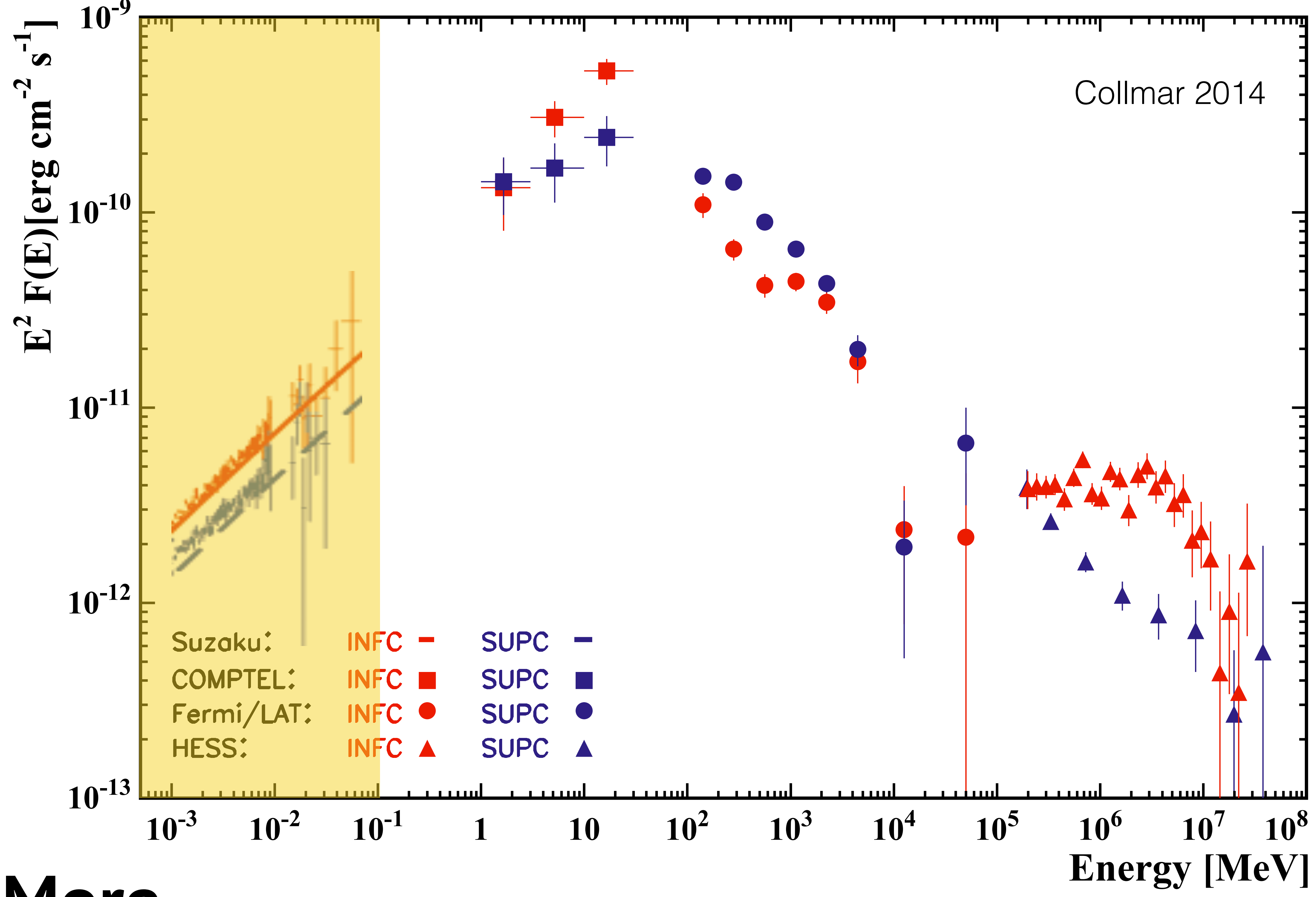
Variable Galactic Gamma-Ray Sources VI
University of Innsbruck, April 12-14 (2023)

X-rays in gamma-ray binaries

Hiroki Yoneda

Julius Maximilians Universität Würzburg, Germany

Gamma-ray binaries seen in X-rays



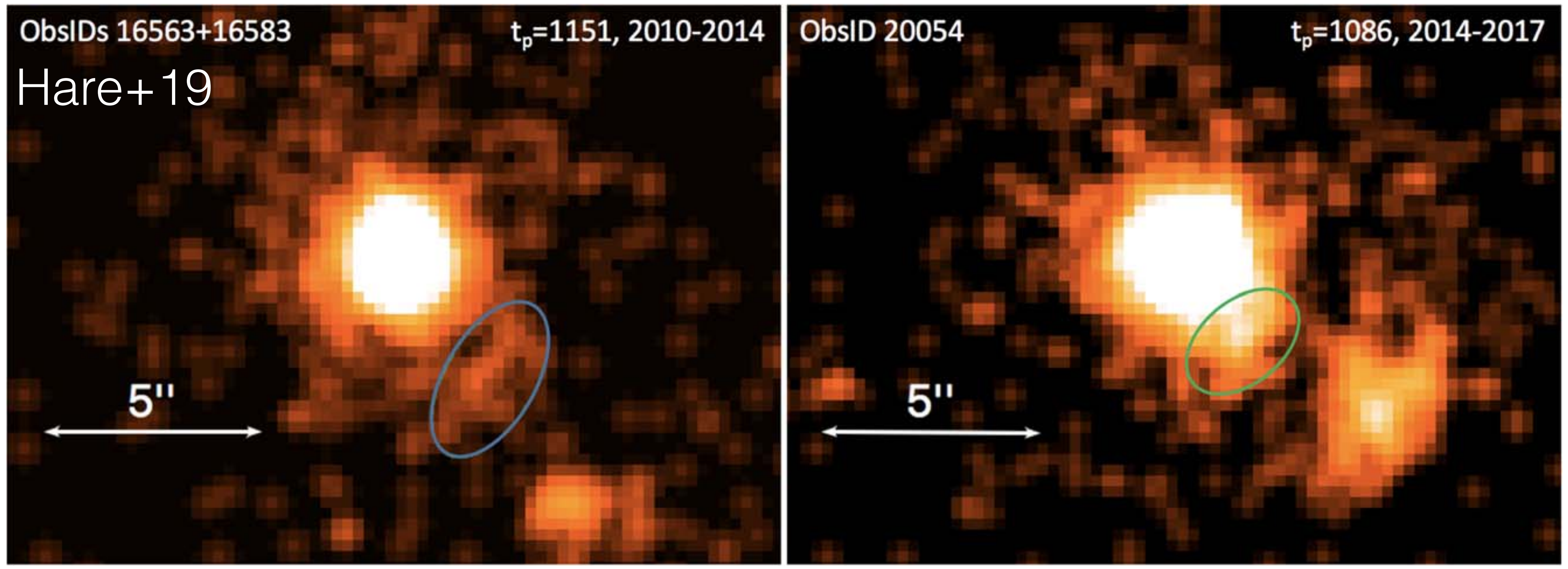
Synchrotron emission from accelerated electrons

- spectral index
  - → energy distribution
- flux ratio between X-ray and TeV
  - → magnetic field
- spectral cut-off
  - → acceleration efficiency, Emax

More...

- timing information
  - → phase-resolved spectroscopy
  - → pulse search (Rea+11, HY+20, Volkov+21)
- imaging,

  e.g., a clump from PSR B1259? (Hare+19,23)

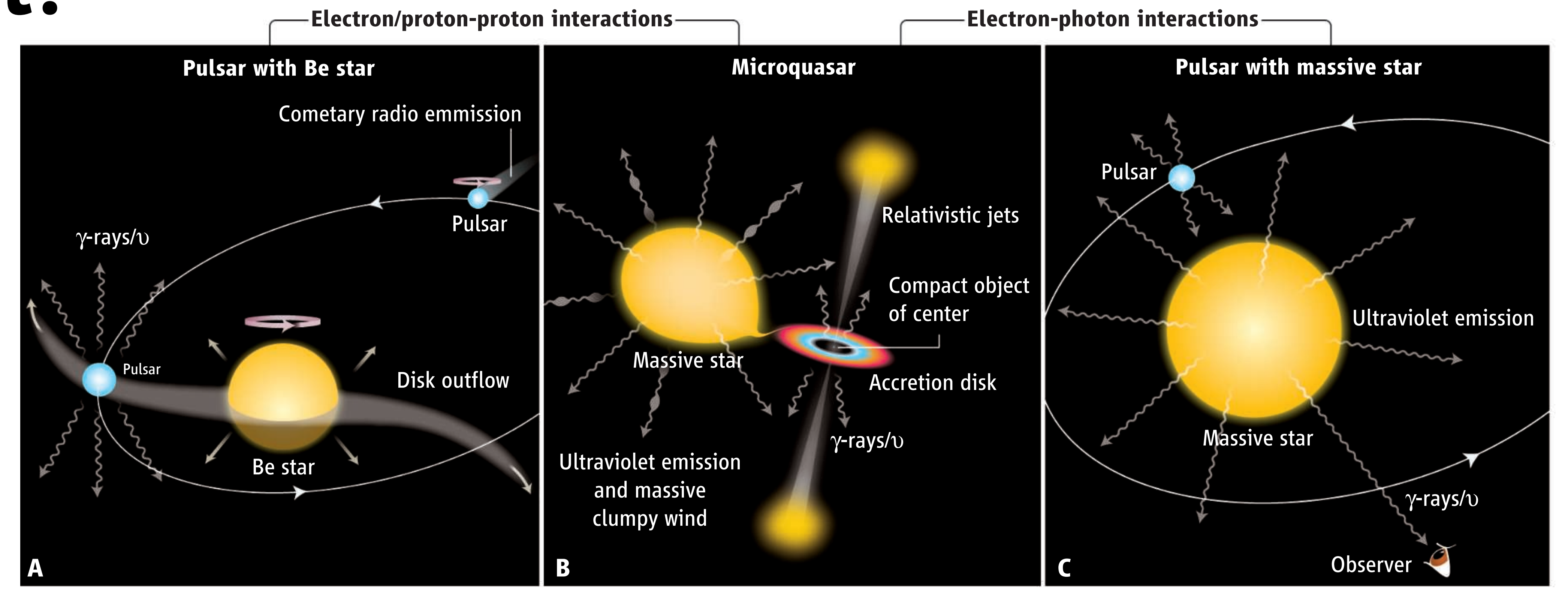


Questions to be solved for gamma-ray binaries

1. The nature of compact objects? Physical environment?

-> Long-term soft X-ray stability of LS 5039 (HY+23)

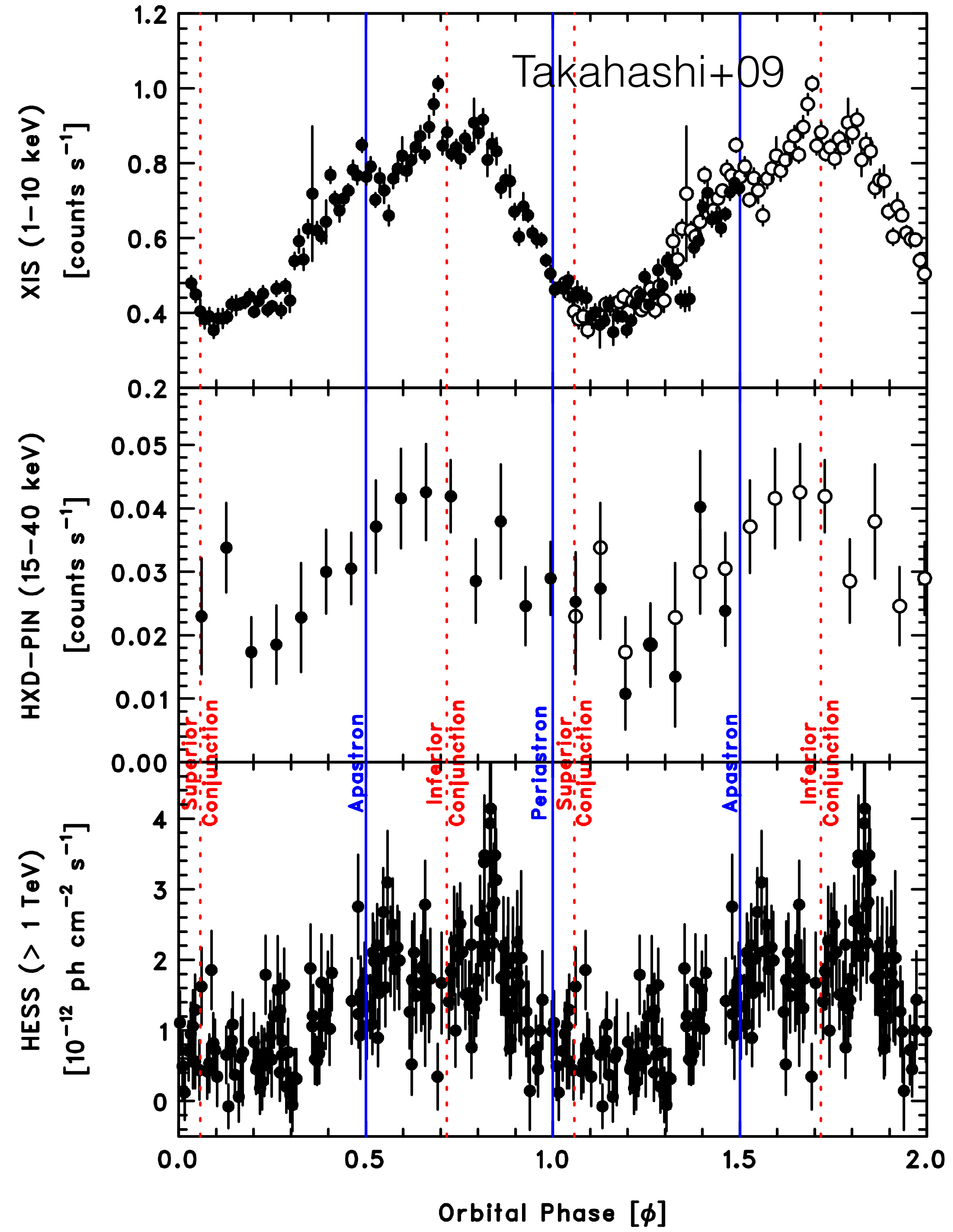
- Pulsars? Blackholes? or…?
- How the stellar winds and CO are interacted?
  - Wind-collision? Accretion+Jet?



2. Physical mechanism of the particle acceleration

-> MW observations of LS 5039 w/ NuSTAR and Fermi (HY+21)

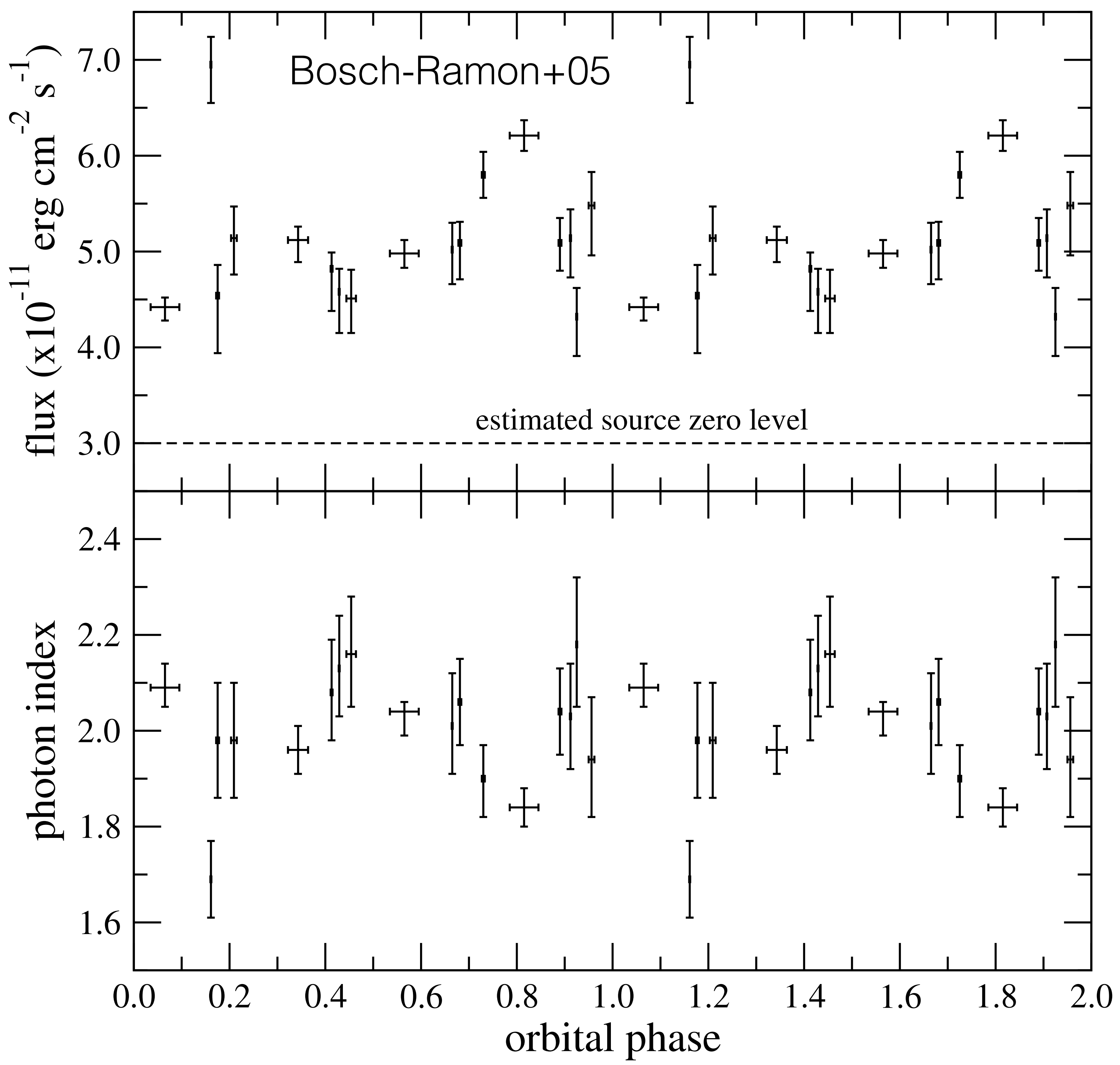
- Extremely efficient electron accelerator? How does it occurs?
- Ex.) Orbital modulation of X-ray/TeV emission of LS 5039 suggests
  - a short acceleration time scale ~ second (Khangulyan+08, Takahashi+09)
  - acceleration efficiency is close to the maximum rate allowed in magnetohydrodynamic sources

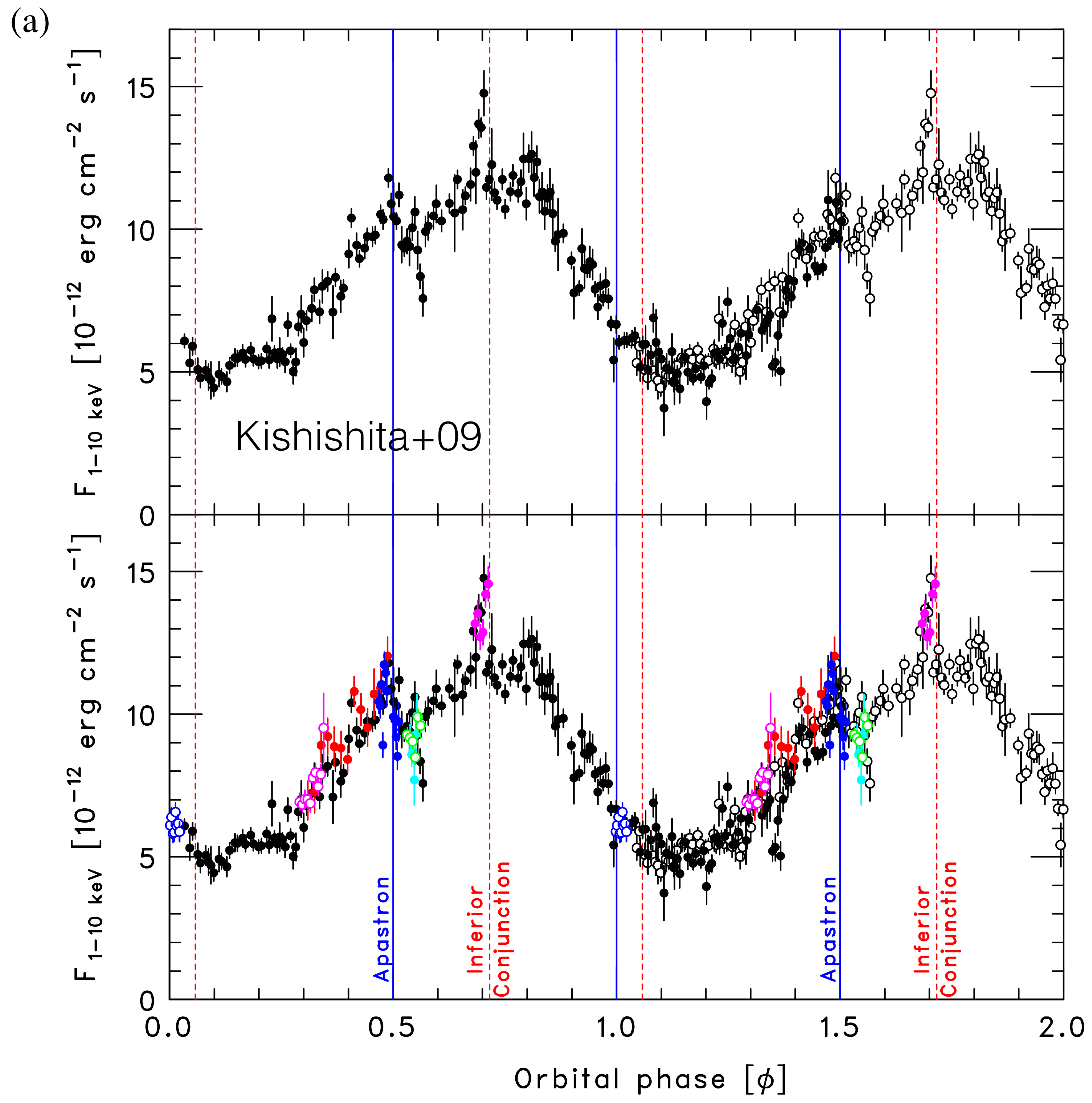


Orbital light curve of LS 5039 in the soft X-ray band

LS 5039: one of the brightest gamma-ray binaries in the Galaxy

the orbital period is ~3.9 days, a companion star is an O star with 23 Msun





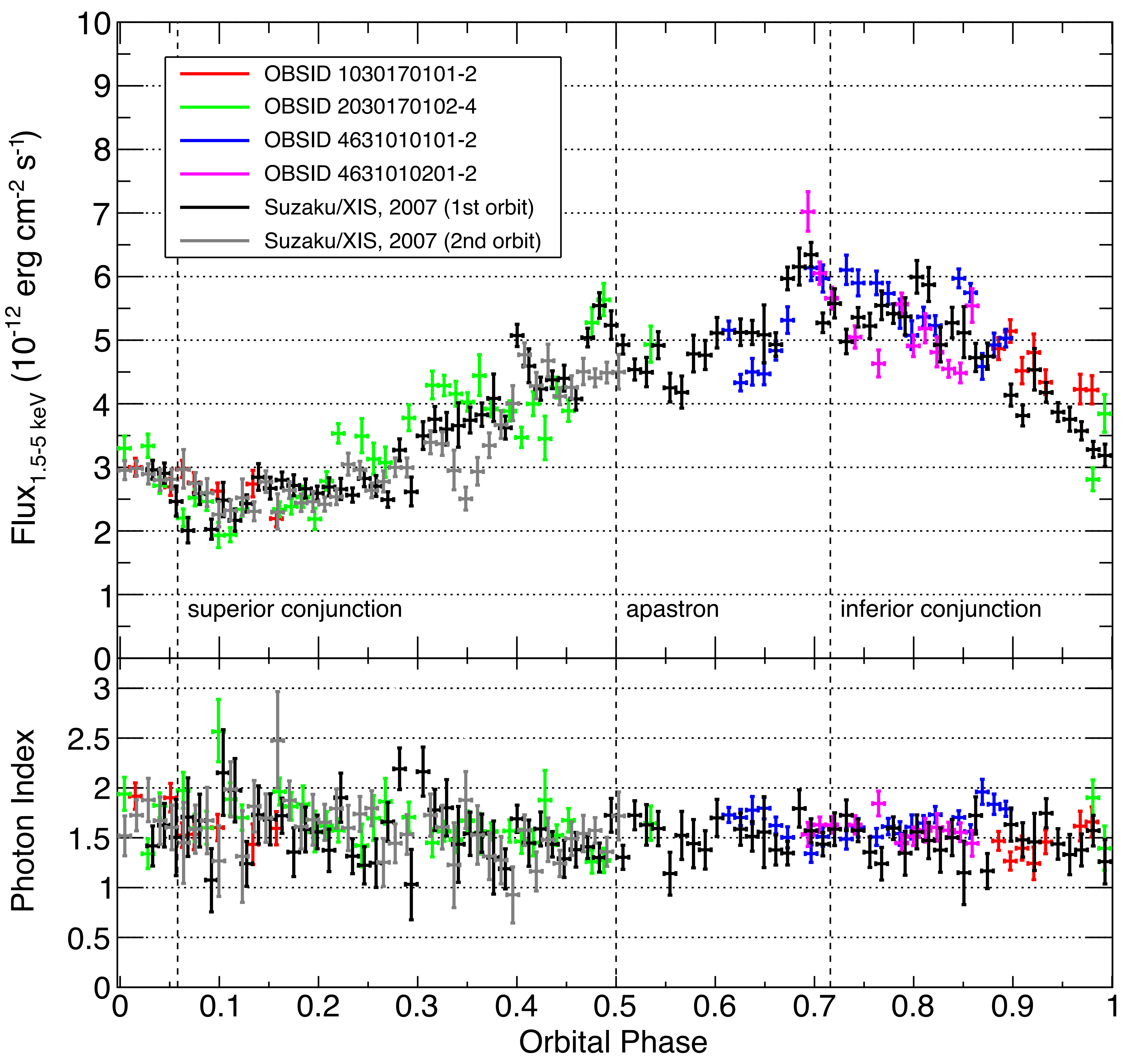
X-ray orbital light curves has been studied. e.g., Bosch-Ramon+05, Kishishita+09

At least, around apastron, and INFC, the synchrotron emission in soft X-rays is reproducible over ~8 years.

Four NICER observations were performed from 2018 to 2021

- As a total, the NICER data covers the orbit
- The soft X-ray emission over the orbit can be compared with Suzaku observation in 2007

Soft X-ray orbital light curve (1.5-5 keV) with NICER in 2018-2021



Over ~10 years we re-confirmed that the soft X-ray orbital curve shows good reproducibility

From this figure, we see two features

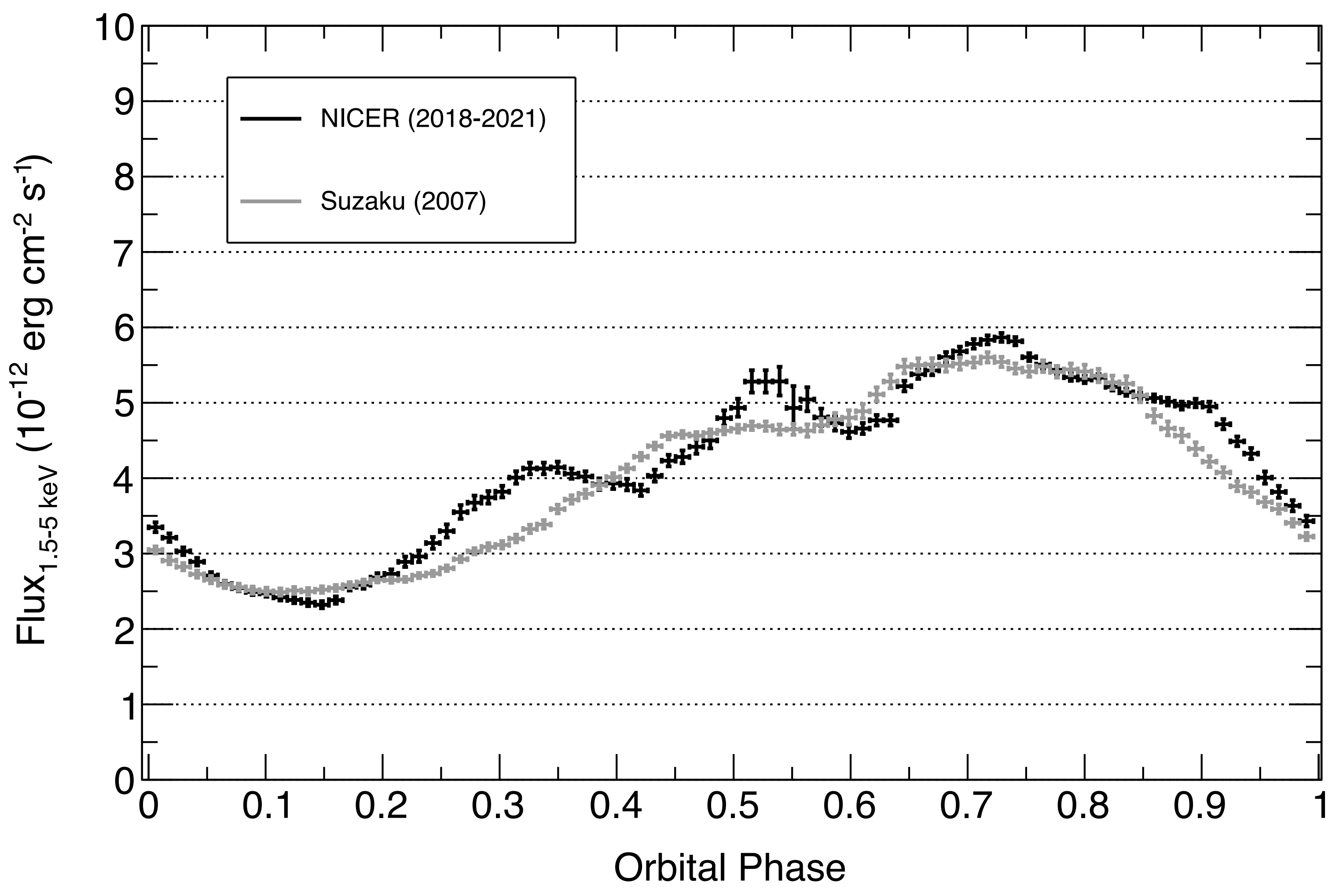
1) the light curves are almost consistent when they are smooth, e.g., ϕ ~0.1-0.2

2) but also there are short “flare-like” features, e.g., ϕ~0.5 in green

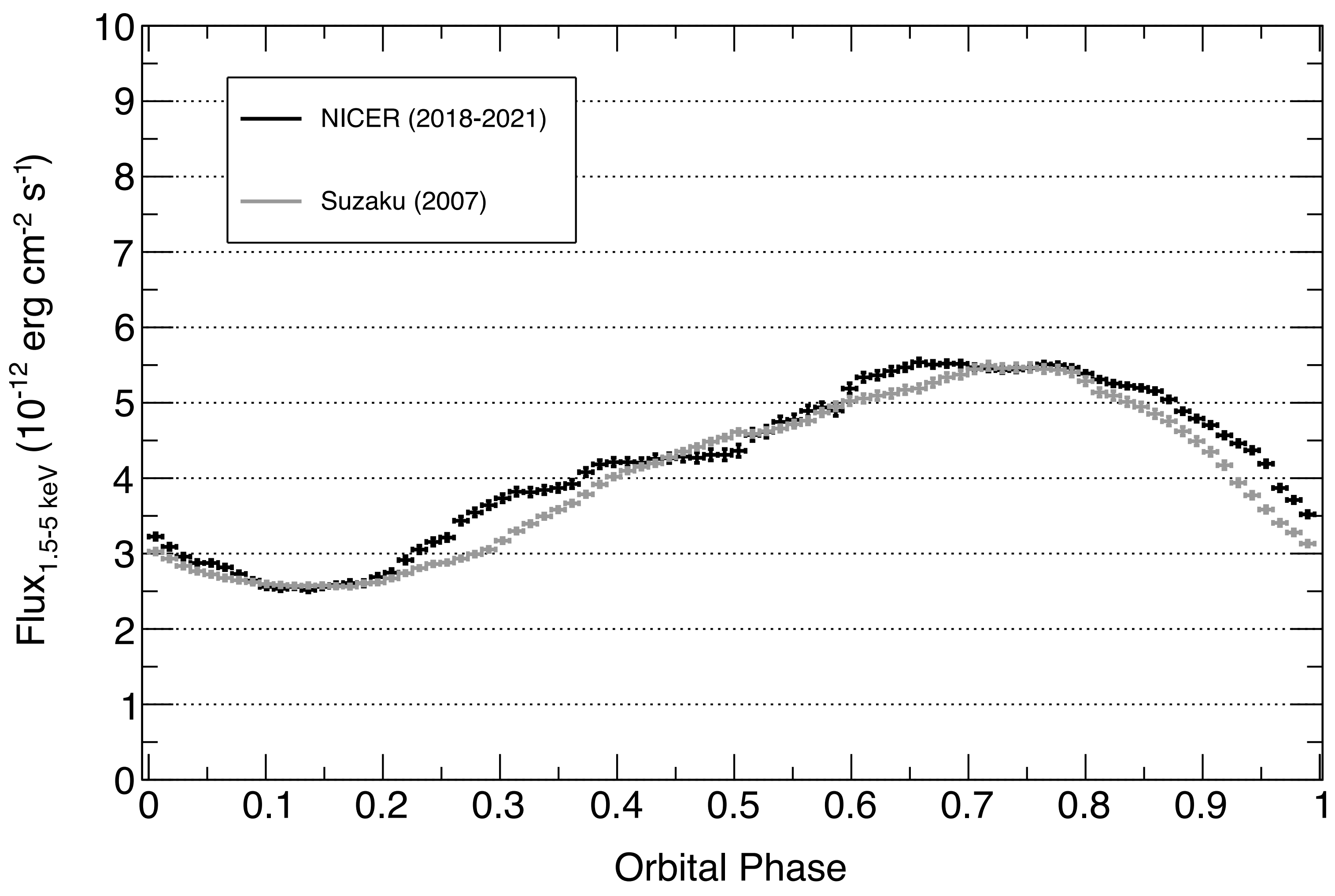
Hour-scale variability on top of the very stable overall light curve?

The running-averaged light curve

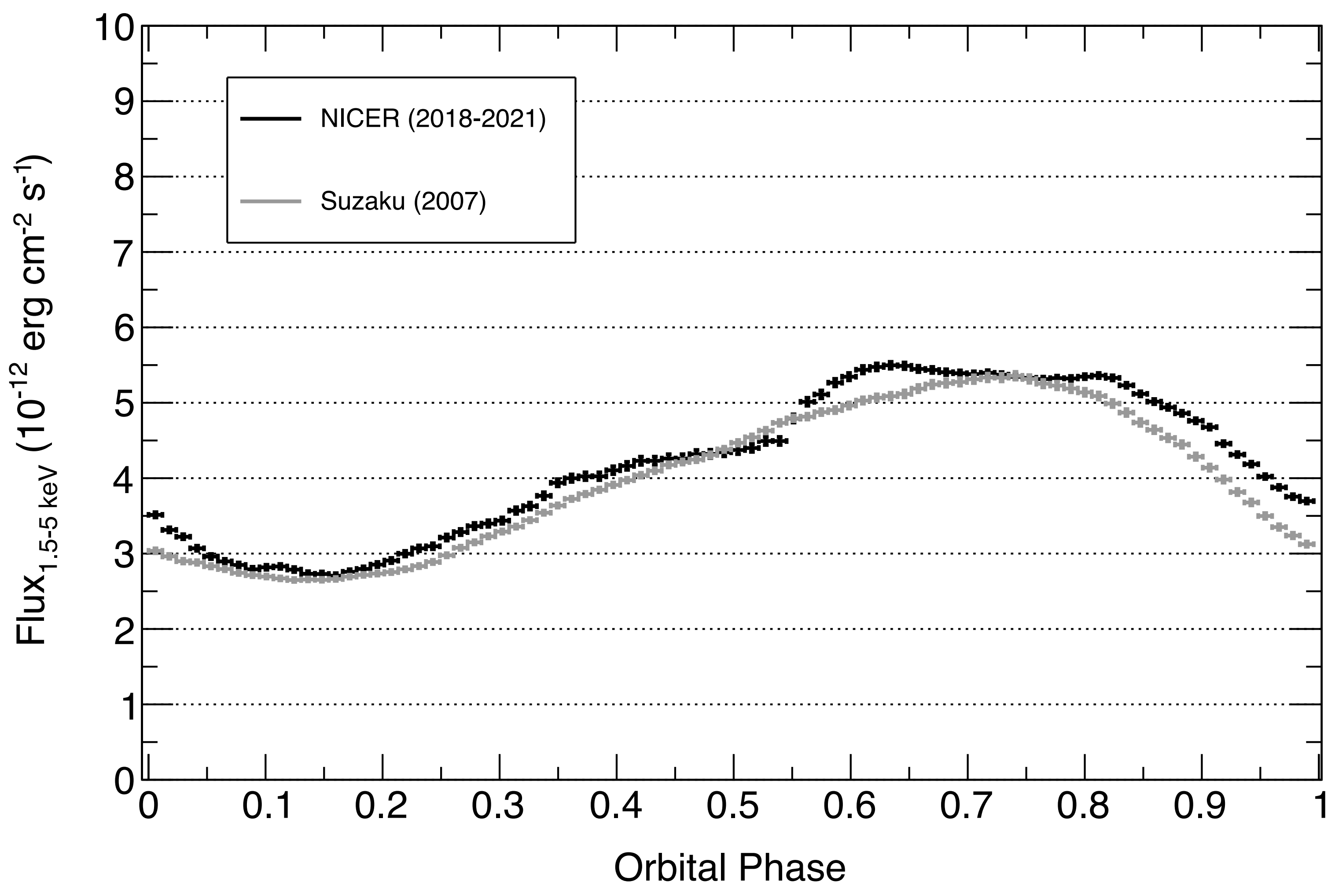
window size = 35 ks
~ 0.1 orbit



window size = 70 ks
~ 0.2 orbit



window size = 100 ks
~ 0.3 orbit

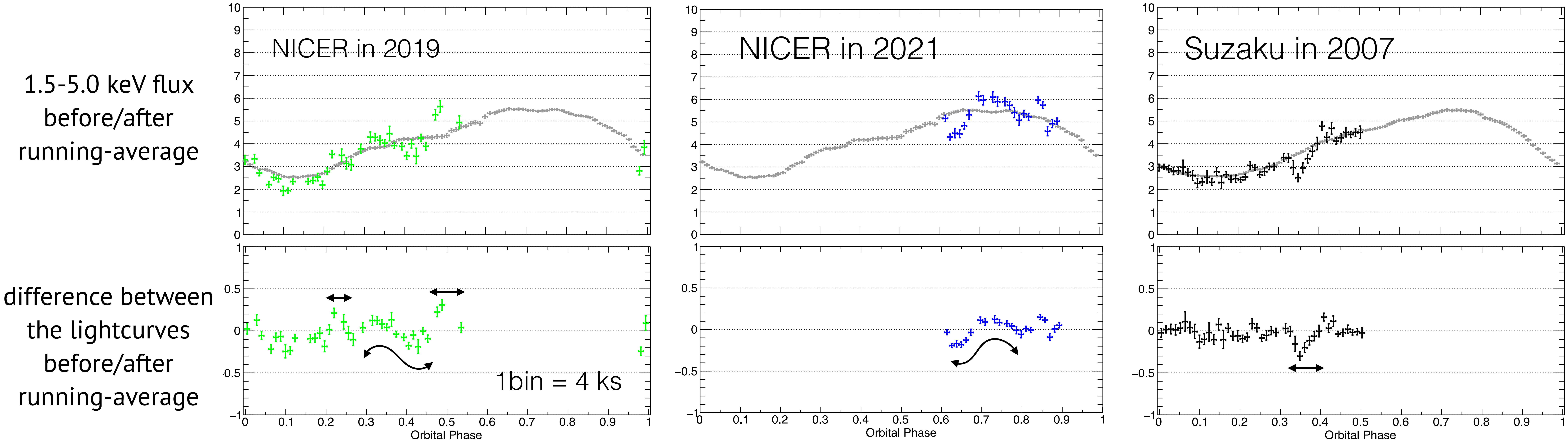


By smearing out the short-time-scale components,
the two light curves, NICER and Suzaku, show remarkable consistency

More than 70 ks time scale, the system seen in soft X-rays is in a very stable physical condition over 10 years

Variability on the top of the averaged orbital curve

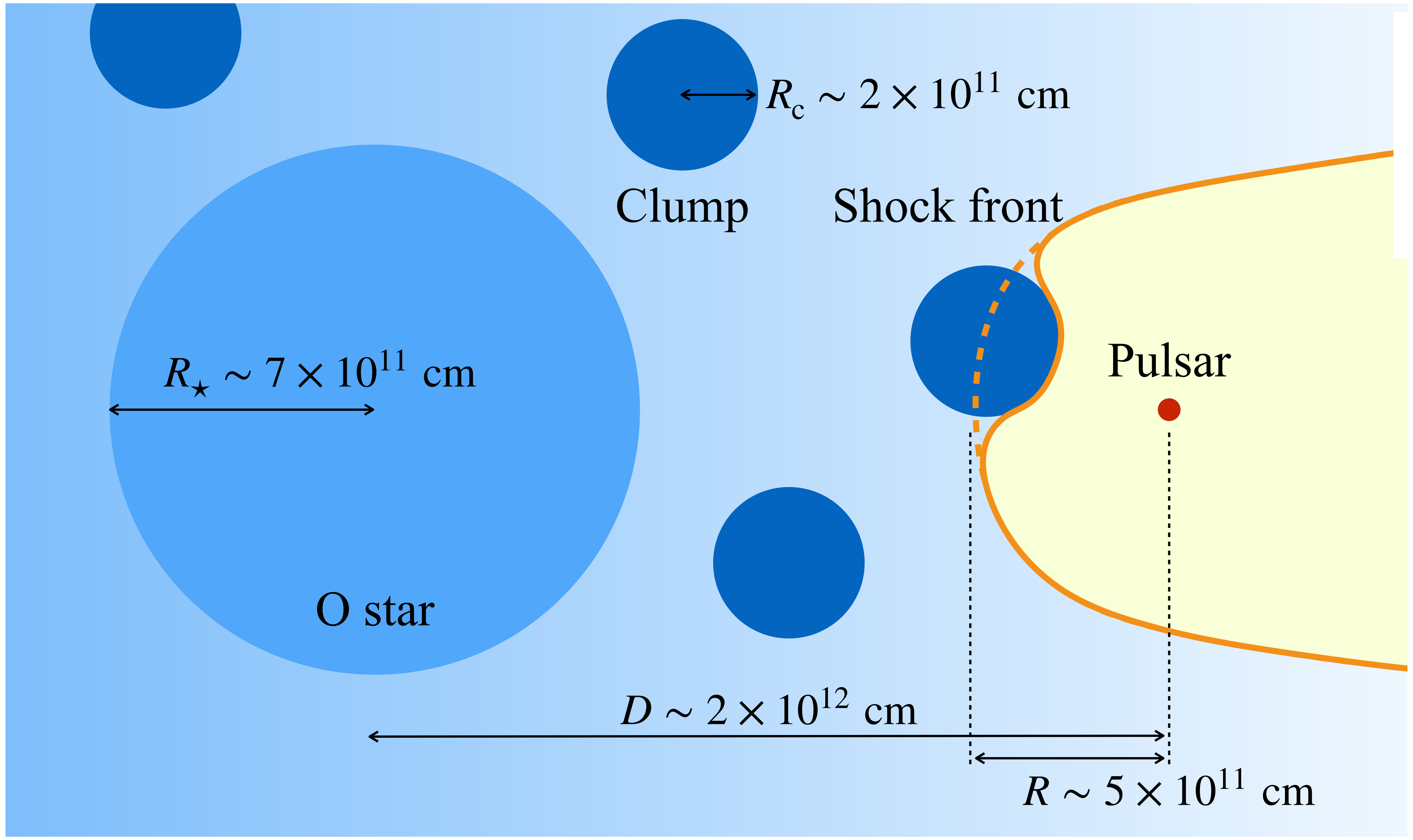
To illuminate the variable components, we calculate the difference between the original and running-averaged curves.



The short-term variability has the following features:

1) a few ten ks of duration , 2) a few events per orbit, 3) the column density in the flare $\lesssim 10^{22}$ cm^{-2}

An interpretation of the origin of the variability



$$t_c \approx \frac{f^{-1/2} R_c}{V_w} ,$$

(crossing-time of the sound speed in a clump)

$$R_c \approx 2\times10^{11}\ \mathrm{cm} \times \left(\frac{f}{0.01}\right)^{1/2} \left(\frac{t_c}{10\ \mathrm{ks}}\right) \left(\frac{V_w}{2000\ \mathrm{km/s}}\right)$$

- Long-term stability in > 10 yr favors the colliding-wind system than the accreting-jet model
- The clumpiness in the stellar wind can cause the short-term variability (Bosch-Ramon13, Kefala+23)
  - A clump can explain the duration, occurrence, and no change in column density
  - The soft X-ray short-term variability can be a tool to study the wind structure

Questions to be solved for gamma-ray binaries

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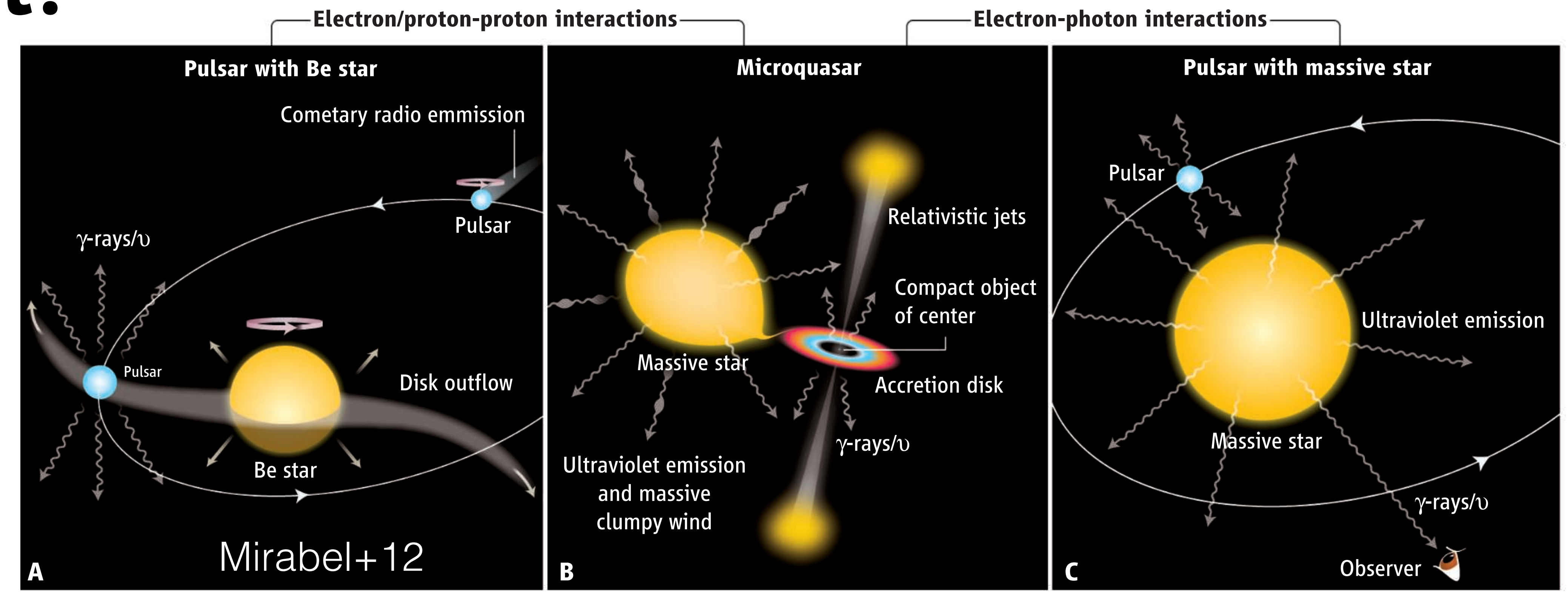

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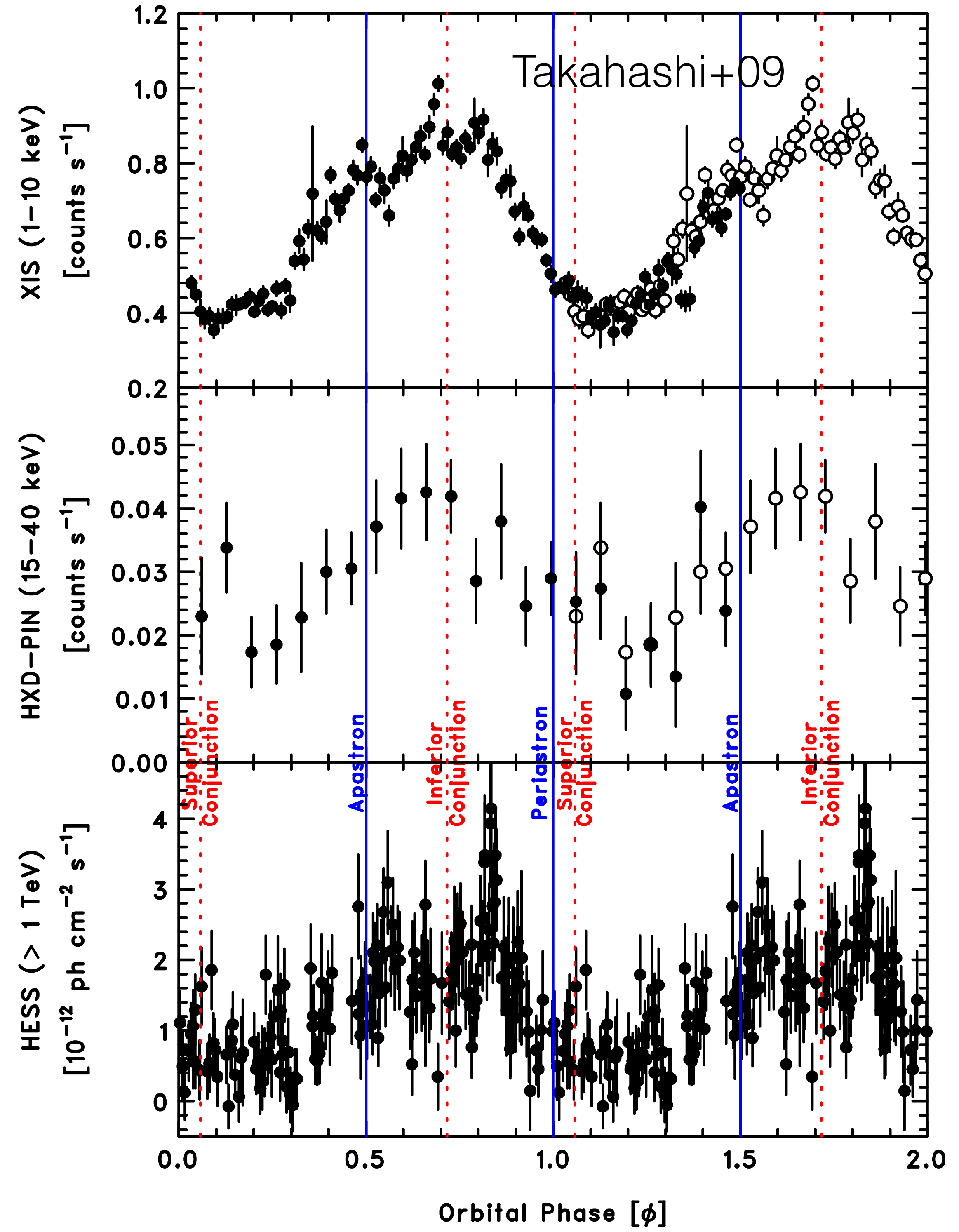

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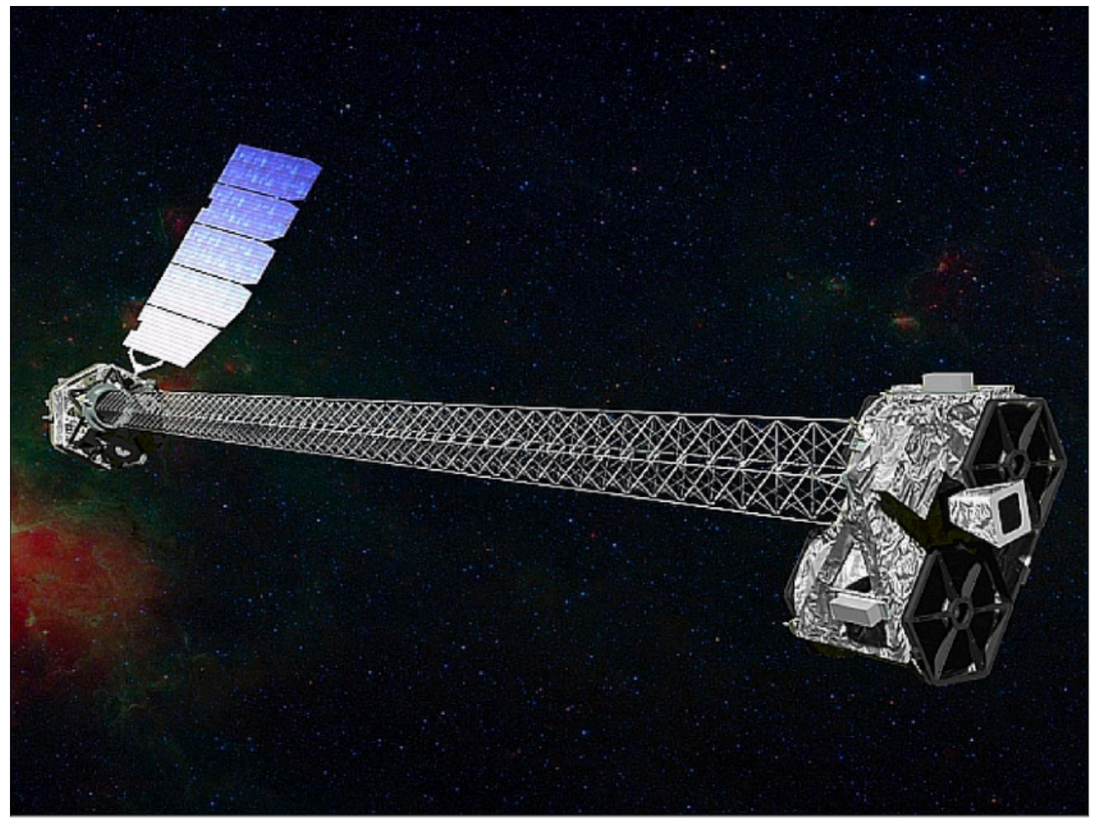
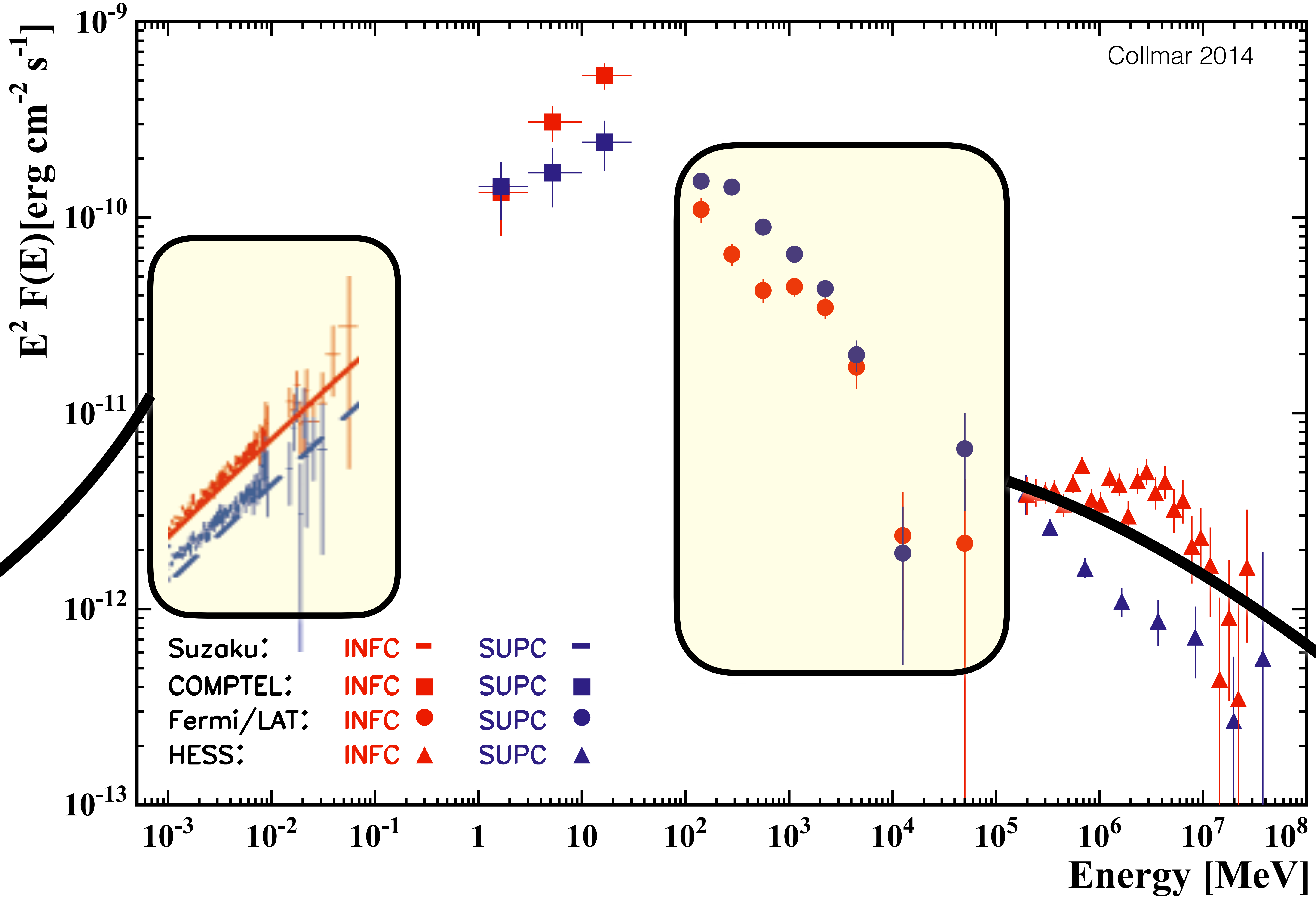


Suzaku data

(Takahashi+09),

Now we have NuSTAR data!

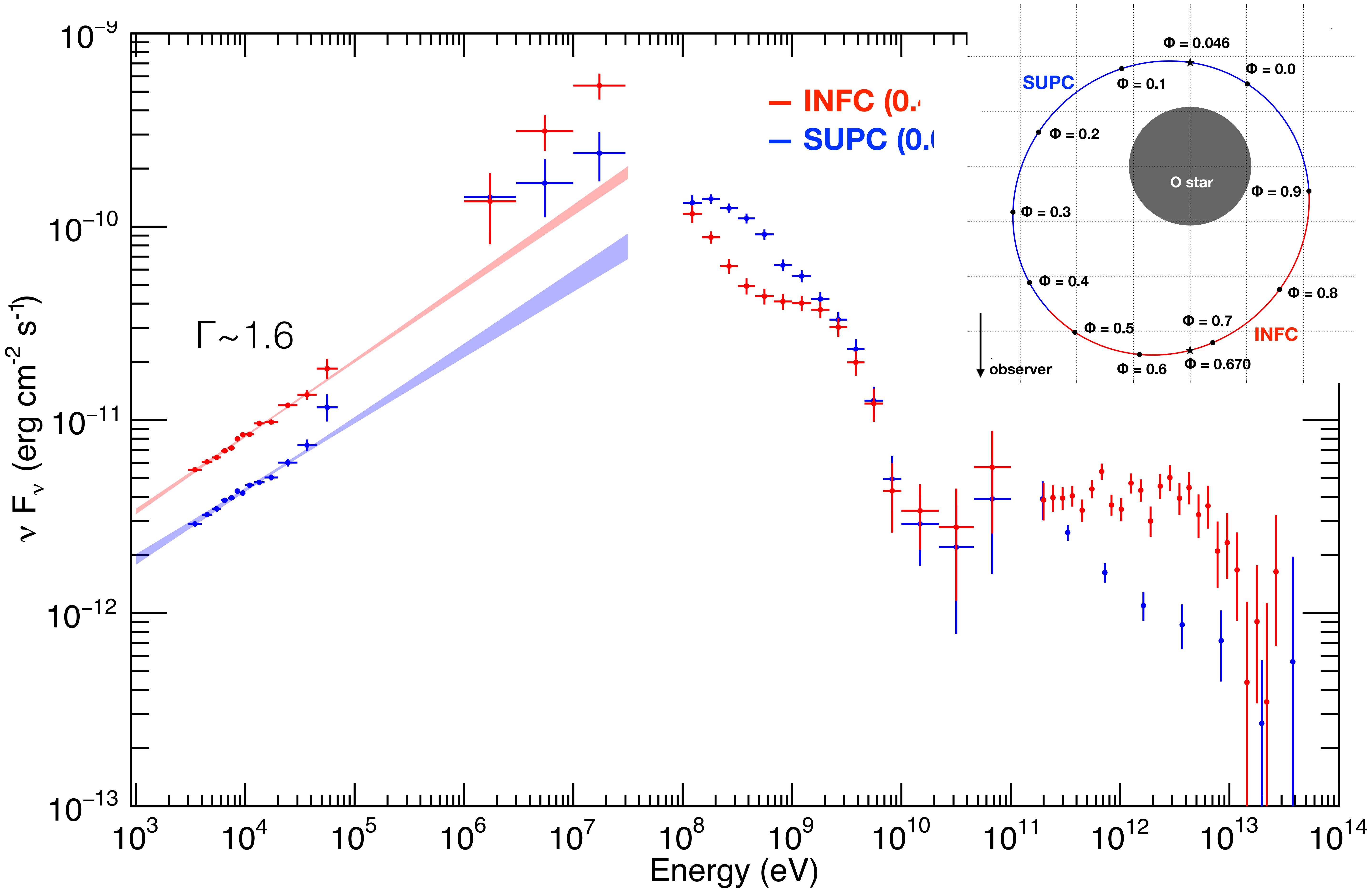


~ 3 years Fermi data

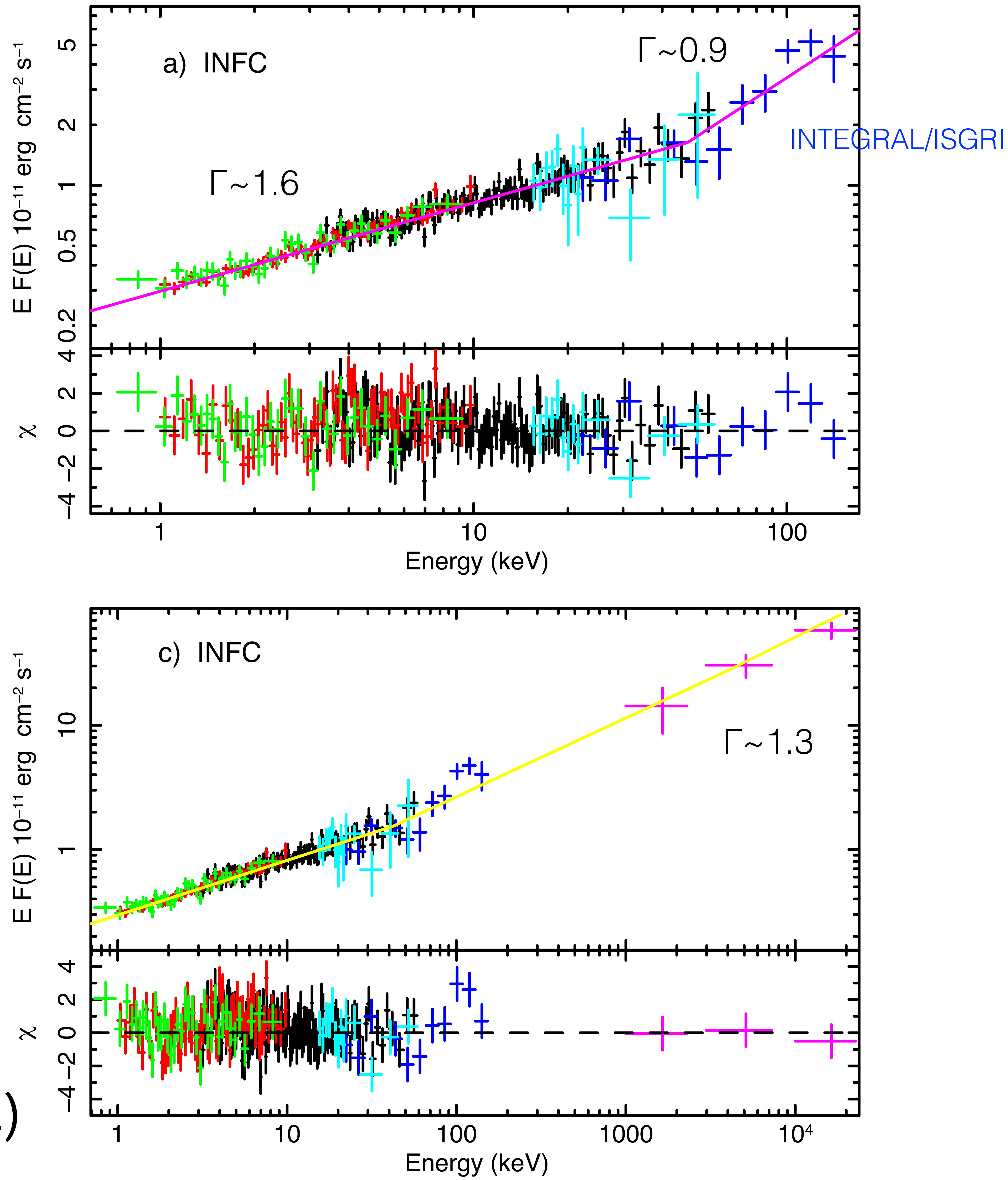
(Hadasch+12),

Now we have 11 years data!

Spectral hardening above ~100 keV



Falanga+21

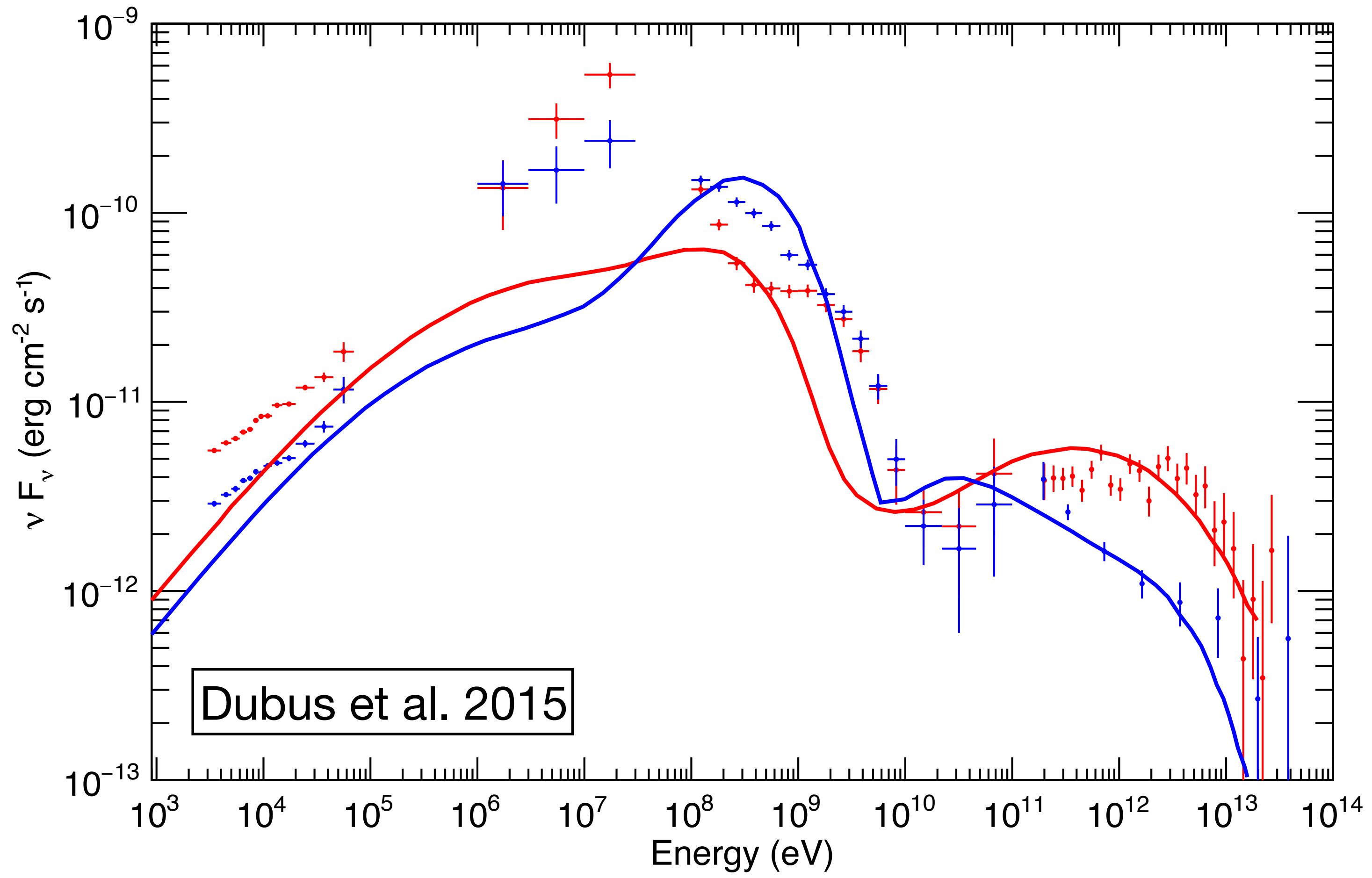


NuSTAR data does not connect to the MeV data (HY+21)

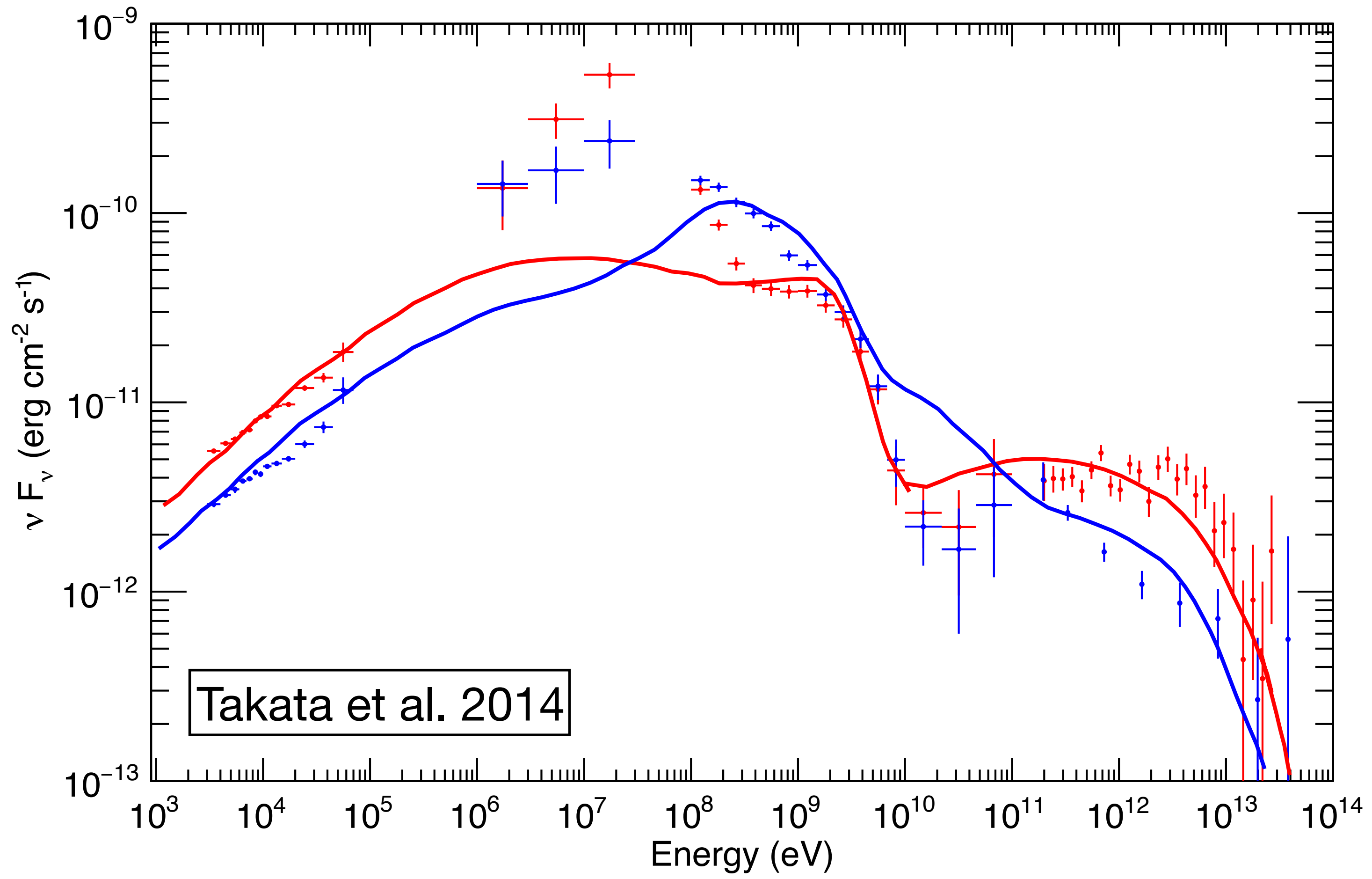
INTEGRAL data favors the broken power-law (Falanga+21, Malizia+21)

New SED vs. previous theoretical models

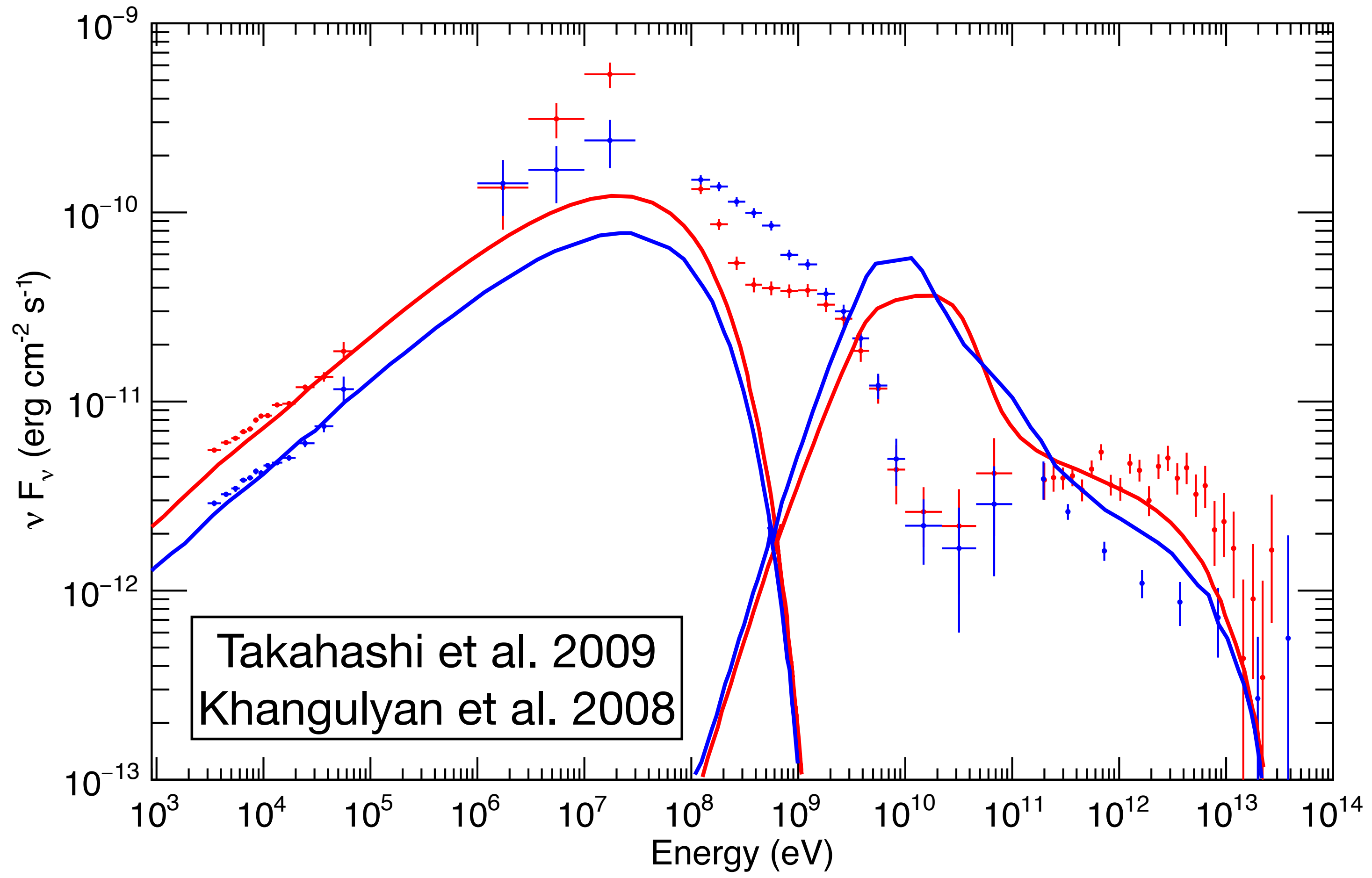
Pulsar model



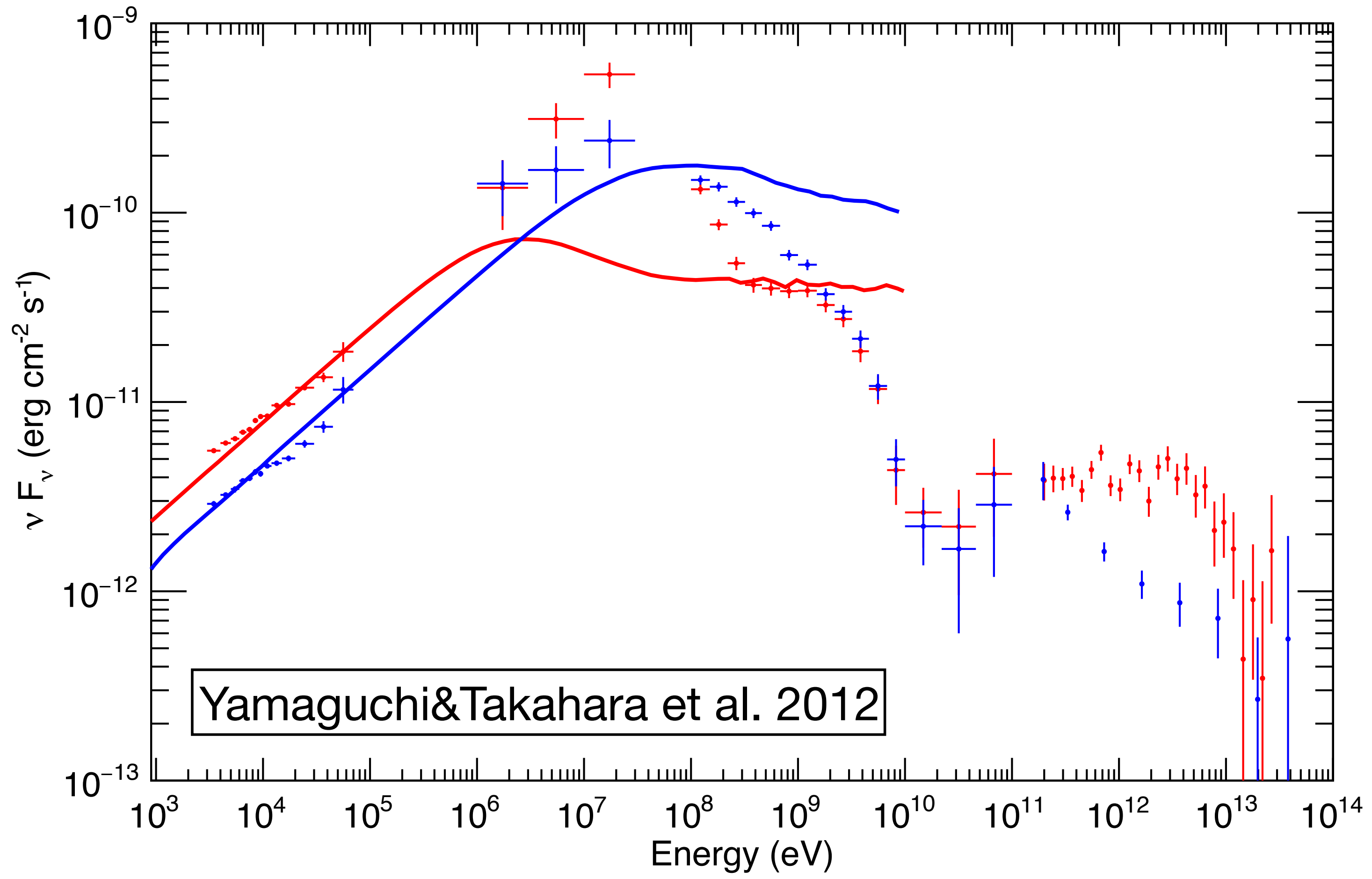
Pulsar model



Jet-like stucture

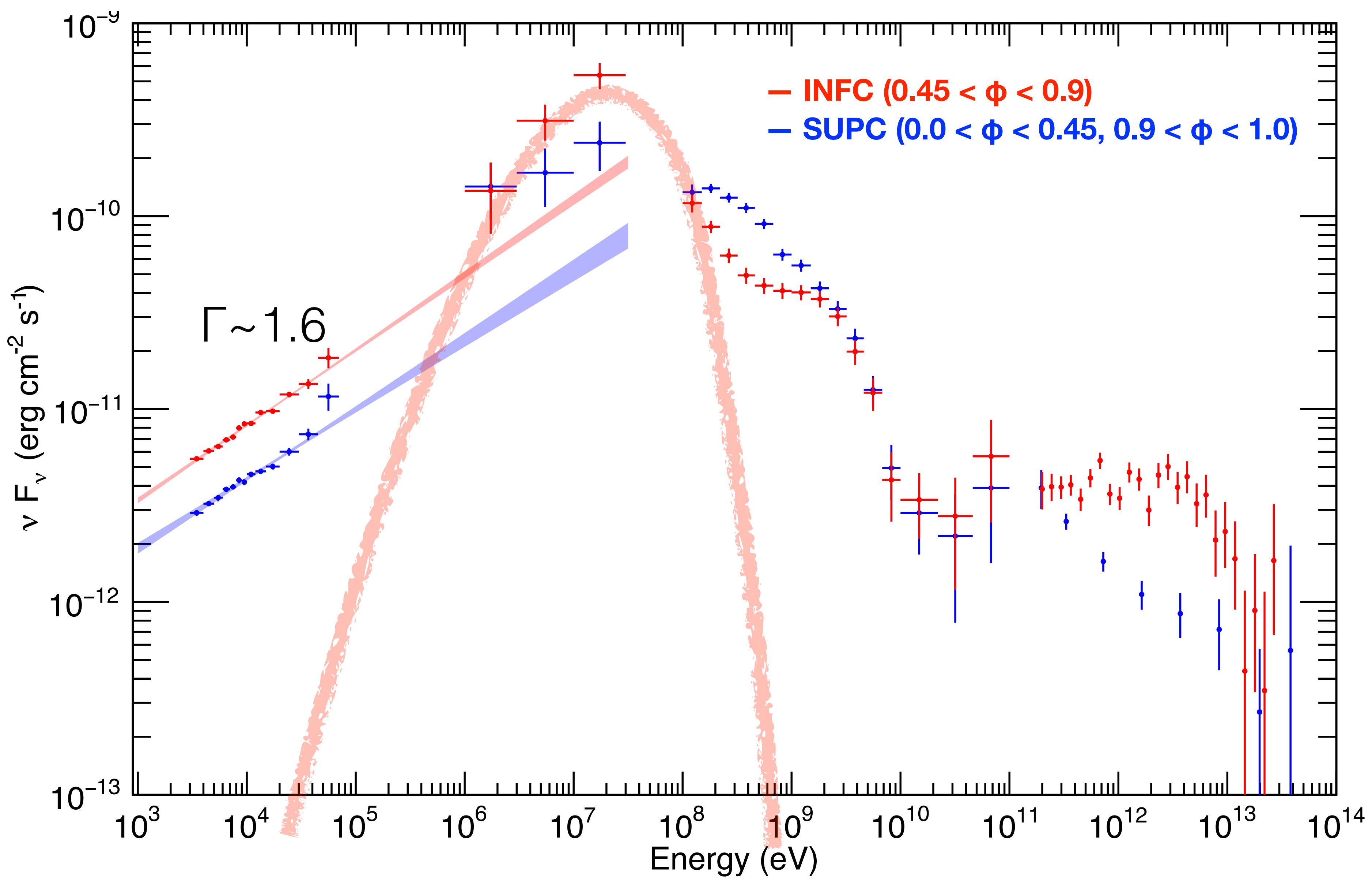


Two IC component



X-ray/TeV are explained by the pulsar/miscroquasar model, but MeV is not explained

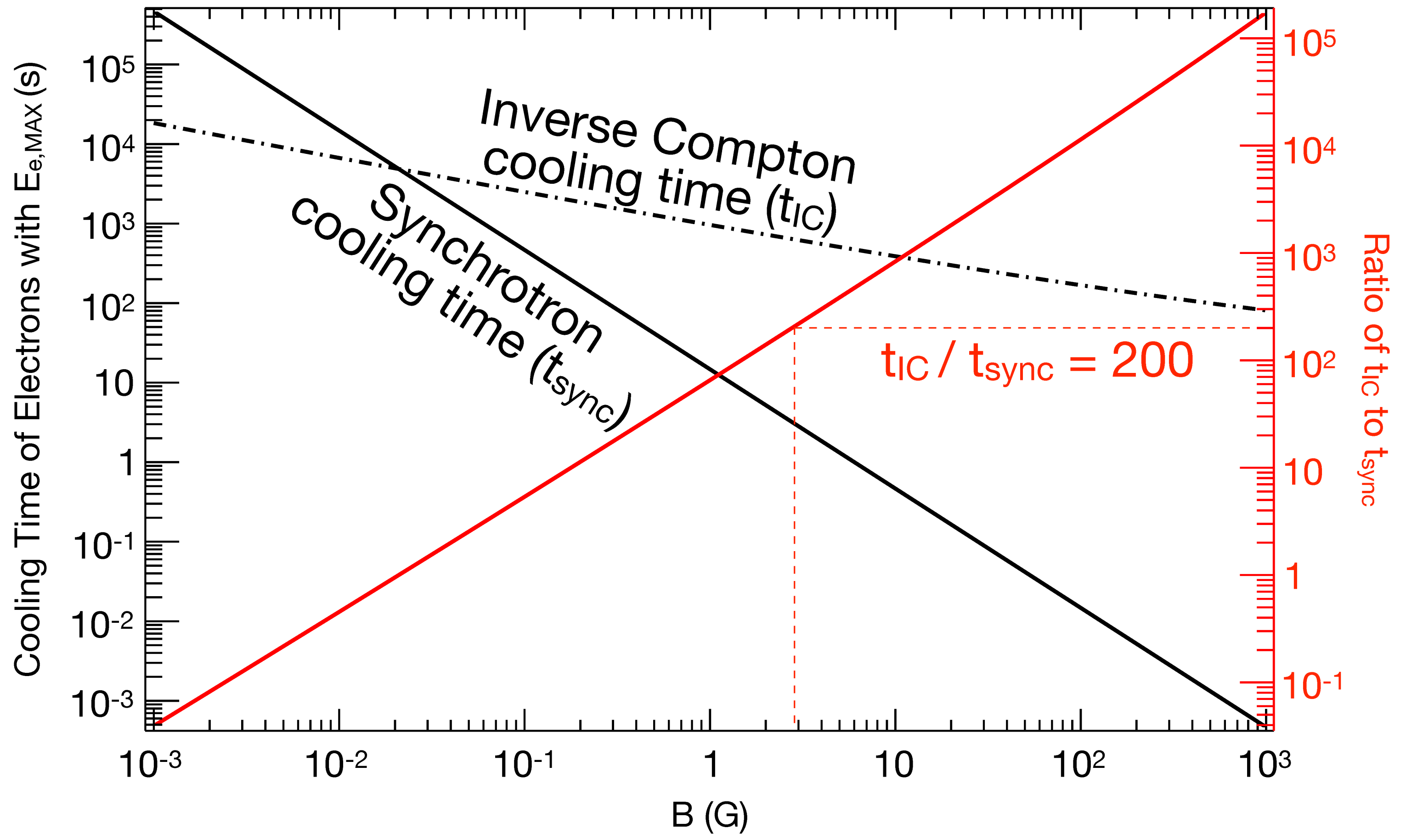
Particle acceleration under the MeV gamma-ray emission



Synchrotron emission in strong B field ?

- peak at 20-30 MeV → η< 10
- Not to overestimate the TeV emission → B > a few gauss
- To explain the hard photon index → hard electron spectrum (< 2)

cooling time ratio $L_{TeV}/L_{MeV} \propto t_{sync}/t_{IC}$



Several ideas are proposed so far

- relativistic magnetic reconnection stimulated by a possibility of a magnetar binary? (HY+20, HY+21)
- high-sigma) magnetized cold wind close to a pulsar (Bosch-Ramon20)
- re-acceleration like in the bow shock PWNe (Bykov+17, Falanga+21)

MeV gamma-ray observation will come soon with COSI

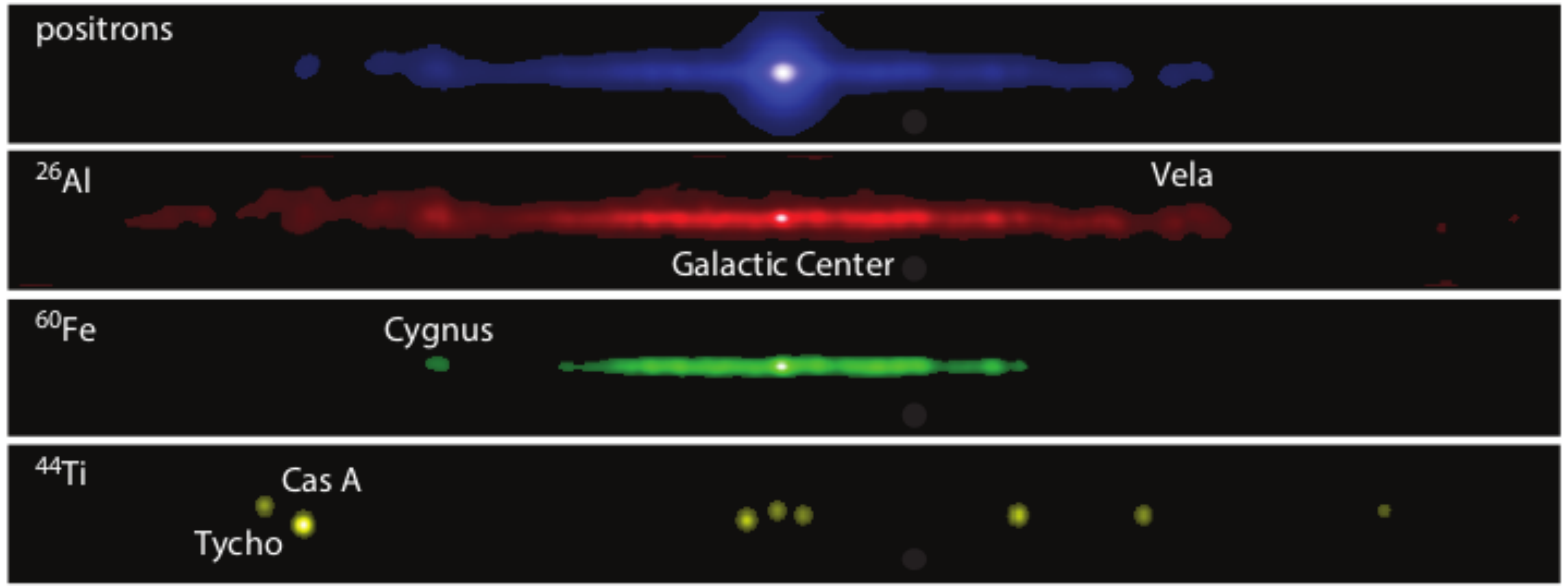
COSI (The Compton Spectrometer and Imager)

- was selected as a NASA Small Explorer satellite
- planned to be launched in 2027
- a Compton telescope observing gamma-rays in 0.2 - 5.0 MeV

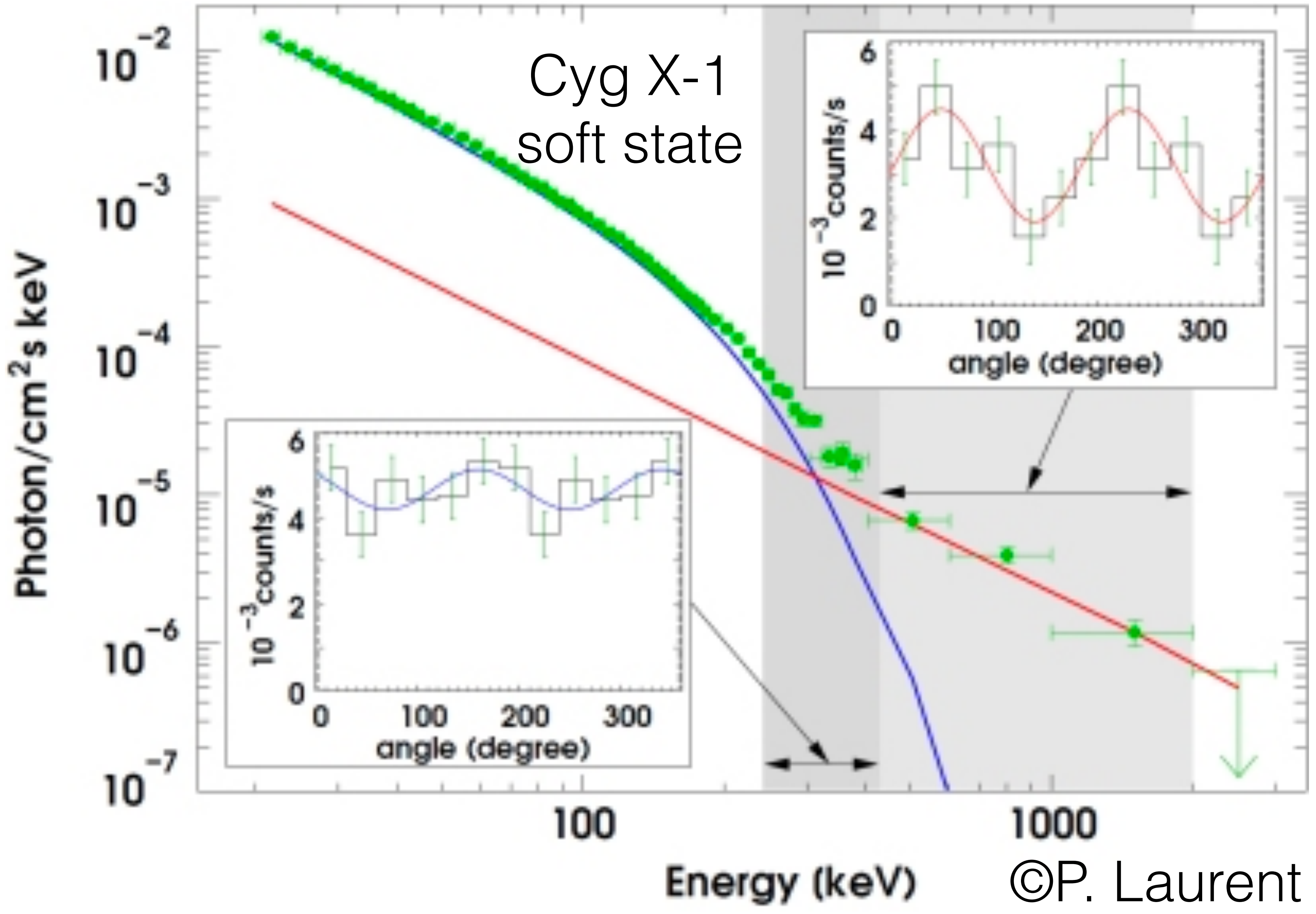
Performance (requirements)

- Excellent energy resolution w/ Ge detectors
  6.0 keV at 511 keV, 9.0 keV at 1.157 MeV
- Large FoV
  >25%-sky instantaneous FOV, 100%-sky each day
- Line sensitivity ~10x better than COMPTEL
  3.0×10^{-6} ph cm^{-2} s^{-1} at 1.8 MeV (Galactic 26Al flux is 230x brighter)
- Angular resolution (FHWM): 2.1 deg. at 1.8 MeV

Primary science goals



A. Uncover the origin of Galactic positrons
B. Reveal Galactic element formation
C. **Gain insight into extreme environments with polarization**
D. **Probe the physics of multimessenger events**



MeV gamma-ray polarization measurement can probe physical processes in the accreting BHs

several Galactic BHs (e.g. Cyg X-1)

Observations of the gamma-ray binaries (e.g. LS 5039, LS I+61 303) are being discussed in the science team

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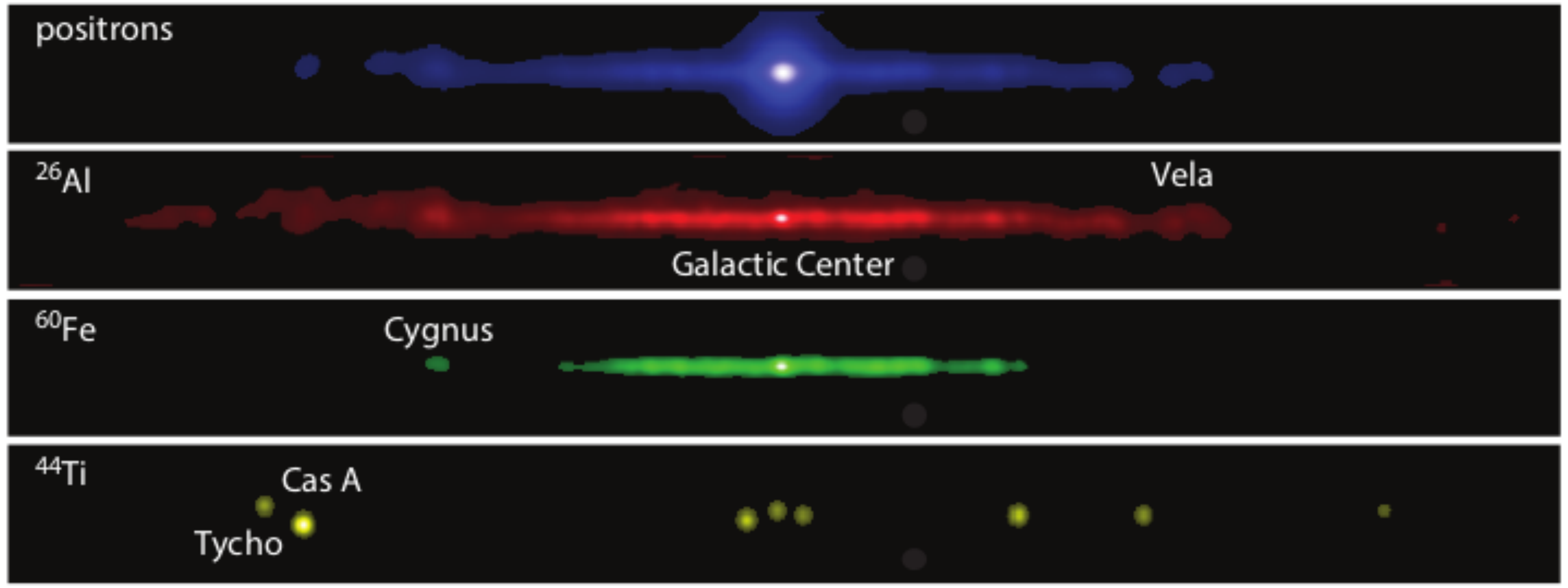

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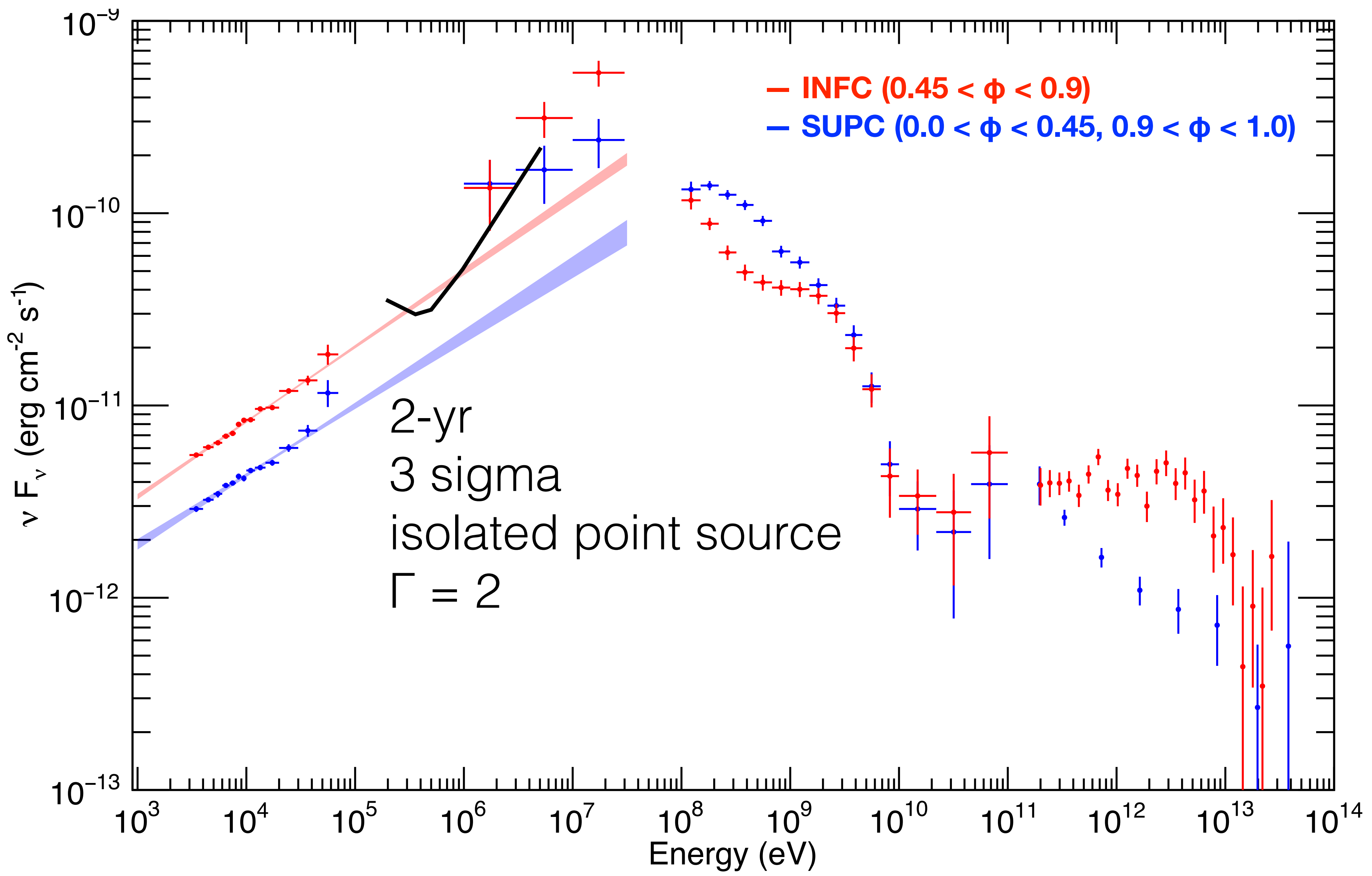

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Conclusions

1. The nature of compact objects? Physical environment around CO?

-> Long-term soft X-ray stability of LS 5039 (HY+23)

- With a time scale of > 70 ks, the orbital light curve shows a remarkable reproducibility over 10-20 years.
- Also, a few 10 ks variability is observed, which would caused by the clump-wind interaction in a binary system consisting of NS and Ostar.

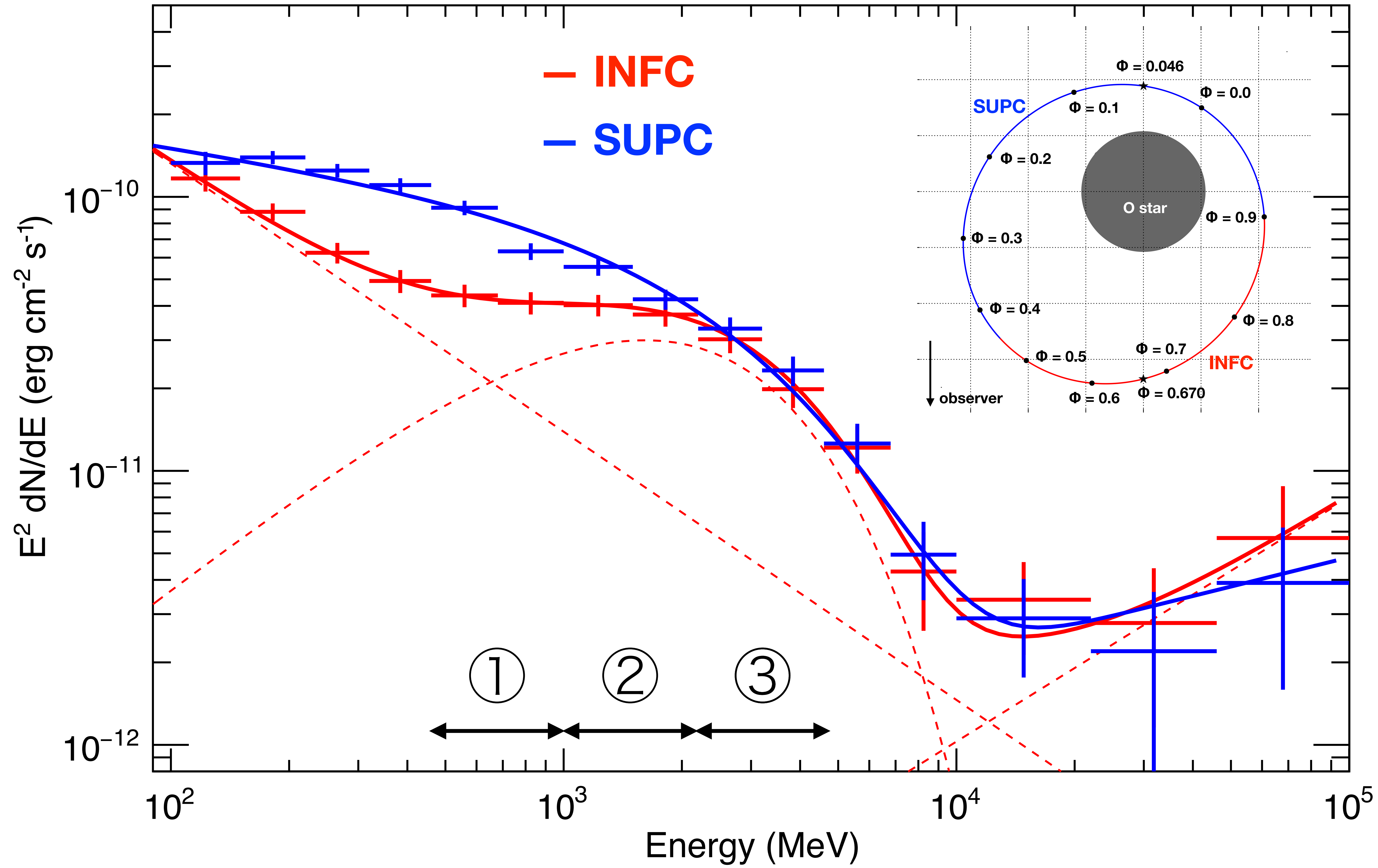
2. Physical mechanism of the particle acceleration

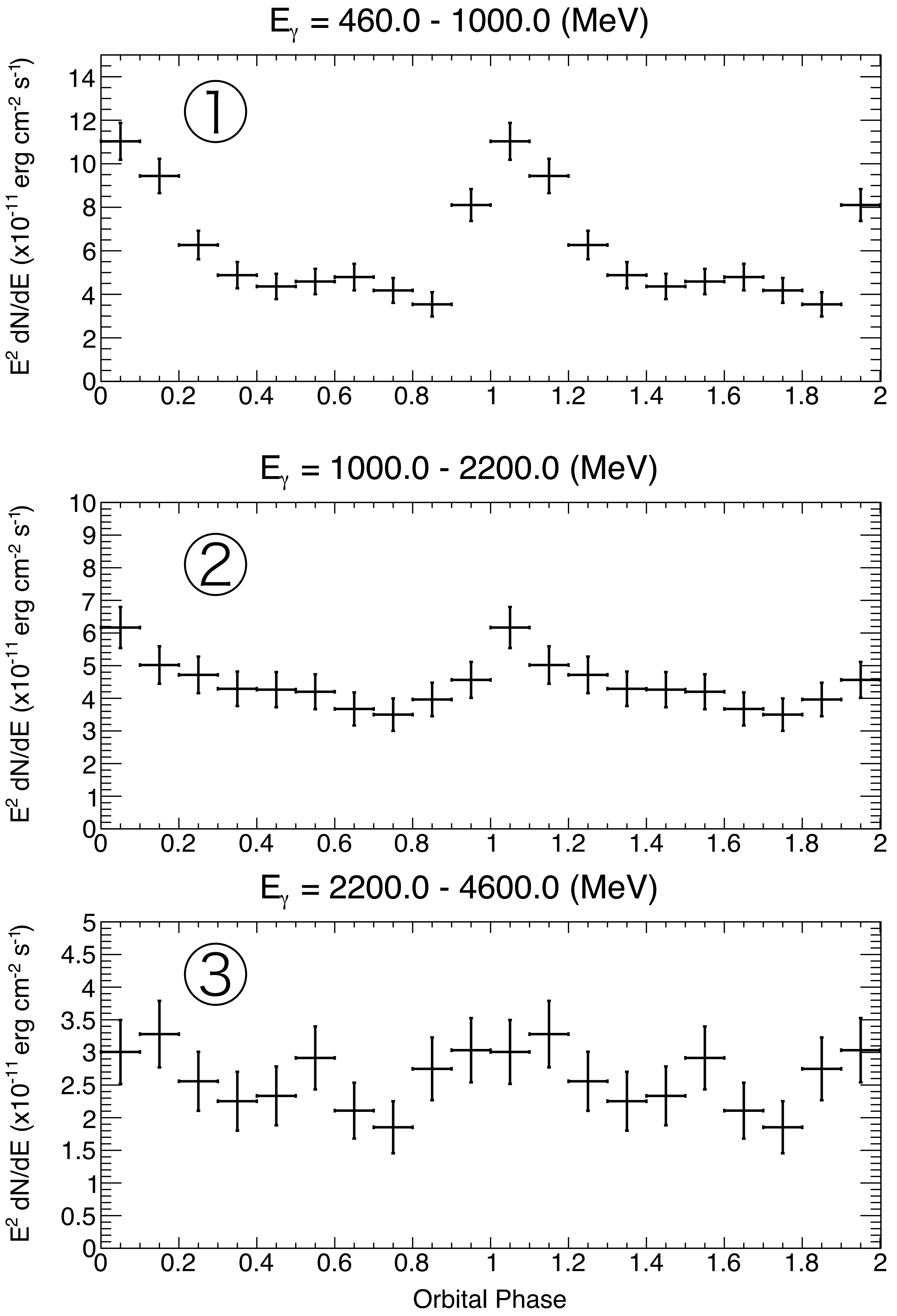
-> MW observations of LS 5039 w/ NuSTAR and Fermi (HY+21)

- SED shows a spectral hardening above ~100 keV
- Additional leptonic population with an hard index is required to explain MeV to subGeV component
- MeV gamma-ray observations will can be performed with COSI in 2027!

bkup

GeV spectra with 11 years of Fermi/LAT data



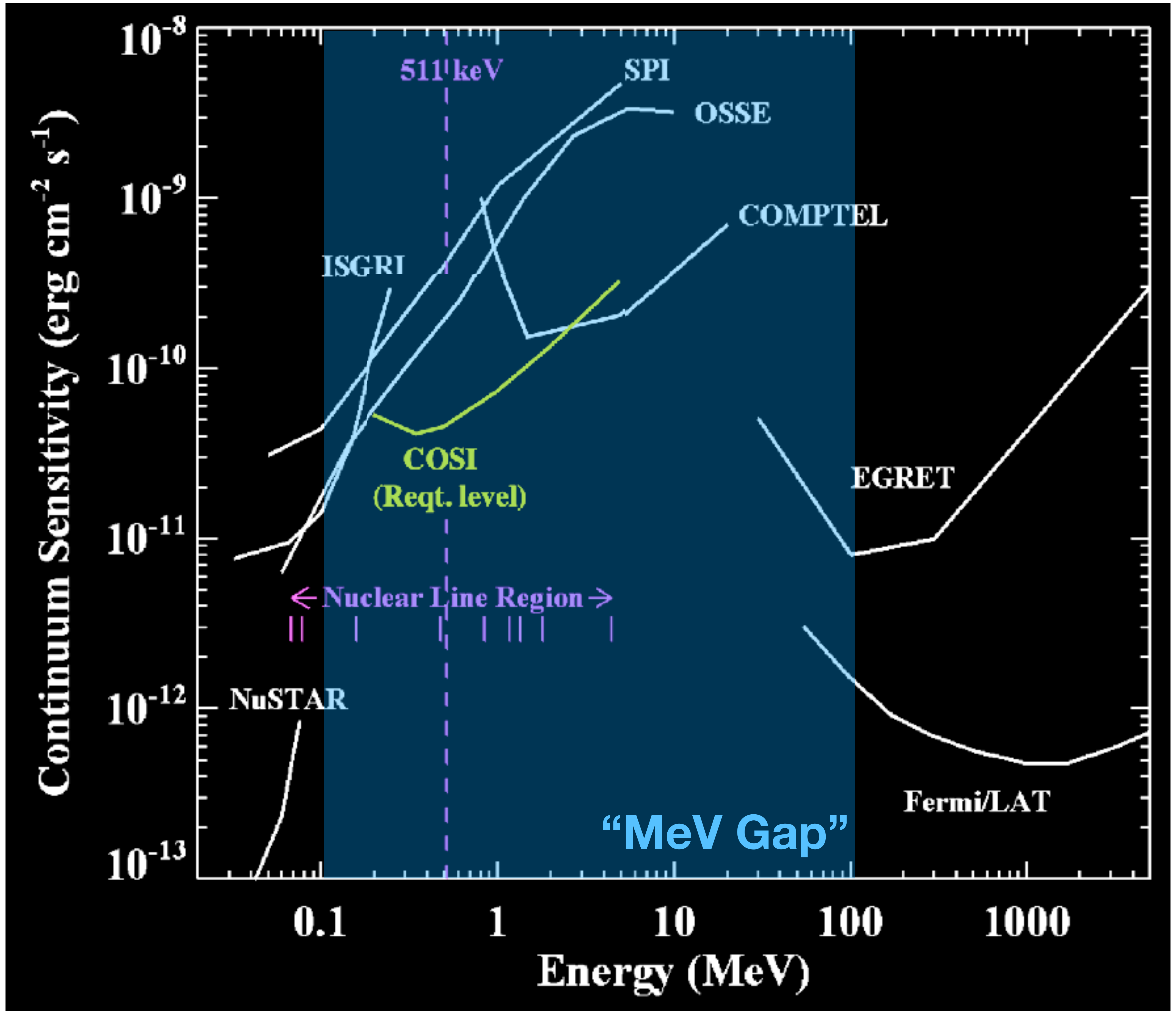


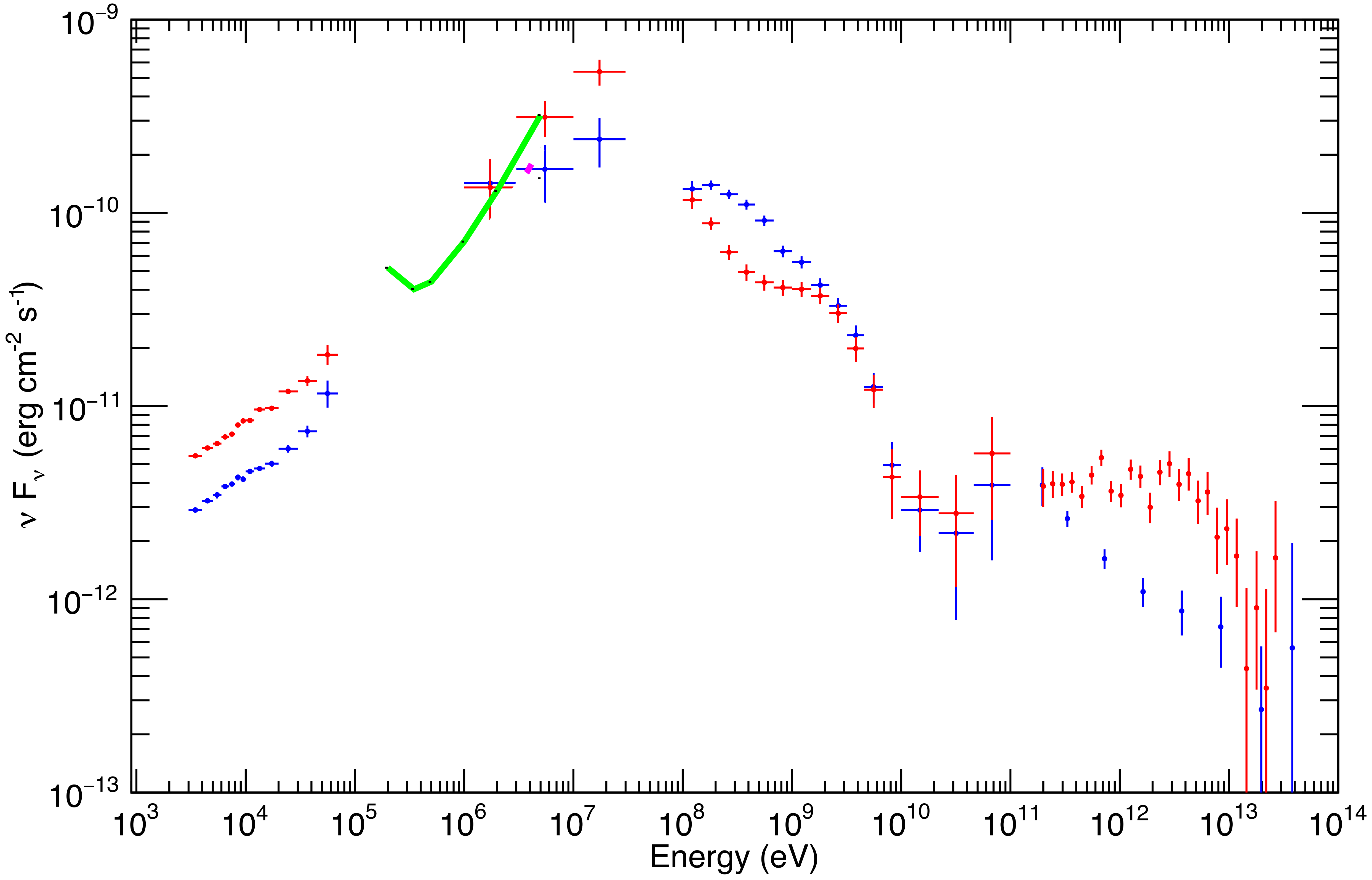
The two spectral components

- < 1 GeV: the photon index changes with orbital phase
- > 1 GeV: independent of the orbital phase

Compact binary science with COSI

The bright gamma-ray binaries can be detected from ~0.2 to 5 MeV, e.g., Cyg X-1/3, LS 5039, LS I+61 303, while the feasibility study is ongoing.





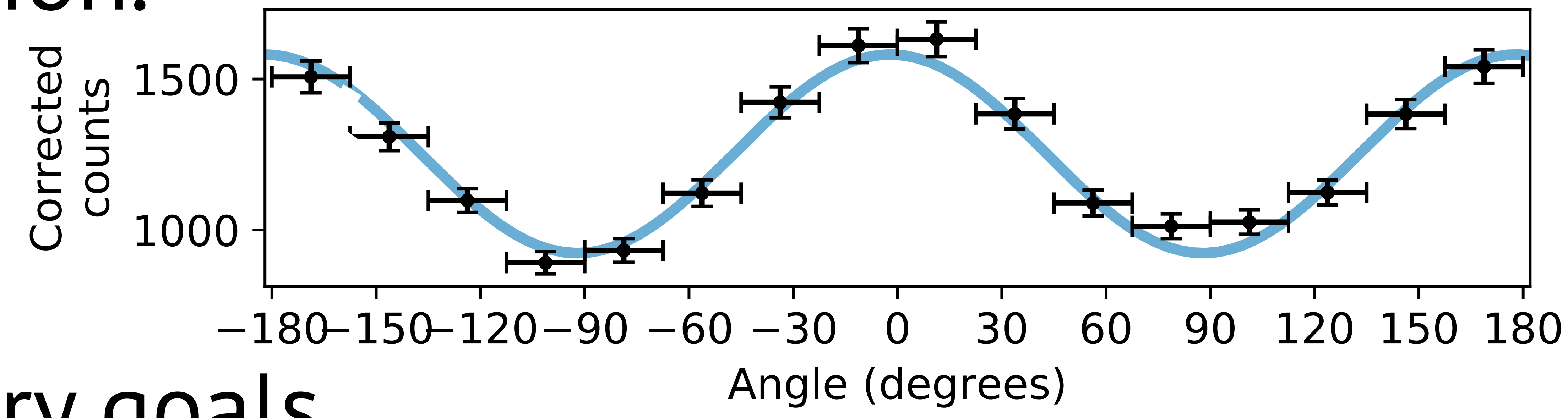
Compact binary science with COSI

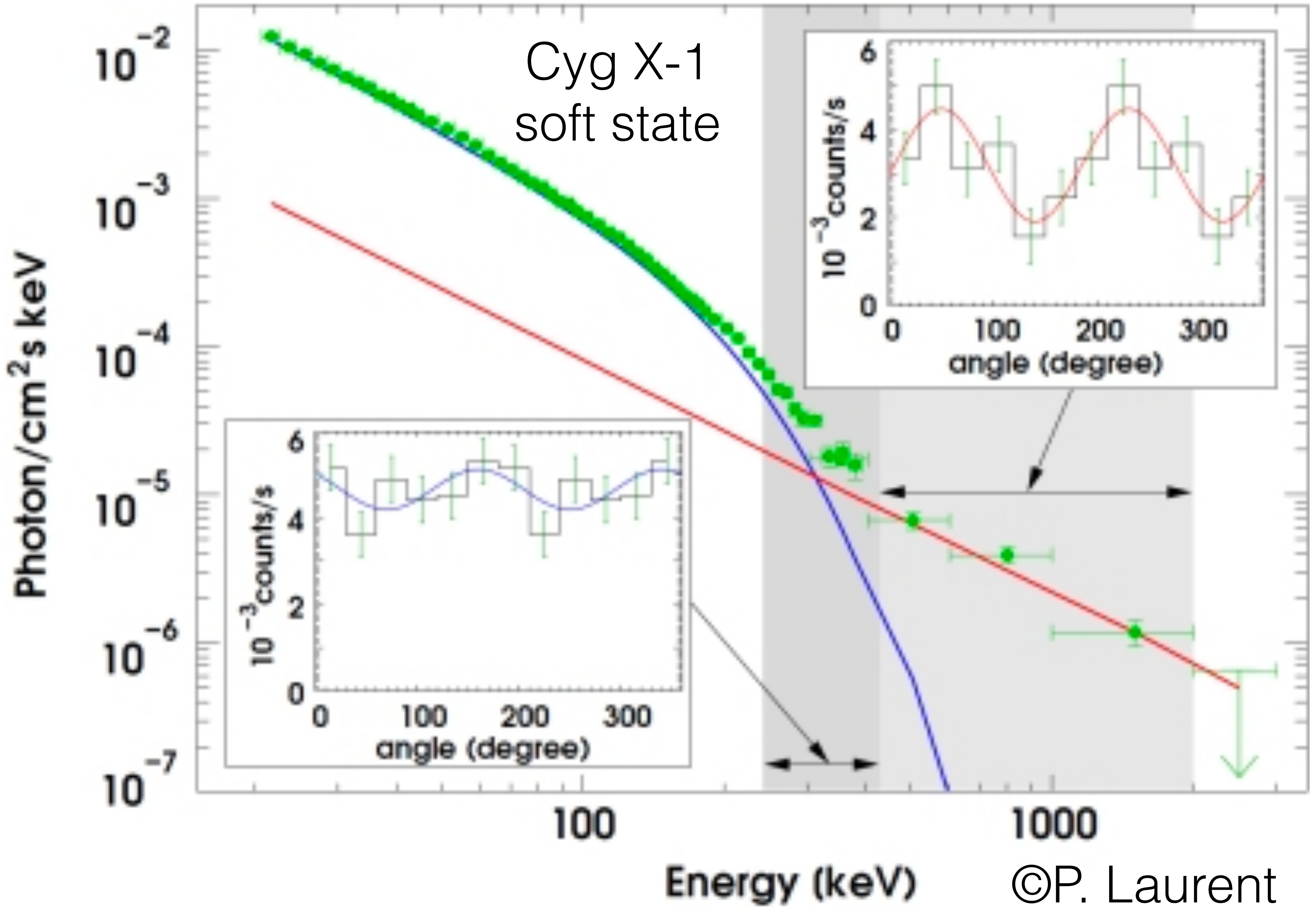
Compton telescope can measure the polarization.

$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2}\left(\frac{E'_\gamma}{E_\gamma}\right)^2\left(\frac{E'_\gamma}{E_\gamma} + \frac{E_\gamma}{E'_\gamma} - 2\sin^2\theta\cos^2\chi\right)$$

Polarization measurement is one of our primary goals

Lowell, phD, 17





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