

Hard X-ray Sources Detected by INTEGRAL and Implications for GLAST



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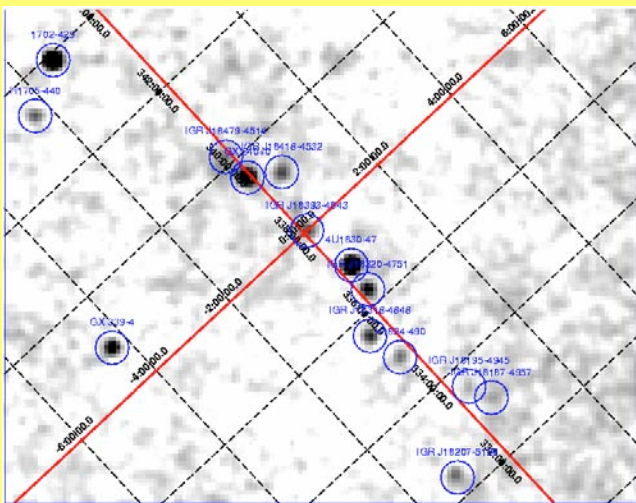
Outline:

- INTEGRAL Hard X-ray survey (Talk 3.2 on Monday: Pietro Ubertini)
- Systematic EGRET/INTEGRAL cross-correlation
- Galactic INTEGRAL sources to consider as possible GLAST sources

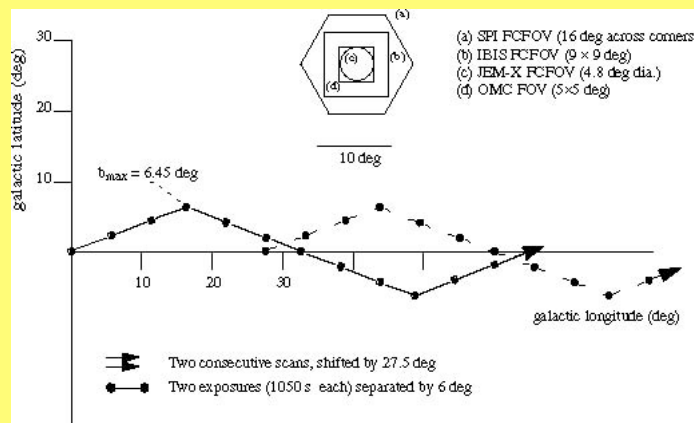
INTEGRAL Hard X-ray Imaging Survey

The primary survey instrument is **IBIS** (Imager on-Board the INTEGRAL Satellite):

- Coded-aperture mask imaging with $\sim 10 \times 10$ degree FOV
- 15 keV - 1 MeV (survey is mostly 20-100 keV)
- 12 arcminute resolution (source positions to 1-3 arcmin)



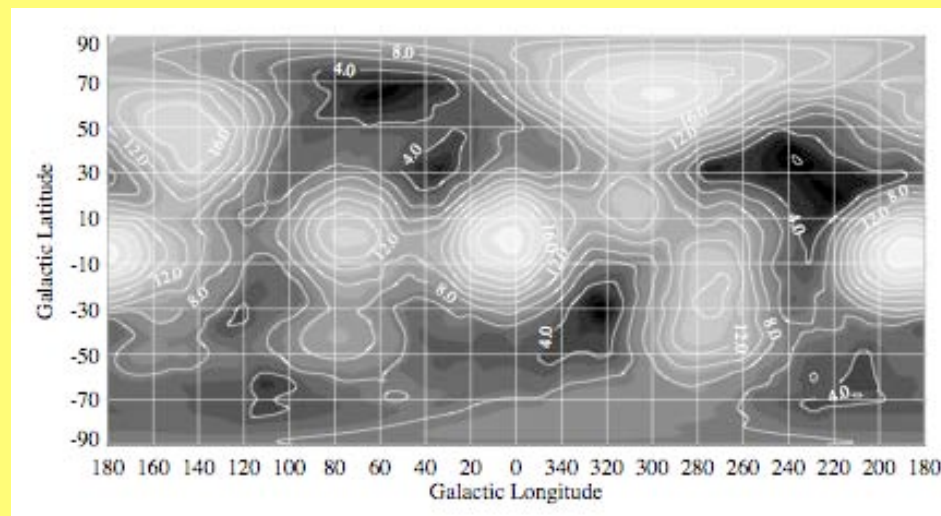
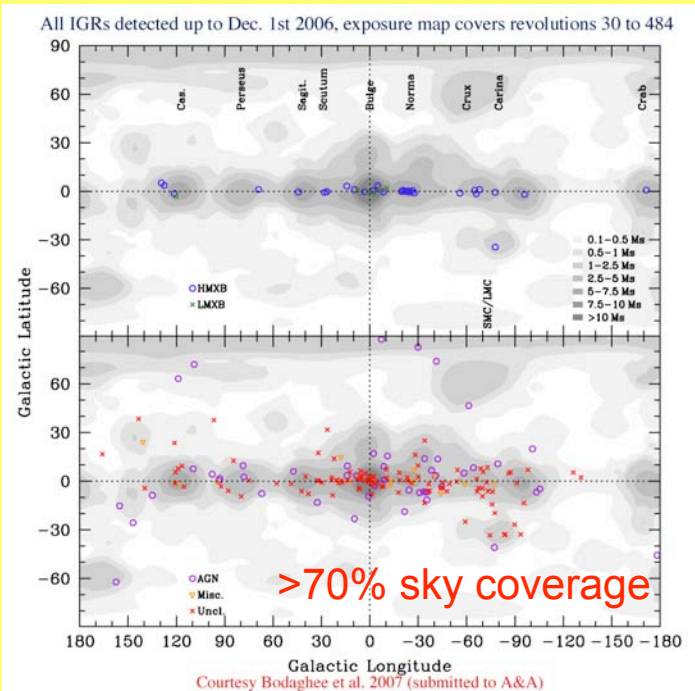
Example 20-40 keV IBIS image from a 300 ks observation of the Norma Region (Tomsick et al. 2004, 2005)



One of the survey observing strategies

Comprehensive results reported:
 Bird et al. (2004, 2006, 2007);
 Bodaghee, Rodriguez et al. (2007);
 Krivonos et al.; Kuulkers et al.; Bazzano et al.

INTEGRAL and EGRET Surveys



EGRET Exposure Map (4 years):

- $E > 100 \text{ MeV}$
- Units are $10^8 \text{ cm}^2 \text{ s}$ (corresponds to about 1.5 Ms of on-axis time at the Galactic Center)
- **271** sources detected
- 3EG Catalog (Hartman et al. 1999)

INTEGRAL Exp. Map (4 years):

- $E = 20\text{-}100 \text{ keV}$
- About 10 Ms at Galactic Center
- **499** sources detected (214 new hard X-ray “IGR” sources)
- Flux limit below 1 milliCrab
- 27th general catalog

2/8/07

Tomsick - UCB and UCSD

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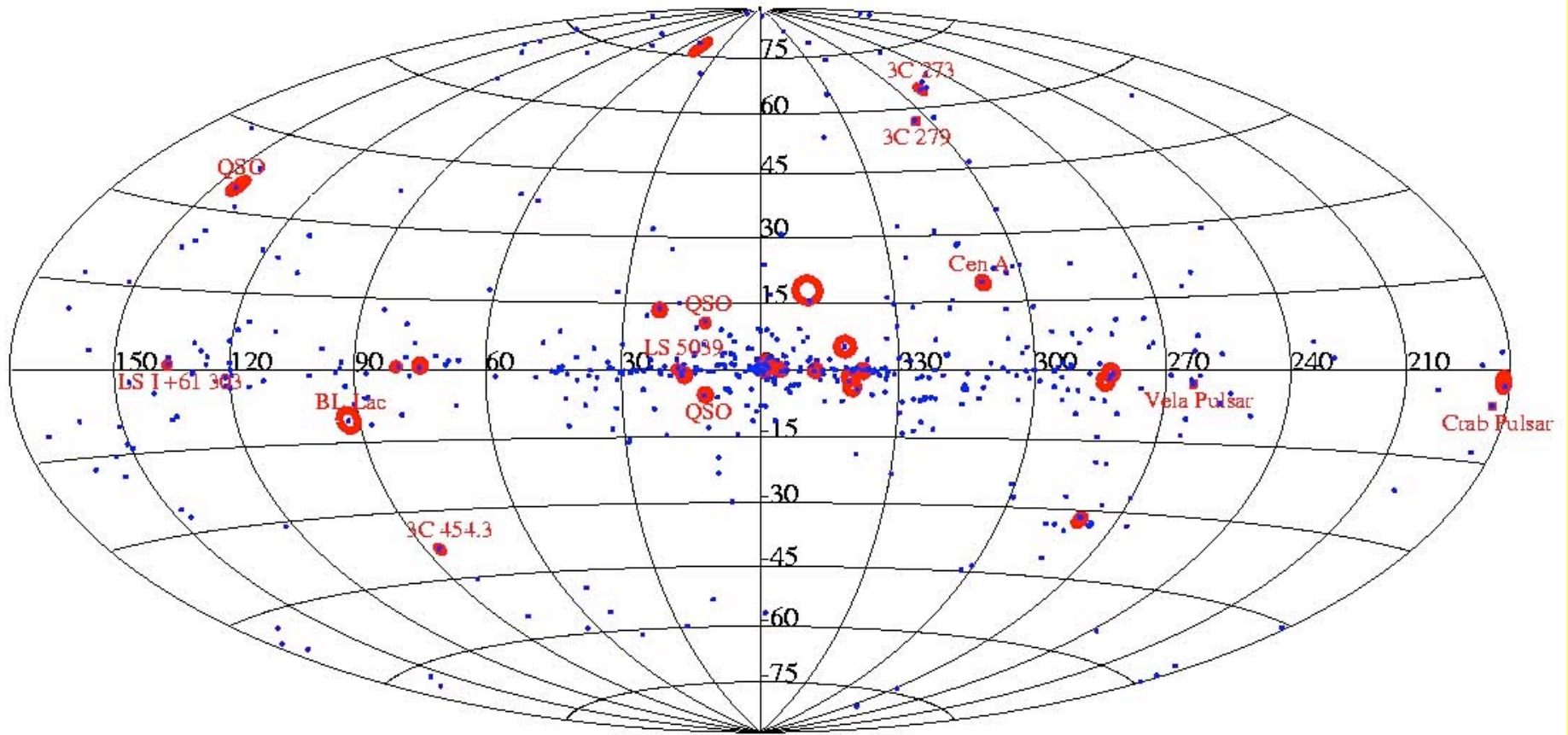
Types of INTEGRAL-Detected Sources

Extra-galactic	
AGN (QSOs, Blazars, Seyferts, etc.)	161 sources (~1/3)
Clusters of Galaxies?	3 sources
Galactic	
Low-Mass X-ray Binaries?	87 sources
High Mass X-ray Binaries?	76 sources (32 new) (~1/3)
Gamma-ray Binaries	2 sources (LS 5039 and LS I +61 303)
Cataclysmic Variables/Symbiotics	23 sources
Rotation-Powered Pulsars	16 sources ($B = 10^{12} - 10^{15}$ G)
Supernova Remnants	4 sources
Stars (RS Canum Venaticorum)	2 sources
Molecular Cloud (Sgr B2)	1 source
Unclassified	123 sources (~1/4)

EGRET/INTEGRAL Cross-Correlation

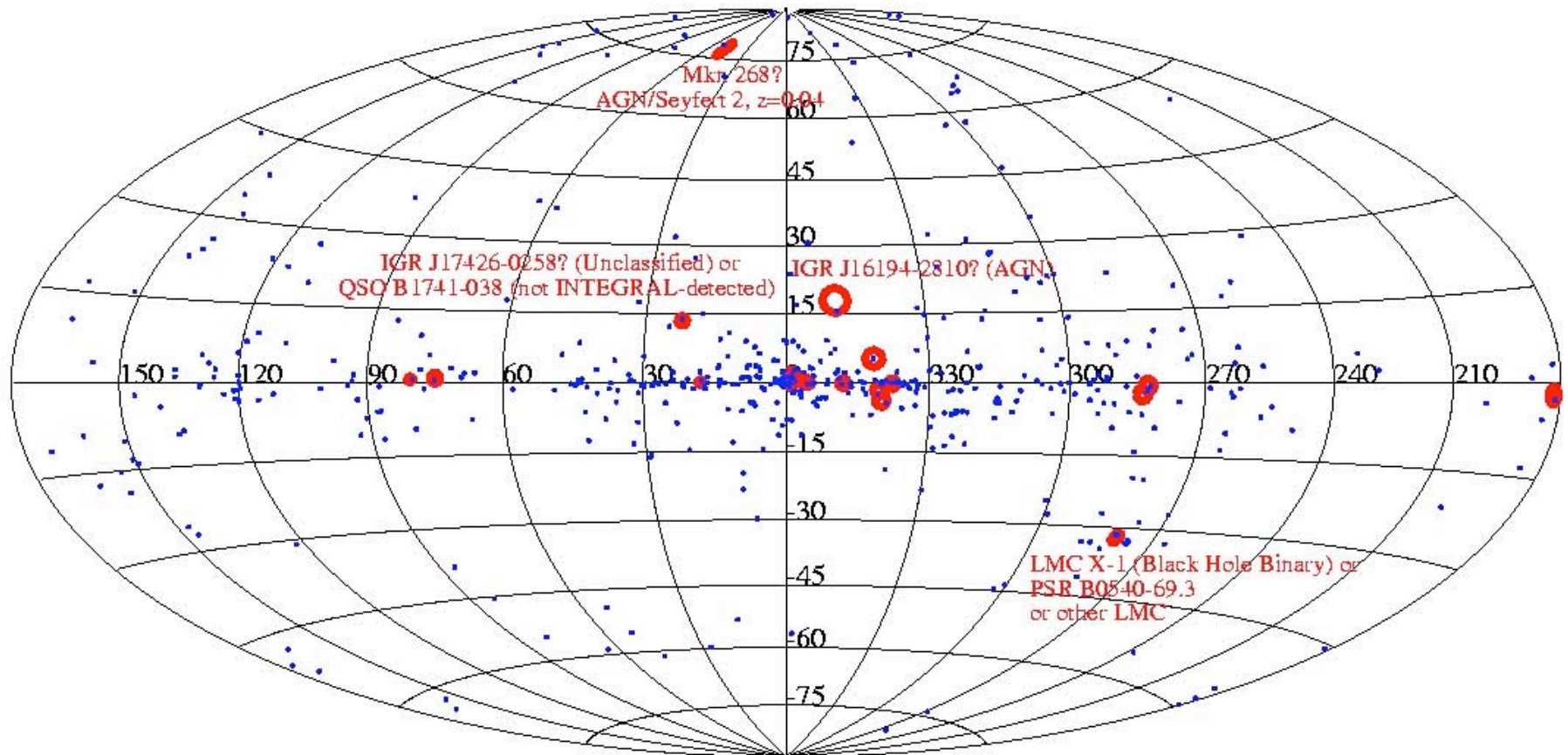
- Error region for each EGRET source is characterized by a 95% confidence radius in Hartman et al. (1999): Θ_{95} .
- Searched for INTEGRAL sources within $2\Theta_{95}$ of the best EGRET positions.
- The values of Θ_{95} are mostly in the $0.4 - 0.9^\circ$ range.
- **Results:**
 - **31** (of 271) EGRET sources have at least 1 coincident INTEGRAL source.
 - 12 of the EGRET sources have good associations ...

Certain or Nearly Certain Associations



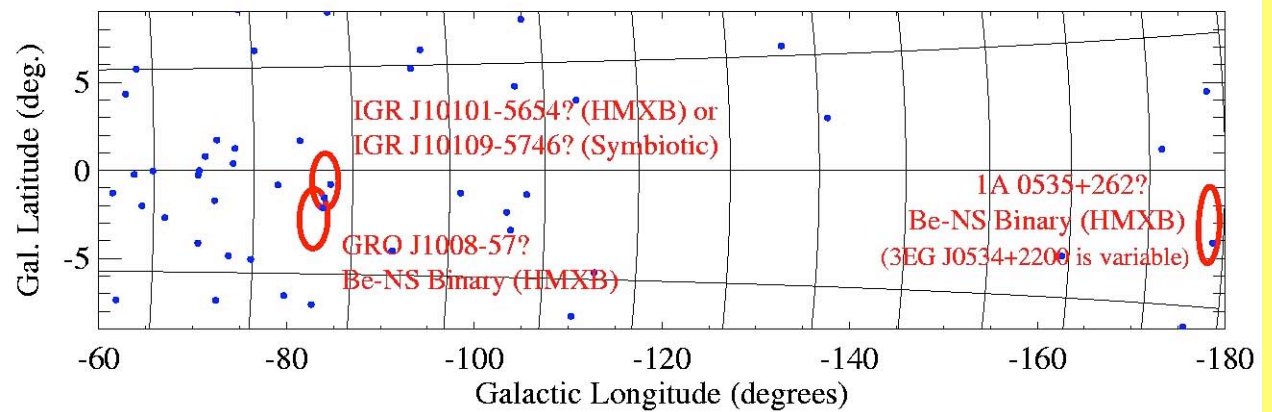
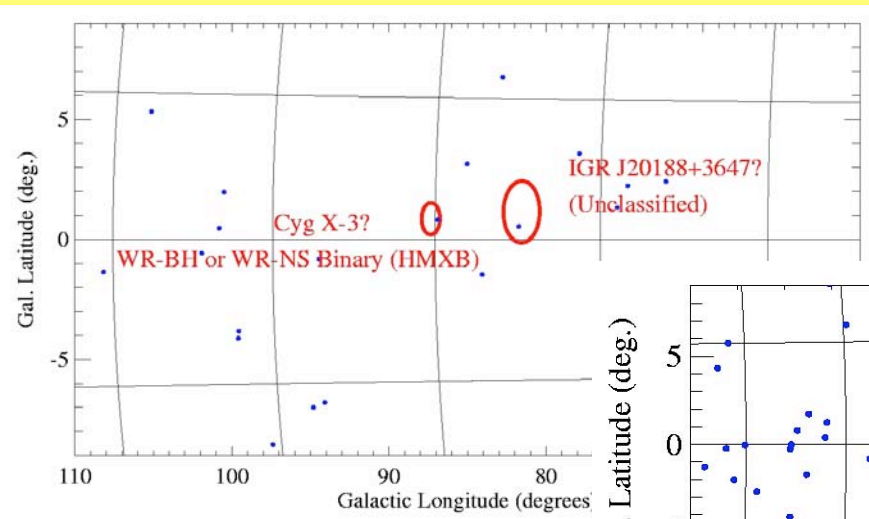
- 2 rotation-powered pulsars (Crab and Vela)
- 2 Gamma-ray Binaries (LS 5039 and LS I +61 303)
- 8 AGN/QSOs

Possible Associations: High Latitude



- Source or sources in LMC (Black Hole Binary, Pulsar, ...)
- 2 possible new associations with AGN (Mkn 268, IGR J16194-2810)
- New possibility that 3EG J1744-0310 could be IGR J17426 instead of QSO

Possible Associations: Galactic Disk

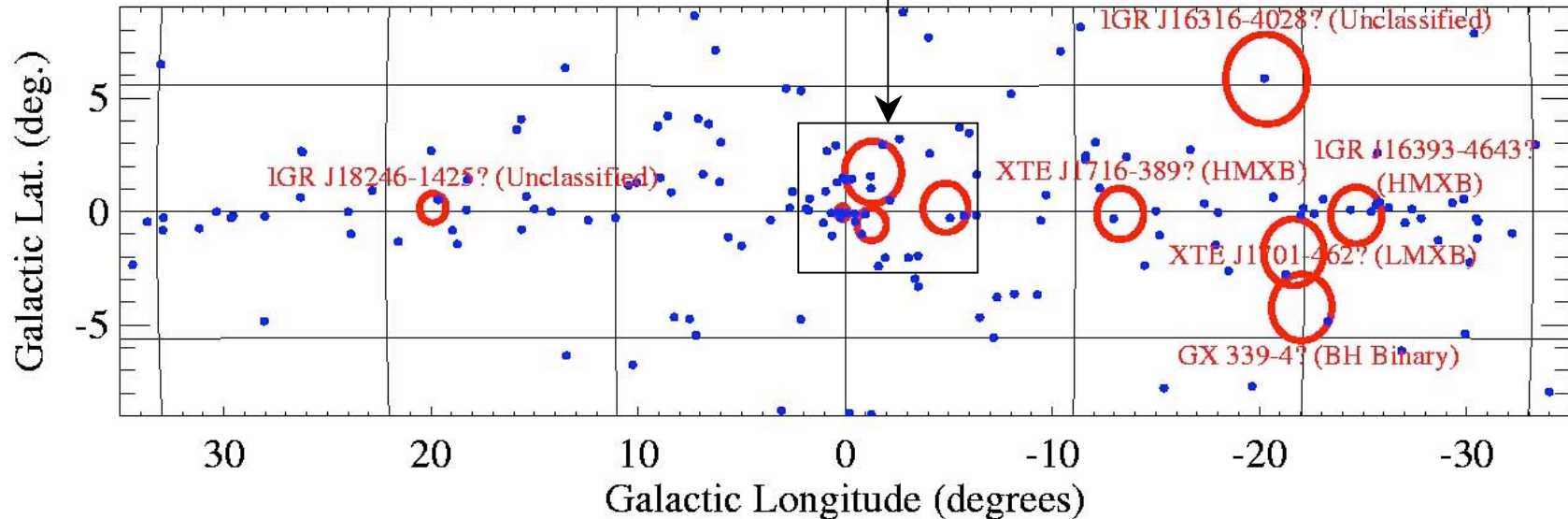


4 possible associations with HMXBs:

- **1A 0535+26**: HMXB with a B0IIIe star and an X-ray pulsar ($P_{\text{spin}} = 104$ s, $P_{\text{orb}} = 111$ d). Romero et al. (2001) previously suggested this association.
- **IGR J10101-5654**: HMXB with spectral confirmation (Masetti et al. 2006)
- **GRO J1008-57**: HMXB with a B0 star and an X-ray pulsar ($P_{\text{spin}} = 93.5$ s, $P_{\text{orb}} = 135$ d).
- **Cyg X-3**: HMXB with a WR star and radio jets ($P_{\text{orb}} = 0.2$ d). Black Hole?

Possible Associations: Galactic Center

These 4 have between 2 and 5 X-ray counterparts per source. They include some intriguing possibilities: 1E 1740.7-2942 (BH Binary); Sgr A* (not necessarily detected by INTEGRAL), other LMXBs and HMXBs



- **IGR J16316-4028**: Unclassified transient. Discovered in 2003 October, but not detected with Chandra in 2004 January.
- 2 possible HMXBs (IGR J16393-4643 and XTE J1716-389)
- 2 possible LMXBs (GX 339-4 and XTE J1701-462)

Galactic INTEGRAL Sources to Consider as Possible GLAST Sources

Rotation-Powered Pulsars:

- **Radio Pulsars or Pulsar Wind Nebulae**

Crab: $F_{\text{gamma}} = 2 \times 10^{-6}$ ph/cm²/s, $F_x = 1000$ milliCrab

Vela: $F_{\text{gamma}} = 9 \times 10^{-6}$ ph/cm²/s, $F_x = 7$ milliCrab

7 other INTEGRAL Pulsars (e.g., PSR J1509-58): $F_x = 1 - 9$ milliCrab

- **Also, 7 Soft Gamma-Ray Repeaters or AXPs (?)**

Gamma-ray Binaries:

- **LS 5039**

$F_{\text{gamma}} = 5 \times 10^{-7}$ ph/cm²/s

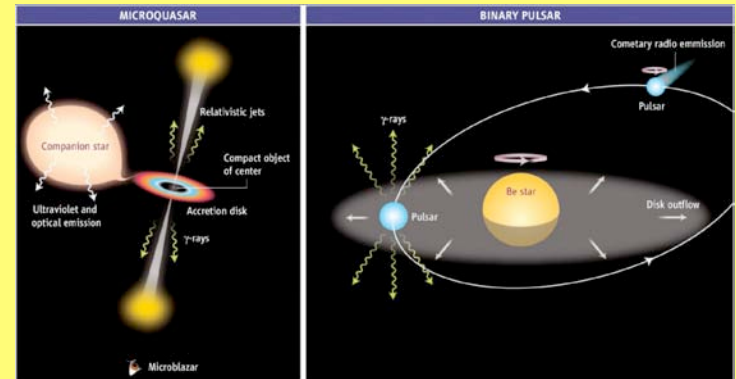
$P_{\text{orb}} = 26.5$ days, extended radio

- **LS I +61 303**

$F_{\text{gamma}} = 8 \times 10^{-7}$ ph/cm²/s

$P_{\text{orb}} = 3.9$ days, extended radio

- **PSR B1259-63** (not INTEGRAL-detected)



Microquasar or Rotation-Powered Pulsar? (Figure from Mirabel 2006)

Galactic INTEGRAL Sources to Consider as Possible GLAST Sources (HMXBs)

High Mass X-ray Binaries?

- Probability for the 4 Galactic Disk HMXB Associations:

Source	INTEGRAL sources per deg ²	Θ_{95}	Poisson Probability (within $2\Theta_{95}$)
1A 0535+26	0.007	0.70 degrees	4%
GRO J1008-57	0.038	0.72 degrees	19%
IGR J10101-5654	0.038	0.67 degrees	17%
Cyg X-3	0.020	0.28 degrees	2%

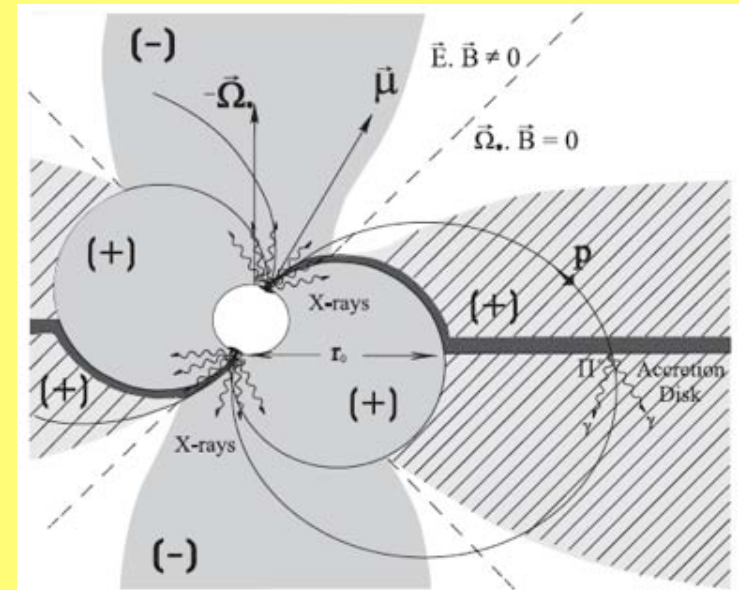
The probability that all 4 associations are spurious is **0.003%**.

Other Considerations for HMXBs ...

- Bias caused by the tendency for supernovae, rotation-powered pulsars, and HMXBs to be found in **star-forming regions**.
- No obvious gamma-ray/X-ray correlation in **variability** observed.

However, there are still arguments in favor of HMXBs as gamma-ray sources:

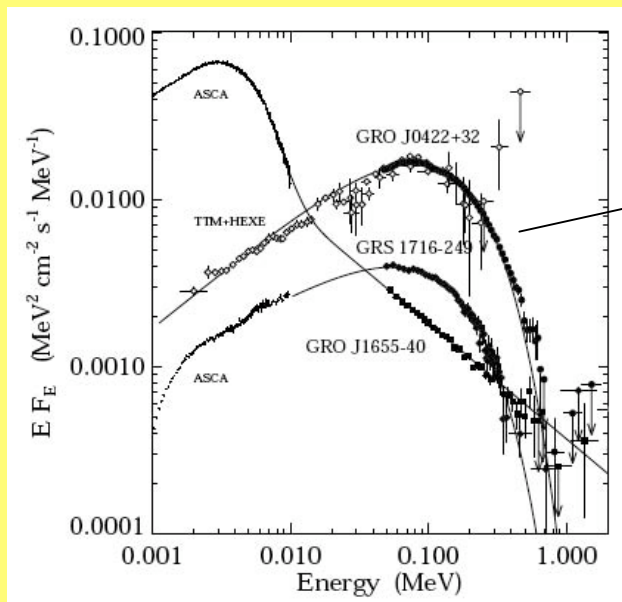
- In addition to these 4 sources, gamma-ray pulsations from Cen X-3 ($P_{\text{spin}} = 4.8 \text{ s}$, $P_{\text{orb}} = 2.09 \text{ d}$) were probably (99.5% confidence) detected (Vestrand et al. 1997).
- There is a model ...



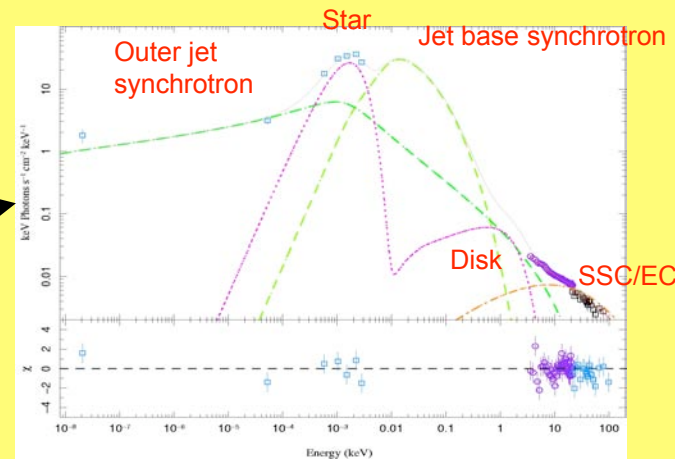
Romero et al. (2001);
Cheng & Ruderman (1991)

Galactic INTEGRAL Sources to Consider as Possible GLAST Sources (BHBs)

Black Hole Binaries (microquasars)? GX 339-4, Cyg X-3, 1E 1740.7-2942



Transient
Steep Power Law and
Hard States
(Grove et al. 1998)



Hard State:
Results from Tomsick et al. multi-wavelength study fitted with the Markoff et al. jet model (Migliari et al. 2007).

Steep Power Law State:

- Extrapolating to >100 MeV gives a predicted flux near $10^{-7} \text{ ph/cm}^2/\text{s}$ (easy for GLAST, but spectrum may break).

Summary and Conclusions

- EGRET/INTEGRAL cross-correlation comes up with 31 EGRET sources with possible hard X-ray matches.
- 12 have good associations with AGN/QSOs, Rotation-Powered Pulsars, or Gamma-ray Binaries.
- Of the 19 remaining candidate associations:
 - 4 HMXBs in the Galactic Disk (0.003% probability that this is by chance). **Note that INTEGRAL has discovered 32 new HMXBs.**
 - 7 associations with newly discovered IGR sources (1 AGN, 2 HMXBs, 4 Unclassified).
 - Transient gamma-ray emission from microquasars may be detectable in 2 different states.