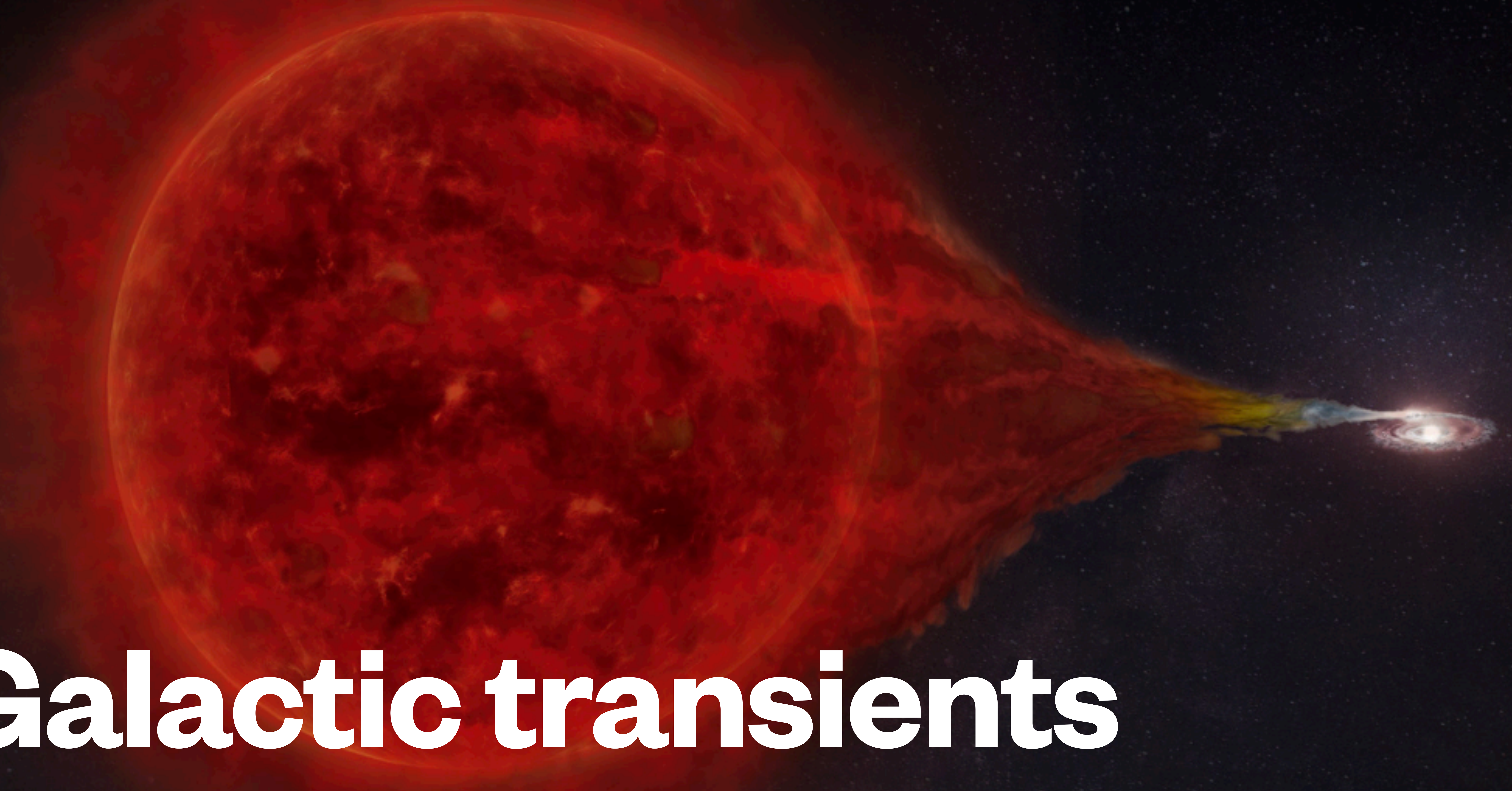
Exploring the Universe's extreme events



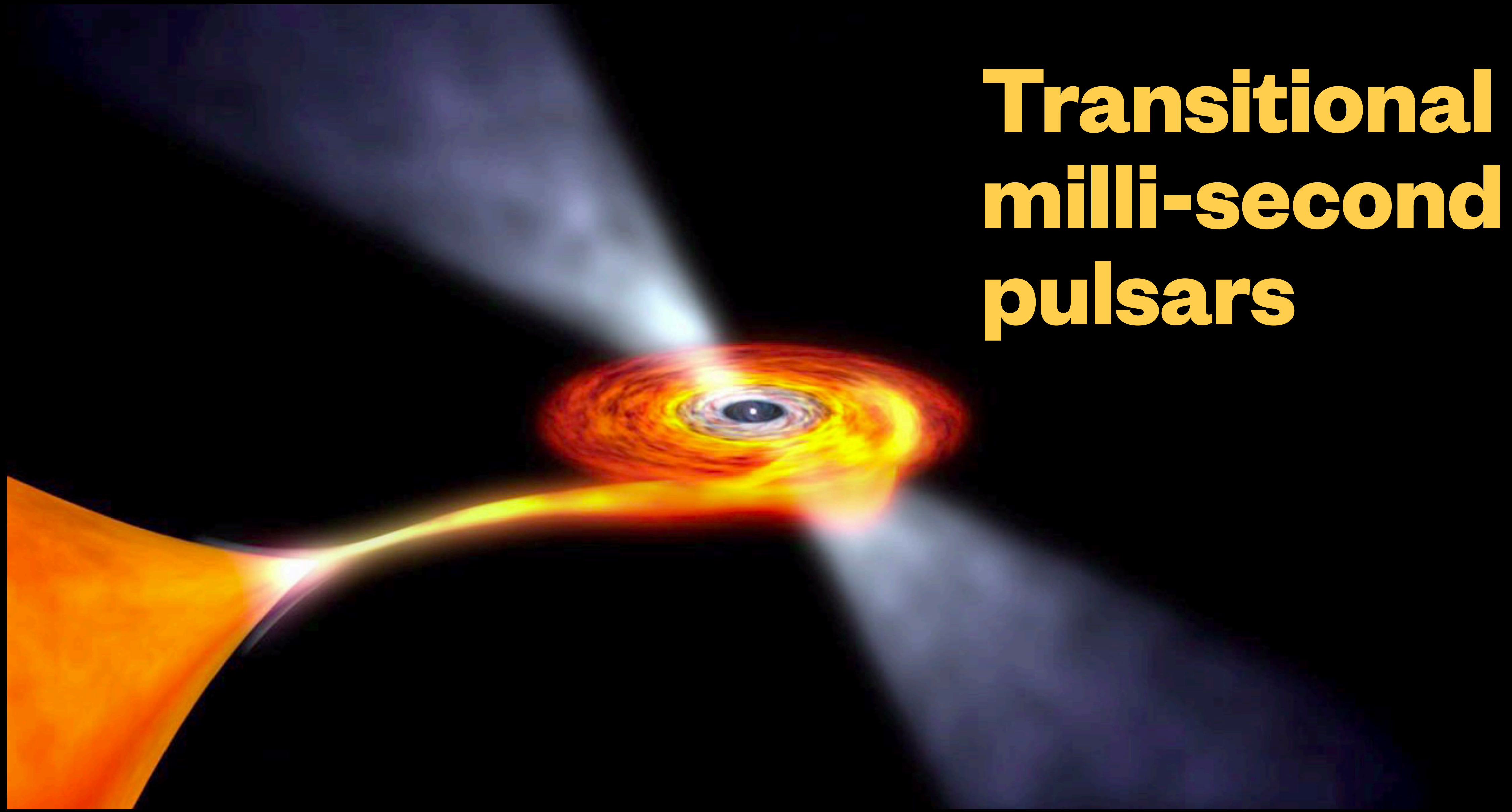
Galactic transients

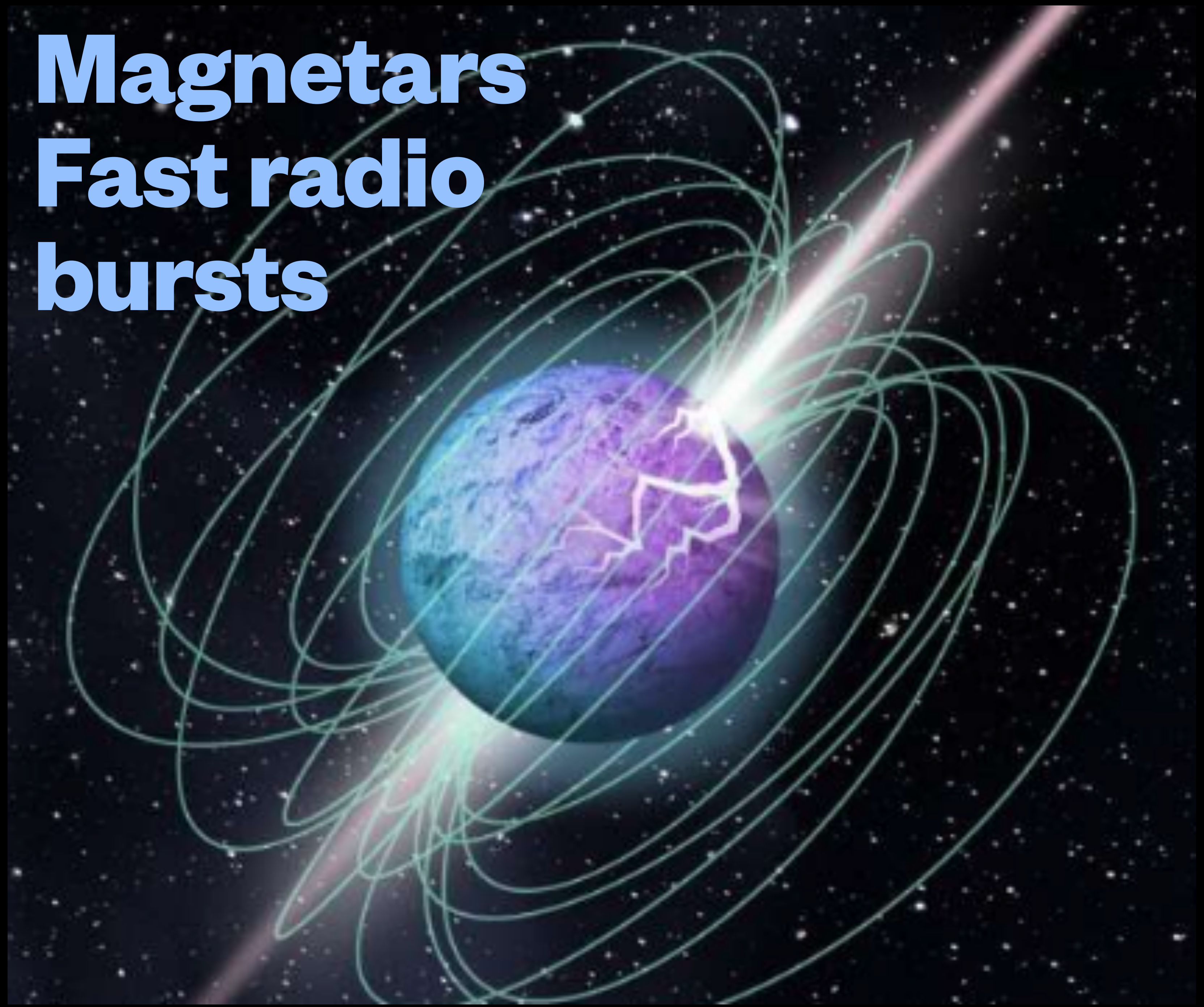
DANIELA HADASCH, AUGUST 8, 2023

superbossa/MPP

Definition of Transient sources

- A transient event refers to a **sudden and temporary change** in the brightness of a celestial object and is characterized by **significant changes** in the emitting object's properties.
- Unlike variability, transient events are **not part of the regular behavior** (e.g. AGN flares) of the object but are caused by specific and often rare processes or interactions.


Transitional
milli-second
pulsars


Magnetars
Fast radio
bursts

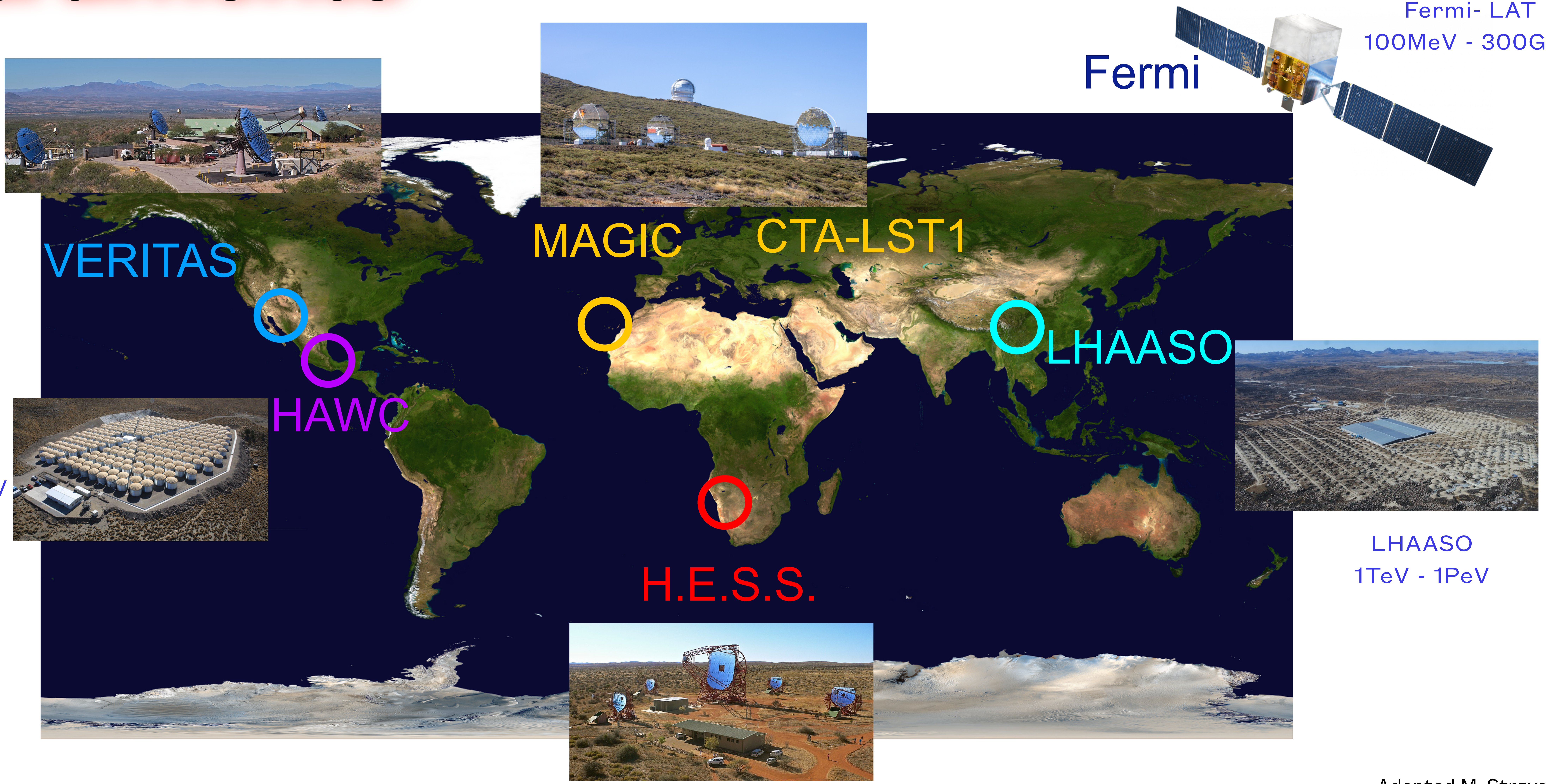

Supernovae


Novae

Instruments

Fermi-GBM
8keV - 30MeV
Fermi- LAT
100MeV - 300GeV

Cherenkov
telescopes
50GeV - 50TeV



HAWC
100GeV - 100TeV

LHAASO
1TeV - 1PeV

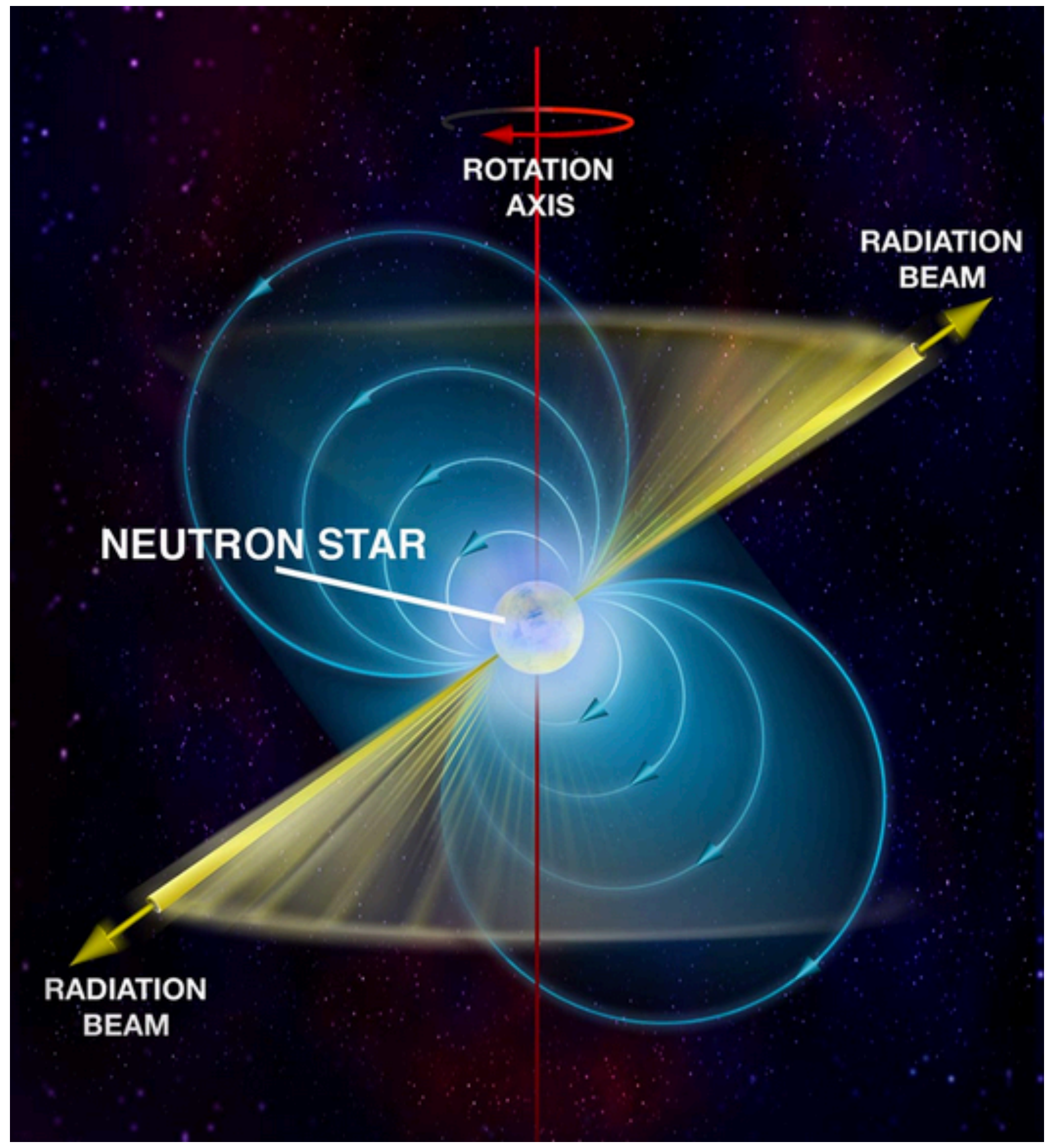
Adapted M. Strzys

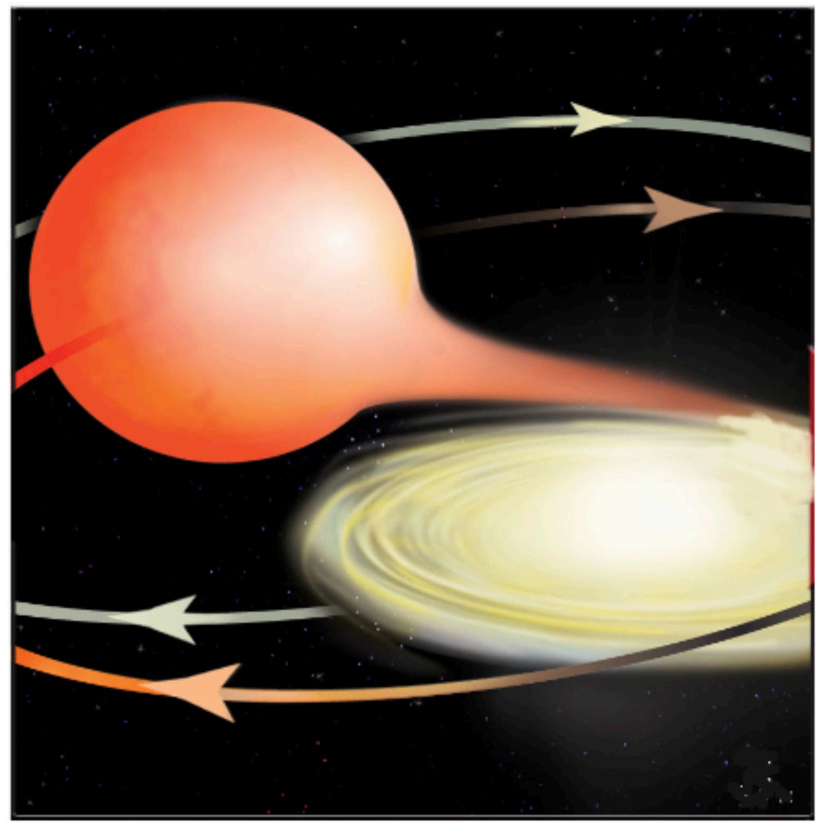
Transitional milli-second pulsars

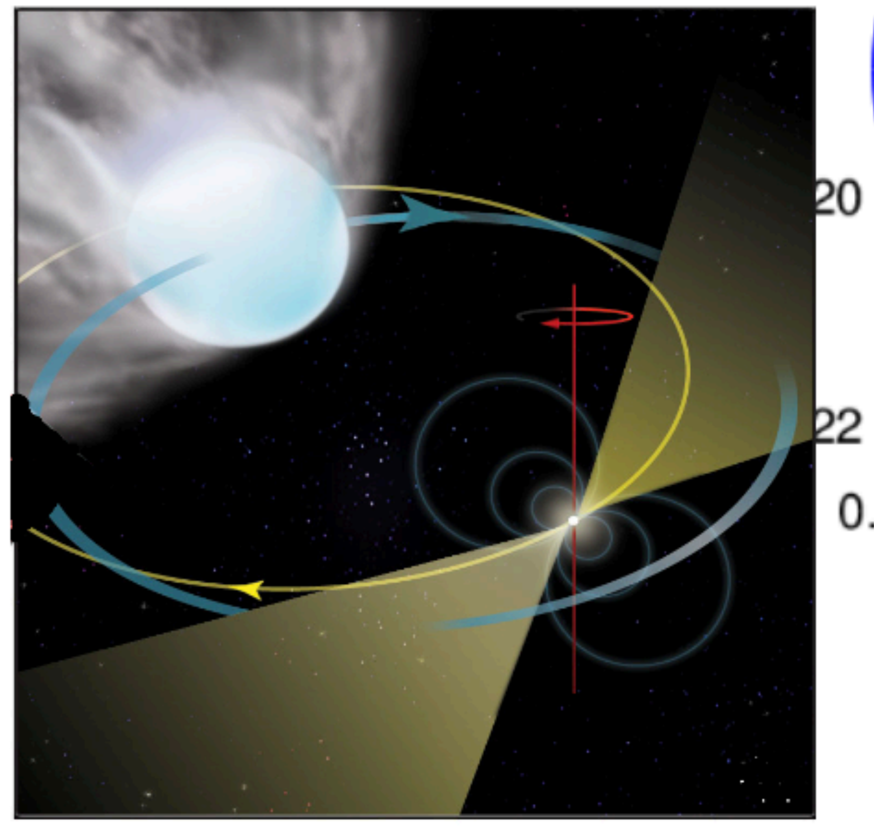
Milli-second pulsars (MSPs)

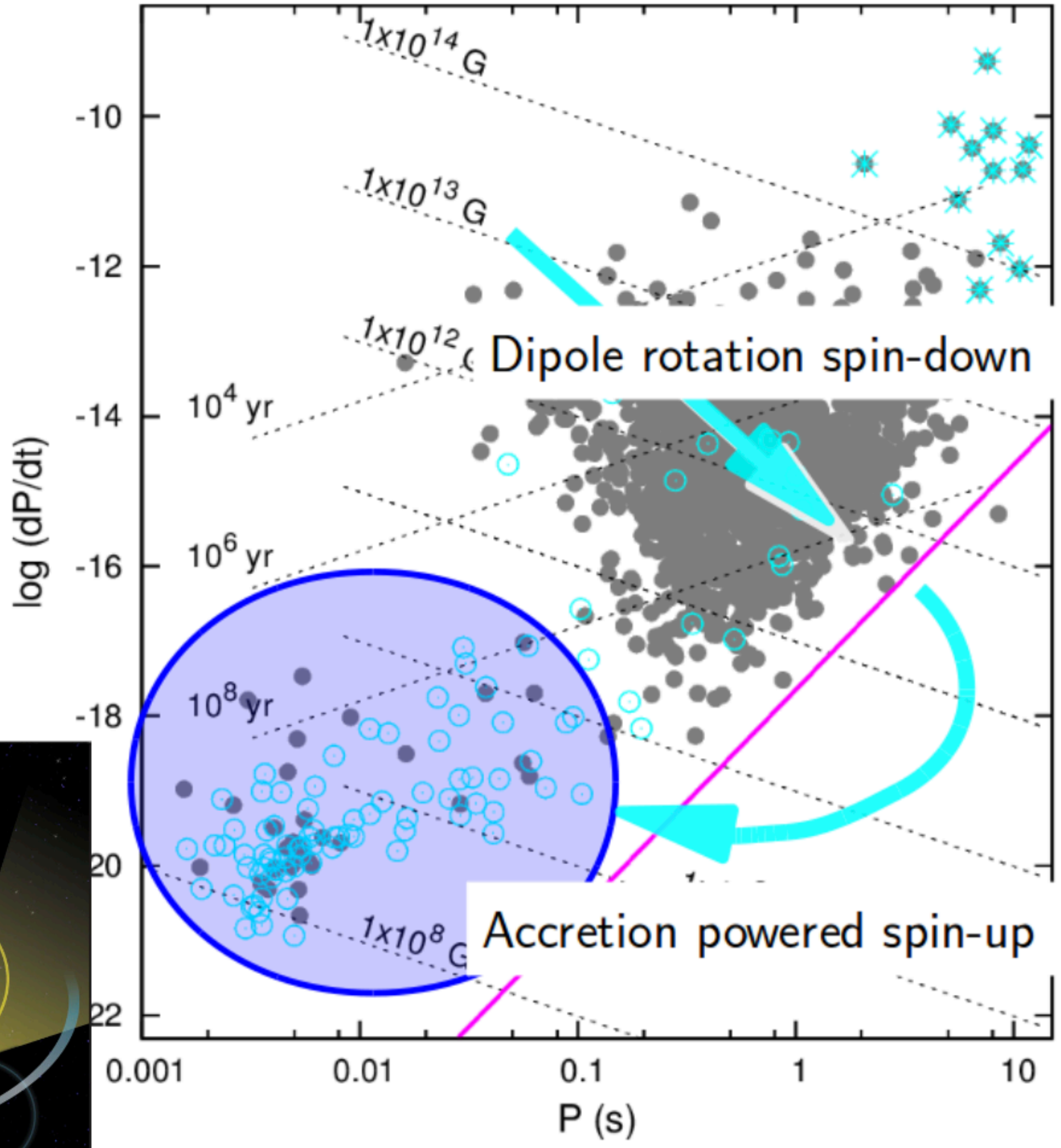
- Weakly magnetized neutron stars
  - **Neutron star**: collapsed core of a massive star; densest known stellar object: r ~10 km, m~1.4 $M_\odot$
  - **Pulsar**: rotating neutron stars emitting beams of electromagnetic radiation
- Often found in globular clusters
  - Old systems
- Often part of close binary systems

➡ **Recycled low-mass X-ray binaries** [Backer+1982, Alpar+1982]









Slide adapted from Papitto

Transitional milli-second pulsars (tMSPs)

Composed by milli-second pulsar + low mass star

Switch between two states

Low Mass X-Ray Binary (LMXB)

High mass in-flow rate:

Gravity dominates

↓

Accretion disc

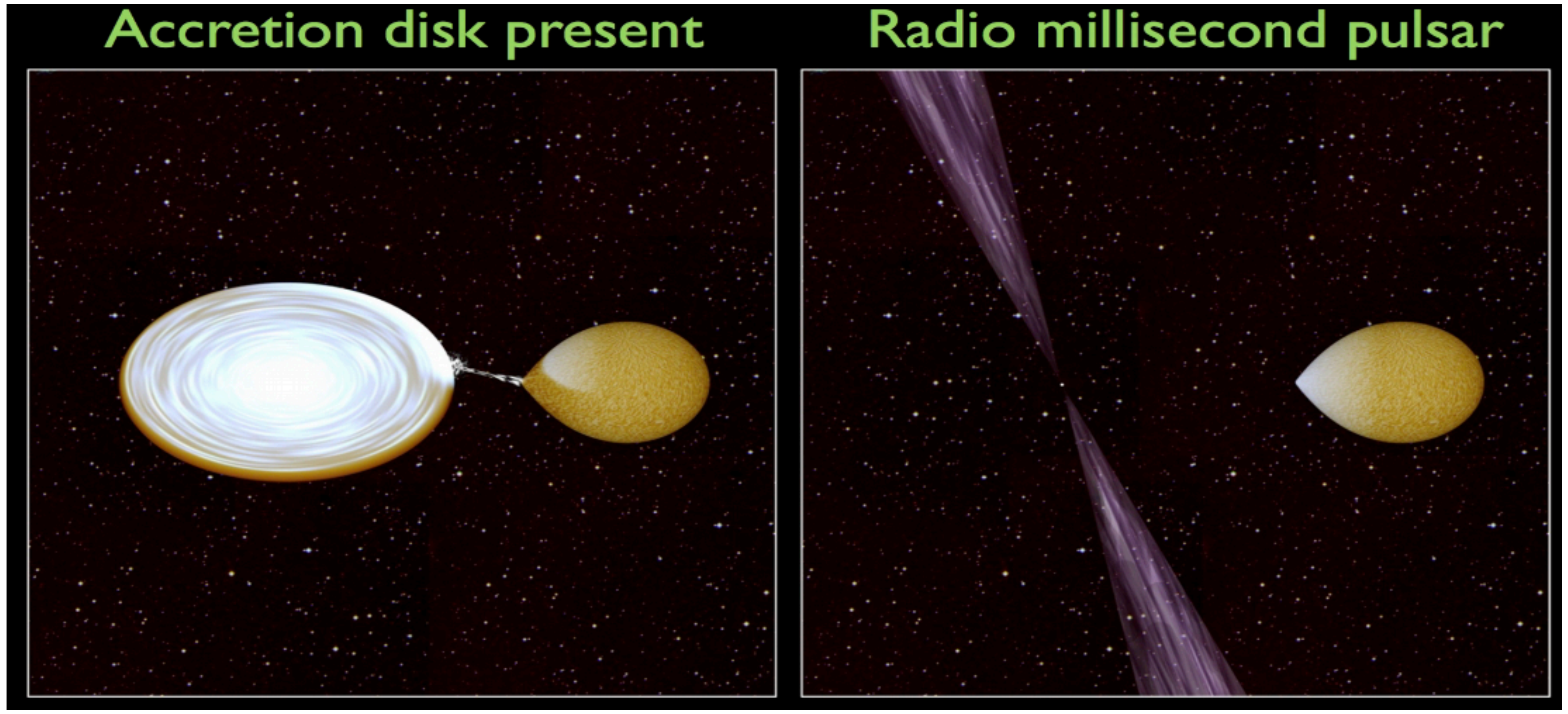
Radio MSP

Low mass in-flow rate:

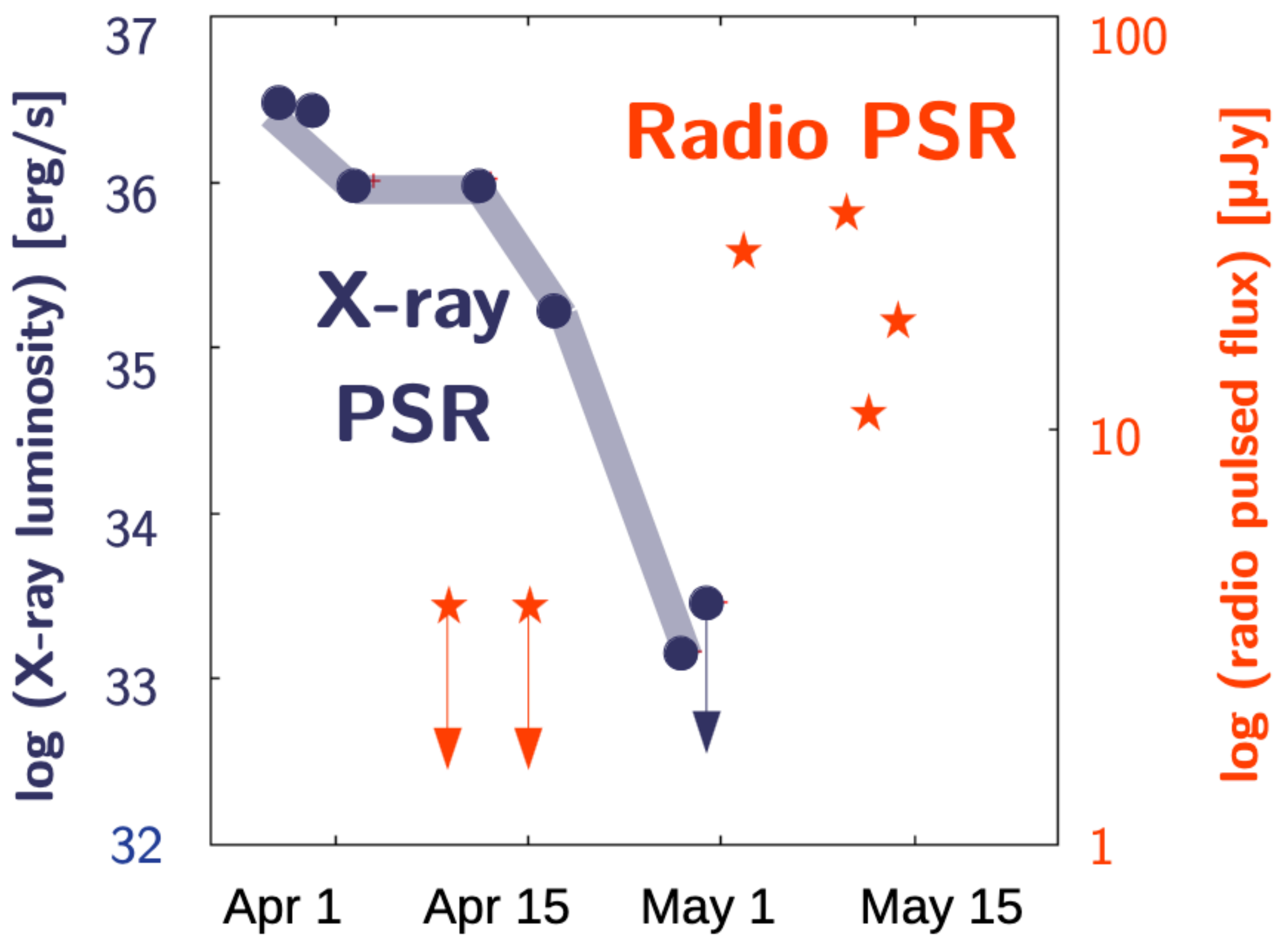
Magnetic field dominates

↓

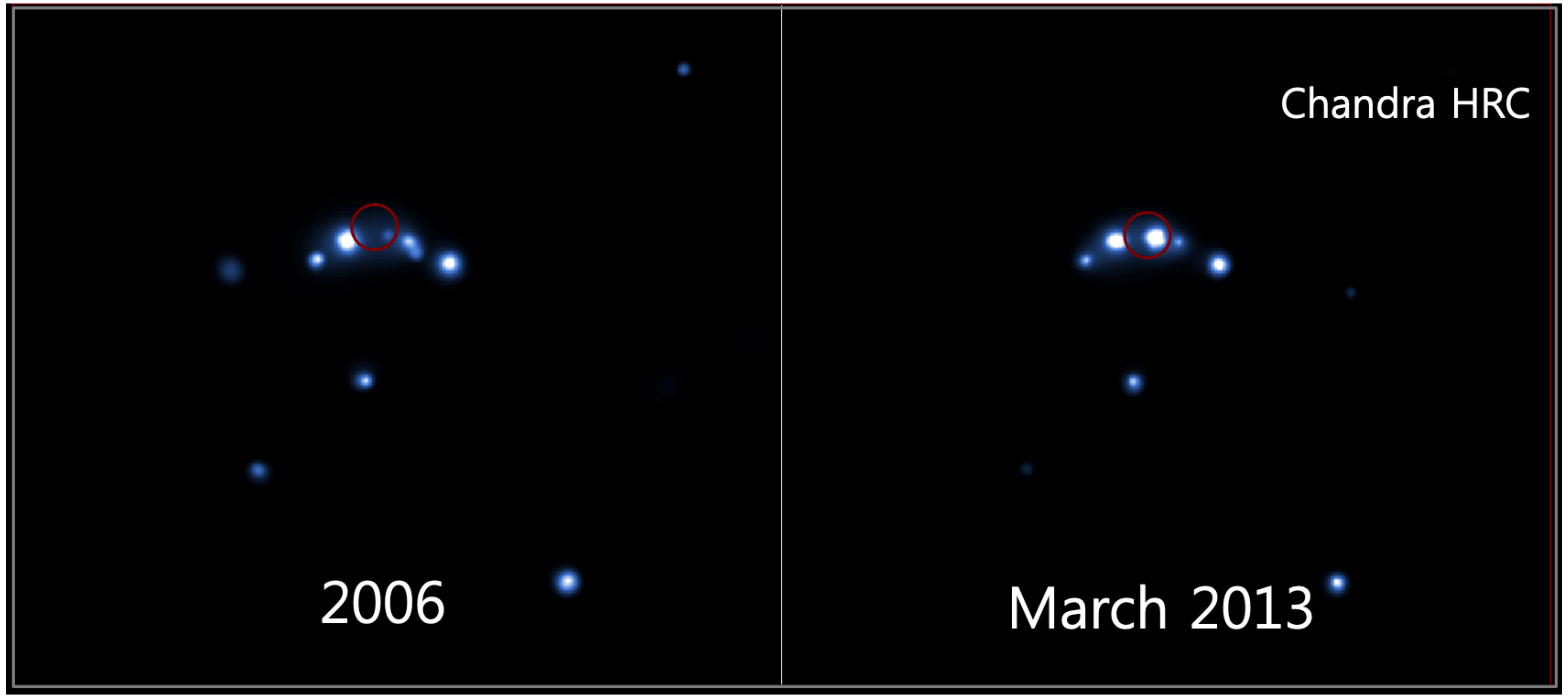
Rotation powered MSP



Swinging milli-second pulsar in M28

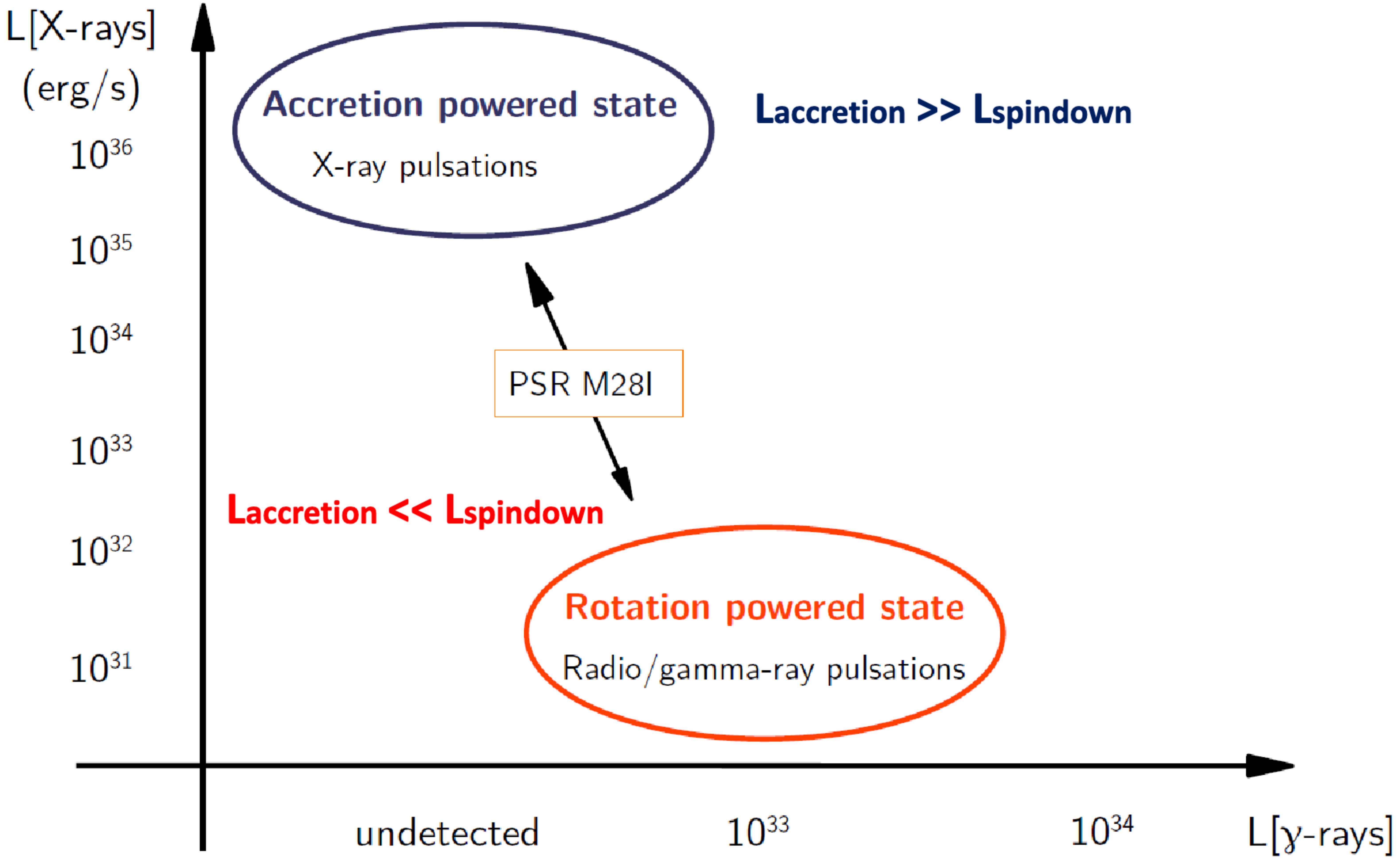


X-ray luminosity ~ few x 10^{36} erg/s → accretion power

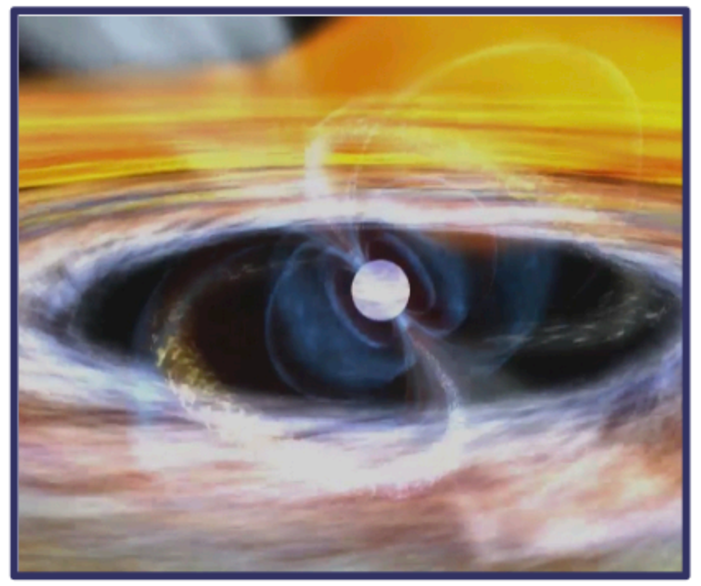


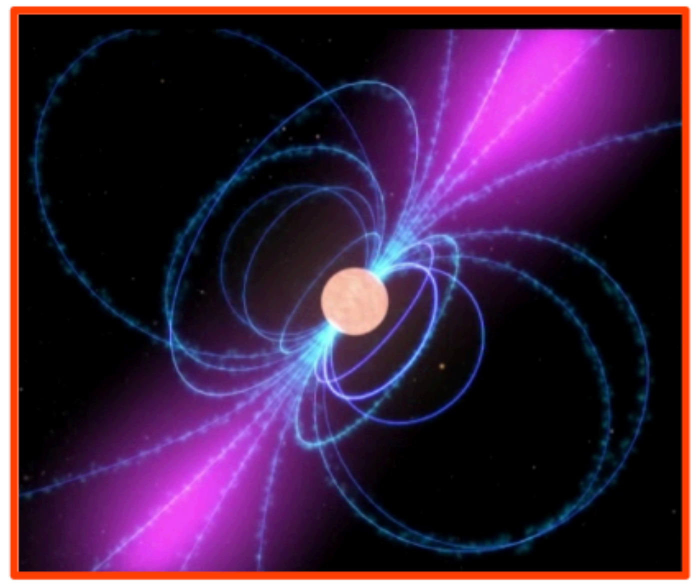
Papitto+2013

Transitional milli-second pulsars



Xray PSR accretion powered



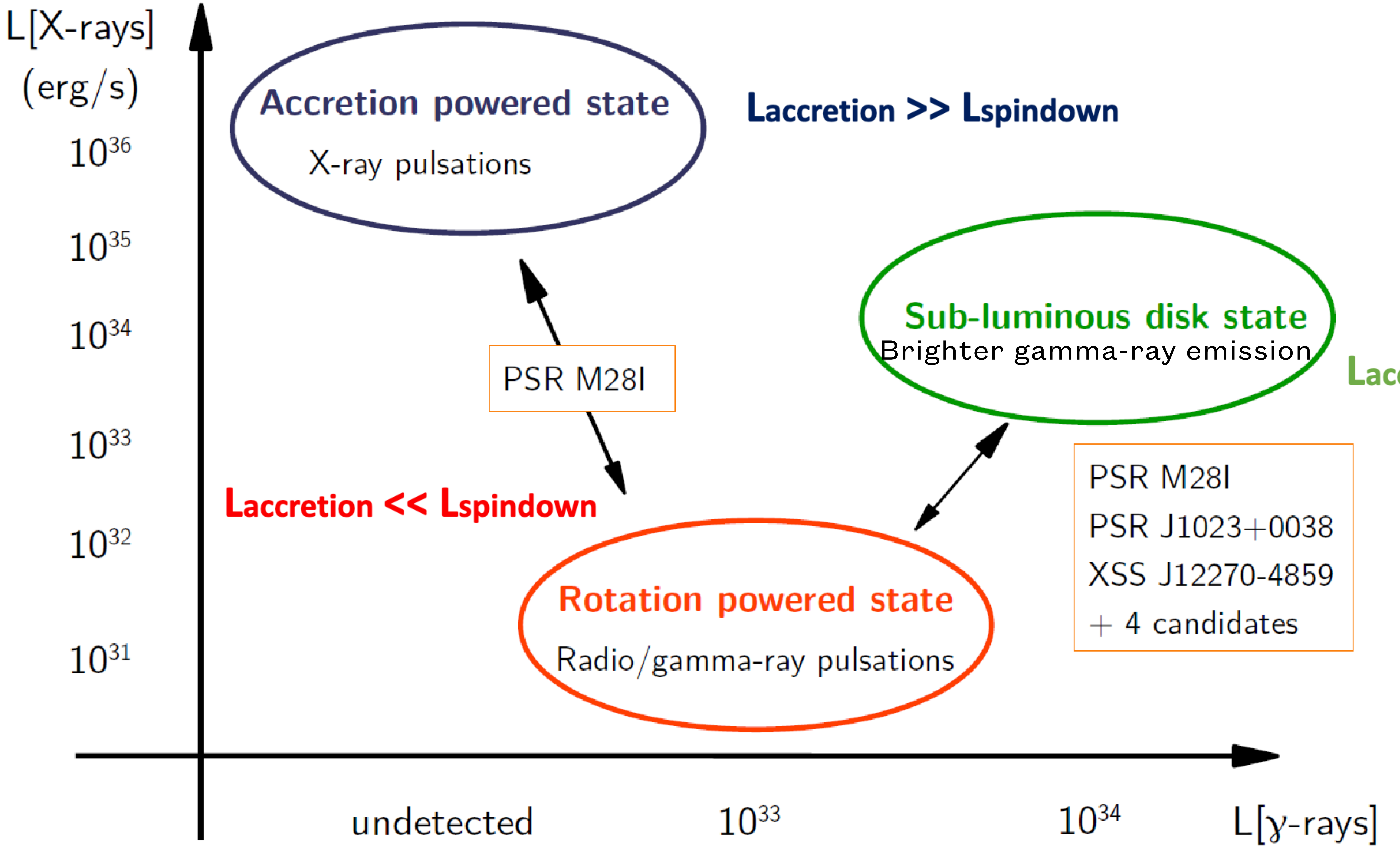


Mass in-flow rate

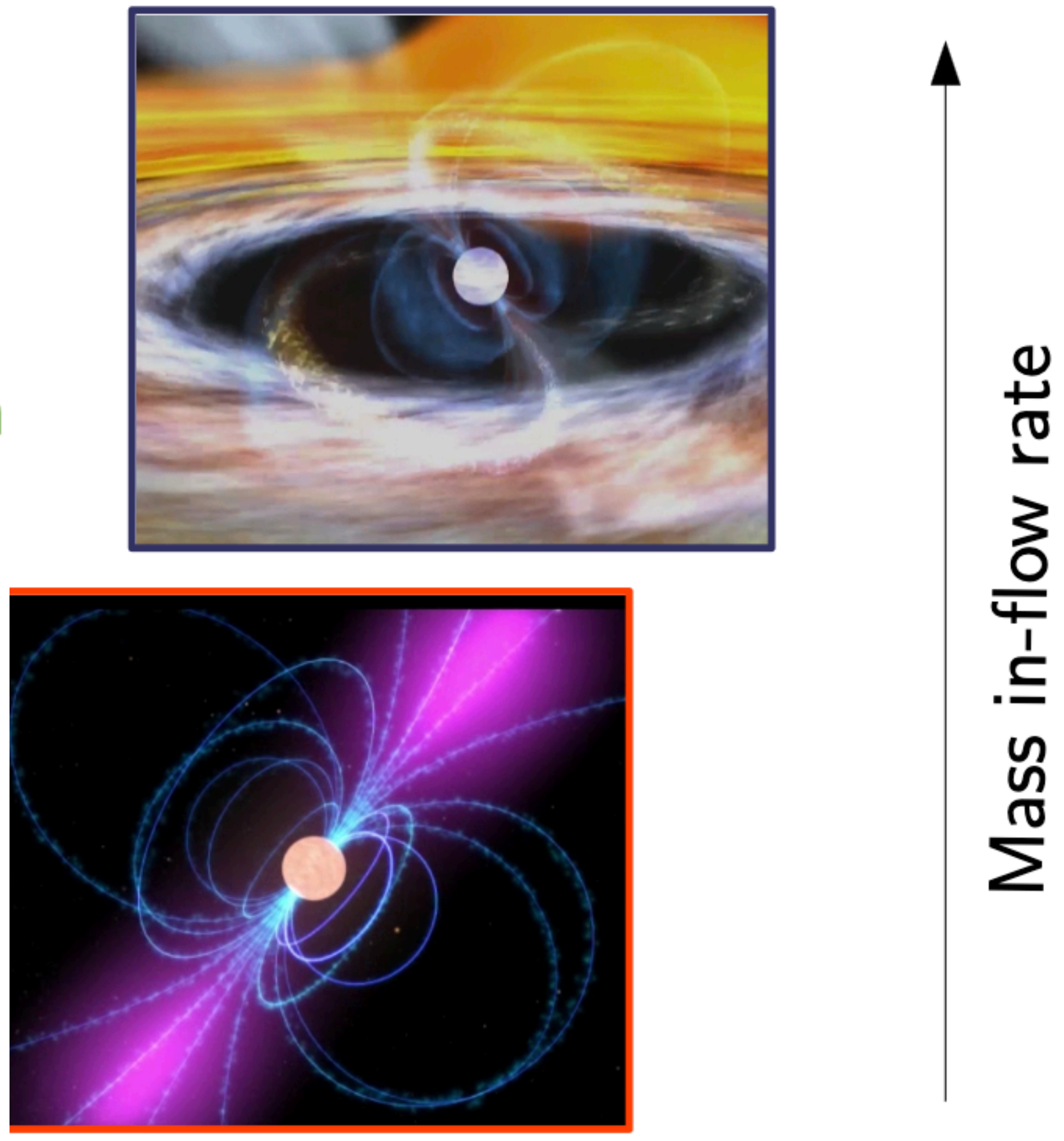
Rotation powered Radio PSR

Papitto, VGGRS, 2023

Transitional milli-second pulsars



Xray PSR accretion powered

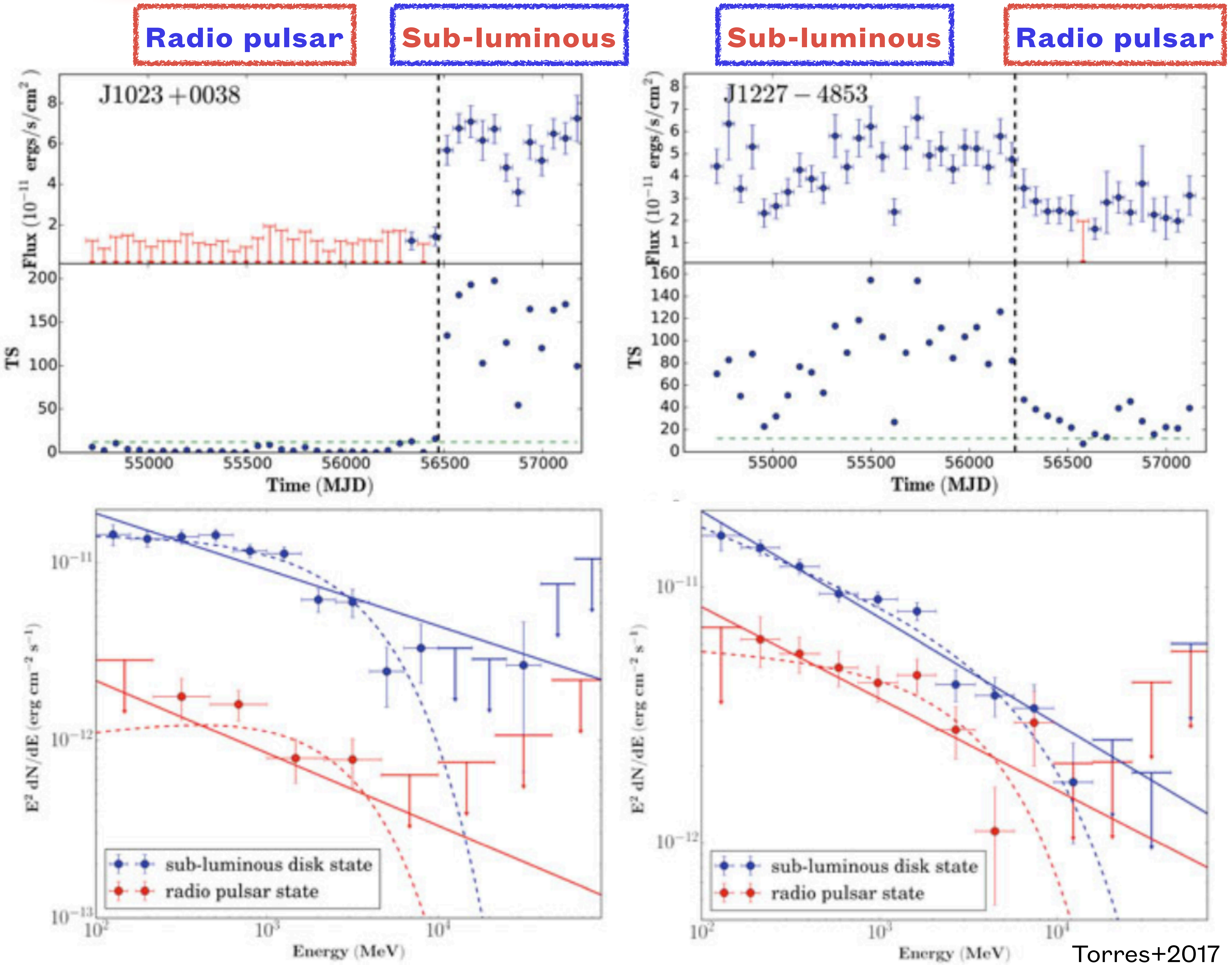


:ation powered Radio PSR

Papitto, VGGRS, 2023

tMSPs at high energies

- **Search for transitions** in 7 years of *Fermi*-LAT data [Torres+2017]
  - Transition found in 2 out of 3 known systems (PSR J1824−2452I not included in analysis since it is located in globular cluster M28 that is a bright gamma-ray source)
  - gamma-ray flux varies by a factor of 2–5
- **High gamma-ray state is variable**
  - Shorter-timescale phenomena like in radio/X-ray/optical
- **High-energy cutoffs at a few GeV**
  - TeV emission possible? Second component?
  - Non-detection of J1023 at TeV by VERITAS [Aliu+2016]



Torres+2017

Open questions

- What drives variations of the mass in-flow rate?
  - Tidal interactions? Mass accumulation?
- Origin of the gamma-ray emission during the intermediate accretion stage?
  - Propeller/magnetospheric origin?
- Are all millisecond pulsars in close binary systems transitional?
- Do they emit in the TeV range?
  - Cutoff at GeV does not look promising, but another component coming from much farther out than the surroundings on the pulsar might be possible.

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Observation strategy

Look for distinctive variability in the optical and X-ray band in the error bar of unidentified *Fermi*-LAT sources.

For TeV: Search for the closes ones (e.g. PSR J1023-0038 which is at 1.4 kpc)

Magnetars

Fast radio bursts

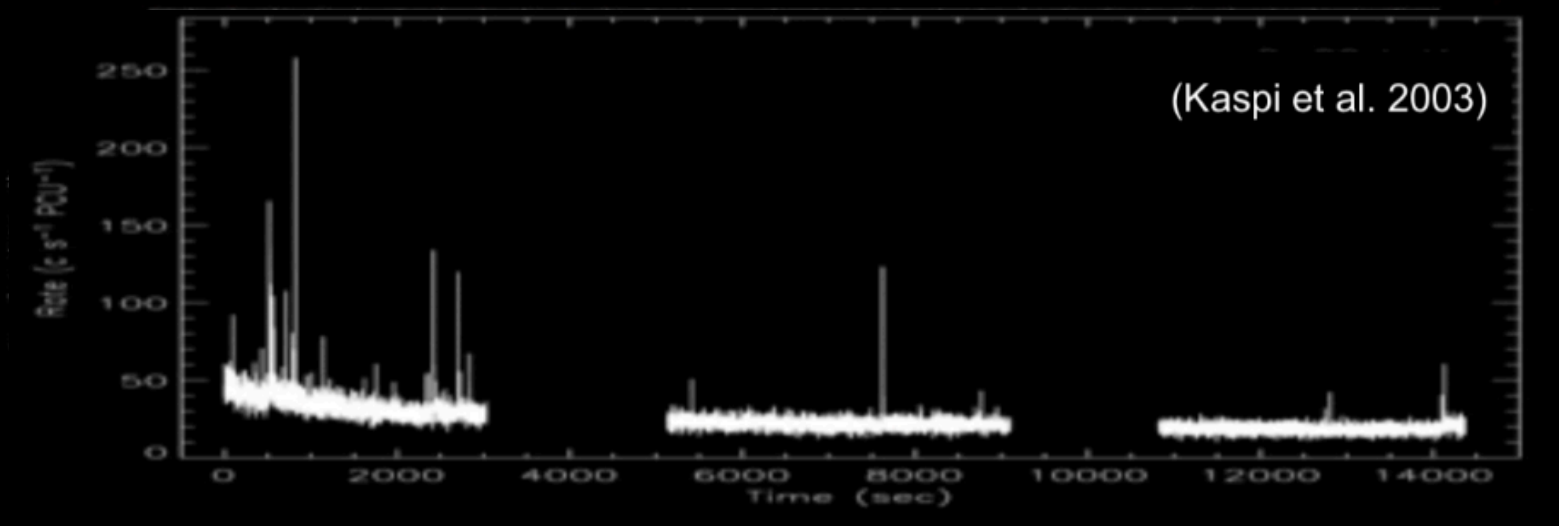
NASA

Magnetars

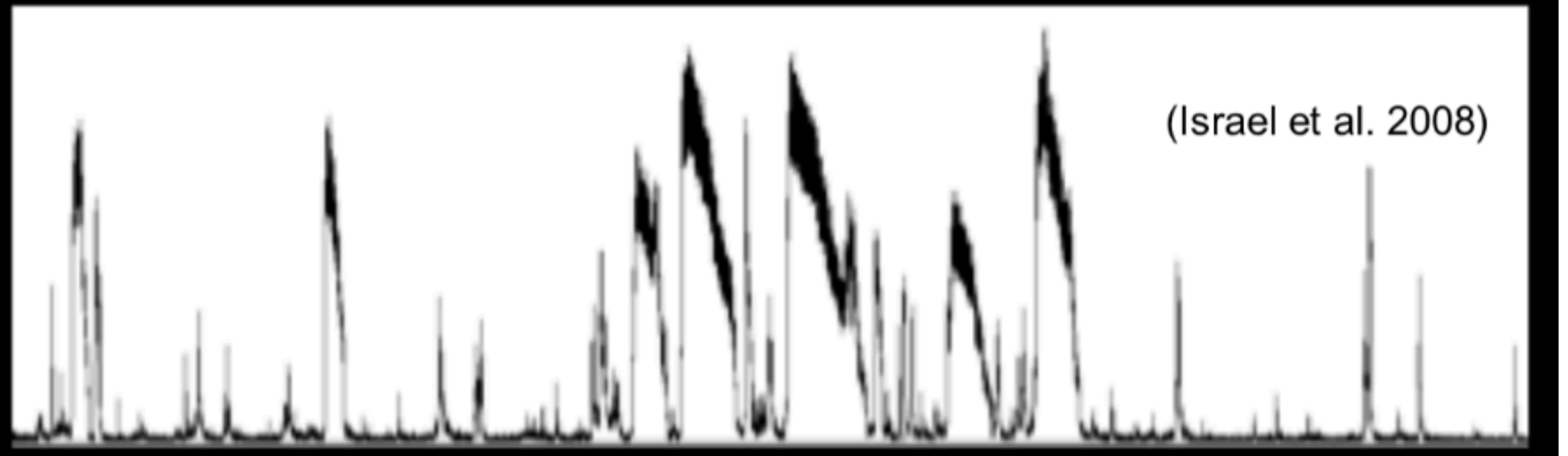
X-rays

- Neutron stars with ultra-high magnetic fields (B~10^{14}-10^{15}G)
- ~30 Magentars known
- Bright X-ray pulsars
  - L_X ~10^{33}-10^{35} erg/s
- Rotating with periods of 2-12s

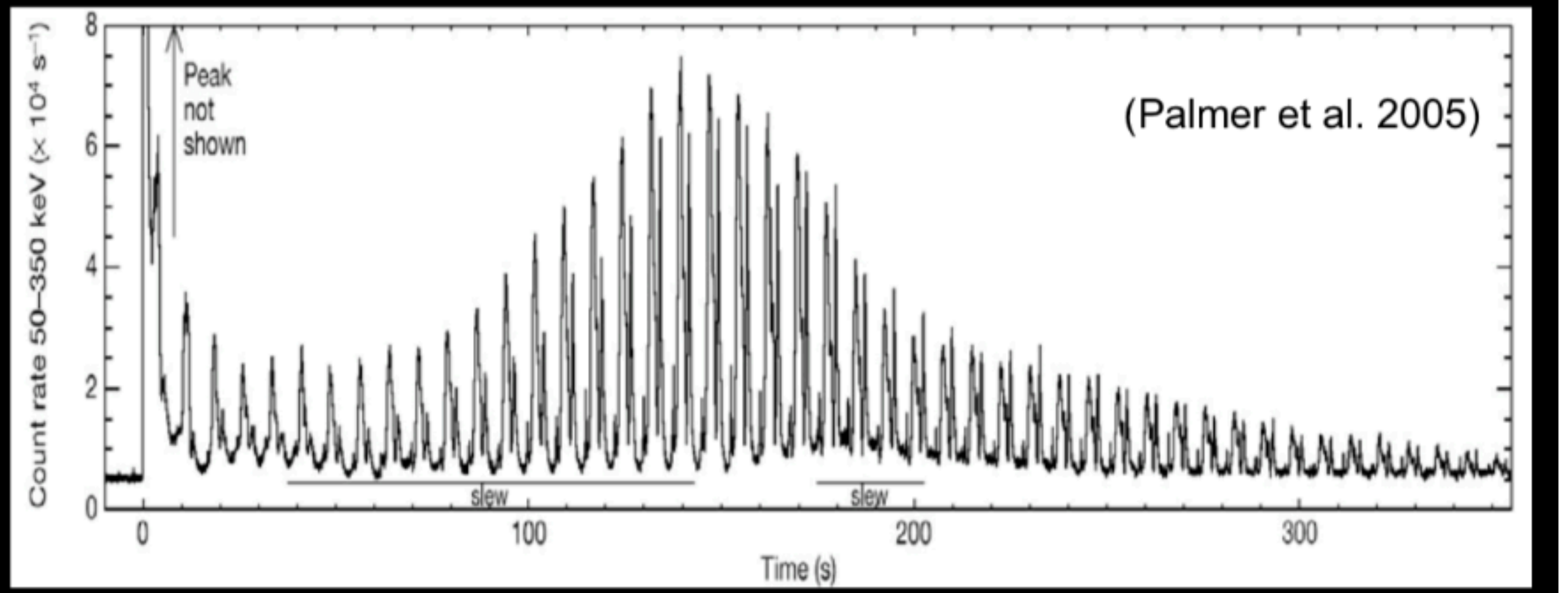
Short bursts
- the most common
- they last ~0.1s
- peak ~10^{41} ergs/s
- soft γ-rays thermal spectra



Intermediate bursts
- they last 1-40 s
- peak ~10^{41}-10^{43} ergs/s
- abrupt on-set
- usually soft γ-rays thermal spectra



Giant Flares
- Output of high energy is exceeded only by blazars and GRBs
- peak energy > 3x10^{46} ergs/s
- burst tail can last >500s, showing the NS spin



Slide from N. Rea

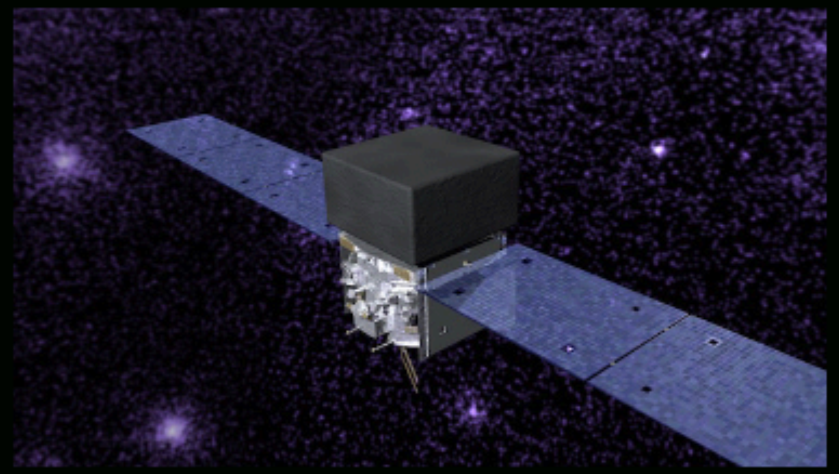
GIANT FLARE NGC253
15 abril 2020

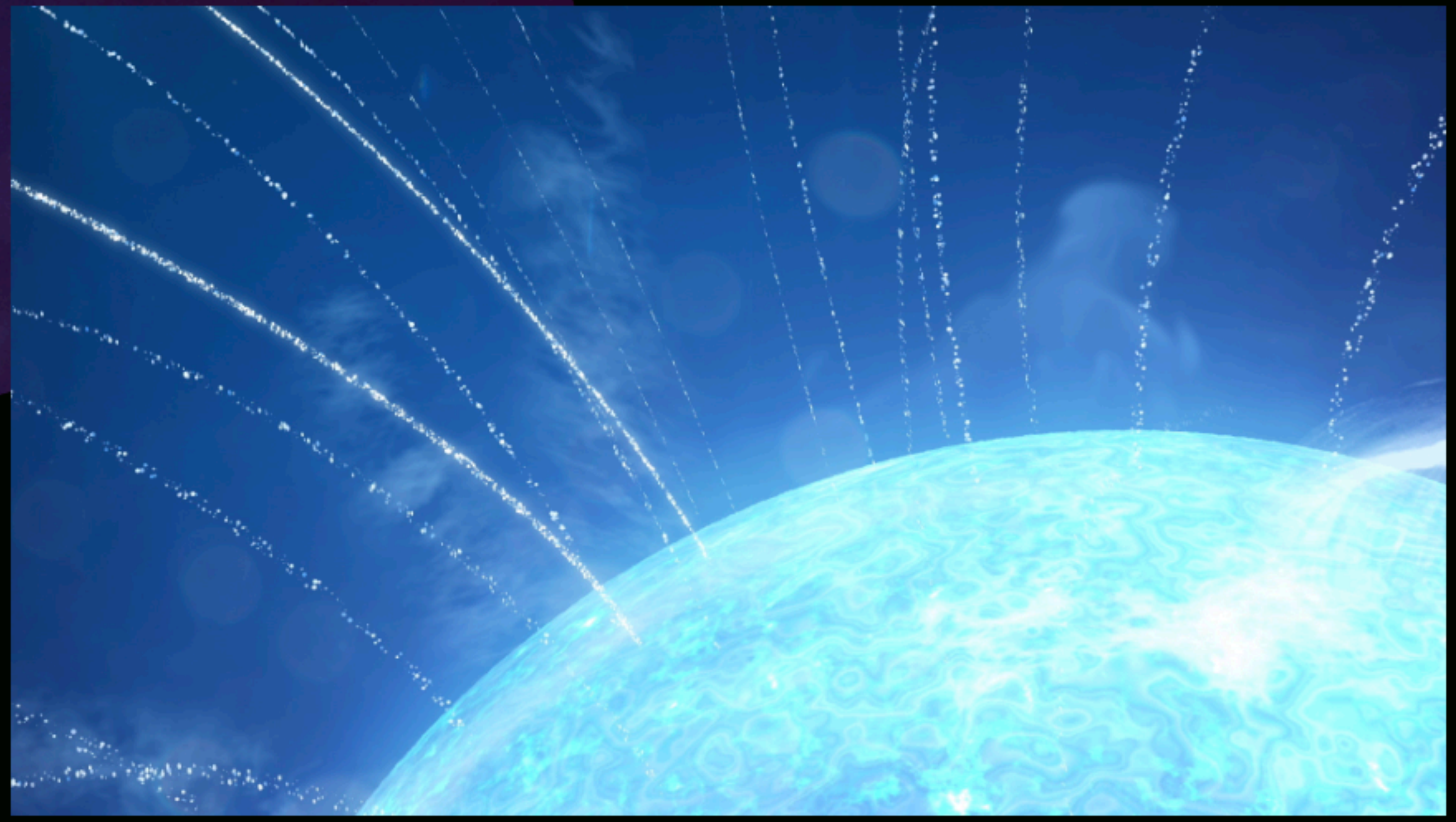
- **Duration: 140 ms**
- Very rapid **flare risetime ~77 μs** (Fermi-GBM coll. 2021)

Slide from A. Lopez

GIANT FLARE NGC253

Fermi-LAT: first GeV detection of a magnetar



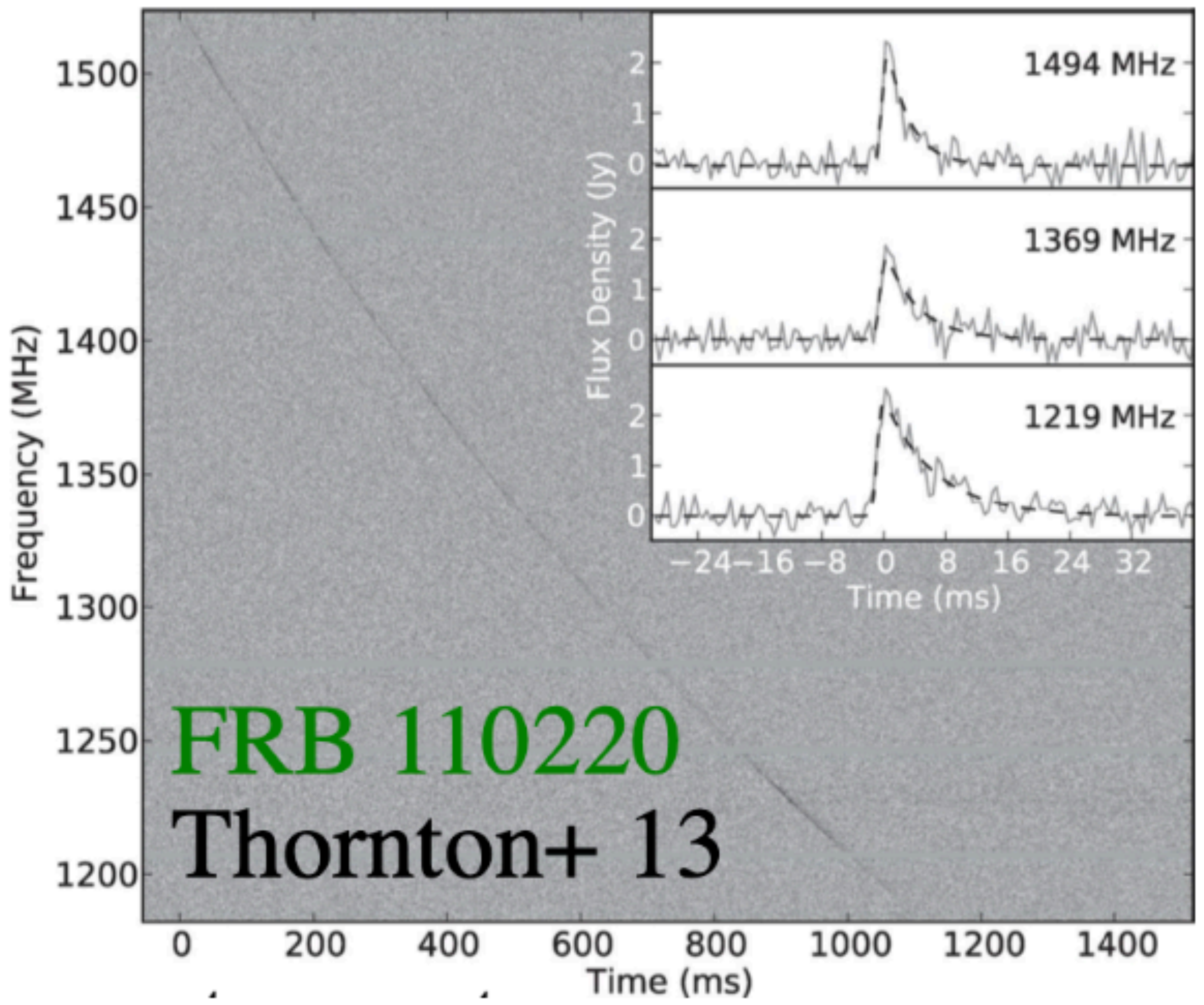


- **Detection of 3 HE photons: 480 MeV, 1.3 GeV and 1.7 GeV** (Fermi-LAT coll. 2021)
- GeV emission arises from dissipation associated with the collision between an ultra-relativistic outflow from the GF and an external shell of swept-up material

Slide from A. Lopez

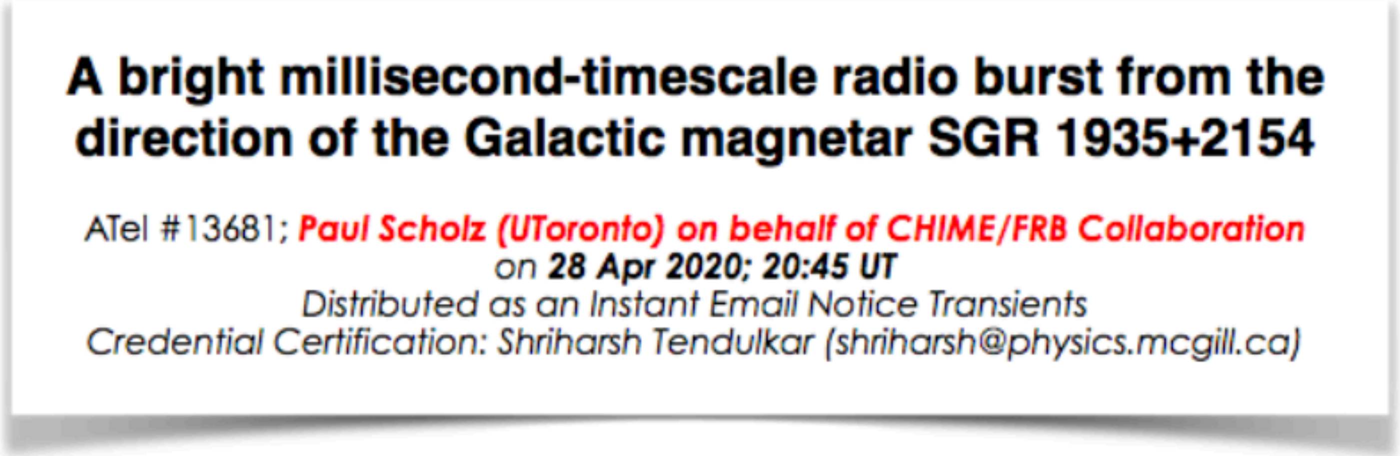
Fast radio bursts (FRBs)

- **Transient radio pulses of milli-sec duration**
- Likely extragalactic, several confirmed with host galaxy ID (z~0.034-0.66)
  - Outer regions of galaxies within spiral arms or beyond central bulge
- Over 150 FRBs have been discovered (http://frbcat.org/), ~20 repeating
- Radio analysis pipelines tailored to search for short bursts in almost real-time —> emit alerts for multi wavelength observations
- No counterpart to radio emission was detected before April 27, 2020…



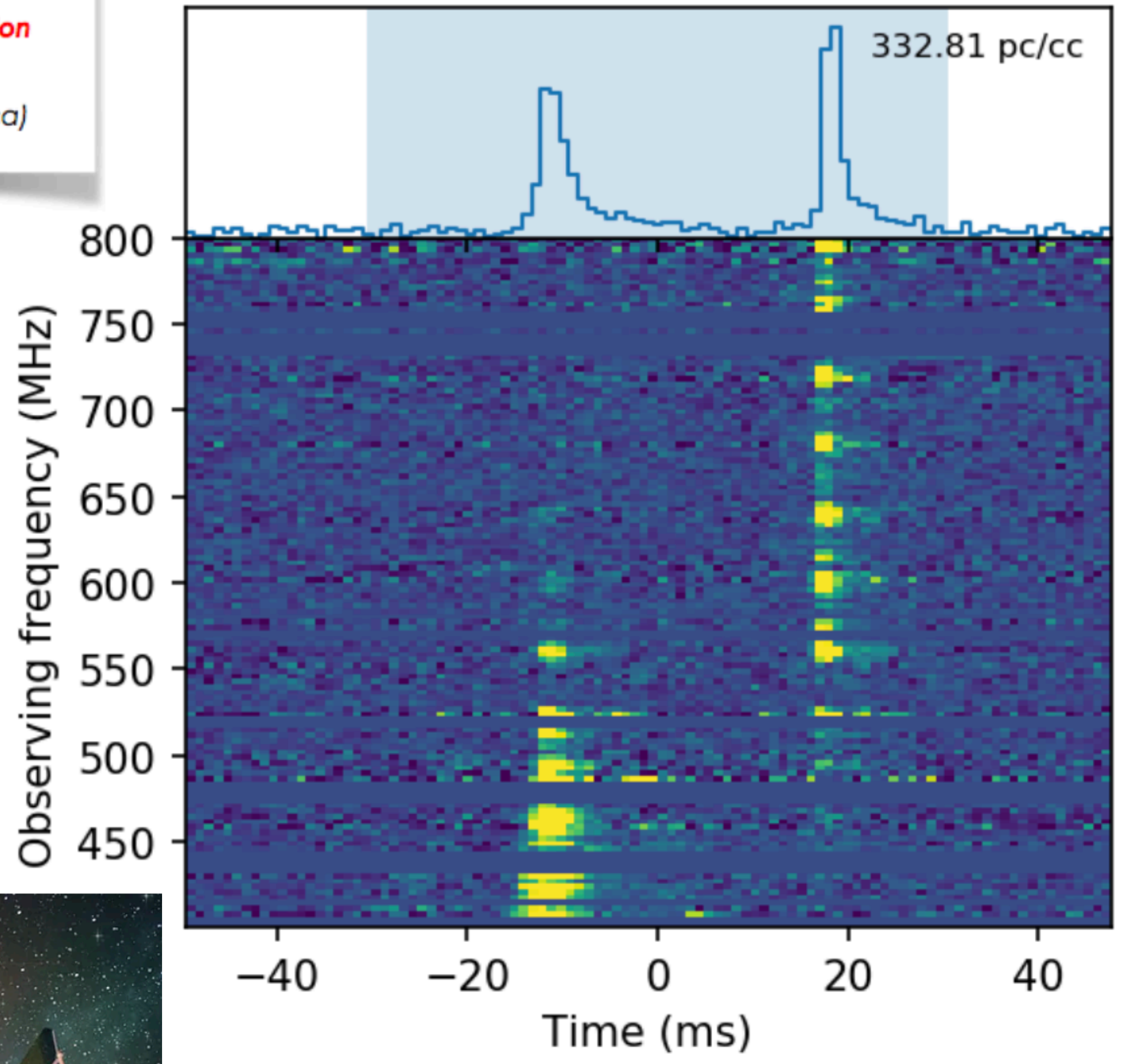
FRB200428: a unique case

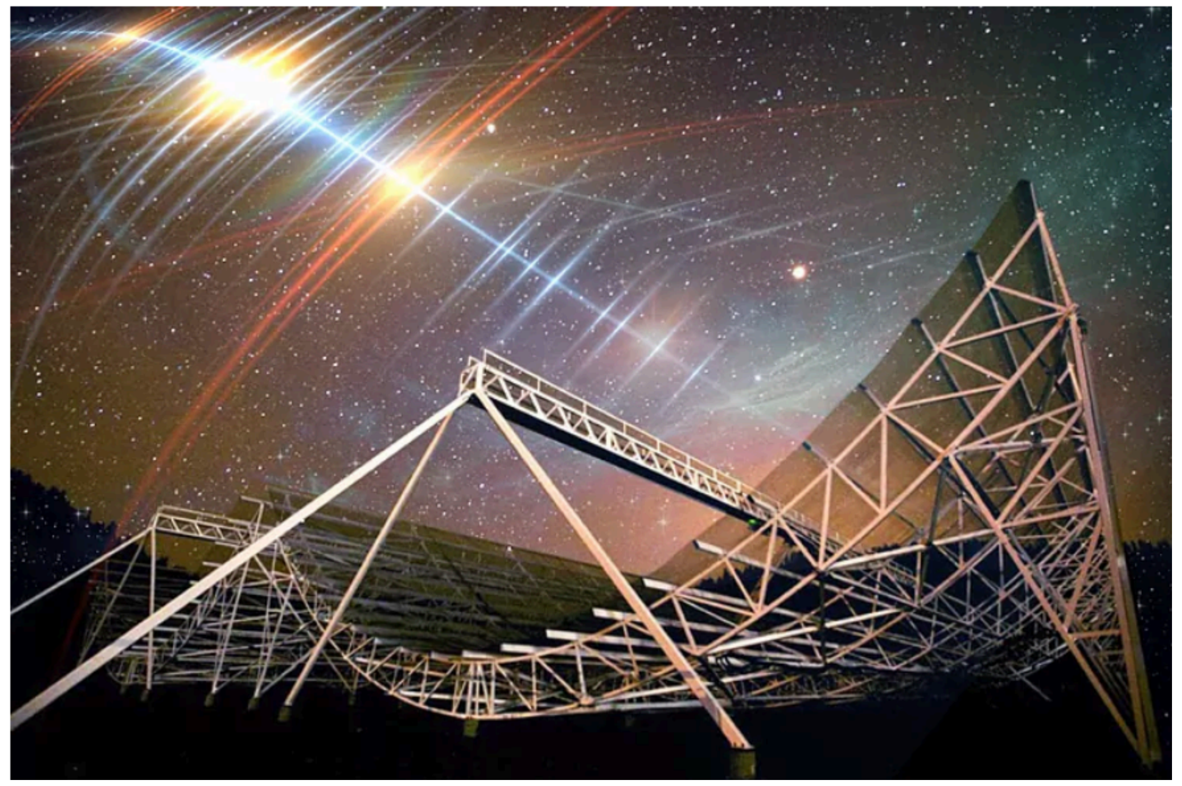
- April 28, 2020: CHIME detects FRB in coincidence with a magnetar (ATel #13681)
- The burst had a double-peak structure with two components ~5 ms wide separated by ~30 ms
- Confirmation at different wavelengths:
  - STARE2 (Bochenek et al. 2020) and European dishes: Westerbork, Onsala, Toruń (Kirsten et al. 2020)
  - X-ray bursts by Swift (Barthelmy et al. 2020), INTREGRAL (Mereghetti et al. 2020)
  - AGILE (Tavani et al. 2021), Konus-Wind (Ridnaia et al. 2021),NICER (Younes et al. 2021), Insight HXMT (Li et al. 2021)
- MAGIC (TeV) could not observe due to pandemic lockdown, H.E.S.S. put upper limits.


A bright millisecond-timescale radio burst from the direction of the Galactic magnetar SGR 1935+2154

ATel #13681; *Paul Scholz (UToronto) on behalf of CHIME/FRB Collaboration*
on 28 Apr 2020; 20:45 UT
Distributed as an Instant Email Notice Transients
Credential Certification: Shriharsh Tendulkar (shriharsh@physics.mcgill.ca)

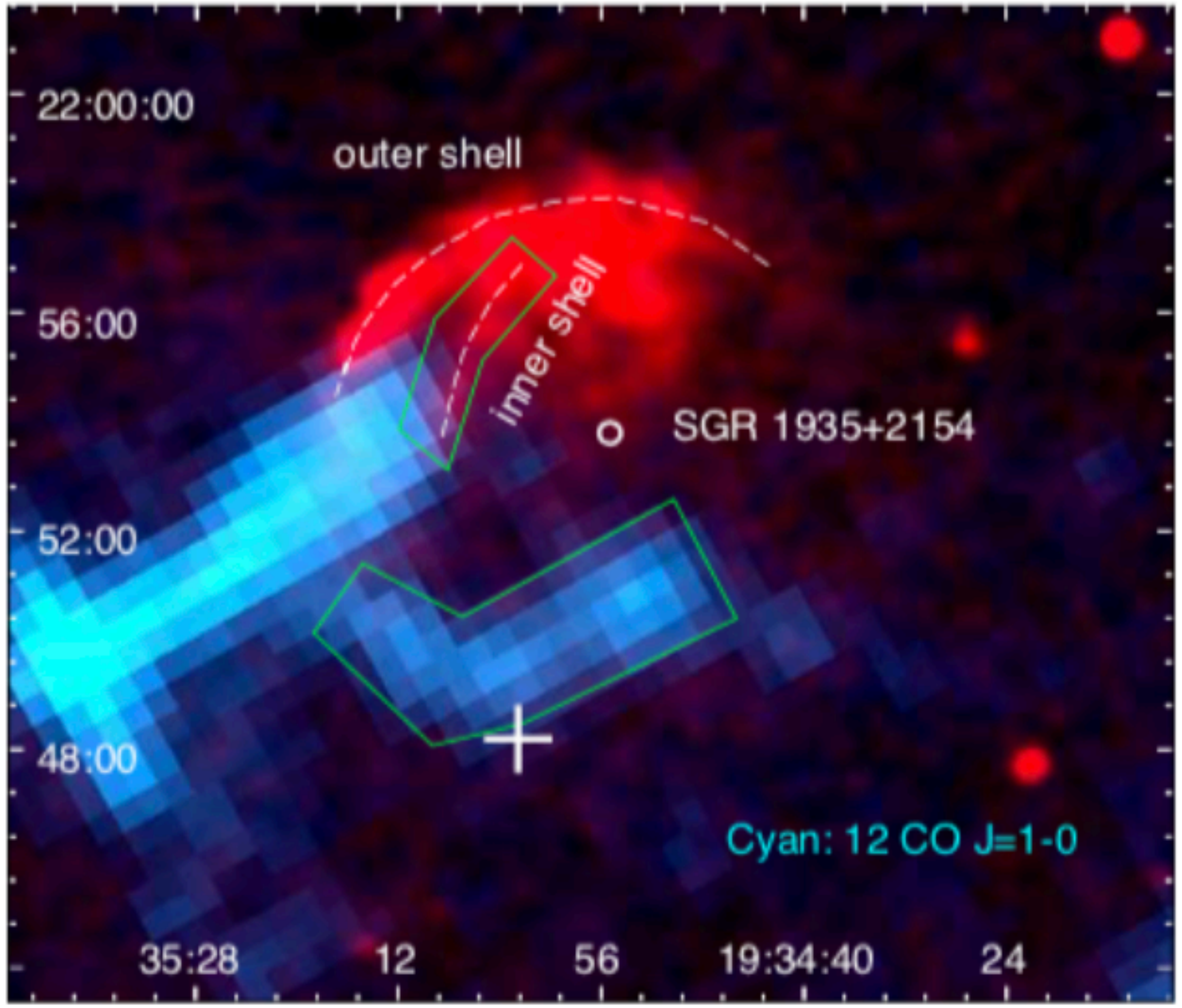
CHIME 2020





Source of interest: SGR 1935+2154

- Galactic magnetar located at 6.6 kpc [Zhou+2020]
  - Spin period P=3.24 sec
  - Dipole magnetic field B_m=2x10^{14}G
  - Started period of X-ray bursting on April 22, 2020
- Hosted in an evolved SNR (G57.2+0.8) and (likely) interacting with a surrounding molecular cloud
- April 2020: a fast radio burst (FRB) is detected by CHIME/FRB in coincidence with this magnetar [Andersen+2020]



SGR 1935 +2154 is the first FRB in the Galaxy and the first identified FRB source.

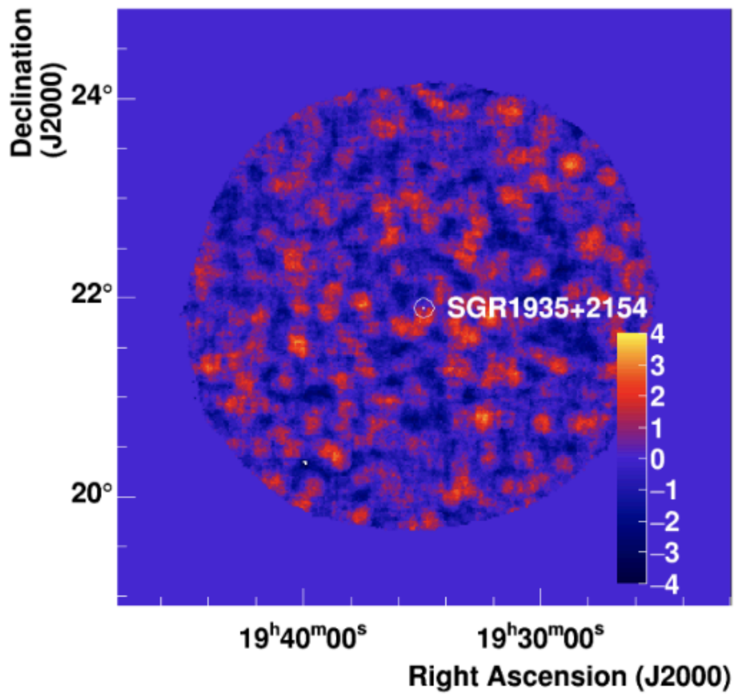
Very high energy constraints

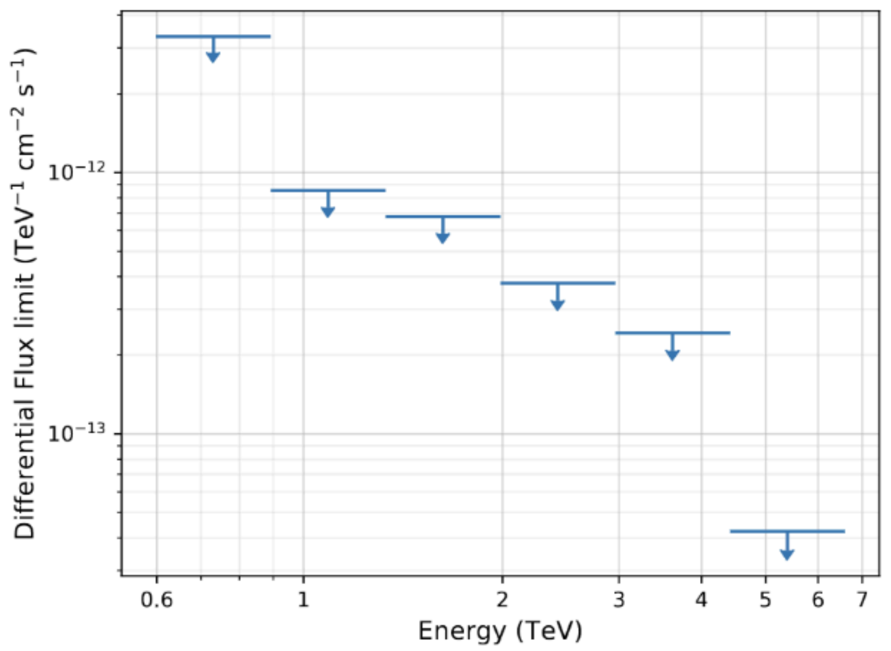
- It was not a giant flare but **intermediate burst**
- Different models for the site of emission (see Zhang 2020 for a review):
  - inside magnetosphere
  - relativistic outflow interacting with surrounding ISM
- TeV emission can be expected according to theoretical models [Lyubarsky 2014, Murase et al. 2016, Metzger et al. 2020]

H.E.S.S.

Start time (UTC)	Duration	Average Zenith Angle
2020 April 28 01:55:00	28 minutes	55.0 deg
2020 April 28 02:26:55	28 minutes	51.0 deg
2020 April 28 02:56:08	28 minutes	48.1 deg
2020 April 28 03:25:24	28 minutes	46.2 deg

Table 1. Summary of the H.E.S.S. observations of SGR 1935+2154. **Note:** The observations overlapped with magnetar bursts detected by INTEGRAL and Fermi-GBM.



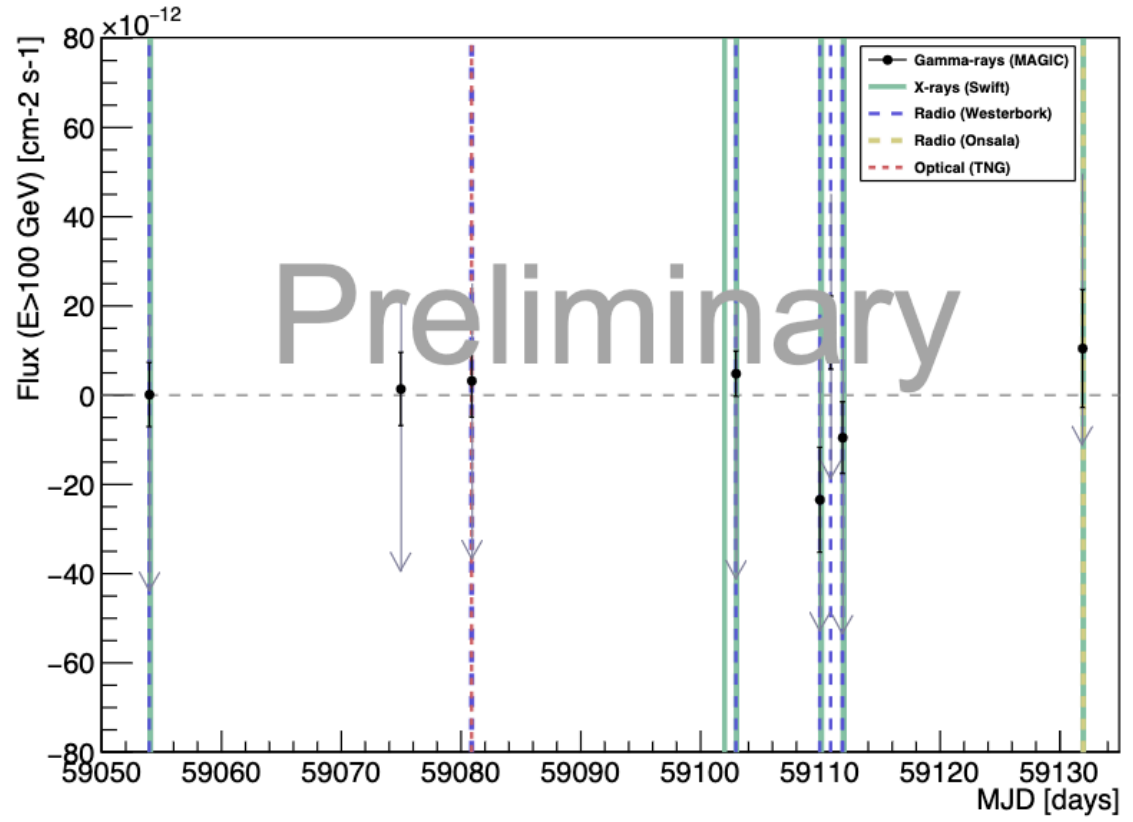


H.E.S.S. coll. 2021

16

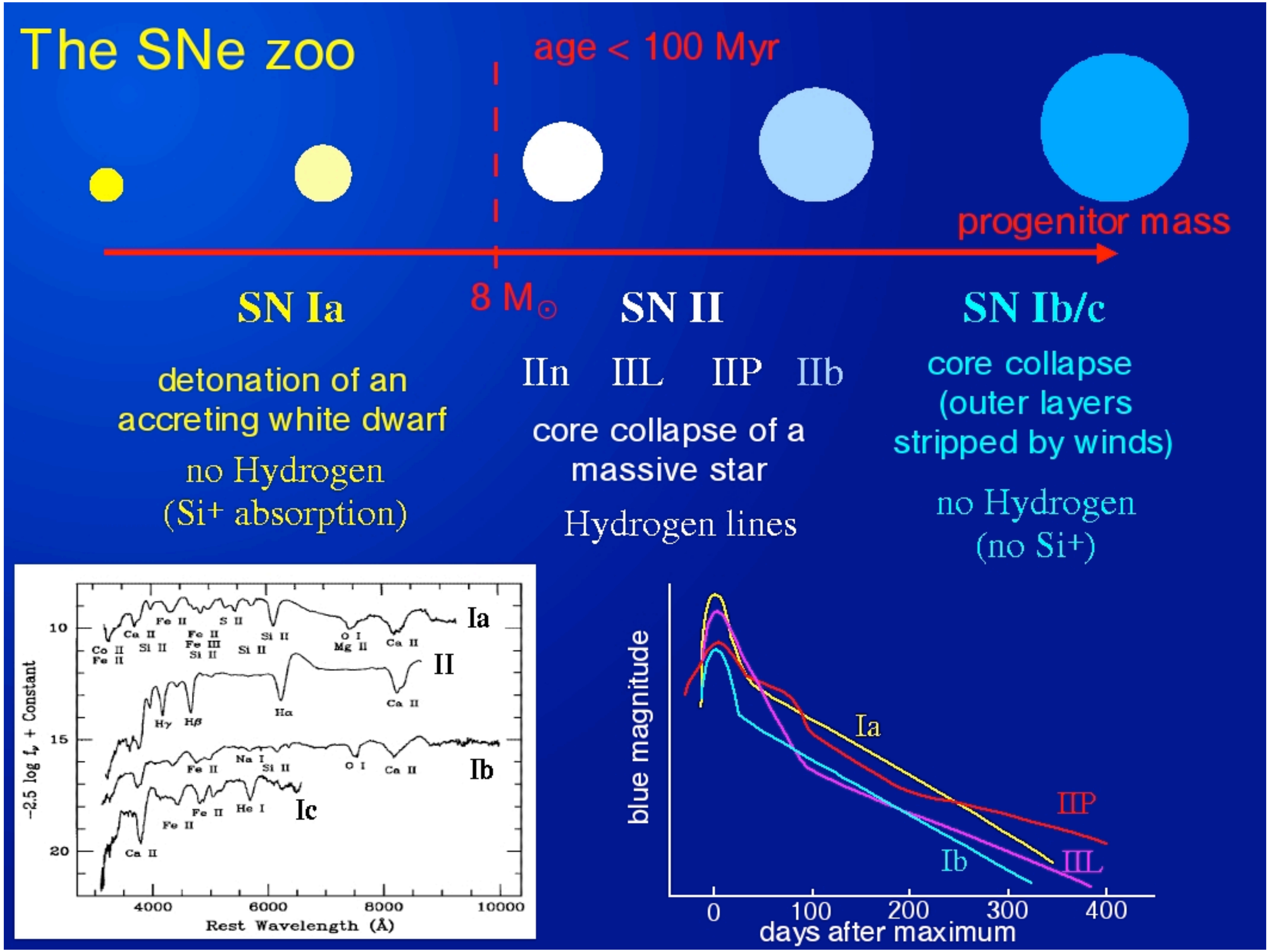
MAGIC

- MWL monitoring campaing



López-Oramas et al. 2021

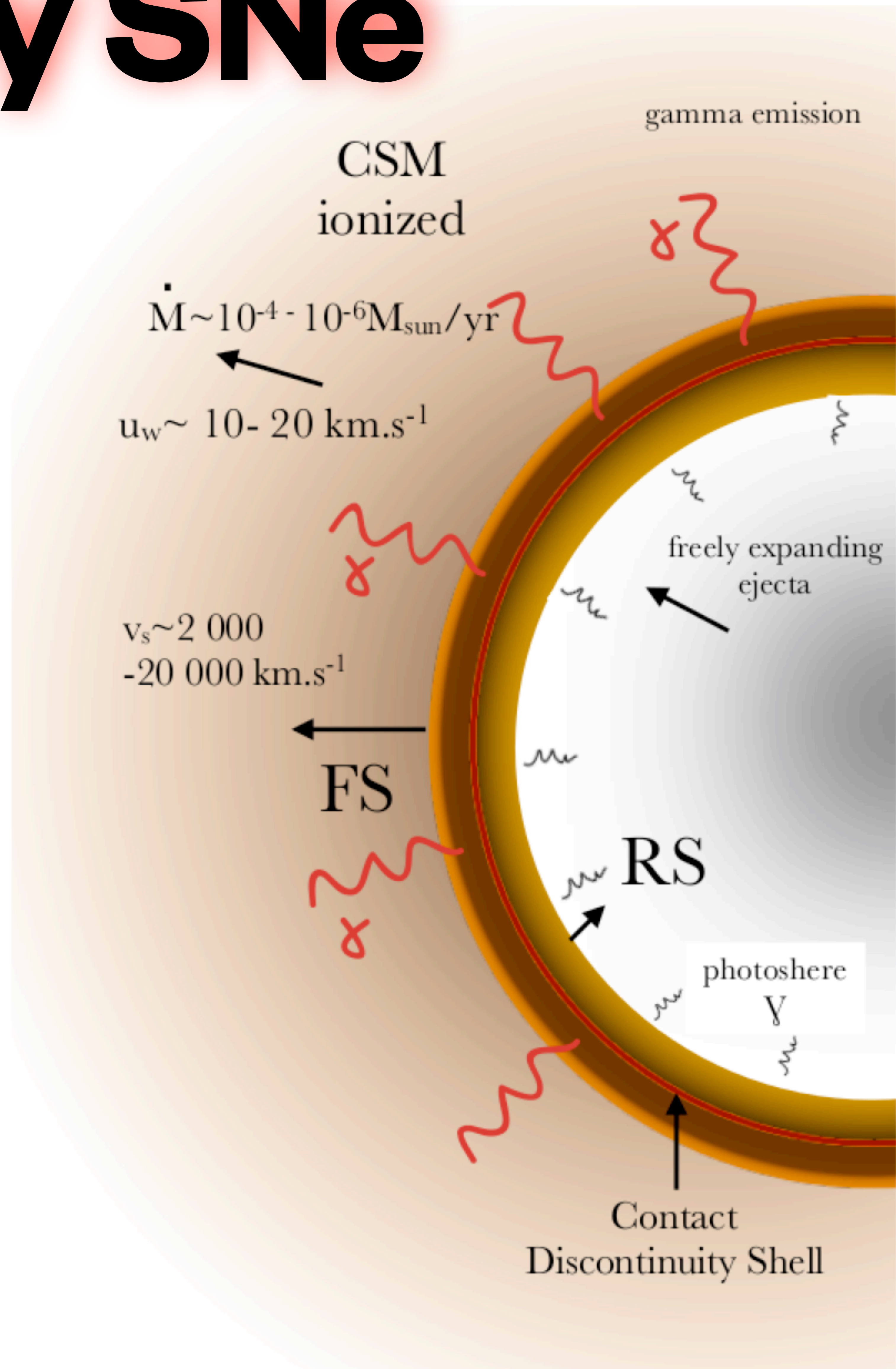
Supernovae



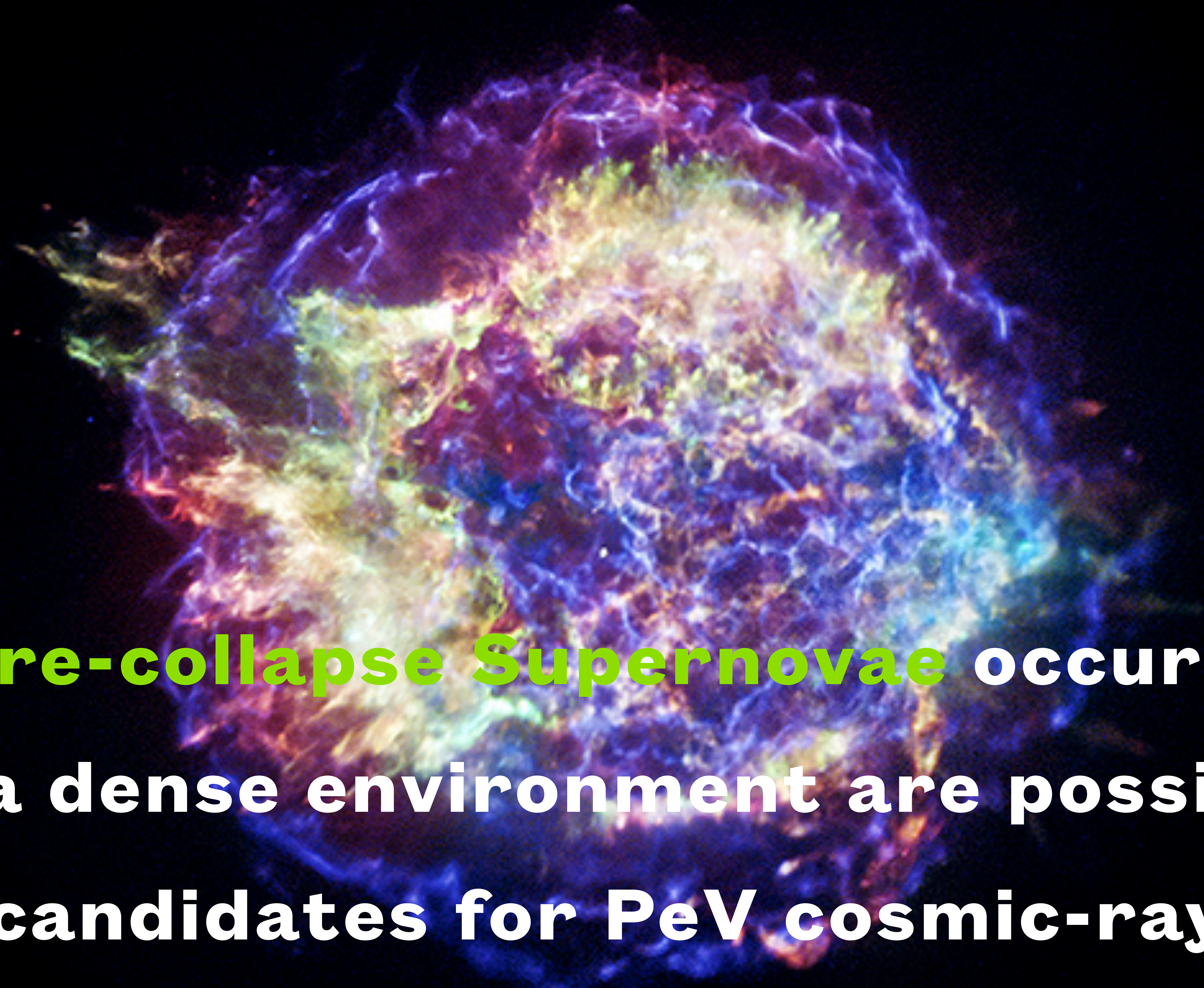
https://www.arcetri.inaf.it/science/SNe/zoo.jpg

Cosmic Ray acceleration by SNe

- Core-collapse (cc-)SNe, occurring in dense circumstellar medium (CSM), are possible candidates for accelerating Cosmic Rays to PeV energies. **Need very dense environment (progenitor wind).** [Katz et al. 2011; Murase et al. 2011; Bell et al. 2013, Cristofari et al. 2022, Brose et al. 2022]
- SN shock propagates in very dense CSM -> a collision-less shock [Ptuskin 2005, Murase et al 2011, Katz et al 2011, Cardillo 2015, Marcowith 2014,2018,]
  - High density: more p-p collisions -> gamma-ray emission
- **Fast magnetic field amplification** [Bell 2004].
  - High magnetic field of the order of Gauss are recorded in radio SNe, instead of the 10 to 100 µG measured in young SNRs.
  - Necessary to accelerate particles to very high energies at an early stage.
  - Nearby Type IIb SN 1993J, a magnetic field as high as 100 G and **shock speeds** as high as 20,000 km s^{-1} [Fransson & Björnsson 1998, Tatischeff 2009]
    - TeV Gamma ray emission should have been detected weeks after the outburst [Tatisheff 2009, Markowith et al 2018]



https://www.mpi-hd.mpg.de/HESS/pages/home/som/2019/07/

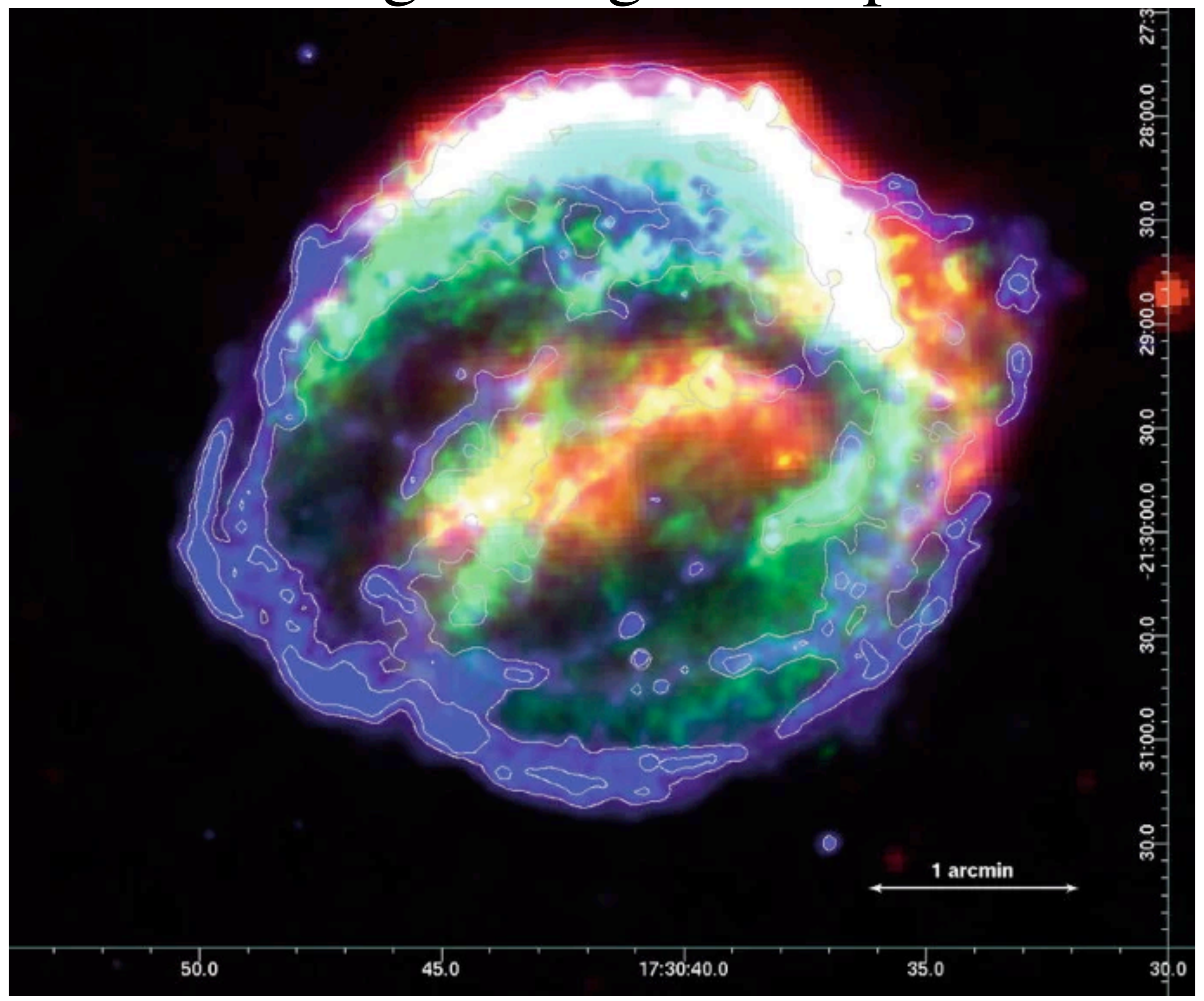


Core-collapse Supernovae occuring in a dense environment are possible candidates for PeV cosmic-ray acceleration.

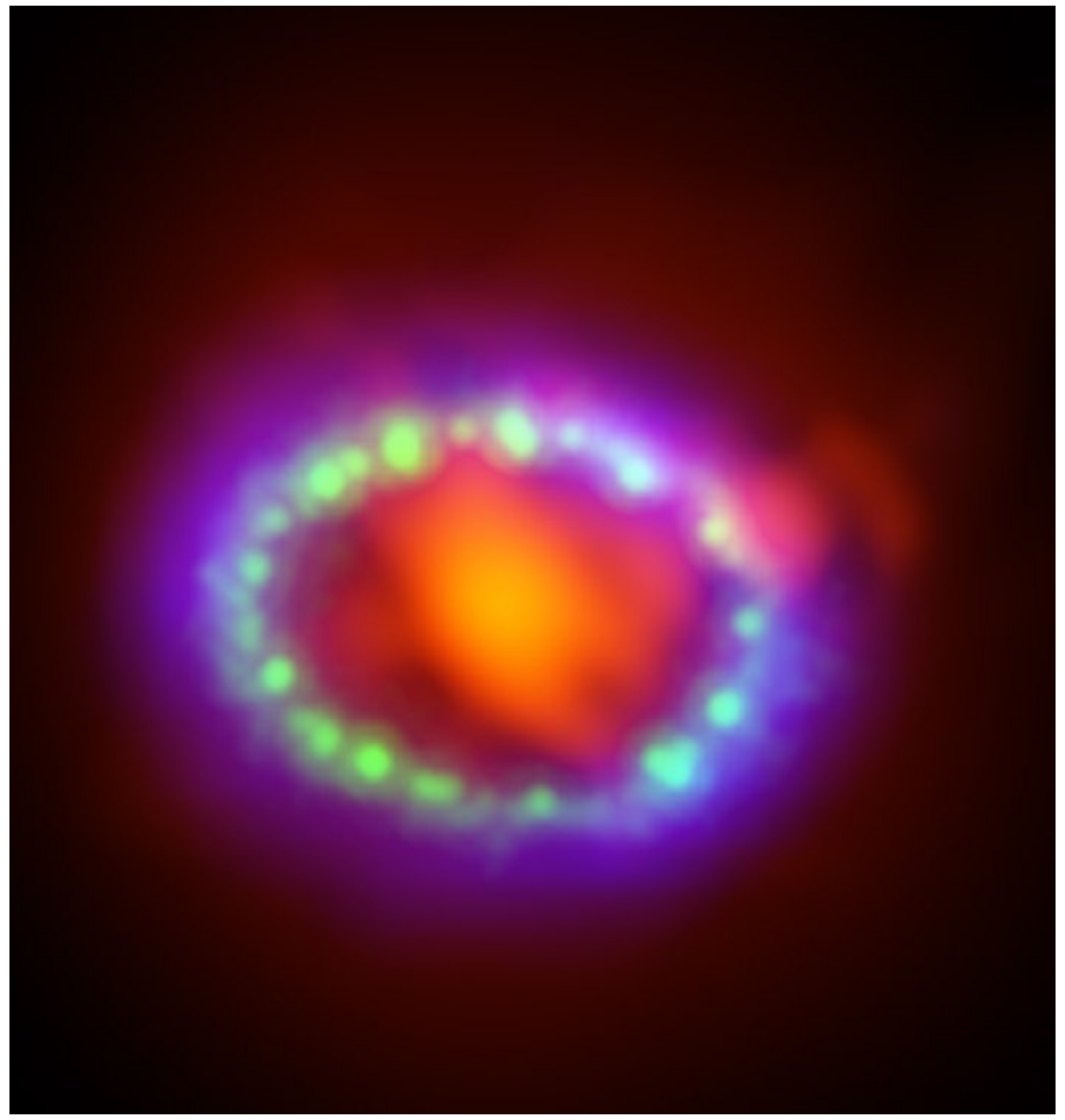
Supernova (SN)

- Most recent SN in our Galaxy visible by unaided eye: **SN 1604** (Kepler's Supernova)
    - Type Ia supernova (d=3.2-12 kpc [Danziger and Goss 1980; van den Bergh et al. 1973])
    - Brighter than stars and planets at its peak [Vink 2017]
- Most recent extra-galactic unaided eye SN: **SN 1987A** in the Large Magellanic Cloud [Arnett et al. 1989]
    - Type II SN; d~50kpc
    - Beginning of neutrino astronomy: (Kamiokande II: 12 antineutrinos; IMB: 8; Baksan: 5) in ~ 10 s burst (core collapse)
    - What is happening at higher energies?

Multiwavelength image of Kepler's SNR



[Vink 2017]

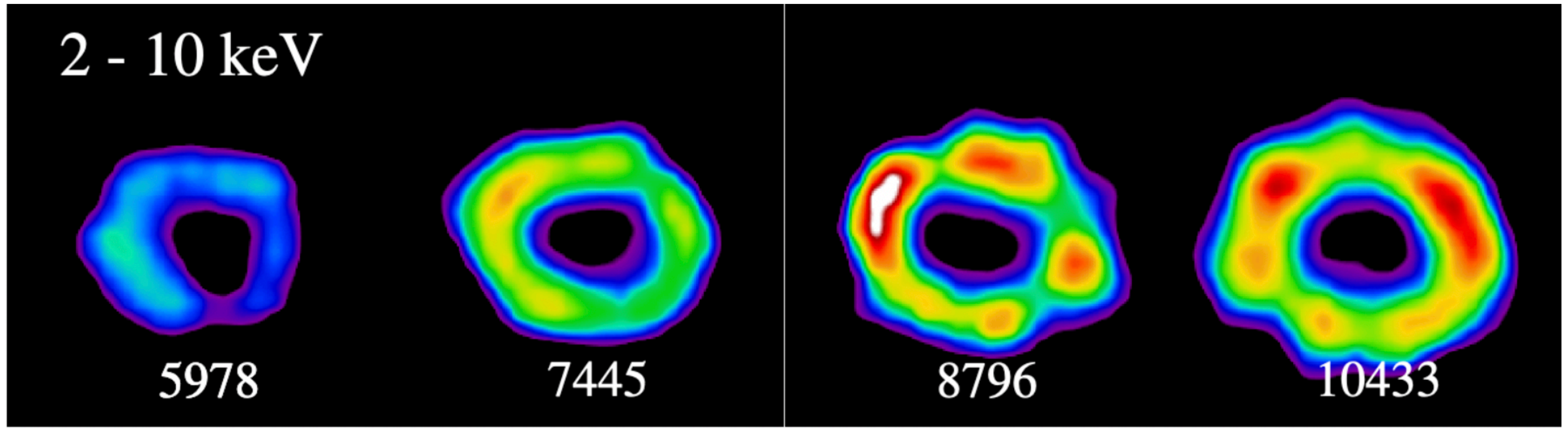


http://www.eso.org/public/images/eso1401a/

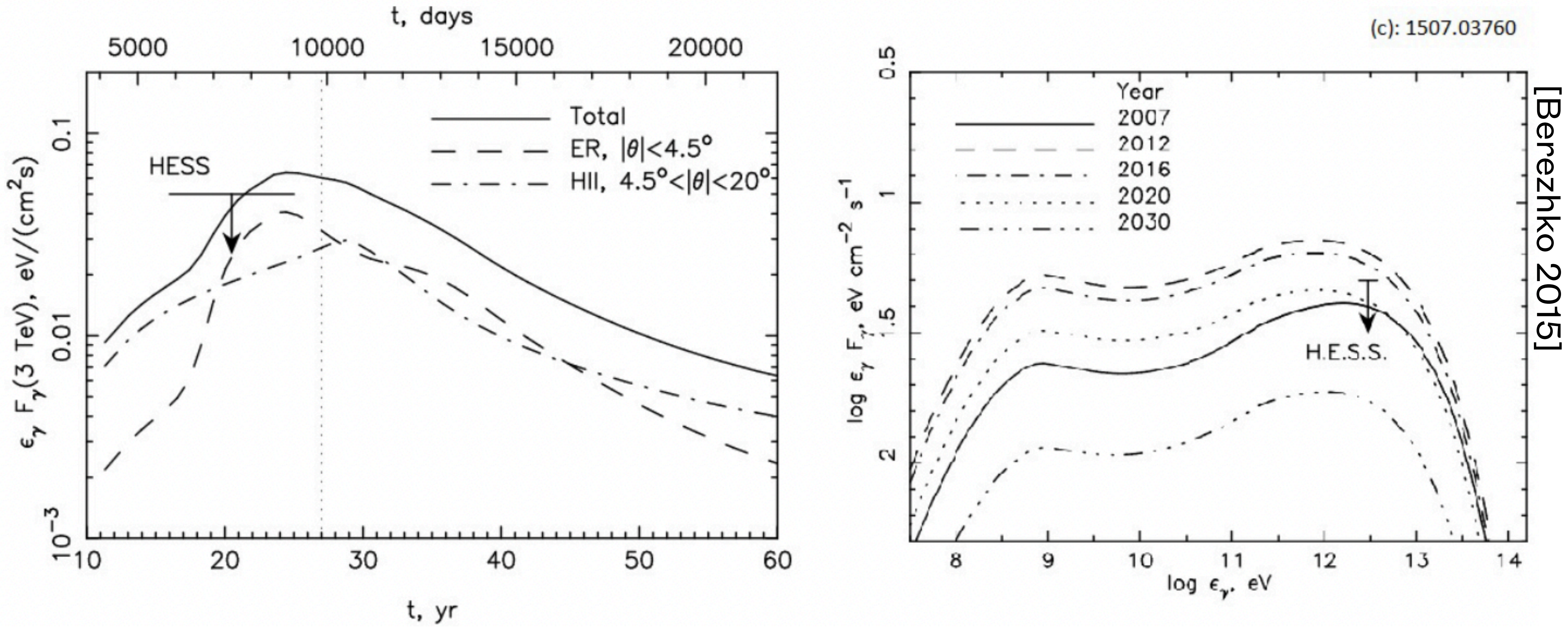
Composite image of SN1987A remnant

The case of SN 1987A

- Hints in X-rays that the blast wave is leaving the dense equatorial ring [Frank 2016].
  - Laboratory for SN explosion and SNR expansion modeling and particle acceleration on the shock modeling.
- Within Diffuse Shock Acceleration (DSA) models emission from SNR 1987 A is expected [Berezhko 2015]:
  - The emission is hadronic (cosmic ray protons are accelerated on the shock).
  - Emission is variable (variable density of the medium + acceleration timescale)
- Maximum of emission expected 2008-2018
  - **NO emission detected in GeV (Fermi) nor TeV (H.E.S.S.)** [Fermi Coll. 2015; H.E.S.S. Coll. 2015] **But…**



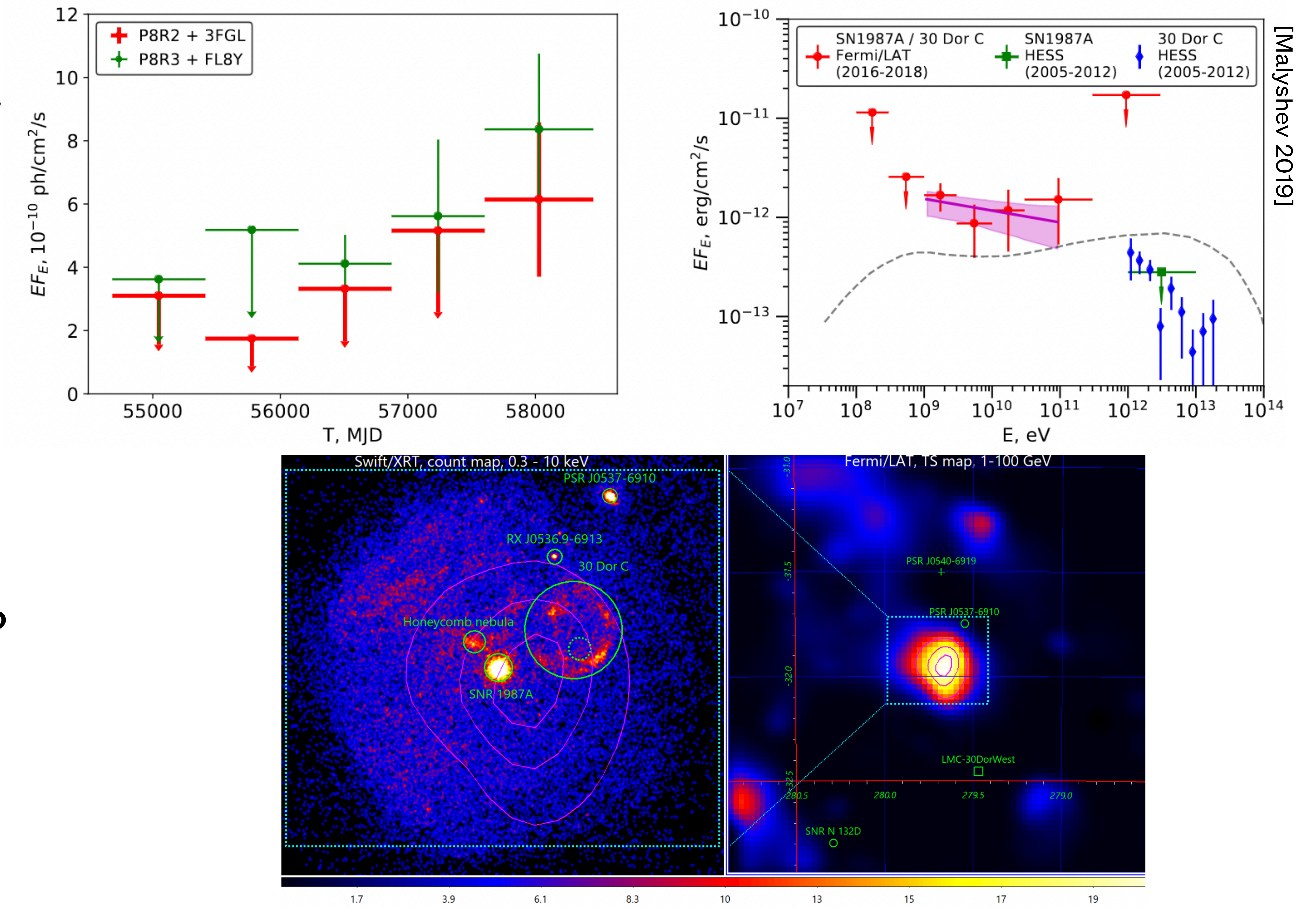
[Frank 2016]



[Berezhko 2015]

GeV brightening of SN 1987A region

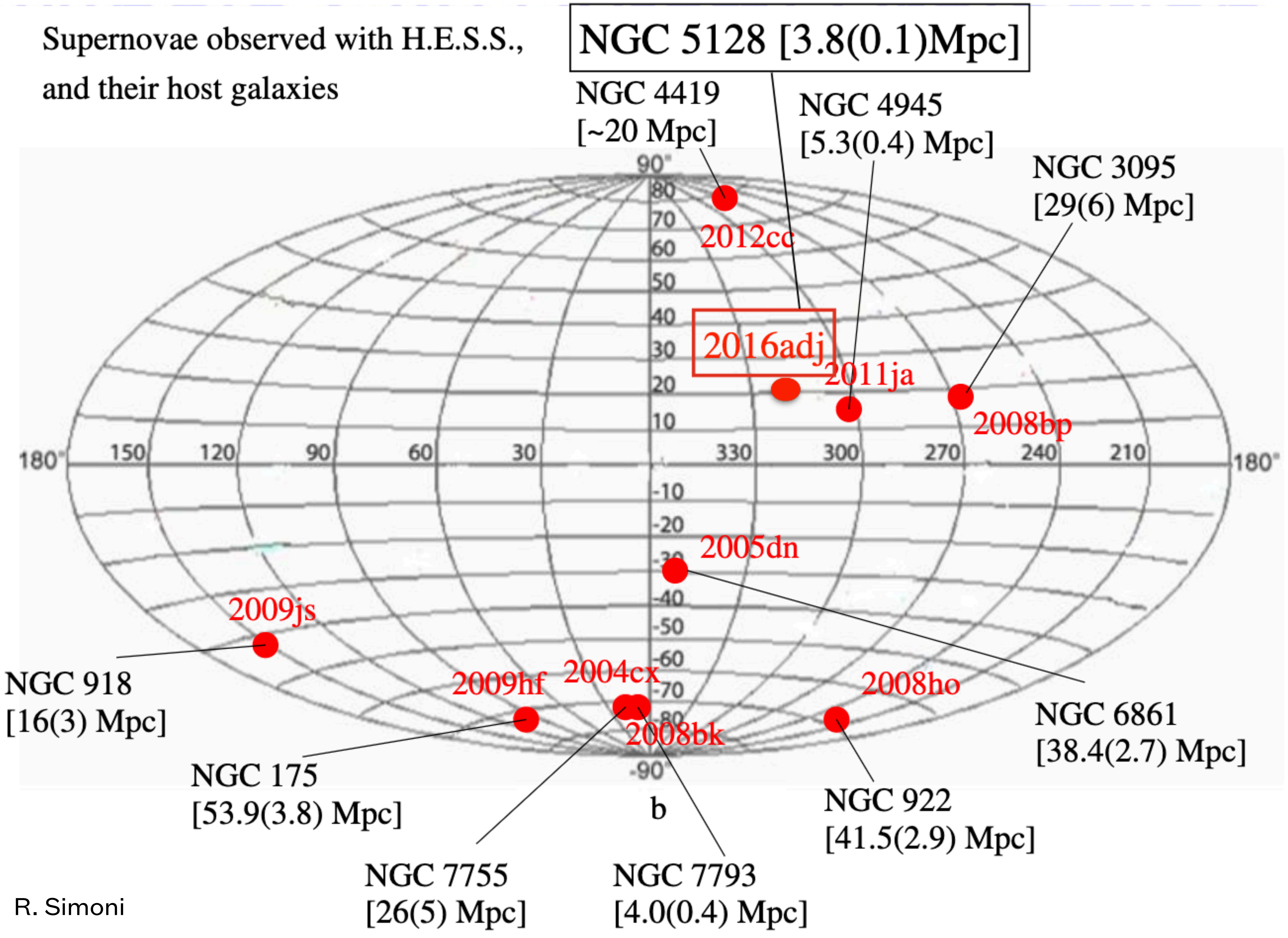
- Enhancement (4σ) of the GeV emission from the SN 1987A region as observed with Fermi-LAT [Malyshev 2019]
- Signal is seen only at >1 GeV energies and comparable to predictions by DSA models.
- Poor localization allows several other counterparts
- No clear variability in X-rays – a hint for hadronic emission from SN 1987A?
- Let's stay tuned!
  - More sensitive instrument to come: Cherenkov telescope array (CTA)



Core-collapsed SNe searches

H.E.S.S. Coll. 2019

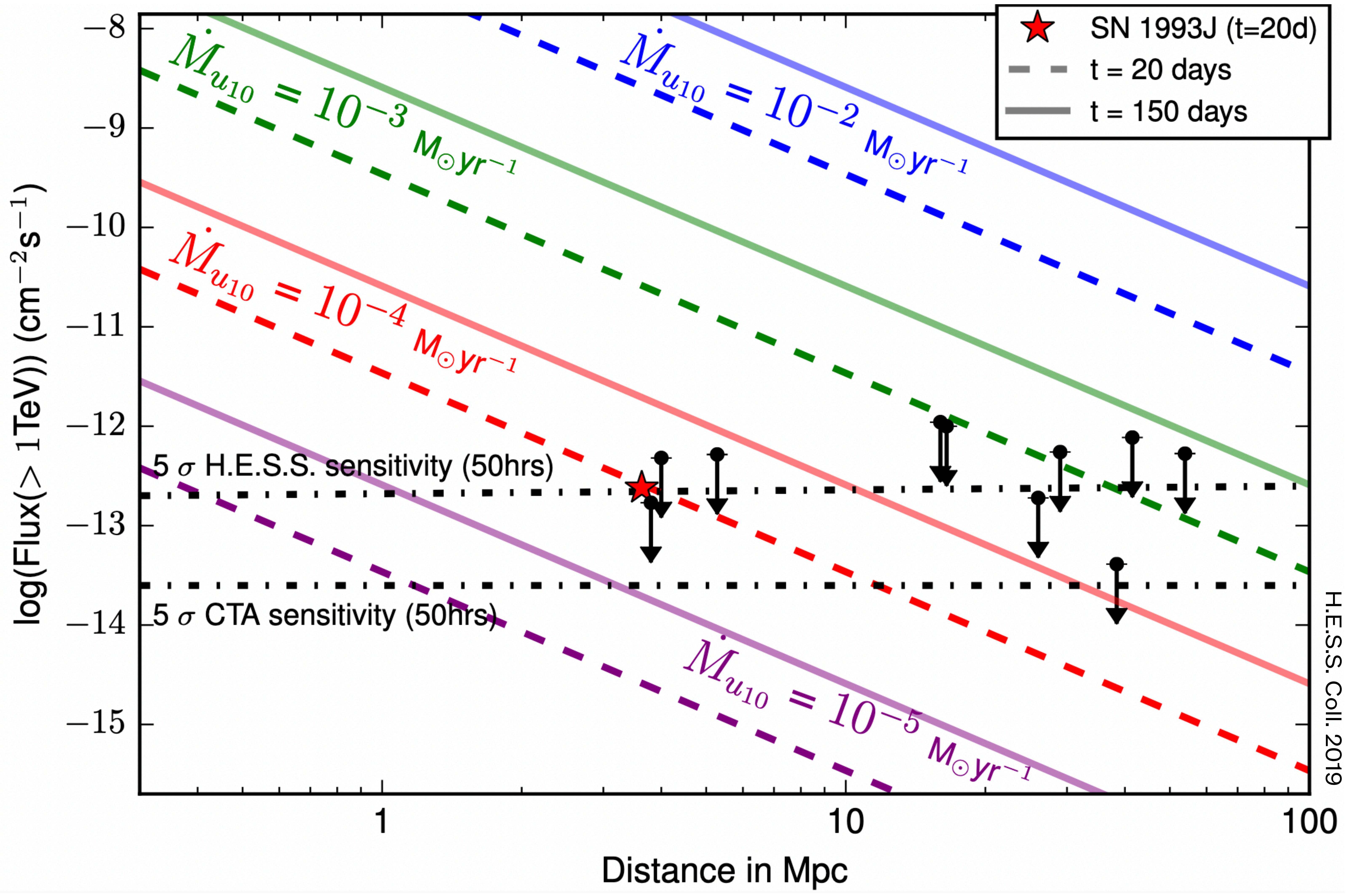
A final sample of 10 type II SNe was selected.



R. Simoni

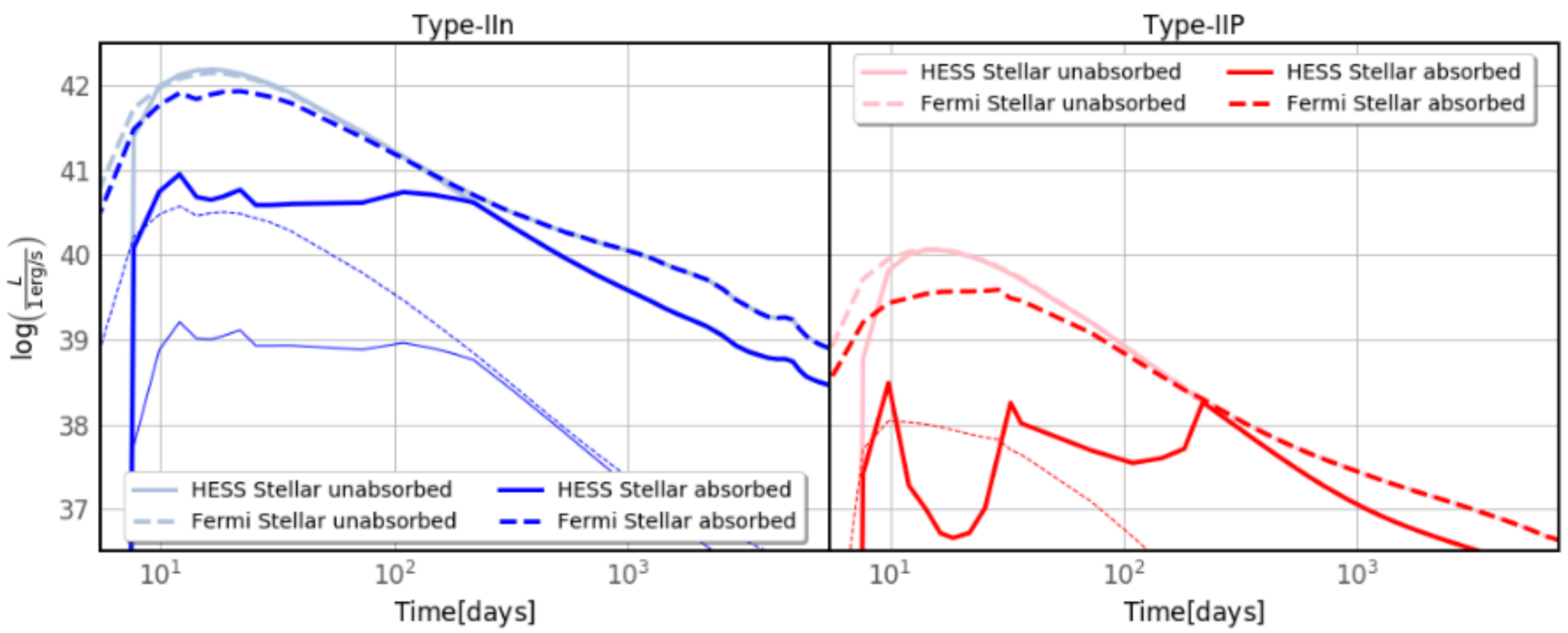
- Non-detection -> environment before outburst was not dense enough.
- Constraints on progenitor's mass loss rates [Dwarkadas 2013]
- No detection in Fermi-LAT data search [Fermi-LAT Coll. 2015]
- Transient γ-ray signal tentatively associated with **SN iPTF14hls** by Yuan et al. (2018), but quasar in FoV.
- Search by Xi et al. 2020: fading GeV gamma ray source spatial coincidence with **SN 2004dj** (chance coincidence 0.2%)

Expected Flux versus Distance

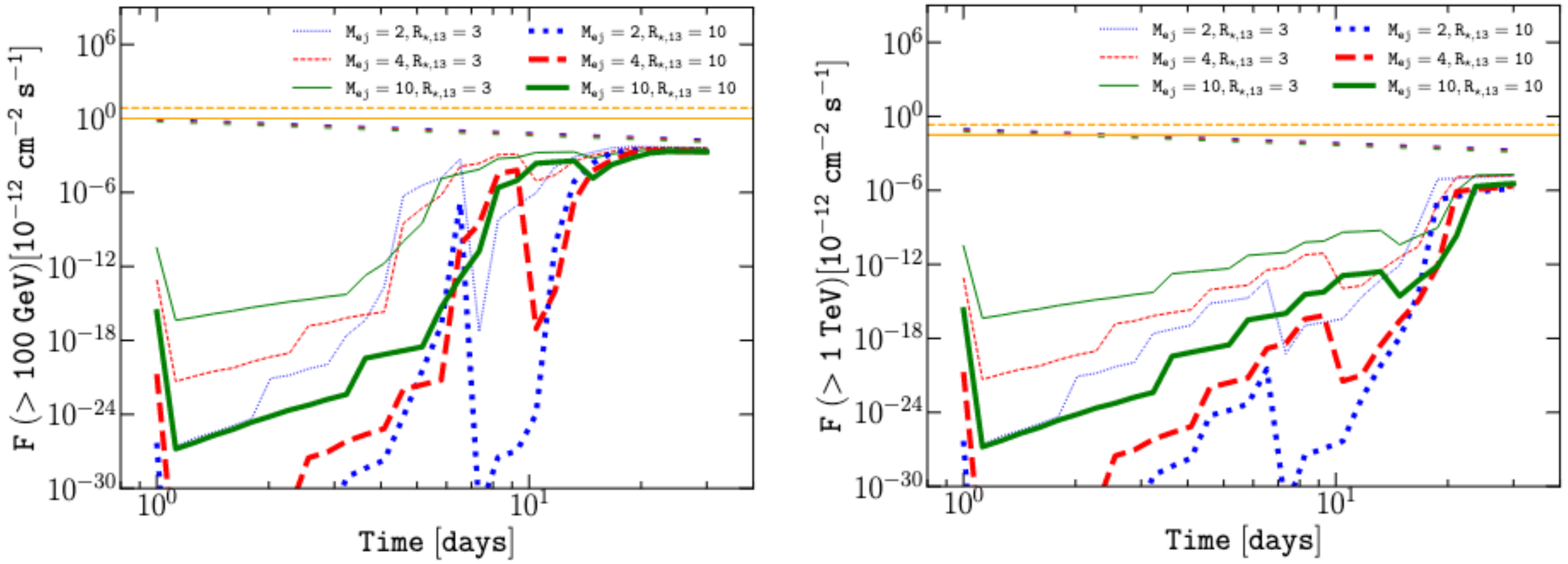


What to expect at very high energies?

- Very high energy emission is expected, but
  - gamma-ray signal can be attenuated in the first days when photosphere and the shock are the closest, and the photosphere luminosity is the highest. [Cristofari 2022]
  - Rise again about 5-10 days later and even show enhanced emission ~20-30 days later.
- Only very local SNe visible with typical detection distances from 20 kpc (HAWC) to 3 Mpc (CTA-South), e.g. within our Galaxy or in the Magellanic Clouds [Brose 2022: Cristofari 2022]



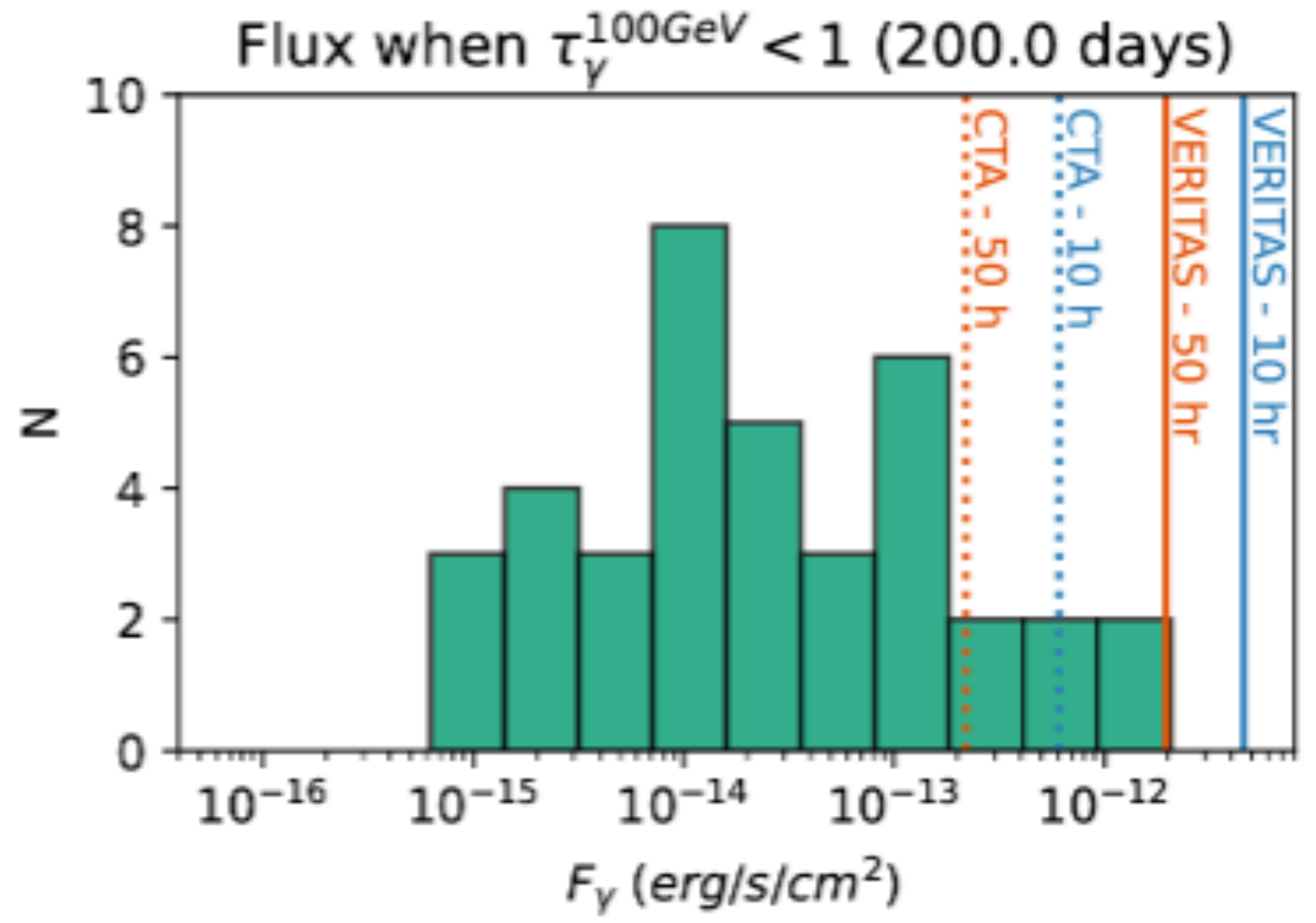
Brose 2022

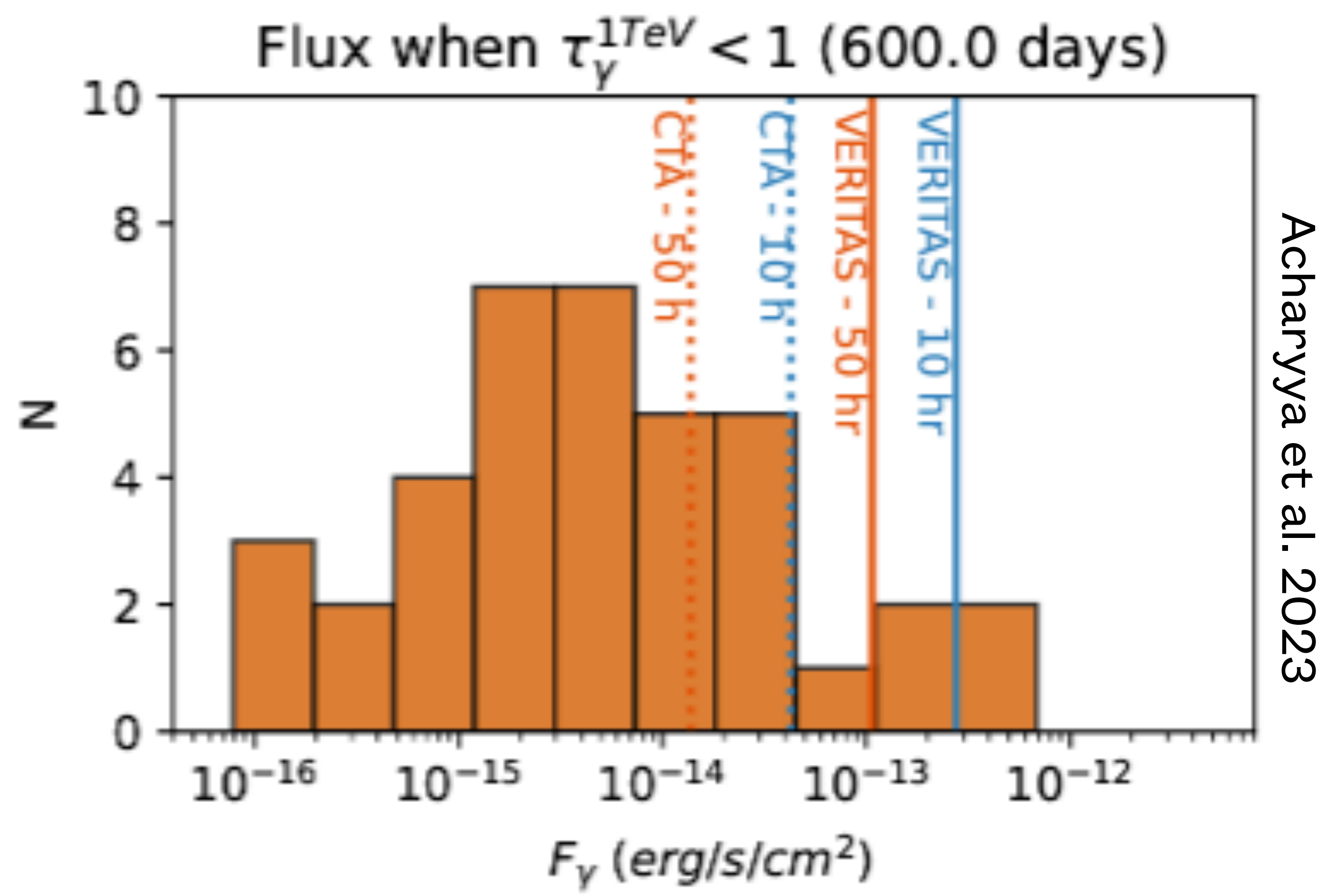


Cristofari 2022

Type Ia and super luminous SNe

- Closest Type Ia supernova (d=3.6Mpc in M82) observed by MAGIC: SN 2014J [MAGIC Coll. 2017]
  - No detection. Expected emission ≈10^{-24}photons cm^{-2} s^{-1} -> not detectable, even by future CTA.
- Super luminous supernovae (SLSNe) have luminosities ~10–100 times greater than ordinary core-collapse SNe [review Gal-Yam 2019]
  - Additional power source from standard SNe Types I and II: injection from a rapidly spinning magnetar? [Woosley&Heger2012;Quataert&Kasen2012;Margalit&Metzger2016;Moriyaetal. 2018]
  - No detection of 2 candidates with VERITAS and Fermi-LAT, but predictions are [Acharyya et al. 2023]:
    - 0.4 and 4 events per year can be observed by VERITAS from 10hr and 50hr observation, respectively.
    - 8 and 80 events per year can be expected by CTA.

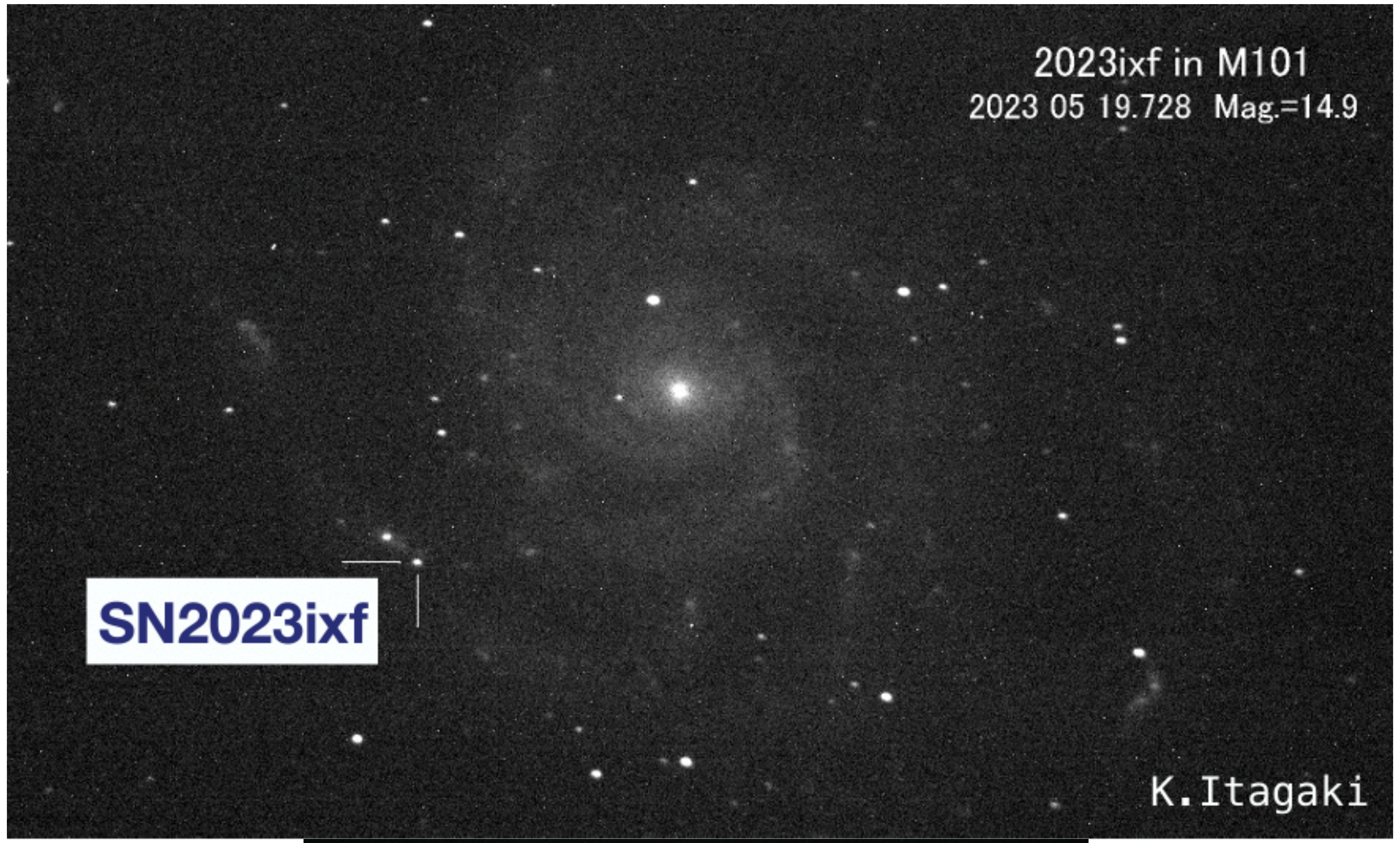


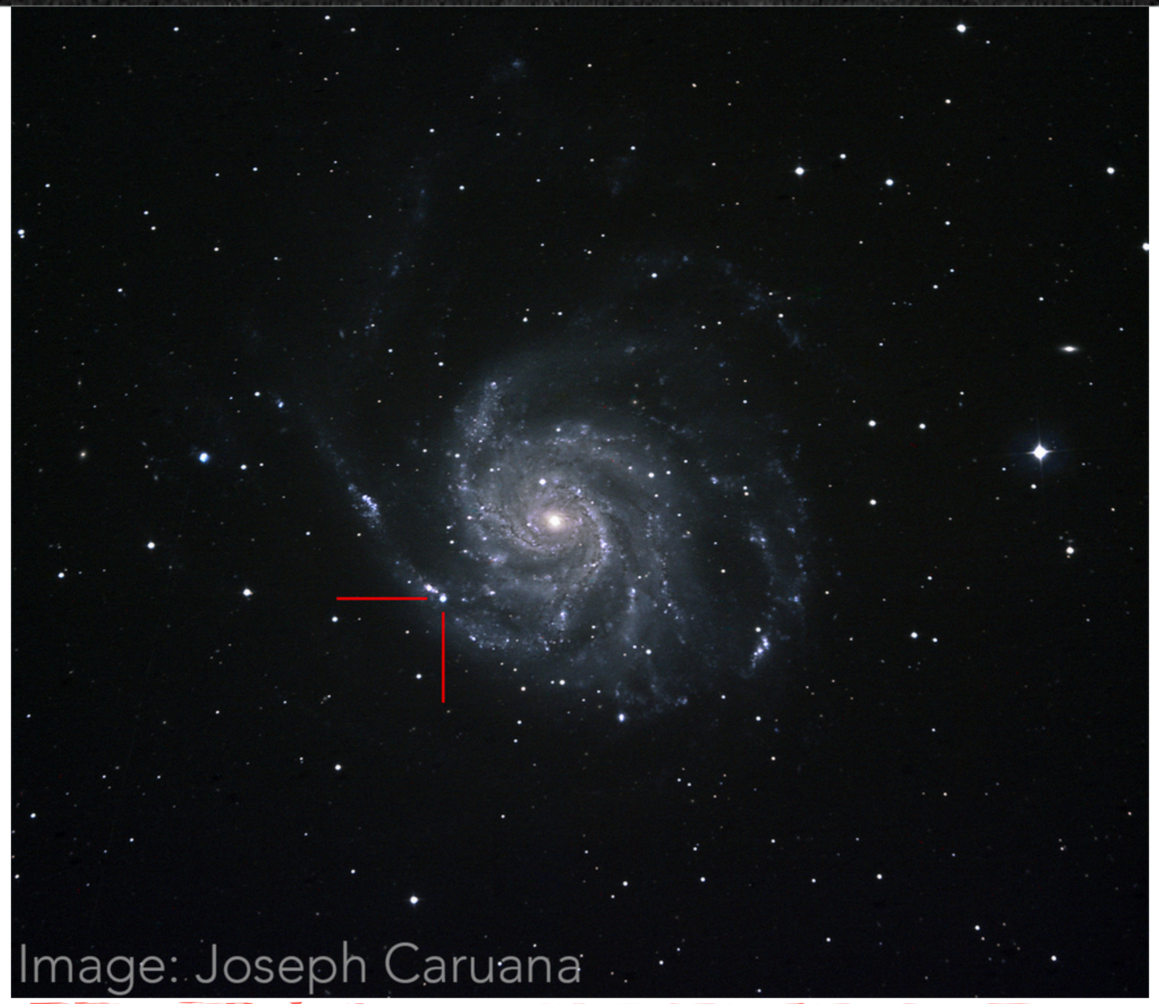


Acharyya et al. 2023

Most recent: SN2023ixf

- Discovered on May 19 (17:27:15 UTC) and reported (21:42:21) by K. Itagaki [TNS #178084]
  - Estimated explosion time: May 18, 18:00 UTC (MJD 60082.75) [Hosseinzadeh et al. 2023]
  - Mag 14.9; z= 0.000804 (~6.4 Mpc), located in M101 [Perley et al., AstroNote 2023-119]
  - **Closest core-collapse** (type II, possible II-L) SN in the northern hemisphere in the last few decades [Biancardi 2023]
  - SN 2023ixf is the second brightest supernova (SN) among all-type SNe discovered after the discovery of SN 1987A in optical bands [Yamanaka et al. 2023]
  - X-ray: detected by Chandra [ATel #16073]
  - Fermi-LAT reported no GeV emission [ATel #16075]
    - Constraints on particle acceleration models to be expected
  - No reports from TeV instruments yet.





Novae

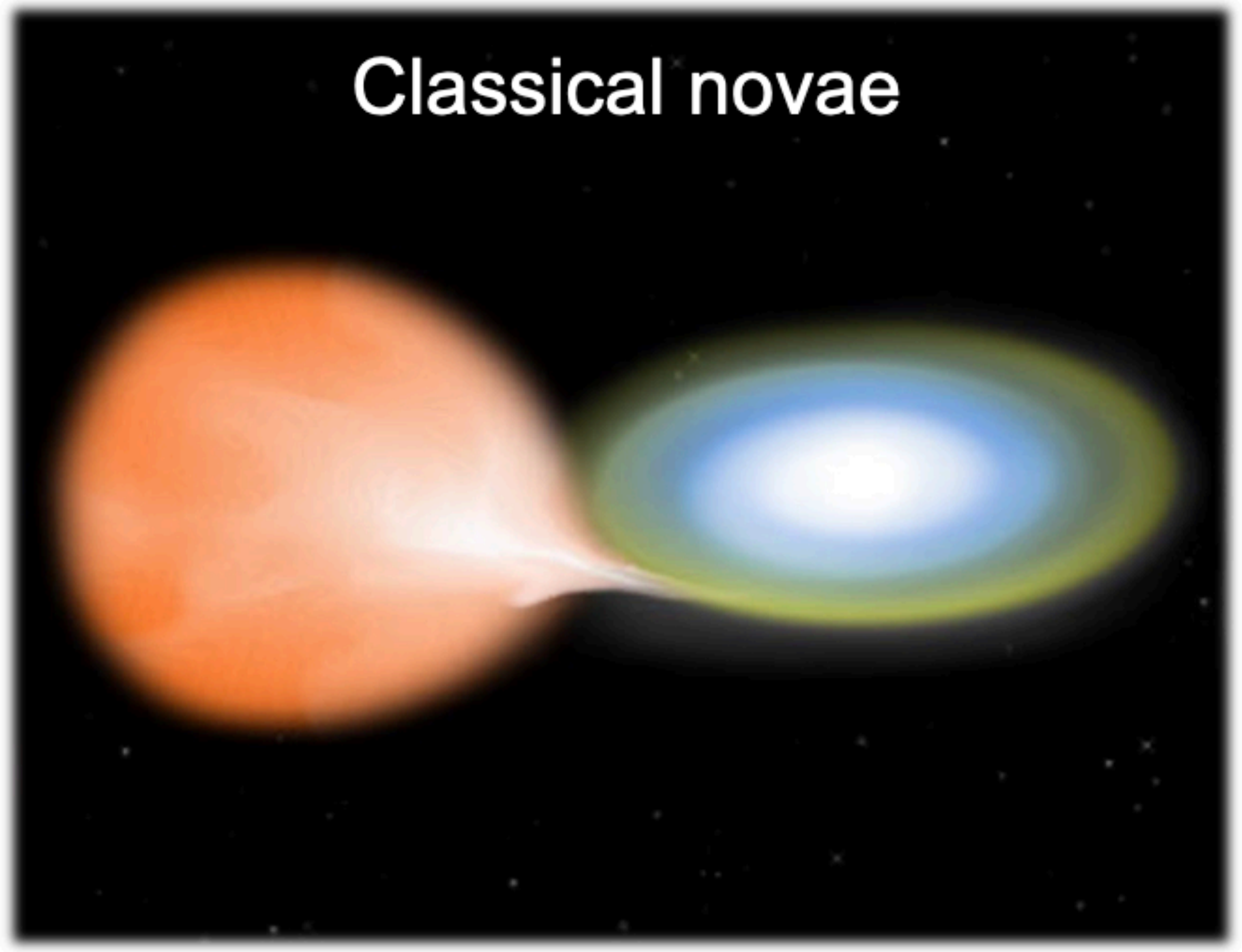
superbossa/MPP

Novae - White Dwarfs in Close Binary Systems

Compact cataclysmic variable:

WD + Main Sequence

Roche lobe overflow



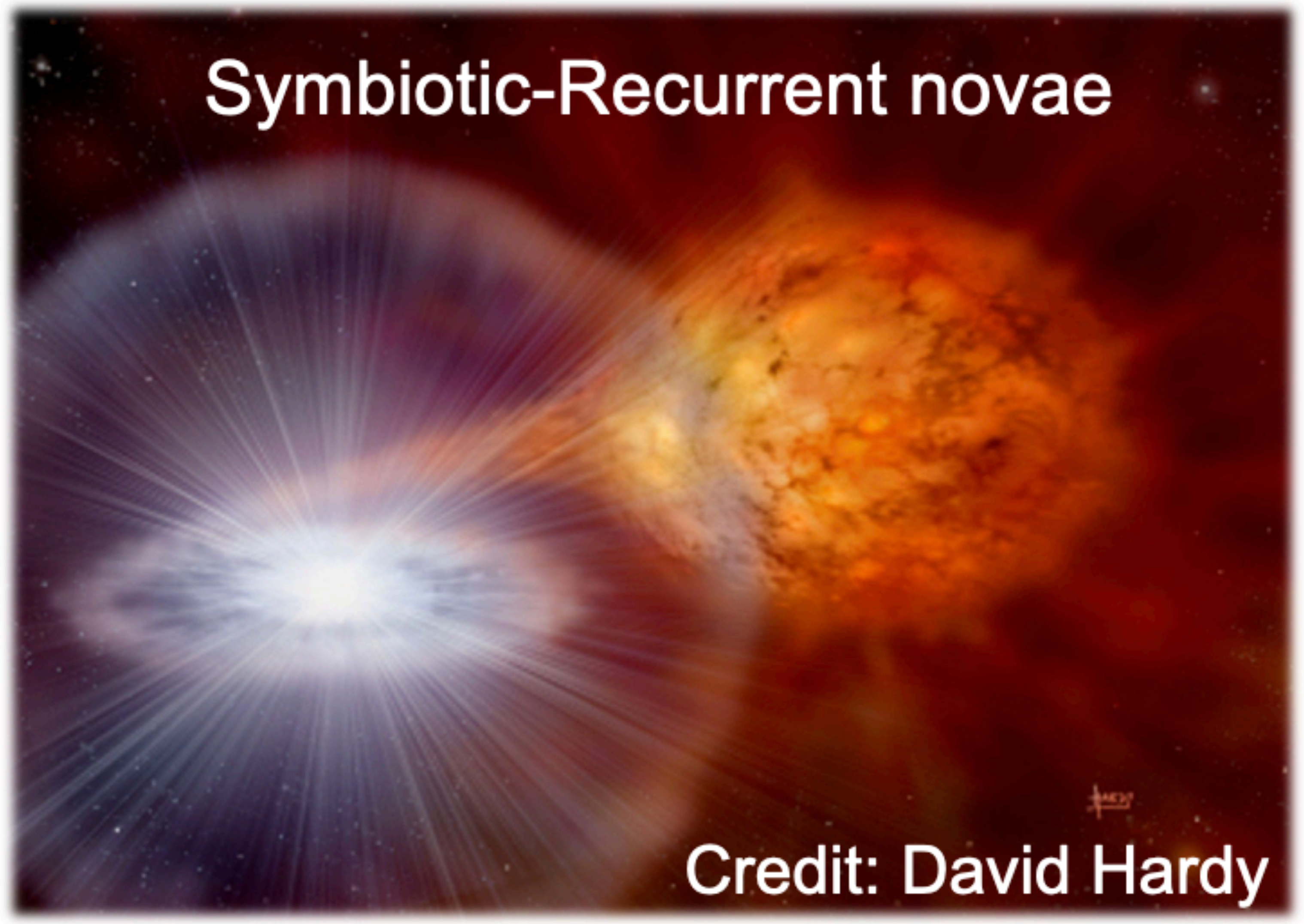
- separations, a ~ 10^{11}cm ~ $R_\odot$
- P_{orb}~ hr-day
- P_{rec} >~ 10^4 yr
- rate ~ 30 – 50 / yr in Galaxy

Hydrogen burning in degenerate conditions on top of the white dwarf

Symbiotic system:

Massive WD + Red Giant

accretion from red giant wind



- a ~ 100's $R_\odot$
- P_{orb}~ years
- P_{rec} < 100 yrs
- ~10 known symbiotic-recurrents

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Processes and electromagnetic signals

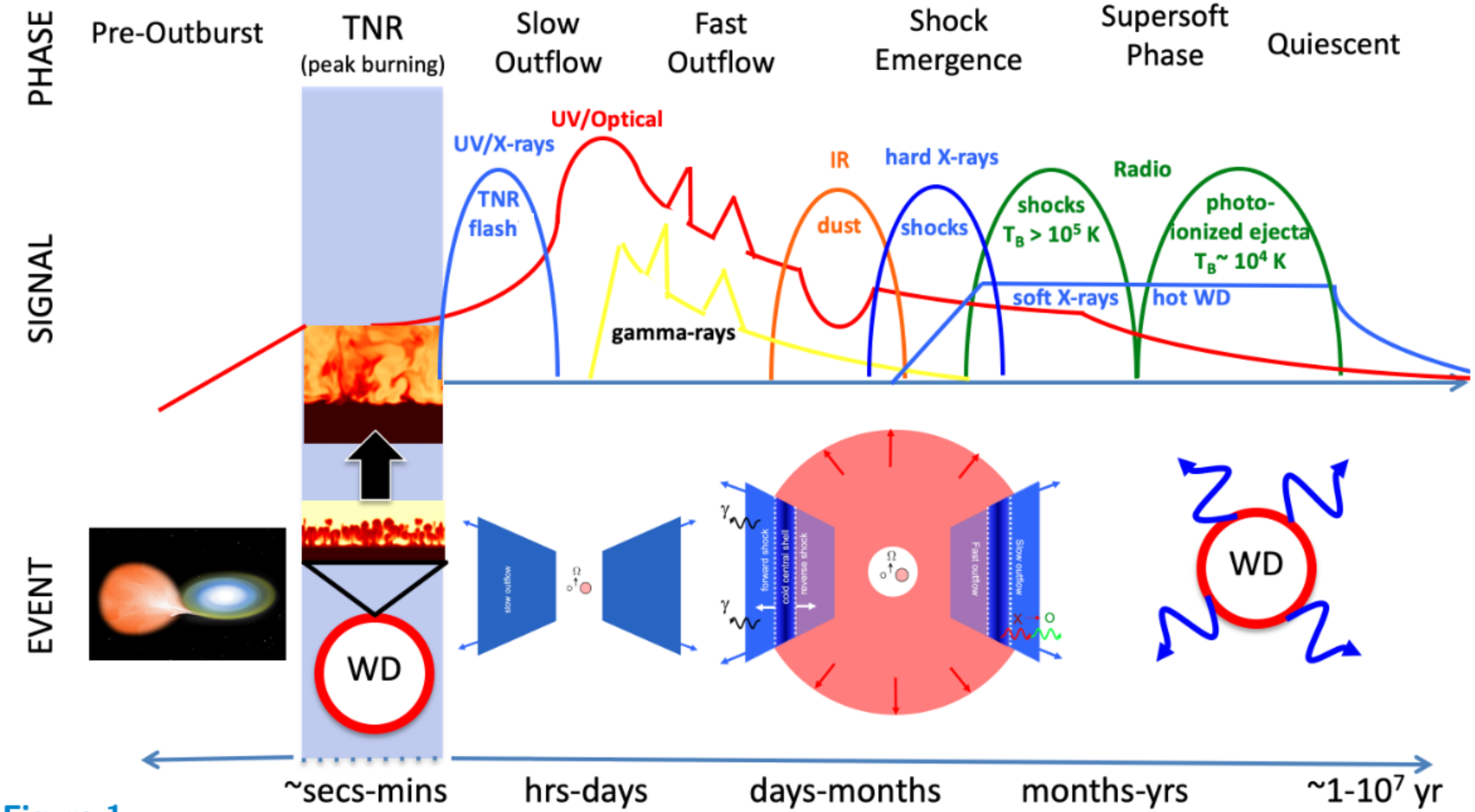


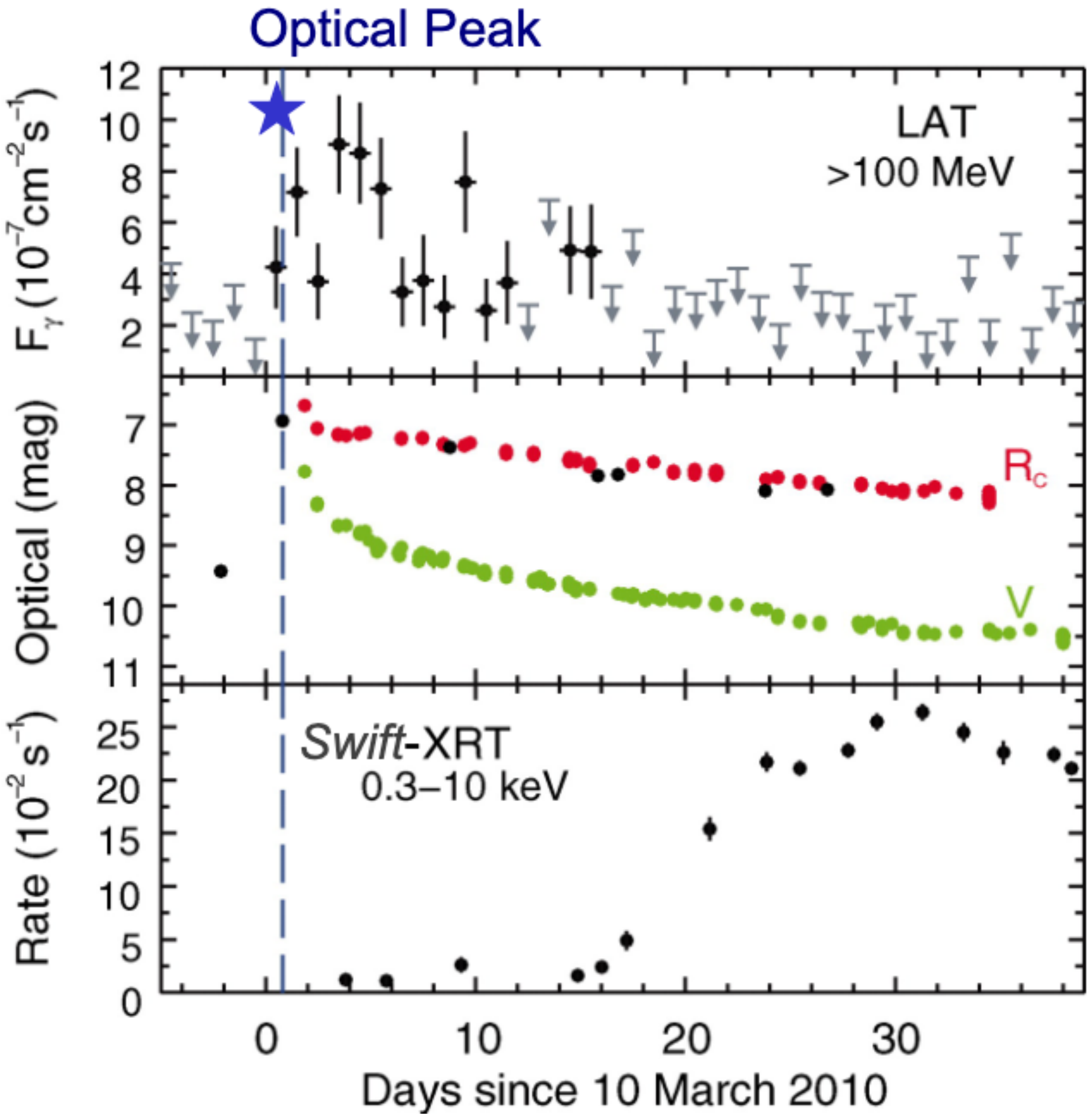
Figure 1

Schematic timeline of the physical processes and electromagnetic signals from novae. The figure includes modified images of convection/mixing during the thermonuclear runaway from Casanova et al. (2016, reproduced with permission ©ESO) and internal shocks from Metzger et al. (2015).

Chomiuk+2021

Fermi Discovery of a gamma-ray nova

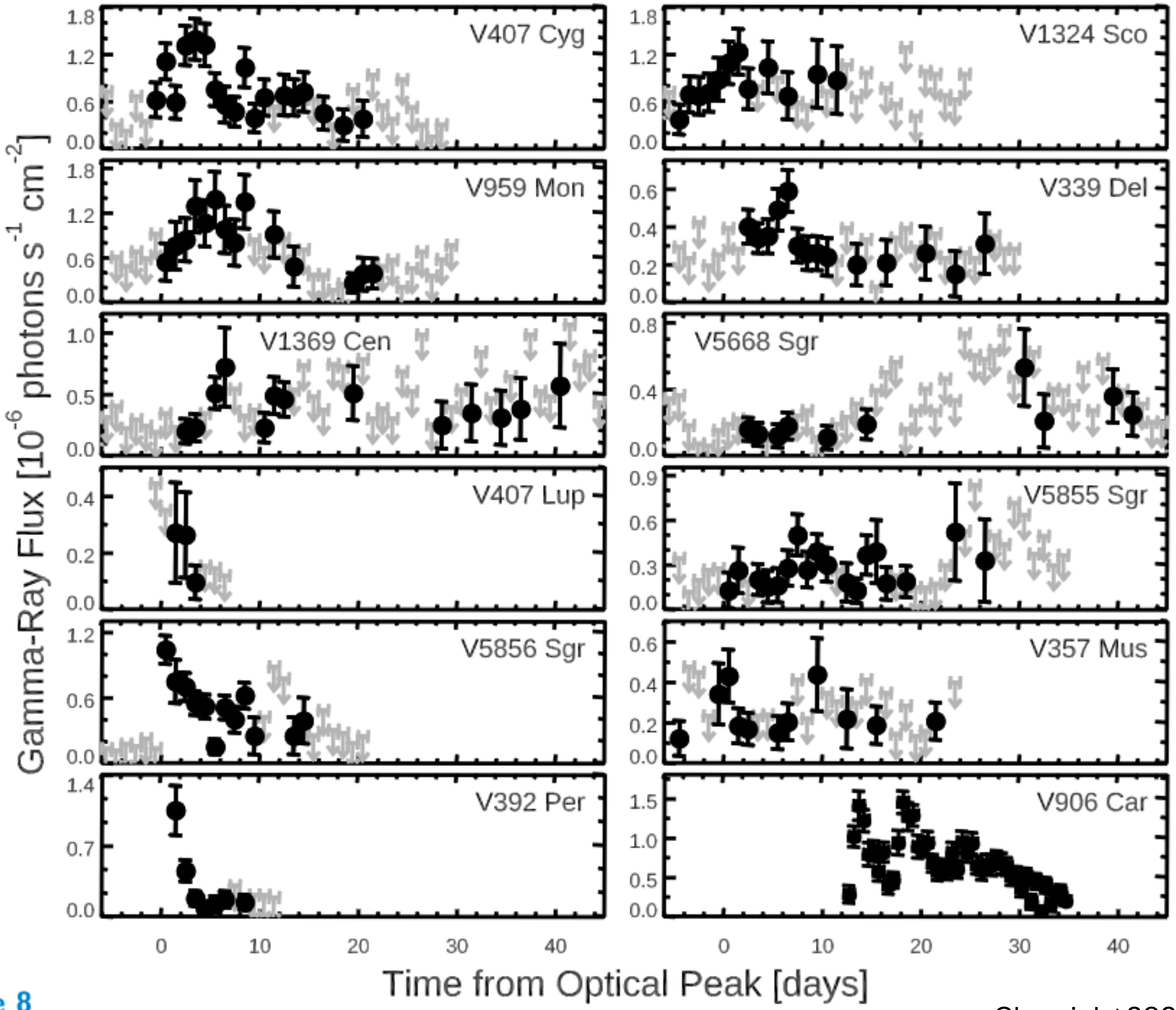
- Particle acceleration in nova ejecta through **interactions with dense wind of Red Giant companion** (proposed for RS Oph by Tatischeff & Hernanz 2007)
- Initial *Fermi*-LAT detection **2010 March 10**, same day as nova V407 Cyg optical discovery by Nishiyama & Kabashima
- γ-ray identification via spatial ($r_{95\%}$=3.7') & temporal coincidence with a symbiotic- like recurrent nova
- Observation with VERITAS during days 9–16
  - No detection; Upper limits constrain hadronic model parameters. [Aliu et al. 2012]



Abdo+2010

Gamma-ray properties

- Durations ~ 5-55 days
- t_{rise} ~ t_{fall} ~ 2-7 days (shortest duration = 0.75 days in fastest nova Her 2021; Sokolovsky+23)
- Flux peaks (>0.1 GeV) ~ 0.1- 5 x 10^{-6} ph cm^{-2} s^{-1}
  - Power law (Γ = 1.8-2.3); many with cutoffs (Ec ~ GeV) (slightly harder in symbiotics) [Frankowiack 2018]
- Average luminosities (>0.1 GeV) ~ 10^{34} - 4 x 10^{36} erg s^{-1} (highest in the bulge)



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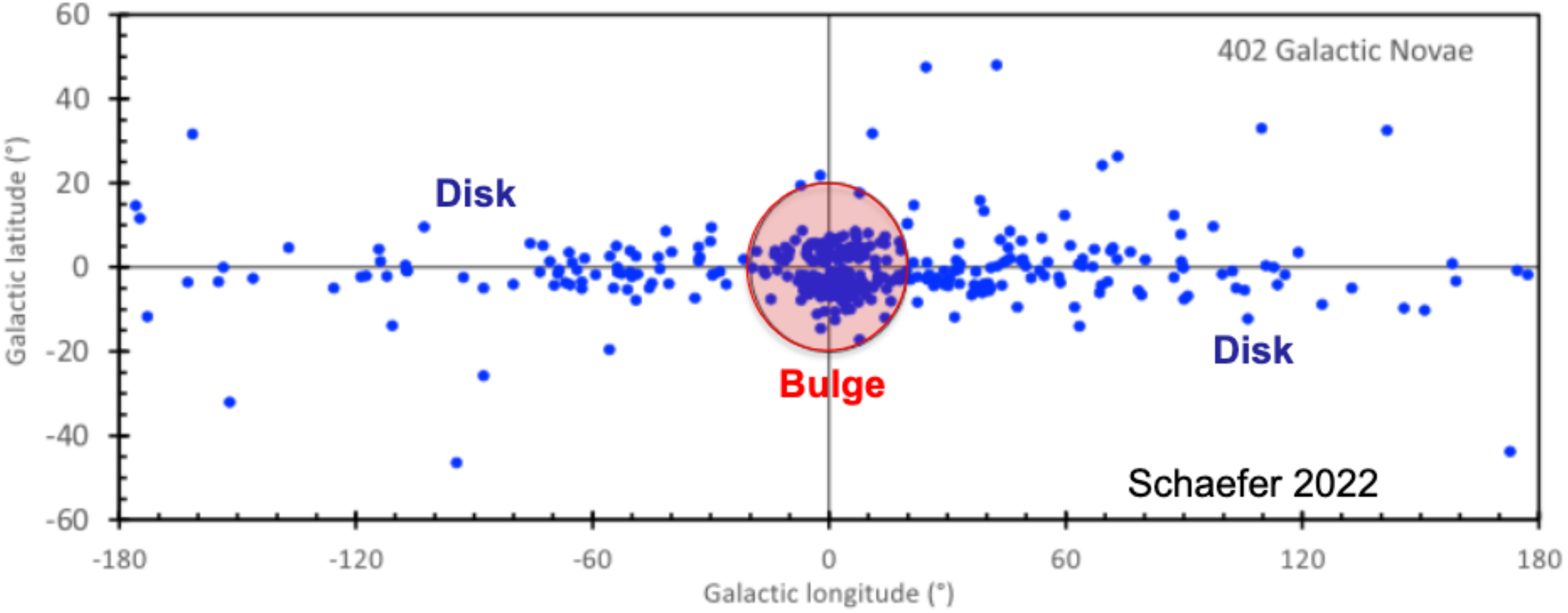
Chomiuk+2021

Distances to Galactic Novae



- Bayesian distances to 402 Galactic novae using Gaia DR3 parallax (74 “good”, i.e., with <30% uncertainty) and non-parallax distance measures (220 distances with <30% uncertainty) [Schaefer 2022]
  - 124 novae occurred in Fermi-era (2008 - 2021.6)
- Two observed populations:
  - ~40% in Galactic Bulge (D ~ 8.0 +/ 0.8 kpc); rest in Galactic Disk (scale height 140 +/- 10 pc), i.e., the local population to Earth
  - Symbiotic (red giant) systems relatively rare in disc population (5 +/-2 %) vs. bulge population (35 +/- 8%) –> no simple explanation
  - Otherwise, populations indistinguishable (e.g., absolute optical mag, lightcurve decline times, optical spectral types)

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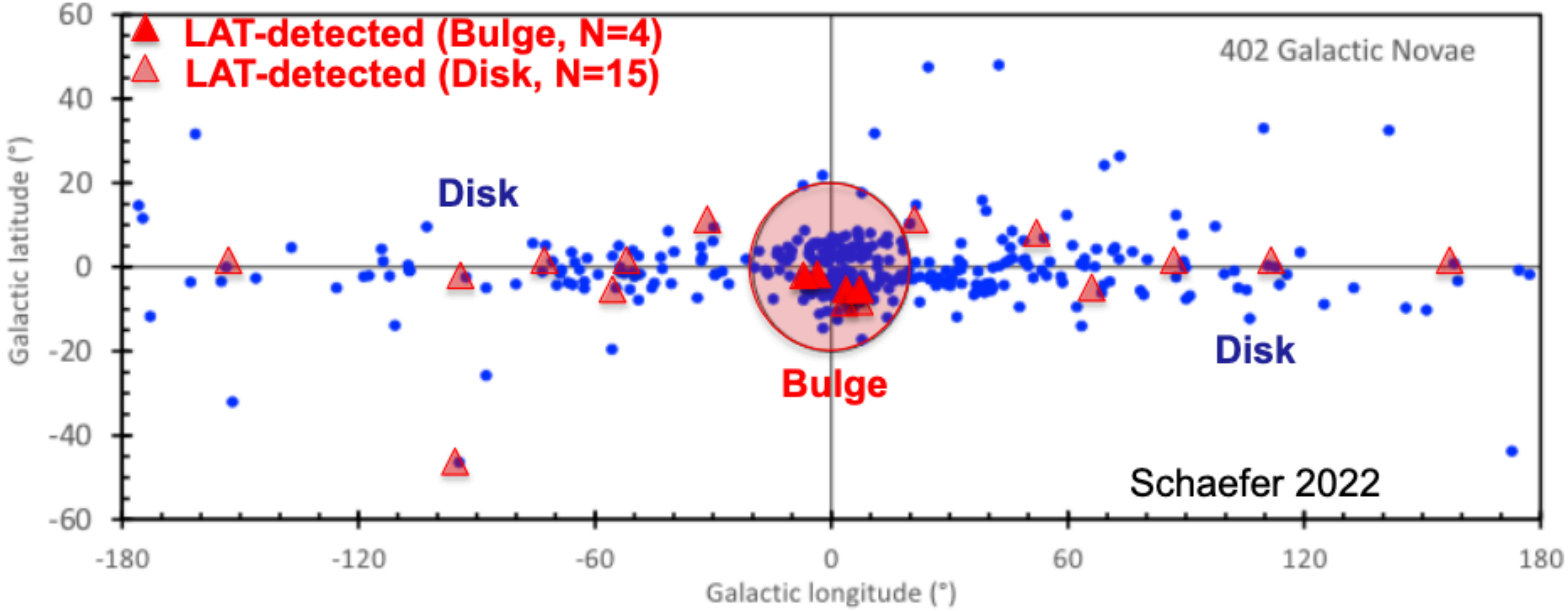
Fermi-LAT GeV Novae population



- Total N =19 LAT detections from 2008 - 2023
  - Majority (N=15) of LAT detections in the Galactic disk (2/15 are seen through the sightline of the bulge)
  - 4 LAT detections in the Galactic Bulge (including symbiotic recurrent nova V3890 Sgr)

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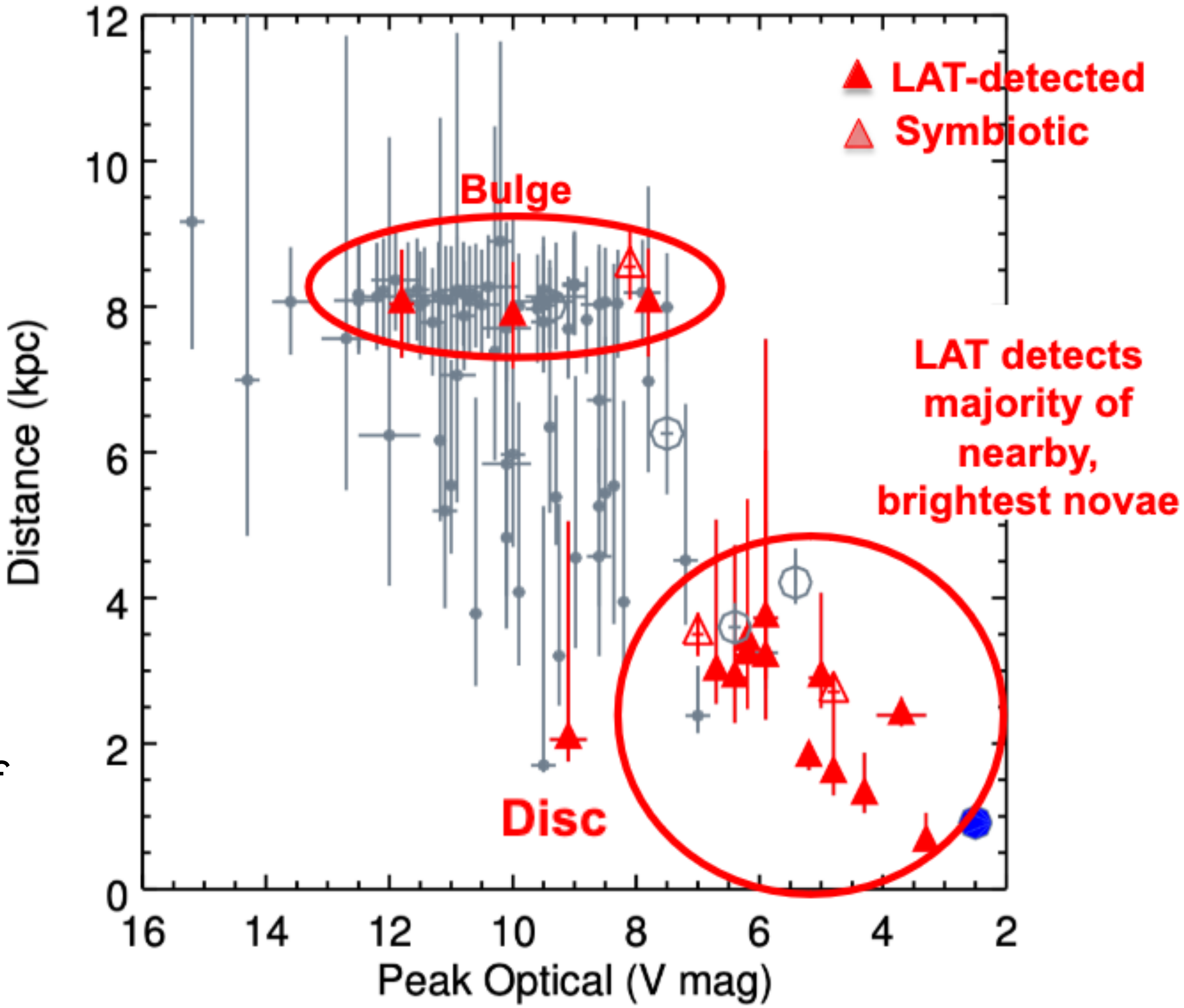
Fermi-LAT GeV Novae: 2008 - 2023

- Fermi-LAT detected novae in Galactic disk tend to be closest and brightest.
- In fact, LAT detected 13/17 of the optically brightest novae during Fermi era; Exceptions:
    - two recurrent novae: KT Eri (V = 5.4), T Pyx (V = 6.4)
    - FM Cir 2018 (V = 5.9) – larger end of distance range?
    - V5583 Sgr 2009 (V = 7) viewed through the Galactic bulge
- 4 LAT detections (including symbiotic-recurrent V3890 Sgr) are in the Galactic bulge with range of V peaks consistent with general population.



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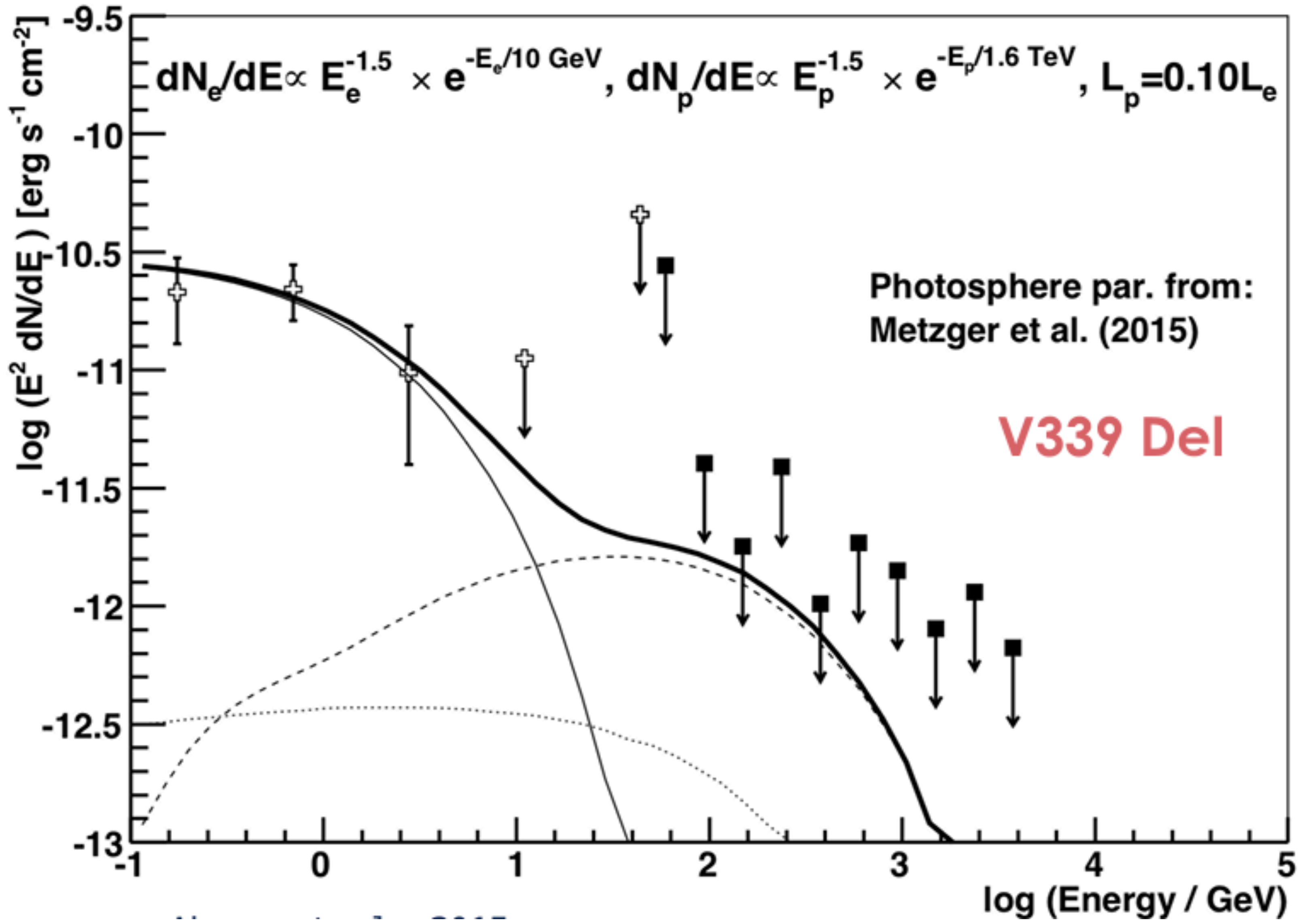
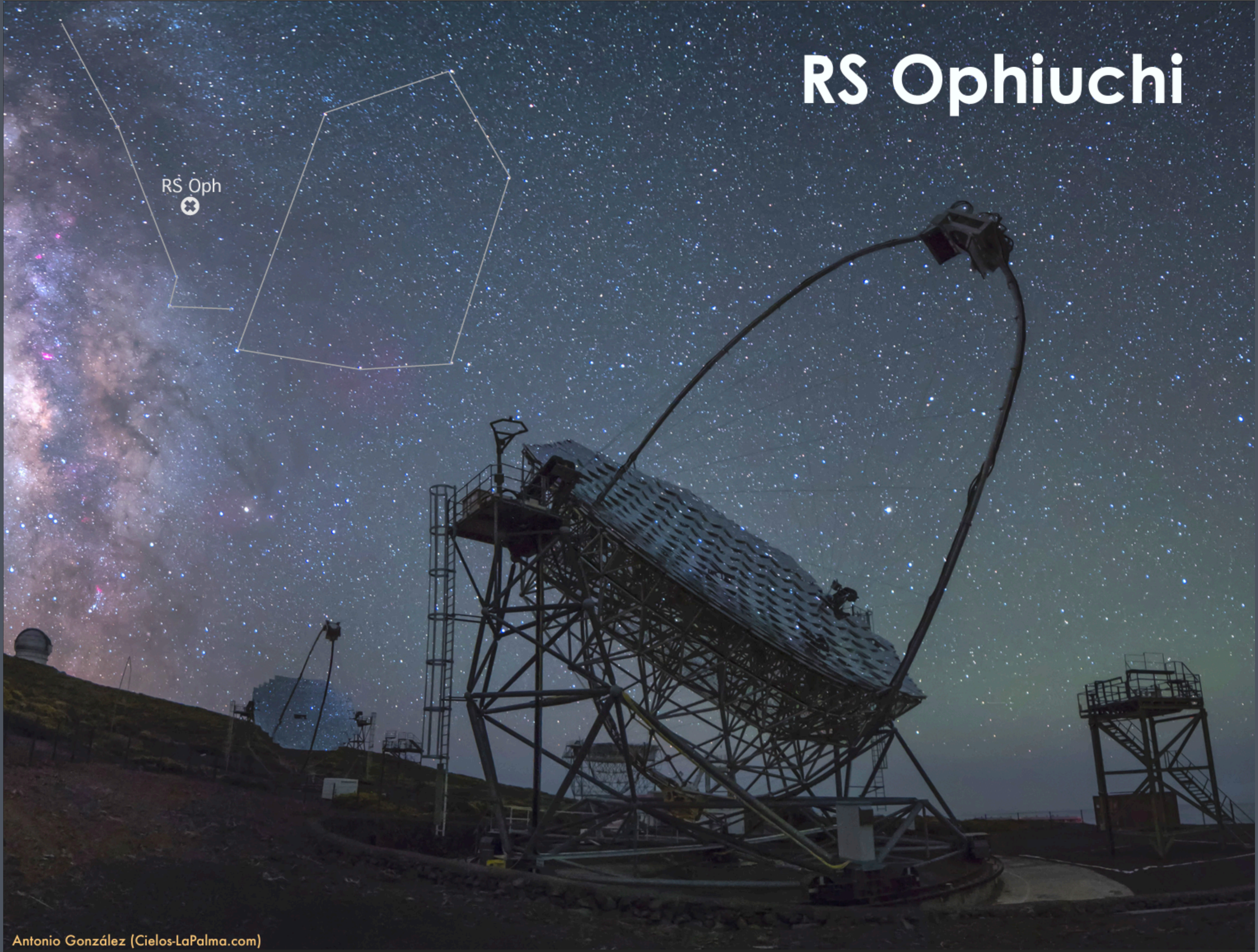
Searching for very high energy emission

- High energy data alone not enough to disentangle electron and proton acceleration models
- Particles are accelerated in nova shock: non-thermal processes
    - Protons can reach much higher energies due to lower energy losses and thus possibly produce a second component detectable by Cherenkov Telescopes
- Cherenkov Telescopes had searched for a VHE component in novae for more than a decade (Aliu et al. 2012, Ahnen et al. 2015)



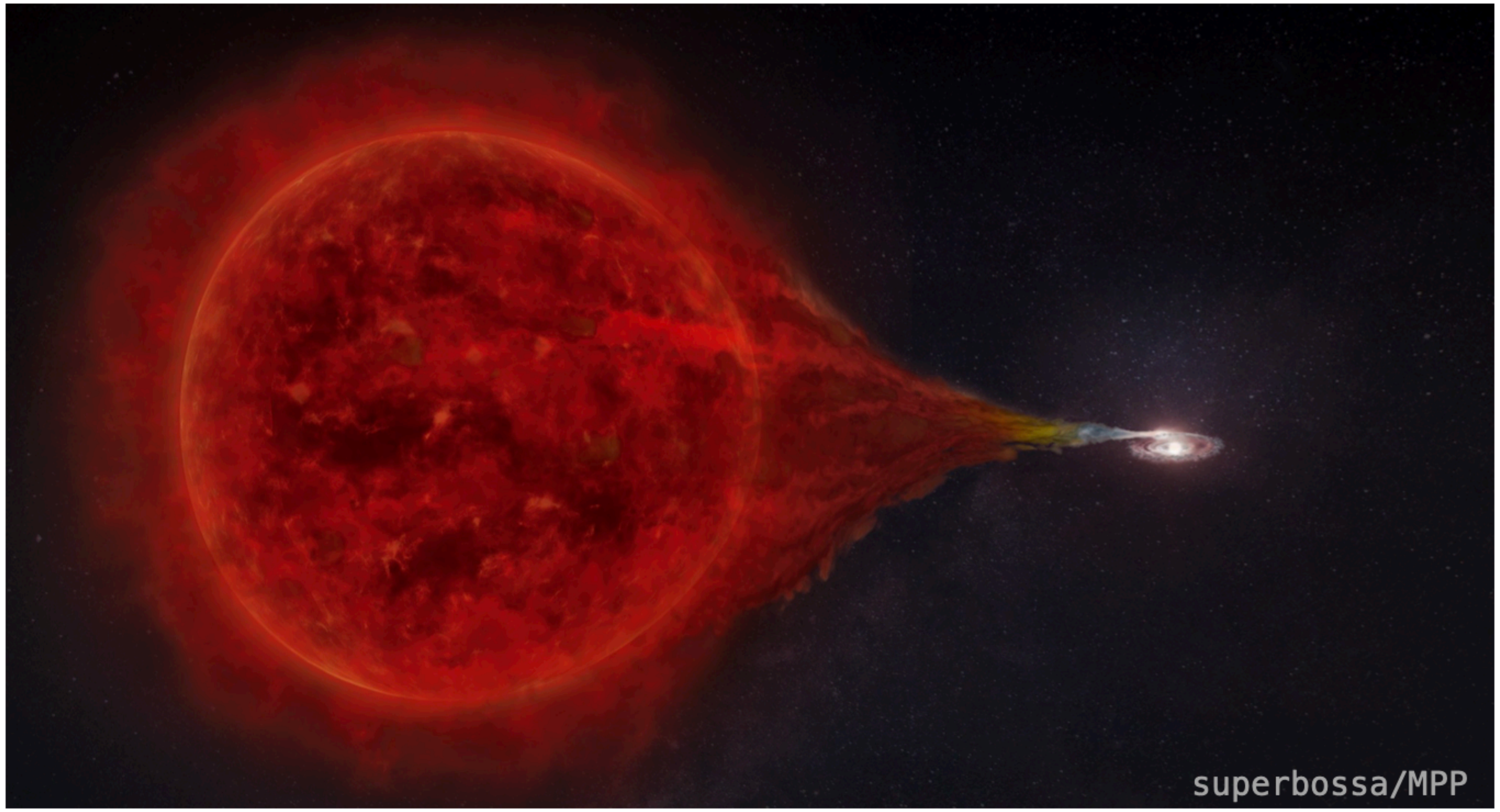
RS Ophiuchi



Antonio González (Cielos-LaPalma.com)

First detection of nova at VHE: RS Ophiuchi

- RS Oph is a **recurrent symbiotic nova** which displays major **outbursts every ~15 years**
  - WD + M0-2 III RG star
    - M_{WD} = and M_{RG} = 0.68–0.80$M_\odot$
  - Distance: 2.45 pc (Rupen et. al. 2008)
    - Recent Gaia DR3: parallax distance of 2.69 ± 0.18 kpc
  - Nine eruptions between 1898 and 2021
    - **Latest outburst: August 2021**



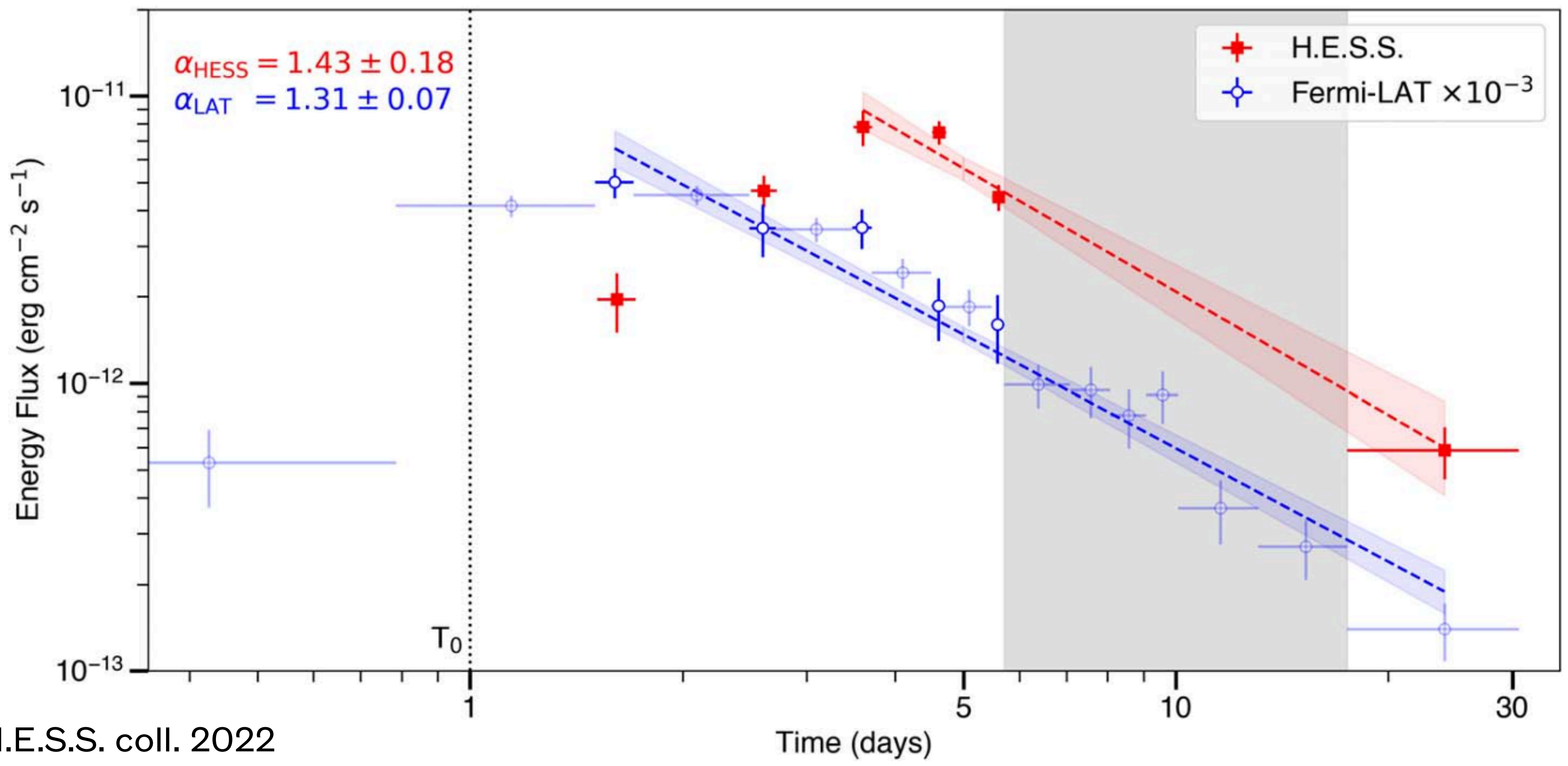
- **GeV emitter candidate:**
  - 2006 outburst of RS Oph detected by Swift/BAT could not be accounted by the decay of radioactive isotopes
  - Emission could be explained **via the production of non-thermal particles by diffuse shock acceleration** (Tatischeff et al. 2007)

Slide from A. Lopez

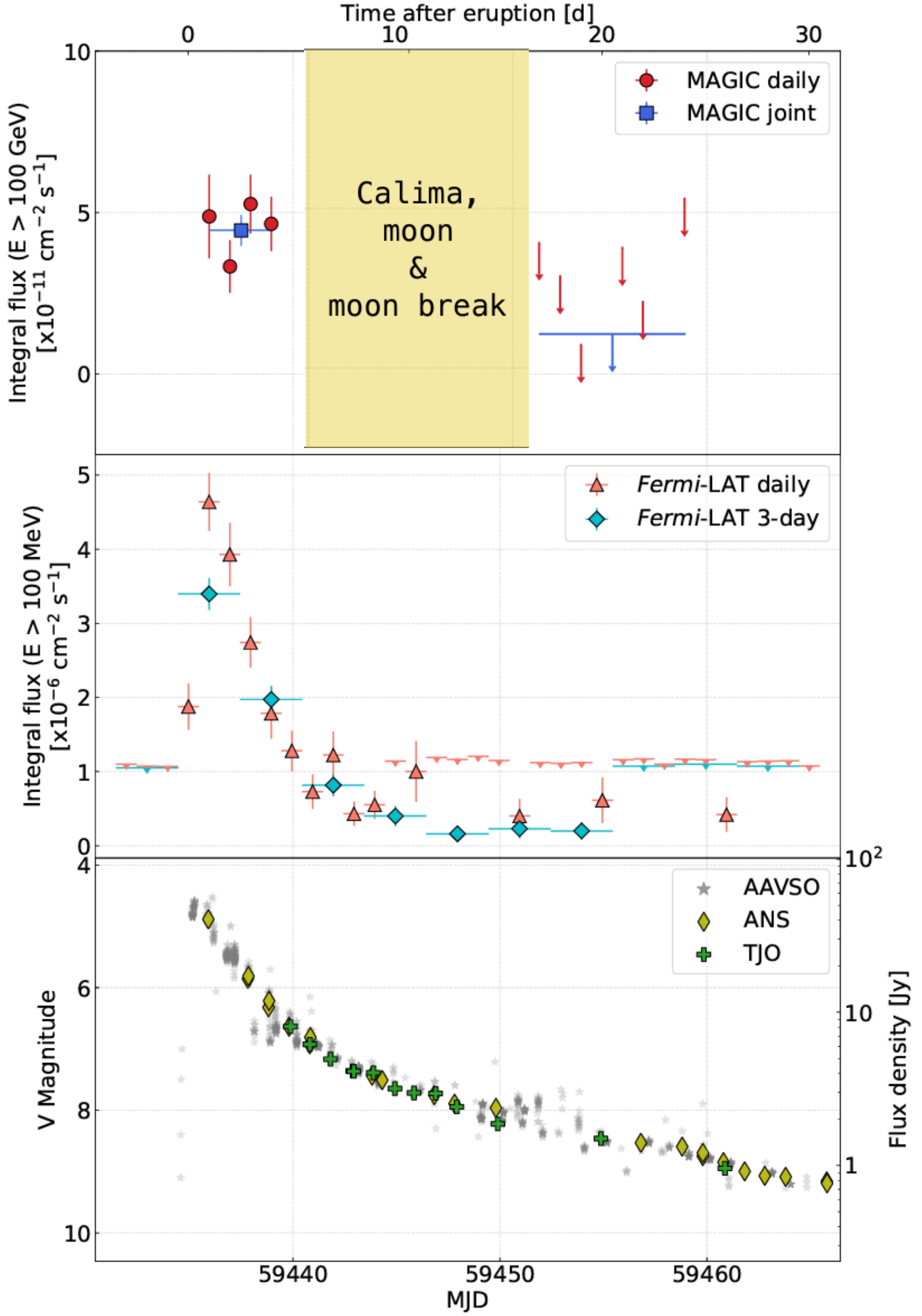
First detection of Nova at very high energies

- First nova detected in the very high energy regime
(HESS coll. Science 2022, MAGIC coll. Nature Astr. 2022)
    - CTA-LST1 obtained comparable results.

Novae established as new source class at VHE gamma rays

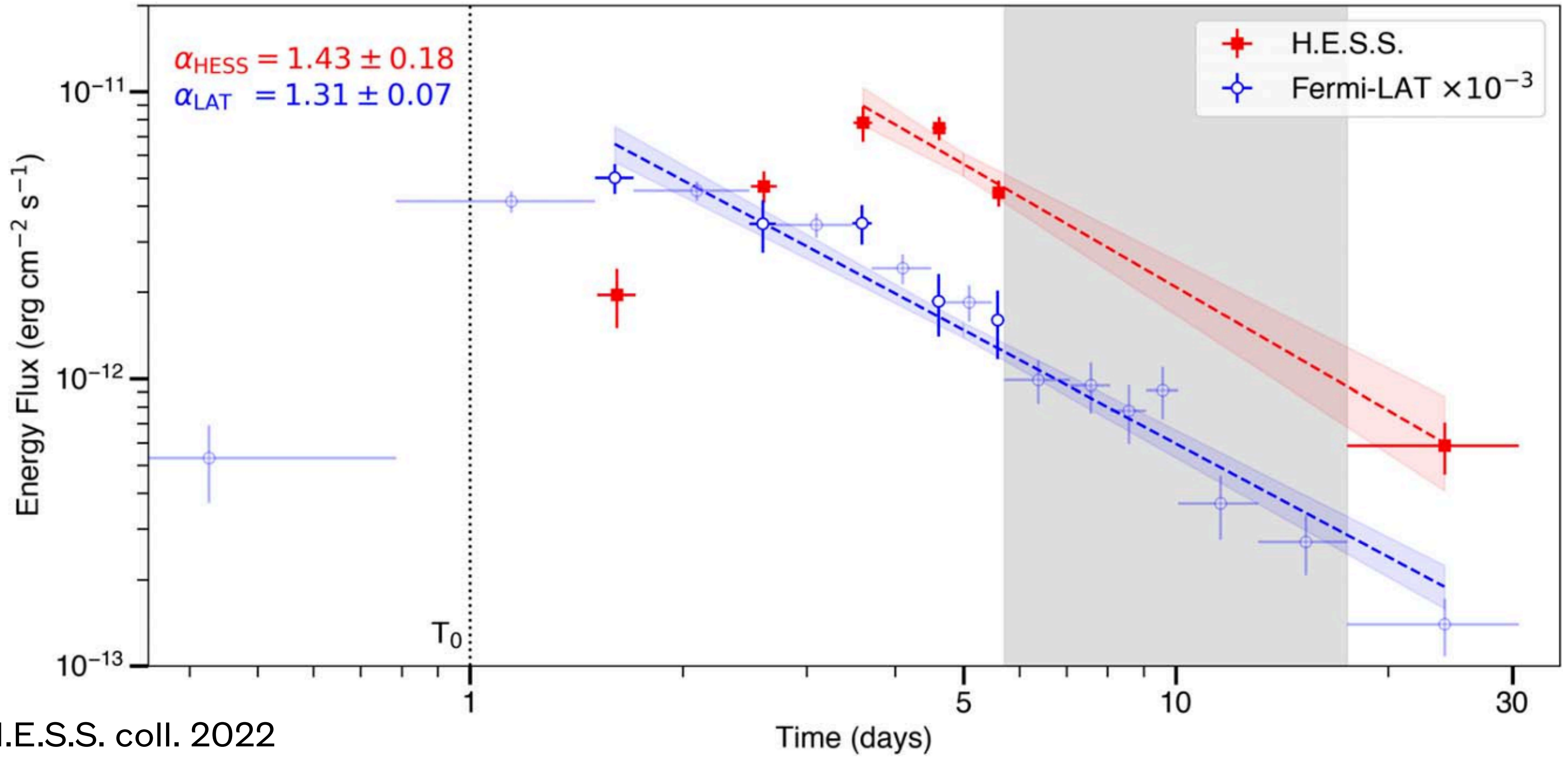


H.E.S.S. coll. 2022

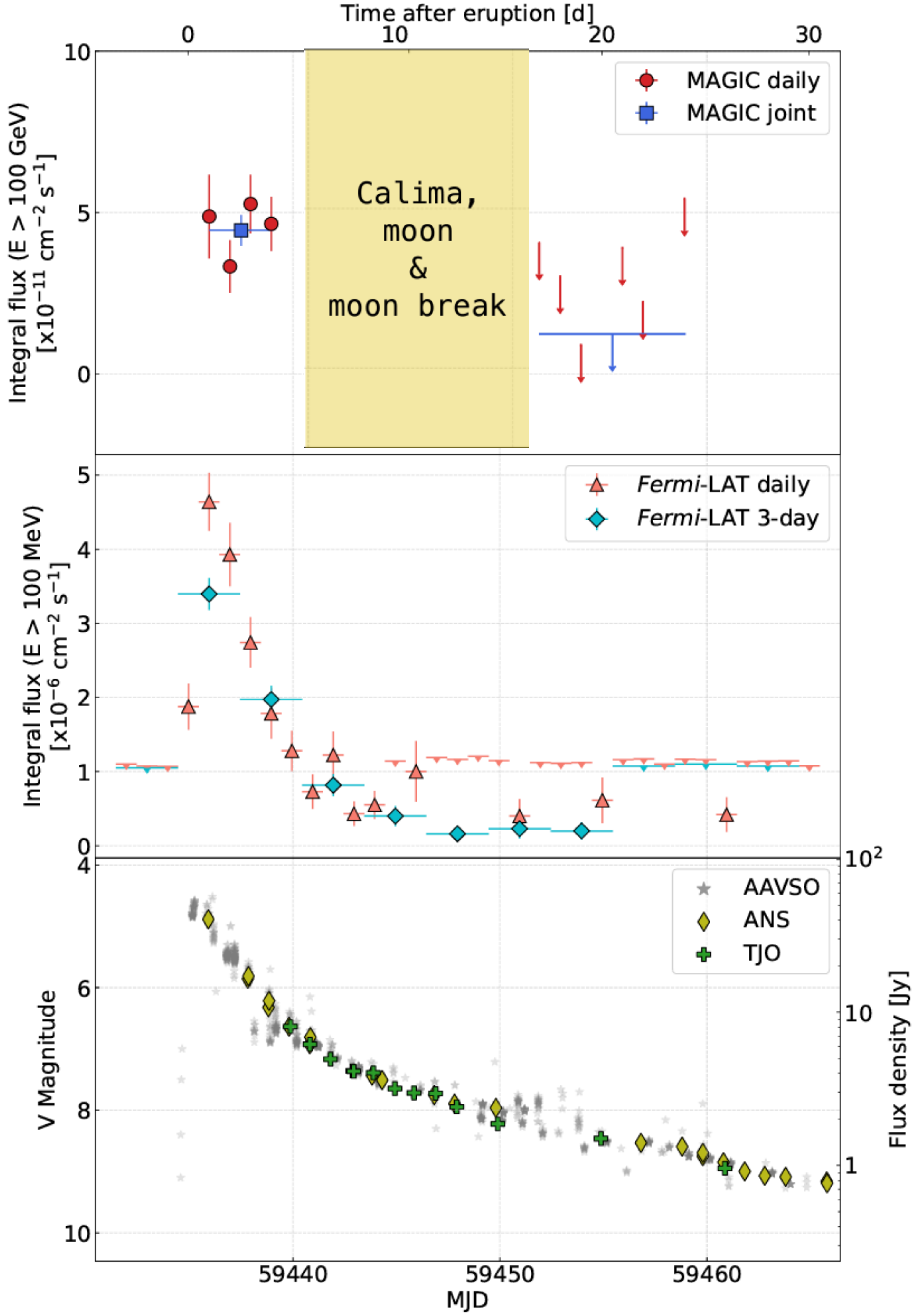


First detection of Nova at very high energies

- Emission peaked at optical and GeV
  - MAGIC VHE emission is consistent with being constant over the first 4 days; H.E.S.S. VHE emission peaks with 2 days delay to Fermi-LAT
- Fast decay at high energies: 2.2 day halving timescale
- During the nova outburst the photospheric emission creates the dominant radiation field



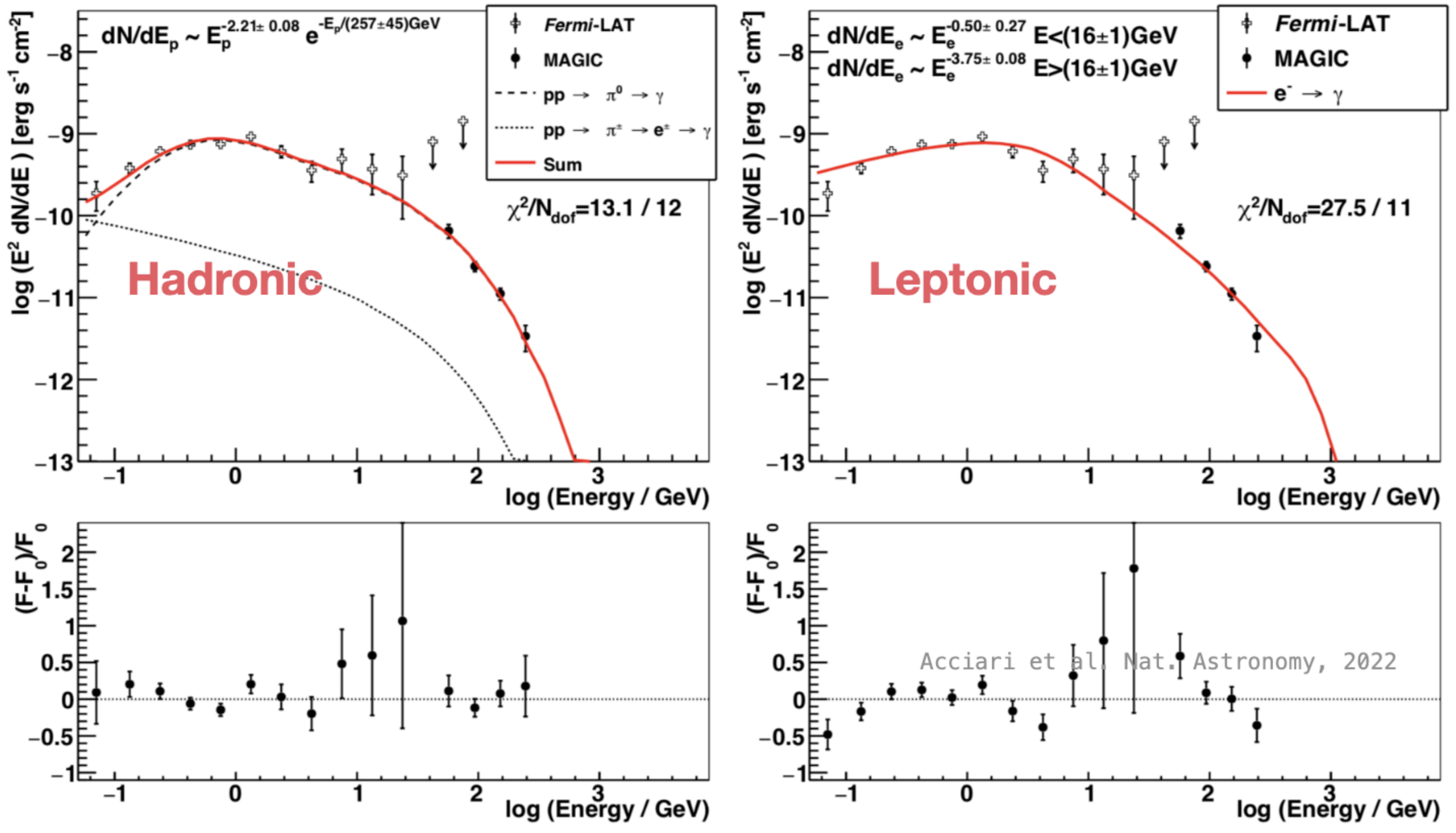
H.E.S.S. coll. 2022



RS Ophiuchi - spectral energy distribution

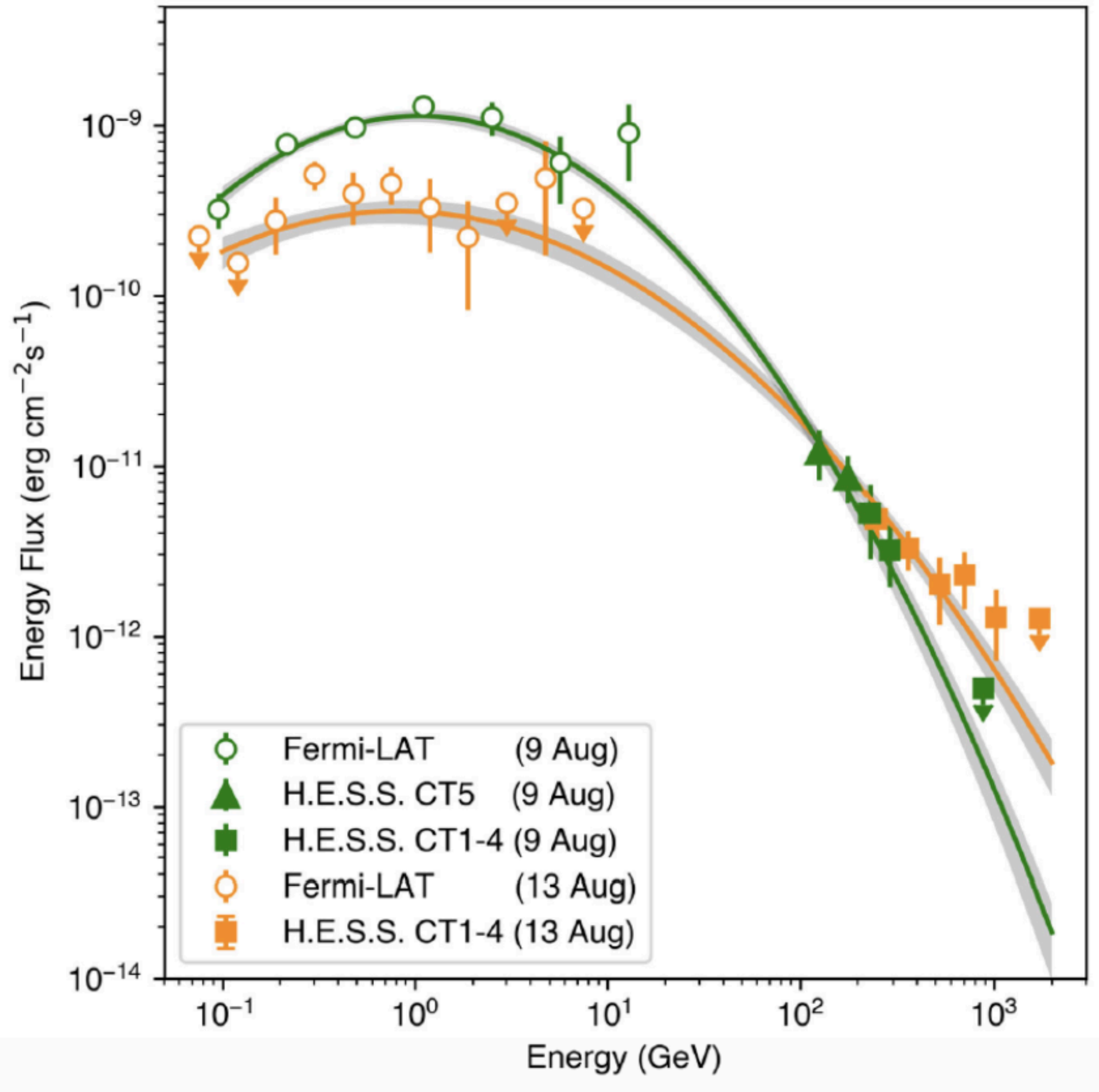
- Hadronic scenarios is favored, because
  - **Better fit** to the data
  - **Protons injected** with standard parameters, while electrons would need an ad-hoc strong spectral break.
  - **Protons have slow cooling**, electrons cool too fast to reach that high energies.
  - **Spectral hardening with time**: behaviour in line with the expectations from the cooling and acceleration time scales for protons.

MAGIC



Acciari et al. 2022

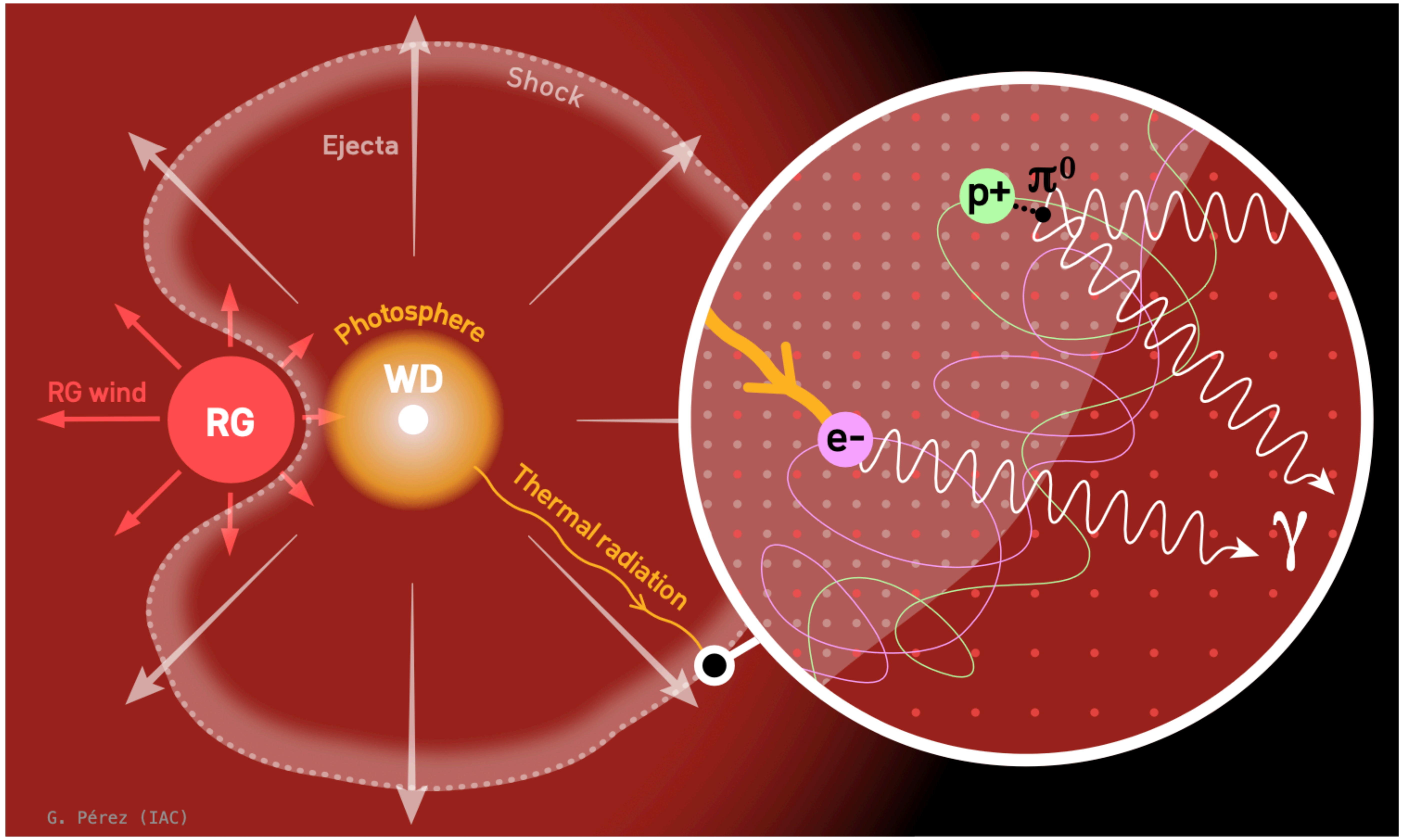
H.E.S.S.

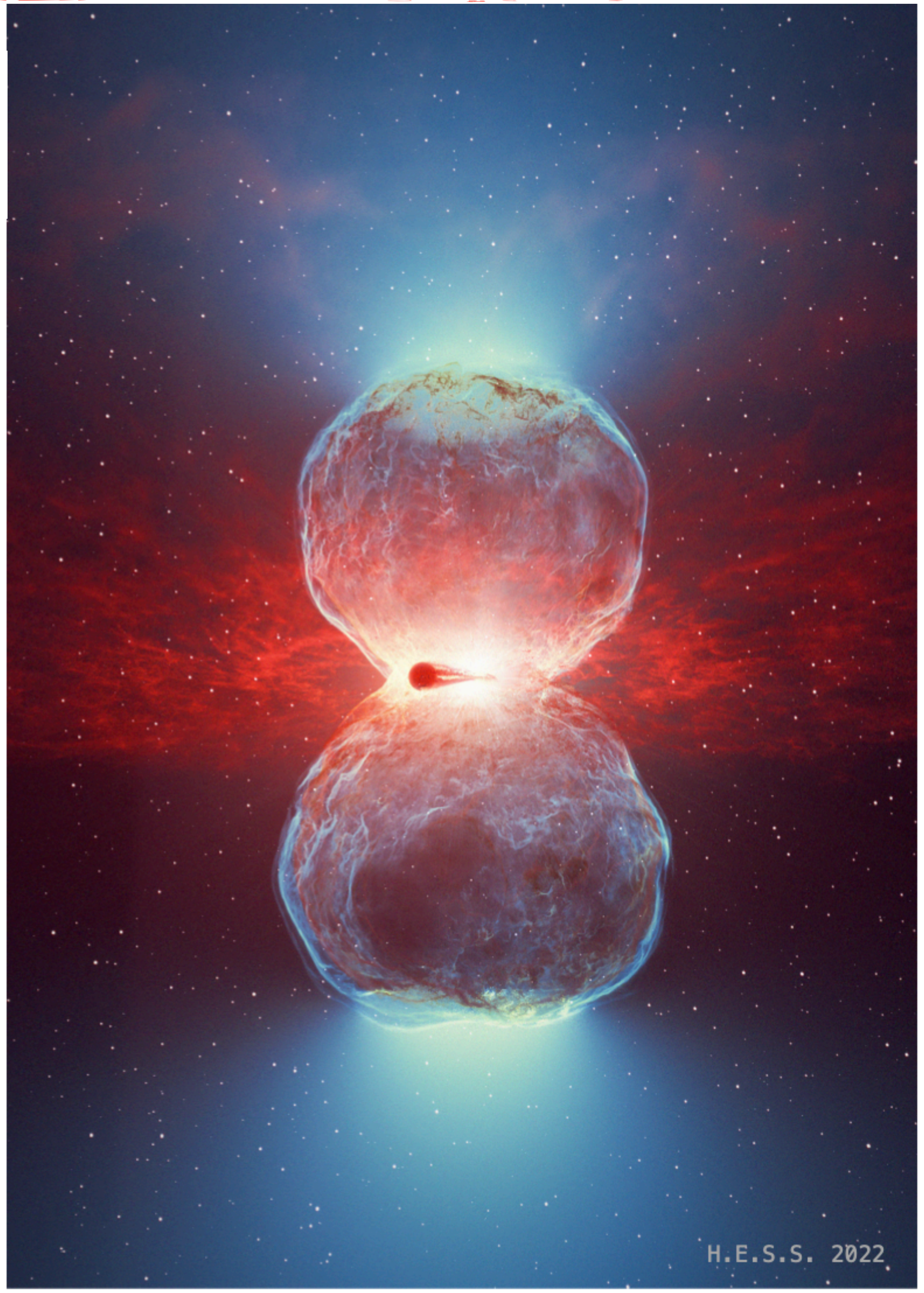


H.E.S.S. coll. 2022

Hadronic scenario is favored.

Acceleration

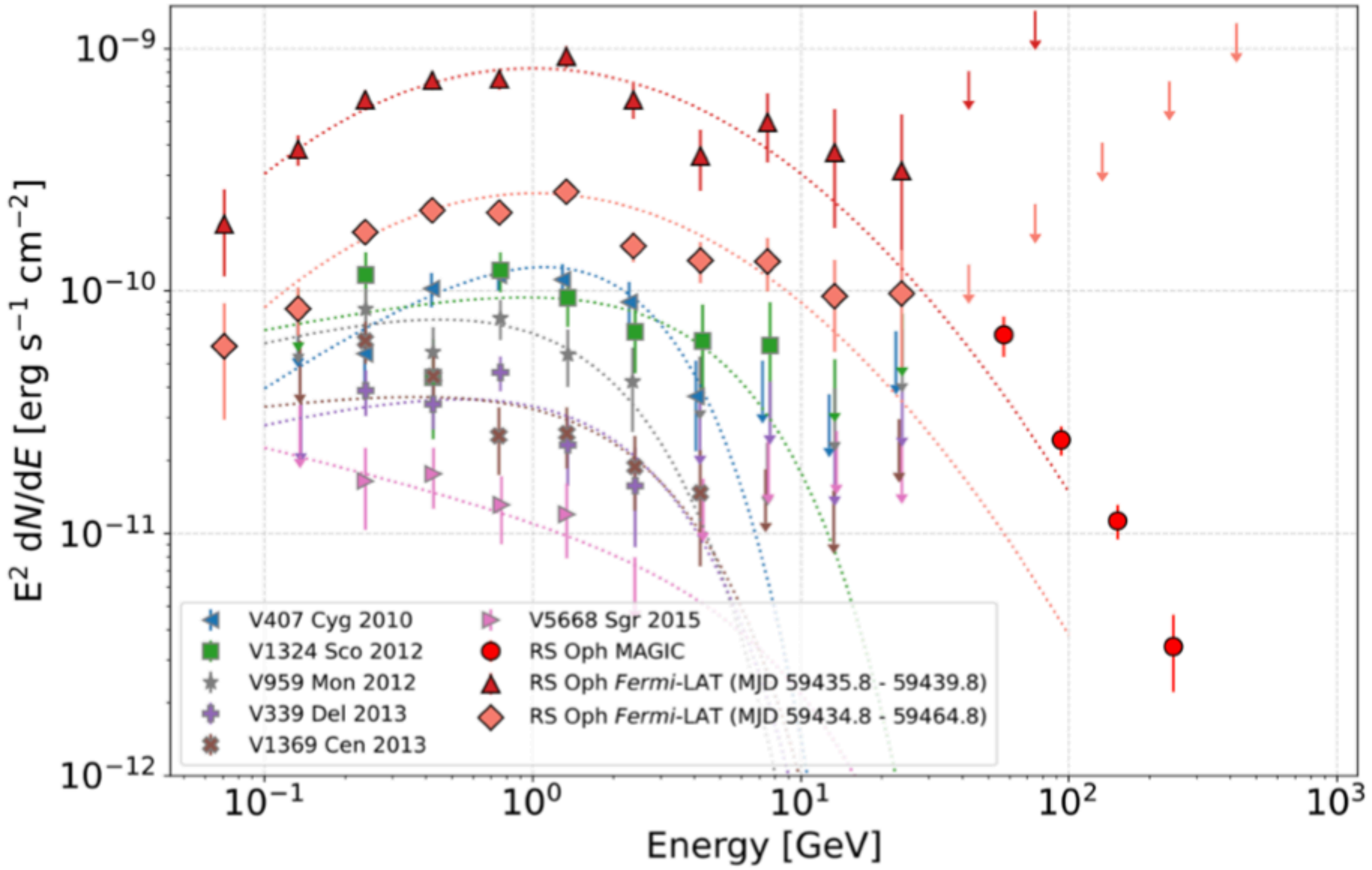


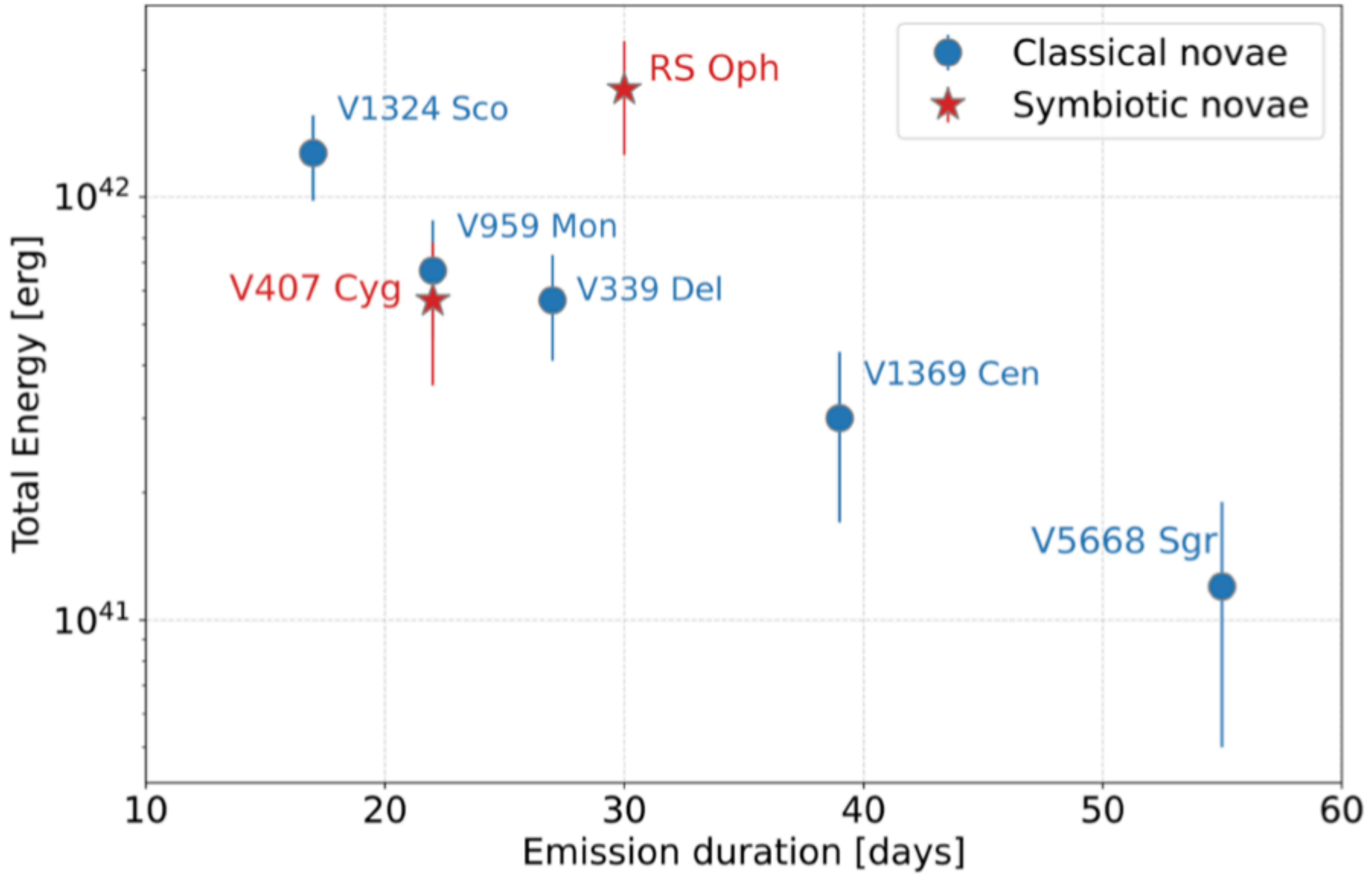


- **Protons**: pp interaction on **nova ejecta** (with some contribution from RG wind)
- **Electrons**: IC on thermal radiation of the **WD photosphere**
- Modeling: particles are injected and either **cool down completely (electrons)** or we gather their emission during the **acceleration time (protons)**

Slide from A. Lopez

Comparison with other novae



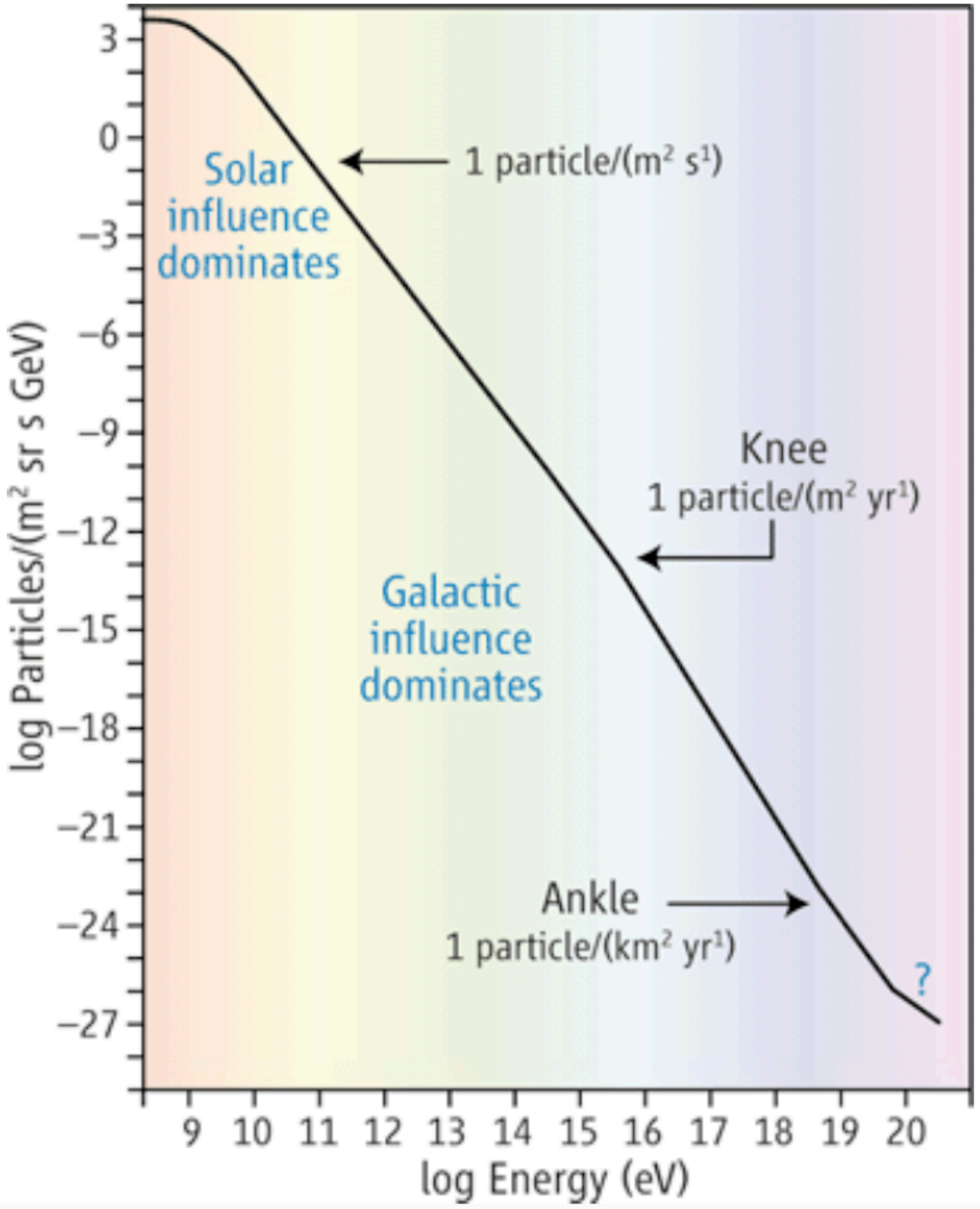


- RS Oph is the nova with the **highest flux** and **brightest nova**
  - Almost two orders of magnitude larger than previously-detected eruptions
- **Comparison does not reveal any peculiarity** in the emission of RS Oph, except for its brightness

Slide from A. Lopez

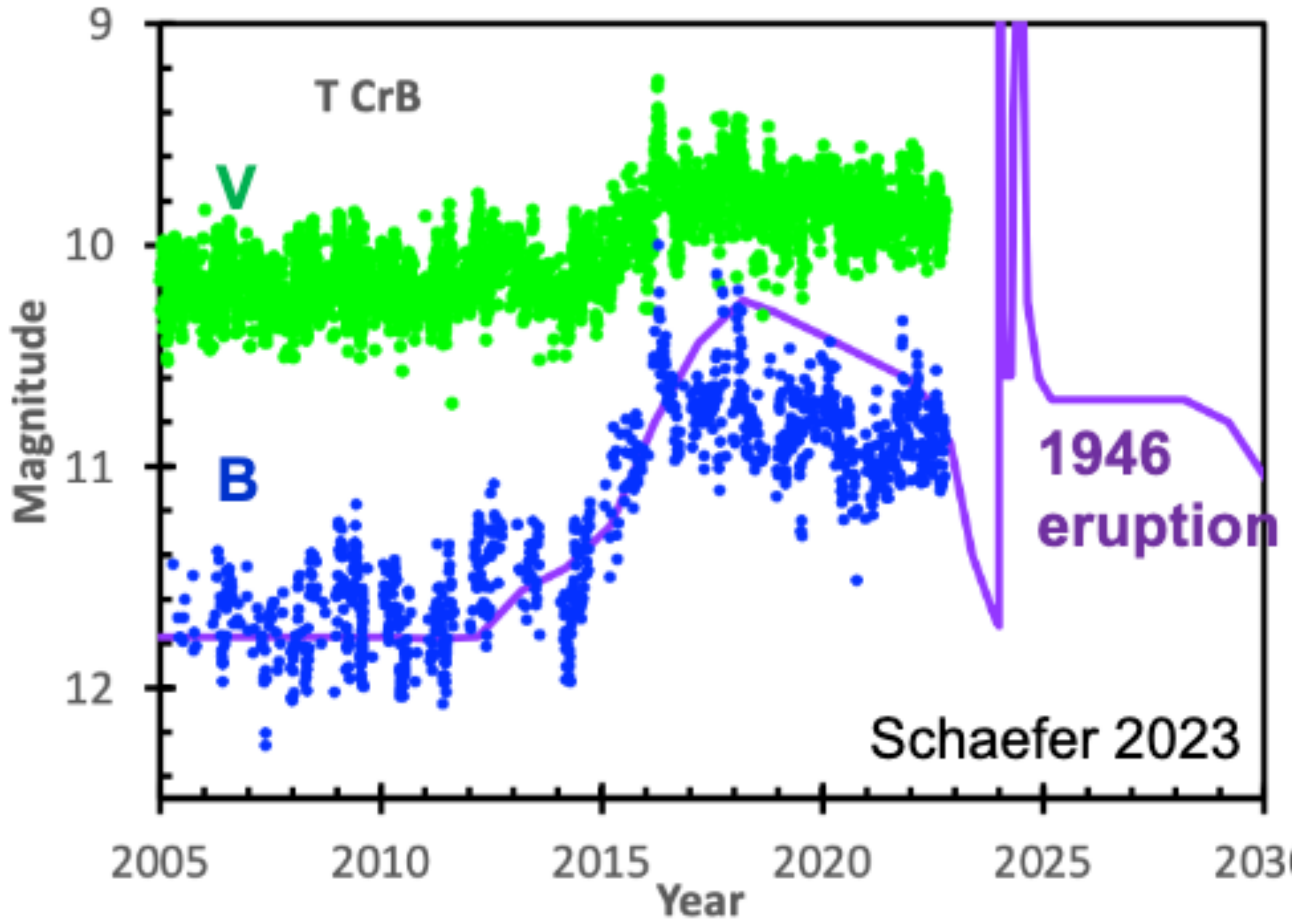
Galactic novae and Cosmic rays

- **Accelerated protons will eventually escape the nova shock** carrying away most of their obtained energy. Such protons can **contribute to the Galactic Cosmic Ray sea**
- Using the CR energetic derived for RS Oph (~ 4.4 × 10^{43} erg): **<0.2% of the contribution from supernovae**
- Despite the small contribution to the overall CR sea, **novae would significantly increase the CR density in its close environment**: E_density(nova)>E_density(CR)
- In the case of **recurrent novae, protons will accumulate in a ~10 pc bubble with enhanced CR density**



T CrB Watch – keystone system

- **T CrB (T Coronae Borealis)**
  - RA, Dec (J2000) = 15 59, +25 55 (north)
  - M4.5 III red giant companion, P_{orb} = 227.57 day (Fekel et al. 2000)
  - M_{WD} = 1.37 (0.13) M_{sun} (Stanishev et al. 2004)
- **Eruptions in 1866, 1946, P_{rec} ~80 year**
  - Optically very bright: peaks of 2 mag and 3 mag, respectively
- **Closest known recurrent-symbiotic nova**, D = 0.91 +/- 0.02 kpc (Schaefer 2022)
- Earlier predictions by Luna+20 and others
- All other known recurrent-symbiotic novae have exploded during Fermi-era (V745 Sco 2014, V3890 Sgr 2019, RS Oph 2021; also symbiotic V407 Cyg 2010)
- **3x closer than RS Oph; naively scale by distance => ~10x brighter?**
- Other symbiotic binary systems: Neutron star GX 1+4/ V2116 Oph; Black hole V404 Cyg



Predicted eruption date:
~2024.2 (as shown)to 2026.8.
Data shown up to epoch 2022.8.

T. Cheung VGGRS 2023

Gamma-ray Novae: Questions

- Are all novae GeV gamma-ray sources ?
  - Yes, with reliable distances, majority of novae within ~4 kpc detected; subset of Bulge novae (D ~ 8 kpc).
- Symbiotics (and recurrents) as keystone systems ?
  - Hadronic emission has outsized role in RS Oph, and likely other symbiotics.
  - Expect outburst of T CrB (D~0.9 kpc), in 2020's, with prompt ~MeV (<1 day). Additional outbursts from other known systems (RS Oph 203X?)
- Role of future VHE observations, particularly with the Cherenkov Telescope Array?
  - Provide useful constraints on the maximum energy of accelerate particles.

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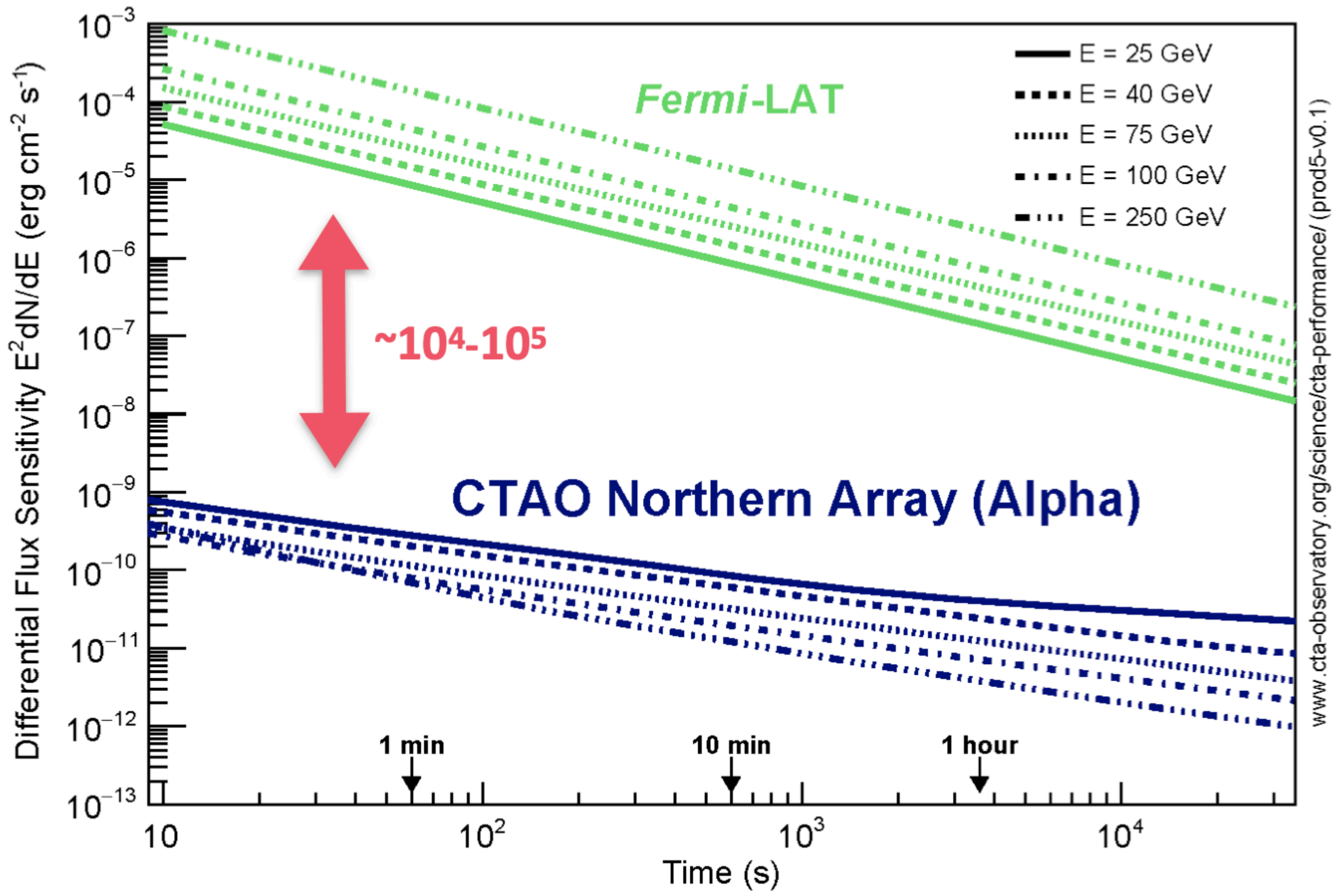
Summary

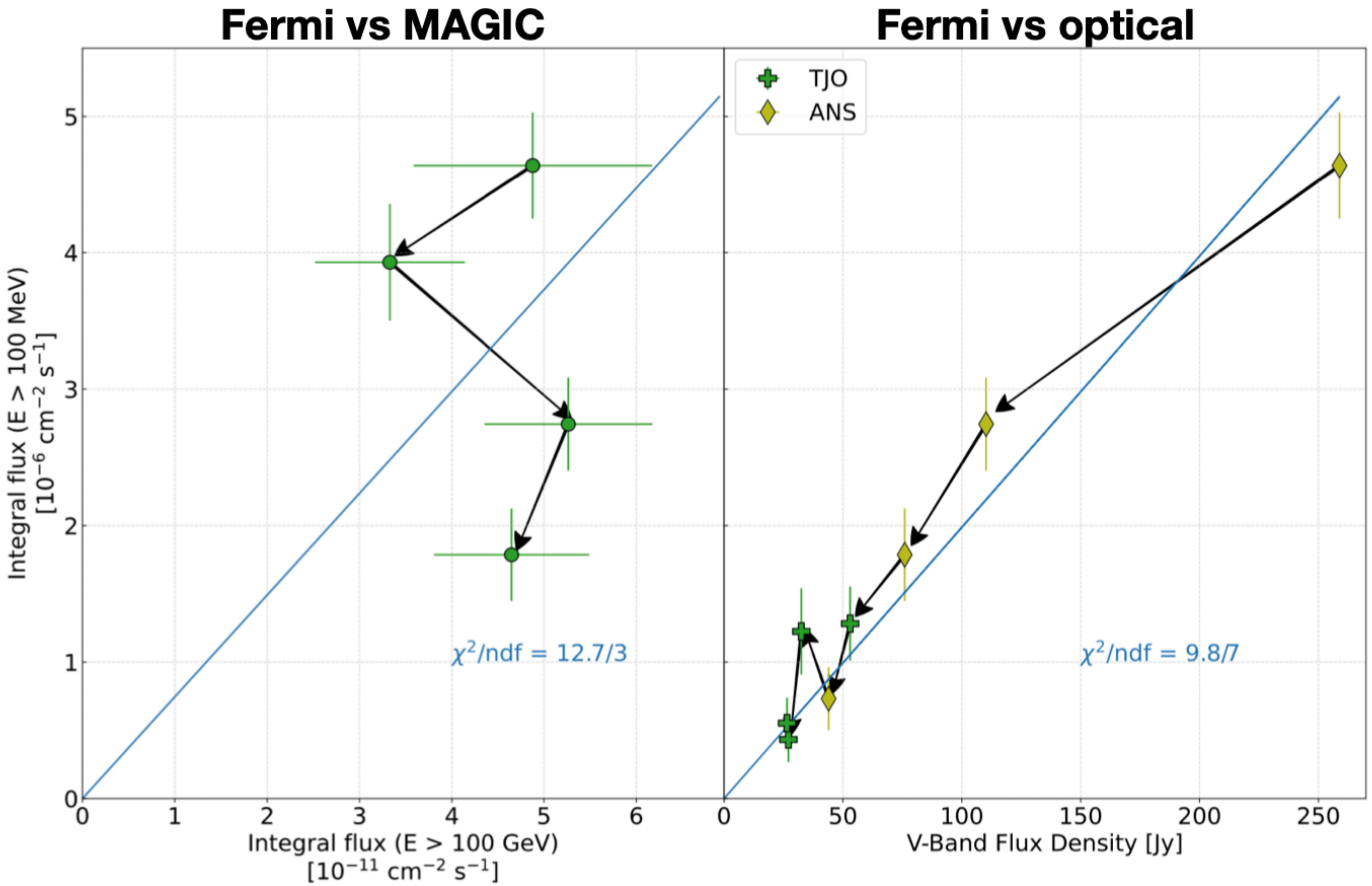
- New source classes to be discovered still.
  - Supernovae at GeV and TeV energies.
  - Transitional milli-second pulsars at TeV energies.
- Next nova detection to come soon?
  - T Coronae Borealis
- More sensitive instruments to come soon at TeV energies
  - Cherenkov Telescope Array (CTA)



Thank you very much for your attention!

Back up

MWL flux evolution

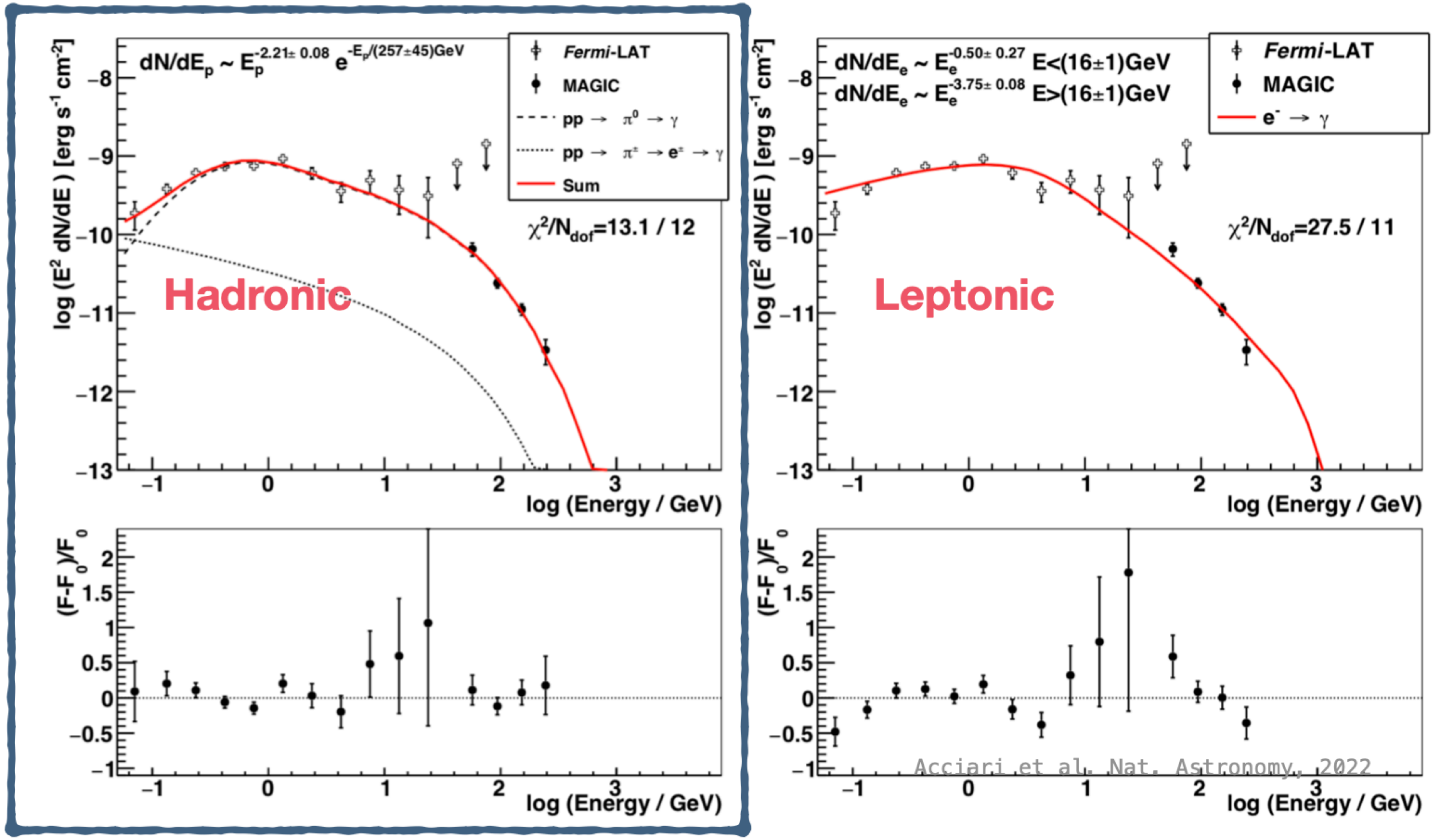


Acciari et al. Nat. Astronomy, 2022

- **VHE roughly flat, while HE decays faster**: can be explained as **hardening of the emission** during its decay
- **HE and optical** emission show **similar decay**: **not compatible with IC** model
  - IC emission should decay faster (due to increase of distance to photosphere)

- **Protons are favored**

Gamma-ray modelling



- **Joint Fermi-LAT +MAGIC** spectrum can be described as a **single**, smooth **component** spanning **from 50 MeV to 250 GeV**

- **Hadronic scenario is favored**

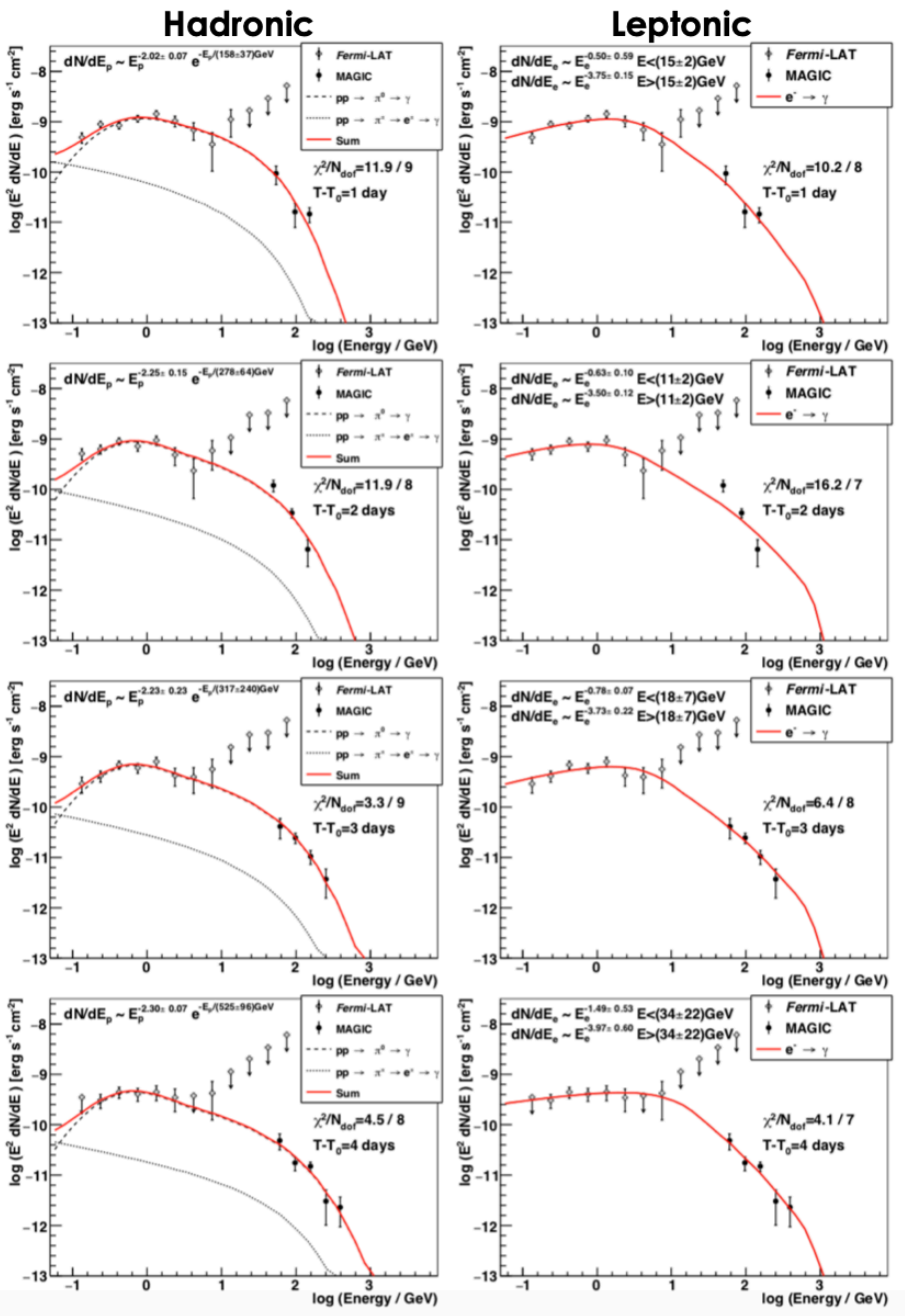
Gamma-ray modelling: daily proton acceleration

Aug 09

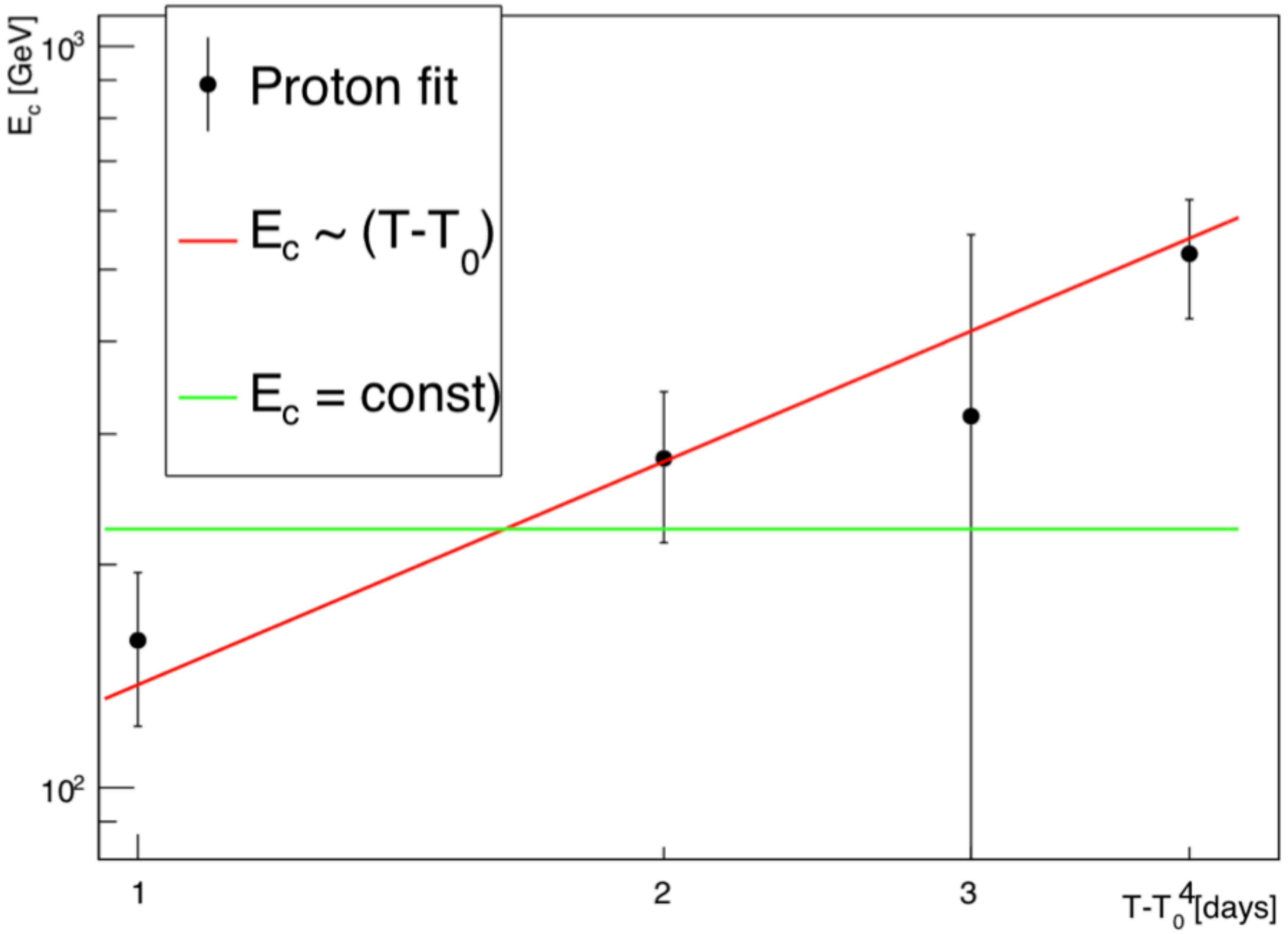
Aug 10

Aug 11

Aug 12



- **Daily SED**
  - **Hadronic scenario favored**
- **Increase of the cut-off energy with time:** hint of spectral hardening
  - In line with the expectations from the cooling and acceleration timescales
  - **Hadronic scenario favored**

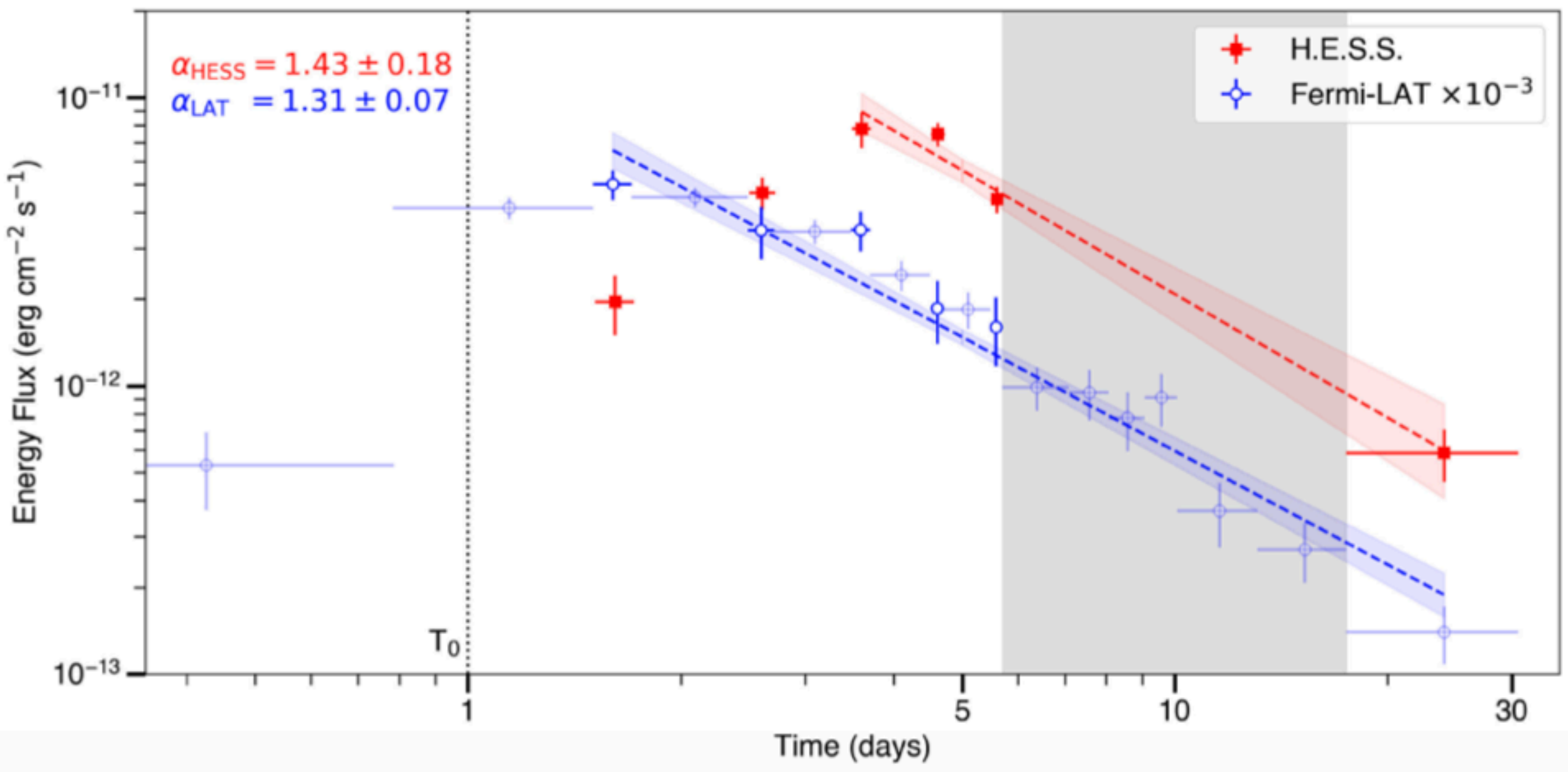


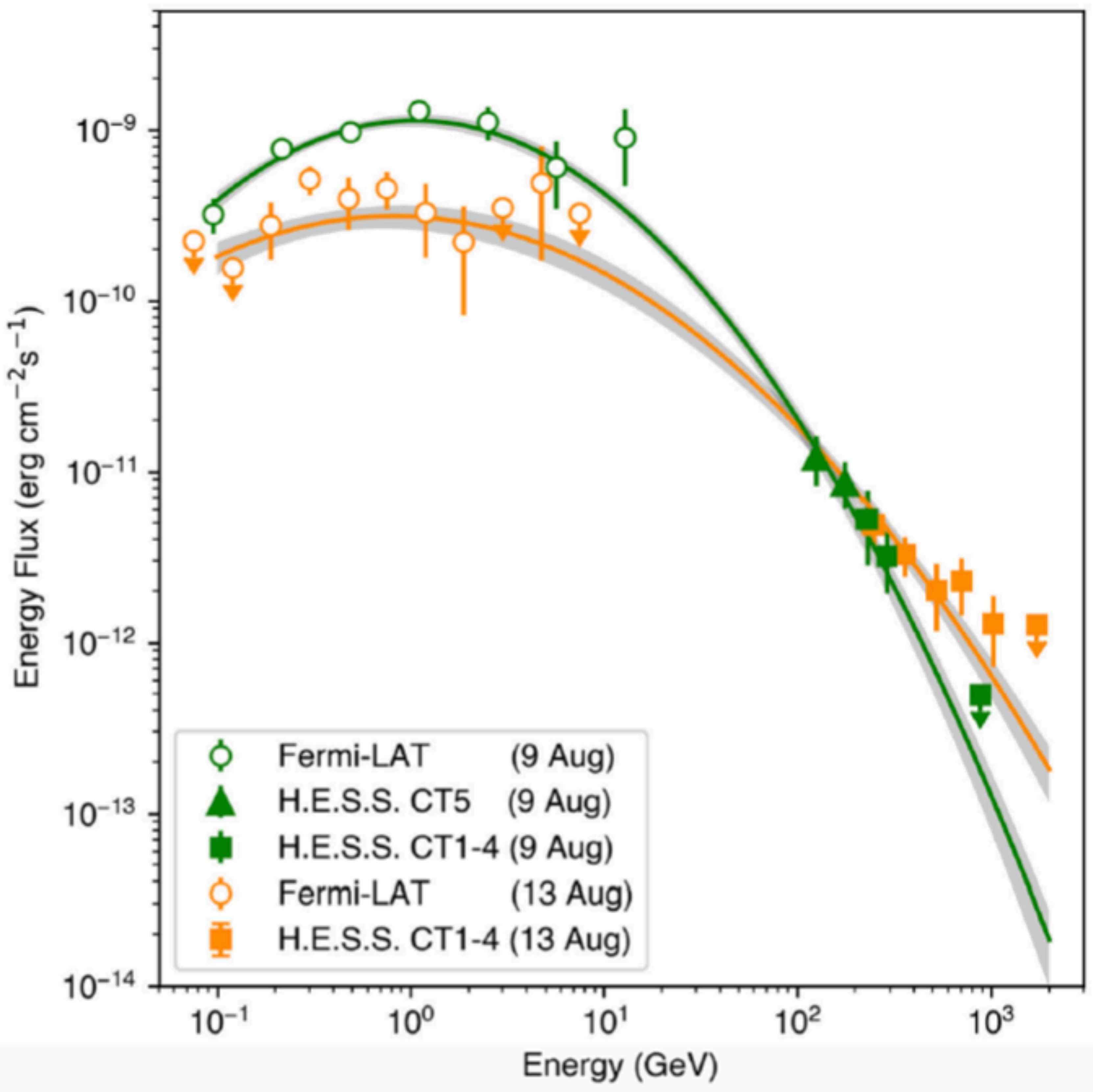
RS Oph at gamma rays: H.E.S.S.

- Fermi-LAT & H.E.S.S. combined analysis
  - Finite acceleration of VHE protons (delayed VHE peak)
  - Single γ-ray component (similar temporal profiles & spectra)

Source: H.E.S.S. Collaboration 2022

- Hadronic scenario is preferred
  - Efficient acceleration up to $E_{p,max} \approx 10$ TeV





Relative numbers

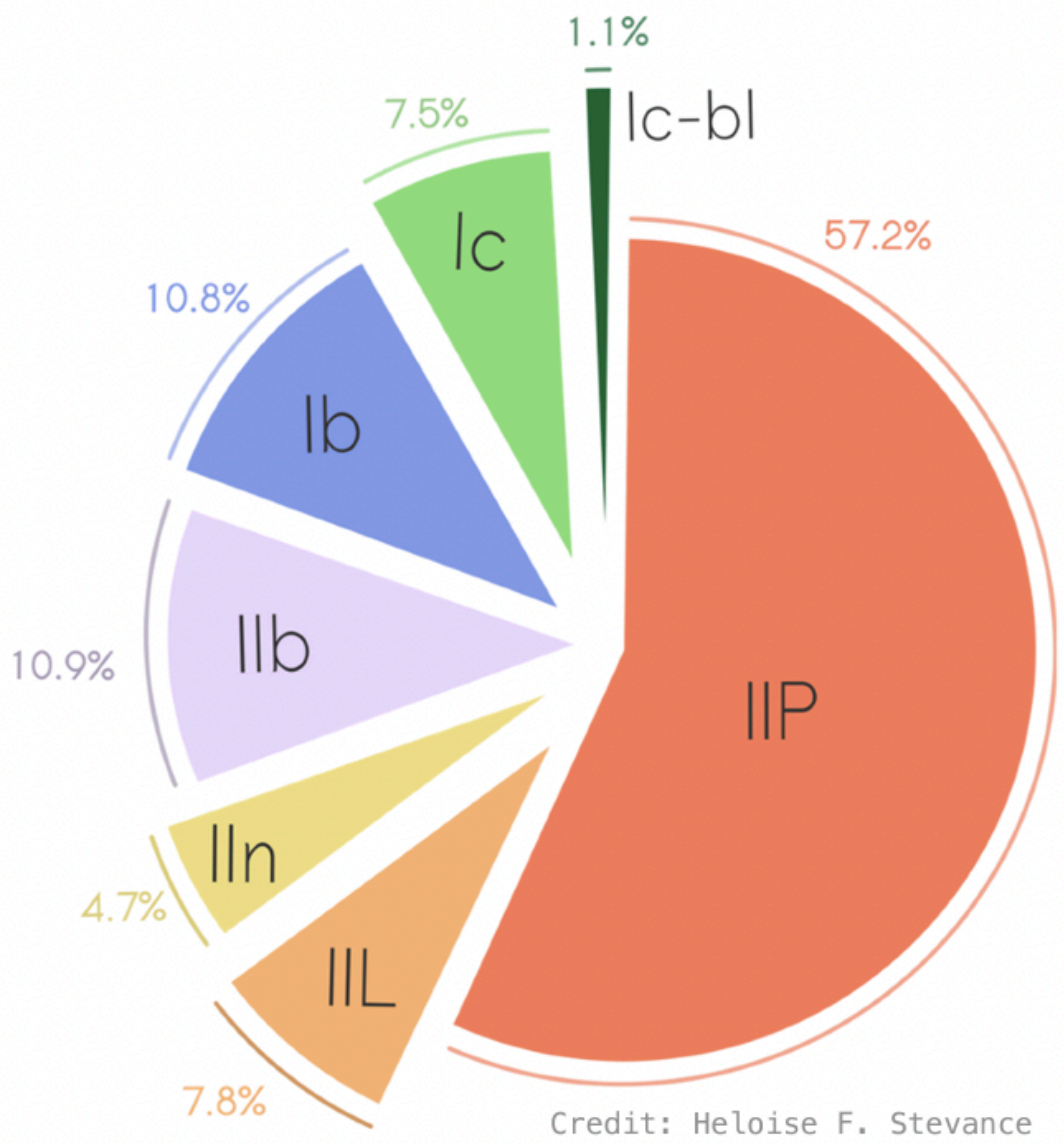


Figure 2: Relative numbers of core collapse SNe as calculated from table 3 of Shivvers et al. (2017) and fig. 9 of Li et al. (2011).

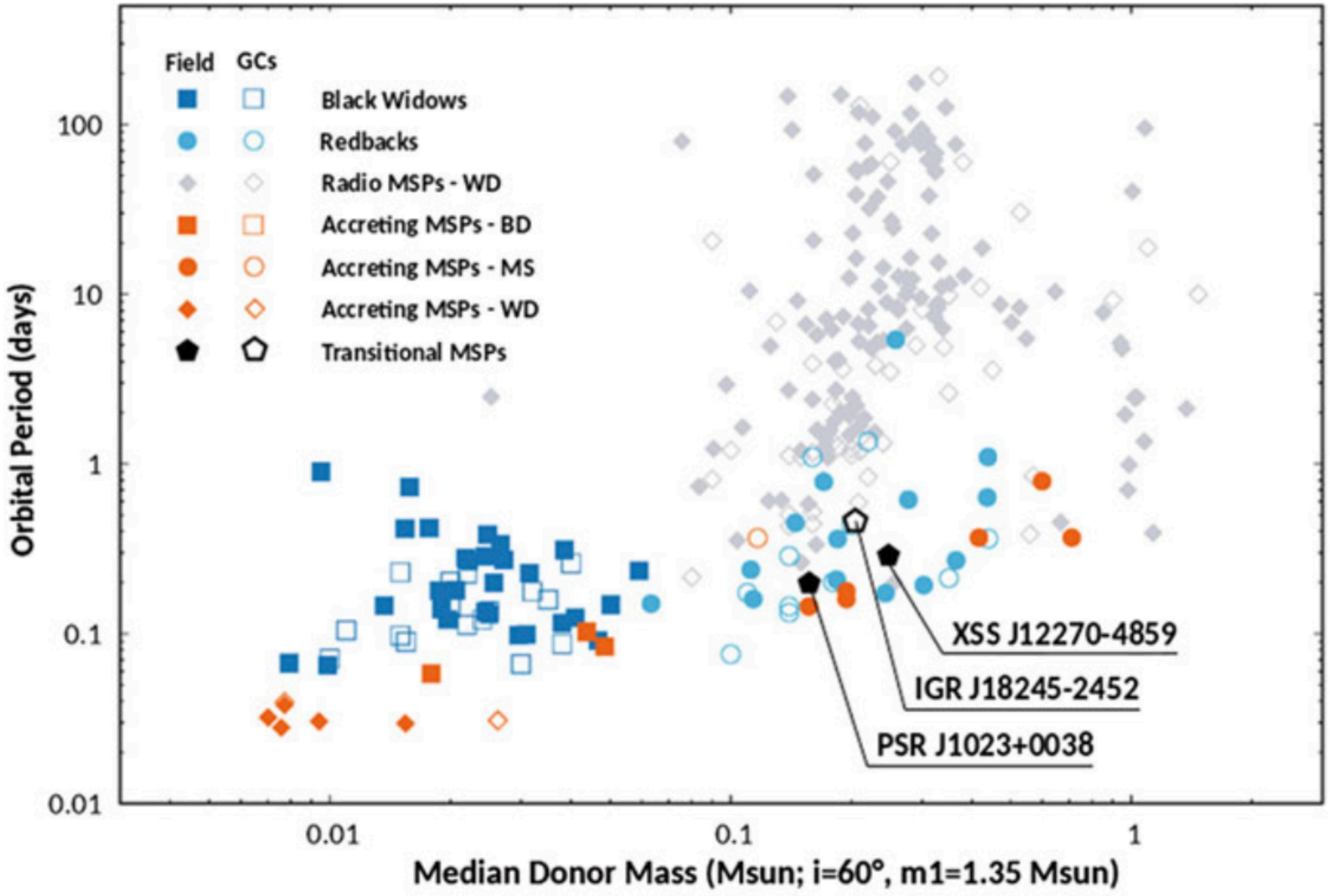
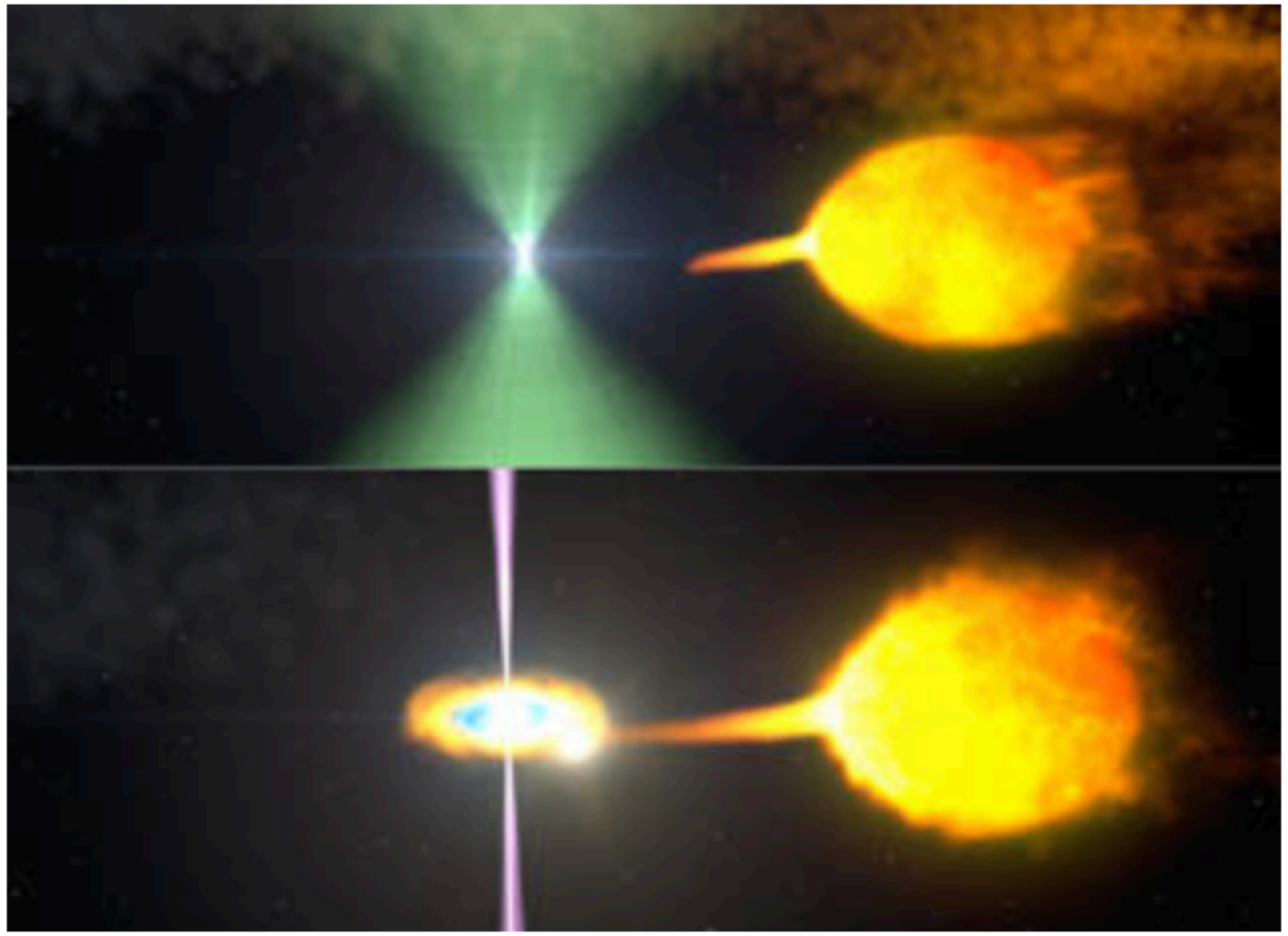
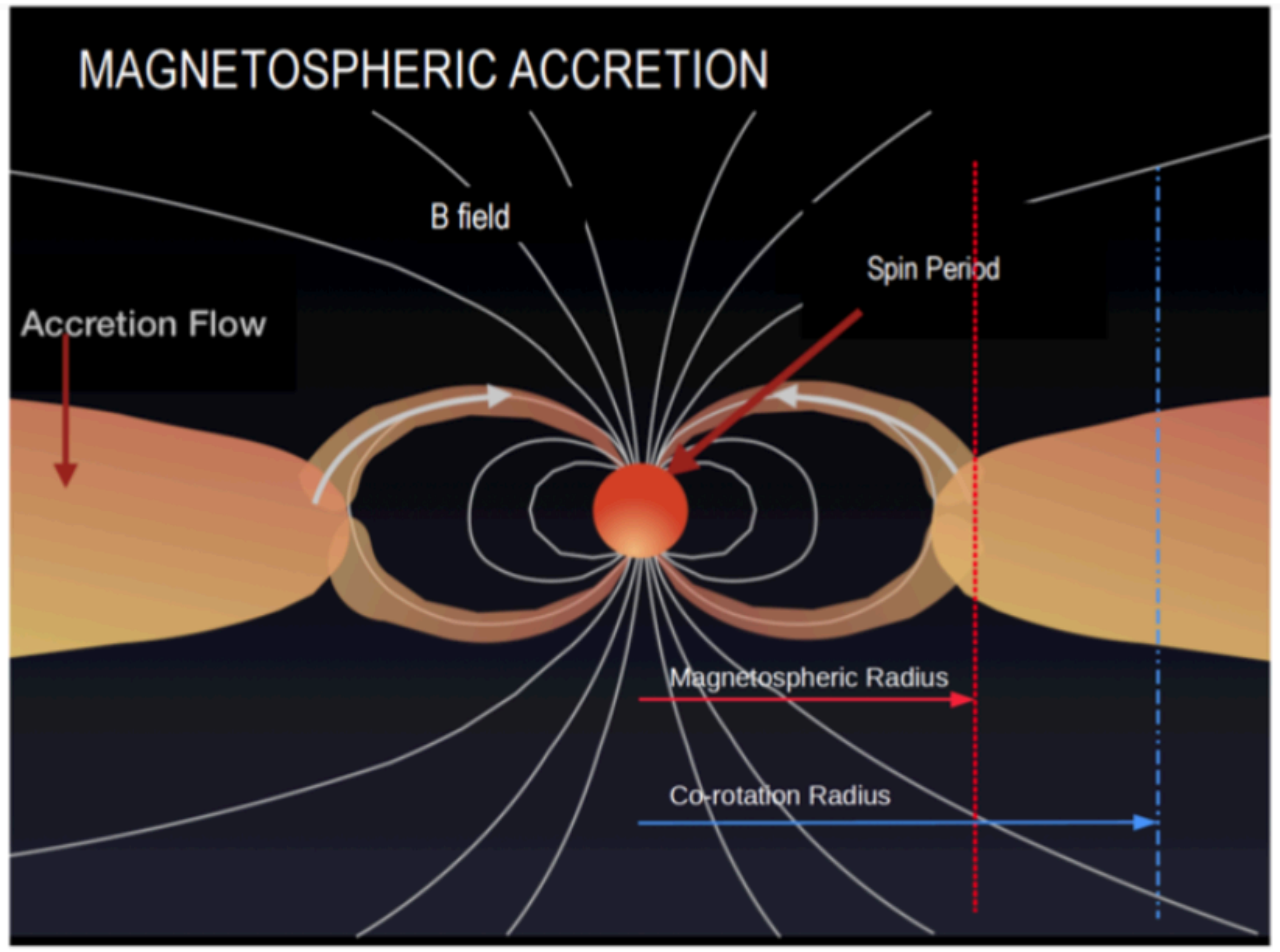


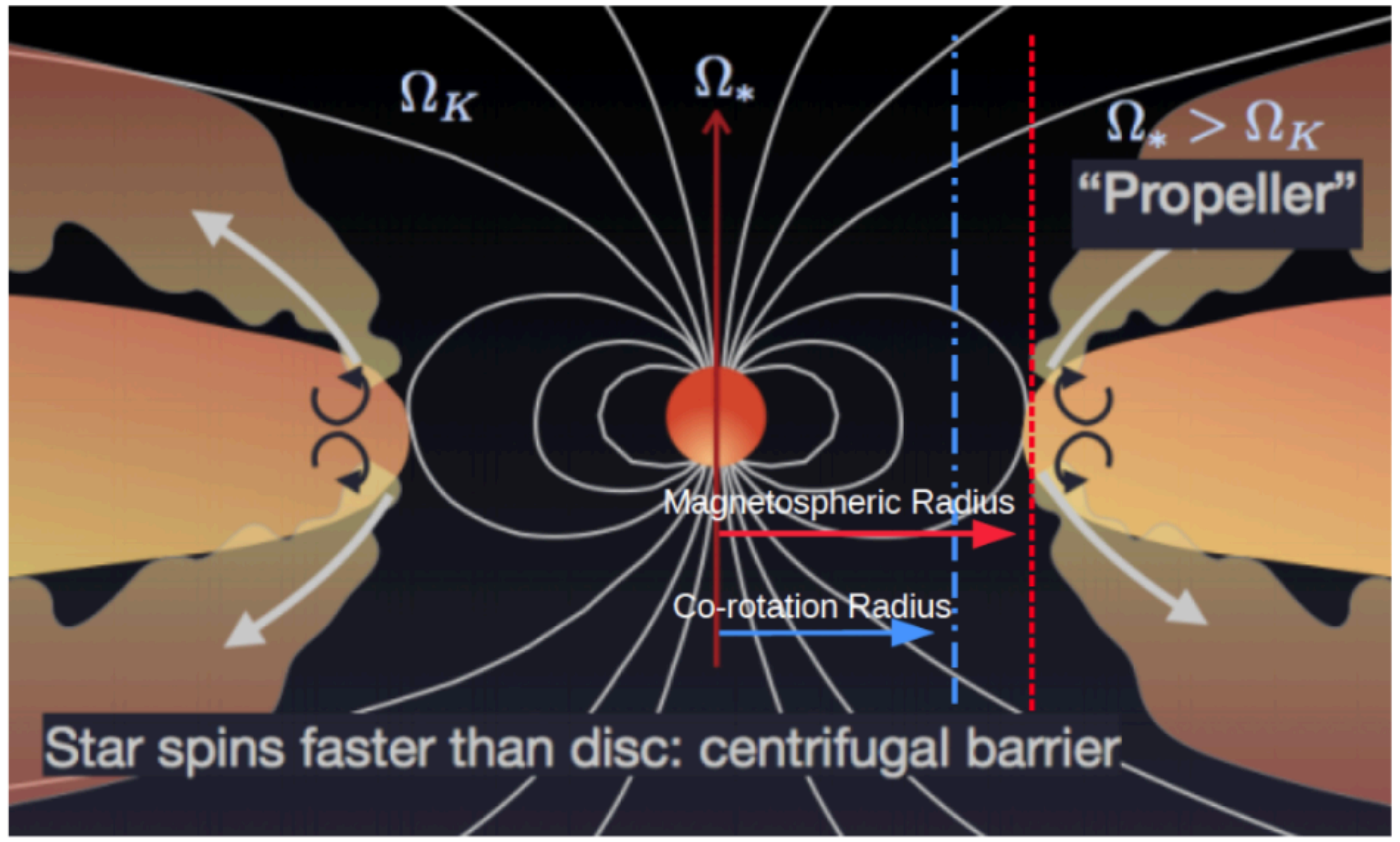
Fig. 6.1 Orbital period and median mass (evaluated from the pulsar timing parameters assuming an inclination of 60° and an NS mass of 1.35 M_{odot}) of black widows (blue squares), redbacks (cyan circles), non-interacting radio MSPs with a white dwarf companion (grey diamonds), AMXPs (orange symbols with shape depending on the donor type, squares for brown dwarfs, circles for main-sequence stars and diamonds for white dwarfs) and tMSPs (black pentagons). Filled and hollow symbols mark sources found in the Galactic field and globular clusters, respectively



These artist's renderings show one model of pulsar J1023 before (top) and after (bottom) its radio beacon (green) vanished. Normally, the pulsar's wind staves off the companion's gas stream. When the stream surges, an accretion disk forms and gamma-ray particle jets (magenta) obscure the radio beam.
Credits: NASA's Goddard Space Flight Center

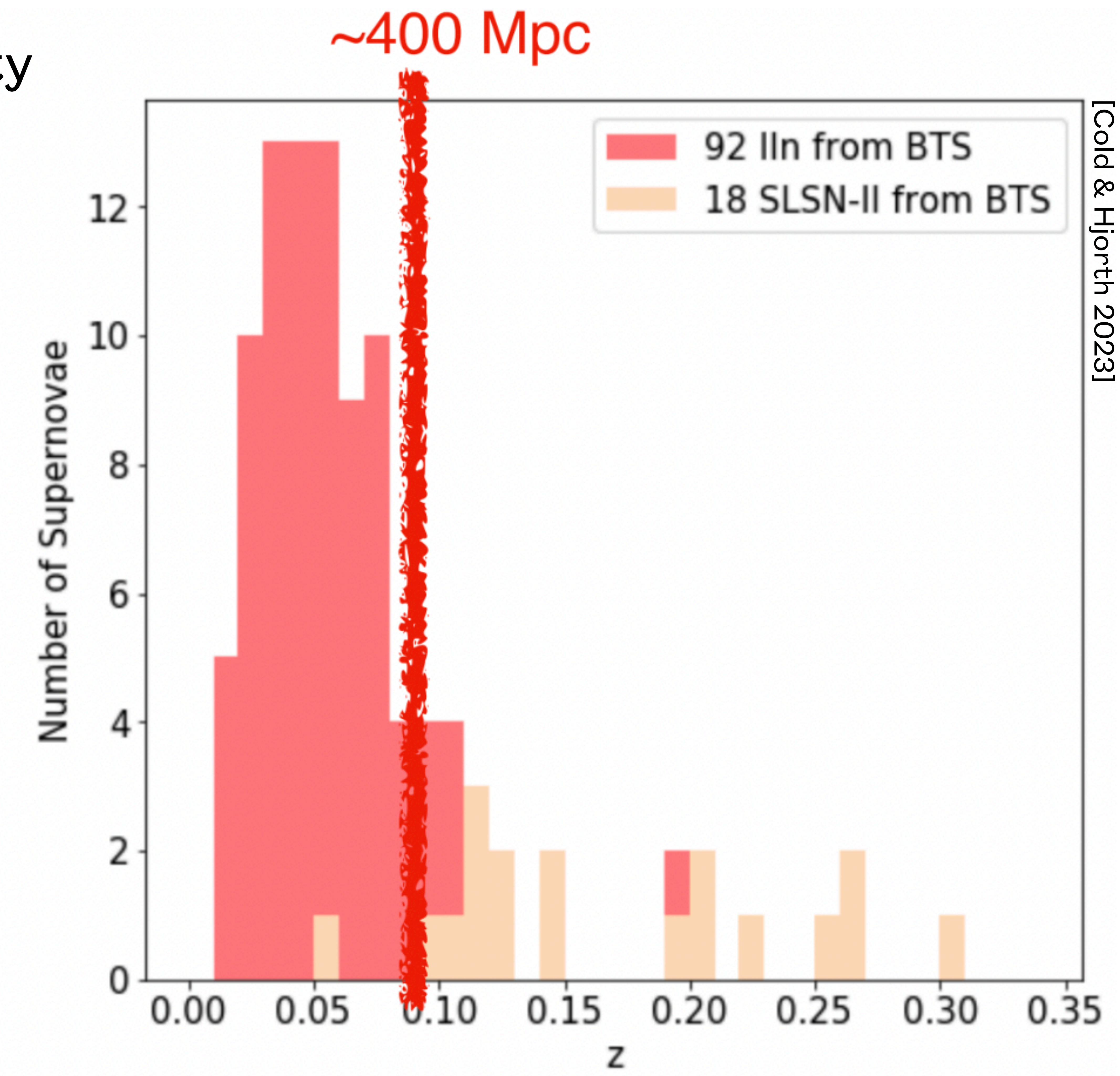
Mechanism of emission of tMSP





Number of Type IIn ccSNe

- Bright transient survey (BTS) Zwicky Transient Facility (ZTF)
- Frequency: a few objects within 10 years of CTA



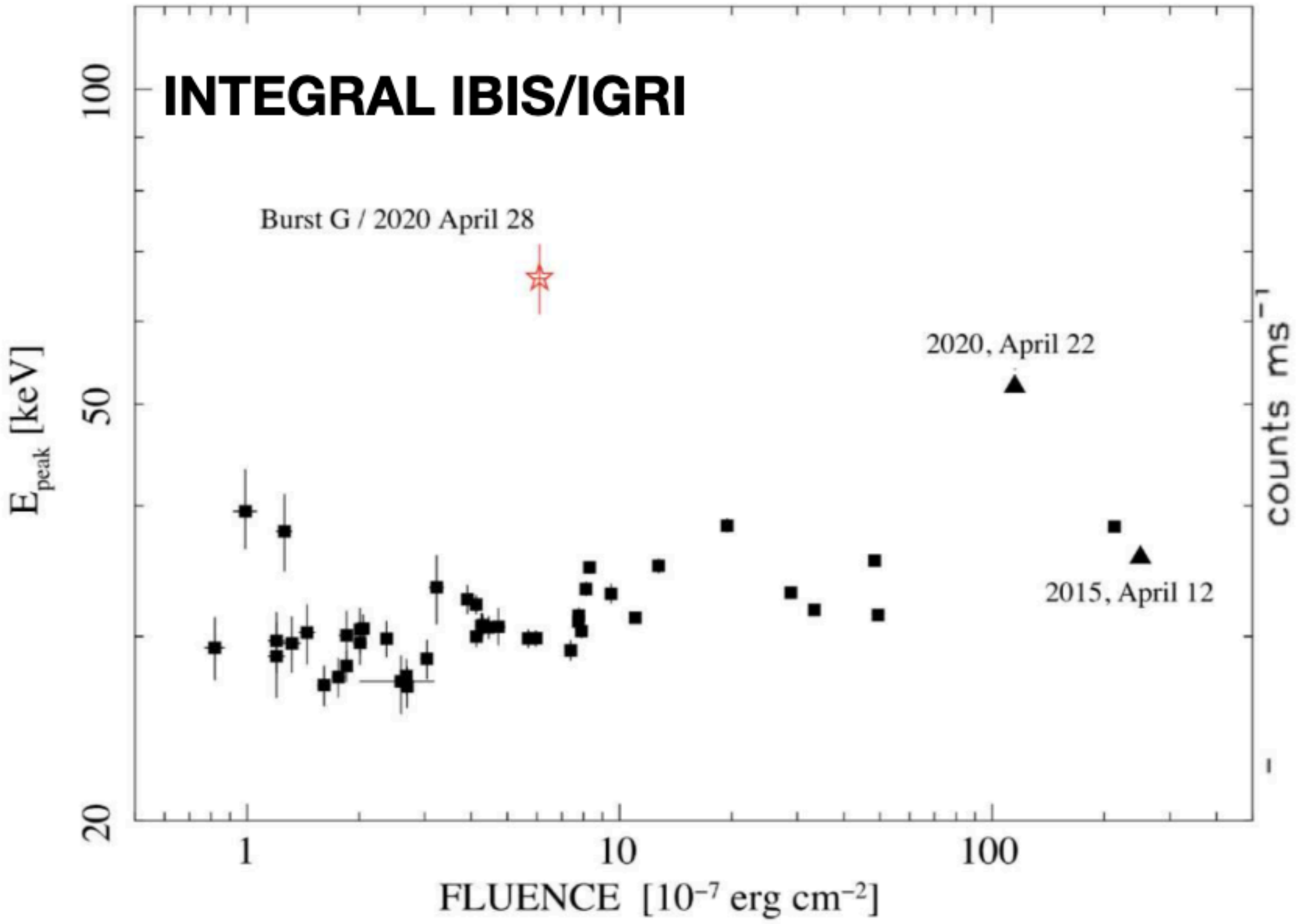
[Cold & Hjorth 2023]

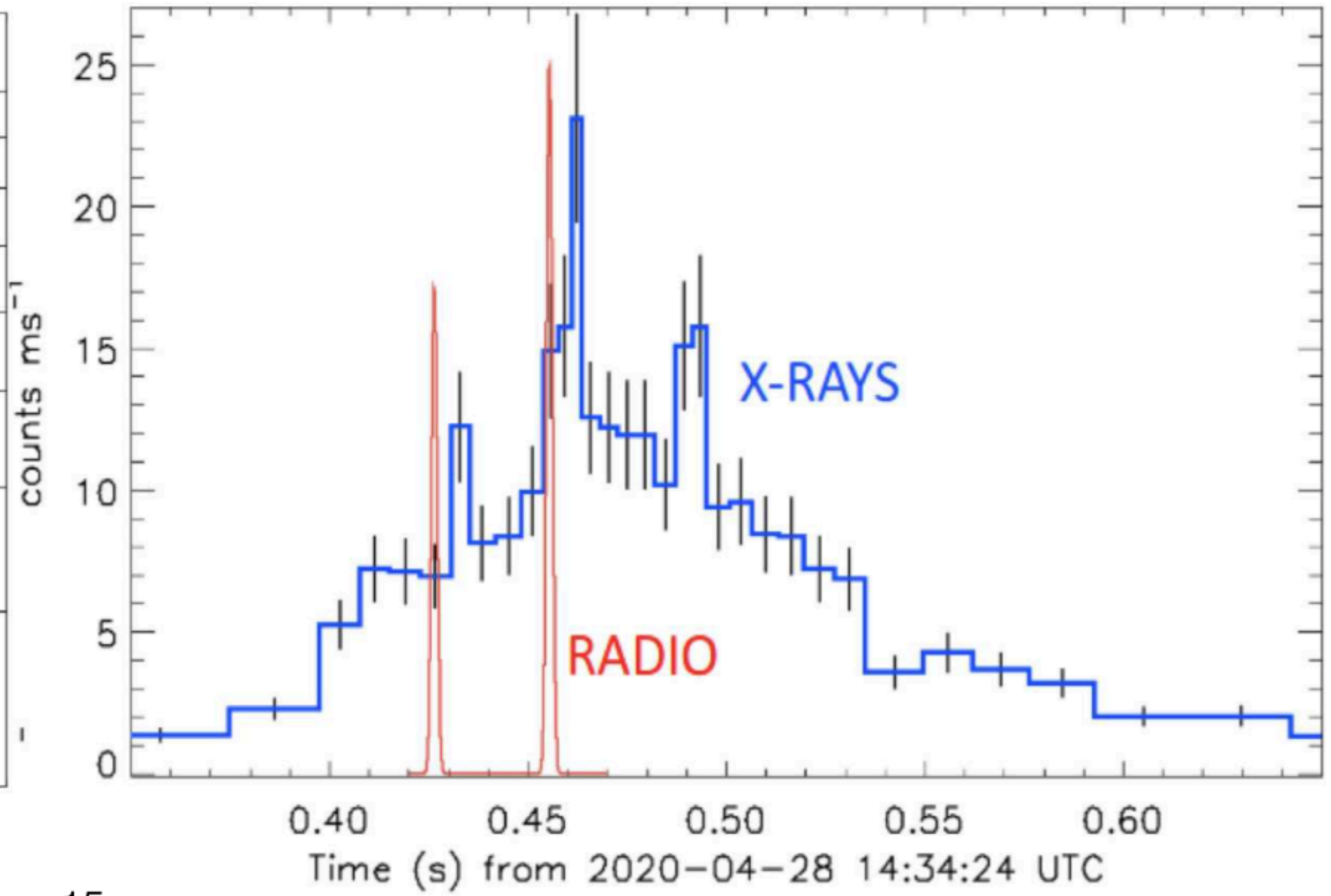
Search at GeV energies

- Systematic search for γ-ray emission in Fermi-LAT data
  - 100 MeV to 300 GeV from the ensemble of 147 SNe Type IIn exploding in a dense CSM [Fermi-LAT Coll. 2015].
    - **No candidate found** -> limits on the ratio of γ-ray and optical luminosity: exclude ratio >0.1
  - 55,880 candidates from Open Supernova Catalog with a variable-size sliding-time-window analysis [Prokhorov et al. 2023].
    - **4.0σ evidence** for γ-ray emission from transient sources occurring in the directions of **2 SN candidates**.
    - Transient γ-ray signal tentatively associated with **SN iPTF14hls** by Yuan et al. (2018), but quasar in FoV.
- Search by Xi et al. 2020: fading GeV gamma ray source spatial coincidence with **SN 2004dj** (chance coincidence 0.2%)
  - -> γ-ray emission arising from the supernova ejecta interacting with surrounding high-density shell, which decelerates the ejecta and converts ~1% of the SN kinetic energy to relativistic protons.

FRB200428 : SGR 1935+2154

- It was not a giant flare but **intermediate**
- The X-ray burst was **not especially energetic but it was harder than other flares** (Mereghetti et al. 2020)
- Different models for the site of emission (see Zhang 2020 for a review):
  - inside magnetosphere
  - relativistic outflow interacting with surrounding ISM
- TeV emission can be expected according to theoretical models (Lyubarsky 2014, Murase et al. 2016, Metzger et al. 2020)





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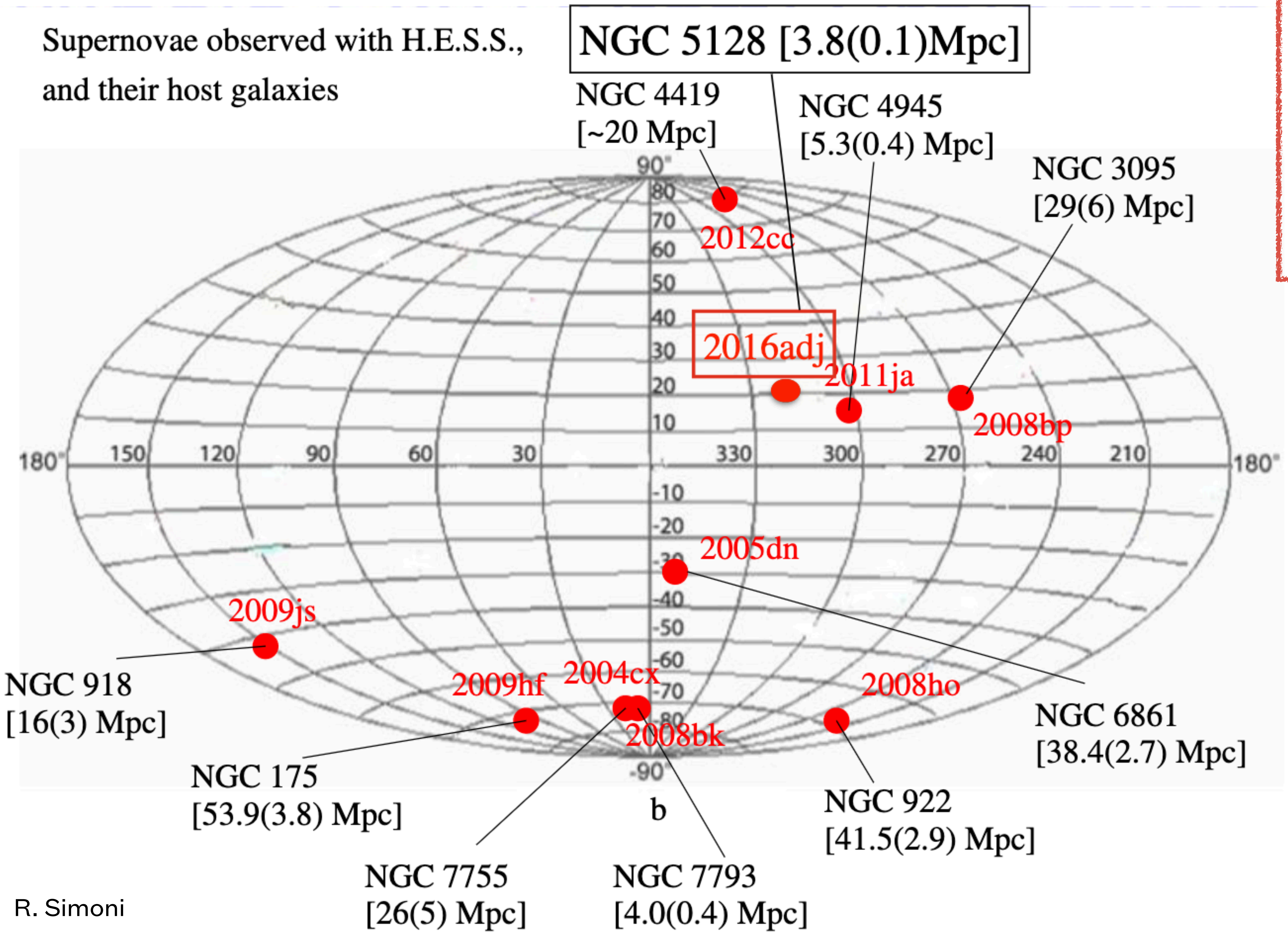
from Mereghetti et al. 2020

Core-collapsed SNe searches

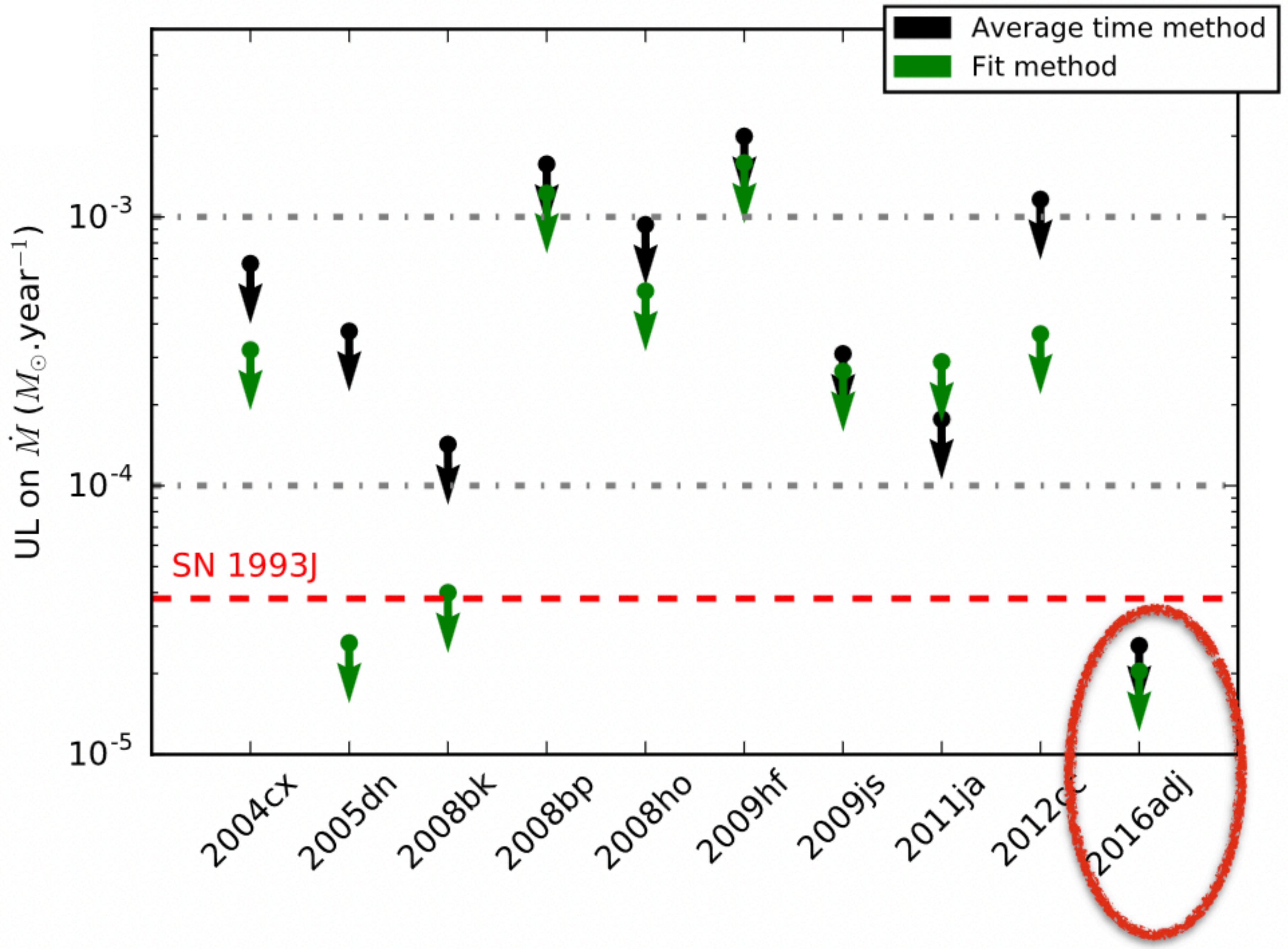
H.E.S.S. Coll. 2019

A final sample of 10 type II SNe was selected.



R. Simoni

- Non-detection -> environment before outburst was not dense enough.
- Constraints on progenitor's mass loss rates [Dwarkadas 2013]



Embedded Nova: A nova where the WD is fed material from a giant companion star, usually via wind accretion.

Symbiotic Novae: The subset of embedded novae that evolve slowly, over decades or even centuries.

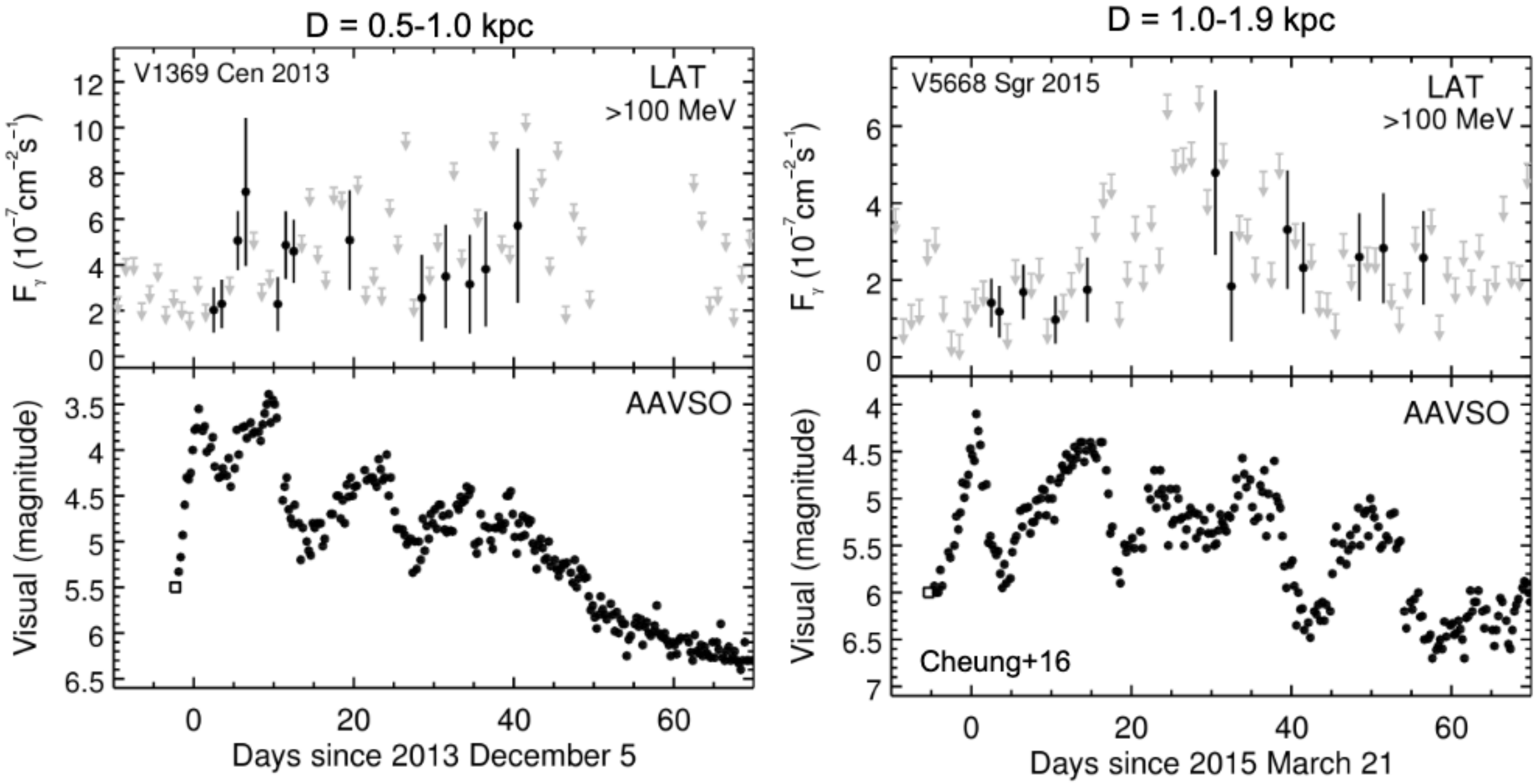
Recurrent Nova: A nova observed to undergo more than one thermonuclear eruption in recorded history.

Classical Nova: Thermonuclear eruption from a WD accreting hydrogen-rich material from a Roche lobe-overflowing main sequence or moderately evolved companion.

Cataclysmic Variable: A mass-transferring binary system containing a WD and main sequence secondary that is overflowing its Roche lobe.

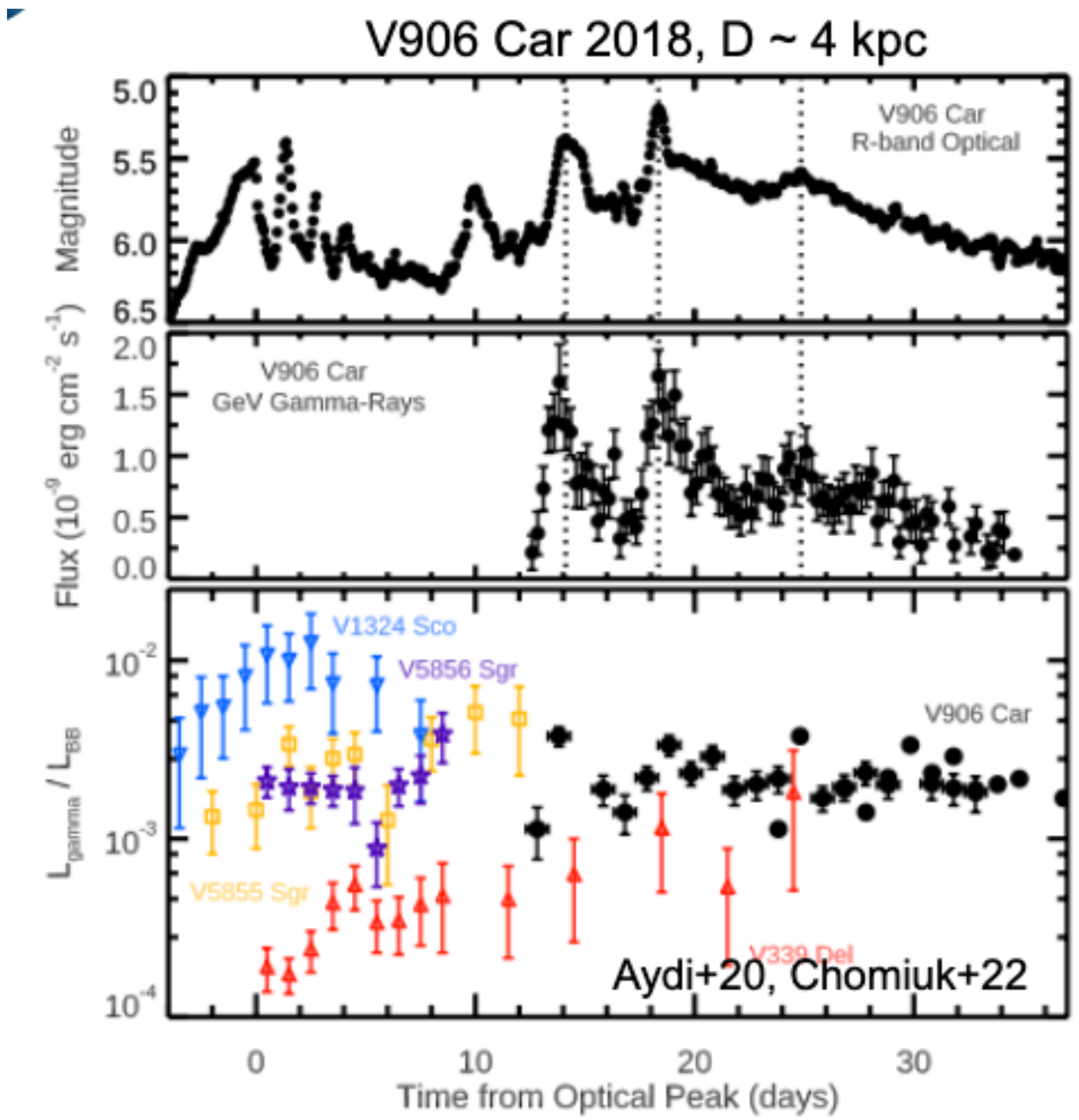
- While it is plausible that all novae host internal shocks and emit gamma-rays, the rate of gamma-ray detected novae ($\sim 1\ yr{-}1$) is only a small fraction of the optical discovery rate ($\sim 5 - 10\ yr{-}1$). The Fermi detections tend to be of relatively nearby novae ($\sim 2 - 5$ kpc) and of marginal significance (Supplemental Table 1 and Supplemental Figure 1), suggesting that many novae go undetected due to the limited flux sensitivity of Fermi-LAT.

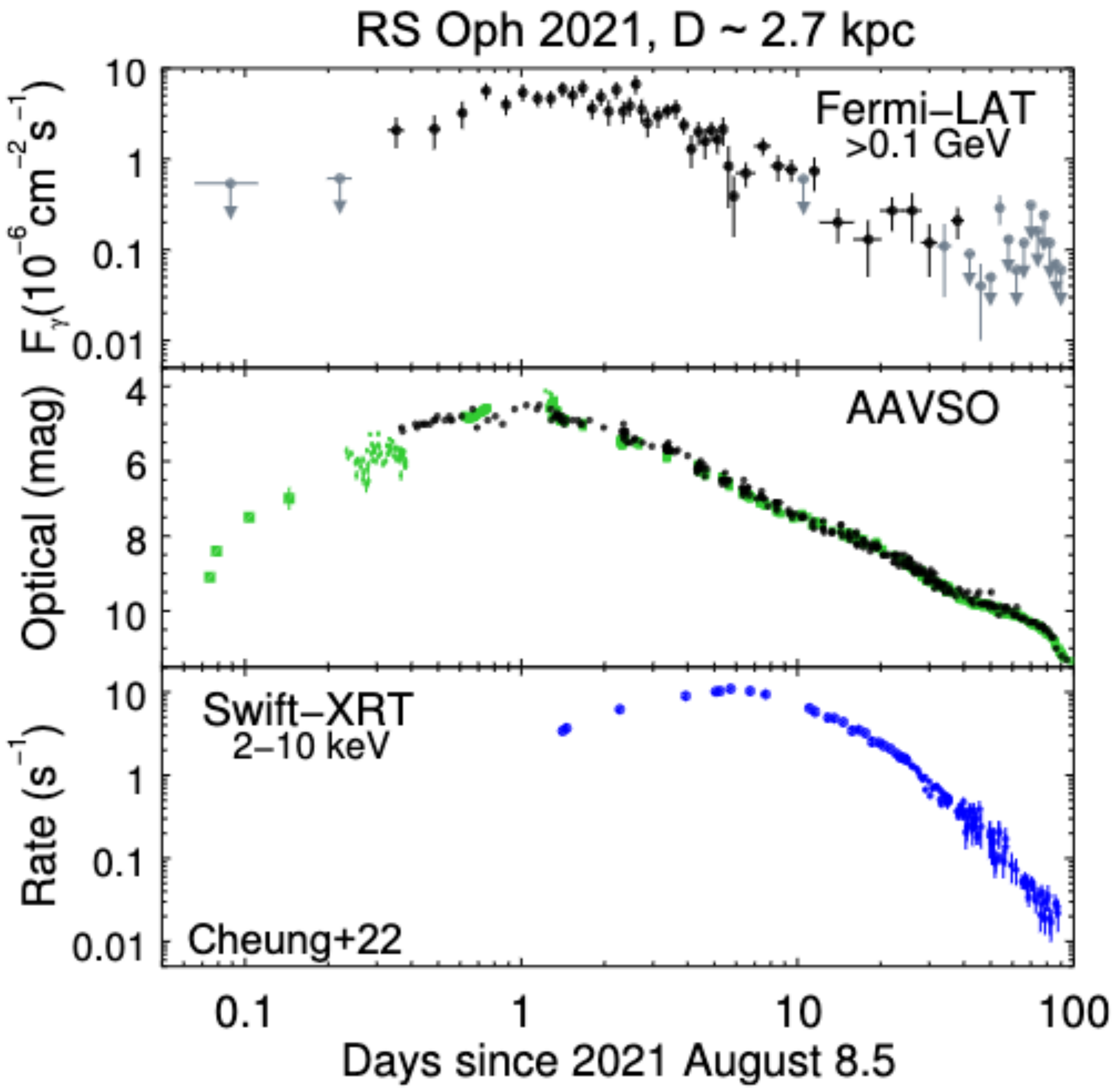
Late-time LAT emission in nearby novae



- Late-time emission (39-55 days) observed for classical novae within ~2 kpc (above, and V1405 Cas 2021, Buson+21)
- Late-time emission (55 days) in symbiotic recurrent RS Oph 2021 (D~2.7 kpc); future explosion from T CrB (closer system; D ~ 0.9 kpc)?

Correlated light curves in brightest LAT novae





- Range of optical vs. gamma-ray lightcurve behaviors in classical novae, with a subset strongly correlated (e.g., V906 Car; Aydi+20)
- Late-time emission (55 days) in symbiotic recurrent RS Oph 2021; future explosion from T CrB (closer system; D ~ 0.9 kpc)?

Fermi-LAT GeV Novae: 2008 - 2023

N=19 LAT detections, 0-3 novae each year, average ~1.3 per year

Nova	D (kpc)	t_γ^{a} (days)	Γ^{b}	E_c^{c} (GeV)	F_γ^{d} (10^{-7} cm^{-2} s^{-1})	Refs
V407 Cyg 2010	3.5 ± 0.3	22	1.3 ± 0.2	2.0 ± 0.5	3.5 ± 0.4	1,14,20
V1324 Sco 2012	7.1 – 8.6	17	1.9 ± 0.2	7.7 ± 4.7	4.4 ± 0.9	2,14,21
V959 Mon 2012	2.5 – 4.1	22	1.5 ± 0.3	1.3 ± 0.5	2.6 ± 0.5	2,14,22
V339 Del 2013	1.3 – 2.9	27	1.7 ± 0.2	3.0 ± 1.8	1.5 ± 0.2	2,14,23
V1369 Cen 2013	0.53 – 1.0	39	2.0 ± 0.3	2.0 ± 1.0	2.5 ± 0.5	3,14,24
V5668 Sgr 2015	1.0 – 1.9	55	2.1 ± 0.1	-	0.6 ± 0.1	3,14,5
V407 Lup 2016[e]	2.3 – 4.7	3	2.2 ± 0.3	-	1.6 ± 0.7	4,5
V5855 Sgr 2016	7.3 – 8.8	26	2.3 ± 0.1	-	3.0 ± 0.8	6
V5856 Sgr 2016[f]	2.3 – 6.0	15	1.9 ± 0.1	5.9 ± 2.6	5.4 ± 0.5	7,5
V549 Vel 2017[g]	1.8 – 5.1	33	1.8 ± 0.2	-	0.4 ± 0.2	8,5
V357 Mus 2018	2.5 – 5.1	27	2.2 ± 0.1	-	1.3 ± 0.2	5
V906 Car 2018[h]	2.9 – 7.6	> 20[i]	1.8 ± 0.1	5.9 ± 1.1	12.2 ± 0.4	9
V392 Per 2018	3.1 – 4.2	$\gtrsim 8$[j]	2.0 ± 0.1	-	2.2 ± 0.4	10,25
V1707 Sco 2019	7.3 – 8.8	5	2.1 ± 0.2	-	2.9 ± 1.0	11,12
YZ Ret 2020	2.2 – 2.6	18	2.2 ± 0.1	-	2.6 ± 0.2	12,13,26

2008 - 2015

"First" six

2016 - 2020

From Chomiuk+21, ARAA

V1405 Cas 2021 1.6 – 1.8
V1674 Her 2021 2.5 – 5.4
RS Oph 2021 2.6 – 2.9
2022 and 2023 - none

2021 - onward

V3890 Sgr 2019 8.1 – 9.1

See Koji Mukai's updated list: https://asd.gsfc.nasa.gov/Koji.Mukai/novae/novae.html

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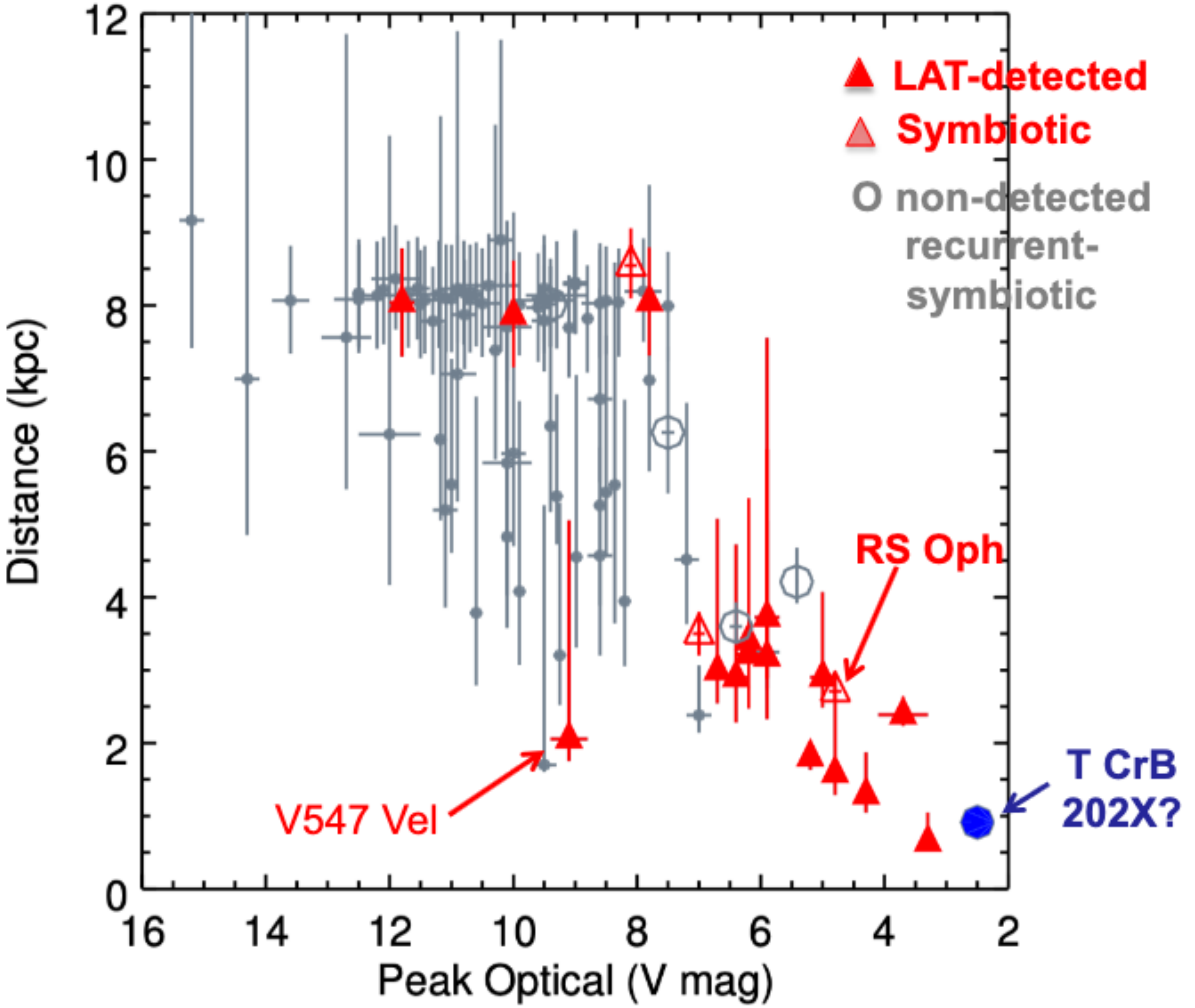
Fermi-LAT GeV Novae: 2008 - 2023

- V549 Vel 2017 is fainter both optically (V = 9.1, D ~2-5 kpc) and in gamma rays, and is one of the least luminous gamma-ray novae [Li et al. 2020]
- RS Ophiuchi: First Nova detected at TeV energies
- T CrB 202X?: Stay tuned.



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