Galactic transients at very high energies

Alicia López Oramas
(Instituto de Astrofísica de Canarias)

Synergies at new frontiers at gamma rays, neutrinos and gravitational waves
Tokyo, Japan, March 24-25, 2022

Galactic transients

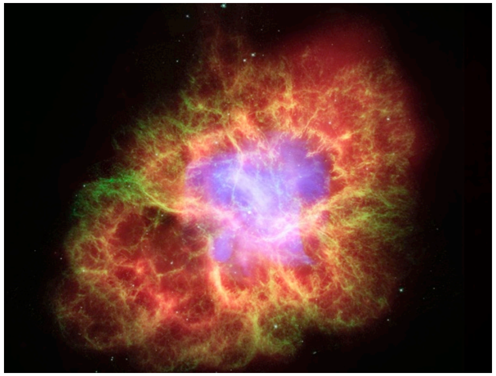
- A wide range of sources in our Galaxy exhibit transient emission via **accretion/ejection processes** and interactions between e.g. jets, **outflows and/or strong winds**

- These events can accelerate particles up to relativistic energies, leading to the **production of high-energy (HE, E>100 MeV) radiation**

- **Some objects** such as microquasars, magnetars (giant flares), novae or flares from pulsar wind nebulae (PWNe) **have already been detected in the MeV- (few) GeV regime** (see e.g. Fermi collaboration 2010, Fermi collaboration 2012) **-> TeV emitters?**

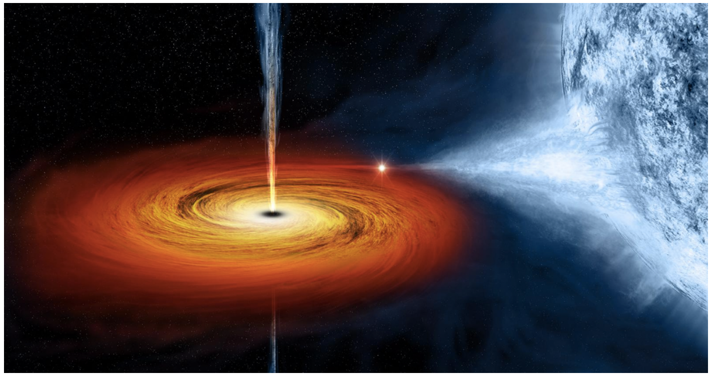
- What are the possible gamma-GW-neutrino **synergies**?

PWN flares



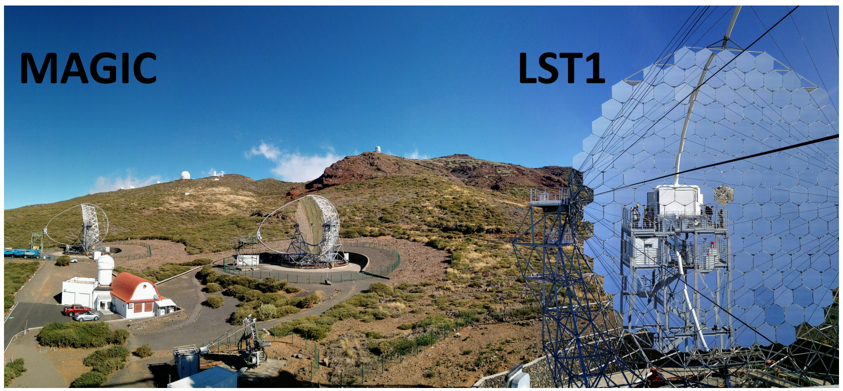
magnetars

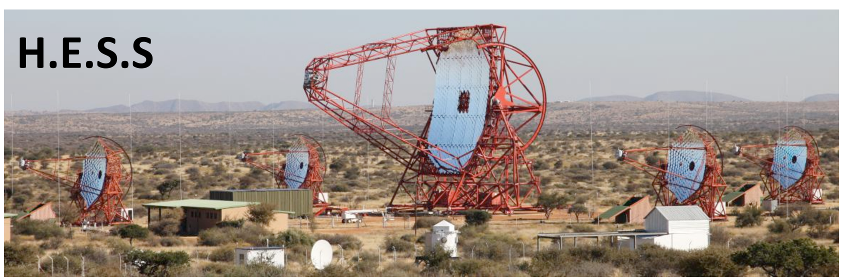
microquasars

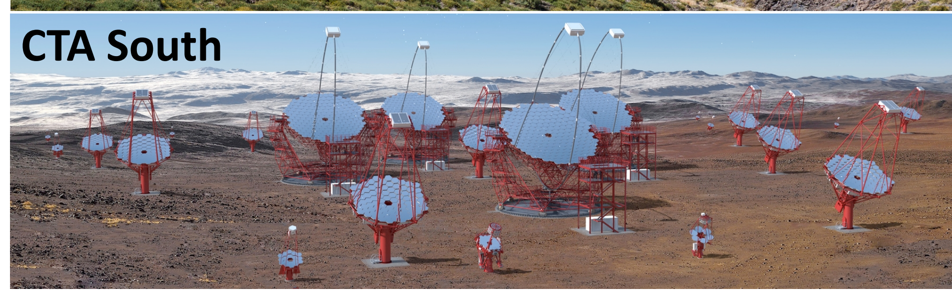


Imaging Air Cherenkov Telescopes (IACTs)

- **Current generation** of IACTs composed of three large experiments:
  - **H.E.S.S** (Namibia), **MAGIC** (La Palma, Spain), **VERITAS** (USA)
- **Future** observatory: Cherenkov Telescope Array (**CTA**)
  - First Large Size Telescope (**LST1**) under **commissioning** (La Palma)



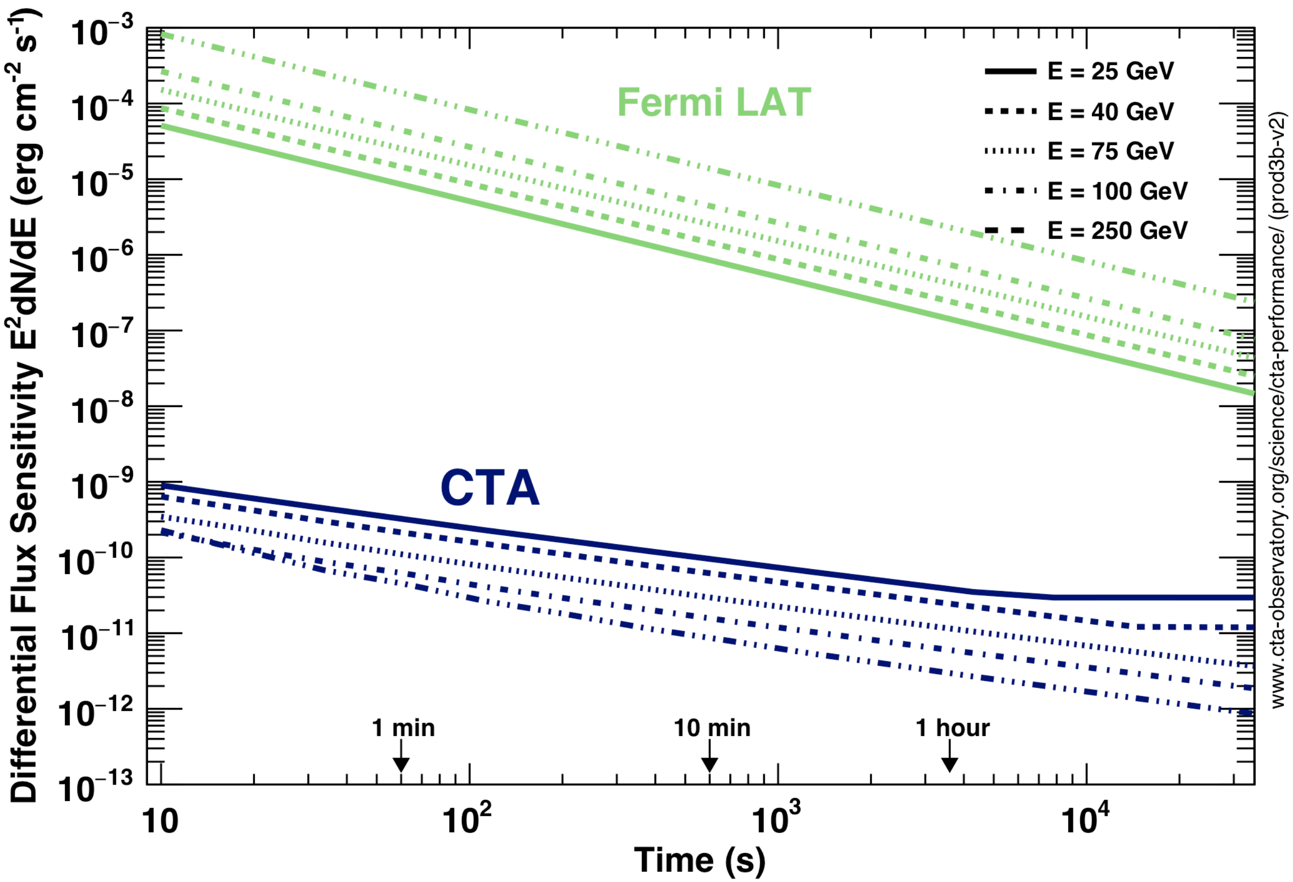




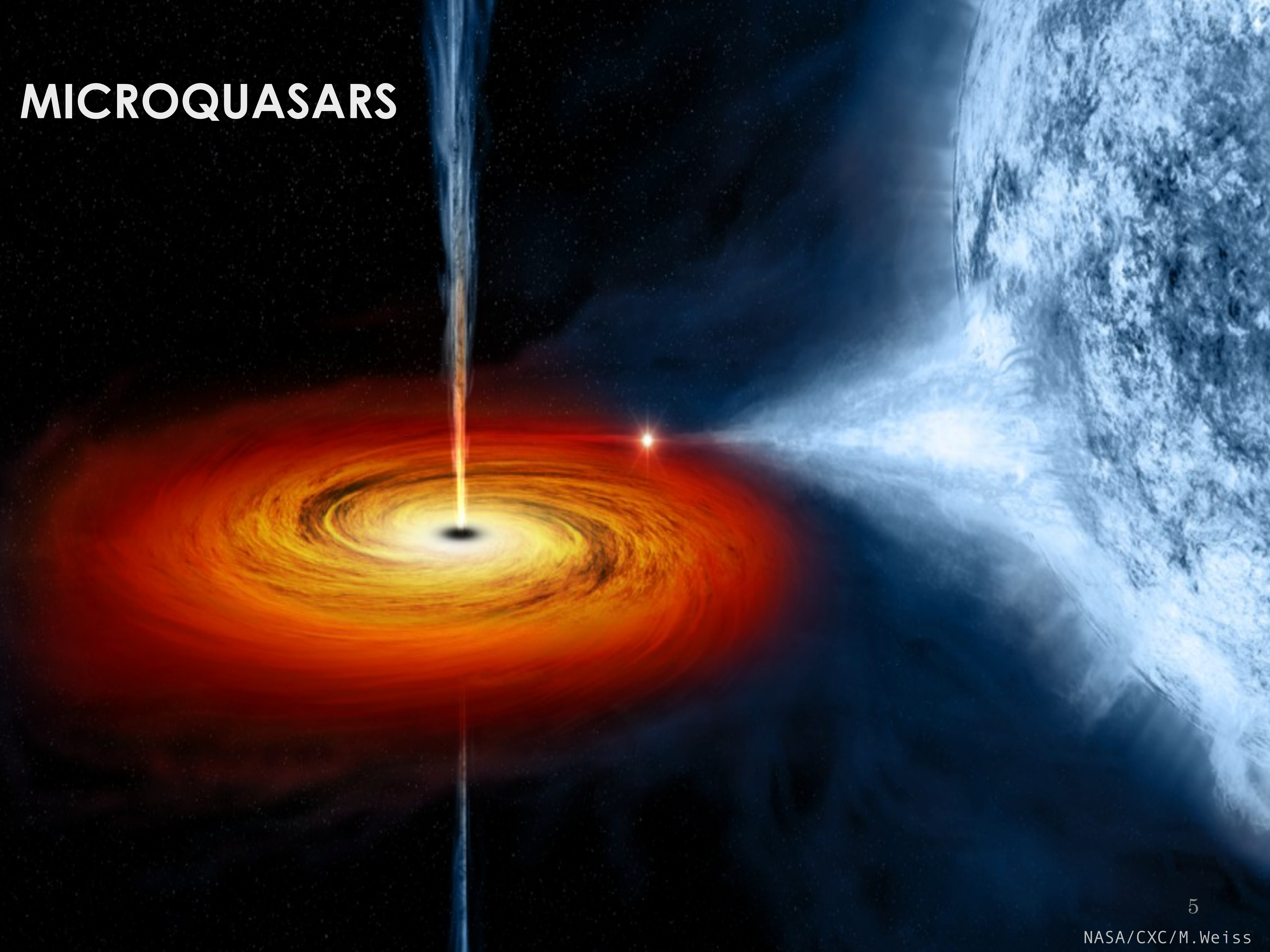
Credit: Gabriel Pérez Diaz (IAC)

CTA: unprecedent transient detection

- Unprecedent sensitivity at short timescales



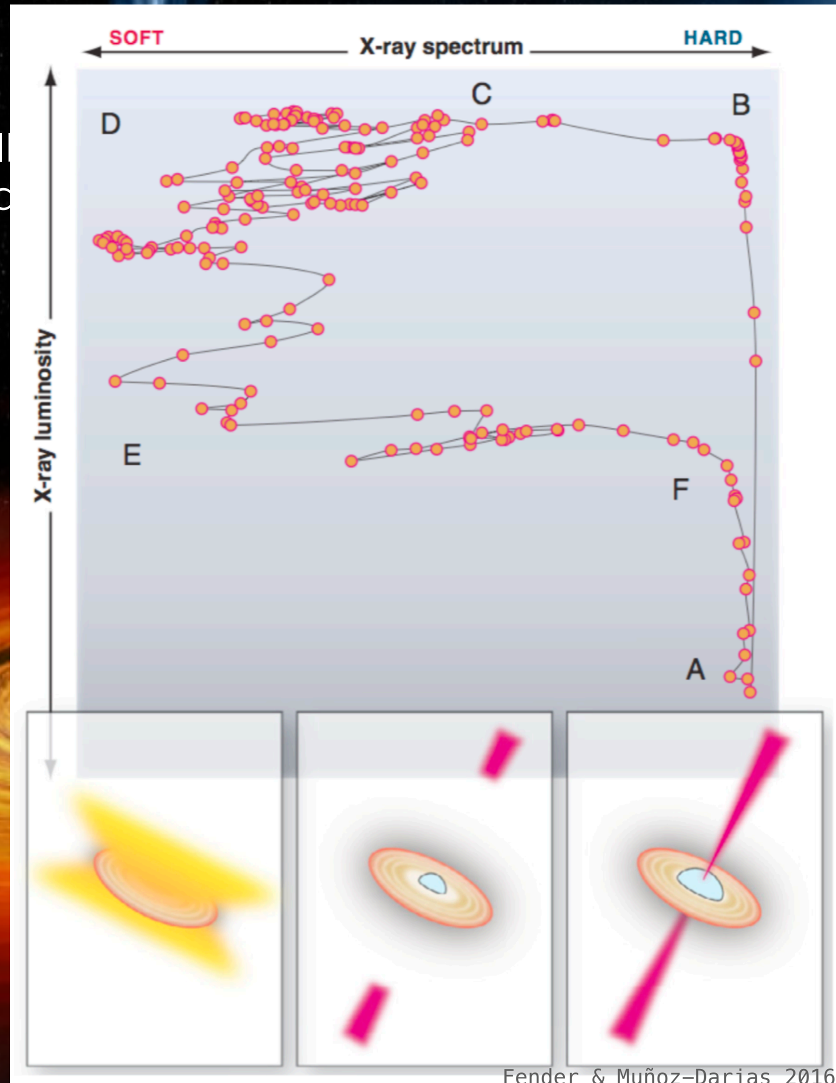
MICROQUASARS



Jets
(radio, mm, OI
X-rays, soft gamma

Accretion disk
(optical, UV, soft X-rays)

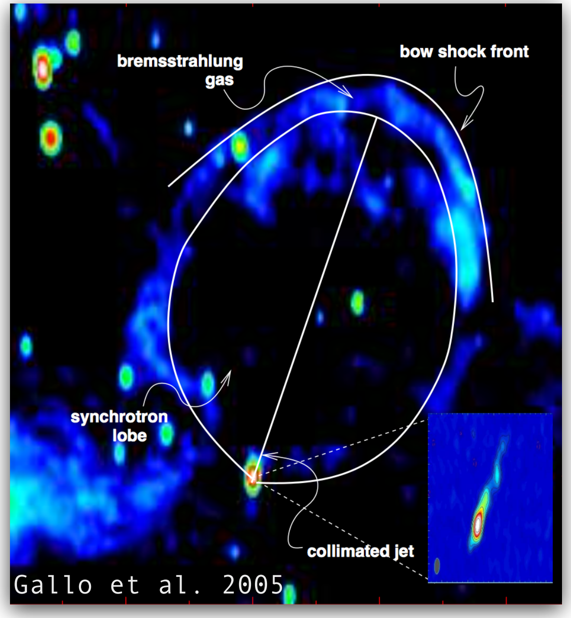
star
IR)



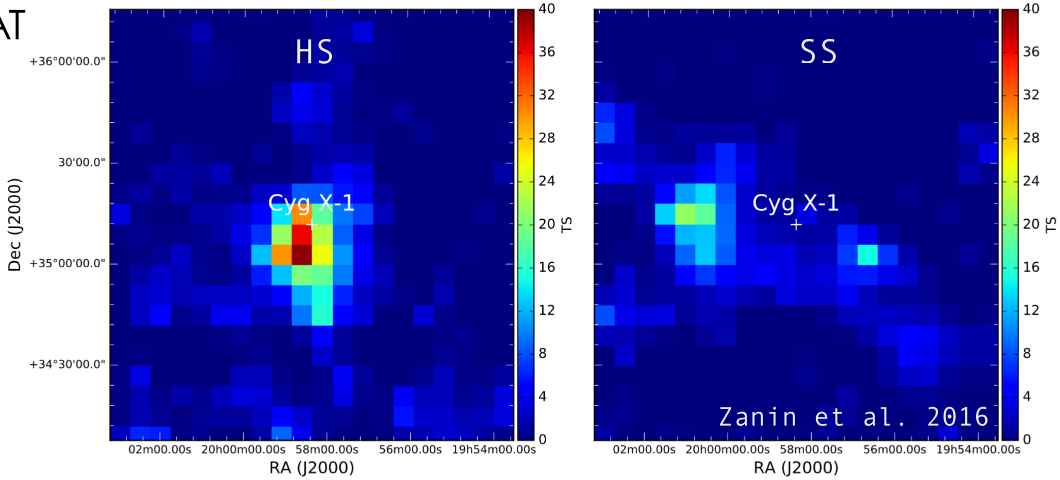
NASA/CXC/M.Weiss

Cygnus X-1: transient+steady emission

- Massive O star + BH
- Highly collimated **jet** (Stirling et al. 2001)
- Surrounded by radio/optical **nebula** (Gallo et al. 2005, Russell et al. 2007)
- Three transient episodes with AGILE (Bulgarelli et al. 2008, Sabatini et al. 2010, 2013)

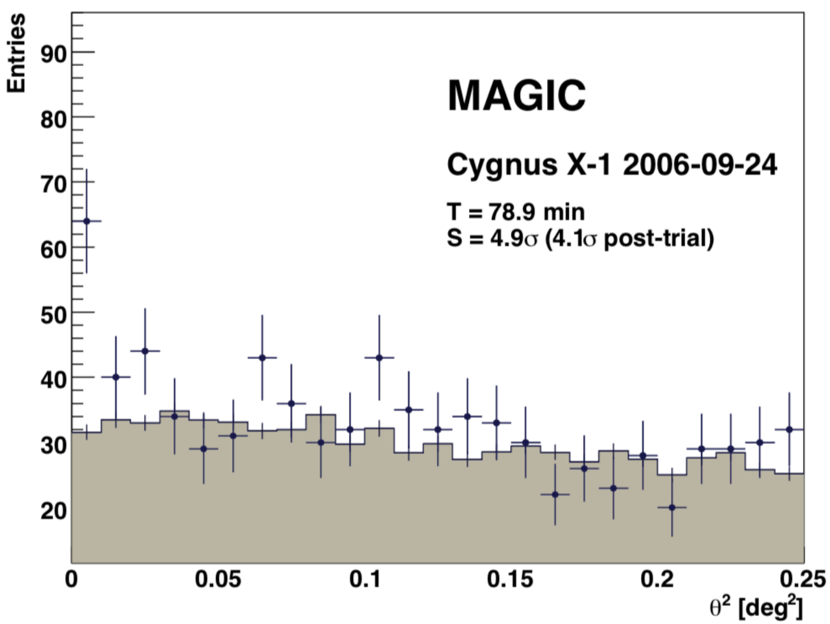


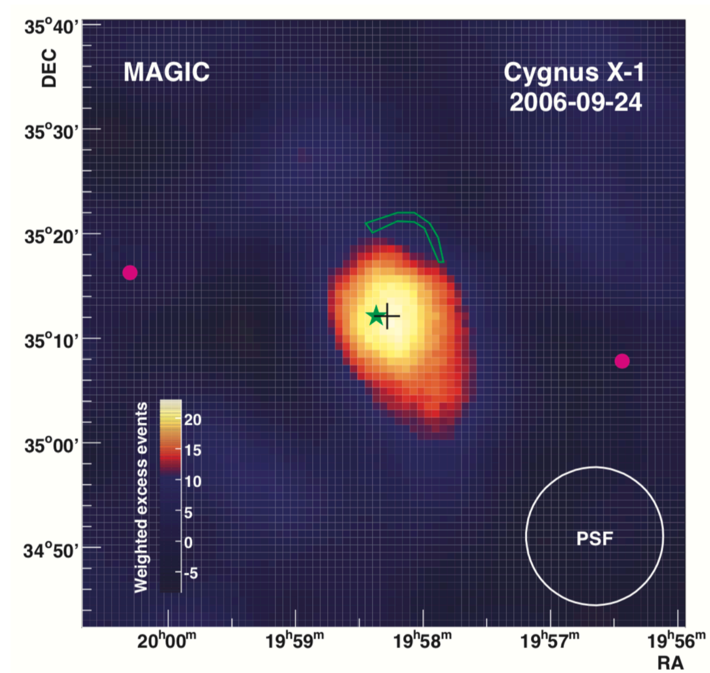
- **Detected at HE during HS**: **7.5yr** Fermi-LAT (Zanin et al. 2016)
    - **Likely jet origin**
    - Evidence of flux orbital variability: anisotropic **inverse-Compton** on stellar photons as the mechanism at work
    - Different hadronic component might exist at higher energies



Transient emission: Cygnus X-1

- **Hint of transient emission with MAGIC**:
  - 4.9σ (4.1σ post-trial) in 80 min `(Albert et al. 2006)`
  - Simultaneously with hard X-ray flare
  - During HS and SUPC
  - **First evidence of transient emission from an accreting binary** (microquasar)

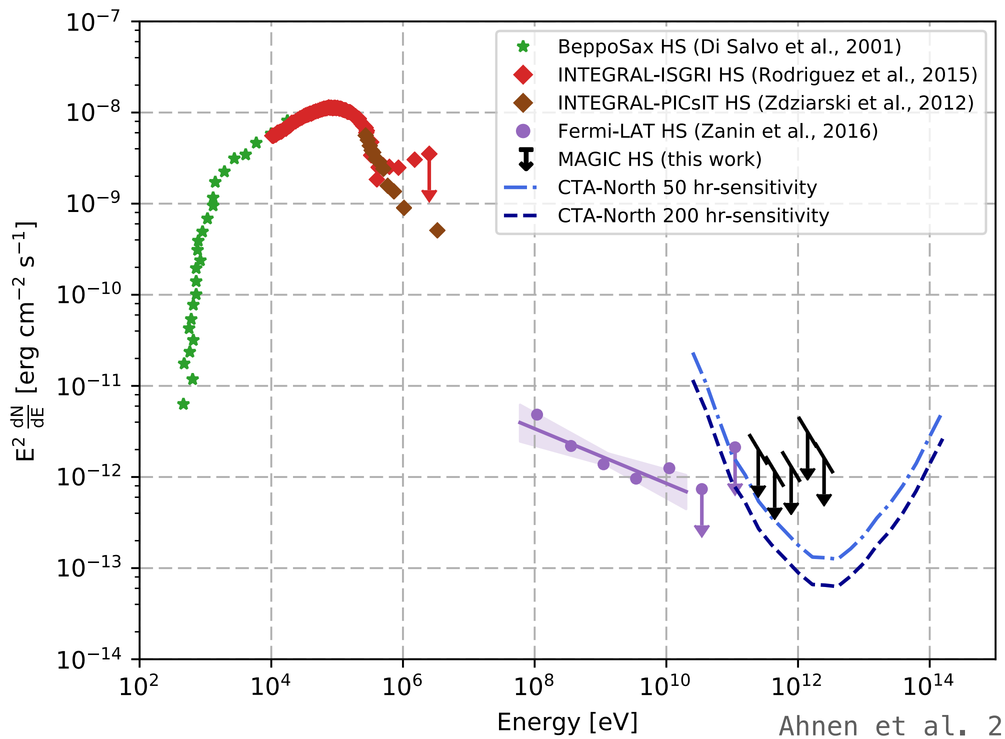




Albert et al. 2006

Steady emission: Cygnus X-1

- **100 h** (2007-2014) of MAGIC observations **mainly at HS** (83h)
- **No significant excess** at either X-ray state for steady, orbital or daily basis emission (Ahnen et al. 2017)
- No emission due to interaction between jet and ISM
  - **Jet-medium interaction discarded** (not affected by γ−γ absorption)
- **Transient emission** (Albert et al. 2007) **still possible** at binary scale

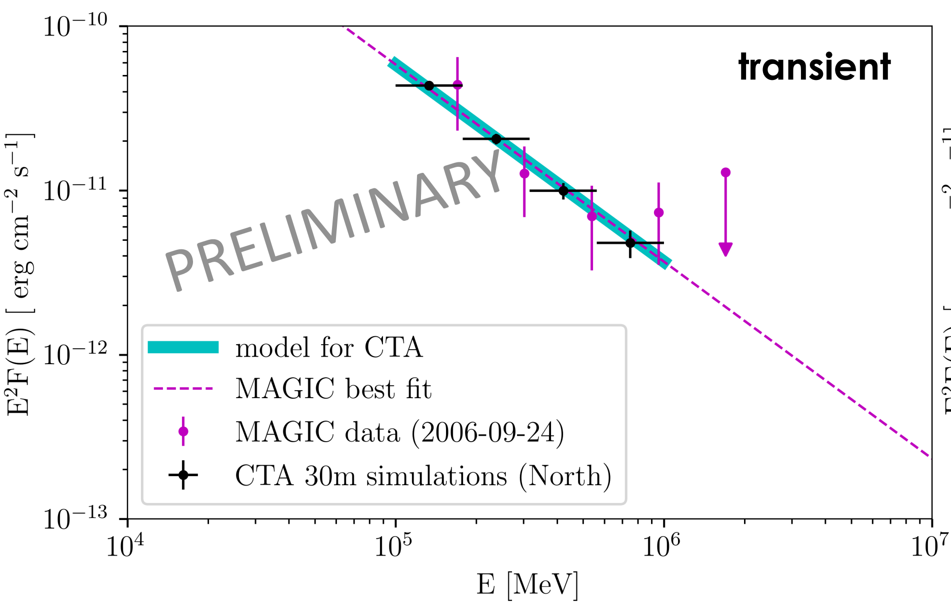


Ahnen et al. 2017

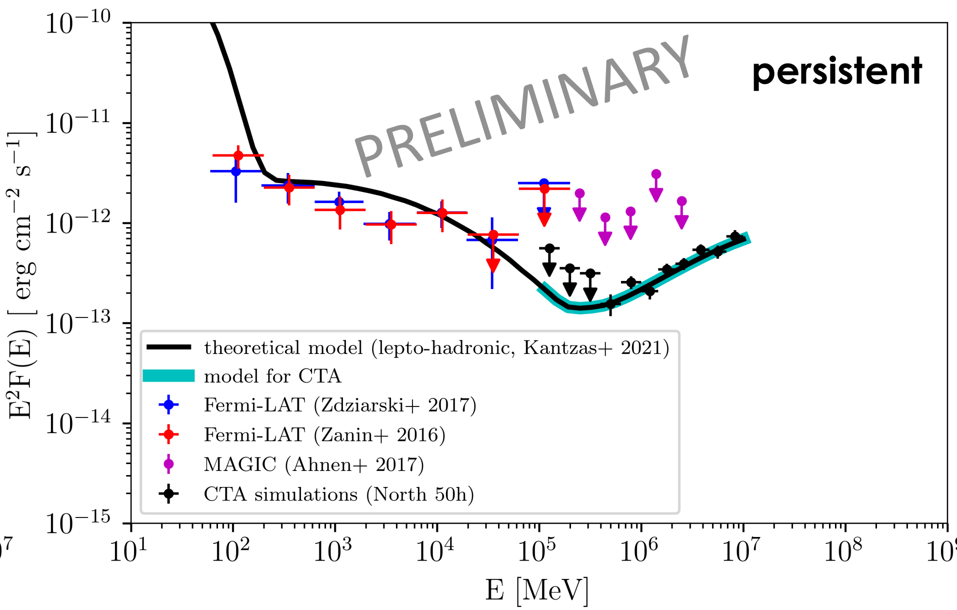
- Will CTA detect transient and/or steady emission from CygX1?

Cygnus X-1

- **CTA simulations** (100 GeV – 1 TeV) to search for:
  - Transient emission: 30-minute observation with MAGIC hint SED as input
  - Persistent emission: lepto-hadronic model by `Kantzas et al. 2021`, assuming 50 h of observations
- **Detection of transient** (44σ, TS=1907) **and persistent emission** (39σ, TS= 1537) **with CTA-North**



CTA Consortium in prep.

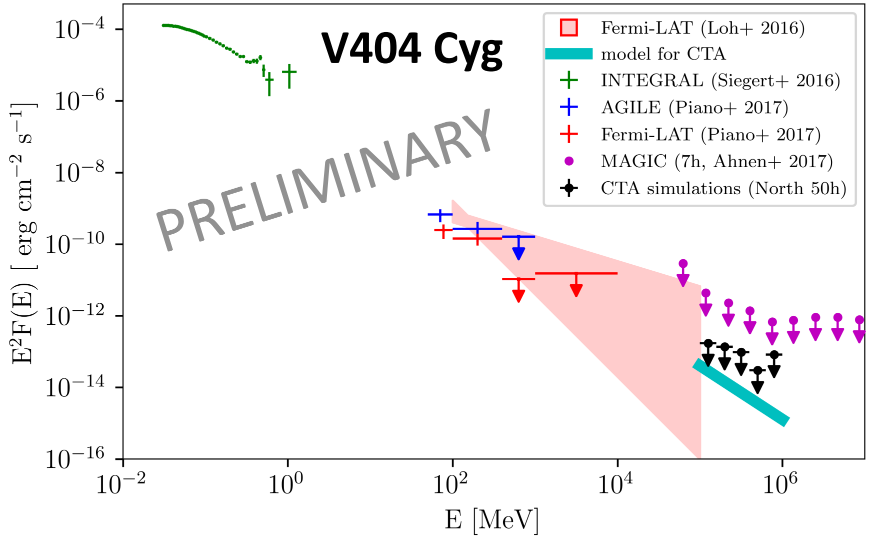


CTA Consortium in prep.

Other microquasars

- **ULs to the flux of different microquasars**: Sco X-1 (Aleksić et al. 2011) MWC 656 (Aleksić et al. 2015), V404 Cyg (Ahnen et al. 2017), Cyg X3 (MAGIC 2017), SS433 (Ahnen et al. 2018), GRS 1915+105, Circinus X-1, and V4641 Sgr (Abdalla et al. 2018), MAXI J1820+070 (Hoang et al. 2019, Molina et al. 2021)
  - Including low-mass and high-mass systems and BH and NS as compact objects

- **LMXB**: low mass star + BH
- **Major outburst** in June 2015 after 26 years in quiescence
  - **Hint of transient detection (~4σ) in Fermi-LAT** data (Loh et al. 2016) coincident with the brightest peak of luminosity in radio, hard X-ray and soft γ-ray (Loh et al. 2016; Siegert et al. 2016, Piano et al. 2017)
  - **No VHE emission detected by MAGIC** (Ahnen et al.2017)
- CTA simulations (100 GeV-1 TeV): extension of the PWL spectrum observed by Fermi-LAT (Loh et al. 2016)
- **No detection expected with CTA**

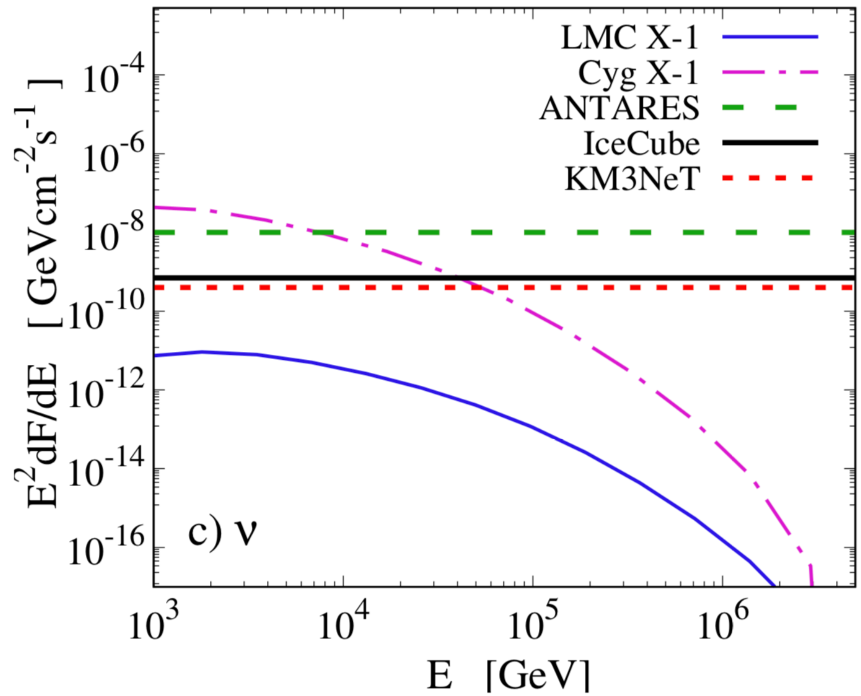


CTA Consortium in prep.

Connected gamma-neutrino emission?

- **Protons can be accelerated in microquasar jets -> likely production of neutrinos**

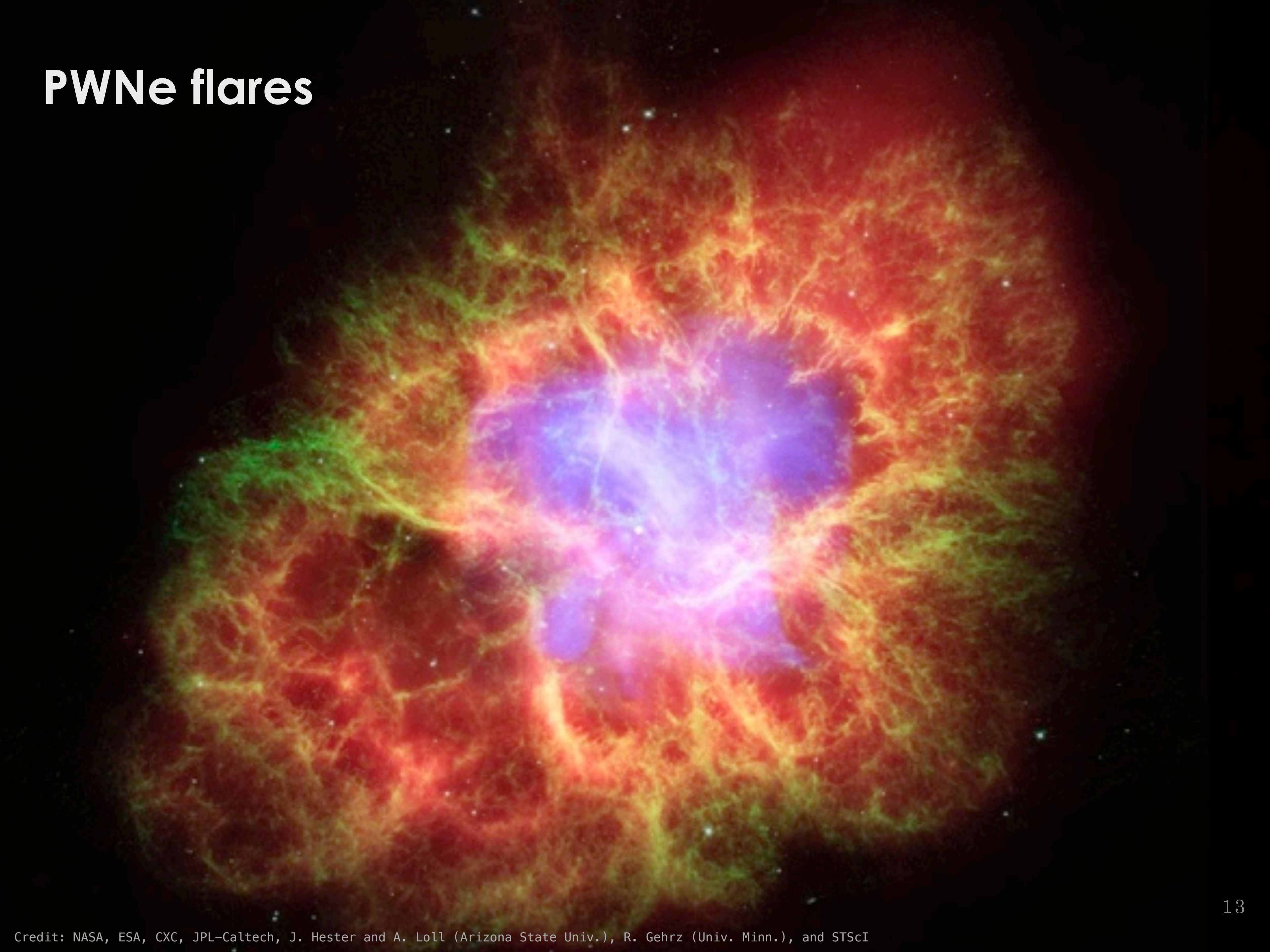
- Models on **CygX1** and LMC X1 suggest **possible neutrino detection** associated to the former source **(Papavasileiou et al. 2021)**
- Hadronic dark **jets of SS433 could produce neutrino** emission (Reynoso et al. 2008)
  - Predicted neutrino flux at 1 TeV of $\phi_\nu = 2 \times 10^{-12}$ $cm^{-2}\,s^{-1}$ (averaged over all precessional phases)
  - **UL at 1 TeV** (8 years): $2.71 \cdot 10^{-13}$ TeV $cm^{-2}\,s^{-1}$ (Aartsen et al. 2019), however it is spatially extended (angular size of up to several degrees >PSF_Icecube) -> analysis sensitivity is reduced



Papavasileiou et al. 2021

- Icecube has set **ULs to the steady** neutrino flux of many high-mass microquasars such as SS433, CygX1, CygX3 (Aartsen et al. 2019) after 8 years of data-> **is transient emission still possible?**

PWNe flares



Credit: NASA, ESA, CXC, JPL-Caltech, J. Hester and A. Loll (Arizona State Univ.), R. Gehrz (Univ. Minn.), and STScI

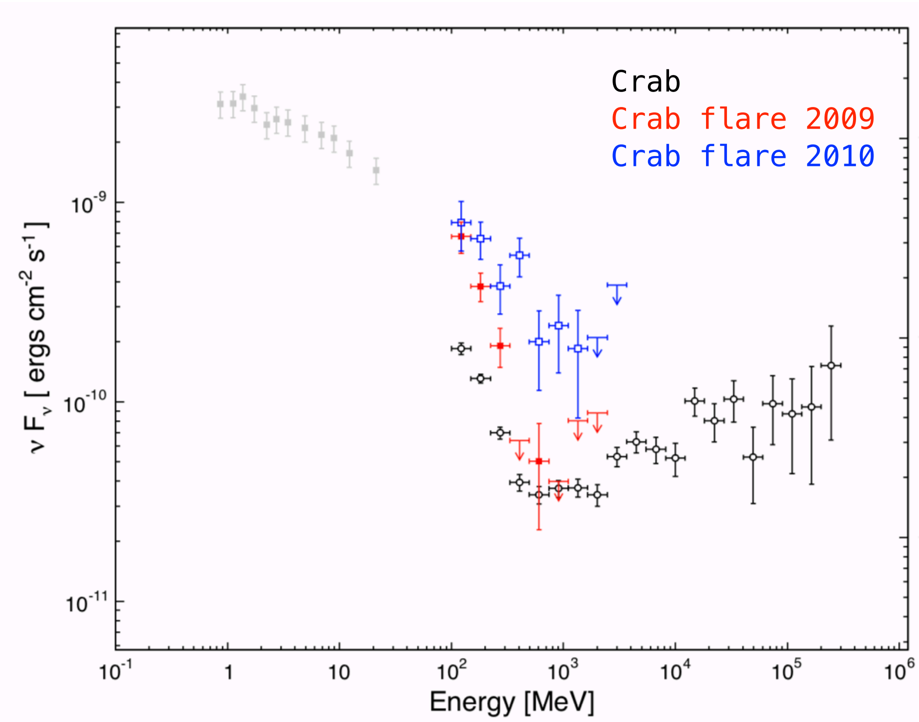
PWNe flares

- Crab Nebula is the **standard candle at VHE**
  - **IC emission detected up to 100 TeV** by HAWC (Abeysekara et al. 2019) and **MAGIC** via VLA observations (Acciari et al. 2020)
  - **Pulsar emission** detected by MAGIC from ~25 GeV **to few TeV** (Aliu et al. 2008, Ansoldi et al. 2016)

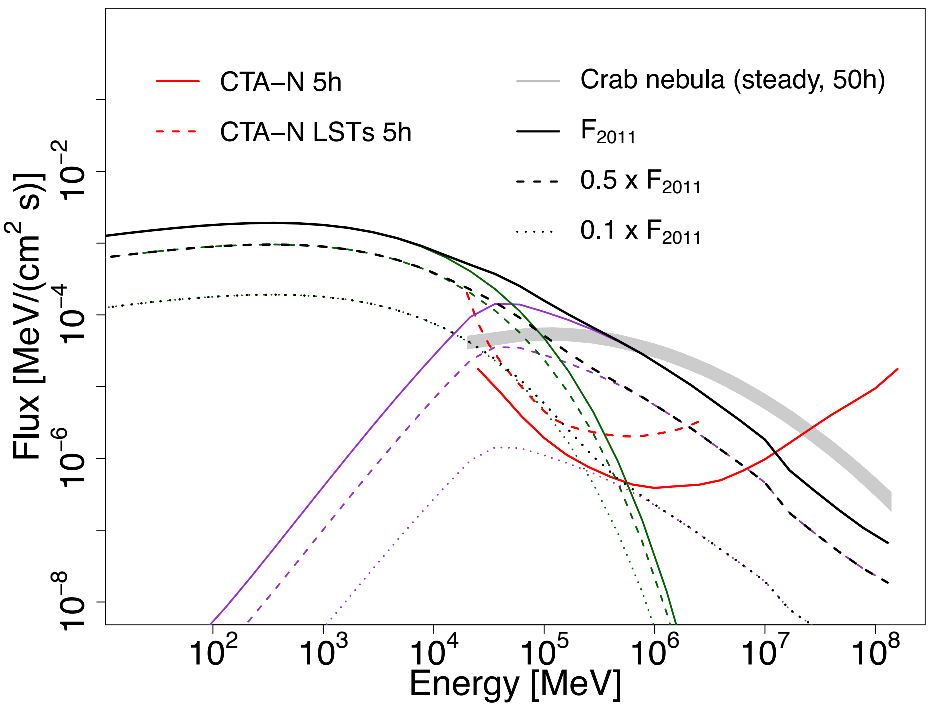
Credit: NASA, ESA, CXC, JPL-Caltech, J. Hester and A. Loll (Arizona State Univ.), R. Gehrz (Univ. Minn.), and STScI

Crab Nebula flares

- **Rapid and bright MeV flares** observed in Crab (Tavani et al. 2011, Abdo et al. 2011) with **timescales of hours**
  - **No TeV detection** with current IACTs
- Studying the capabilities of CTA to detect the Crab flares (Mestre et al. 2021, CTA consortium in prep)
- **Good prospects for CTA** and specially LSTs

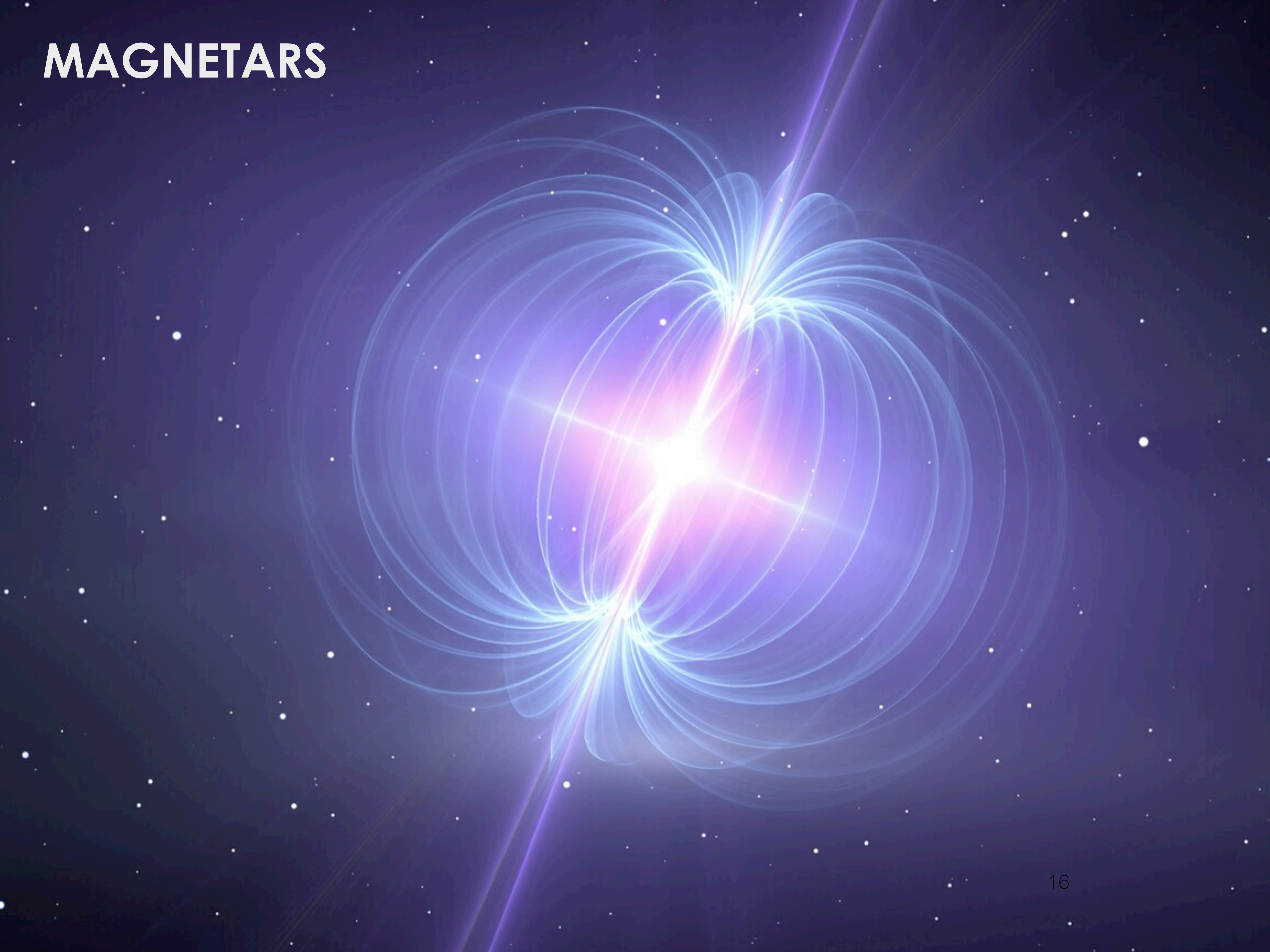


Abdo et al. 2011



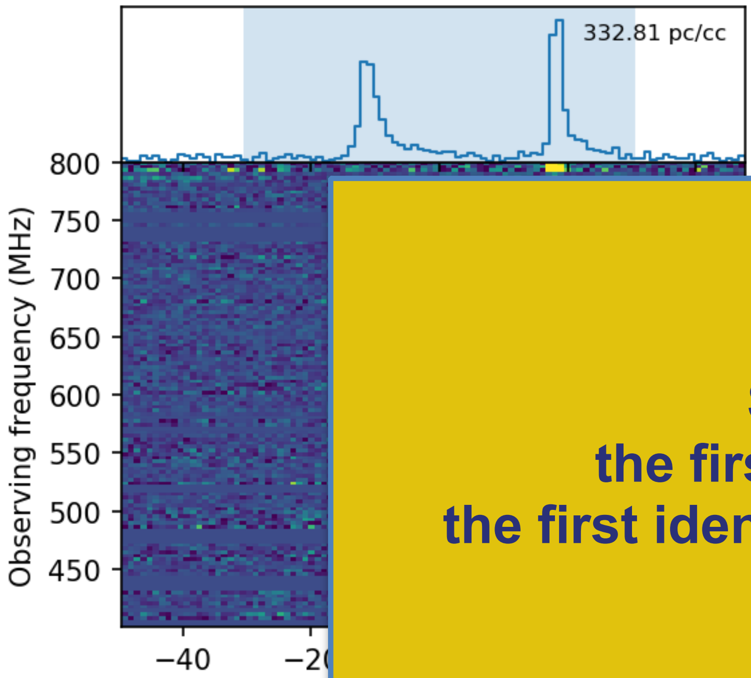
CTA Consortium in prep.

MAGNETARS



Magnetar-FRB connection

MAGIC



- About 24 known magnetars in the Galaxy + Magellanic clouds
- **SGR 1935+2154:** Galactic magnetar **hosted in an evolved SNR** and (likely) interacting with a **surrounding molecular cloud**

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ms wide

ghetti et al.
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2020)

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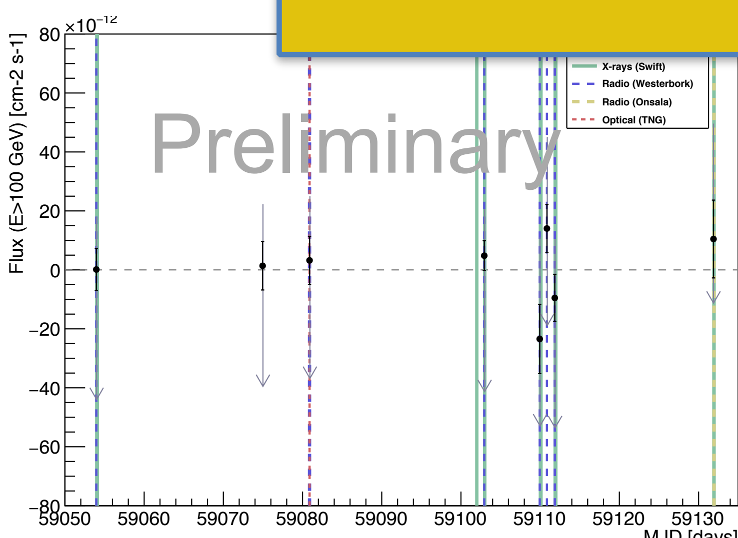
SGR 1935 +2154 is
the first FRB in the Galaxy and
the first identified FRB source: a magnetar



López-Oramas et al. 2021 (MAGIC collaboration)

- **MWL monitoring campaign** to search for contemporaneous FRB events with optical/radio/X-ray/gamma rays (López-Oramas et al. ICRC 2021)

- Different models for the site of FRB emission (see Zhang 2020 for a review):
  - inside magnetosphere
  - relativistic outflow interacting with surrounding ISM

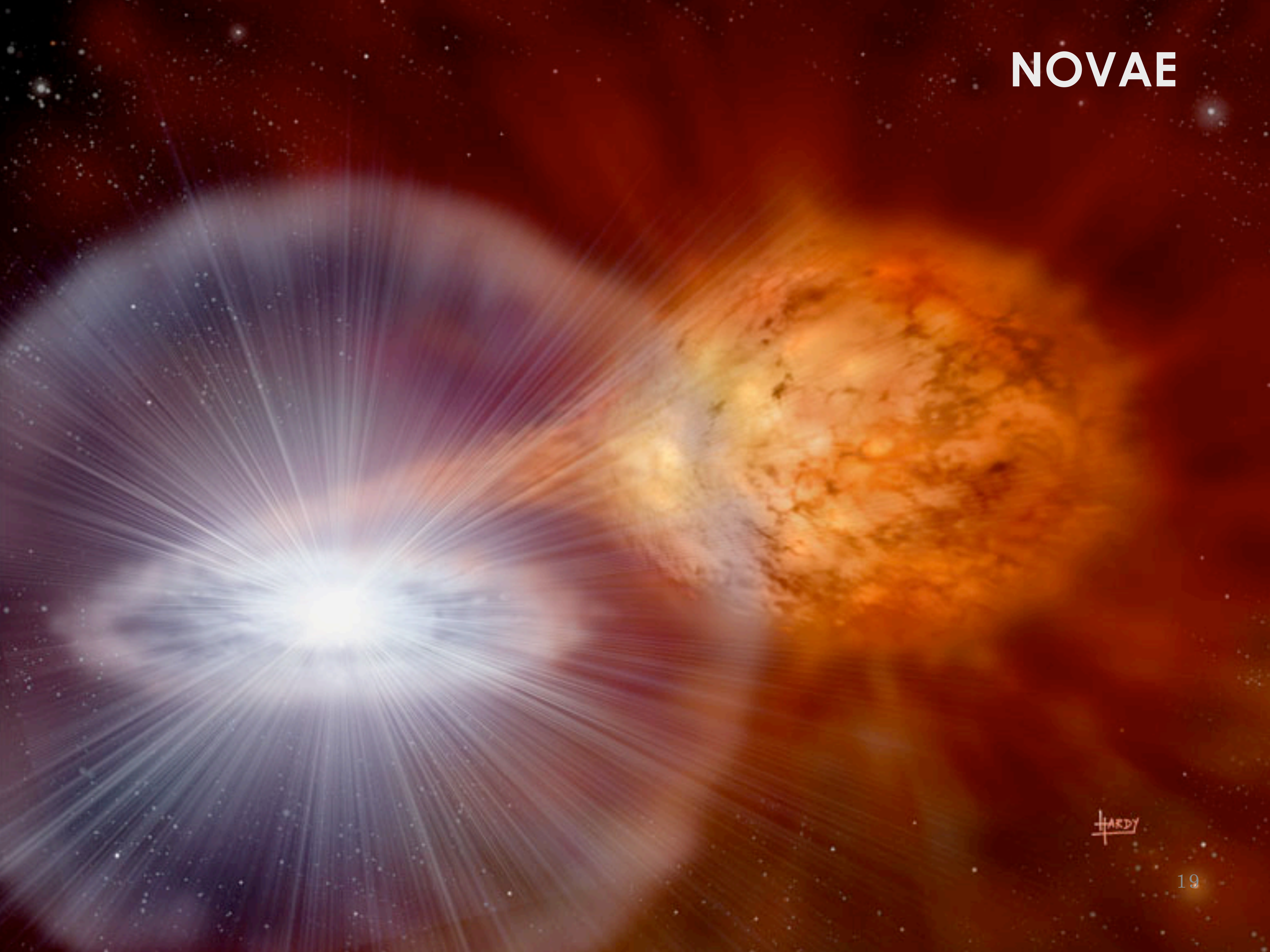
HE emission from an extragalactic magnetar

- Magnetars were never detected at E>100 MeV… until April 15, 2020
- Detection of flaring emission from an **extragalactic magnetar**
  - During a **Giant Flare**
    - Short very energetic (~10^{44}–10^{47} erg s^{-1}) hard spikes followed by pulsating tail
    - Very rare events: only three events in the last 40 years in the Galaxy
- Detected by **Fermi-GBM** (Roberts et al. , Nature Astronomy, 2021)
- **HE emission discoverd with Fermi-LAT** (Fermi-LAT coll. , Nature Astronomy, 2021)
  - Three associated events with energies 480 MeV (arrival time 19 s), **1.3 GeV** (180 s) and **1.7 GeV** (284 s)

Time since T_0 (s)	Energy (MeV)	R.A. (°)	Dec (°)	Prob.	Dist._{NGC253} (°)	σ_{68} (°)
19.18	**480**	**11.8**	**−25.0**	**0.990**	**0.3**	**1.0**
130.21	110	359.2	−26.4	0.13	11.4	6.7
135.92	410	19.9	−25.7	0.13	7.3	2.3
157.96	131	5.9	−28.9	0.26	6.4	2.9
180.22	**1300**	**11.7**	**−25.7**	**0.988**	**0.5**	**0.9**
221.92	310	7.1	−26.8	0.50	4.5	1.5
262.17	350	16.3	−25.9	0.31	4.1	1.3
276.87	530	12.8	−27.2	0.73	2.1	1.0
284.05	**1700**	**11.0**	**−25.0**	**0.999**	**0.9**	**0.4**
357.32	350	17.5	−30.9	0.14	7.5	2.6
471.16	140	10.1	−21.5	0.75	4.2	2.8

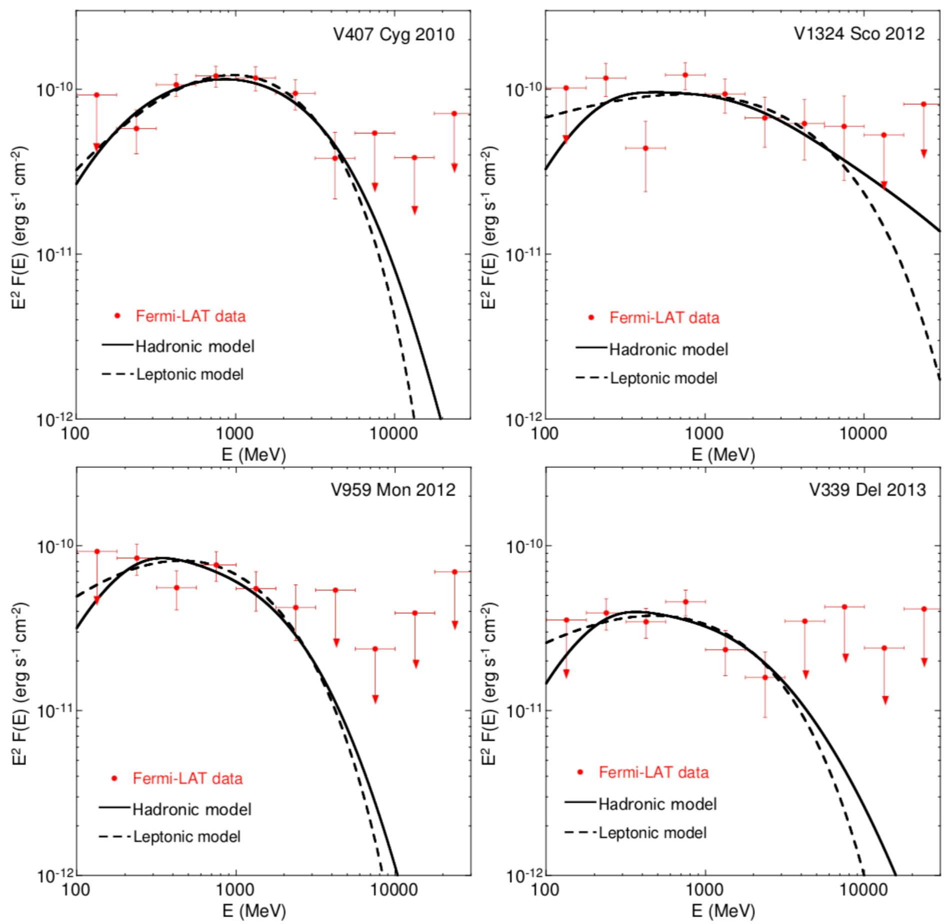
Fermi-LAT coll. , Nature Astronomy, 2021

NOVAE



Novae

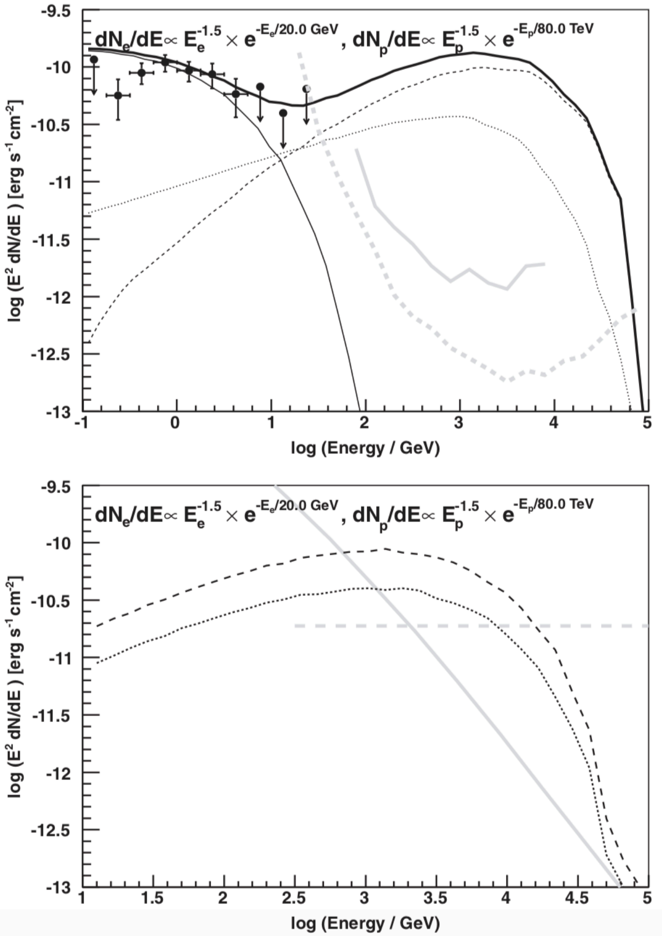
- Novae are **thermonuclear explosions** caused by accumulation of material from **donor star** on a surface of a **white dwarf (WD)**
    - If the donor star is a **red giant (RD)** this can produce a **symbiotic binary** with the **WD immersed in the RG wind**
- Novae outbursts usually last from weeks to months
- Some novae show repeated outbursts within few years/ human lifetime: **recurrent novae (RN)**
    - For a **symbiotic nova to be RN**, the **WD must be massive** (≥1.1 M⊙)
- The first nova to be detected by **Fermi-LAT** was the **symbiotic** system V407 Cyg `(Fermi-LAT, Science, 2010)`
- Several **classical** novae (WD+low-mass star) have also been **detected** by Fermi-LAT `(Fermi-LAT, Science, 2014)`
- Most of the **Fermi-detected novae show a cut-off** in their SED
    - All spectra of gamma-ray novae have been measured only up to 6 – 10 GeV



Fermi-LAT, Science, 2014

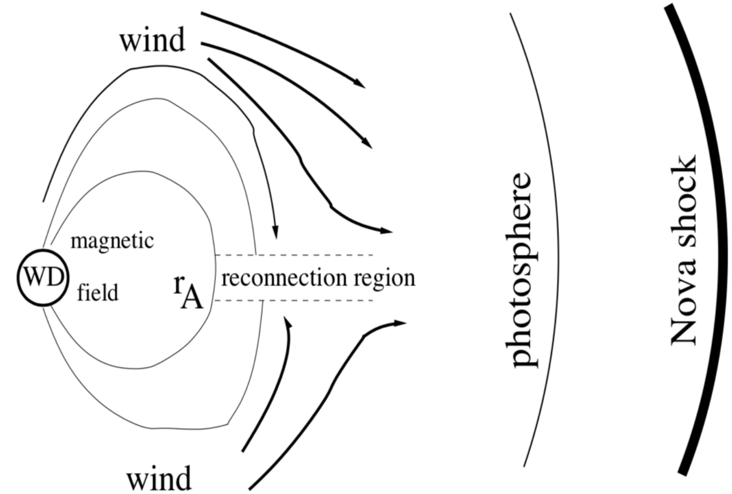
Gamma and neutrino predictions

- TeV neutrinos are expected to be produced during novae explosions and be connected with the VHE gamma-ray emission



Sitarek & Bednarek 2012

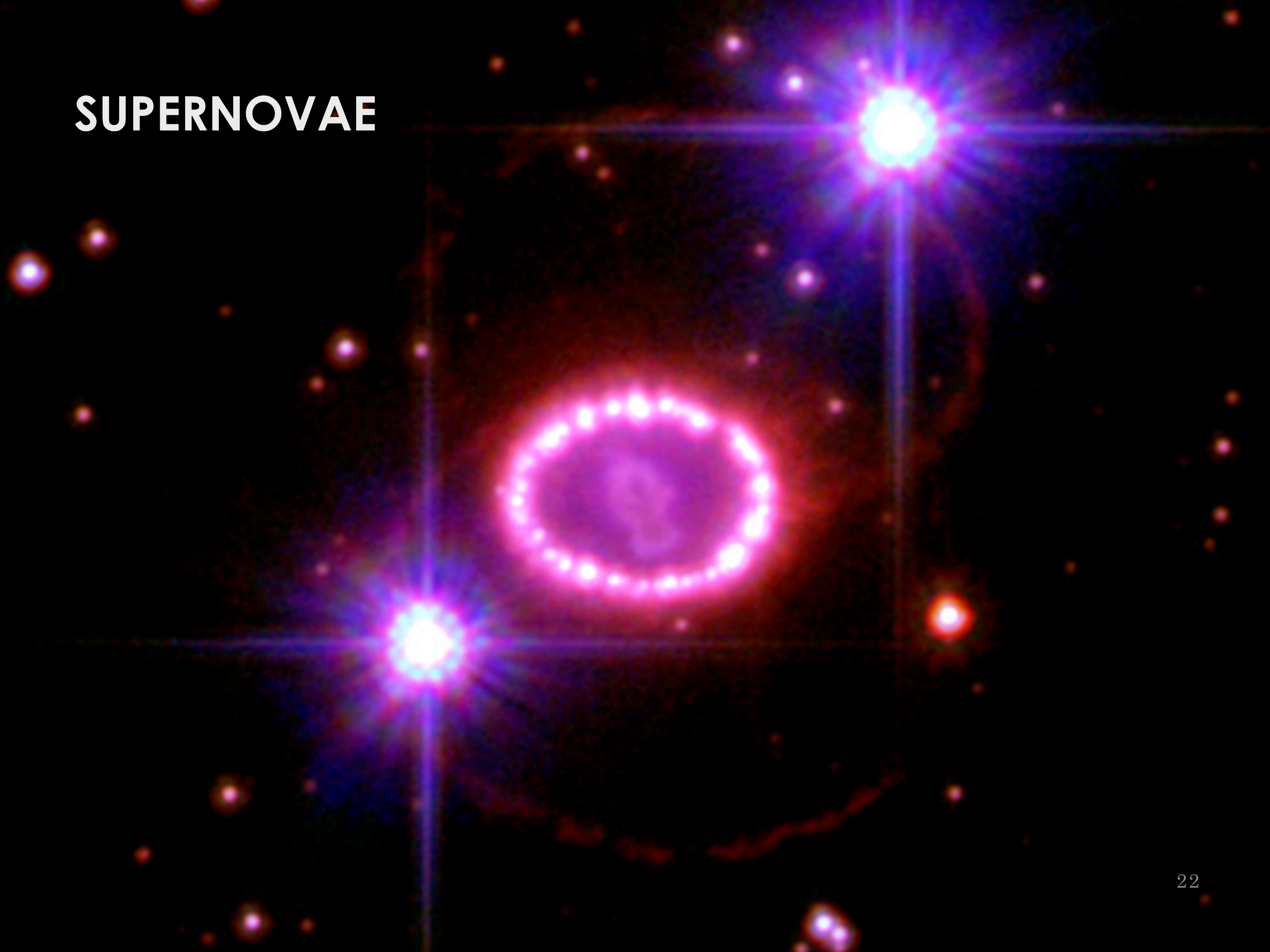
- Prediction **VHE and neutrino emissions from symbiotic nova** explosions (V407Cygni-like) (Sitarek & Bednarek 2012)



Bednarek & Smialkowski 2022

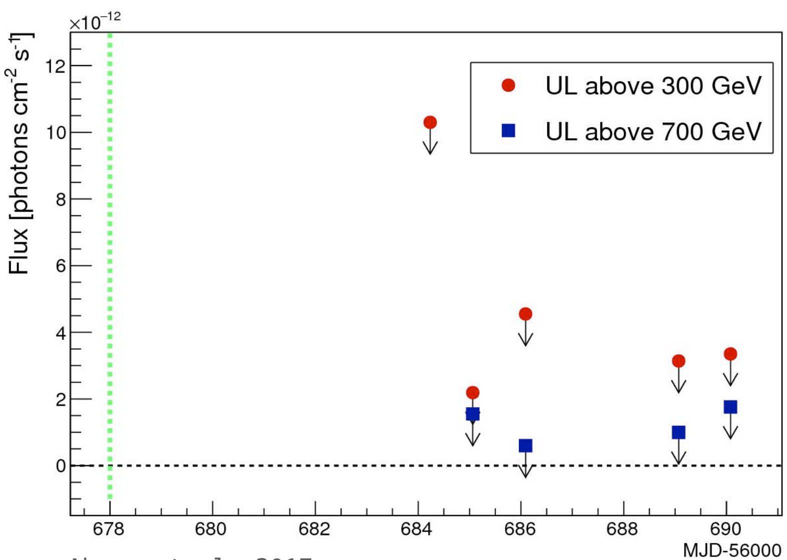
- Production of **neutrinos in collisions of relativistic protons with the matter of the fast wind from the WD** (Bednarek & Smialkowski 2022)

SUPERNOVAE



Supernovae at VHE

- IACTs campaigns on **extragalactic SNe**
  - **MAGIC ULs on type Ia SN 2014J** (Ahnen et al. 2017), located at M82 (3.6 Mpc) -> nearest Type Ia SN in the last 50 years
  - **H.E.S.S. ULs on 10 core-collapse SNe** (CCSNe) observed within a year of the supernova event (Abdalla et al. 2019)
    - The lack of detection does not necessarily indicate that the early phase of SN evolution is not generally conducive to CR acceleration
    - The non-detection **suggests that the circumstellar mediums in this subsample are not likely to be dense enough for particle acceleration**



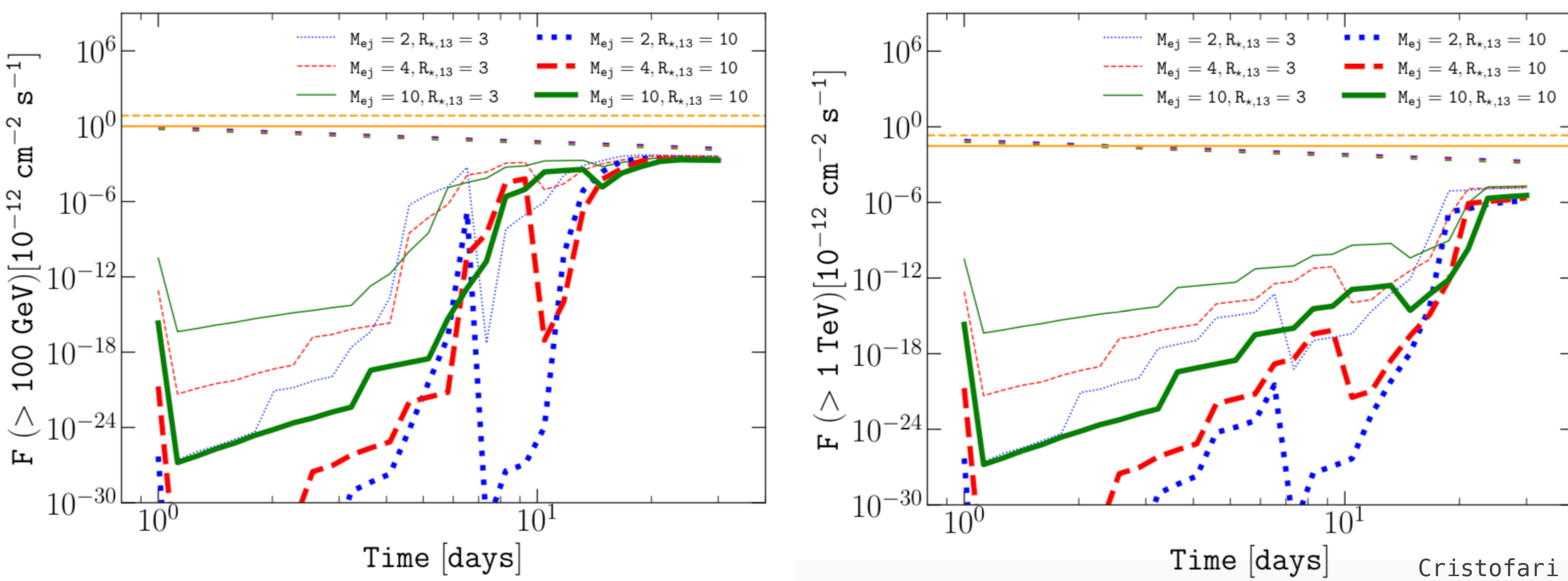
Ahnen et al. 2017

SNe	E_{Th} (TeV)	Flux UL ($> E_{Th}$)	Flux UL ($>$ 1TeV)	UL on L ($> E_{Th}$)	UL on L ($>$ 1TeV)	ULs on $\dot{M}/u_w$ Average time	Fit
		(10^{-13} cm^{-2}s^{-1})		(10^{40} erg s^{-1})		(10^{-5} M$_\odot$ yr^{-1} km^{-1} s)	
SN 2004cx	0.18	10	1.9	13.0	2.5	6.7	3.2
SN 2005dn	0.21	2.2	0.41	6.2	1.2	3.8	0.26
SN 2008bk	0.21	6.0	4.8	0.18	0.15	1.4	0.4
SN 2008bp	0.21	29	5.5	46.7	8.9	15.9	12.3
SN 2008ho	0.33	16	7.7	52.8	25.4	9.4	5.3
SN 2009hf	0.21	20	5.3	111	29.5	19.9	15.9
SN 2009js	0.63	15	11	7.3	5.4	3.1	0.9
SN 2011ja	0.21	20	5.2	1.1	0.28	1.77	1.6
SN 2012cc	0.72	15	10	11.5	7.7	11.6	3.7
SN 2016adj	0.196	8.8	1.7	0.24	0.05	0.25	0.20

Abdalla et al. 2019

CCSNe as TeV candidates

- CCSNe can **fulfil the right conditions for CR acceleration** (Katz et al. 2011; Murase et al. 2011; Bell et al. 2013, Cristofari et al. 2022)
  - Detection at **radio frequencies confirm the presence of relativistic electrons** and shows that they could be efficient energetic particle accelerators
  - Some author **predicts a gamma-ray flux of hadronic origin** from SNe and young SNRs (Kirk et al. 1995, Dwarkadas 2013)
  - VHE emission is expected in Type II CC-SNe but the **gamma-ray signal can be attenuated in the first 10-20 days** (Cristofari et al. 2022)
    - The gamma-ray signal is expected to be significantly lower than the typical sensitivity of IACTs for objects located at 1 Mpc
    - Galactic CCSNe and those located inthe Magellanic Clouds are expected to be detectable by CTA
- In the case of **Galactic CCSNe observations can be triggered by an observation of a prompt neutrino flare, since the EM signal is expected to be delayed** with respect to neutrinos by minutes to hours
-



Cristofari et al. 2022

Summary

- **Current generation of IACTs** are searching for the **TeV counterpart of several Galactic sources**
    - Detection of the **first (symbiotic recurrent) nova at VHE**
- **CTA** will perform detections of **Galactic transients with unprecedent sensitivity**
- **Microquasars**:
    - Current generation of IACTs have set constraining limits
    - **CTA** will **detect for the first time several microquasars**
        - **Putative detection of CygX1 (steady+transient)**
    - If protons are accelerated, microquasars could contribute to Galactic CR budget and neutrinos can be produced

- **Flares from the Crab Nebula**:
    - GeV detection by Fermi-LAT, not yet detected by IACTs
    - **Detection both with CTA-N and with LSTs subarray** in **<5 h**

- **Magnetars**
    - First F**RB connected to a magnetar**
    - **GeV** detection of an extragalactic magnetar (giant flare)

- **Novae**
    - **RS Oph as first nova to be detected at VHE**
    - Observations proved a **hadronic origin of the gamma-ray emission**
    - No neutrino counterpart reported

- **Supernovae**
    - **CCSNe** as perfect **candidates as TeV emitters**
        - **Gamma-ray flux likely to be attenuated in the first 10-20 days**
    - **Galactic and Magellanic sources** have better chances to be detected

- **Open questions:** Can neutrinos be detected from any of these sources during transient episodes? Can they be used as trigger for putative VHE emission? Can we detect magnetar/FRB emission? Are classical novae gamma-ray emitters?

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Synergies at new frontiers at gamma rays, neutrinos and gravitational waves
Tokyo, Japan, March 24-25, 2022