「すざく」による白鳥座に発見されたガンマ線超過のX線探査(2)

(“*Suzaku* Observation of the *Fermi* Cygnus Cocoon: Search for a Signature of Young Cosmic-Ray Electrons”, arXiv:1502.01390)

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Tsunefumi Mizuno (Hiroshima Univ.)

T. Tanabe, H. Takahashi (Hiroshima Univ.), K. Hayashi (ISAS/JAXA), R. Yamazaki (AGU), I. Grenier (CEA Saclay), L. Tibaldo (SLAC)

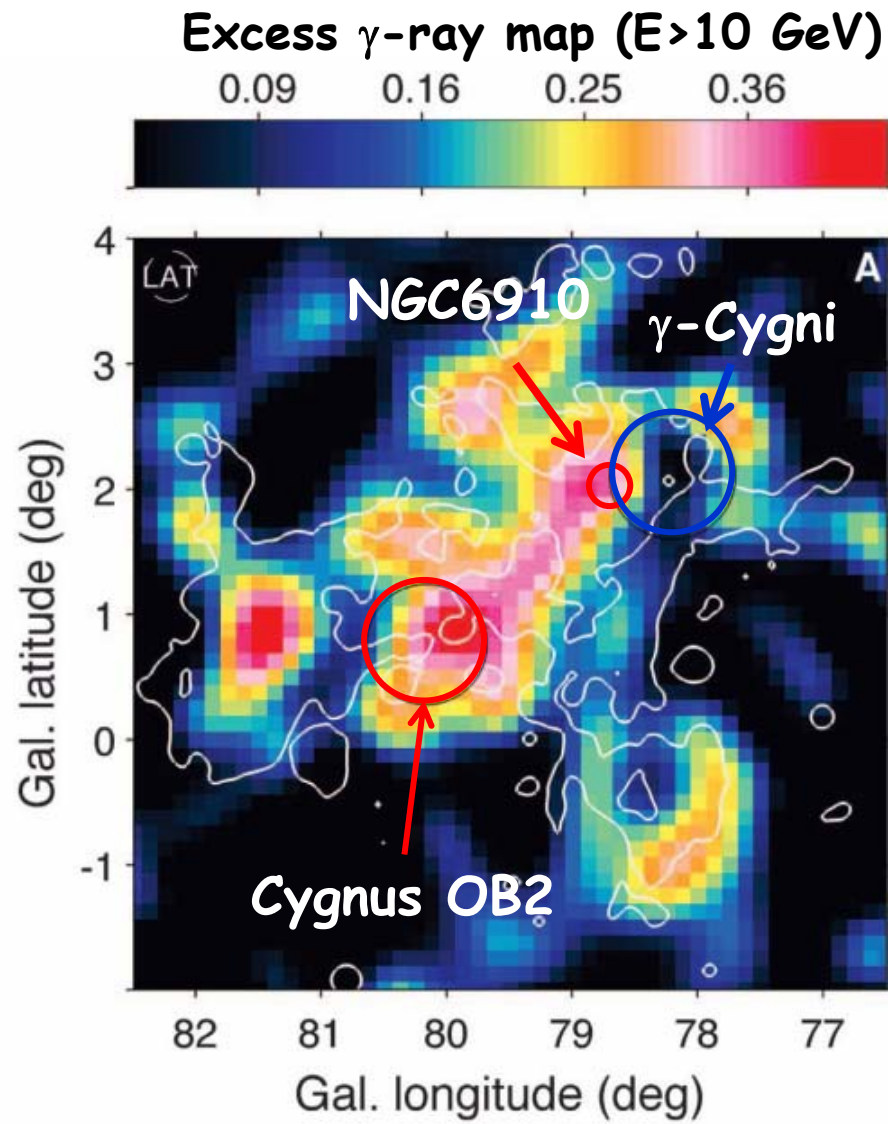
Contents

- Introduction (γ-ray excess "Cygnus cocoon")
- Observations by *Suzaku*
- Data Analysis and Results
- Discussion
- Summary

Cygnus cocoon (Morphology)

- GeV γ-ray excess revealed by *Fermi* in star-forming region Cygnus-X
- Morphology follows the region bounded by the ionization fronts. No apparent spectral variations across the region.

- Interstellar origin rather than a superposition of unresolved sources



Ackermann+11, Science 334, 1103

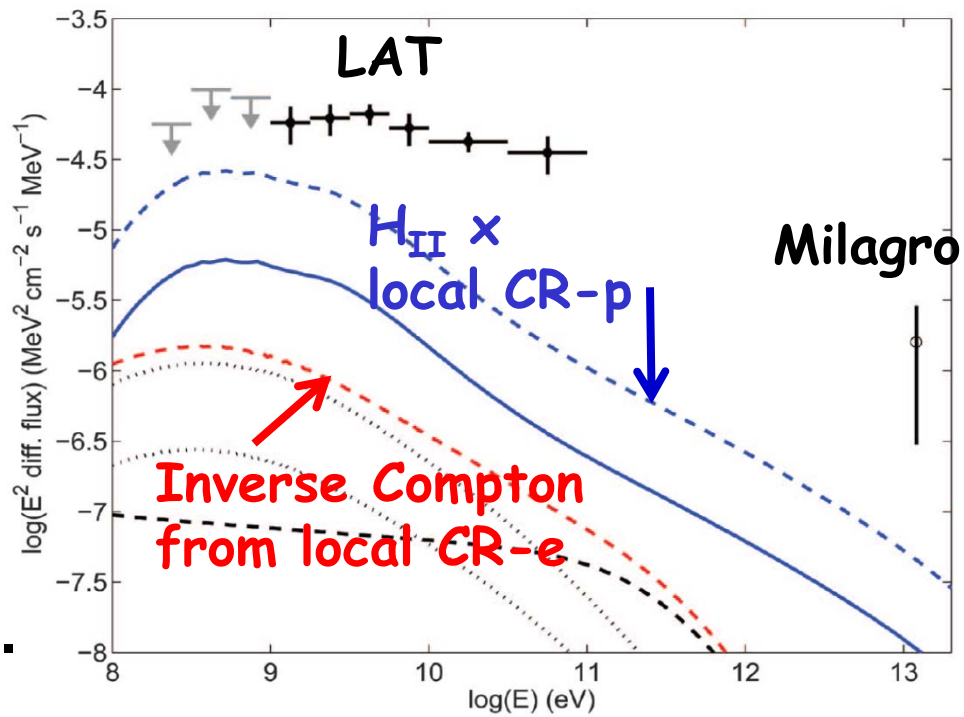
Cygnus cocoon (γ-ray Spectrum)

- "Cygnus cocoon" = GeV γ-ray excess revealed by *Fermi* in star-forming region Cygnus-X
- Freshly-accelerated CRs are required to explain γ-ray spectrum

$$\left(\frac{dN_p}{dE}\right)_{\rm loc} \times (1.5-2)\left(\frac{E}{10\ {\rm GeV}}\right)^{0.3}$$

$$\left(\frac{dN_e}{dE}\right)_{\rm loc} \times 60\left(\frac{E}{10\ {\rm GeV}}\right)^{0.5}$$

- Their origin and properties to be studied by multiwavelength obs. including X-rays



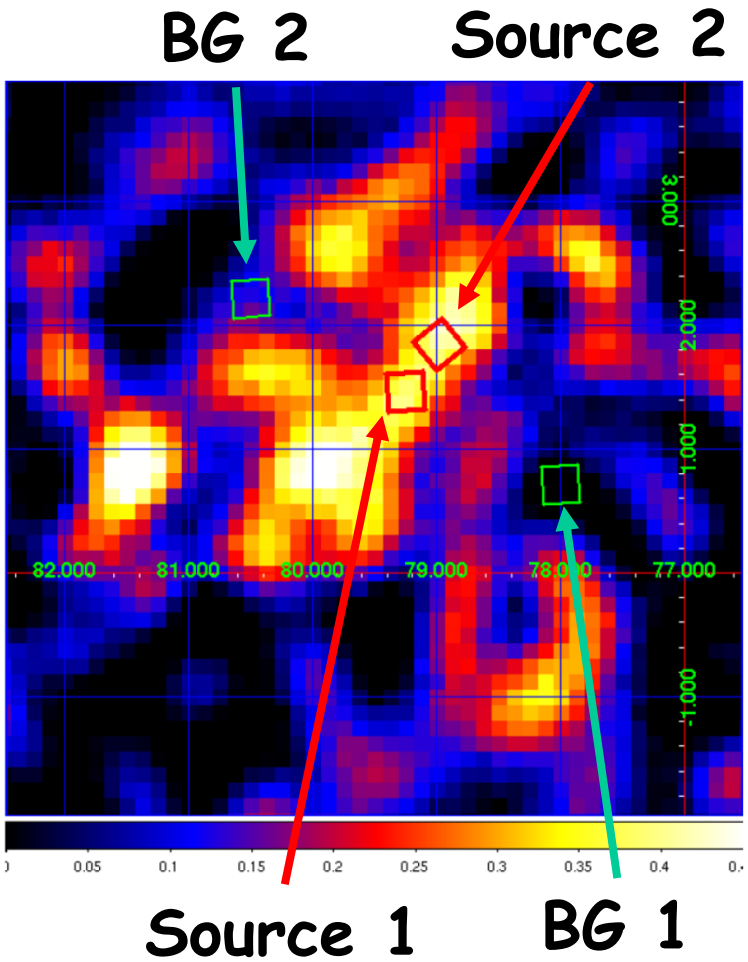
Ackermann+11, Science 334, 1103

Observations

- **We performed *Suzaku*-XIS observations to investigate properties of CRs responsible for the cocoon (particle type, spectrum, etc.)**

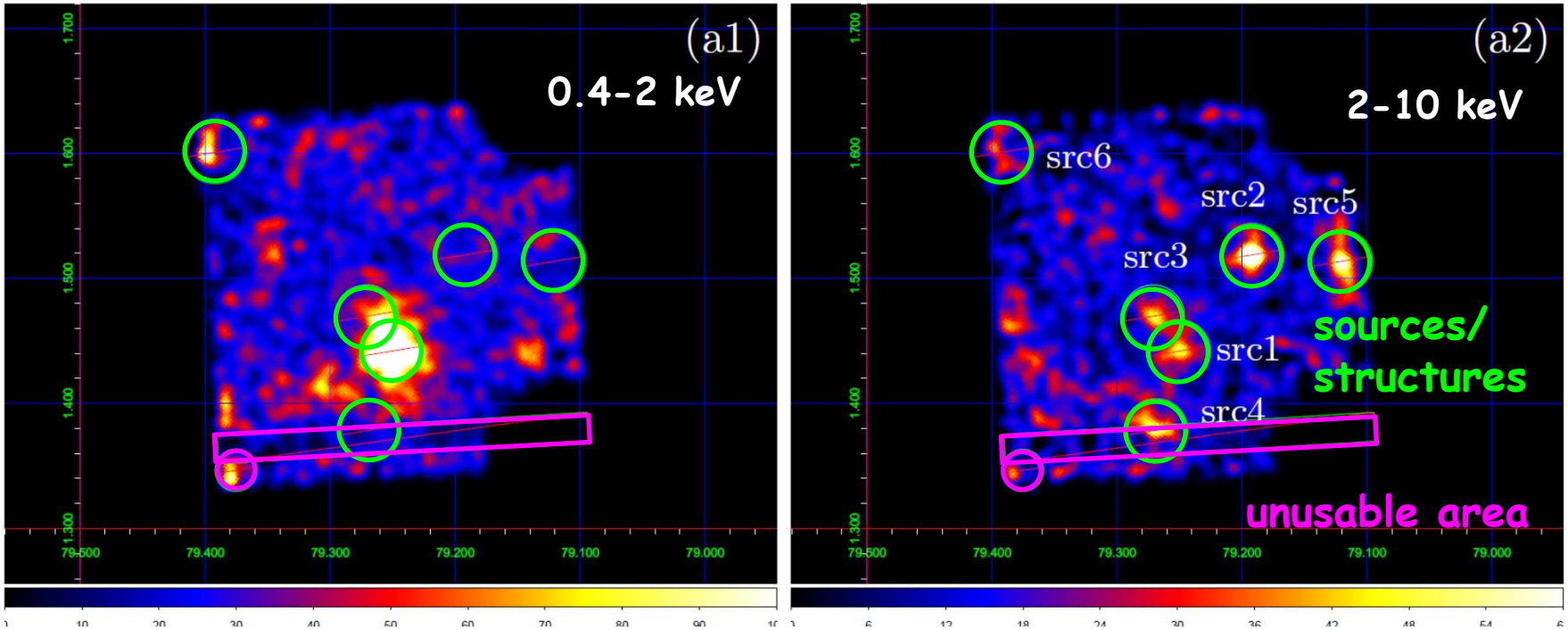
Region	Pointing[a]		Net exposure
	l (deg)	b (deg)	(ks)
Source 1	79.25	1.49	43.3
Source 2	78.99	1.86	42.0
Background 1	78.00	0.74	19.9
Background 2	80.50	2.24	25.6

Excess γ-ray map (E>10 GeV) & X-ray observation positions



XIS Image (Source 1)

- Count map of XIS0+3, smoothed with σ=0.28 arcmin
- A few sources and/or small structures were identified and excluded to investigate the (possible) extended emission from the Cygnus cocoon

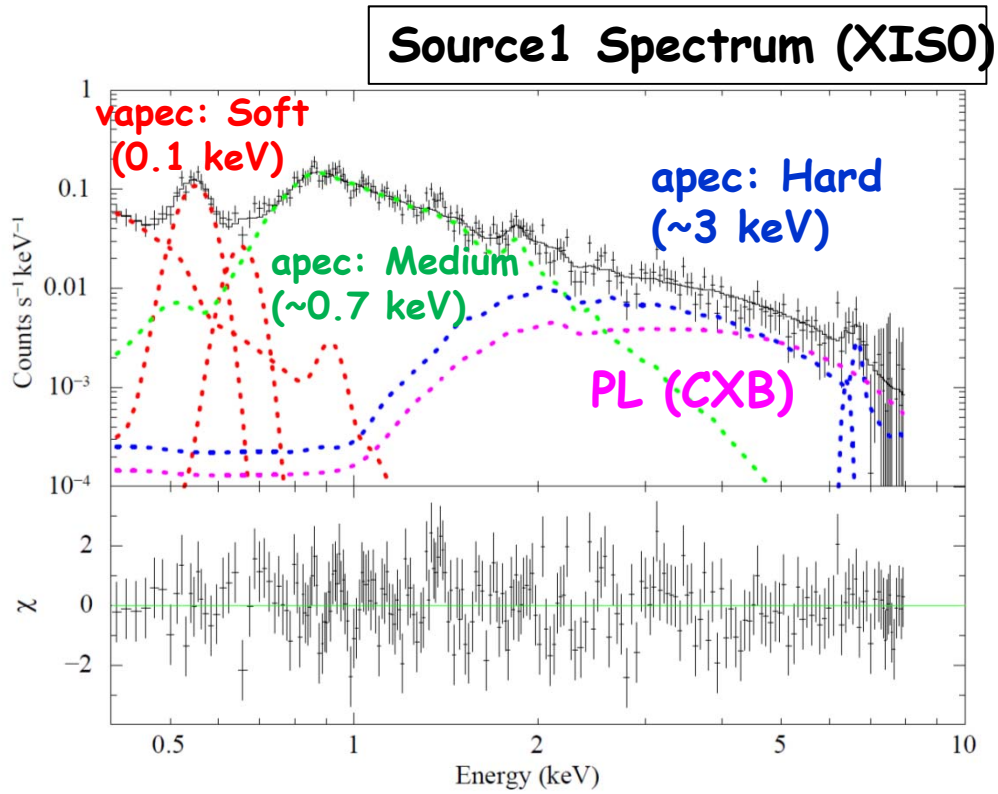


Modeling of Extended Emission (1)

- Point sources and/or small structures removed
- Non X-ray Background (NXB) subtracted (xisnxbgen)
- The remain = Cosmic X-ray background (CXB)
  +Galactic Ridge X-ray Emission (GRXE)
  +local diffuse X-rays (SWCX/Local Bubble)
  +possible emission from Cocoon
  - CXB was fixed to PL of (Γ=1.4, N=9.4x10^{-4} [photons/s/cm^2/keV]) based on Kushino+02. N(H)=N(H_I+2H_2)=(2.5-3.1)x10^{22} [cm^2] was assumed based on γ-ray obs. (Ackerman+12, A&A 538, 71)
  - GRXE + local diffuse X-rays were modeled by three-temperature plasma (vapec/apec) based on previous studies
  - Then we examined residuals in spectrum to see if there are any excess (=possible emission from the cocoon)

Modeling of Extended Emission (2)

- **Point sources and NXB subtracted**
- **The remain = CXB+GRXE+local diffuse(+possible emission from the cocoon)**
  - **CXB was fixed to PL of Γ=1.4.**
  - **GRXE + local diffuse were modeled with three-temp. plasma**



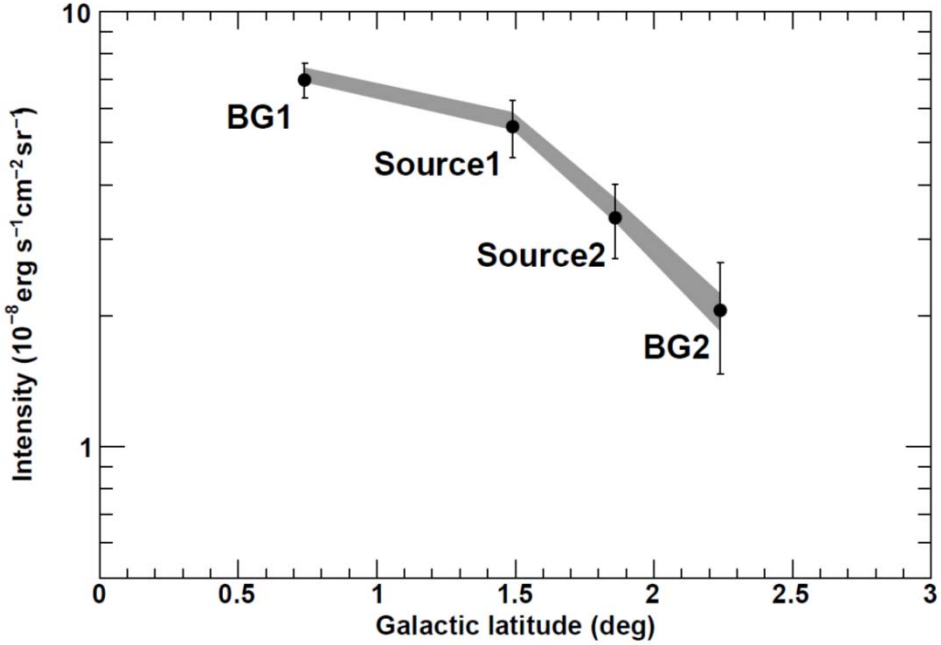
CXB-subtracted intensity = 5.4×10^{-8} [erg/s/cm²/sr] @2-10 keV

No apparent excess in residual, but emission from the cocoon might be hidden by models for GRXE => examine b-dependence

Latitude Dependence of Extended Emission

- Point sources and NXB subtracted
- The remain = CXB+GRXE(+possible emission from the cocoon)
- CXB-subtracted intensity (2-10 keV) shows monotonous decrease as latitude increases (as GRXE does) even if we take the uncertainties into account

- shaded band: systematic uncertainty of assumed absorption
- error bars: uncertainties due to CXB fluctuation and NXB reproducibility

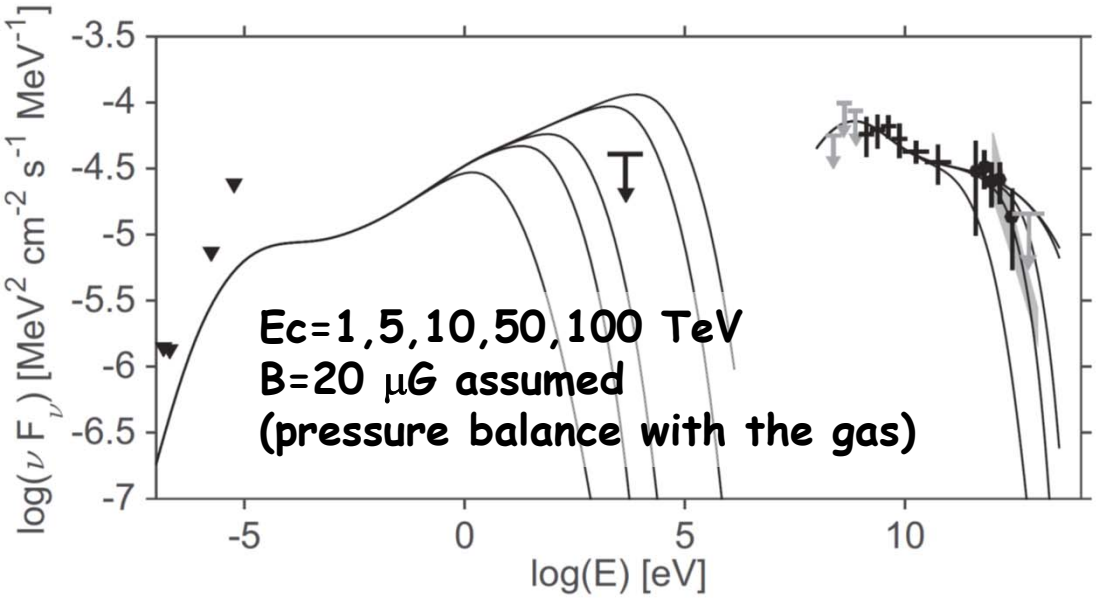


Most of (CXB-subtracted) emission comes from GRXE

(I_{BG2}=lower limit of GRXE at S1/S2)

CRs to Explain Cygnus Cocoon in X- and γ-rays

- **Most of CXB-subtracted emission comes from GRXE**
- **Conservative upper limit of X-rays from the cocoon is obtained by subtracting brightness of BG2 (=lower limit of GRXE at source positions)**



Upper limit of X-rays (av. of S1 and S2) = 2.4×10^{-8} [erg/s/cm²/sr] ~ 1/3 of the expectation of electron scenario

γ-ray excess is due to (1) CR protons, or (2) CR electrons with cutoff at <50 TeV (in agreement with the marked decline in TeV seen >= 2 TeV)

Summary

- We observed Cygnus cocoon (γ-ray excess in Cygnus-X found by *Fermi*) by *Suzaku*-XIS
- Most of extended emission in X-rays (2-10 keV) comes from CXB+GRXE
- Conservative upper limit of X-rays from the cocoon is ~1/3 of electron scenario expectation, suggesting
  - (1) γ-ray excess is due to protons, or
  - (2) electrons with cutoff at <= 50 TeV (confirmation of the spectral cutoff inferred from TeV data)
- See the paper (arXiv:1502.01390) for more details

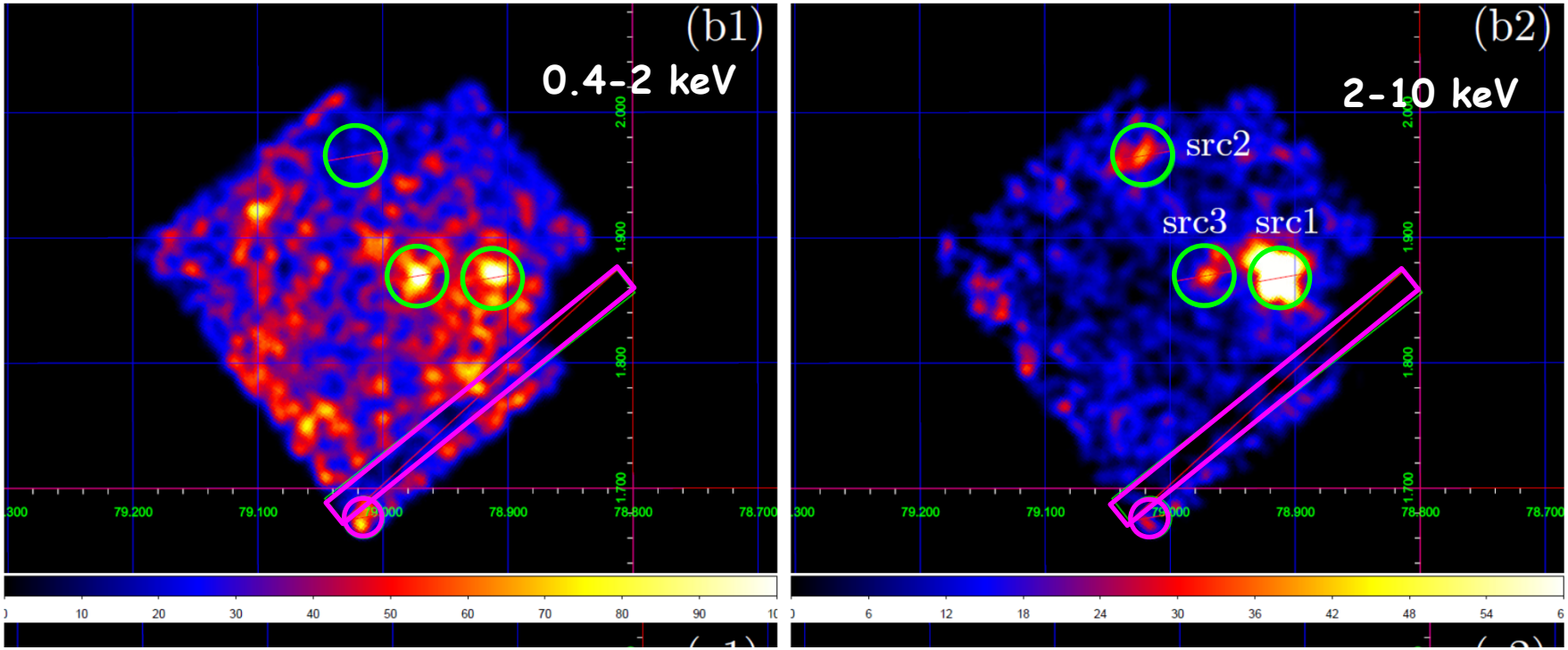
Reference

- Ackermann+11, Science 334, 1103
- Abdo+12, A&A 538, 71
- Kushino+02, PASJ 54, 327
- Kaneda+97, ApJ 491, 638
- Uchiyama+09, PASJ 61, S189
- Kataoka+13, ApJ 779, 57
- Abdo+12, ApJ 753, 159
- Bartoli+14, ApJ 790, 152
- Uyaniker+01, A&A 371, 675

Backup Slides

XIS Image (Source 2)

- Count map of XIS0+3, smoothed with σ=0.28 arcmin
- A few sources and/or small structures were identified and excluded to investigate the (possible) extended emission from the Cygnus cocoon



XIS Image (BG 1)

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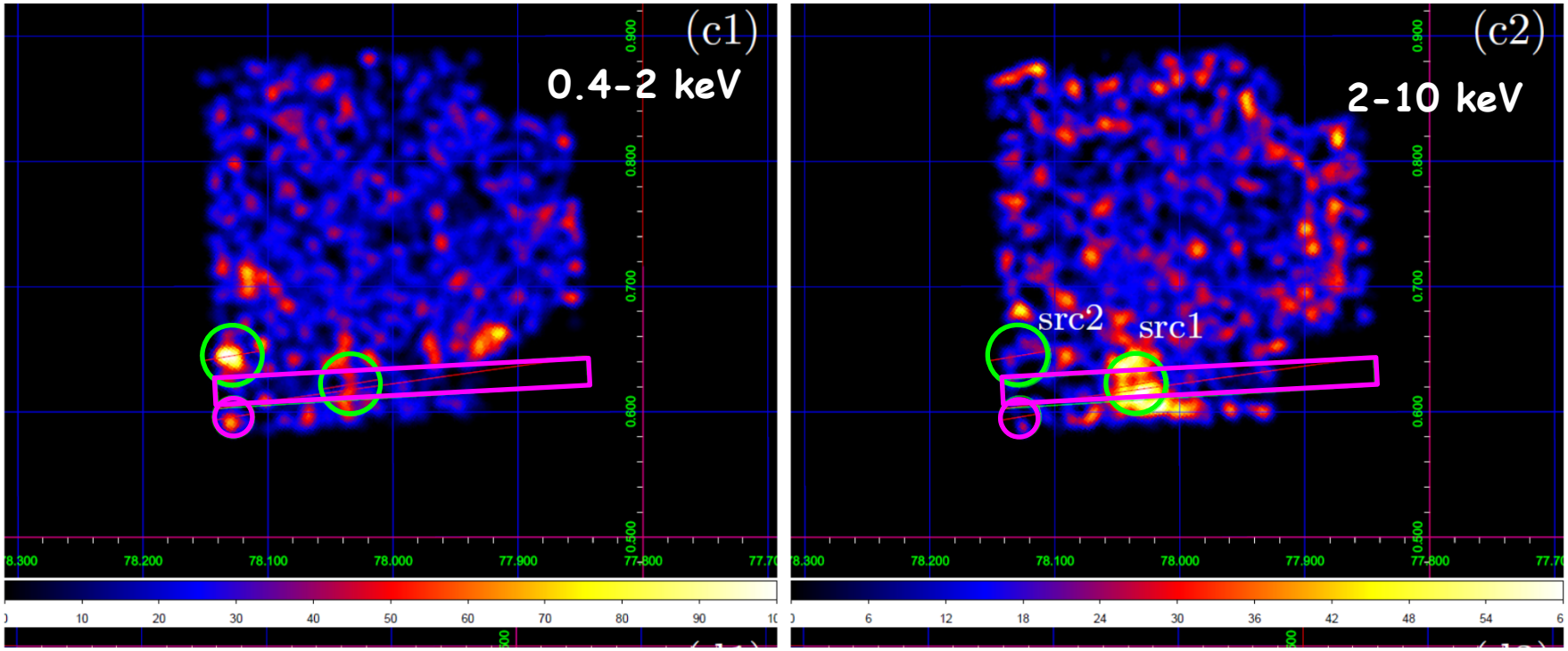

XIS Image (BG 2)

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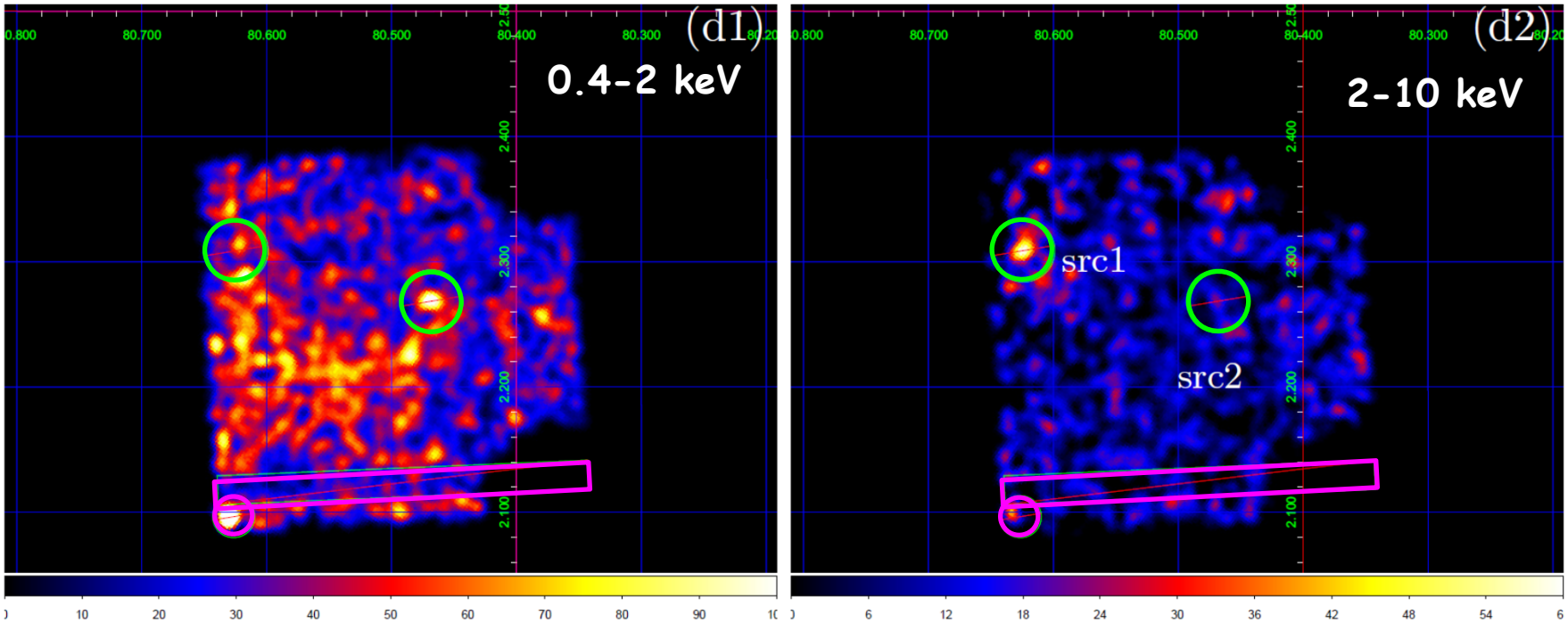
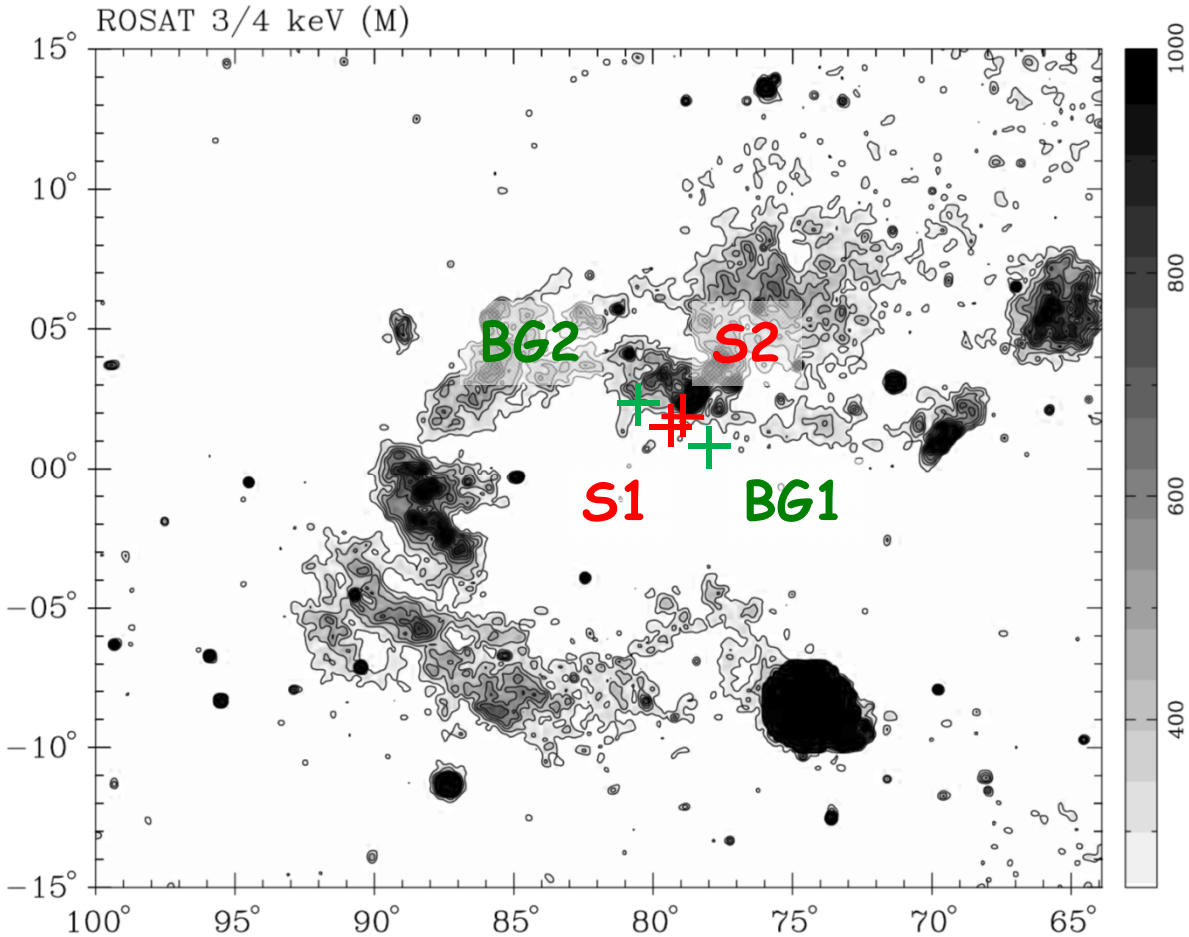


Position of Observations

- **Position of Suzaku observations and ROSAT ¾ keV map**



Uyaniker+01, A&A 371, 675

Summary of Extended Emission Spectra

	Source1	Source2	Background1	Background2
E_1(keV)	0.548 ± 0.004	0.545 ± 0.006	0.551 ± 0.007	$0.554^{+0.009}_{-0.010}$
Norm_1	$23.8^{+3.7}_{-3.9}$	24.4 ± 3.1	$22.1^{+5.4}_{-4.7}$	$14.9^{+5.3}_{-4.0}$
E_2(keV)	0.653(fixed)[a]	$0.648^{+0.013}_{-0.014}$	$0.673^{+0.031}_{-0.035}$	–
Norm_2	$2.3^{+0.8}_{-0.9}$	5.3 ± 1.1	$2.0^{+0.9}_{-0.8}$	–
E_3(keV)	6.40(fixed)	–	–	–
Norm_3	$0.12^{+0.09}_{-0.10}$	–	–	–
$N(\mathrm{H})_{\mathrm{low}}(10^{22}\ \mathrm{cm}^{-2})$	0(fixed)	0(fixed)	0(fixed)	0(fixed)
kT_{low}(keV)	0.1(fixed)	0.1(fixed)	0.1(fixed)	0.1(fixed)
$A_{\mathrm{low}}(Z_\odot)$	1(fixed)	1(fixed)	1(fixed)	1(fixed)
EM_{low}	103 ± 18	144^{+21}_{-20}	99^{+23}_{-24}	139^{+36}_{-34}
$N(\mathrm{H})_{\mathrm{mid}}(10^{22}\ \mathrm{cm}^{-2})$	$0.39^{+0.07}_{-0.09}$	$0.46^{+0.04}_{-0.06}$	$0.73^{+0.11}_{-0.14}$	$0(\leq 0.02)$
kT_{mid}(keV)	$0.73^{+0.02}_{-0.03}$	0.62 ± 0.02	$0.62^{+0.11}_{-0.04}$	$0.60^{+0.02}_{-0.01}$
$A_{\mathrm{mid}}(Z_\odot)$	$0.13^{+0.06}_{-0.04}$	$0.29^{+0.27}_{-0.10}$	$0.27^{+1.25}_{-0.15}$	$0.37^{+1.22}_{-0.11}$
EM_{mid}	256^{+31}_{-49}	242^{+64}_{-98}	$(20^{+9}_{-16}) \times 10$	73^{+26}_{-31}
$N(\mathrm{H})_{\mathrm{high}}(10^{22}\ \mathrm{cm}^{-2})$	$3.1^{+1.4}_{-1.5}$	$1.9(\leq 3.0)$[b]	$2.6^{+0.8}_{-1.0}$	$2.0^{+0.7}_{-1.4}$
kT_{high}(keV)	$3.1^{+2.4}_{-0.9}$	$2.6^{+1.0}_{-0.6}$	$2.4^{+0.8}_{-0.4}$	$1.5^{+1.7}_{-0.3}$
$A_{\mathrm{high}}(Z_\odot)$	$0.36^{+0.22}_{-0.17}$	$0.28^{+0.31}_{-0.26}$	$0.19^{+0.16}_{-0.14}$	$0.4(\leq 1.1)$
EM_{high}	106^{+59}_{-43}	76^{+39}_{-23}	217^{+78}_{-65}	103^{+65}_{-37}
I_{low}(0.5–10 keV)[c]	2.46×10^{-8}	2.86×10^{-8}	2.38×10^{-8}	1.55×10^{-8}
I_{mid}(0.5–10 keV)[c]	5.66×10^{-8}	6.38×10^{-8}	3.01×10^{-8}	8.42×10^{-8}
I_{high}(0.5–10 keV)[c]	4.88×10^{-8}	3.15×10^{-8}	7.20×10^{-8}	2.39×10^{-8}
$N(\mathrm{H})_{\mathrm{CXB}}(10^{22}\ \mathrm{cm}^{-2})$	2.92(fixed)	2.47(fixed)	3.07(fixed)	2.67(fixed)
I_{CXB}(0.5–2 keV)[c]	0.12×10^{-8}(fixed)	0.16×10^{-8}(fixed)	0.11×10^{-8}(fixed)	0.14×10^{-8}(fixed)
I_{CXB}(2–10 keV)[c]	4.85×10^{-8}(fixed)	4.97×10^{-8}(fixed)	4.81×10^{-8}(fixed)	4.92×10^{-8}(fixed)
$I_{0.5-2}$[c]	7.69×10^{-8}	9.22×10^{-8}	5.72×10^{-8}	10.44×10^{-8}
I_{2-10}[c]	10.29×10^{-8}	8.33×10^{-8}	11.79×10^{-8}	6.98×10^{-8}
χ^2/d.o.f.	538.1/501	565.7/521	320.1/252	370.5/336

Spectra of Point Sources

- **Among sources identified, seven have a hard PL spectrum (Γ<2.5) and large absorption (N(H)>2x10^{22} cm^{-2}). (cf. 2-3 uncatalogued active galactic nuclei are expected in each XIS field-of-view)**

Table 3: Spectra of point sources and small-scale structures

Region/source	N_H 10^{22} cm^{-2}	Γ	kT keV	A $Z_\odot$	$f_{0.5-2}$ erg s^{-1} cm^{-2}	f_{2-10} erg s^{-1} cm^{-2}	χ^2/d.o.f.	possible counterpart[a]
Source 1								
src1	$0.03(\leq 0.09)$	–	$0.94^{+0.08}_{-0.14}$	0.07 ± 0.03	1.81×10^{-13}	0.29×10^{-13}	71.6/64	1RXS J202725.2+405428
src2	$5.1^{+5.2}_{-2.7}$	$2.3^{+1.5}_{-1.0}$	–	–	0.03×10^{-13}	1.52×10^{-13}	41.6/40	NVSS J202655+405408
src3	$0.79^{+0.59}_{-0.45}$	$-1.0(\geq -2.2)$	$0.55^{+0.48}_{-0.36}$	1(fixed)	0.19×10^{-13}	1.27×10^{-13}	28.1/25	NVSS J202723+405706
src4	$2.2(\leq 6.7)$	$1.5^{+1.6}_{-1.3}$	–	–	0.06×10^{-13}	1.47×10^{-13}	16.0/25	TYC 3156-1302-1
src5	9^{+15}_{-7}	$1.6(\leq 4.1)$	–	–	$\leq 0.01 \times 10^{-13}$	1.75×10^{-13}	32.1/26	NVSS J202642+405138
src6	$0(\leq 0.07)$	$1.72^{+0.47}_{-0.43}$	–	–	0.48×10^{-13}	0.86×10^{-13}	18.1/13	–
Source 2								
src1	$2.33^{+0.86}_{-0.69}$	$1.58^{+0.34}_{-0.30}$	–	–	0.24×10^{-13}	5.46×10^{-13}	120.8/101	–
src2	2.47(fixed[b])	$1.23^{+0.73}_{-0.83}$	–	–	0.02×10^{-13}	0.92×10^{-13}	20.3/24	–
src3	$0.36^{+0.42}_{-0.30}$	$1.92^{+0.49}_{-0.41}$	–	–	0.32×10^{-13}	0.91×10^{-13}	81.7/58	–
Background 1								
src1	$2.5^{+1.7}_{-1.3}$	$2.6^{+1.0}_{-0.9}$	–	–	0.34×10^{-13}	3.00×10^{-13}	18.0/19	several[c]
src2	$3.1^{+8.8}_{-1.8}$	–	$0.05^{+2.05}_{-0.02}$	1(fixed)	0.47×10^{-13}	$\leq 0.01 \times 10^{-13}$	1.1/1	–
Background 2								
src1	$0(\leq 18)$	$1.0(\leq 5.4)$	–	–	0.15×10^{-13}	0.79×10^{-13}	15.0/17	NVSS J202754+423205
src2	$1.5^{+3.7}_{-1.3}$	–	$0.17^{+0.89}_{-0.14}$	1(fixed)	0.13×10^{-13}	$\leq 0.01 \times 10^{-13}$	17.5/23	TYC 3160-1261-1

Simple Argument of CR Electron Cutoff

- **Conservative upper limit of X-ray emission is ~1/3 of the expectation, requiring cutoff of CR electron (in electron scenario)**

Synchrotron X-ray

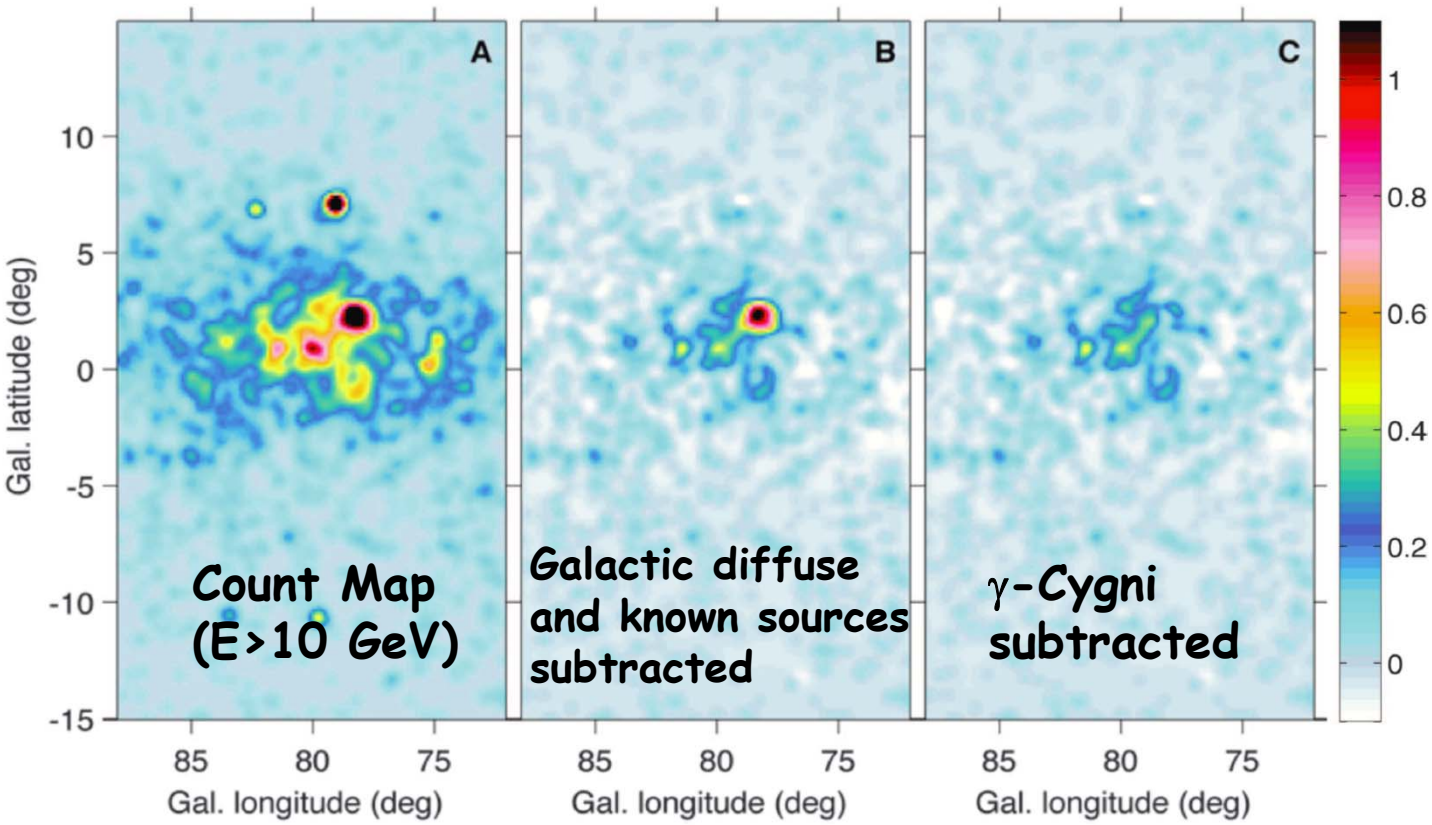
$$h\nu_{\mathrm{max,sync}} \sim 2000\left(\frac{B}{10\ \mu\mathrm{G}}\right)\left(\frac{E_{\mathrm{e}}}{100\ \mathrm{TeV}}\right)^2 \sin\theta\ \mathrm{eV}$$

For B=20 μG, E_e of 50 TeV required to produce 1 keV X-ray

In electron scenario, cutoff in <= 50 TeV is required to explain (non-detection of) X-rays

γ-ray Count Map

- γ-ray emission = diffuse emission (ISM x Galactic CR)+point sources
- Excess is a signature of unknown high-energy objects/phenomena



Radiation Field inside Cocoon

- **Optical from Cygnus OB2 and NGC 6910**
- **Infrared (dust emission) measured by IRAS**