X-ray observations of neutron stars and black holes in nearby galaxies

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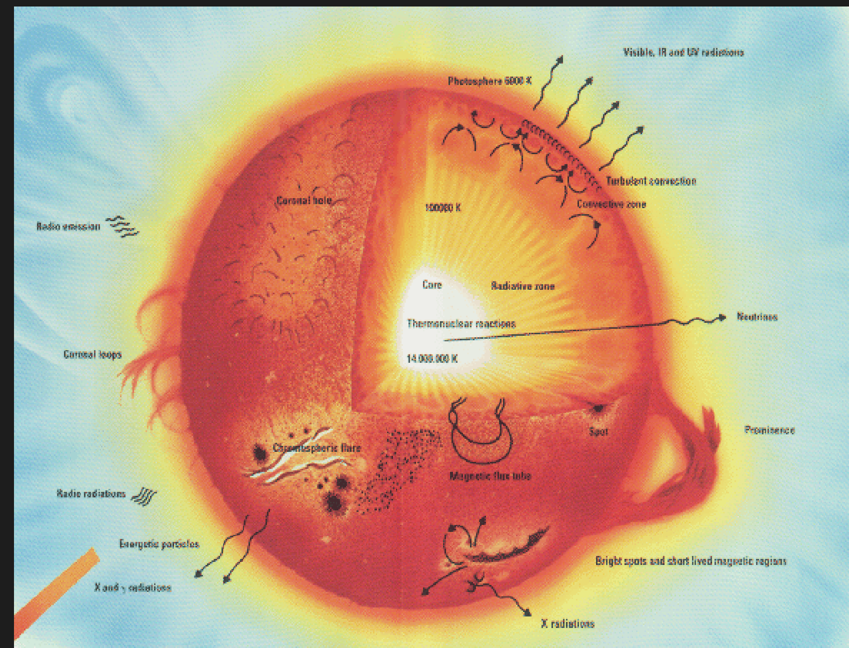
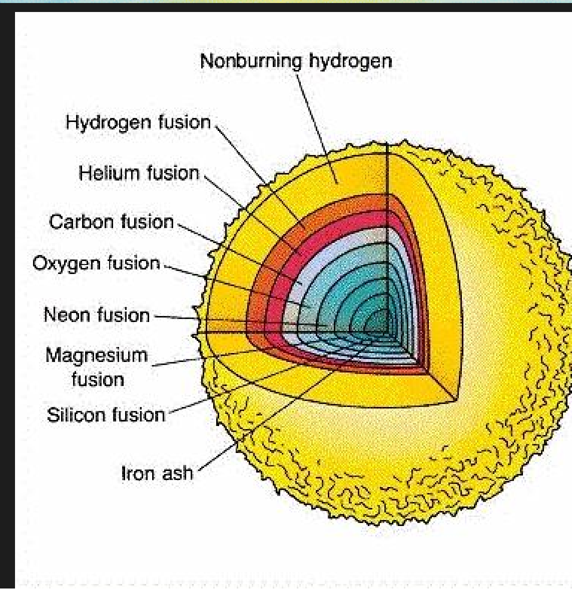
The lives of stars : fighting against gravity

- Defining parameter :
  Mass

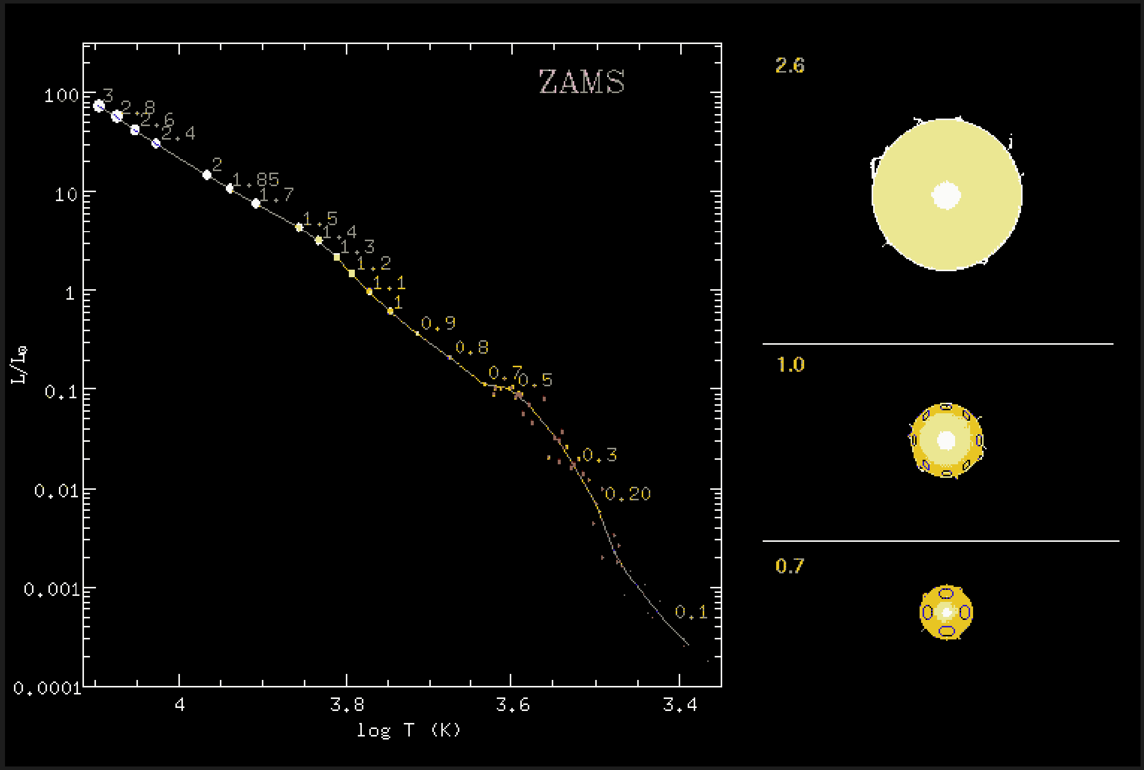
- To avoid implosion stars must generate energy from fusion reactions

- The stages of stars are determined by the type of fuel left: hydrogen, helium, carbon etc





…and then the end



… but, after some time they run out of fuel

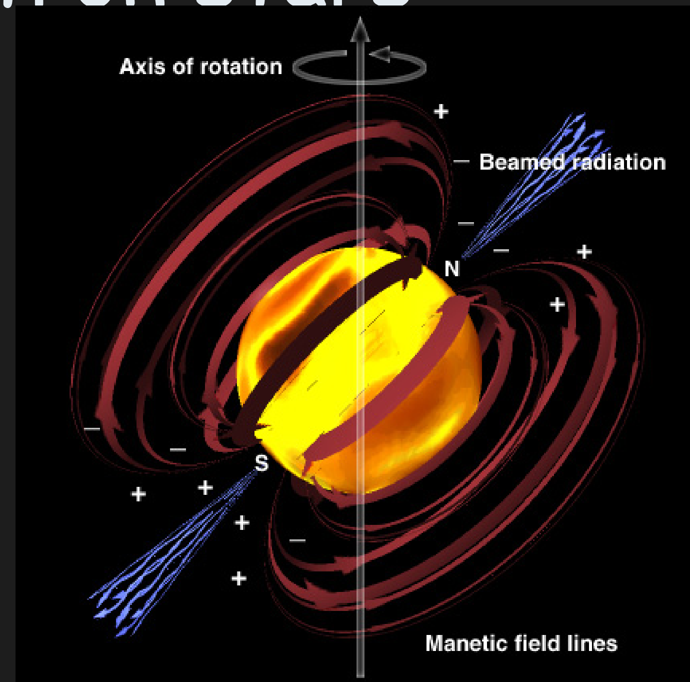
White dwarf ($\lesssim$8 $M_\odot$)

Supernova ($\gtrsim$8 $M_\odot$)

Neutron star (M~1.4-3.0 $M_\odot$)

Black-hole (M >3.0 $M_\odot$)

Black-holes and Neutron stars



- Neutron stars (~$1.4 M_\odot$) :
  Pulsars (magnetized NS)
  Non-magnetized NS

- "Stellar" Black-holes (1.4 - ~$20 M_\odot$)

- "Supermassive" Black-holes (>10^6 $M_\odot$)

Some numbers :

	Mass	Radius	Temp.	Density	Rotation
	M	km	K	ton/cm^3	s^{-1}
White Dwarves :	<1.4	5×10^3	10^4-10^5	1.0	
Neutron stars :	1.4 -3	10-20	~10^7	2×10^8	10^{-3}-10^3
Black holes :	>3	>10	10^5-10^7	inf	?
Sun :	1	7×10^3	5700	1.4×10^{-6}	27 days

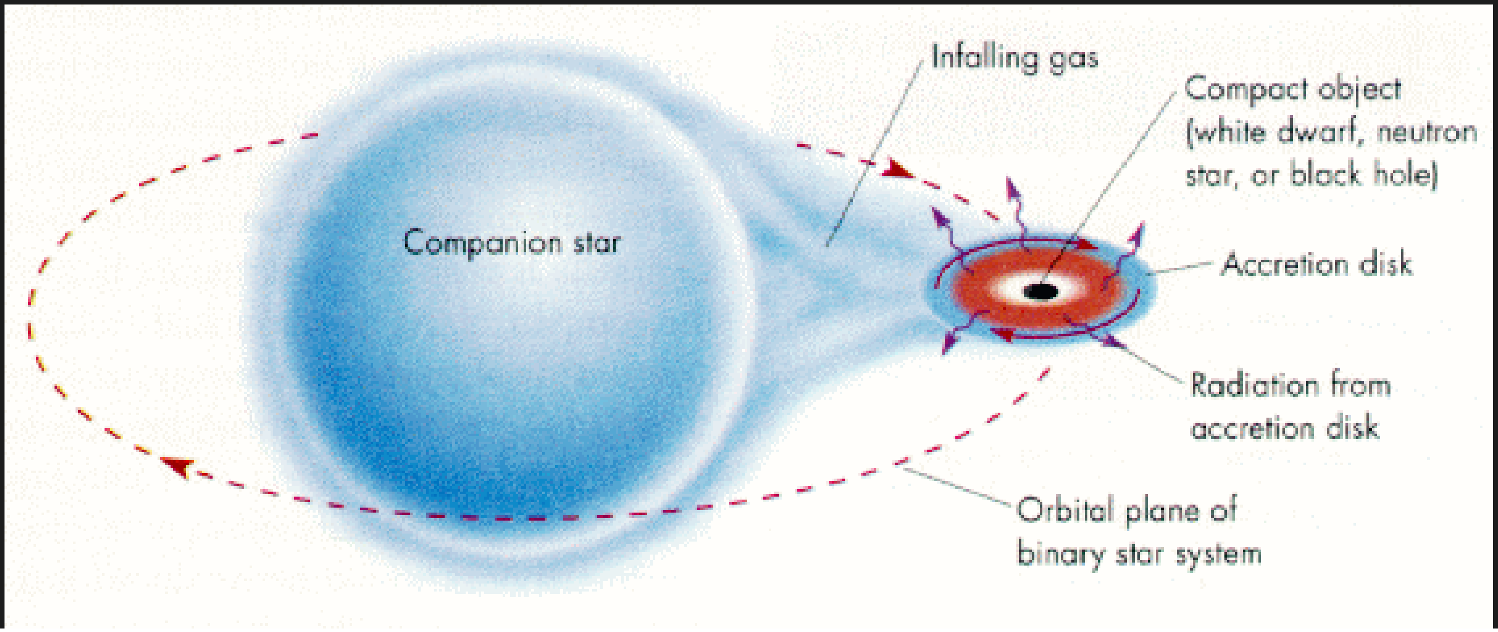
How do we find them

- Accretion !

  binary stars (X-ray binaries)

  interstellar gas (supermassive BH)

When gas falls onto a BH/NS it forms a rotating accretion disk, like water swirling down the drain.



How do we find them

- **Accretion disks :**

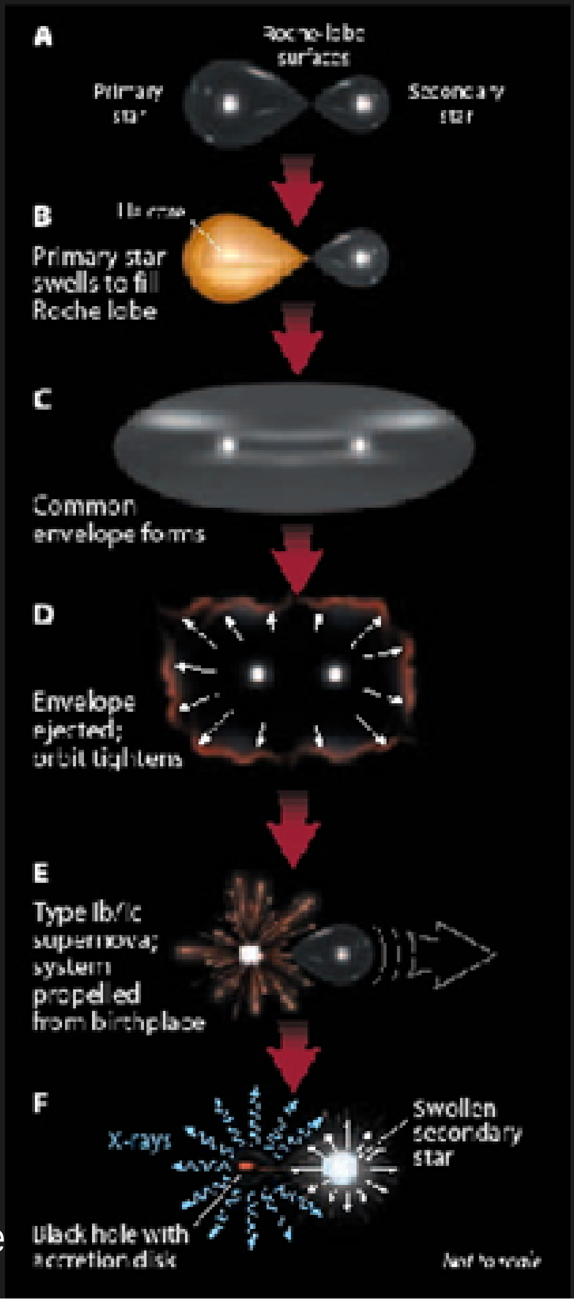
Gravitational energy of gas is converted to thermal energy $L = \frac{GM}{R} mc^2$

For BH, NS $GM/R \sim 0.1$

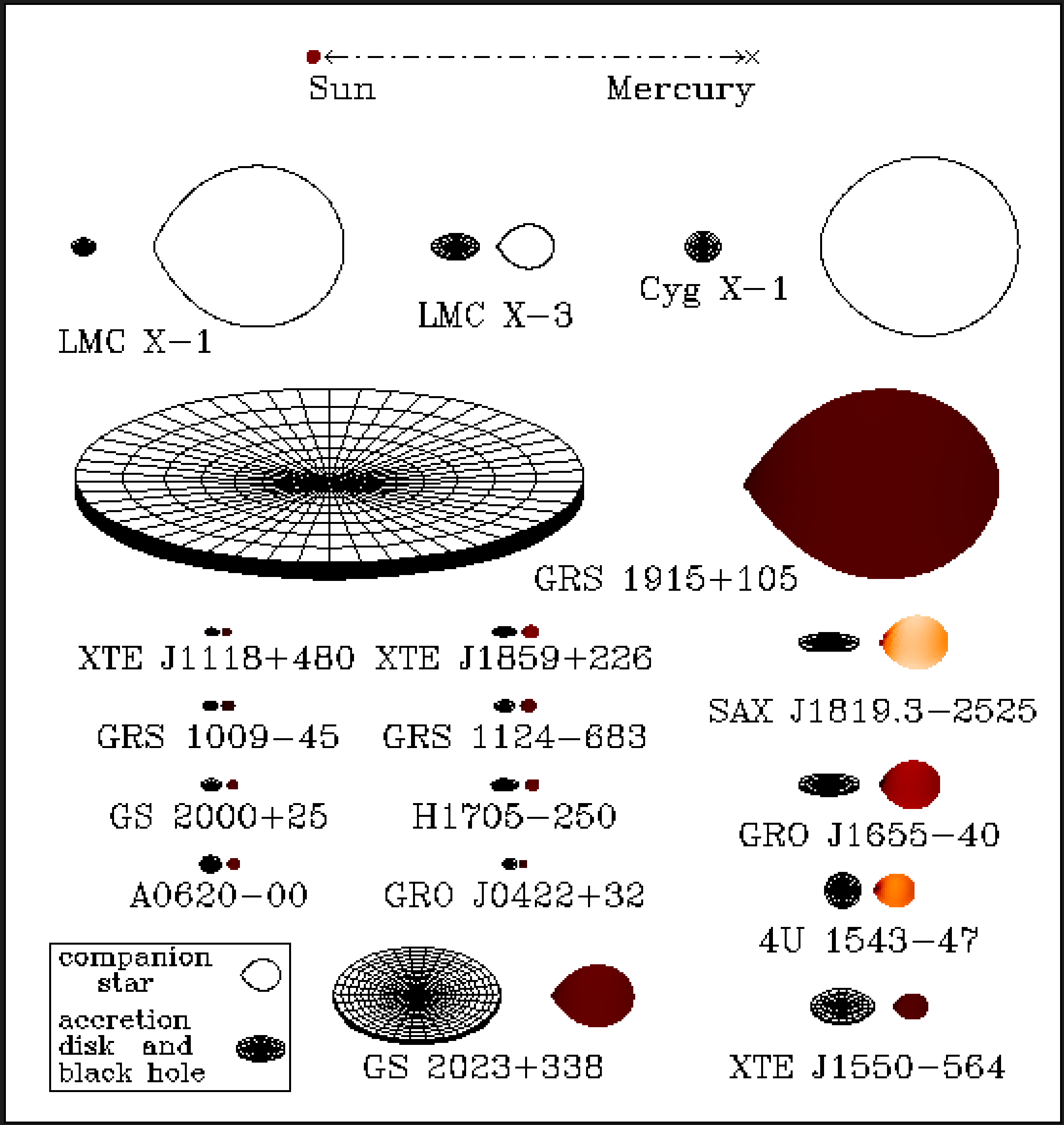
For $M=10\ M_\odot$, $L = 2\times10^{32}$ W $= 10^7\ L_\odot$

$M=1\ M_\odot$, $L = 2\times10^{31}$ W $= 10^6\ L_\odot$

The *complicated* lives of *binary* stars



Sky & Telescope

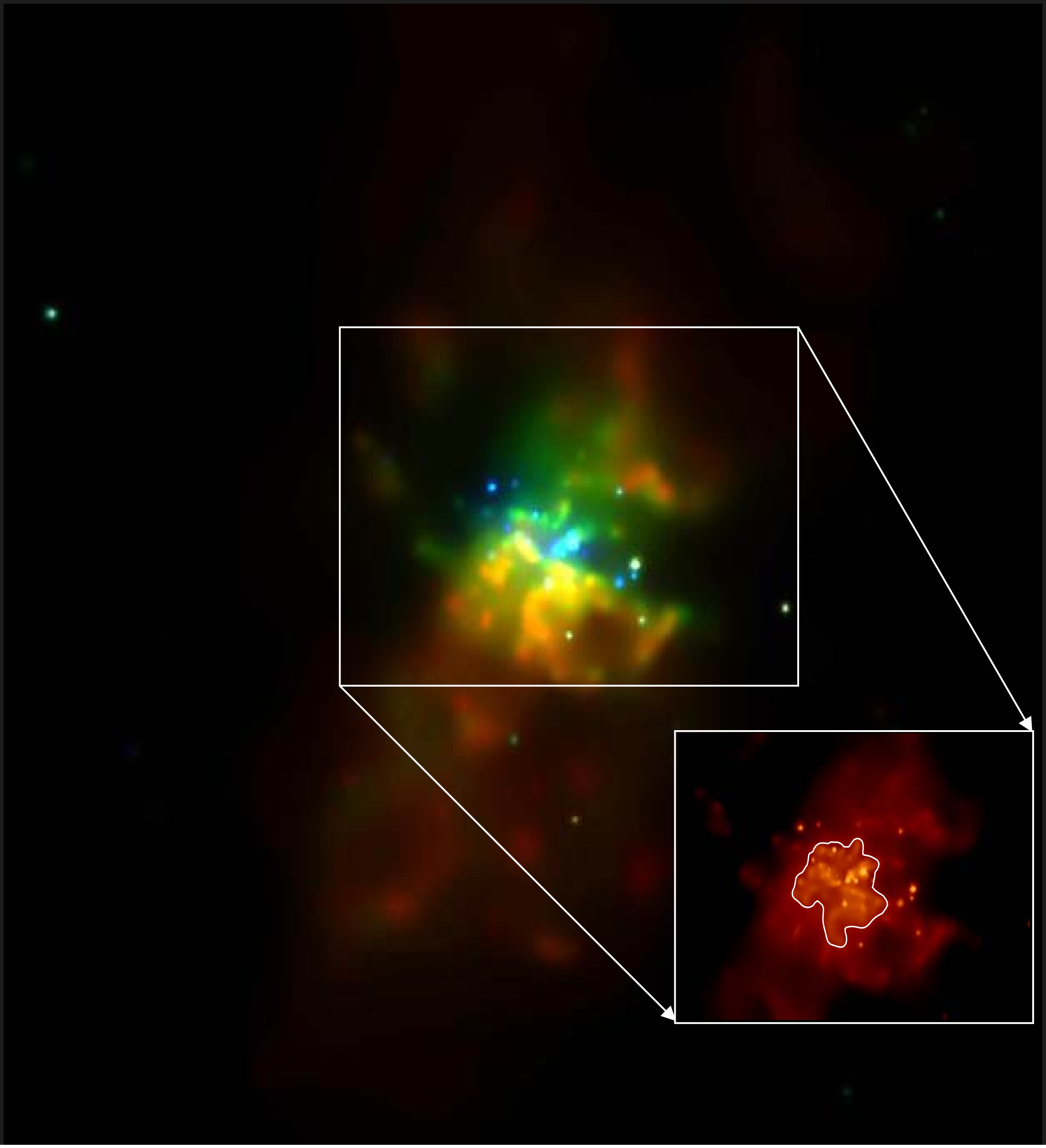


Studying X-ray binaries

- Why bother ?
  - Stellar evolution
  - General relativity (extreme gravity)
  - Extreme physics (very hot, dense matter)
  - Is exciting !

- How ?
  - Find them (detection)
  - Spectroscopy
  - Timing (light curves, power spectra etc)
  - Spatial distribution

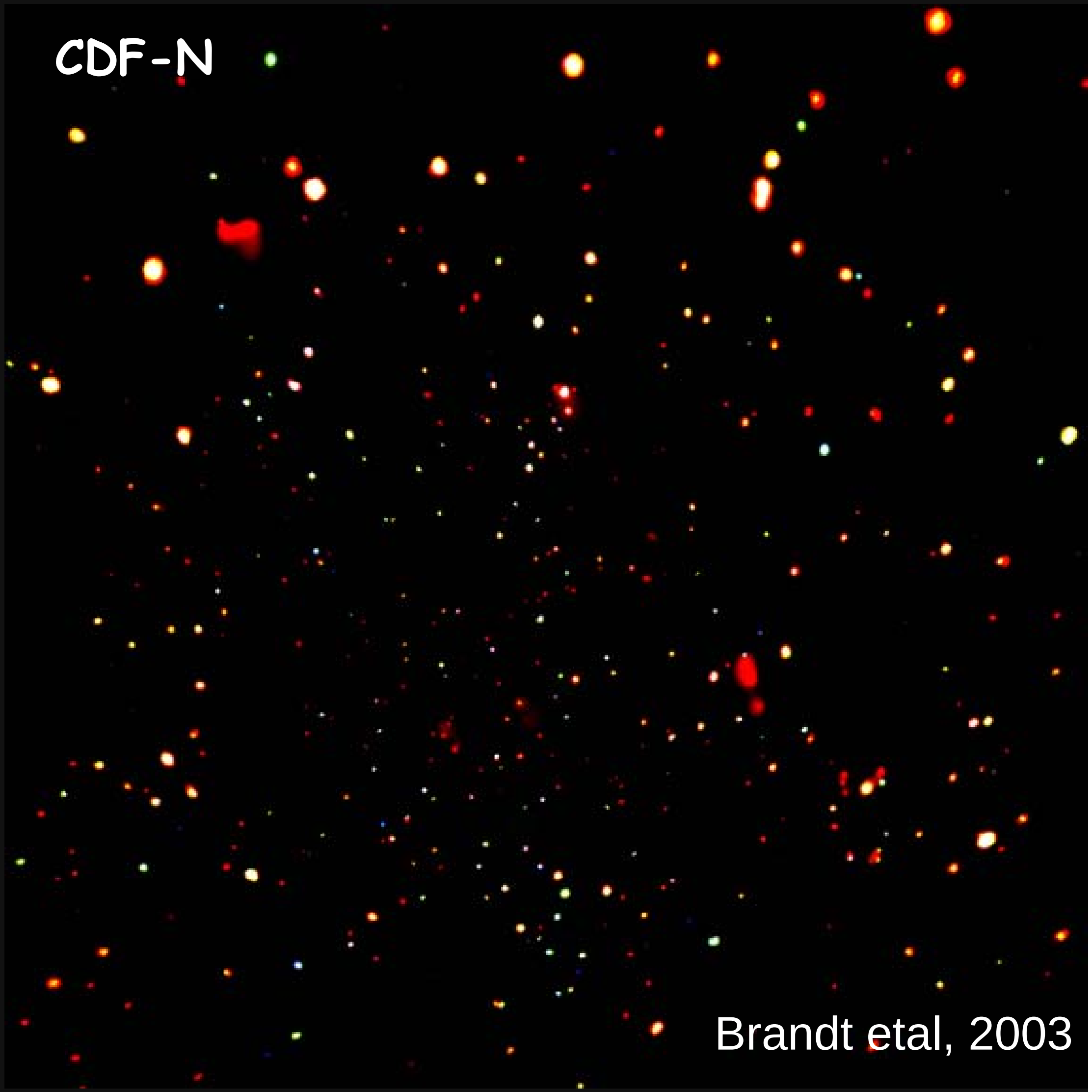
Detection



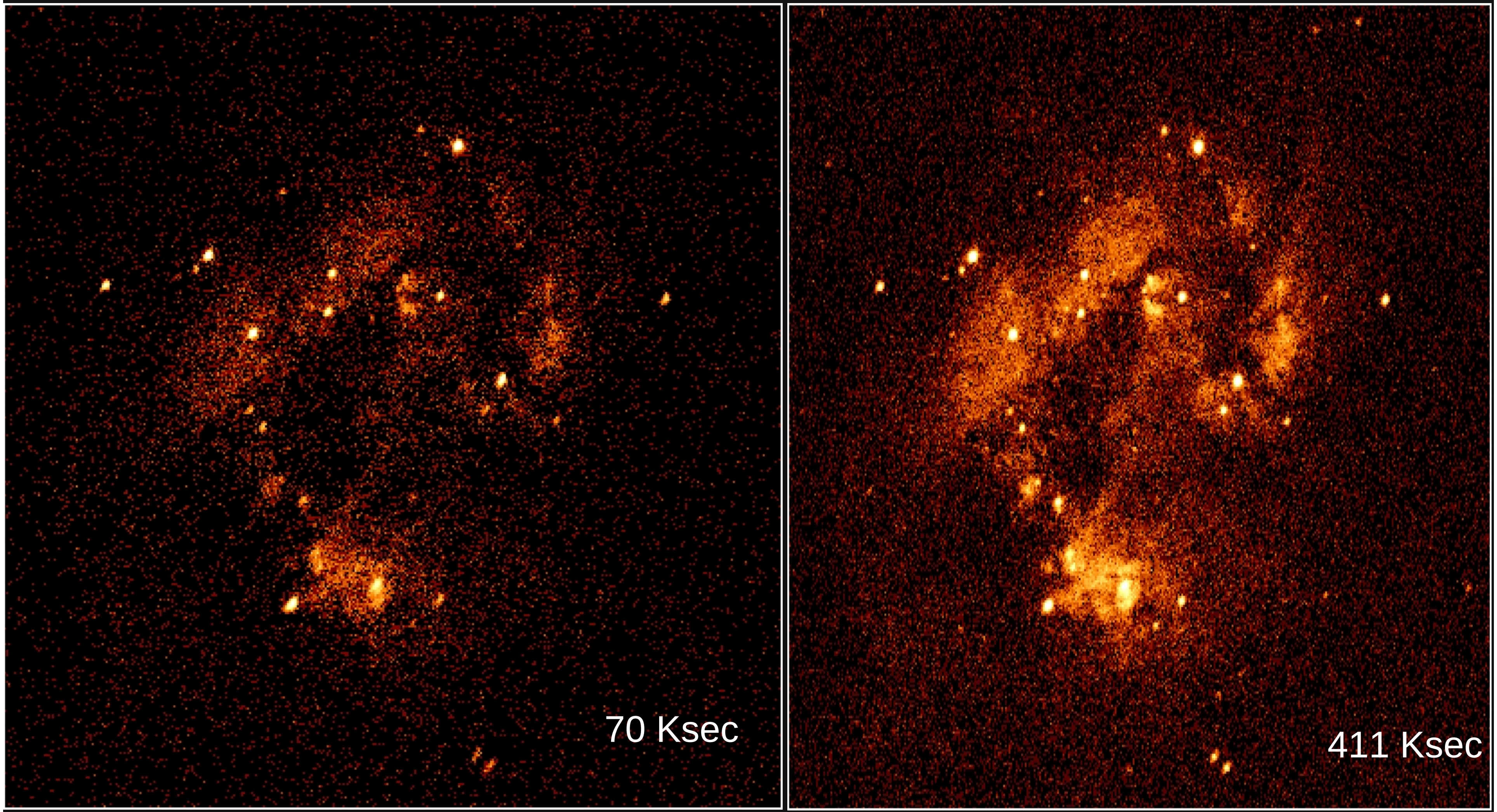
- Problems
  - Background
  - Confusion

Detection

- Problems
  - Background
  - Confusion
  - Point Spread Function
  - Limited sensitivity

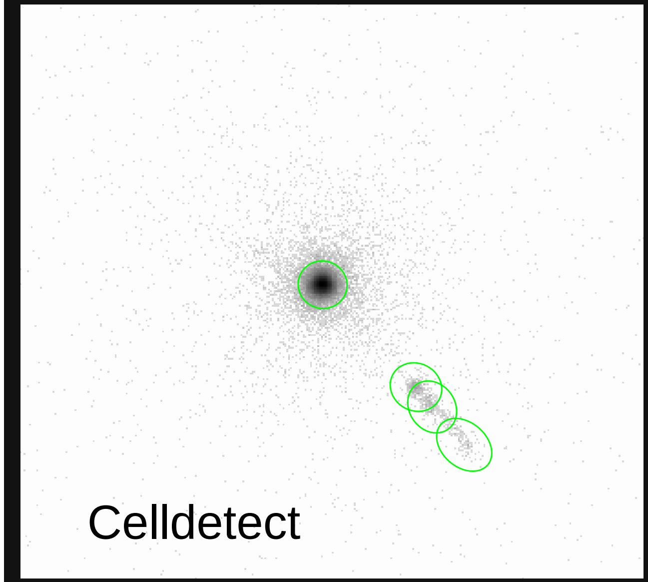


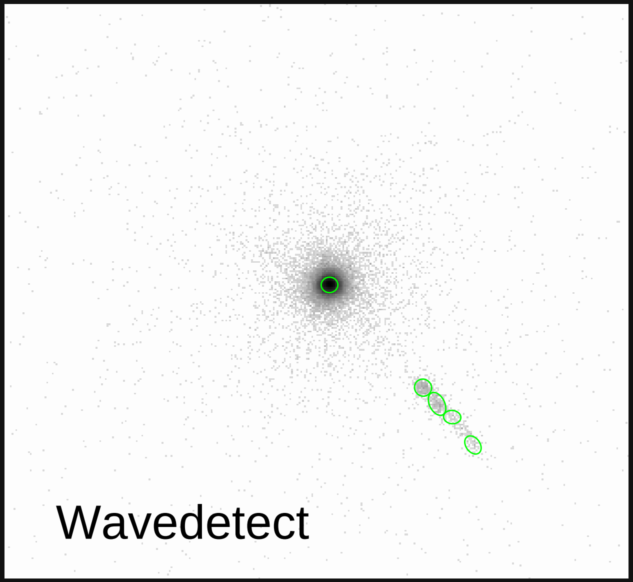
Detection

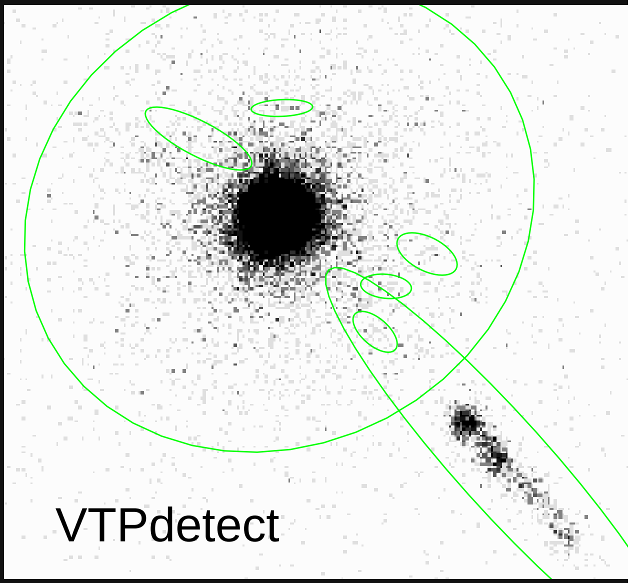


Detection

- Methods
  - Sliding cell
  - Wavelets
  - “Divide and conquer”







CXC Detect manual

Detection

- Statistical issues
  - Source significance : what is the probability that my source is a background fluctuation ?
  - Intensity uncertainty : what is the real intensity (and its uncertainty) of my source given the background and instrumental effects ?
  - Extent : is my source extended ?
  - Position uncertainty : what is the probability that my source is the same as another source detected 3 pixels away in a different exposure ?

    what is the probability that my source is associated with sources seen in different bands (e.g. optical, radio) ?
  - Completeness (and other biases) : How many sources are missing from my set ?

Spectra

- Spectra : Intensity as function of energy

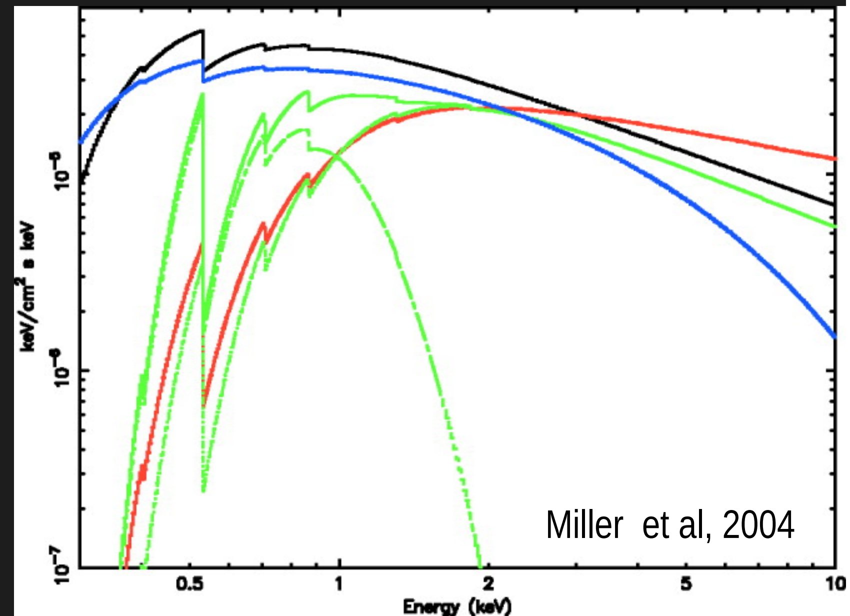
- Standard method : Fit spectra with models describing physical processes

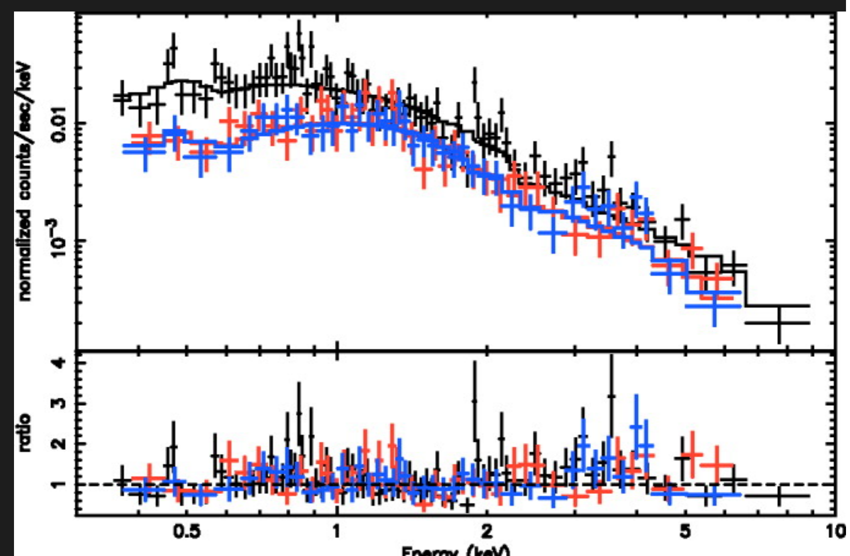
e.g. Disk-BB to measure BH mass

$$T \approx 2 \times 10^{7} \left(\frac{M}{M_{\odot}} \right)^{-1/4} K$$

power-laws to distinguish pulsar from BH binaries

$$I_E = K \times e^{-N_H \sigma(E)} E^{-\Gamma}$$





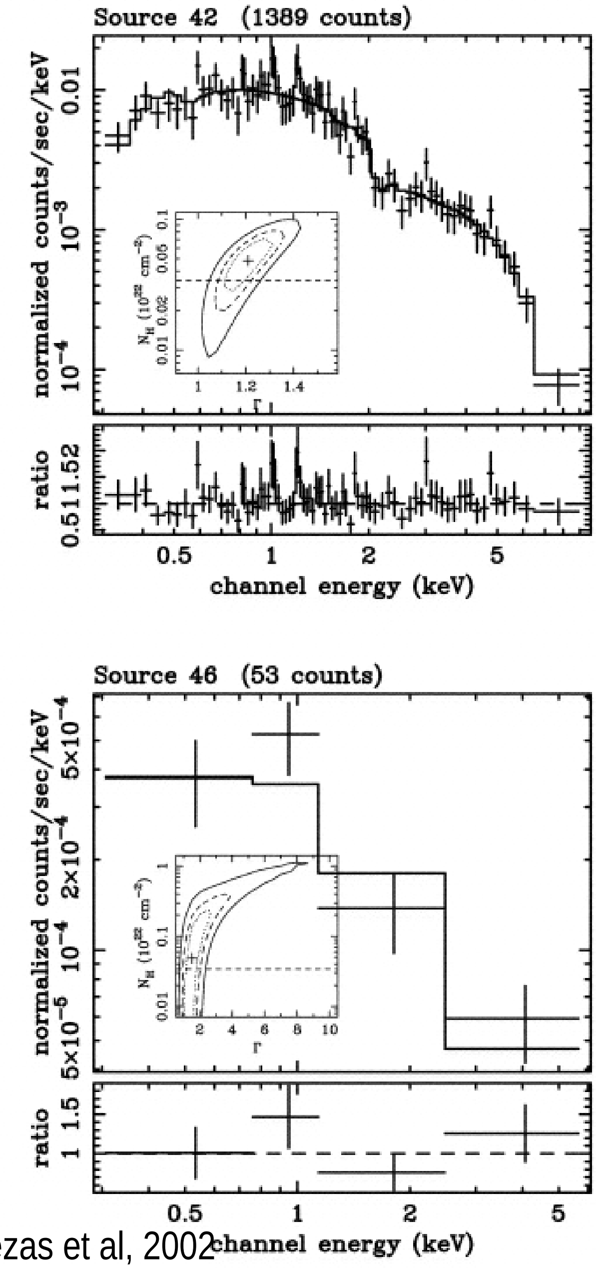
Spectra : bright sources

Statistical issues :

- Significance of components
- Correlated parameter uncertainties
- Estimation of source intensity

$$I \approx \int_{E_{low}}^{E_{up}} I(\text{params}, E)\,dE$$

where params (e.g. T, N_H, photon index) often have correlated uncertainties



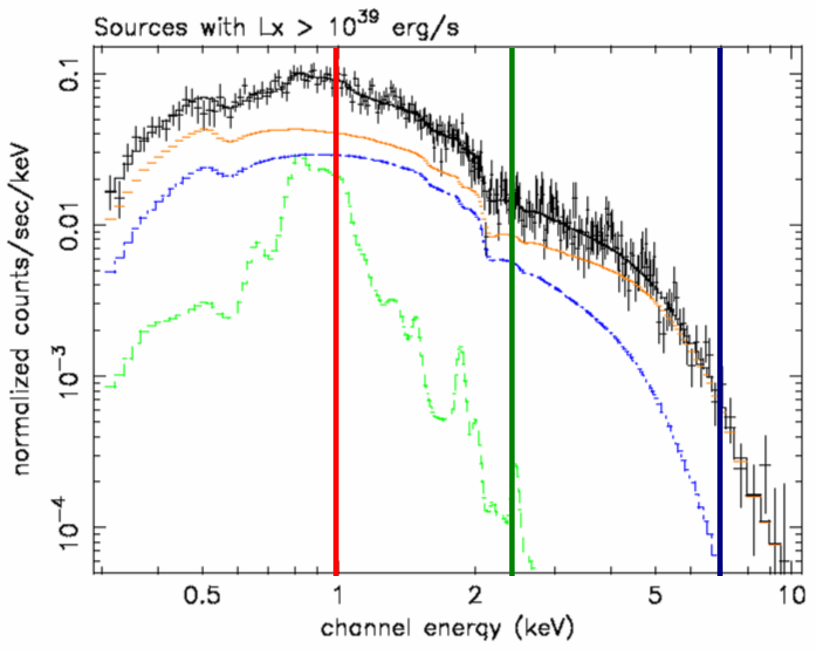
Zezas et al, 2002

Spectra : few counts

- Few counts: Use hardness ratio

Ratio (in various flavors) of intensity in two bands, e.g. :

$$R = \frac{H}{S}, \; R = \frac{S-H}{S+H}, \; C = \log\left(\frac{H}{S}\right)$$



Zezas et al, 2002

- Problems :
  - HRs in the Poisson regime (T. Park)
  - Separate source populations in HR diagrams (mixing etc)

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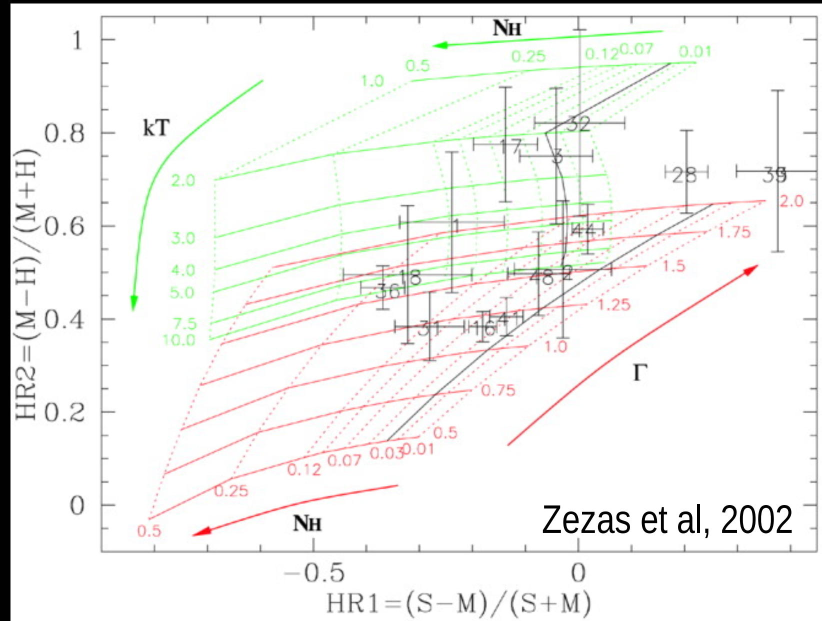
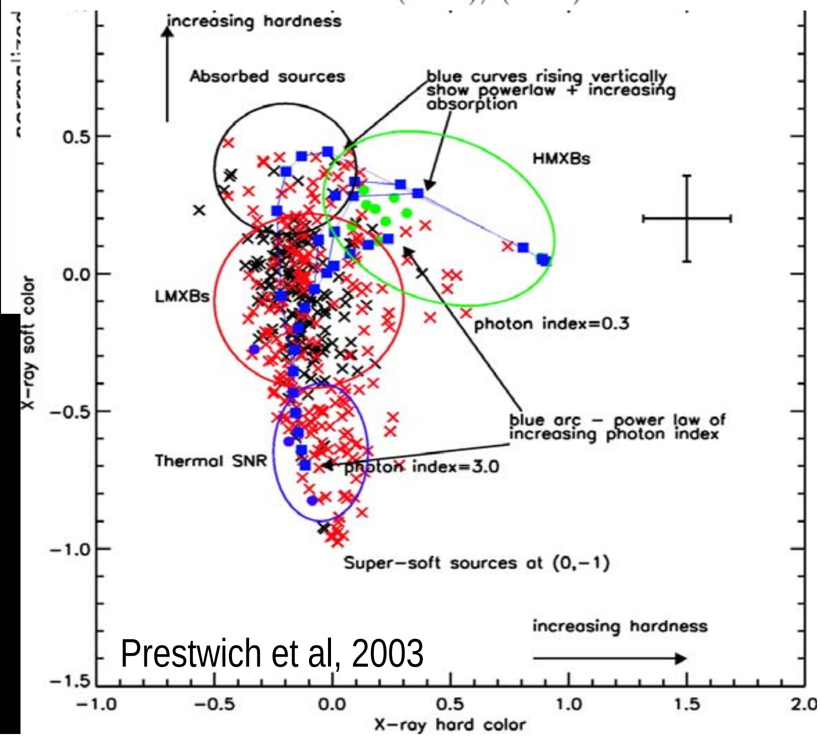
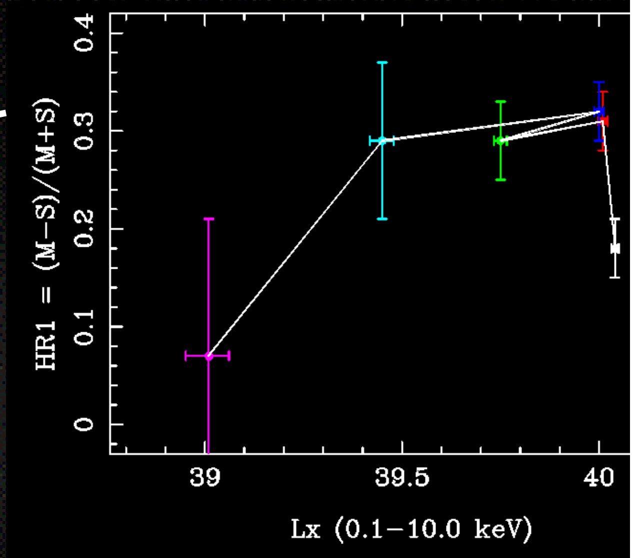




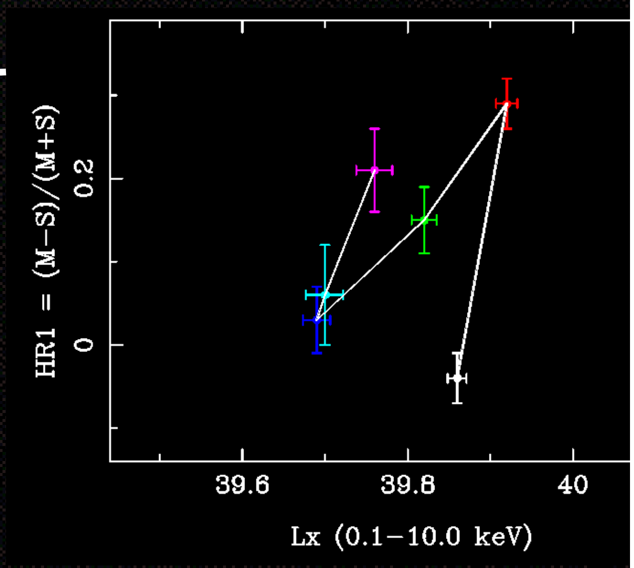
Variability

- Accreting sources are variable

  Now we can do this in other galaxies !

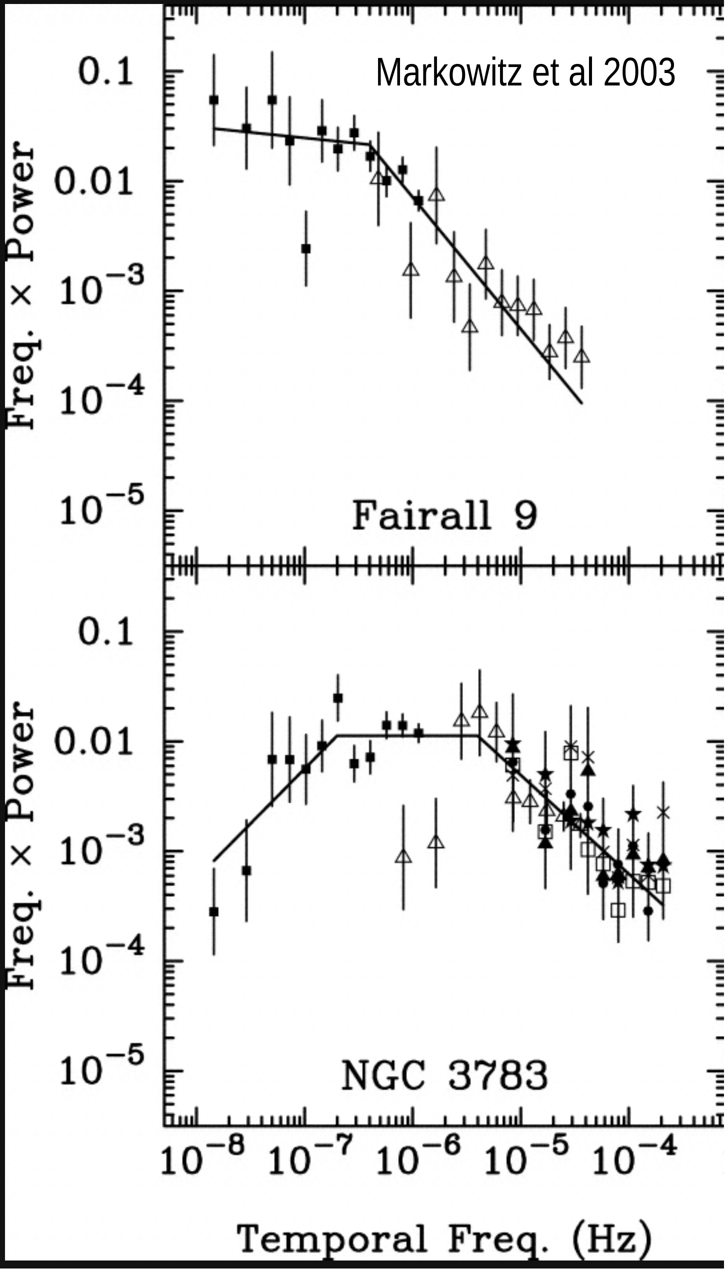


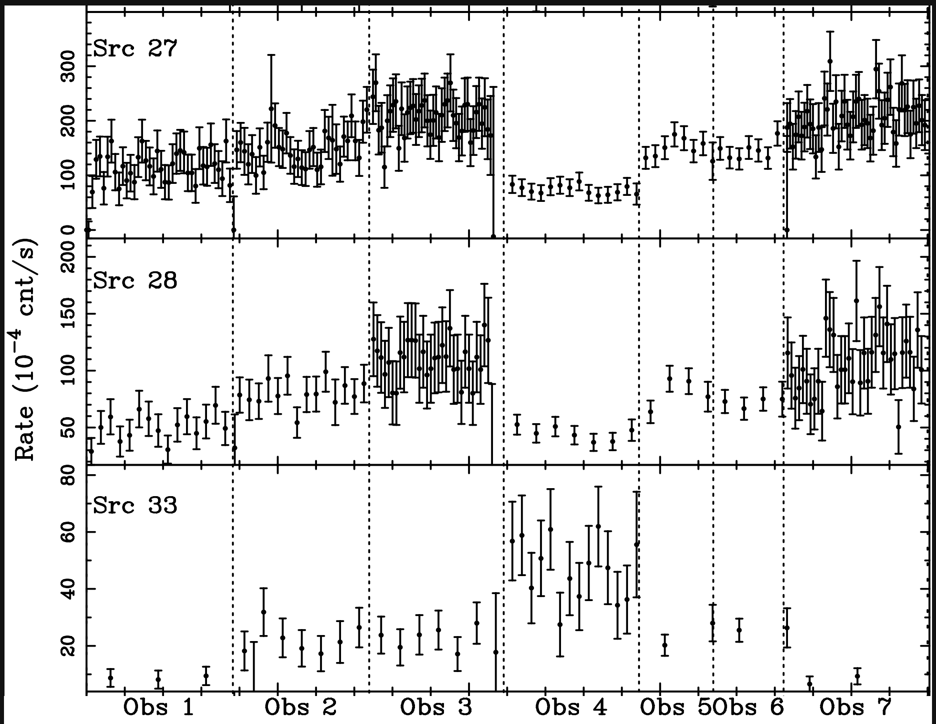
- Looking for :
  - Variable sources (flickering, systematic trends) → Identify binaries
  - Pulsations → Identify pulsar binaries
  - Variability amplitude
  - Spectral variability → Determine binary types; study the accretion process

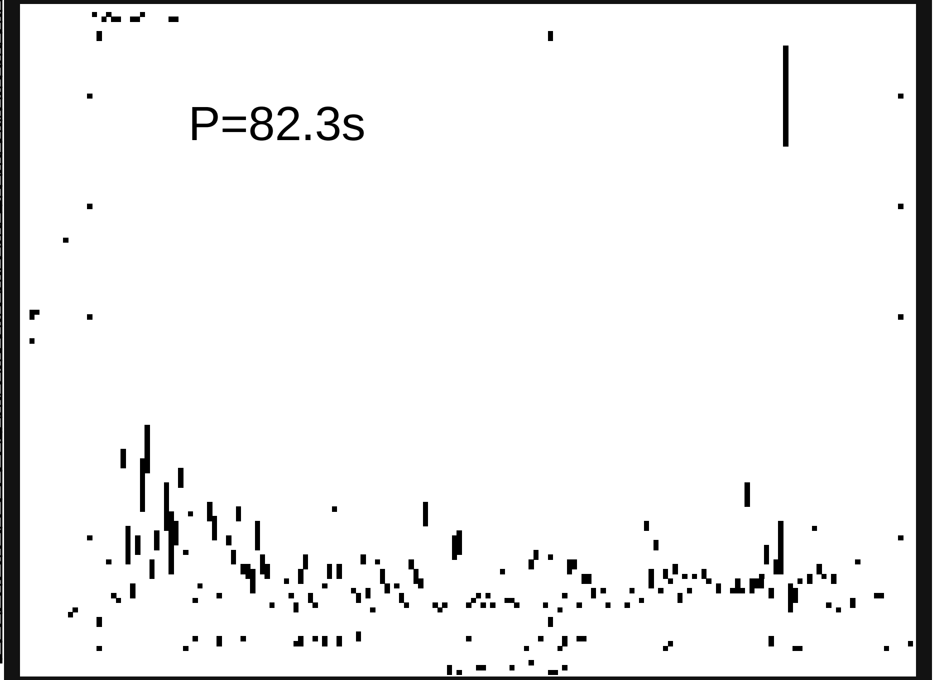


Variability

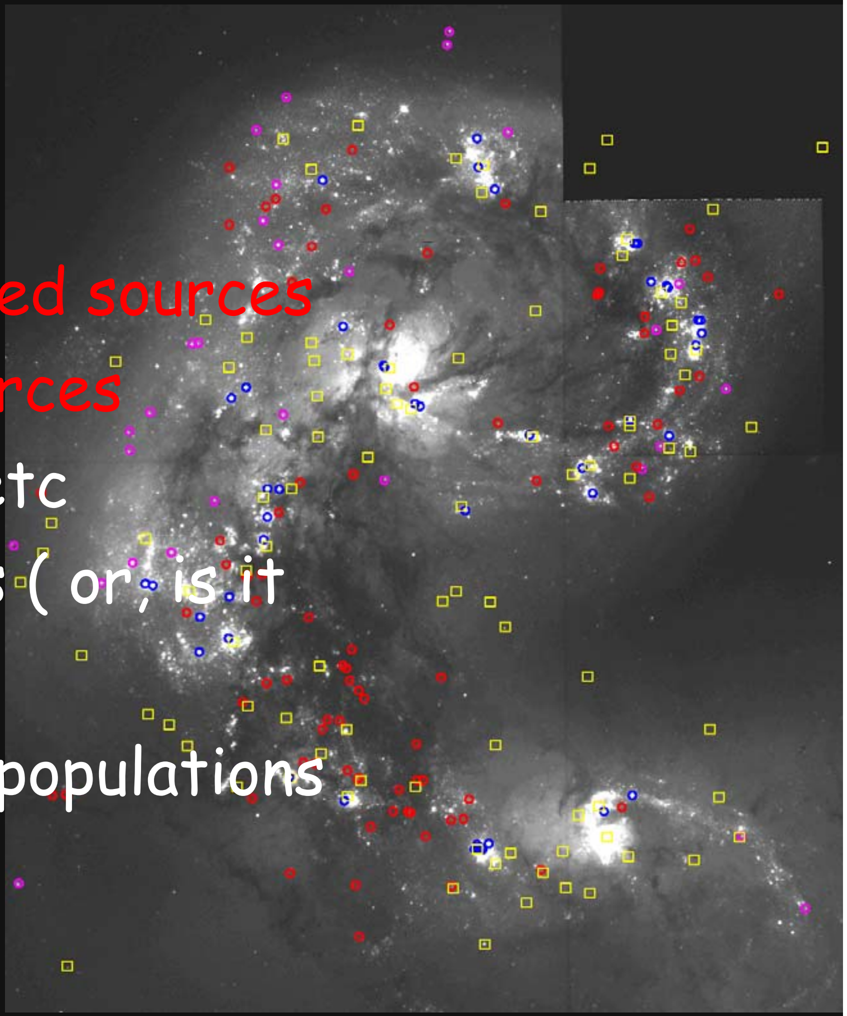
- Methods
  - χ^2, KS test
  - rms excess variance
  - Fourier analysis (power-spectra)
  - Bayesian blocks
- Problems:
  - FAINT sources
  - uneven sampling




Src 27
Src 28
Src 33
Rate (10^{-4} cnt/s)
Obs 1
Obs 2
Obs 3
Obs 4
Obs 5
Obs 6
Obs 7


P=82.3s

Spatial distribution

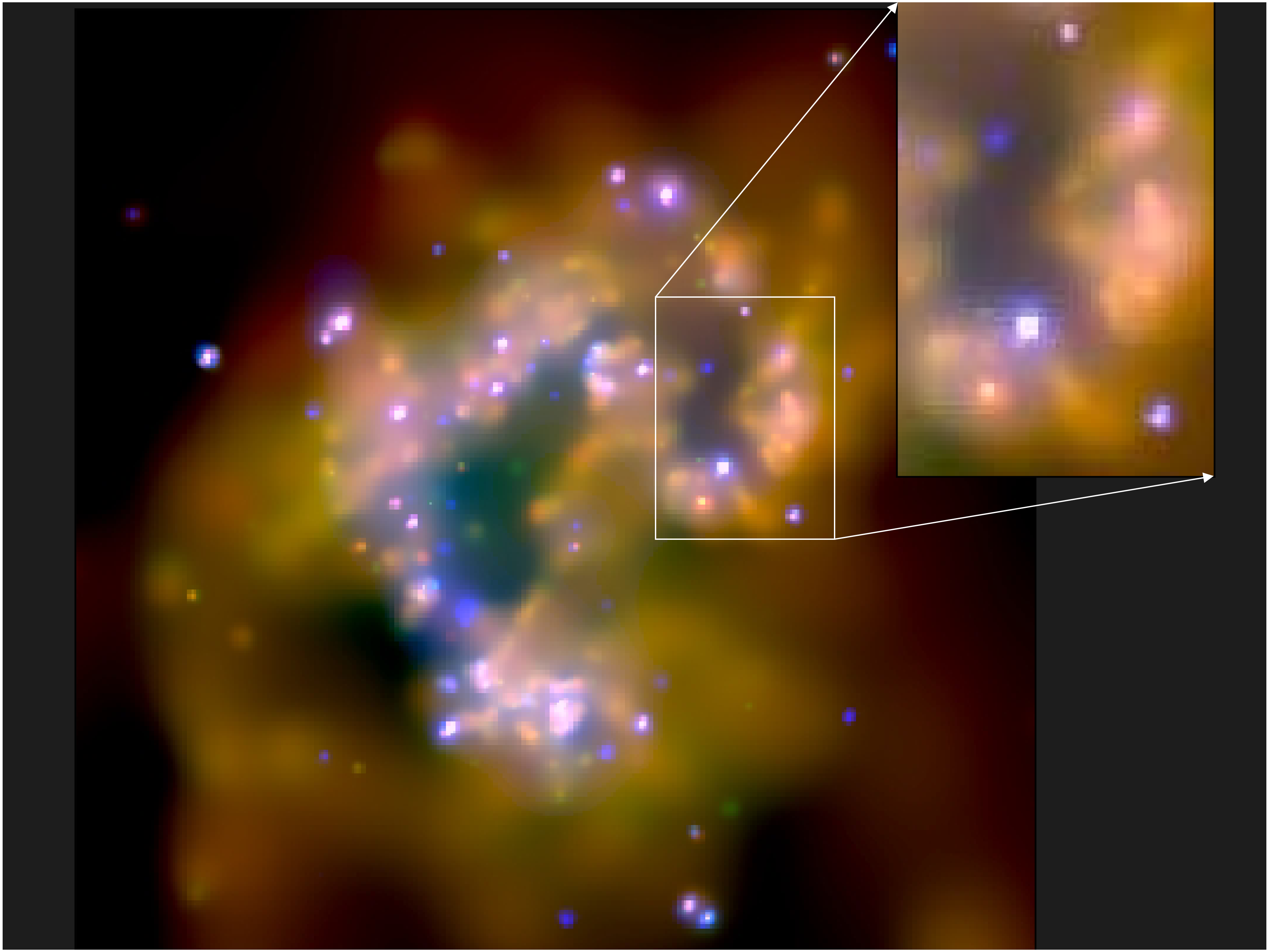


- Questions :
  - Separate point-like from extended sources
  - Study spatial distribution of sources

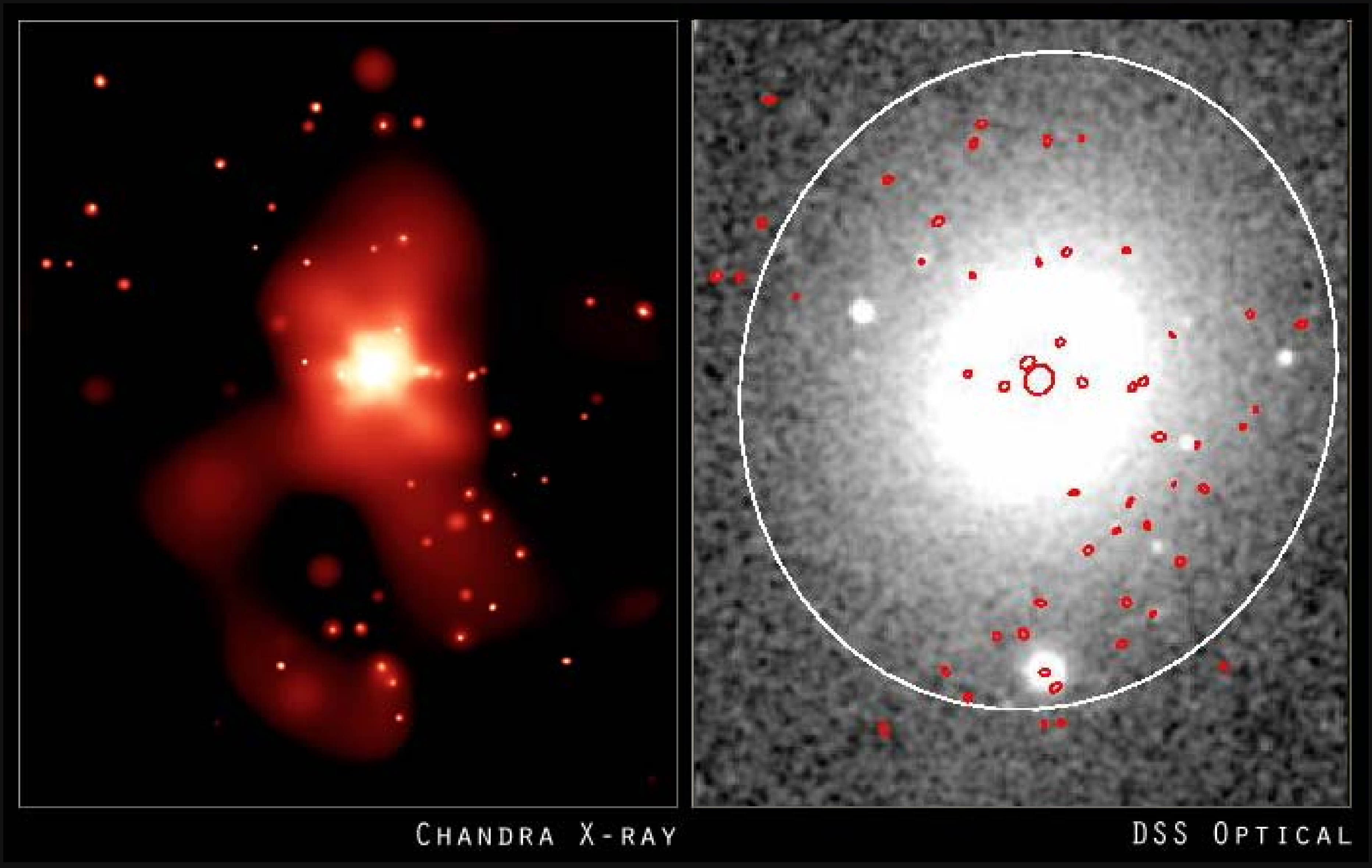
    Comparison with optical/radio etc

    Significance of spatial patterns (or, is it really spiral ?)

    Comparison between different populations (e.g. BH, neutron stars, SSS)



Spatial distribution



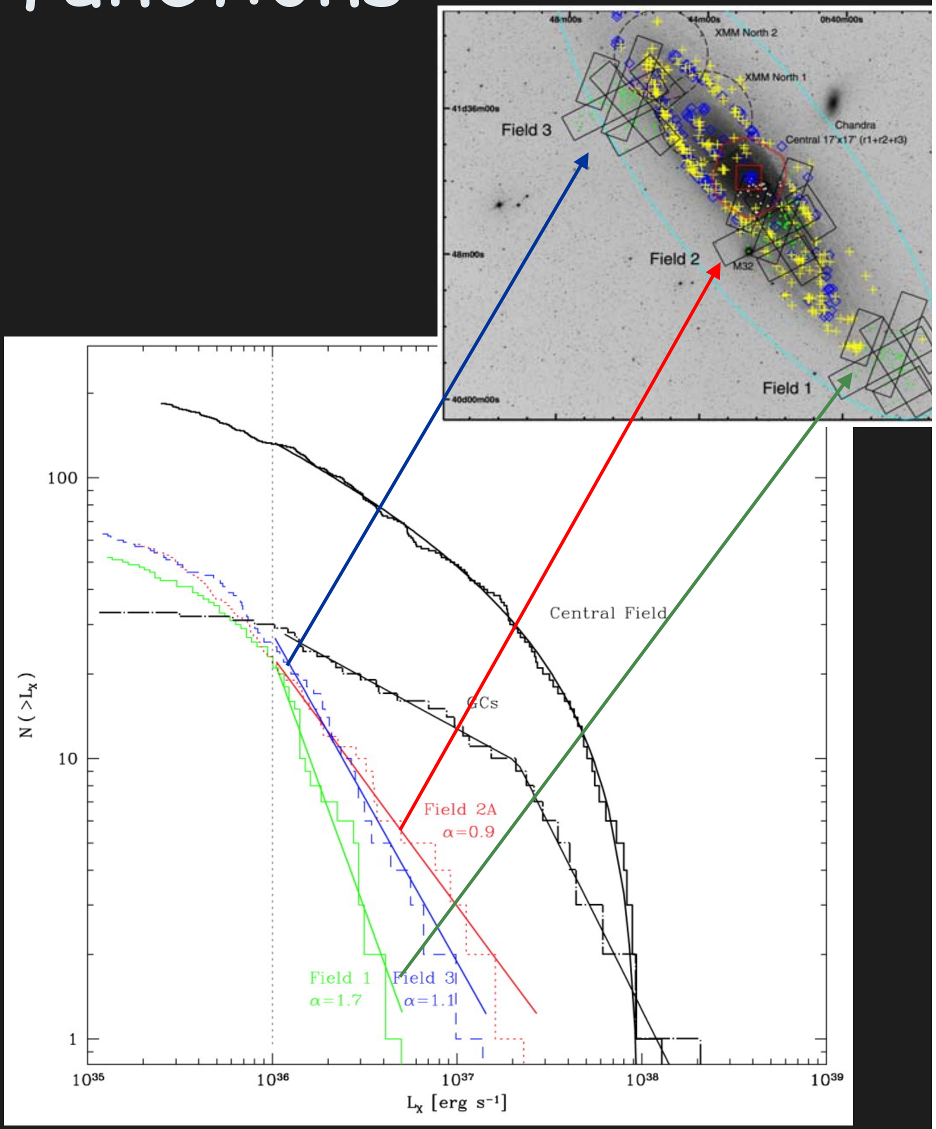
Luminosity functions

- Definition

$$\frac{dN}{dL} = K' \times L^{-(\alpha+1)}$$

or $$N(>L) = K \times L^{-\alpha}$$

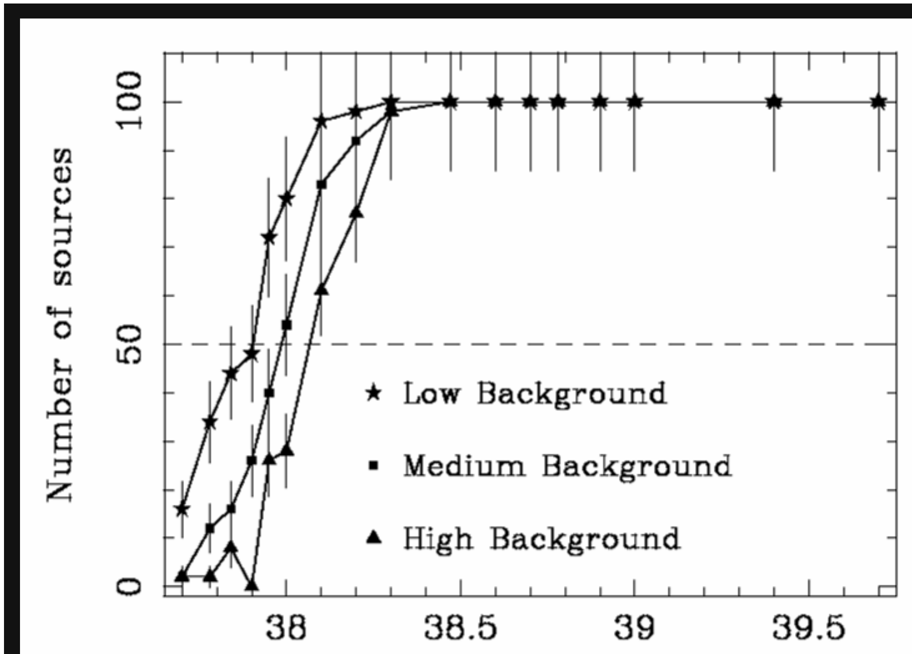
- Why is important ?
  - Provides overall picture of source pops
  - Compare with models for binary evolution



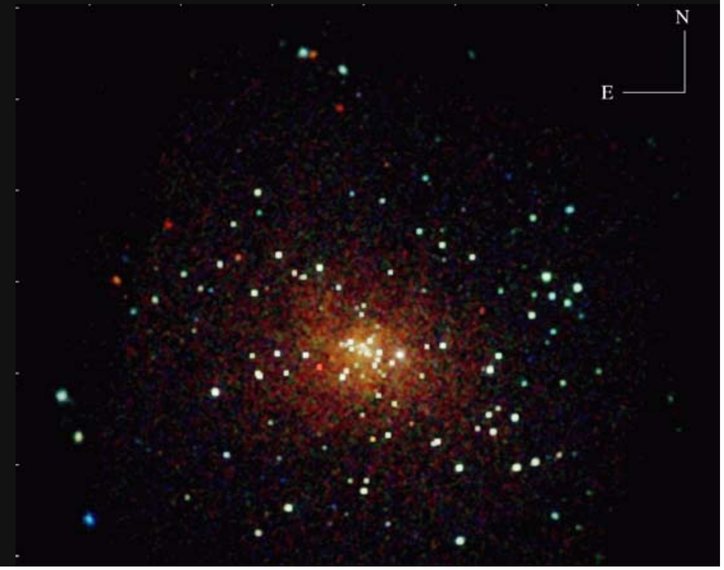
Kong et al, 2003

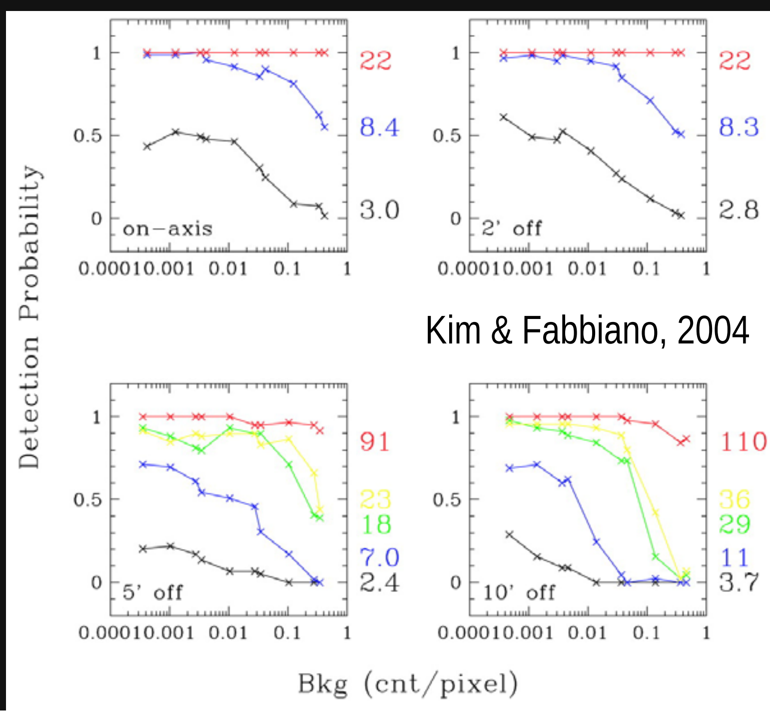
Luminosity functions

- Statistical issues
  - Incompleteness
    - Background
    - PSF
    - Confusion
  - Other biases
  - Non parametric comparison taking into account all sources of uncertainty

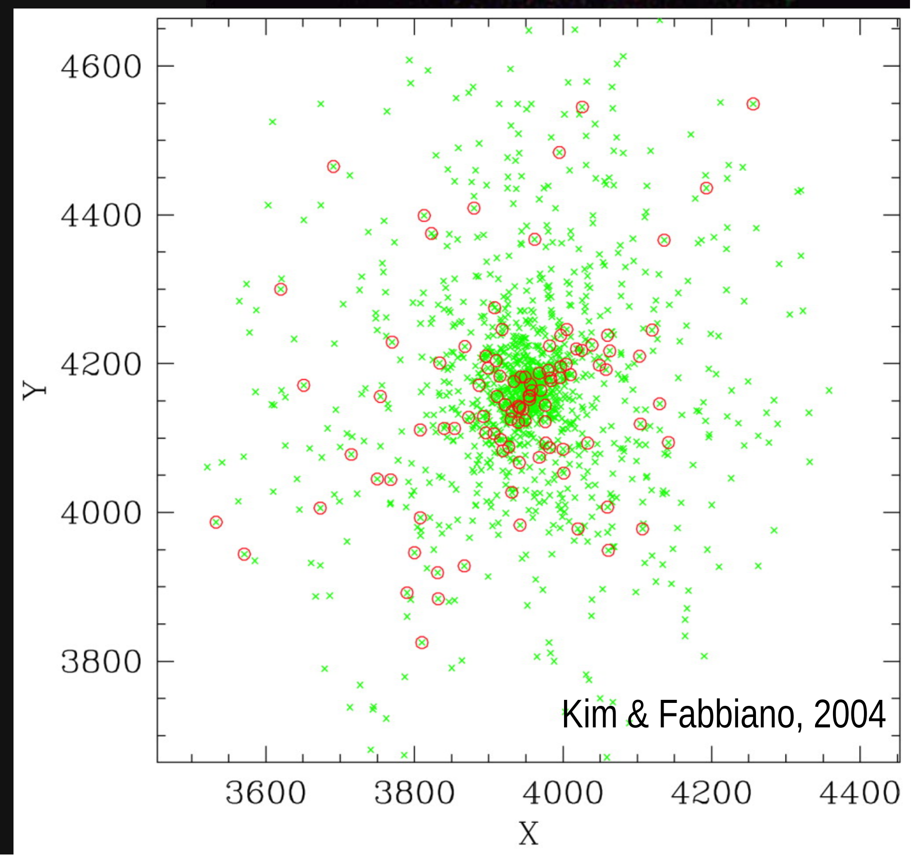


Zezas et al, 2002

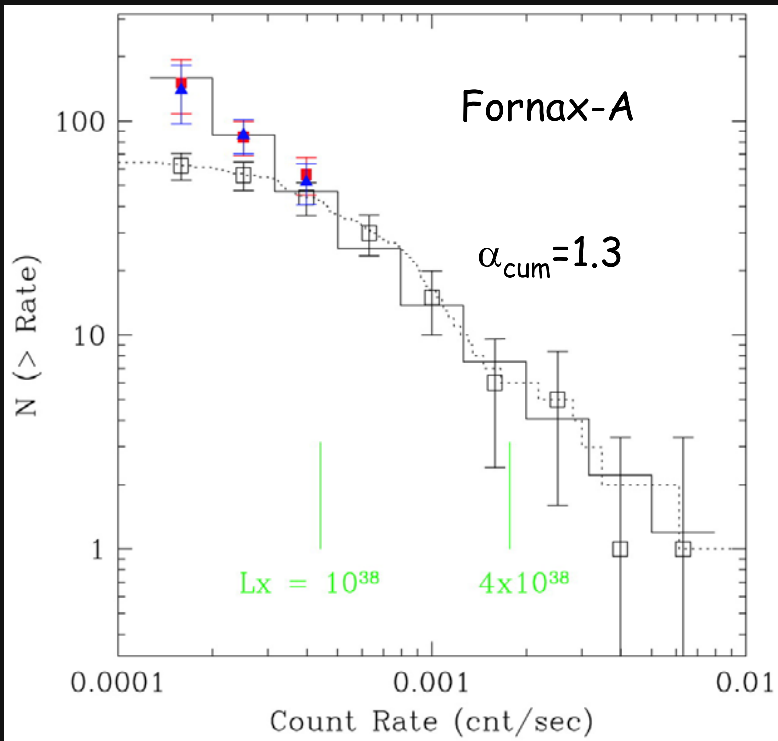




Kim & Fabbiano, 2004



Kim & Fabbiano, 2004



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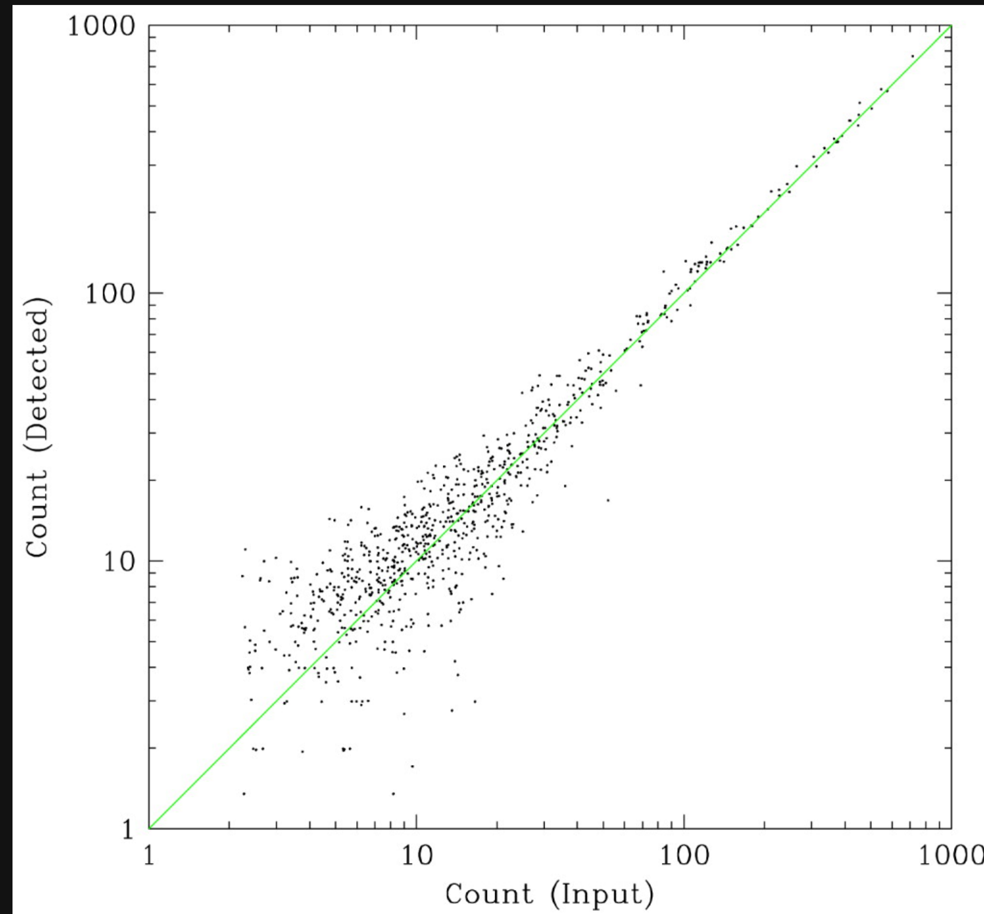
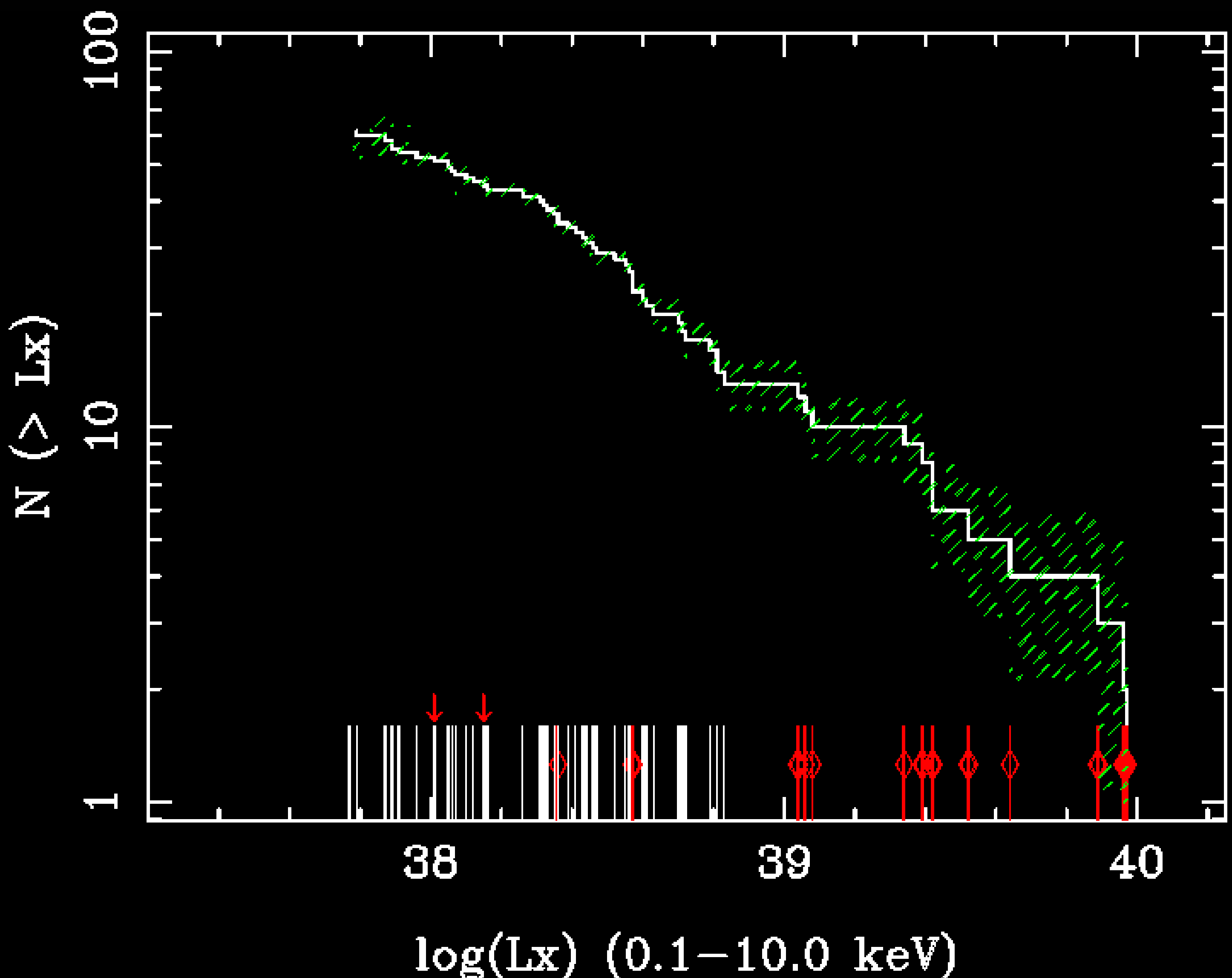
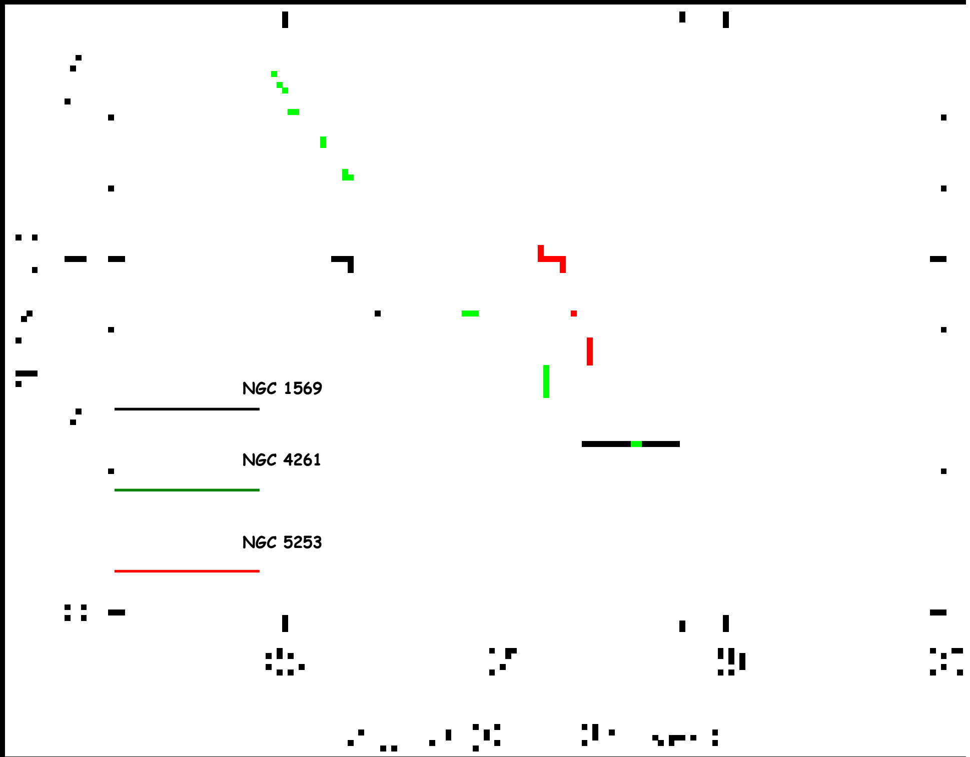


Luminosity functions



Luminosity functions

- Statistical issues
  - Incompleteness
  - Other biases
  - Non parametric comparison taking into account all sources of uncertainty
  - Spectrum dependent incompleteness



Summary

• Accreting binary systems are very interesting objects which allow us to study aspects of fundamental physics and astrophysics

• For these studies we use techniques involving spectral, timing and spatial data.

• With the new generation of X-ray satellites, we can study black-holes and neutron stars in environments other than our galaxy.

• However, we still need powerful statistical tools in order to apply these techniques on our data.