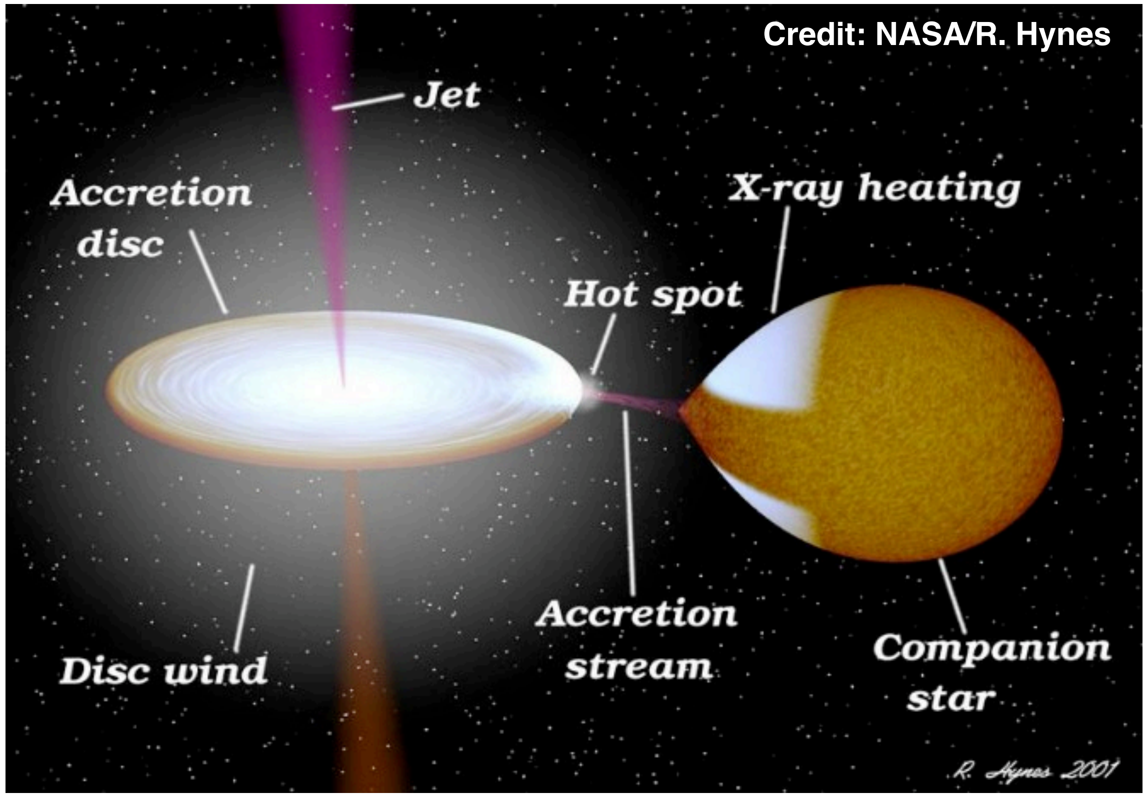
The mystery of the MeV gamma-ray emission from gamma-ray binary systems

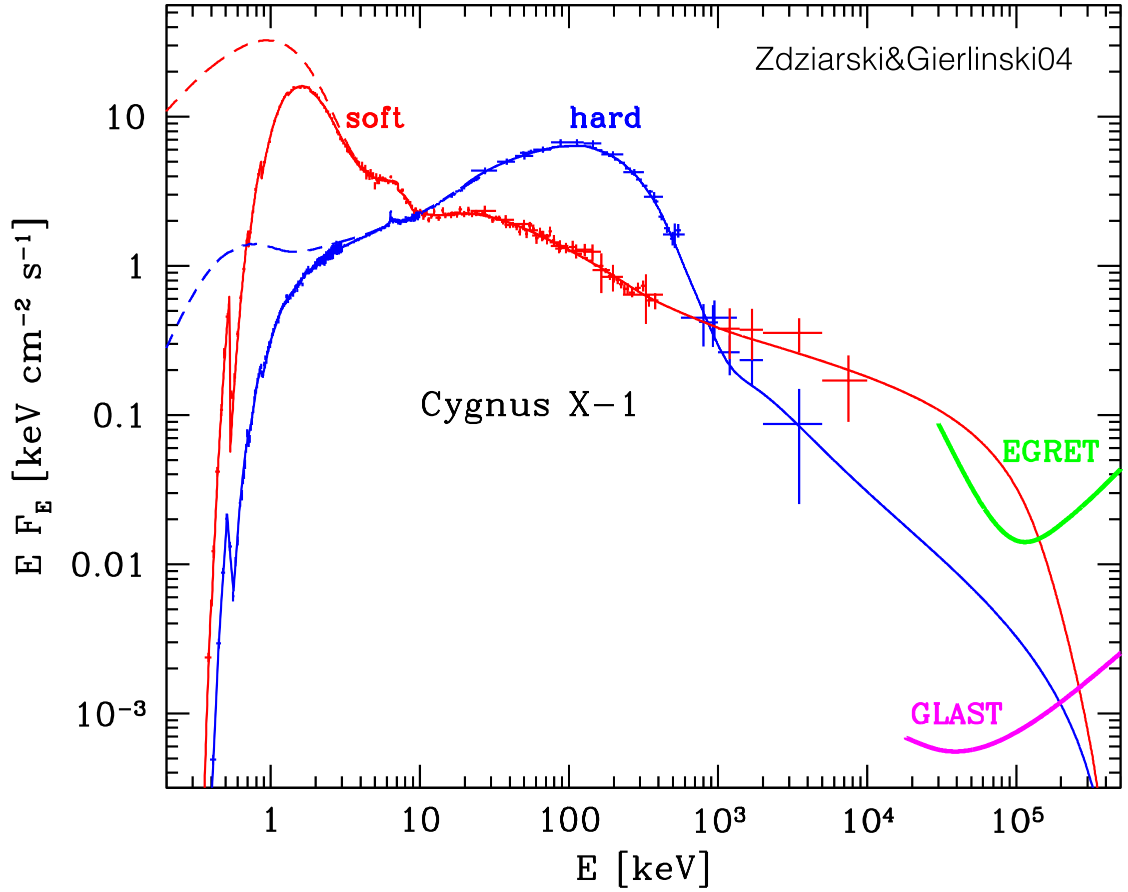
RIKEN, High Energy Astrophysics Laboratory
(← phD student in IPMU, Takahashi group untill last March)

Hiroki Yoneda

Compact Binaries in Universe

About 70% of X-ray sources in our Galaxy are binary systems that contain BHs or NSs (Grim+02)





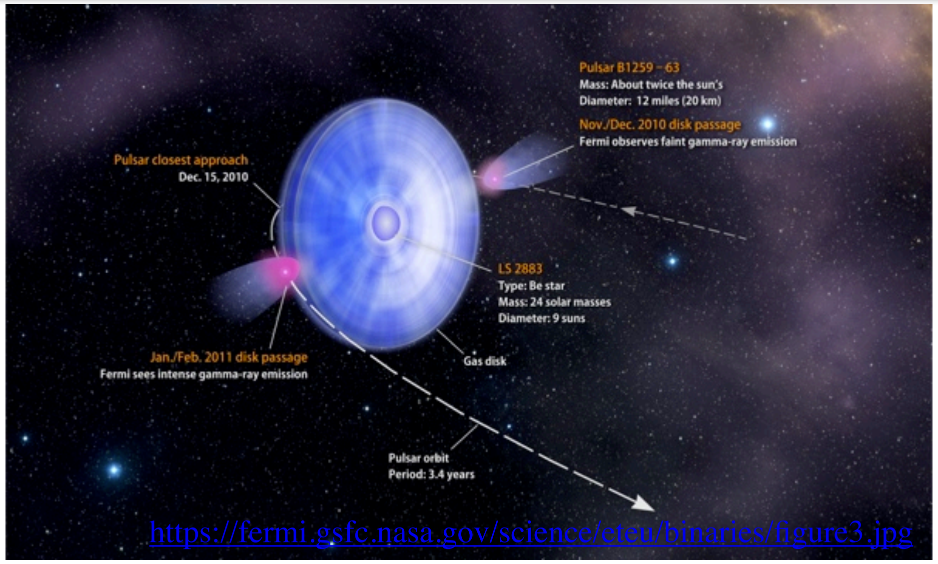
Standard picture:

- A compact object captures material from a companion star
- Its gravitational energy is efficiently converted to radiation

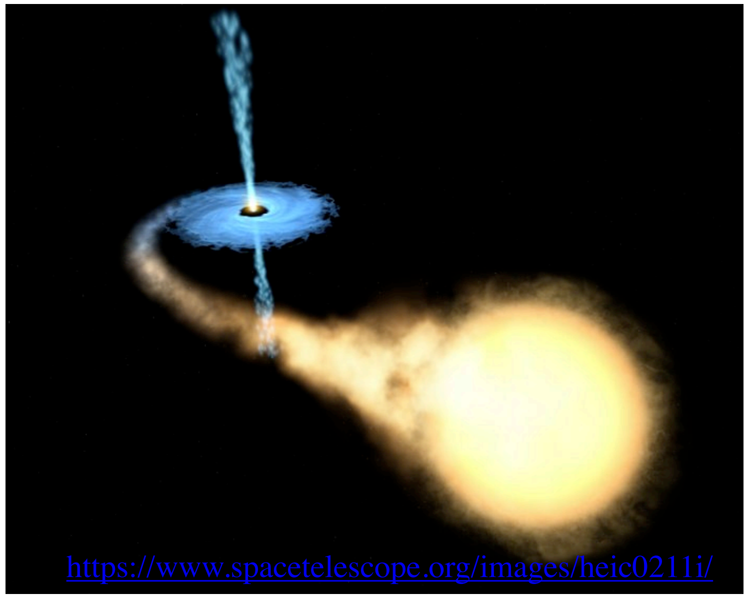
From the 2000s, several binary systems that cannot be explained by this picture, were discovered

High Energy Emissions From Binaries

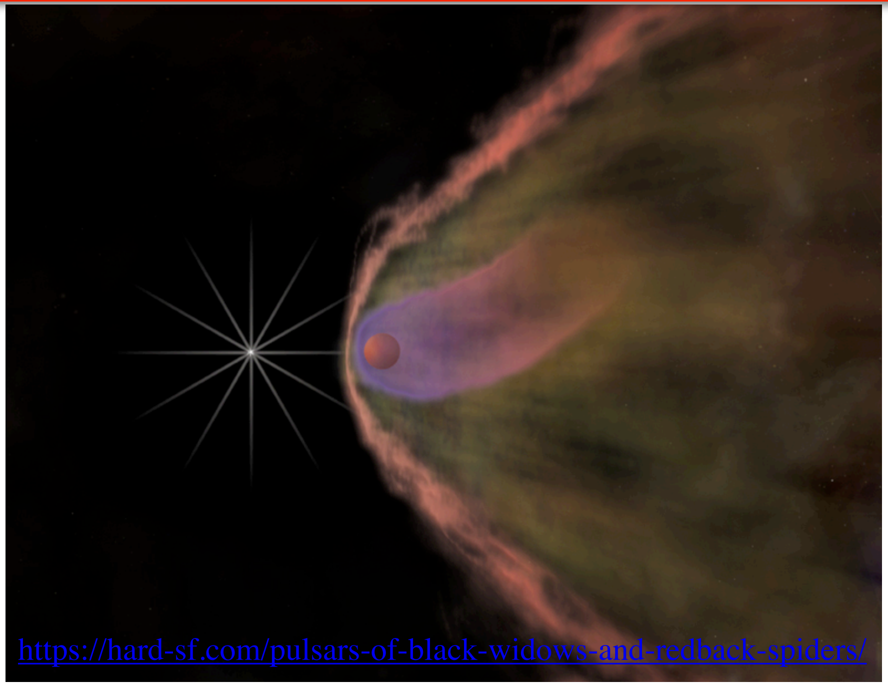
Owing to *Fermi, HESS, MAGIC, VERITAS*…,
GeV/TeV emissions from binaries have been discovered!



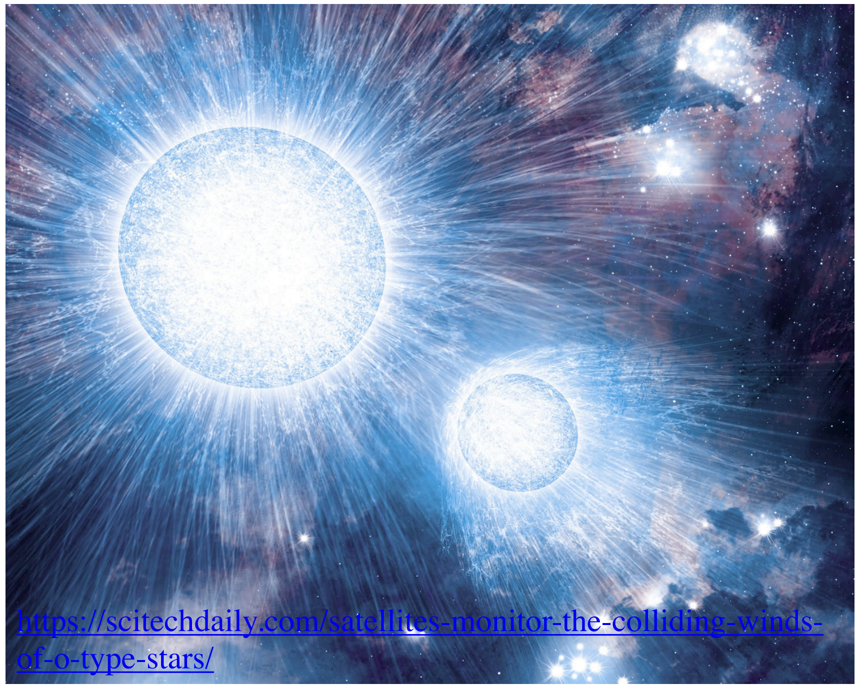
Gamma-ray Binaries



Microquasars



Red back, black widow



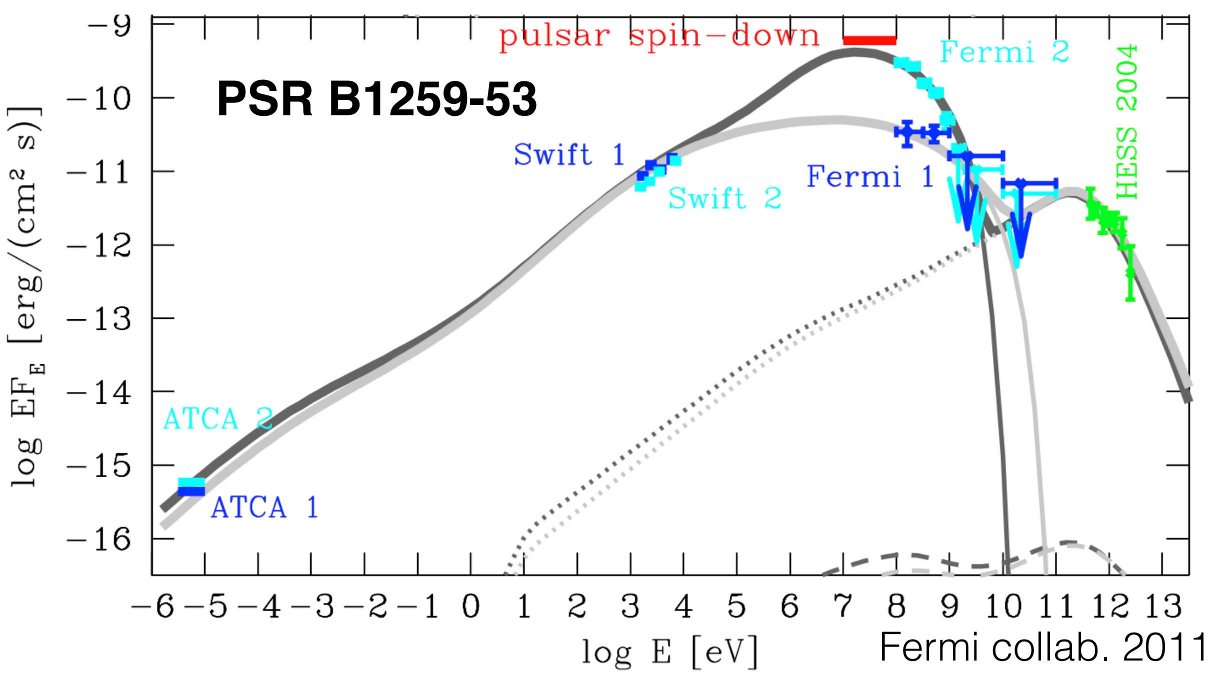
Colliding-wind binary

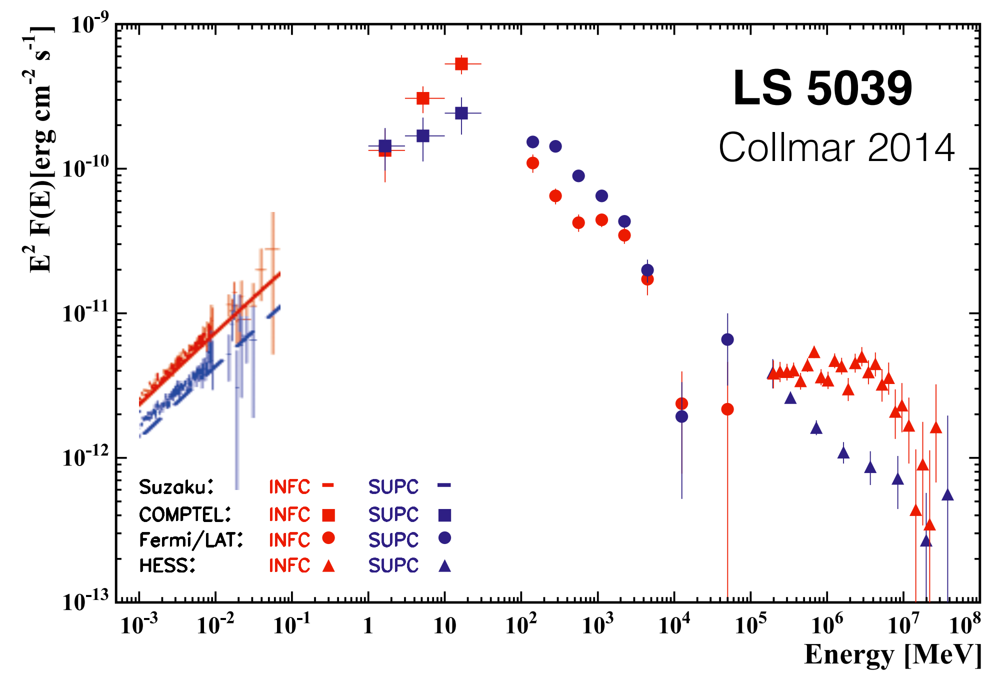
Gamma-ray Binary Systems

Sub-class of high-mass X-ray binaries with these features,

- **Dominant non-thermal emission up to the TeV band**
- **Their SEDs have peaks beyond 1MeV**

➔ Completely different features from X-ray binaries !





Name	Star	Compact object	Orbital Period
LS 5039	O	?	3.9 day
FGL J1018.6-5856	O	?	16.6 day
LMC P-3	O	?	10.2 day
LS I +61 303	Be	?	26.5 day
HESS J0632+057	Be	?	315.5 day
4FGL J1405.1-6119 (Corbet+19)	O	?	13.7 day
PSR J2032+4127	Be	143 ms pulsar	50 year
PSR B1259-53	Be	43 ms pulsar	3.4 year

Unknown Nature

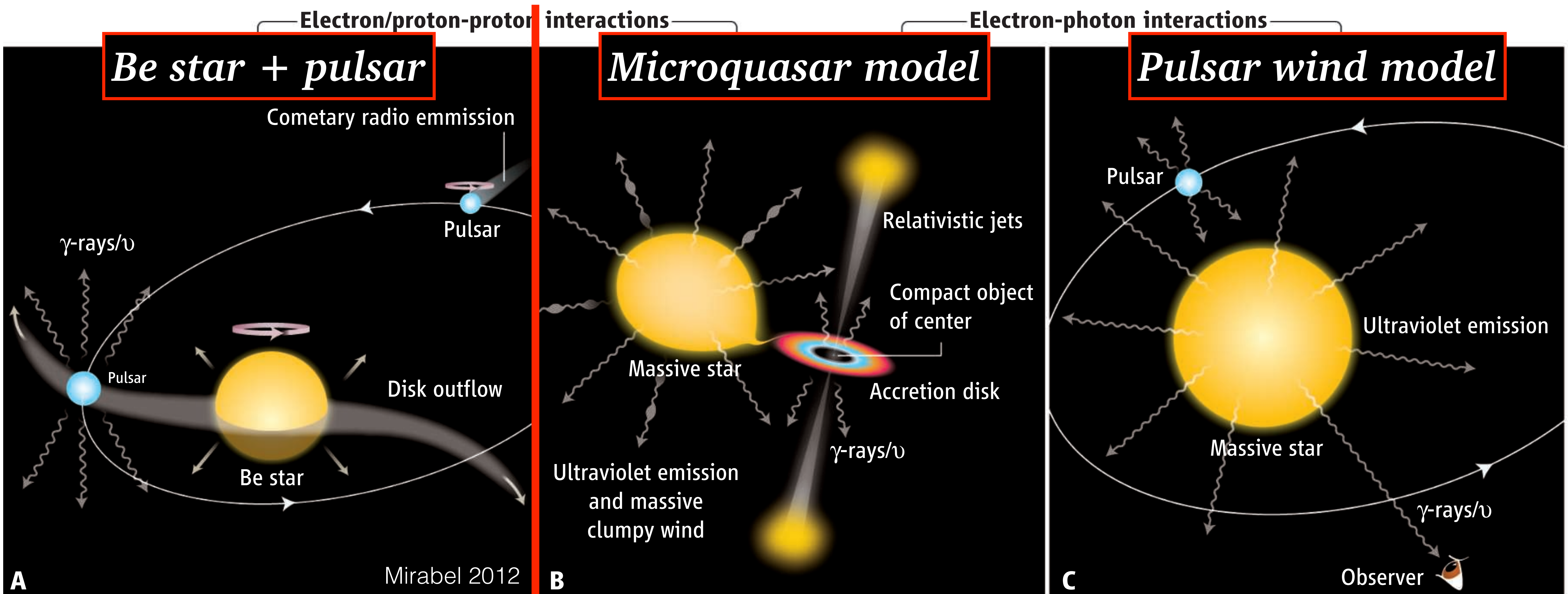
Day ~ Week

Millisecond Pulsar

Year

Standard Pictures

Dominant Non-thermal Emission of Gamma-ray Binaries
→ How are particles accelerated ?



Interaction between a dense disk and pulsar winds

- PSR B1259-53
- PSR J2032+4127

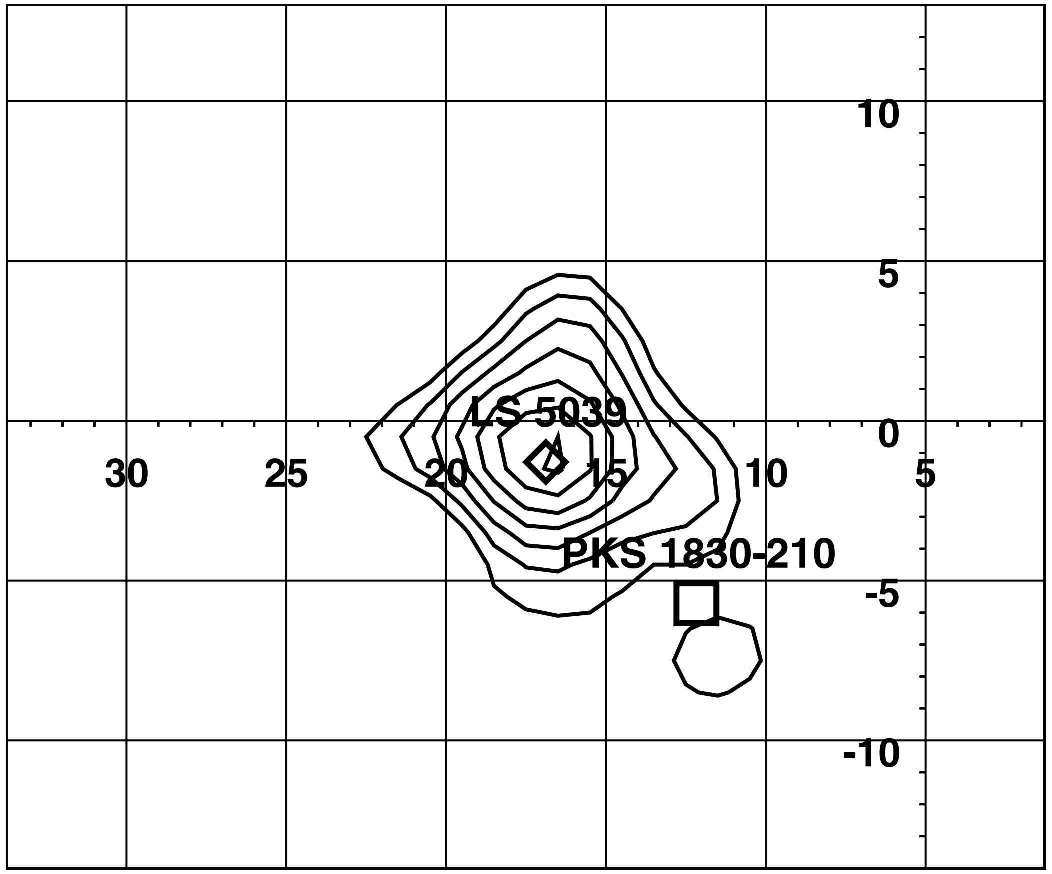
High-energy Emission from BH jets

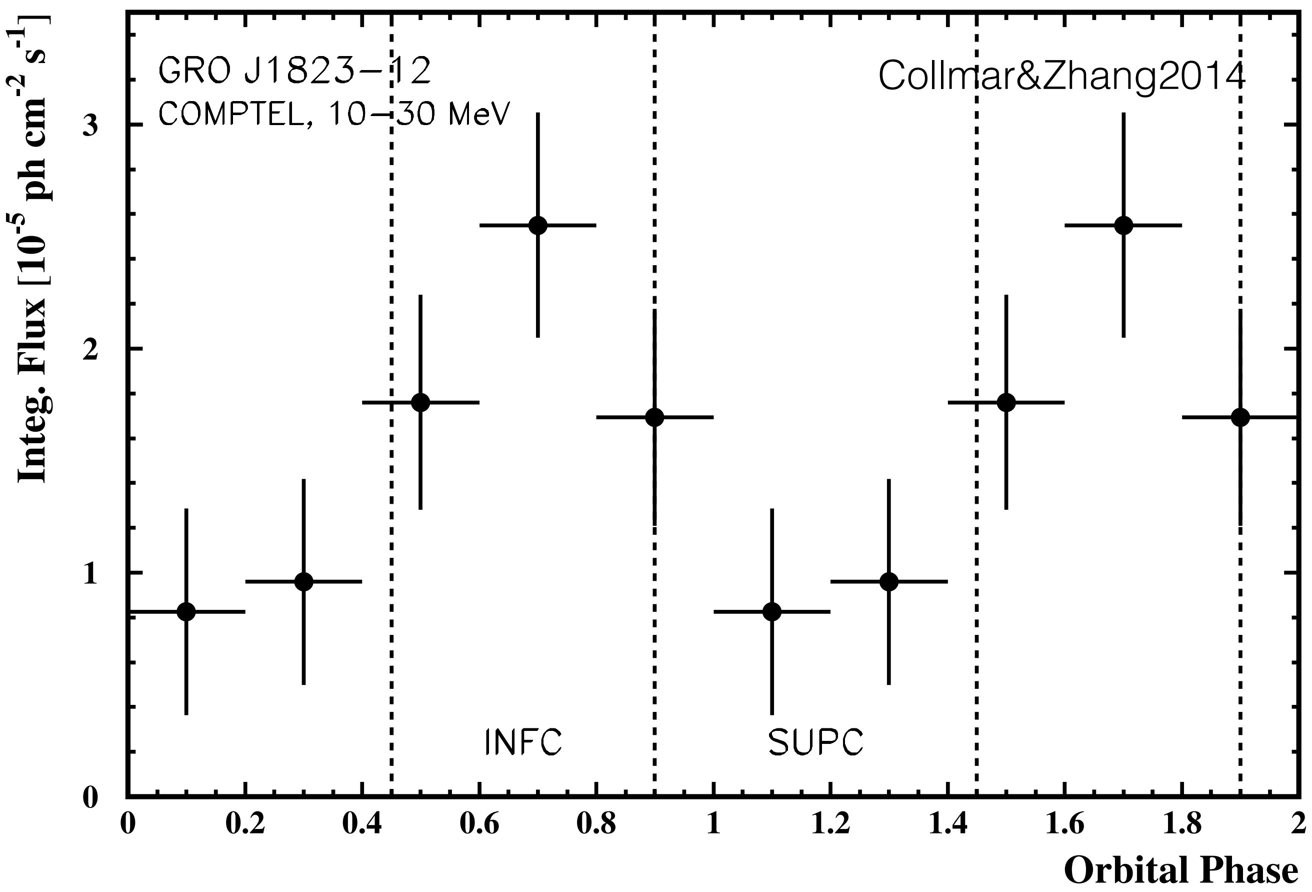
Interaction between stellar winds and pulsar winds

Which is true?? → Open question still…

New Question: MeV emission ?

Collmar&Zhang2014 re-analyzed the *COMPTEL* data of a gamma-ray binary LS 5039, a brightest one in our galaxy
They found a strong MeV emission from LS 5039

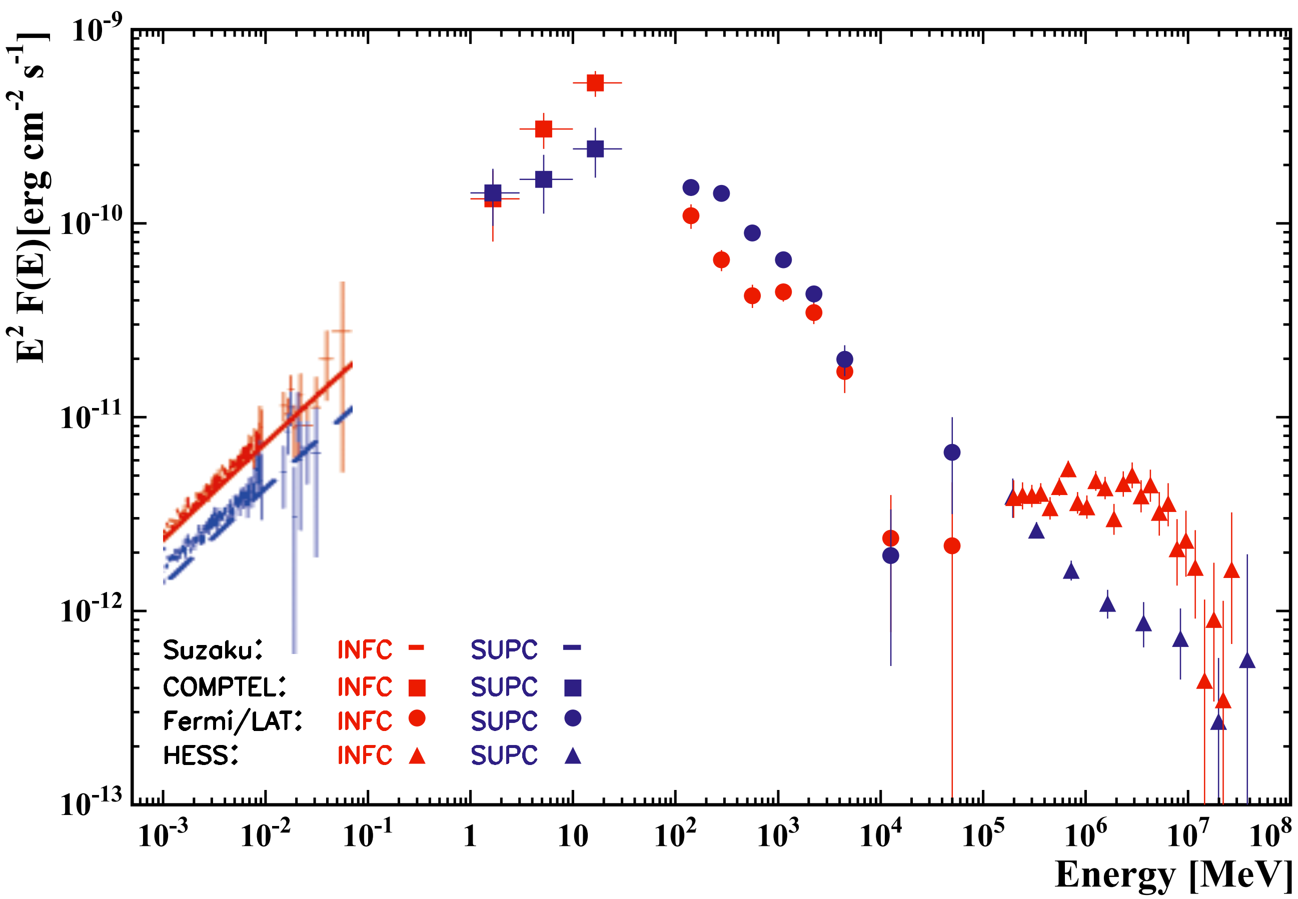




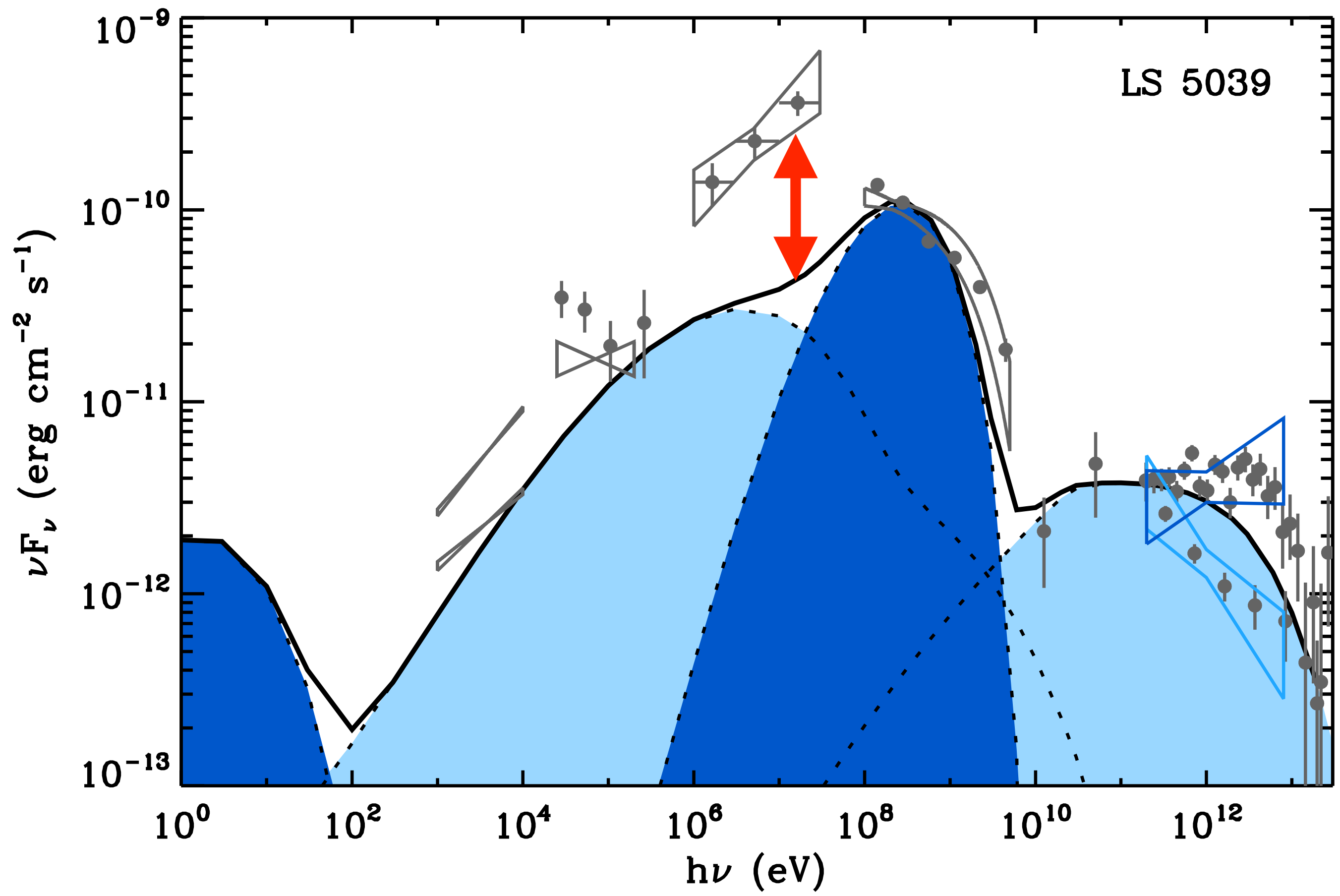
The angular resolution of COMPTEL is few degrees, but the MeV flux is modulated along the binary orbit of LS 5039!

New Question: MeV emission ?

- **Both the microquasar model and the pulsar wind model seem difficult to explain the MeV emission…**



Pulsar wind model (Dubus+2015)



What physics are we missing ? or do we need another model ?

New Question: MeV emission ?

- In both cases, it is assumed that Fermi acceleration takes place
- In general, the acceleration is described phenomenologically as

$$\dot{\gamma}_e m_e c^2 = \frac{qBc}{\eta}$$

η : acceleration efficiency
B : magnetic field

- In Fermi acceleration (DSA), $\eta \simeq 10\,(V/c)^{-2} \gtrsim 10$.
- When $\gamma_{e,MAX}$ is determined by the balance between the acceleration and the synchrotron cooling, the synchrotron peak is (Aron 2012)

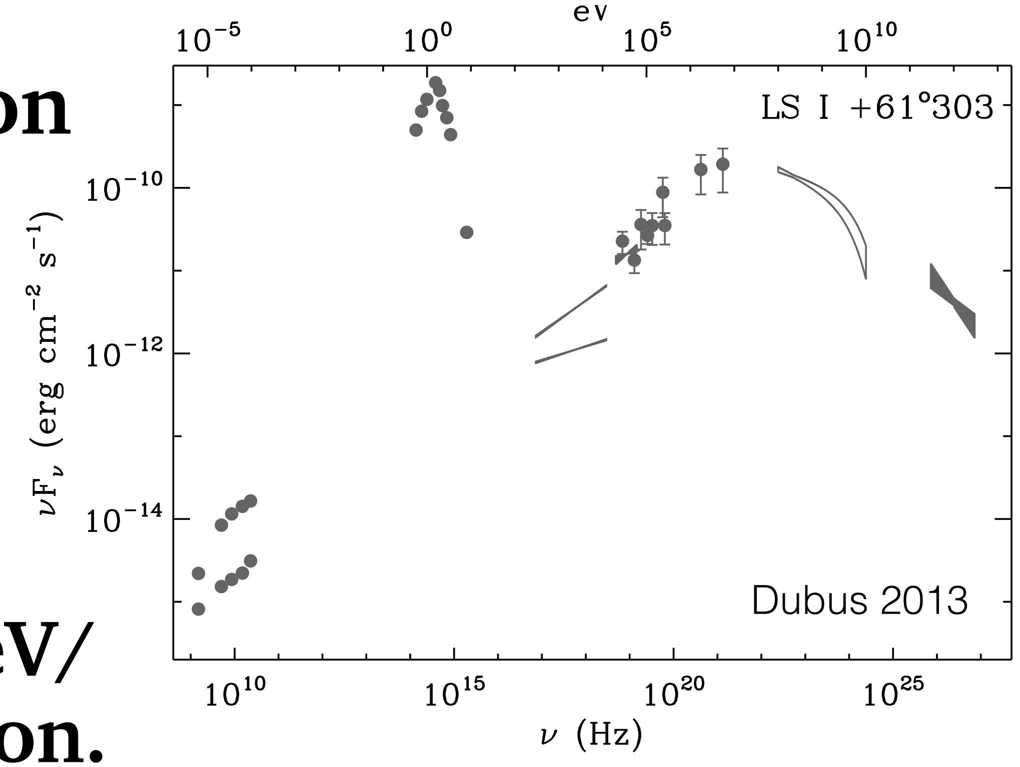
$$h\nu = 236 \text{ MeV} \times \eta^{-1}$$

- So, in Fermi acceleration, $h\nu < 20$ MeV , but gamma-ray binaries shows $h\nu \sim 20 - 30$ MeV

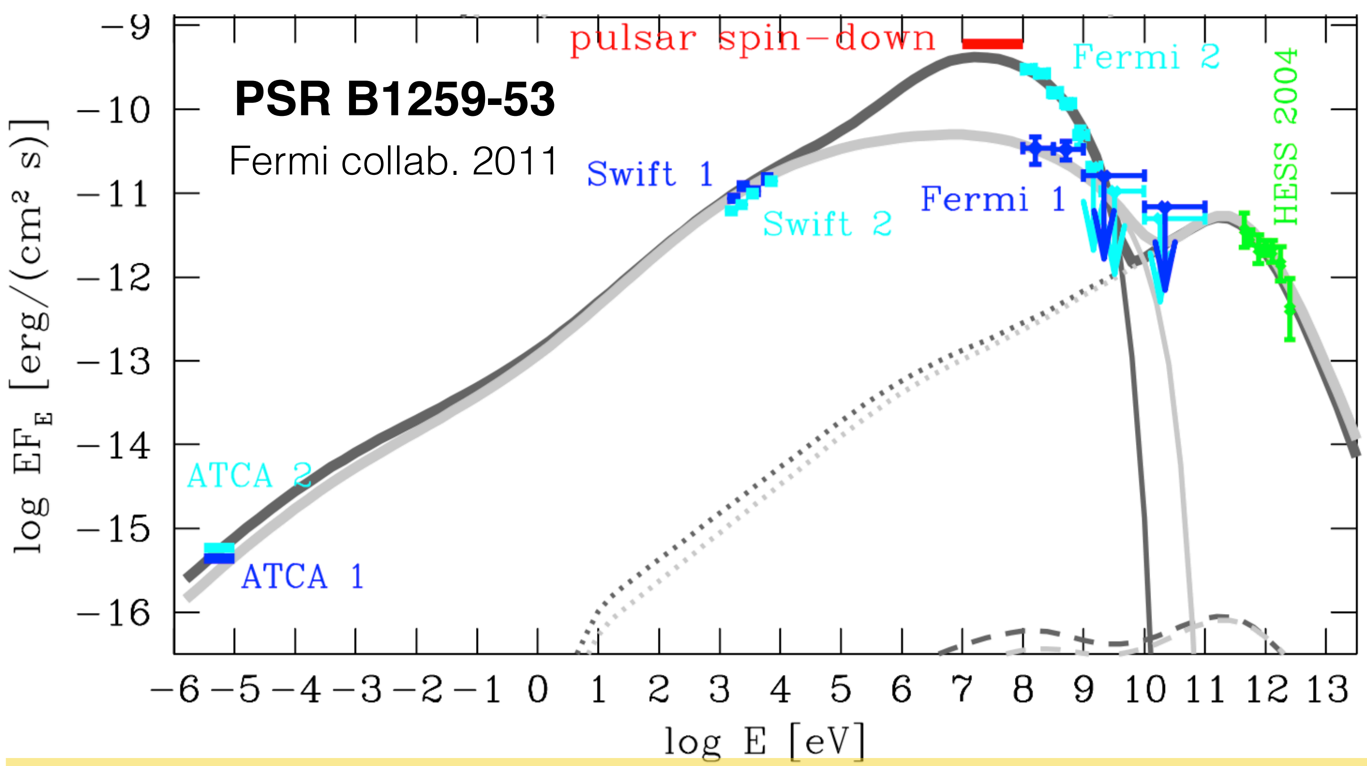
How to explain such an extreme acceleration ?

MeV emission from other sources?

- **COMPTEL detected the MeV emission from LS I 61°+303 (?)**



- **PSR B1259-53 shows a very bright MeV/GeV flare ~ 30 days after the periastron.**



Peak Luminosity

~ 8 x 10^{35} erg s^{-1}

↕ comparable !!

Spin-down Luminosity

~ 8.3 x 10^{35} erg s^{-1}

The MeV emission in gamma-ray binaries is a challenging subject

Today's talk

- **Gamma-ray binaries are new particle accelerator in the Universe.**
- **The acceleration/emission mechanism are unclear.**
- **Some of them show the MeV gamma-ray emission.**

- **To tackle with these questions observationally, we analyzed LS 5039, the brightest gamma-ray binary.**

1. **Multi-band spectrum analysis using NuSTAR&Fermi**
   (Yoneda et al. in prep.)

2. **Pulsation search in the hard X-ray band**
   (Yoneda et al. 2020, PRL, arXiv:2009.02075)

3. **Magnetar binary hypothesis with reconnection**

Today's talk

- Gamma-ray binaries are new particle accelerator in the Universe.
- The acceleration/emission mechanism are unclear.
- Some of them show the MeV gamma-ray emission.

- To tackle with these questions observationally,
  we analyzed LS 5039, the brightest gamma-ray binary.

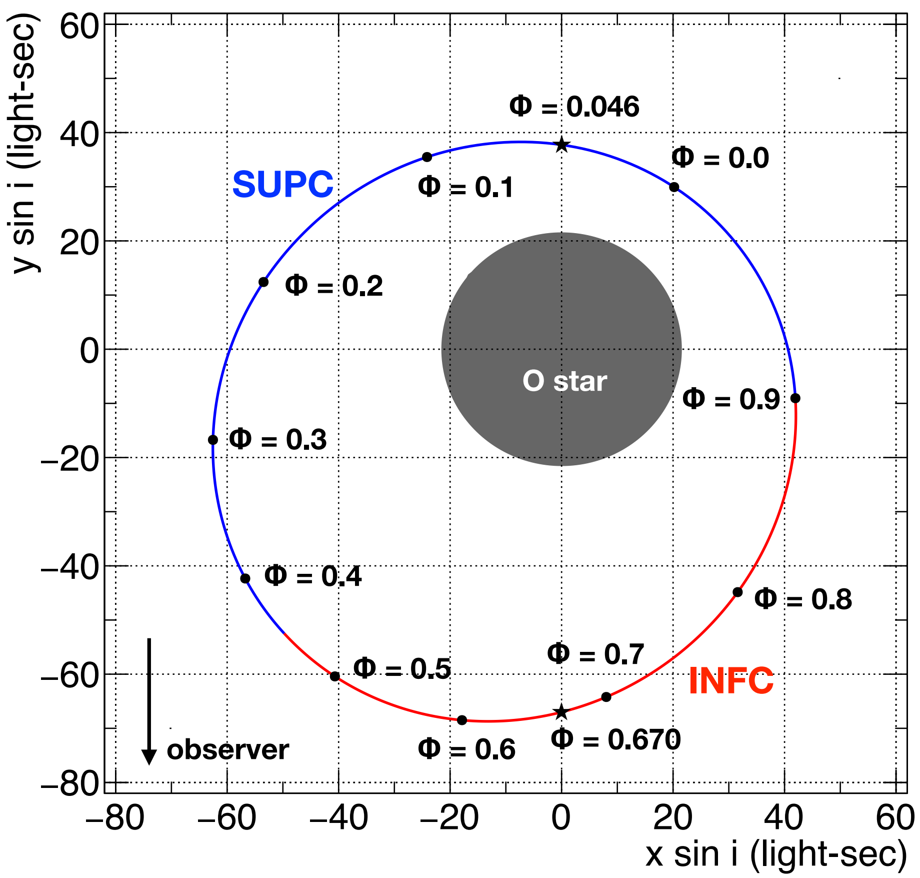
1. Multi-band spectrum analysis using NuSTAR&Fermi
   (Yoneda et al. in prep.)

2. Pulsation search in the hard X-ray band
   (Yoneda et al. 2020, PRL, arXiv:2009.02075)

3. Magnetar binary hypothesis with reconnection

Gamma-ray Binary System LS 5039

LS 5039 is the brightest gamma-ray binary with a short orbital period (3.9 day) → **Observable deeply over its entire orbit**



Distance : 2.5 ± 0.1 kpc (Casares+05)

Companion : $22.9^{+3.4}_{-2.9}$ $M_{\odot}$, O star

Eccentricity : 0.35 ± 0.04 (Casares+05)

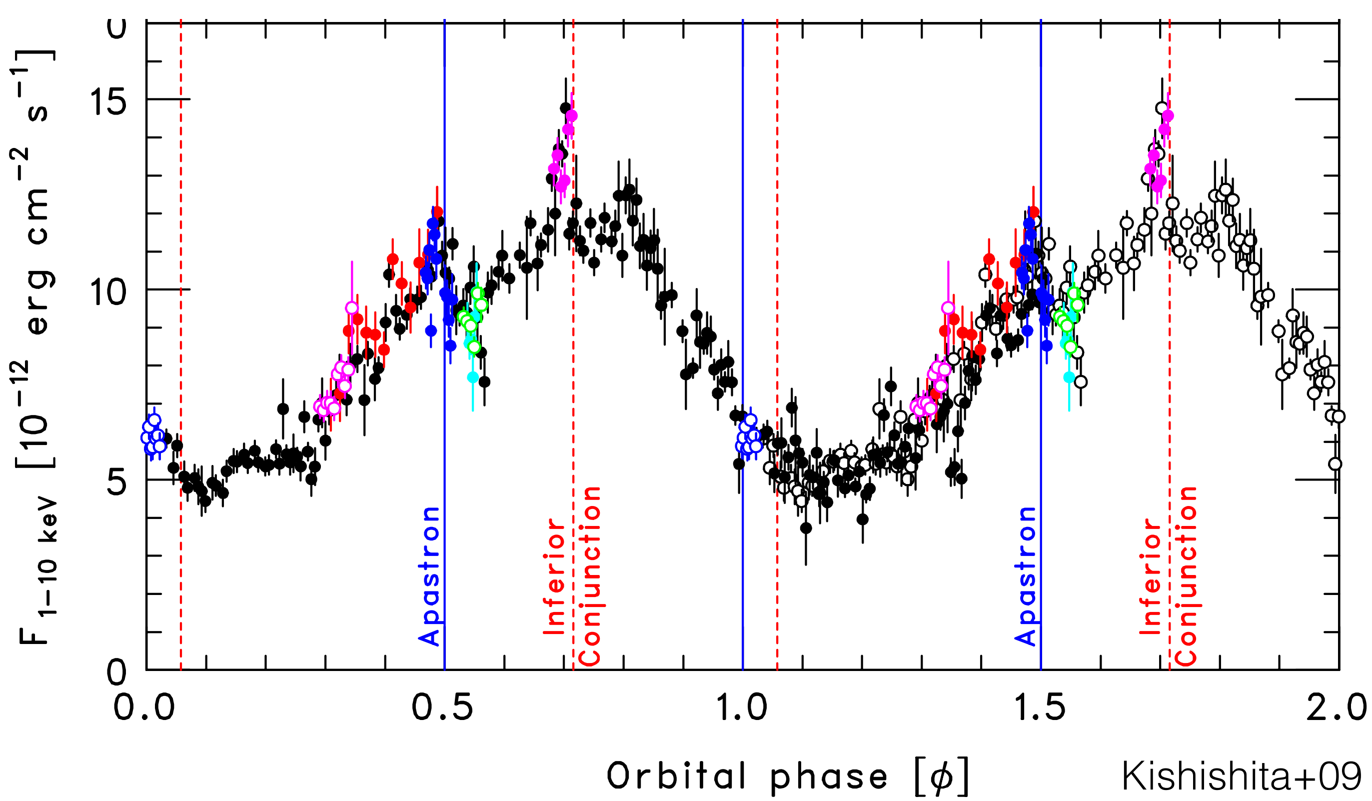
Compact Star : > 1.5 $M_{\odot}$ (Casares+05)

It is unknown whether the compact star is a BH or NS.

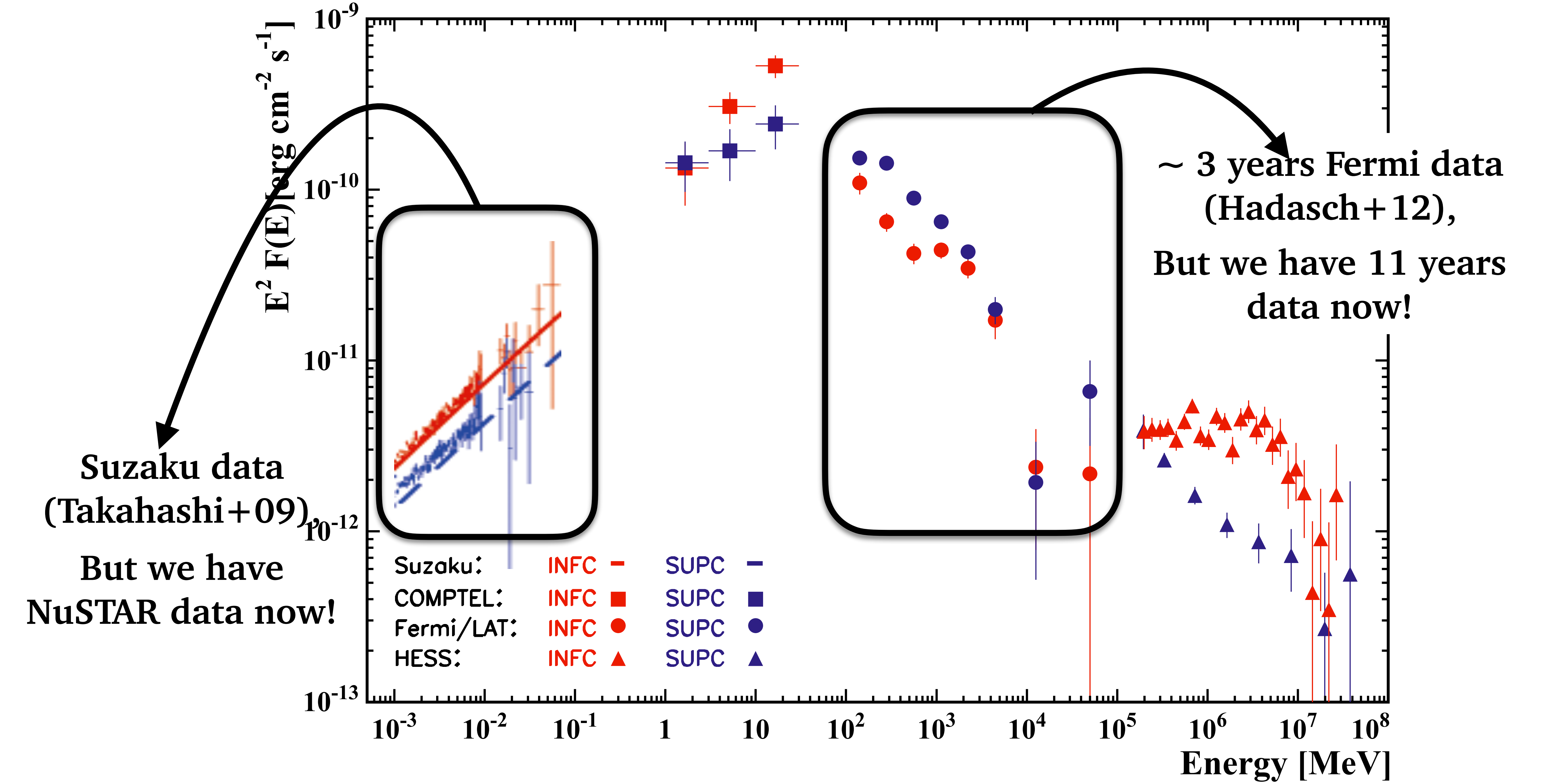
Remarkable Reproductivity in soft X-rays

➔ Non-accreting system is favored

➔ pulsar wind system?



SED of LS 5039

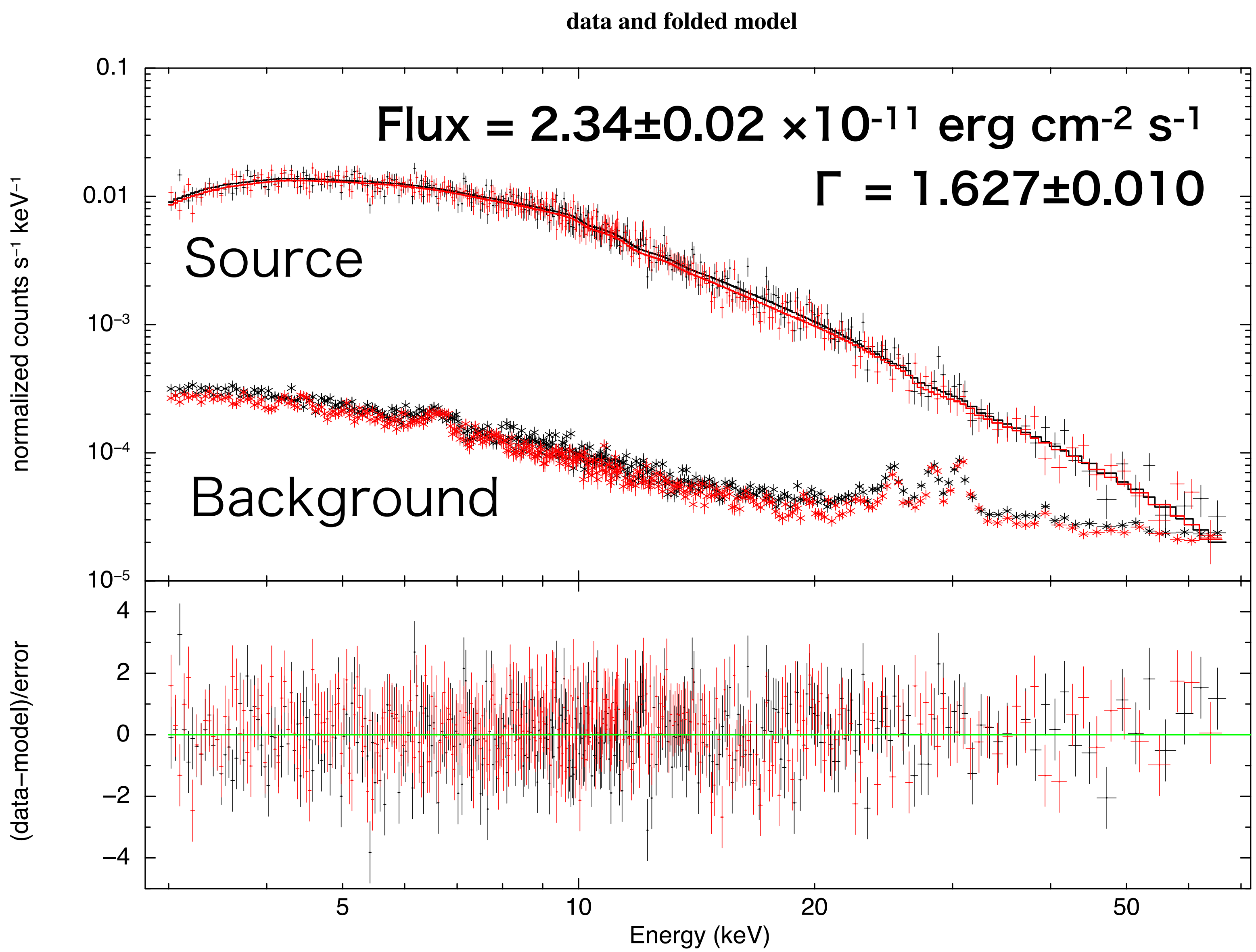


Collmar 2014

Let's update the SED using the latest data!

NuSTAR observation

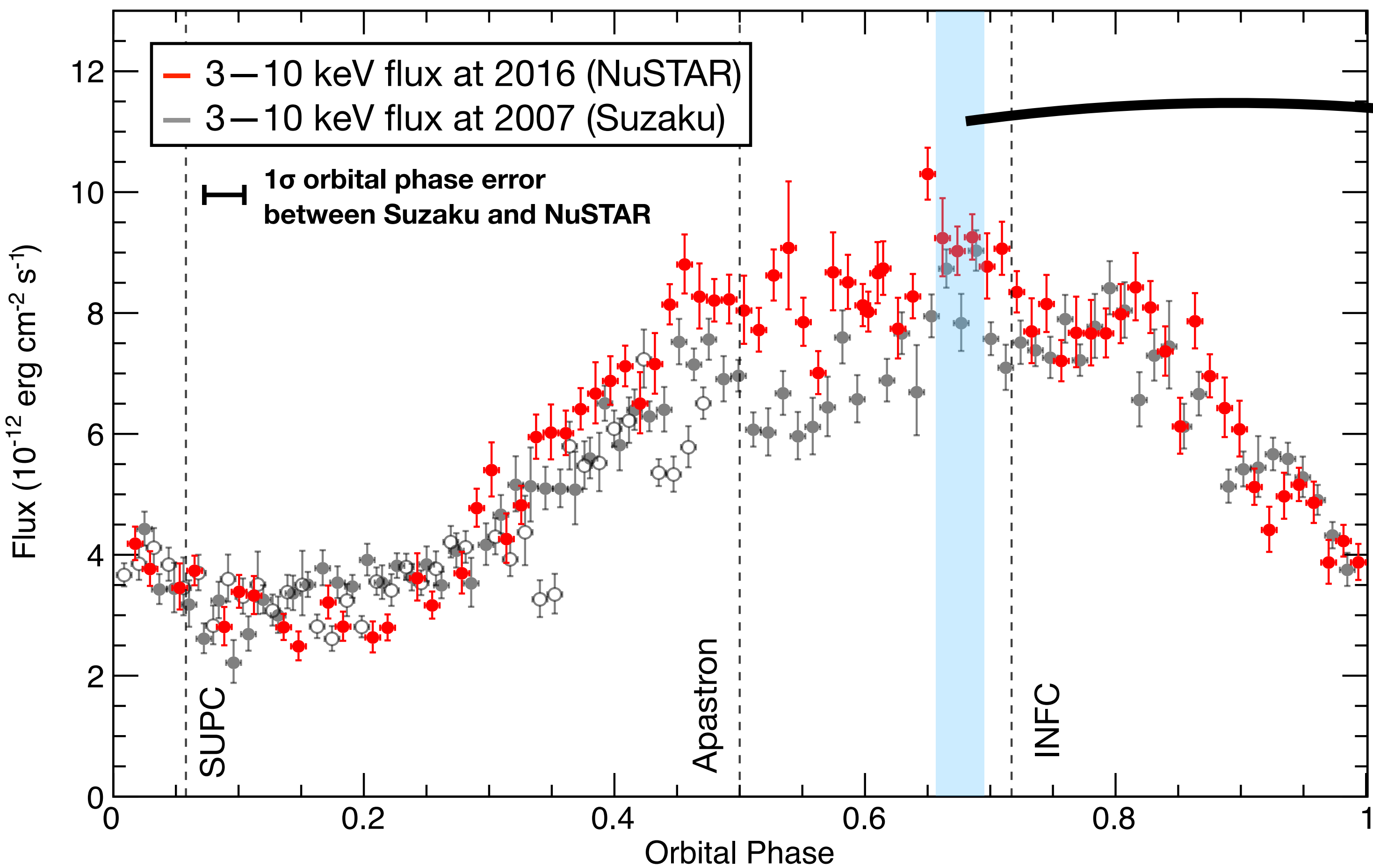
- NuSTAR observed LS 5039 in 2016
- The exposure is 350 ks, which covers one-full orbit of LS 5039

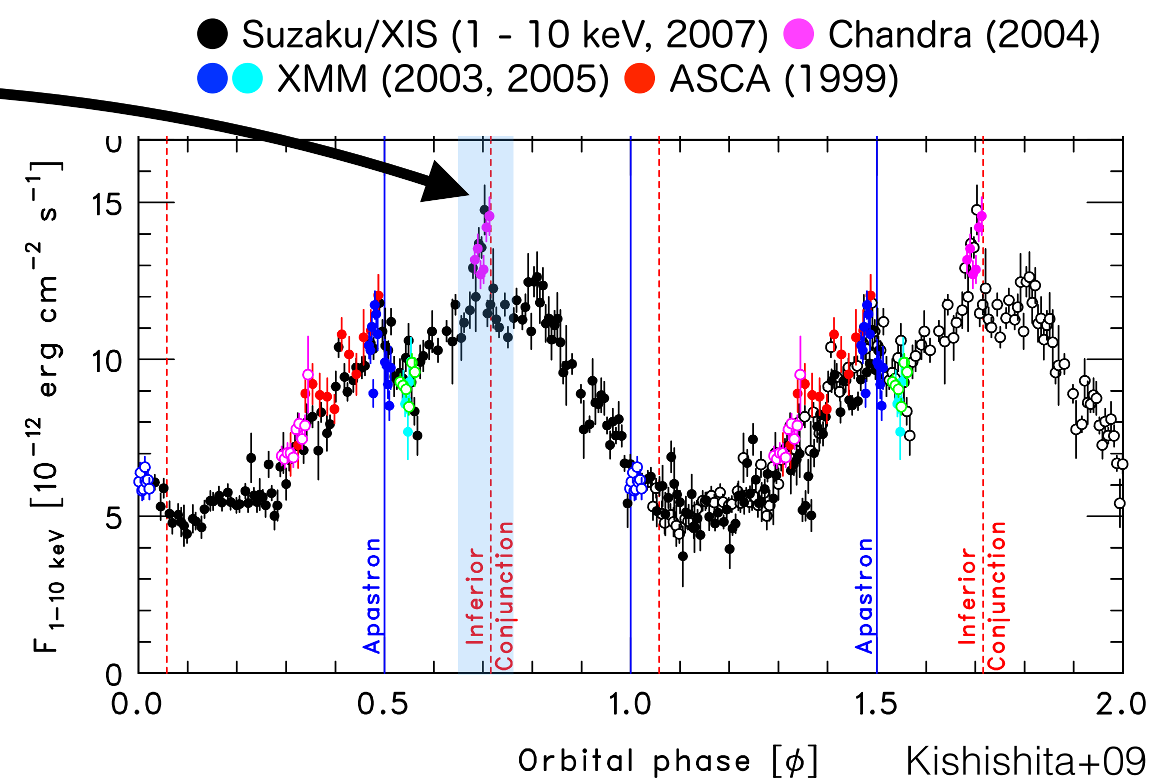


The phase-averaged spectrum is well-described by a single powerlaw, up to 80 keV

Orbital Light Curve

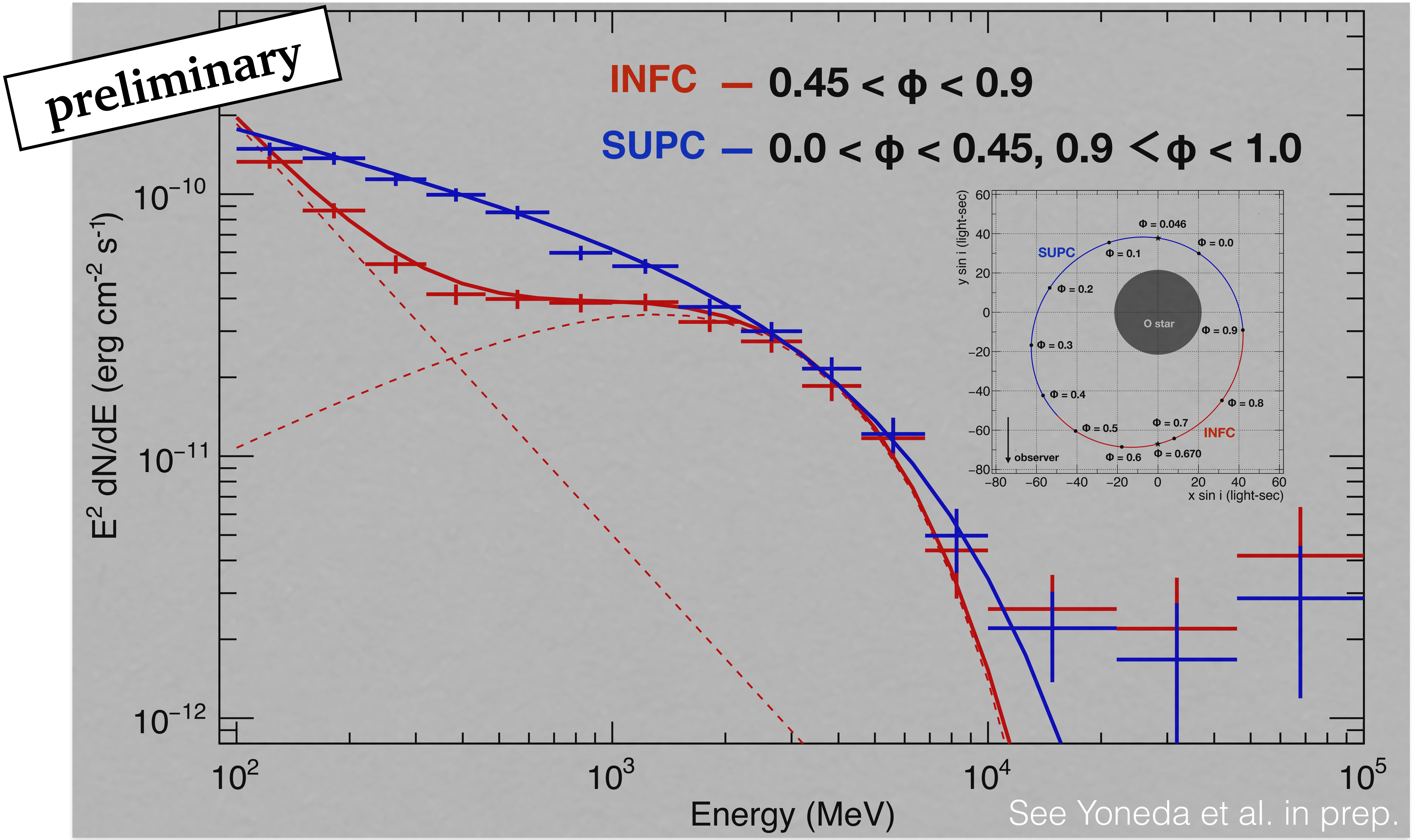
Calculated the flux by dividing data with a bin width of 4 ks
Compared the results with the previous Suzaku results





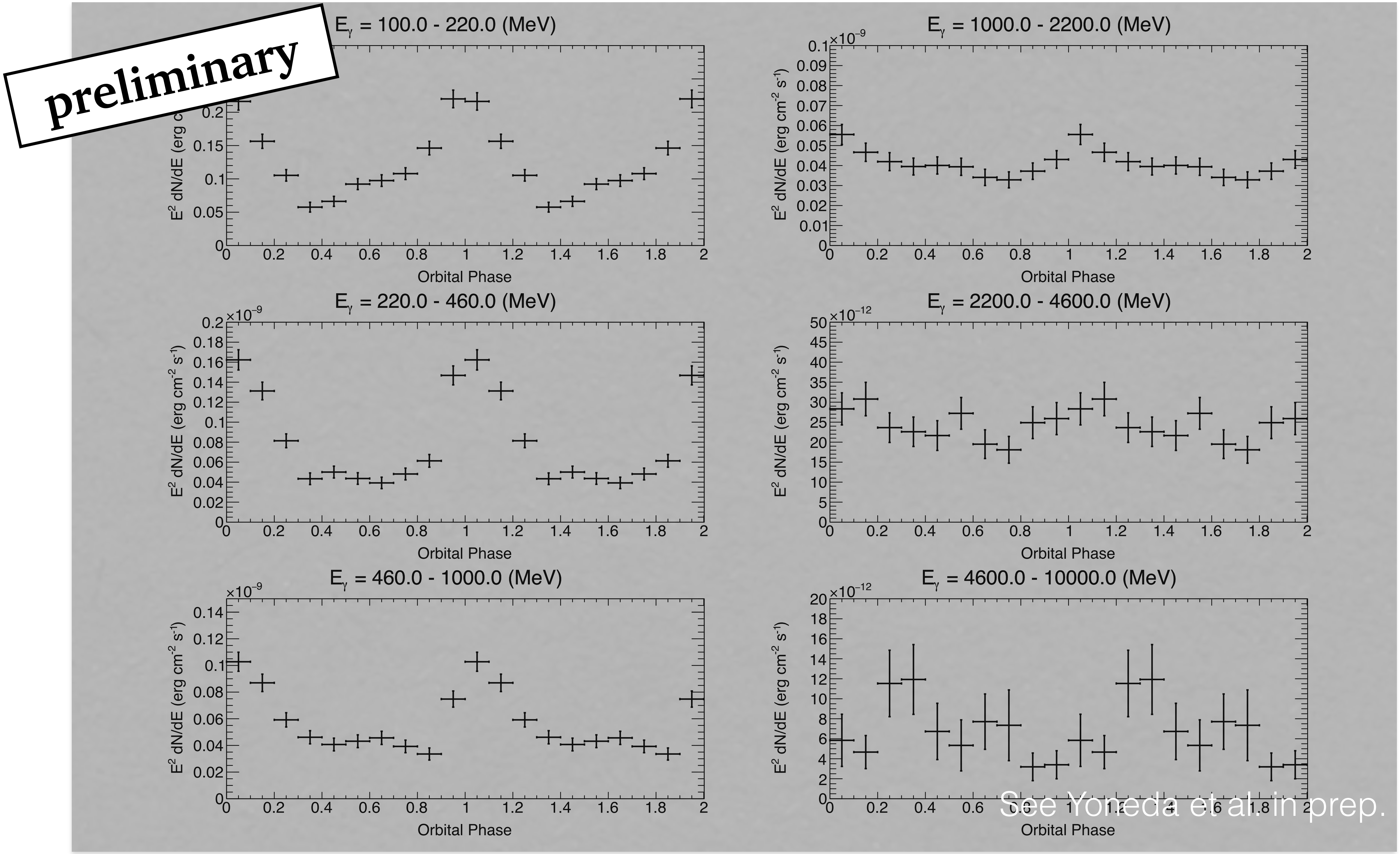
- ***From apastron to INFC, the 3-10 keV flux are different between the NuSTAR and Suzaku***
- ***Doppler boosting? Another spectral component in hard X-rays?***

11 years Fermi observation (Pass 8 data, 2008–2019)



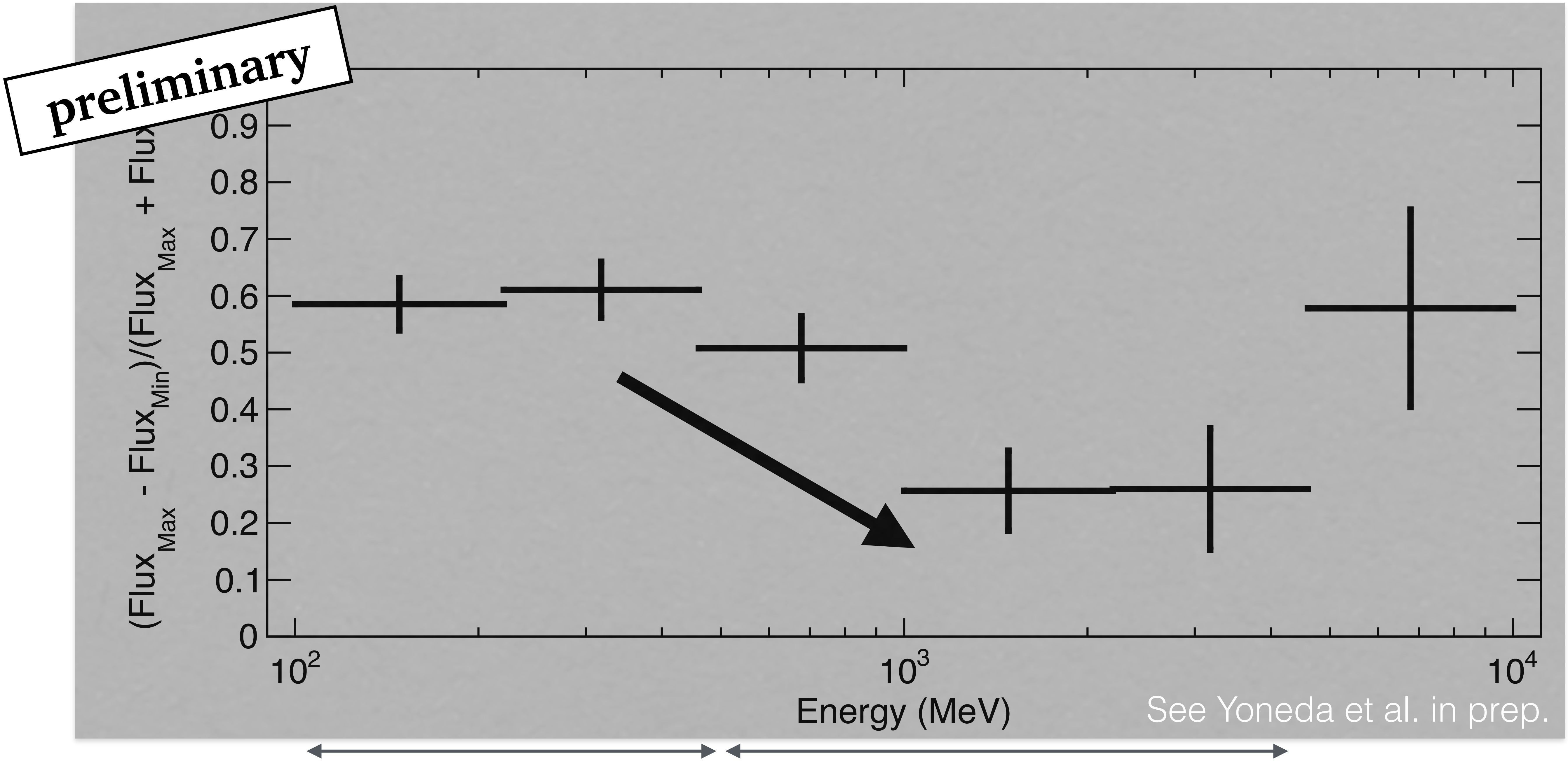
The spectrum in INFC is well-described by powerlaw + cutoff-powerlaw

Orbital Light Curve



Peak is at φ~0.0, but the amplitude changes with the energy

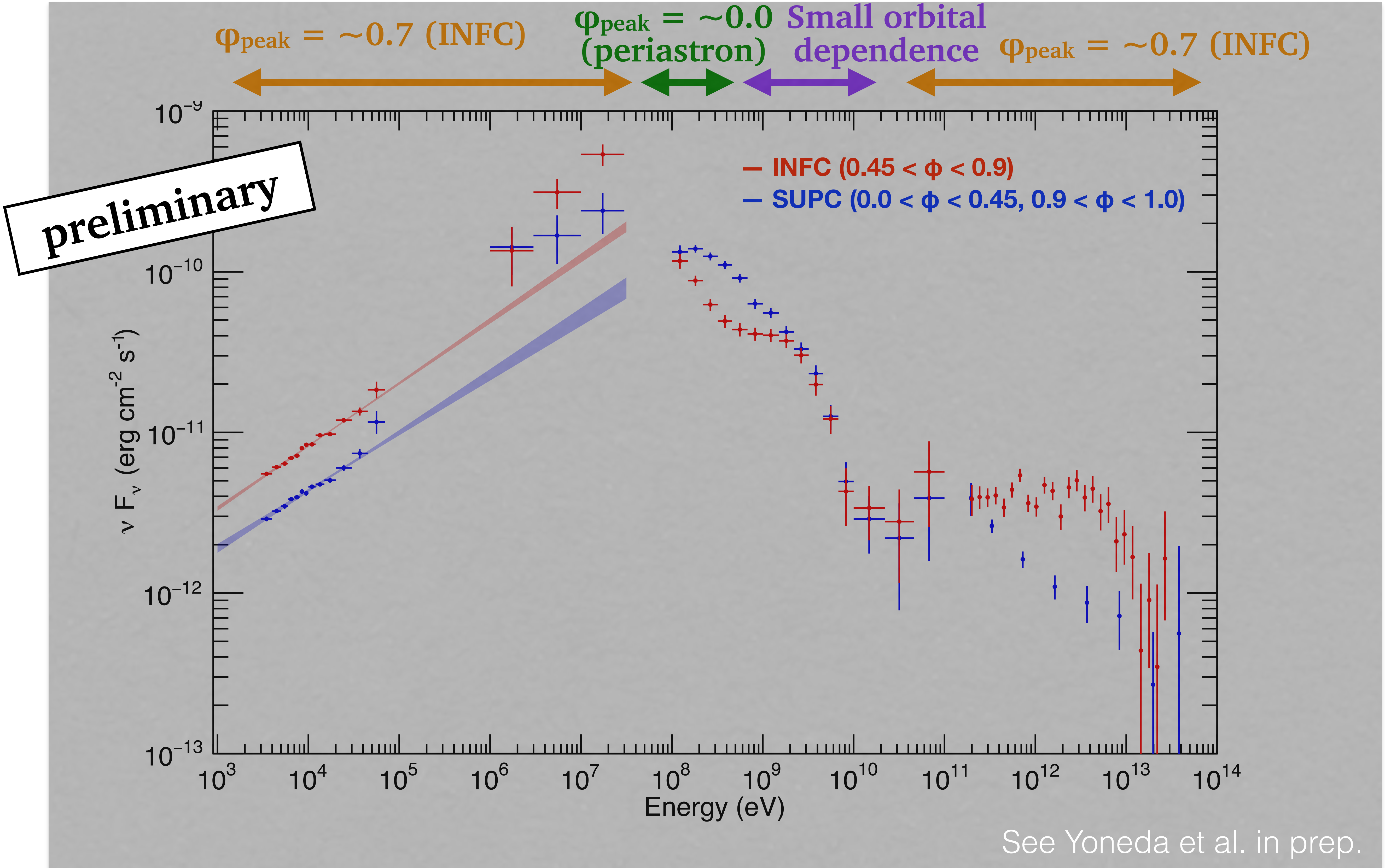
Ratio of the variable component to the total



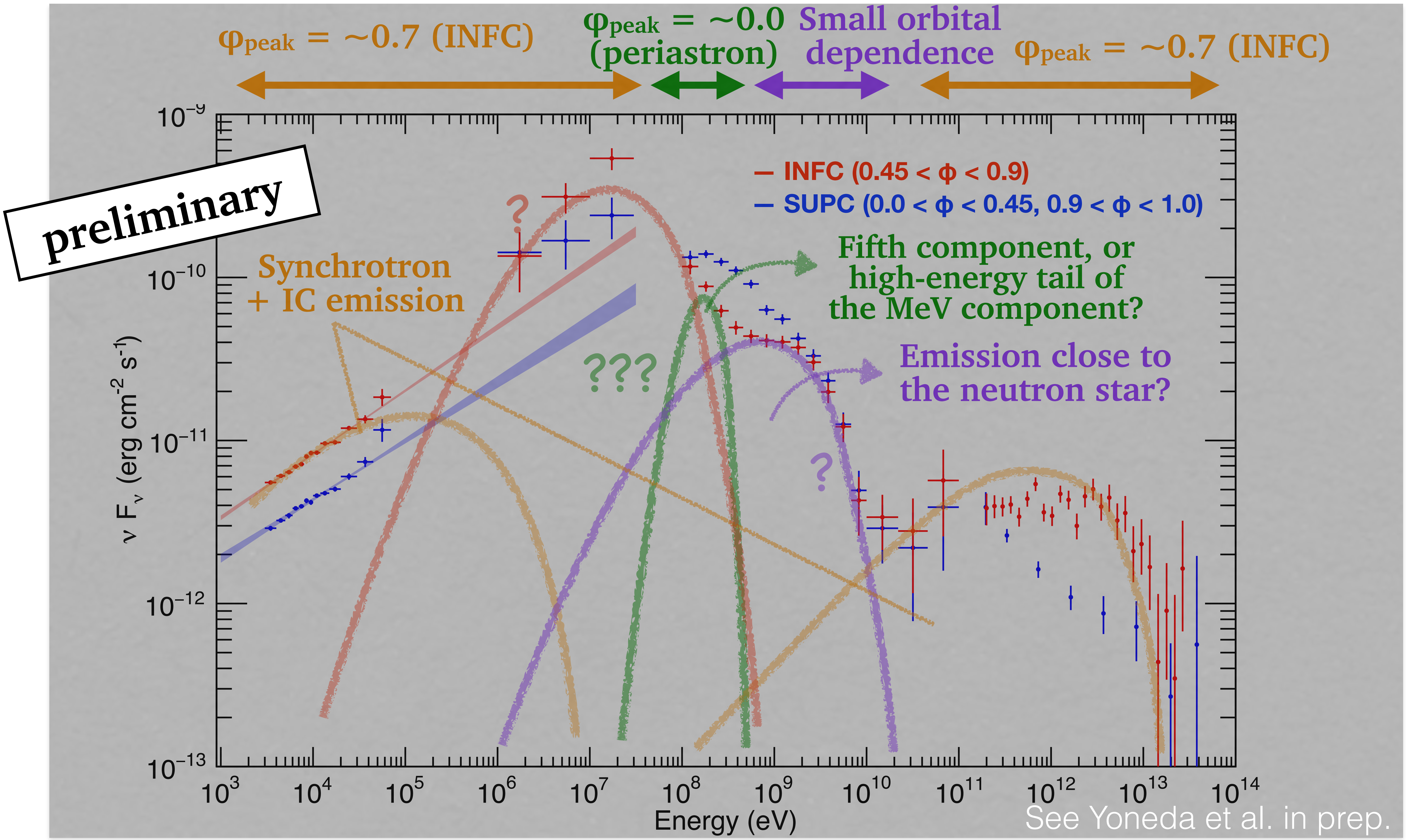
Spectral Analysis | Low-energy comp. | High-energy comp.

There are two spectral components.
These have different orbital dependence!

Updated SED of LS 5039

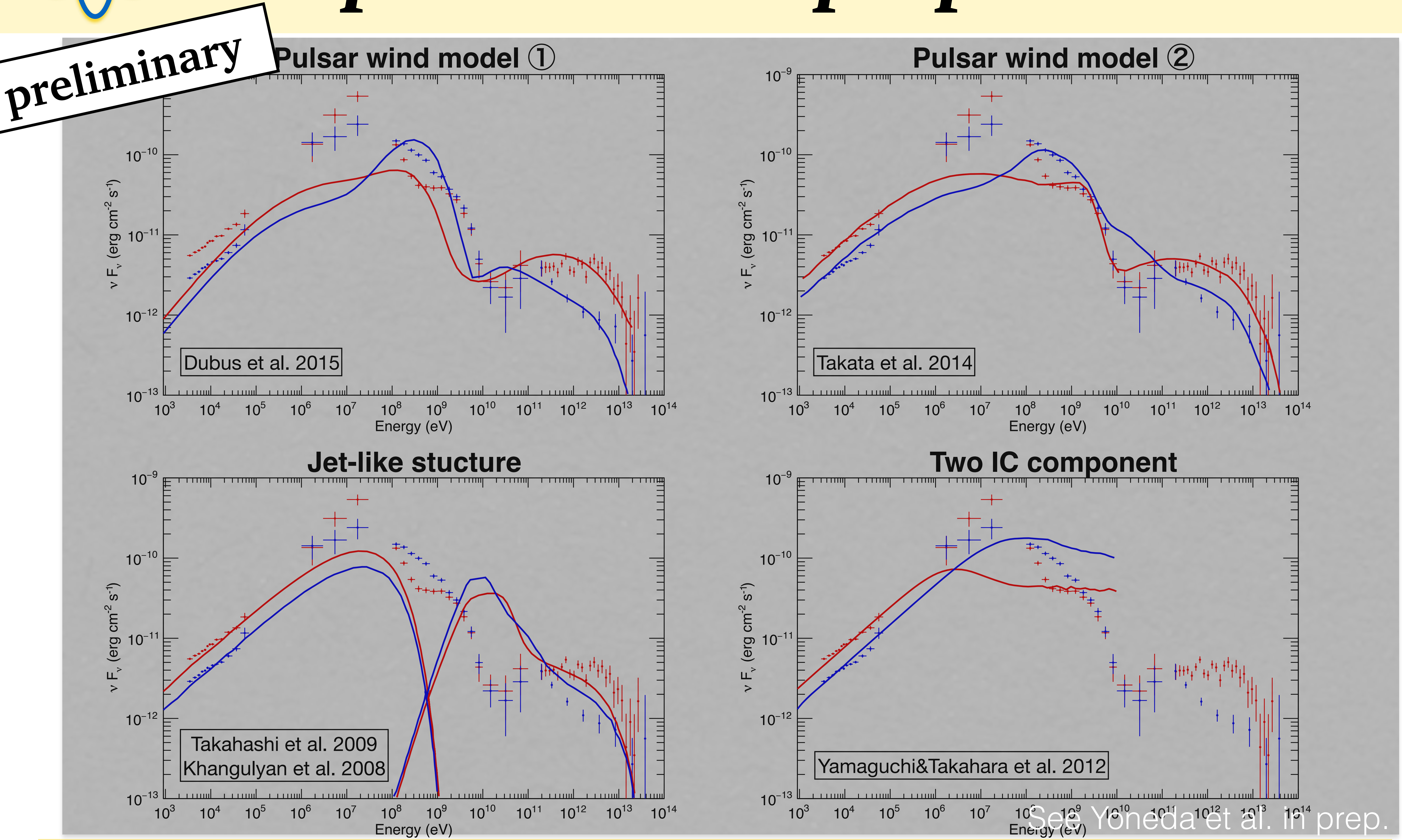


Updated SED of LS 5039



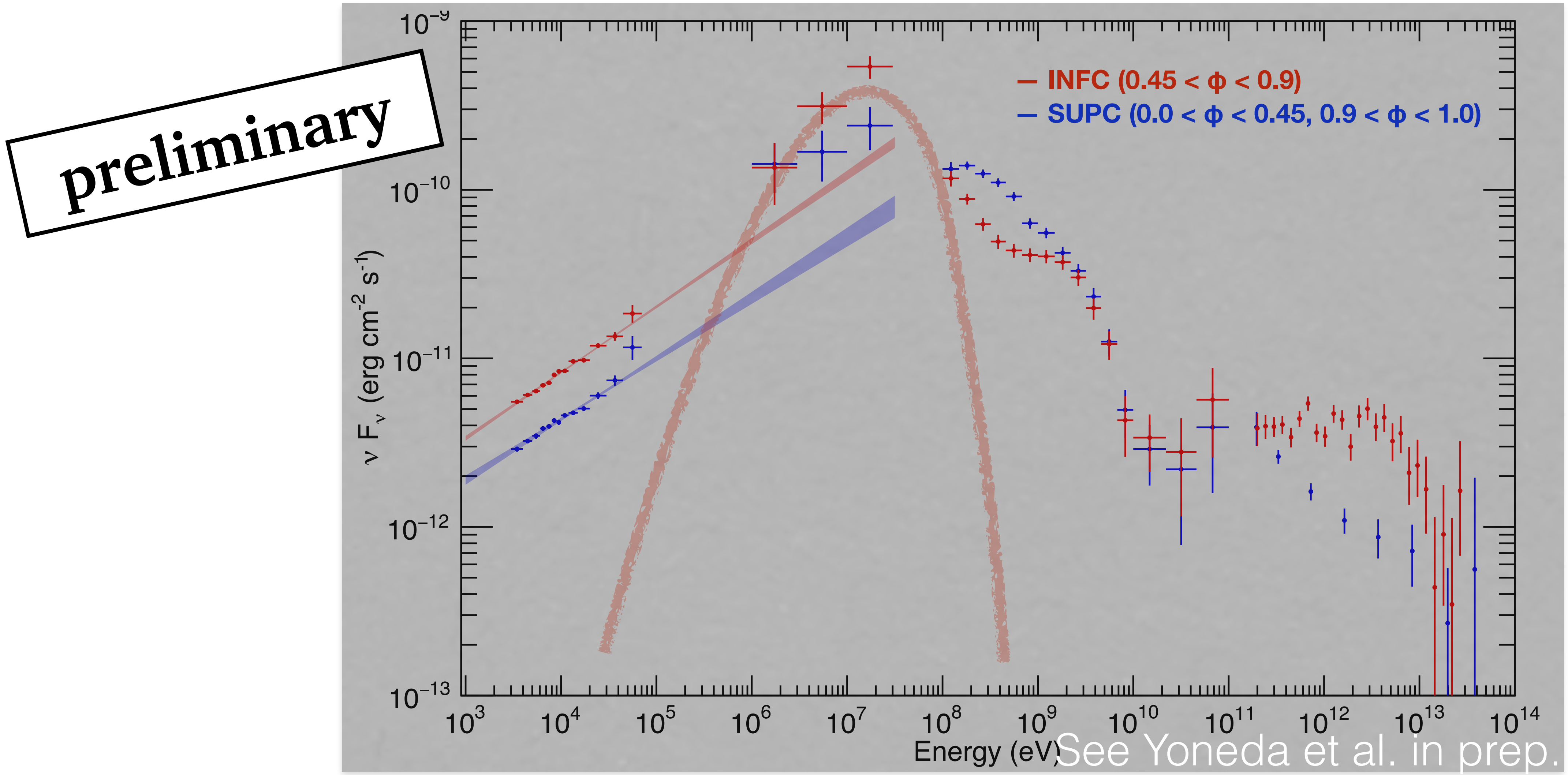
At least, four spectral components

Comparison with proposed models



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

Possible interpretations for the MeV emission



① Synchrotron emission in strong B field

- peak at 20-30 MeV → $\eta < 10$
- Not to overestimate the TeV emission
  → B $\gtrsim$ 3 G
- To explain the hard photon index
  → hard electron spectrum (< 2)

→ efficient acceleration in strong B field ?

② Inverse Compton with GeV e-

Seed photons are UV ones (~10 eV) from the optical companion

\+ Upscattered photons are MeV

→ Electrons should be ∼GeV

→ In shock regions, many GeV electrons in addition to TeV electrons

Today's talk

- **Gamma-ray binaries are new particle accelerator in the Universe.**
- **The acceleration/emission mechanism are unclear.**
- **Some of them show the MeV gamma-ray emission.**

- **To tackle with these questions observationally, we analyzed LS 5039, the brightest gamma-ray binary.**

1. **Multi-band spectrum analysis using NuSTAR&Fermi**
   (Yoneda et al. in prep.)
2. **Pulsation search in the hard X-ray band**
   (Yoneda et al. 2020, PRL, arXiv:2009.02075)
3. **Magnetar binary hypothesis with reconnection**

Previous Work in Pulse Search

The pulsation is good evidence of existence of NS…

<u>Previous Works</u>

Non-detection in radio band (4.1 - 14.5 μJy, McSwain+11)

Non-detection in soft X-ray band (0.3 - 10 keV, Rea+11)

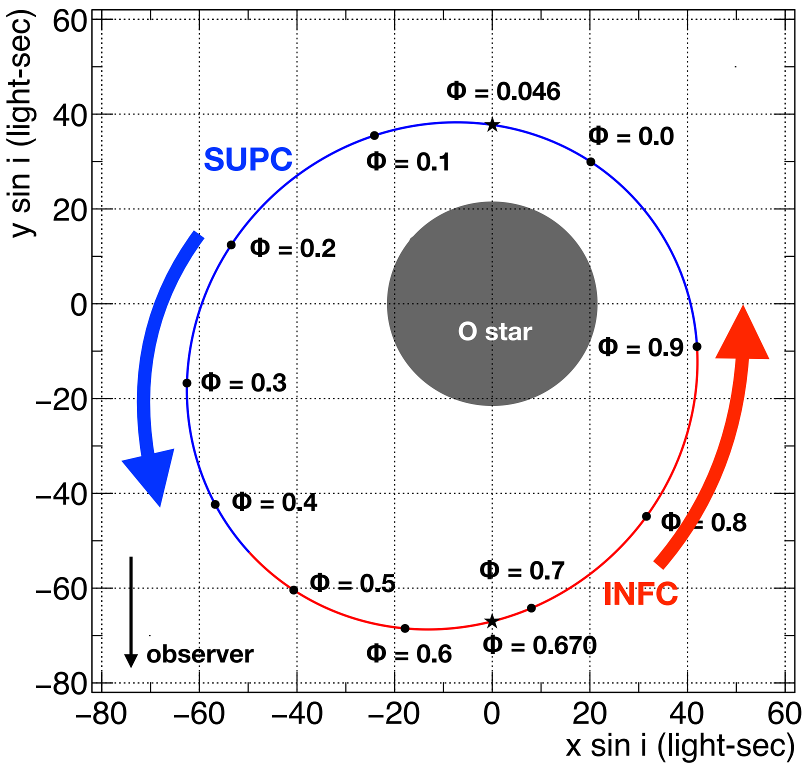
→ **Pulses might be absorbed by stellar winds?**

Higher energy band is better

- **Less stellar wind absorption in higher energy band**
- **In hard X-rays, we have long observation data of Suzaku, NuSTAR**

We focus on hard X-ray band (> 10 keV) for pulsation search

1st Step: Timing Analysis by diving data



Effect of orbital motion

- Orbital velocity of NS is ~ 0.001 c

  ➔ smears the pulse signal

- Large parameter space,

  ➔ it is difficult to search pulse with correcting the orbital modulation

Simple and Best Way

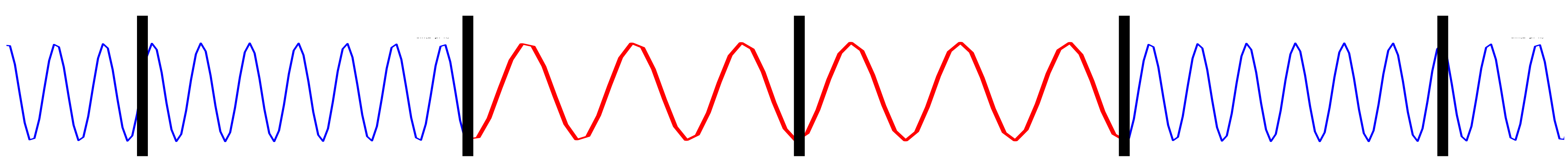
1. Divide the data into subsets with a time interval of T_{sub}.

   Resolution of timing analysis ($1/T_{sub}$) > Orbital modulation ($0.001/P$)

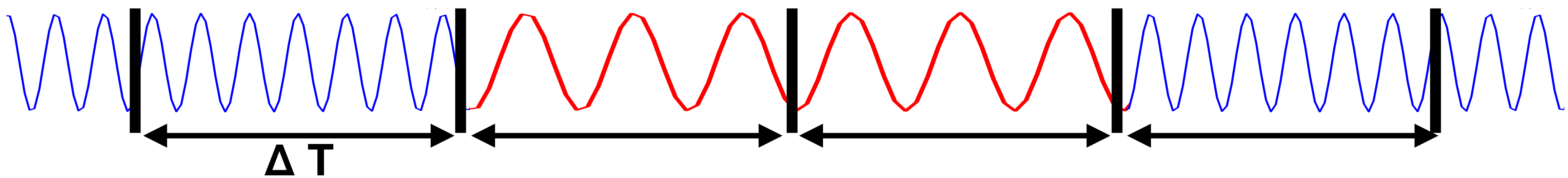
   ➔ $T_{sub} < 1000 \times$ Pulse Period

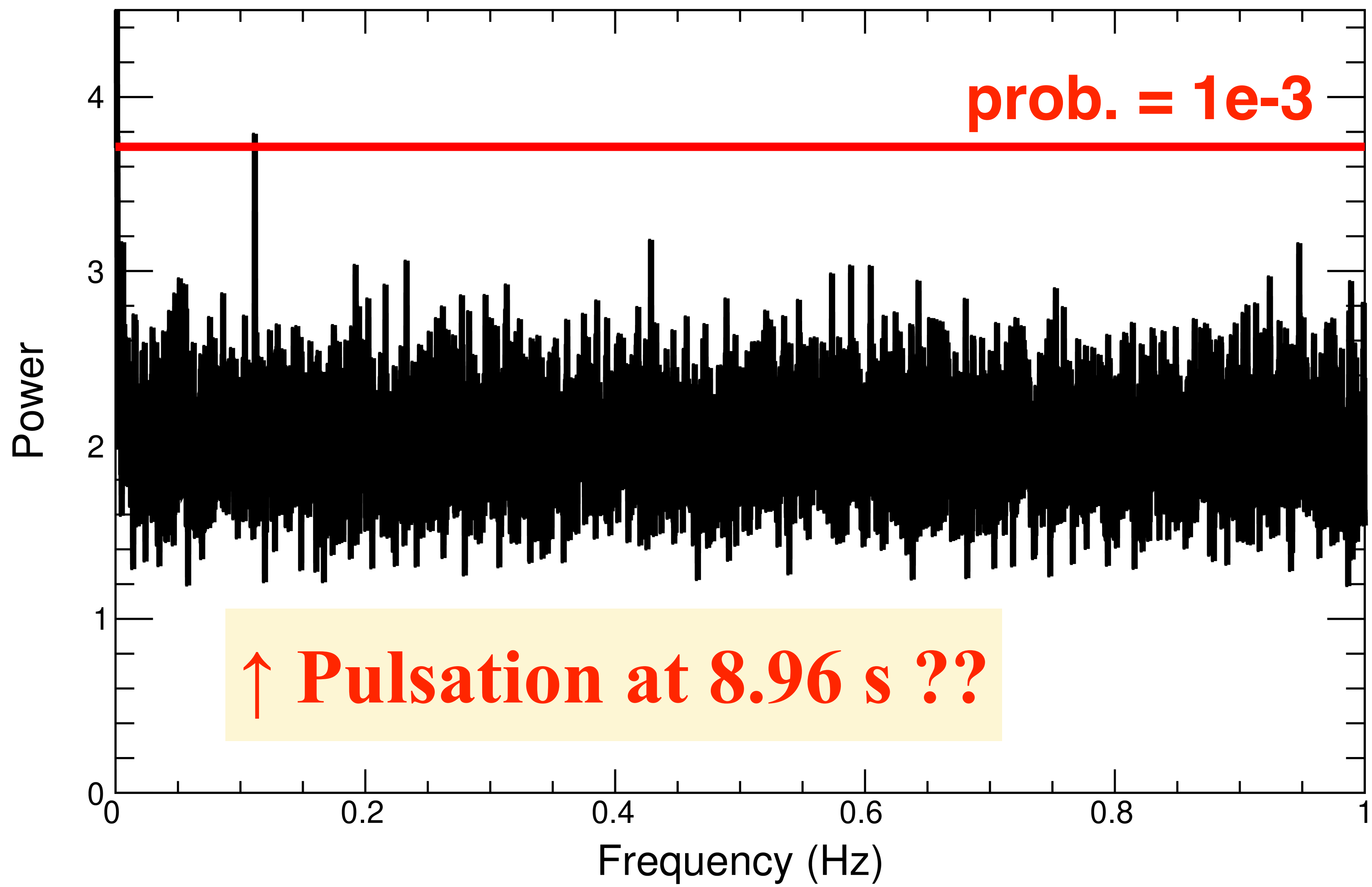
2. Apply Fourier analysis to each subset, and merge the result incoherently

※ To get enough photons in subsets (>10 events), we focus on pulse signal < 1 Hz.



Fourier Analysis with Suzaku





Δ T = 4096 s

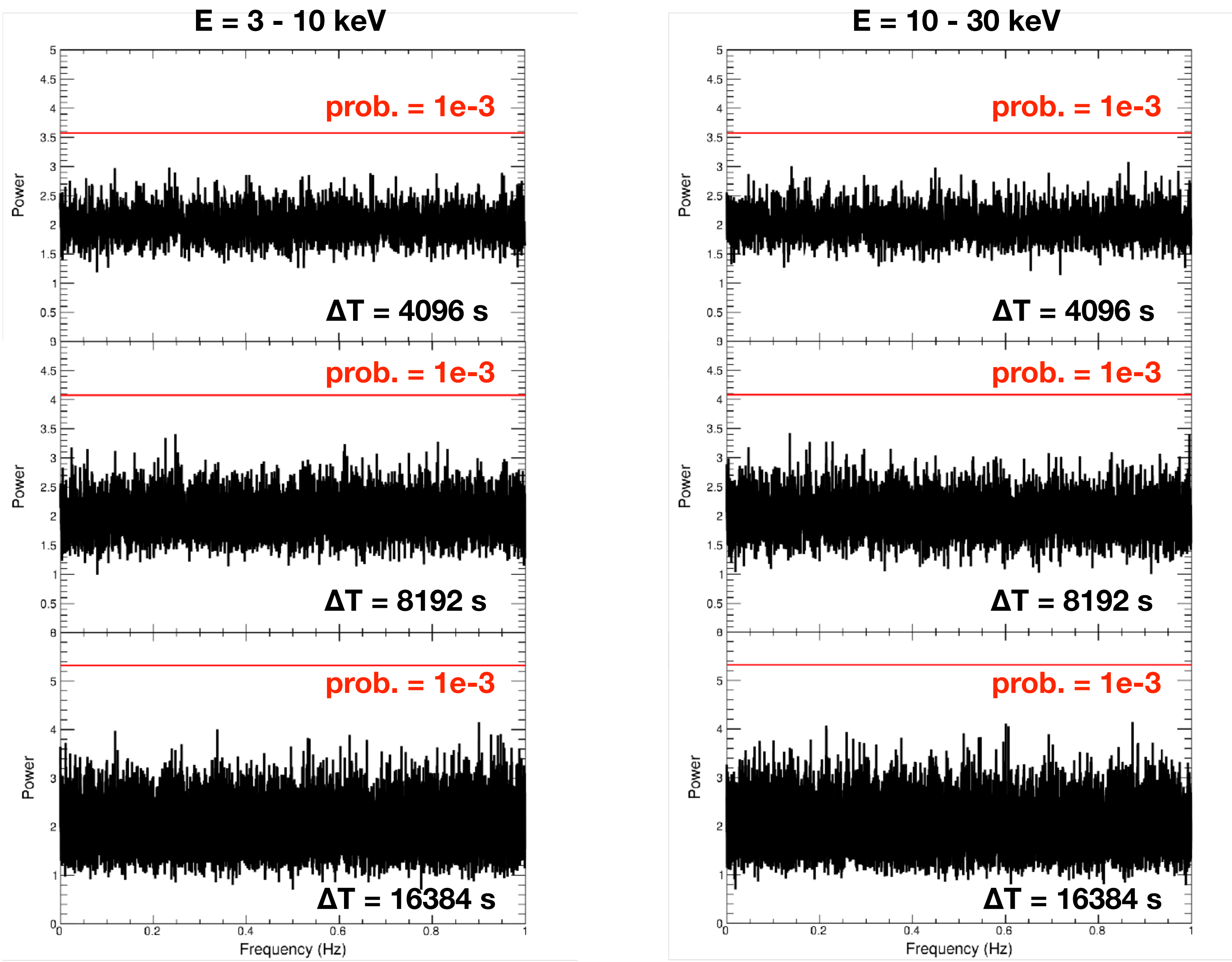
Δ T = 8192 s

Δ T = 16384 s

We found a periodicity at 8.96 s with post-trial of 1.1×10^{-3}

Fourier Analysis with NuSTAR

We applied the same analysis to the NuSTAR data (3–10, 10–30 keV)



No significant peak… We search for weak pulsed signal!

Z^2 analysis

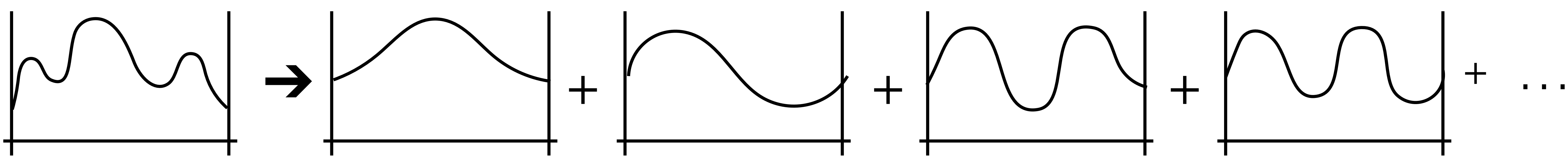
To check the peak at 8.96 s, we analyzed the Suzaku data with Z^2 statistics.

Z^2 statistics (De Jager+89)

- A common technique to search a weak periodic signal
- Unbinned likelihood analysis (better than ordinary chi-square evaluation)

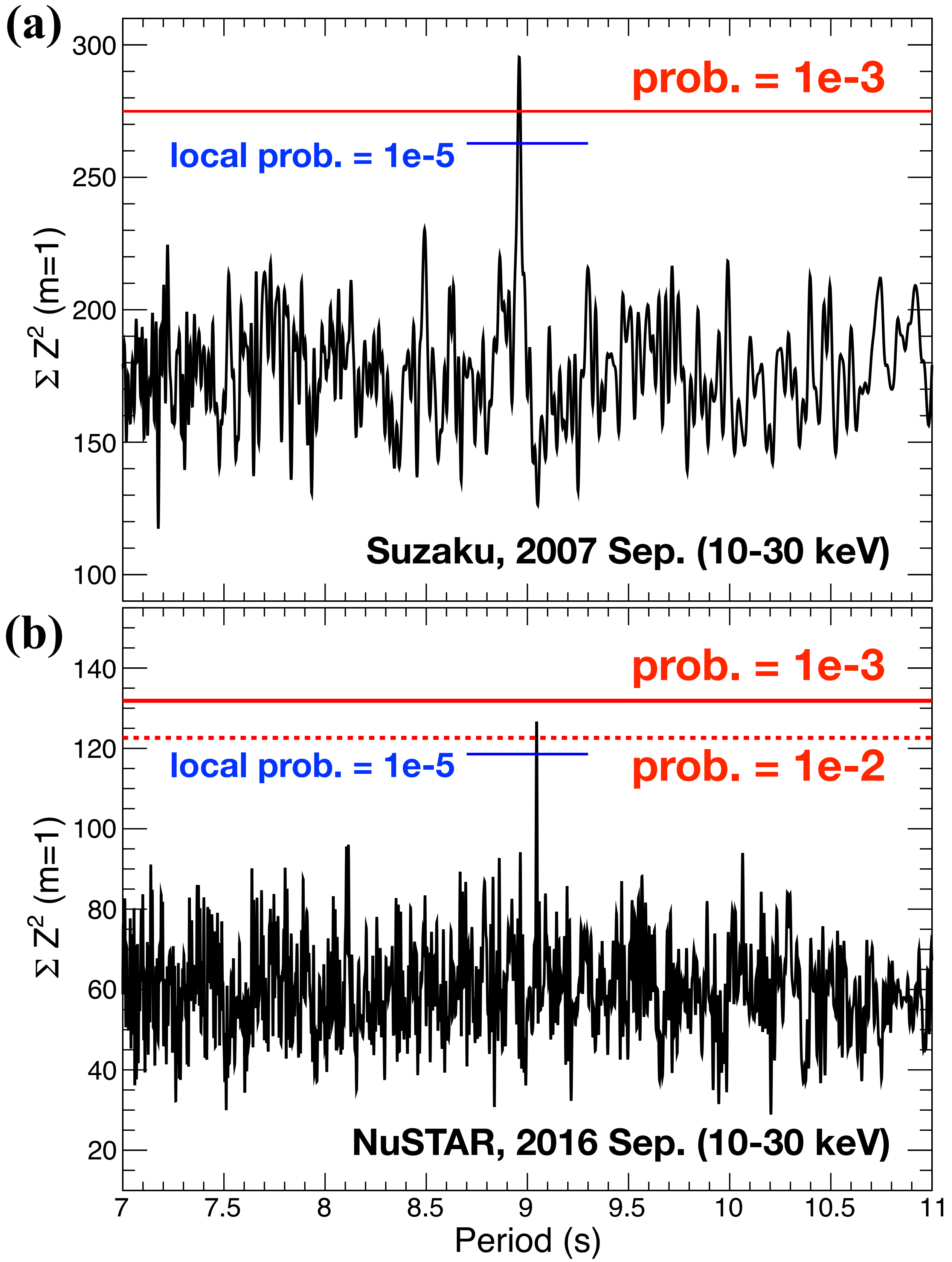
$$Z_m^2 = \frac{2}{N} \sum_{l=1}^{l=m} \left(\left(\sum_i \cos 2\pi l \frac{t_i}{P} \right)^2 + \left(\sum_i \sin 2\pi l \frac{t_i}{P} \right)^2 \right) \simeq \log L$$

1. Make a folded light curve assuming a period.
2. Calculate Fourier component of the obtained profile
3. Sum up the power of the component upto m-th harmonics.



Relying on the Suzaku 8.96 s peak,
we constrain the period search range to 7-11 sec…

Sign of the pulsation at 9 s in the NuSTAR data



A sign of a pulse at 9.046s with 7-11 s, ΔT = 10000 s, post trial is 3.5×10^{-3}

Suzaku (2007 Sep.)

P = 8.960 ± 0.009 s

NuSTAR (2016 Sep.)

P = 9.046 ± 0.009 s

⇓

(If this is real)

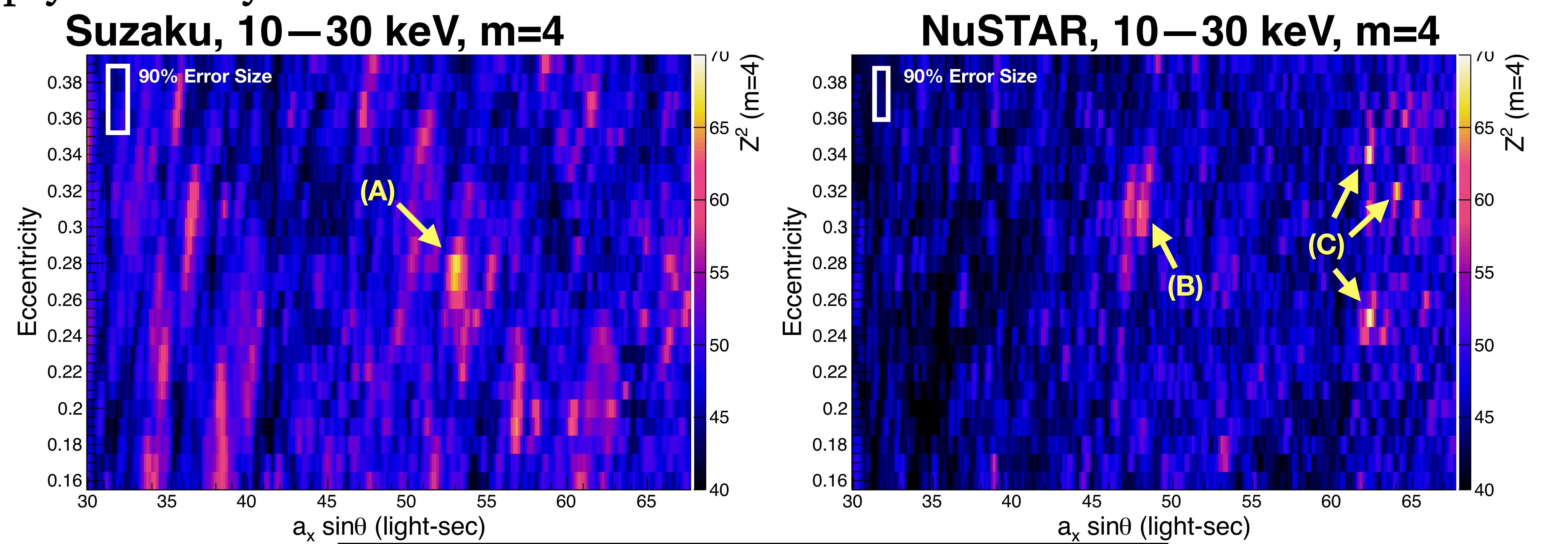
The compact star in LS 5039 is suggest to be a NS with

P ~ 9s

Pdot ~ 3×10^{-10} s s^{-1}

A concern: orbital motion correction

1. Assume a set of orbital parameters, and calculate the orbit of NS
2. correct the photon arrival time to the time on NS
3. apply Z^2 analysis to corrected data.



	$a_x \sin\theta$ [light sec.]	e	ω [deg.]
Suzaku	$53.05^{+0.70}_{-0.55}$	$0.278^{+0.014}_{-0.023}$	$54.6^{+5.1}_{-3.3}$
NuSTAR	$48.1^{+0.4}_{-0.4}$	$0.306^{+0.015}_{-0.013}$	$56.8^{+2.3}_{-3.1}$

The solutions from the two data are not consistent.
A modulation different from the orbital motion? Or just noise?
Stay tuned for future hard X-ray observations…

If the peak is real, what is the Energy Source?

How is the luminosity of LS 5039 (10^{36} erg/s) explained?

① Spin-down Luminosity ($P_{\rm NS} \sim 9$ s, $\dot{P}_{\rm NS} \sim 3 \times 10^{-10}$ s s^{-1})

$$L_{\rm SD} = \frac{(2\pi)^2 I \dot{P}_{\rm NS}}{P_{\rm NS}^3} \sim 10^{34}\ {\rm erg\ s^{-1}} \tag{8.1}$$

② Gravitational Energy From Accretion -> Difficult

- **P is increasing**
- **Non-thermal spectrum unlike accreting system**
- **No time-variability like accreting system**

③ Kinetic Energy from Stellar Winds

$$L_{\rm w} \sim \frac{1}{2}\dot{M}_{\rm w} v_{\rm w}^2 \times \frac{\pi R_{\rm A}^2}{4\pi D_{\rm sep}^2} = 6 \times 10^{31}\ {\rm erg\ s^{-1}} \tag{8.2}$$

④ Magnetic Energy in the neutron star

$$L_{\rm BF} = \frac{B_{\rm NS}^2 R_{\rm NS}^3}{6\tau} \sim 10^{37} \times \left(\frac{B_{\rm NS}}{10^{15}\ {\rm G}}\right)^2 \left(\frac{R_{\rm NS}}{10\ {\rm km}}\right)^3 \left(\frac{\tau}{500\ {\rm yr}}\right)^{-1}\ {\rm erg\ s^{-1}}, \tag{8.3}$$

The neutron star in LS 5039 has 10^{15} G magnetic field?

A new hypothesis: LS 5039 contains a magnetar?

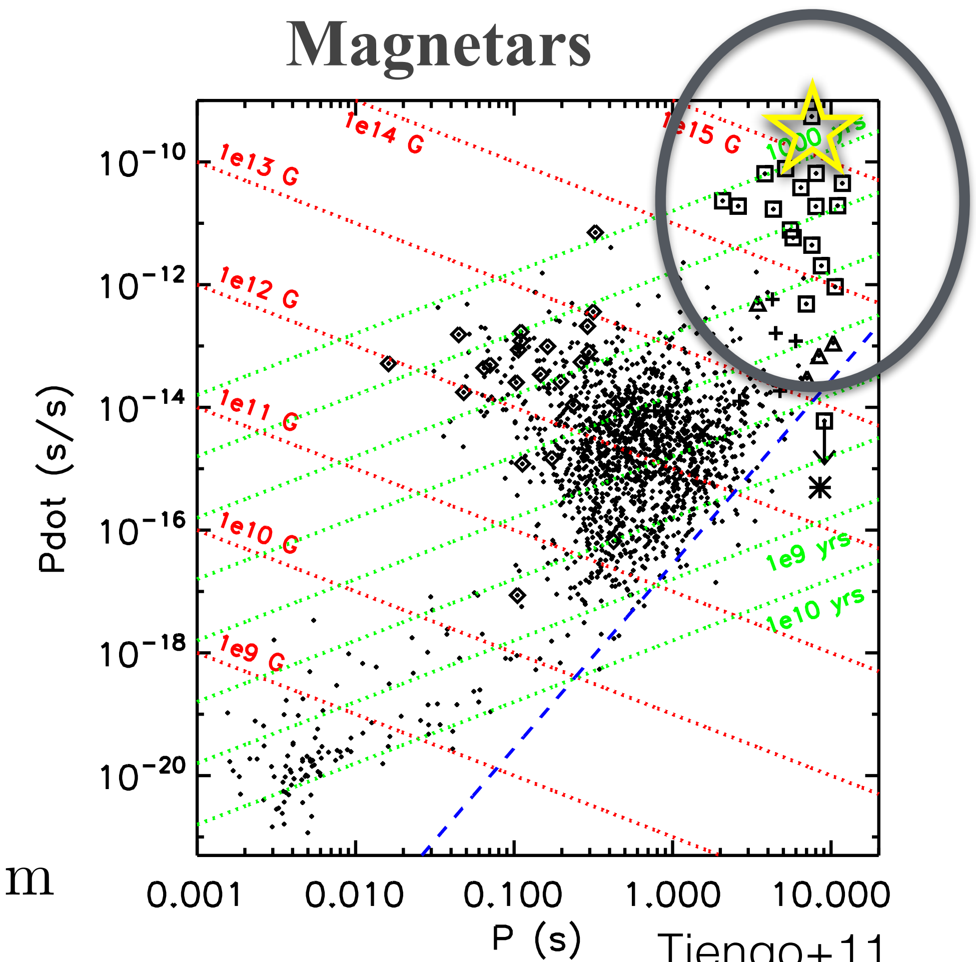
B ~$10^{14\text{-}15}$ G ➔ Magnetar ?

Moreover,

① **The period of 9s is similar to magnetars**

② **Strong magnetic field forms the shock region. Accretion is prevented**

➔ LS 5039 has no thermal components



Tiengo+11

Bondi-Hoyle Radius

$$R_{\rm B} = \frac{2GM_{\rm NS}}{v_{\rm w}^2} \sim 1\times 10^8 \times \left(\frac{v_{\rm w}}{2000\ {\rm km\,s^{-1}}}\right)^{-2}\ {\rm m}$$

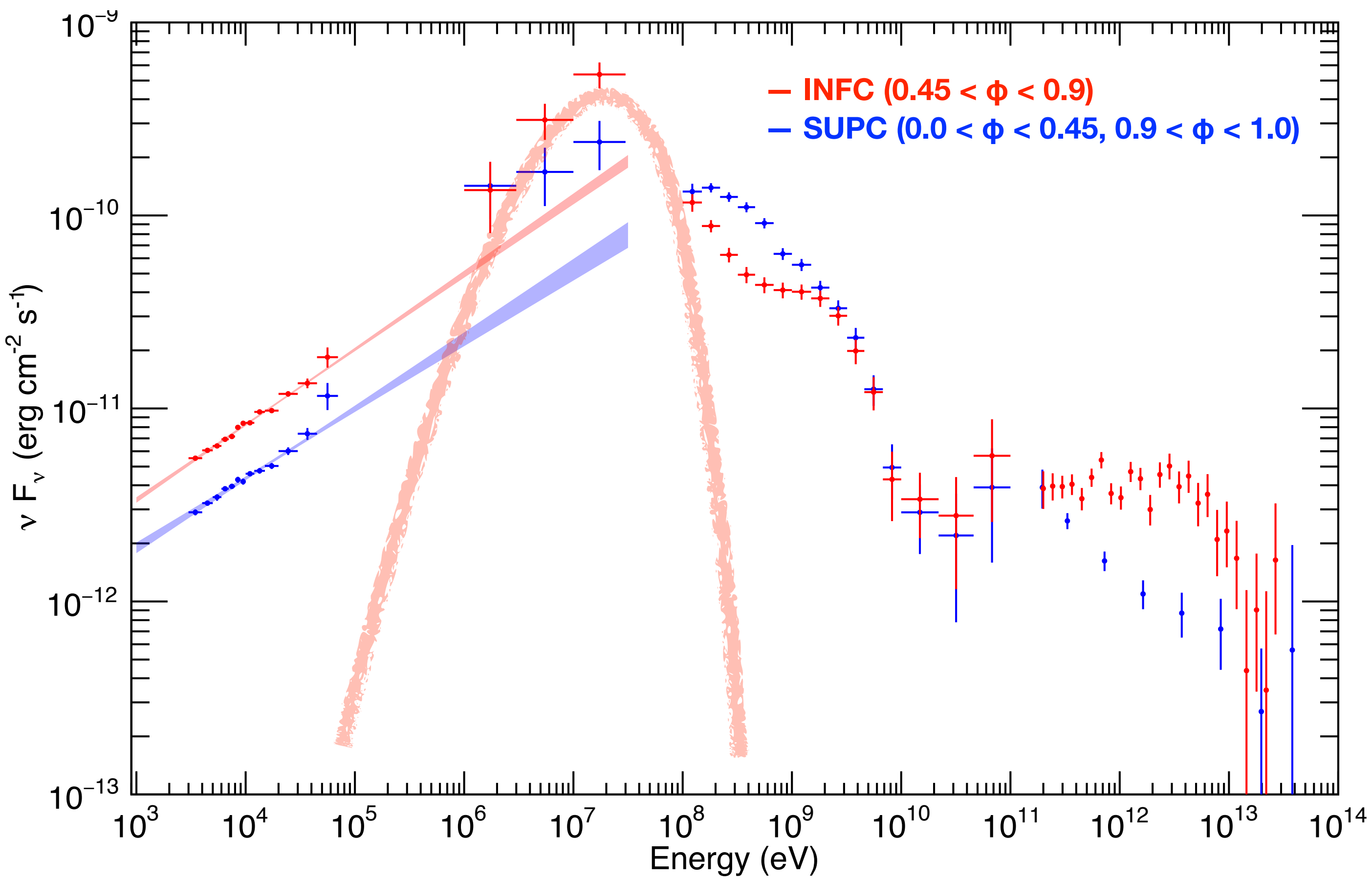
$\wedge$

Alfven Radius

$$R_{\rm Al} = \left(\frac{B_{\rm NS}R_{\rm NS}^3 D_{\rm sep}}{\sqrt{2\dot{M}_{\rm w}v_{\rm w}}}\right)^{1/3} \sim\ 2\times 10^8 \times \left(\frac{B_{\rm NS}}{10^{11}\ {\rm T}}\right)^{1/3} \left(\frac{\dot{M}_{\rm w}}{10^{-6}M_\odot\ {\rm yr}^{-1}}\right)^{-1/6} \left(\frac{v_{\rm w}}{2000\ {\rm km\ s}^{-1}}\right)^{-1/6}\ {\rm m},$$

③ **The magnetar binary hypothesis was proposed for another gamma-ray binary LS I 61+303, based on magnetar-like X-ray flare (Torres+12)**

Strong B fields of the magnetar explain the MeV emission?



We proposed two possibilities for the MeV emission

(1) Synchrotron emission in strong B field, with efficient acceleration

(2) Inverse Compton with GeV electrons

The former scenarios seems to match with the magnetar binary hypothesis

→ Efficient acceleration is driven by the magnetar?

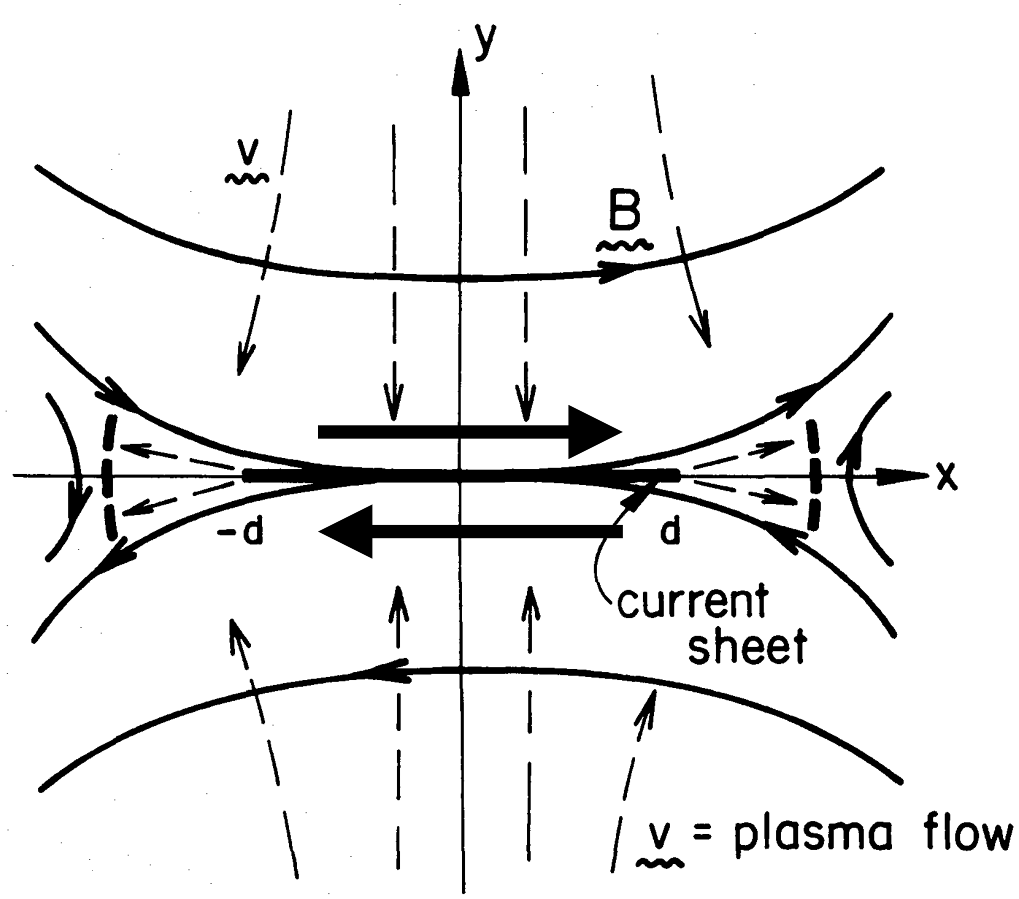
An idea: Magnetic Reconnection

The magnetar binary hypothesis + the synchrotron MeV emission scenario

- Energy source is the magnetar's magnetic energy
- Efficient acceleration (η < 10)
- Very hard injection electron spectrum (s < 2)

"A direct acceleration powered by magnetic field" seems a good candidate

➔ Magnetic Reconnection !



Romanova & Lovelace 1992

① Anti-parallel magnetic field

② Direct acceleration at the X point

③ Accelerated particles leave the region as their trajectories are bent by the magnetic field

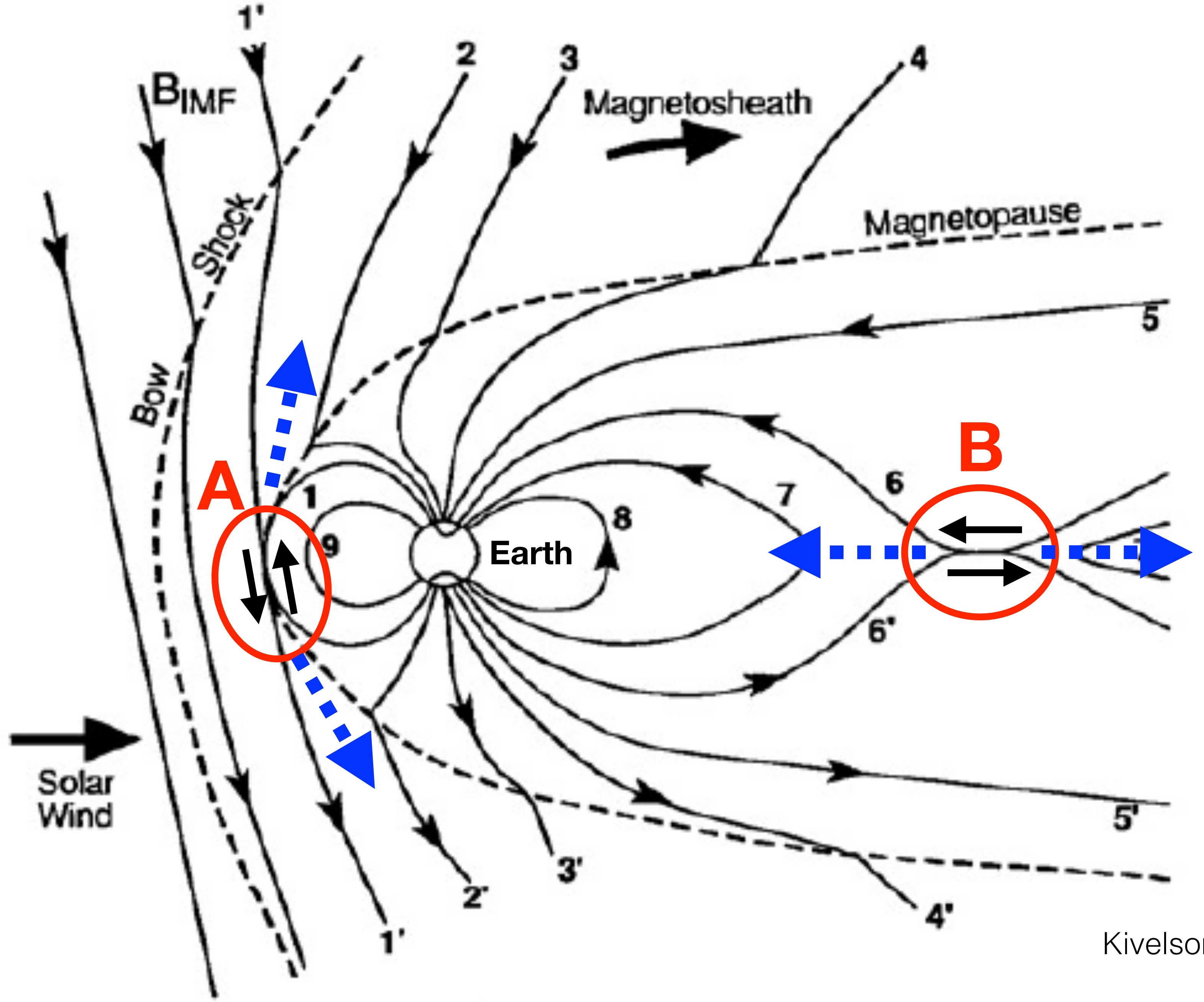
➔ hard injection electron & efficient acceleration (e.g. Zenitani&Hoshino01)

But reconnection in binary is possible?

Magnetic reconnection in binaries ???

→ ***A hint: the magnetic field around the Earth***

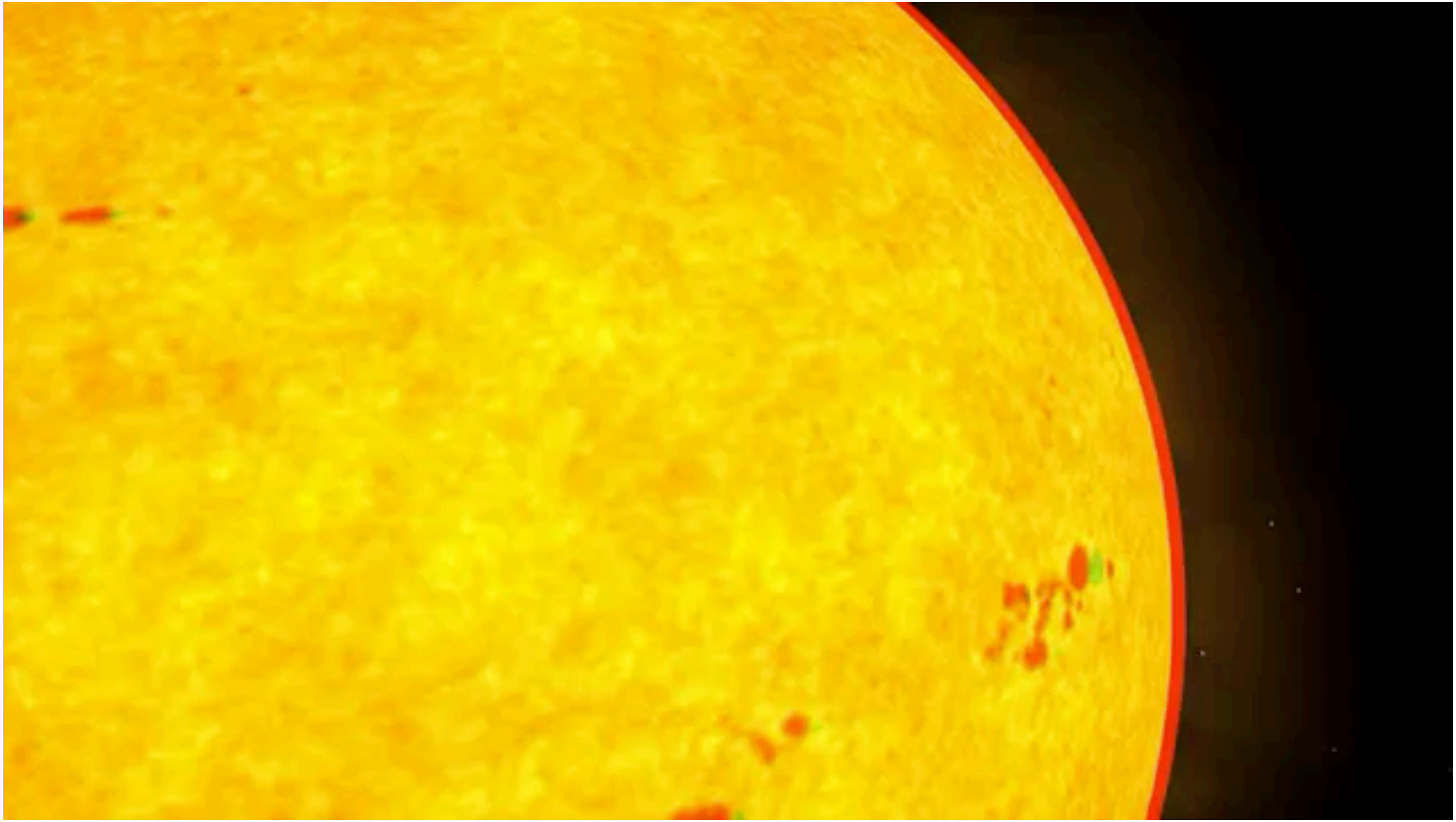
(***Earth, Solar Wind***) ↔ (***Magnetar, Stellar Wind***)



Kivelson & Russell 1995

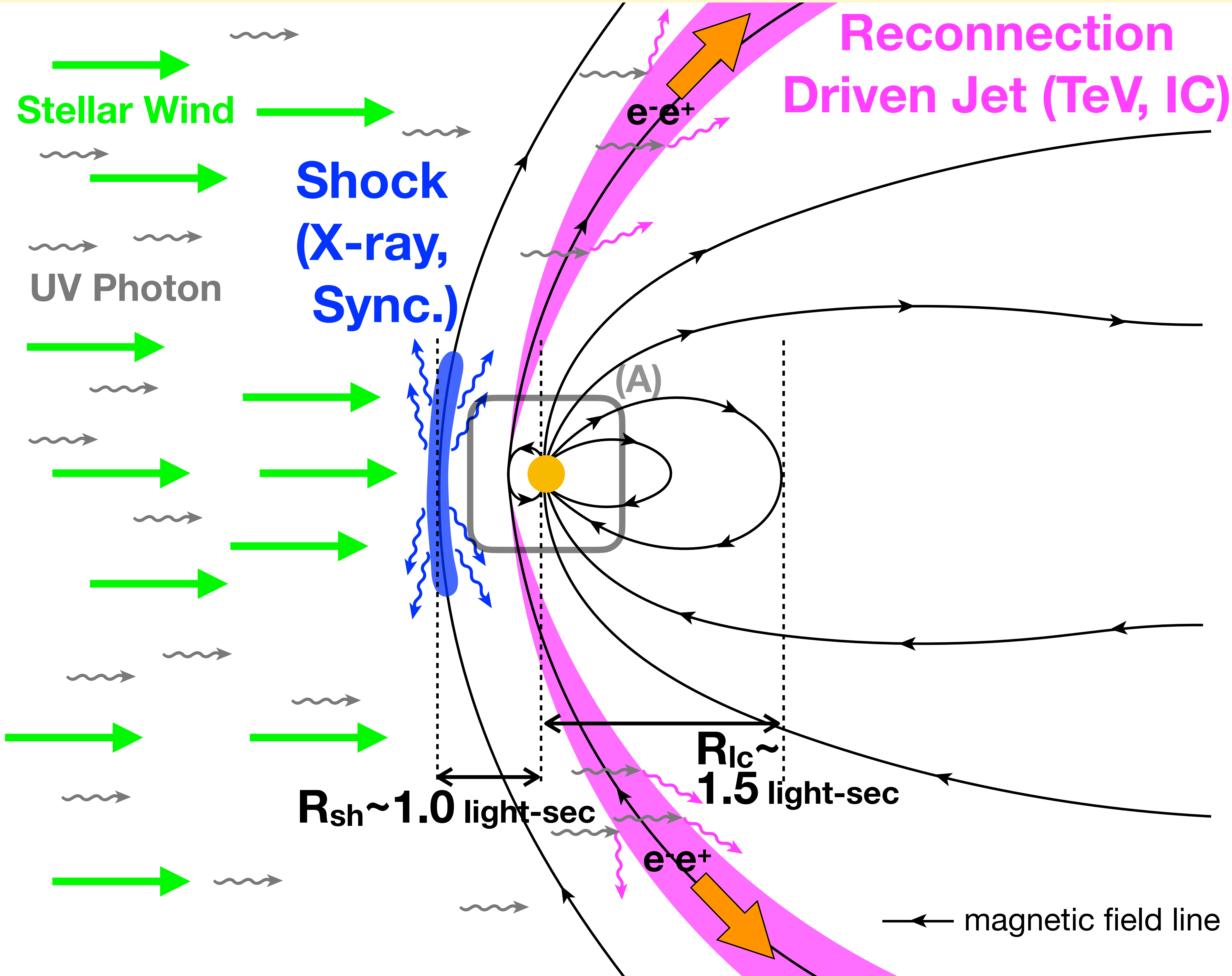
Reconnection around the Earth

NASA video on YouTube

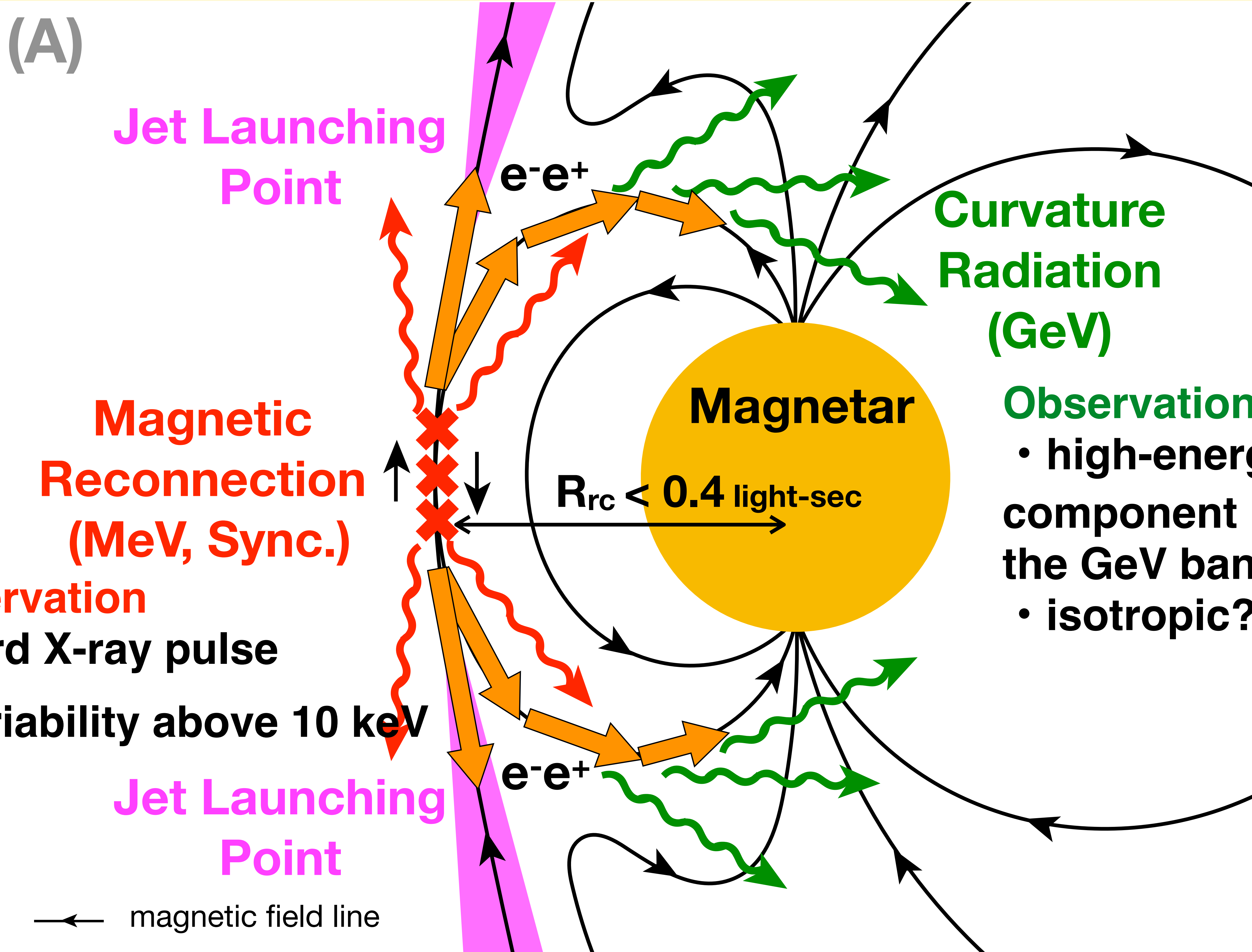


https://www.youtube.com/watch?v=2TnFXddv37E

A Plausible Configuration of Magnetic Field in LS 5039



A Plausible Configuration of Magnetic Field in LS 5039



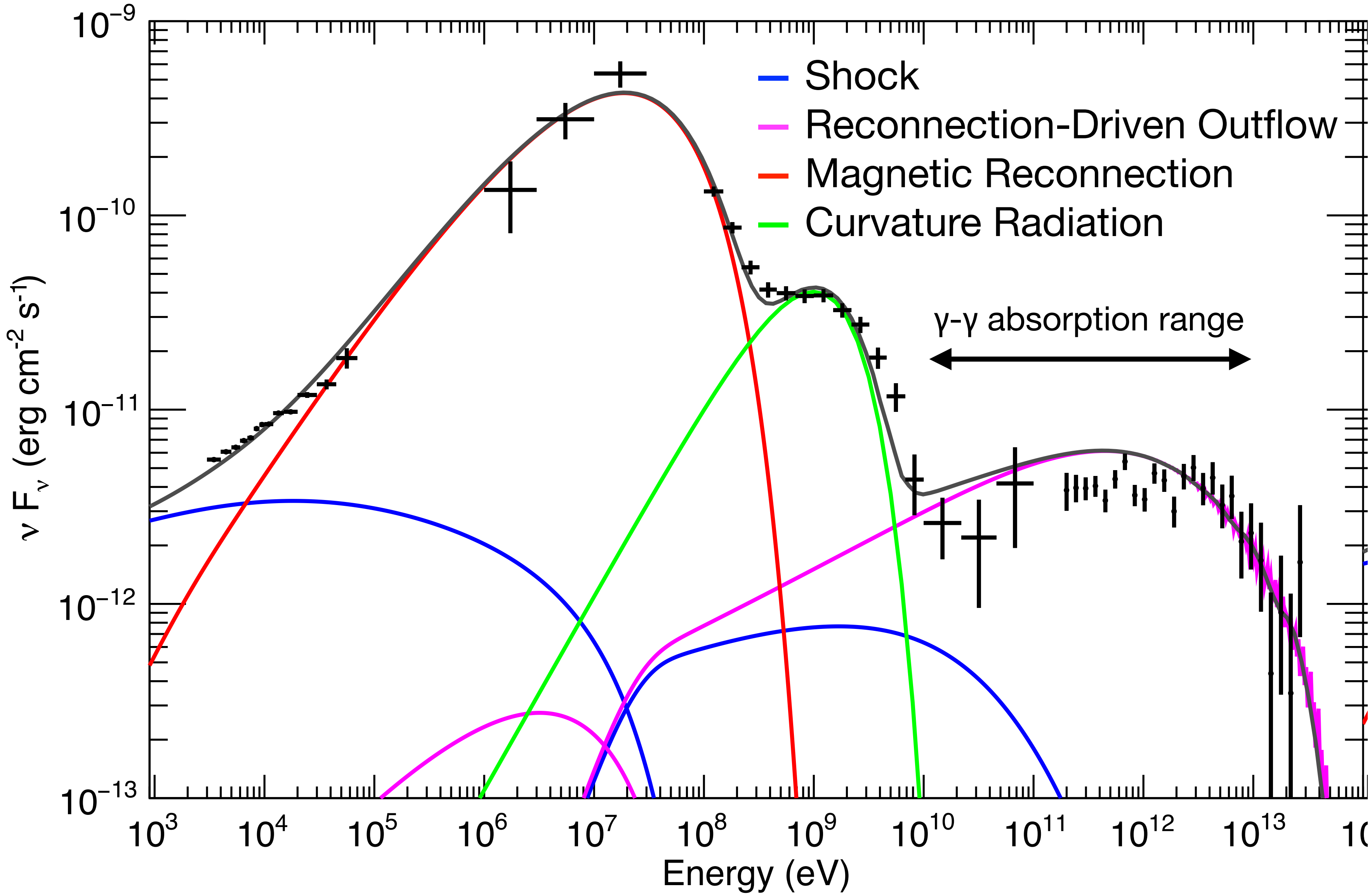
Observation

- high-energy component in the GeV band
- isotropic?

Observation

- hard X-ray pulse
- variability above 10 keV

Spectral Model using one-zone model



One zone model considering synchrotron/IC/adiabatic losses, assuming several emission regions with electron distributions of $Q(\gamma) \propto \gamma^{-s}$.

	Shock	Jet	Reconnection
$R_{\rm acc}$ (light sec)	5.0	100.0	10^{-6}
B (G)	50.0	0.1	2×10^4
$D_{\rm acc}$ (light sec)	50.0	100.0	50.0
η	10.0	10.0*	2.5
s	2.4	2.0	1.0
$\mathrm{Norm_{INFC}/Norm_{SUPC}}$	1.66	4.0	2.0

① **Direct Acceleration** $\eta \sim 1$

② **Strong B,** Synchrotron

$$h\nu = 236\ \mathrm{MeV} \times \eta^{-1}$$

➔ **hard spectrum in the MeV band**

Towards deeper understanding…

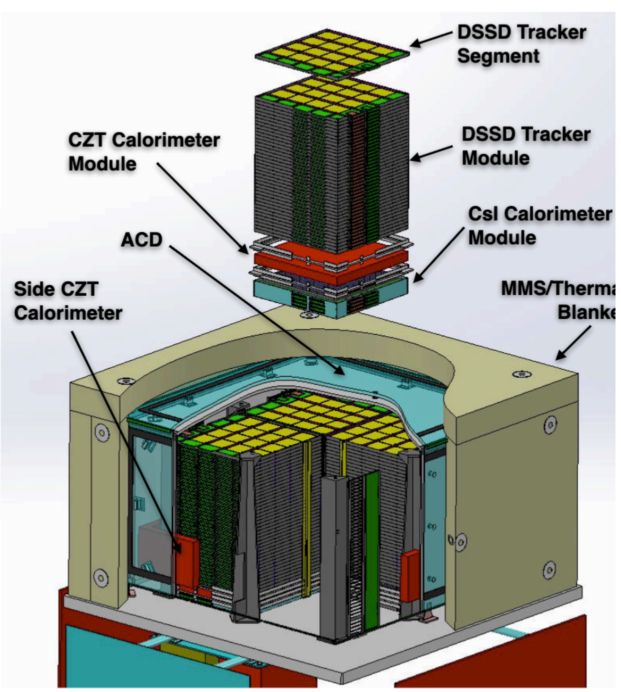
・*Confirmation of 9 sec hard X-ray pulsation*

NuSTAR proposal for additional observation, or to analyze other X-ray data

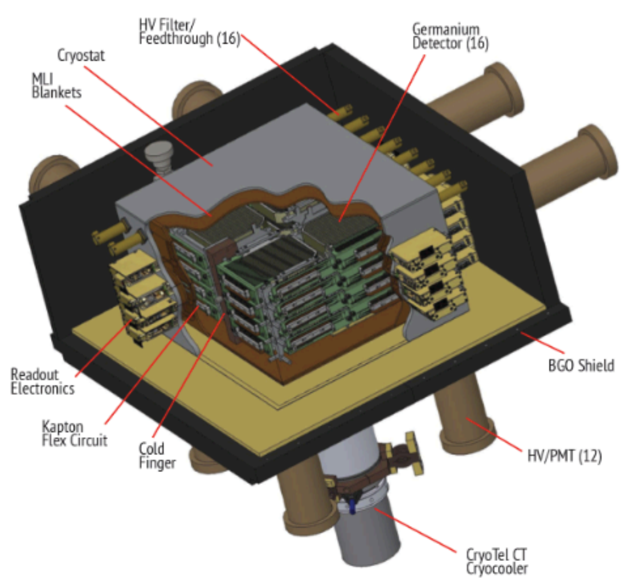
・*Brush up the magnetar binary model*

・*Need for a new MeV gamma-ray observation*

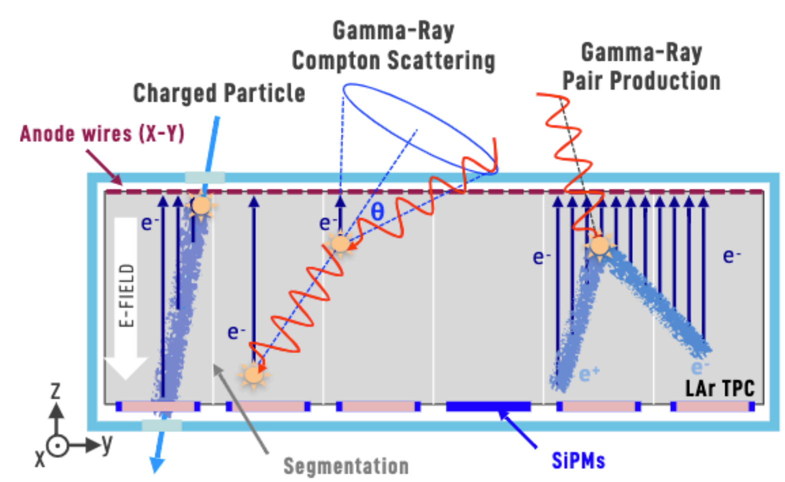
Several Compton telescope missions are being prepared! Hope to get new results of gamma-ray binaries



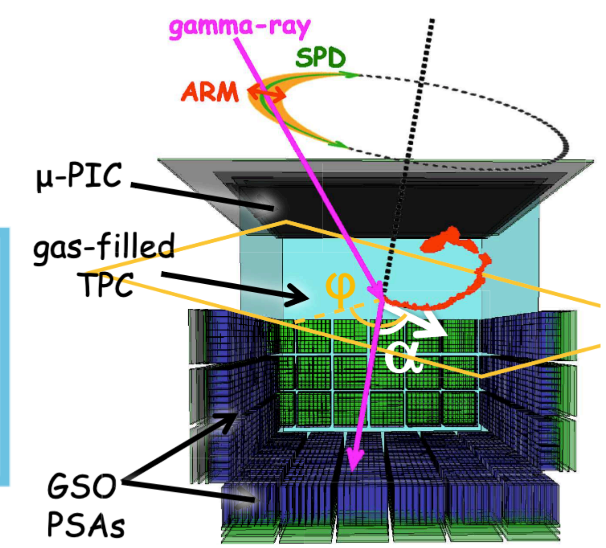
AMEGO,
60 DSSD layers!
planed to be
launched in > 2029



COSI,
Germanium Compton
telescope, SMEX
proposal is selected



GRAMS,
Liquid argon TPC
Compton telescope



SMILE,
Gas TPC Compton
telescope

Conclusion

- We analyzed the NuSTAR and Fermi 11 years data of LS 5039.
- LS 5039 has at least four spectral components from X-rays to TeV
- Especially, current models cannot explain the MeV/GeV components

- We also performed the pulse search in hard X-rays for the first time
- A sign of 9 sec pulsation is found from both Suzaku and NuSTAR data, which suggests that LS 5039 contains a magnetar

- We propose a new scenario that the compact star in LS 5039 is a magnetar with a strong magnetic field of ~ 10^{15} G, and its magnetic energy is the dominant energy source for non-thermal activity of LS 5039, through magnetic reconnection.