Gamma Rays From Nebulae Associated with Microquasars and Ultra-Luminous X-ray Sources

Yoshiyuki Inoue (ISAS/JAXA)
Shiu-Hang (Herman) Lee (ISAS -> Kyoto), Yasuyuki T. Tanaka (Hiroshima), Shogo B. Kobayashi (Tokyo)

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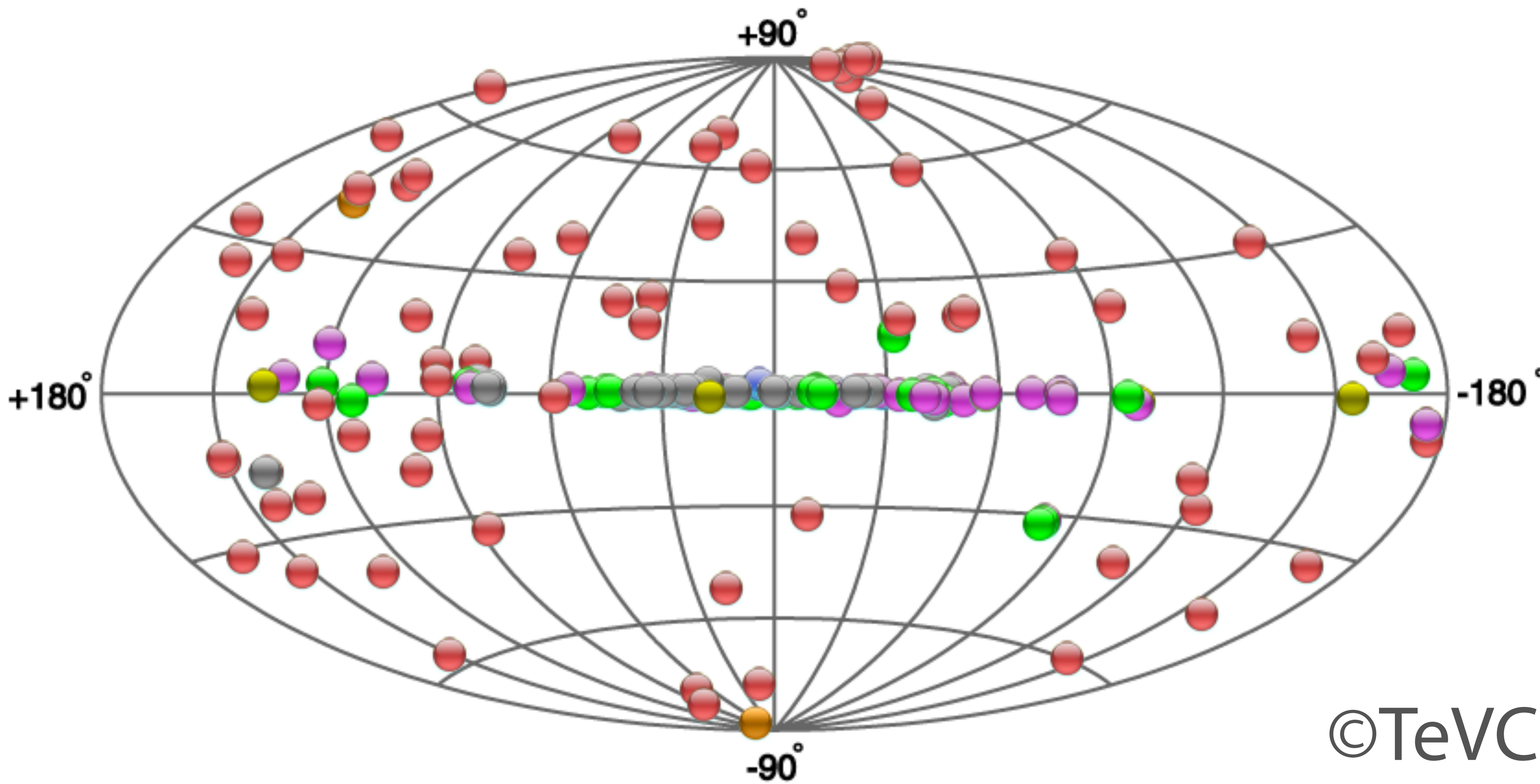
Current View of VHE Gamma-Ray Sky



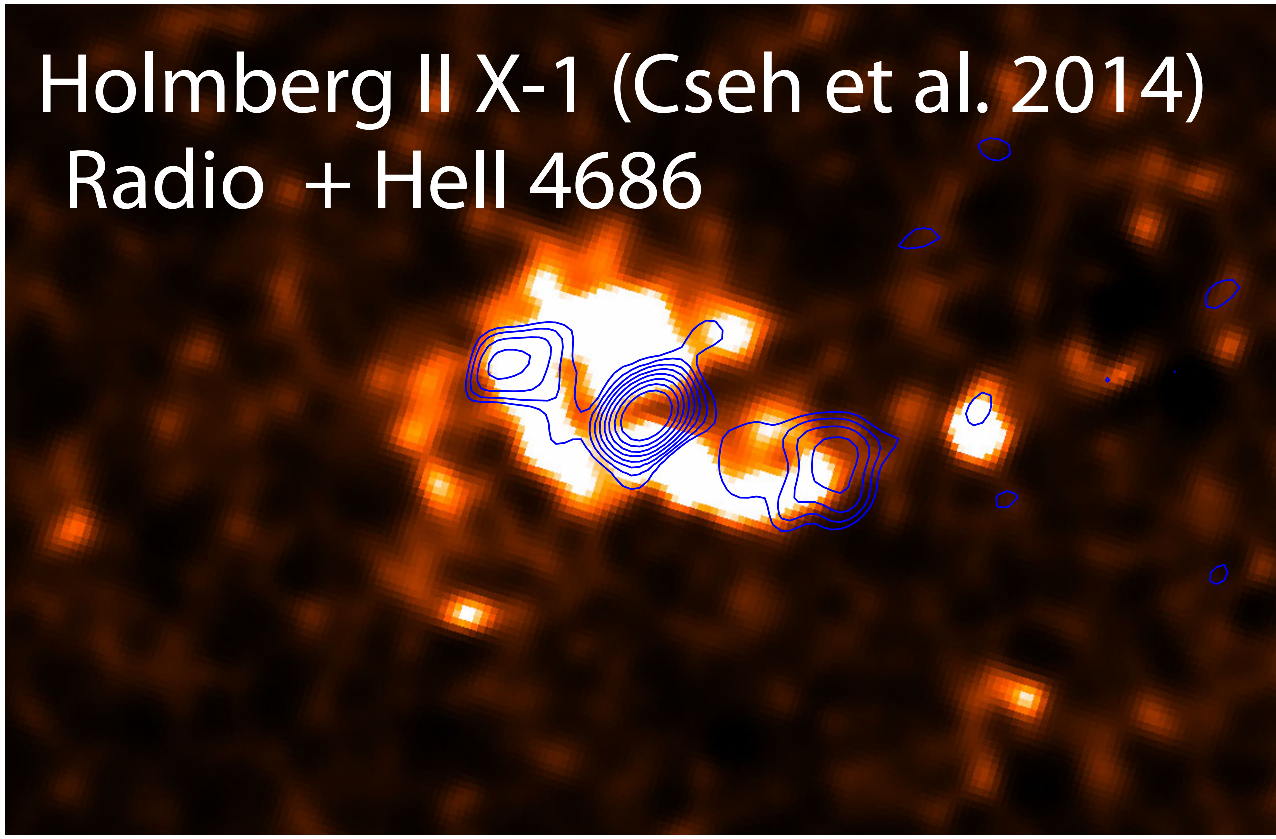
- ~180 very high energy (VHE; >50 GeV) objects by imaging atmospheric Cherenkov telescopes (IACTs; see TeVCat)

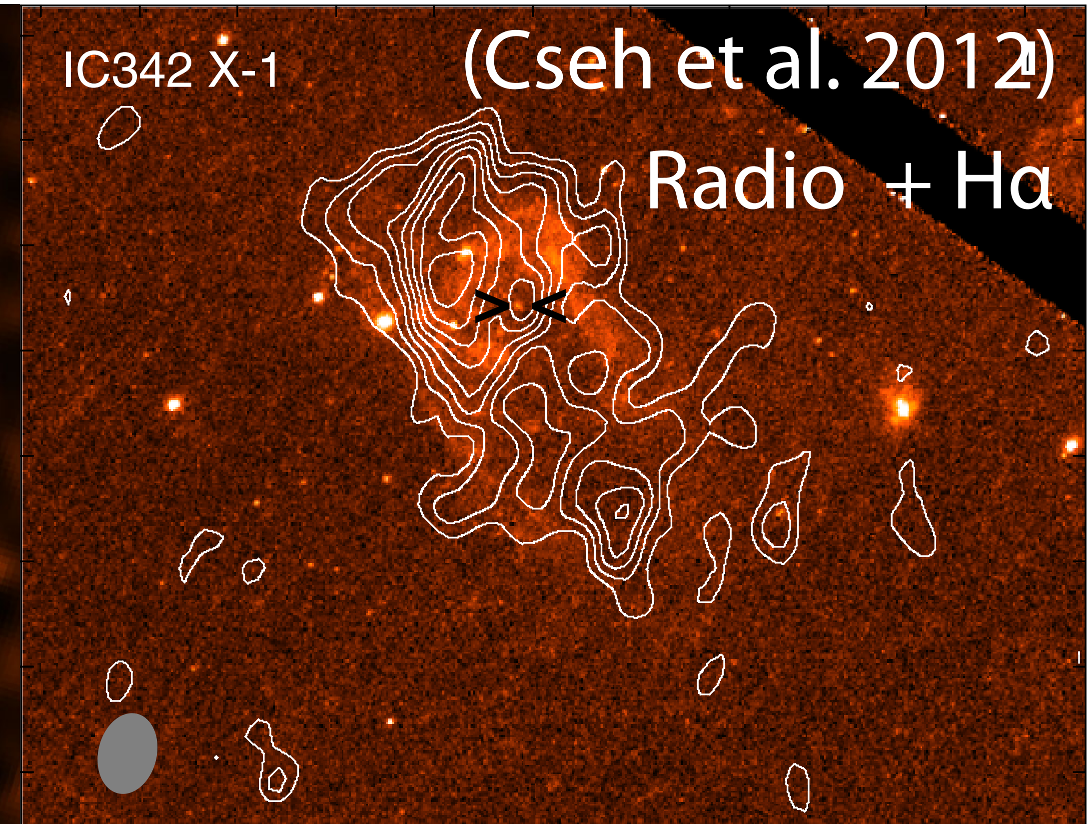
- CTA will discover new cosmic-ray accelerators.

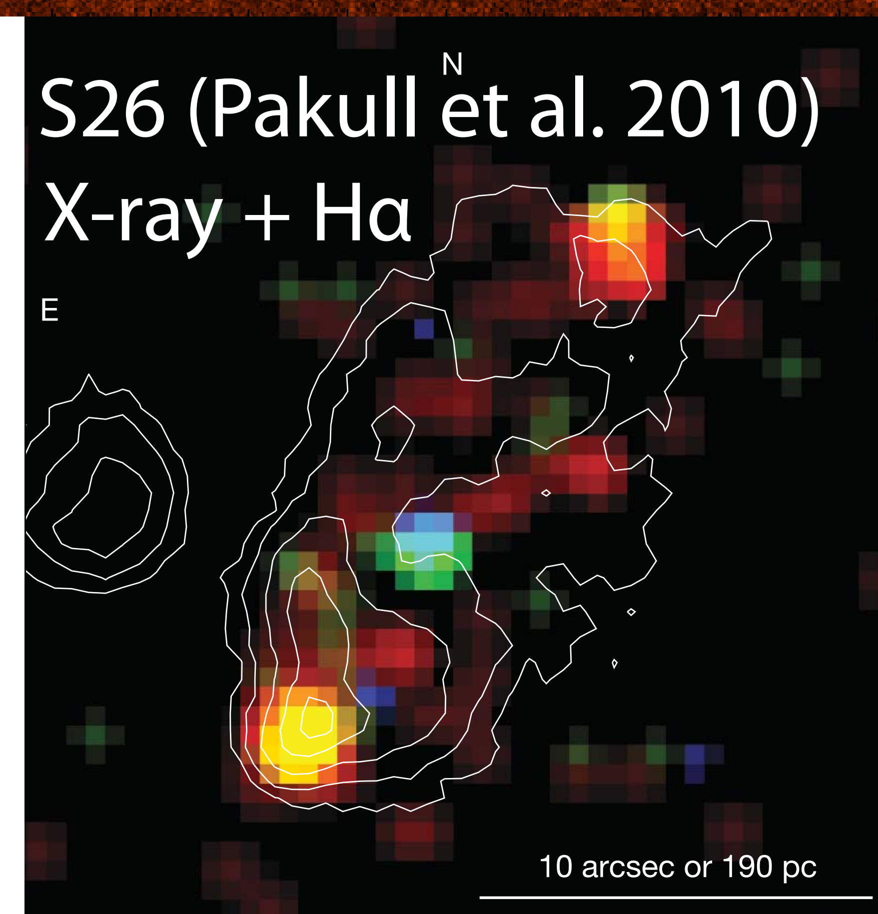
Microquasars and ULXs in Extragalactic Sky

- Microquasars and ultra-luminous X-ray sources (ULXs) are
  - X-ray binary systems
    - Black hole mass is still under debate (intermediate or stellar)… or powered by pulsars (Bachetti+'14)
  - kinetic/radiative power >$10^{39\text{-}40}$ erg/s (Mirabel & Rodriguez '99, Feng & Soria '11)
  - associated with star-forming regions (e.g. Swartz+'09, Poutanen+'13)

Micro-quasars and ULXs Bubbles







- Some microquasars and ULXs associate with expanding bubbles.
  - R_b~200 pc
  - v_s ~ 80-250 km/s

Expanding Power of Bubbles

- Self-similar expansion law gives (Weaver+'77; Kaiser & Alexander '97)

$$R_b \approx 0.76 (P_{\rm kin}/\mu m_p n_{\rm gas})^{1/5} t^{3/5}$$

  - The characteristic age:

$$\tau = 3R_b/5v_s \sim 4.9 \times 10^4 R_{b,20.8} v_{s,7.1}^{-1}\ {\rm yr}$$

  - The time-average kinetic power of the bubble:

$$P_{\rm kin} \approx 18 \mu m_p n_{\rm gas} R_b^2 v_s^3 \sim 3.6 \times 10^{40} R_{b,20.8}^2 v_{s,7.1}^3 n_{\rm gas,0.5}\ {\rm erg\ s^{-1}}$$

10^{40} erg/s power is available.

Shock Condition

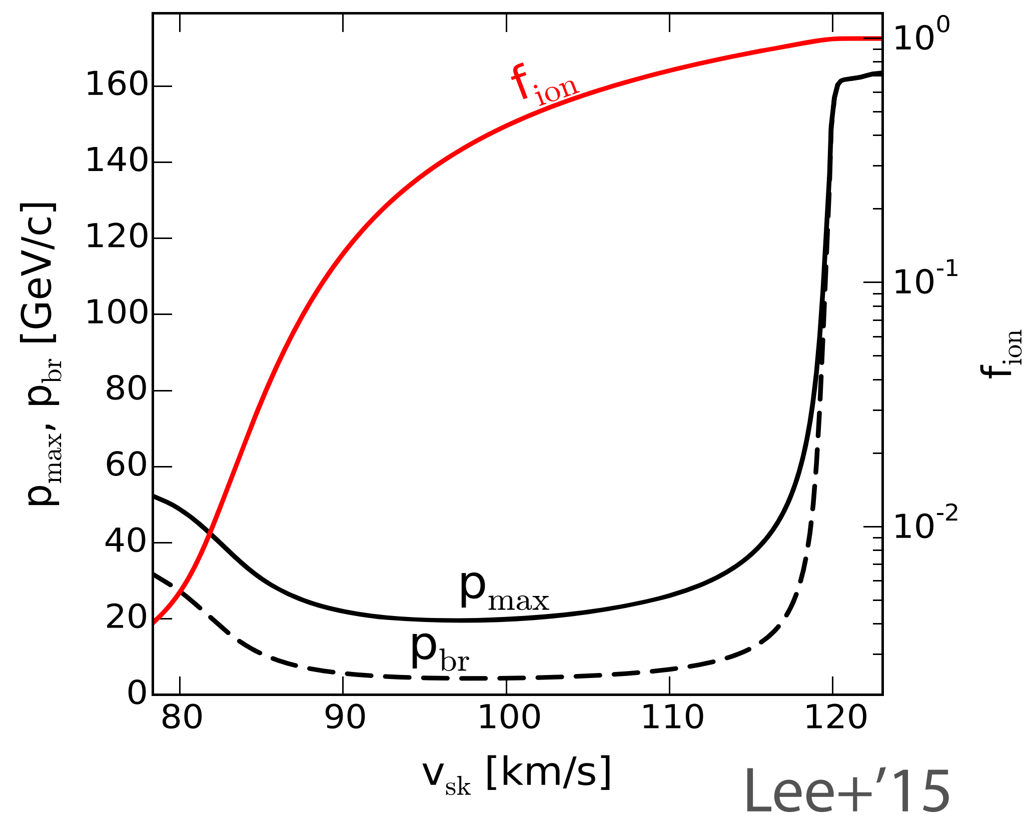
- Downstream temperature

$$T_d \sim 2.0 \times 10^5 v_{s,7.1}^2 \text{ K}$$

- Radiative cooling time scale (Draine '11)

$$t_{\rm rad} \sim 1.4 \times 10^3 n_{\rm gas,0.5}^{-1} v_{s,7.1}^{17/5} \text{ yr}$$

➡Radiative shock



Lee+'15

- Ionized fraction strongly depends on the shock velocity
  (Shull & McKee '79; Hollenbach & McKee '89, Lee+'15)

- Ion-neutral collisions will hamper particle acc.

$$E_{\rm cr,br} \sim 1.9\ T_{u,4}^{-0.4} B_{u,-6}^2 (1 - f_{\rm ion})^{-1} f_{\rm ion}^{-1/2} n_{\rm gas,0.5}^{-3/2} \text{ GeV}$$

Gamma-ray production

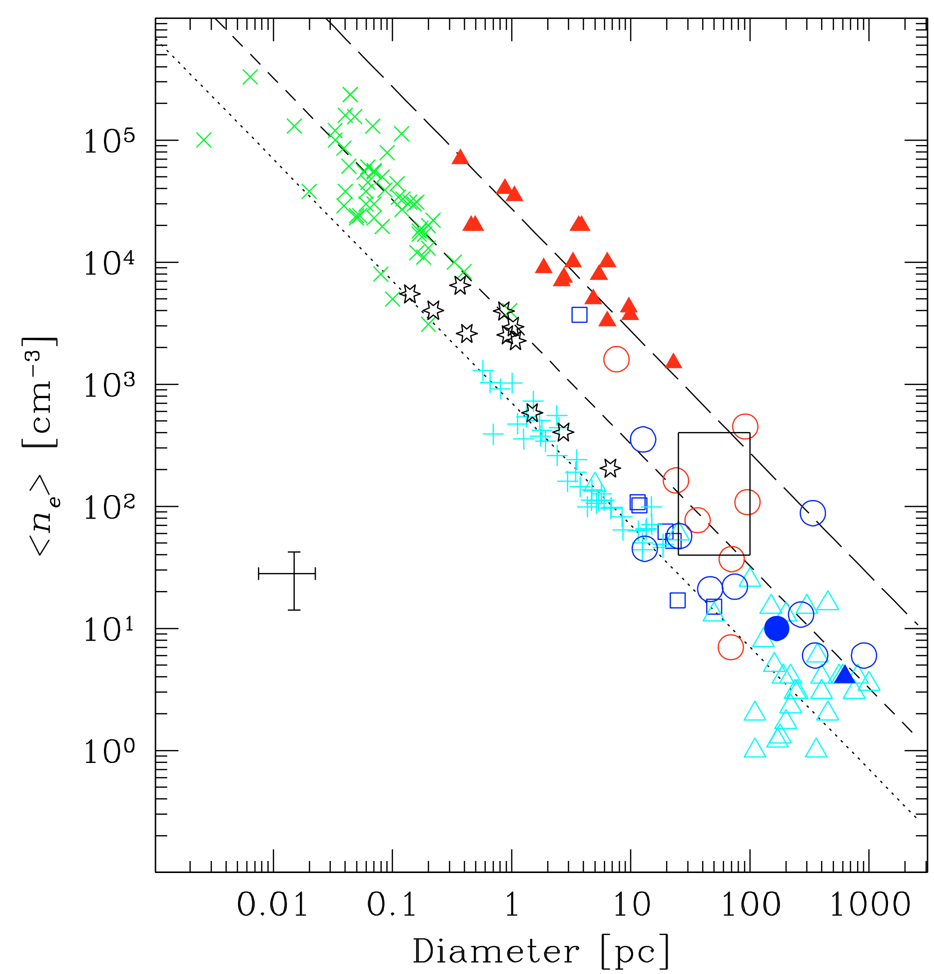
- The maximum cosmic-ray energy

$$E_{\rm cr,max} \sim 1.3 \times 10^2 \eta_0 n_{\rm gas,0.5}^{1/2} v_{s,7.1} R_{\rm b,20.8}~{\rm TeV}$$

- ULXs are known to be associated with star forming regions (Swartz+'09)
    - $n_{\rm gas}$ ~ 1-10 $\rm cm^{-3}$ (Hunt & Hirashita '09)

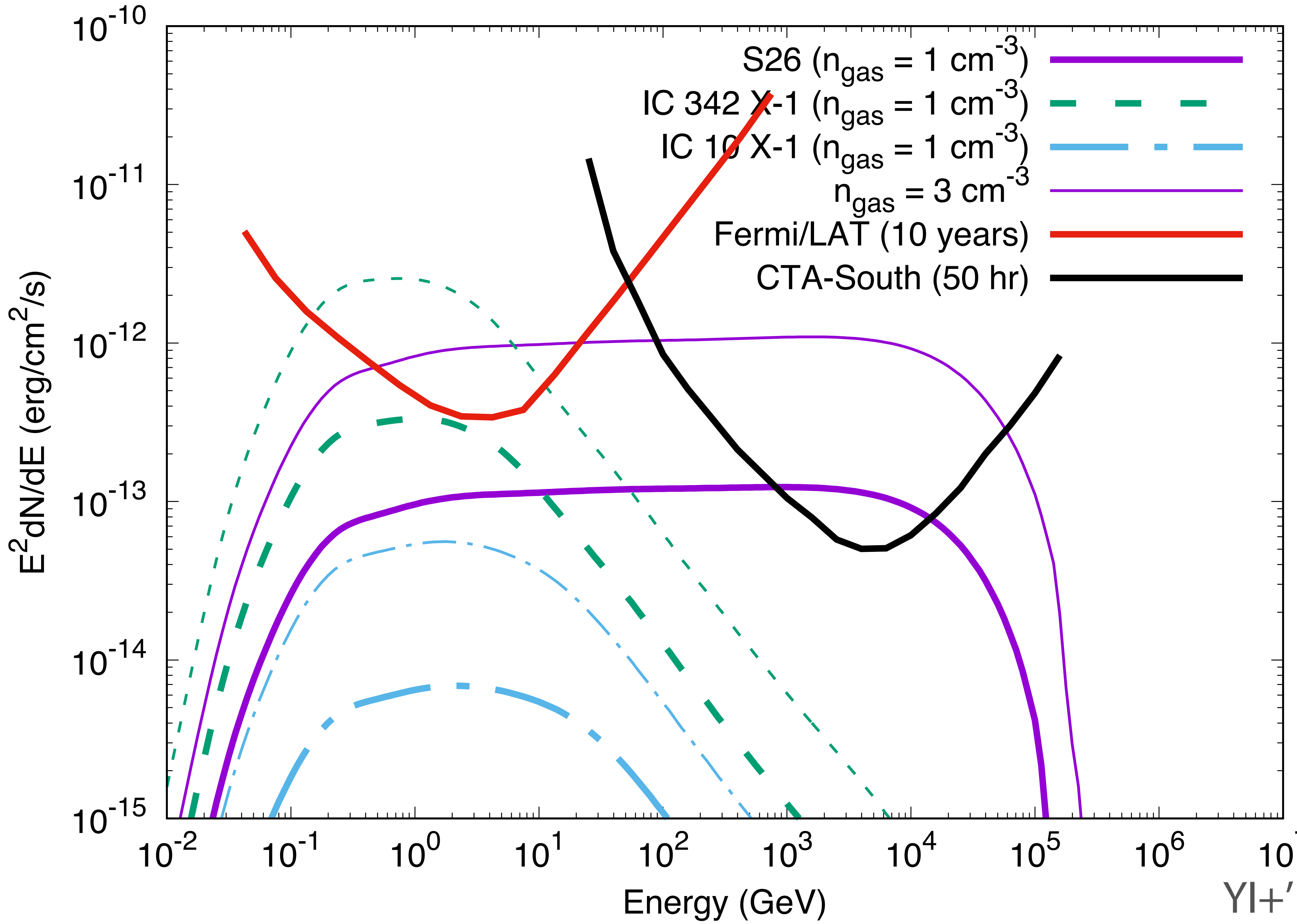
- Hadronuclear interaction efficiency

$$f_{\rm pp} \sim 0.28 R_{\rm b,20.8} v_{s,7.1}^{-1} n_{\rm gas,0.5}$$



Hunt & Hirashita '09

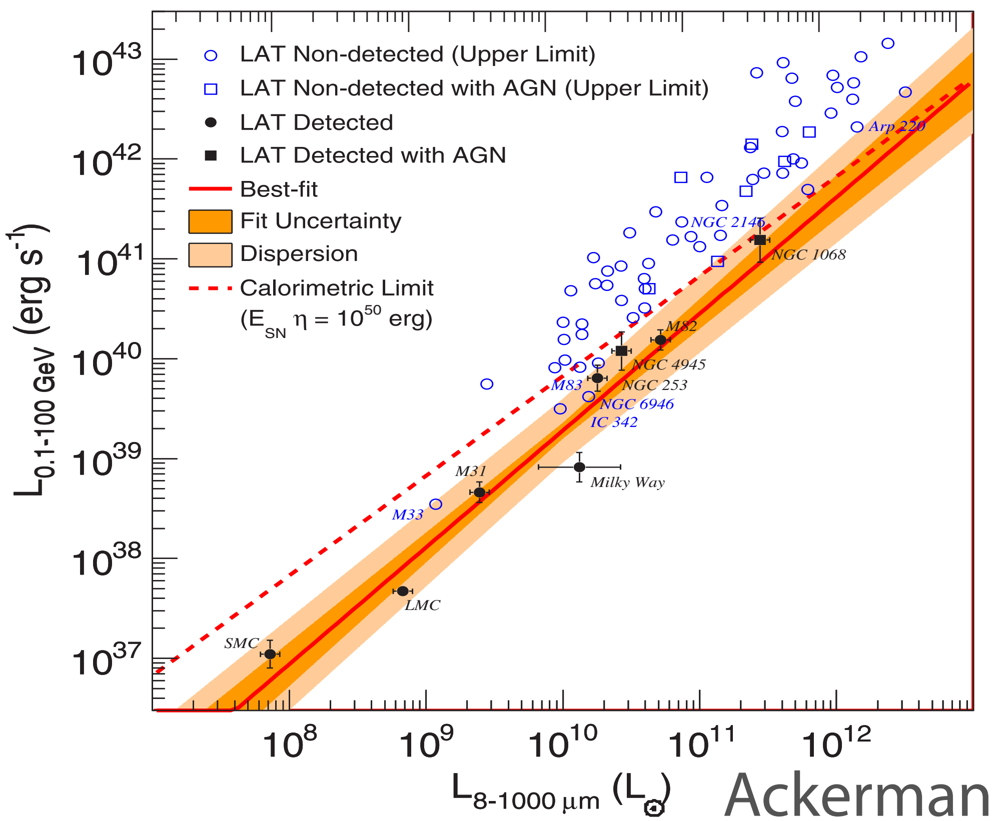
Expected Gamma-ray Spectra



YI+'16

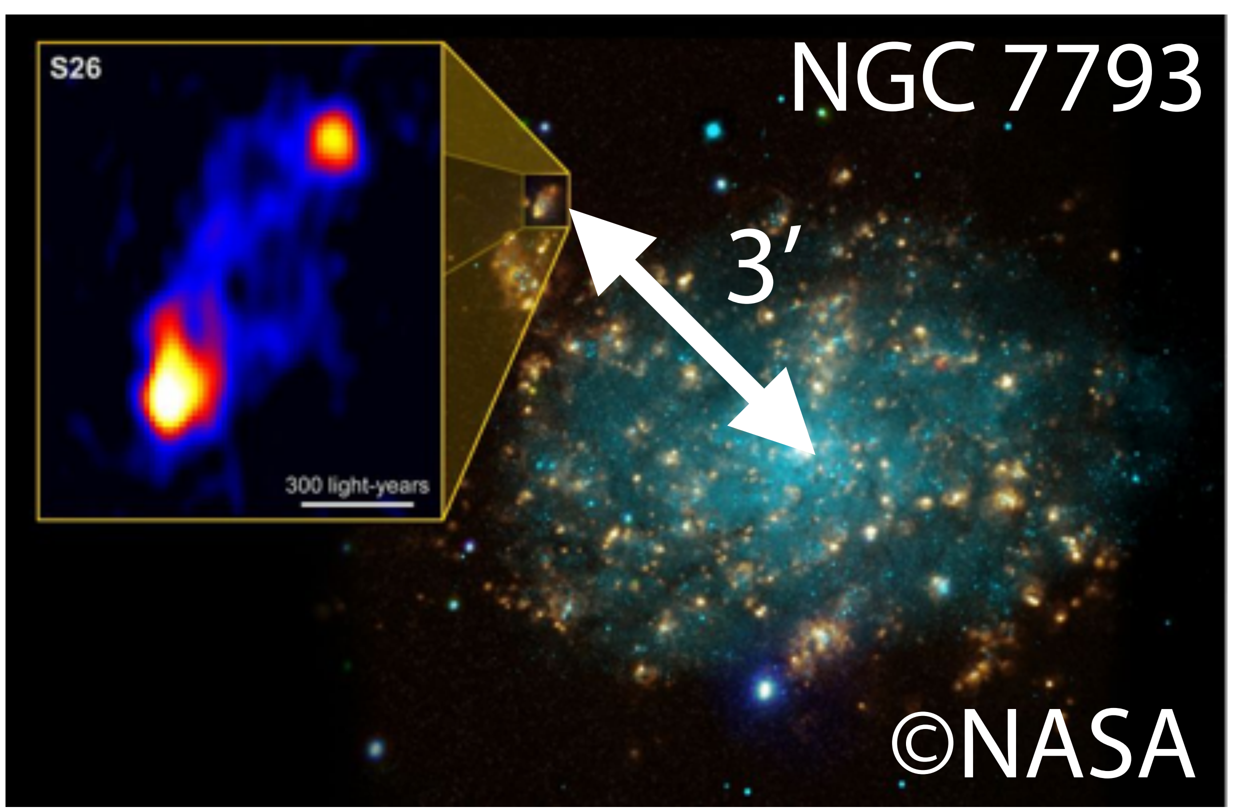
- Assuming 10% of kinetic energy goes into particle acc.
- Microquasar nebula S26 would be a good target for CTA

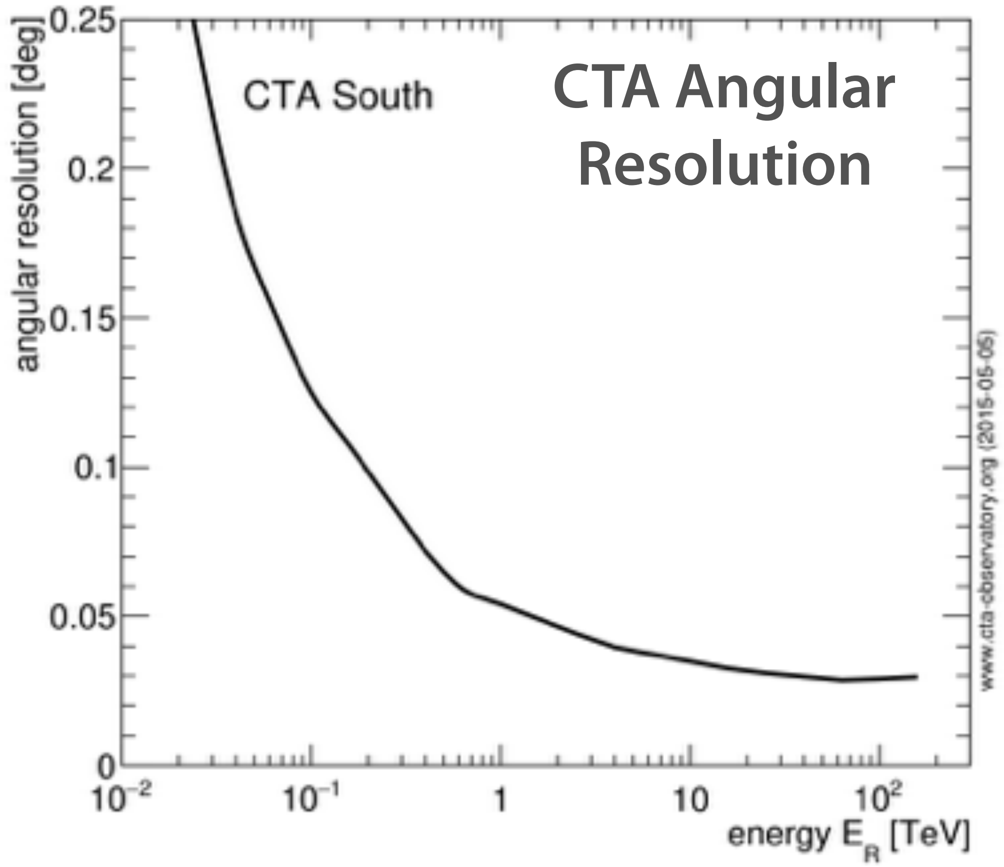
Emission in Galaxies



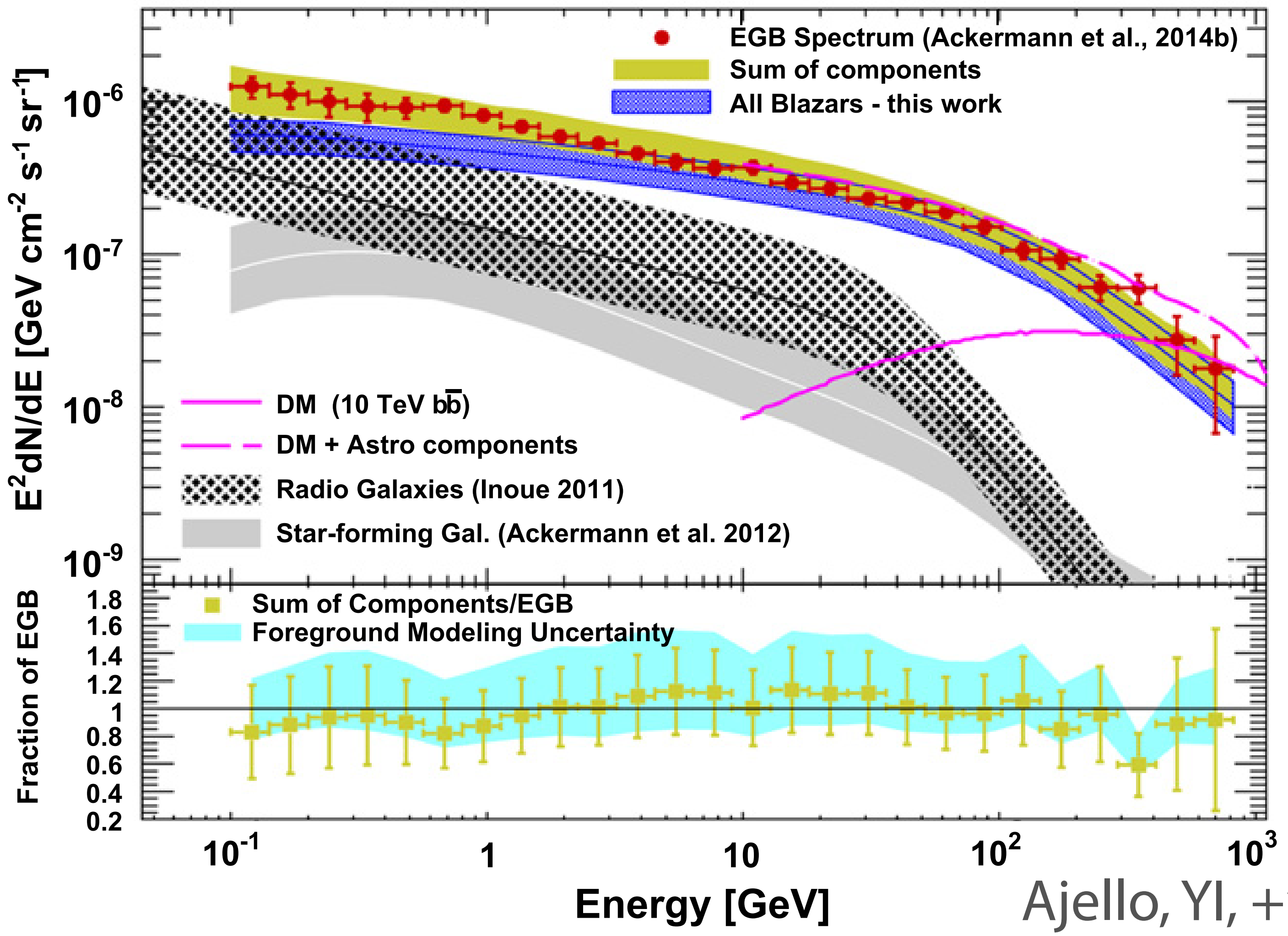
Ackermann+'12

- Host galaxy of S26 would have comparable gamma-ray flux for n_{gas} = 1 cm^{-3}
- S26 is ~3′ away from the nucleus





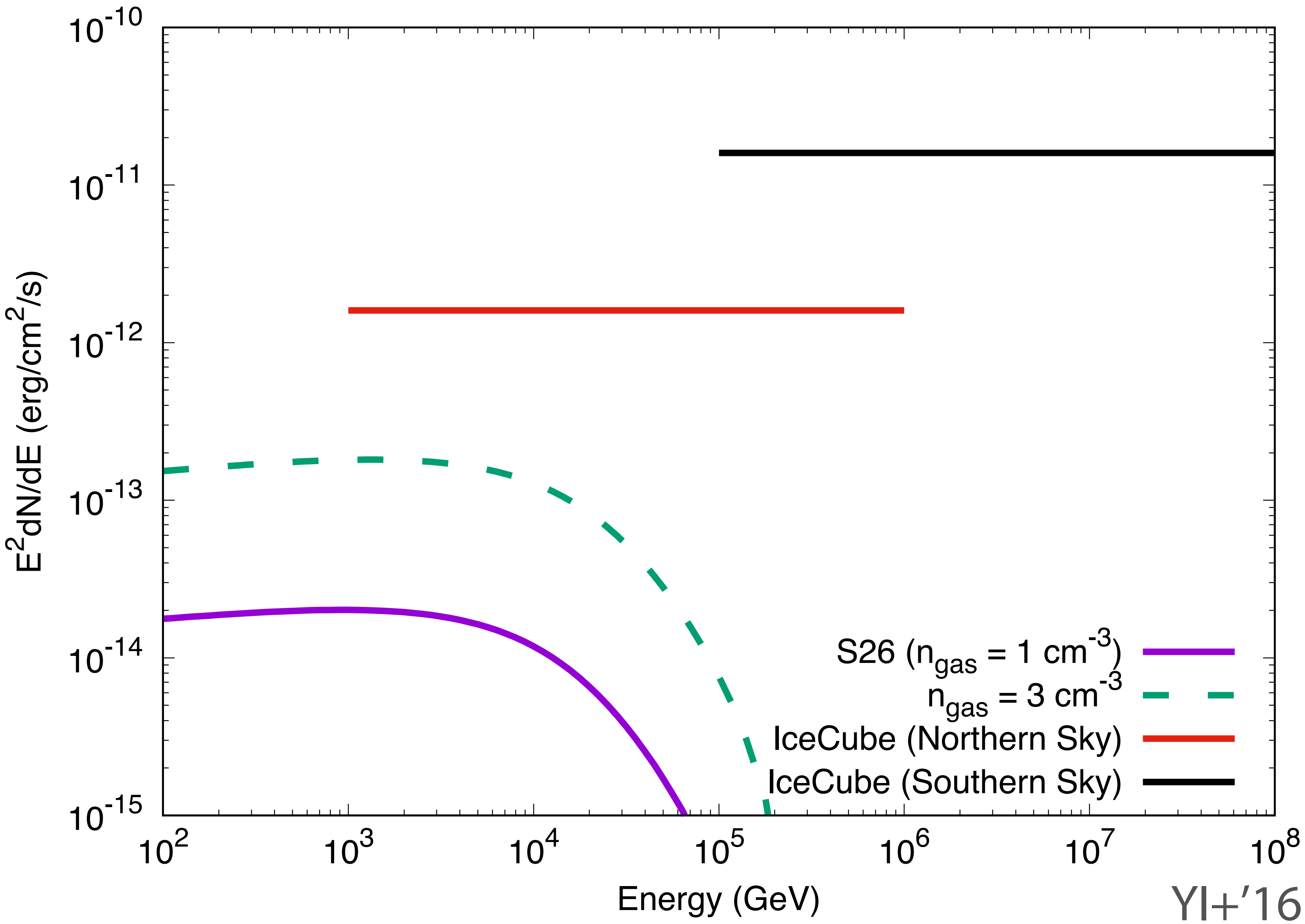
Cosmic Gamma-ray Background Radiation



Ajello, YI, +'15

- Blazars (YI & Totani'09; Ajello, YI+'15), Radio galaxies (YI'11), Starburst galaxies (Ackermann+'12)
    - 60-70 % of the cosmic gamma-ray background is not resolved yet (Ackermann+'14).
- ULX bubbles would contribute to ~7 % of the unresolved background flux.

Neutrino Production?



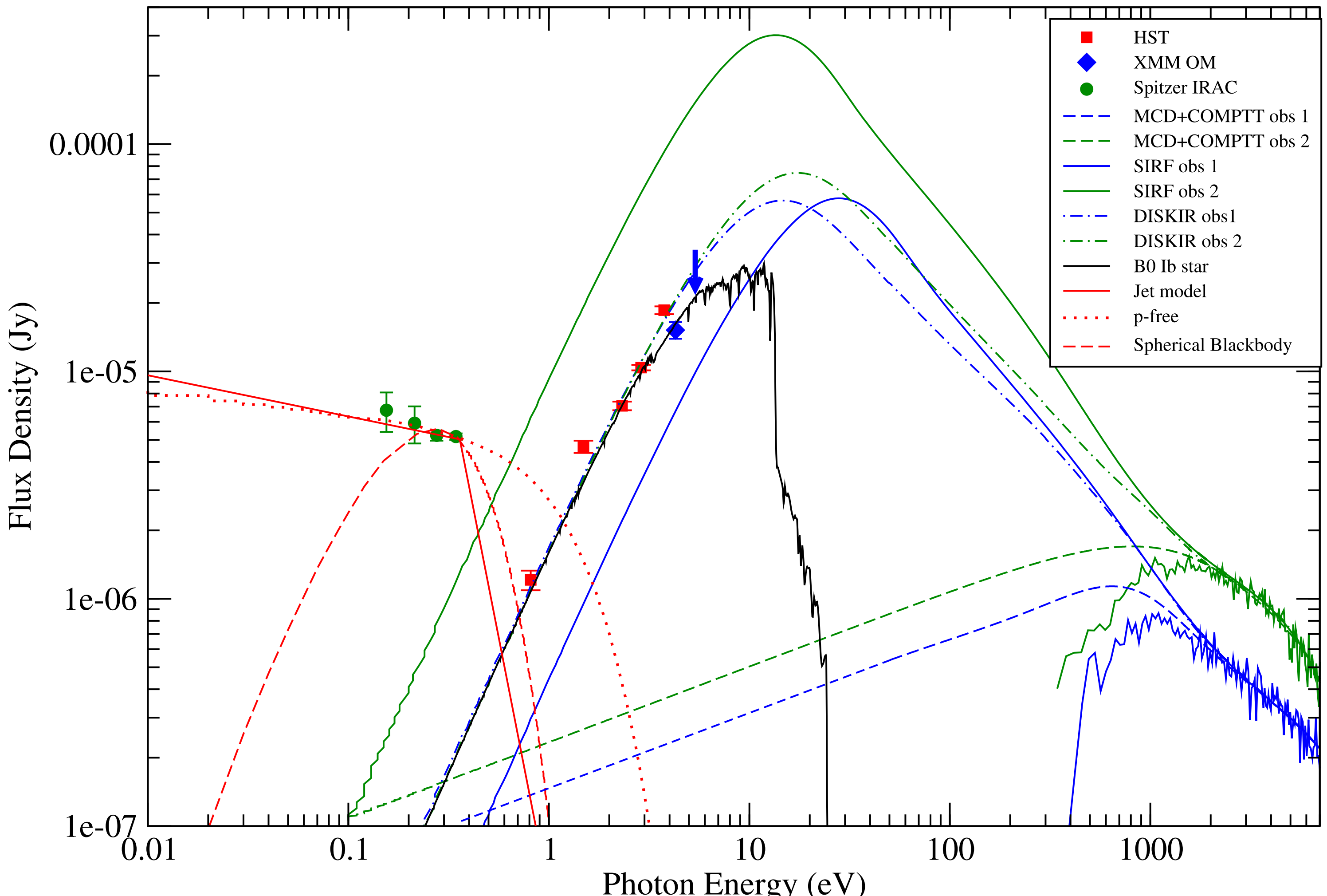
YI+'16

- A factor of ~10 sensitive neutrino detectors will be able to see the object.
  - But, contamination of host galaxies would be significant.

Summary

- Microquasar/ULX bubbles are efficient cosmic-ray accelerators.
  - Especially, the bubbles of S26 will a good target for future CTA observations.
  - Host galaxy contamination can be removed by CTA's angular resolution.
  - These bubbles would make up ~7% of the unresolved gamma-ray background.
  - ULX workshop @ ISAS, 2017/3/6-7

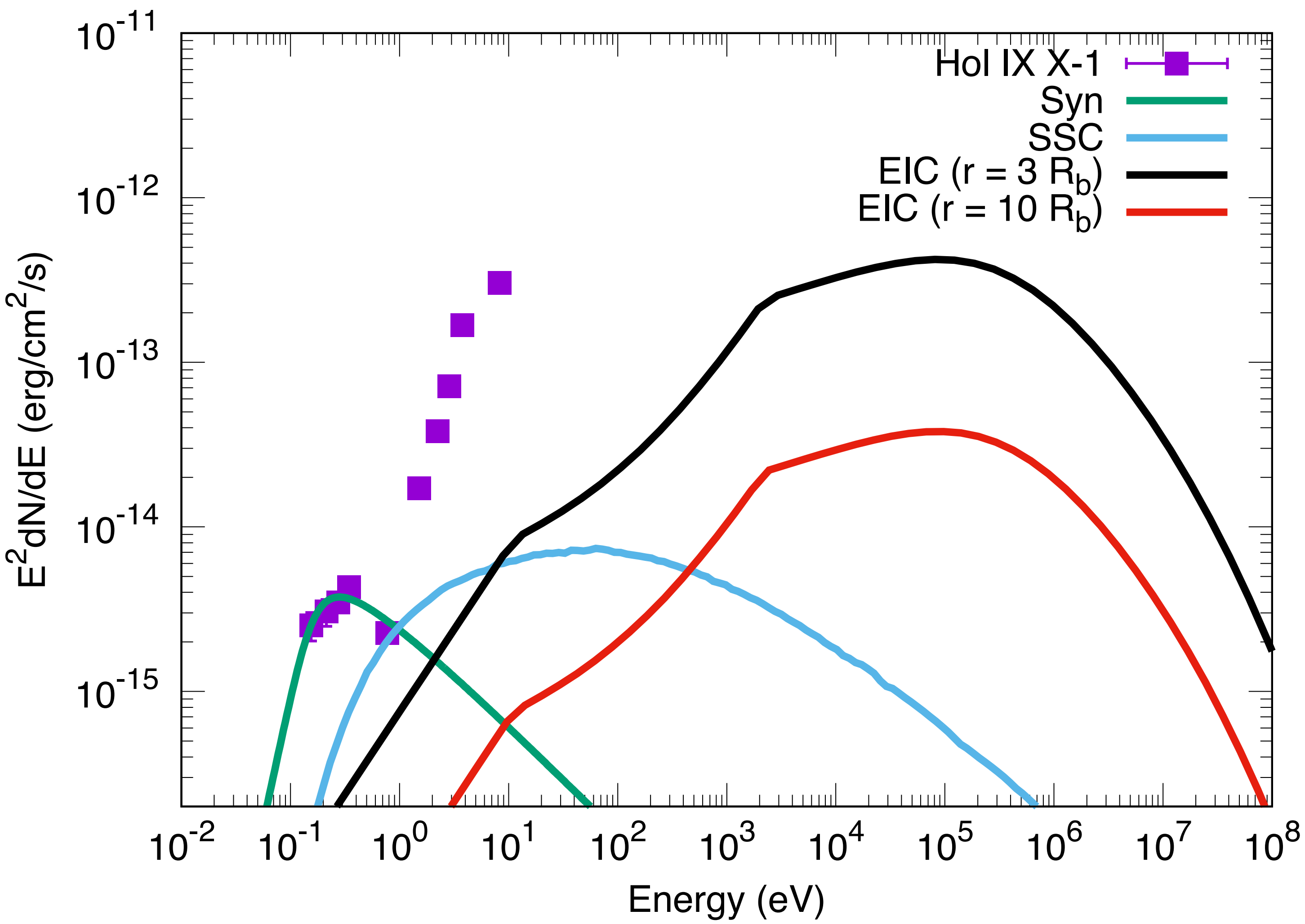
Evidence of ULX Jets?



Dudik+'16

- ULX jets are not established yet.
- Possible synchrotron self-absorption (SSA) feature is discovered for Hol IX X-1 (Dudik+'16).
- or, circumbinary disk?

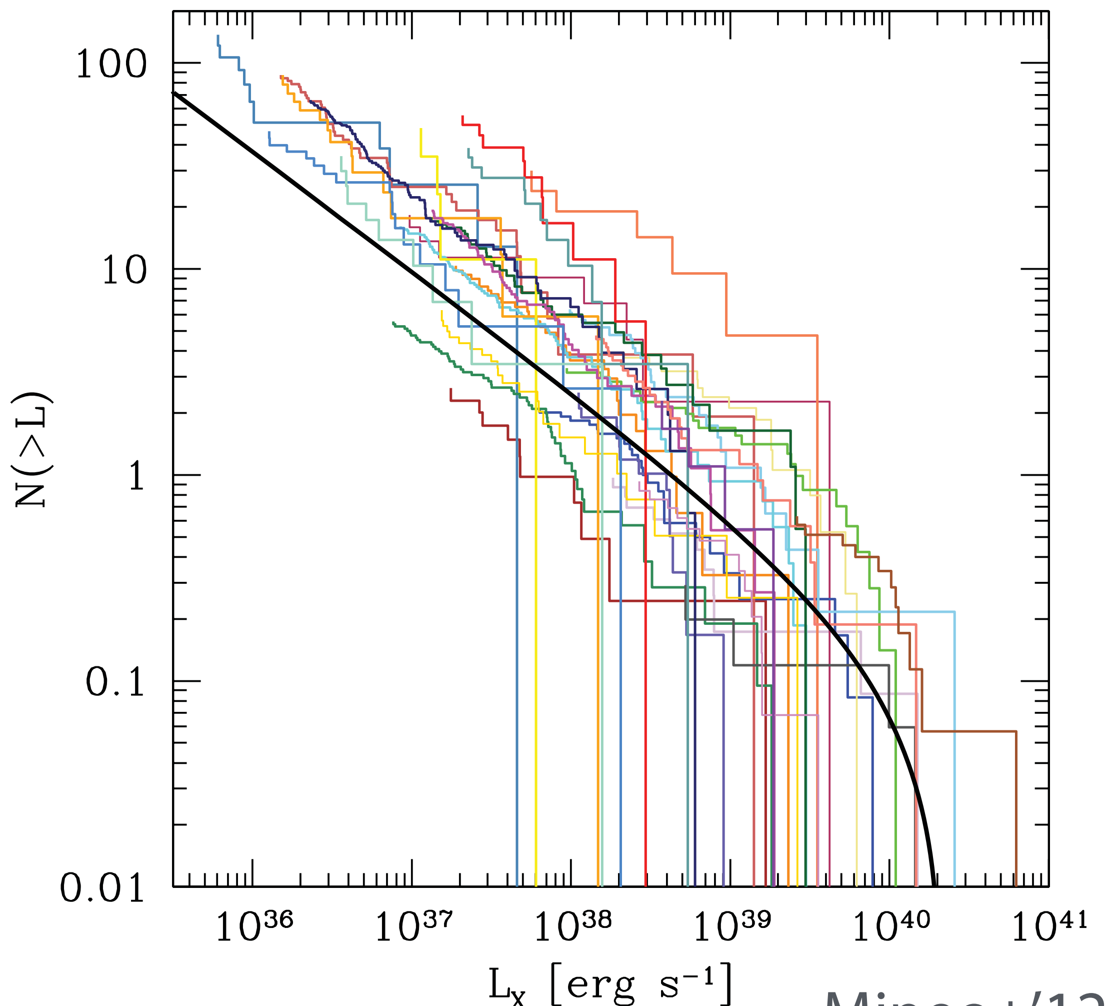
MWL Spectrum of Hol IX X-1 from Jet



- Assuming SSA, B ~ 3.4 x 10^4 G & R_b ~ 1.6 x 10^9 cm
  - Similar to Galactic X-ray binaries (e.g. Tanaka, YI+'16 for V404 Cyg)
- location r > 2 R_b
  - ~1000 r_s for 10 M_{sun}
  - 10 r_s for 1000 M_{sun}

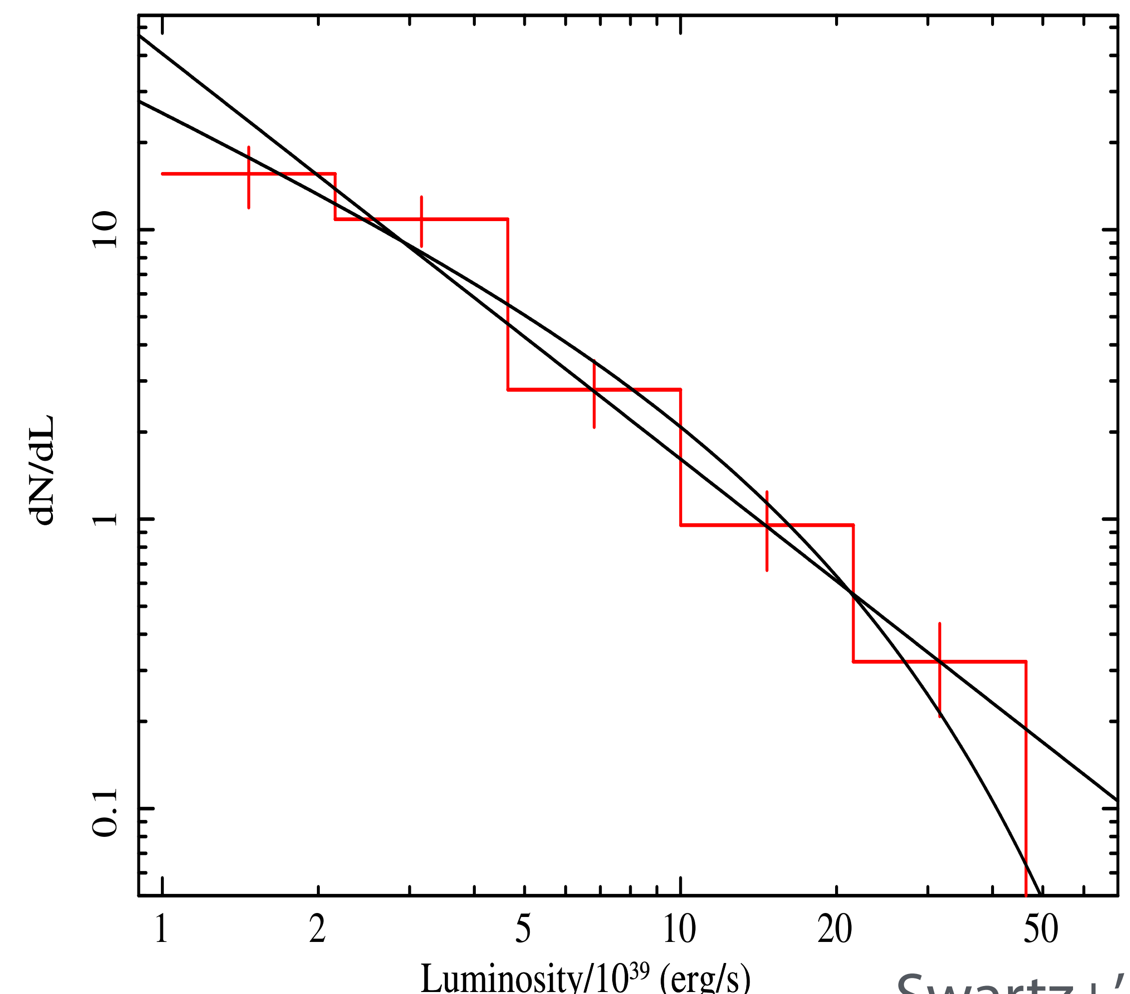
ULX Luminosity Function

XRB LF in each galaxy



Mineo+’12

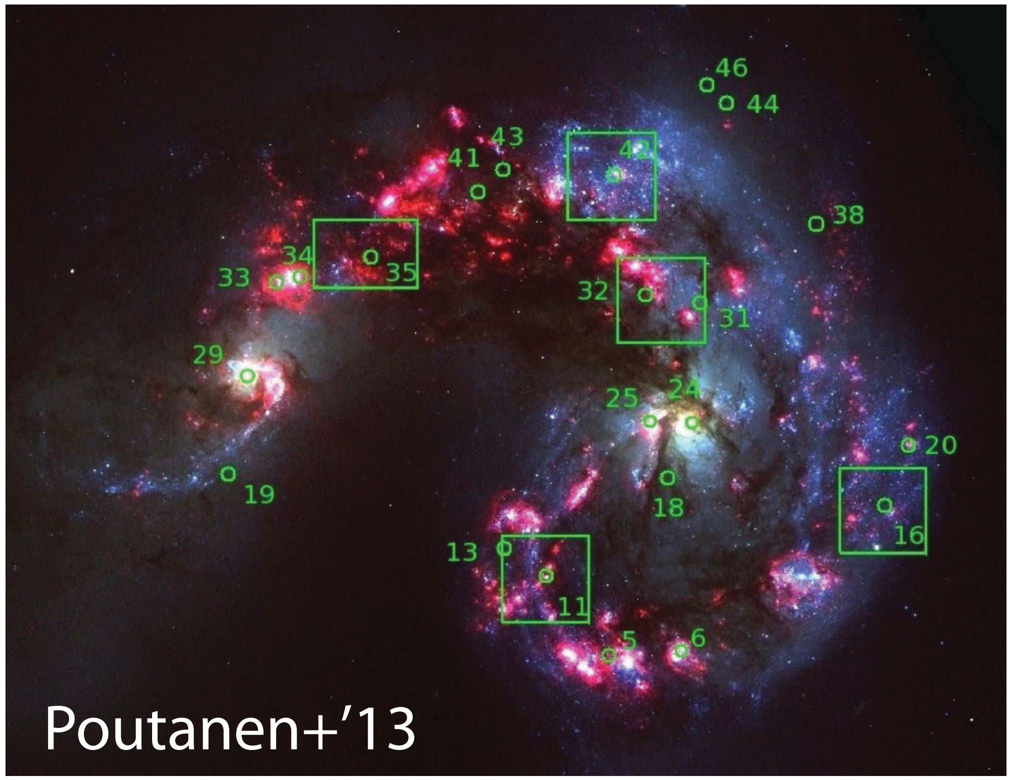
ULX LF in the local Universe



Swartz+’11

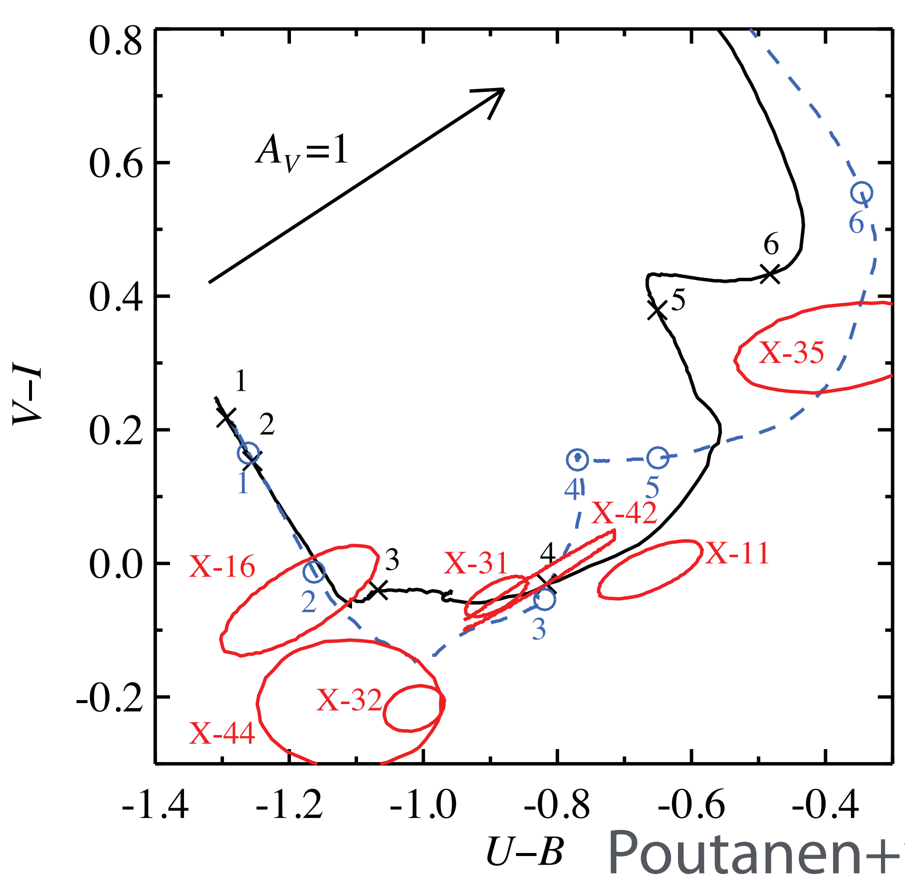
- A simple power-law (γ~1.6) + cutoff (10^{40} erg/s)
  - Various studies are consistent (e.g. Grimm+’03, Swartz+’11,Walton+’11,Mineo+’12).
  - Swartz+’11 provides a ULX LF from a complete sample in the volume of 6100 Mpc^3.
  - By setting Eddington ratio, we can convert ULX LF to ULX BH mass function.

ULX Lifetime

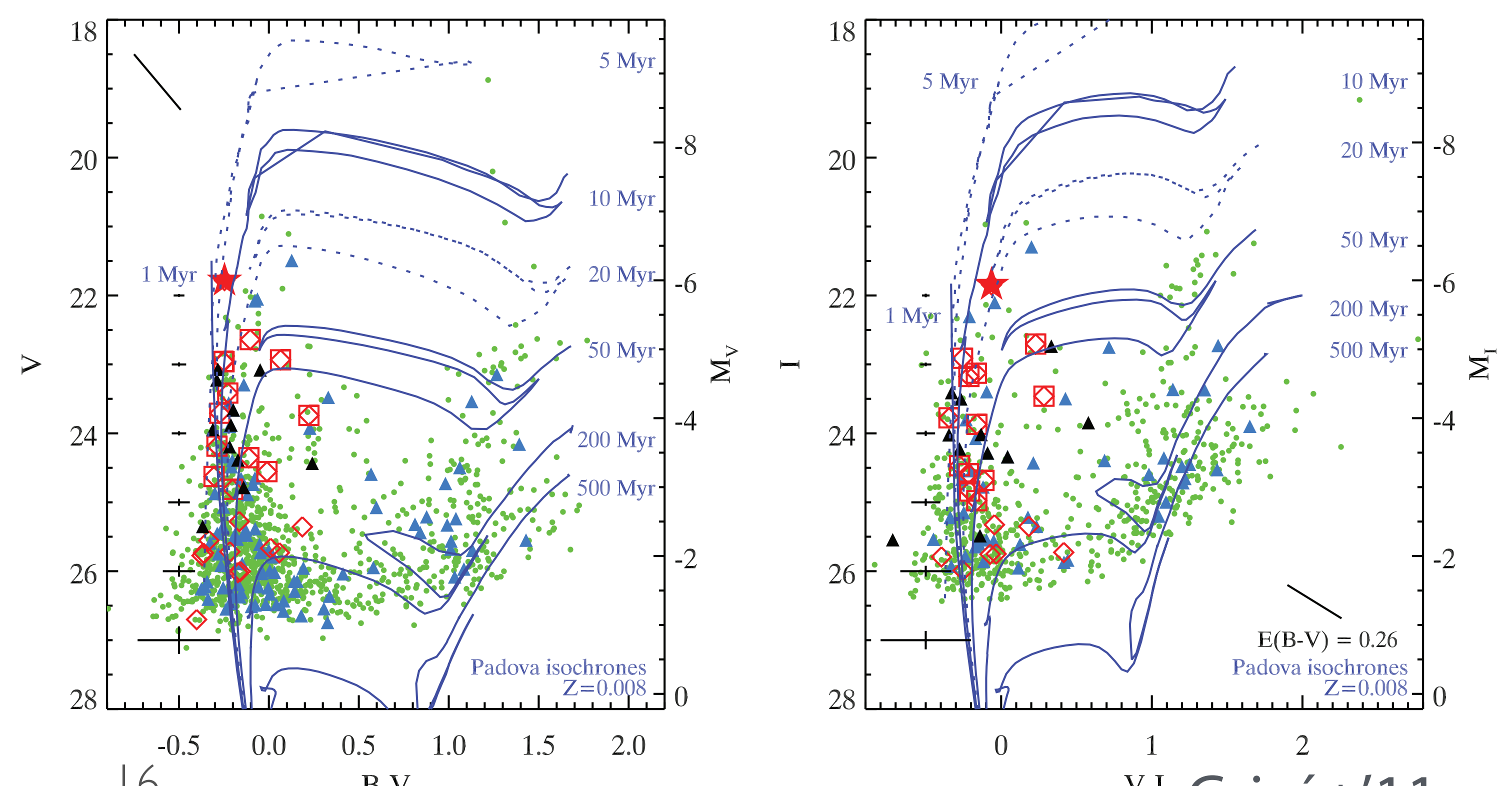


Poutanen+'13

- Binary models predict X-ray activity time scale t_{ULX}~0.1 Myr for high mass X-ray binary systems (Mineo+'12).
- ULXs are known to be associated with stellar clusters (Grisé+'11, Poutanen+'13)
    - the age of those clusters are <~5 Myr (Grisé+'11, Poutanen+'13)

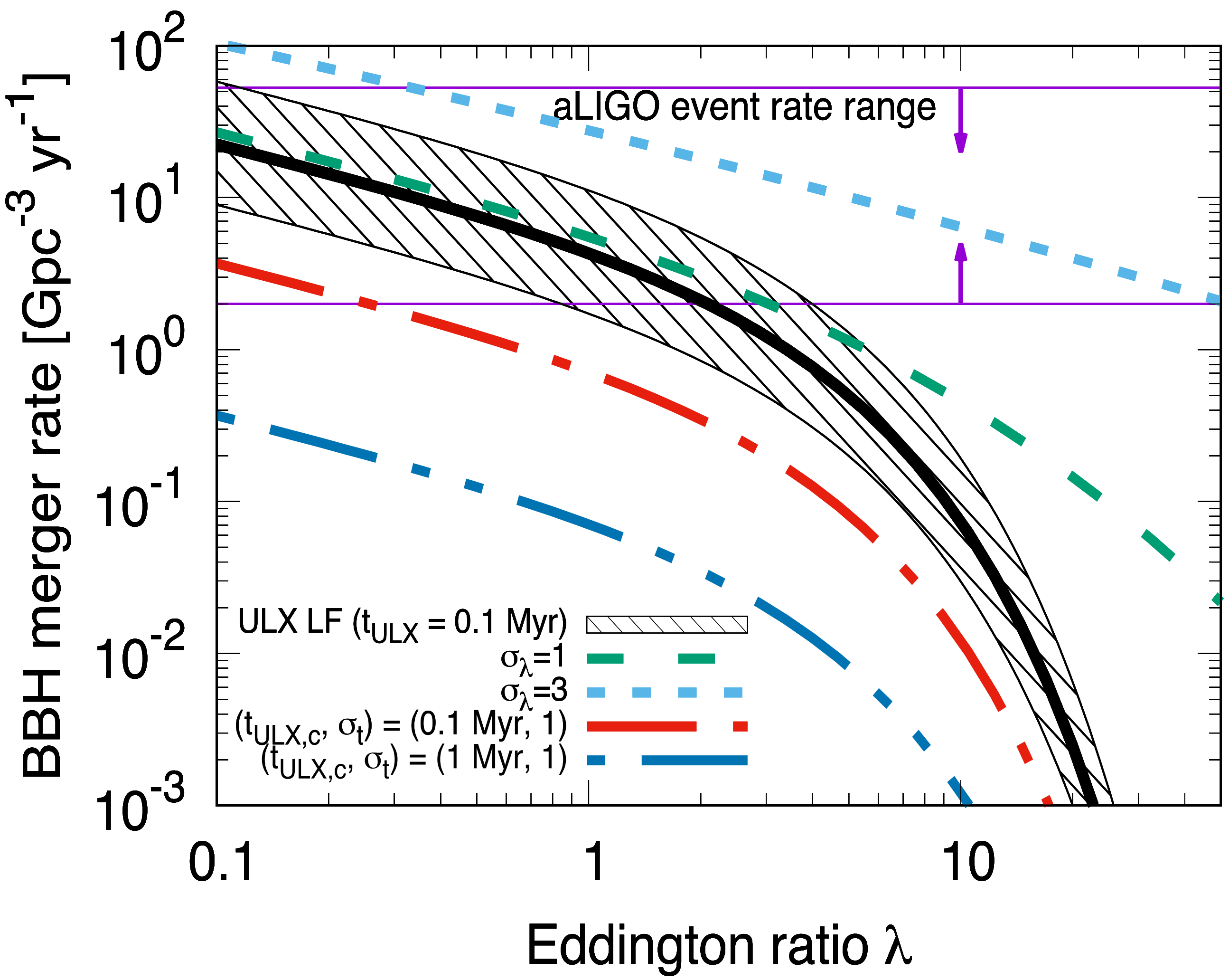


Poutanen+'13



Grisé+'11

Binary BH Merger Rates inferred from ULXs



YI, Tanaka, & Isobe '16

- We can estimate the expected merger rate, if all binary black holes evolves through X-ray emitting phases.
  - The expected rate is coincident with the measured merger rate.

$$\dot{\rho}(M_{\rm BH};\lambda) \approx M_{\rm BH}\frac{dn}{dM_{\rm BH}}\frac{f_{\rm HMXB}f_{\rm ratio}}{t_{\rm ULX}}$$

$$\simeq 50\left(\frac{\lambda M_{\rm BH}}{M_\odot}\right)^{-0.6}\exp\left(-\frac{\lambda M_{\rm BH}}{1.2\times10^2 M_\odot}\right)\left(\frac{t_{\rm ULX}}{0.1\ {\rm Myr}}\right)^{-1}\left(\frac{f_{\rm HMXB}}{0.6}\right)\left(\frac{f_{\rm ratio}}{0.2}\right)\ [{\rm Gpc^{-3}\ yr^{-1}}]$$