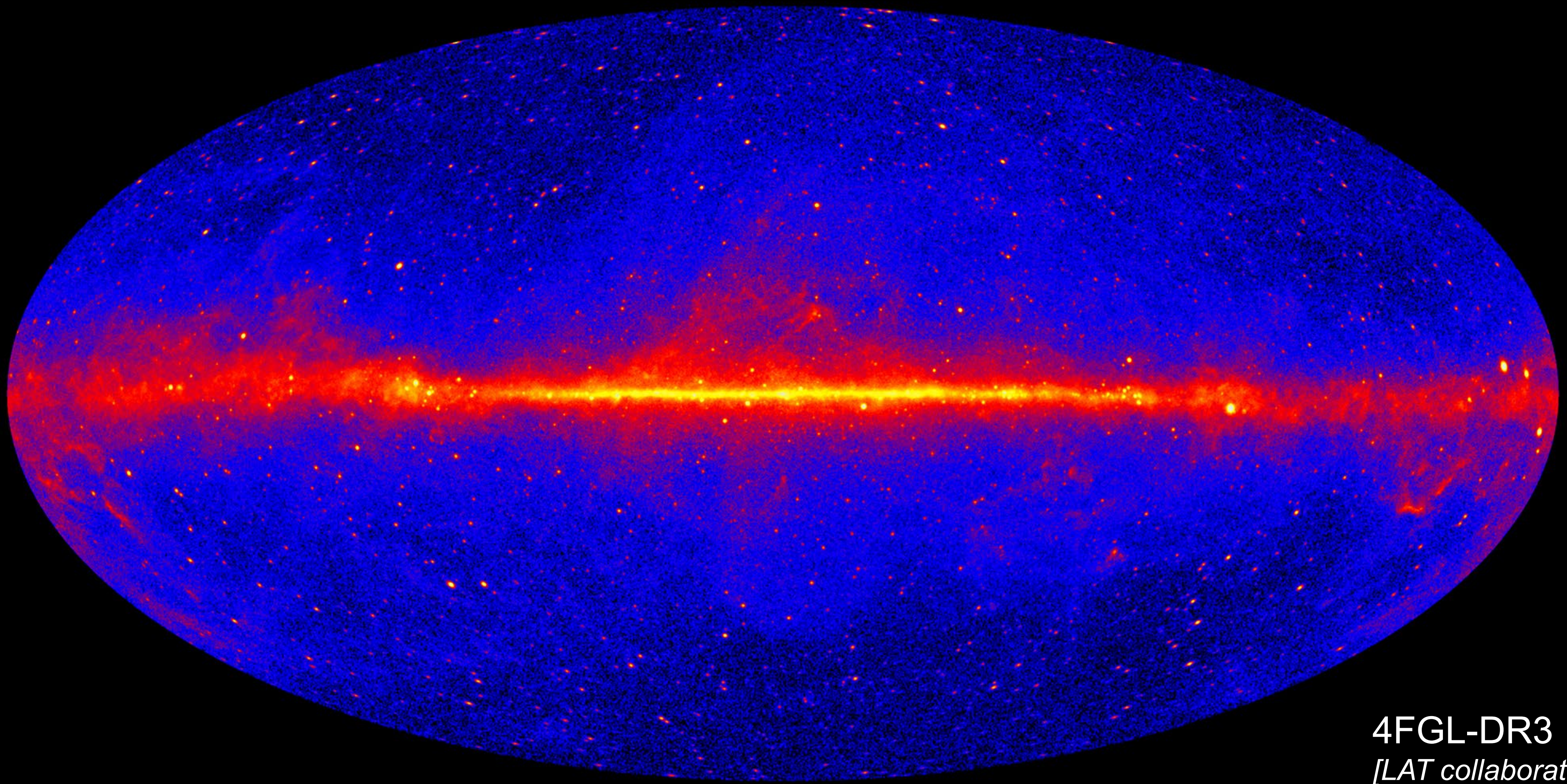
Olaf Reimer Universität Innsbruck, Institute for Astro- & Particle Physics & University of Tokyo, ICRR

PHYSICS AT THE EXTREME IN OUR GALAXY AS VIEWED IN VHE GAMMA-RAYS

The extreme Universe viewed in VHE gamma-rays, Kashiwa, February 7, 2023

Fermi-LAT Gamma-Ray Sky as we know: > 50 MeV

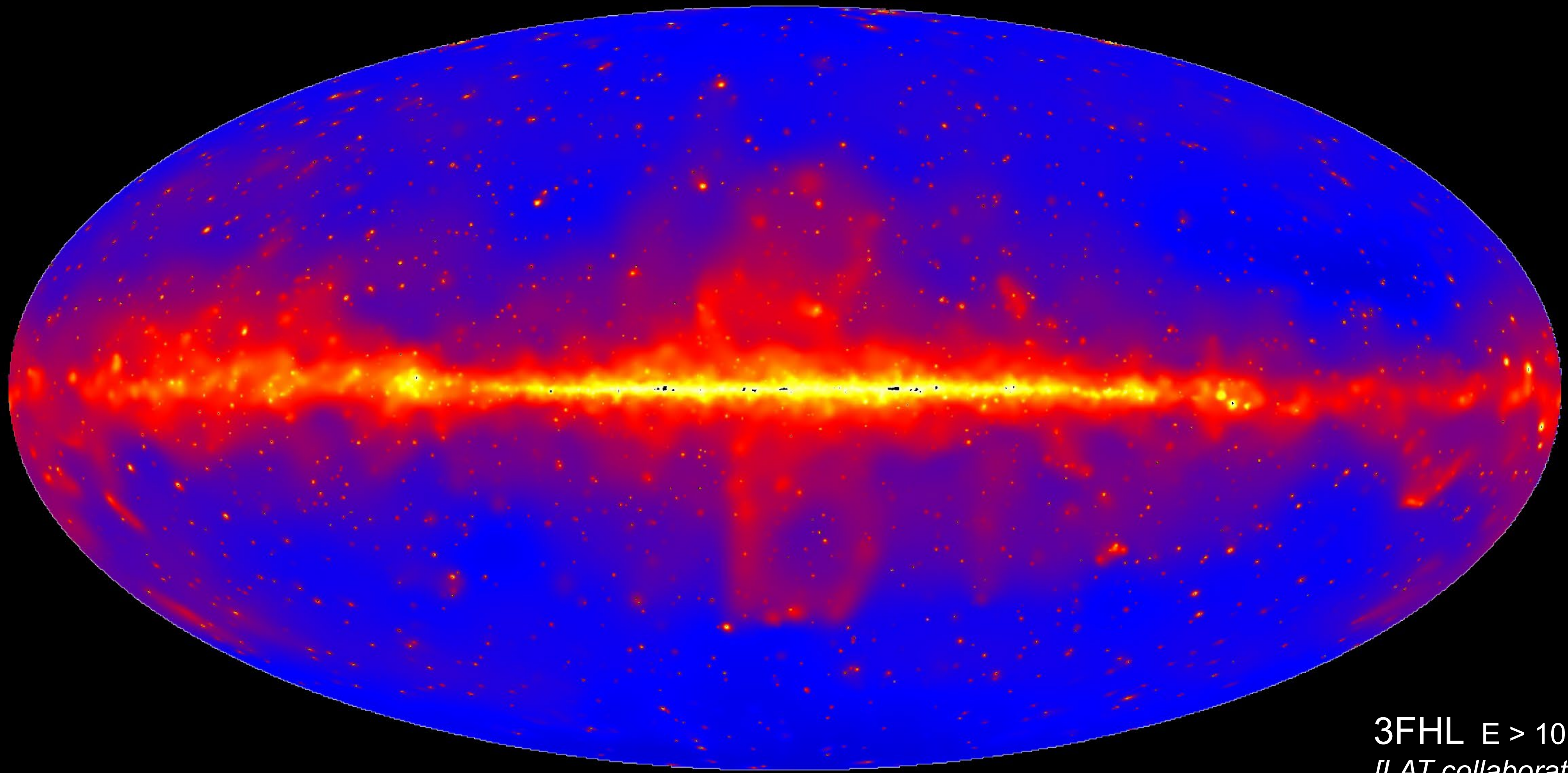


4FGL-DR3 E > 50 MeV
[LAT collaboration, ApJS 260, 2022]

~ 90% of all observed photons in the Galactic plane are of diffuse origin

- ☞ billions of photons → 6658 sources
- ☞ location uncertainty source specific: 19 matrix elements f(E, psf)

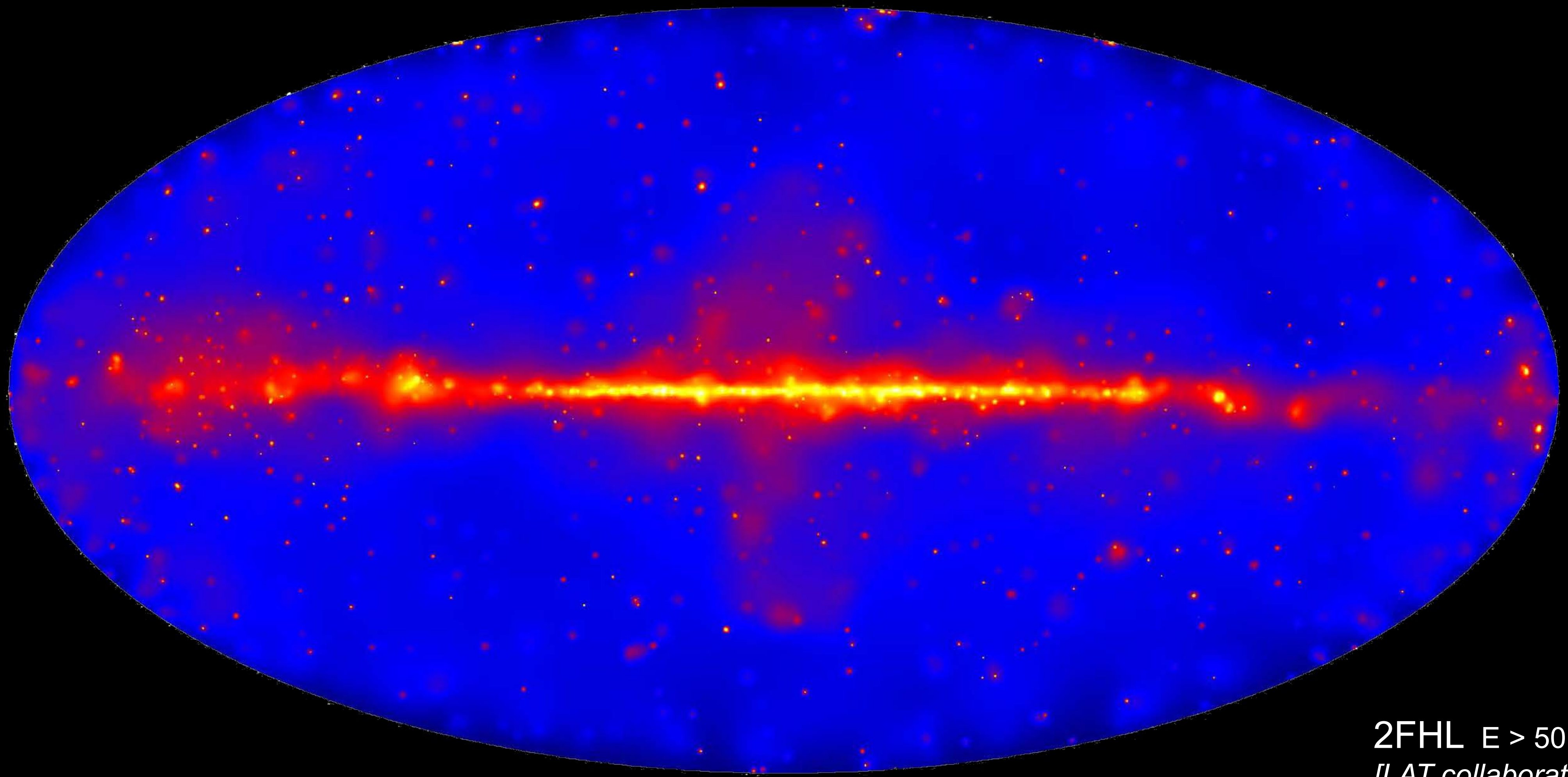
Fermi-LAT Gamma-Ray Sky as we know: > 10 GeV



3FHL E > 10 GeV
[LAT collaboration ApJS 232, 2017]

- ☞ 699.582 photons
- ☞ median location uncertainty of 9 arcmin (68%)

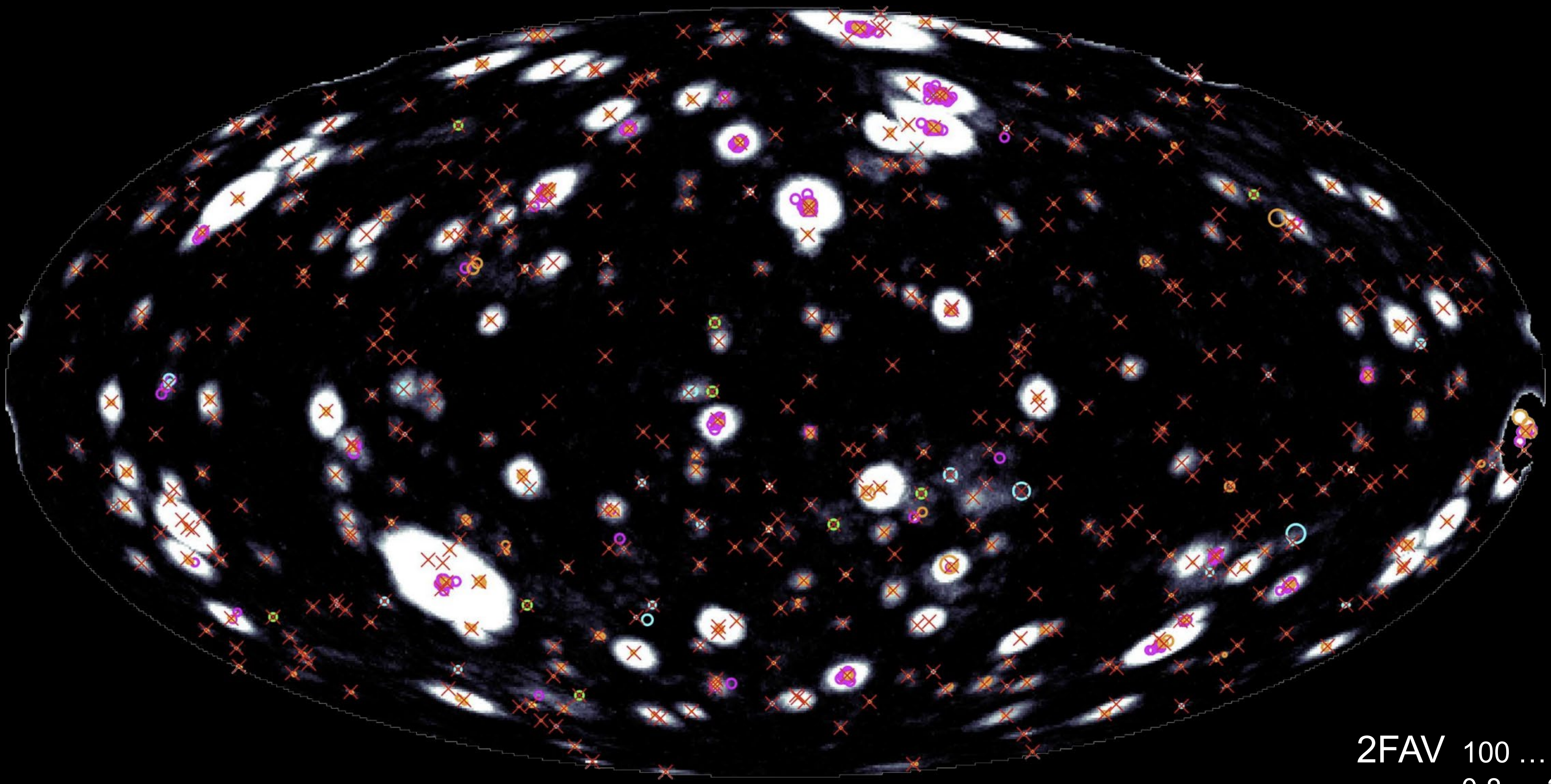
Fermi-LAT Gamma-Ray Sky as we know: > 50 GeV



2FHL E > 50 GeV
[LAT collaboration ApJS 222, 2016]

- ☞ 60.978 photons
- ☞ median location uncertainty of 1’.7 ! (68%)

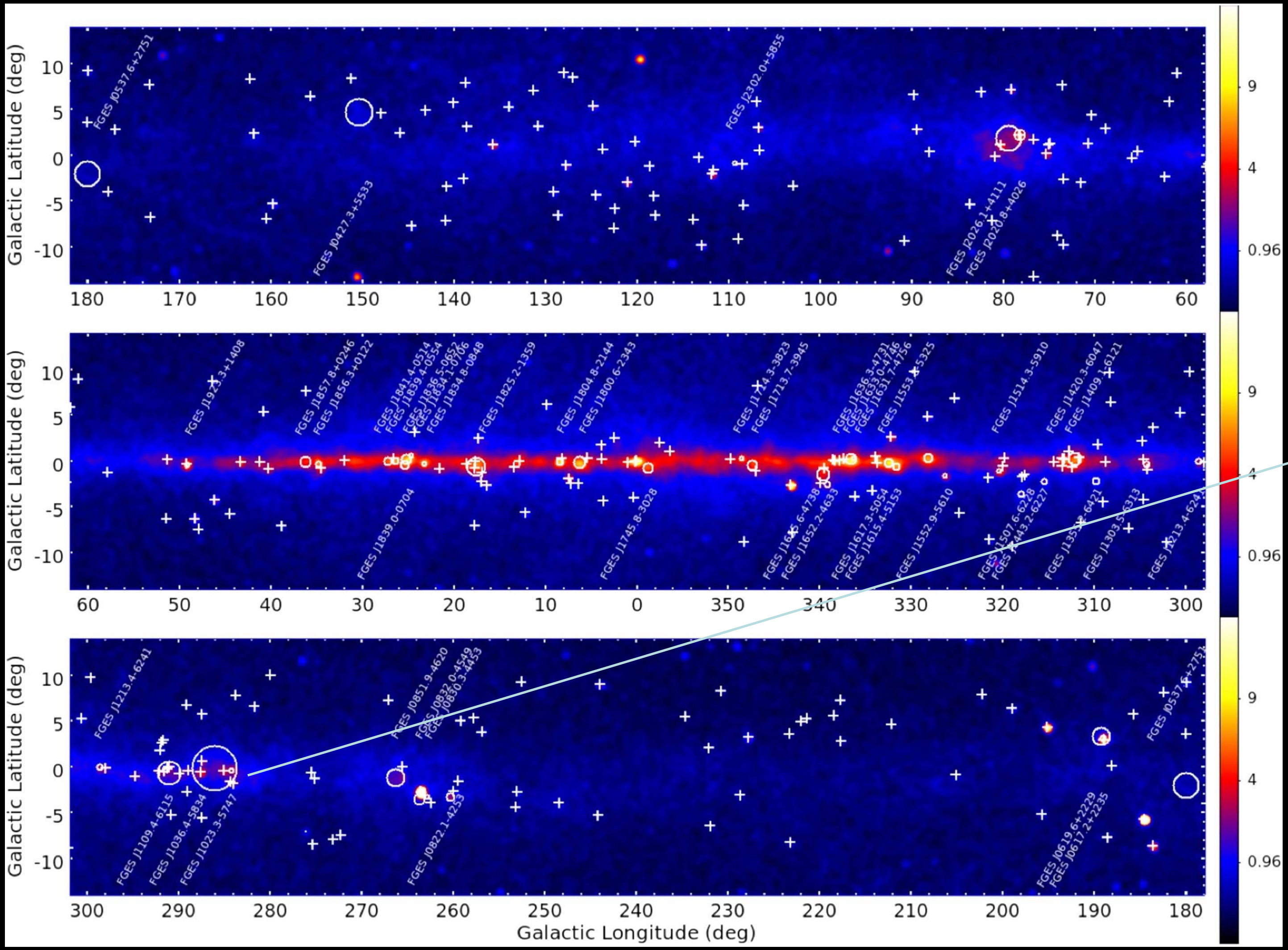
Fermi-LAT All-Sky Variability as we know: > 100 MeV

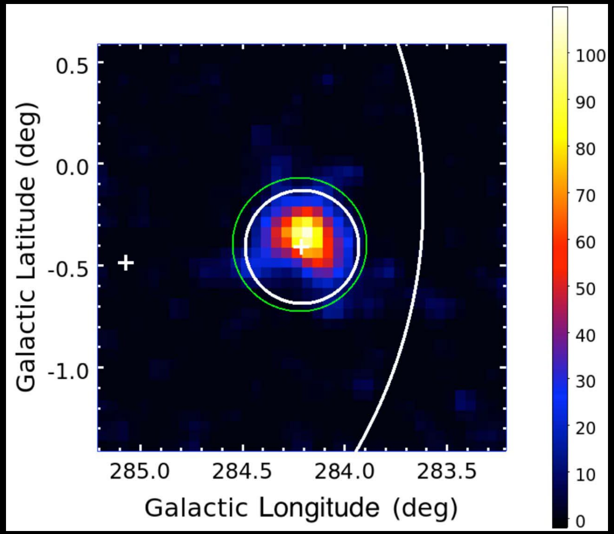


2FAV 100 … 800 MeV
0.8 … 300 GeV
[LAT collaboration ApJ 846, 2017]

- ☞ 518 variable gamma-ray sources
- ☞ FAVA probes spatial clustering on weekly timescale

Fermi Galactic Extended Source Catalog

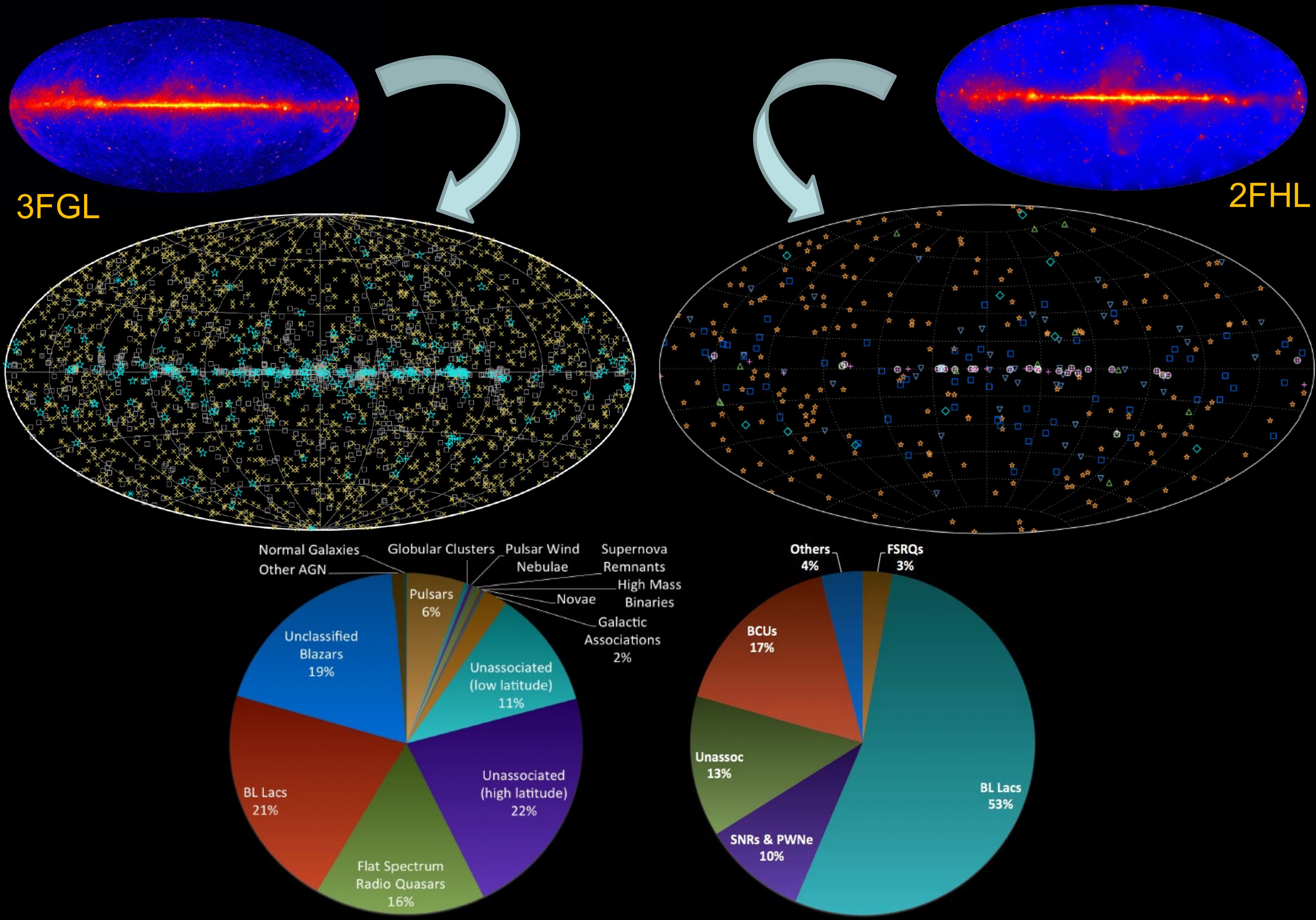




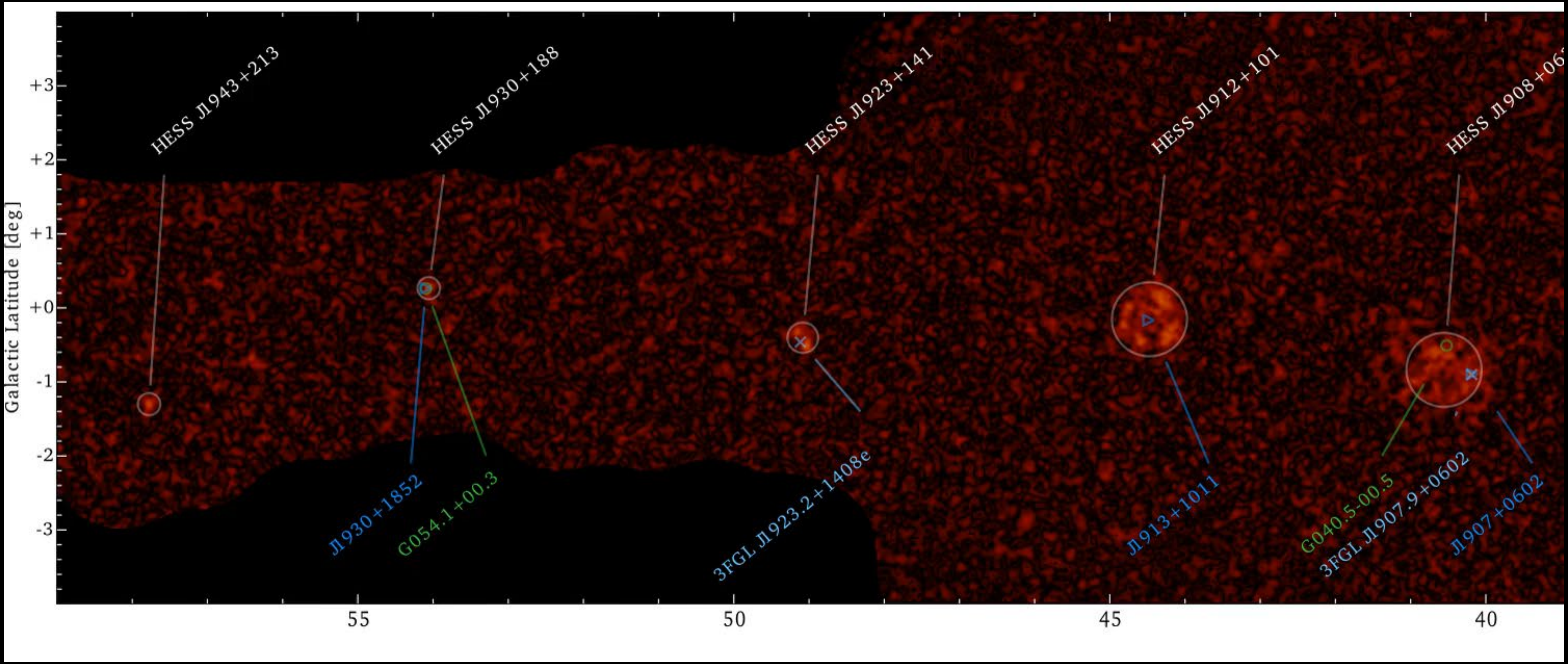
FGES J1023.3-5747 (Westerlund 2)

FGES 10 GeV … 2 TeV
[LAT collaboration
ApJ 843, 2017]

☞ 46 extended sources at |b| < 7°

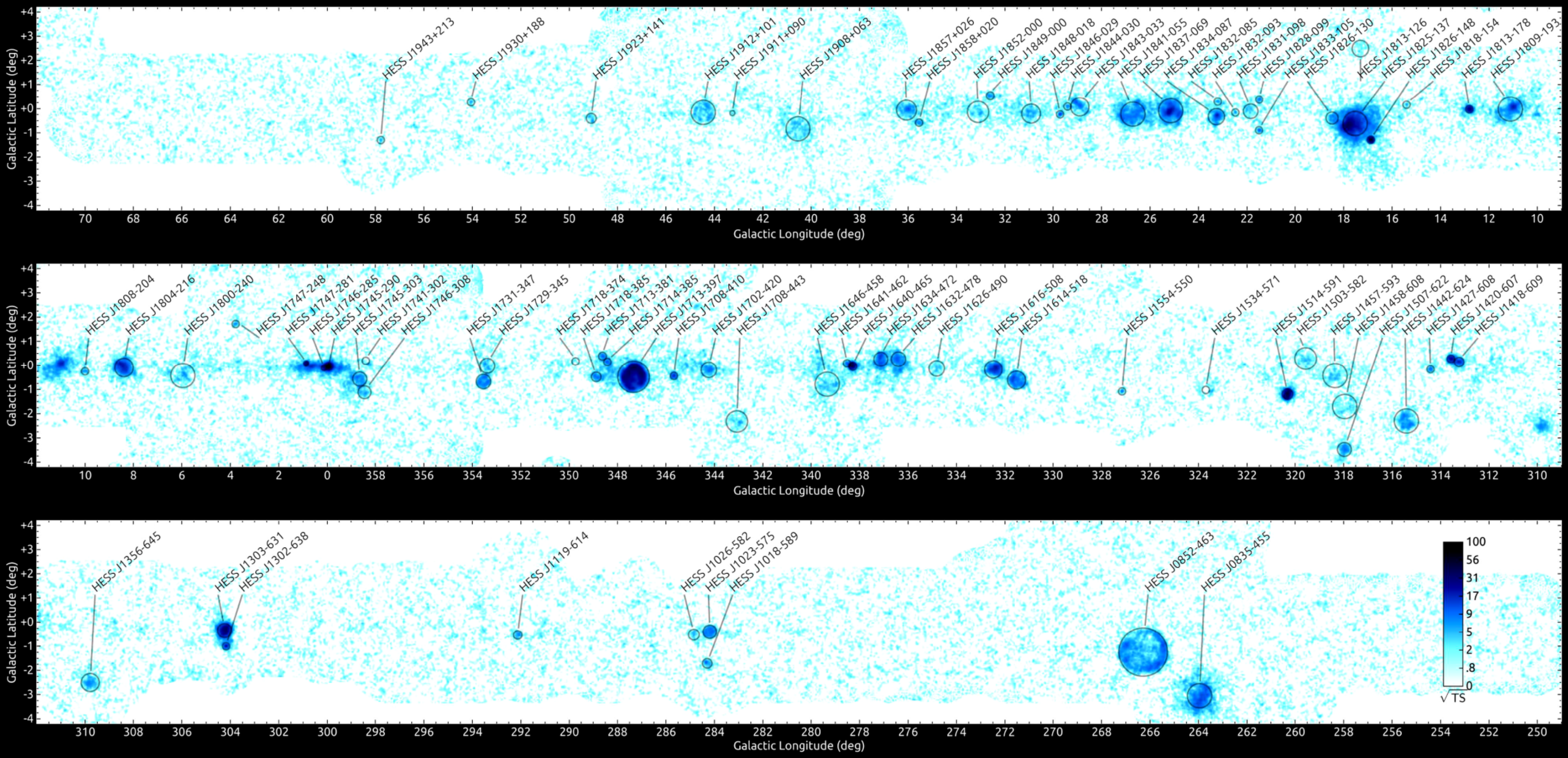

3FGL
2FHL
Normal Galaxies
Other AGN
Globular Clusters
Pulsar Wind Nebulae
Supernova Remnants
High Mass Binaries
Novae
Galactic Associations 2%
Pulsars 6%
Unclassified Blazars 19%
Unassociated (low latitude) 11%
Unassociated (high latitude) 22%
BL Lacs 21%
Flat Spectrum Radio Quasars 16%
Others 4%
FSRQs 3%
BCUs 17%
Unassoc 13%
SNRs & PWNe 10%
BL Lacs 53%

The VHE Galactic Gamma-ray Sky seen by H.E.S.S.



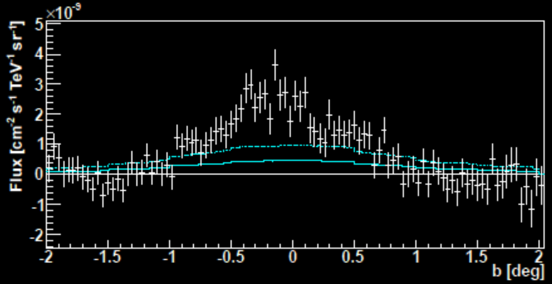
- ☞ published based on 2700 h obs time (2004 – 2013)
- ☞ 78 sources between 250°…65°, |b| < 3 °

The VHE Galactic Gamma-ray Sky as seen by H.E.S.S.



Diffuse Galactic TeV-emission has been assessed, too:

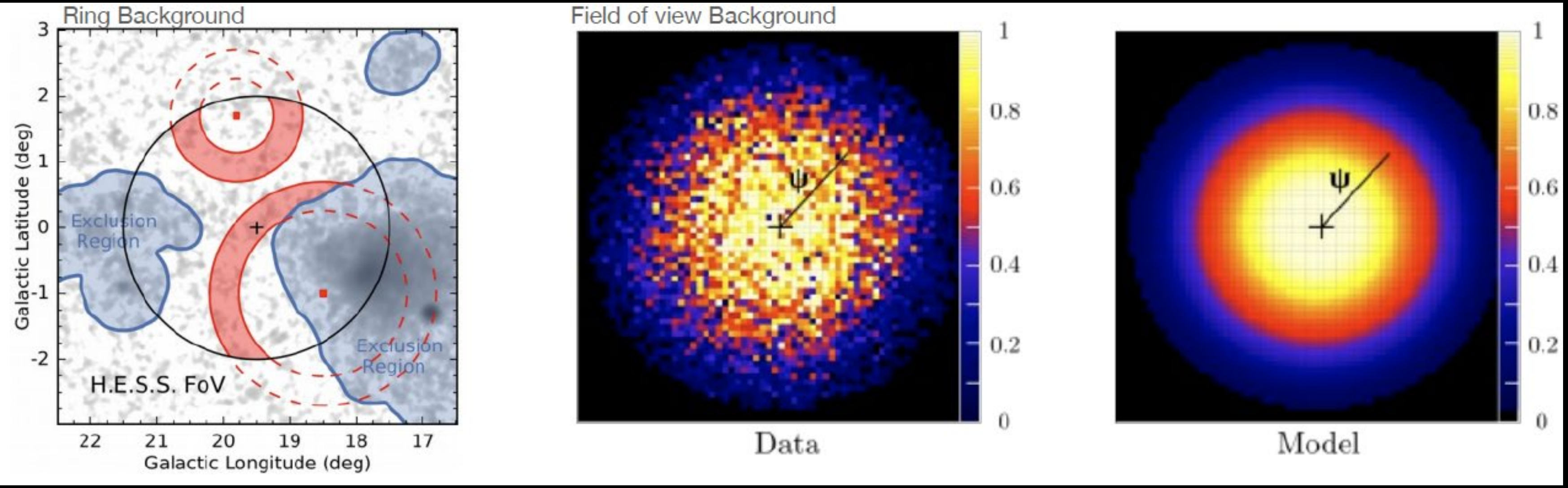
- Galactic Center Ridge emission [Nature 2006 & 2016]
- Diffuse Galactic γ-ray emission with H.E.S.S. [PRD 2014] →
- Diffuse template b=0 centered 1D-Gaussian [HGPS, A&A 2018]



The VHE Galactic Gamma-ray Sky as seen by H.E.S.S.

Since then, focus on improvements in analysis plus deeper exposure in interesting/enigmatic regions.

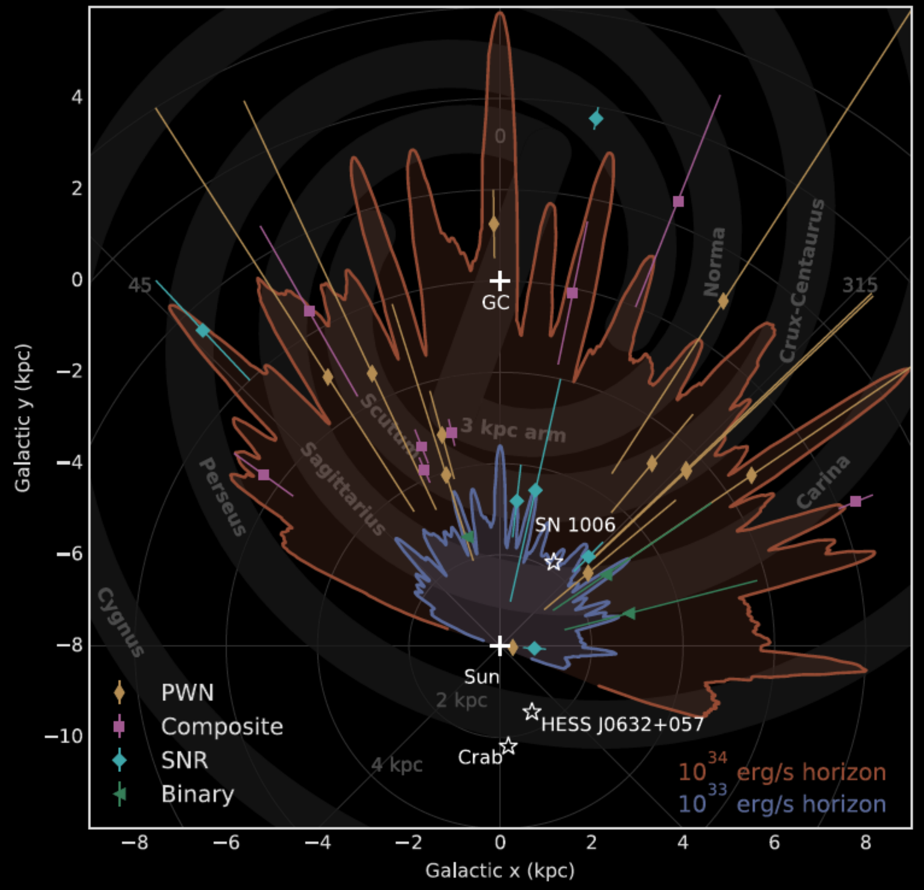
Principal problem: *Classic* background estimation techniques are inadequete for large FoV analysis.

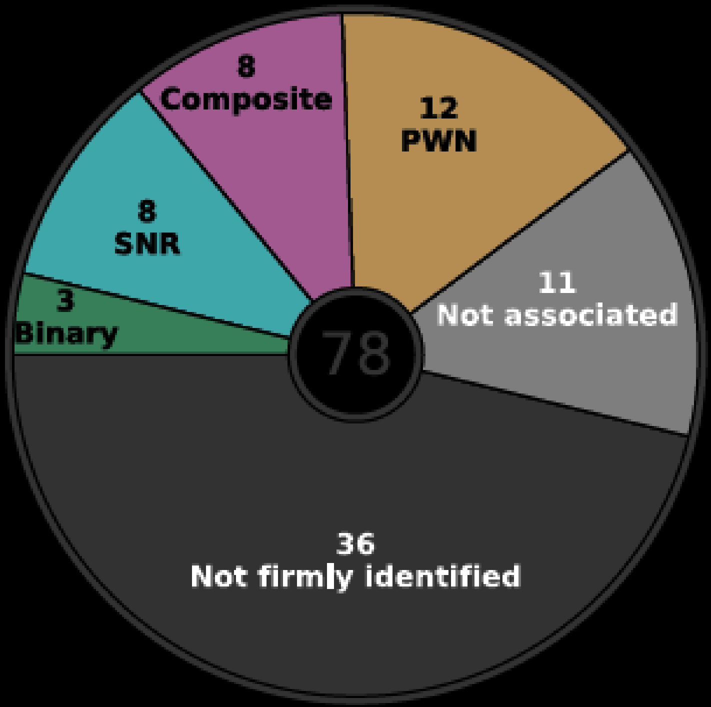


- appropriate for whole FoV
- deduced from extragalactic FoVs*, tabulated by zenith angle
- applied to each run individually
- assume simple symmetry (radial)*

* improvements beyond that using RWS (Holler et al. 2020) & synthetic background generation

The VHE Galactic Gamma-ray Sky as seen by H.E.S.S.

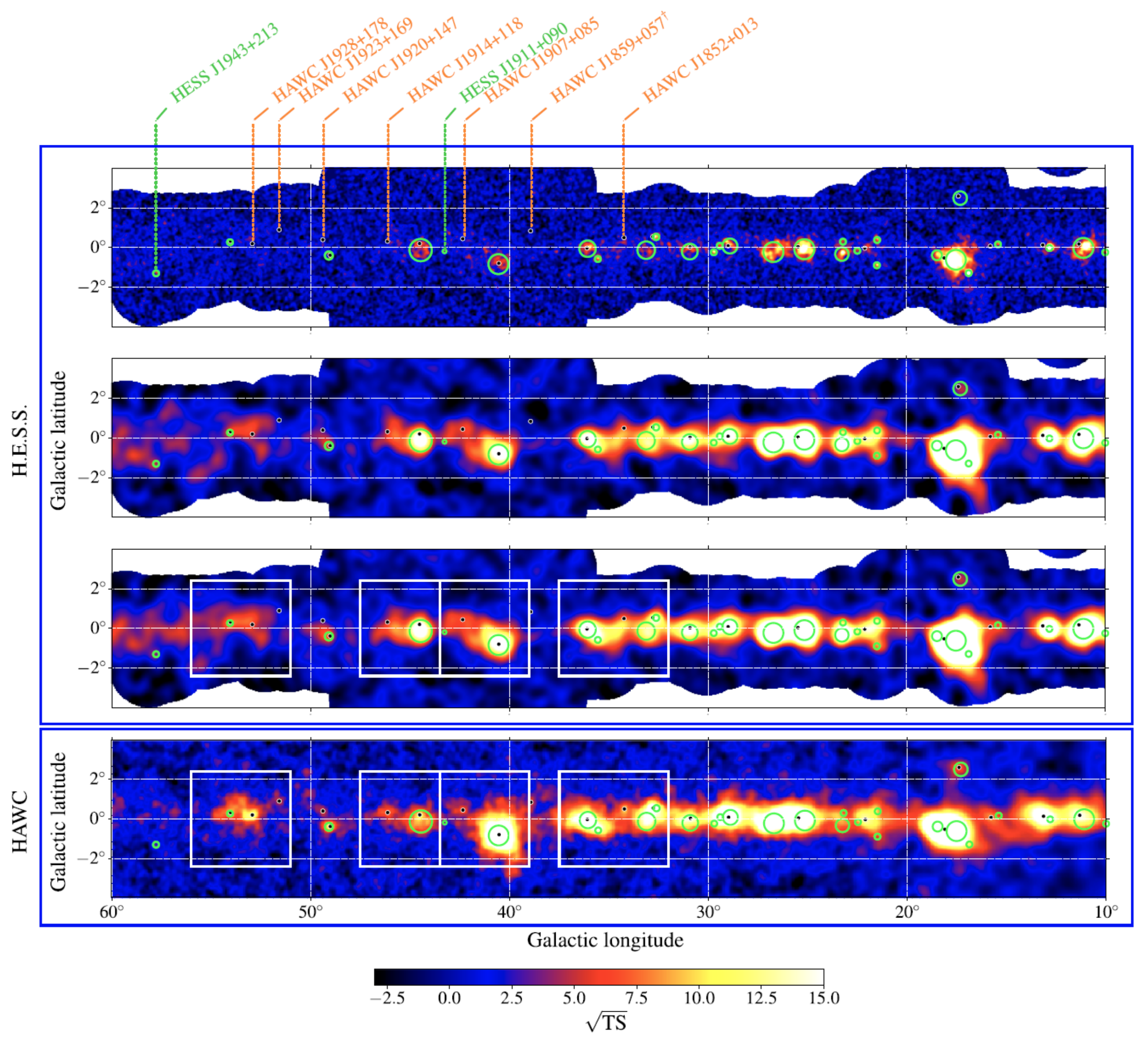




Abdalla et al. (H.E.S.S.) 2018

← source luminosity for detection of point-like source with 5σ

The Galactic Gamma-ray Sky as seen by HAWC *(LHAASO → Ruizhi)*



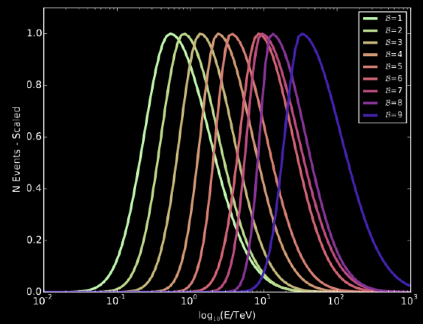
Abdalla et al. (H.E.S.S./HAWC) 2021

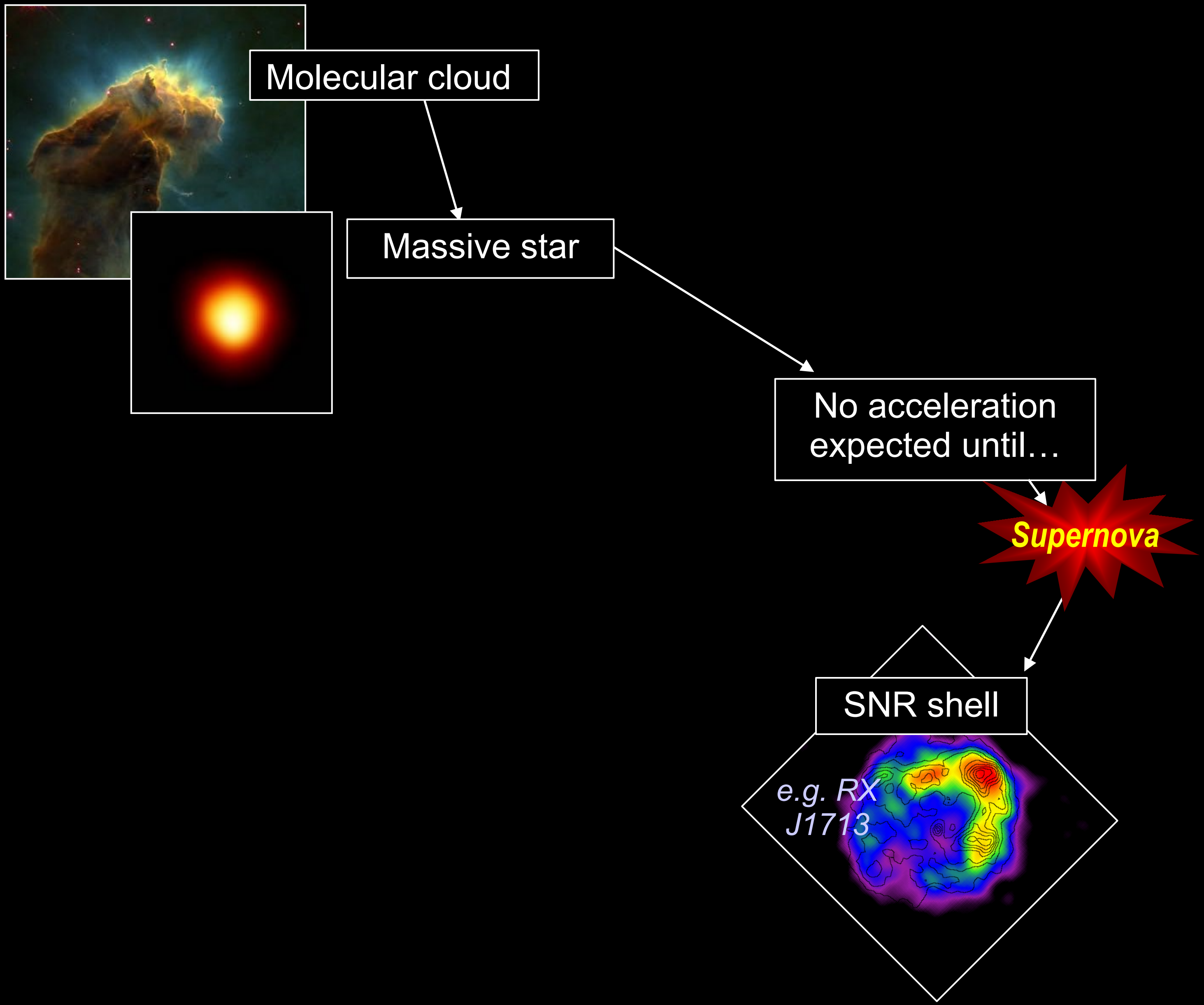
← H.E.S.S. GPS > 1 TeV (Impact3D)

← H.E.S.S. GPS > 1 TeV (Impact3D)
smoothed with Gaussian 0.4°

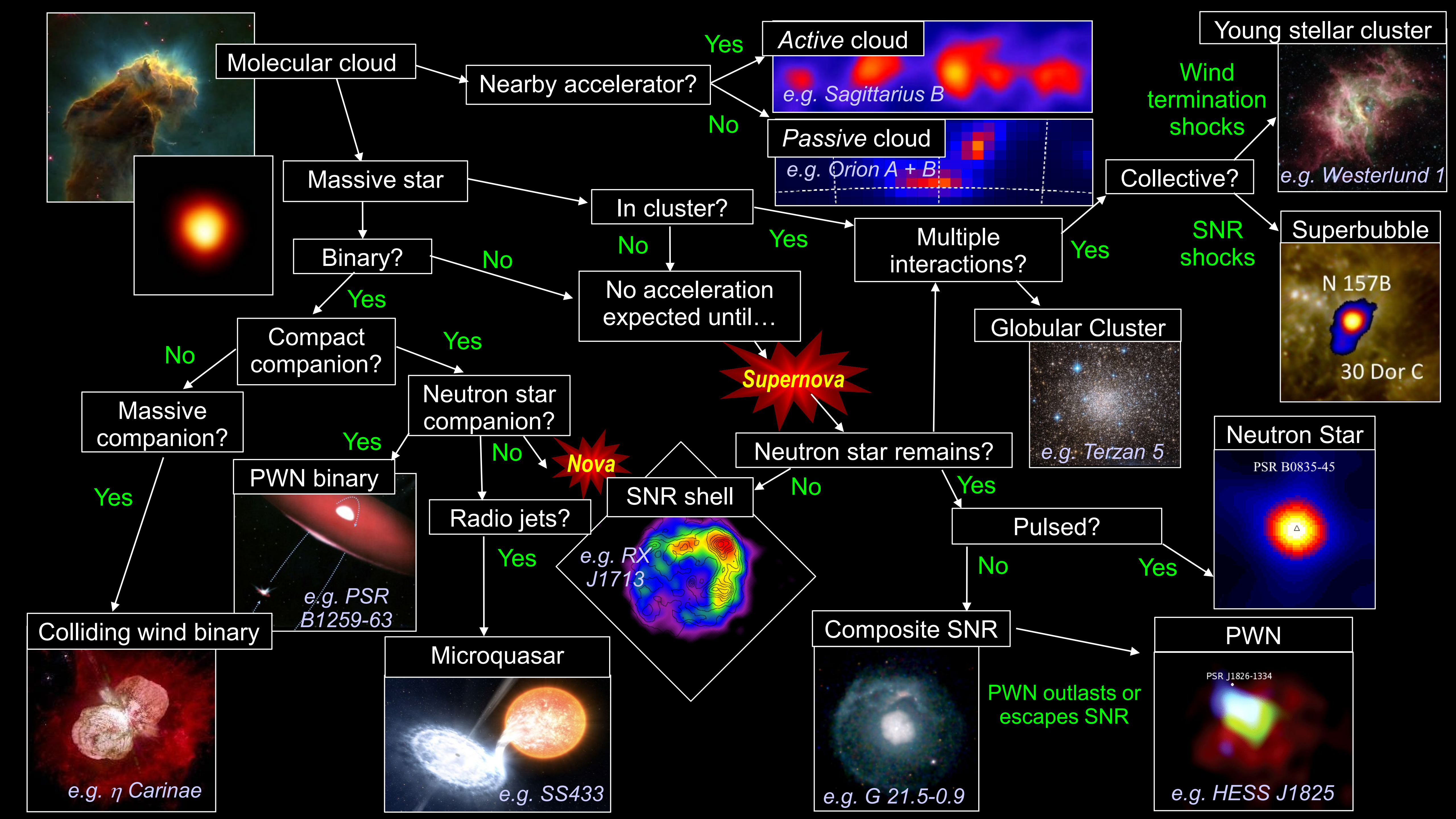
← H.E.S.S. GPS > 1 TeV (Impact3D)
different background estimation
smoothed with Gaussian 0.4°

← HAWC Galactic Plane map, analysis bin 4-9

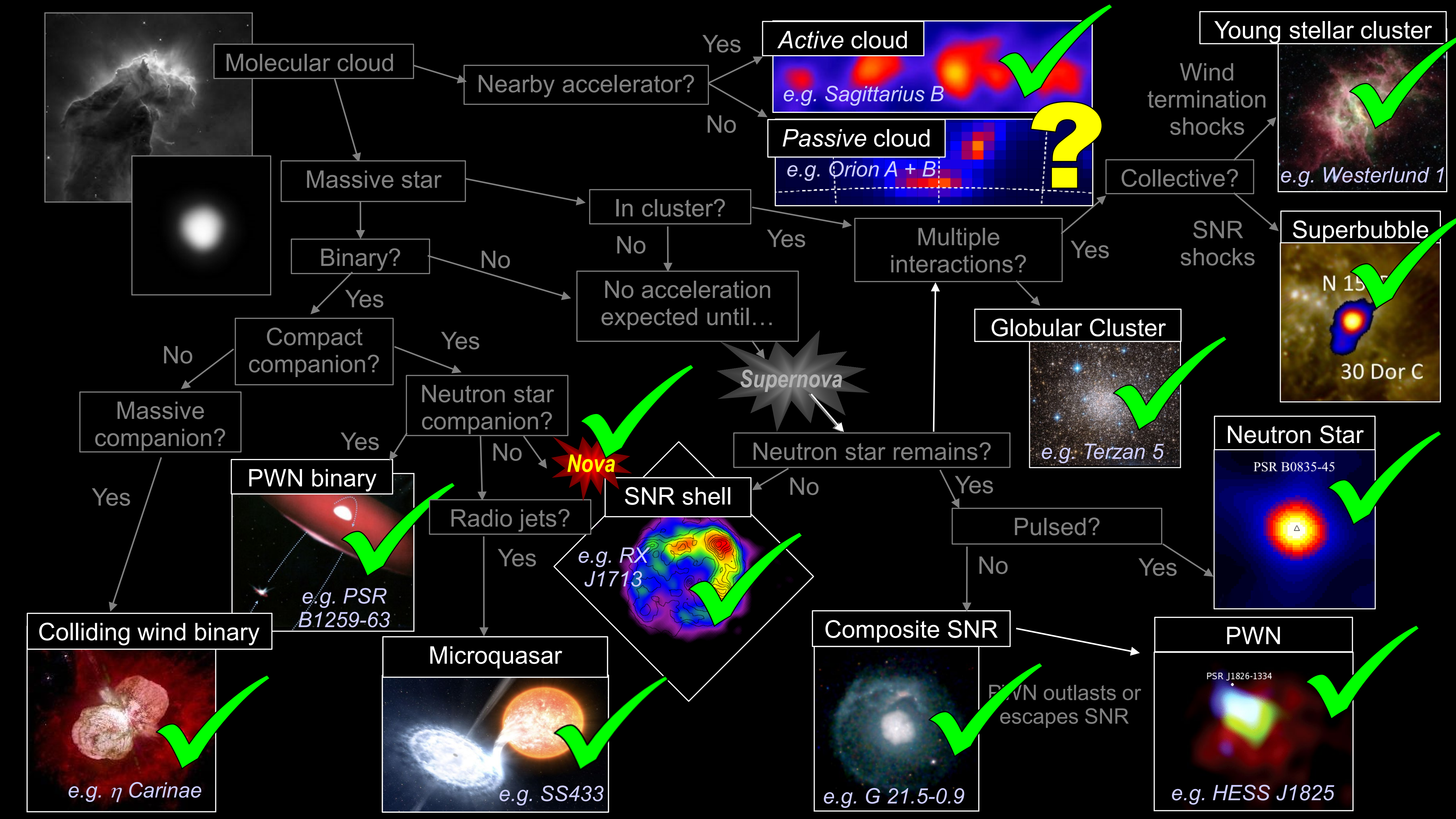




[expanded from Skilton & Hinton]



Molecular cloud
Nearby accelerator?
Yes
Active cloud
e.g. Sagittarius B
No
Passive cloud
e.g. Orion A + B
Young stellar cluster
Wind termination shocks
e.g. Westerlund 1
Collective?
SNR shocks
Superbubble
N 157B
30 Dor C
Massive star
In cluster?
Yes
Multiple interactions?
Yes
No
Binary?
No
No acceleration expected until…
Yes
Compact companion?
Yes
No
Globular Cluster
e.g. Terzan 5
Supernova
Massive companion?
Neutron star companion?
Yes
No
Nova
Neutron star remains?
No
Yes
Neutron Star
PSR B0835-45
PWN binary
e.g. PSR B1259-63
Yes
SNR shell
e.g. RX J1713
Radio jets?
Yes
Pulsed?
No
Yes
Colliding wind binary
e.g. η Carinae
Microquasar
e.g. SS433
Composite SNR
e.g. G 21.5-0.9
PWN outlasts or escapes SNR
PWN
PSR J1826-1334
e.g. HESS J1825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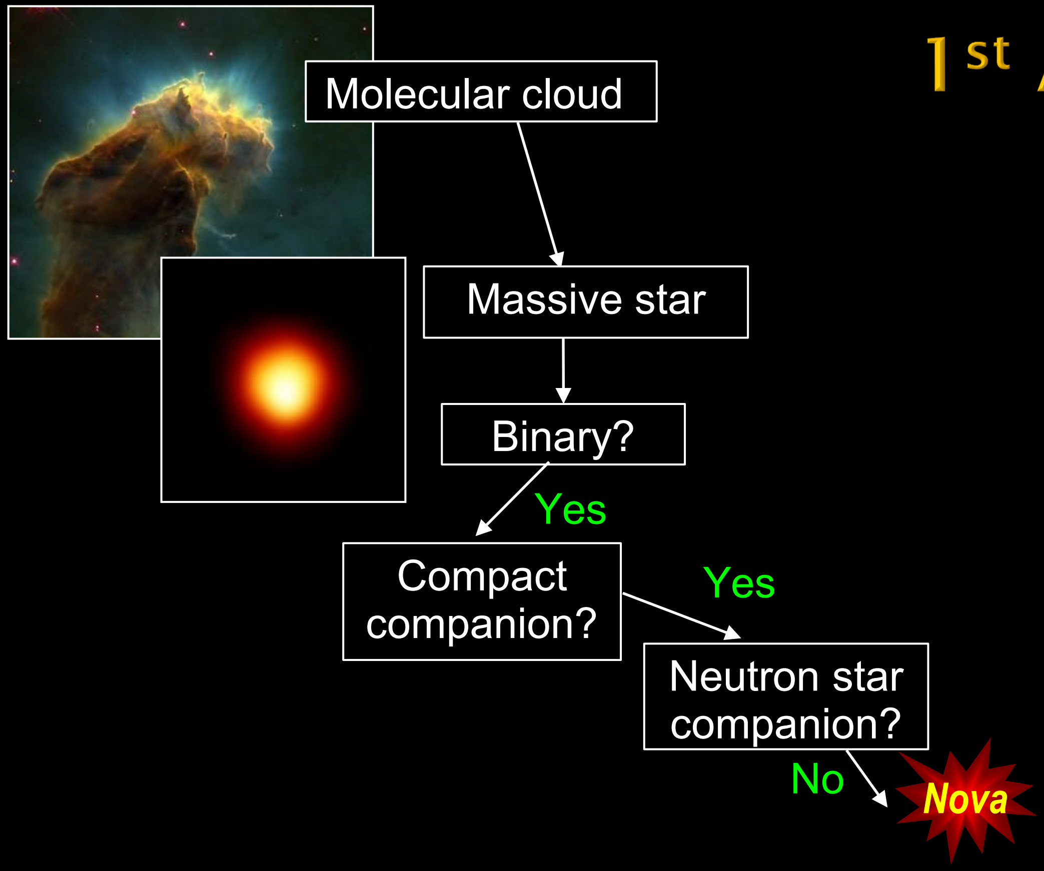
1st Aspect: Nova RS Oph Aug 8, 2021



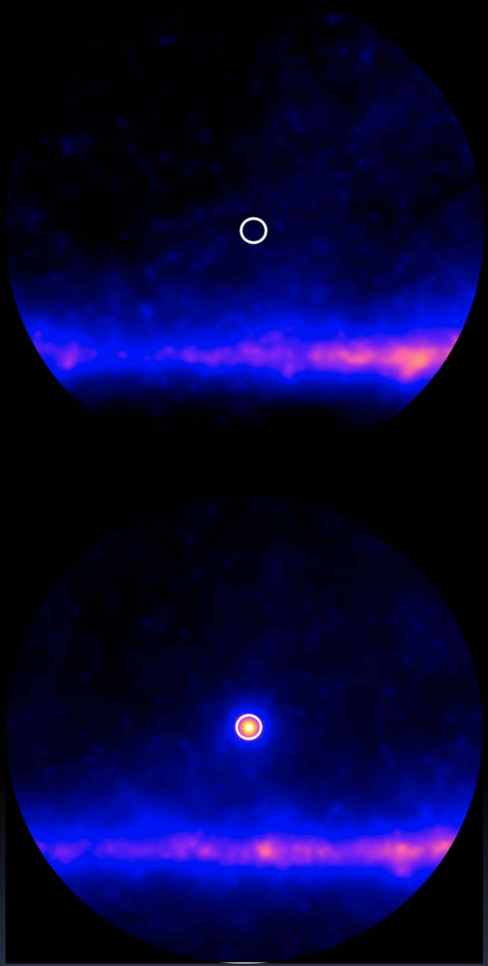
Novae…

…are outbursts from accreting (WD+massive donor) binaries

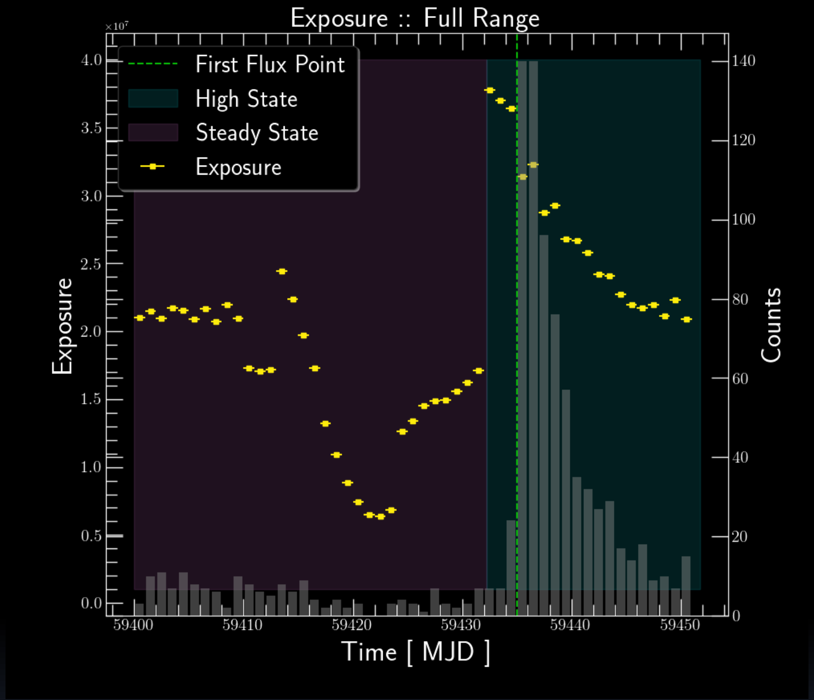
Classical Novae → outbursts from cataclysmic variables
Symbiotic Novae → red giant / “evolved” donor star
***Recurrent* Novae → multiple outbursts**
Dwarf Novae → mini-outbursts (not thermonuclear)

☞ thermonuclear explosion ignited on surface of WD
☞ increase in optical brightness $\Delta m_v \sim 8$ to 15
☞ typical optical duration weeks to months

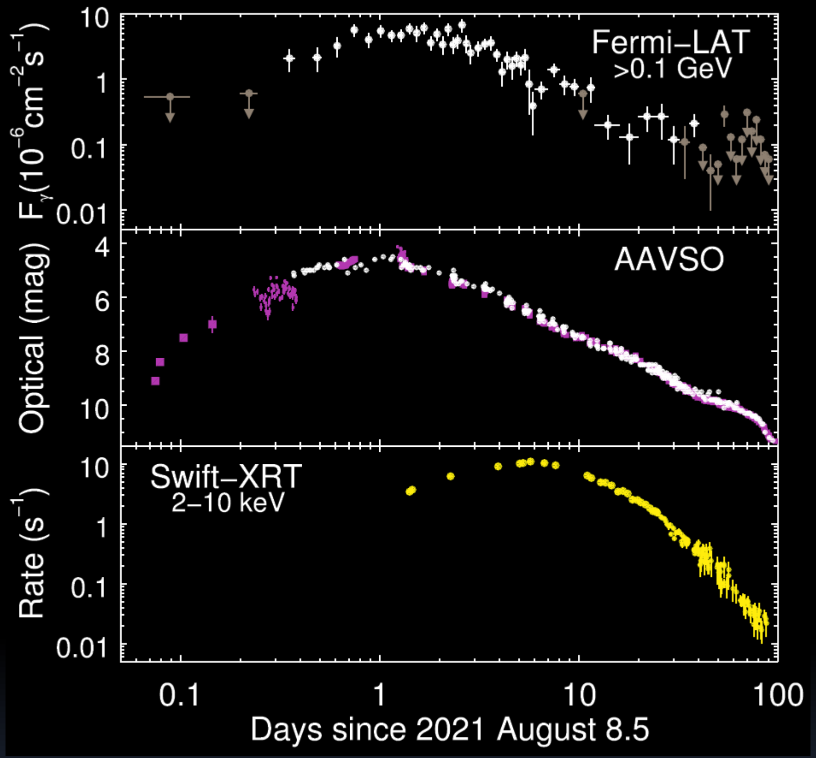
1st Aspect: Nova RS Oph Aug 8, 2021



Fermi-LAT



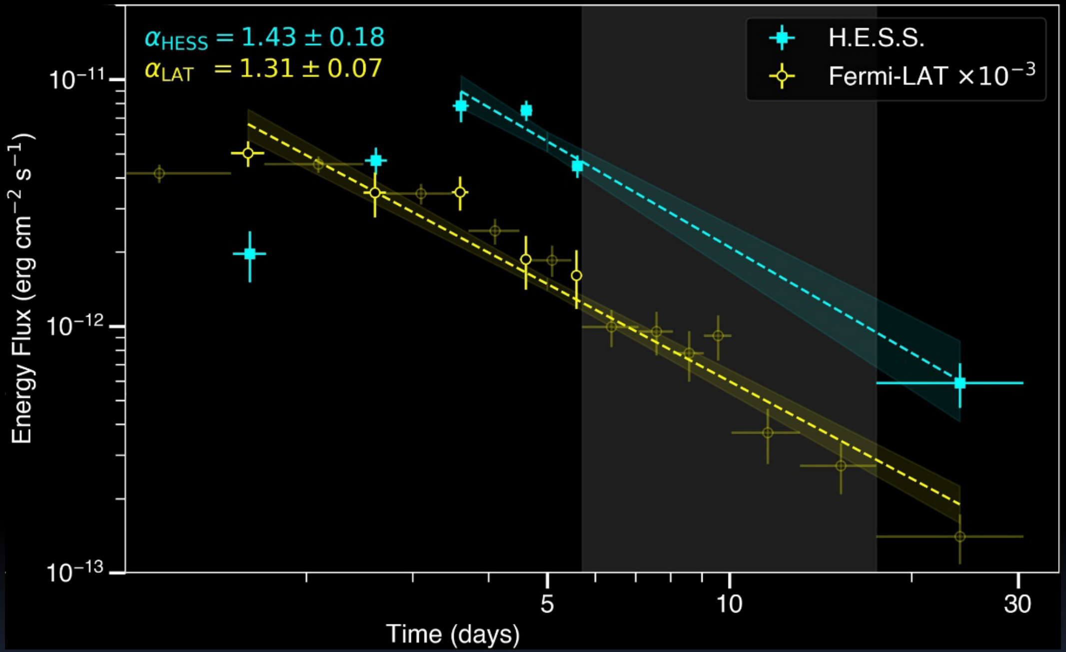
AASVO even before



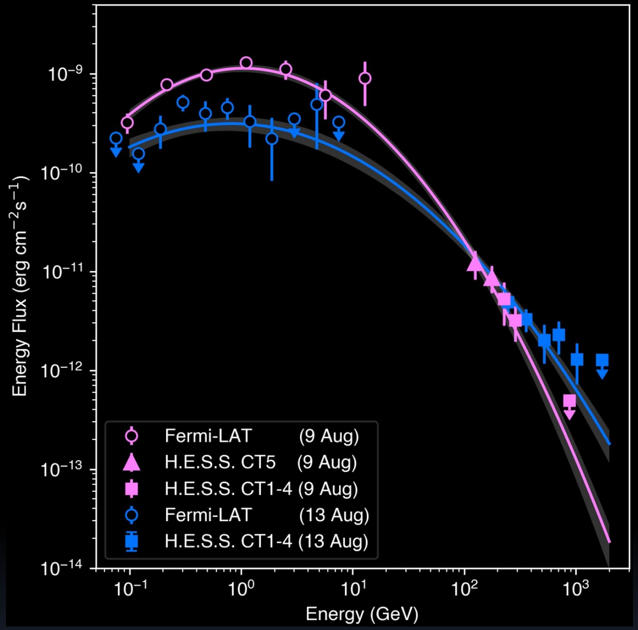
Cheung et al. (Fermi-LAT) 2022

1st Aspect: Nova RS Oph Aug 8, 2021

"Time-resolved hadronic particle acceleration in the recurrent nova RS Ophiuchi" (H.E.S.S.)
"Proton acceleration in thermonuclear nova explosions revealed by gamma rays" (MAGIC)



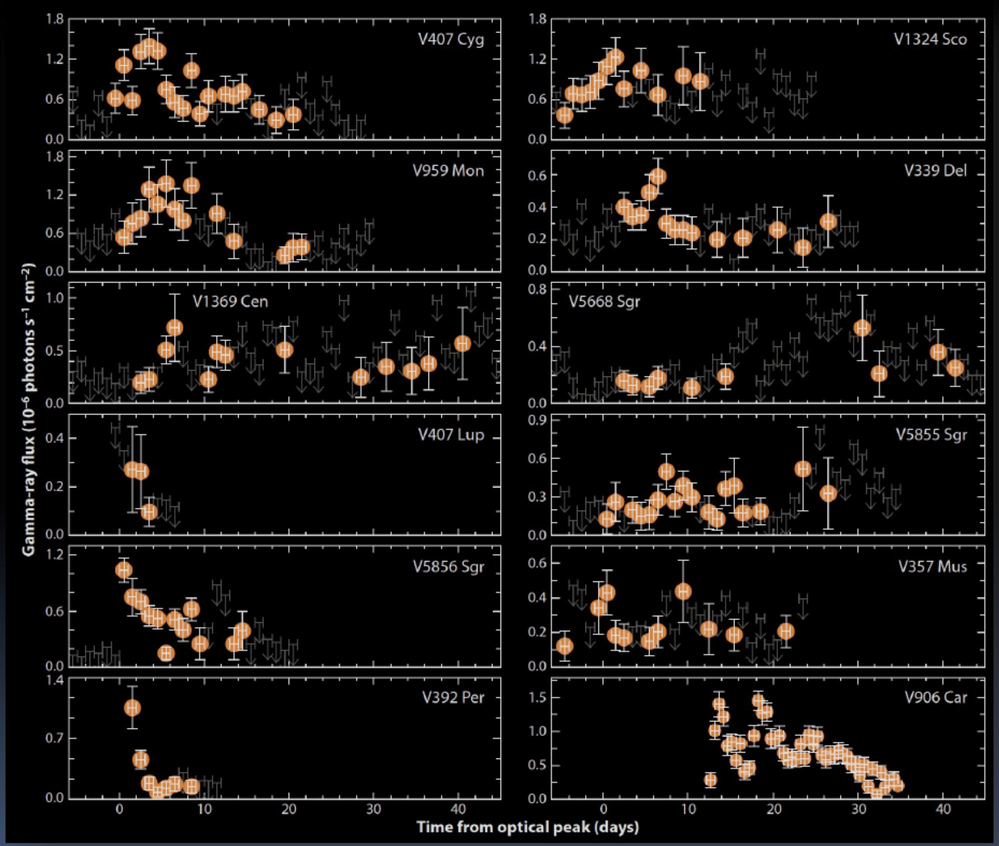
time-evolution



spectral-evolution

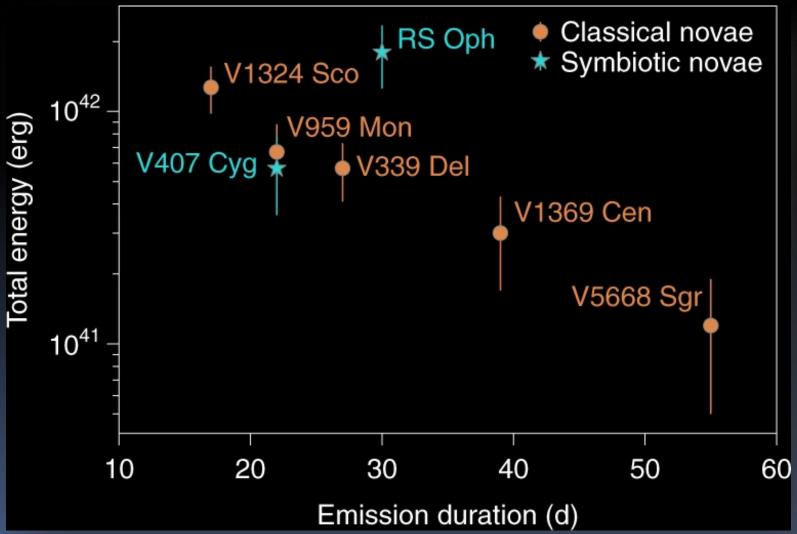
1st Aspect: Nova RS Oph Aug 8, 2021

Population aspects remain driven by Fermi-LAT (allsky GeV).



Chomiuk, Metzger & Chen (2021)

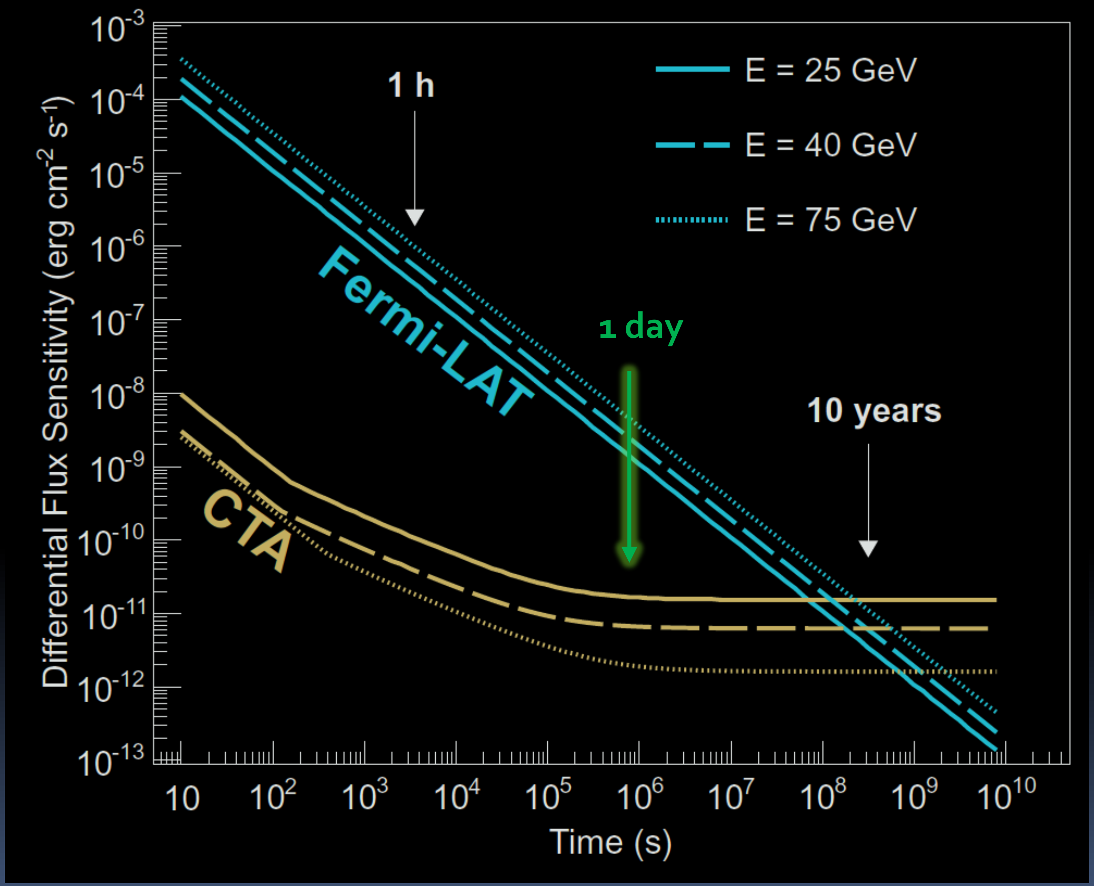
- ☞ 22 novae detected in gamma-rays by Fermi-LAT as of mid 2022
- ☞ typical duration days to weeks
- ☞ typical spectral cut-off ~1-10 GeV
- ☞ types: classical & symbiotic/recurrent novae



Acciari et al. (MAGIC) 2022

1st Aspect: Nova RS Oph Aug 8, 2021

Imaging Atmospheric Cherenkov Telescopes deliver what they were promised to excel in!



Science with the Cherenkov Telescope Array (2019)

photon statistics on short time intervals

☞ time-resolved light-curves from a galactic transient (novel!)

☞ time-resolved spectral evolution (novel!)

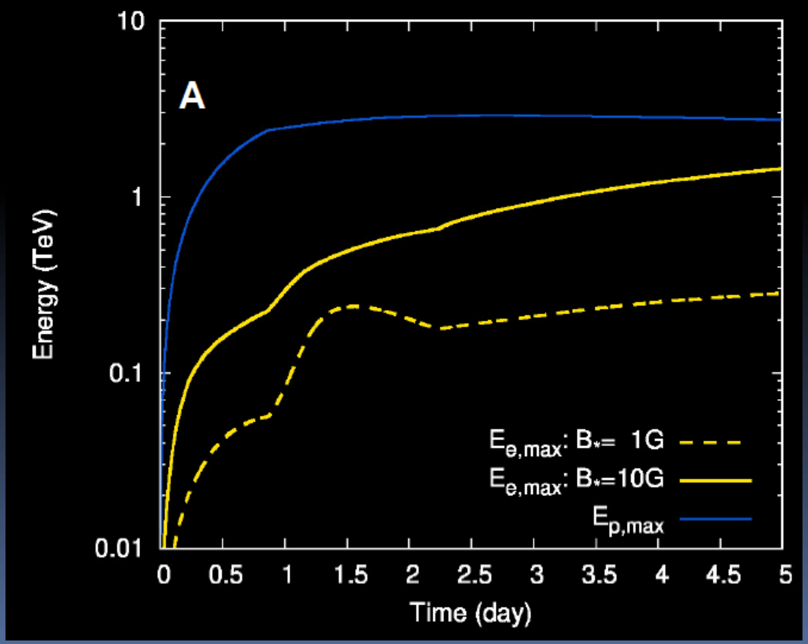
observables for *no-nonsense* model constraints

1st Aspect: Nova RS Oph Aug 8, 2021

Imaging Atmospheric Cherenkov Telescopes deliver what they were promised to excel in!

…along the first five days, GeV flux ↓ whereas TeV flux ↑
→ compare to time to reach the theoretical maximum energy

Conjecture:
time taken before radiative cooling dominates acceleration of particles allowed to escape shock (confinement limit)



$$E_{\rm max} = 1.5|Z|\left(\frac{\xi_{\rm esc}}{0.01}\right)\left(\frac{\dot{M}/v_{\rm wind}}{10^{11}\ {\rm kg\ m^{-1}}}\right)^{1/2}\left(\frac{u_{\rm sh}}{5000\ {\rm km\ s^{-1}}}\right)^{2}\ {\rm TeV}$$

$$\dot{M}/v_{\rm wind} = 6\times10^{11}\ {\rm kg\ m^{-1}}$$

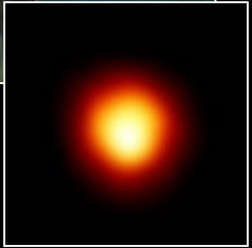
ξ_{esc} for high-Mach-number shocks ~ 1%
$u_{sh} \approx$ 4000…5000 km/s

→ **E_{max} ~ 10 TeV** (corresponds well to max E_γ ~ 1 TeV)

☞ **acceleration reaching the theoretical limit for maximum achievable particle energy via DSA**

2^{nd} Aspect: Colliding Wind Binaries

Molecular cloud



Massive star

Binary?

Yes

Compact companion?

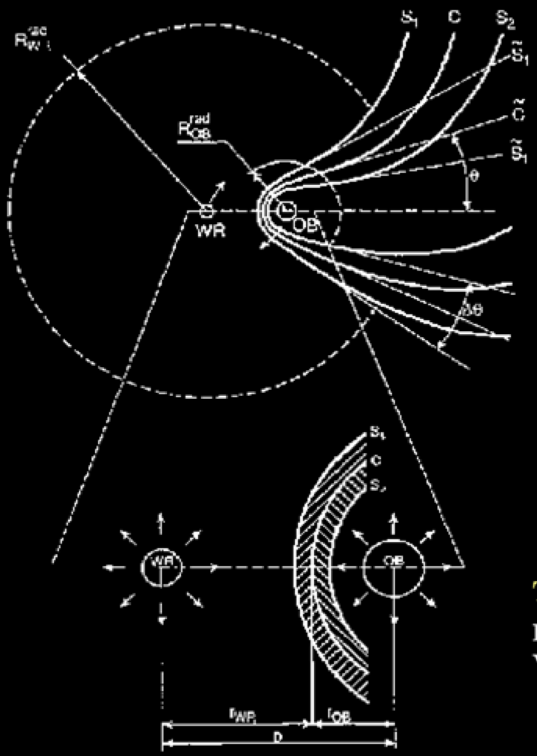
No

Massive companion?

Yes

Colliding wind binary

e.g. η Carinae



stagnation point (ram pressure balance):

$$r_{OB} = x = \frac{\sqrt{\eta}}{1+\sqrt{\eta}} D \qquad \text{with} \quad \eta = \frac{\dot{M}_{OB} V_{\infty,OB}}{\dot{M}_{WR} V_{\infty,WR}}$$

magnetic field:

$$B \approx B_s \times \begin{cases} \left(\frac{R_\star}{\tilde{r}}\right)^3 & \text{for} \quad R_\star \le \tilde{r} \le r_A \\ \frac{R_\star^3}{r_A \tilde{r}^2} & \text{for} \quad r_A \le \tilde{r} \le R_\star \frac{V_\infty}{V_{rot}} \\ \frac{V_{rot}}{V_\infty} \frac{R_\star^2}{r_A \tilde{r}} & \text{for} \quad R_\star \frac{V_\infty}{V_{rot}} \le \tilde{r} \end{cases}$$

Typical parameter values:

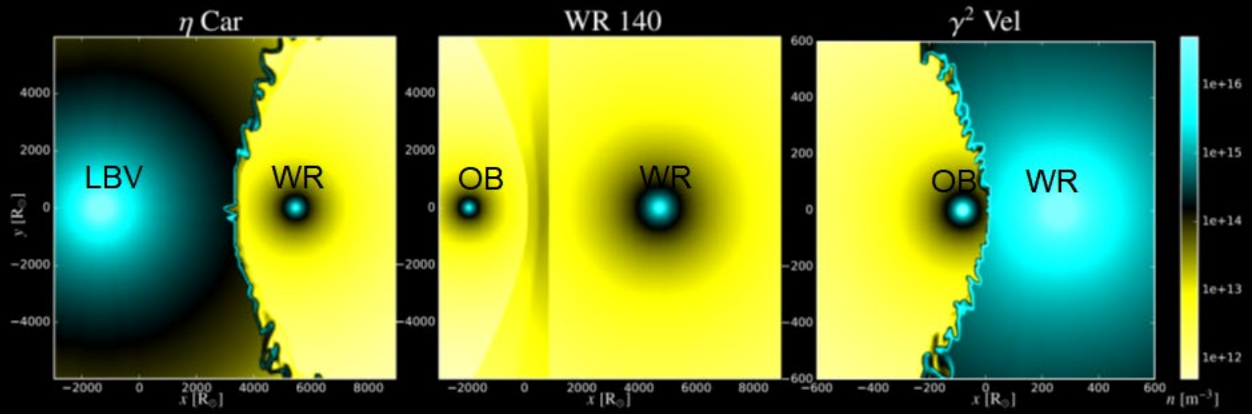
$L_{bol,OB} \approx 10^{38...39}$ erg/s, $T_{eff} \approx 43000$ K, $\dot{M}_{OB} \approx 10^{-6} M_\odot yr^{-1}$, $\dot{M}_{WR} \approx 10\,\dot{M}_{OB}$,
$V_\infty \approx 2000 \ldots 3000$ km/s, $V_s \approx 10$ km/s, $r_A \approx 3 \ldots 5 R_\star$, $D \approx 10^{12...16}$ cm
$\longrightarrow x \approx 0.1 \ldots 0.2\,D$

e.g. Eichler & Usov 1993

2nd Aspect: Colliding Wind Binaries

Formulation of the problem:

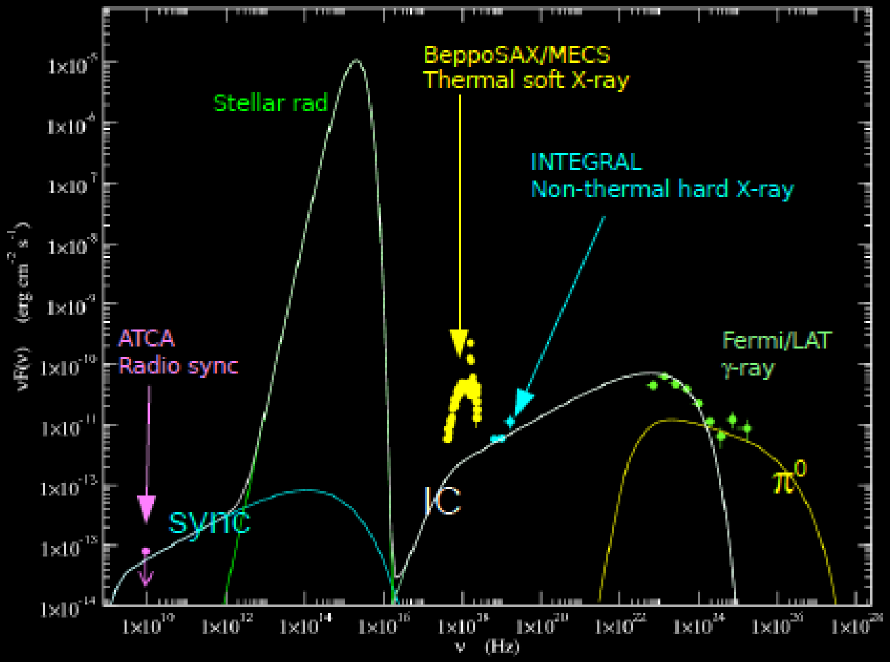
- There are many, many massive stars in our Galaxy.
- Binarity is rather a common property in stellar evolution than a rarity.
- There are only two solidly detected CWBs in the Fermi-LAT sky.
- There is apparently just one CWB in the VHE sky.
- Stellar systems are simple. DSA is not stretched. Predicted systems are not necessarily detected. And why so few?



Reitberger et al. 2017

	ηCar	WR 140	γ^2Vel	
box width	12	12	1.2	10^3 $R_\odot$
Maximum density in WCR	1×10^{16}	3×10^{13}	9×10^{16}	m^{-3}
Apex wind velocity WR wind	2900	2800	1300	km s^{-1}
Apex wind velocity OB/LBV wind	540	3000	2000	km s^{-1}
Maximal temperature in WCR	1.1	1.4	0.6	10^8 K

2^{nd} Aspect: Colliding Wind Binaries



	Parameter	Value	
Environment	Photon energy density	2.7	erg/cm^3
	Magnetic field	0.5	G
	Density	$3 \cdot 10^9$	cm^{-3}
Electron distribution	Power law index	2.25	
	$\gamma_{max,e}$	10^4	
	Total energy	10^{40}	erg
Proton distribution	Power law index	2.25	
	$\gamma_{max,p}$	10^4	
	Total energy	$1.3 \cdot 10^{40}$	erg

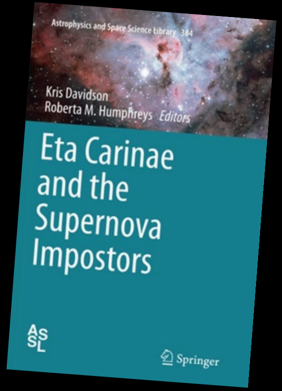
η **Carinae: a very large hadron collider** (Farnier+ 2011)

e^- IC with intense UV radiation field+ π^0 decay pp interaction of the stellar winds

- Simple model explaining both hard X-ray and GeV fluxes
- maximal proton energy not constrained by Fermi/LAT

… and many other models to explain gamma-ray eta Carinae phenomenology since then (Bednarek & Pabich, Reitberger et al., Ohm et al., Walter & Balbo, White et al., …=

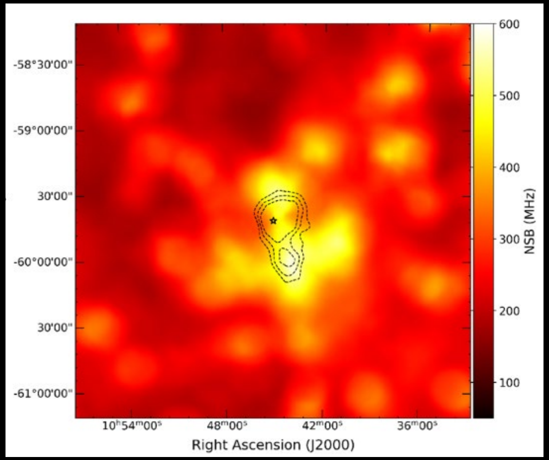
2nd Aspect: Colliding Wind Binaries



Formulation of the problem:

- There are many, many massive stars in our Galaxy.
- Binarity is rather a common property from stellar evolution than a rarity.
- There are only two solidly detected CWBs in the Fermi sky.
- There is just one CWB in the VHE sky. $\rightarrow$ eta Carinae
- Stellar systems are simple. DSA is not stretched. Predicted systems are not the detected systems. Why so few?

Detection of eta Carinae in VHE by H.E.S.S. had been a tale of woe:



Abdalla et al. (H.E.S.S.) 2000

extremely high NSB region, non-trivial morphology

↓

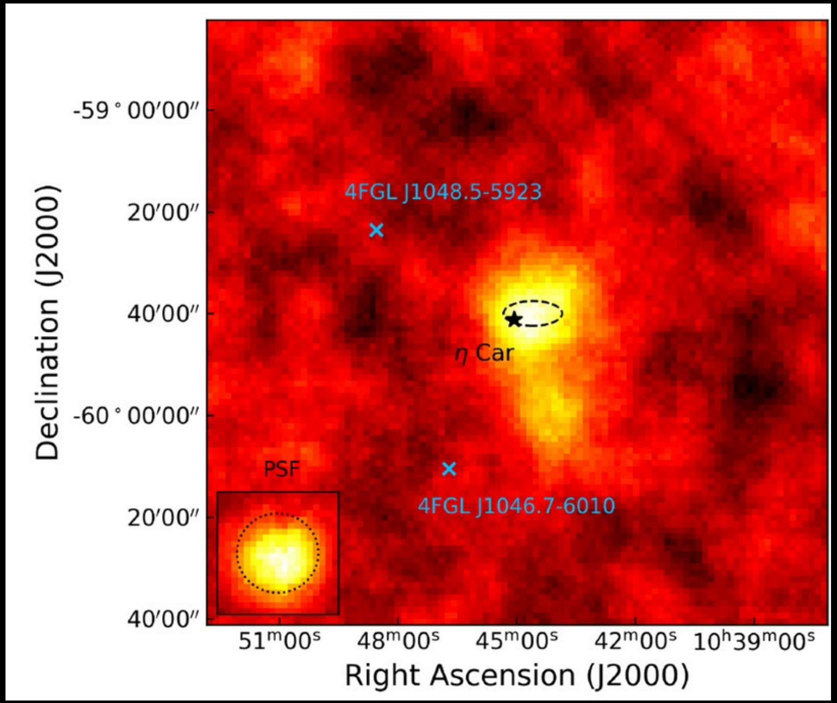
asymmetric acceptance

↓

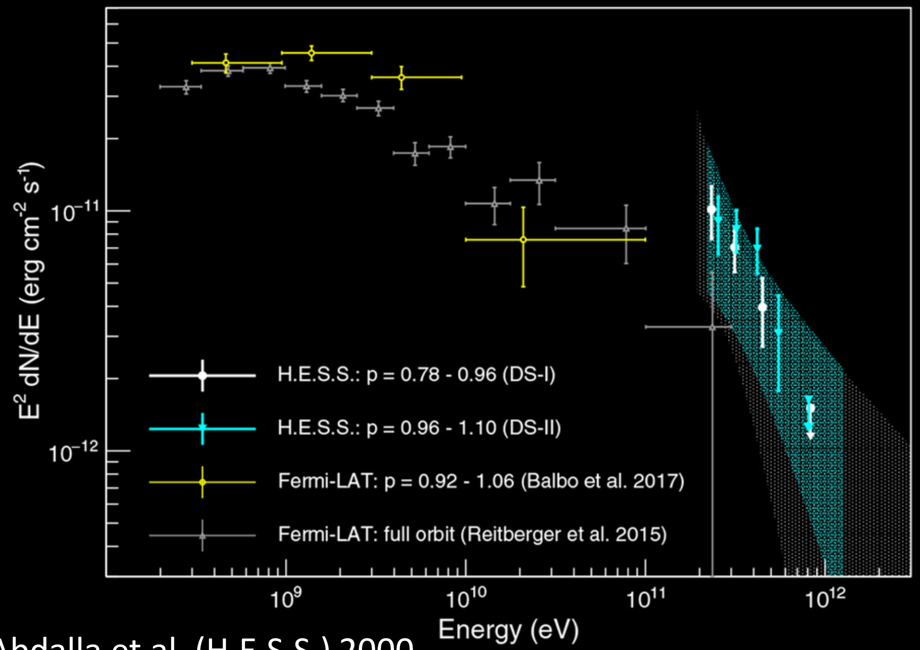
different data sets from different telescope combinations (CT1-4 , CT5 mono)

↓

comparison to non-contemporaneous Fermi-LAT multiyear-orbit spectrum



2^{nd} Aspect: Colliding Wind Binaries



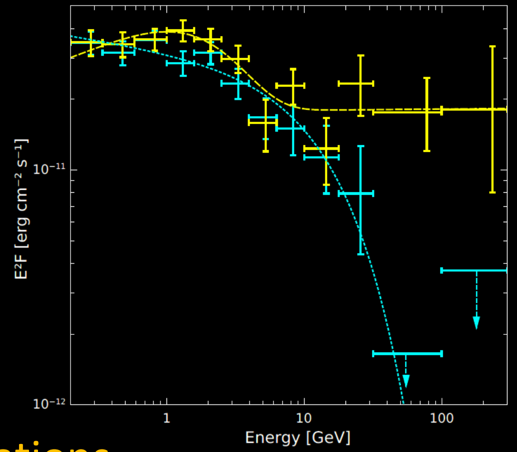
Abdalla et al. (H.E.S.S.) 2000

What we now know better from the GeVs meanwhile:

☞ Flux- & Spectro-variability.

Different spectra around periastron and apastron.

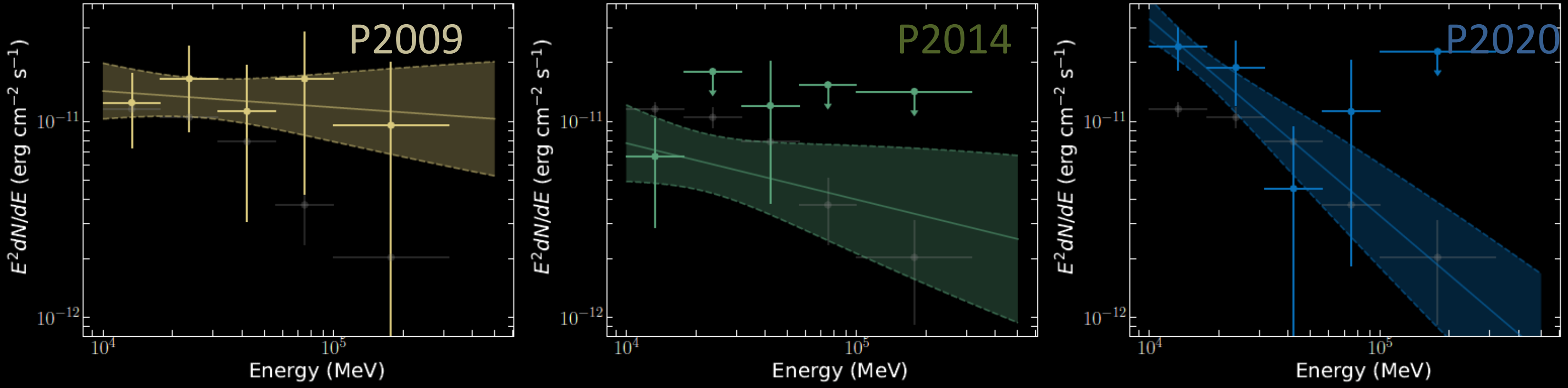
(Reitberger et al. 2015)



☞ Orbit-to-orbit variations.

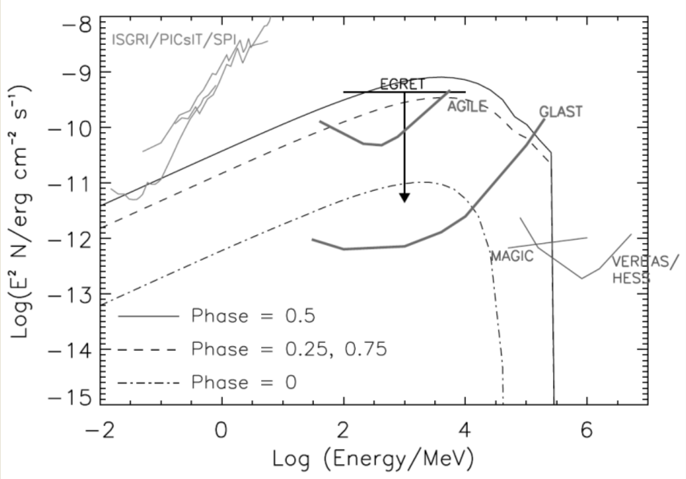
Each (5.5y) orbit has notable (lc, flux, spectra) differences.

(Marti-Devesa & Reimer 2022)



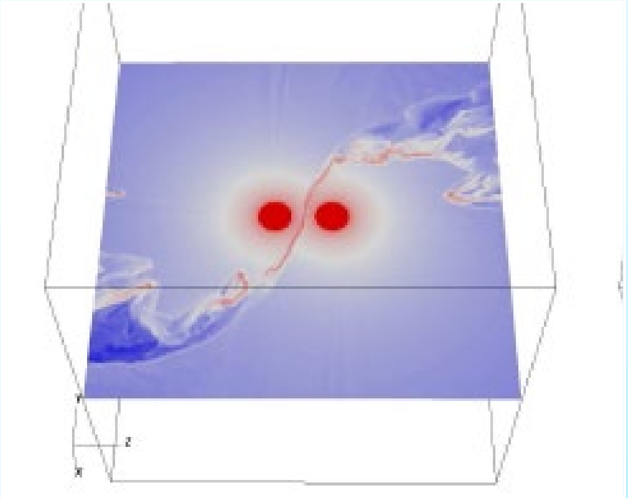
2^{nd} Aspect: Colliding Wind Binaries

Interpretation/modeling requires (and reached) a complexity that is beyond analytical capabilities.



analytical models solving a transport eq. for accelerating particles and subsequently computing γ-ray fluxes.

(e.g., Reimer et al. 2006)



numerical hydrodynamic models simulating the dynamics of wind acceleration and collision in course of orbital cycle.

(e.g., Kissmann 2018)

We combine both approaches in a common numerical framework.

2^{nd} Aspect: Colliding Wind Binaries

- 3D MHD code
  - radiative line-acceleration to generate stellar winds
  - B-field determined by choice of stellar surface-magnetic field
  - radiative cooling considered

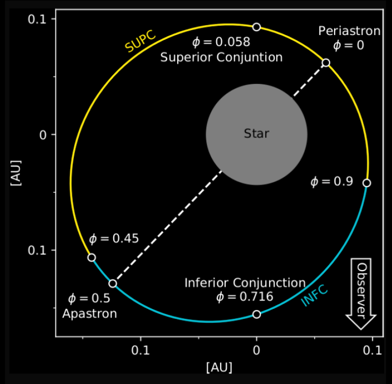
- 200 advected scalar fields representing $\boldsymbol{e^-}$ and $\boldsymbol{p}$ at different energy bins
  - solution of transport equation for each computational cell and time step

$$\frac{\partial j}{\partial t} - \underset{(1)}{D(E)\nabla^2 j} + \underset{(2)}{\nabla \cdot (\vec{u} j)} - \frac{\partial}{\partial E}\left[\underset{(3)}{\left(\frac{E}{3}\nabla \cdot \vec{u} + \dot{E}_{\text{loss}}\right)} j(E)\right] = \underset{(4)}{Q_0 \delta(E - E_0)}$$

1) spatial diffusion with $D = D_0 E^\delta$
2) spatial convection
3) energy gains and losses
4) particle injection at E_0

- Finally, gamma-ray emission yields computed from particle spectra and surrounding conditions (per orbit section)
  - IC
  - Bremsstrahlung
  - π^0-decay
  - attenuation by photon-photon absorption

2nd Aspect: CWBs → Gamma-ray Binaries



There are off-springs from CWB modelling: PWN /massive star binaries → LS5036

(Huber et al. 2021a) (Huber et al. 2021b)

Stellar Winds

- Relativistic HD
- Conserved Quantities
  - Density $D = \gamma\rho$
  - Momentum $m^j = \gamma\rho h u^j = \gamma^2 \rho h v^j$
  - Energy density $\tau = \gamma^2 \rho h - p - D$
- Solver: Cronos MHD / RHD code

Relativistic Hydrodyamics

$$\frac{\partial D}{\partial t} + \nabla \cdot \left(\frac{1}{\gamma} D \mathbf{u} \right) = 0$$

$$\frac{\partial \mathbf{m}}{\partial t} + \nabla \cdot \left(\frac{1}{\gamma} \mathbf{m} \otimes \mathbf{u} + p\mathbb{1} \right) = \mathbf{f}$$

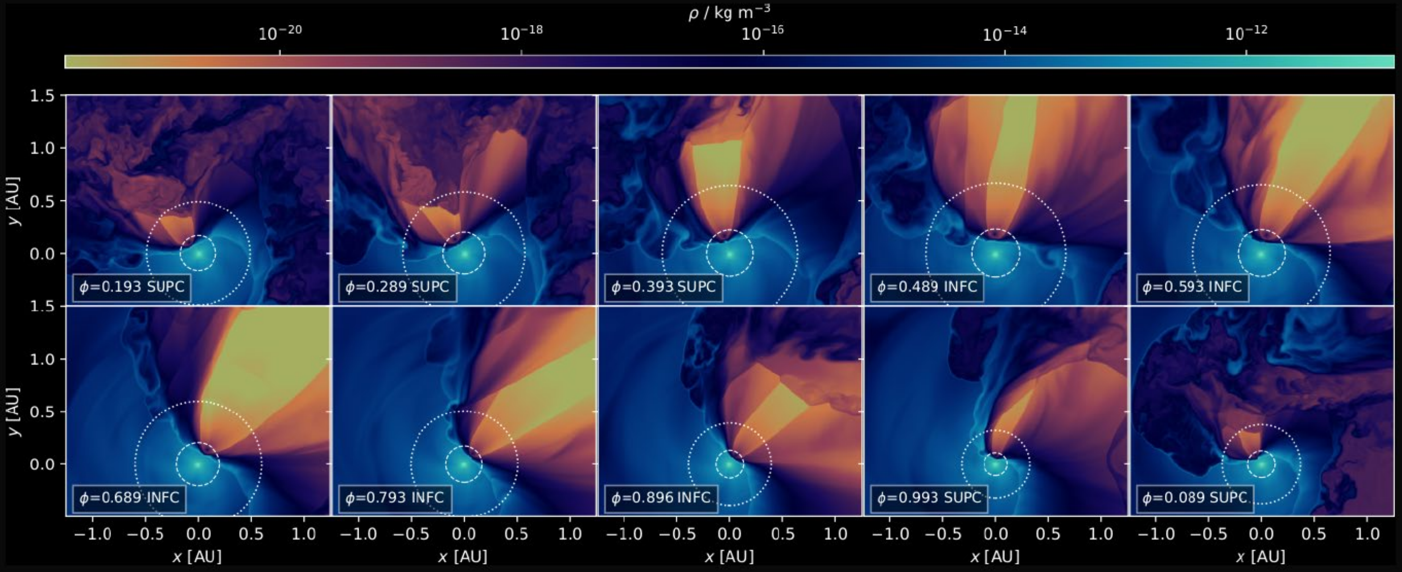
$$\frac{\partial \tau}{\partial t} + \nabla \cdot \left((\tau + p) \frac{1}{\gamma} \mathbf{u} \right) = S_\tau$$

Equation of state

$$h = h(\rho, p) = 1 + \frac{\Gamma}{\Gamma - 1} \frac{p}{\rho}$$

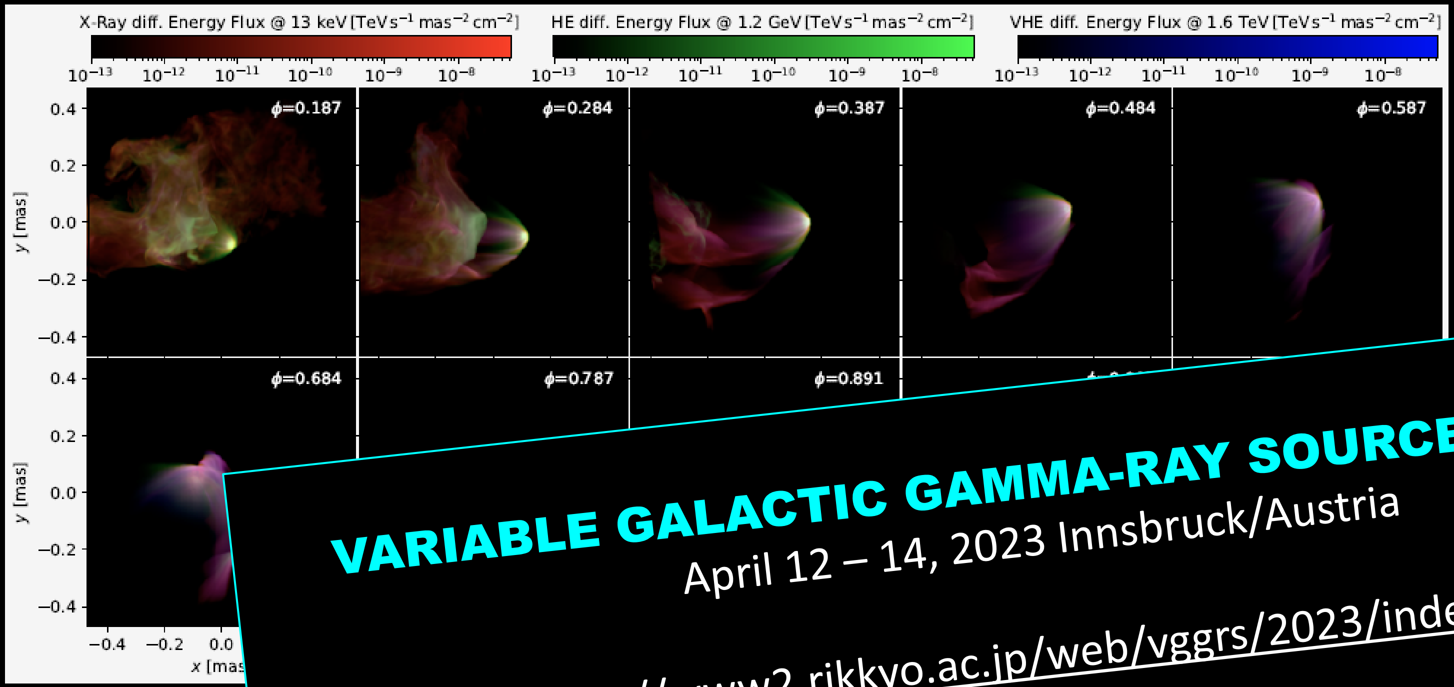
(Huber & Kissmann 2021c)

Stellar-Wind Interaction

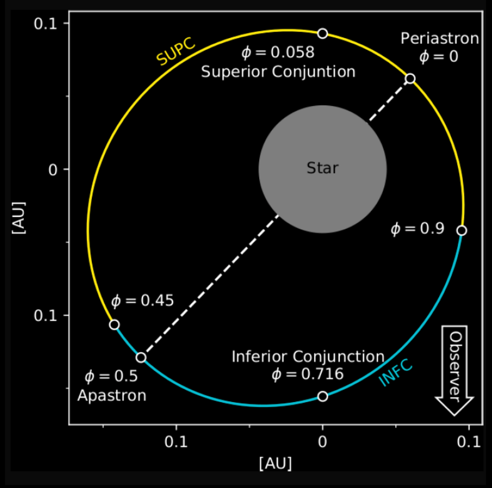


(Huber et al. 2021b)

2nd Aspect: CWBs → Gamma-ray Binaries



(Huber et al. 20



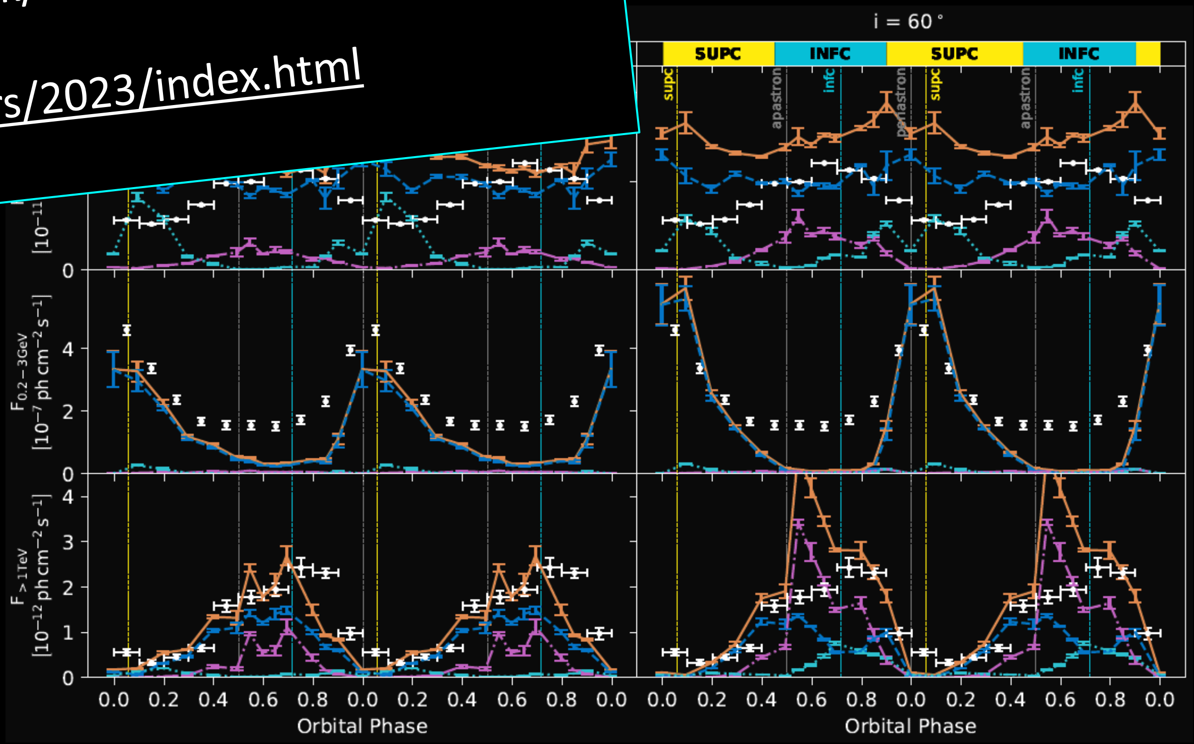
VARIABLE GALACTIC GAMMA-RAY SOURCES VI

April 12 – 14, 2023 Innsbruck/Austria

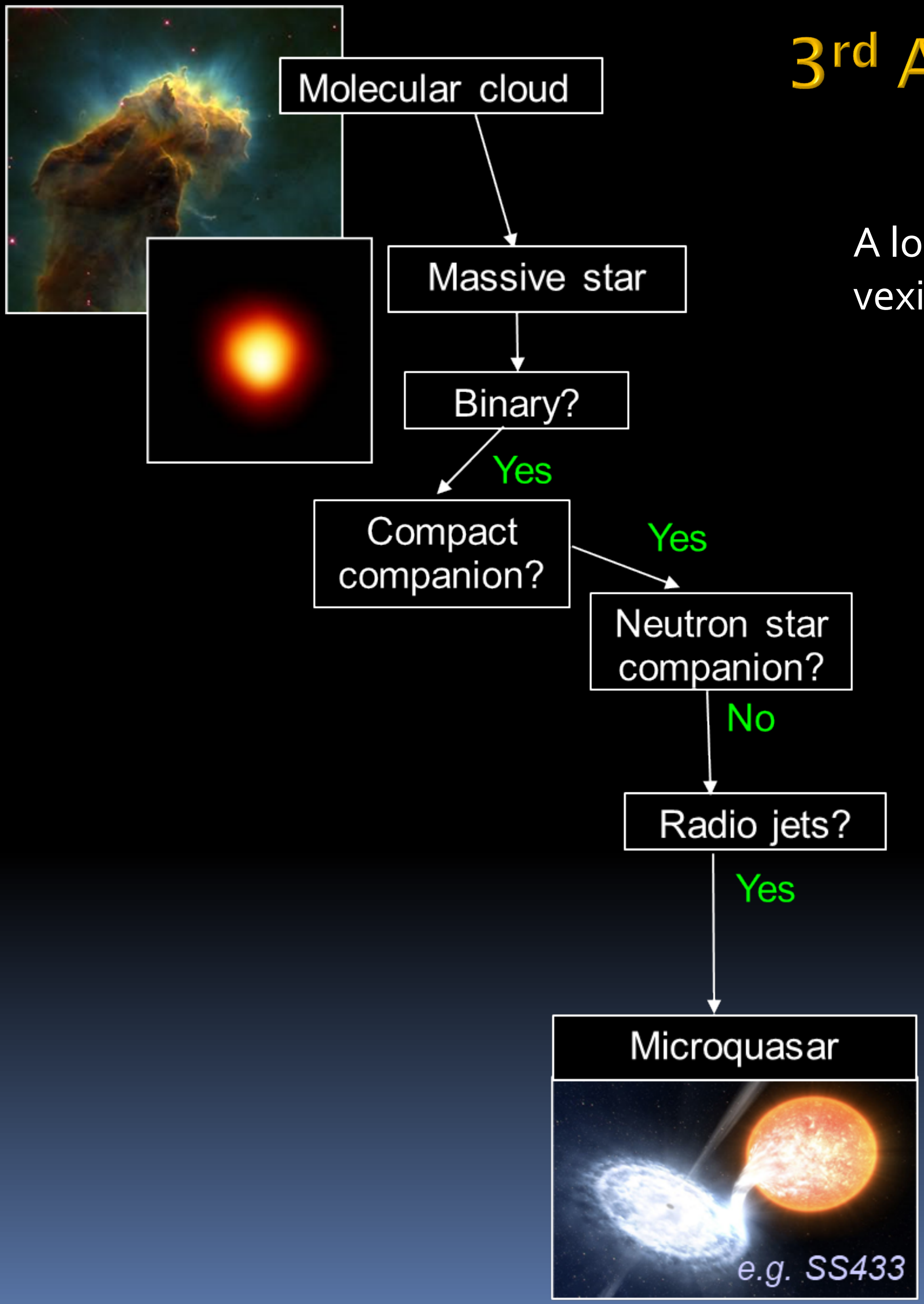
https://www2.rikkyo.ac.jp/web/vggrs/2023/index.html

Investigation of Inclination dependence:

- ☞ anisotropic IC
- ☞ relativistic beaming
- ☞ $\gamma\gamma$ attenuation



3^{rd} Aspect: Microquasar(s)



A loaded topic from the dawn of ground-based gamma-ray astronomy, with vexing relics occasionally seen even today…

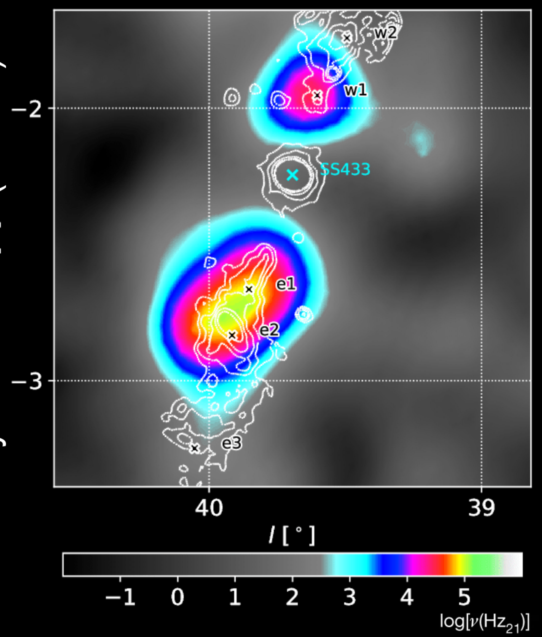
Credible contemporary VHE gamma-ray astronomy:

Cyg X-1 (MAGIC) ? unclear ? (MAGIC 2007, 2017, VERITAS)
Cyg X-3 (MAGIC, VERITAS) ∅
LS I 61 303 (MAGIC, VERITAS) ~~μQSO~~, finally (Weng et al. 2022)

…but along came lately SS433: HAWC (2018), H.E.S.S. (2022)

3rd Aspect: Microquasar(s)

Abeyesekara et al. (HAWC) 2018

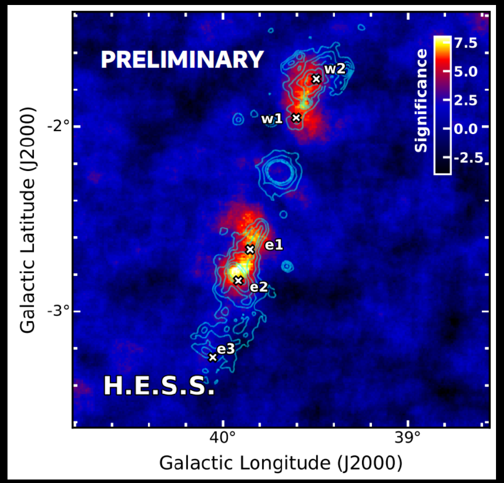


$$dN/dE \propto E^{-\alpha}\exp(-E/E_{\max})$$

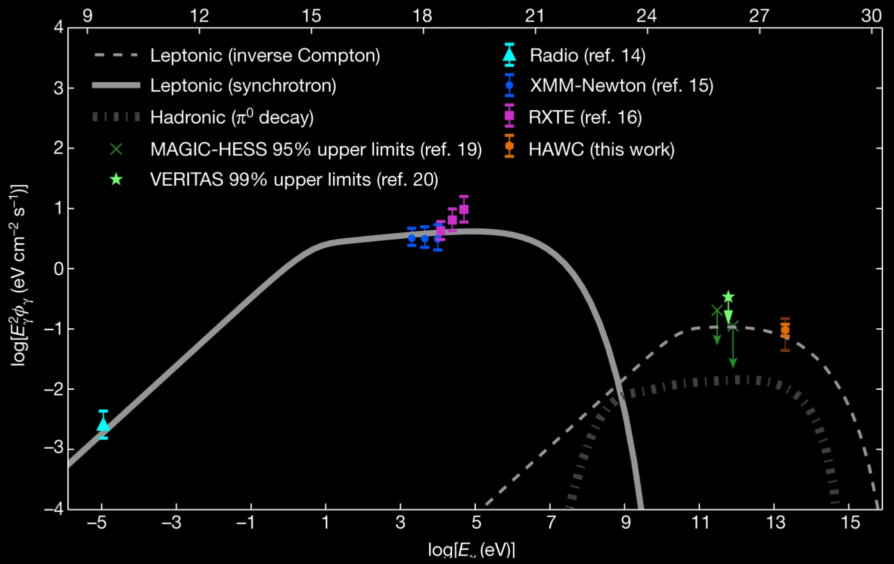
$$\alpha = 1.87^{+0.04}_{-0.07} \quad B = 16.04^{+2.60}_{-2.23}\,\mu\text{G}$$

$\rightarrow E_{\text{max, e-}} \sim 3.5$ PeV (!)

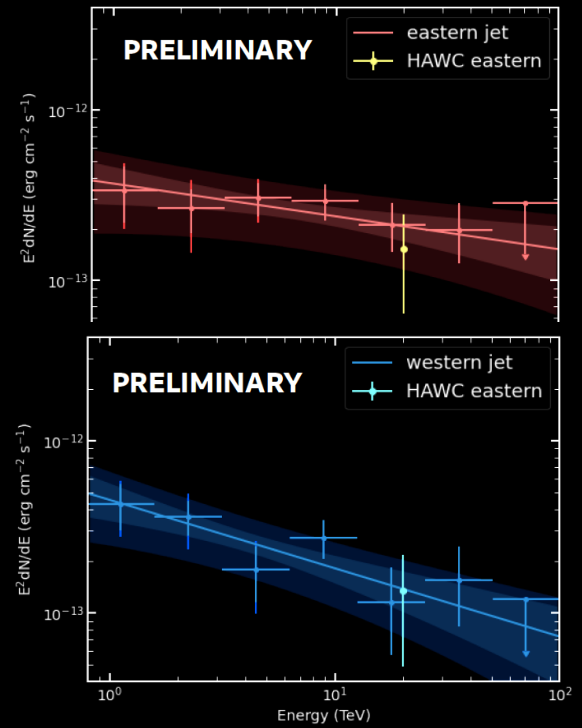
@5.5 kpc $\rightarrow E_{\text{tot, e-}} \sim 2.9 \times 10^{47}$ erg (at % level of total energy budget)



Nieto et al. (H.E.S.S.) 2022



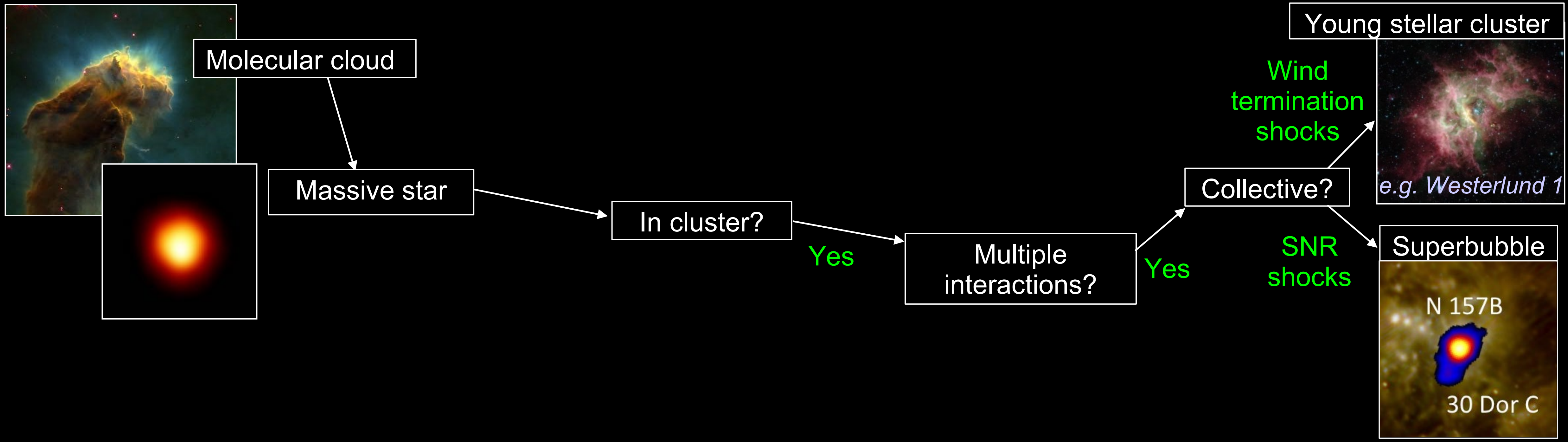
… could ease if Alvén speed in jet lobes (~160 km/s) could relate to jet flow velocity?



acceleration rate $\dot{\gamma} \approx eBv/m_e c^2$ > cooling rate $\dot{\gamma} \approx 4c\sigma_T\gamma^2\left(B^2/8\pi\right)/3m_e c^2$

$\rightarrow E_{\text{max, e-}} \sim 217$ TeV $(v/100\text{ km/s})^{-1/2}\,(B/16\mu\text{G})^{-1/2}$

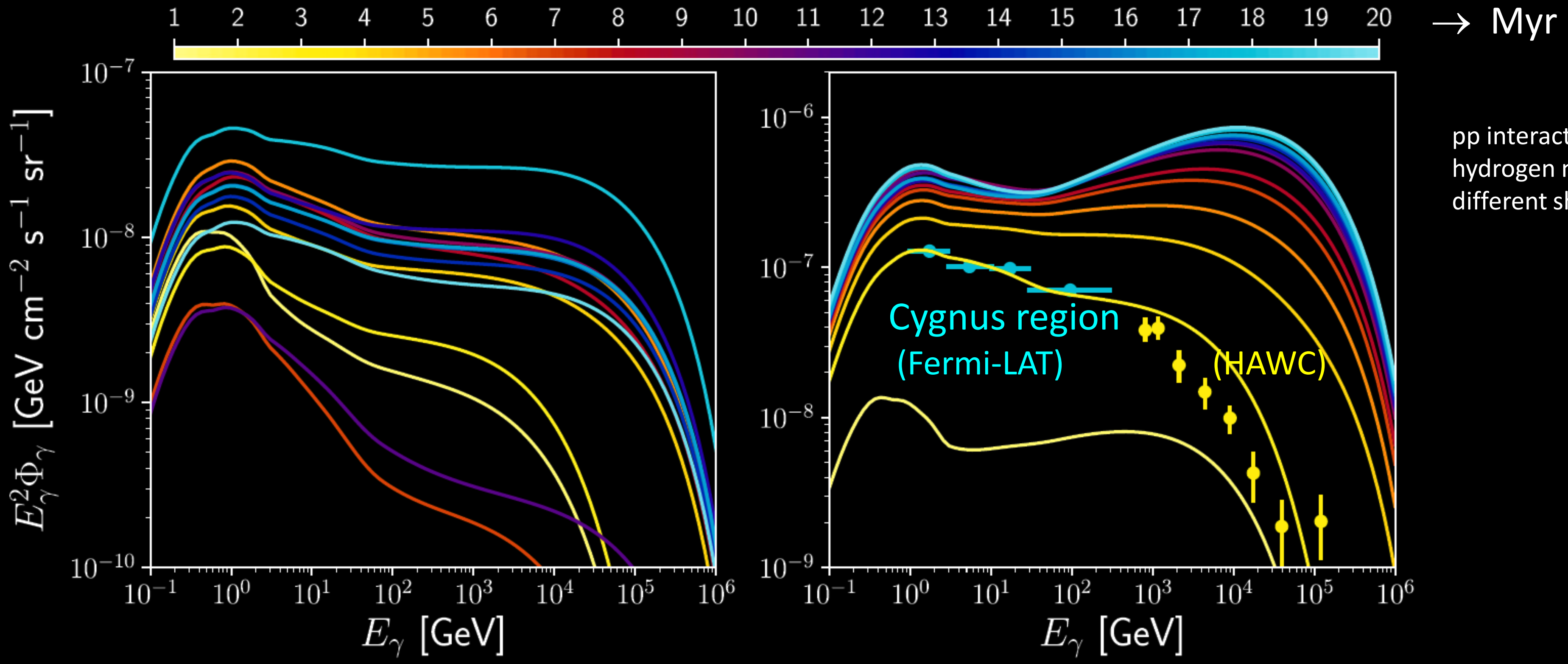
4th Aspect: Young Stellar Clusters



4^{th} Aspect: Young Stellar Clusters

There is plenty of literature on particle acceleration in superbubbles (Bykov, Parizot, Marcowith, Vieu, …)

Most recent refinements predict that there is no universal spectrum to be expected (Vieu et al. 2022):

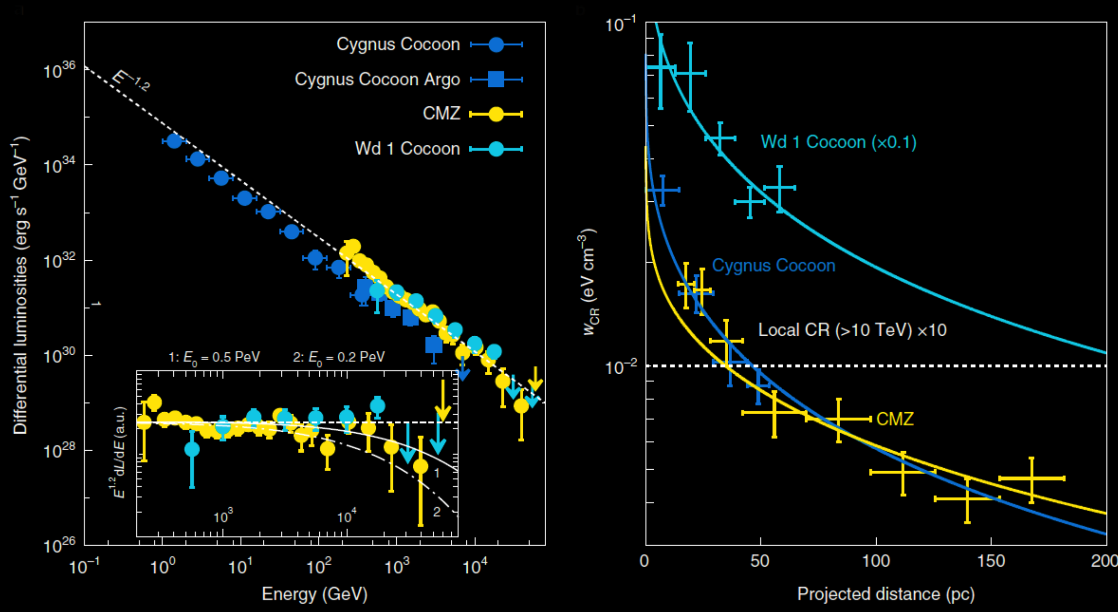


pp interactions in a superbubble shell of hydrogen n_H = 40 cm $^{-3}$ (n_{ISM} = 10 cm $^{-3}$) , for different shell confinements

4th Aspect: Young Stellar Clusters

Revitalized interest given coincidences with enigmatic gamma-ray sources at GeV and TeV.

Aharonian et al. 2019



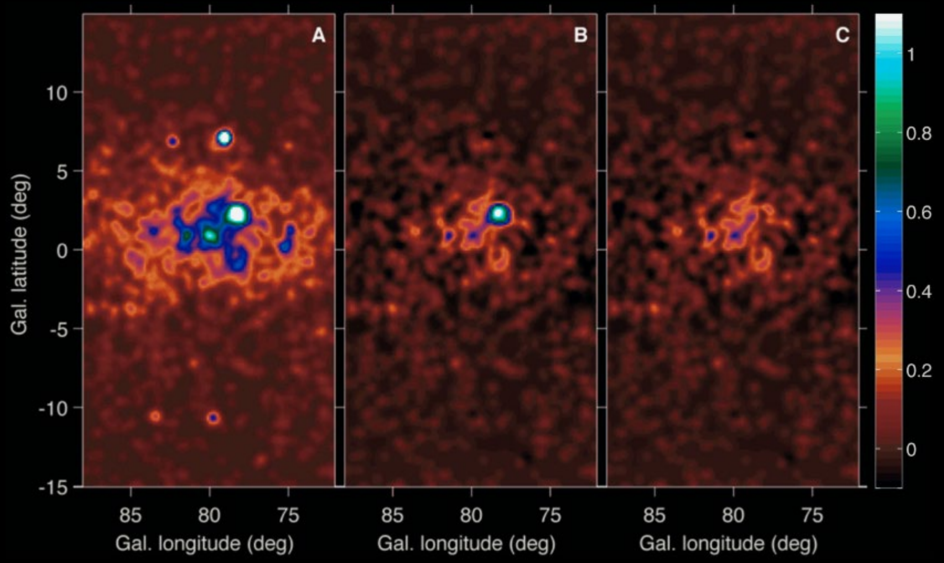
Massive stars as major factories of Galactic cosmic rays

Felix Aharonian[1,2,3,7], Ruizhi Yang[2,7]* and Emma de Oña Wilhelmi[4,5,6,7]

The identification of the main contributors to the locally observed fluxes of cosmic rays is a prime objective in the resolution of the long-standing enigma of the source of cosmic rays. We report on a compelling similarity of the energy and radial distributions of multi-TeV cosmic rays extracted from observations of very-high-energy γ-rays towards the Galactic Centre and two prominent clusters of young massive stars, Cygnus OB2 and Westerlund 1. We interpret this resemblance as evidence that cosmic rays responsible for the diffuse very-high-energy γ-ray emission from the Galactic Centre are accelerated by the ultracompact stellar clusters located in the heart of the Galactic Centre. The derived 1/r decrement of the cosmic ray density with the distance from a star cluster is a distinct signature of continuous cosmic ray injection into the interstellar medium over a few million years. The lack of brightening of the γ-ray images towards the stellar clusters excludes the leptonic origin of γ-ray radiation. The hard, $\propto E^{-2.3}$-type, power-law energy spectra of parent protons continues up to ~1 PeV. The efficiency of conversion of the kinetic energy of stellar winds to cosmic rays can be as high as 10%, implying that young massive stars may operate as proton PeVatrons with a dominant contribution to the flux of the highest-energy Galactic cosmic rays.

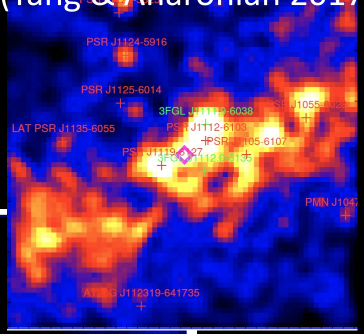
!!

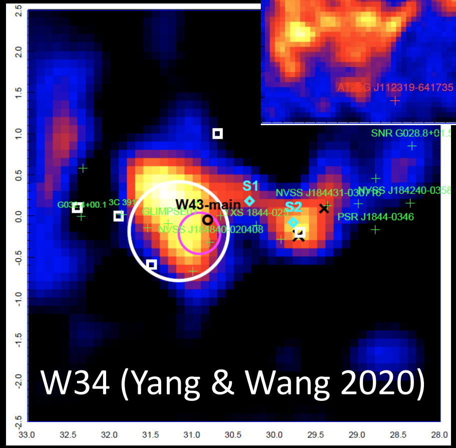
4th Aspect: Young Stellar Clusters



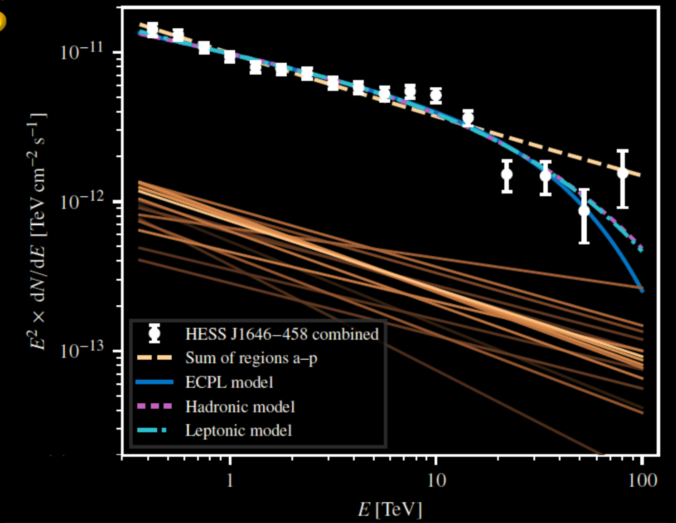
Cygnus X (Ackermann et al. (Fermi-LAT) 2011)

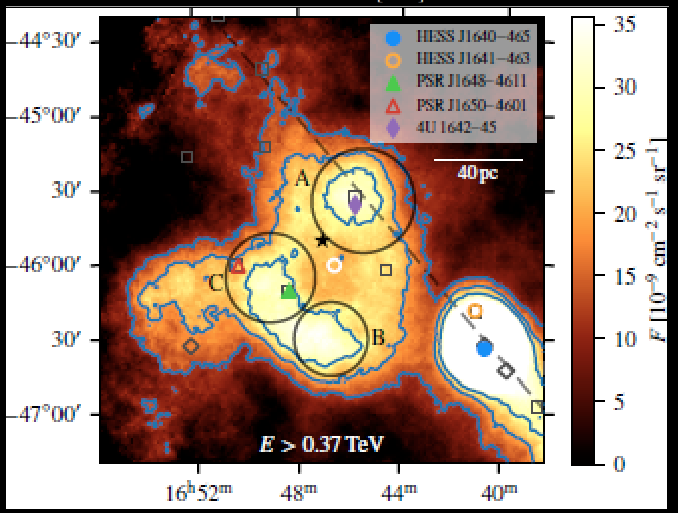
NGC 3603 (Yang & Aharonian 2017)





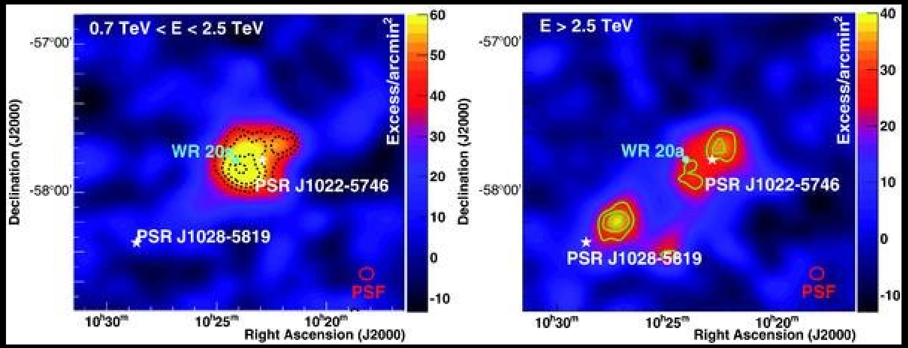
W34 (Yang & Wang 2020)

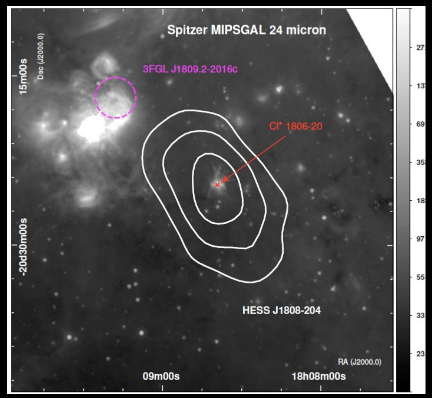




Westerlund 1 (Abdalla et al. (H.E.S.S.) 2022)

RCW49 / Westerlund 2 (Abramowski et al. (H.E.S.S.) 2011)



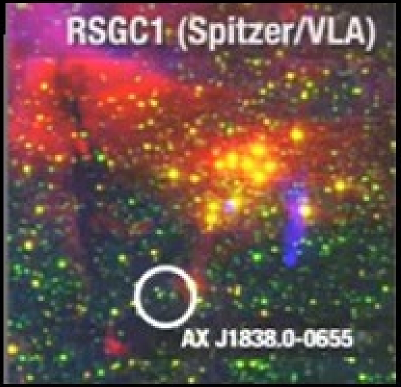


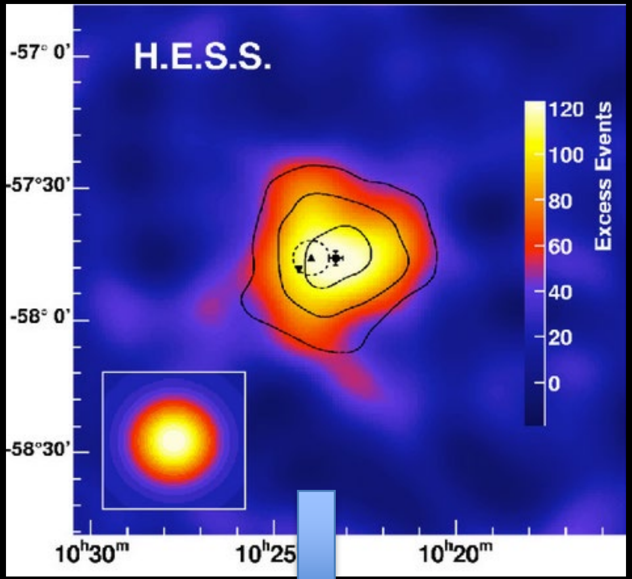
Cl* 1806-20 (Abdalla et al. (H.E.S.S.) 2018)

4th Aspect: Young Stellar Clusters

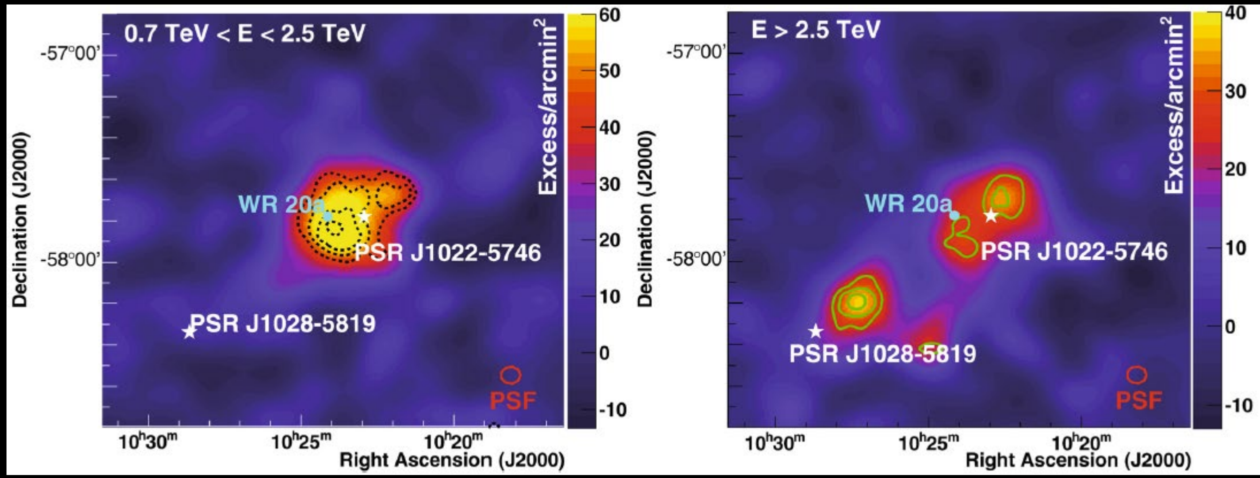
…but there are associations of neutron stars with massive star clusters

Ben Davies 2011





Westerlund 2, H.E.S.S. 2007



Westerlund 2, H.E.S.S. 2011

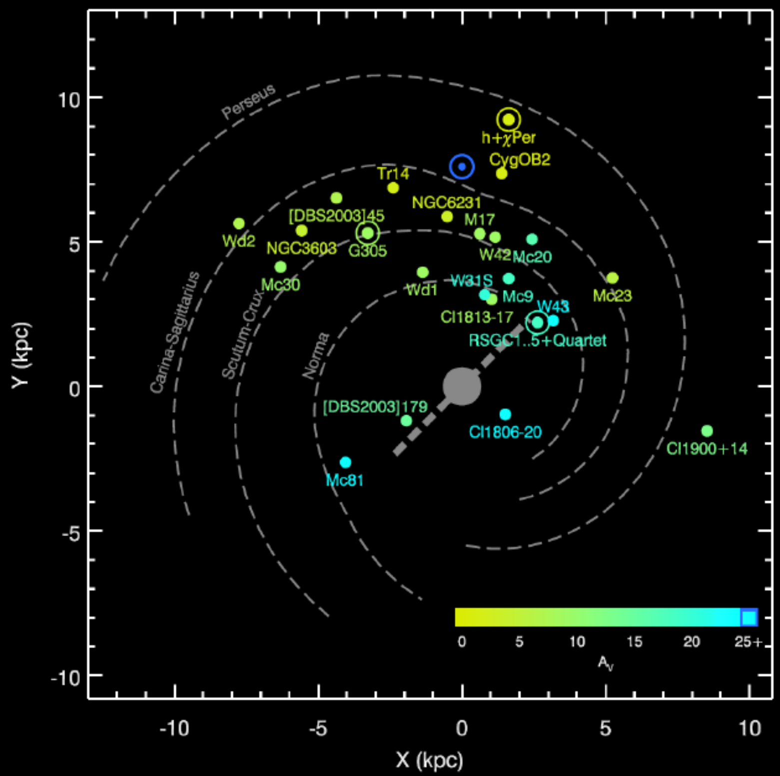
Note: There are now 286 pulsars in the upcoming 3PC from Fermi-LAT.
Pulsars (established through timing) are still a rariety at VHE.

4th Aspect: Young Stellar Clusters

About time to look if this becomes a consistent picture.

- order-parameter for translating stellar cluster properties into gamma-ray luminosity
- consistency among observations of already detected stellar clusters
- consistency of gamma-ray flux / limits and broadband stellar cluster properties
- analysis based on comparable Fermi-LAT exposure baseline (13 years)

$\rightarrow$ Bourriche et al., in progress



Ben Davies 2011

Summary & Outlook

- **There is an incredible diversity and richness in the Galactic γ-ray sky!**
  ☞ many sources, many source classes, even different phenomena within sources classes; not too much transients, though
  ☞ unassociated sources (angular resolution, no or too many MWL counterparts)

- We prepare still conservatively for early CTA science. Analysis & interpretation challenges will be non-generic once high-quality data will be taken.
  ☞ obstacle for extension/morphology measurements will be diffuse emission (both from unresolved source contribution and from classic diffuse processes from CR interactions with matter and radiation fields) - *we got a good taste from Geminga PWN halo already (although mildly since being in anticenter region)*
  ☞ New physics challenges all around (near source diffusion different? Galactic wind in inner Galaxy different? Individual vs. collective processes? SNR paradigm for galactic CRs? …)

- constraints from best-observed individual sources towards population physics
  ☞ Fermi-LAT went this way already
  ☞ Limit from systematics in analysis will increasingly encounter systematics/degeneration from modeling/interpretation

Discovery space, however, opens up at sensitivity limit / end of dynamic range of present instrumentation. CTA unlikely to plough a lonely furrow!