Gamma-ray heartbeat powered by the microquasar SS 433

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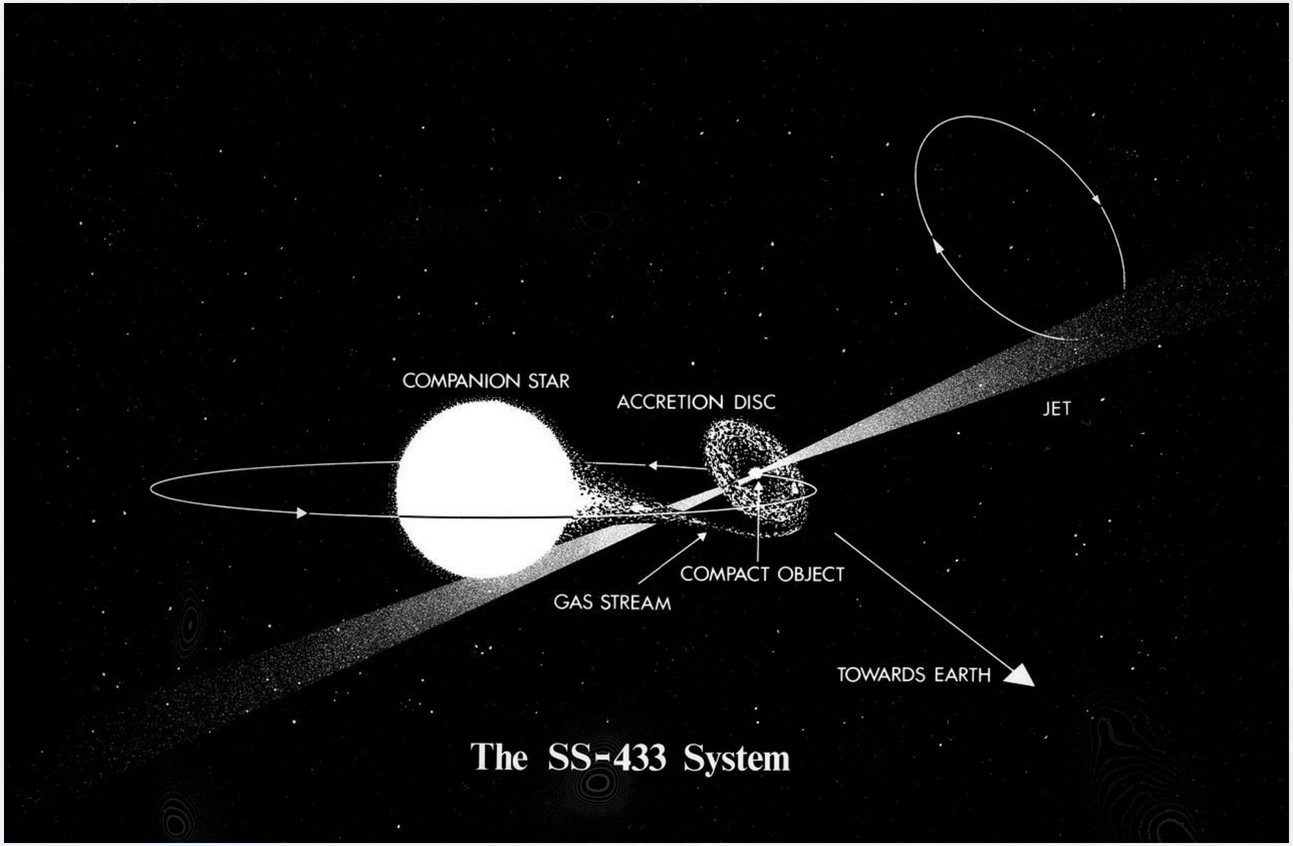
Illustration credit:
DESY/Science Communication

SS 433: A very powerful Galactic microquasar

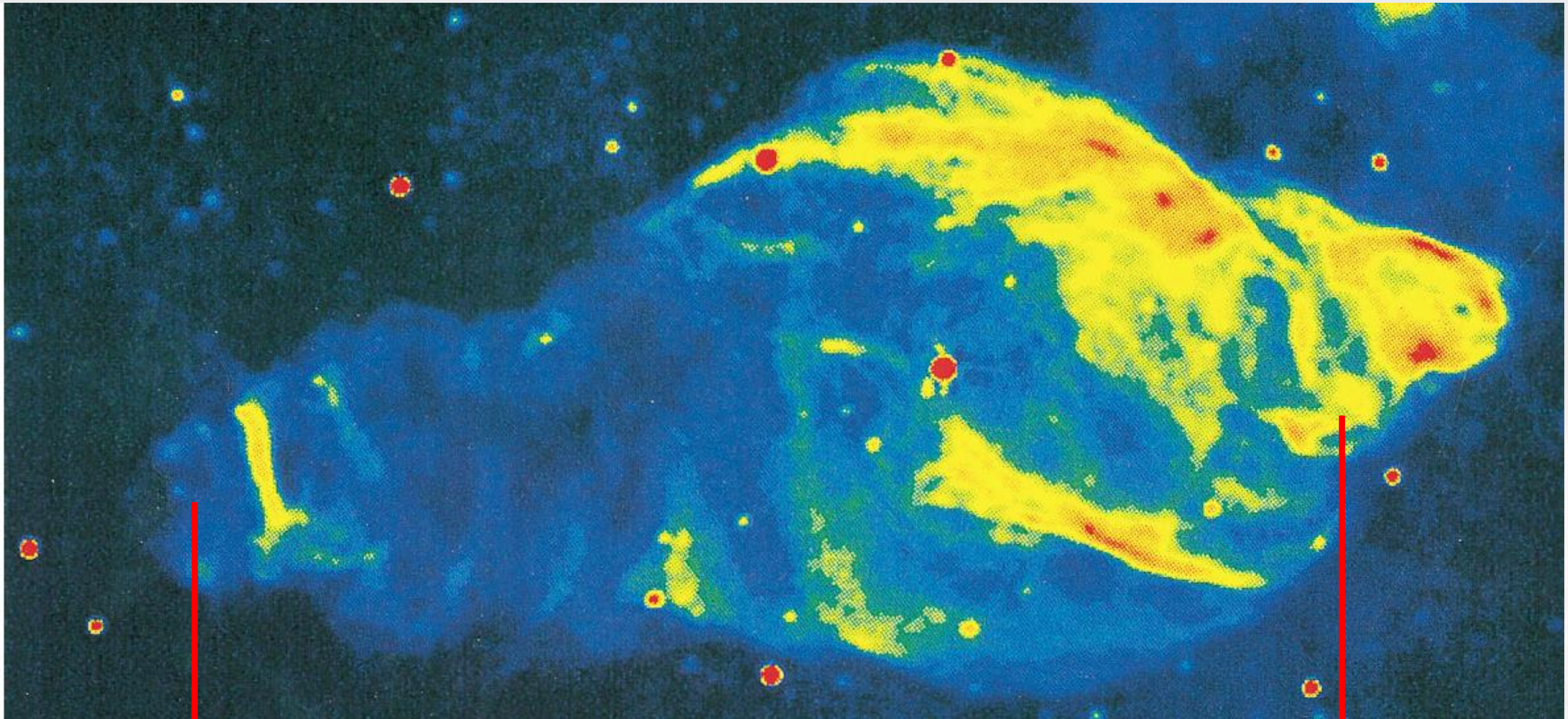
- SS 433 is a unique galactic accreting microquasar with mildly relativistic (v =0.26c), precessing jets located at a distance of 4.6 kpc

- It is composed by a compact object (10-20 M_{sun} black hole) and a 30 M_{sun} A7Ib supergiant star.



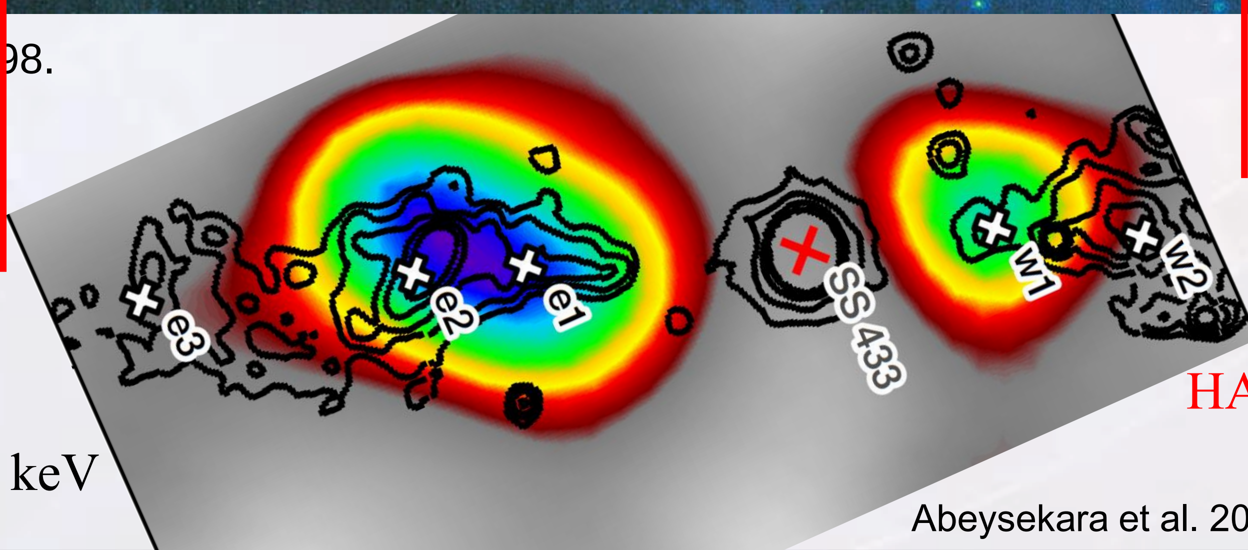
- The system exhibits photometric and spectral periodicities related to precession (~162.5 days) and orbital (13.082 days) period

SS 433: X-ray and TeV emission from jet termination lobe



Dubner et al. 1998.

ROSAT 0.9-2 keV



HAWC ~20 TeV

Abeysekara et al. 2018, Nature

SS 433 in multi-TeV photons (detected by HAWC)

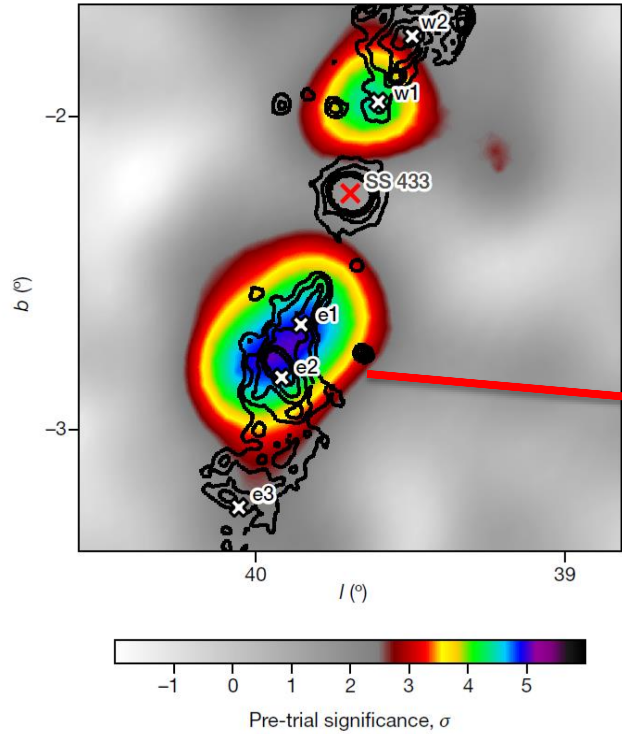


Fig. 1 | VHE γ-ray image of the SS 433/W50 region in Galactic coordinates. The colour scale indicates the statistical significance of the excess counts above the background of nearly isotropic cosmic rays before accounting for statistical trials. The figure shows the γ-ray excess measured after the fitting and subtraction of γ-rays from the spatially extended source MGRO J1908+06. The jet termination regions e1, e2, e3, w1 and w2 observed in the X-ray data are indicated, as well as the location of the central binary. The solid contours show the X-ray emission observed from this system.

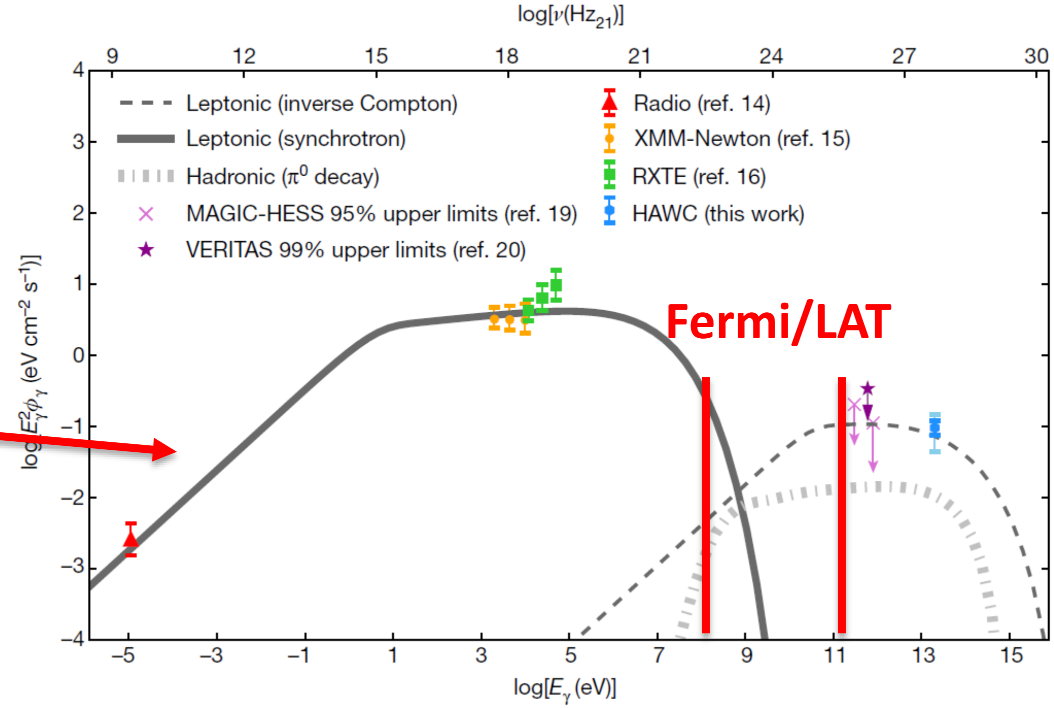


Fig. 2 | Broadband spectral energy distribution of the eastern emission region e1. The data include radio[14], soft X-ray[15], hard X-ray[16] and VHE γ-ray upper limits[19,20], and HAWC observations of e1. Error bars indicate 1σ uncertainties, with the thick (thin) errors on the HAWC flux indicating statistical (systematic) uncertainties and arrows indicating flux upper limits. The multiwavelength spectrum produced by electrons assumes a single electron population following a power-law spectrum

Abeysekara et al. 2018, nature

Summary of previous studies

Previously, there have been studies of SS 433 region using Fermi/LAT data.

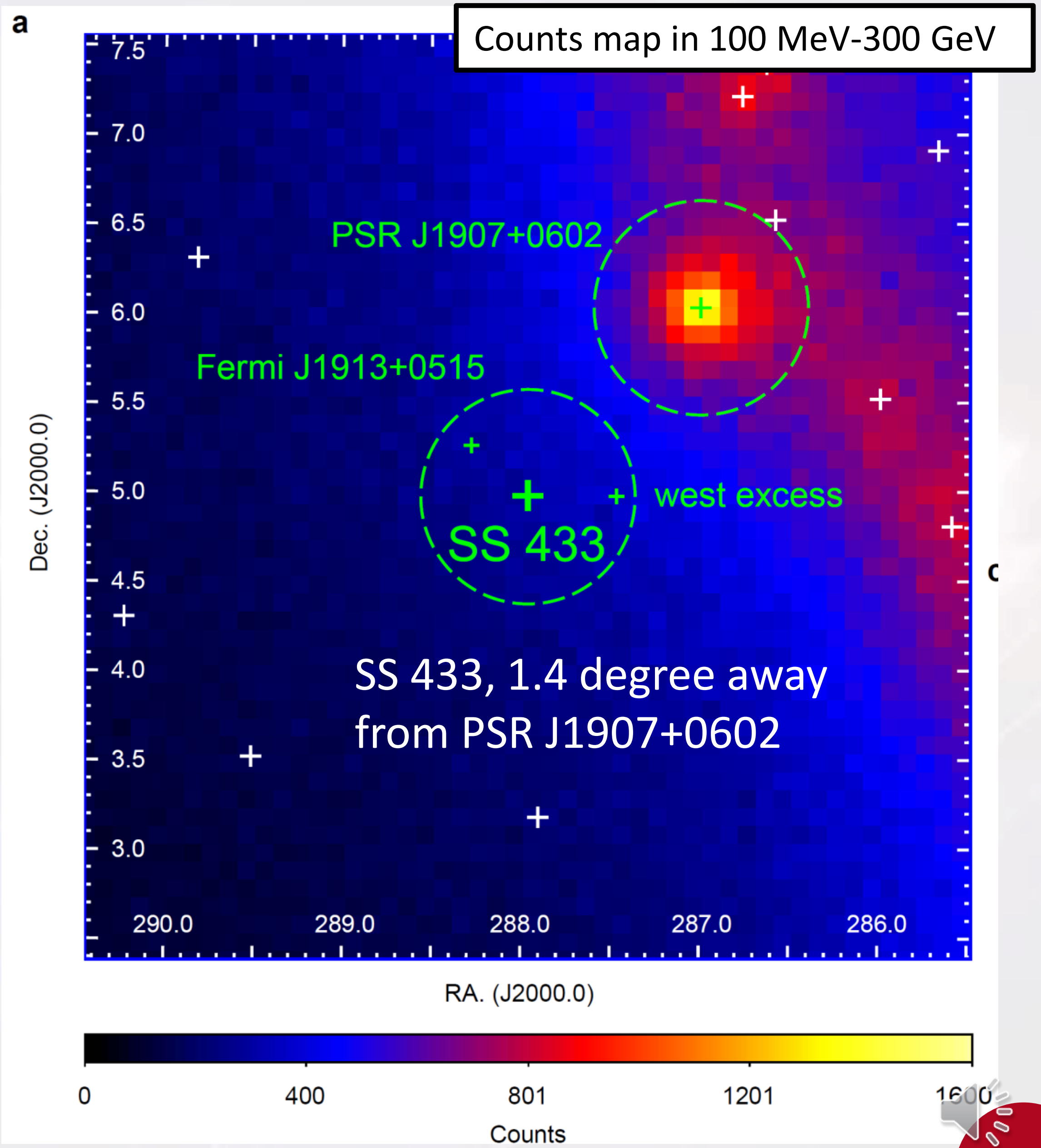
However, these studies arrived at inconsistent conclusions and, lacked a proper treatment for the contamination produced from nearby bright gamma-ray pulsar PSR J1907+0602, are thus at risk of systematic biases

SS 433 in GeV: our analysis

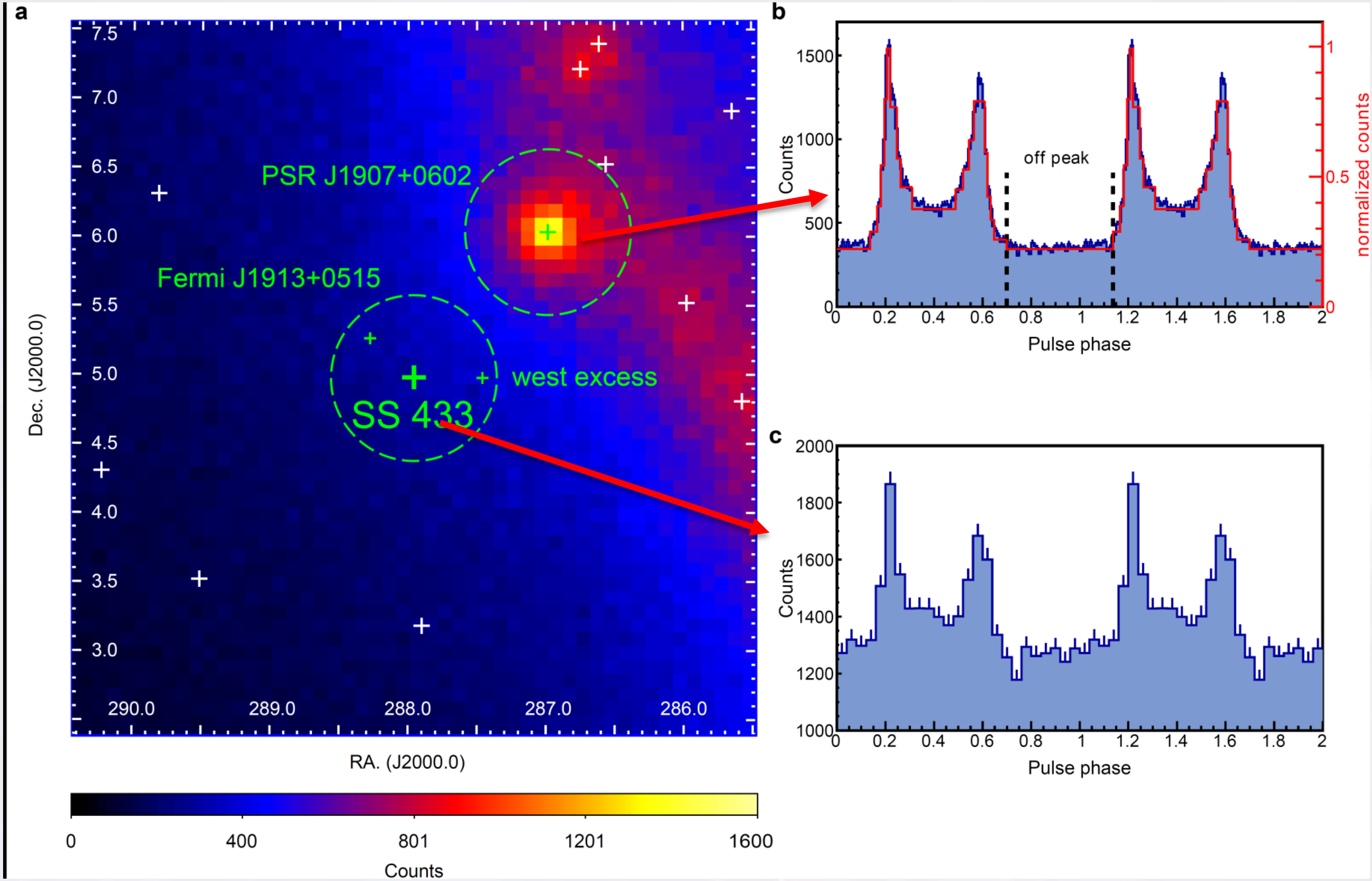
- ~10.5 years Pass 8 data: 2008-08-04
  2019-01-28
  4FGL catalog

- The map is dominated by a very bright pulsar nearby

- PSR J1907+0602 has TS=22142

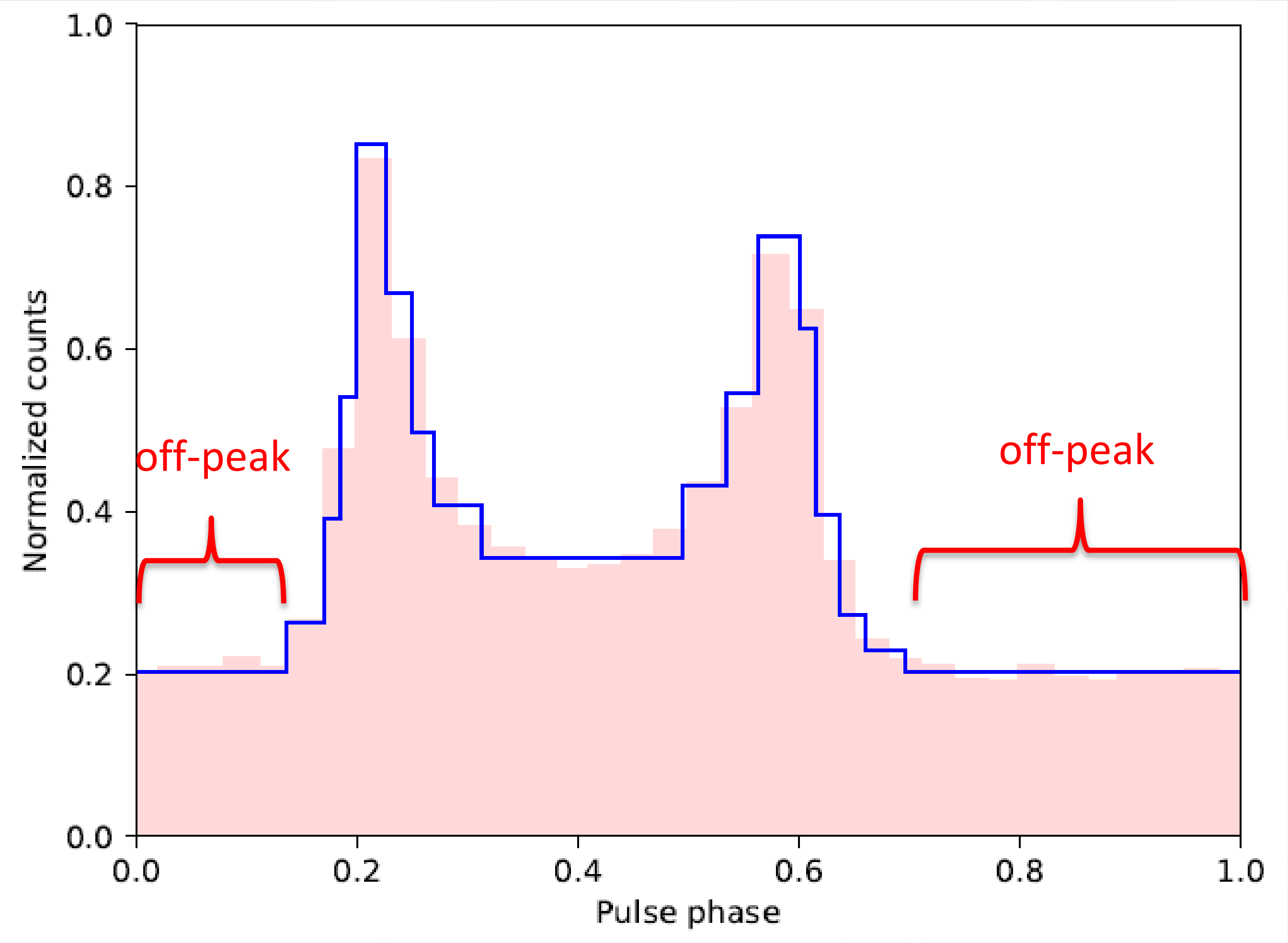


Need of gating: one can discover the pulsation at the SS433 position



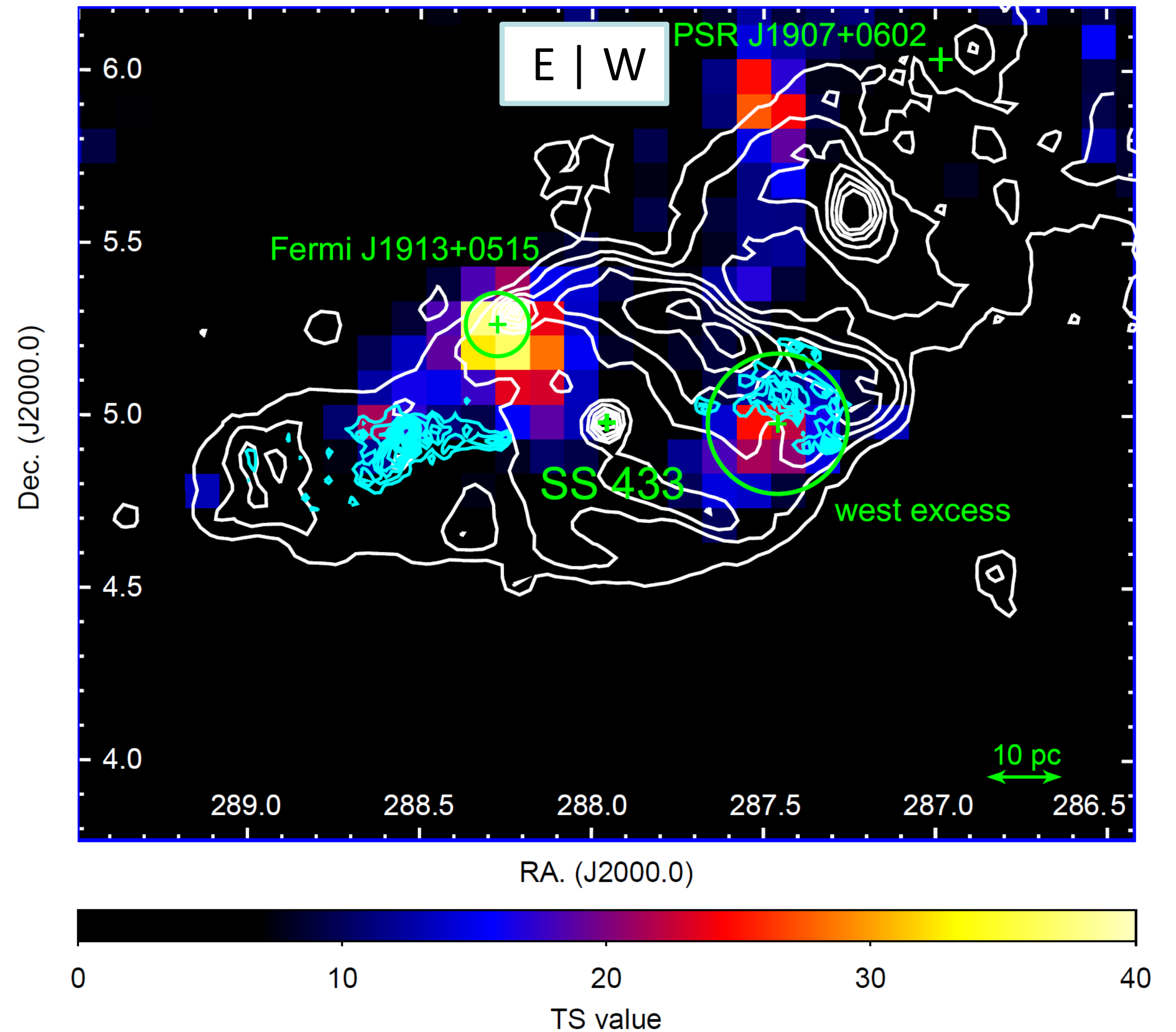
Timing of all photons centered on SS 433, above 100 MeV, with a radius of 0.6 degree, and folded with pulsar period provides a good signal (> 8σ).

SS 433 in GeV: Gating



- PSR J1907+0602 is a very bright gamma-ray pulsar.
- With a valid timing ephemeris, we defined the off-peak phase.
- We analyzed SS 433 in these off-peak phases

SS 433 in GeV: the first reliable map of the source



TS map (0.1-300 GeV, off peak phase of PSR J1907+0602)

White contour is Effelsberg 11cm radio continuum (2695 MHz) while cyan contour is X-ray ROSAT observation in 0.9-2 keV.

Two regions of TS excesses are apparent in the map.

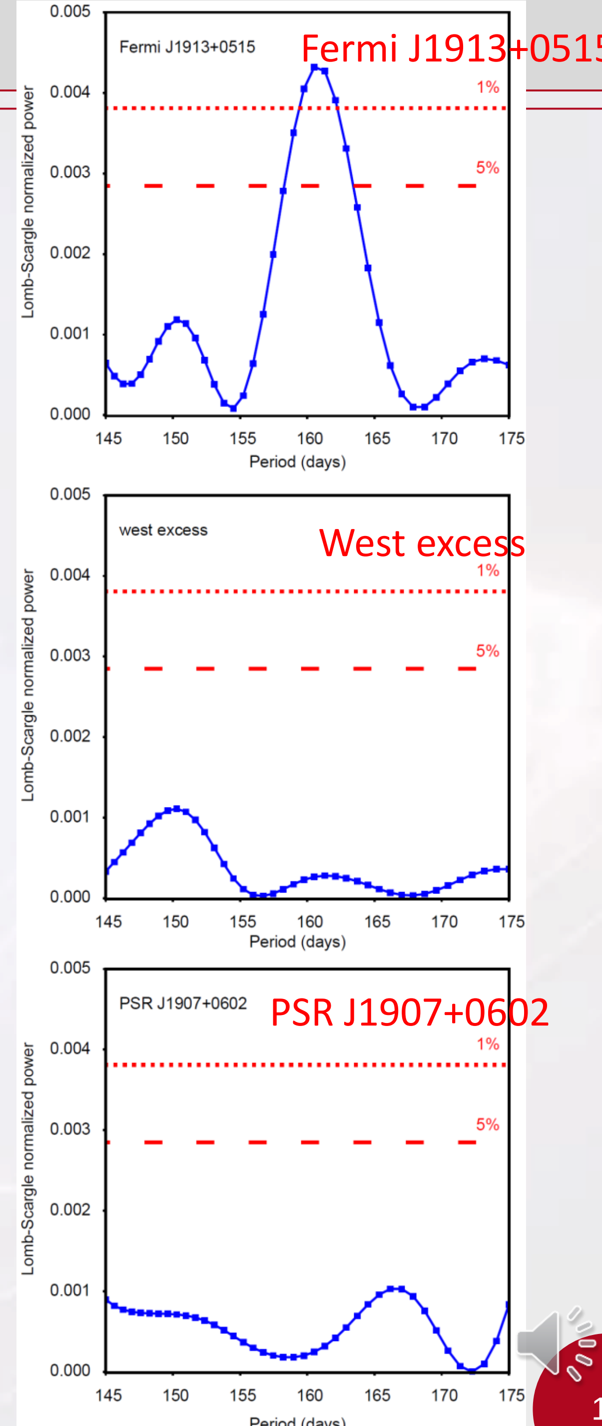
The west excess location is consistent with the one found in X-rays. Not the east one.

Surprising signal

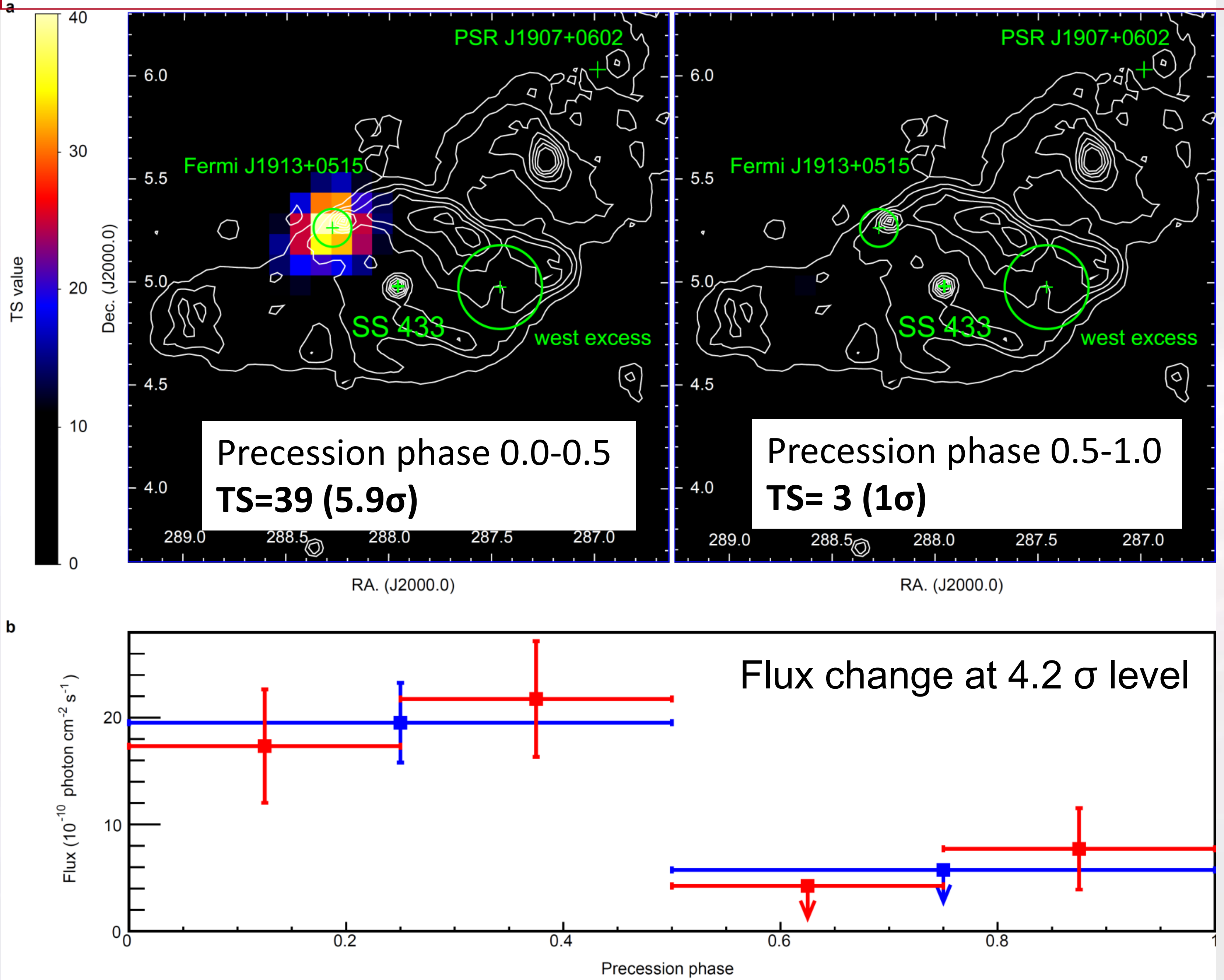
- We produced weighted light curves above 1 GeV with a bin of 1 days and searched using Lomb Scargle periodogram.

- **A relevant hint for a period signal at 160.88+/-2.66 days is detected from the east side excess (J1913) with a single frequency significance of 3.5σ, which is consistent with the jet precession period of 162.25 days.**

- Neither the west excess nor other sources in the vicinity show the same periodicity.



The periodicity hint is confirmed by likelihood analysis



Detecting a periodicity from the source is actually something expected and predicted, since the precession period itself is long-known.

But why the location of the source does not match SS 443 or the jets?

What is the origin of the periodicity detected?

A periodicity was indeed predicted (Reynoso et al. 2008), as caused by gamma-gamma absorption between GeV and X-ray photons.

- However, **all of this supposed to happen at the very base of the jet**, at very high ambient densities so that photon interactions can proceed

- This is very **far from the position of our detected signal.**

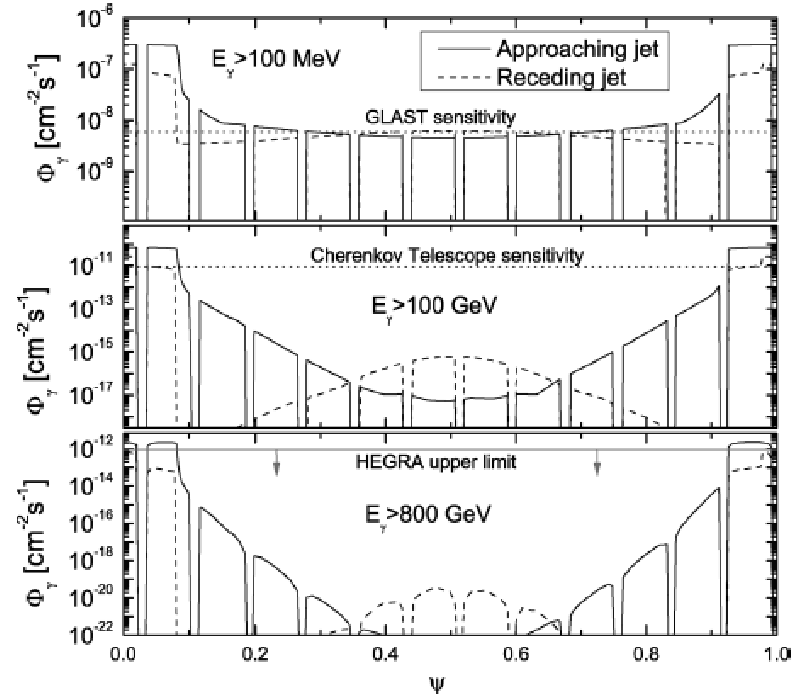
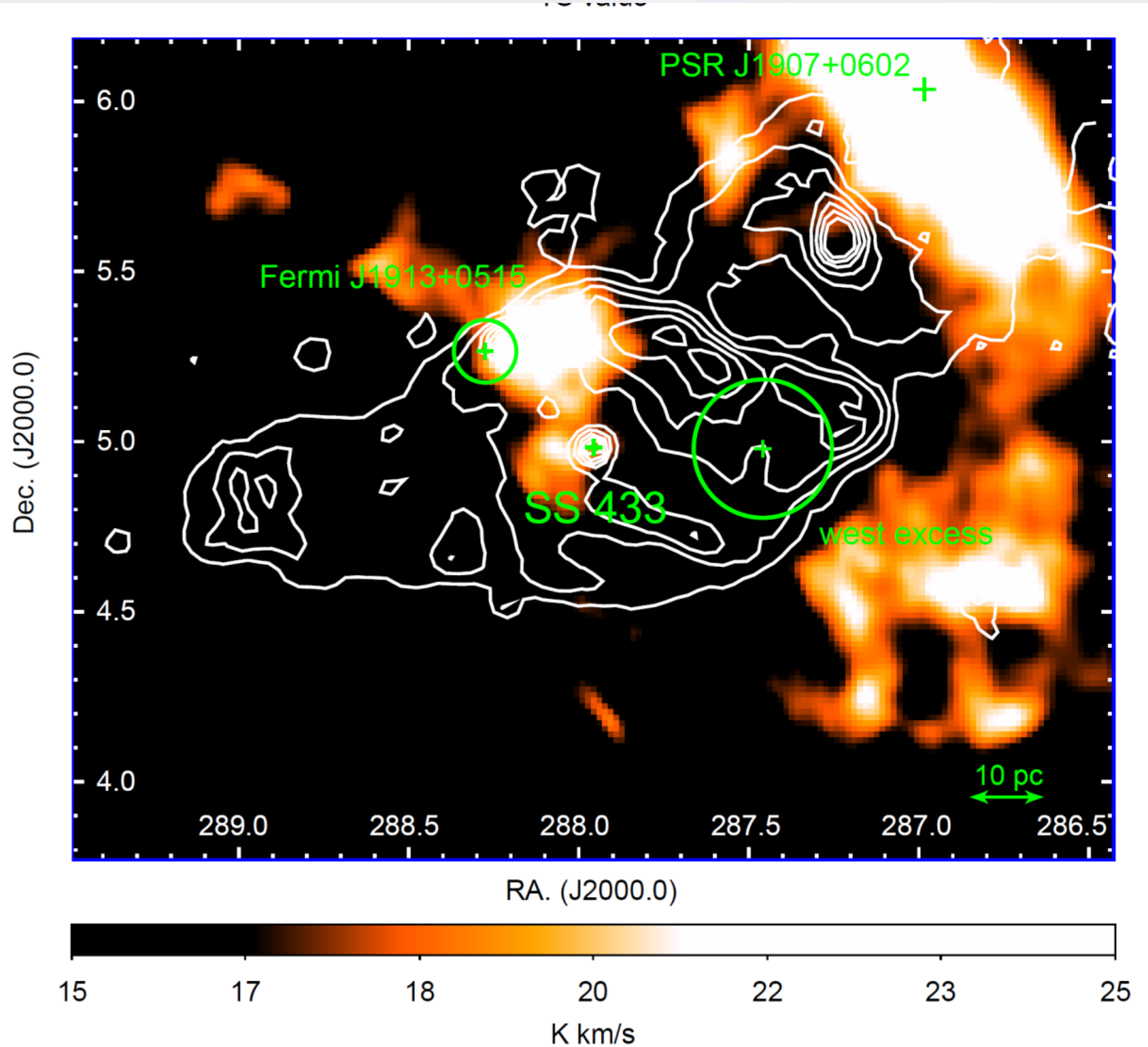


Figure 12. Gamma-ray fluxes arriving at the Earth as a function of the precessional phase for 100 MeV $< E_\gamma <$ 300 GeV in the upper panel, for $E_\gamma >$ 100 in the middle panel, and for $E_\gamma >$ 800 GeV in the lower panel. The contributions of the two jets are shown separately: the solid line for the approaching jet and the dashed line for the receding one.

Dark area, only notable thing at the location of the excess is a cloud

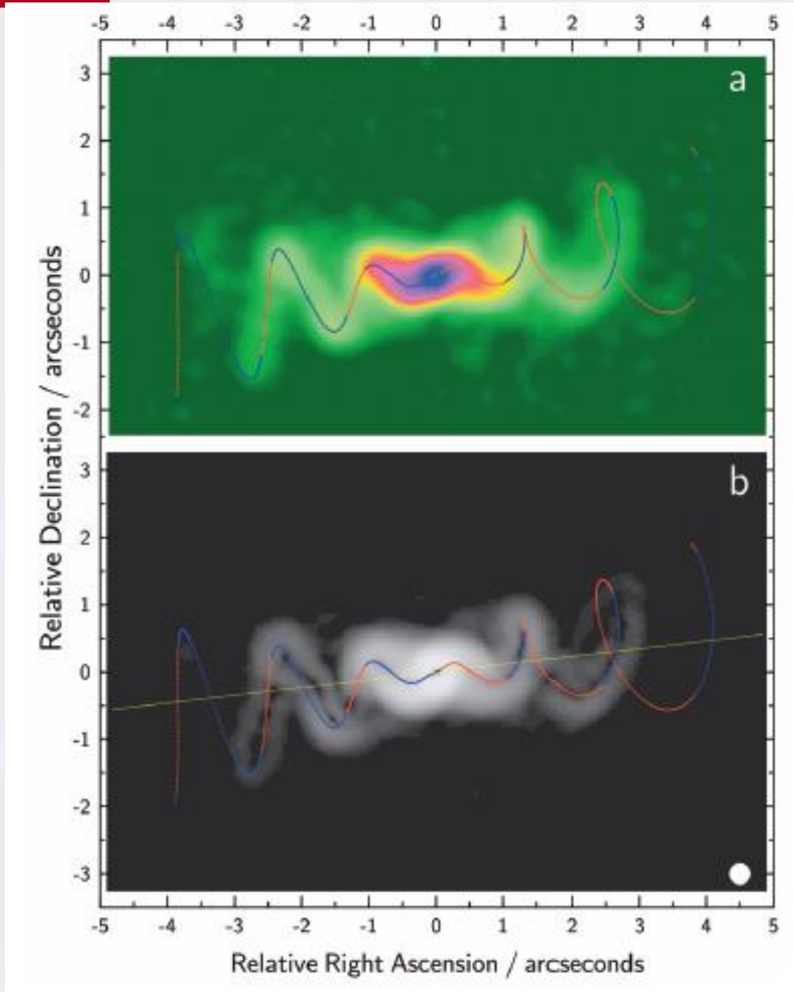


Su et al. (2018) reported atomic HI clouds associated with SS 433.

One such cloud (R~15 pc size, <n>~22 cm^{-3}, M~25000 Solar Masses) positionally coincides with the GeV excess.

Arecibo HI emission integrated in the interval 65-82 km s^{-1}.

SS 433 in GeV: is the cloud illuminated by the jets?



- If so.. Perhaps a periodic particle injection leads to a periodic emission.

- However, the motion of SS 433 jet is helical and coherence of the radio jet only appears to be sustained in the arcsecond.

Radio image of SS 433 in 4.85 GHz (Blundell et al. 2004)

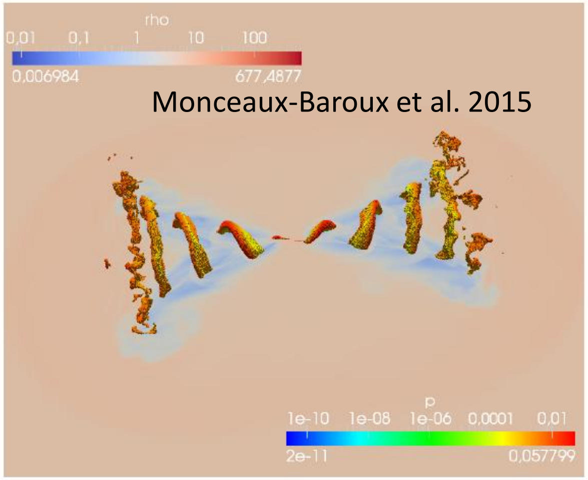
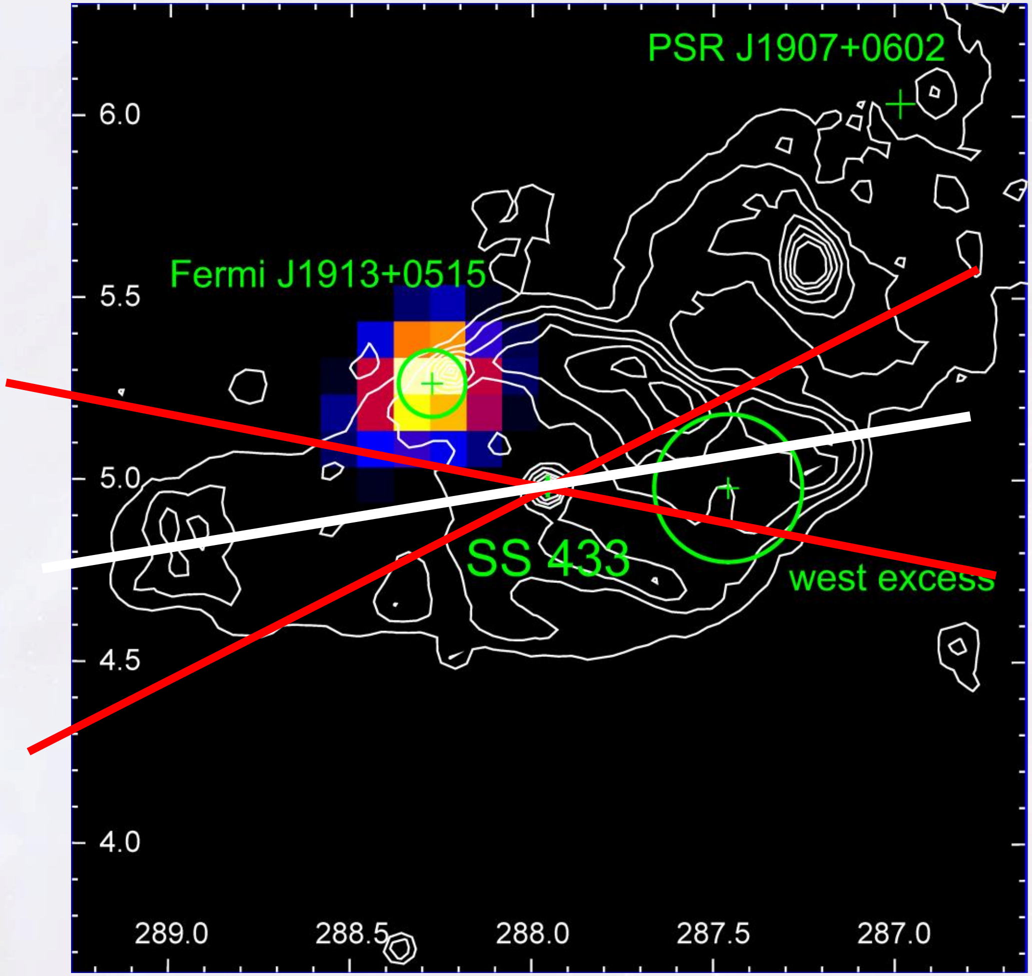


Fig. 1. Overall view of the large simulation of SS433 zoomed to the scale reached at $t = 2$ (6.5 years), i.e. $O(0.1)$ pc. The jet volume is rendered using the tracer to locate the jet. The jet volume is colored with the pressure. The 2D cut shows the proper density.

- Simulations also show that the jet loses the helical morphology after ~4 precession cycles, because of interaction with the surrounding medium

The position of the timing excess is off the center and the jets' path



…and the cloud is not in jet direction and precession path.

Another source of high energy particles: relativistic outflow

- The line-of-sight outflow velocity is 0.14-0.29c.
- Precession of the outflow in solidarity with the jet and the accretion disk, having a favorable geometry.

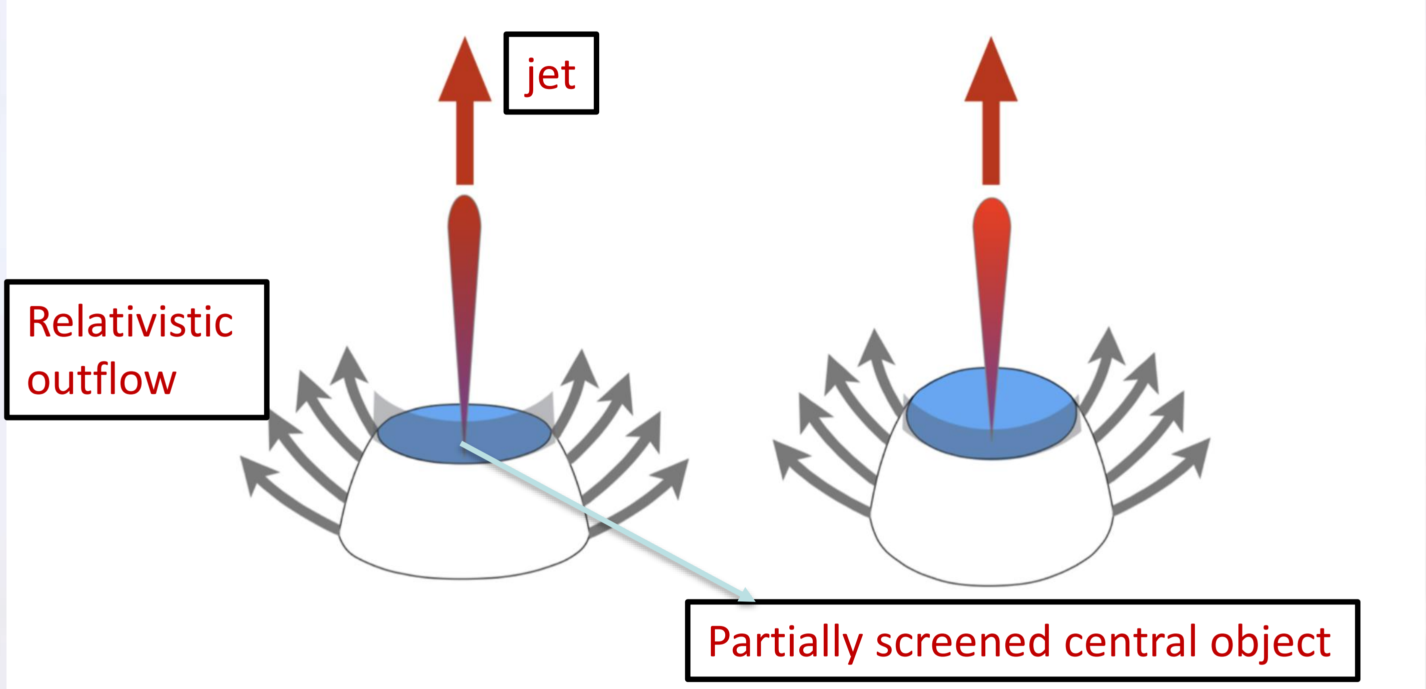
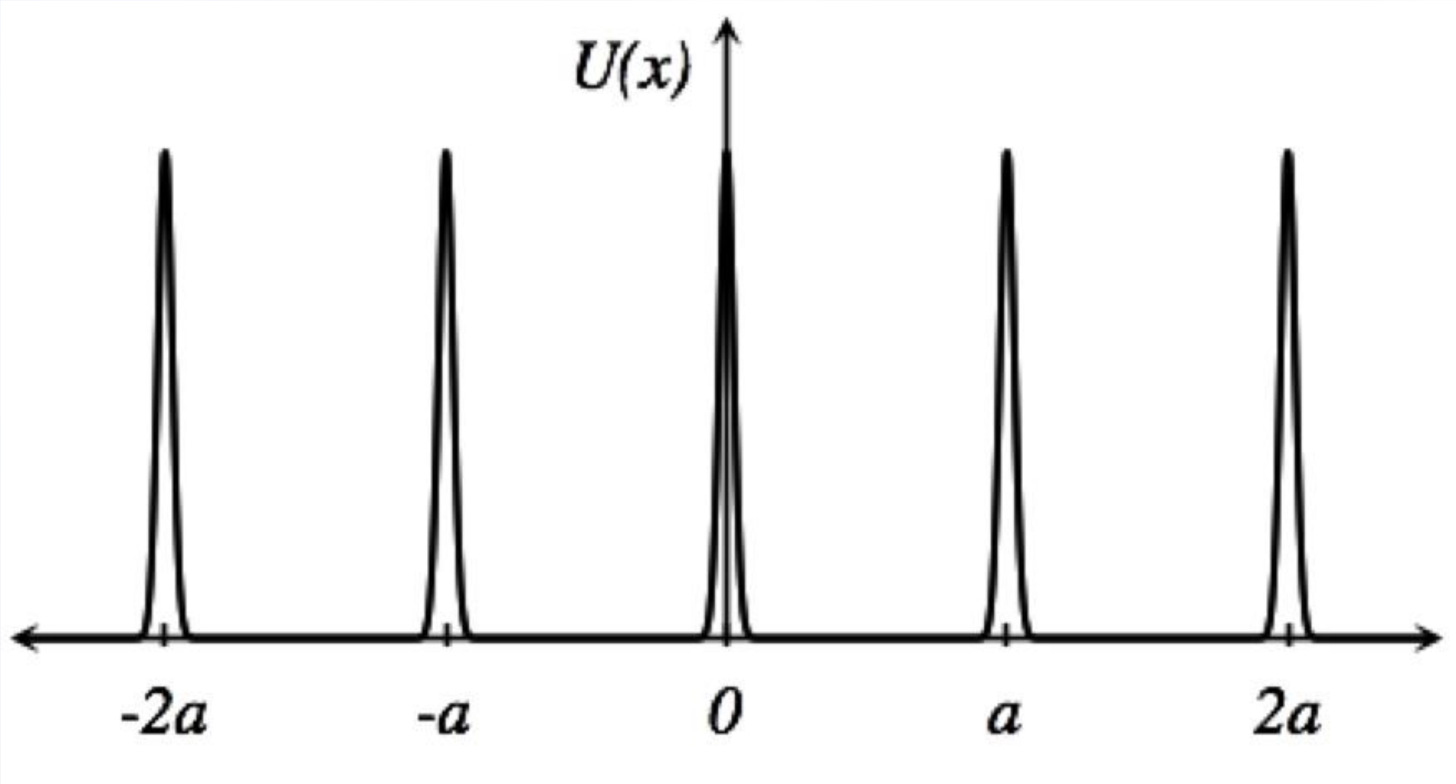


Figure 2: Schematic of SS433 based on our observations as a function of precessional phase. In both plots, the inflated disc launches an optically thick wind (grey arrows) which also presents a screen to the X-ray bright regions within the wind-cone (blue). As the system precesses to more face-on inclinations (left to right) the jet emission (red) at soft X-rays becomes brighter due to relativistic boosting whilst the reflected flux increases with the visible area of the open wind-cone[27].

Middleton et al. 2018

We considered a periodic impulsive injection from the central source (or the termination shock) and found that isotropic diffusion would not produce a periodic gamma-ray signal at the cloud.



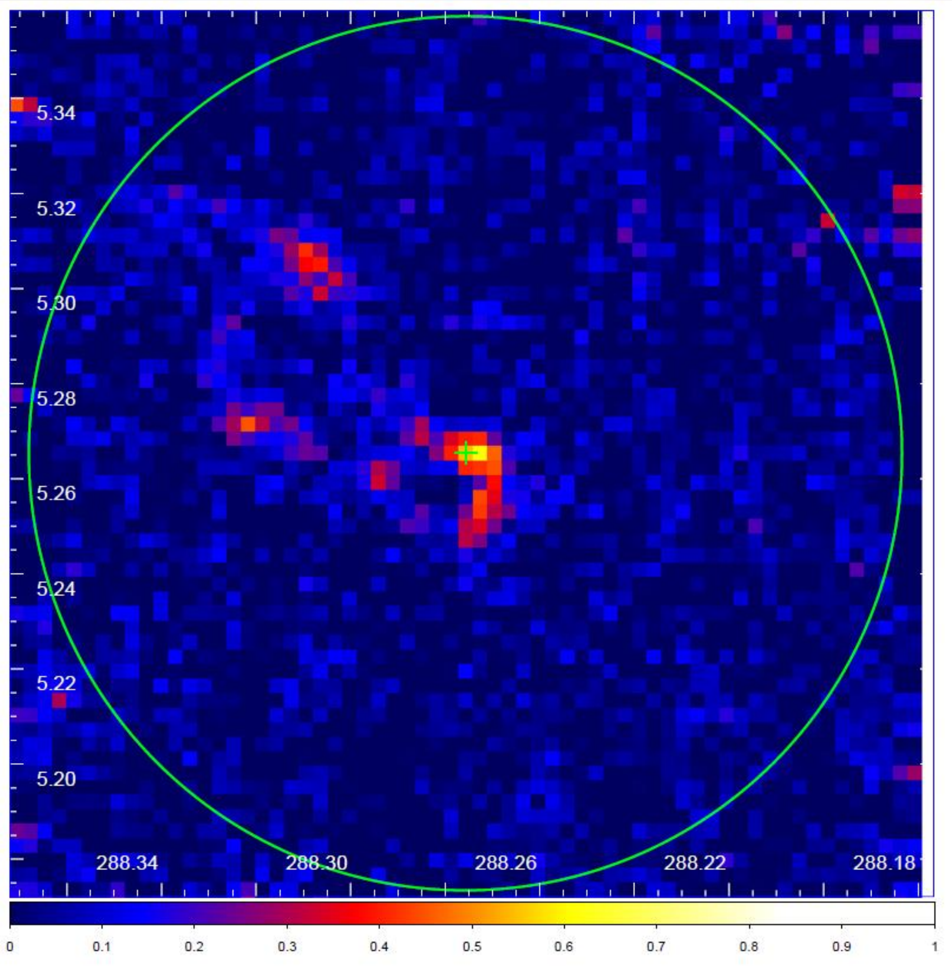
SS 433 in GeV: cloud heart-beating via anisotropic diffusion?

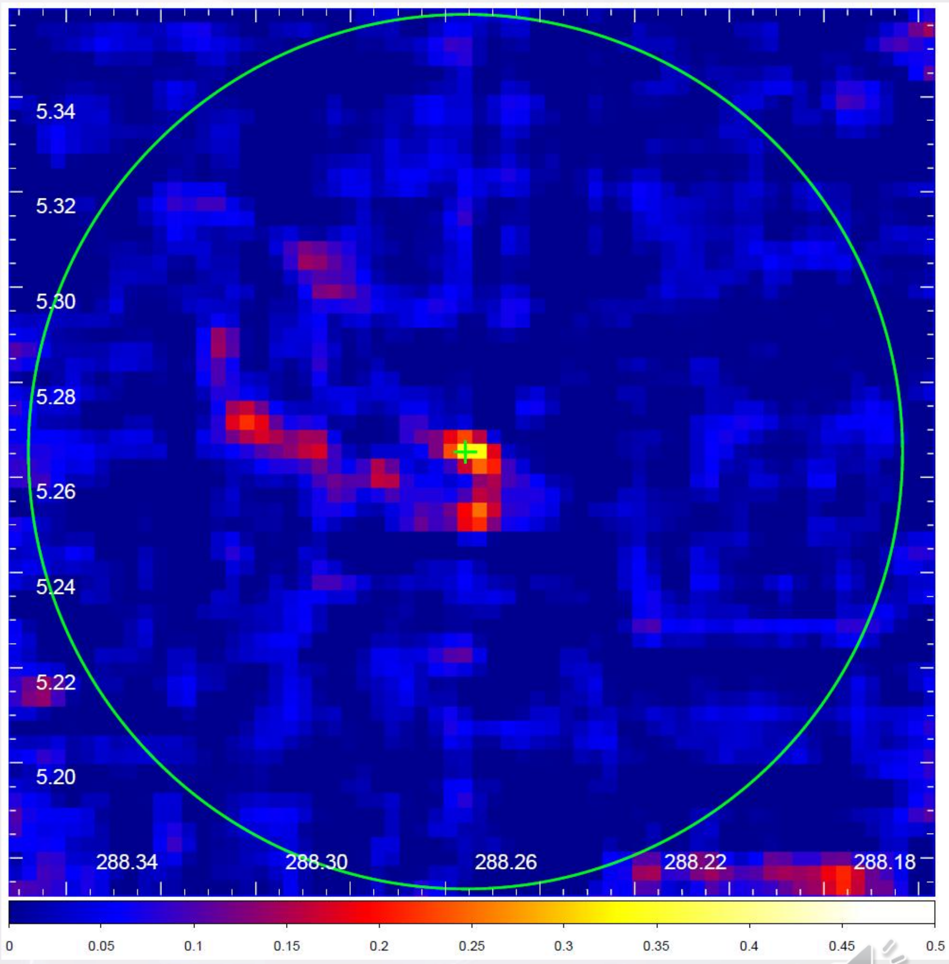
- The anisotropic diffusion (if the cloud and the source are magnetically connected) could ease the energetics, and allow that most of the CR content in the outflow is channeled into the HI cloud region.

- Once there, particles must interact in clumps (or the cloud cusp) with $n \gg n_{average}$ in order to increase the gamma-ray yield and allow for a periodicity maintenance

SS 433 in GeV: molecular clouds in the center of gamma-ray excess

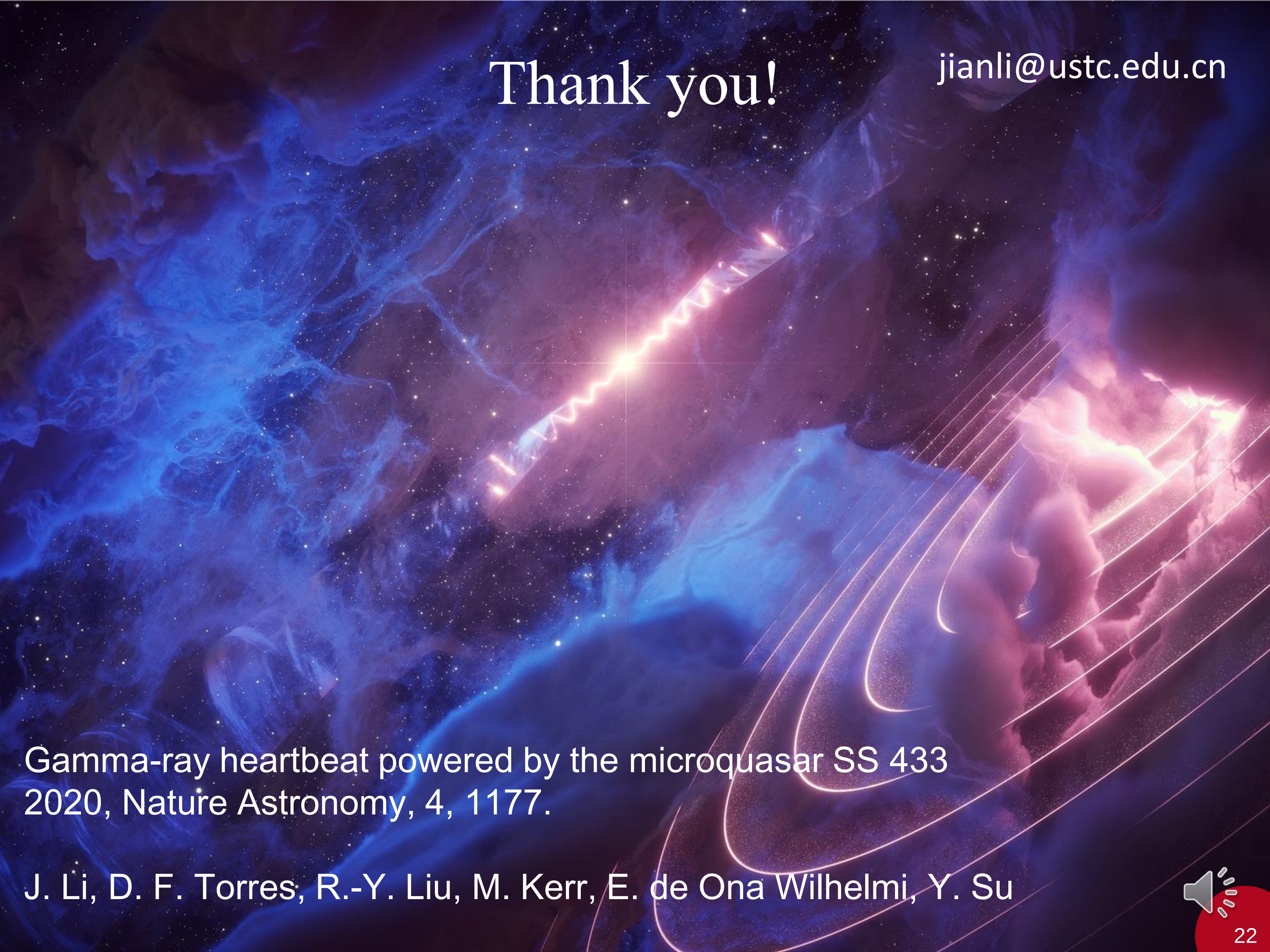
IRAM 30m telescope ^{12}CO (1-0) and ^{12}CO (2-1) map in 70-73 km/s (the distance is consistent with J1913)





Information to take away

- After gating off the nearby, bright pulsar PSR J1907+0602, **SS 433 is finally detected in GeV gamma-rays**
- An east-side excess are identified, being associated to the source via **timing to the precessional period of SS 433**
- The east excess is spatially associated with a HI cloud, distant ~35 pc from the central object
- Anisotropic diffusion could link the cloud with relativistic protons from the outflow of SS 433, providing a possible picture for a periodic signal in gamma-rays.



Thank you!

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2020, Nature Astronomy, 4, 1177.

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An artistic view of SS 433 and Fermi J1913+0515 within W50 nebula. The microquasar SS 433 and its precession jet with helical structures are shown in the middle of the figure. In the foreground, the glowing from a cloud represents Fermi J1913+0515, the gamma-ray source revealed by Fermi/LAT in this study. The concentric circles represent the gamma-ray heartbeats found, in sync with SS 433 precession period. Other filaments/structures in the background denote the environment of W50 nebula.