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CSIC IEEC

High Energy Emission from Compact Objects

Emma de Oña Wilhelmi
Ramon y Cajal Fellow
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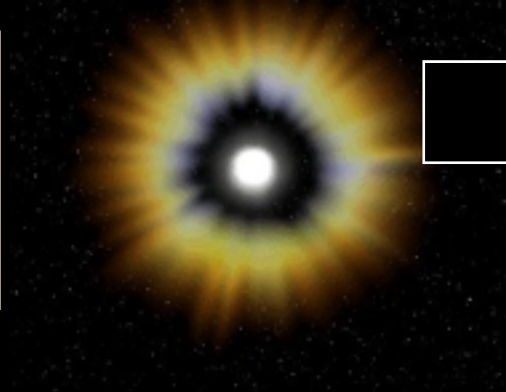
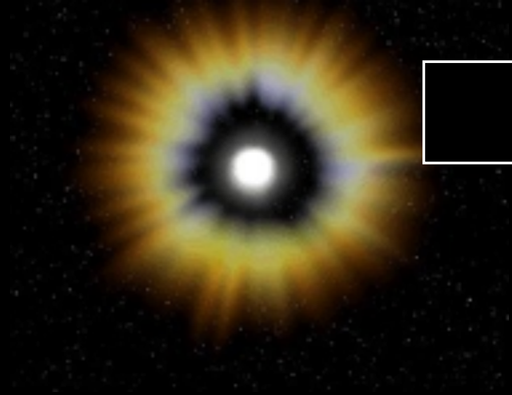
TeVPA 2017 7-11 August, Columbus, Ohio

COMPACT OBJECTS



Massive Star



Massive Star

Massive Star

Binary?

yes

Compact companion?

no

Massive companion?

Massive Star

Binary?

yes

Compact companion?

no

Massive companion?

Colliding wind sys.

e.g. Eta Carina

Massive Star

Binary?

yes

Compact companion?

no

Massive companion?

yes

Neutron star?

Colliding wind sys.

e.g. Eta Carina

Massive Star

Binary?

yes

Compact companion?

no

Massive companion?

Colliding wind sys.

e.g. Eta Carina

yes

Neutron star?

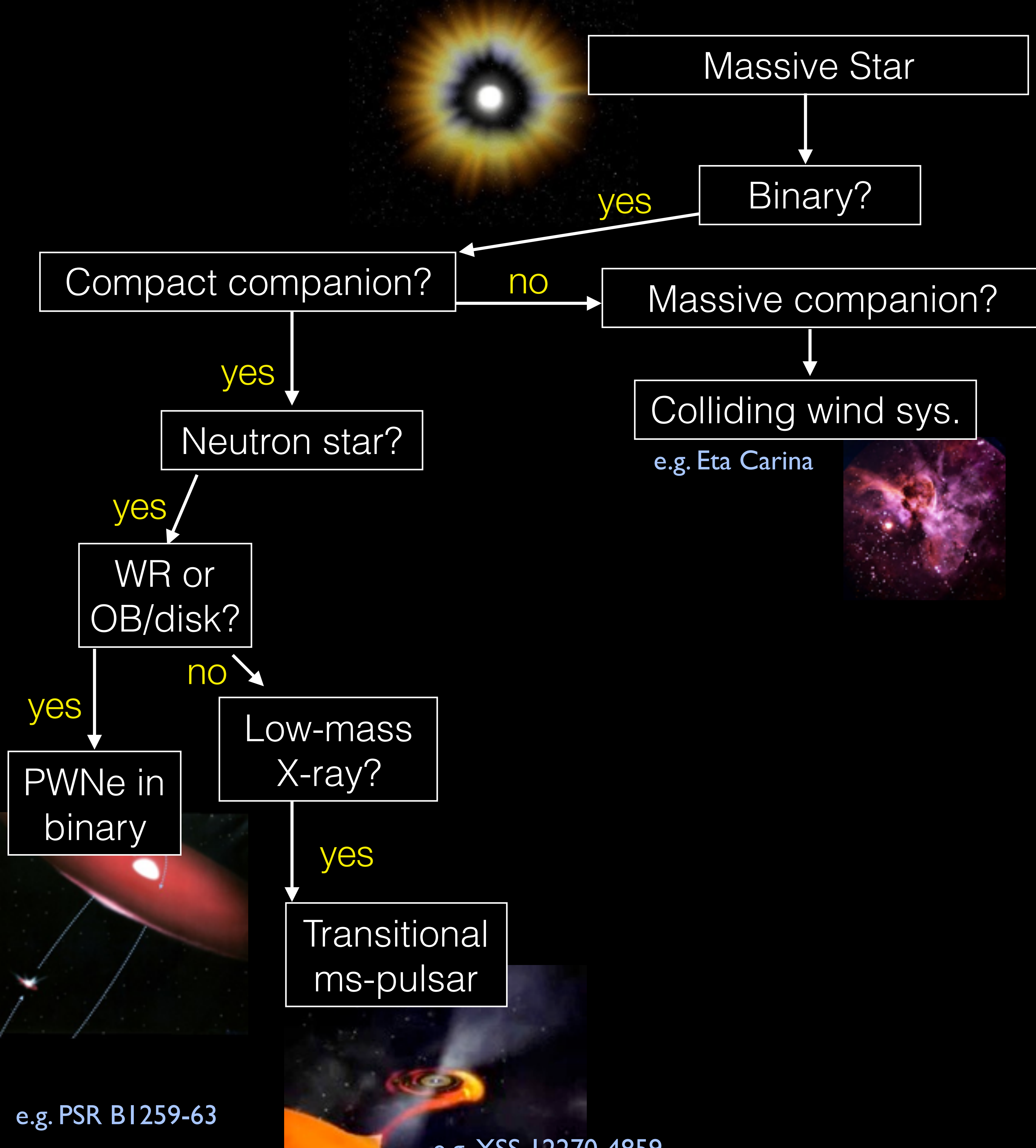
yes

WR or OB/disk?

yes

PWNe in binary

e.g. PSR B1259-63


Massive Star
Binary?
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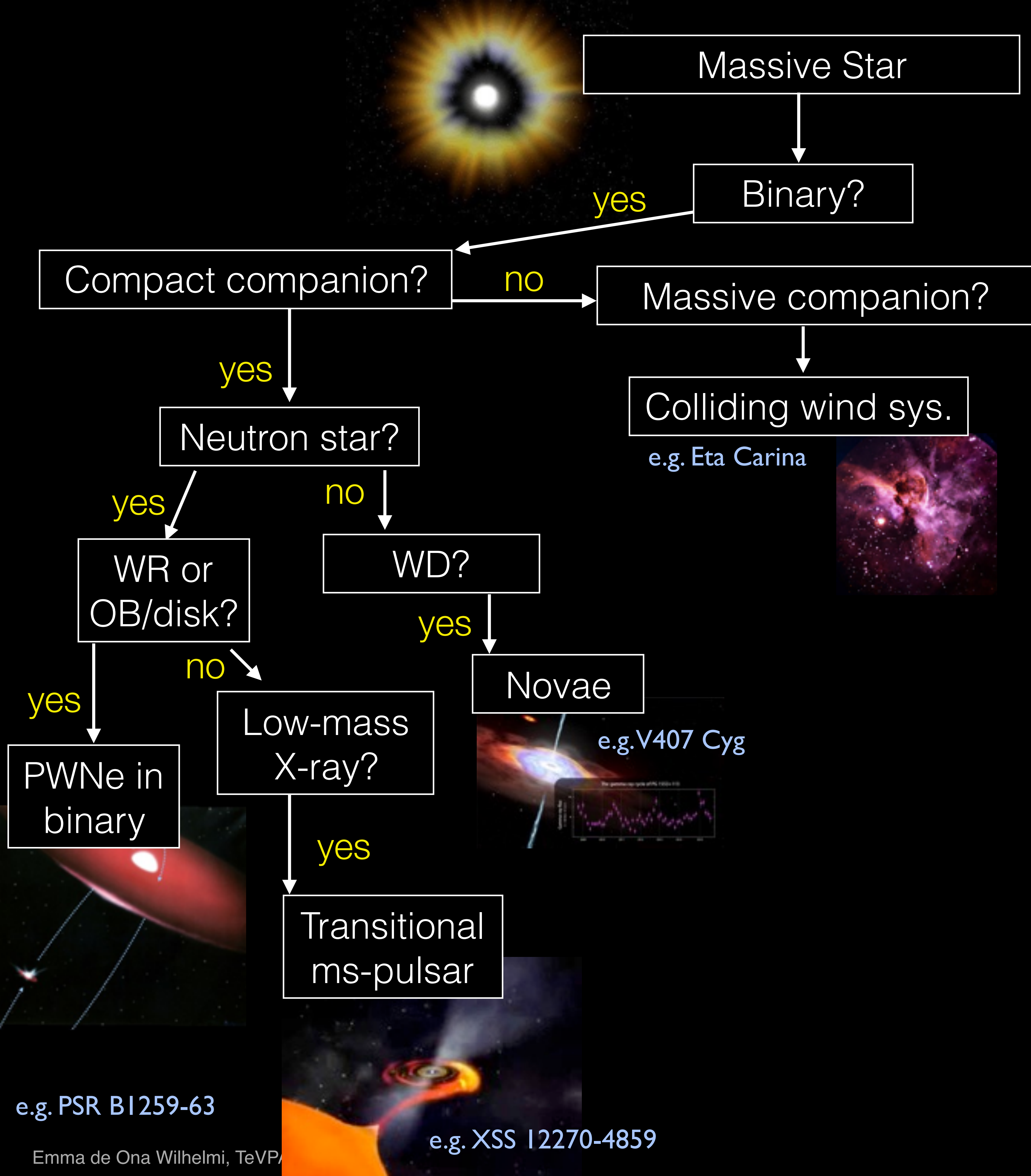
Compact companion?
no
Massive companion?
Colliding wind sys.
e.g. Eta Carina
yes
Neutron star?
yes
WR or OB/disk?
no
yes
PWNe in binary
Low-mass X-ray?
yes
Transitional ms-pulsar
e.g. PSR B1259-63
e.g. XSS 12270-4859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WD?
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Novae
e.g.V407 Cyg
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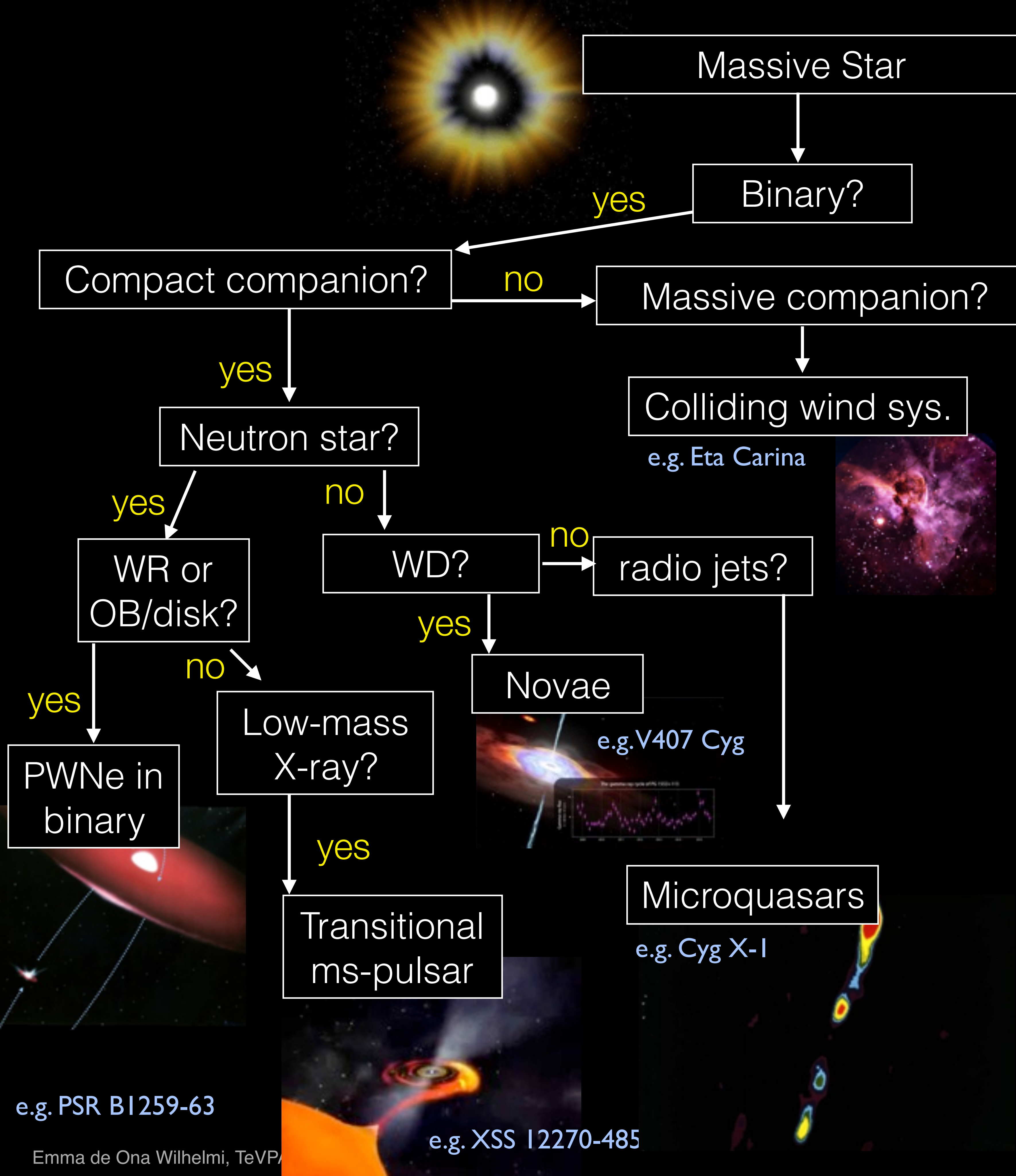
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no
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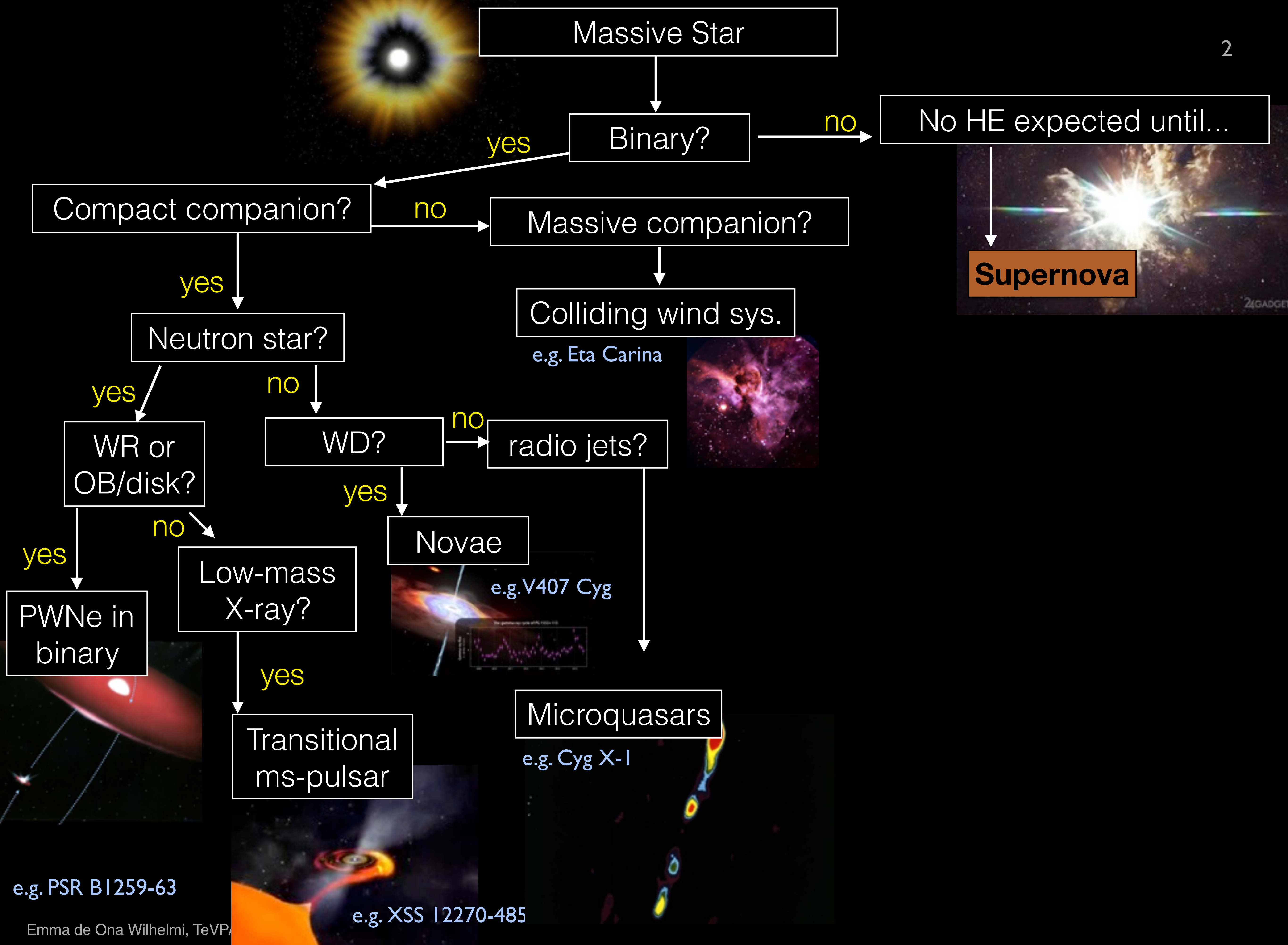
Low-mass X-ray?
PWNe in binary
yes
Transitional ms-pulsar
Microquasars
e.g. Cyg X-1
e.g. PSR B1259-63
e.g. XSS 12270-485


Massive Star
Binary?
no
No HE expected until...
Supernova
yes
Compact companion?
no
Massive companion?
Colliding wind sys.
e.g. Eta Carina
yes
Neutron star?
yes
no
WR or OB/disk?
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yes
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e.g.V407 Cyg
no
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Low-mass X-ray?
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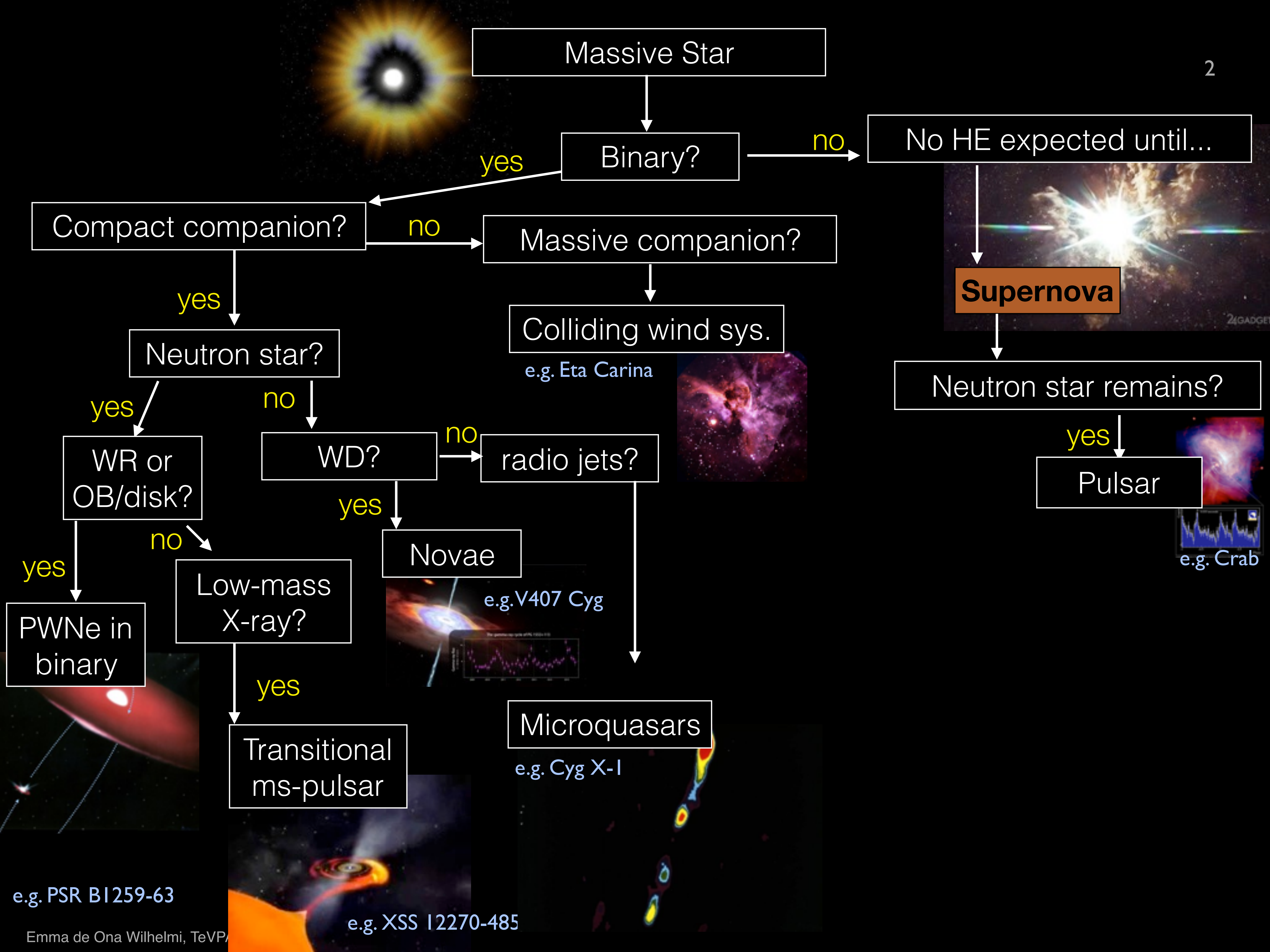
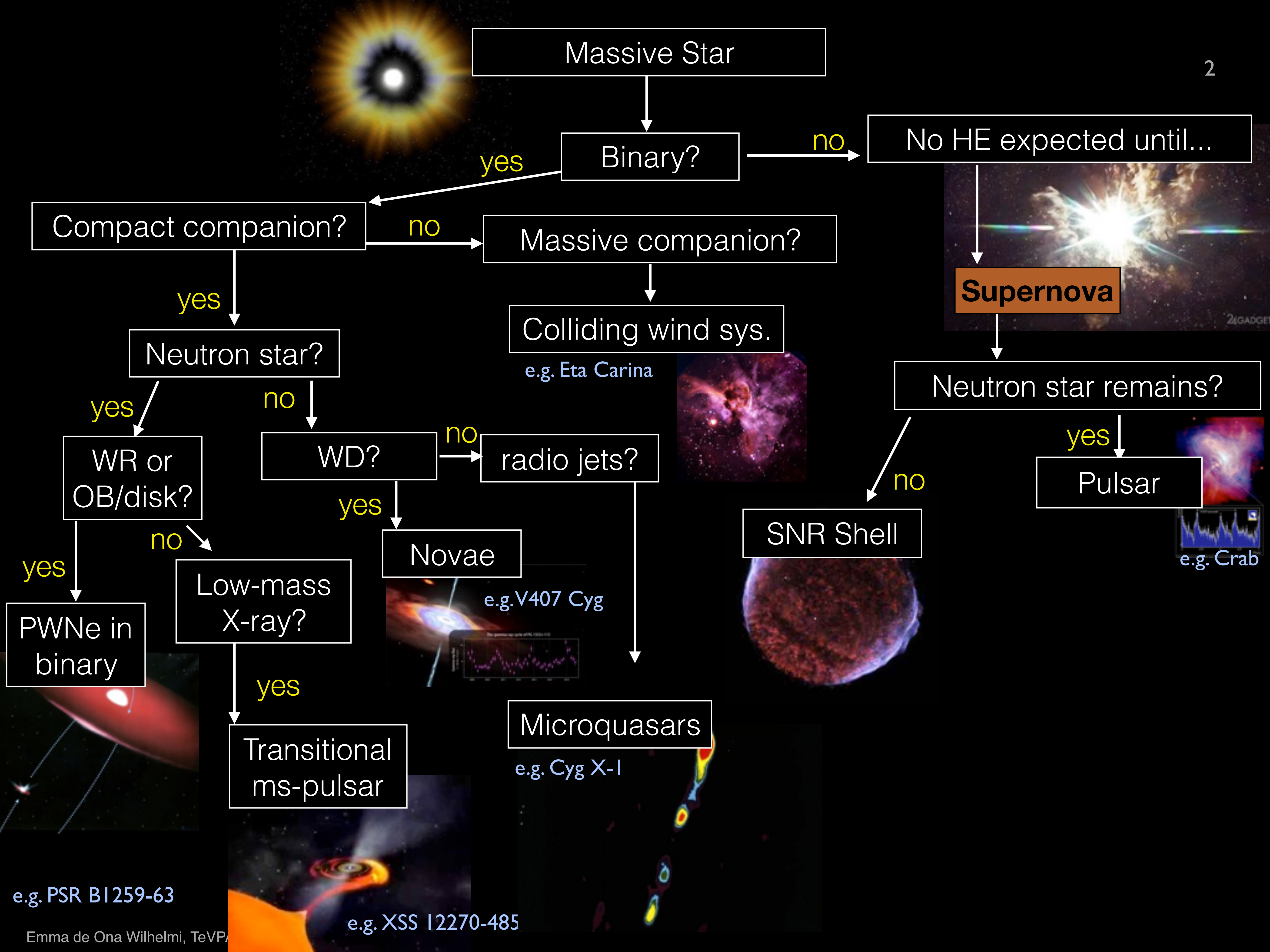

Massive Star
Binary?
no
No HE expected until...
Supernova
Neutron star remains?
yes
Pulsar
e.g. Crab
yes
Compact companion?
no
Massive companion?
Colliding wind sys.
e.g. Eta Carina
yes
Neutron star?
yes
no
WR or OB/disk?
WD?
no
radio jets?
yes
Novae
e.g. V407 Cyg
yes
no
PWNe in binary
e.g. PSR B1259-63
Low-mass X-ray?
yes
Transitional ms-pulsar
e.g. XSS 12270-485
Microquasars
e.g. Cyg X-1
Emma de Ona Wilhelmi, TeVP


Massive Star
2
Binary?
no
No HE expected until...
yes
Compact companion?
no
Massive companion?
Supernova
yes
Colliding wind sys.
Neutron star?
e.g. Eta Carina
Neutron star remains?
yes
no
WR or OB/disk?
WD?
no
radio jets?
yes
Pulsar
no
yes
no
SNR Shell
yes
Novae
e.g. Crab
Low-mass X-ray?
e.g. V407 Cyg
PWNe in binary
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Microquasars
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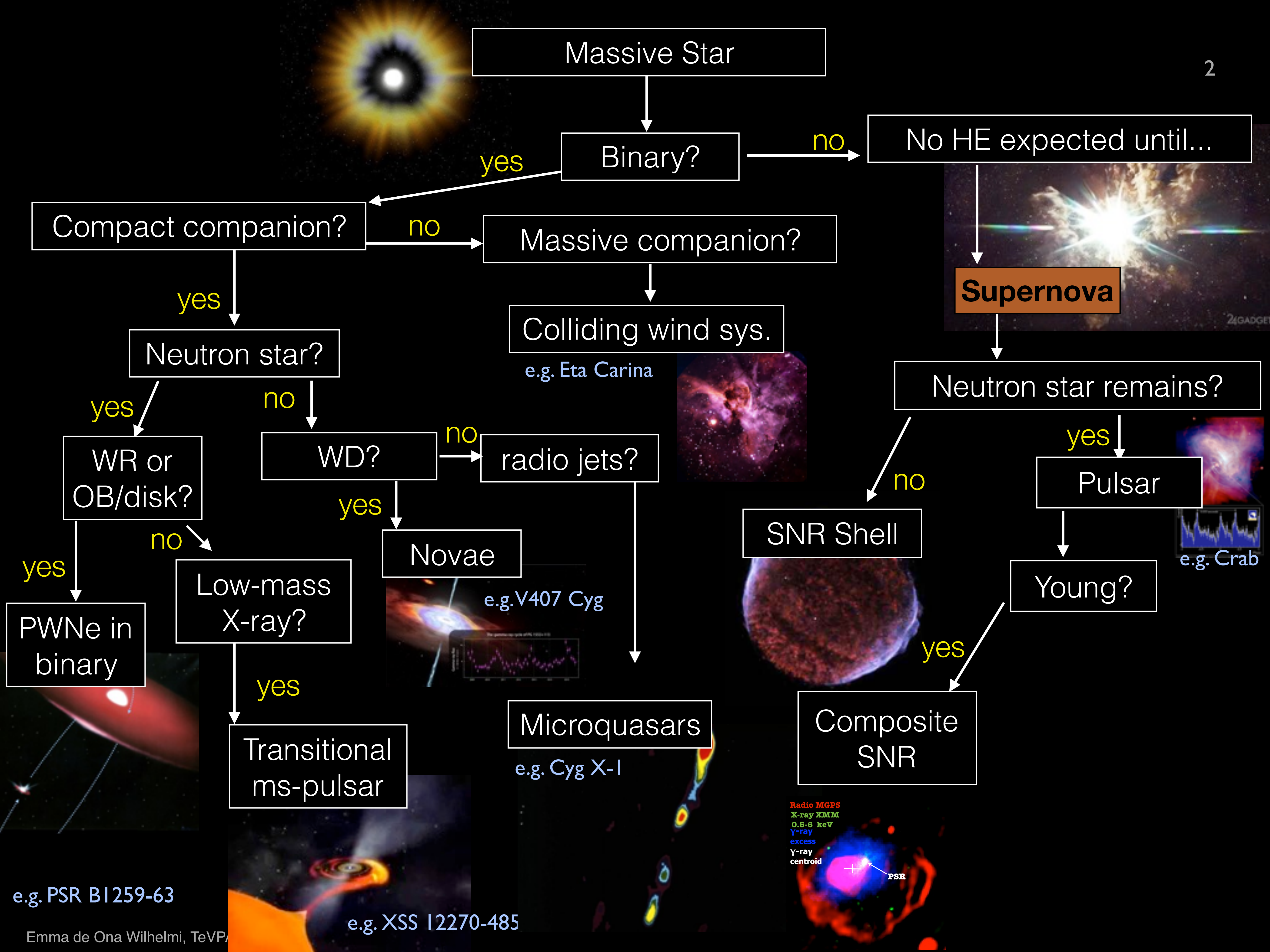
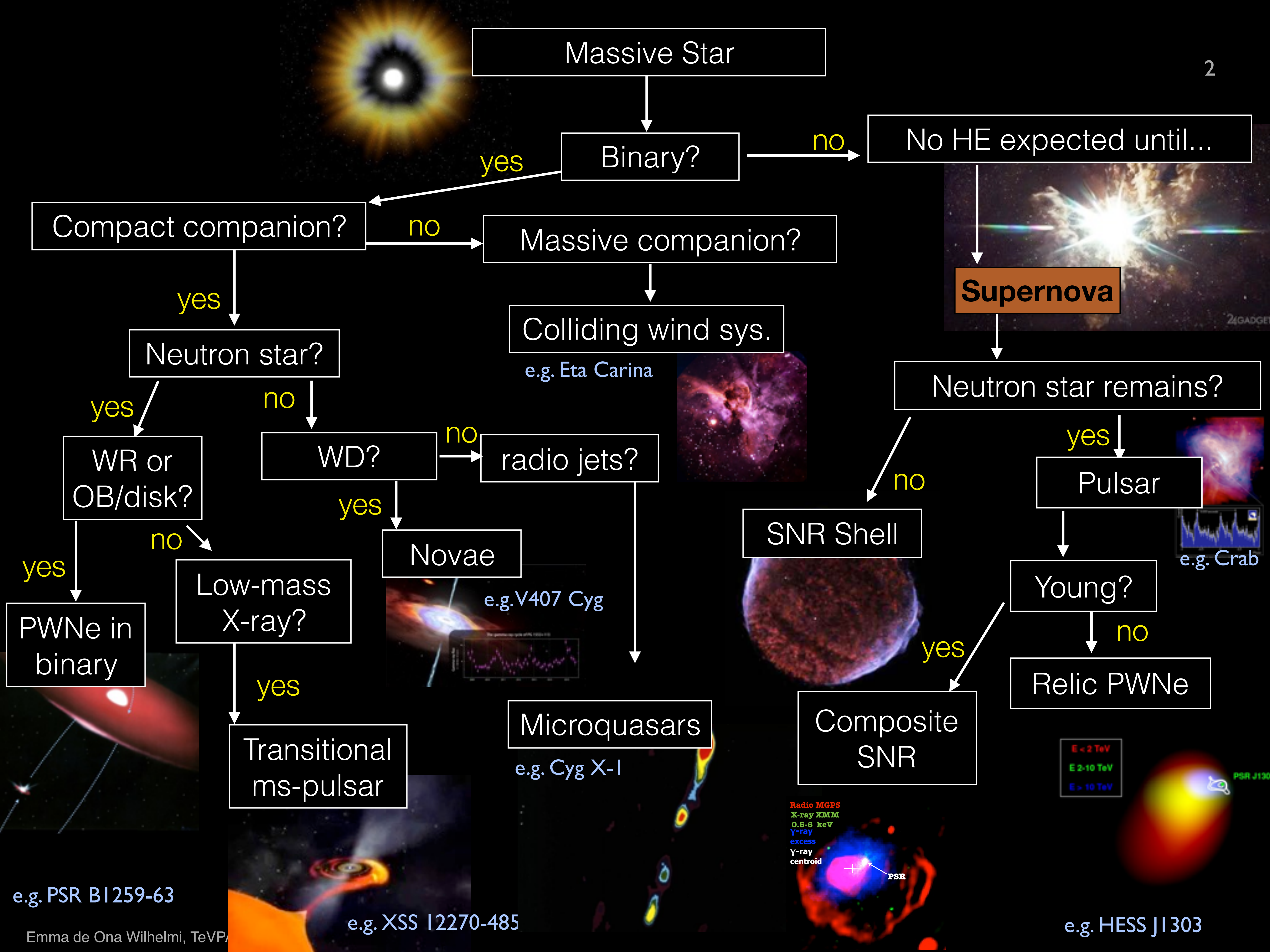


2
Massive Star
Binary?
no
No HE expected until...
yes
Compact companion?
no
Massive companion?
Supernova
yes
Colliding wind sys.
e.g. Eta Carina
Neutron star?
Neutron star remains?
yes
no
WR or OB/disk?
WD?
no
radio jets?
yes
no
Pulsar
yes
SNR Shell
no
Novae
yes
Young?
e.g. Crab
yes
Low-mass X-ray?
e.g. V407 Cyg
PWNe in binary
yes
yes
Composite SNR
Transitional ms-pulsar
Microquasars
e.g. Cyg X-1
Radio MGPS
X-ray XMM 0.5-6 keV
γ-ray excess
γ-ray centroid
PSR
e.g. PSR B1259-63
e.g. XSS 12270-485
Emma de Ona Wilhelmi, TeVPA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e.g. Eta Carina
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WR or OB/disk?
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Pulsar
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e.g. Crab
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Young?
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PWNe in binary
no
yes
Relic PWNe
yes
Microquasars
Composite SNR
Transitional ms-pulsar
e.g. Cyg X-1
E < 2 TeV
E 2-10 TeV
E > 10 TeV
Radio MGPS
X-ray XMM
0.5-6 keV
γ-ray excess
γ-ray centroid
PSR
e.g. PSR B1259-63
e.g. XSS 12270-485
e.g. HESS J1303

HIGH ENERGIES

To radiate high-energy gamma-ray, particles (electrons and hadrons) have to be accelerated to TeV energies or more:

huge gravitational, magnetic and electric fields

very dense background radiation

relativistic bulk motions (black hole jets and pulsar winds)

shock waves (SNRs), highly excited (turbulent) media, etc...

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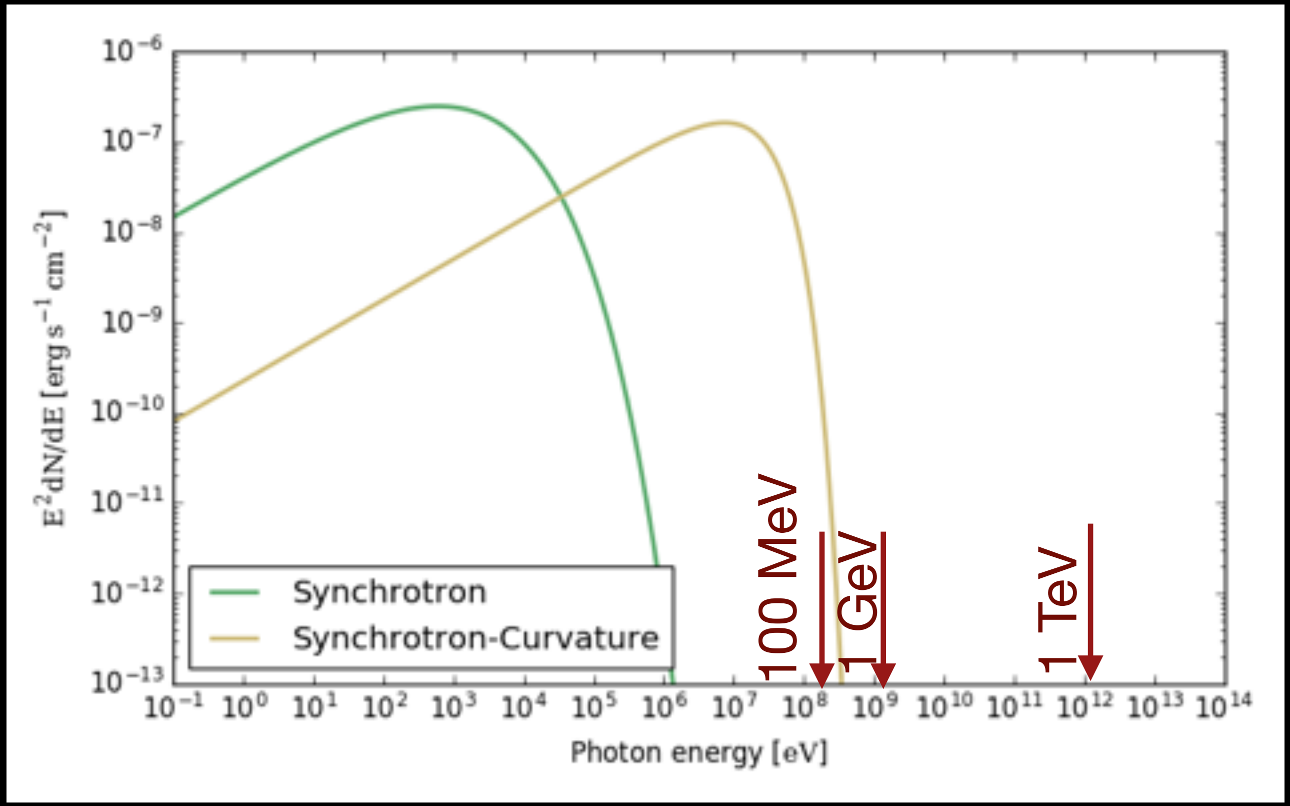

Synchrotron-Curvature

$e^{\pm} + \mathbf{B} \Rightarrow \Upsilon + e^{\pm}_{lowerE}$

Pulsars, Binaries, uQuasars…

Bremsstrahlung: e N(e) → e' γN(e) Eγ~1/2 Ee
Pair Production: γN(e) → e+e- N(e)
e+e- annihilations: e+e- → γ γ (511 keV line)

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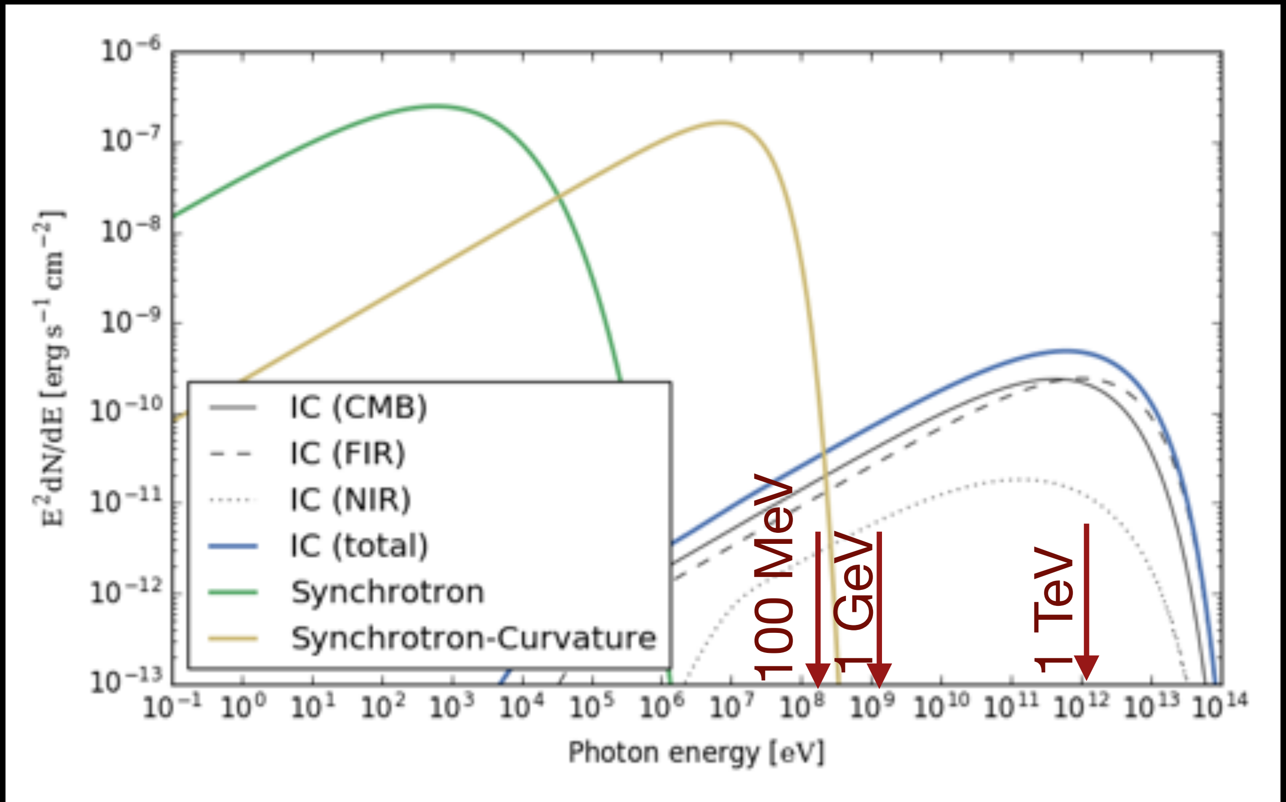

Inverse Compton

$e^{\pm}_{HE} + \Upsilon_{LE} \Rightarrow e^{\pm}_{lowerE} + \Upsilon_{LE}$

Binaries, PWNe, Pulsars!

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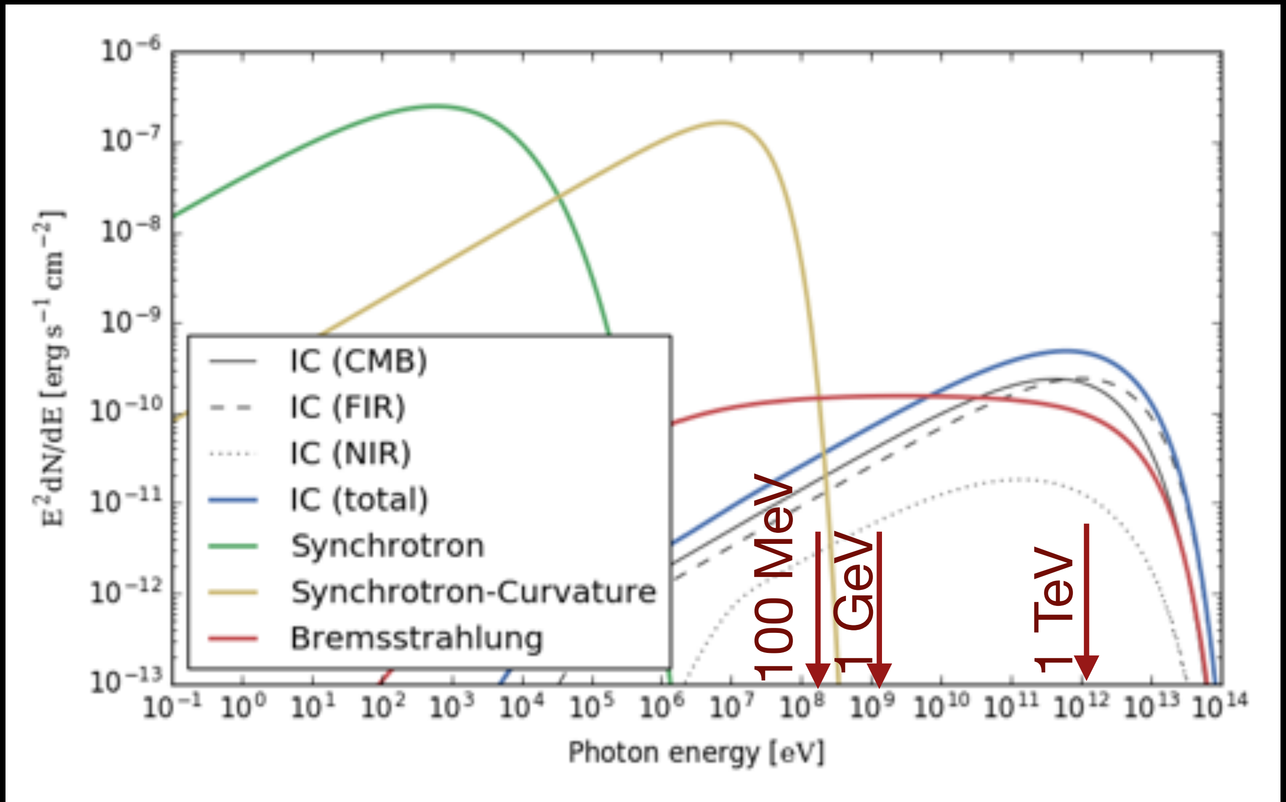

<u>Bremsstrahlung</u>

$e^{\pm} + N(e) \Rightarrow e' \gamma N(e)$

Regions of high density: Galactic Center, dense clouds

HIGH ENERGIES

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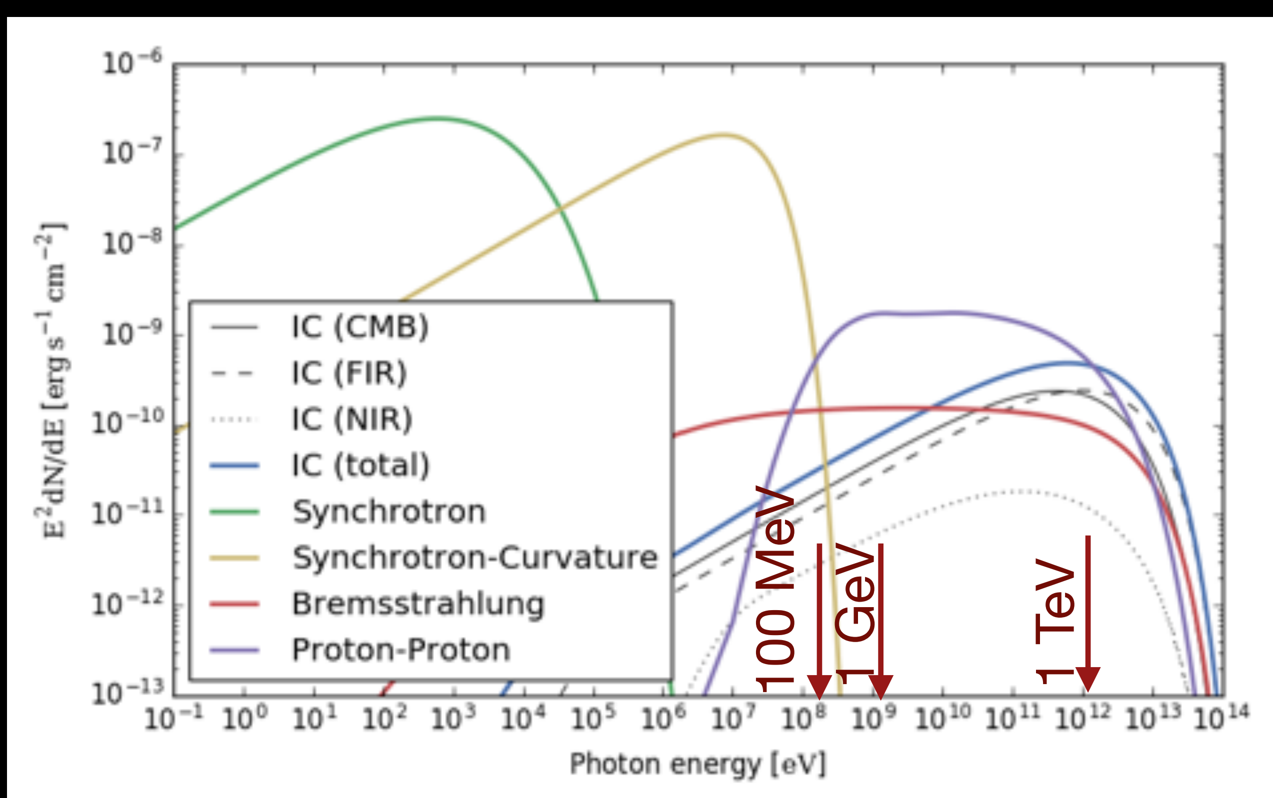


Proton-Proton

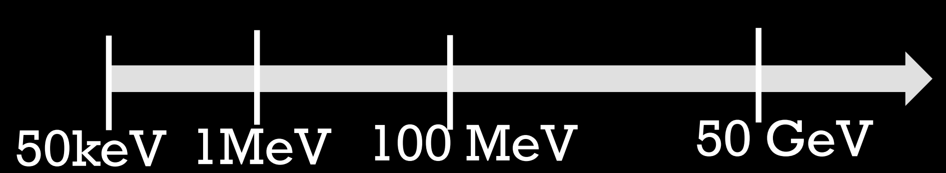
$$p + p \rightarrow \pi^0 + X + \ldots + \pi^{\pm}$$
$$\pi^0 \hookrightarrow \gamma + \gamma \qquad \pi^{\pm} \hookrightarrow \nu_\mu + \nu_e + \ldots$$

SNRs, Novae, Diffuse…

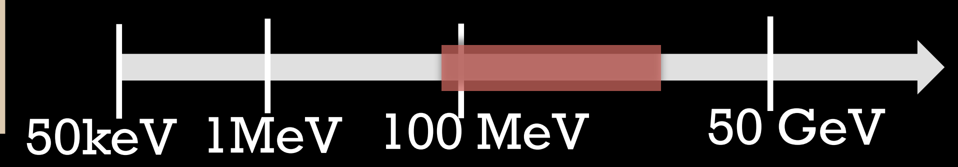
see Helzen talk at TeV PA 2017

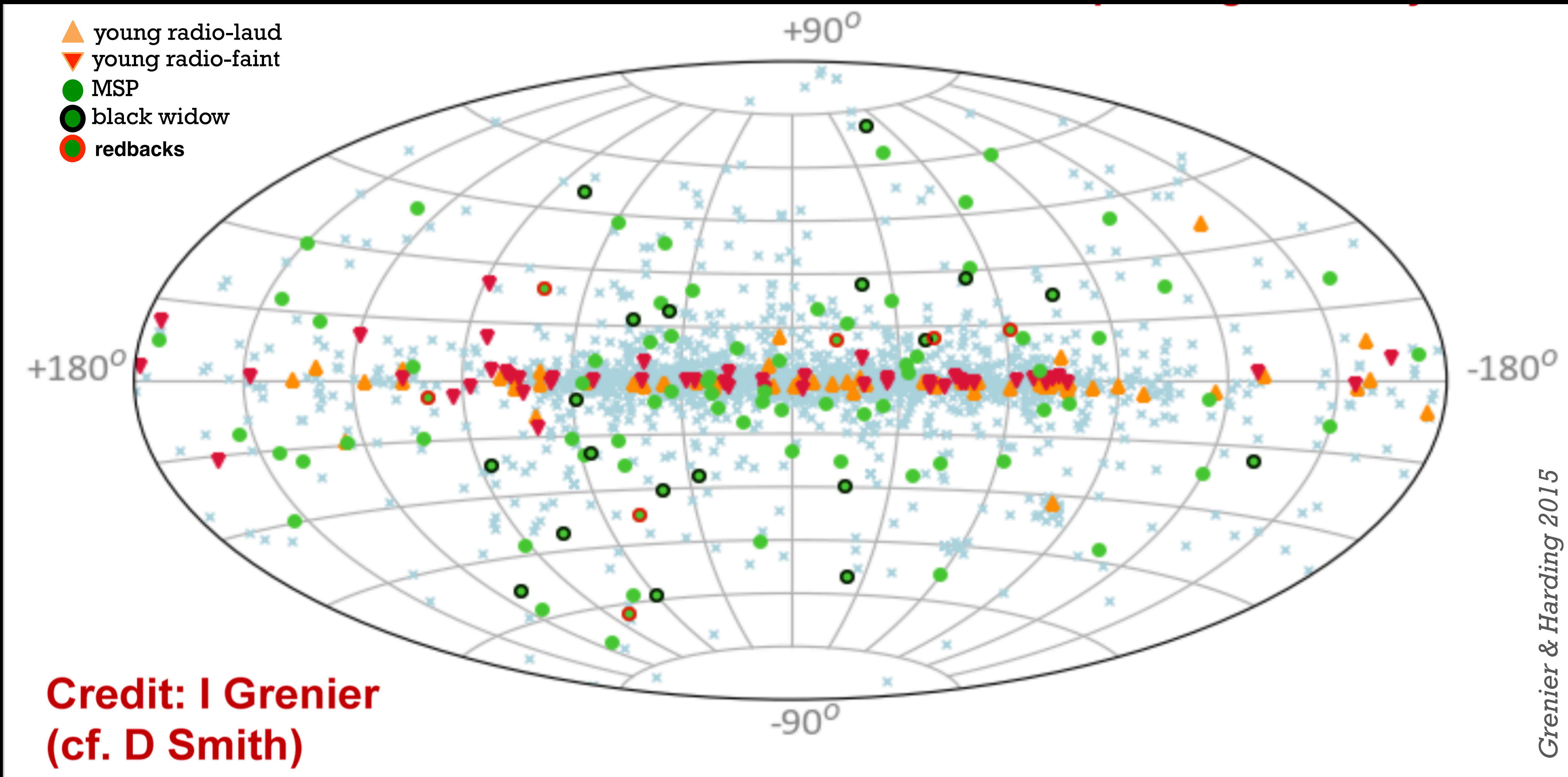
Outlook

- **Pulsars in the GeV/TeV regime**
  Neutron Stars that behave like pulsars
- **Transitional Pulsars**
  Neutron Stars that sometimes behave like pulsars, sometimes not
- **High-energy binaries**
  Neutron Stars that do not behave like pulsars
- **Novae at high-energies**
  The big cousins of Neutron Stars
- **Compact objects with jets**
  The wild cousins of Neutron Stars
- **SNRs and PWNe**
  The extended family



The Fermi-LAT Pulsar Legacy



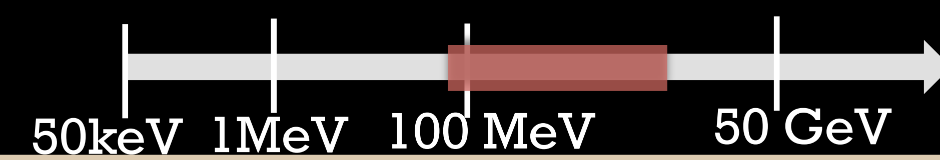


Energy	# of pulsars
Radio	~2200
Fermi, >100MeV	161
IACT, >50GeV	2

Phase folding using radio (X-ray) timing solutions
Blind periodicity searches in Fermi data:
- GW algorithms (*Plesch+2012*) + Einstein@home
- Mostly radio-quiet (*Clark+2017*) + few MSP (*Clark+2016*)

Radio follow-up of Fermi unidentified sources

Gamma-ray Pulsars



YOUNG PULSARS

Radio loud/quiet : not an intrinsic property, but a function of the viewing angle

Larger $\dot{E}$ than radio : probably selection effect

$F_\gamma \propto \dot{E}$, $10^{11}<B_{NS}<10^{14}$ G, 23% of known PSRs

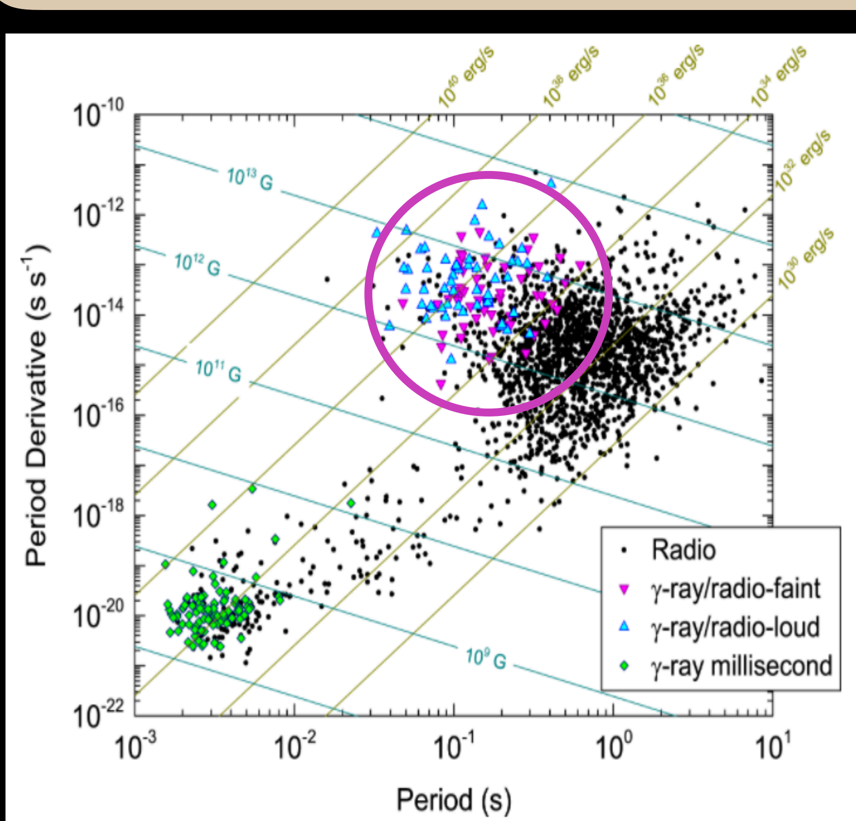
MS PULSARS

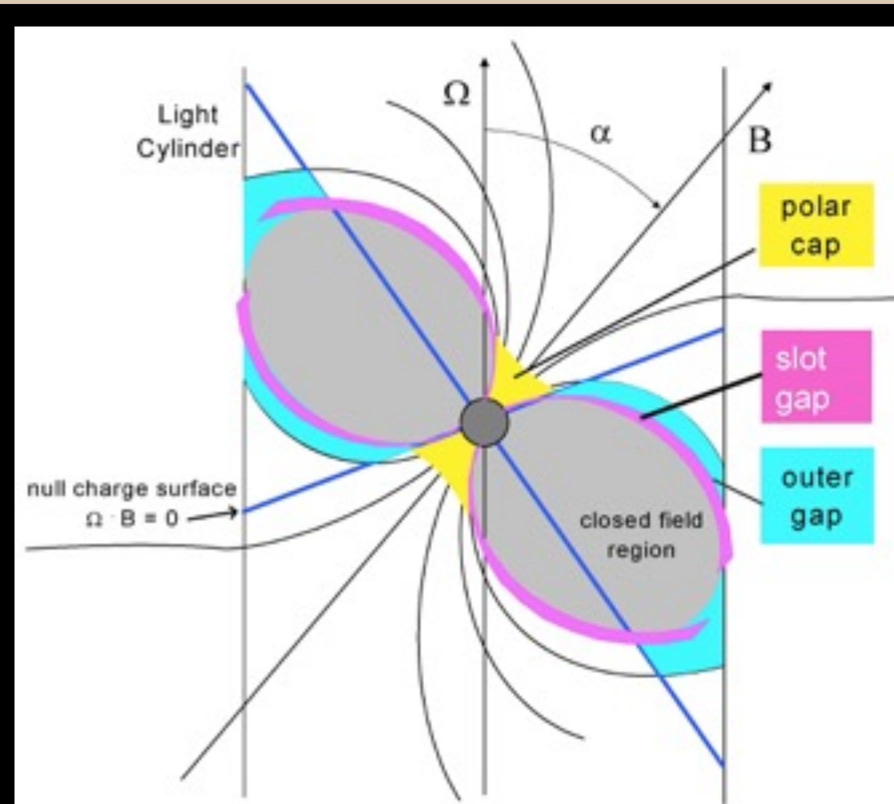
ms P spun up by accretion from a binary companion

$10^{8}<B_{NS}<10^{11}$ G

50% of the known MSP

Despite the difference in B and $\dot{E}$, similar observables





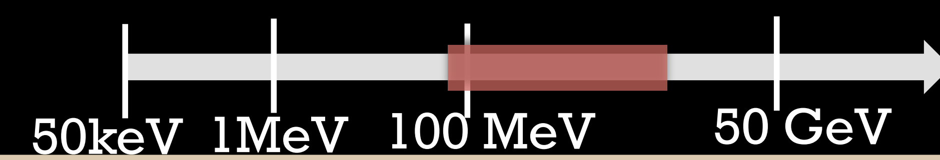
Gamma-ray properties result from:

- acceleration
- radiation
- cascading

'Gaps' where particles are accelerated:

- polar cap
- outer gap
- slot gap

Gamma-ray Pulsars



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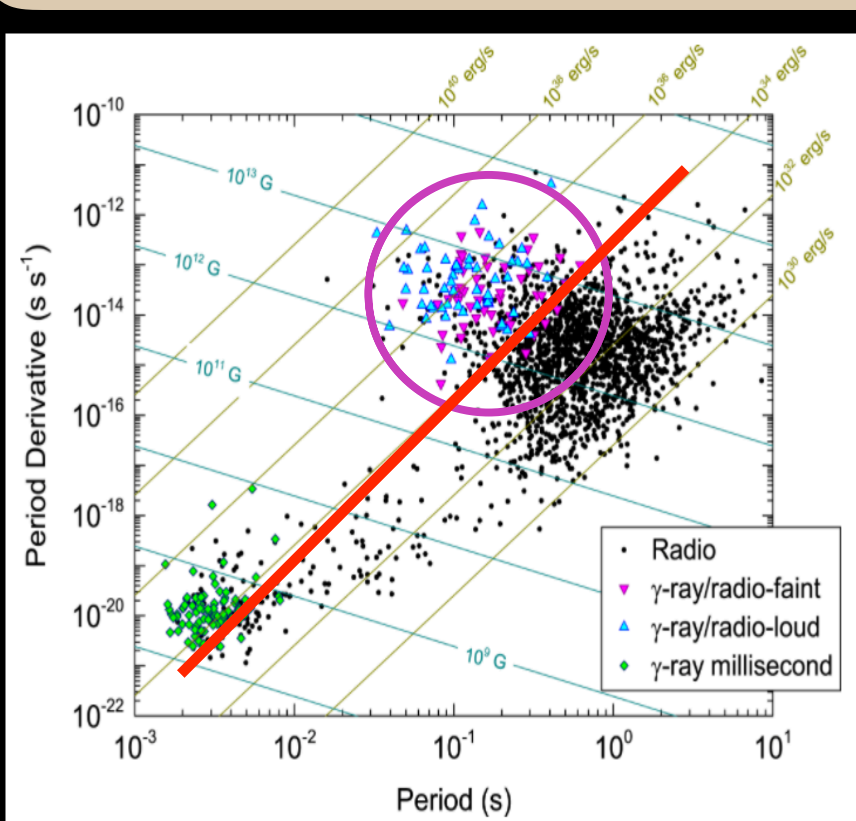

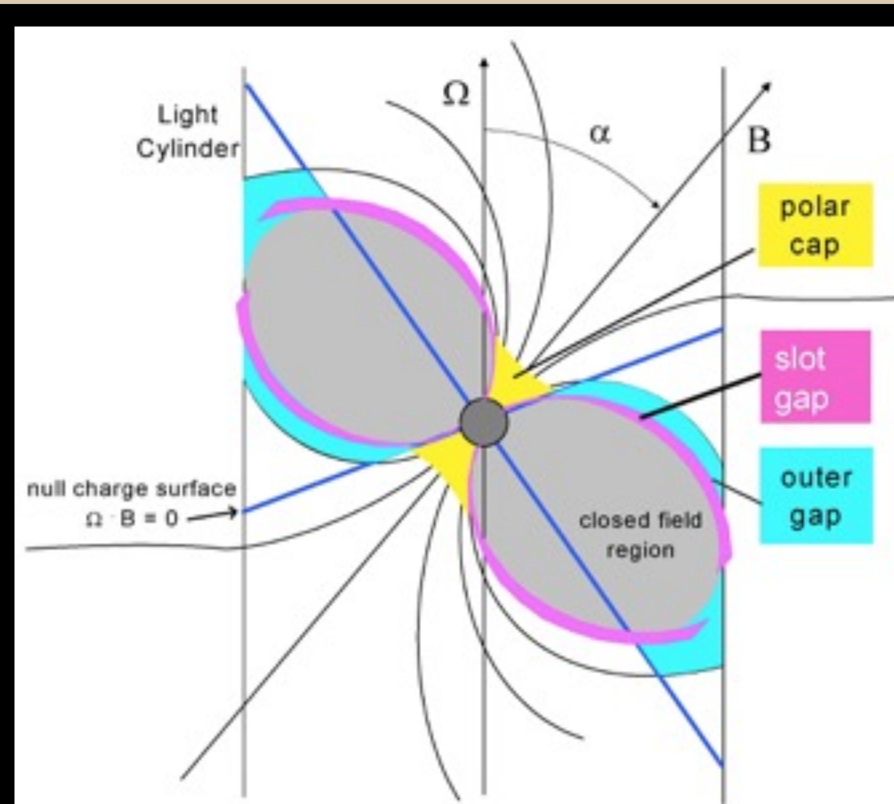

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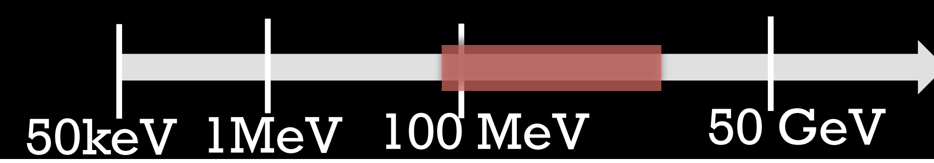
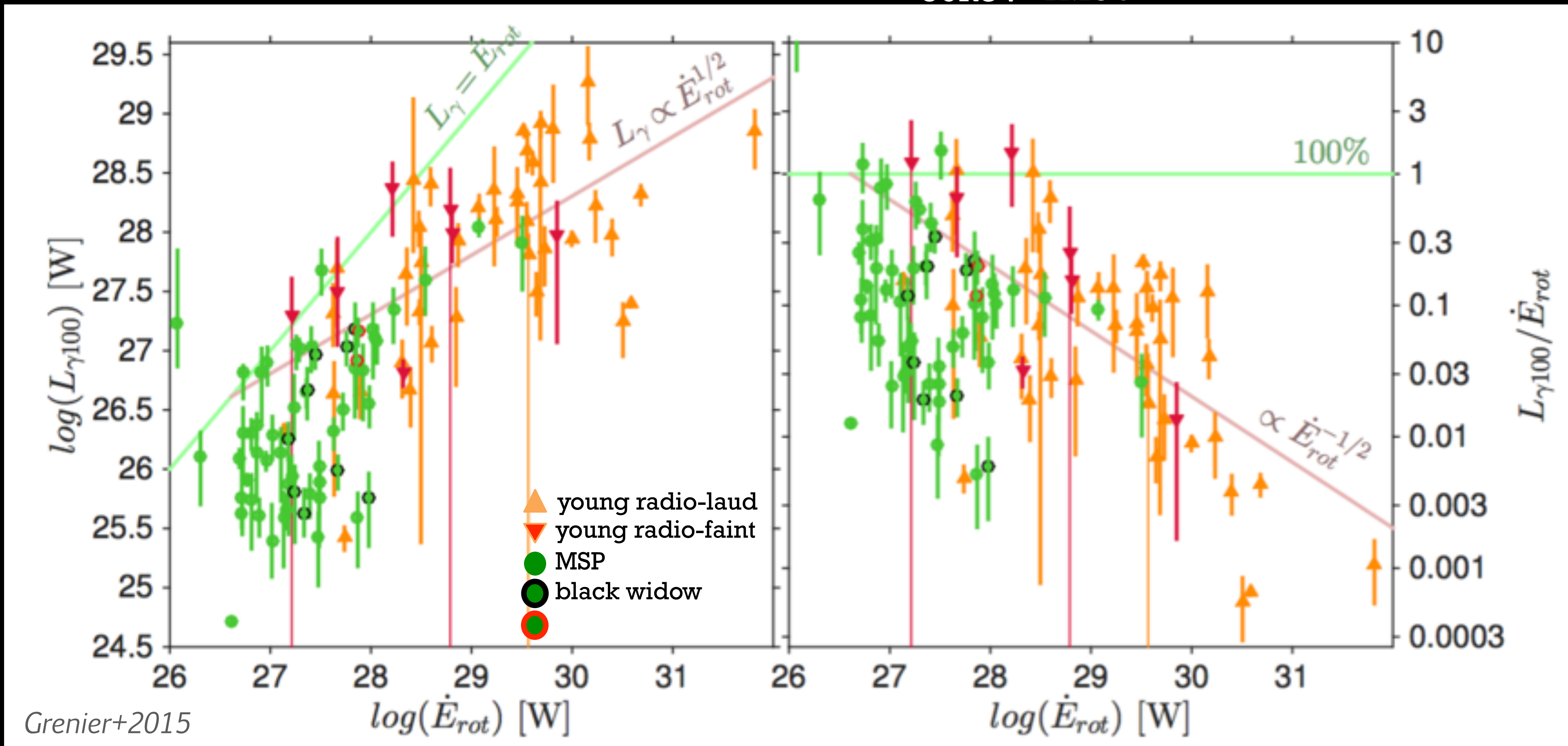
Gamma-ray Pulsars





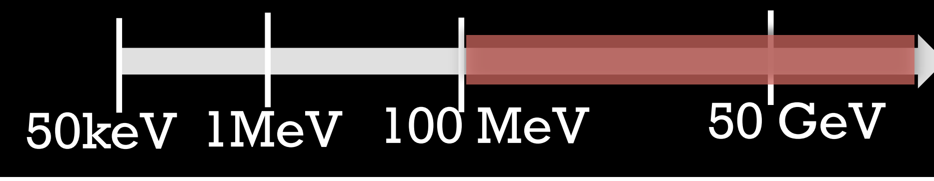
$L\gamma \sim \dot{E}_{rot}^{1/2}$ vs $L\gamma \sim \dot{E}_{rot}$: efficient screening vs pulsars with $V_o < 10^{13}$ V.

Large scattering, however data point to free-free magnetosphere (pair production)

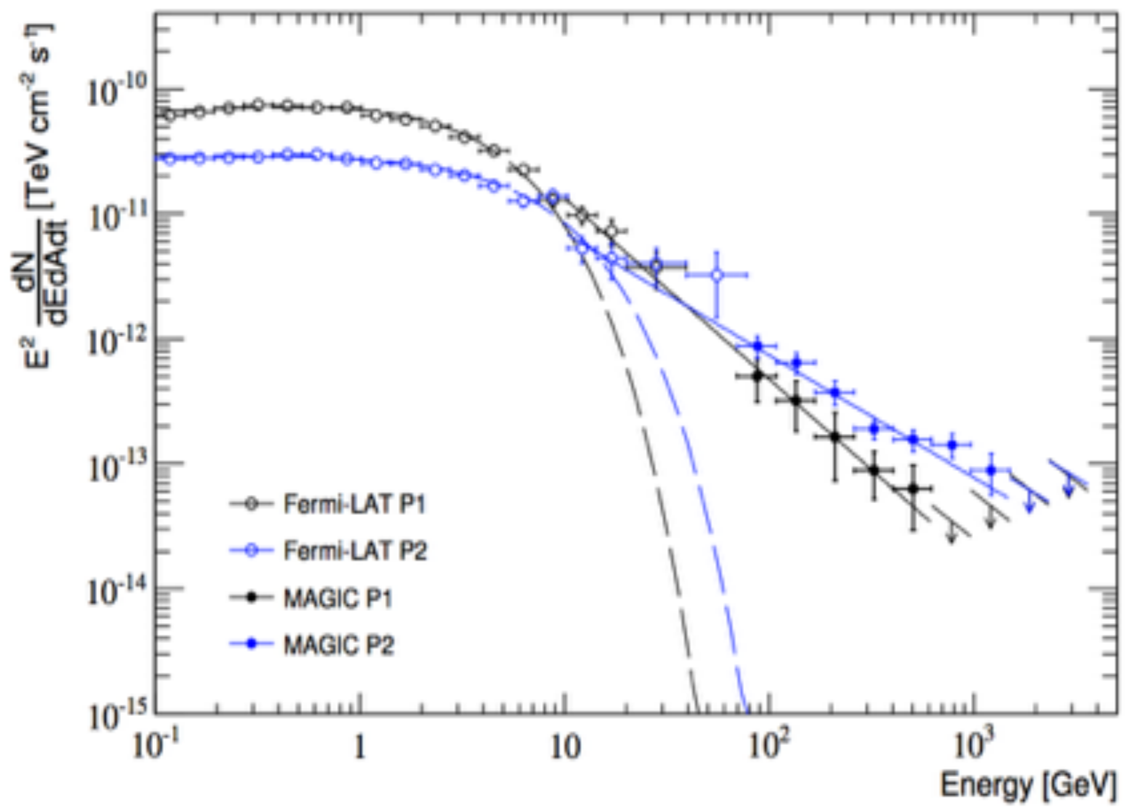
Young pulsars are more efficient when the slow down ($V_o = 6\times10^2 V (P/1s)^{-2} (B/10^8 T)$)

Old ms pulsars are the most efficient ones (>10%): large B_{field} in the outer regions of the compact MSP magnetosphere

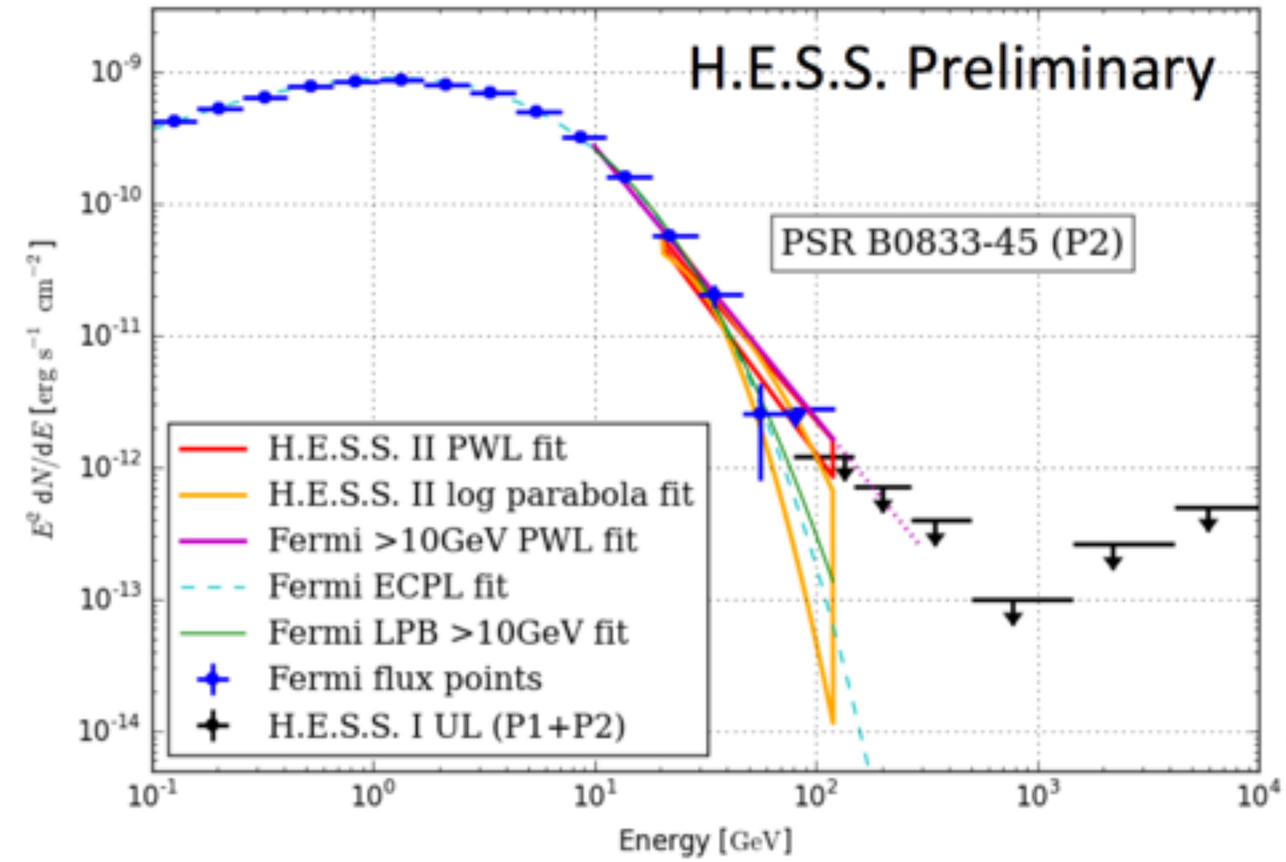
Gamma-ray Pulsars



MAGIC Coll. 2016



Fermi-LAT coll. 2010, Djannati-Atai 2017



Spectral shape due to synchro-curvature of accelerated particles along acceleration gaps

Fine spectroscopic studies result in b<1 sub-exponential cutoffs : Caustics? *Grenier et al 2015, Harding 2016,* **Different emission heights?** *Vigano et al 2015*

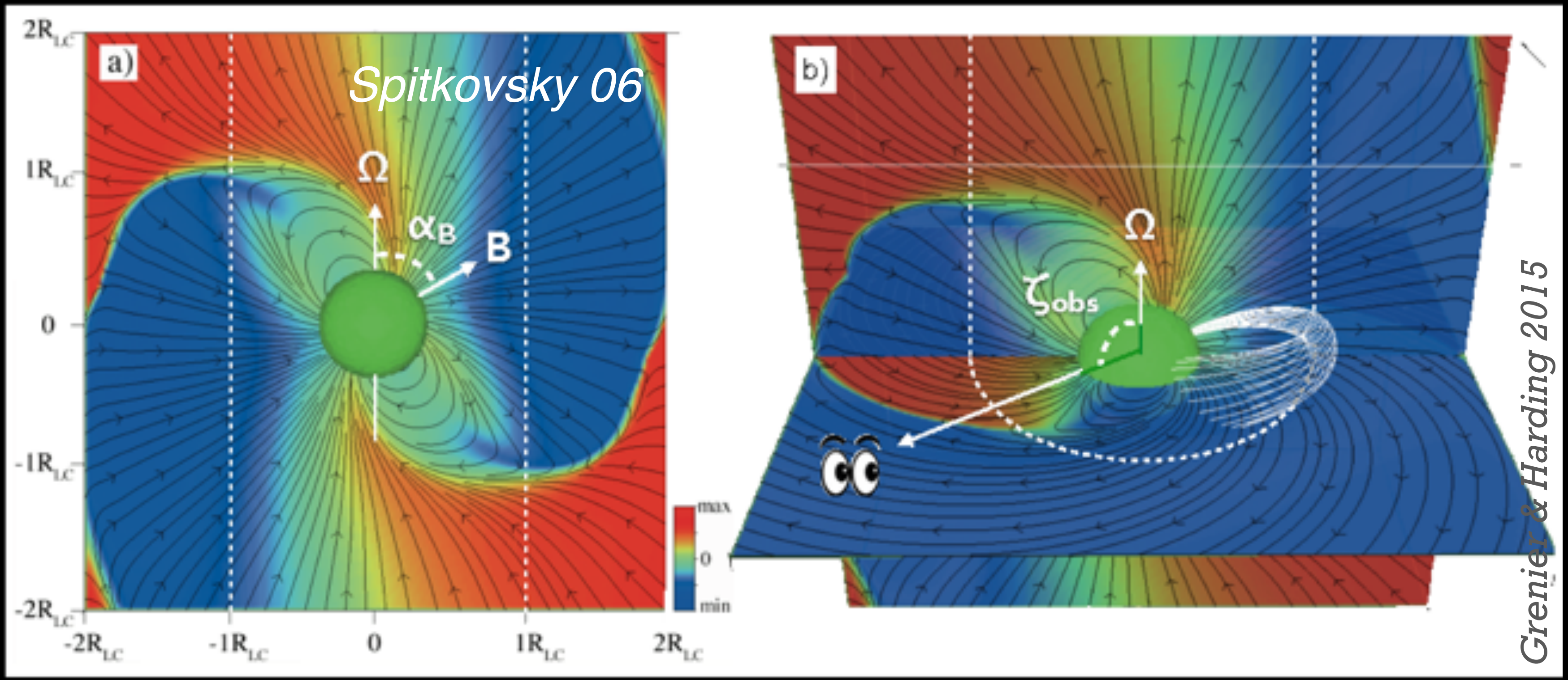
Power-law extension to E>TeV: Inverse Compton emission from the wind? from the outer magnetosphere? *see Talk by Rodriguez et al, MAGIC Col. TeVPA 2017*

(Lyutikov et al 2012,Hirotani 2015, Petrí 2012, Mochol et al 2015, Bogovalov 2000, Aharonian et al 2012)

Several Models to explained the pulsed emission:

Polar cap / Outer gap / slot gap
Stripped Wind

-> they all result in pulsed radiation due to synchro-curvature radiation, but different shape

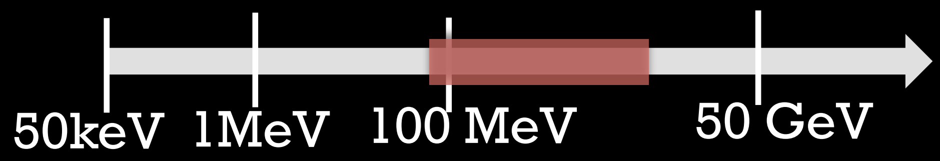


PIC & MHD simulations show a more complex picture.
Bai 2010, Lyubarskii 1990, 2001, Contopoulos 1999, Spitkovsky 2006, Kalapotharakos 2009, Tchekhovskoy 2013, Cerutti 2015

The current sheet corrugates in oblique pulsars producing stripped winds
Coroniti 1990, Bogovalov 1999, Kirk 2002, Mochol 2015

The high energy particles accelerated beyond the LC via reconnection
Tchekhovskoy 2013, Philipopov 2014, Cerutti 2015, 2016, Aharonian 2013, Mochol 2015

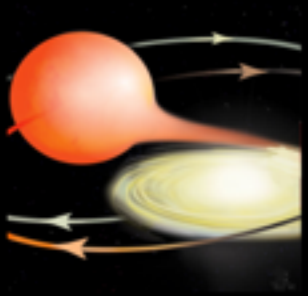
Variable Pulsars

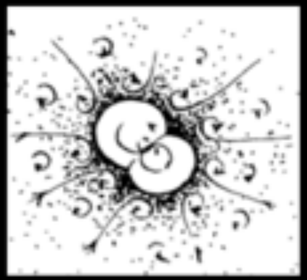


- Pulsars in Binary Systems
  - Transitional MSPs: Probing the recycling scenario

Accretion powered state

Bright X-ray outburst (~10^{36} erg/s)
X-ray pulsations



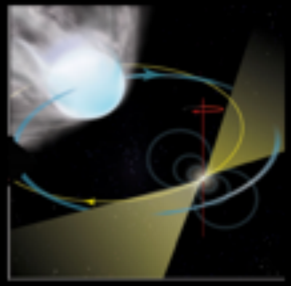


An intermediate (propeller?) state

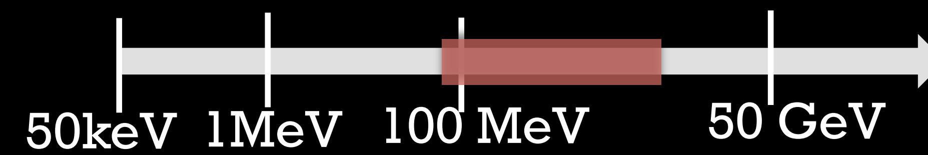
Sub-luminous accretion (~10^{34} erg/s)
Brighter gamma-ray emission
X-ray pulsations (10% level)

Rotation powered state

Faint in X-rays (~10^{32} erg/s)
Radio/gamma-ray pulsations



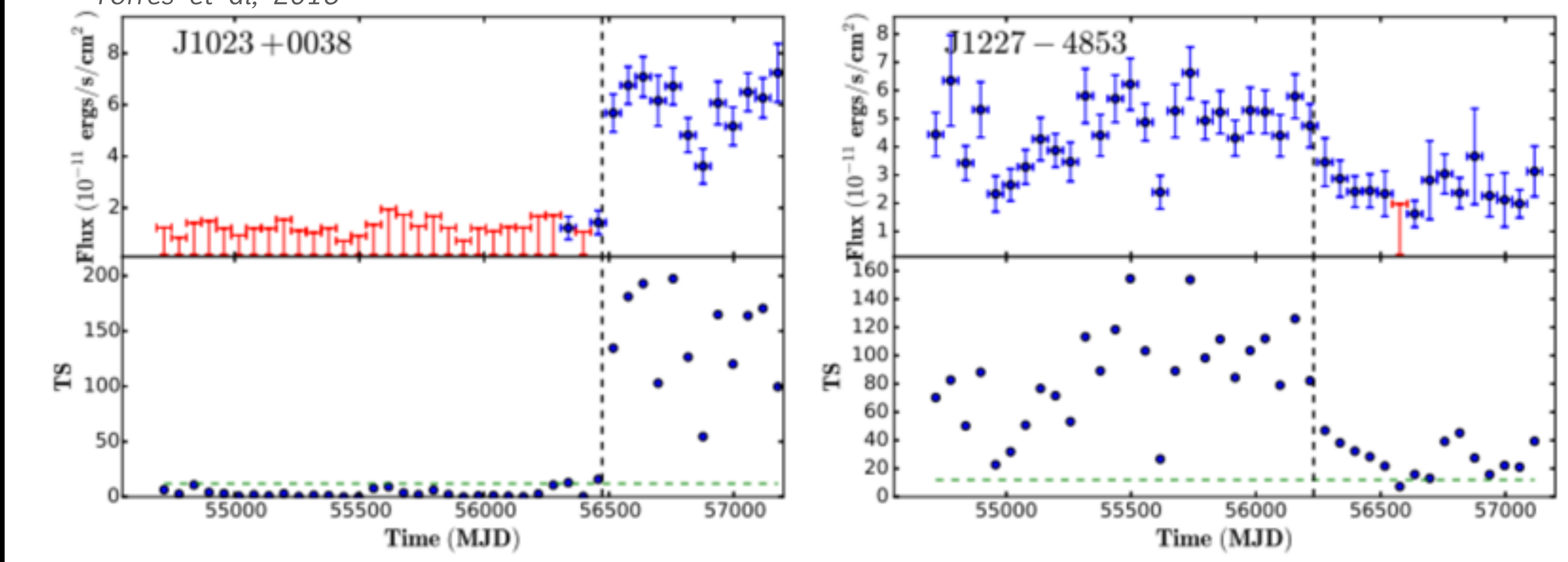
Variable Pulsars



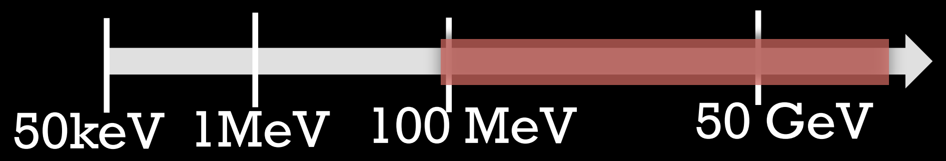
- Pulsars in Binary Systems
  - Transitional MSPs: Probing the recycling scenario

Balance between gravity and field pressure
SSC of relativistic electrons accelerated during propeller state
Acceleration in the intra-shock?

Torres et al, 2016

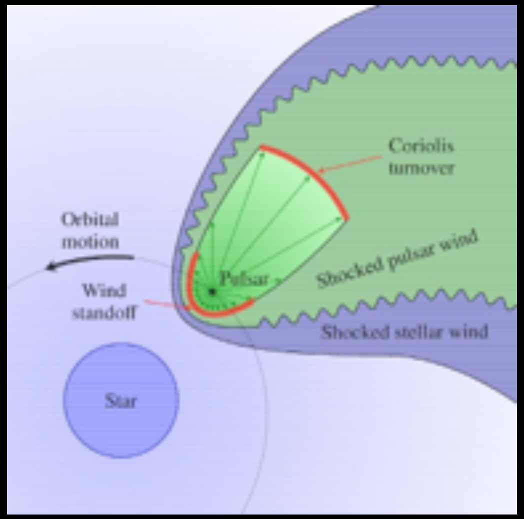


Variable Pulsars



- Pulsars in Binary Systems
  - Transitional MSPs: Probing the recycling scenario
  - High-energy Gamma-ray Binaries

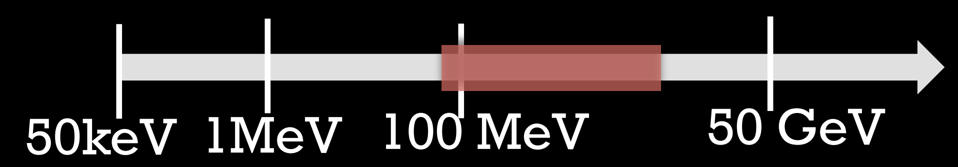
Compact object + Massive Companion (OB/WR)
Point-like Sources at VHE, peaking at high-energies
Modulation of the VHE due to their interaction (5+1?)
Observed in radio, X-ray, HE and VHE
Difficult to reconcile all observations: geometry?
Not a unique behaviour: Ej. LS 5039 vs 1FGL J1018.6



Zabalza et al, 2013

	Flux (% Crab)	D (Kpc)	Flux variability (HE/VHE)	Periodic	Ref
LSI +61 303	0-15	2	yes/yes	yes (~1 month)	*Albert+2006, 2008, Hadasch+2012, Acciari+2008, Anderhub+2009, Ong+2010*
LS 5039	5-15	2,5	yes/yes	yes (~4 days)	*Aharonian+2005,2006, Hadasch+2012*
PSR B1259-63	0-10	1,5	yes/yes	yes (~3.4 years)	*Aharonian+2005, Tam+2010, Mori+2011, Abdo+2011,*
HESS J0632+057	0-3	1,5	no/yes	yes (~300 days)	*Li+2017, Malyshev+2016, Maier+2015, Mori+2013, Veritas2013, Aharonian+2007*
1FGL J1018.6-589	5-15	5	yes/yes	yes (~16 days)	*An&Romani 2017,HESS Col. 2015, 2012, FermiLAT2012*
HESS J1832-093	0-1	4.4	-/no	—	*Eger+2016, HESS Col 2013, Mori+2017*

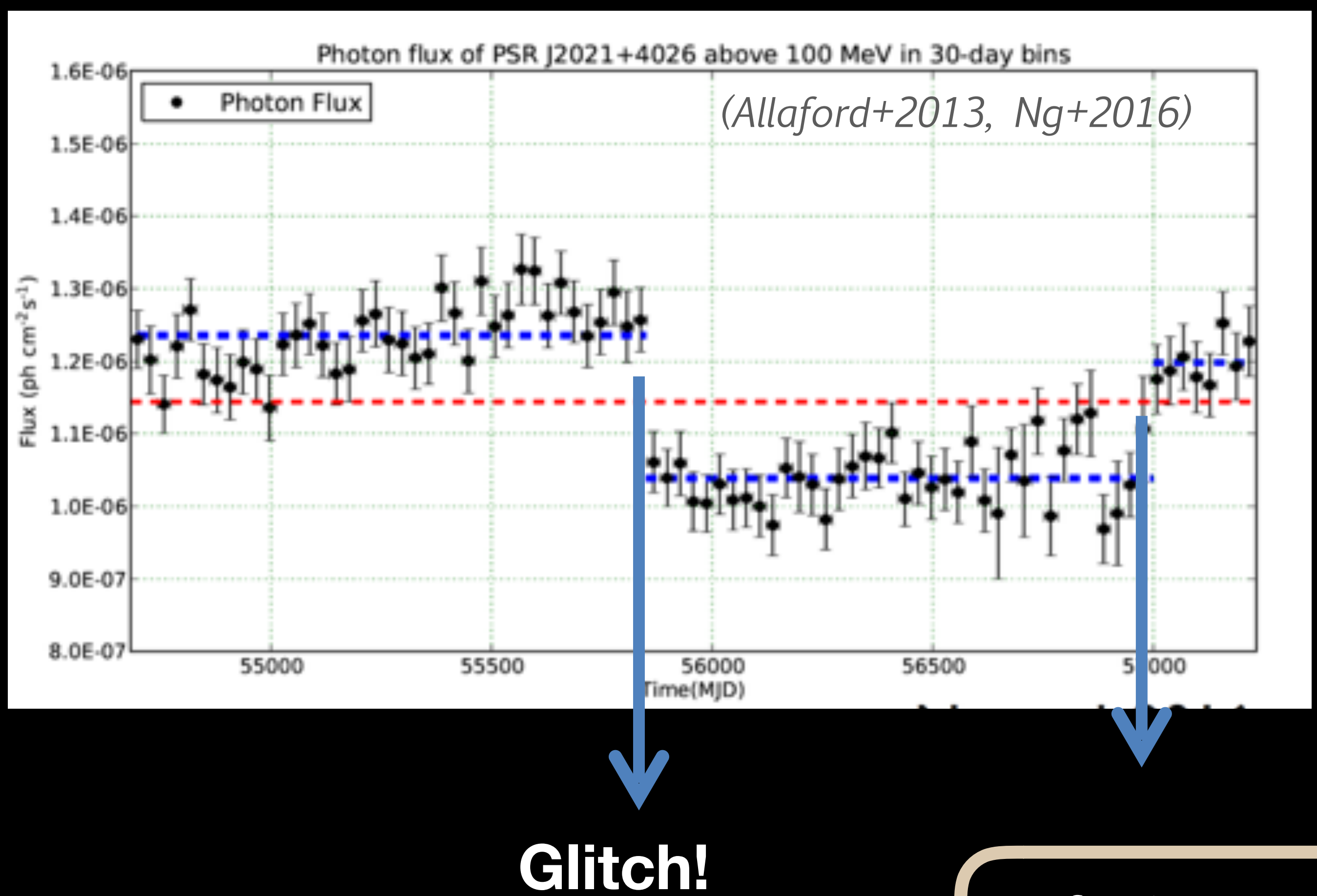
Variable Pulsars



- Pulsars in Binary Systems
  - Transitional MSPs: Probing the recycling scenario
  - High-energy Gamma-ray Binaries
- Isolated Pulsars

  Pulsars are not steady at lower energies (quakes, glitches,…)

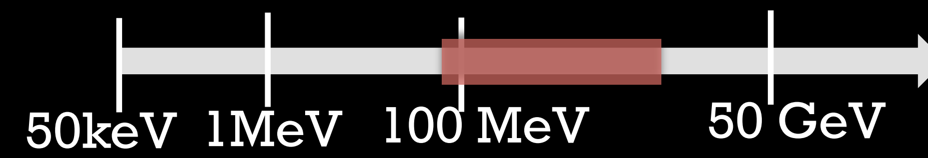
  First observed switch mode in a γ-ray pulsar: J2021+4026



- 20% flux drop
- Increase in spin down rate
- Change in the pulsar profile
- Decrease energy cutoff

✓ glitch cause a re-arrangement of the B structure → α change *(Ng+2016)*

Variable Pulsars



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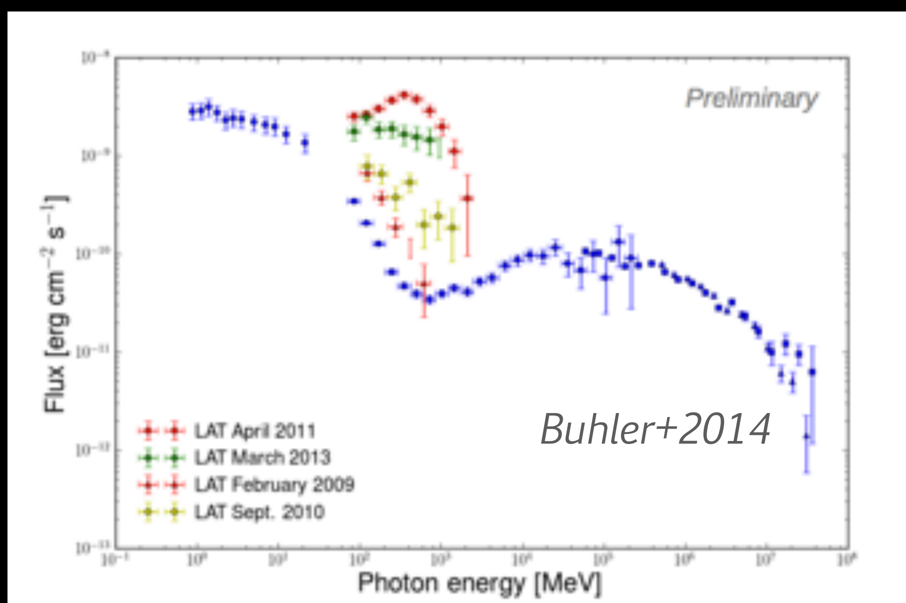

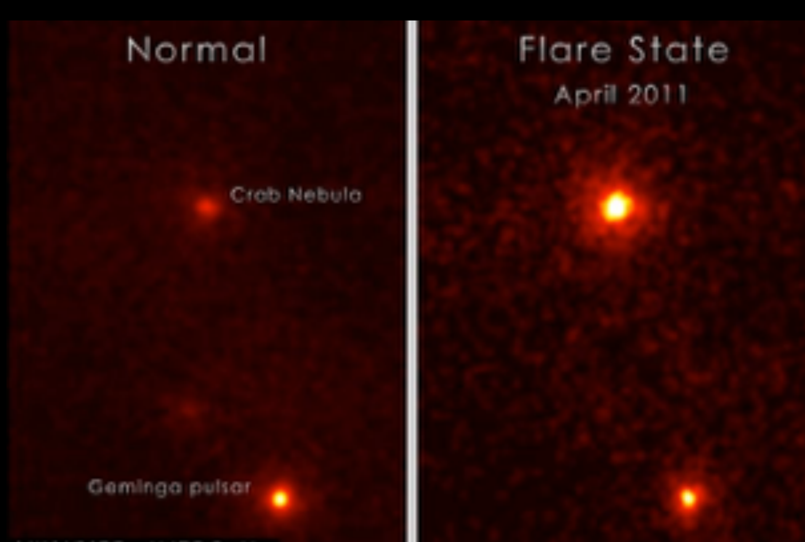

The Crab… Nebula!

Short (~hours) burst happening at a rate of 2-3 per year

Pulsed emission does not show variation, PWN!

Compact region (<10^{-3} pc) with significant energy (~$10^{35\text{-}36}$ erg/s)→ emission anisotropic → doppler/kinetic boosting?

Particle acceleration in magnetic reconnection? $\gamma \sim 10^9$

No detected counterpart at lower energies

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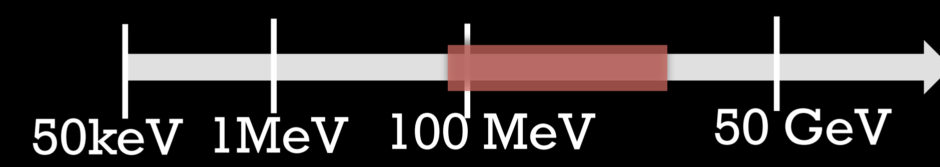

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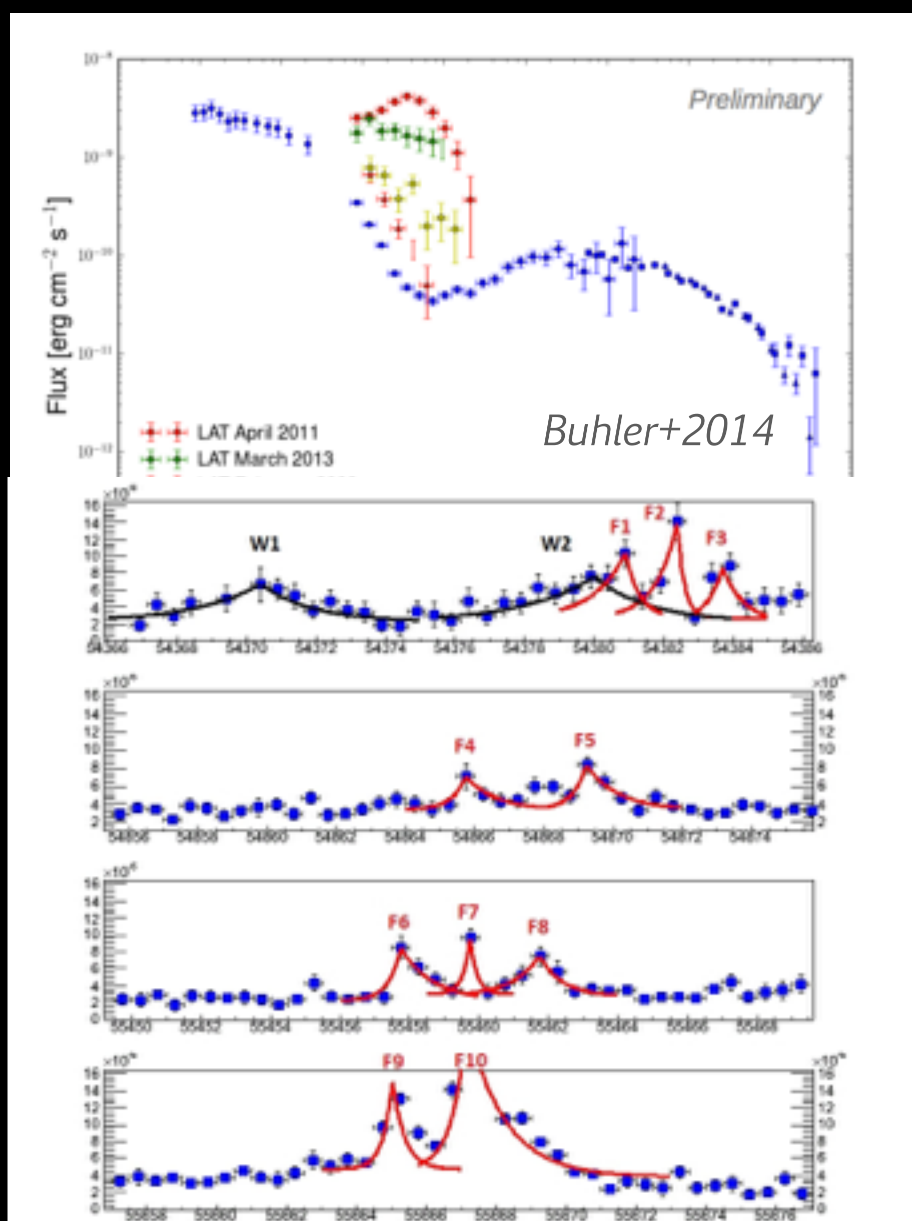

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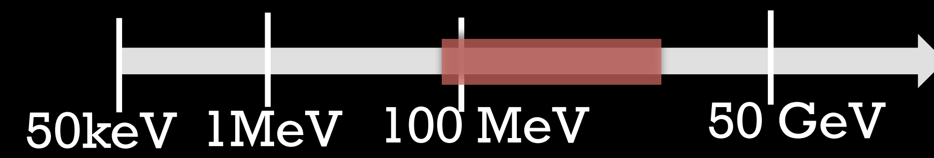
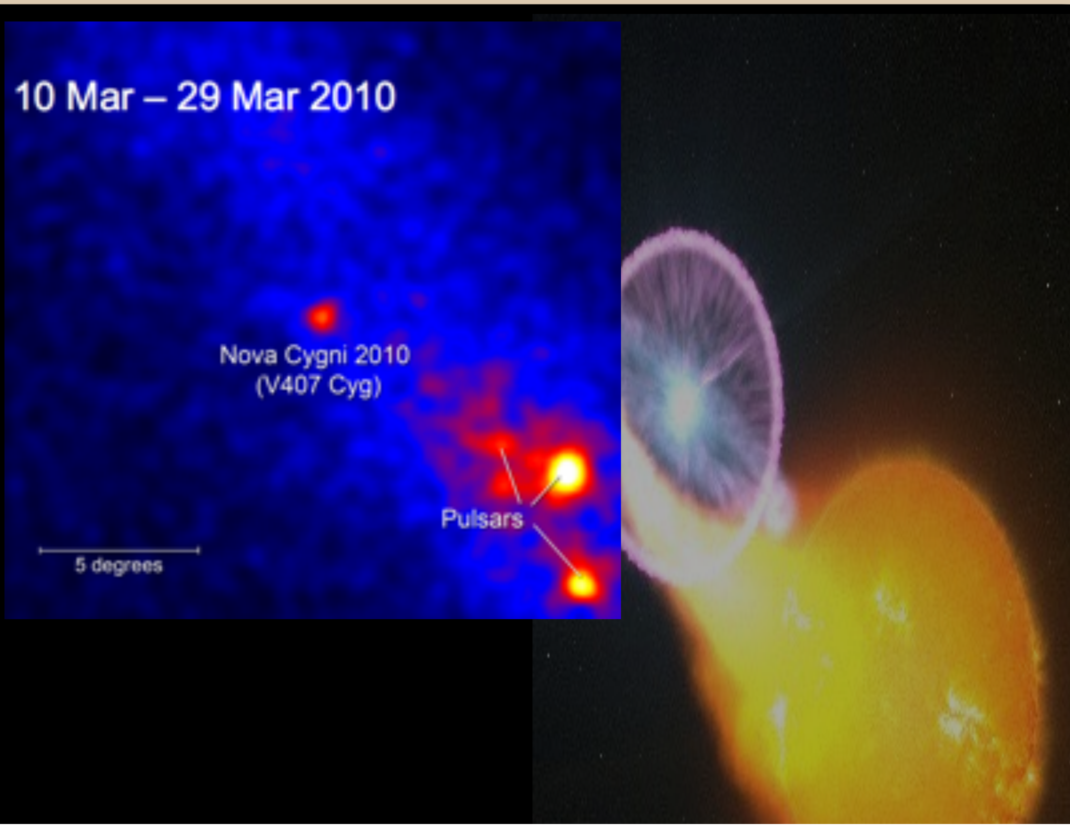
The big and the wild



Novae

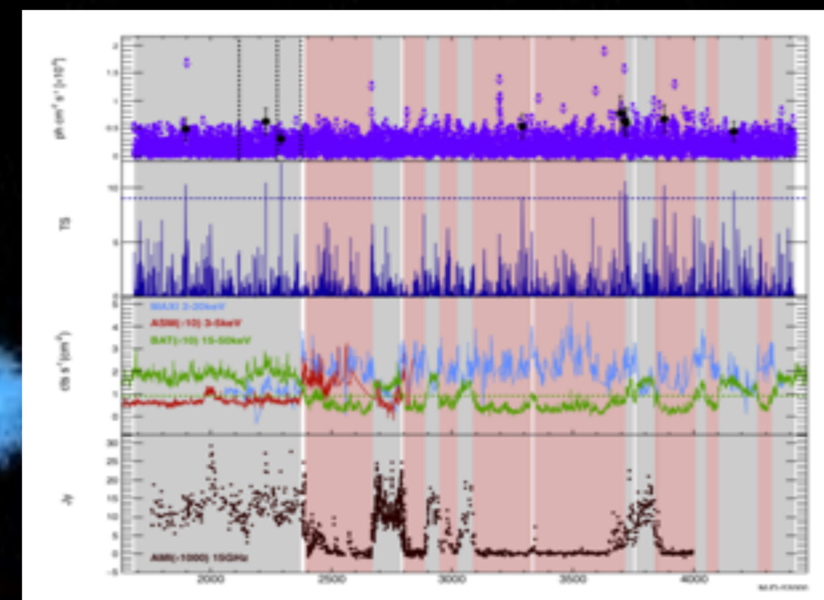


Nova	Distance	Duration	Fluence	Number of Photons	Total Energy
	(kpc)	(days)	(photons cm^{-2})	(10^{45})	(10^{42} erg)
V1324 Sco 2012	4.5	17	0.72 ± 0.04	1.77 ± 0.40	1.27 ± 0.29
V959 Mon 2012	3.6	22	0.79 ± 0.12	1.23 ± 0.39	0.67 ± 0.21
V339 Del 2013	4.2	27	0.45 ± 0.07	0.96 ± 0.27	0.57 ± 0.16
V1369 Cen 2013	2.5	39	0.71 ± 0.14	0.54 ± 0.24	0.30 ± 0.13
V5668 Sgr 2015	2.0	55	0.52 ± 0.11	0.25 ± 0.14	0.12 ± 0.07

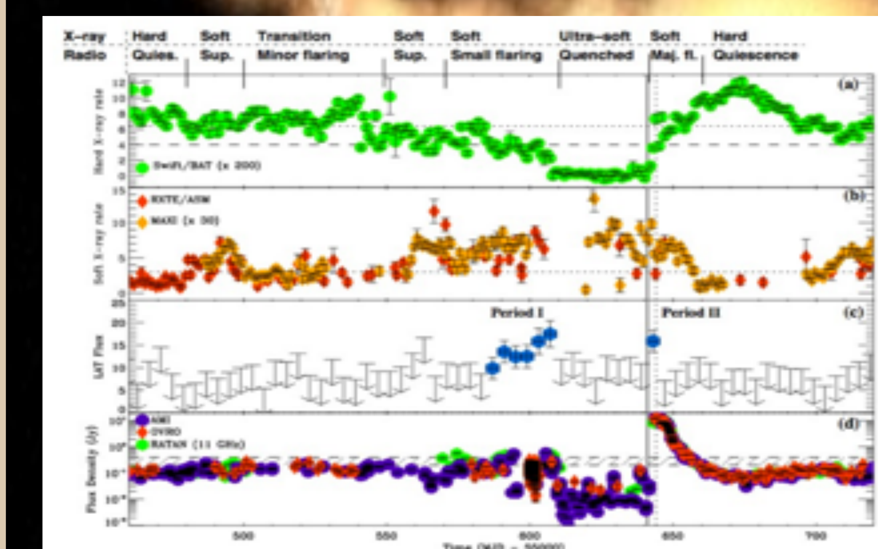
Cheung+2016

uQuasars

Cyg X-1



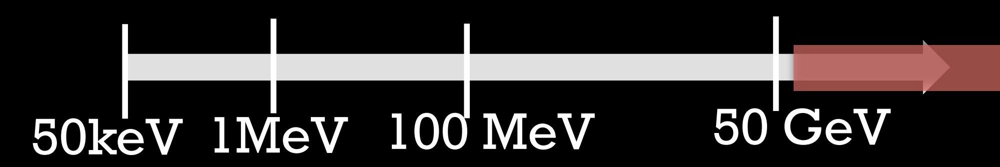
Zanin+2016



Szostek+2012

Cyg X-3

Pulsar Wind Nebulae



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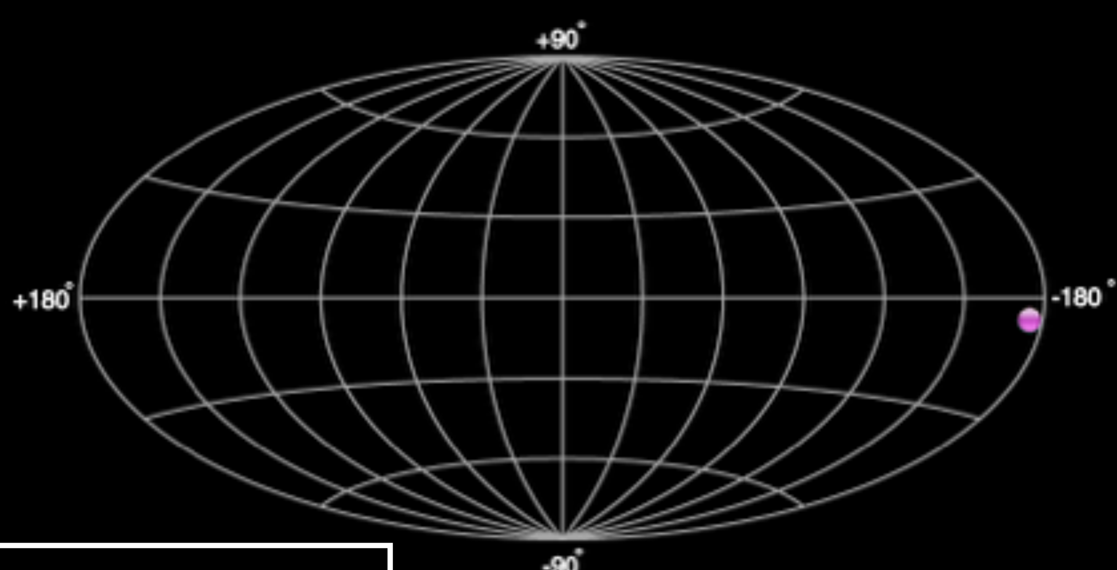
see also Gallant, Weinstein talks in TeVPA 2017

Emission due to off-scattering of CMB/ IR/Synchrotron photons from relativistic electrons

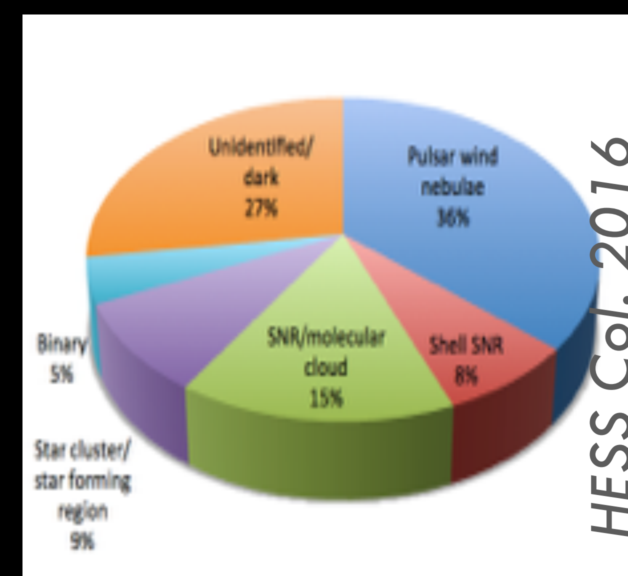
http://tevcat.uchicago.edu/



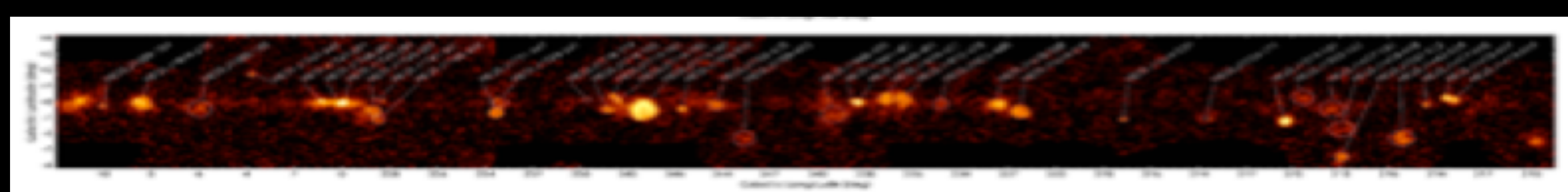
1989-2004

Source Types

PWN 37

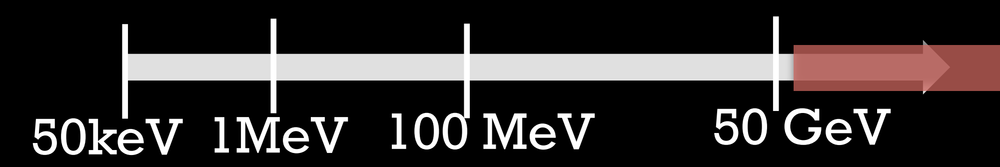


HESS Col. 2016



Donath et al (HESS Col.) 2017

Pulsar Wind Nebulae



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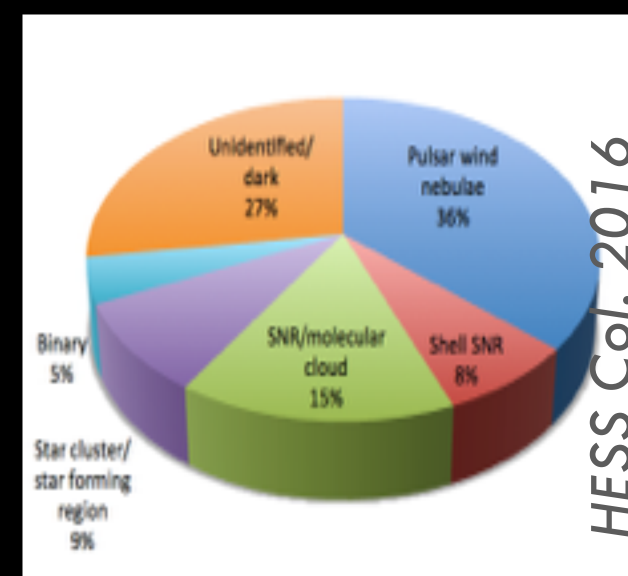

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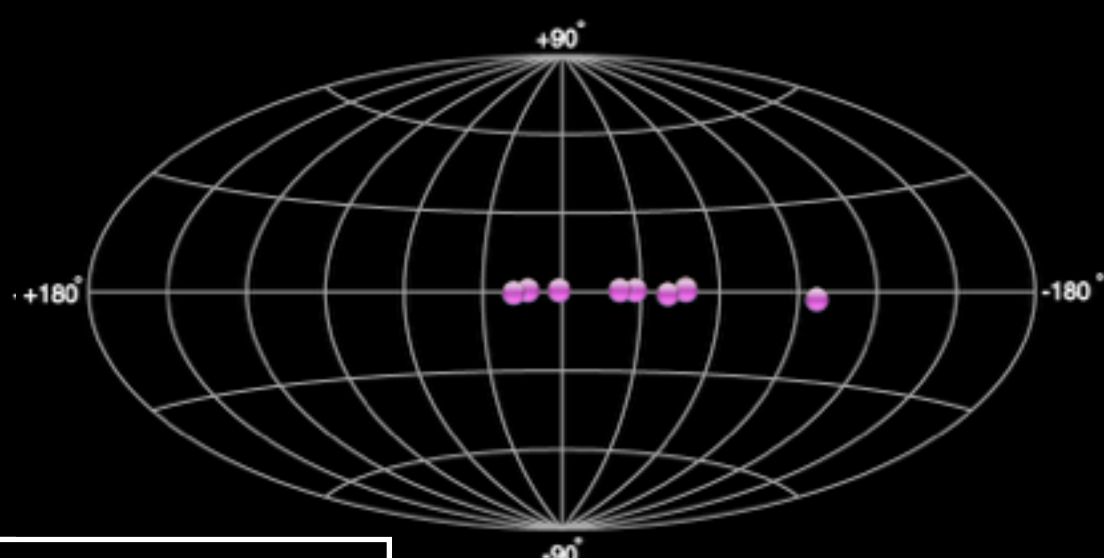

2005-2006

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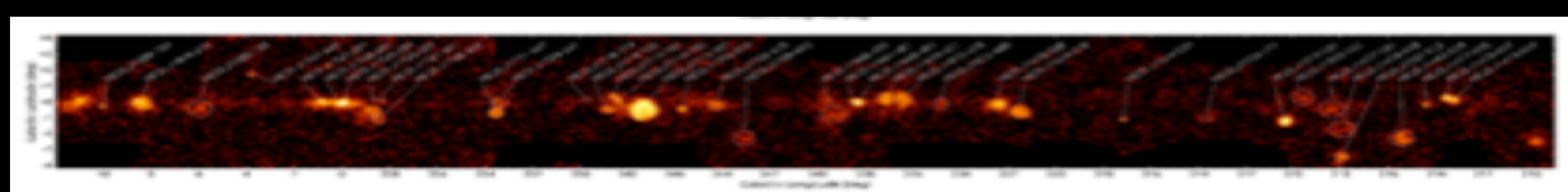
PWN 37



Donath et al (HESS Col.) 2017

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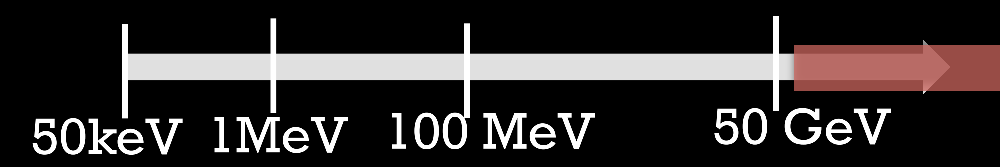

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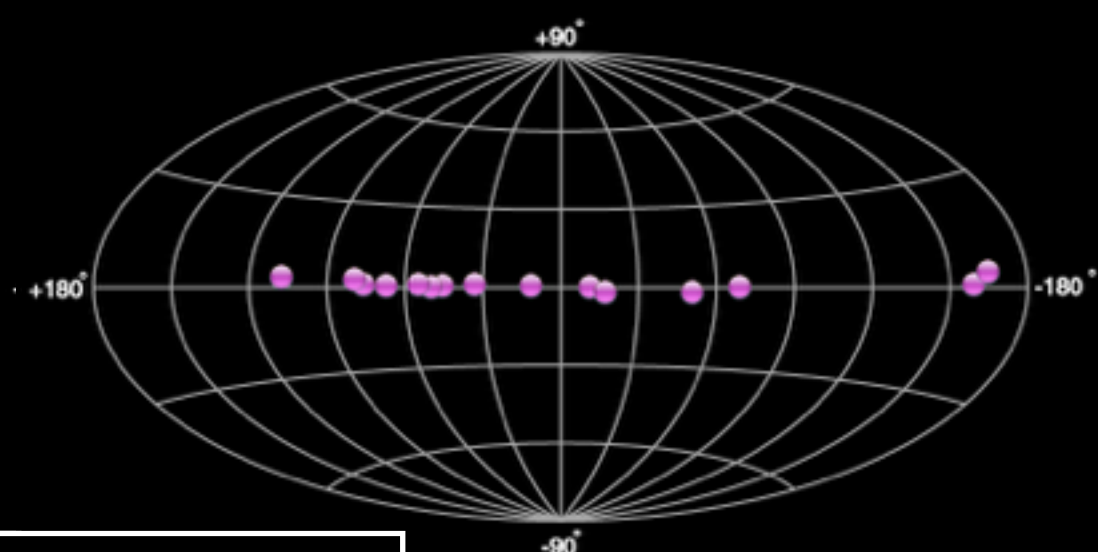
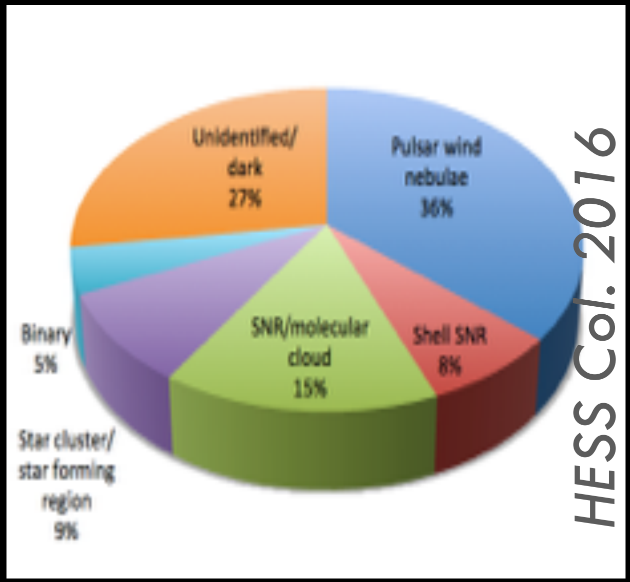
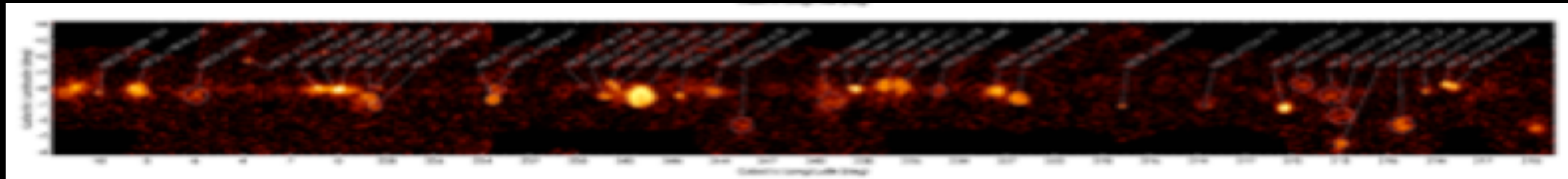




2007-2010

Source Types

PWN 37



Donath et al (HESS Col.) 2017

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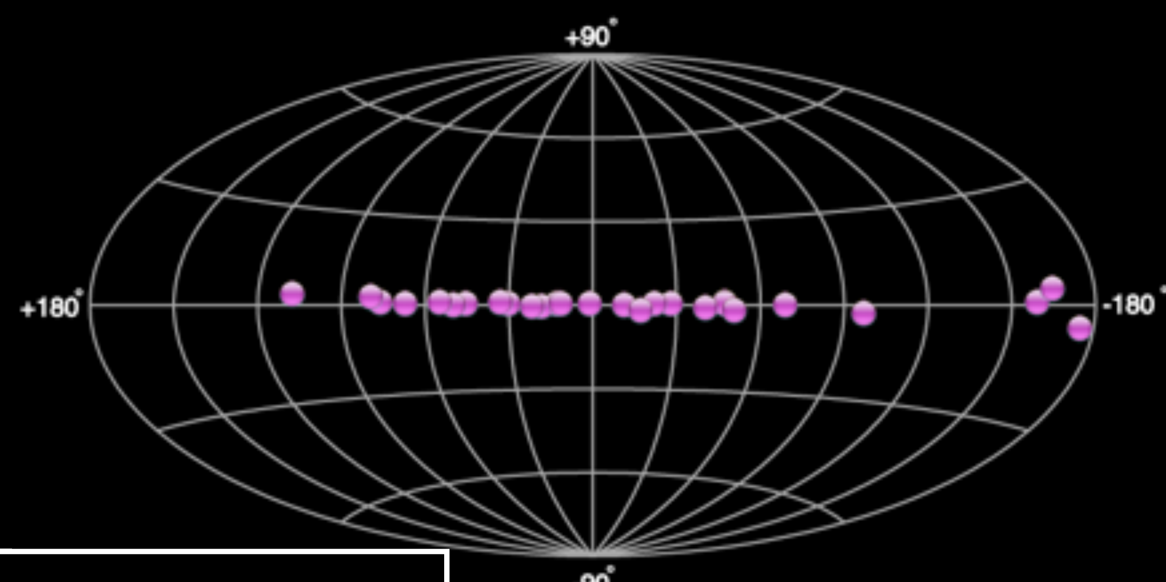

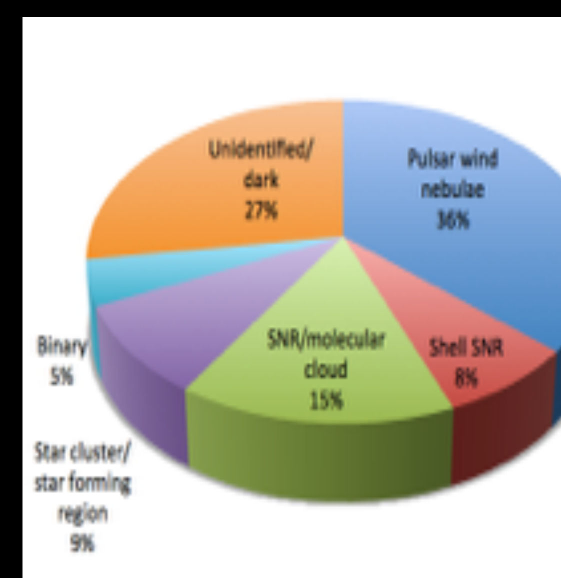

HESS Col. 2016

1989-2017

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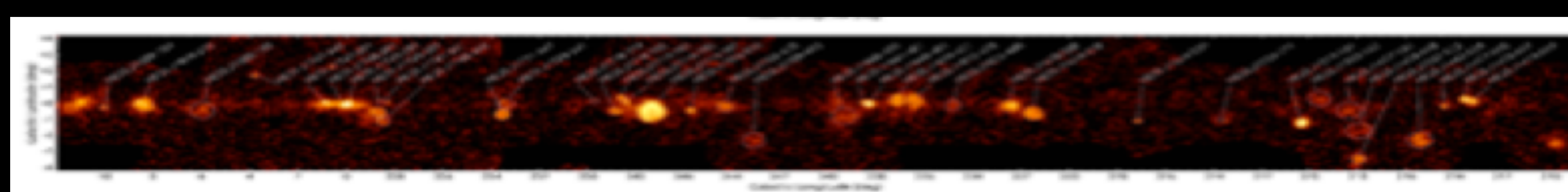
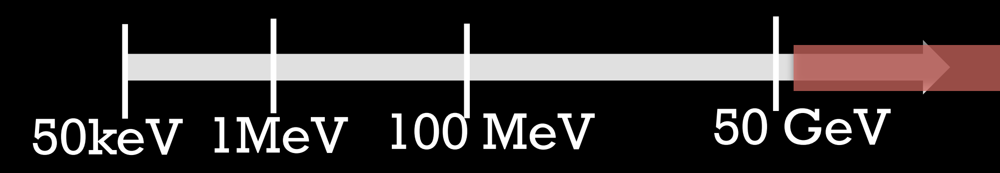
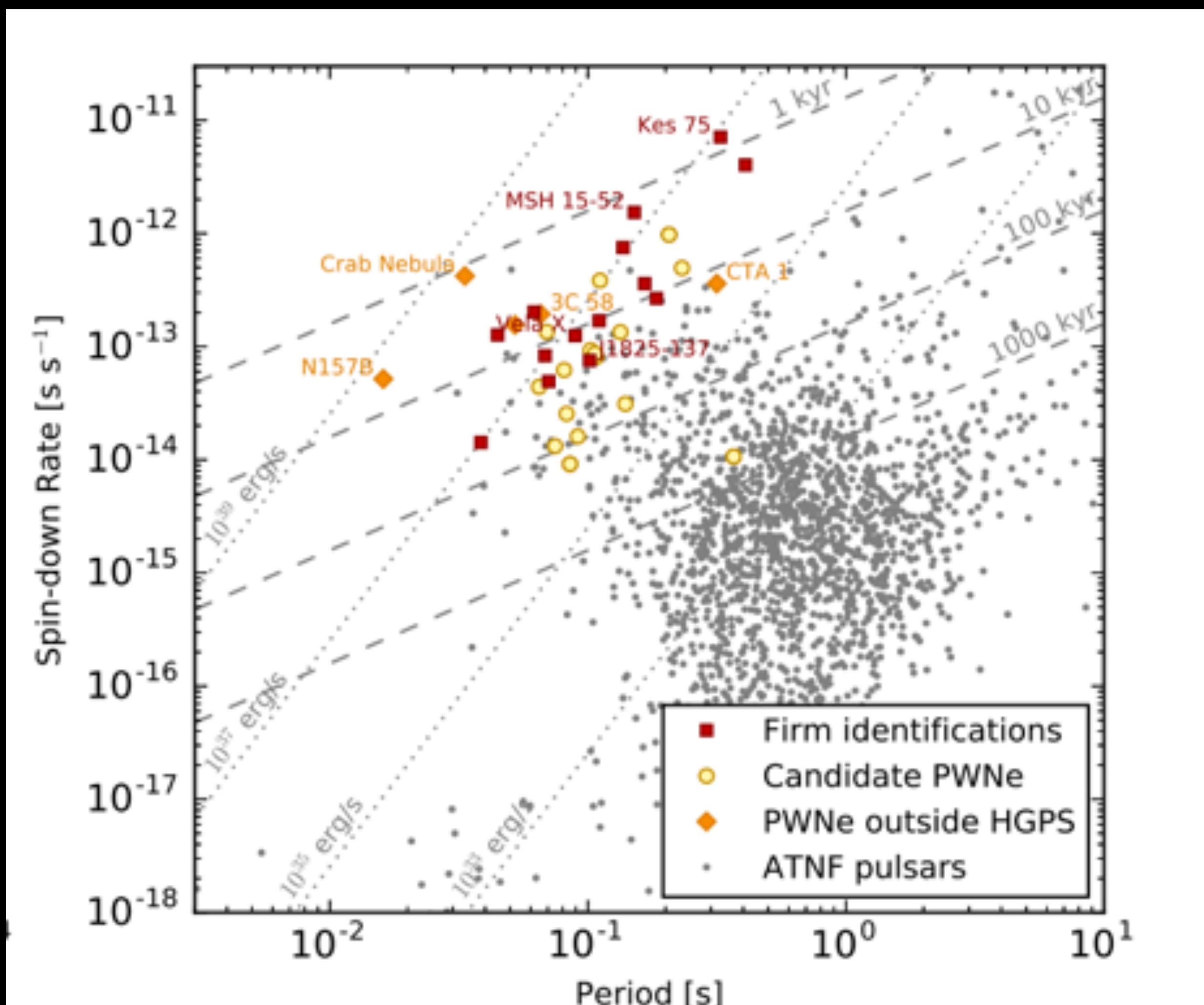


Donath et al (HESS Col.) 2017

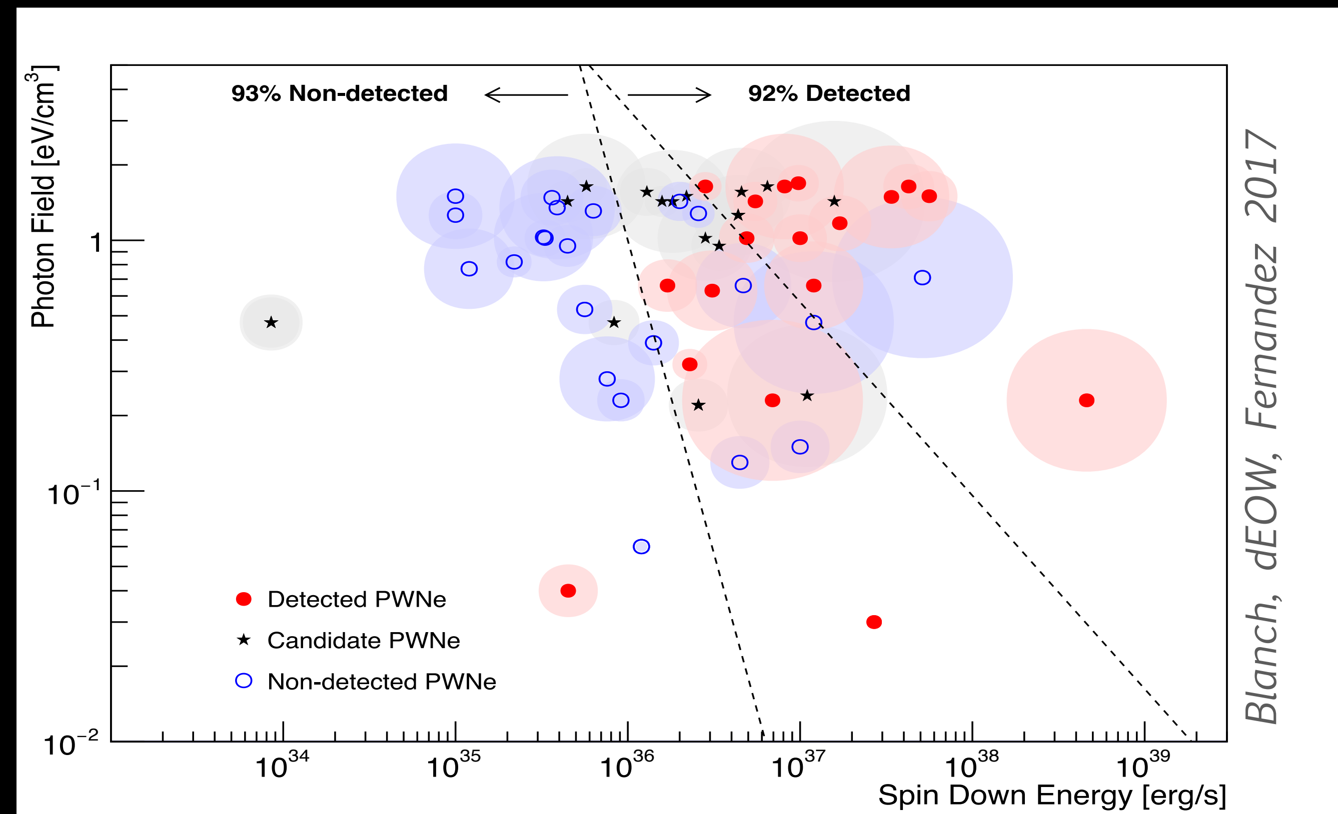
Pulsar Wind Nebula

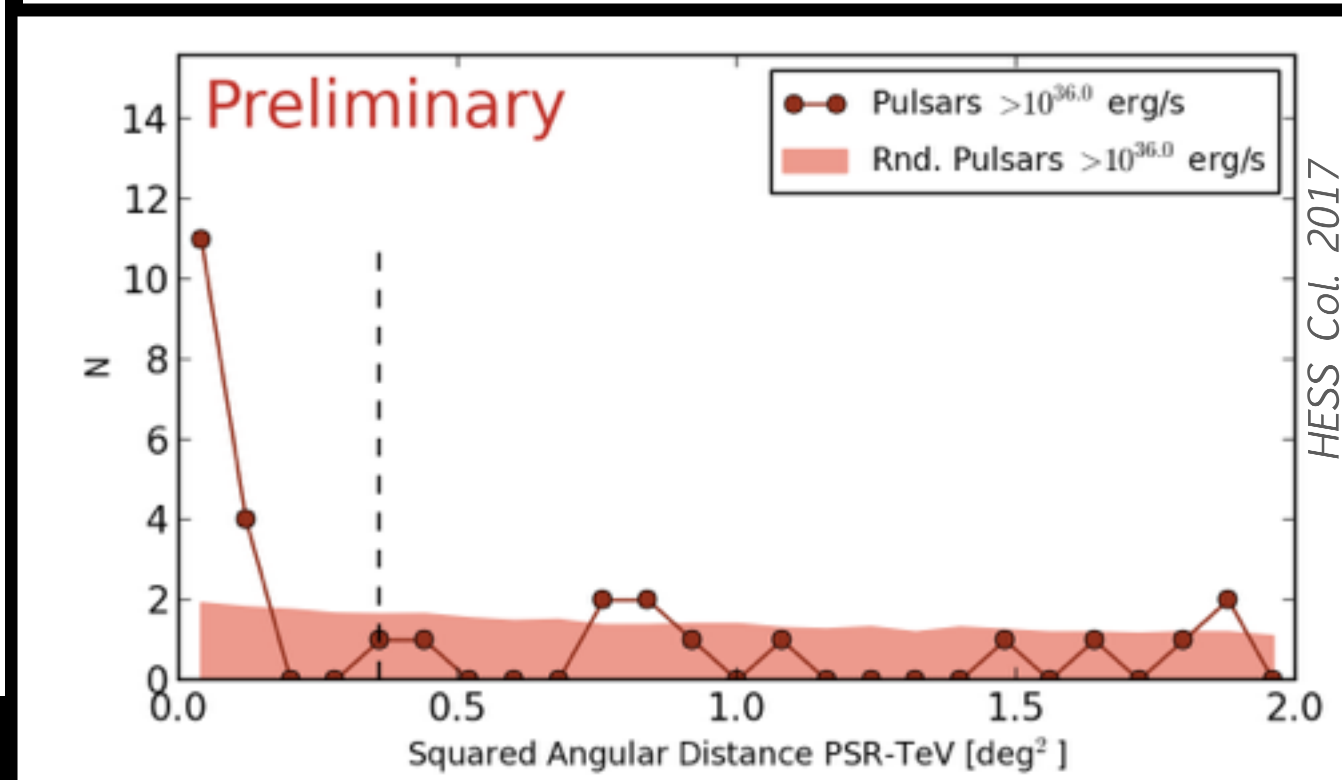


Evidence that the TeV luminosity of PWNe decays with time while they expand in (angular) size.
Time-dependent modeling describes fairly well the general trends.



HESS Col+2016





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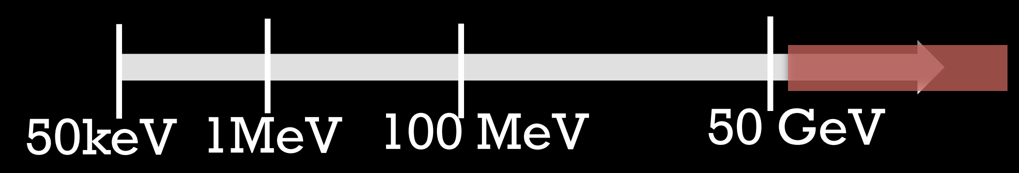

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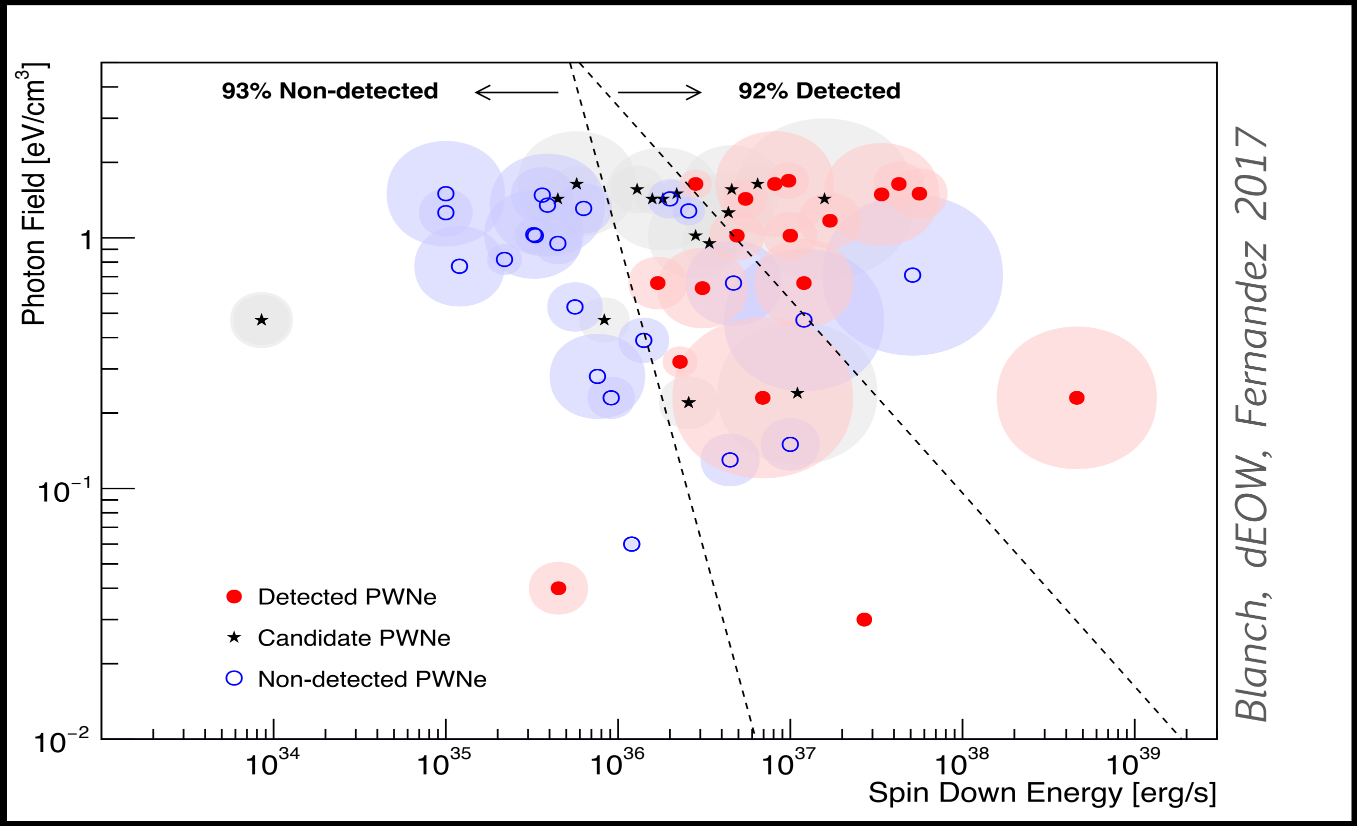

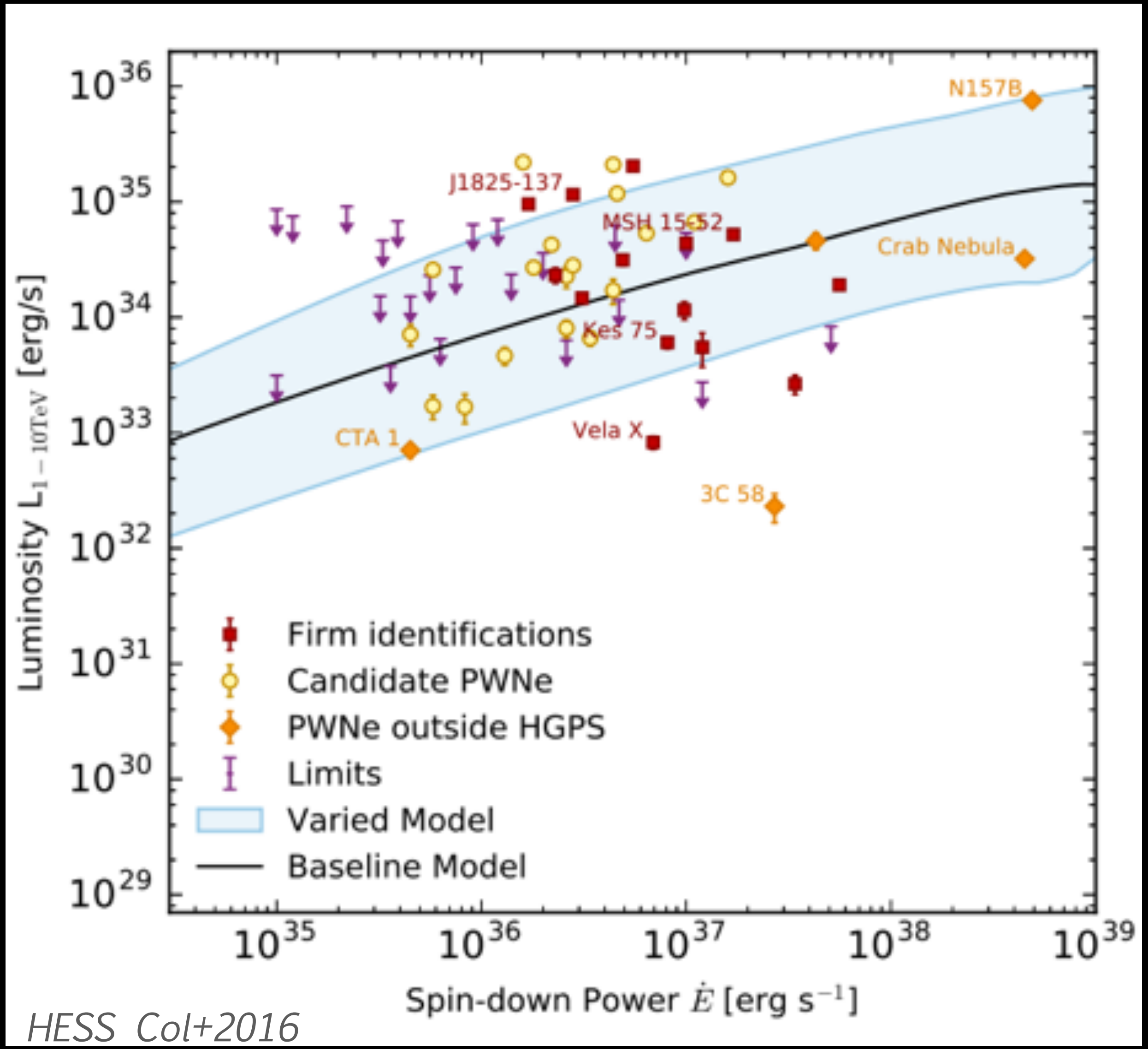

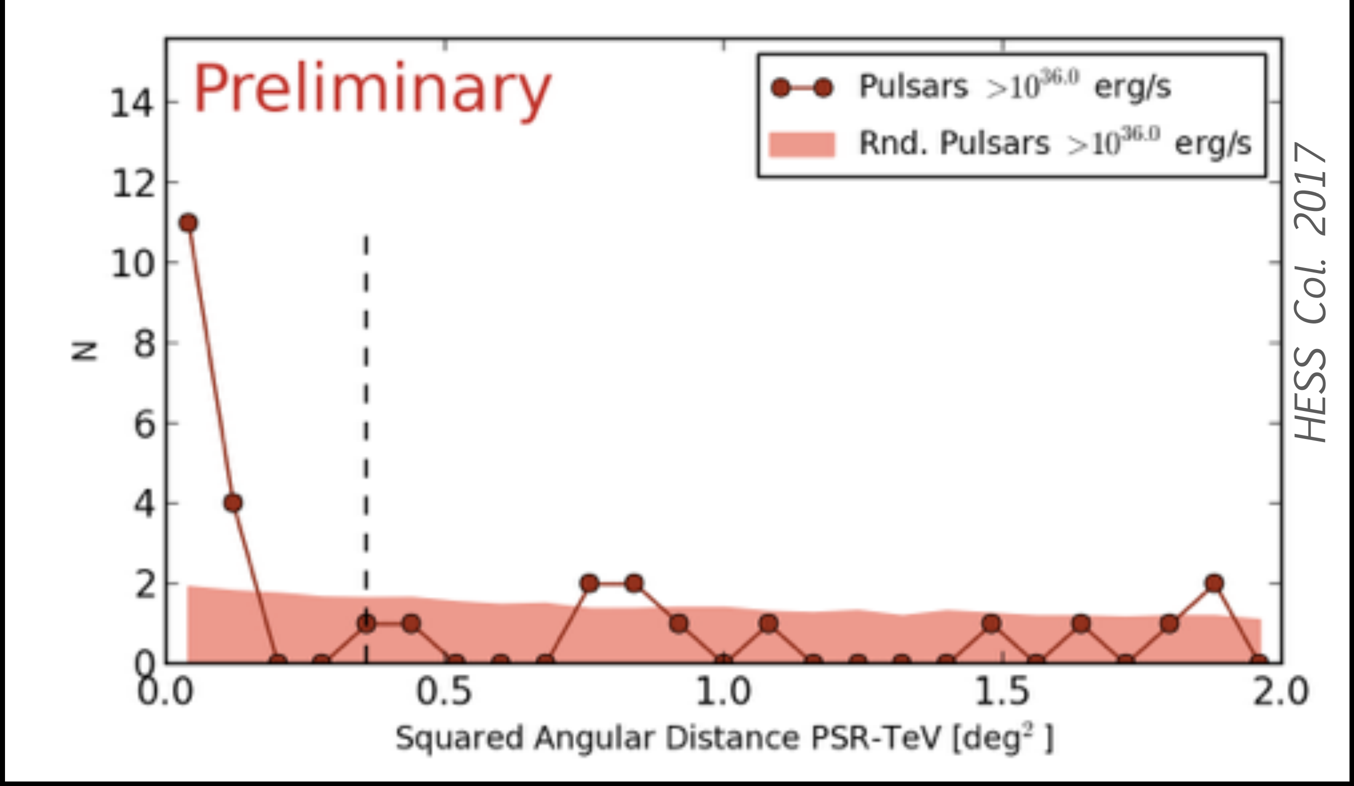

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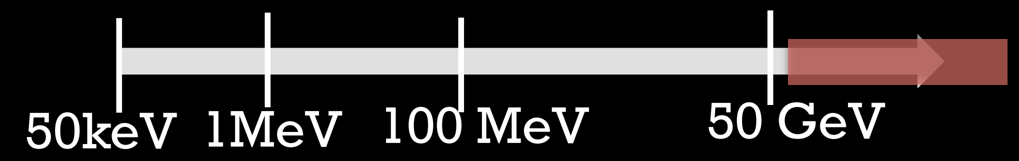

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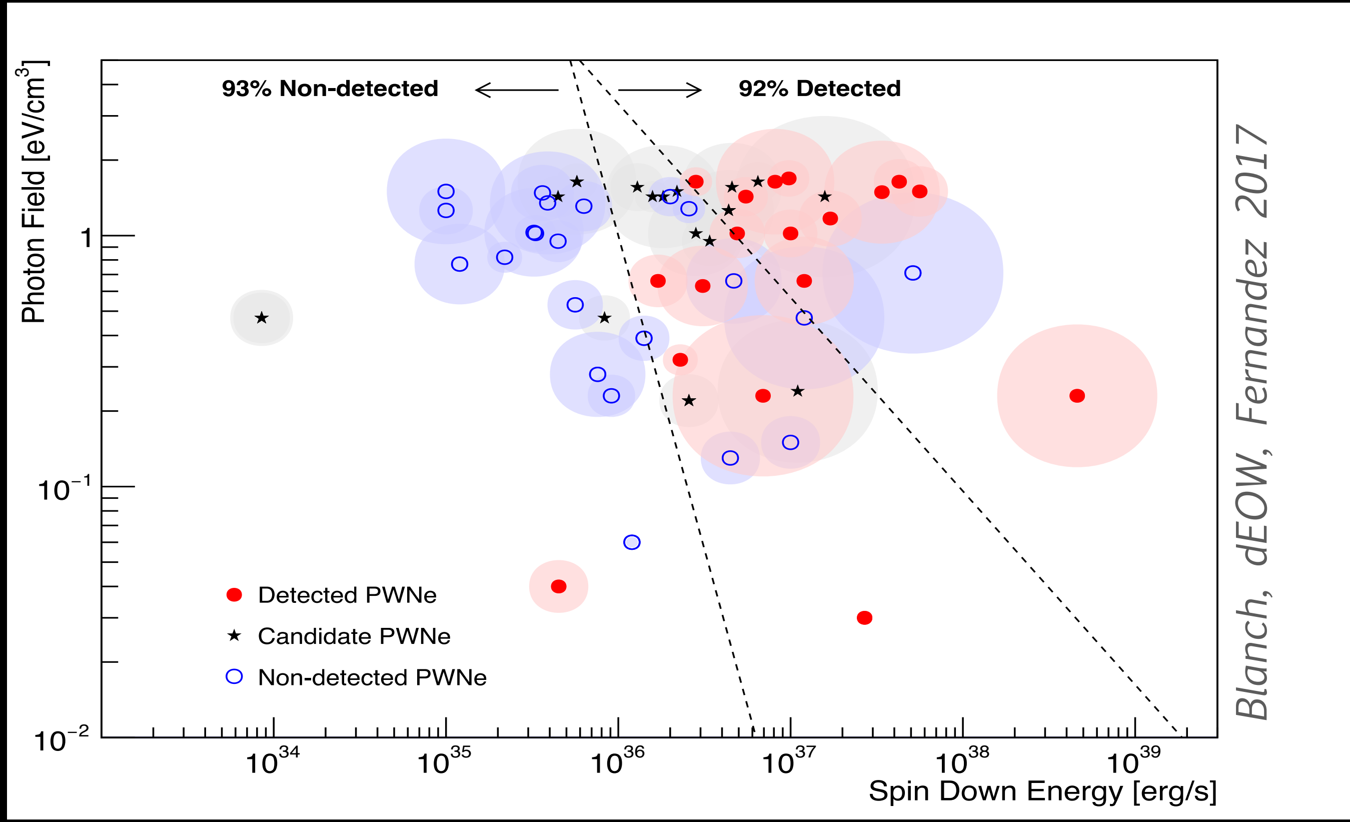
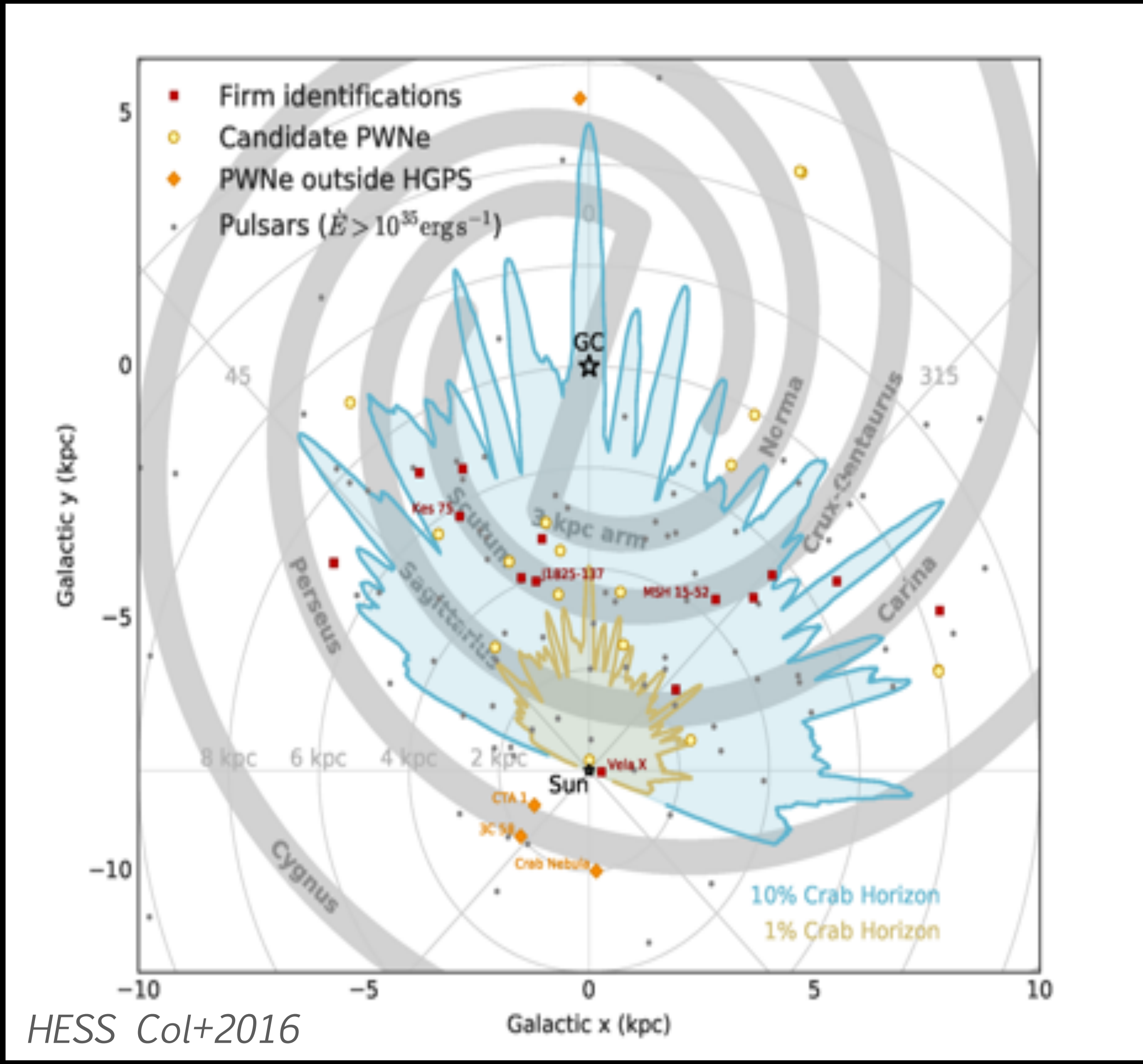
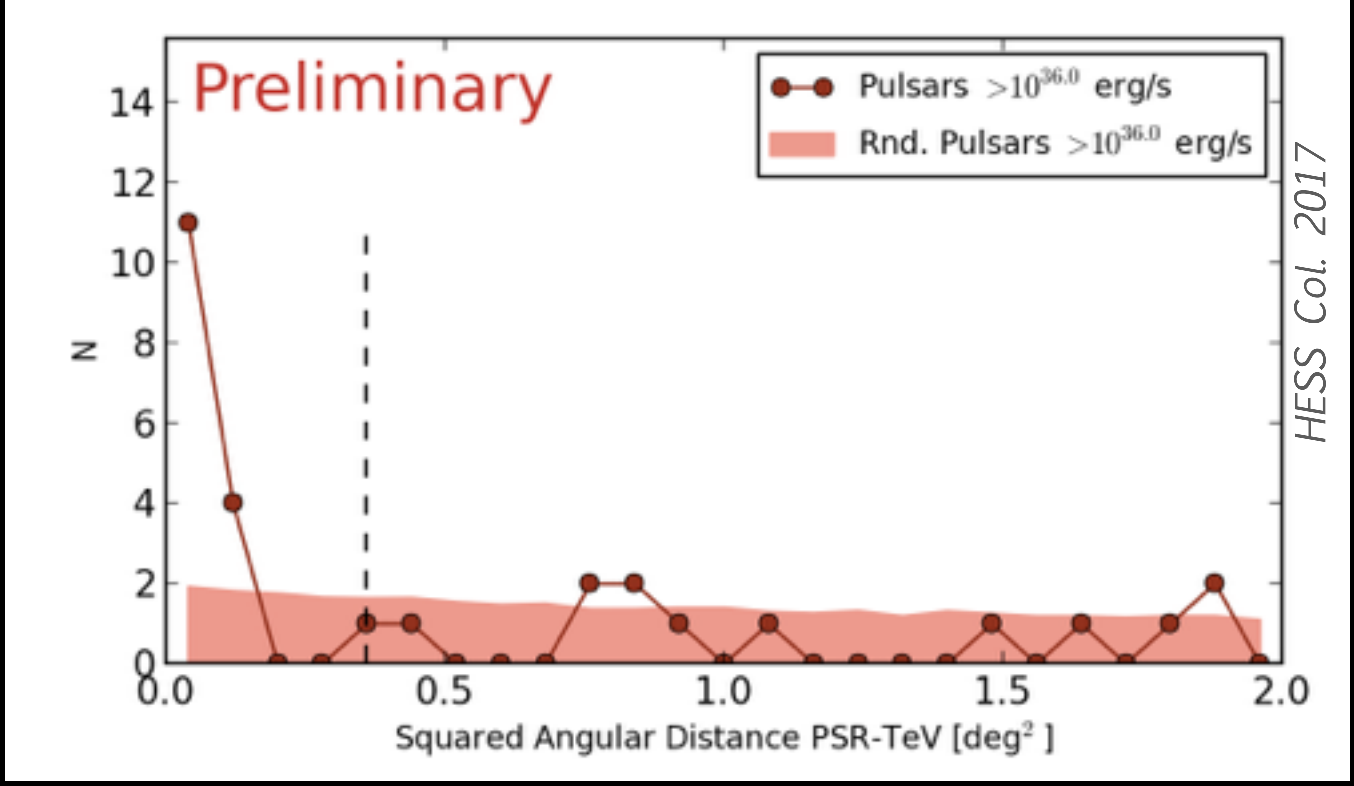
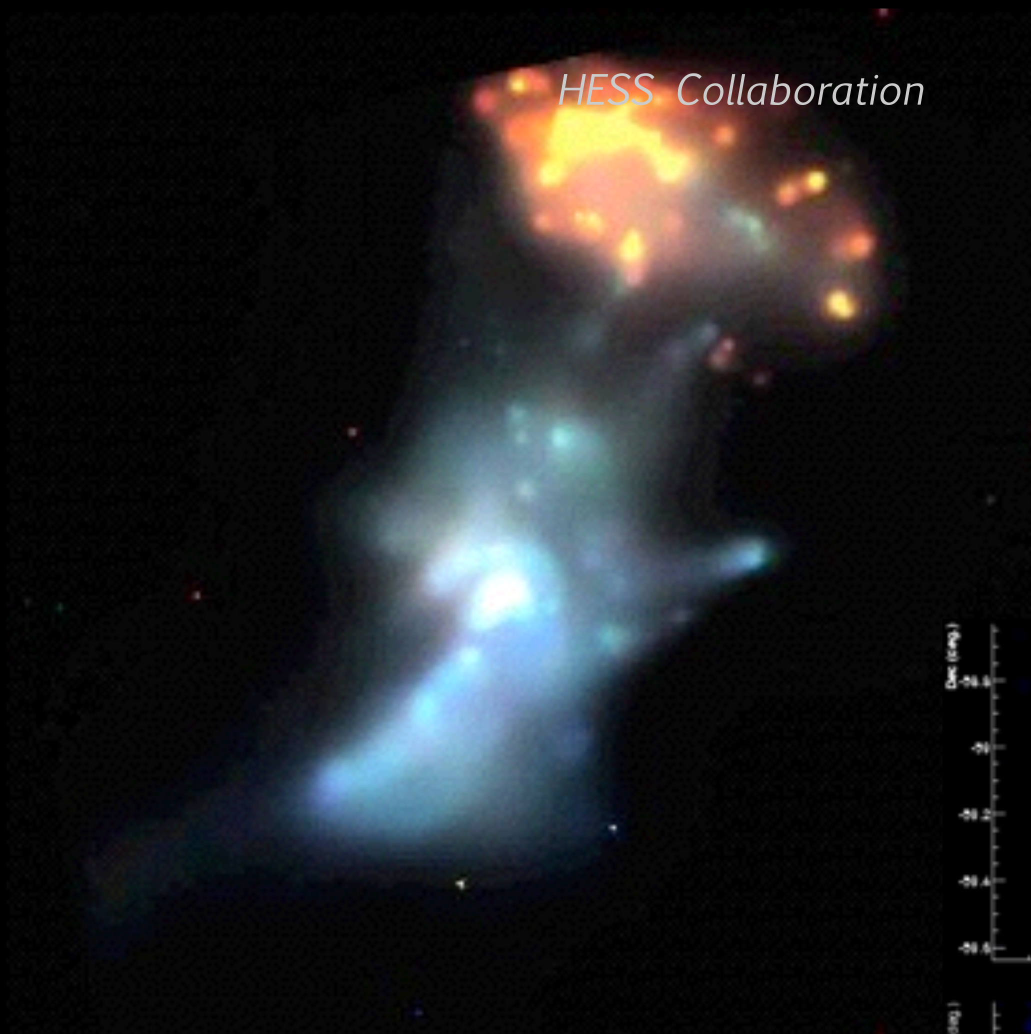






PWNe: Test-bench for particle acceleration and propagation

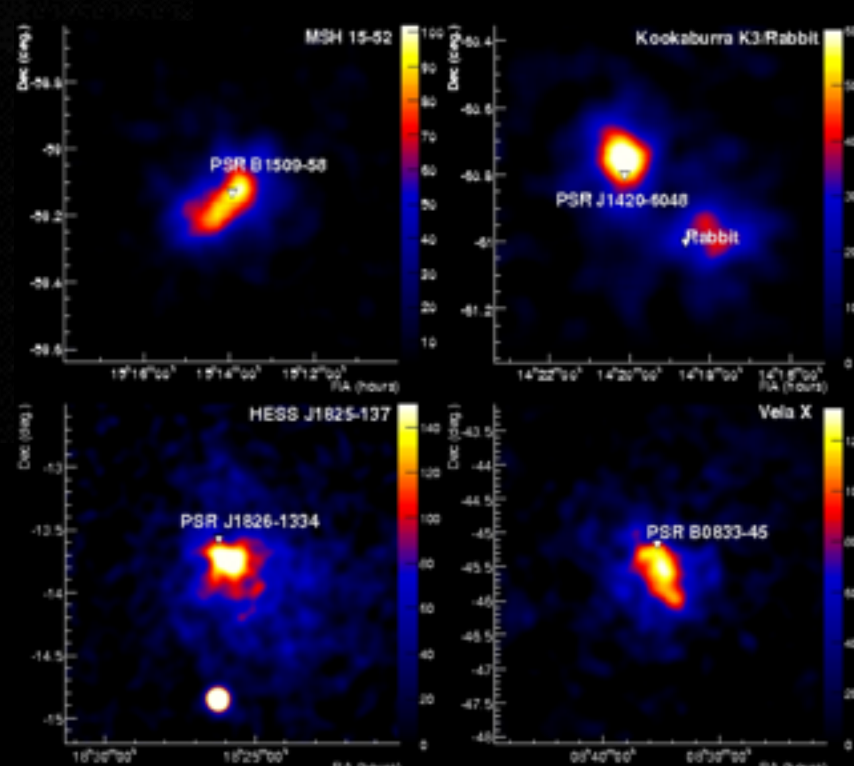
Excellent correlation with X-rays (large size compensates sometimes the relatively poor angular resolution ~0.1°



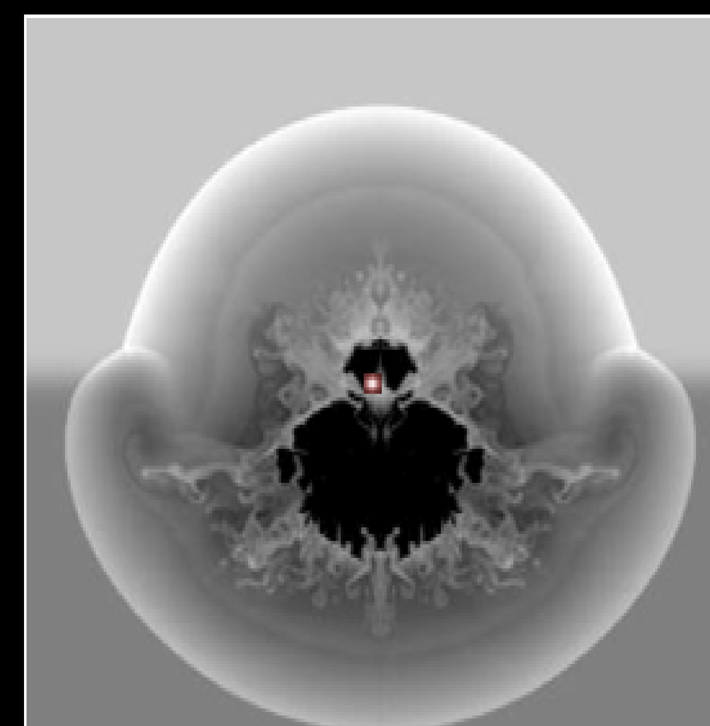
MSH 15-52

- Particle-dominated nebulae, away from equipartition
- High photon field density
- Pulsar offset from the center of the TeV emission: proper velocity or evolution of the SNR in an inhomogeneous medium

see also Slane talk in TeVPA 2017



HESS Collaboration



Blondin et al 2001

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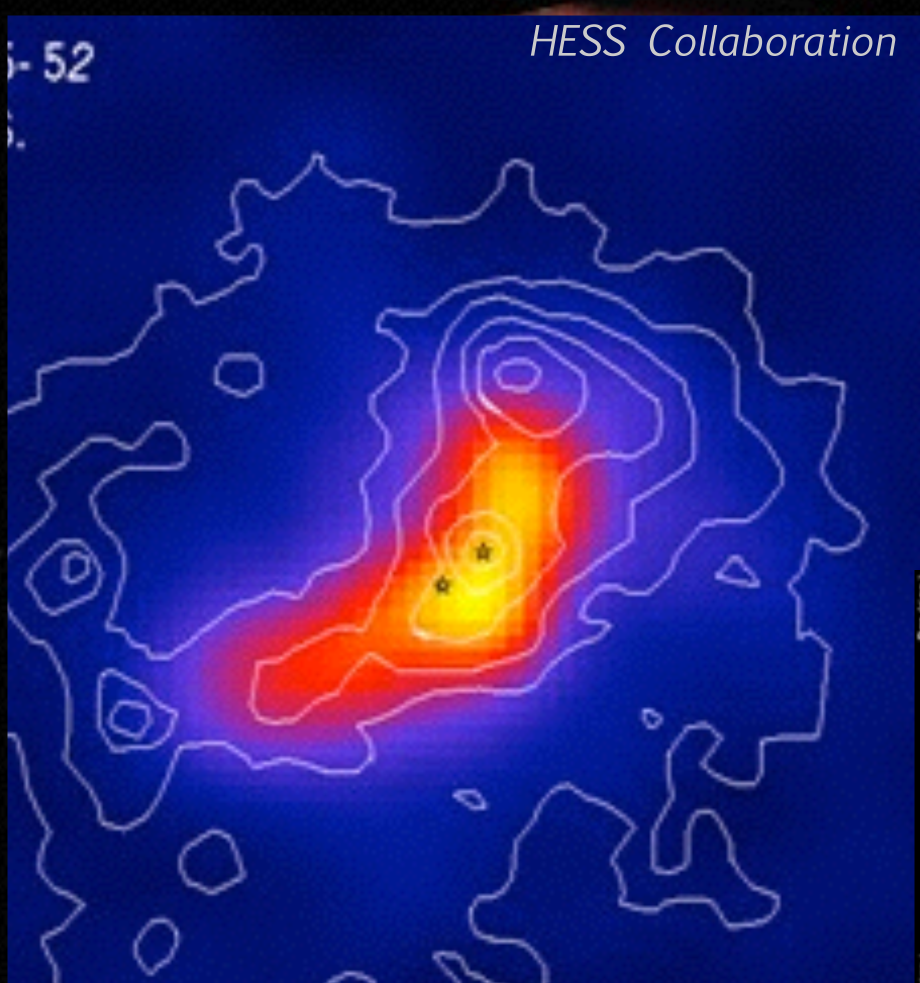

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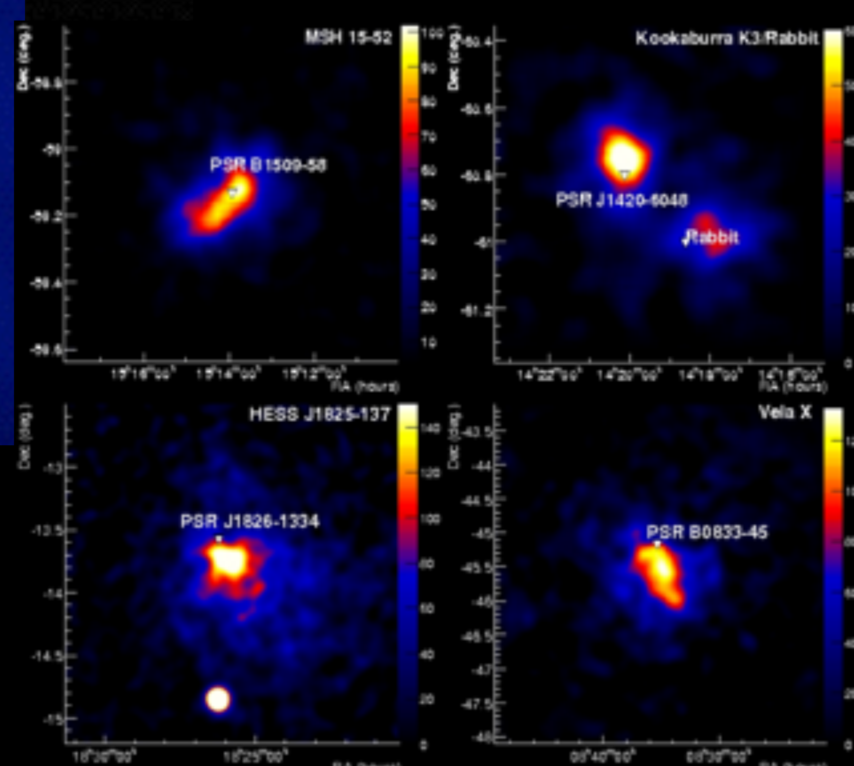

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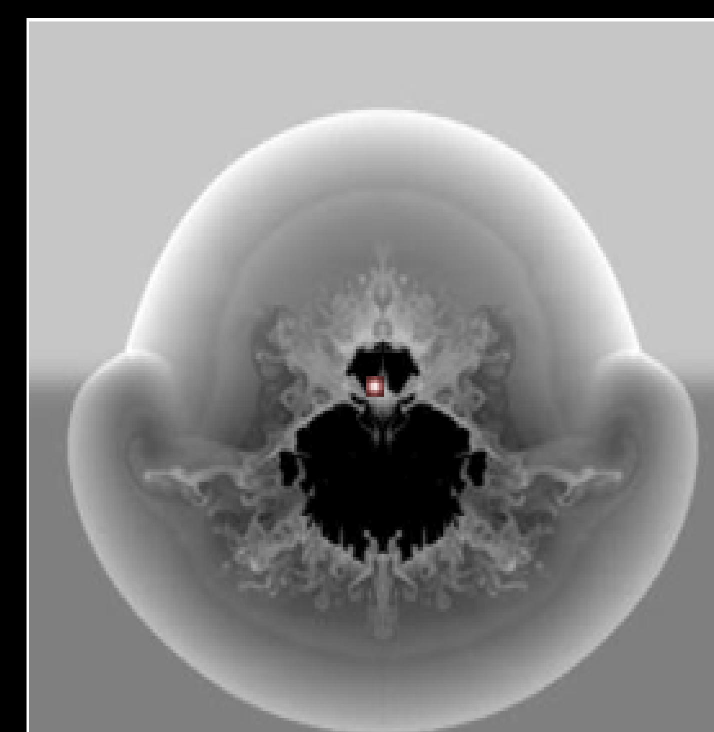

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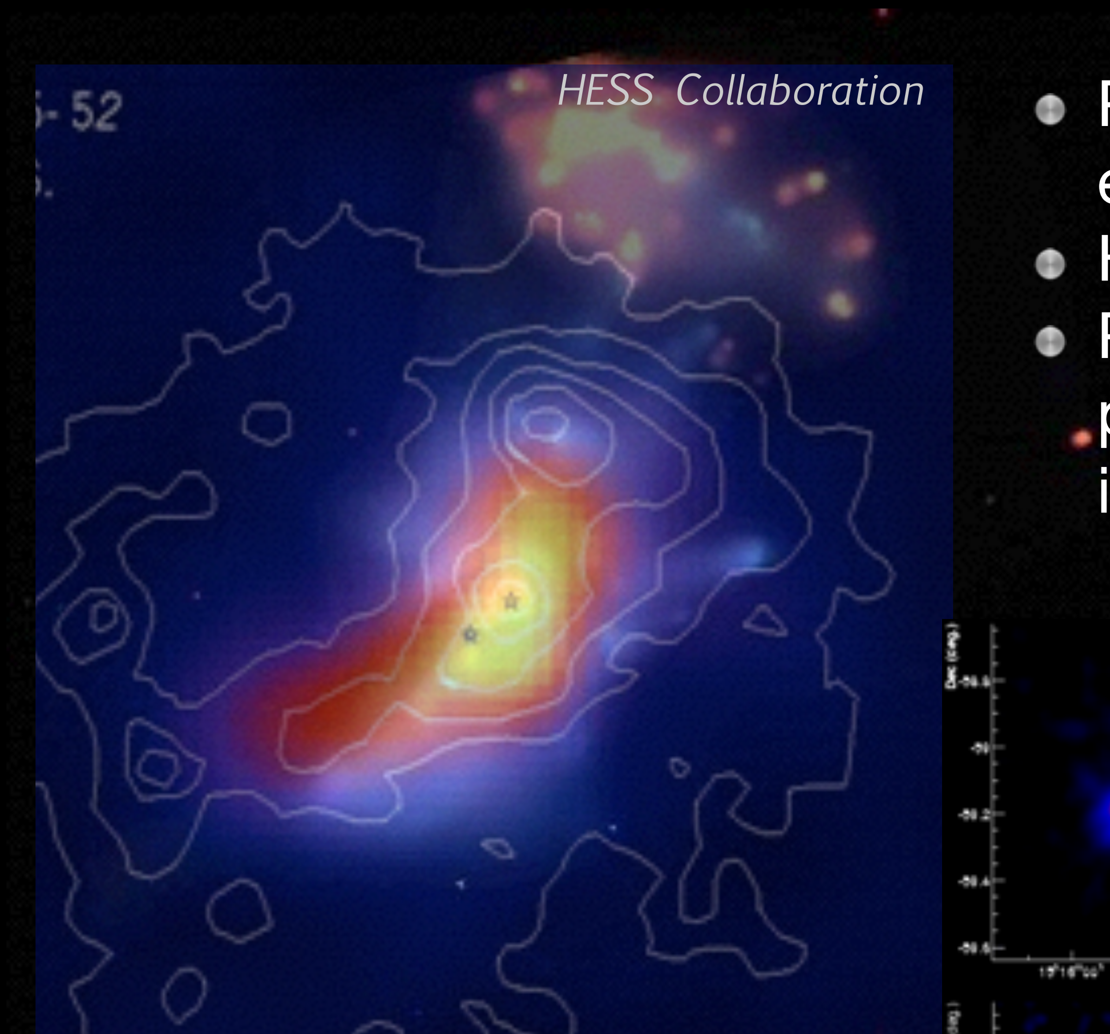

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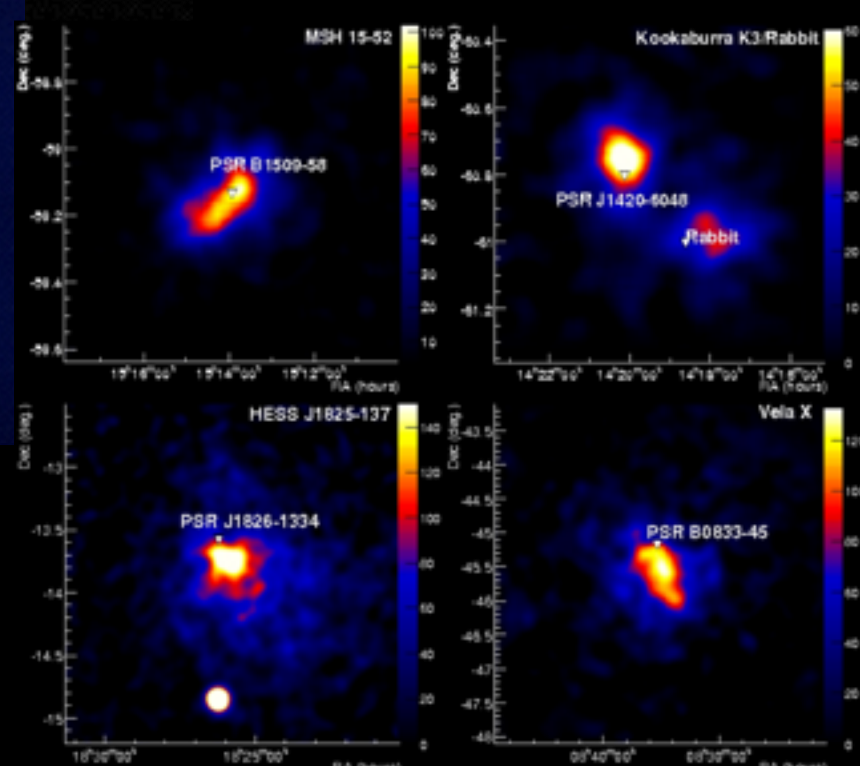

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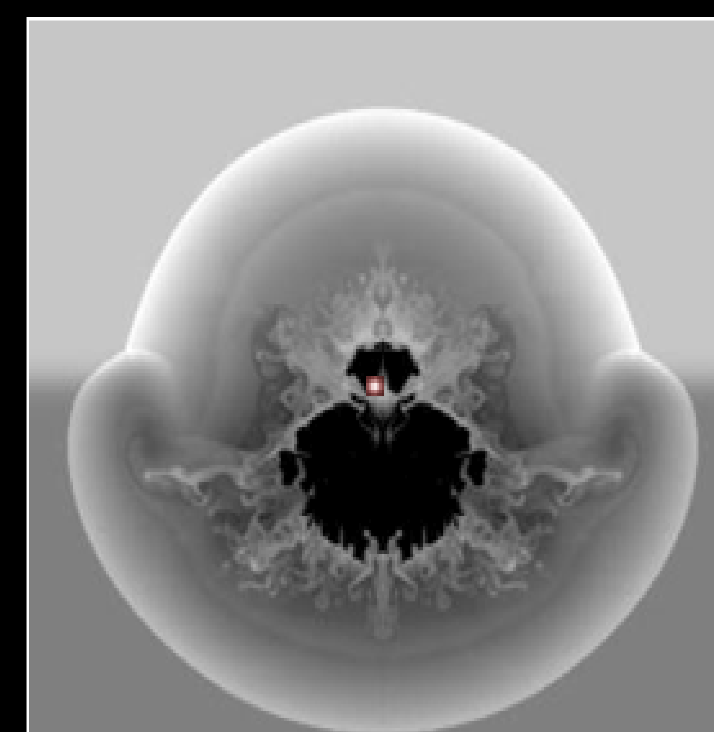

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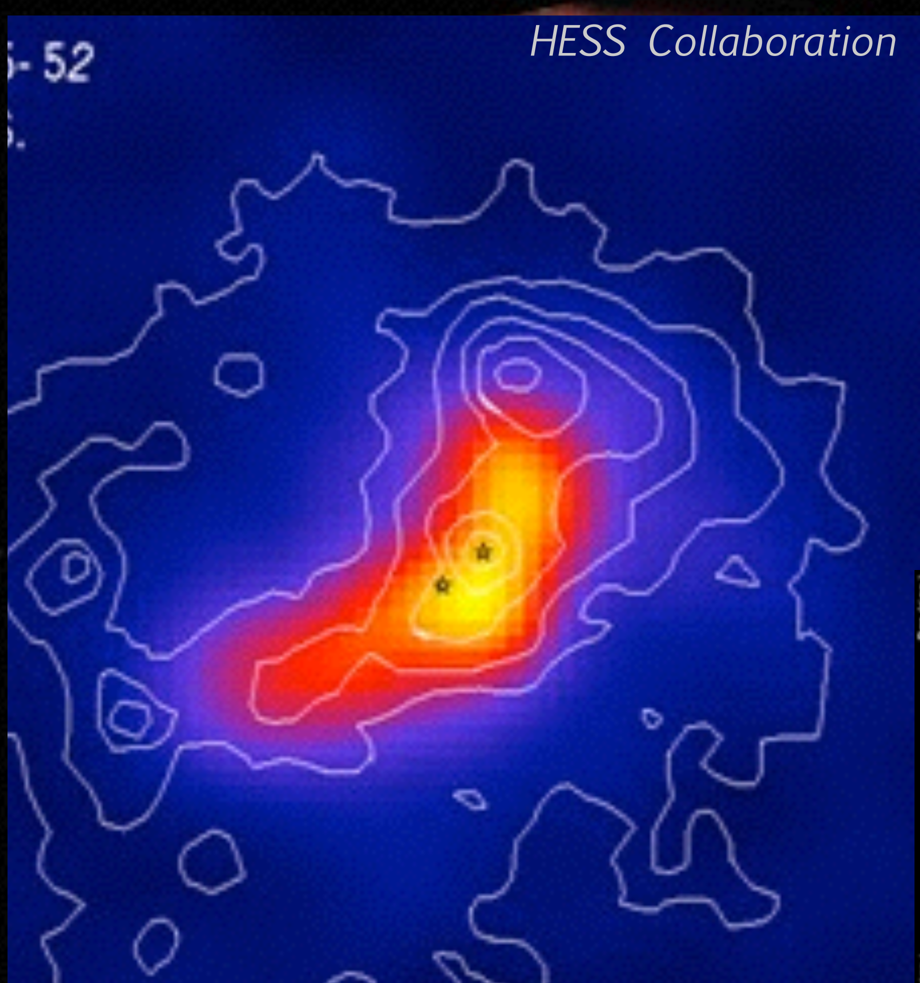

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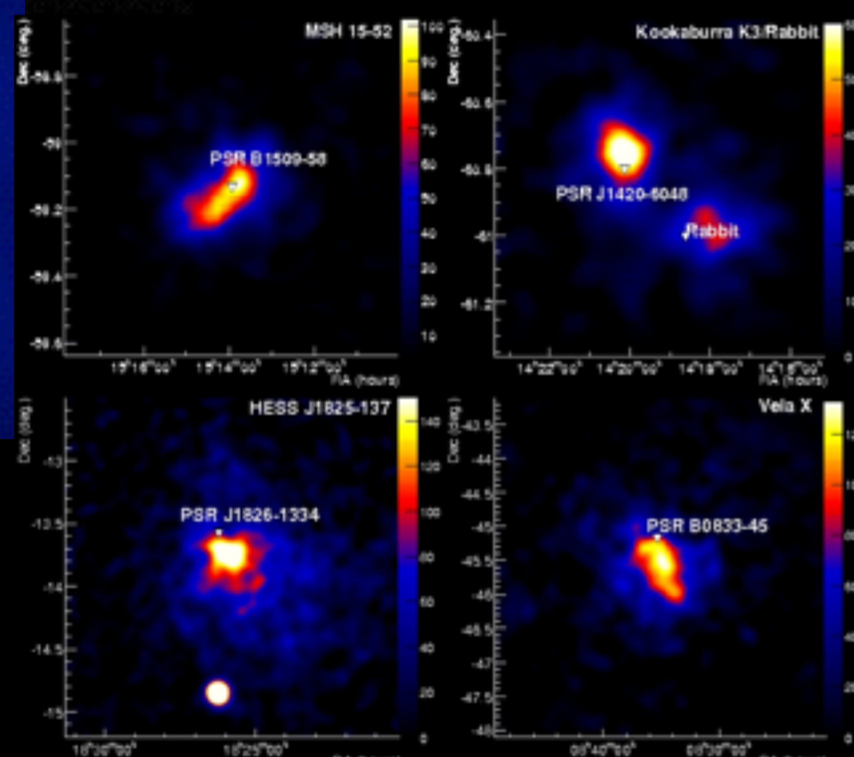

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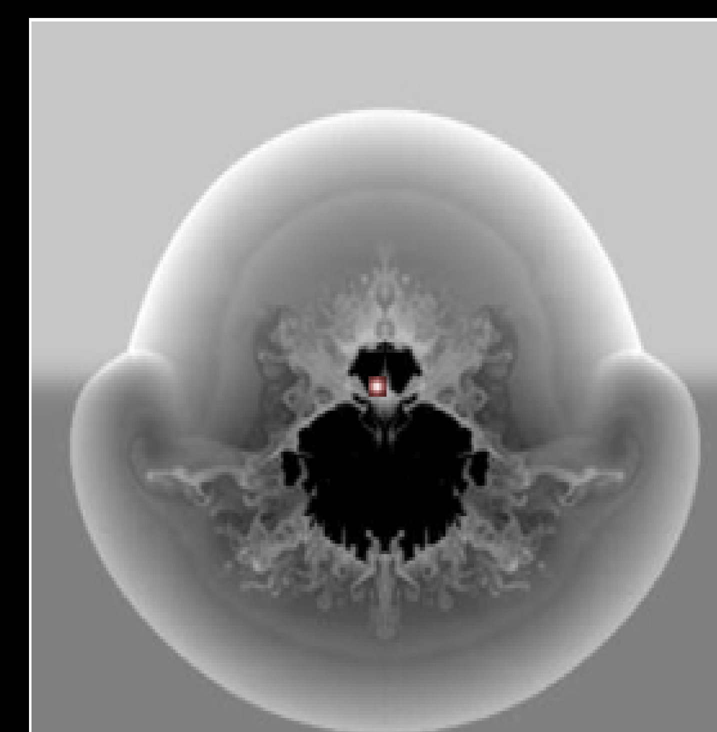

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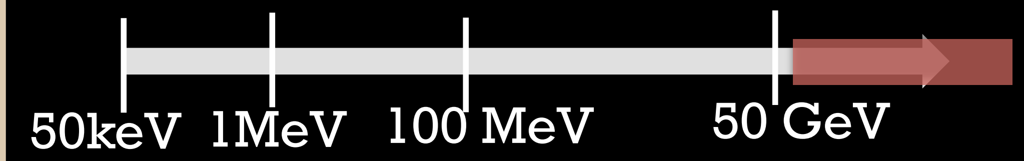
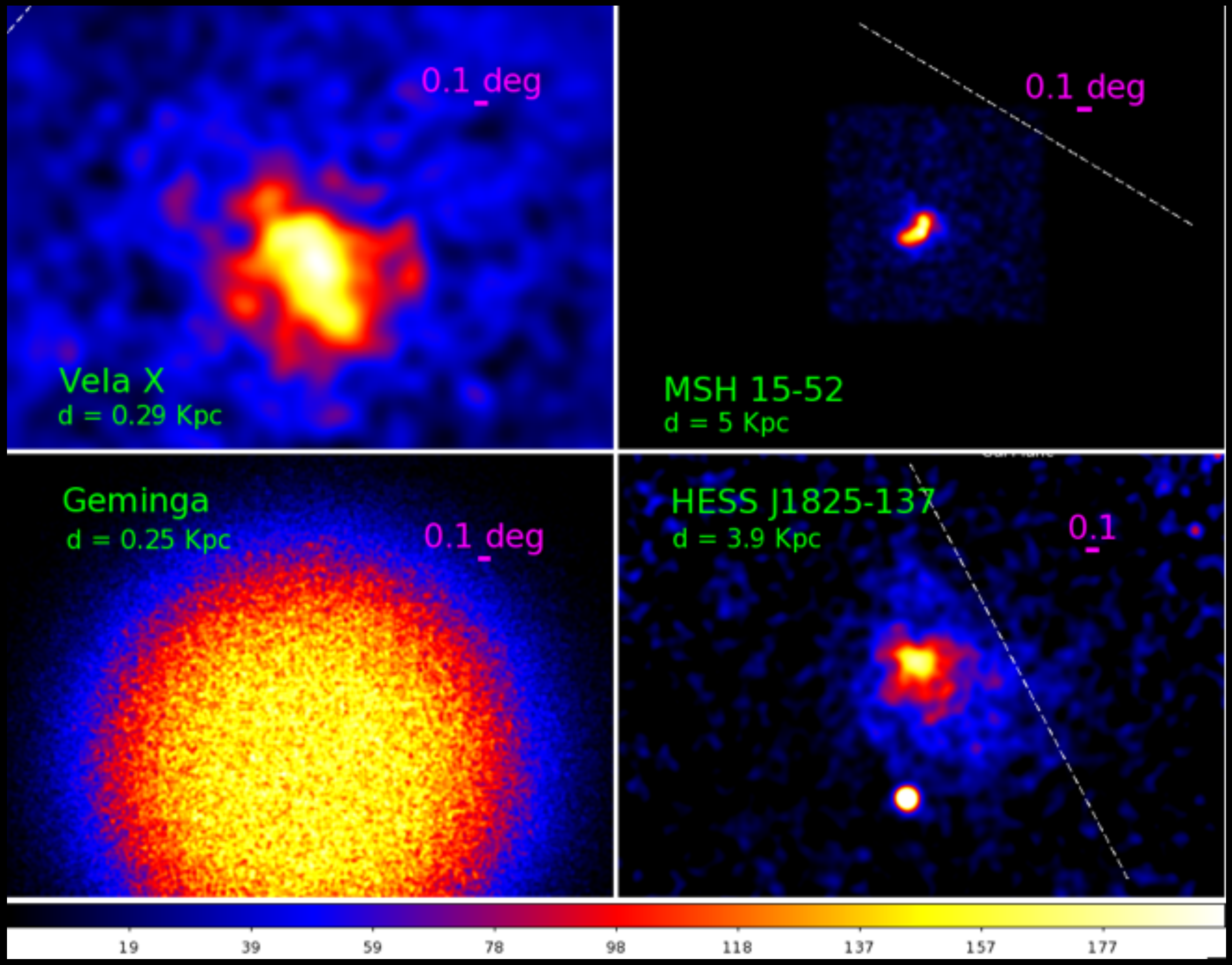


In comparison with other sources of relativistic magnetised plasma, PWNe can be resolved in great detail



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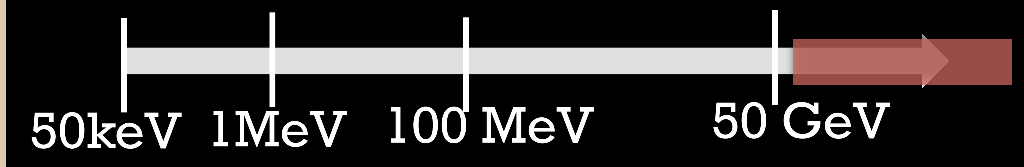

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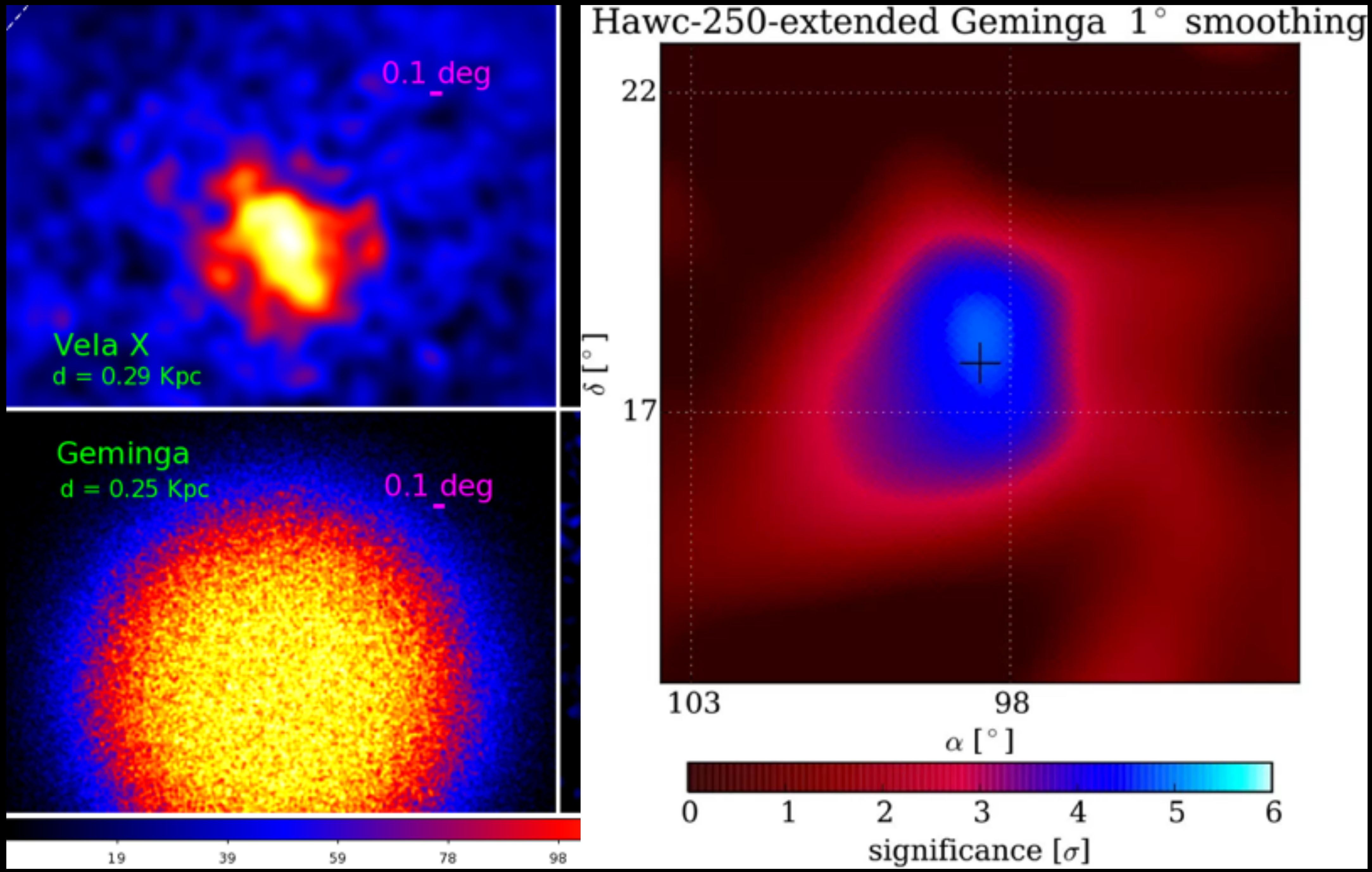

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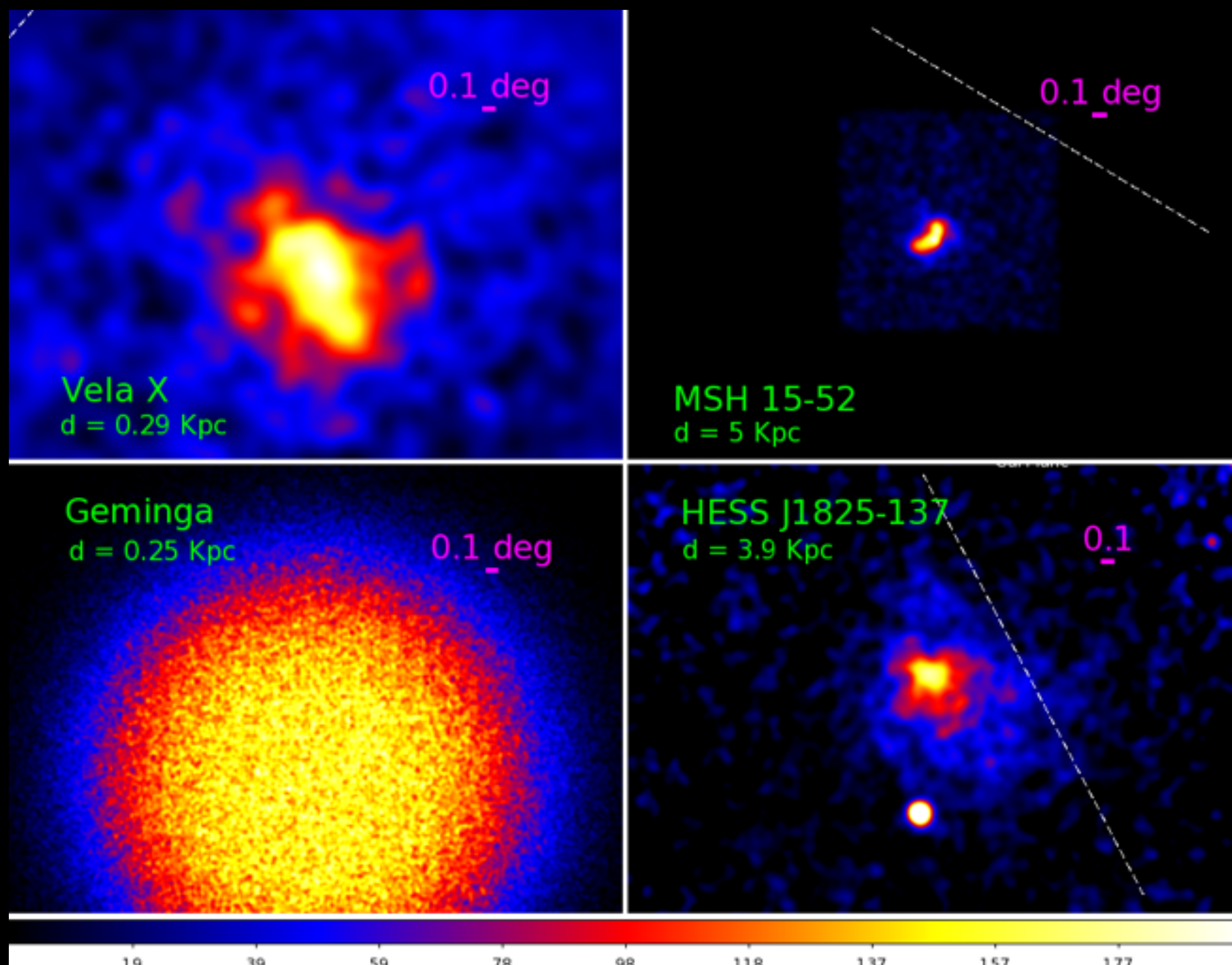

Emma de Ona Wilhelmi, TeVPA2017

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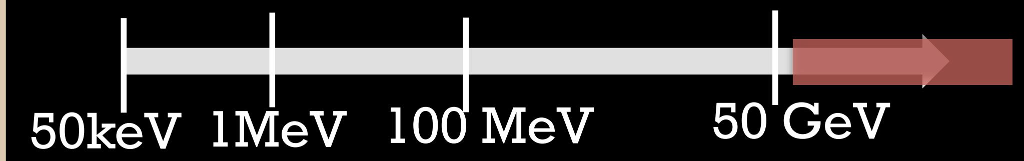

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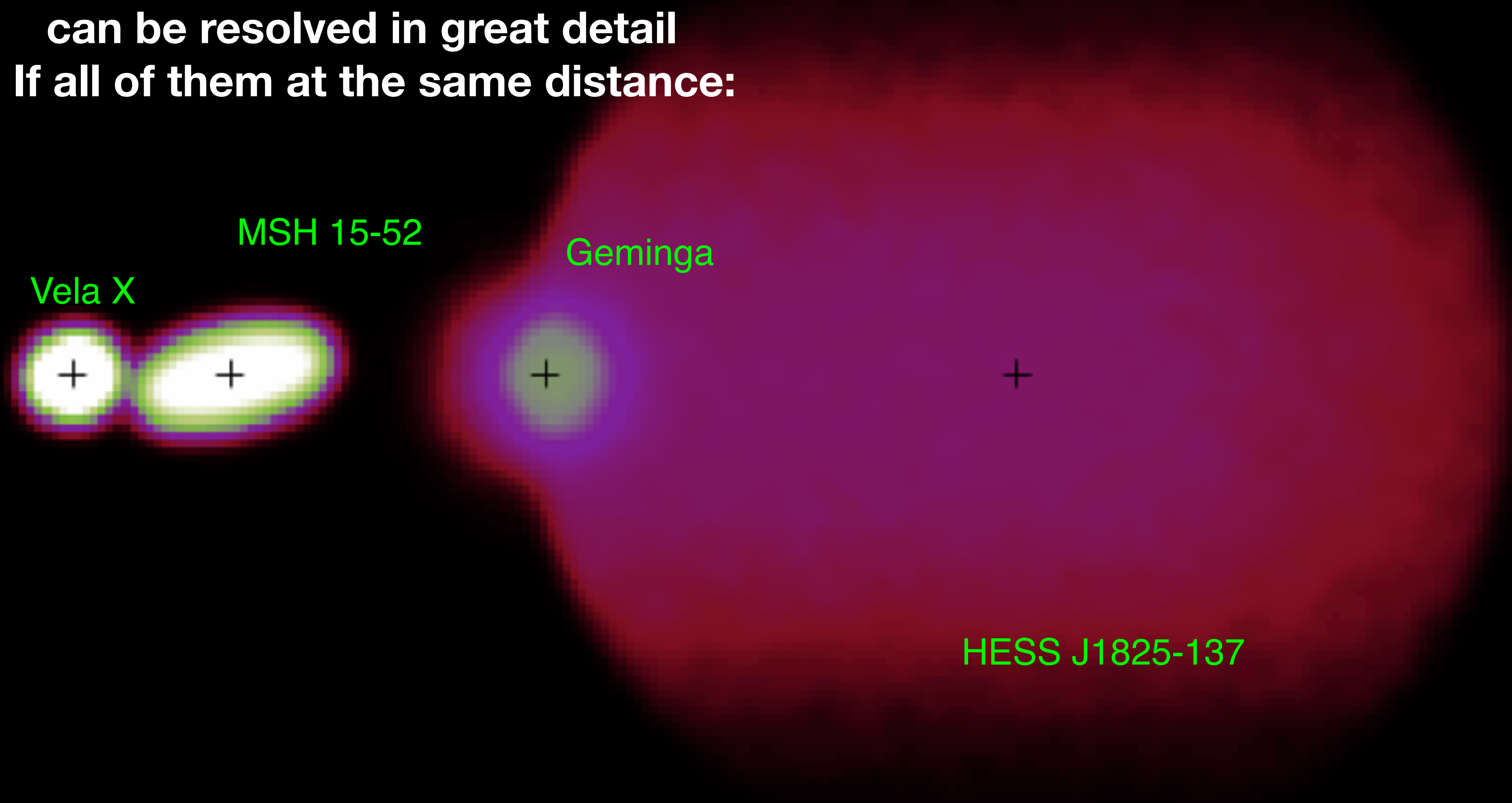

CTA Simulations using ctools* 100h

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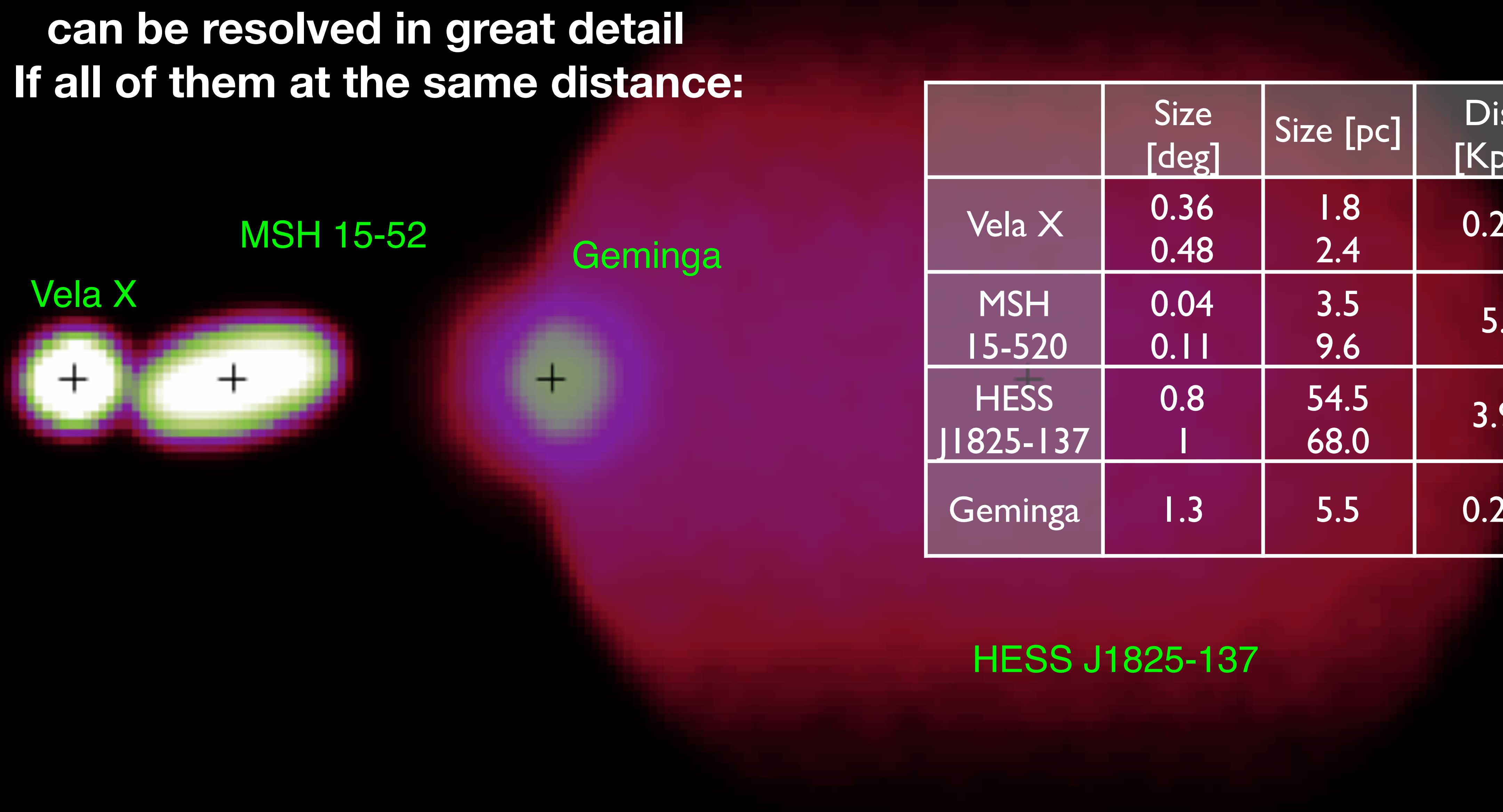

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Geminga	1.3	5.5	0.25	30.

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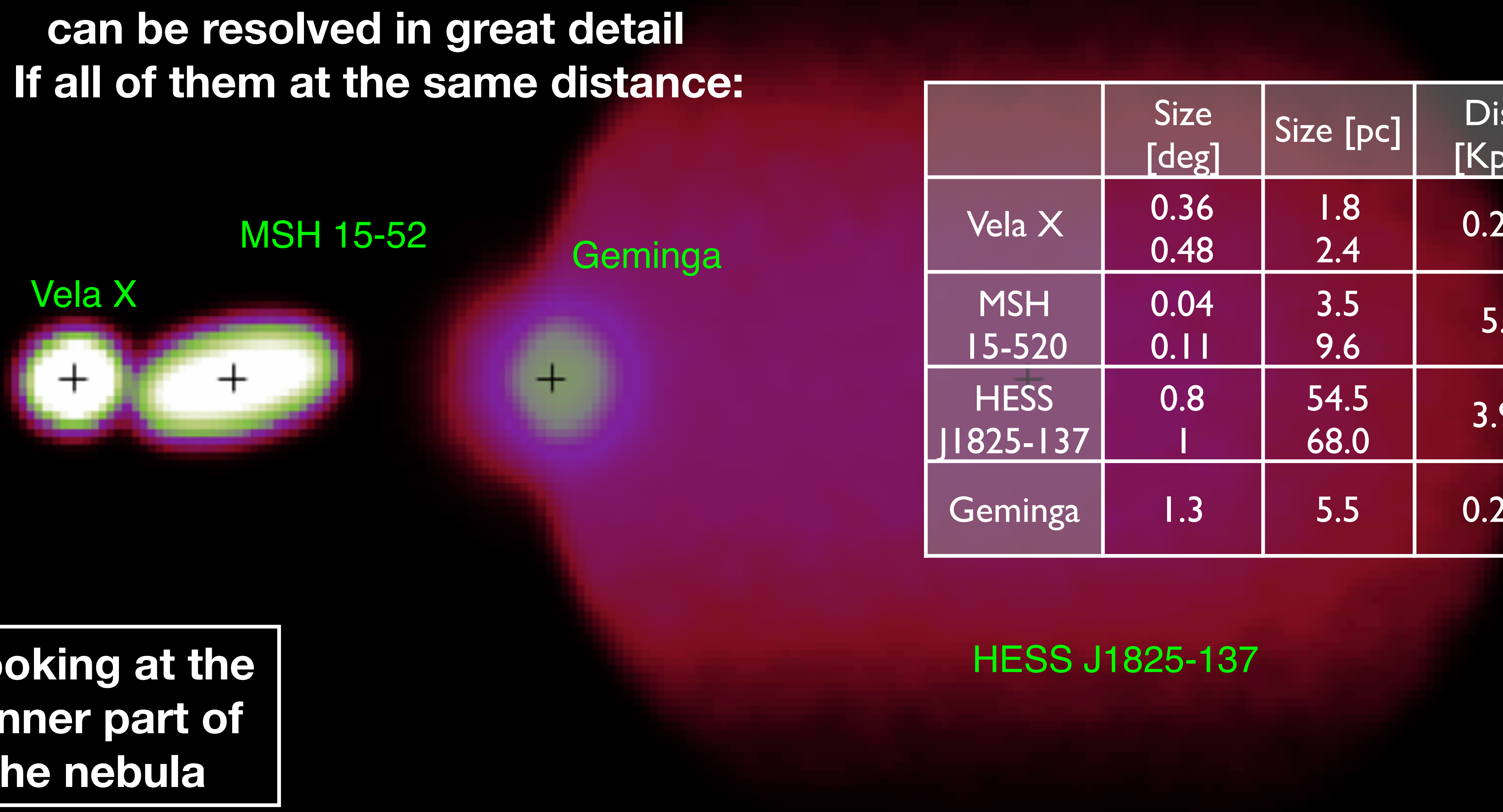

Looking at the inner part of the nebula

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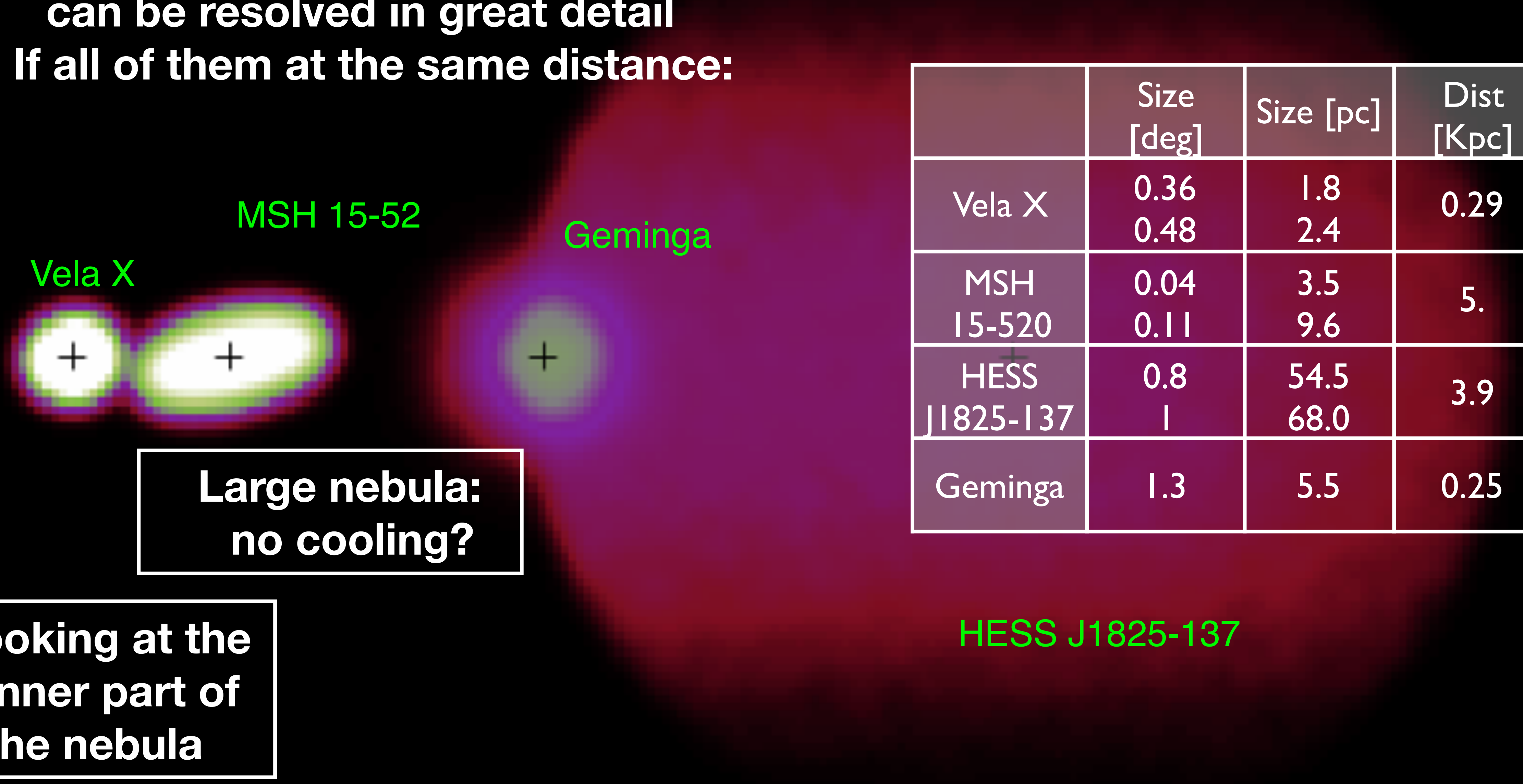

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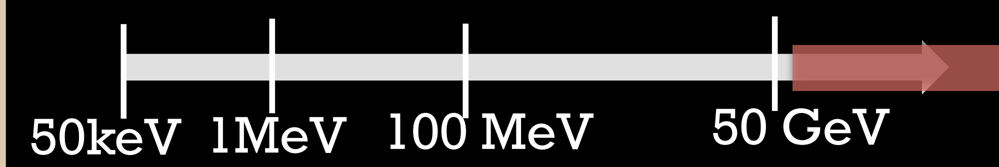

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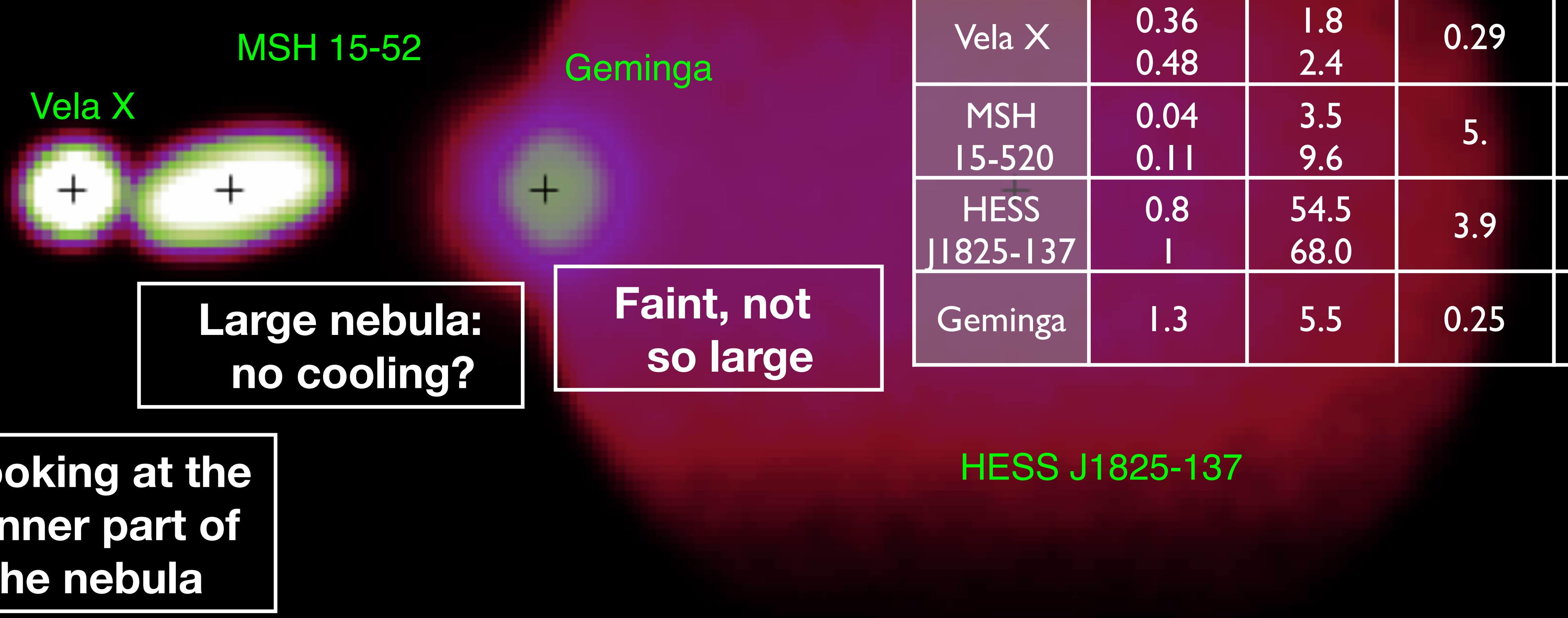

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Faint, not so large

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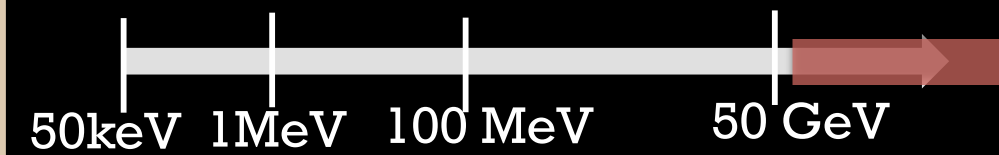

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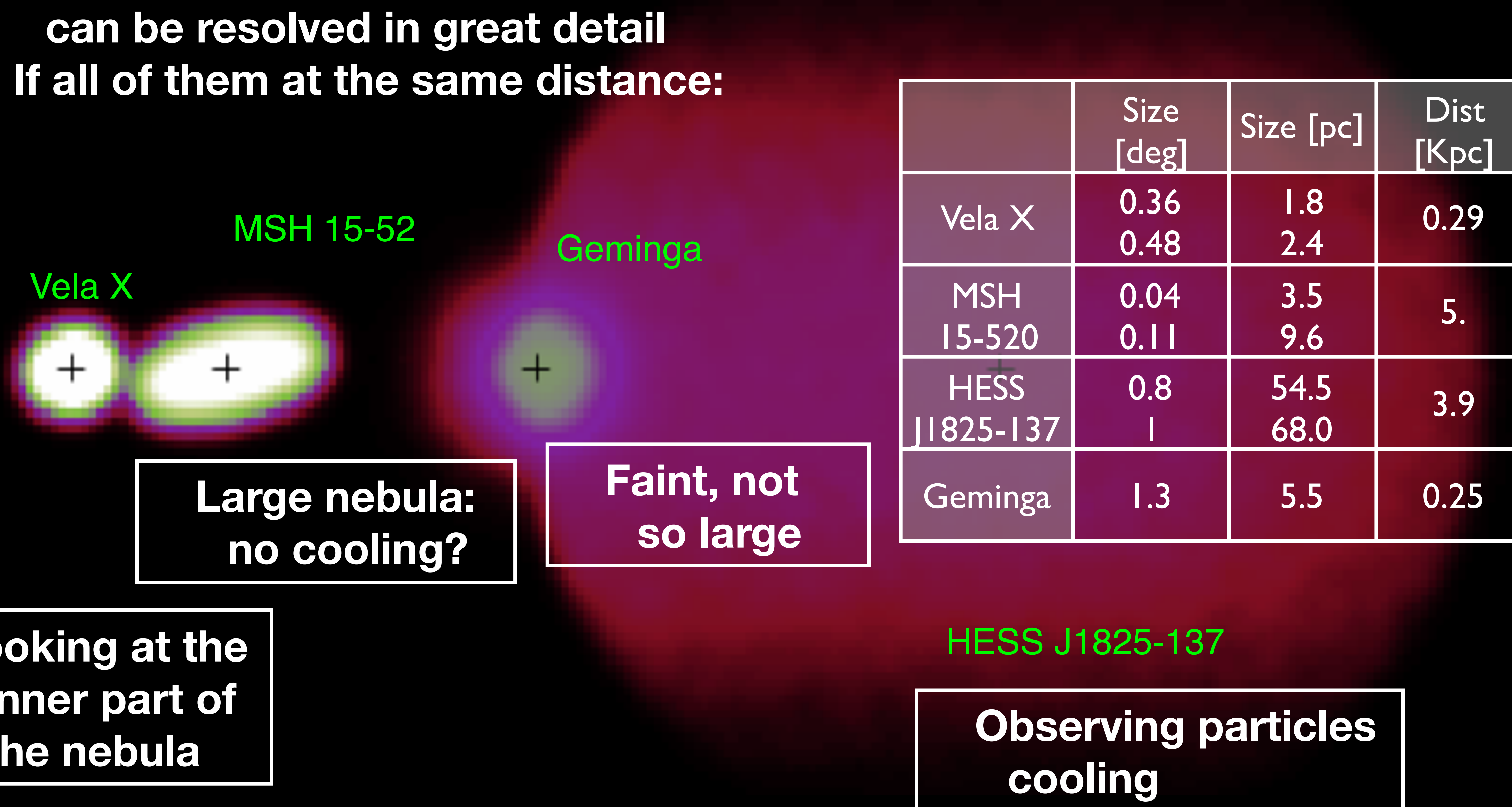

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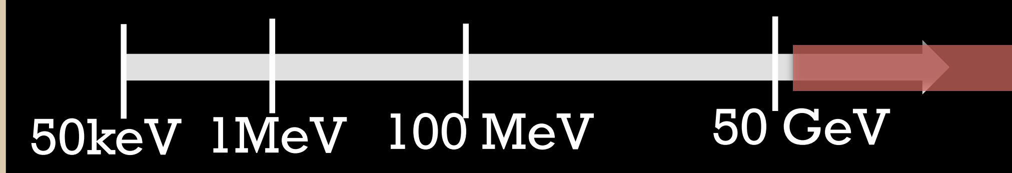

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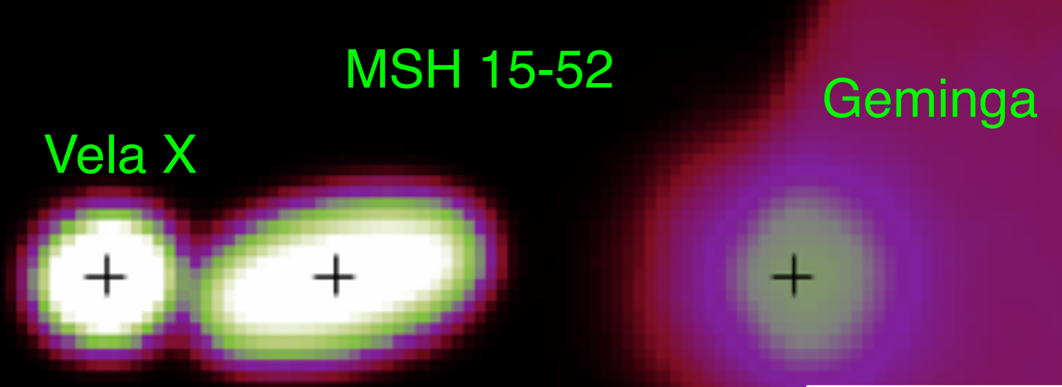

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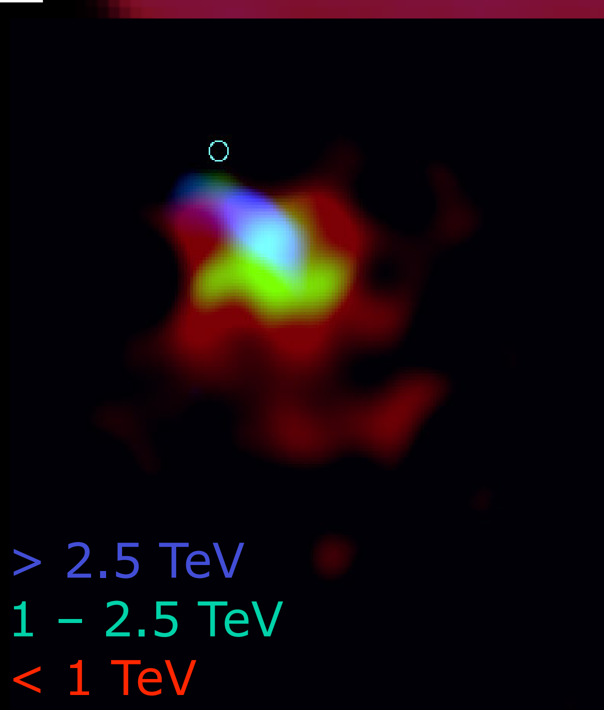

HESS J1825-137

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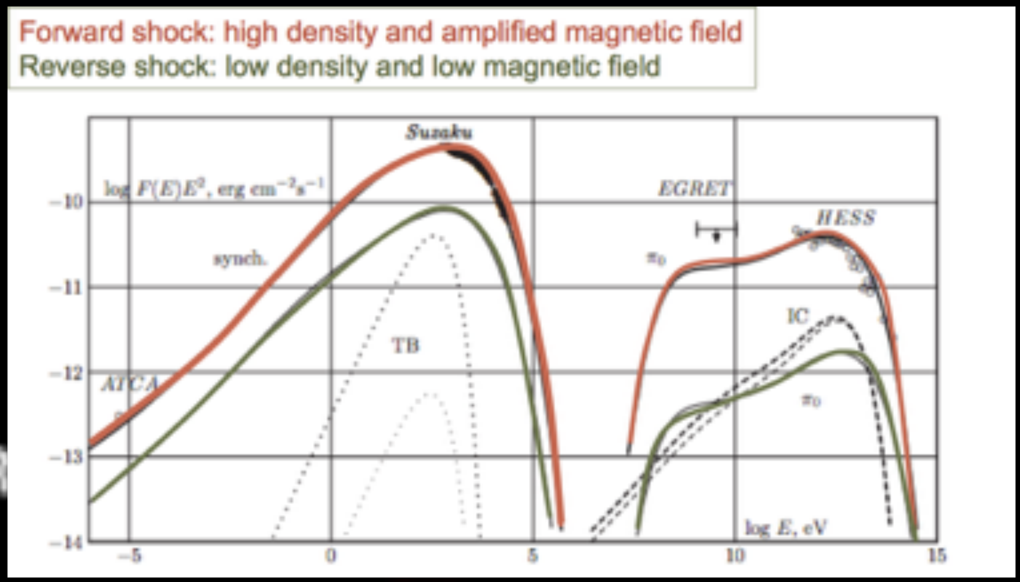
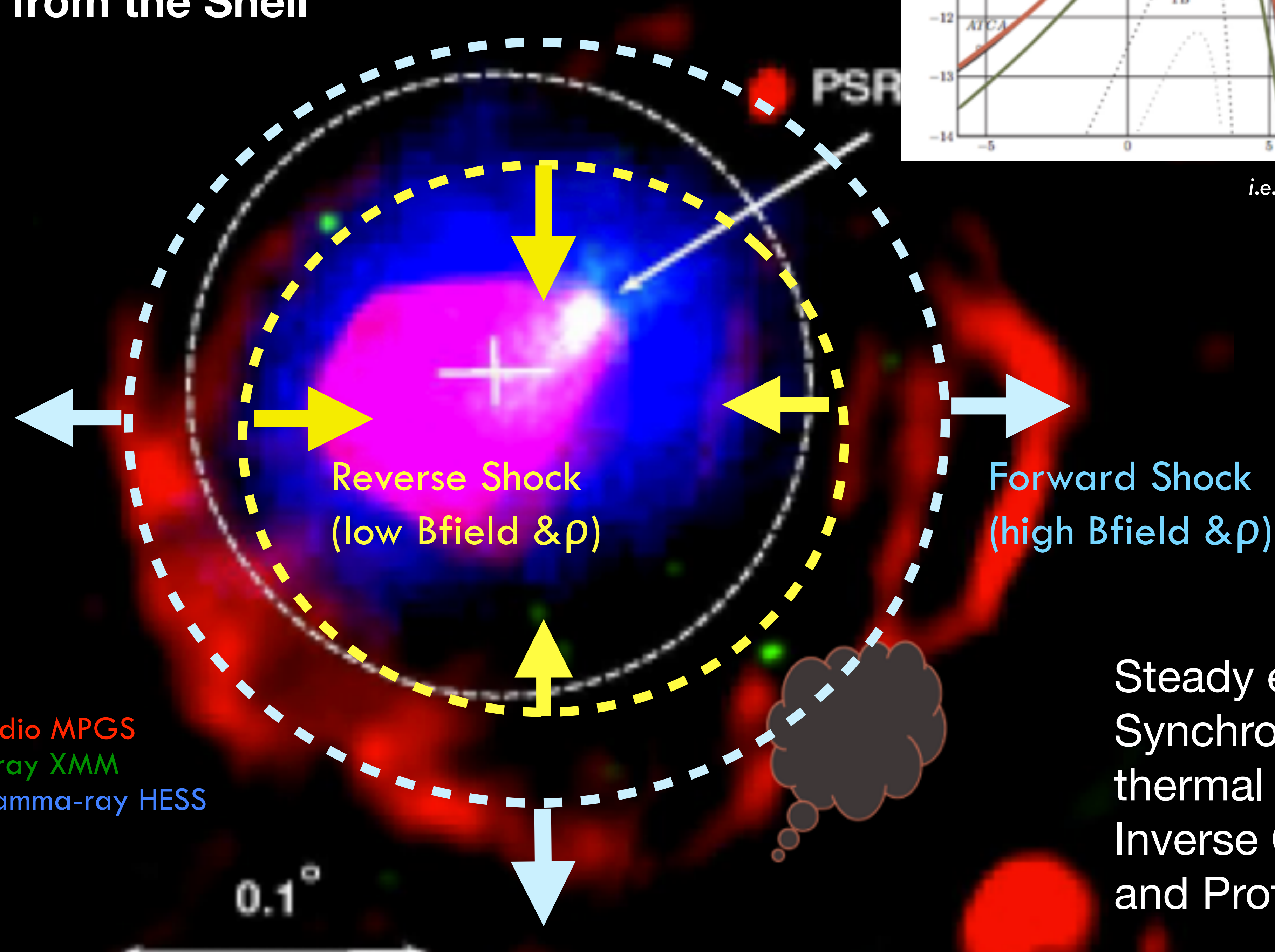
Gamma-ray Emission Regions

- Emission from the pulsar and/or the wind
- Emission from the interaction with the companion
- Emission from the PWNe
- Emission from the Shell



i.e. Zirakashvili & Aharonian, 2009



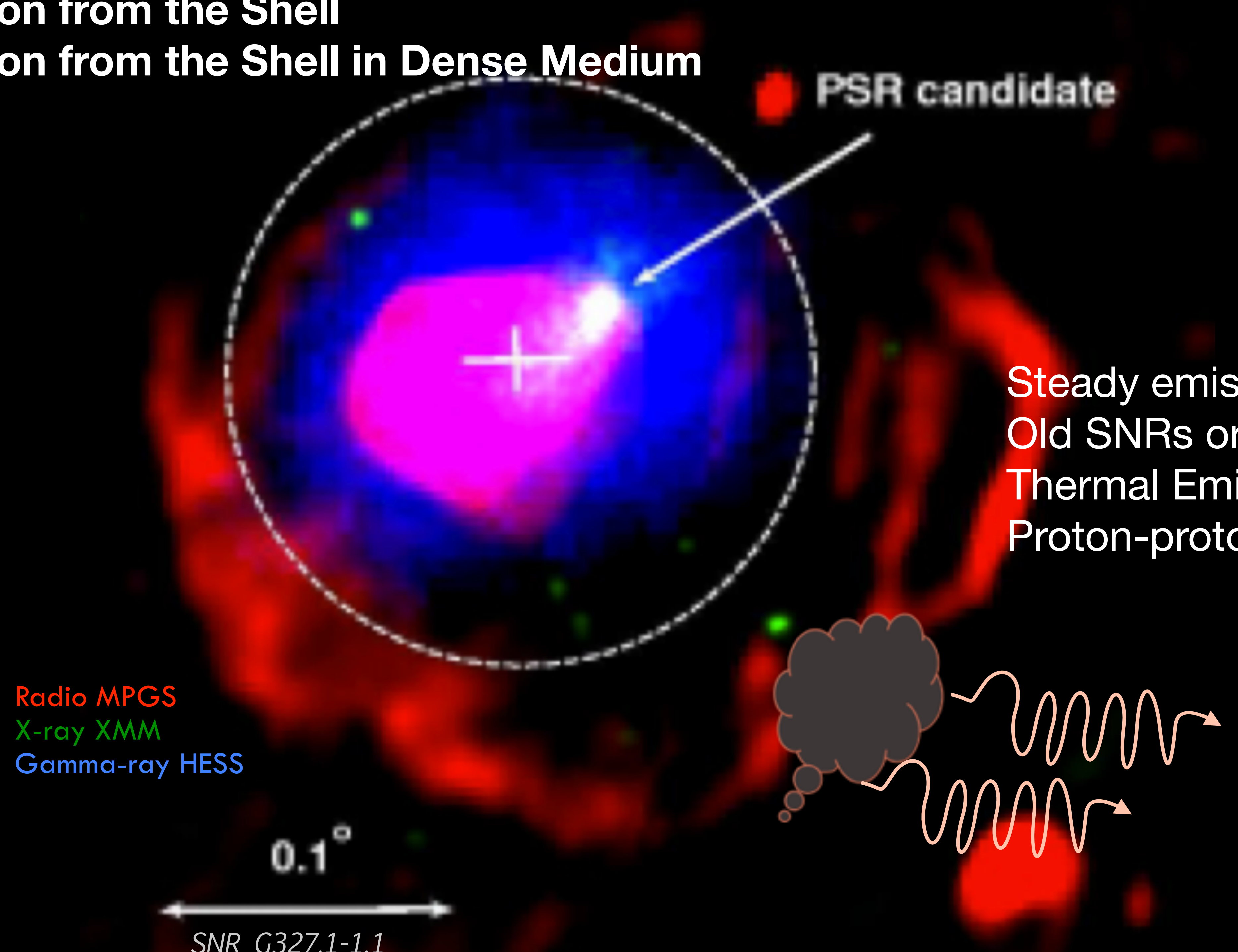
Radio MPGS
X-ray XMM
Gamma-ray HESS

SNR G327.1-1.1
Acero et al (HESS Col) 2011

Steady emission
Synchrotron and thermal Emission
Inverse Compton or/and Proton-proton

Gamma-ray Emission Regions

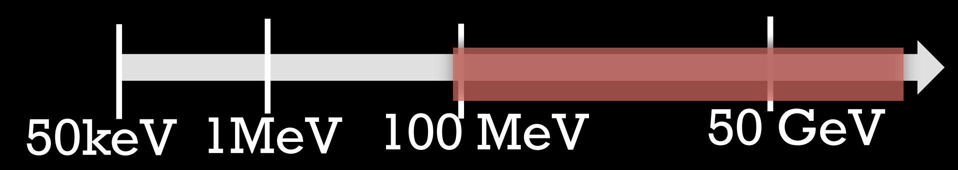
Emission from the pulsar and/or the wind
Emission from the interaction with the companion
Emission from the PWNe
Emission from the Shell
Emission from the Shell in Dense Medium



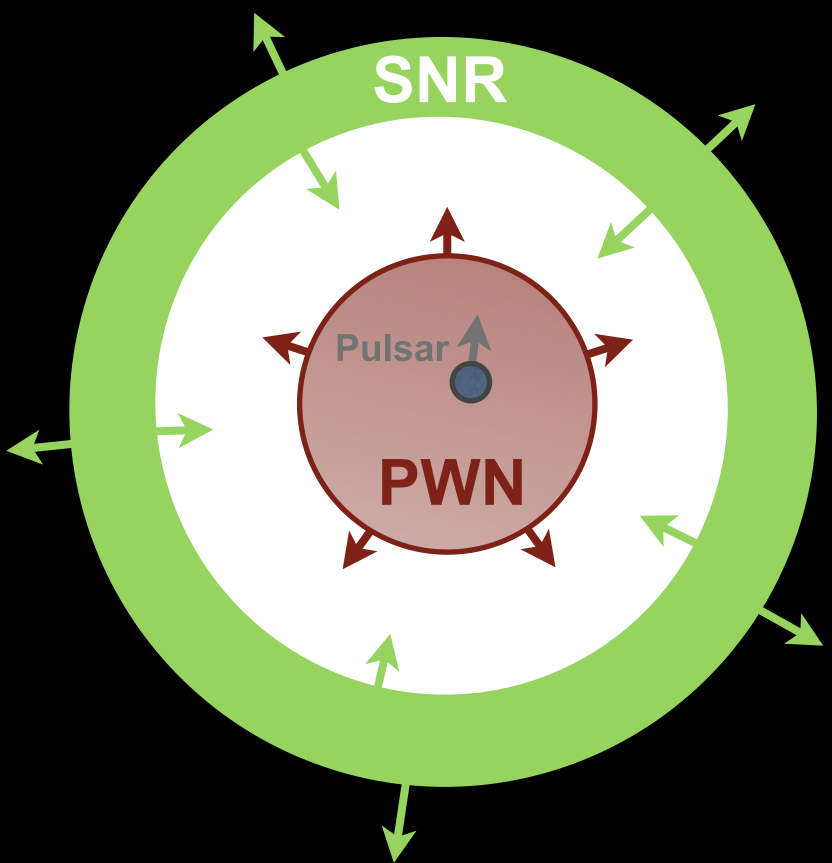
Steady emission
Old SNRs or in dense region
Thermal Emission
Proton-proton

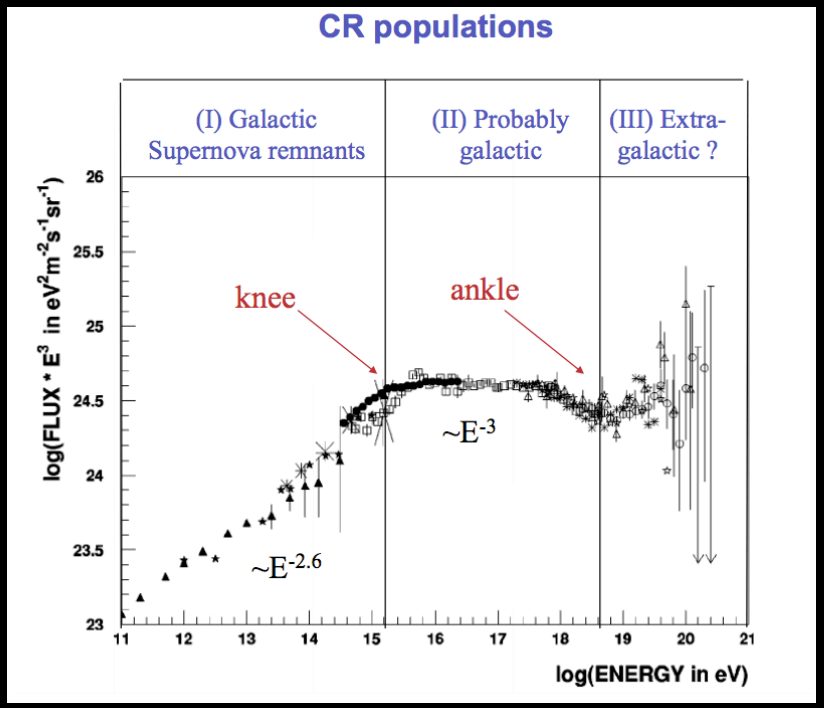
SNR G327.1-1.1
Acero et al (HESS Col) 2011

Supernova Remnants



Question since 1912 :
What is the origen of Galactic Cosmic Rays?

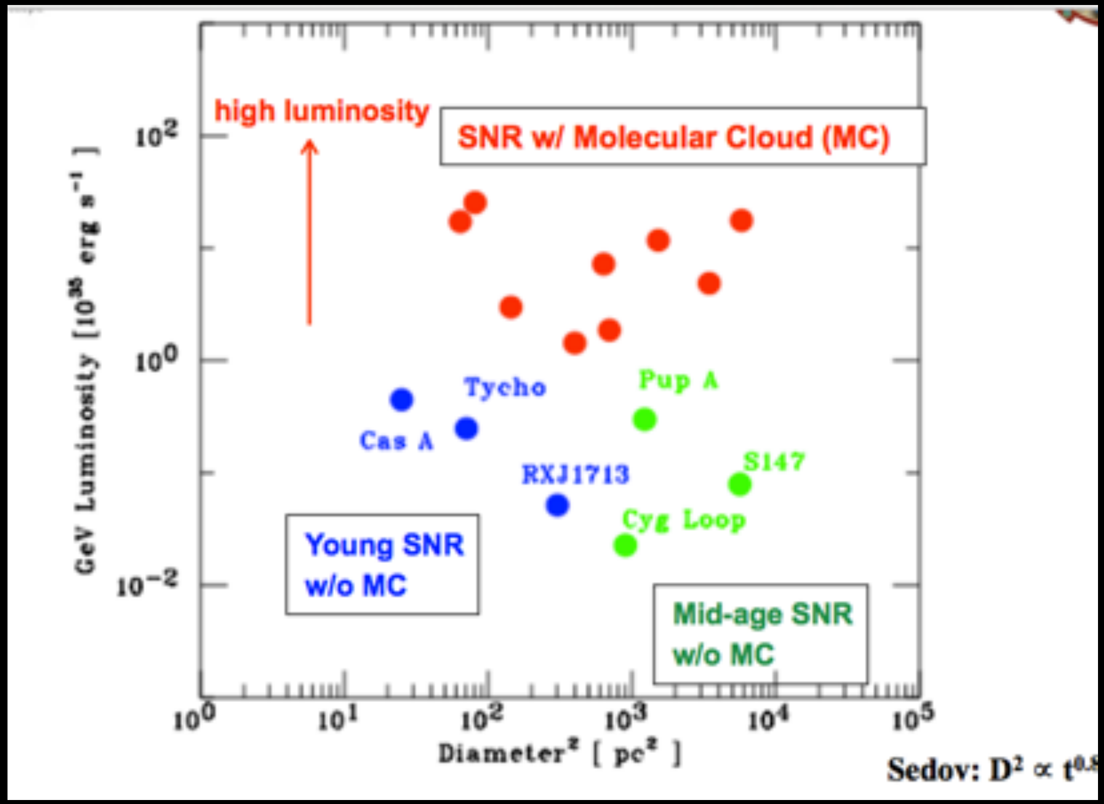




Non-linear diffuse shock acceleration theory (Fermi first order acceleration) in shells provides the right spectral index, high P_{CR}, magnetic field amplification and E_{max}~E_{knee}

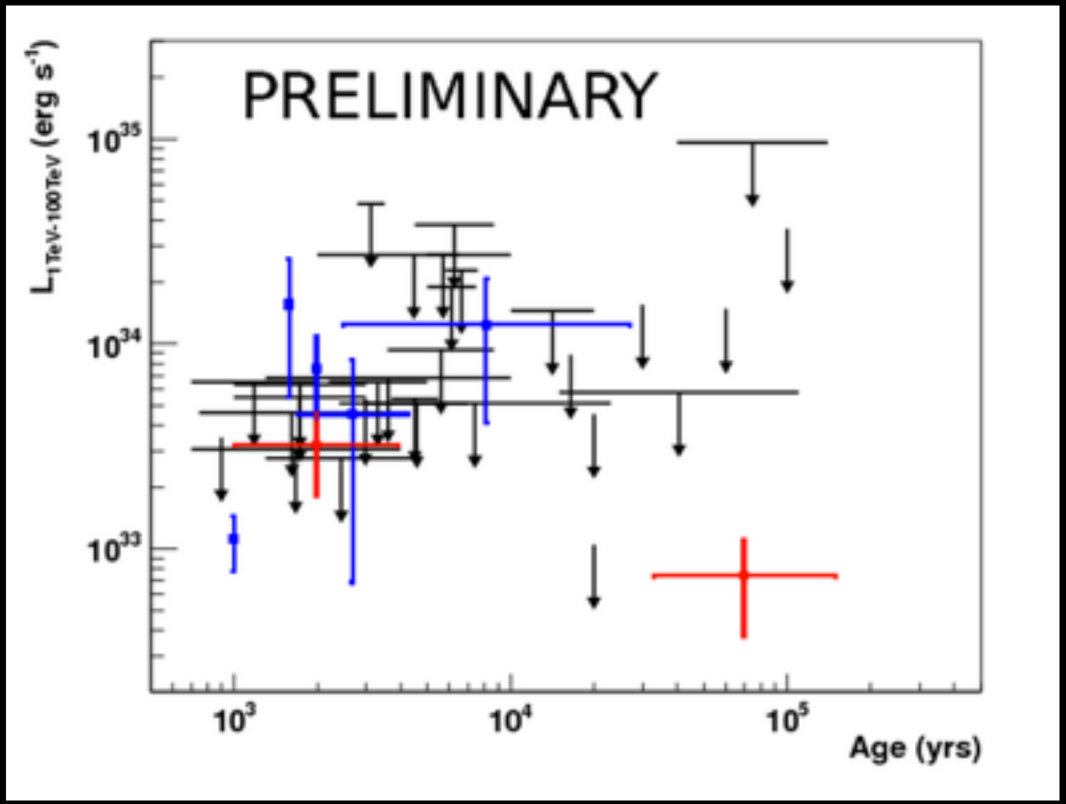
Large GeV & TeV data set has revealed two type of gamma-ray emitter SNRs

GeV



Uchiyama et al (Fermi LAT), 2013
see also Hewitt talk TeVPA 2017

TeV



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GeV: high luminosity in old SNRs, pion decay peak found!
This trend is not present at TeV energies:
Leptonic dominant? Escape of CR in old SNRs? Maximum energy of accelerated particles?

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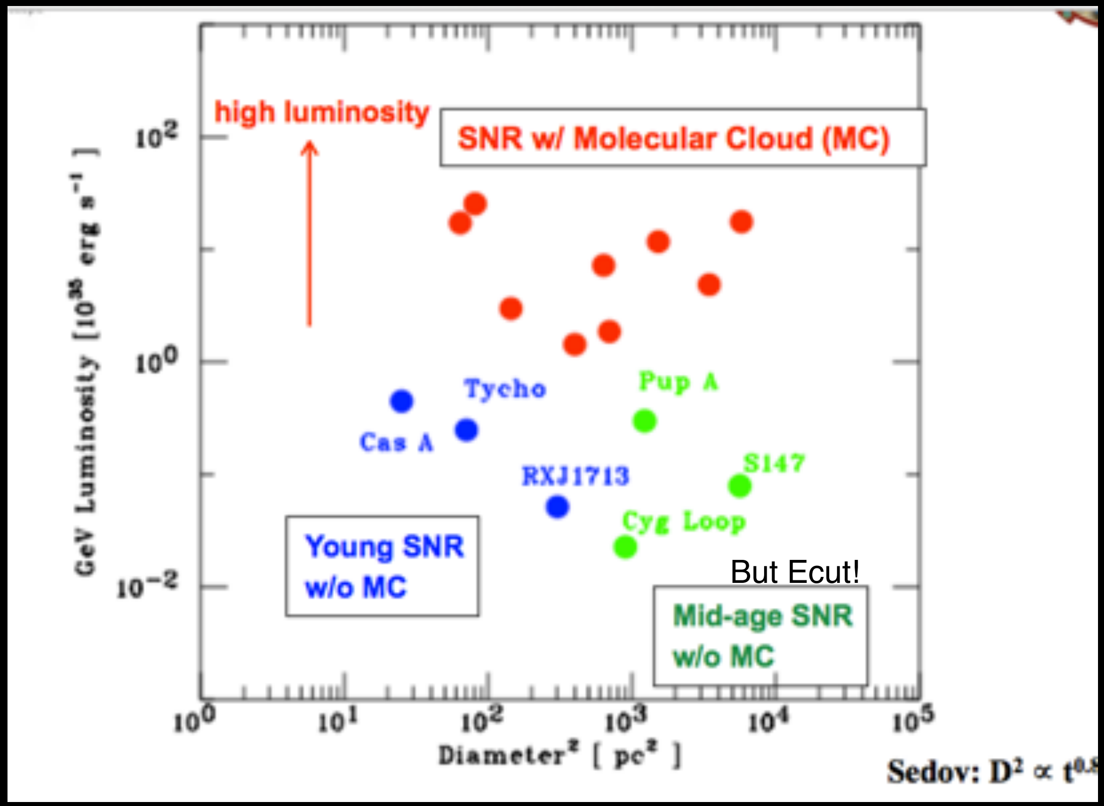

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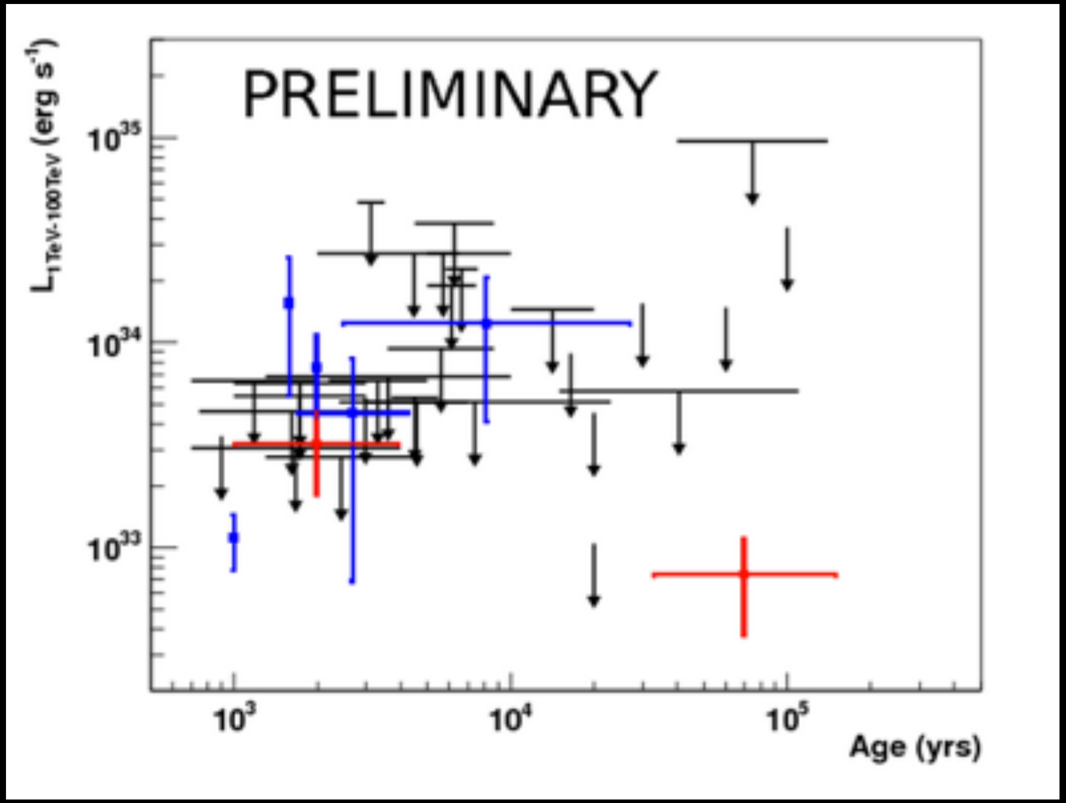

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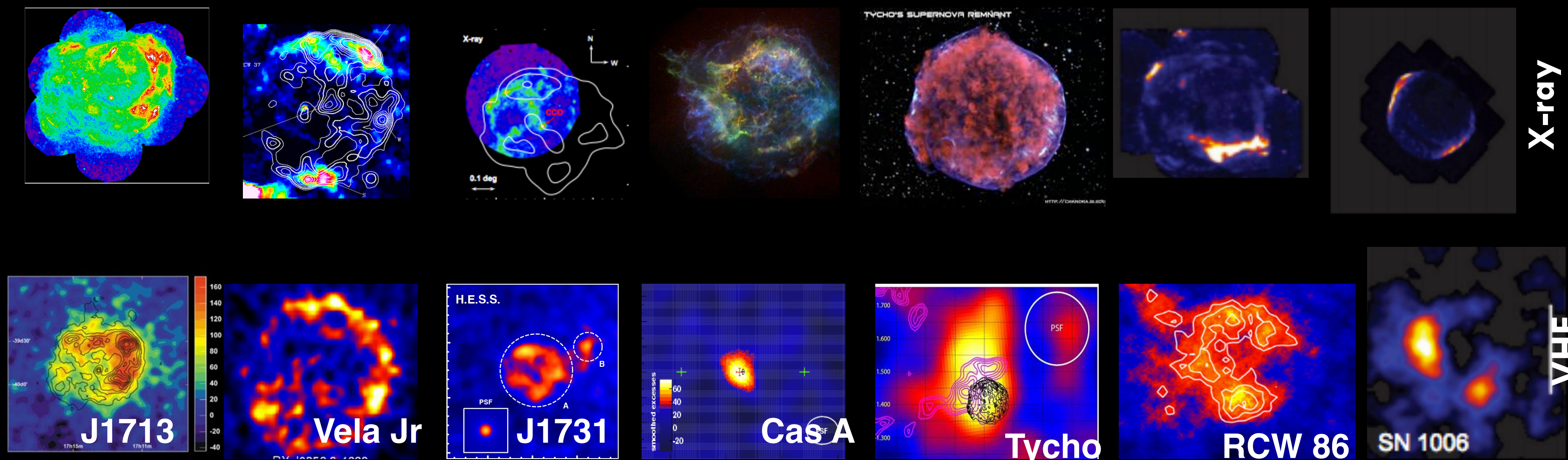
Young (bright TeV) SNRs



Core-collapse SN

SN Type Ia

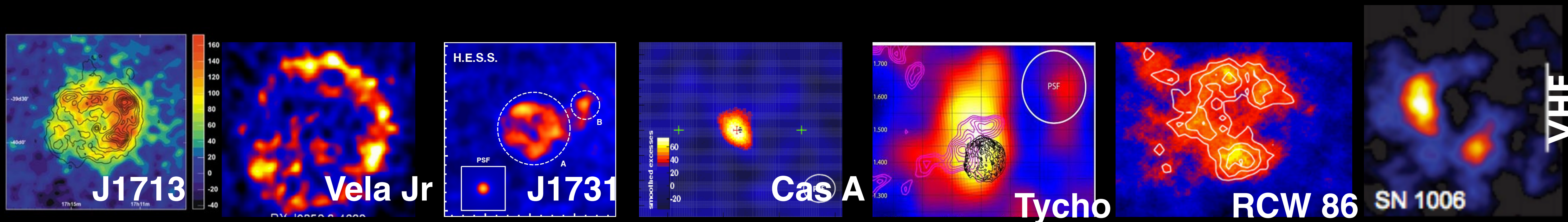
GeV counterpart / Spectral Index

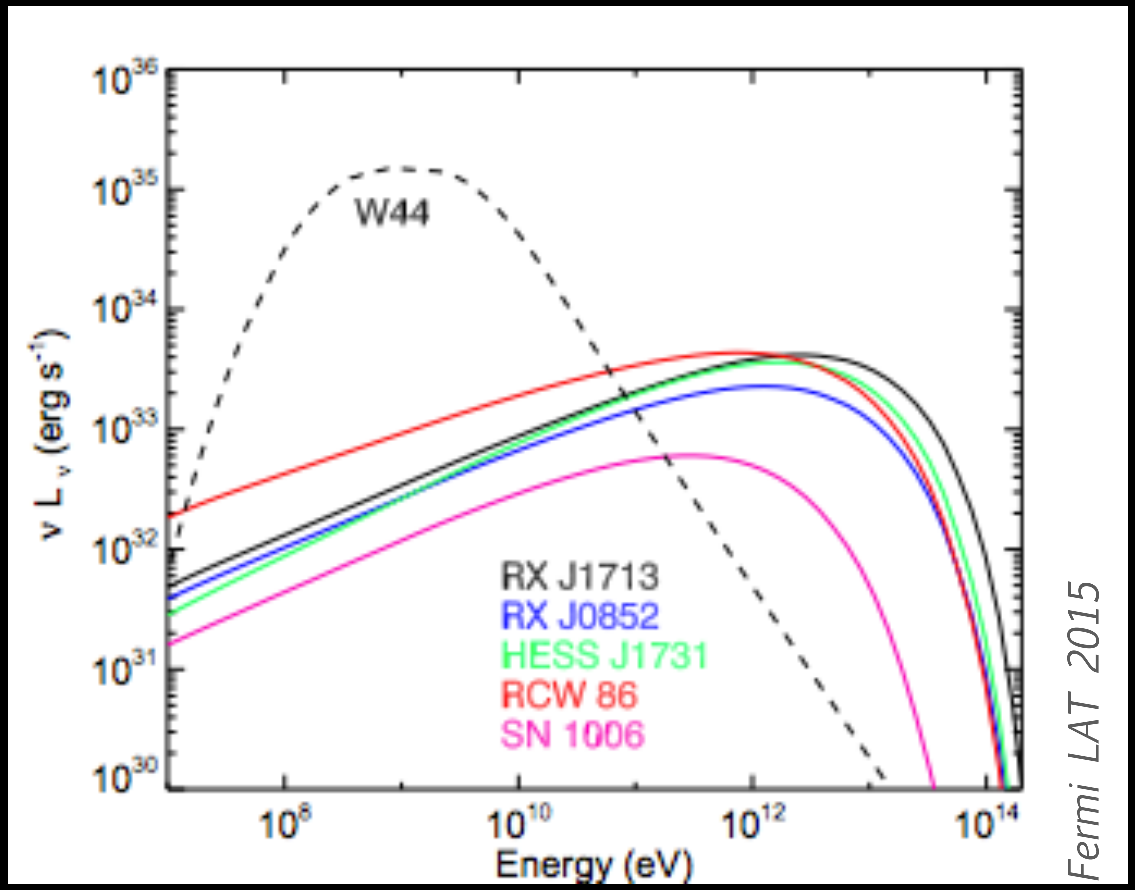
Yes/1.5	Yes/1.85	No/2.32	Yes/2.0	Yes/2.6	Yes/1.8	No/2.0

Density [cm^{-3}]

<0.02	<0.03	<0.02	0.1-1	0.1-1	0.01-1	<0.05

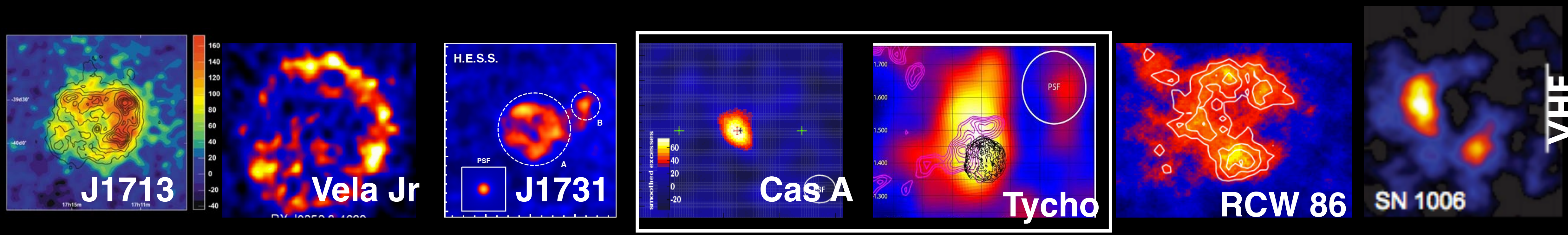
see also Auchettl, Slane in TeVPA 2017



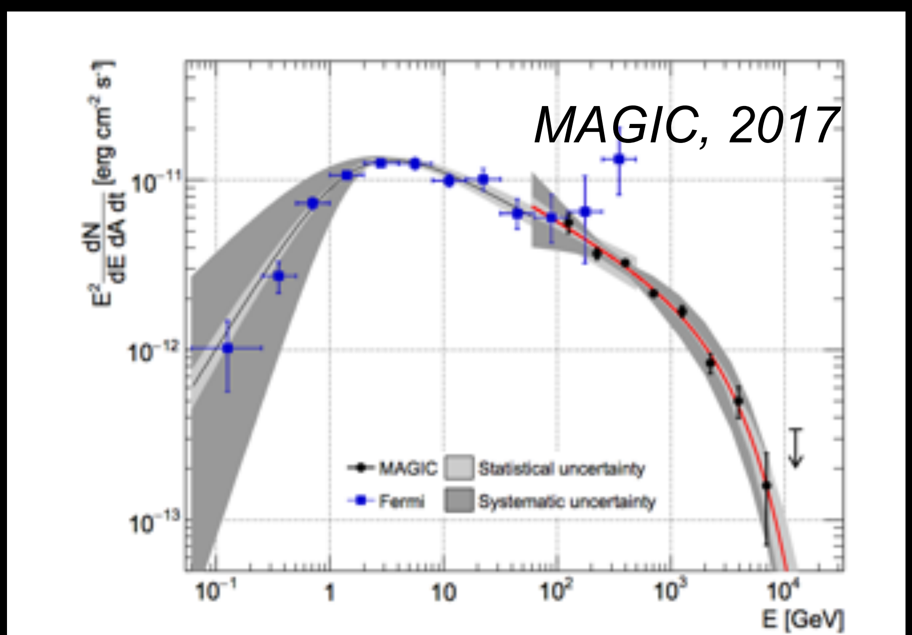


TeV Remnants with low B_{field}

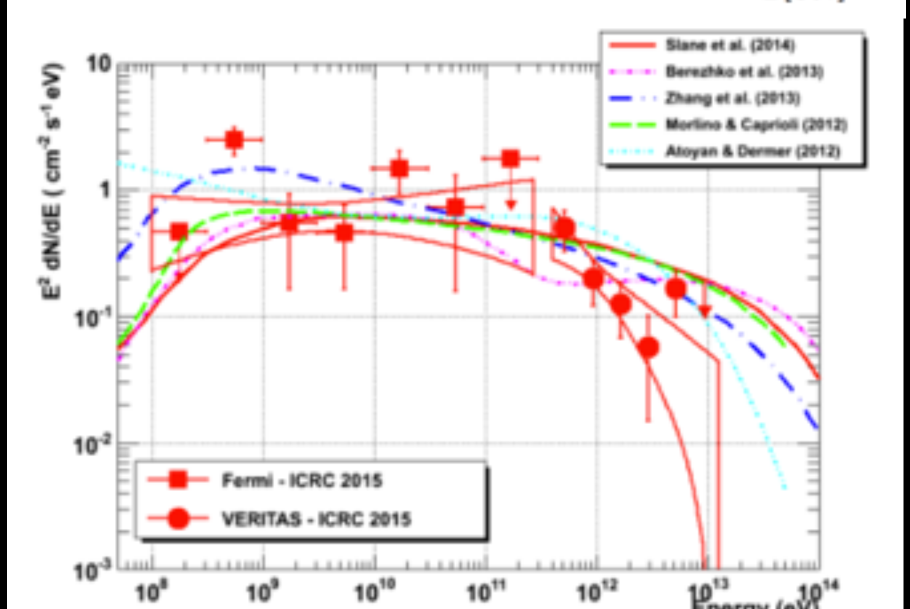
Bfield ~ few uG, low density medium
Different emission region? forward vs reverse shock, clumps…
Energy cutoff measured for several of them (Ep ~100 TeV)



Cas A



Tycho

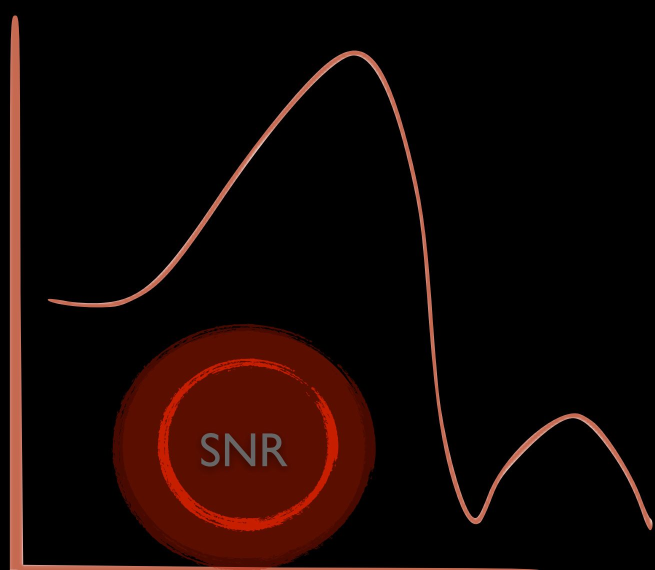


TeV Remnants with high B_{field}

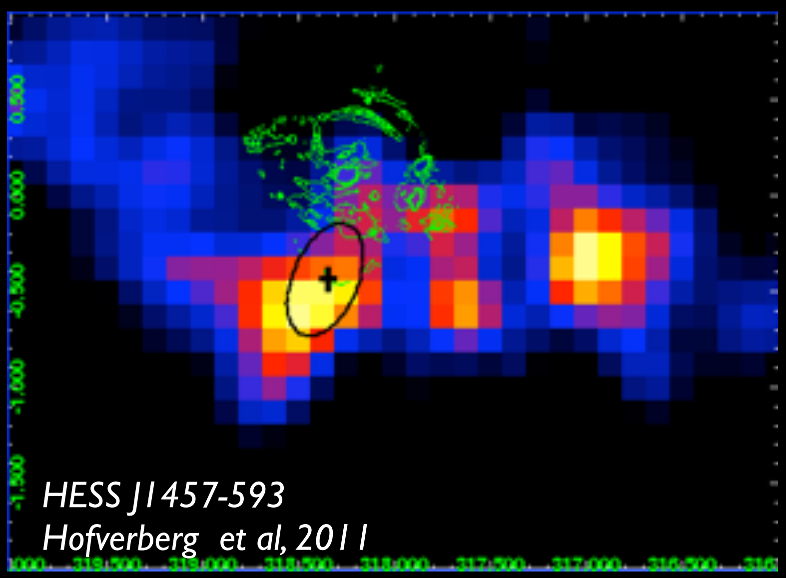
B = 0.3-0.5 mG is inferred from the width of X-ray filaments and X-ray time-variability
If hadronic origin E_{CR}~10-20% of SNR energy
Energy Cutoff at ~3.5 TeV

Where are the PeVatrons?

Hypothesis: PeV particles are accelerated at the beginning of Sedov phase (~200yrs), when the shock speed is high but the SNR is faint
Look at the surroundings, or somewhere else?

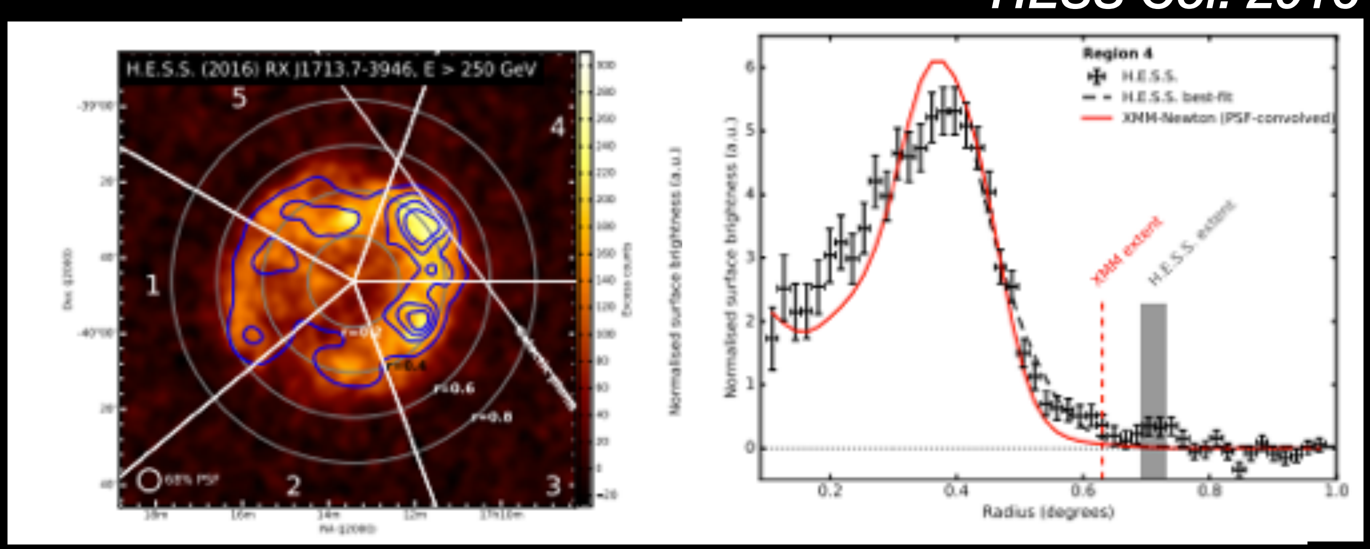


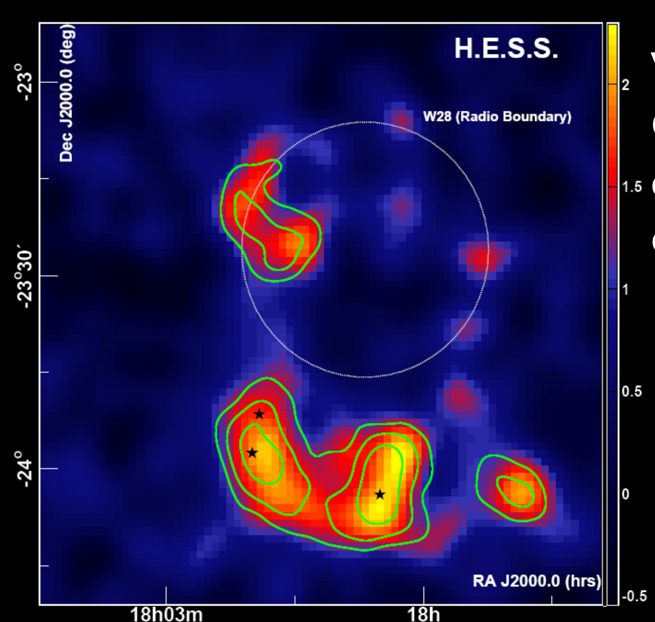
radial profile



- VHE in the vicinity of G318.2+0.1 with a flat spectrum ranging from a few 100 MeV to few tens of TeV
- G318.2+0.1 radio bright North and South shell filled up with thermal emission
- Enhancement of Molecular Content observed by NANTEN and with Fermi LAT
- D~3.5 (9.2) Kpc -> 50 pc if related to the SNR

HESS Col. 2016





W28
Correlation between clouds and TeV emission

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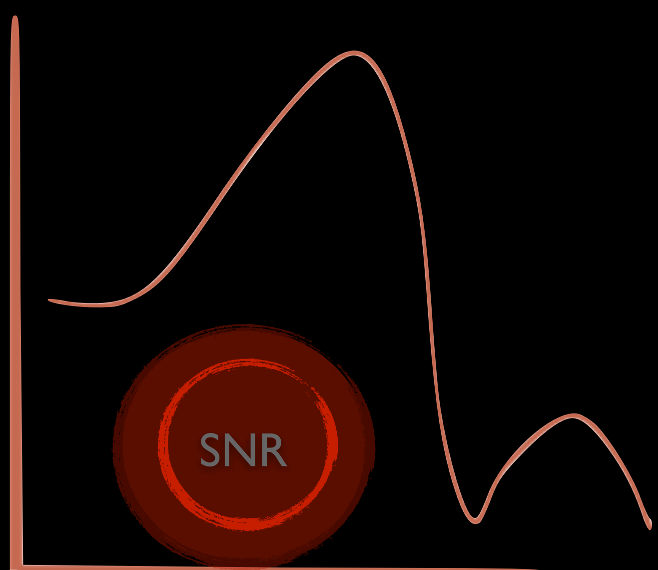

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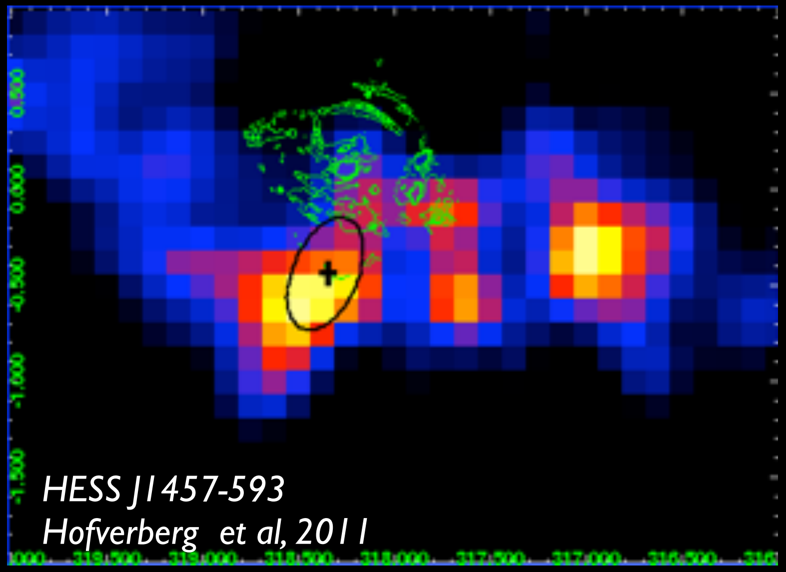

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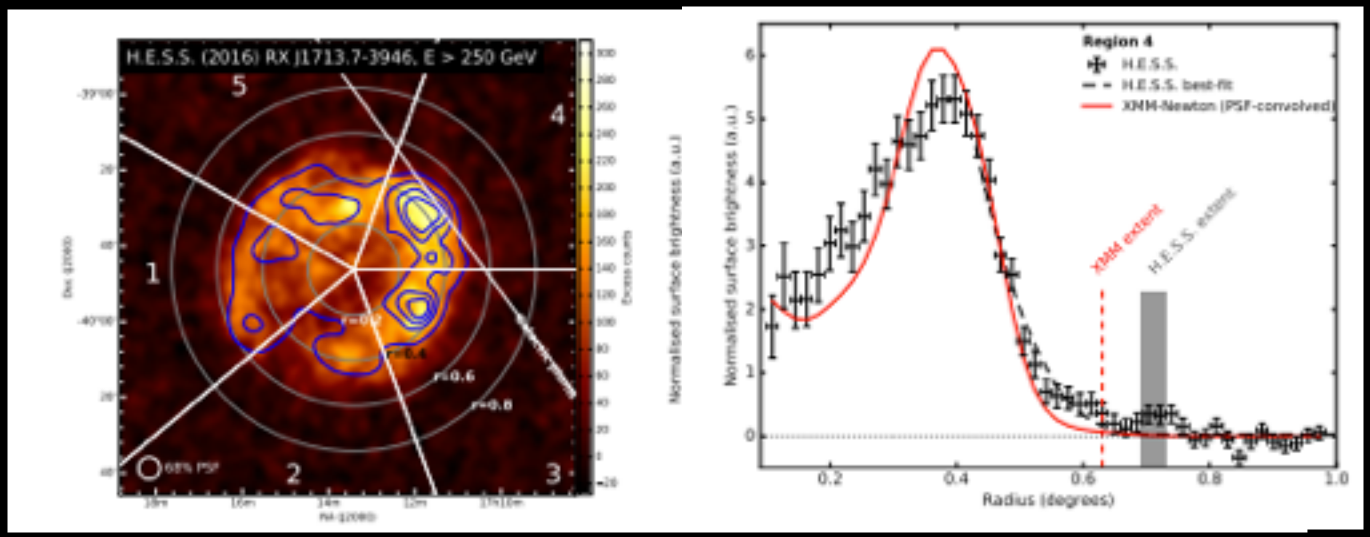

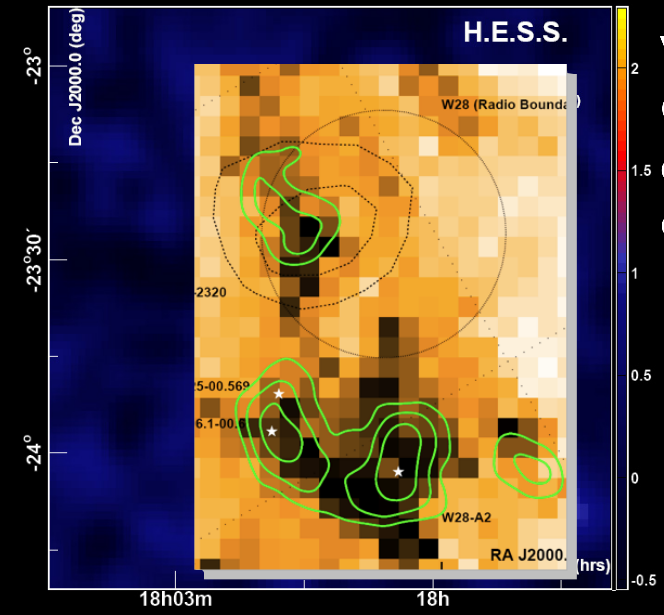

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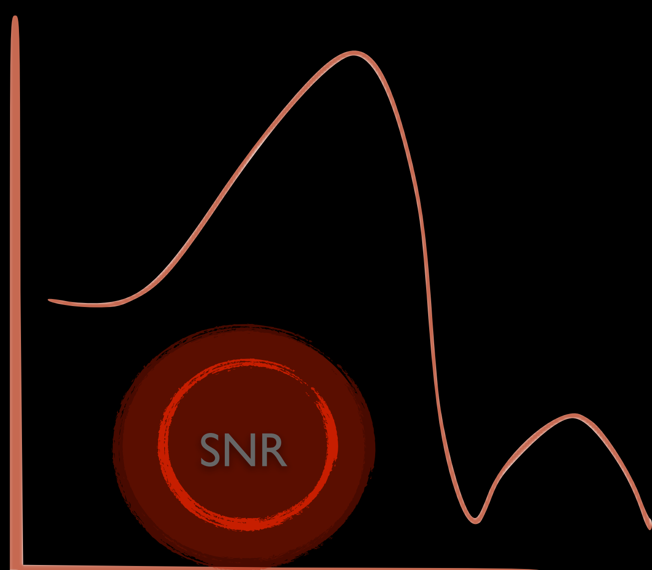

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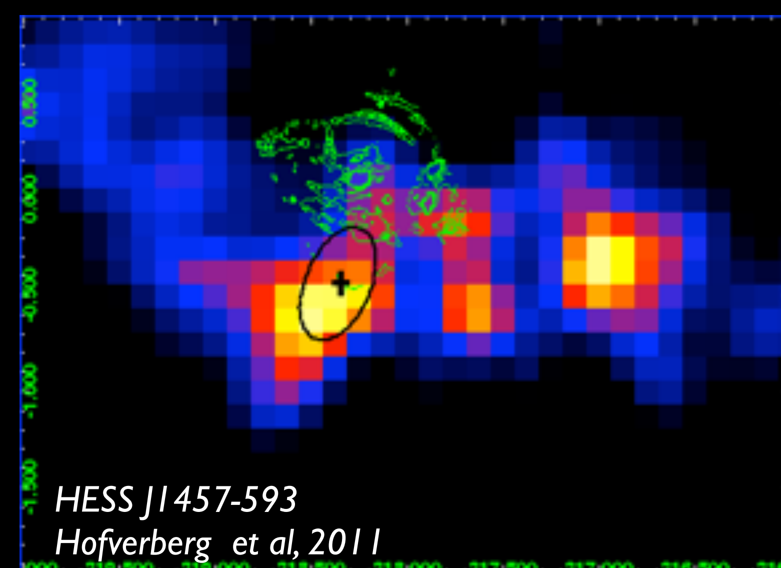

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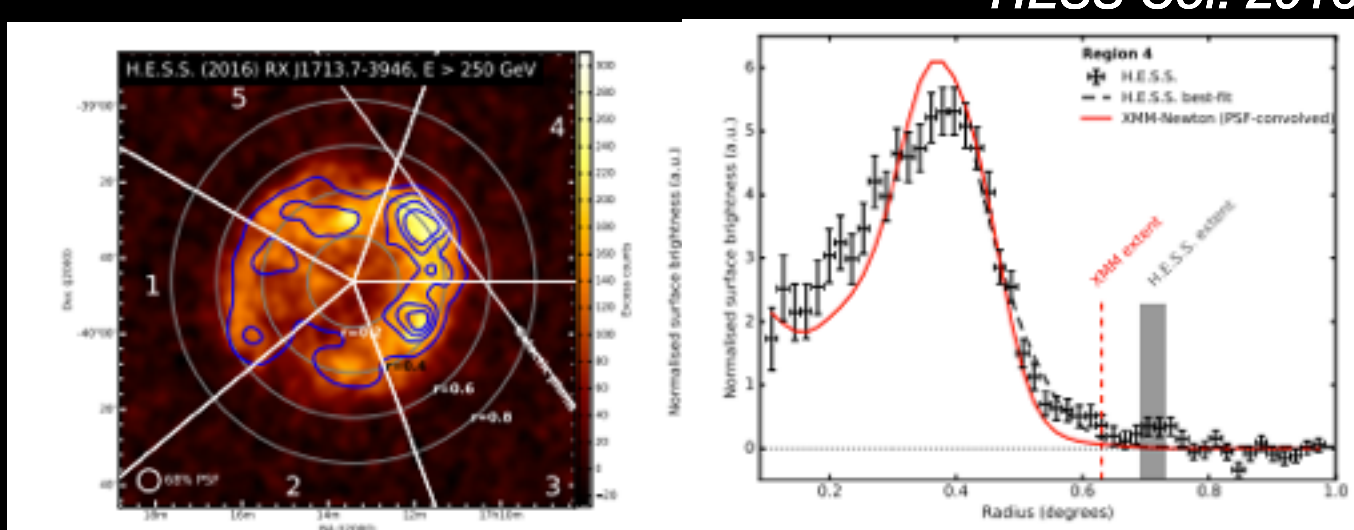

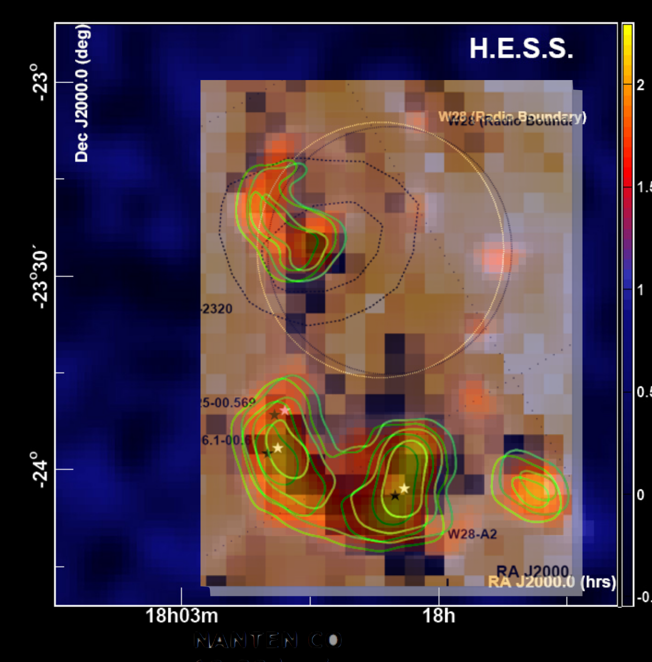

W28
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Summary

- Astrophysical compact objects provide optimal conditions to accelerate particles to GeV/TeV energies
- New, sensitive instruments in the last years such FermiLAT, AGILE, H.E.S.S., MAGIC & VERITAS have stirred up the field with a plethora of exciting results
- Thanks to the large pulsar population obtained, we have significantly advanced in our understanding of pulsar magnetospheres (current sheets, pair production, etc)
- They are the most powerful steady (up to PeV=1×10^{15} eV) and relatively nearby accelerators (and sometime not-steady!)
- They last thousands of years, providing clues about historical evolution of radiative plasma and transport of particles/fields
- They flare! -> efficient & rapid particle acceleration (like in AGNs or GRBs): common mechanisms (magnetic reconnection or shock acceleration)
- The future is bright! stay tune for new results obtained with new detectors (IXPE/XIPE, CTA, eASTROGAM, etc)

Thanks!

Backups

Spectral variation with distance from the pulsar could result from:

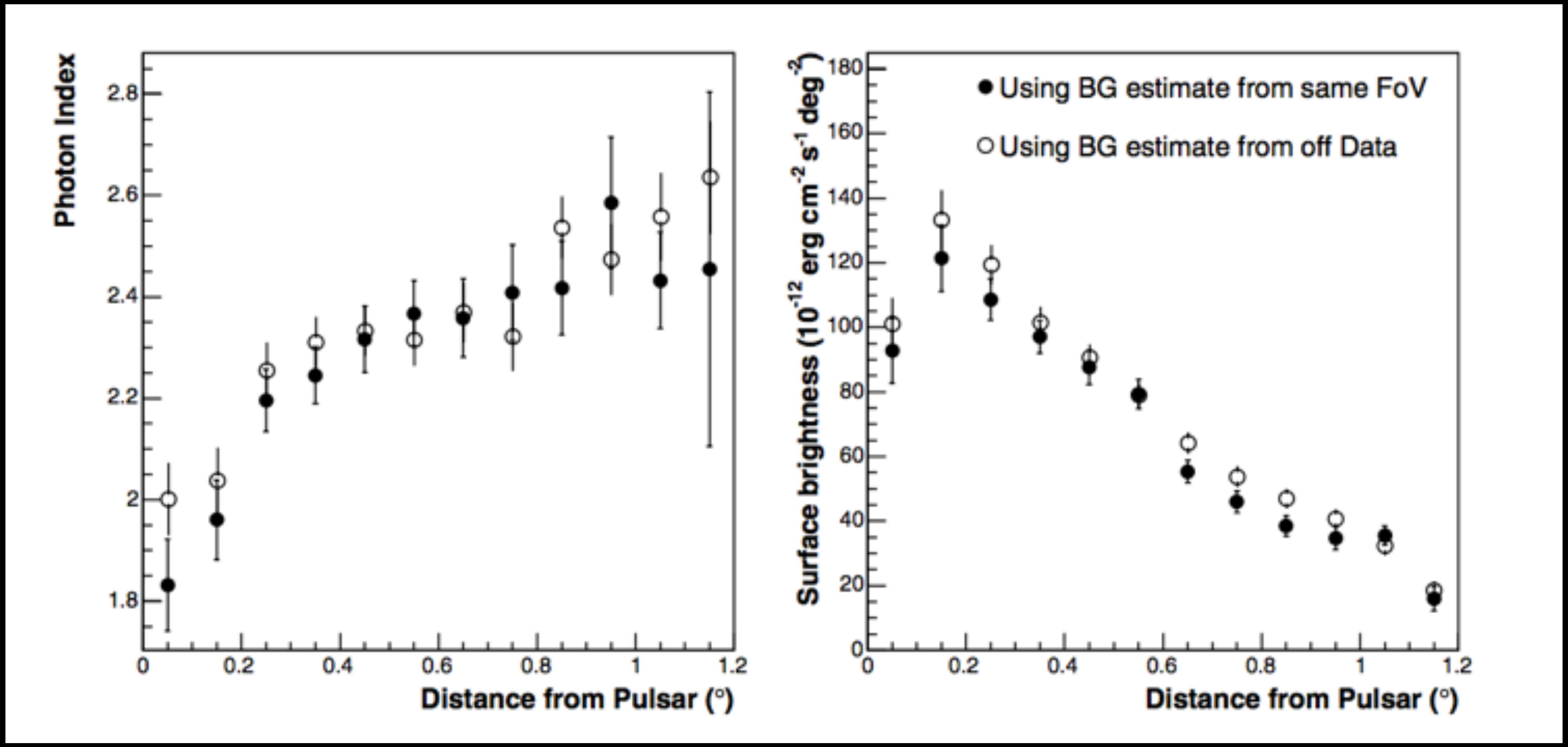
(i) energy loss of particles during propagation, with radiative cooling of electrons propagating outward from the pulsar termination shock

(ii) energy dependent diffusion or convection speeds

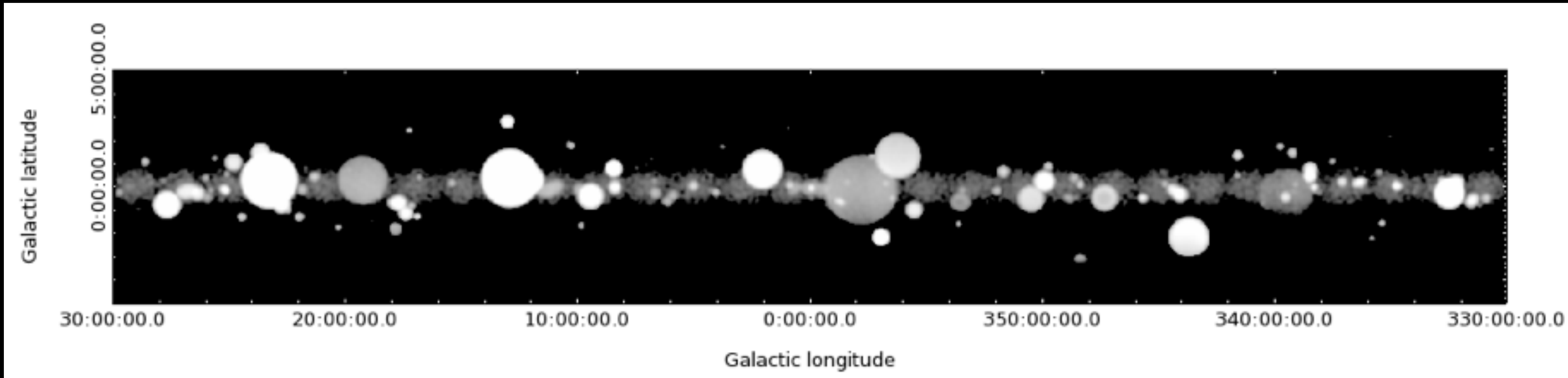
(iii) variation of the shape of the injection spectrum with age of the pulsar which, after propagation, translates into a spatial variation of spectra.

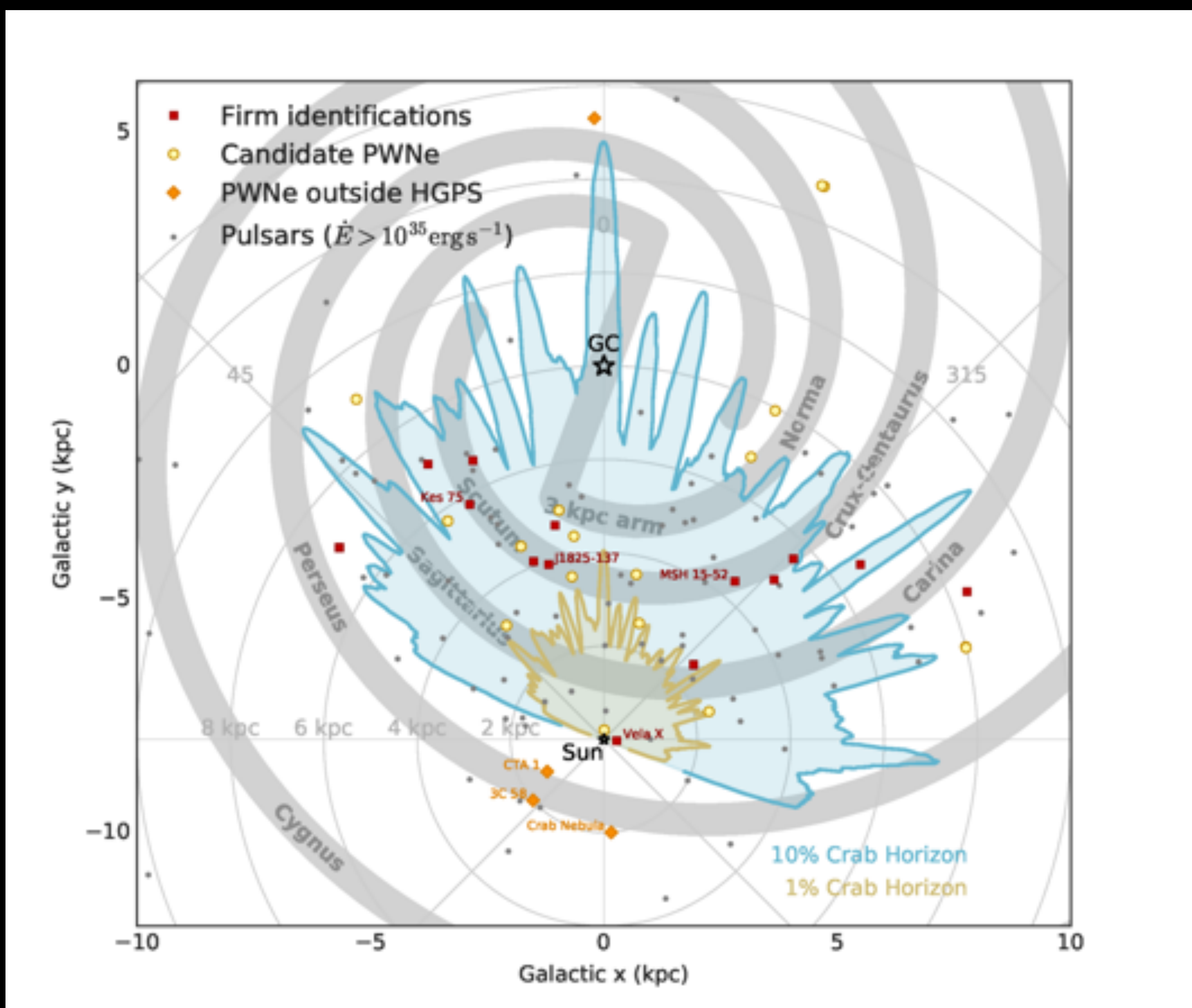
If α = electron index -> synchrotron cooling (τ_{syn} ~400 $B^{-2}_{G} E^{-1}_{TeV}$ s)

$\Delta\alpha = 1 \rightarrow \Delta\Gamma = 1/2$



Simulations based on ATNF PSRs





Which PWNe we see?
- Large density regions
- Middle age (right size!)
- Energetic PSR