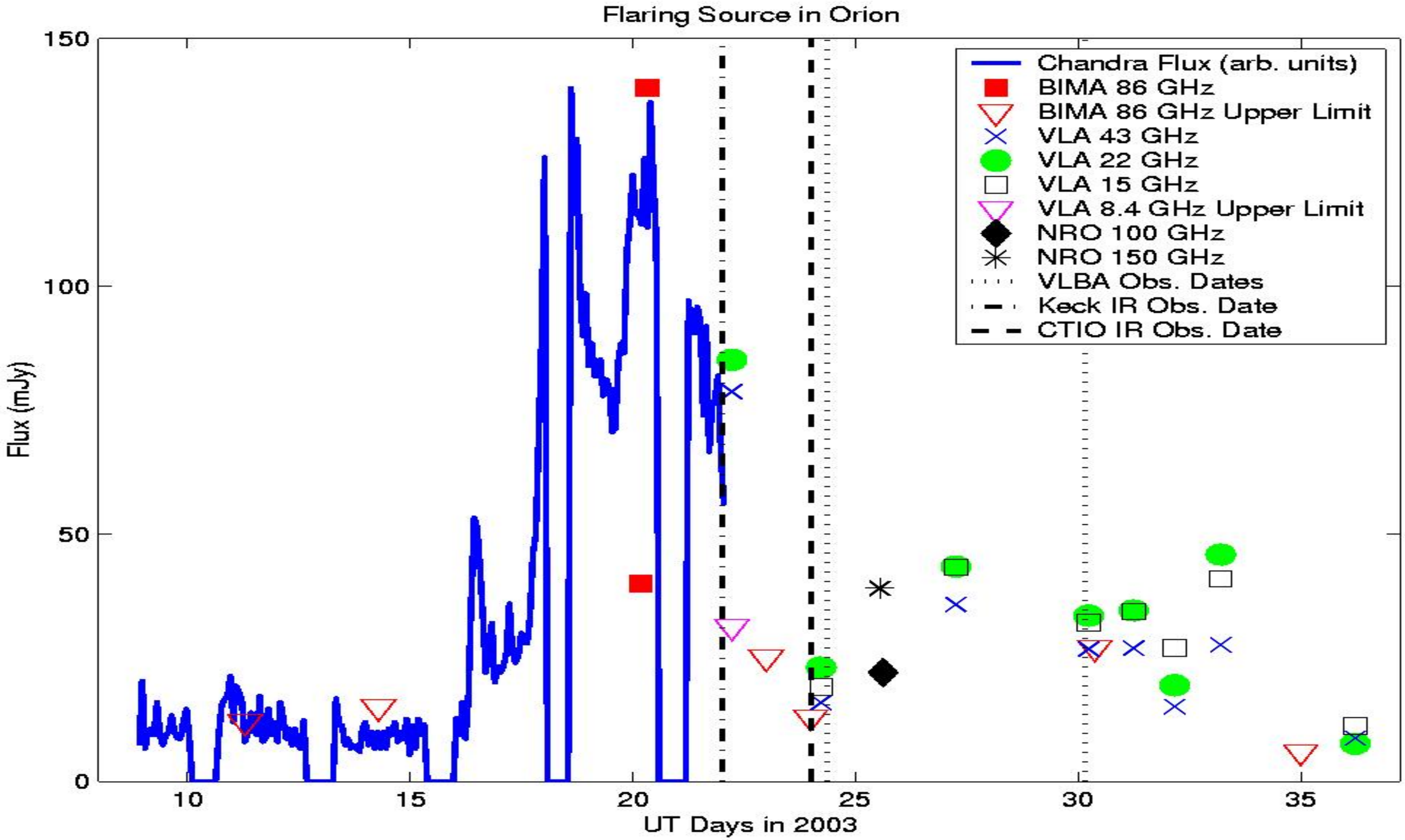
CrA: Optical image

European Southern Observatory

Mid-infrared image



NASA/CXC/CfA/IRAC GTO Team


Flaring Source in Orion
Chandra Flux (arb. units)
BIMA 86 GHz
BIMA 86 GHz Upper Limit
VLA 43 GHz
VLA 22 GHz
VLA 15 GHz
VLA 8.4 GHz Upper Limit
NRO 100 GHz
NRO 150 GHz
VLBA Obs. Dates
Keck IR Obs. Date
CTIO IR Obs. Date
Flux (mJy)
UT Days in 2003
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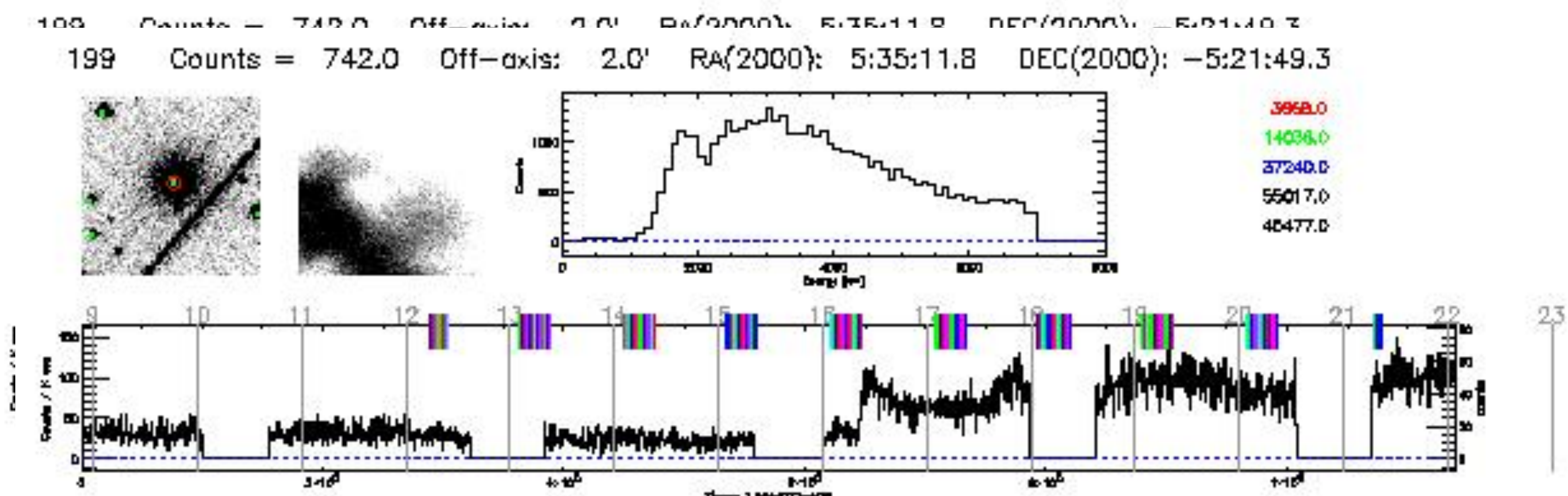
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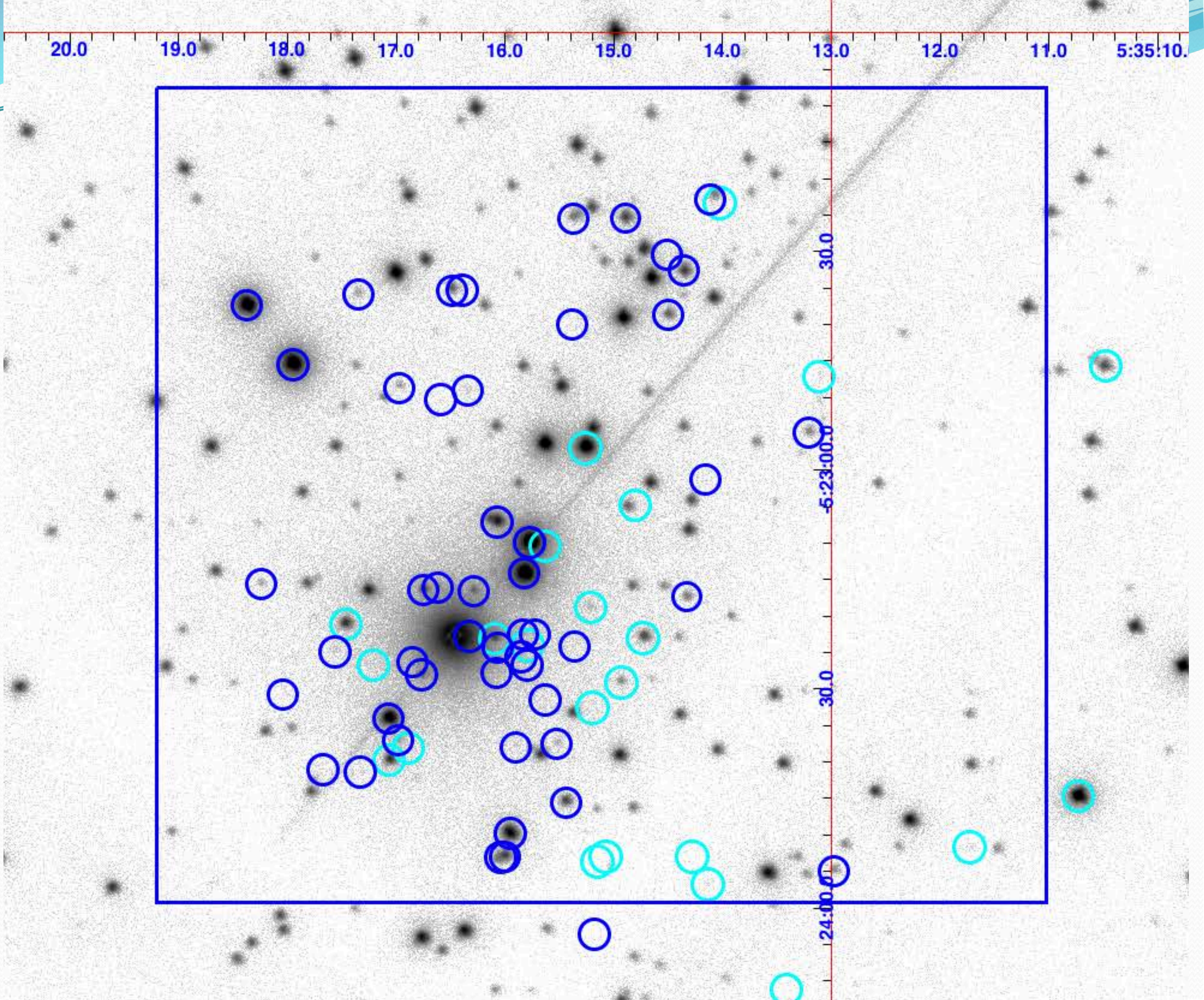
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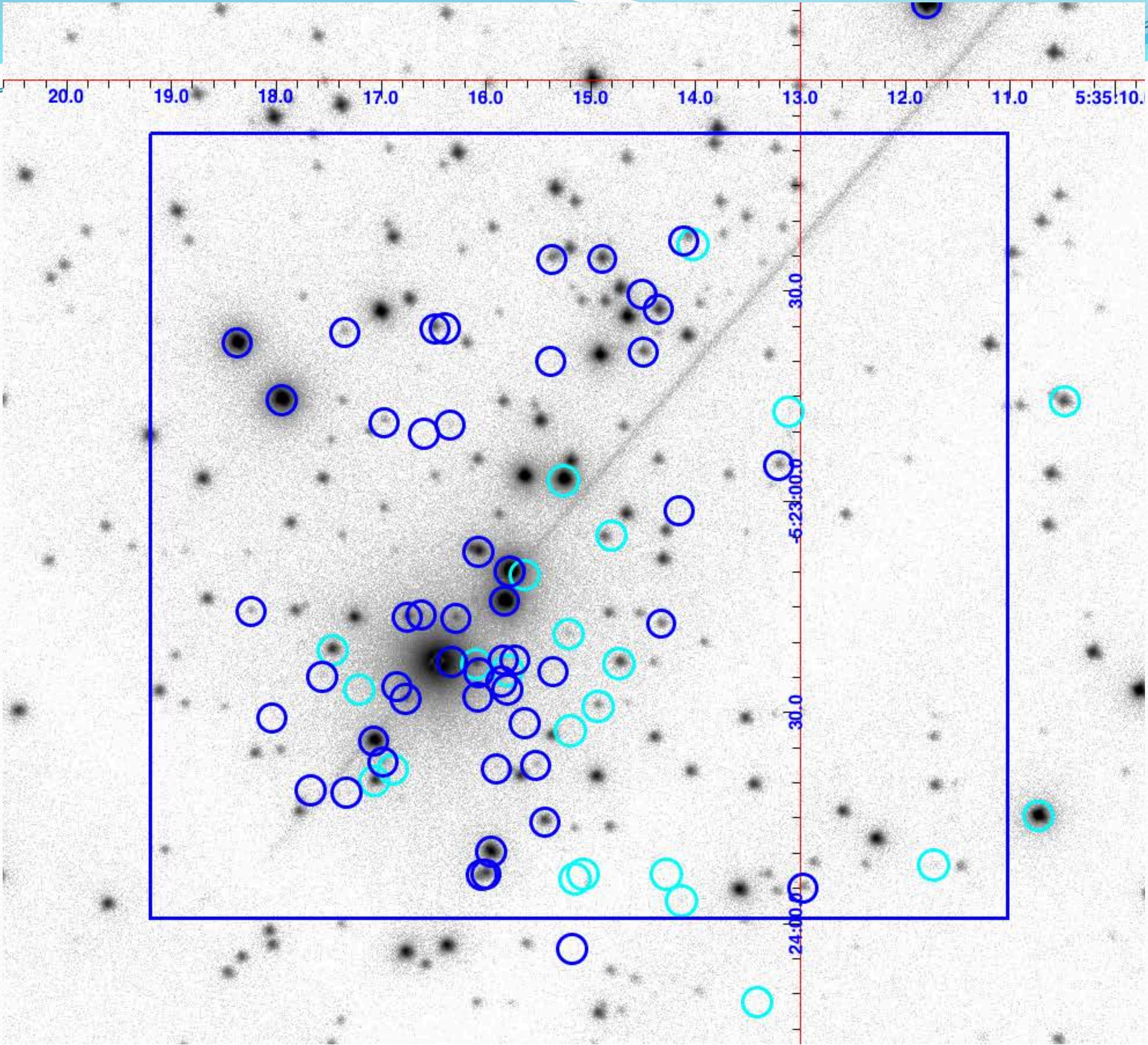
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