RELATIVISTIC OUTFLOWS FROM COMPACT GALACTIC SOURCES

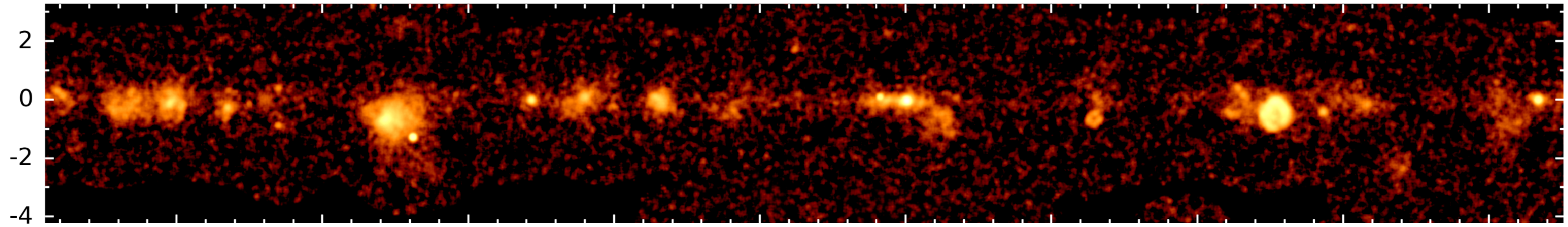
HEPRO VII, Barcelona July 2019

Pol Bordas

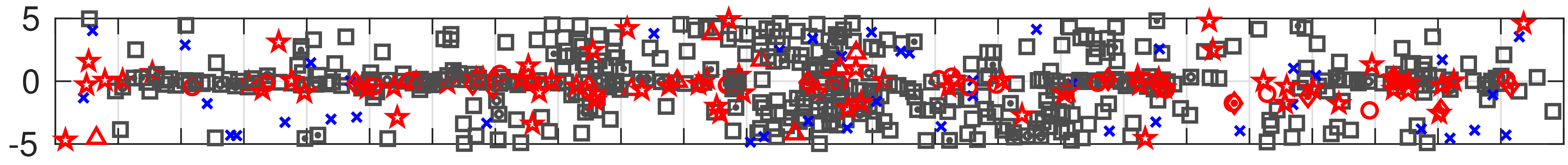
ICCUB / Universitat de Barcelona

ICCUB
Institut de Ciències del Cosmos
EXCELENCIA MARÍA DE MAEZTU
UNIVERSITAT DE BARCELONA

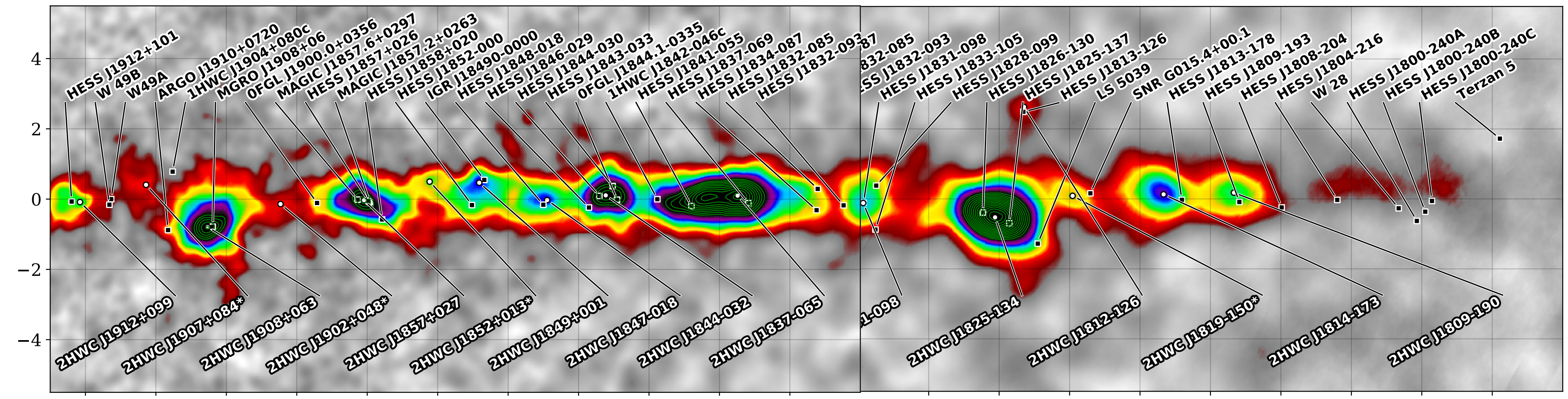
■ HESS Galactic Plane Scan (HGPS)



■ Fourth Fermi LAT Source Catalogue (4FGL)



■ Second HAWC Observatory Gamma-ray Catalog (2HWC)



OUTLINE

- **microquasars**: the case of SS433
- **gamma-ray binaries**: the case of PSR B1259-63
- **runaway PWNe**: the case of IGR J11014-6103

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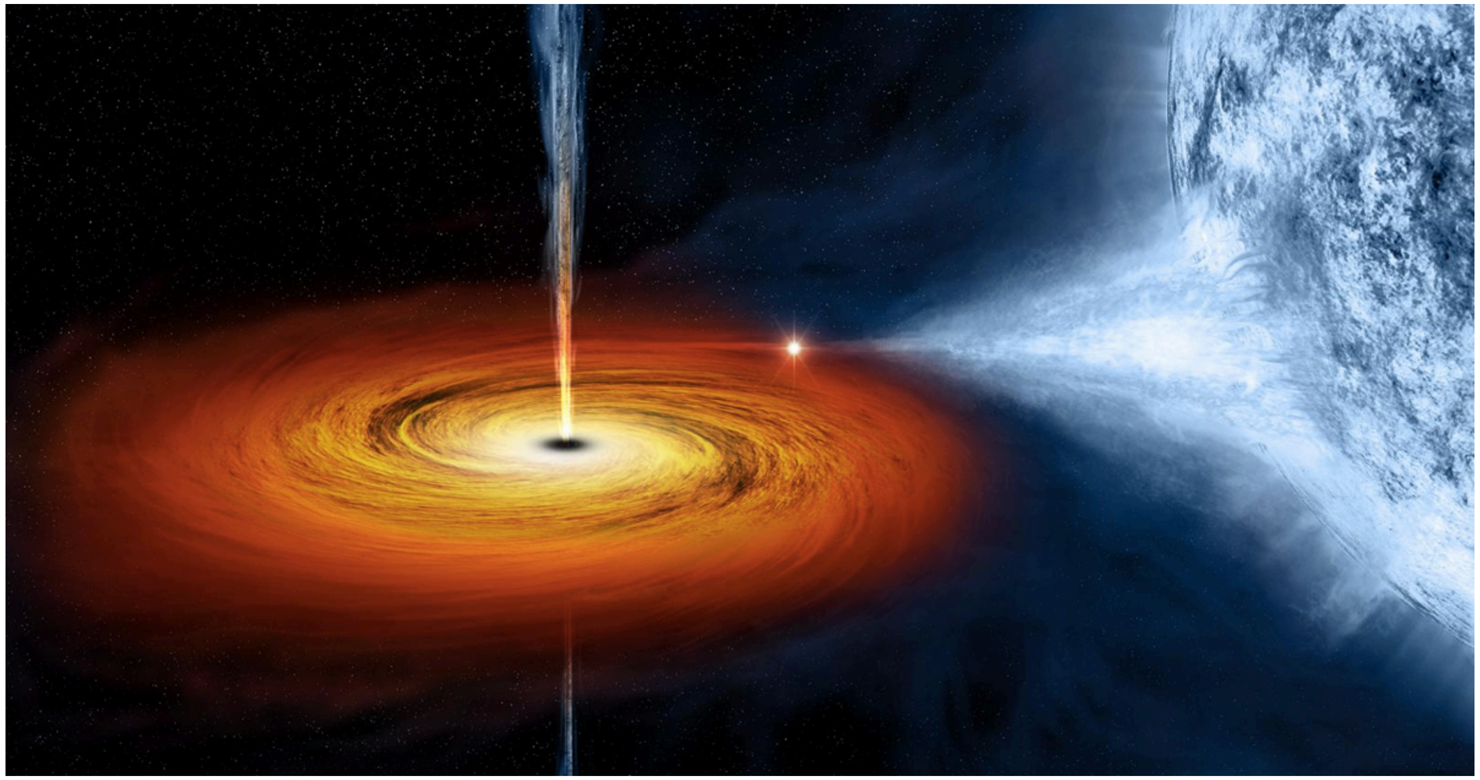
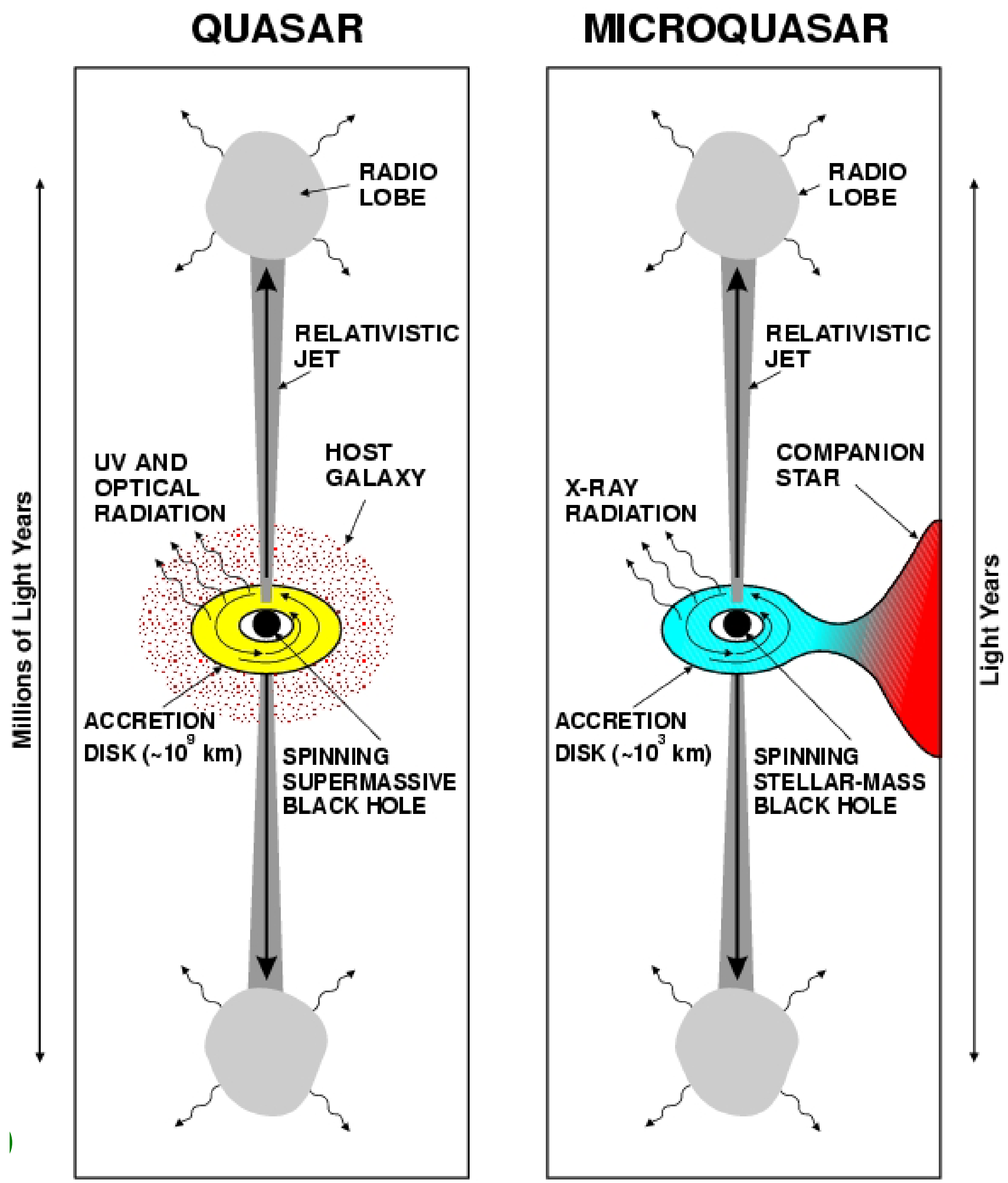


- **µQs: XRBs displaying relativistic jets**
  - compact object (BH/NS) + donor star (LM/HM), accretion disk, hot corona, bipolar jets
    Mirabel & Rodríguez 1998
  - µQs as gamma-ray sources
    Paredes+ 2000
  - broad-band emission from radio-to-X-rays
    Bosch-Ramon+ 2006
  - transient / persistent gamma-ray emission:
    Cyg X-3 (**Tavani+ 2009, LAT 2009**), Cyg X-1(**Zanin+ 2016, Zdziarski+ 2017**), Cyg X-1 flares (**Albert+ 2007**, **Bulgarelli+2001**),
  - large-scale emission - mimicking radio galaxies, e.g. **SS433**, 1E 1740, GRS 1758-258, Cyg X-1 …



from **Mirabel & Rodríguez (1998)**

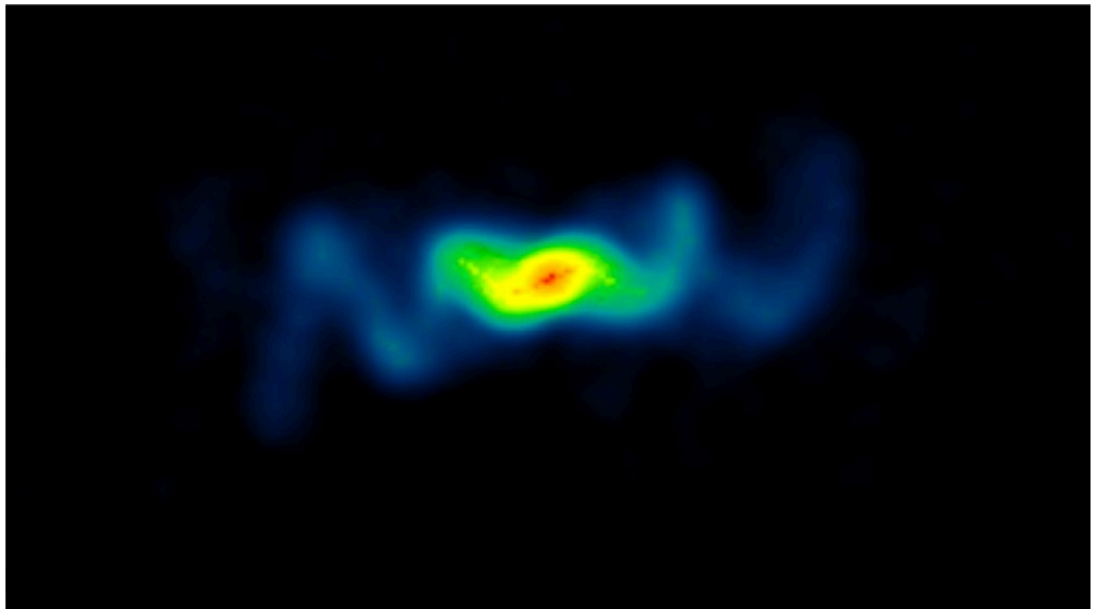
- *γ-rays from Cyg X-1 and Cyg X-3* - A. Zdziarski
- *µQs at Cosmic Dawn* - F. Mirabel
- *time-lag /photon-index correlations in µQs* - N. Kylafis
- *GRS 1758-258 as a winged µQ* - J. Martí
- *Lorentz factors of µQ jets* - P. Saikia
- *Are jets in GRS 1758-258 precessing?* - P. Luque-Escamilla

+ µQs @ HEPRO VII

- **SS433: first discovered μQ** **Abell & Margon 1979**
  - likely BH (M~10-20 M⊙) + A-supergiant (**Fabrika 2004**)
  - supper-critical accretion rate, dM/dt ~ 10^{-4} $M_{\odot}$/yr
  - 13d (162d) orbital (precession) period **Gies+ 2002)**
  - jets mildly relativistic v_{jets}= 0.26 c, i = 78°, θ_{prec} = 21°
  - extremely powerful jets, $L_{jet} \gtrsim 10^{39}$ erg/s
  - evidence for baryons **Marshall+ 2002, Migliari+ 2002**

  - embedded in the W50 nebula **Dubner+ 1998**
  - jets/nebula interaction => "sea-shell"
  - extended radio, optical filaments, X-ray hot spots
  - HE/VHE gamma-rays from interaction regions? **Bordas+ 2015, Rasul+2018, HAWC 2018**

VLA, Blundell & Bowler 2004



(NRAO/AUI/NSF, K. Golap, M. Goss)

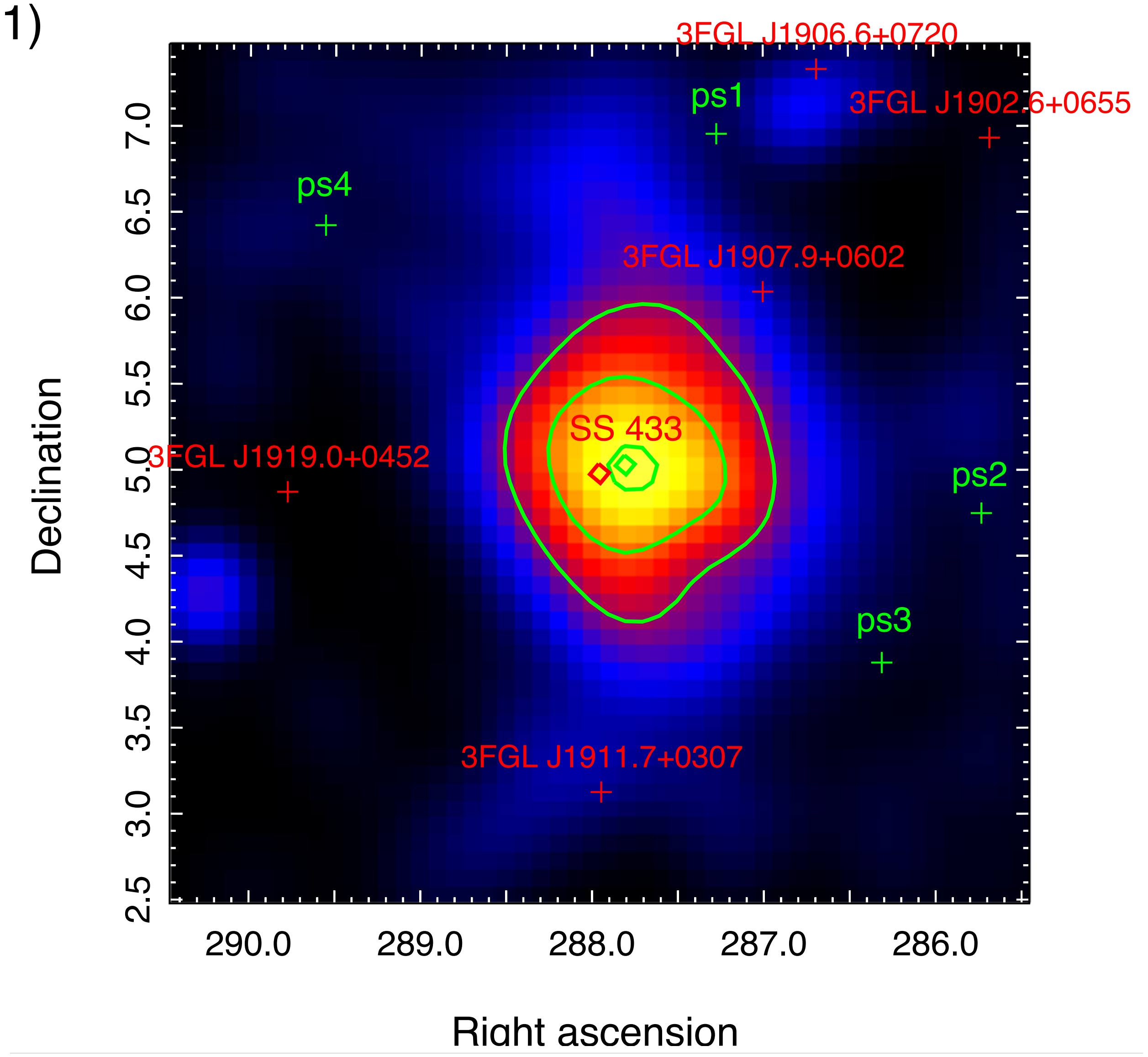
SS433 at HE gamma-rays

- 5 years (7 years) *Fermi*-LAT observations
  Pass7 (Pass8) data, 3FGL, TS = 57.6 (62.41)
  $\Delta\theta$ = 0.4° (0.2°) **Bordas+ 2015, 2017**

- 9 years *Fermi*-LAT observations
  Pass8 data, 3FGL, TS = 165,
  $\Delta\theta$ = 0.18°, TS_{ext}=31 **Rasul+ 2019**

- 10 years *Fermi*-LAT observations
  Pass8 data, 3FGL + FL8Y, TS_{e1} = 65,
  TS_{w1}=30, TS_{ext}<4 **Xing+ 2019**

- 10 years *Fermi*-LAT observations
  Pass8 data, 4FGL, new diff. bkg model,
  TS = 65, extension *vs* point ~ 3.5σ
  Sun+ 2019



Bordas+ 2015, 2017

- HE gamma-rays towards SS433/W50
- SED up to ~700 MeV only, **peak @ ~250 MeV**
- $L_\gamma = 7.2 \times 10^{34}$ erg cm^{-2} s^{-1}

Xing+ 2019

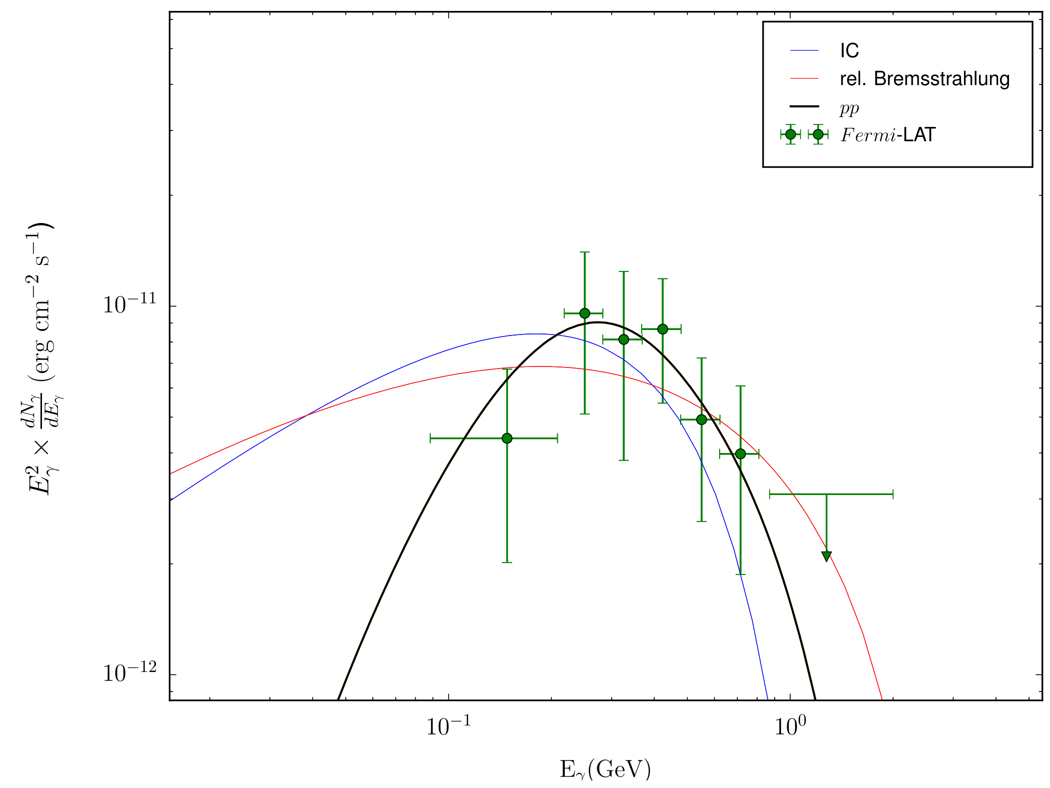
- best-fit position offset **towards w1**
- no model to explain GeV + TeV by single emitter

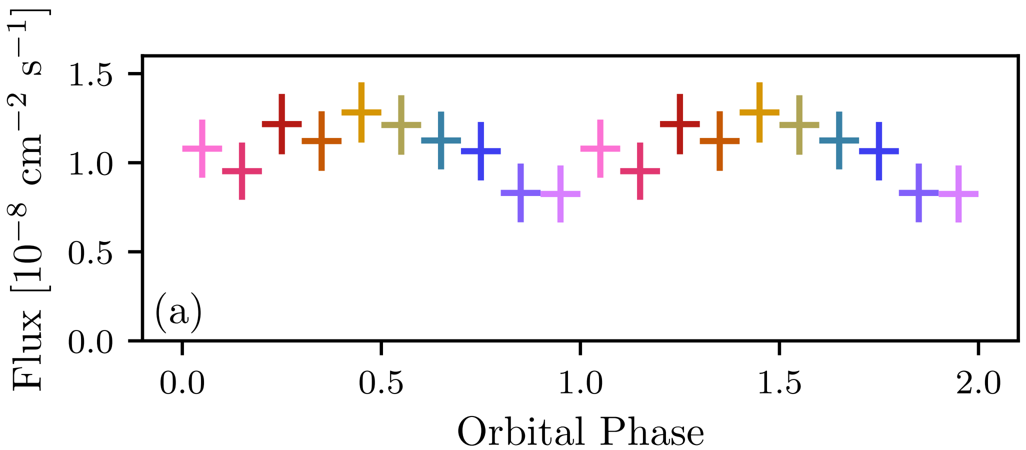
Rasul+ 2019

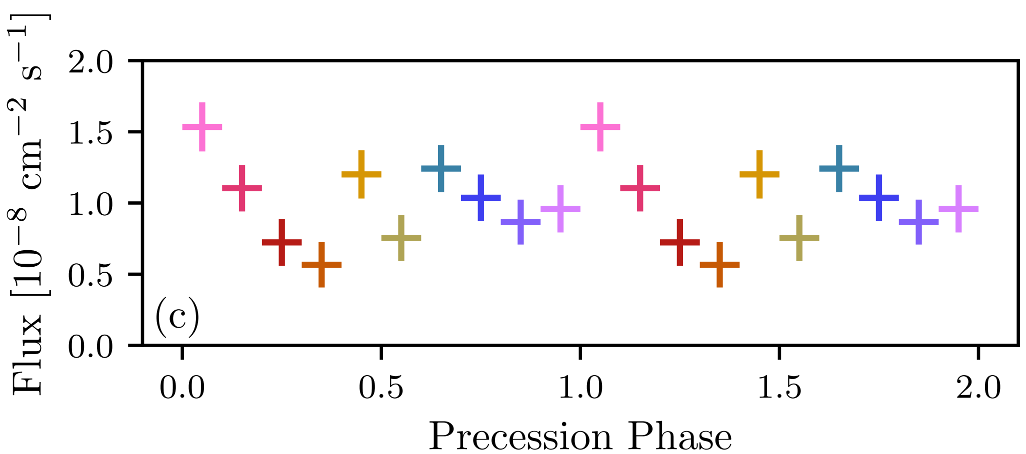
- **periodicity**: 2σ (orbital), 2.9σ (precession)
- to components: variable + large-scale flux ?

Sun+ 2019

- Extended emission **not compatible** with lobes/ filaments observed in radio or X-rays
- gamma-rays from W50 instead?

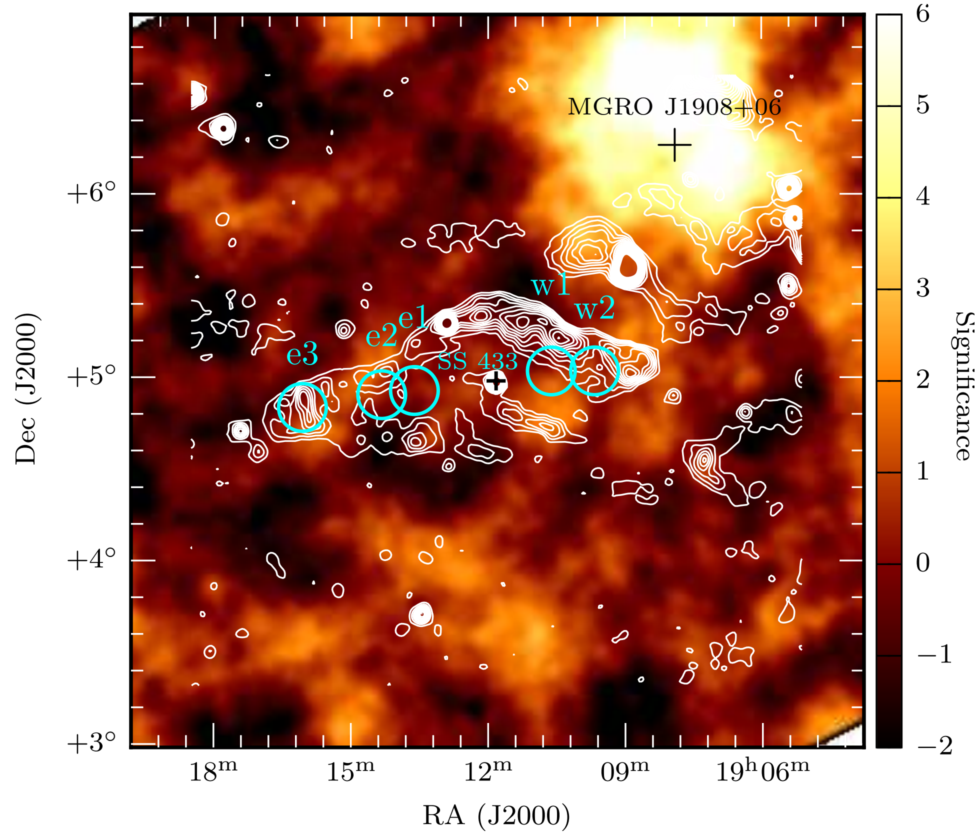




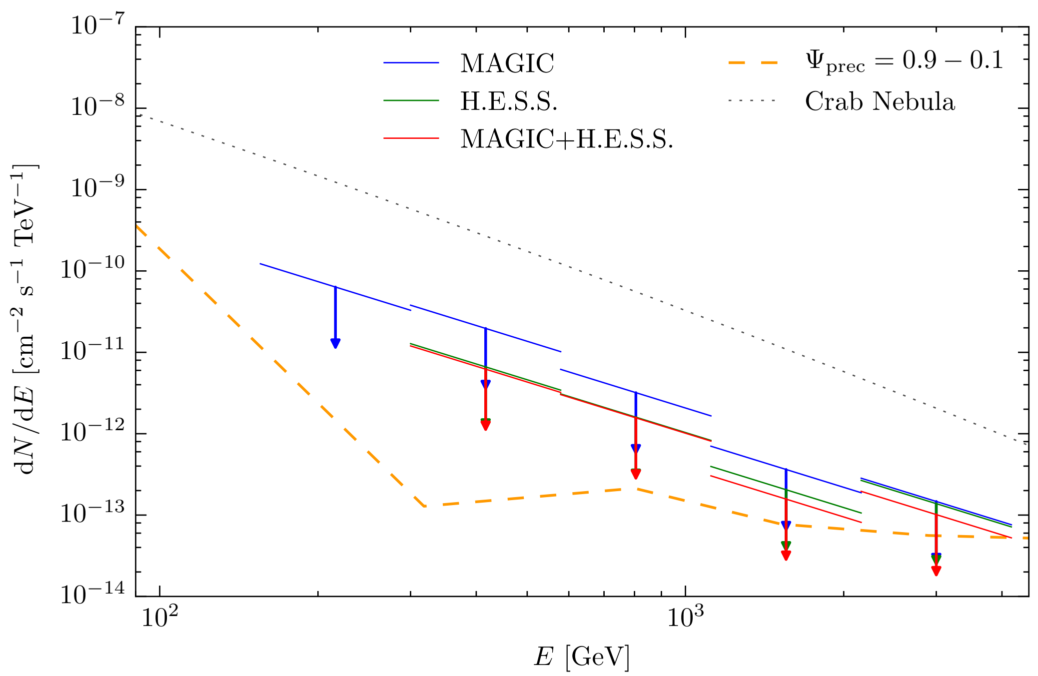


MAGIC & HESS Collaborations 2018

- MAGIC/HESS combined (raw) data sets
- ~10h on SS433 (low-absorption phases), 20h-60h observation of int. regions
- **no VHE γ-rays from SS433 or int. regions**
  - UULL @ E> 300 GeV, 800 GeV (c.f. HEGRA)

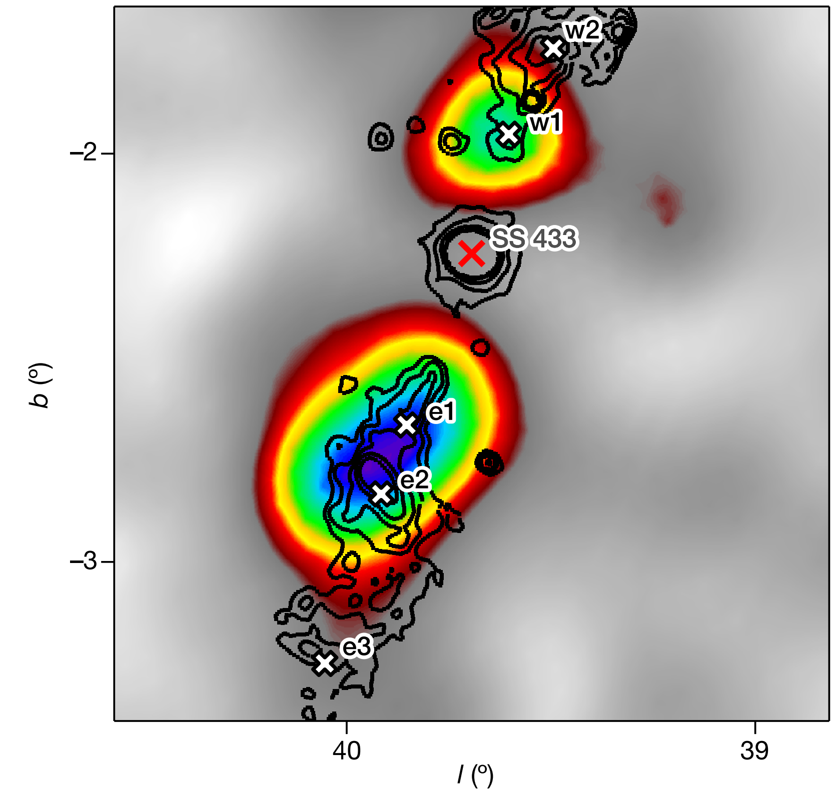


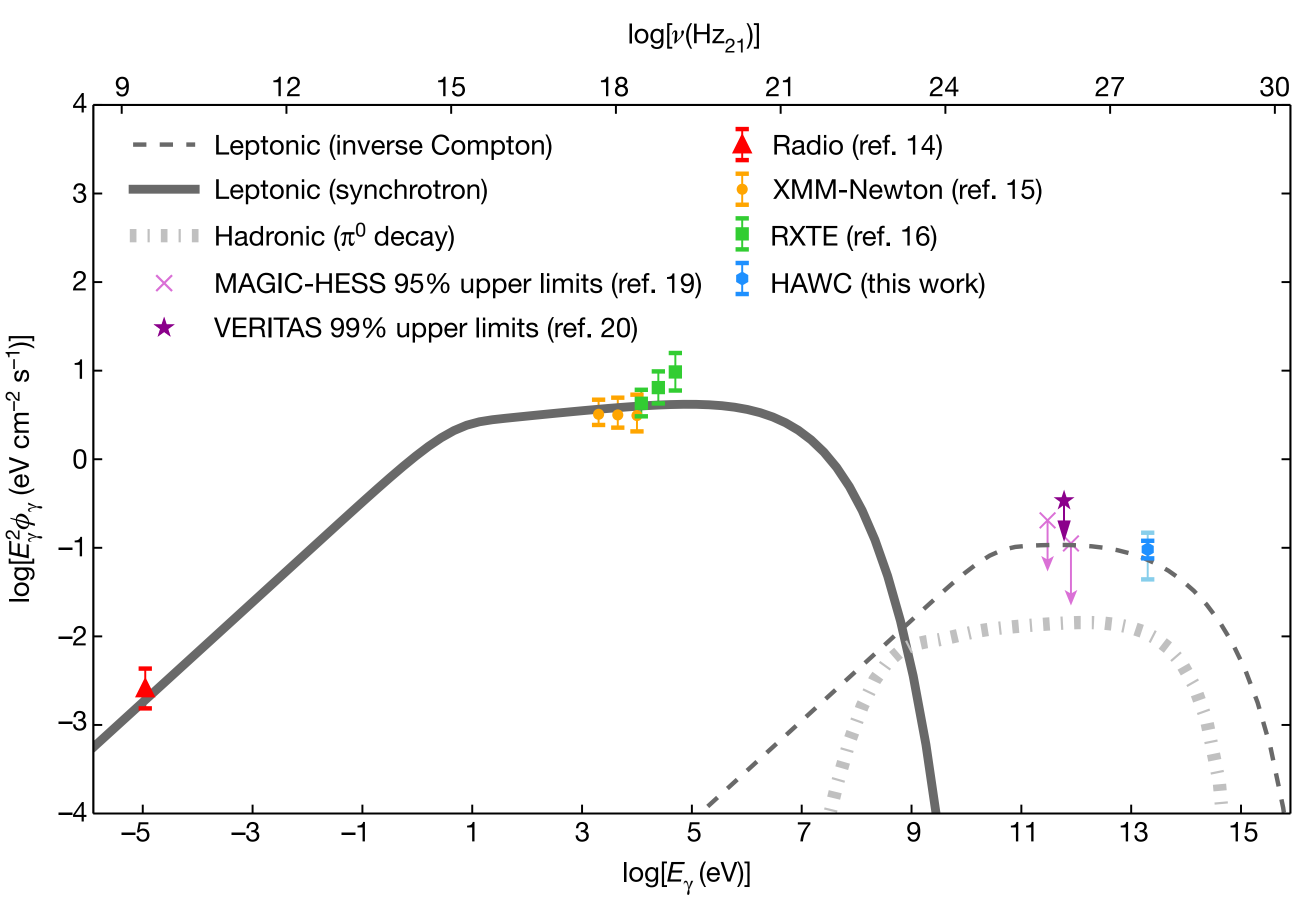
Region	IACT	$t_{\rm eff}$ [h]	300 GeV UL [cm^{-2} s^{-1}]	800 GeV UL [cm^{-2} s^{-1}]
SS 433	HEGRA	96.3	–	8.9×10^{-13}
RA = $19^{\rm h}11^{\rm m}50^{\rm s}$	H.E.S.S.	8.7	2.3×10^{-12}	3.9×10^{-13}
Dec = $04°58'58''$	MAGIC	7.8	1.8×10^{-12}	4.3×10^{-13}
$e1$ RA = $19^{\rm h}13^{\rm m}37^{\rm s}$	HEGRA	72.0	–	6.2×10^{-13}
Dec = $04°55'48''$	H.E.S.S.	36.5	6.8×10^{-13}	1.4×10^{-13}
($r = 0.05°$)	MAGIC	7.8	1.6×10^{-11}	1.9×10^{-12}
$w1$ RA = $19^{\rm h}10^{\rm m}37^{\rm s}$	HEGRA	104.9	–	6.7×10^{-13}
Dec = $05°02'13''$	H.E.S.S.	62.5	2.2×10^{-13}	4.0×10^{-14}
($r = 0.07°$)	MAGIC	7.8	1.3×10^{-11}	2.2×10^{-12}



HAWC Collaboration 2018

- **SS433/W50: first detection @ VHEs with HAWC**
  - e1 + w1 int. regions: ~ 5.4σ (post-trials)
  - photons with at least 20 TeV energies
  - TeV flux consistent with E^{-2} spectrum, $L_\gamma \sim 1.4\times10^{32}$ erg/s
  - no emission from the central system

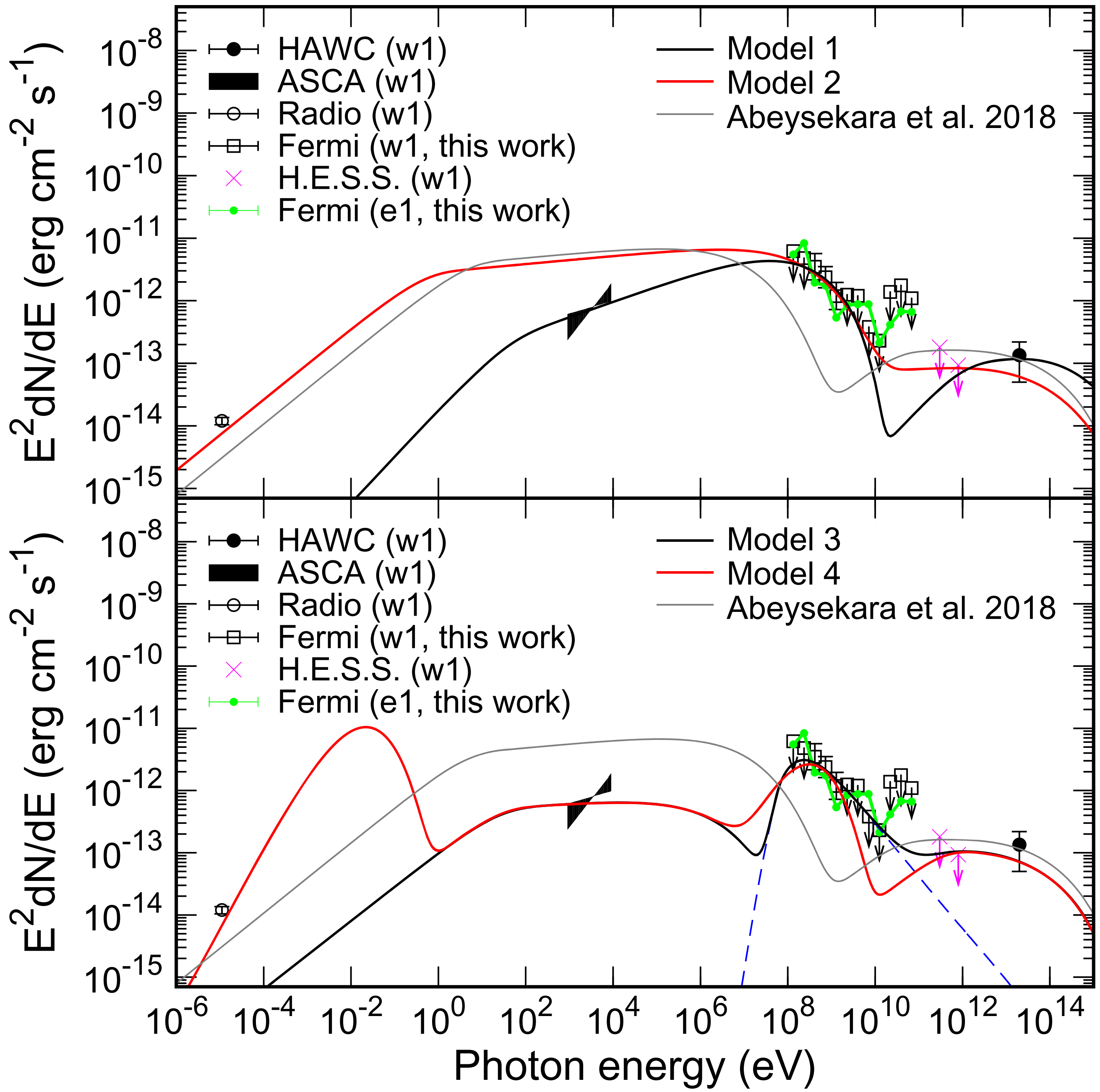




- hadronic scenario
  - $W_p \sim 3\times10^{50}$ erg; $L_{jet} \times \tau_{SS433} \approx 9\times10^{50}$ erg
  - $\Phi_{sync} > \Phi_\gamma$ => sync not from secondaries
- leptonic scenario
  - IC on CMB (opt/NIR suppressed: KN)
  - relatively “cheap”: $W_e \sim 3\times10^{47}$erg
  - Φ_{sync}/Φ_γ => B-field ≈ 16μG

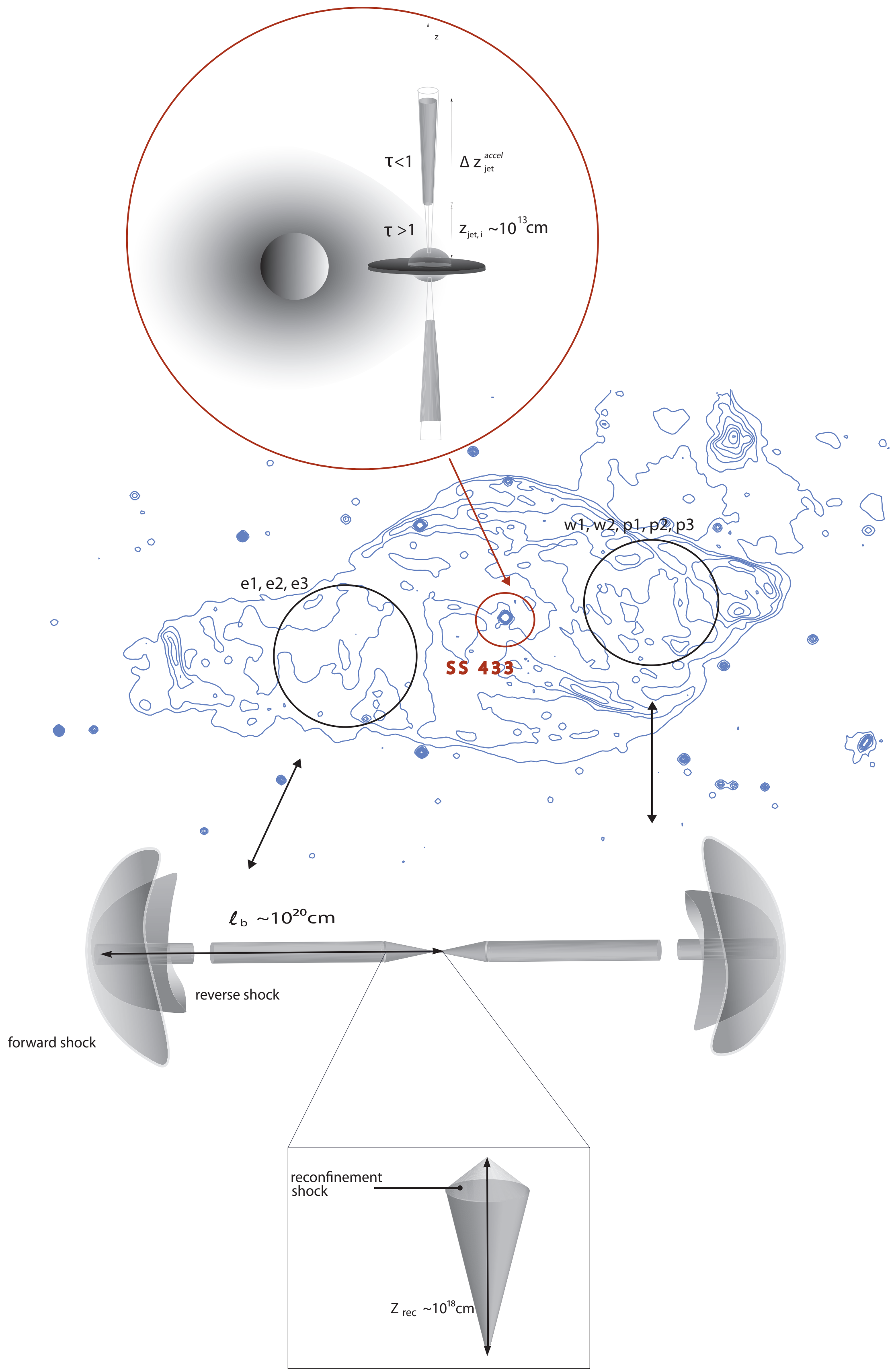
SS433 at GeV and VHE gamma-rays

- **model 1**: pure leptonic
  - radio/X-ray/GeV = sync, TeV = IC
  - ExpCPL, α_e = 1.5, B = 5μG, E_c = 30 PeV
  - radio flux grossly off
- **model 2**: pure leptonic
  - radio/X-ray/GeV = sync, TeV = IC
  - ExpCPL, α_e = 1.9, B = 20μG, E_c = 15 PeV
  - X-ray flux 10 x too large
- **model 3**: + hadronic component
  - ExpCPL: α_p = 2.9, $E_{c,p}$ = 3.0 PeV
  - fails to fit radio flux
  - W_p = 3 x10^{50} erg ~ L_{jet} x lifetime (n = 1)
- **model 4**: + rel. Maxwellian + PL
  - 2D Maxwellian, Epeak = 50 GeV
  - radio index not explained

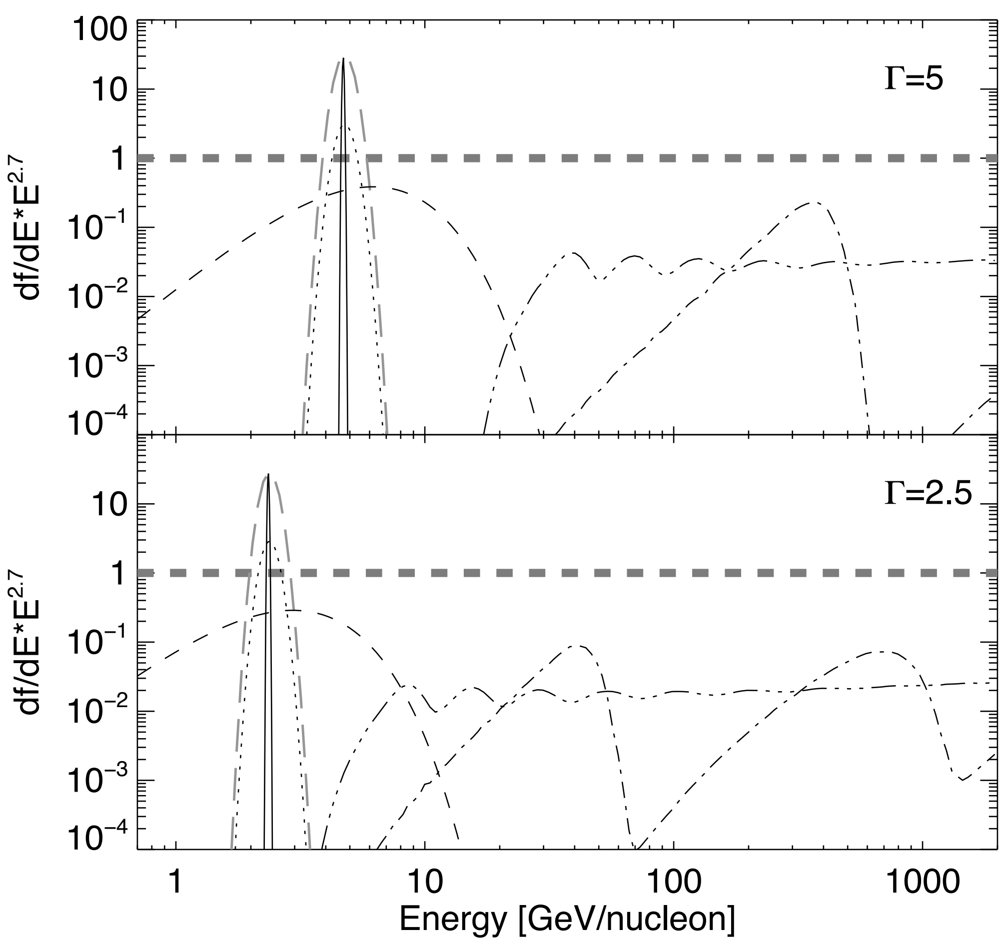


Xing+ 2019

SS433 at gamma-rays



- SS433 @ HEs: 2.9σ precession **variability**
  => central system (Reynoso+ 2008)
  - hints for extension => two-components?
  - sharp **peak at ~250 MeV**: *pp* signature?
  Heinz & Sunyaev 2002
- SS433 @ VHEs: first **probe for large-scale jet/ medium interaction regions in μQs** Aharonian & Atoyan 1998, Bosch-Ramon+ 2005, Bordas+ 2009



Heinz & Sunyaev 2002

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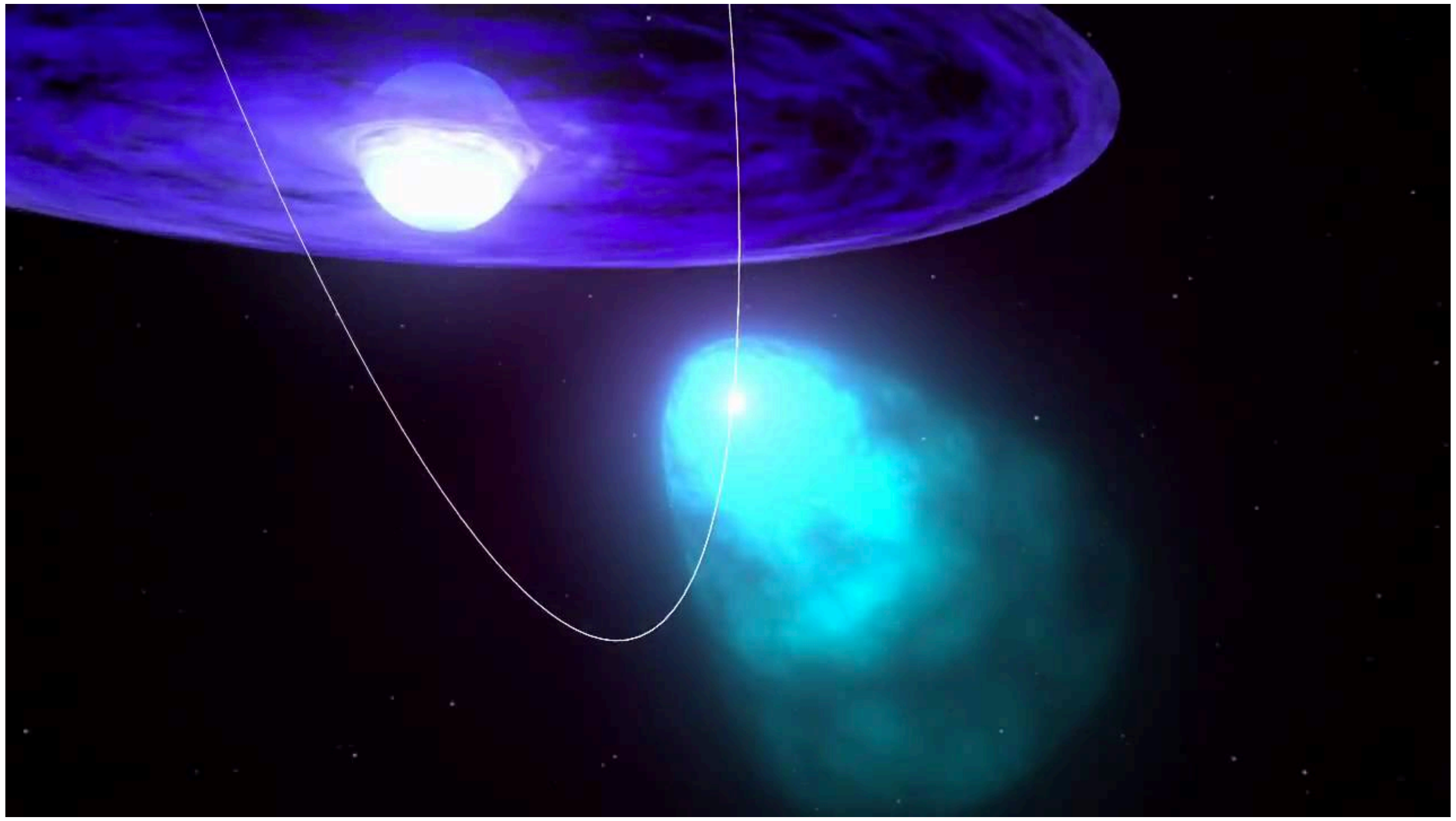
- **gamma-ray binaries**: the case of PSR B1259-63
- **runaway PWNe**: the case of IGR J11014-6103



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gamma-ray binaries: a (slowly) growing class of gamma-ray emitter in the Galaxy

Name	System type	Orbital period (d)	Radio structure (AU)	Multi-wavelength periodicity			
				Radio	X-ray	GeV	TeV
Emission line star companion							
PSR B1259−63	O9.5 Ve + NS	1237	Cometary tail ~ 120	P	P	P	P
LS I +61 303	B0 Ve + ?	26.5	Cometary tail ? $\sim 10-700$	P	P	P	P
HESS J0632+057	B0 Vpe + ?	320	Elongated ~ 60	V	P	P?	P
PSR J2032+057/MT91 213	Be + NS	40-50 yr	?	D	D	D	D
Non-Emission line star companion							
LS 5039	O6,5 V((f)) + ?	3.9	Cometary tail ? $10-1000$	p	P	P	P
1FGL J1018.6−5856	O6,5 V((f)) + ?	16.5	?	P	P	P	P
CXOU J053600.0−673507 (LMC P3)	O5 III + NS?	10.3	?	P	P	P	D

Note: P: Periodic emission, p: Persistent emission, V: Variable emission, D: Detected

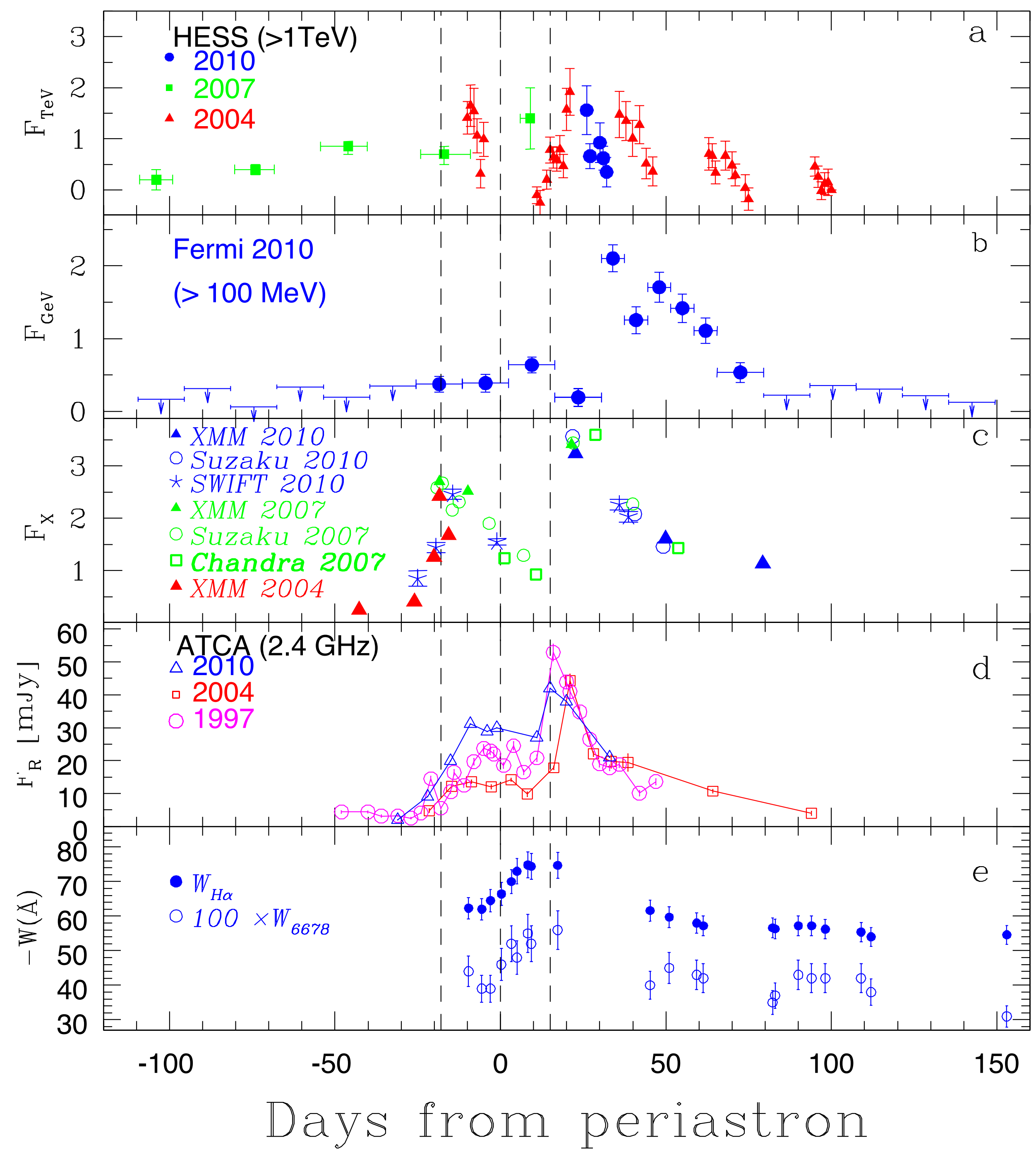
Paredes & Bordas (2019)

Gamma-ray binaries
@ HEPRO VII

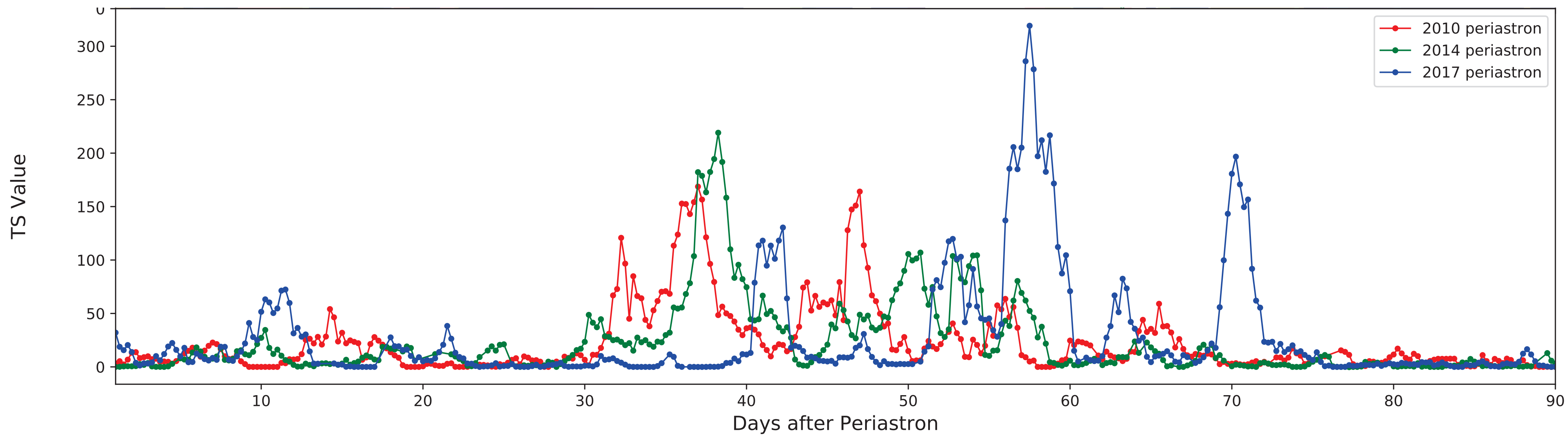
- *Searching for gamma-ray binaries with Gaia* - I. Ayan
- *The pulsar sequence* - C. Kalapotharakos
- *GX 301-2 with X-Calibur* - M. Errando

PSR B1259-63: a pulsar-powered gamma-ray binary

- pulsar (P=48 ms, L_{sd}= 8 ×10^{35} erg/s) + O9.5Ve star (L_{star}= 2.3 × 10^{38} erg/s) + circumstellar disk
  Johnston+ 1992, Melatos+ 1995, Negueruela+ 2011
- binary system: D = 2.7 kpc, P_{orb}= 3.4 years, eccentricity = 0.87, orbital inclination i ~24°
  Miller-Jones et al. 2018)
- **variable/periodic emission** in radio, optical, X-rays, GeV and TeV γ-rays, with pulsations seen only in radio (and away from periastron)
  Chernyakova+ 2014
- **GeV flare** in observed with LAT in 2011; happening again in 2014 and 2017



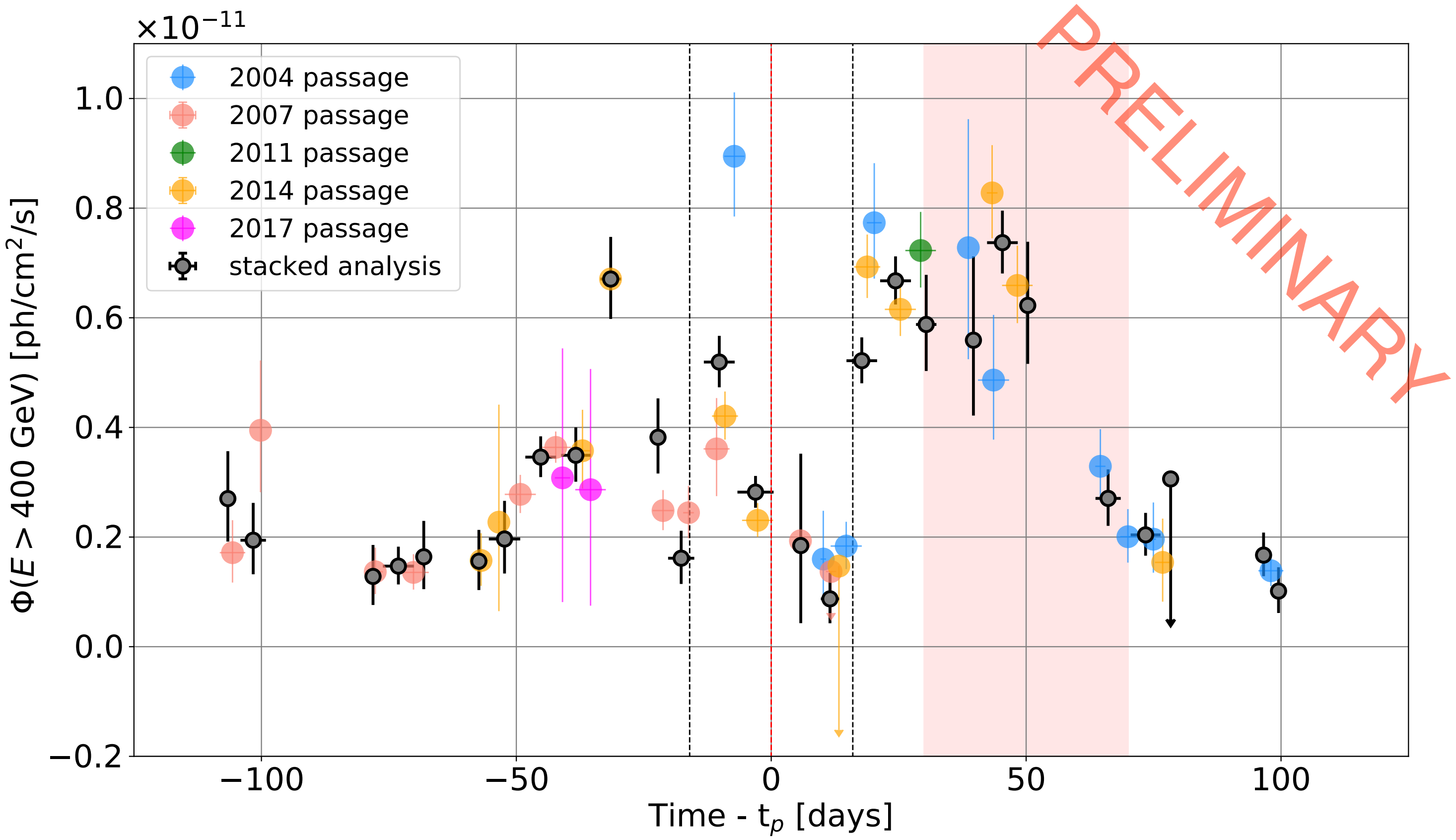
HE flares from PSR B1259-63



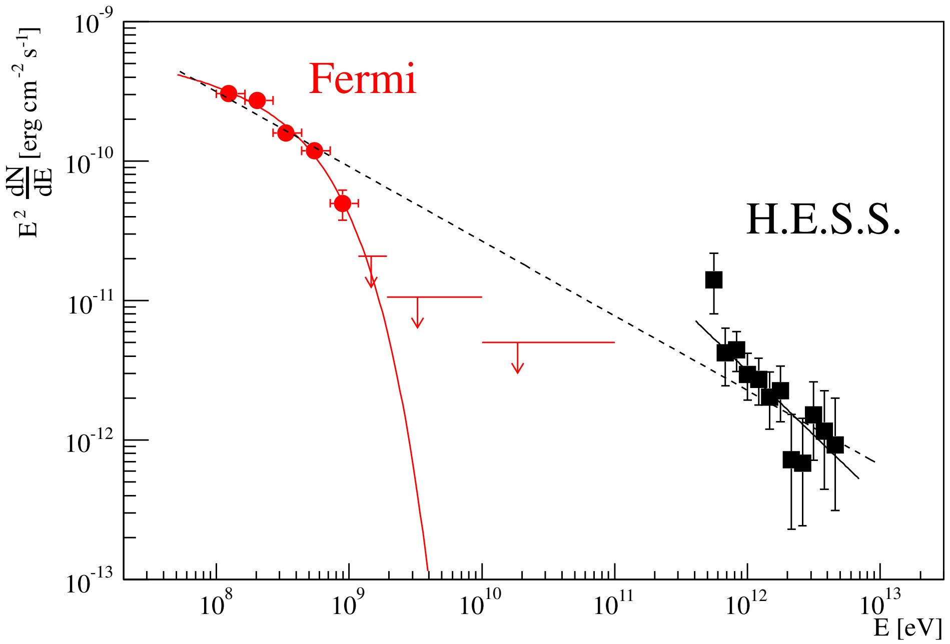
Chang+ 2018

- Unexpected flares observed at HE gamma-rays with LAT in 2010 **Abdo+ 2011**
- Flares starting 30 days (40 days) after t_p in 2010 and 2014 (in 2017), and lasting for more than 50 days (70 days in 2017)
- luminosities almost reaching $L_\gamma \sim L_{sd}$ **Abdo+ 2011, Caliandro+ 2015**
- No counterpart at radio, X-rays or VHEs **Chernyakova+ 2014**

HE flares from PSR B1259-63



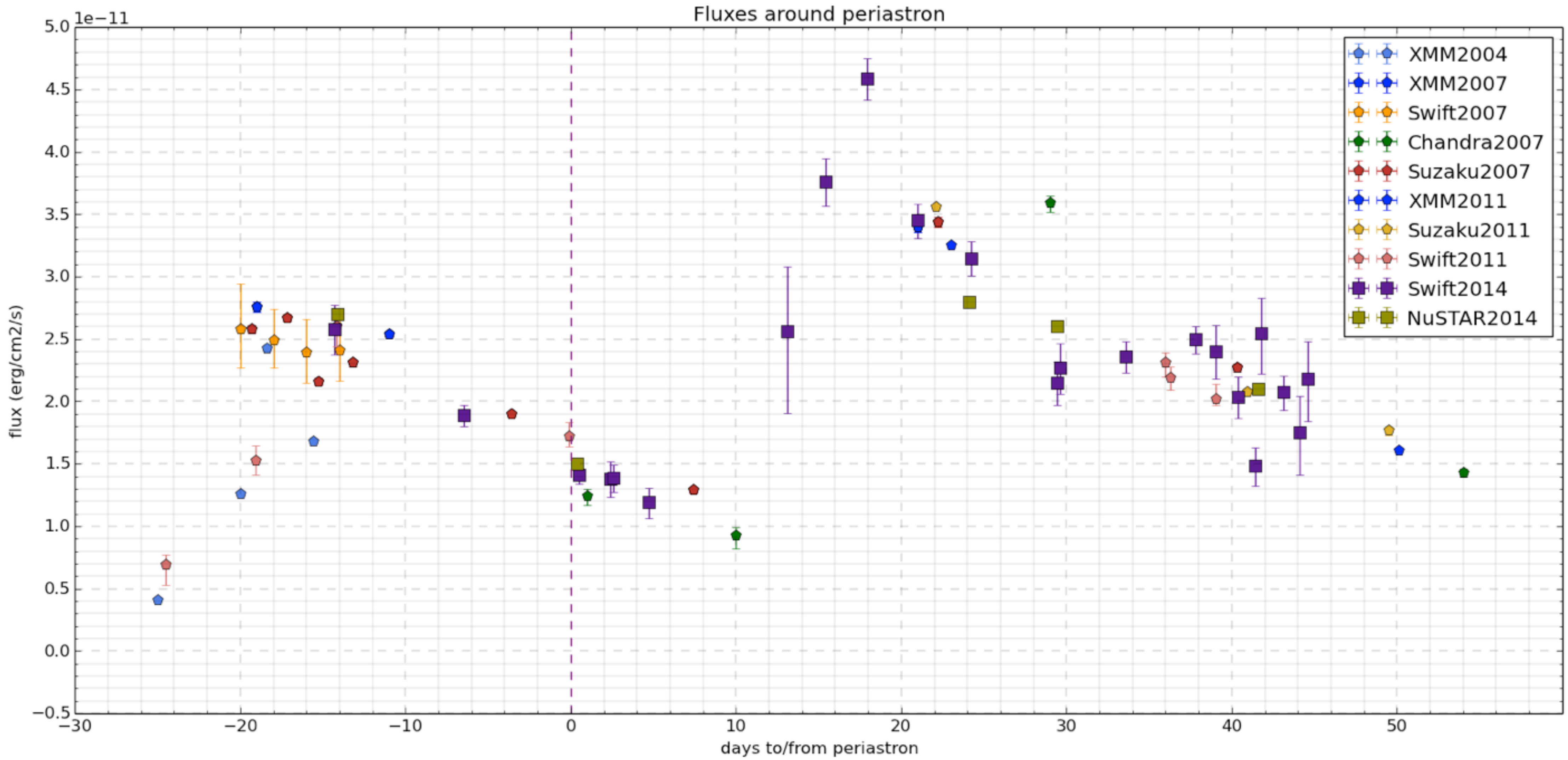
C. Mariaud, PhD thesis (2018)



HESS coll. 2013

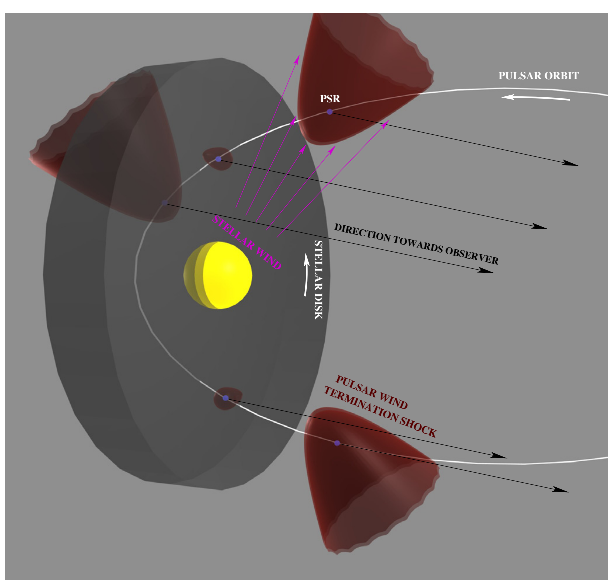
- H.E.S.S. observations of periastron passage in 2004, 2007, 2011, 2014 and 2017
- complex flux profile, no significant super-orbital variability
- high VHE fluxes during HE gamma-ray flare, but no evidence for flares ("sudden" flux increase < 2 at 95% CL)

PSR B1259-63

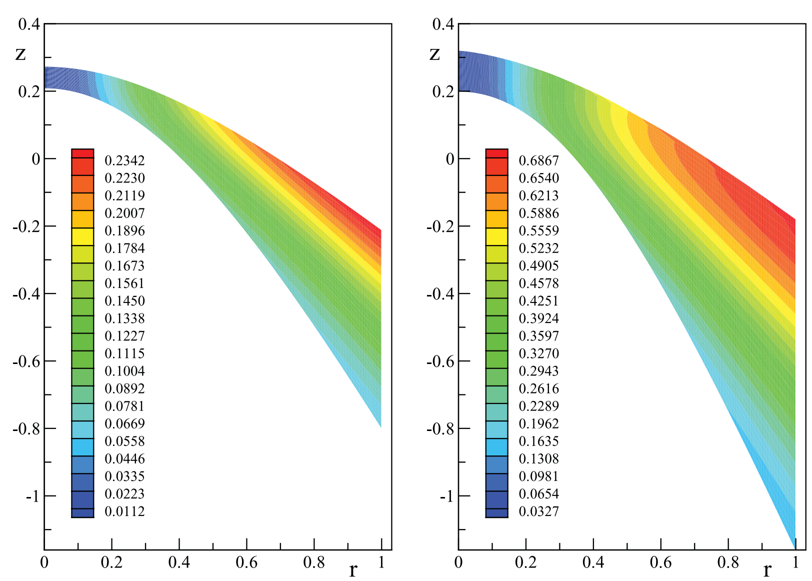

Fluxes around periastron
flux (erg/cm2/s)
1e−11
days to/from periastron
XMM2004
XMM2007
Swift2007
Chandra2007
Suzaku2007
XMM2011
Suzaku2011
Swift2011
Swift2014
NuSTAR2014

■ origin of the HE gamma-ray flares

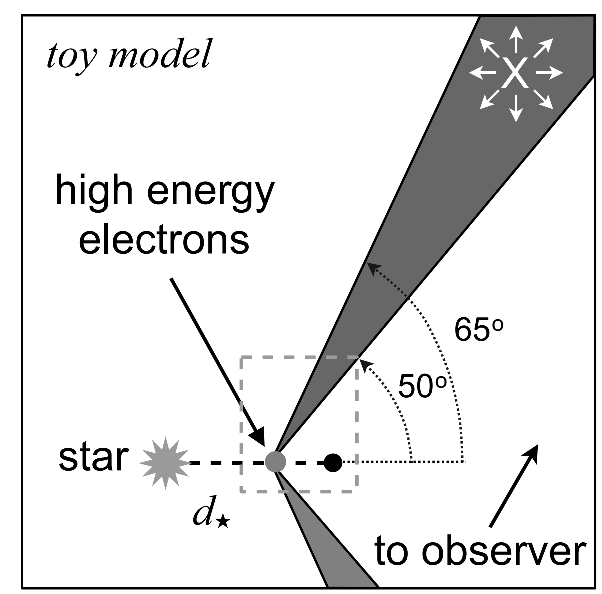
- Comptonisation of un-shocked pulsar wind (**Khangulyan et al. 2007, 2012**).
- Circumstellar disk: feed with additional photon field (**van Soelen et al. 2012**)
- Doopler boosted emission from shocked pulsar wind (**Bogovalov et al. 2012, Kong et al. 2012**)
- Up-scattering of X-ray photons from the PWN (**Dubus & Cerutti 2013**)



Khangulyan et al. (2012)

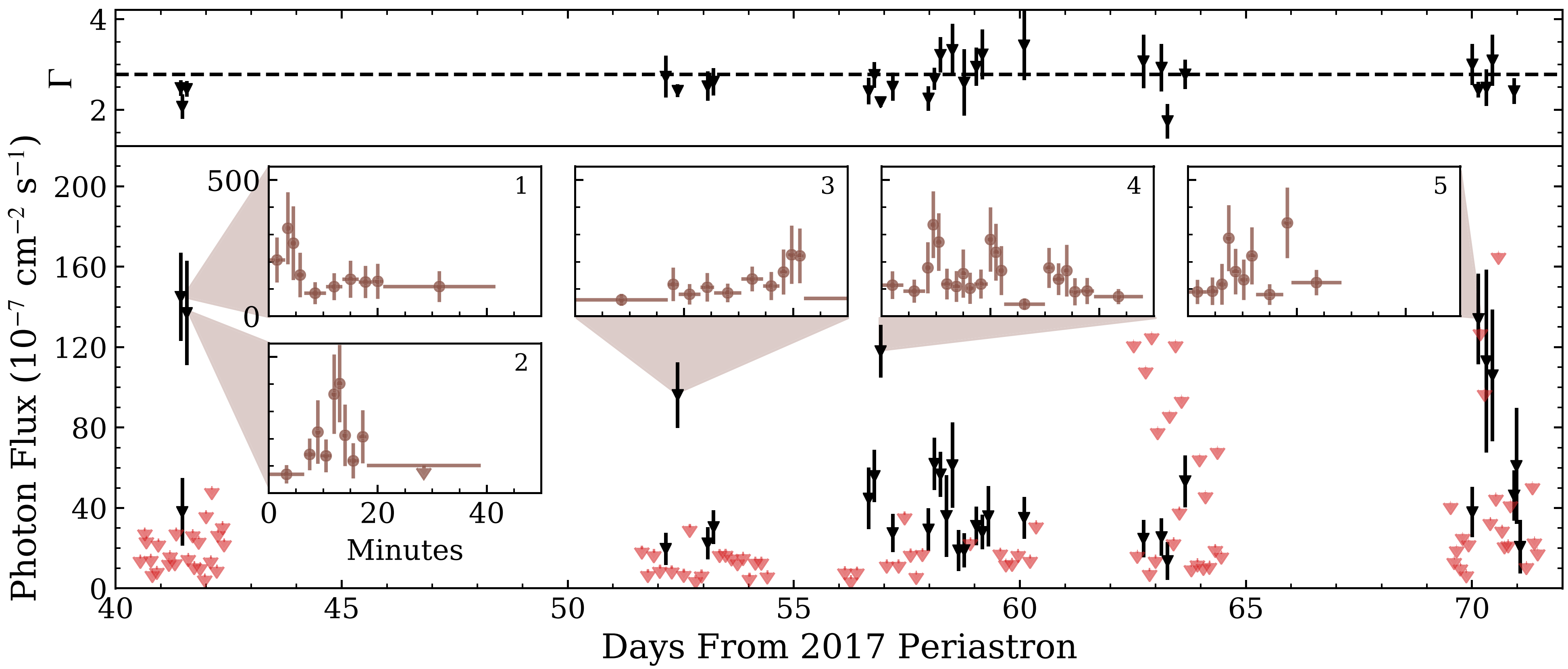


Bogovalov et al. (2012)



Dubus & Cerutti (2013)

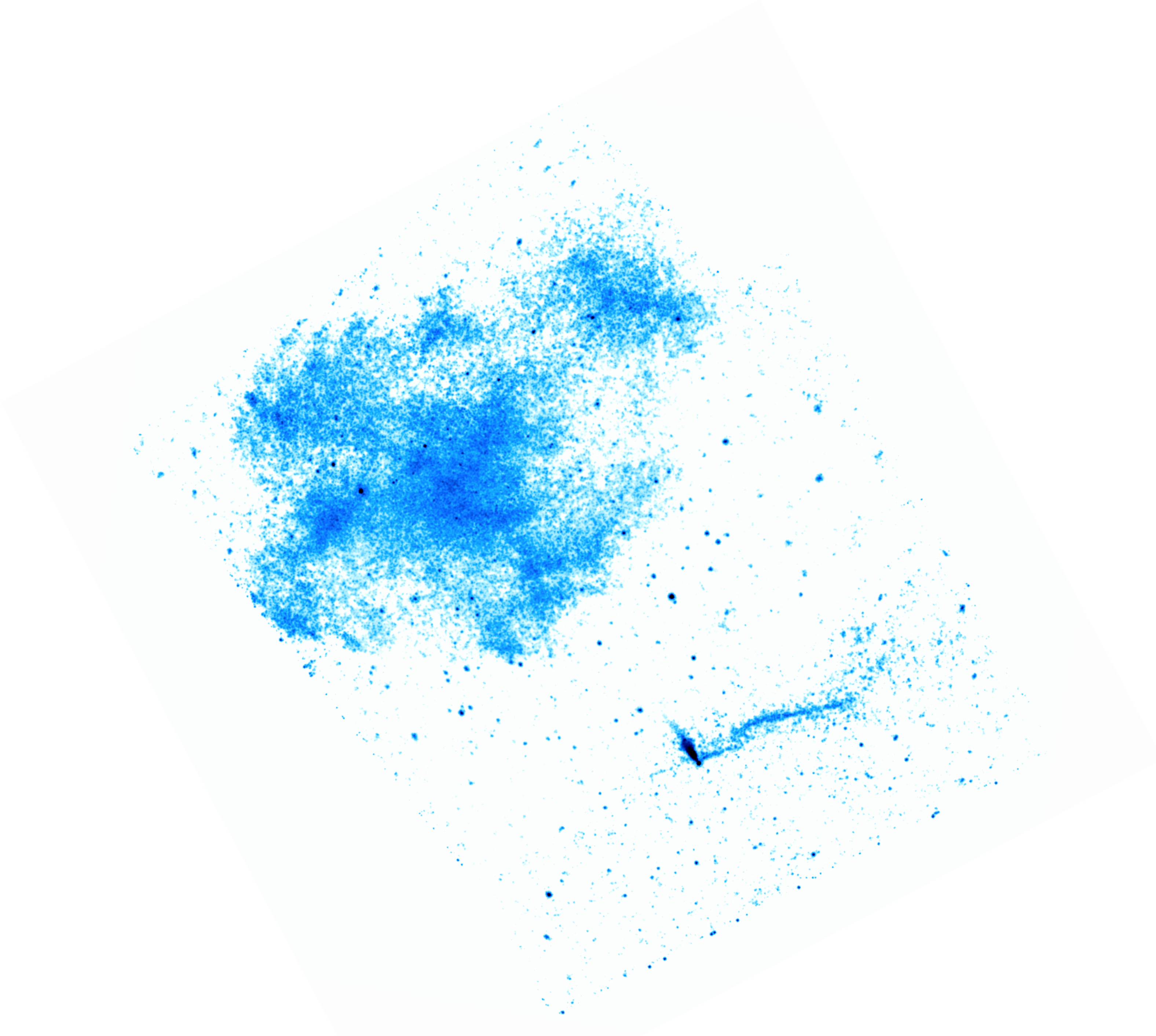
- **2017: gamma-ray variability down to ~minute time-scales**



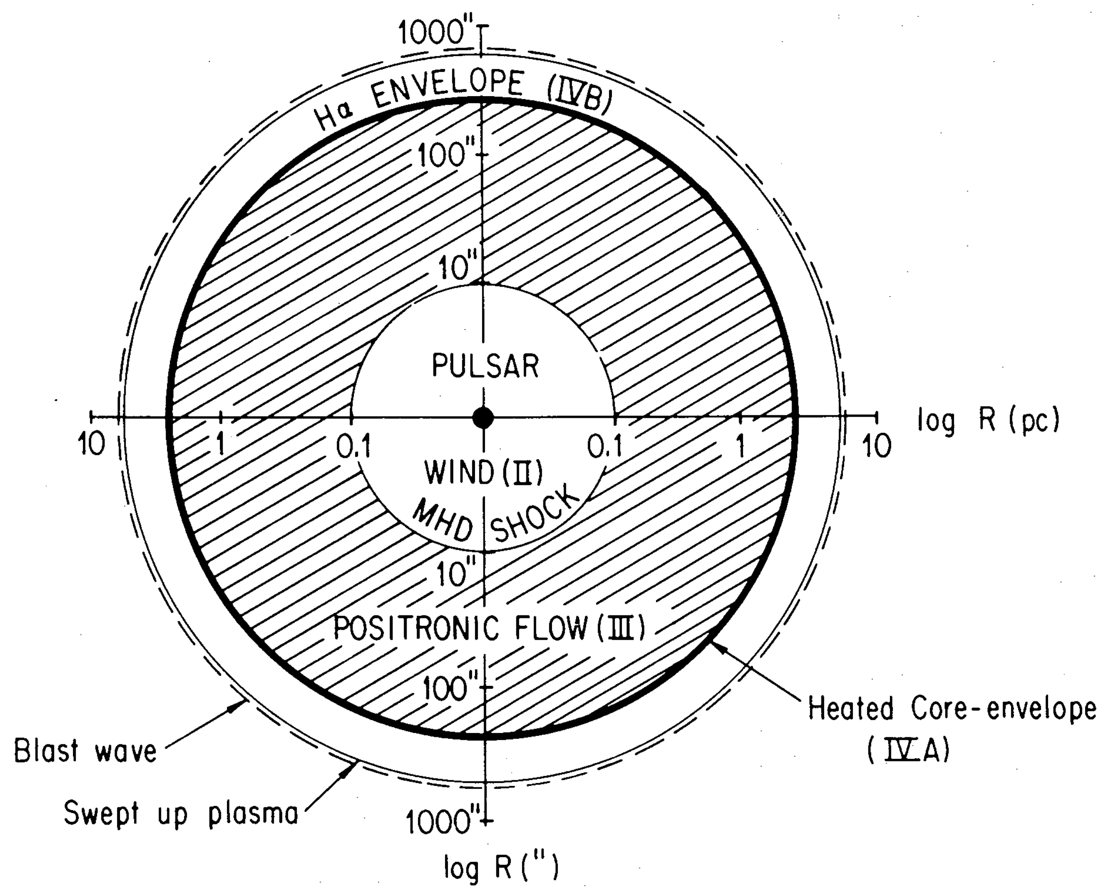
Timescale	G (10^{-10} erg cm^{-2} s^{-1})	L_γ (10^{35} erg s^{-1})	$L_\gamma/\dot{E}$
One-week	7.3 ± 0.6	$6.4^{+2.0}_{-1.6}$	0.8 ± 0.2
One-day	14 ± 2	12^{+4}_{-3}	$1.5^{+0.5}_{-0.4}$
One-orbit	70 ± 16	61^{+18}_{-14}	$7.4^{+2.2}_{-1.7}$
Intra-orbit	280 ± 100	244^{+74}_{-56}	$29.8^{+9.0}_{-6.8}$

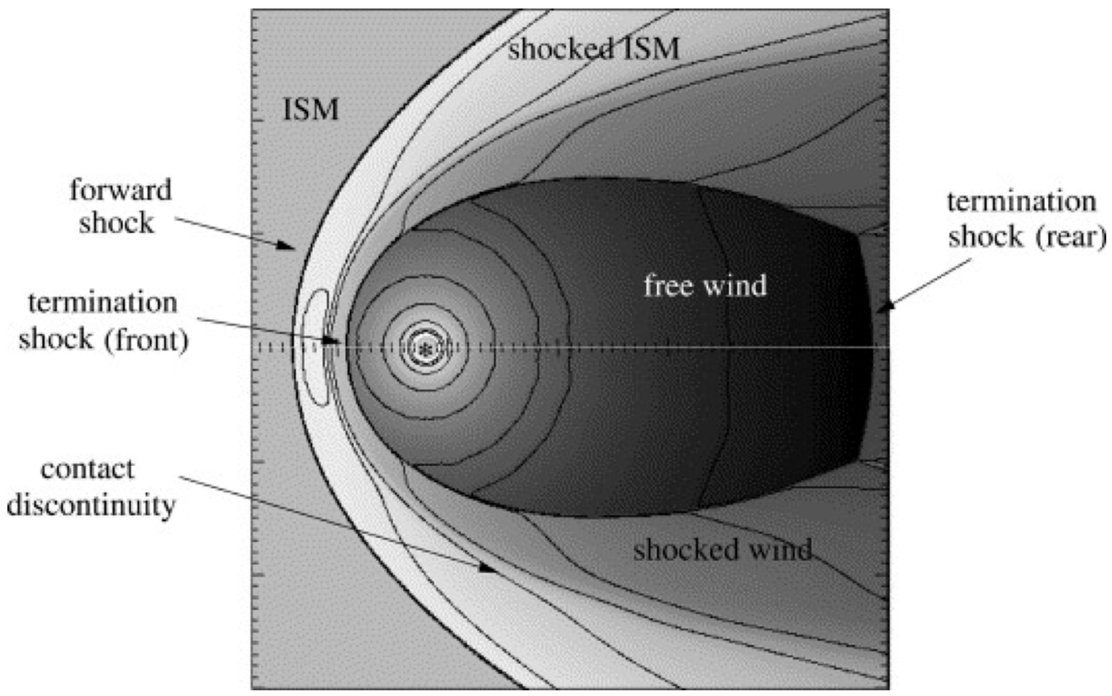
Johnson+ 2018

- **microquasars**: the case of SS433
- **gamma-ray binaries**: the case of PSR B1259-63
- **runaway PWNe**: the case of IGR J11014-6103



runaway PWNe





Pulsar wind structure in the Crab Nebula

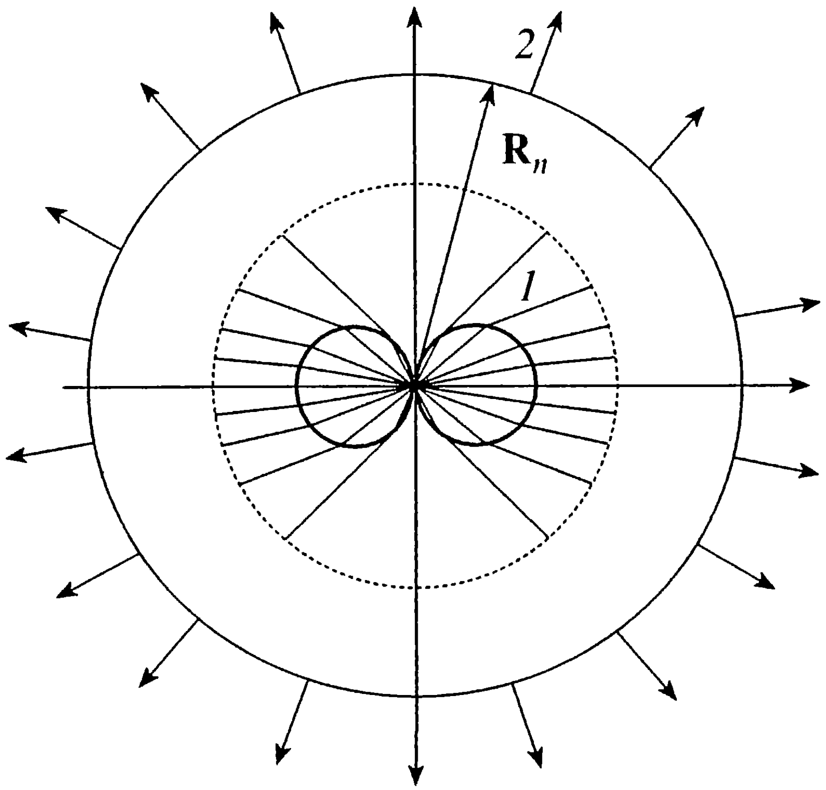
Rees & Gunn (1974), Kennel & Coroniti (1984)

PSR J1747-2958 powering the "Mouse nebula"

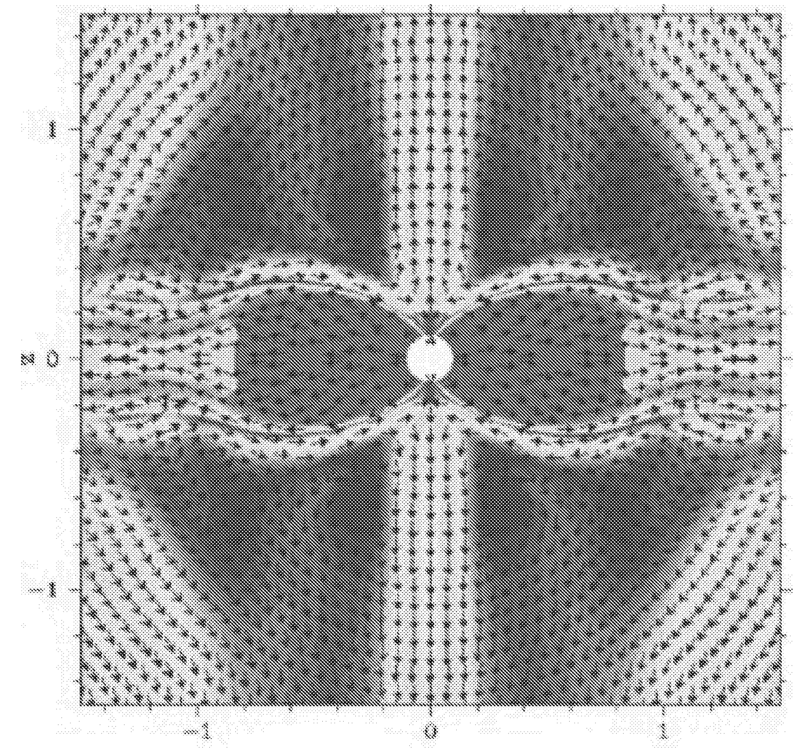
Gaensler et al. (2004)

PSRs/PWNe @ HEPRO VII

- *Theory of PWN* - E. Amato
- *The flaring Crab Nebula* - R. Zanin
- *GX 301-2 with X-Calibur* - M. Errando
- *The pulsar sequence* - C. Kalapotharakos
- *Fast-moving Pulsars with Chandra* - X. Zhang



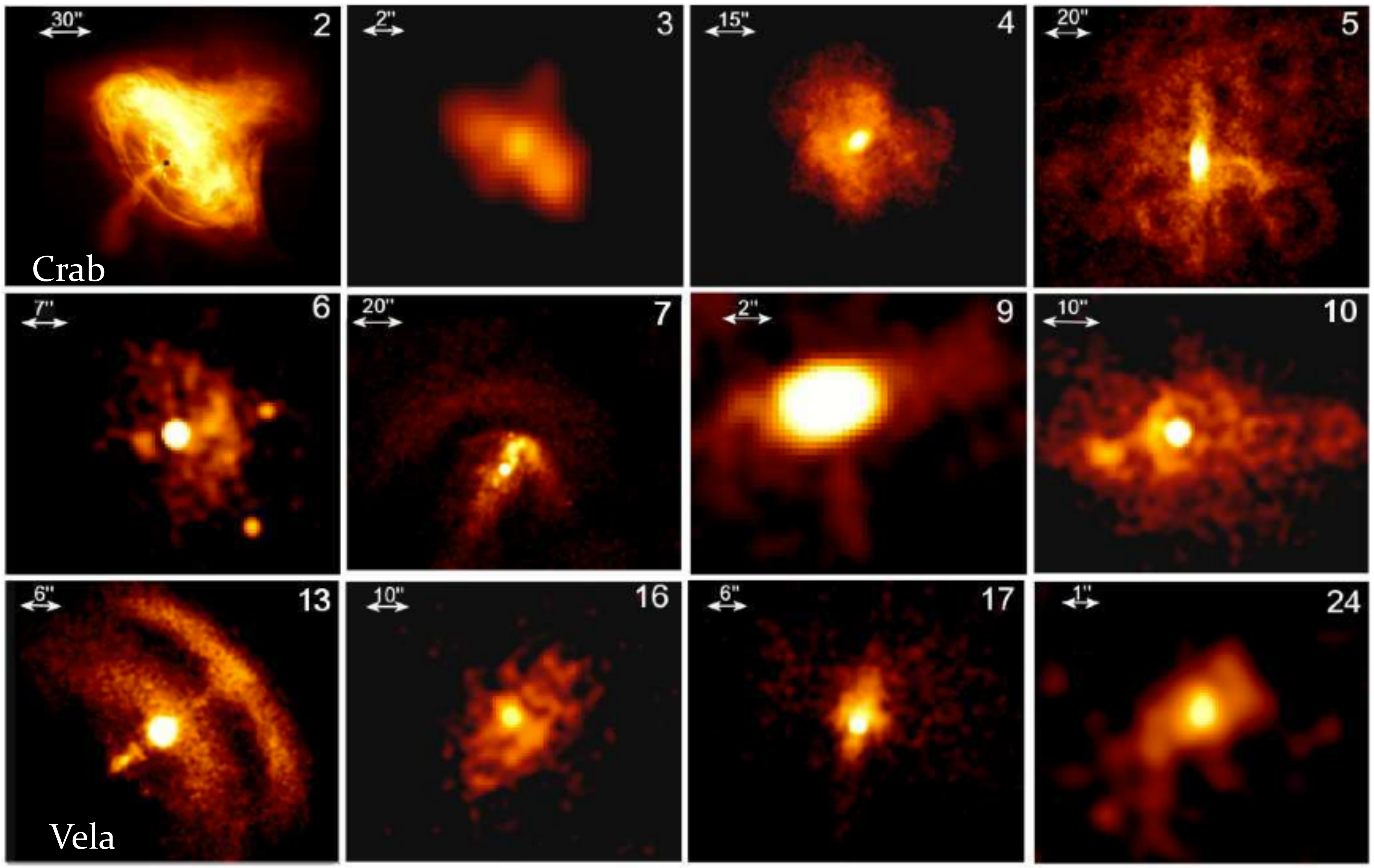
anisotropic distribution in PSR winds
Bogovalov & Khangoulyan (2002)



anisotropic distribution in PSR winds
Komissarov & Lyubarsky (2003)

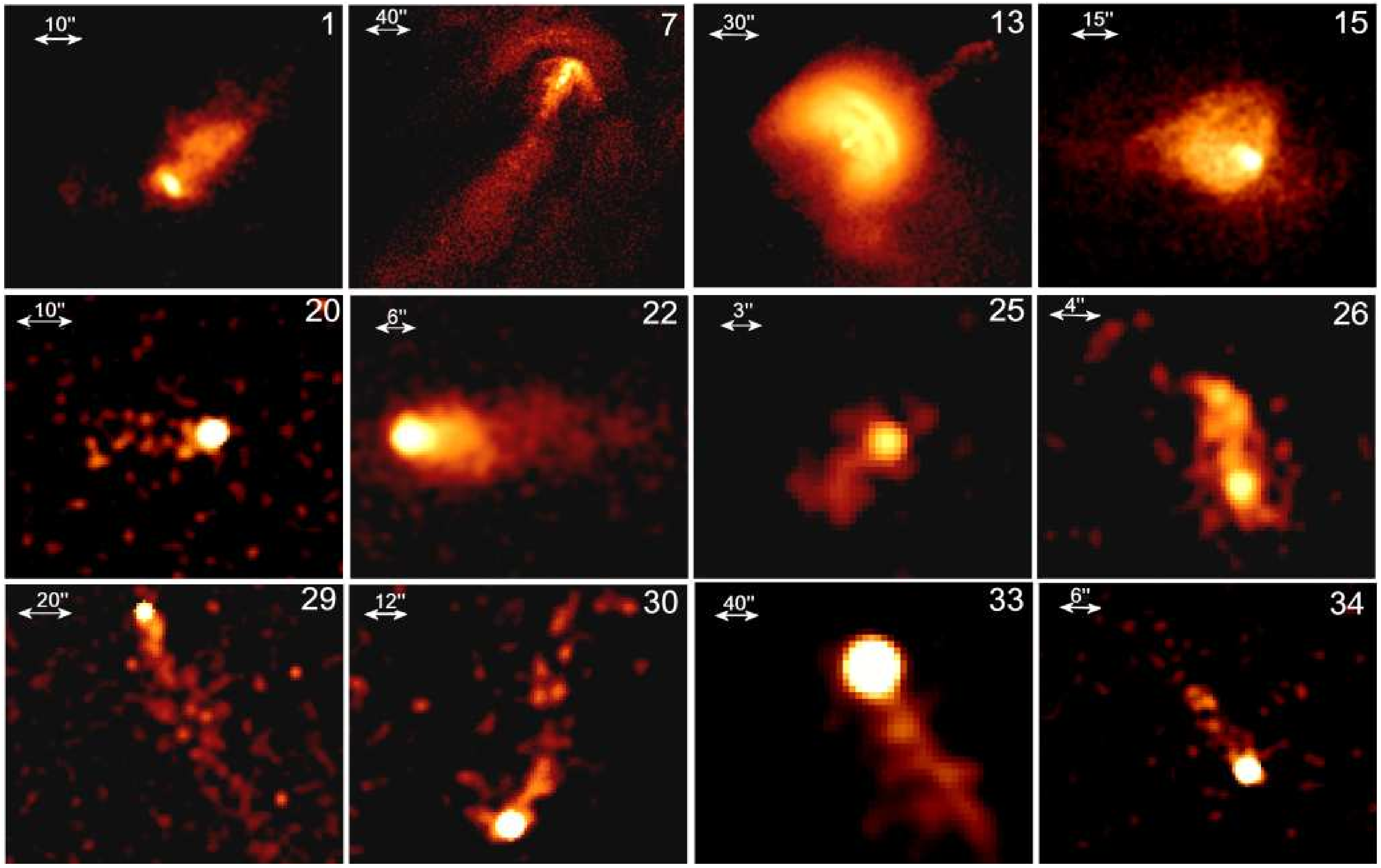
- pulsar wind displays **anisotropic energy flux**
- **collimation** of the ultra-relativistic wind is **rather difficult**
- jet formation ***after*** **wind termination-shock** (e.g. Lyubarsky 2002)
- magnetic hoop stress towards pulsar rotation axis: “jets"

slow-motion PWNe: torus + jet morphologies



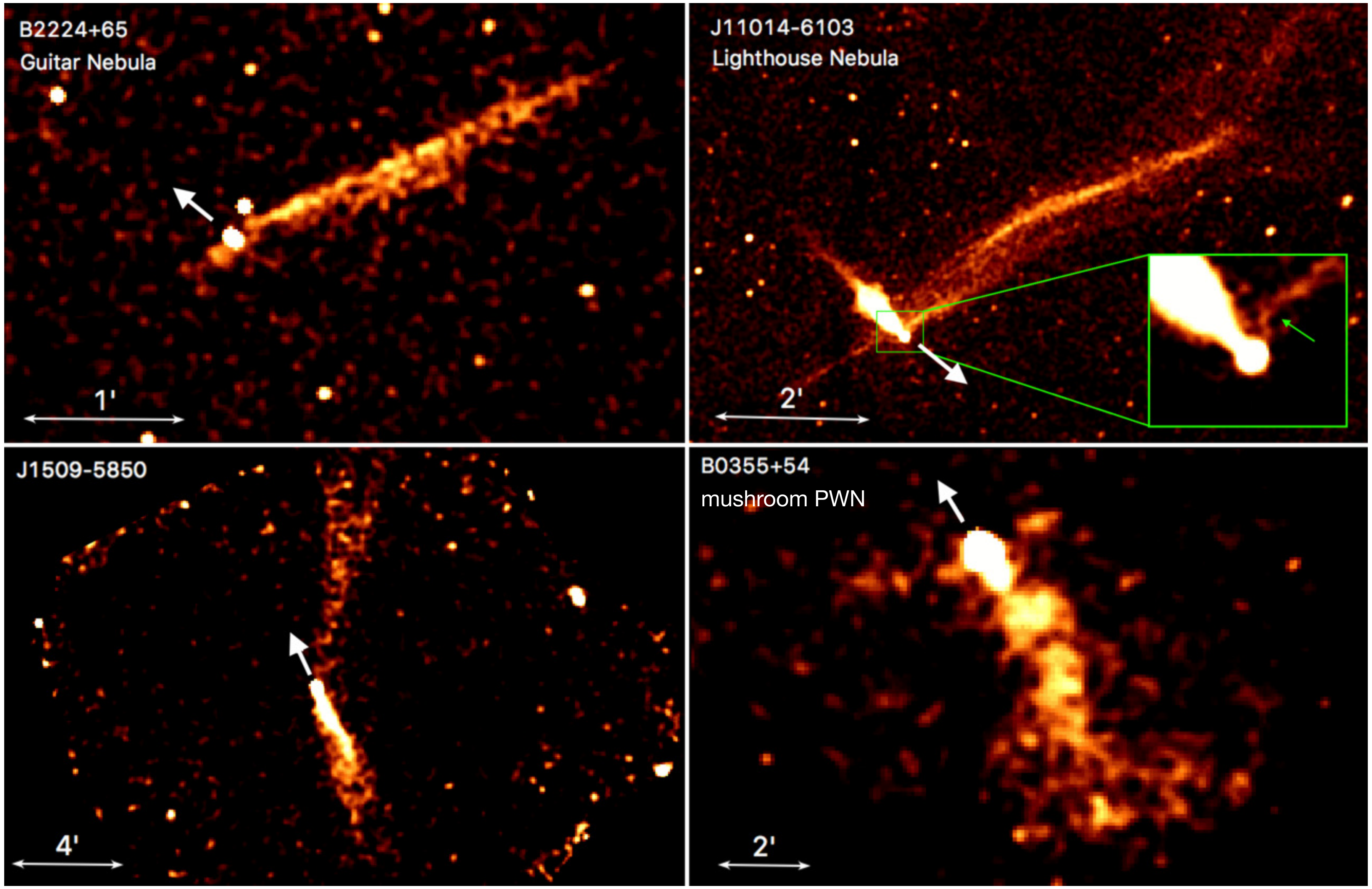
Kargaltsev & Pavlov (2008)

fast-motion PWNe: cometary tails / bullet-like morphologies



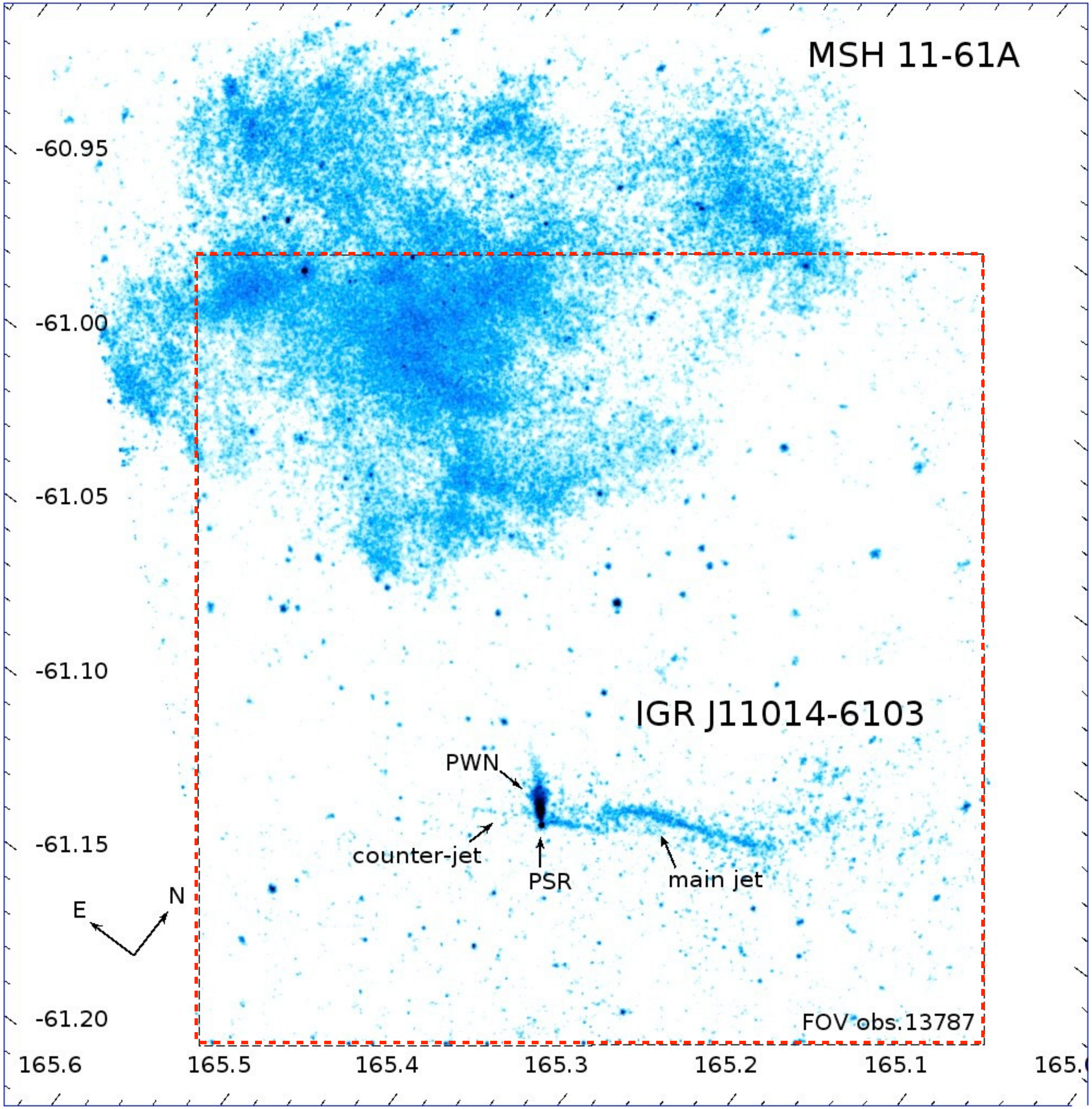
Kargaltsev & Pavlov (2008)

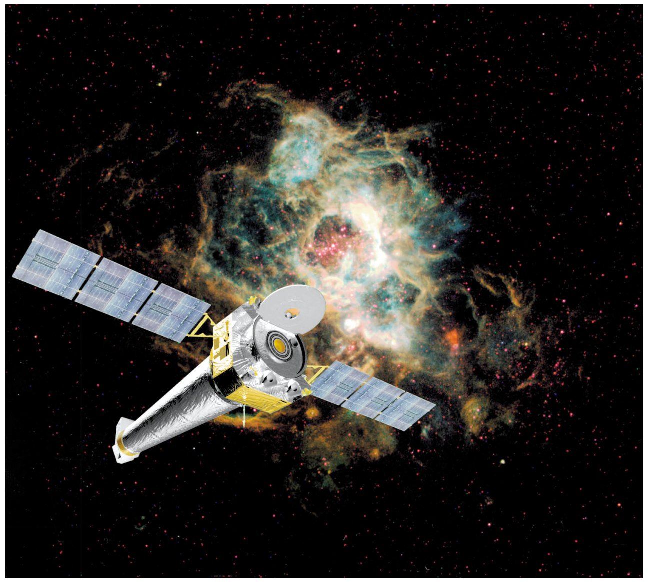
fast-motion PWNe: cometary tails + jet-like outflows



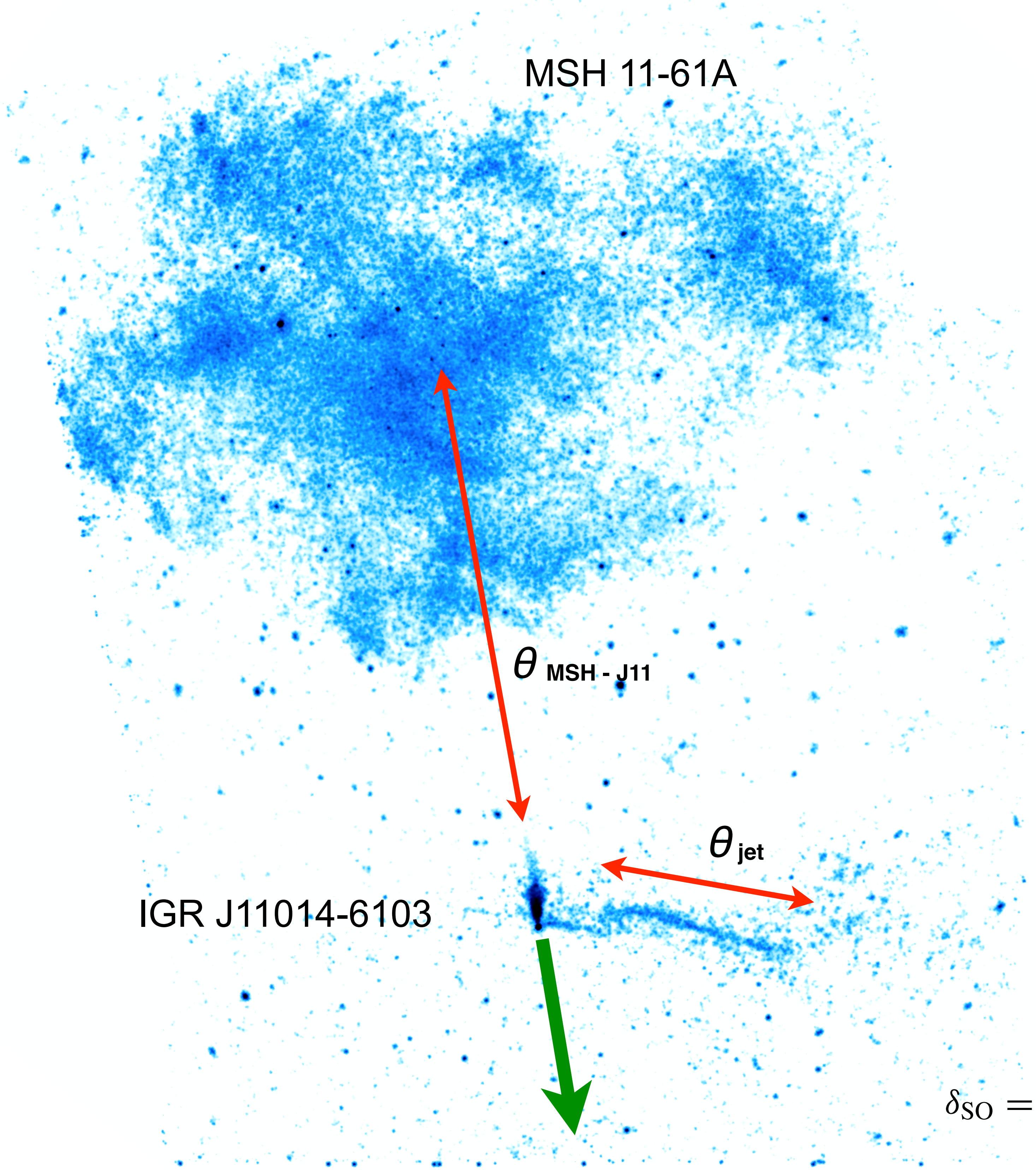
Kargaltsev+ (2018)

IGR J11014-6103





- **IGR J11014-6103**
  (the "Lighthouse Nebula”):
  - PSR: $L_{sd} \sim 3.5 \times 10^{36}$ erg/s (**Halpern+ 2014**)
  - main-jet: 5.5’ from “PSR”, cork-screw pattern bending at ~ 1.4’
  - counter-jet: 1.5’ from “PSR”
- **MSH 11-61-A**:
  - core-collapse SNR
  - t ~ 10-20 kyr (**García+ 2012**)
  - asymmetric shape (“ears”)



- no other point-like source inside SNR
- similar column density

$N_{H,\,J11} = [0.8 \pm 0.2] \times 10^{22}\ \mathrm{cm}^{-2}$
$N_{H,\,MSH} = [0.6 \pm 0.2] \times 10^{22}\ \mathrm{cm}^{-2}$

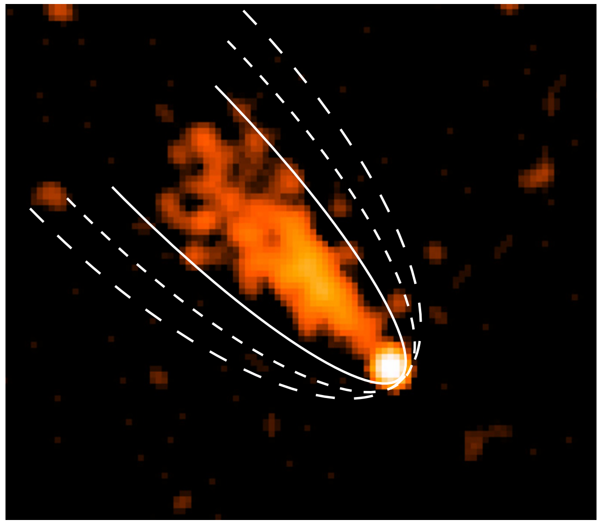
⇒ **$d_{J11} \sim d_{MSH}$ = 7 kpc**

- $\theta_{MSH\text{ - }J11} \sim$ 11 arcmin

⇒ **$v_{J11} \sim$ (1100 - 2200) d_7 km/s**

- $\theta_{jet} \sim$ 5.5 arcmin

⇒ **$l_{jet} \sim$ 11.5 d_7 pc**

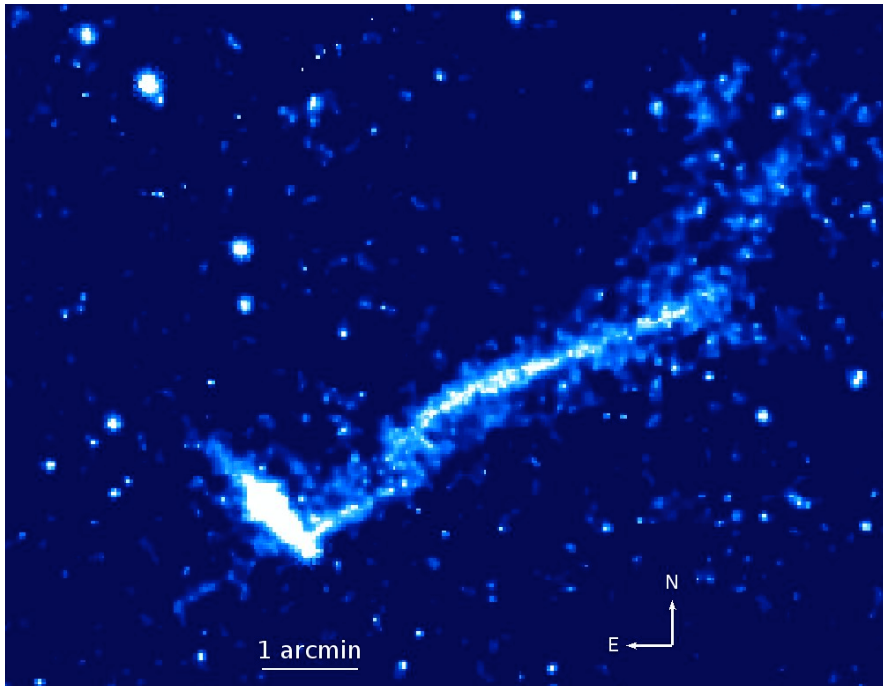


$$\delta_{SO} = 0\farcm266 \frac{\cos^2 i}{v_{t,3} d_{10}} \left(\frac{\dot{E}_{36}}{n_{0.1}} \right)^{1/2} \qquad R(\phi) = \frac{R_{SO}}{\sin\phi} \sqrt{3\left(1 - \frac{\phi}{\tan\phi}\right)}$$

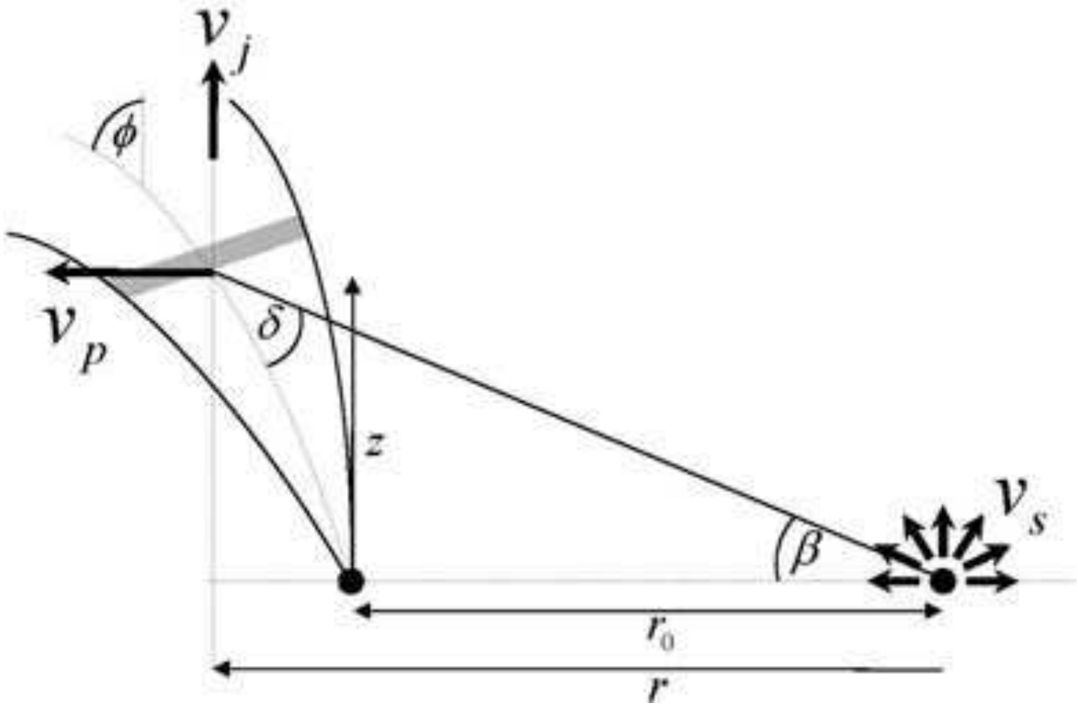
⇒ **$v_{J11} \geq$ 1200 km/s** (d = 7 kpc,, $L_{sd} \sim 10^{36}$, n=0.1)

IGR J11014-6103

- **jet-like structures in the Lighthouse Nebula**
  - @ 7 kpc, ljet ≥ 11.5 pc, longest Galactic X-ray jets
  - precession-like pattern
  - no signatures of jet bending
  - fainter counter-jet
  - chance probability ~ negligible:
    - - alignement jet/counter-jet
    - - flux change @ “PSR” position
  - jet-features provide ~ 1/3 of total X-ray flux



- **extreme properties** as compared to archetypical PWN jets, e.g. Crab, Vela…
- how can ultra-fast runaway pulsars **develop prominent, unbent jets?**



Soker & Bisker 2006

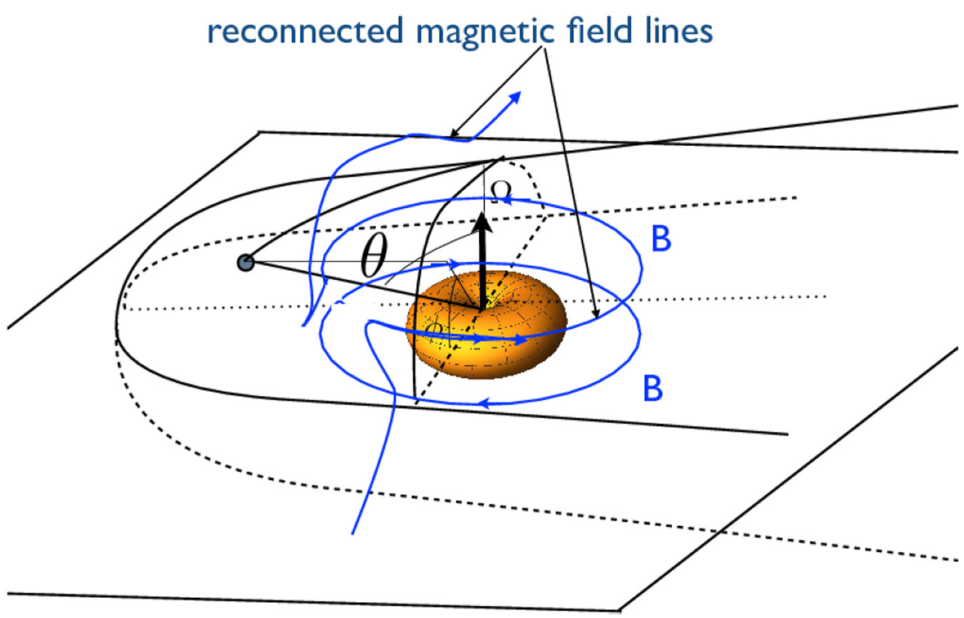
- **Bandiera 2008**
  - highest energy electrons accelerated at the PWN escape from the bow shock and **diffuse into the ambient medium B-field**
  - The linear geometry would reflect the plane-parallel geometry of this B-field, and **avoid bending effects** of ballistic jets
  - live-time of electrons to produce observed X-rays (Guitar Nebula) is ~ 100 yrs, or about 36 pc at v ~ c, much larger than l_{jets}
  - **alternative**: electrons scatter back and forth along the flux tube: plane-parallel large-scale B-field **+ turbulent field** (increase sync. losses, makes “jets" rather bright) - spectral features?

$$\Delta\Phi = \sqrt{3\dot{E}/2c}\,,$$

$$\gamma_{\rm MPD} = \frac{e\Delta\Phi}{2m_e c^2} = \frac{e}{2m_e c^2}\sqrt{\frac{3\dot{E}}{2c}} = 7.2\times 10^7$$

$$R_{\rm gyr} = \frac{m_e c^2}{eB_{\rm bow}}\gamma_{\rm MPD} = \frac{1}{2B_{\rm bow}}\sqrt{\frac{3\dot{E}}{2c}} = \frac{\sqrt{3}}{4}R_{\rm bow}$$

- **Barkov+ 2018**
  - kinetically streaming pulsar wind particles escaping into the ISM due to reconnection between the PWN and ISM magnetic fields
  - Numerical 3D relativistic MHD simulations (PLUTO code **Mignone+ 2012**)
  - contact discontinuity becomes a rotational discontinuity with magnetic fields of similar strength on both sides, prone to reconnection **Komissarov+ 2007**
  - The structure of the reconnecting magnetic fields at the incoming and outgoing regions produces highly asymmetric features



Barkov+ 2018

- fit with ballistic jet model
- best fit values:

  $\beta = 0.8\ c$,

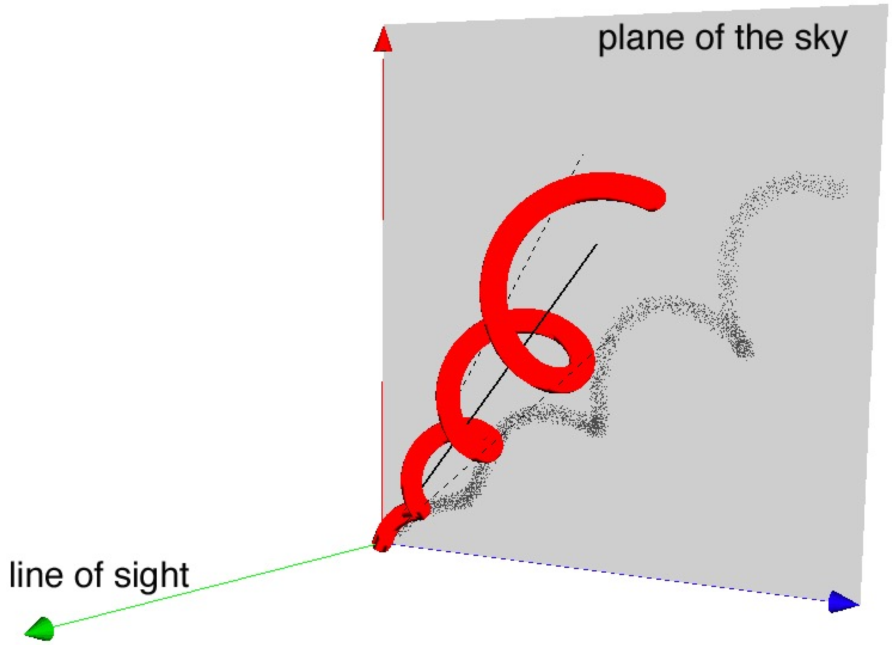
  $\tau_{prec} = 66$ yrs

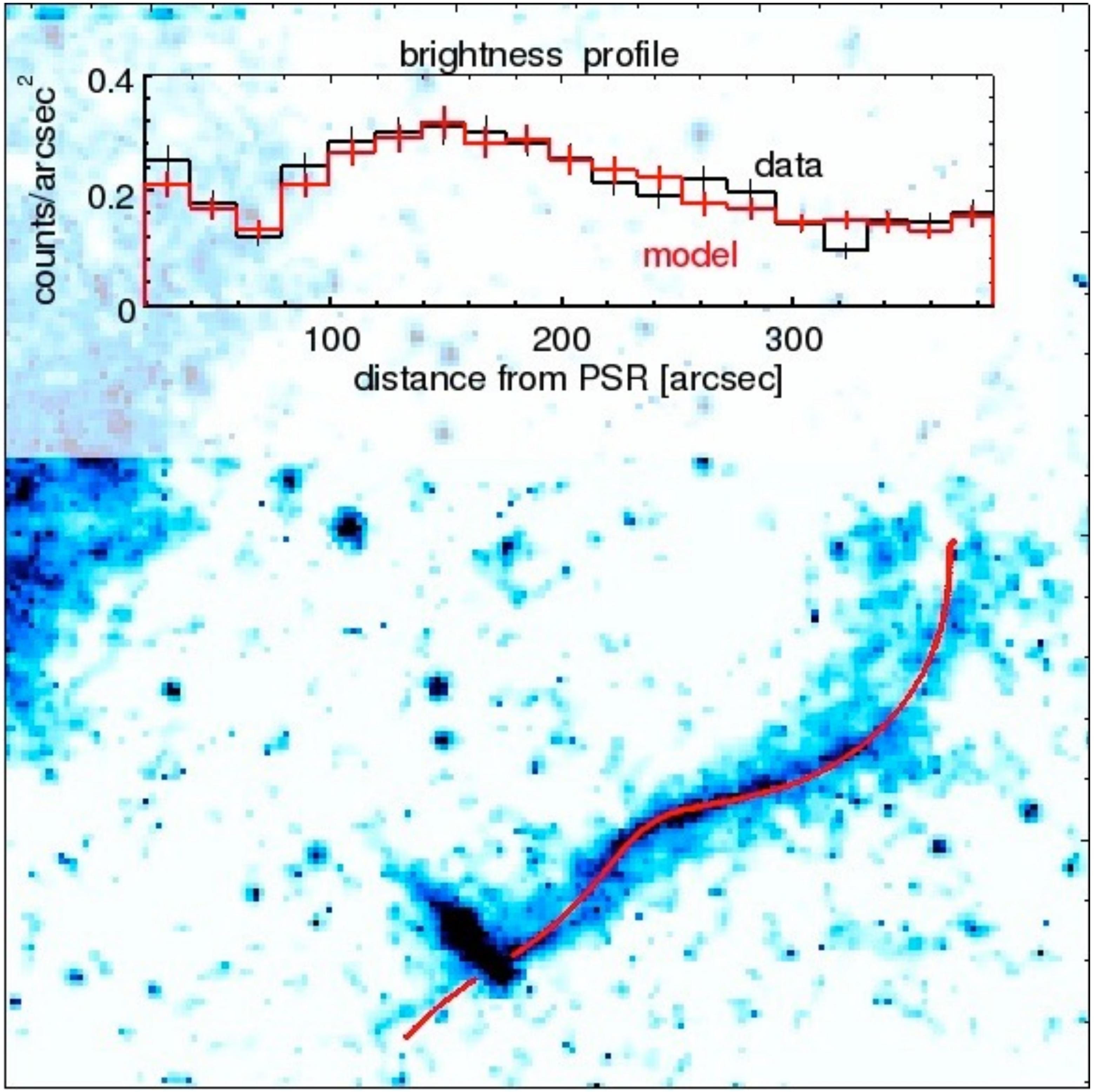
  $\alpha_{prec} = 4.5°$

  inclination = 50°

- byproduct: internal Doppler

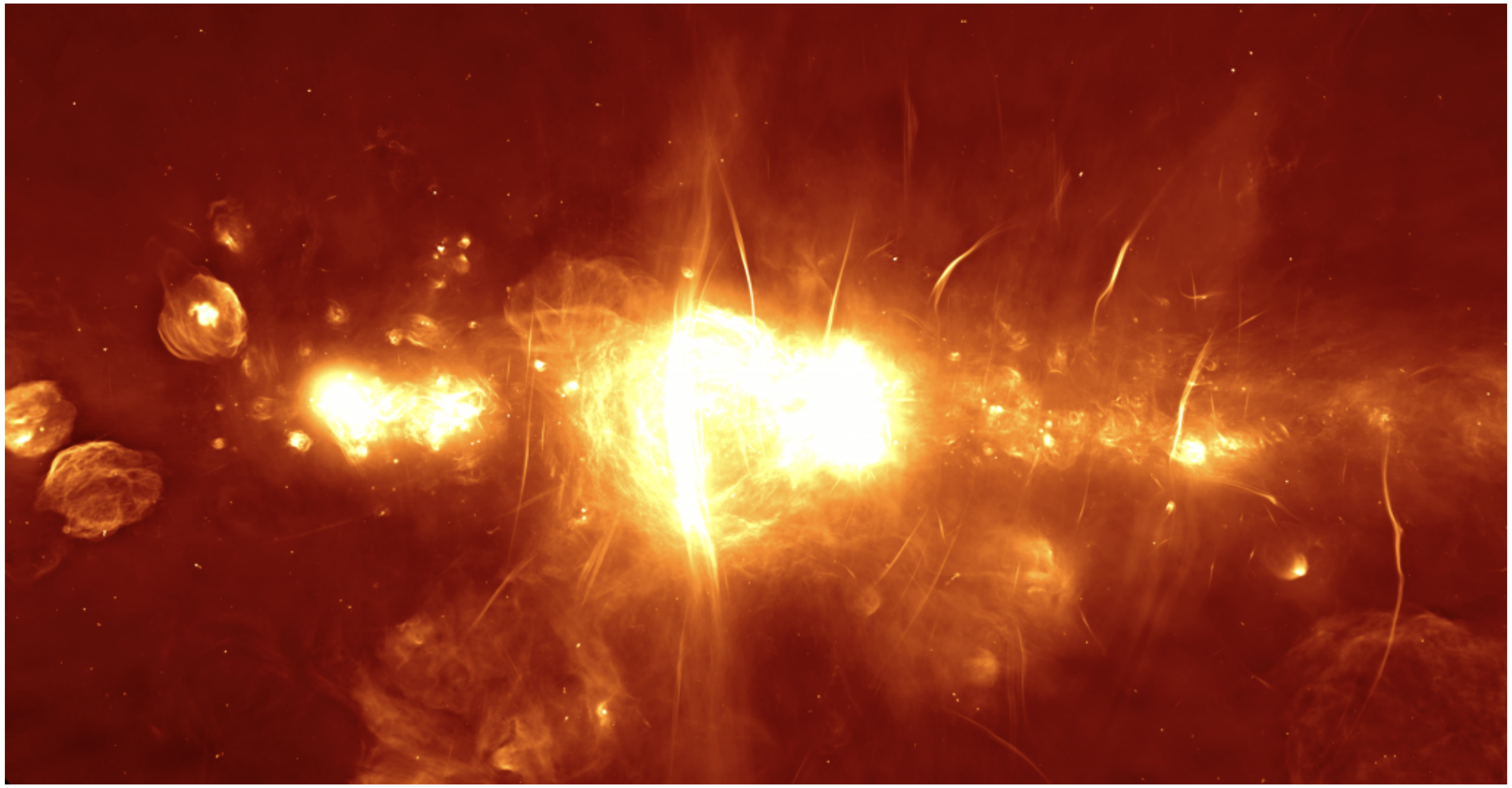
=> cork-screw morphology in ambient + self-generated turbulent B-field?





jet-like structures in the GC

MeerKAT, South African Radio Astronomy Observatory (SARAO) 2018

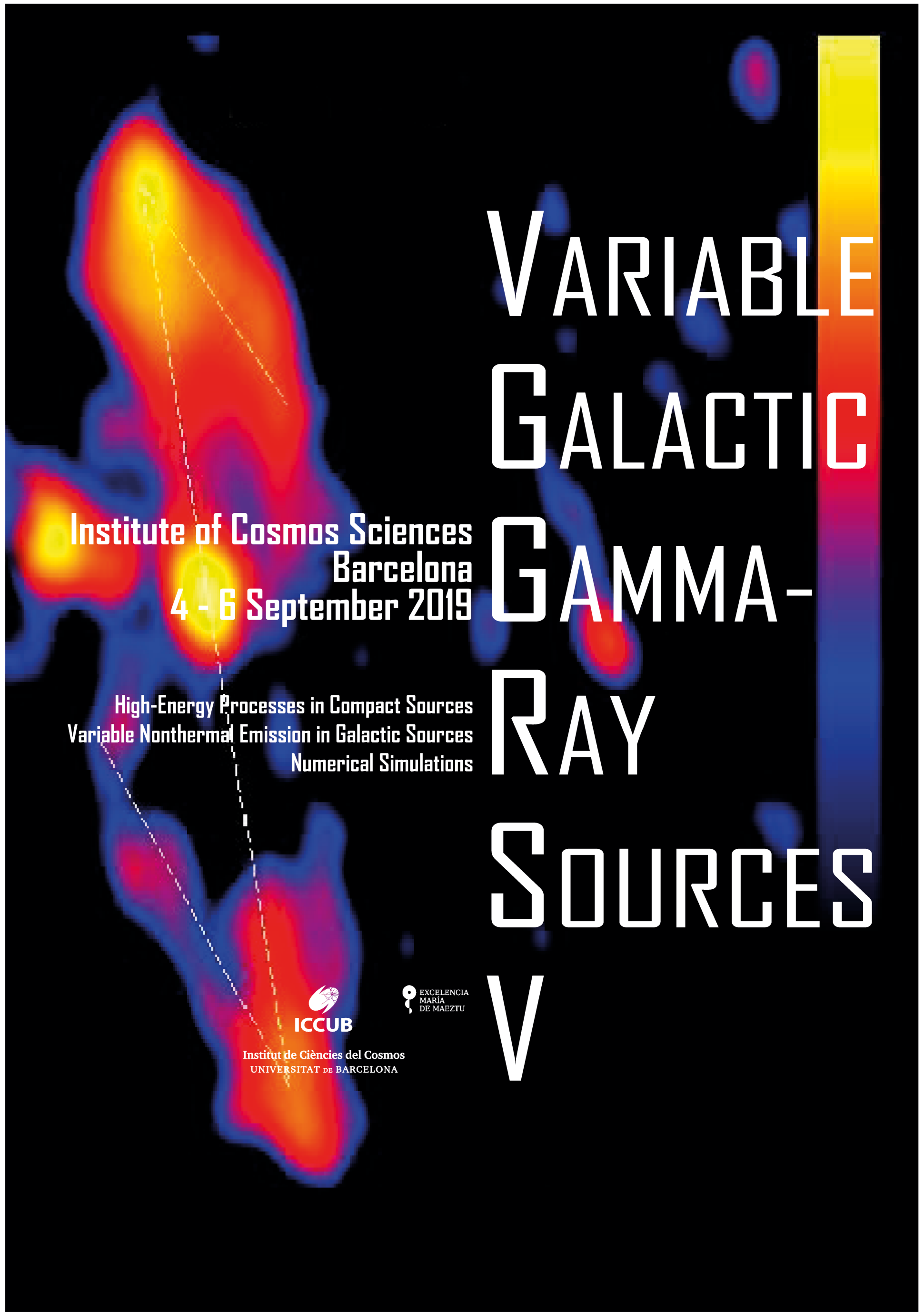


- The central part of the Galaxy shows numerous non-thermal filaments (**MeerKAT Coll. 2018**)
- Filaments are ~linear, extending for a few parsecs to few tens of parsecs
- origin? magnetic flux tubes illuminated by local injection of relativistic particles (**Morris & Serabyn 1996**)
- local injectors: unresolved fast-moving PWNe? **Barkov & Lyutikov 2019**

summary

- Our Galaxy at high-energies is populated (and powered) by a variety of systems harbouring **compact objects displaying relativistic outflows**.
- **Microquasars**: recent detections at gamma-rays support long-predicted theoretical expectations. Ideal lab to study jet launching and propagation mechanisms, in a periodically changing environment. Large-scale interactions now in the game (SS433)
- **Gamma-ray binaries**: few systems so far, all showing “exceptions to the rule”. Extremely efficient accelerators. Many unknowns: powering engine, emitter location, emission/absorption mechanisms
- **Runaway PWNe**: prominent outflows being revealed in X-rays, defying classical (ballistic) jet interpretations. Alternative scenarios include magnetic reconnection and diffusion of highest-energy particles into ambient B-field.

bonus track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RAY
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Institute of Cosmos Sciences
Barcelona
4 - 6 September 2019
High-Energy Processes in Compact Sources
Variable Nonthermal Emission in Galactic Sources
Numerical Simulations
ICCUB
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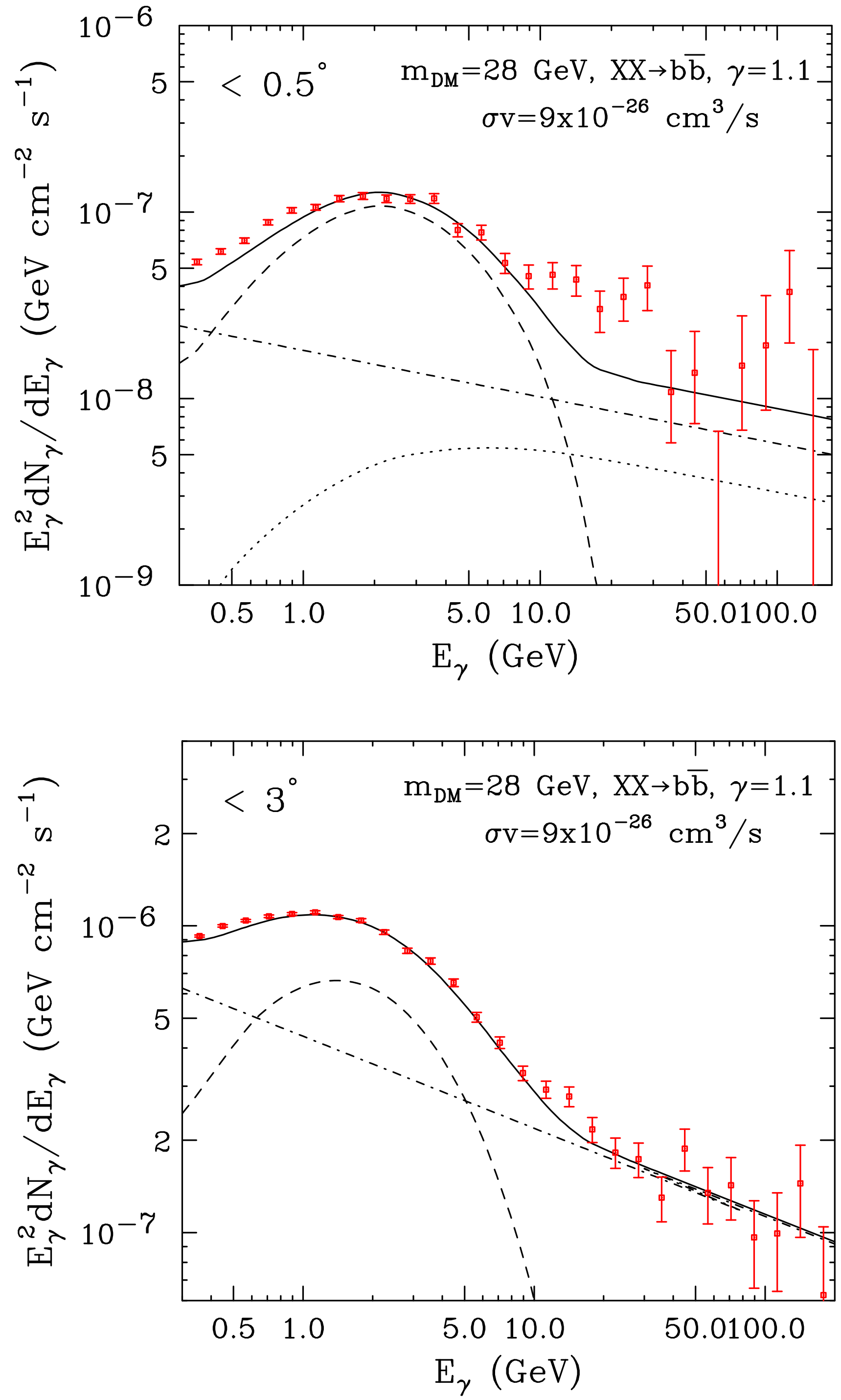
MARÍA
DE MAEZTU

backup

contributor to the "GeV excess"?



Goodenough & Hooper 2009

- gamma-ray excess observed from inner regions of the Galaxy, peaking at ~[1-5] GeV Goodenough & Cooper 2009, Vitale+ 2009, Hooper & Linden 2011, Gordon & Macias 2013, Calore+ 2015
- several interpretations
  - dark matter annihilation
  - cumulative emission from unresolved sources (MSPs?)
  - diffuse CR emission
- can SS433 be the iceberg-peak of a yet un-resolved γ-ray emitting *μQ* population contributing to GeV excess?
  - known jet bulk-Lorentz factors: Γ ~ [1-10]
  - cumulative signal would appear broader
  - cumulative signal would be shifted to ~few GeVs
- spatial distribution of (unknown) pop. of LM-*μQs?*

Chandra & ATCA observations