Millisecond Pulsars in Dwarf Spheroidal Galaxies

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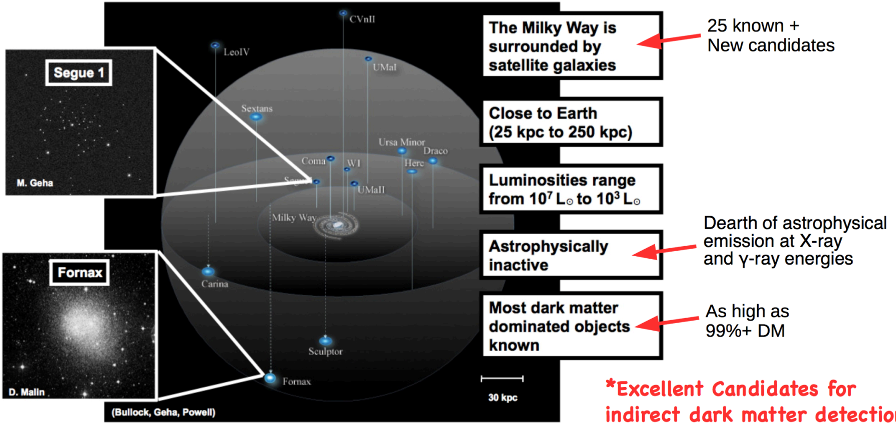
Overview

Estimating the GeV Emission of Millisecond Pulsars in Dwarf Spheroidal Galaxies

- Authors: M. Winter, G. Zaharijas, K. Bechtol, & J. Vandenbroucke
- Category III LAT paper
- Target journal: ApJL
- Timeline: submit for publication in mid June
- Link: `https://confluence.slac.stanford.edu/display/~gzah/MSPs+in+dSphs+Category+III+paper`

Dwarf Spheroidal Satellite Galaxies

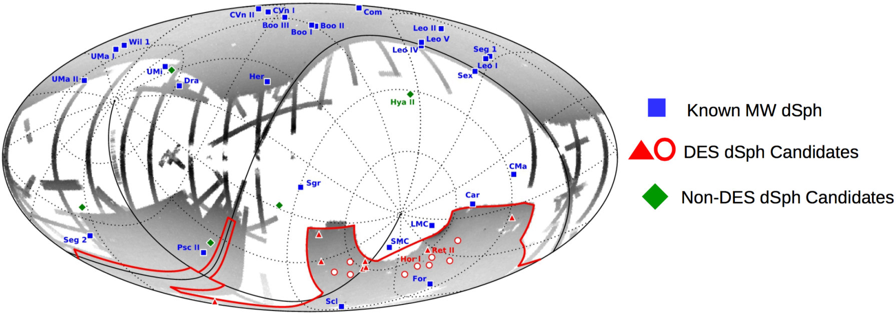
- Dwarf elliptical galaxies of near-spherical shape that lack a nucleus.
  - Characterized by low luminosity and surface brightness
  - Old stellar systems w/ stellar populations ranging from 1-10 Gyrs
  - Stellar masses ranging from $10^2 - 10^7\ M_\odot$ ($M_{*,MW} = 10^{10} M_\odot$)



*Excellent Candidates for indirect dark matter detection

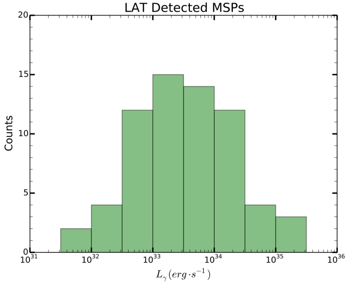
Fermi-LAT Surveys of the Dwarfs

- LAT surveys of the dSphs have not detected any significant DM annihilation signal
- Sets world-leading constraints on the DM annihilation cross section
- dSphs are among the most important targets for indirect DM searches for the foreseeable future
  - If a γ-ray excess exists, it will eventually be detectable: “Super” Fermi
  - This assumes dSphs have a negligible astrophysical background



Are the Dwarfs *Really* Astrophysically Clean?

- LAT *has* detected a significant number of γ-ray emitting MSPs in both the field of the MW and in MW globular clusters
- Concern: Could there be an MSP population in the dwarfs?
  - MW field environment is similar to dSph stellar environment
  - Stellar population/age in GCs is very similar to the dwarf population
  - X-ray observations of dwarfs detect MSP progenitor system (LMXB)



How to estimate the dwarf MSP population using only MW observations?

Millisecond Pulsar X-ray Binary Connection

- Use the progenitor system: MSPs are believed to be an advanced evolutionary stage of low-mass x-ray binaries (LMXBs)
- LMXBs, and by extension MSPs, have two distinct formation channels: dynamical and primordial
  - Dynamical: result of two-body interactions in high ρ_*, high Γ environments, such as GCs
  - Primordial: formation from primordial binaries (i.e. when galaxy was formed) in low ρ_*, low Γ environments
- In the fields of galaxies, where primordial formation is dominant, the number of LMXBs has been found to scale with the stellar mass of the host galaxy (Gilfanov 2004)
- Dwarfs have "field-like" stellar environment $\Rightarrow$ primordial formation!
- **Claim:** If LMXBs scale with stellar mass, then MSPs can reasonably be expected to as well

Estimating the Dwarf MSP Population w/ Fermi Data

- **Approach:**
  - Perform a monte carlo incompleteness correction on the LAT MSP survey
  - MCMC fit to the corrected MSP sample to determine MSP γ-ray luminosity function (LF)
  - Scale the normalized LF to the stellar mass of each dwarf
  - Estimate the γ-ray flux for each dwarf
  - Compare estimated flux to LAT threshold
- **Sources of Uncertainty:**
  - Statistical: LAT detection shot noise
  - Systematic: MSP distances and completeness correction

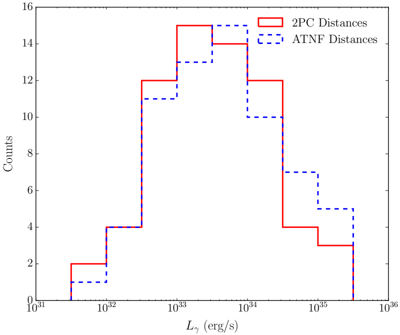
$$\left\{ \begin{array}{c} \text{2PC Distances} \\ \text{ATNF Distances} \end{array} \right\} \times \left\{ \begin{array}{c} \text{Upper Limit Completeness} \\ \text{Lower Limit Completeness} \end{array} \right\}$$

  - Poisson fluctuations in expected flux from dwarfs

Fermi-LAT MSP sample

- Sample: 67 LAT detected field MSPs (2PC + recent publications)
    - Excluding MSPs without distance estimates and those know to reside within globular clusters
    - Luminosity calculated for 2PC and ATNF distances:

$$L_\gamma = 4\pi F_\gamma D^2, \quad \text{where } F_\gamma \text{ is LAT reported } \gamma\text{-energy flux}$$



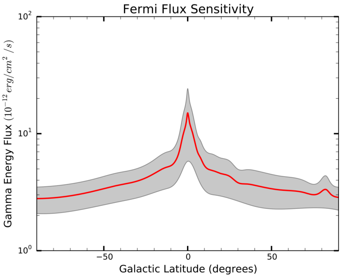
Monte Carlo Incompleteness Correction

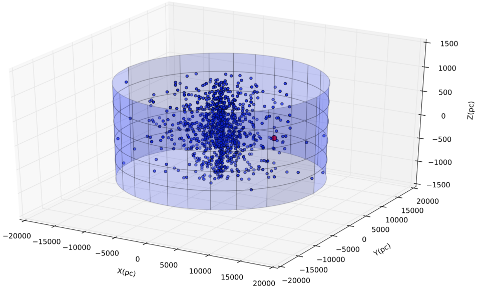
- Assumed spatial distribution: $R_0 = 4.0$ kpc and $z_0 = 1.0$ kpc (Grégoire & Knödlseder, 2013)

$$\rho(R, z) \propto e^{(-R/R_0)} e^{(-|z|/z_0)}$$

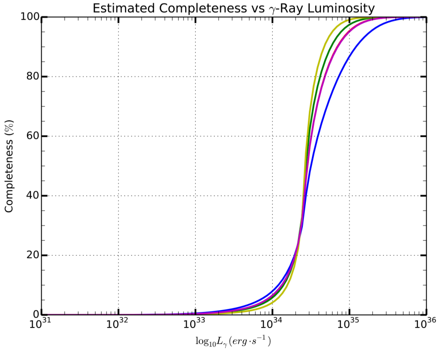
- Account for changing LAT Flux threshold as a function of b (2PC). The threshold detection distance as a function of luminosity is then,

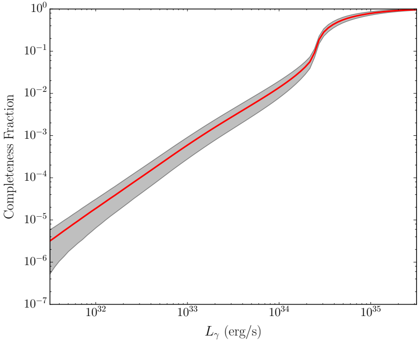
$$D_T(L_\gamma) = 1 \text{ kpc} \times \sqrt{L_\gamma / L_T} \quad \text{where} \quad L_T = 4\pi F_T(b) D^2$$





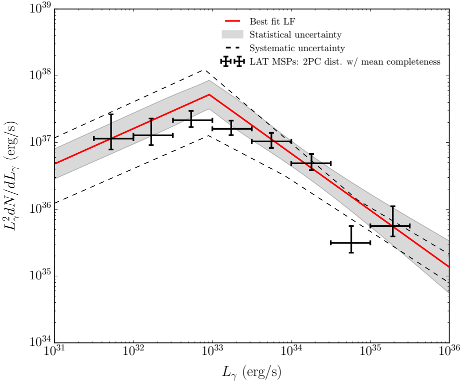
- Final result based on 10^7 simulated MSPs
- Largely complete for luminosities 10^{35} erg $\cdot$ s^{-1} and above
- Predicting $\approx 10^5$ MSPs in the MW field w/ $L_\gamma > 10^{31}$erg $\cdot$ s^{-1}
- Vary R_0 and Z_0 to account for uncertainty in spatial distribution.





MSP Luminosity Function

- Perform MCMC fit to LAT MSP sample to determine the LF
  - Larger syst. unc. at low luminosities due to completeness correction
  - Peak MSPs emission at luminosities $\approx 10^{33}\mathrm{erg} \cdot \mathrm{s}^{-1}$



Assuming broken power law: $\frac{dN}{dL_\gamma} = \begin{cases} K(L_\gamma)^{-\alpha_1} & (L_\gamma \leq L_b) \\ K(L_b)^{\alpha_2 - \alpha_1}(L_\gamma)^{-\alpha_2} & (L_\gamma > L_b) \end{cases}$

LF Comparison

- Comparison to LF constructed by Hooper and Mohlabeng, 2015
- Hooper LF breaks at slightly higher luminosity
- LFs are largely consistent overall

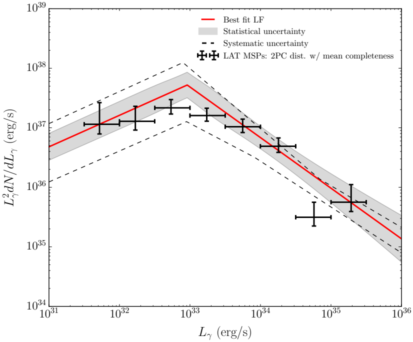


Figure : LF determined in this study

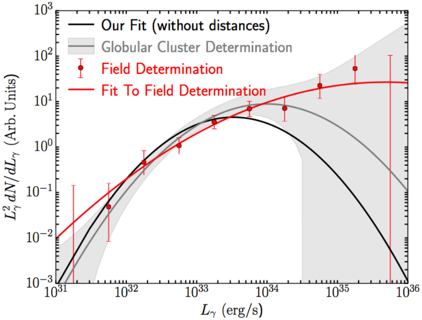
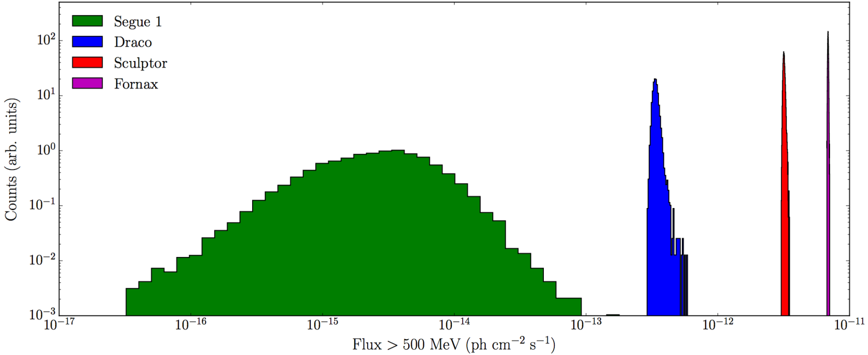


Figure : Best fit LF in black

Poisson Variations - Stellar Mass Dependence

- LAT flux threshold > 500 MeV $\approx 10^{-10}$ ph cm^{-2} s^{-1}
- Width of flux pdf scales with stellar mass
- Larger variations in low stellar mass dSphs because small number of expected MSPs

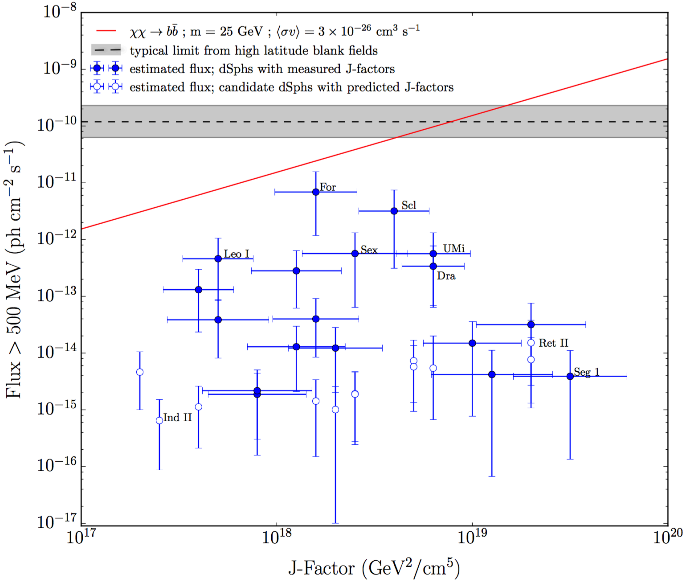


Estimated MSP Flux From the Dwarfs

Galaxy	D(kpc)	$\log_{10}(M_*/M_\odot)$	Flux > 500 MeV (ph cm^{-2} s^{-1}) Mean	Stat.	Syst.	Pois.	Total		$\log_{10}(J \left[\frac{\mathrm{GeV}^2}{\mathrm{cm}^5}\right])$	Ref.
Segue 1	23.0	$2.53^{+0.38}_{-0.20}$	3.88	$^{+1.35}_{-0.89}$	$^{+4.67}_{-2.82}$	$^{+4.03}_{-1.52}$	$^{+7.17}_{-3.77}$	$\times10^{-15}$	19.5 ± 0.29	1,5
Tucana III	25.0	$2.90^{+0.05}_{-0.05}$	7.70	$^{+2.68}_{-1.77}$	$^{+9.26}_{-5.59}$	$^{+5.63}_{-2.93}$	$^{+11.2}_{-6.61}$	$\times10^{-15}$	19.3	4
Ursa Major II	32.0	$3.73^{+0.23}_{-0.23}$	3.18	$^{+1.11}_{-0.73}$	$^{+3.82}_{-2.30}$	$^{+1.03}_{-0.77}$	$^{+4.44}_{-3.04}$	$\times10^{-14}$	19.3 ± 0.28	2,5
Reticulum II	32.0	$3.41^{+0.30}_{-0.03}$	1.52	$^{+0.53}_{-0.35}$	$^{+1.83}_{-1.10}$	$^{+0.68}_{-0.46}$	$^{+2.03}_{-1.25}$	$\times10^{-14}$	19.3	3,6
Willman I	38.0	$3.00^{+0.39}_{-0.22}$	4.19	$^{+1.46}_{-0.97}$	$^{+5.05}_{-3.04}$	$^{+2.74}_{-1.53}$	$^{+7.02}_{-4.13}$	$\times10^{-15}$	19.1 ± 0.31	1,5
Coma Berenices	44.0	$3.68^{+0.22}_{-0.22}$	1.50	$^{+0.52}_{-0.35}$	$^{+1.80}_{-1.09}$	$^{+0.51}_{-0.38}$	$^{+2.09}_{-1.42}$	$\times10^{-14}$	19.0 ± 0.25	2,5
Tucana IV	48.0	$3.34^{+0.08}_{-0.06}$	5.75	$^{+2.01}_{-1.33}$	$^{+6.92}_{-4.17}$	$^{+2.71}_{-1.78}$	$^{+7.77}_{-4.79}$	$\times10^{-15}$	18.7	4
Grus II	53.0	$3.53^{+0.04}_{-0.05}$	7.30	$^{+2.55}_{-1.68}$	$^{+8.79}_{-5.30}$	$^{+2.90}_{-2.03}$	$^{+9.63}_{-5.98}$	$\times10^{-15}$	18.7	4
Tucana II	58.0	$3.48^{+1.01}_{-0.14}$	5.44	$^{+1.90}_{-1.25}$	$^{+6.54}_{-3.95}$	$^{+2.20}_{-1.53}$	$^{+14.5}_{-4.75}$	$\times10^{-15}$	18.8	3,6
Bootes I	66.0	$4.45^{+0.09}_{-0.06}$	4.01	$^{+1.37}_{-0.90}$	$^{+4.83}_{-2.91}$	$^{+0.63}_{-0.54}$	$^{+5.12}_{-3.14}$	$\times10^{-14}$	18.2 ± 0.22	1,5
Indus I	69.0	$2.90^{+0.22}_{-0.22}$	1.01	$^{+0.35}_{-0.23}$	$^{+1.22}_{-0.73}$	$^{+0.73}_{-0.38}$	$^{+1.55}_{-1.00}$	$\times10^{-15}$	18.3	3,6
Ursa Minor	76.0	$5.73^{+0.20}_{-0.20}$	5.63	$^{+1.96}_{-1.30}$	$^{+6.78}_{-4.09}$	$^{+0.25}_{-0.24}$	$^{+7.52}_{-5.02}$	$\times10^{-13}$	18.8 ± 0.19	2,5
Draco	76.0	$5.51^{+0.10}_{-0.10}$	3.39	$^{+1.18}_{-0.78}$	$^{+4.08}_{-2.46}$	$^{+0.19}_{-0.18}$	$^{+4.33}_{-2.70}$	$\times10^{-13}$	18.8 ± 0.16	2,5
Sculptor	86.0	$6.59^{+0.21}_{-0.21}$	3.19	$^{+1.11}_{-0.73}$	$^{+3.83}_{-2.31}$	$^{+0.05}_{-0.05}$	$^{+4.28}_{-2.87}$	$\times10^{-12}$	18.6 ± 0.18	2,5
Sextans	86.0	$5.84^{+0.20}_{-0.20}$	5.66	$^{+1.98}_{-1.31}$	$^{+6.82}_{-4.11}$	$^{+0.23}_{-0.22}$	$^{+7.57}_{-5.05}$	$\times10^{-13}$	18.4 ± 0.27	2,5
Horologium I	87.0	$3.38^{+0.25}_{-0.13}$	1.92	$^{+0.67}_{-0.44}$	$^{+2.31}_{-1.39}$	$^{+0.87}_{-0.58}$	$^{+2.79}_{-1.67}$	$\times10^{-15}$	18.4	3,6
Reticulum III	92.0	$3.30^{+0.13}_{-0.15}$	1.43	$^{+0.50}_{-0.33}$	$^{+1.72}_{-1.04}$	$^{+0.70}_{-0.45}$	$^{+1.97}_{-1.28}$	$\times10^{-15}$	18.2	4
Phoenix II	95.0	$3.45^{+0.19}_{-0.11}$	1.89	$^{+0.66}_{-0.44}$	$^{+2.28}_{-1.37}$	$^{+0.81}_{-0.55}$	$^{+2.64}_{-1.61}$	$\times10^{-15}$	18.4	3,6
Ursa Major I	97.0	$4.28^{+0.13}_{-0.13}$	1.23	$^{+0.43}_{-0.28}$	$^{+1.48}_{-0.89}$	$^{+0.24}_{-0.20}$	$^{+1.60}_{-1.02}$	$\times10^{-14}$	18.3 ± 0.24	2,5
Carina	105.0	$5.63^{+0.11}_{-0.09}$	2.82	$^{+0.82}_{-0.54}$	$^{+3.39}_{-2.04}$	$^{+0.13}_{-0.12}$	$^{+3.56}_{-2.20}$	$\times10^{-13}$	18.1 ± 0.23	1,5
Hercules	132.0	$4.57^{+0.14}_{-0.14}$	1.29	$^{+0.45}_{-0.30}$	$^{+1.55}_{-0.94}$	$^{+0.19}_{-0.16}$	$^{+1.68}_{-1.08}$	$\times10^{-14}$	18.1 ± 0.25	2,5
Fornax	147.0	$7.39^{+0.14}_{-0.14}$	6.88	$^{+2.40}_{-1.59}$	$^{+8.28}_{-4.99}$	$^{+0.05}_{-0.05}$	$^{+8.90}_{-5.69}$	$\times10^{-12}$	18.2 ± 0.21	2,5
Leo IV	154.0	$3.93^{+0.15}_{-0.15}$	2.17	$^{+0.76}_{-0.50}$	$^{+2.62}_{-1.58}$	$^{+0.57}_{-0.45}$	$^{+2.88}_{-1.87}$	$\times10^{-15}$	17.9 ± 0.28	2,5
Canes Venatici II	160.0	$3.90^{+0.20}_{-0.20}$	1.88	$^{+0.66}_{-0.43}$	$^{+2.26}_{-1.36}$	$^{+0.53}_{-0.41}$	$^{+2.56}_{-1.72}$	$\times10^{-15}$	17.9 ± 0.25	2,5
Columba I	182.0	$3.79^{+0.13}_{-0.07}$	1.13	$^{+0.39}_{-0.26}$	$^{+1.36}_{-0.82}$	$^{+0.35}_{-0.26}$	$^{+1.49}_{-0.92}$	$\times10^{-15}$	17.6	4
Indus II	214.0	$3.69^{+0.16}_{-0.14}$	6.48	$^{+2.26}_{-1.49}$	$^{+7.80}_{-4.70}$	$^{+2.19}_{-1.62}$	$^{+8.74}_{-5.59}$	$\times10^{-16}$	17.4	4
Canes Venatici I	218.0	$5.48^{+0.09}_{-0.09}$	3.85	$^{+1.34}_{-0.89}$	$^{+4.63}_{-2.79}$	$^{+0.22}_{-0.21}$	$^{+4.89}_{-3.04}$	$\times10^{-14}$	17.7 ± 0.26	2,5
Leo II	233.0	$6.07^{+0.13}_{-0.13}$	1.31	$^{+0.46}_{-0.30}$	$^{+1.58}_{-0.95}$	$^{+0.04}_{-0.04}$	$^{+1.69}_{-1.07}$	$\times10^{-13}$	17.6 ± 0.18	2,5
Leo I	254.0	$6.69^{+0.13}_{-0.13}$	4.60	$^{+1.60}_{-1.06}$	$^{+5.53}_{-3.34}$	$^{+0.07}_{-0.07}$	$^{+5.92}_{-3.76}$	$\times10^{-13}$	17.7 ± 0.18	2,5
Eridanus II	330.0	$4.92^{+0.09}_{-0.07}$	4.62	$^{+1.61}_{-1.07}$	$^{+5.57}_{-3.36}$	$^{+0.47}_{-0.42}$	$^{+5.89}_{-3.63}$	$\times10^{-15}$	17.3	3,6

REFERENCES. — (1) Wolf et al. (2010), (2) Kirby et al. (2013), (3) Bechtol et al. (2015), (4) Drlica-Wagner et al. (2015a), (5) Ackermann et al. (2015), (6) Drlica-Wagner et al. (2015b)

Summary Figure - Flux vs J-Factor



Conclusions

- **Results:**
  - Our results suggest that the dwarfs, especially those with higher stellar masses, are likely to host a small MSP population
  - Most massive classical dwarfs (For, Scl,...) are within an order of magnitude of LAT flux threshold
  - Estimated emission in ultra-faints (Seg 1, Ret II,...) is well below threshold
  - Most important dwarfs, i.e. ultra-faints w/ largest J-factors, expected to be safe targets for future DM searches
- **Status and Final Steps:**
  - Calculations are effectively complete
  - Put finishing touches on plot and tables
  - Finalize draft
  - Submit in mid June

Extra Slide - LMXBs as M_* Indicators

- Gilfanov, 2004 reports relationship between N_X and M_*
  - $N_X/M_* \approx 166.3 \pm 20.5$ src ($L_X > 10^{37}$ erg/s) per $10^{11} M_\odot$

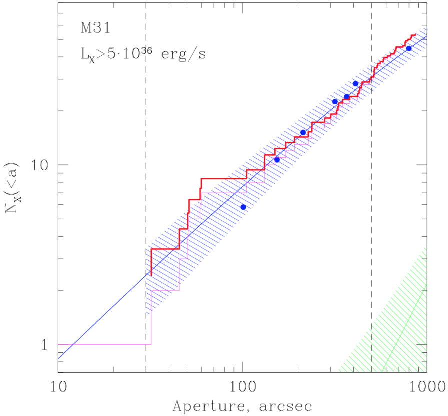


Figure : N_X (red) and near-infrared K-band (pink) growth curves

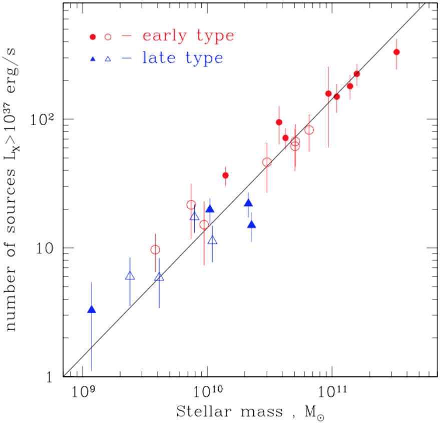


Figure : Number of X-ray Sources per Stellar Mass

Extra Slide - LMXBs as M_* Indicators

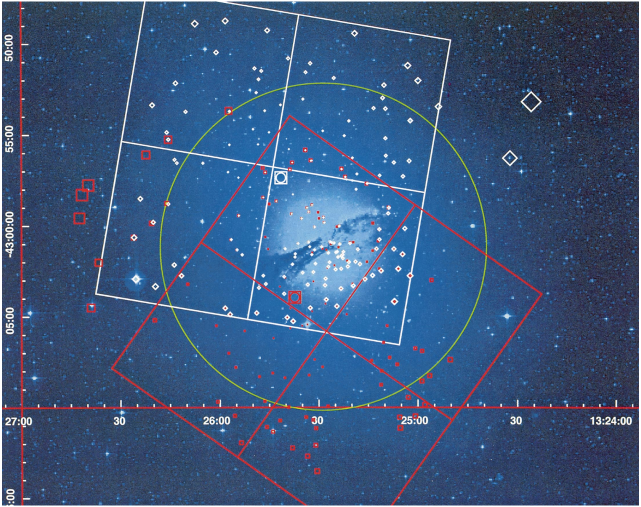


Figure : Chandra: X-ray point sources in Centaurus A (Kraft et al. 2001)