ICE INSTITUT DE CIÈNCIES DE L'ESPAI
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Observation of CR acceleration in late-stage of massive stars evolution through gamma rays

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Cosmic Rays:
- The Origin
- The Standard Paradigm
- Tracing cosmic-rays through gamma-rays

Supernova Remnants:
- Young TeV-bright TeV SNRs
- The case of Cassiopeia A

Other accelerators:
- Source Candidates
- The massive cluster Westerlund 2

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Outlook

What is this talk is about

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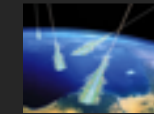
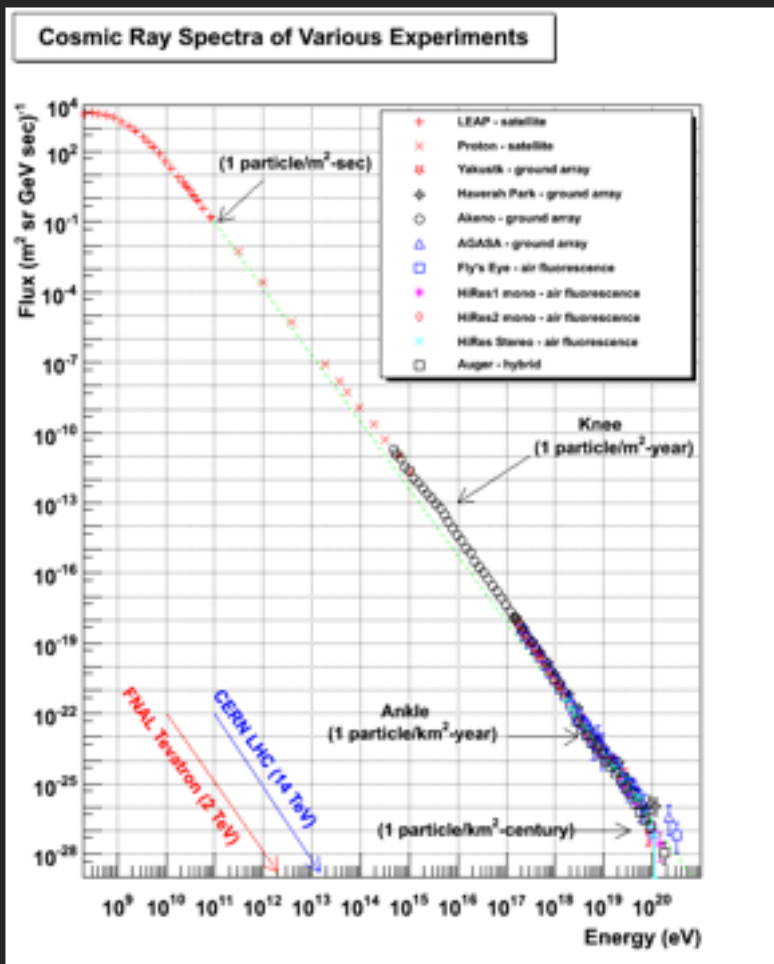


Ginzburg, S.I. Syrovatskii 64, Gaisser 91, Berezinskii et al, 90, Bell 2005, Lagage, Cesarsky 83, Berezhko et al 97, Hillas 05, Malkov, Drury 2001 and reference therein

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



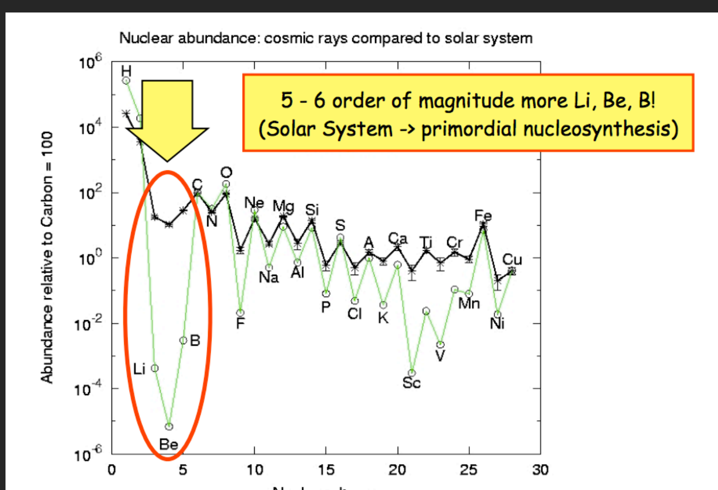
- Mostly protons e/p ~1/100
- As they are charged, they are deflected by fields (only for $E>10^{19}$eV we could trace back the arrival direction, but CMB)
- Extends over 32 orders of magnitude with spectral index ~2.7
- Below ~3 PeV CRs are believed to be of Galactic origin
- Where are PeV CRs accelerated?

CR Energetics

- Energy Density of CRs $u_{CR} \sim 1$ eV/cm^3
- Volume of the Galaxy $V_{gal} = \pi R_{disk}^2(2h) \sim 3\times10^{11}$ pc^3 $\sim 10^7$ cm^3
- Luminosity $L = u_{CR} * V_{gal} / t_{CR}$ = **5×10^{40} erg/s**
- **Isotropic in the Galaxy**

- If we measure the CR confinement time (nuclear abundance) $t_{CR} \sim 10^7$ yrs
- Homogeneity requires $t_{recu} \ll 10^7$ yrs

We need accelerators that can provide the right energy budget, up to PeV energies, at the required rate to make the distribution homogeneous.



Bell

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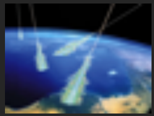
Bell

Cosmic Rays The Standard Paradigm



CR Energetics

- Energy Density of CRs u_{CR}~1 eV/cm^3
- Volume of the Galaxy $V_{gal} = \pi R_{disk}^2(2h) \sim 3\text{x}10^{11}$ pc^3 ~10^7 cm^3
- Luminosity $L=u_{CR}*V_{gal}/t_{CR}$ = **5x10^{40} erg/s**
- **Isotropic in the Galaxy**

- If we measure the CR confinement time (nuclear abundance) t_{CR}~10^7 yrs
- Homogeneity requires t_{recu}<<10^7 yrs

We need accelerators that can provide the right energy budget, up to PeV energies, at the required rate to make the distribution homogeneous.

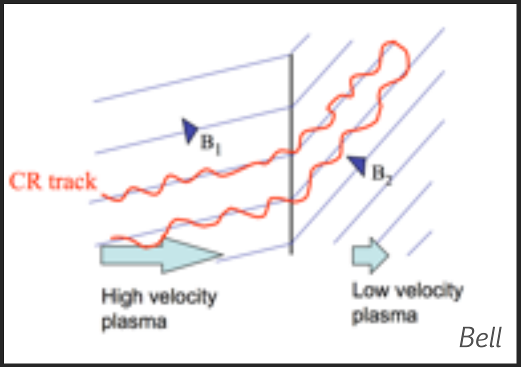
SNRs provide the right energy budget:

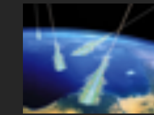
- SN power : $L_{SN}=10^{51}/t_{SN}=6\text{x}10^{41}$ erg/s
- SNe rate is 2-3 century
- SN explosion energy Ekin=10^{51} erg

….seems like all fits nicely
(with lots of caveats)

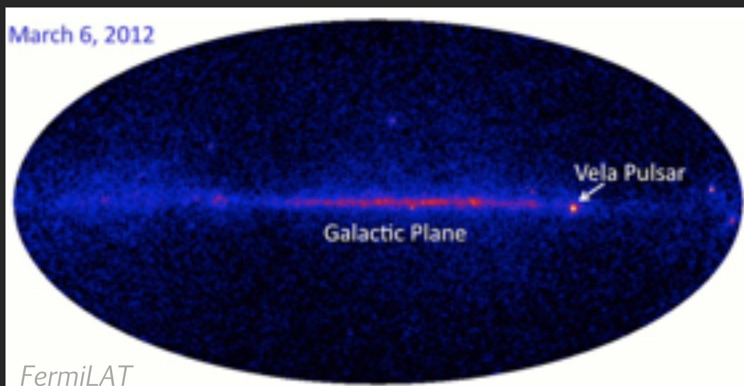
what data says?

DSA theory predicts the right spectral shape assuming magnetic amplification in shocks

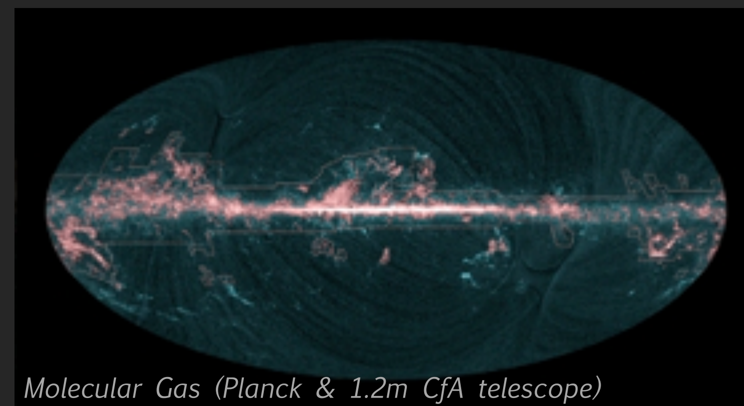




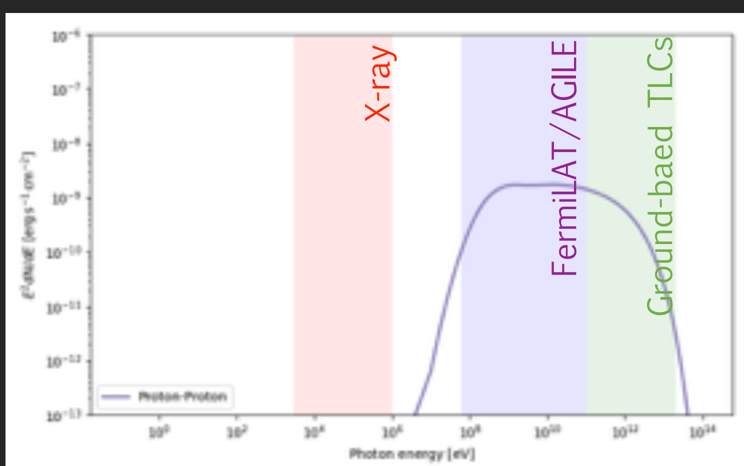
Gamma-rays as by product of CRs interaction with matter



FermiLAT



Molecular Gas (Planck & 1.2m CfA telescope)

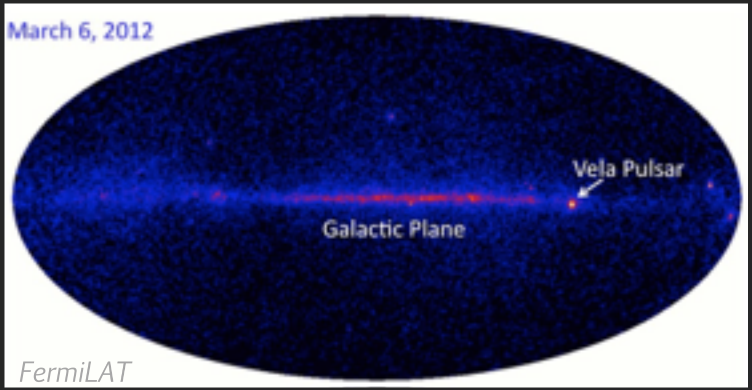


Proton-proton

$$p + p \rightarrow \pi^0 + \chi + \ldots + \pi^\pm$$

$$\hookrightarrow \gamma + \gamma \qquad \hookrightarrow \nu_\tau + \nu_e$$

Gamma-rays as by product of CRs interaction with matter



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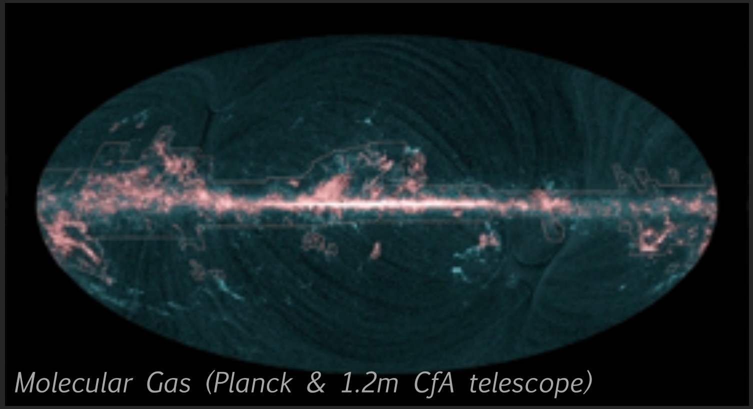

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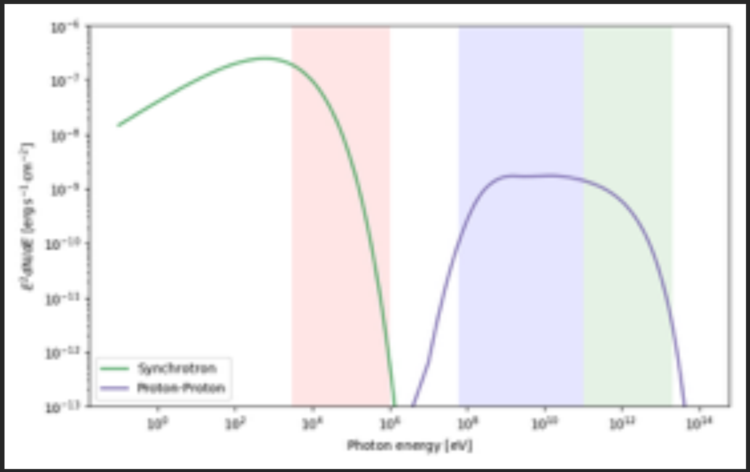

Proton-proton

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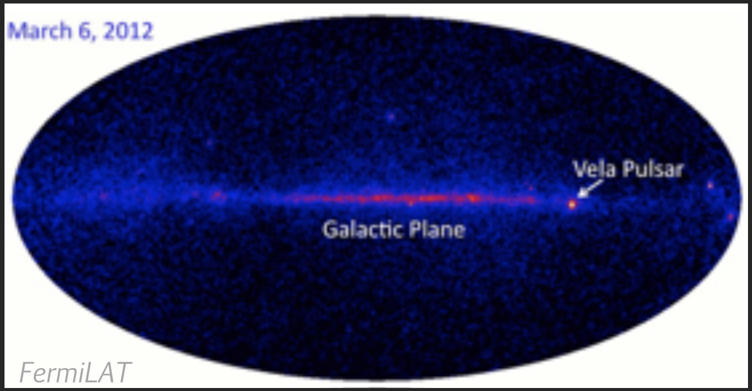
↳ $\gamma + \gamma$ ↳ $\nu_\tau + \nu_e$

Synchrotron

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

Gamma-rays as by product of CRs interaction with matter



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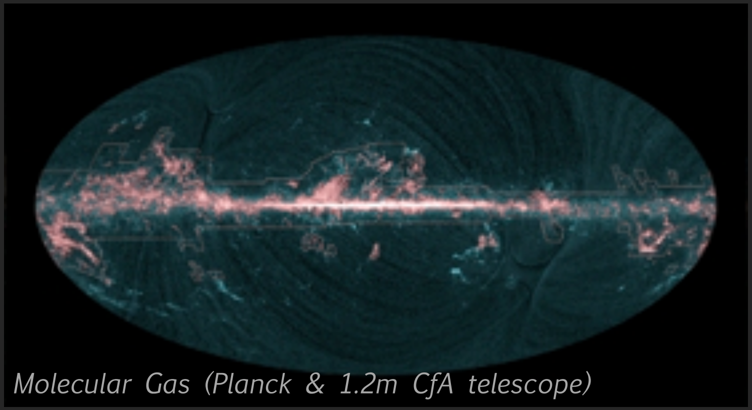
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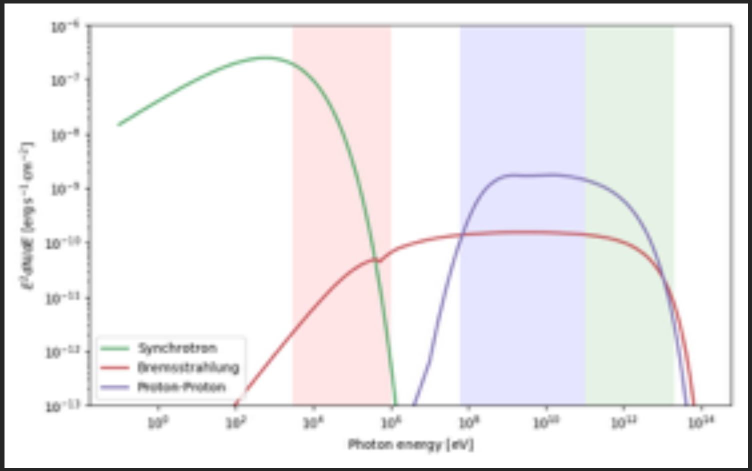

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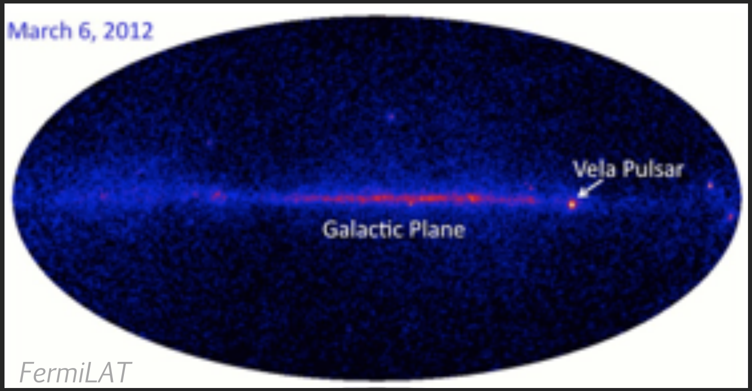
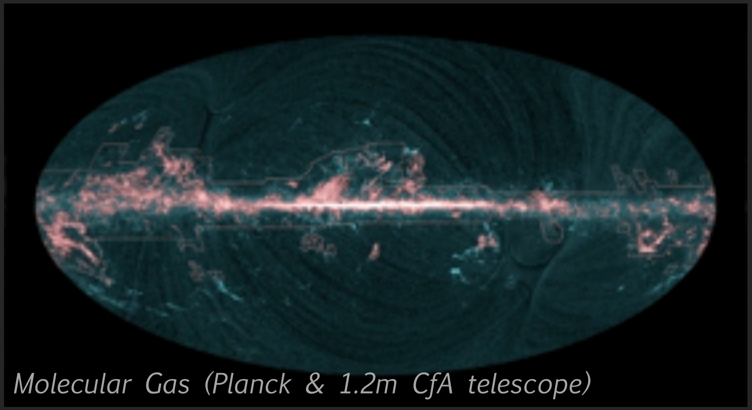
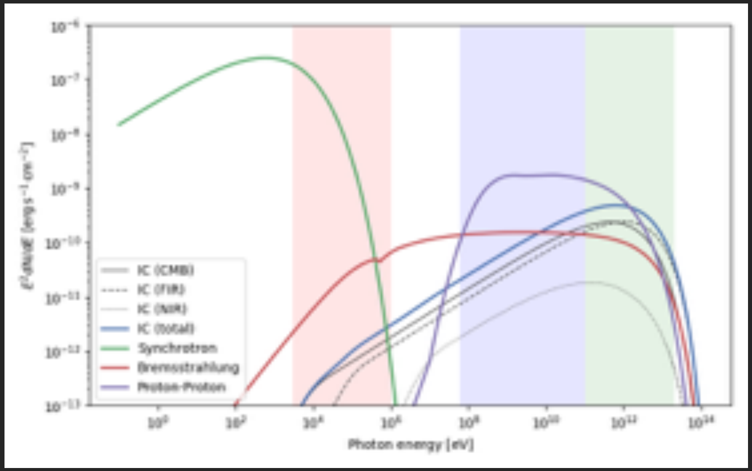
Bremmshtrhalhung

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

Gamma-rays as by product of CRs interaction with matter







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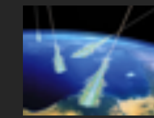
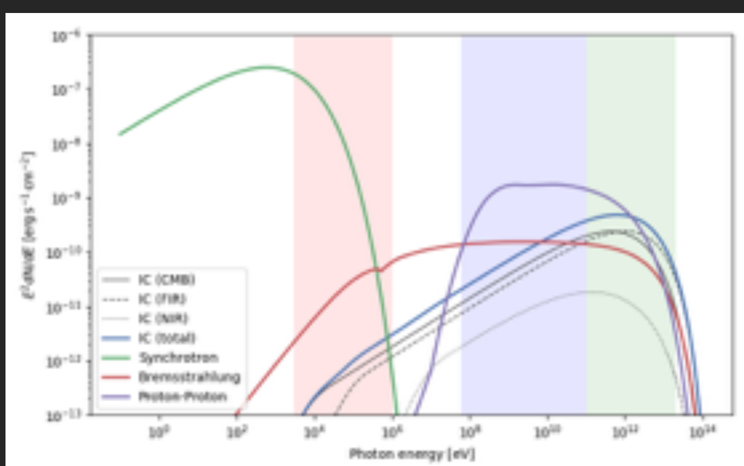
$e^{\pm}HE + \Upsilon_{LE} \Rightarrow e^{\pm}_{lowerE} + \Upsilon_{LE}$



Gamma-rays as by product of CRs interaction with matter

How can we probe protons or heavy nuclei in massive old stars shocks?

- Spectral shape at high and very high energies: pion-peak feature
- Extension of a hard spectrum up to >>10 TeV to probe PeV protons
- Morphological characteristics
- Hard X-ray emission of secondary electrons (?)



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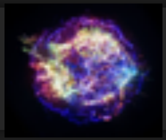
Young TeV SNRs



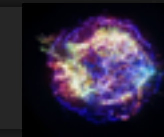
To reach PeV energies we need

- Rapid shocks ~1000 km/s & young remnants
- Amplification of magnetic fields - Strong synchrotron emission
  $E_p \sim B \cdot v_{shock} \cdot \tau$
- To see the SNRs in gamma-rays (and thus probe the CR content):
  At 1 TeV, the ratio of production rates ~ $10^3 (W_e/W_p)(n/1cm^{-3})^{-1}$
  ($n<<1$ cm-3, $B<$ 10 uG $e/p \sim 10^{-3}$) leptonic >> hadronic
  ($n>>1$ cm-3 || $B>>$ 10 uG || $e/p >> 10^{-3}$) hadronic >> leptonic
- We also want to verify that the spectral shape is correct! GeV emission?

$$E_c^p \simeq 450\left(\frac{B}{1\ \mathrm{mG}}\right)\left(\frac{t_0}{100\ \mathrm{yr}}\right)\left(\frac{u_s}{3000\ \mathrm{km/s}}\right)^2\eta^{-1}\ \mathrm{TeV},$$

Lagage & Cesarsky 1983

Young TeV SNRs



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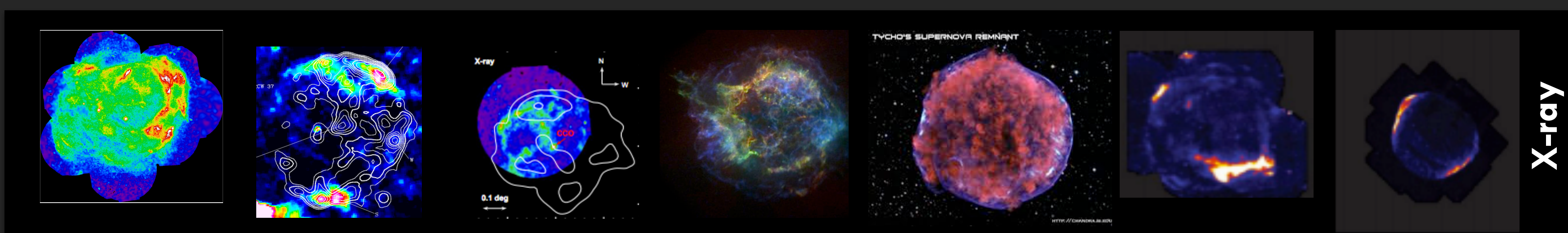

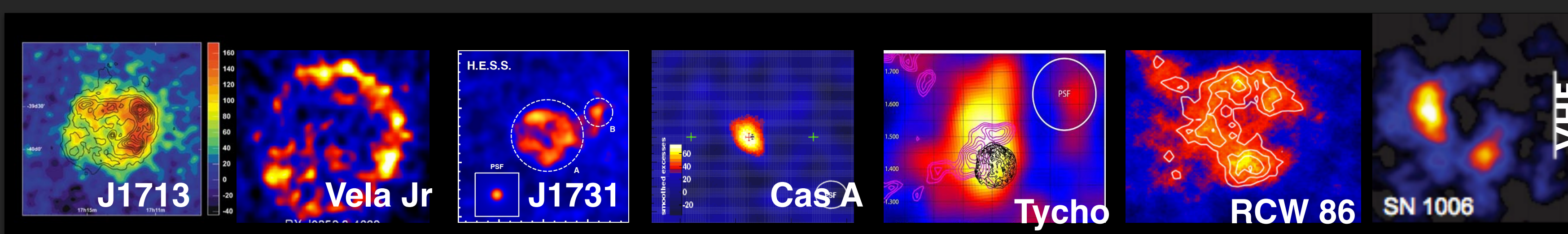

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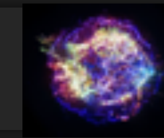
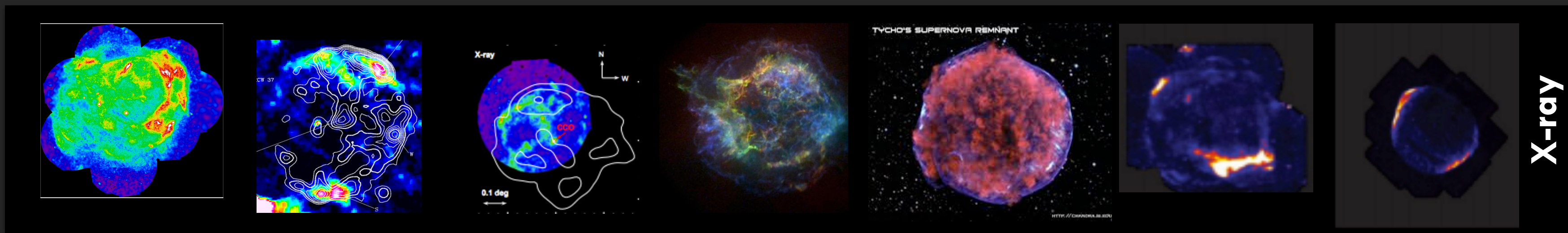
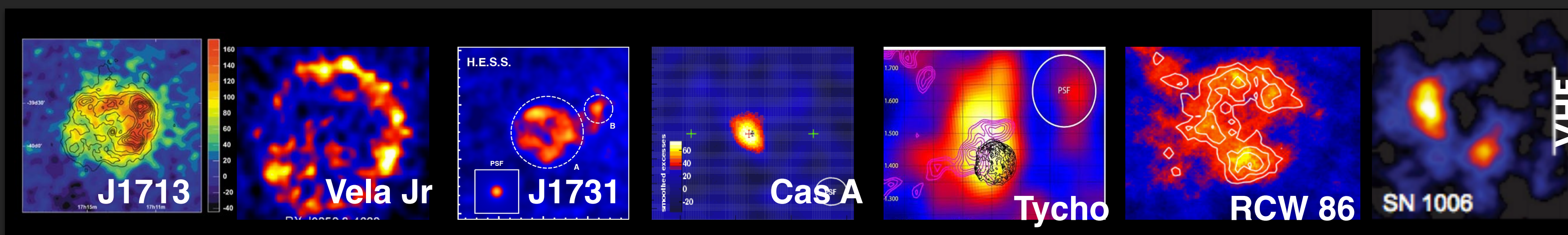






Core-collapse SN | SN Type Ia

GeV counterpart / Spectral Index

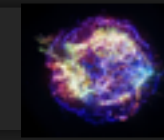
Density [cm^{-3}]

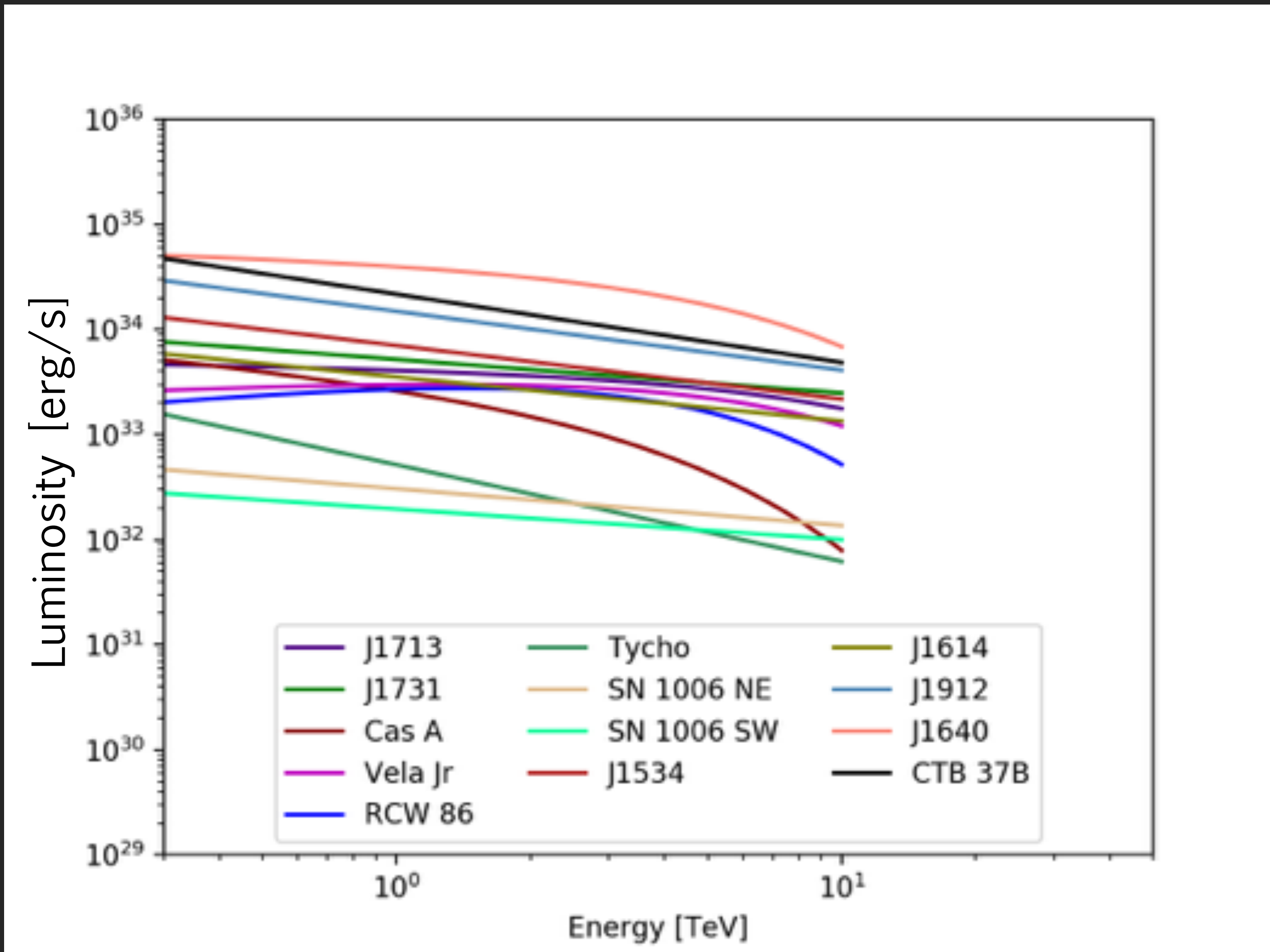
Bfield uG

	J1713	Vela Jr	J1731	Cas A	Tycho	RCW 86	SN 1006
GeV counterpart / Spectral Index	Yes/1.5	Yes/1.85	Yes/2.32	Yes/2.0	Yes/2.6	Yes/1.8	Yes/2.0
Density [cm^{-3}]	<0.02	<0.03	<0.02	0.1-10	0.1-1	0.01-1	<0.05
Bfield uG	~few	~few	~few	~150	~300	~few	~100

Supernova Remnants

Young TeV SNRs





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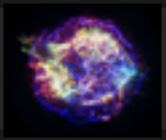
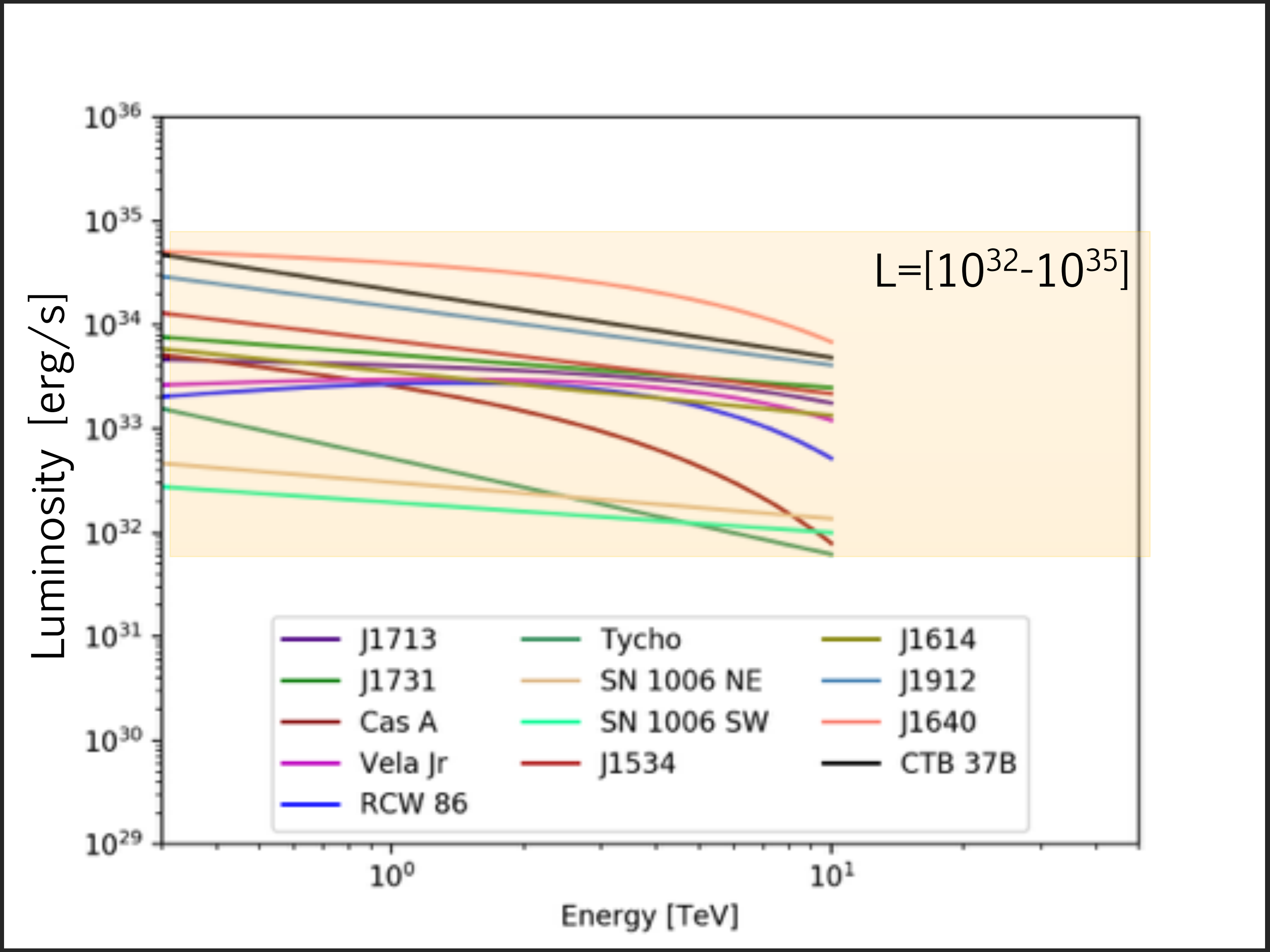
Young TeV SNRs





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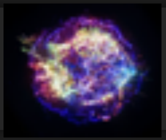

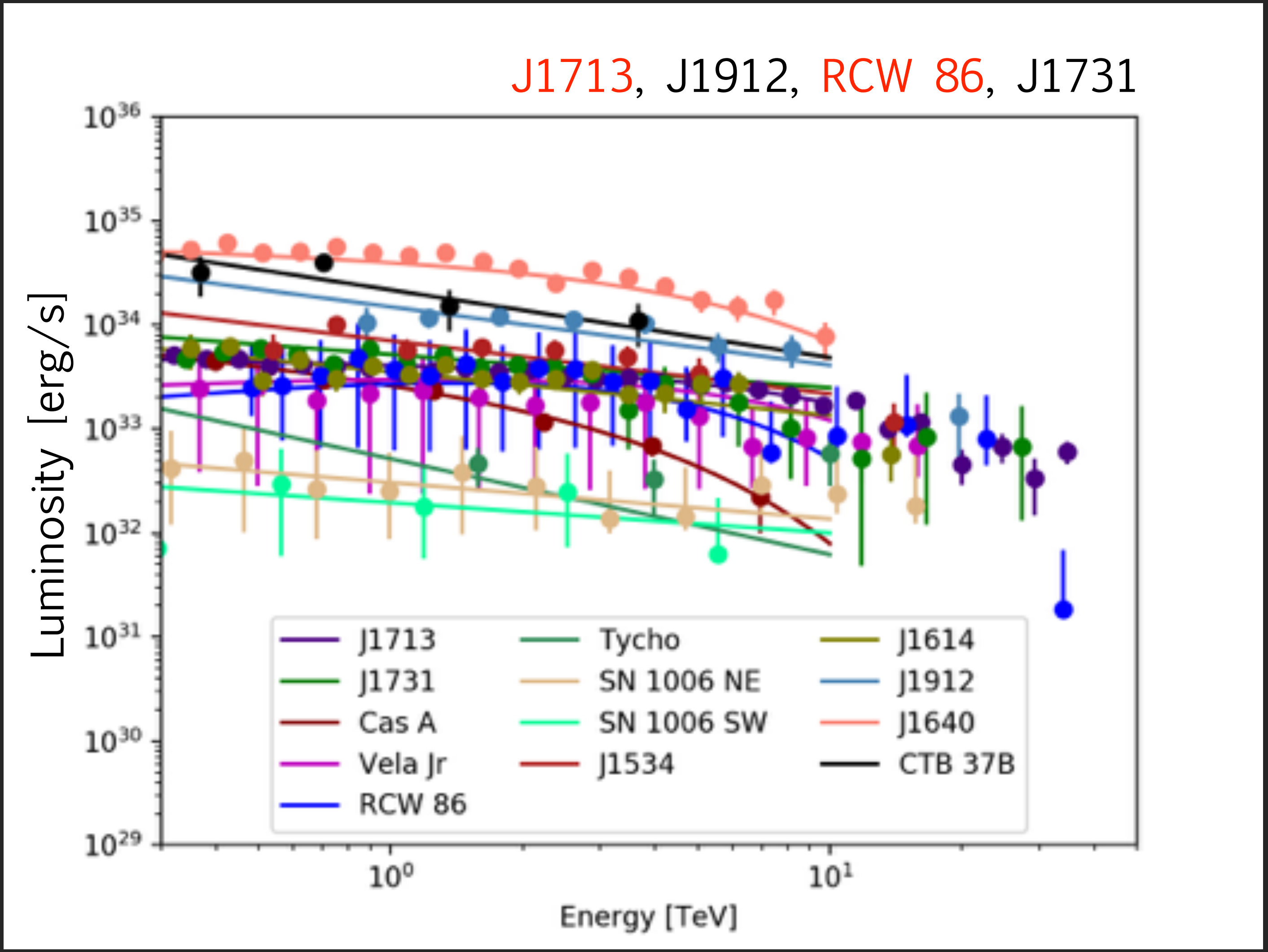

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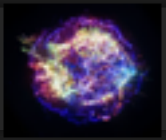

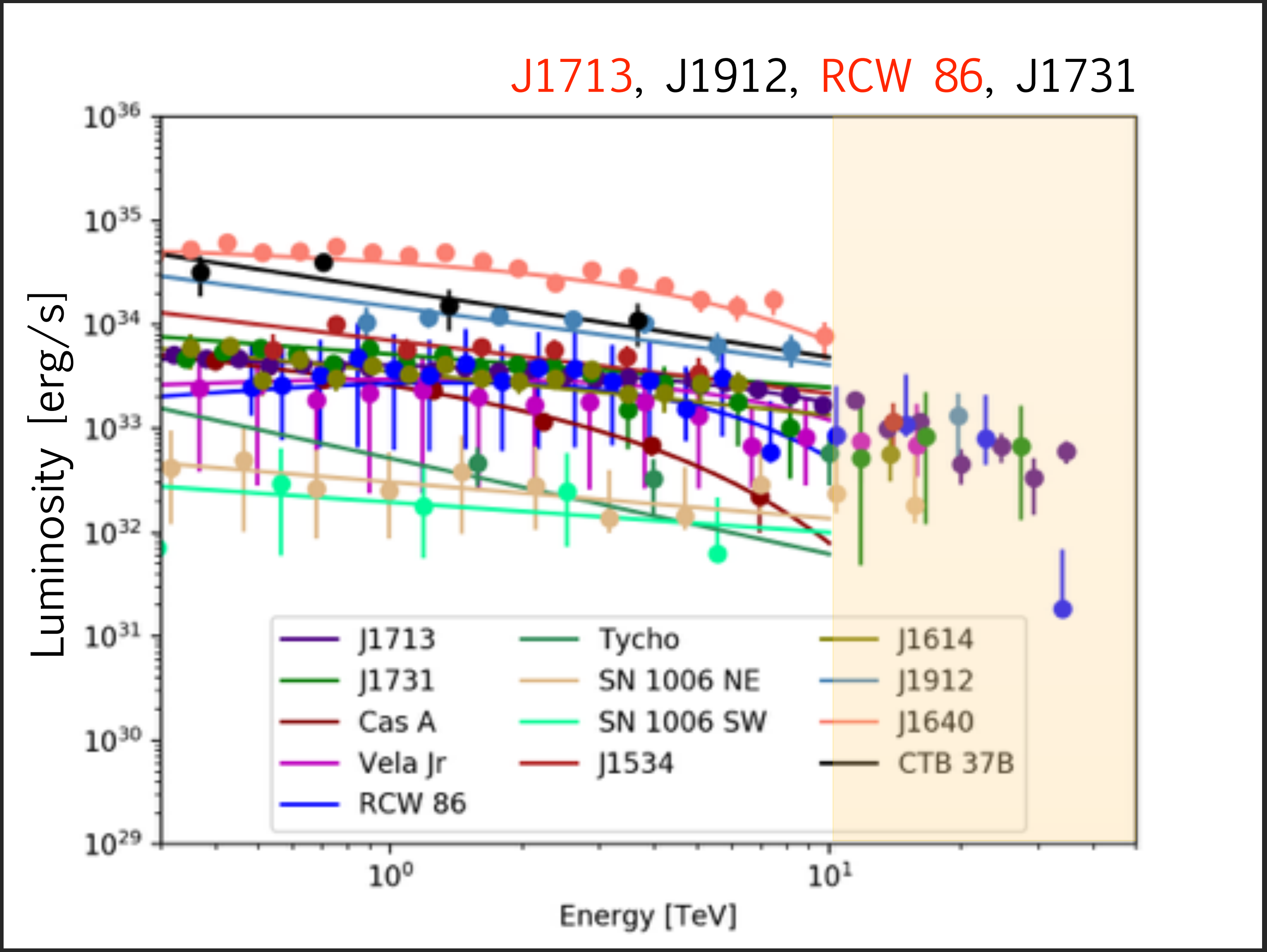

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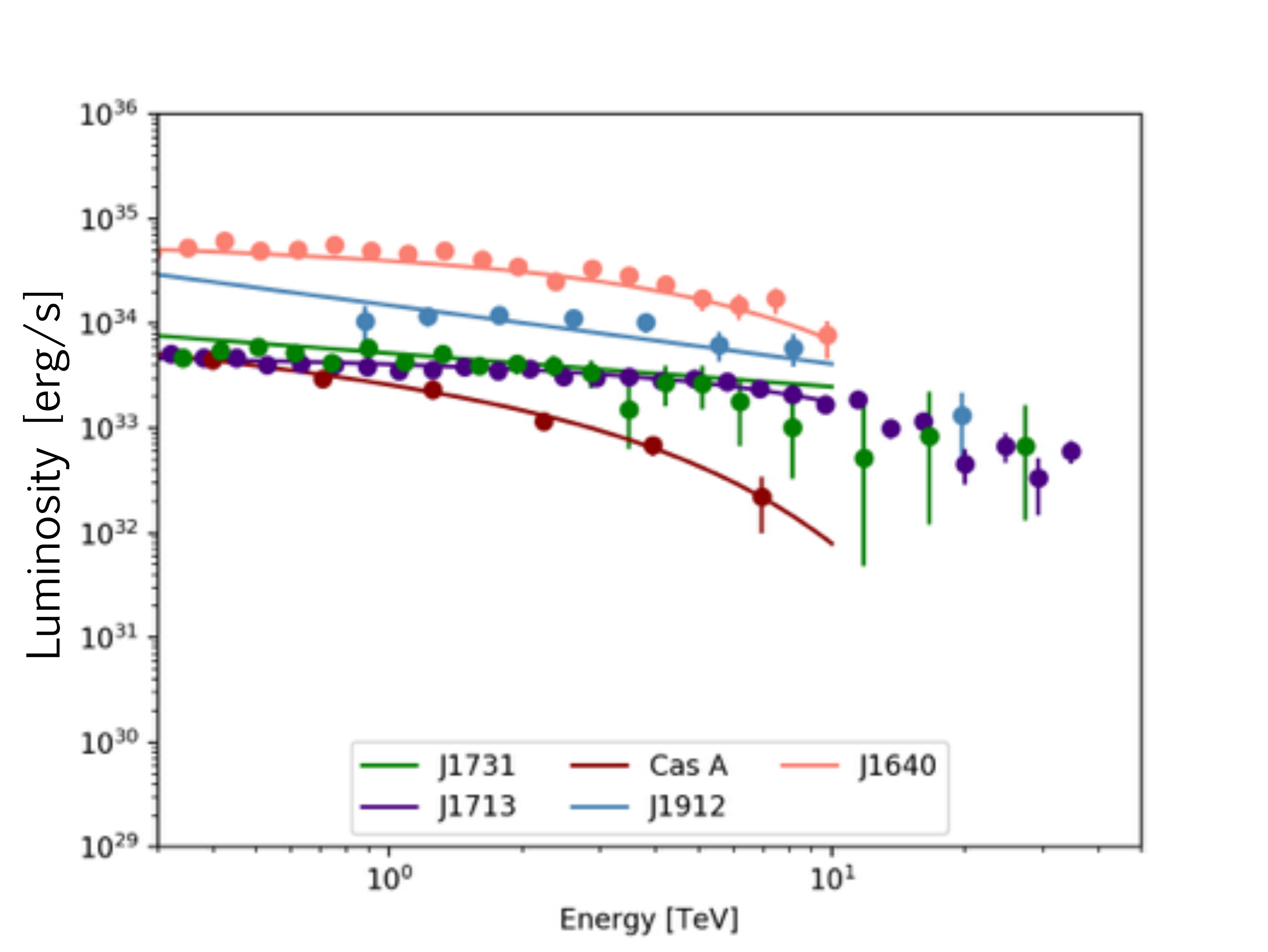

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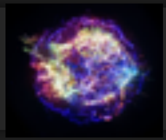

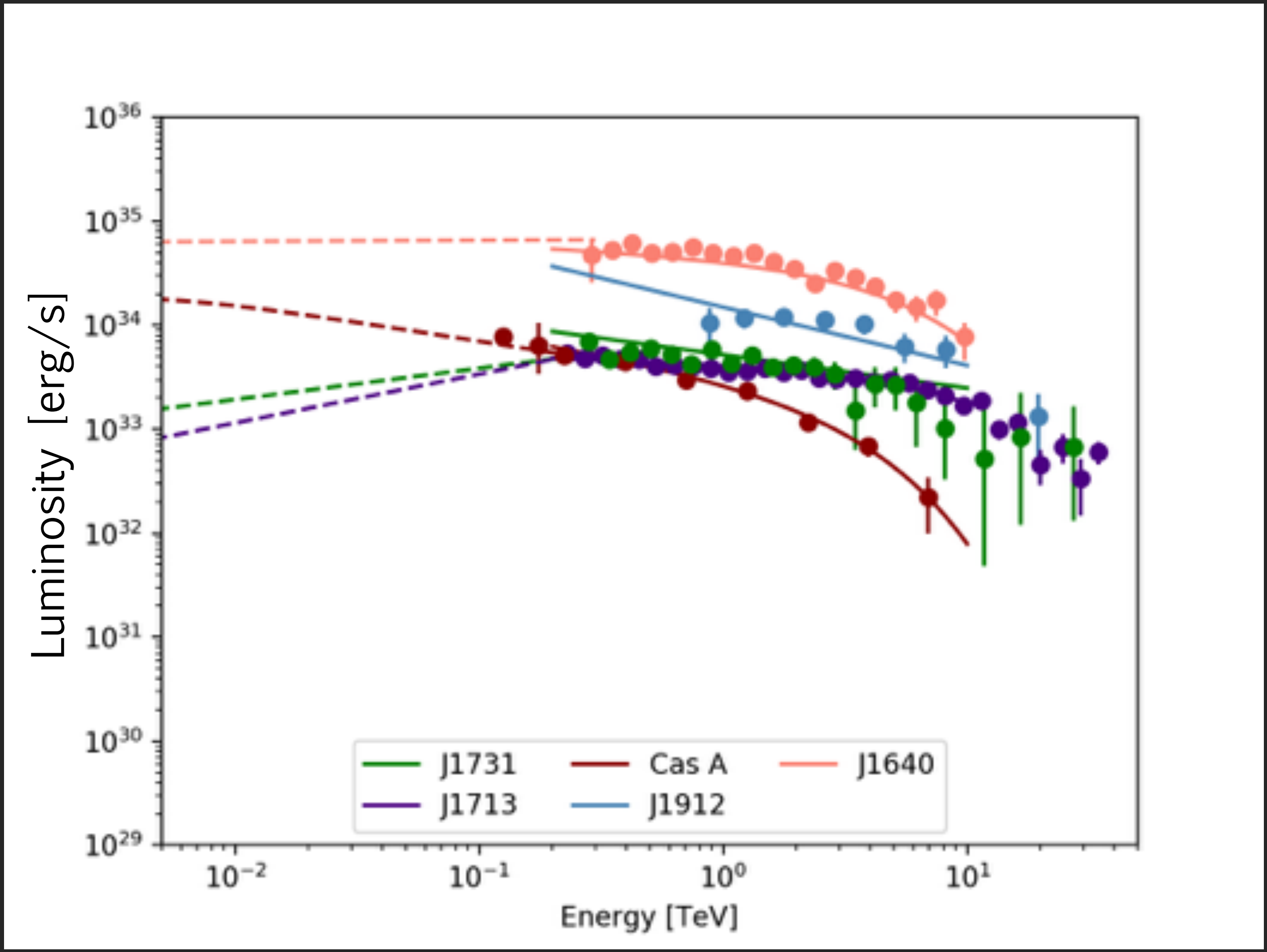

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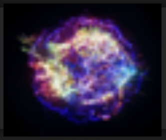
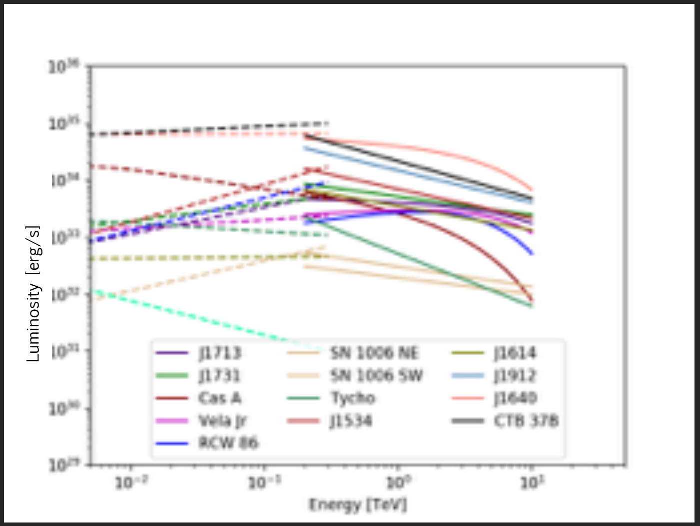
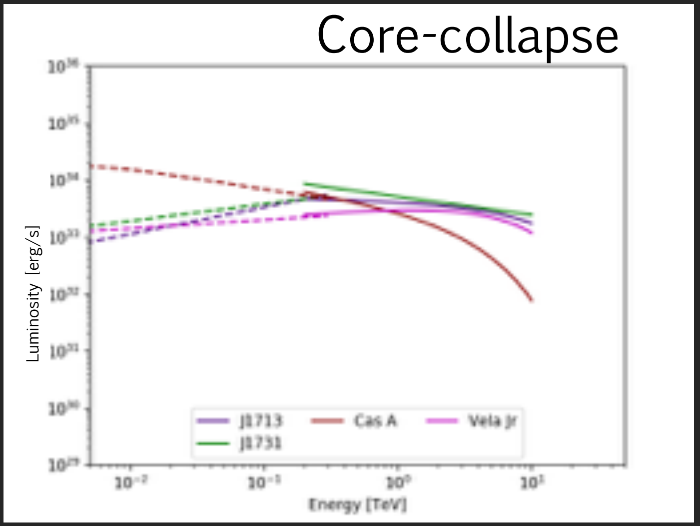
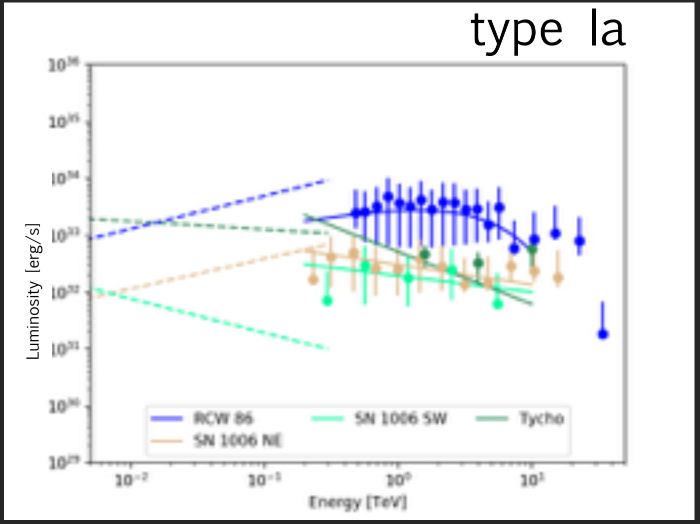
Supernova Remnants

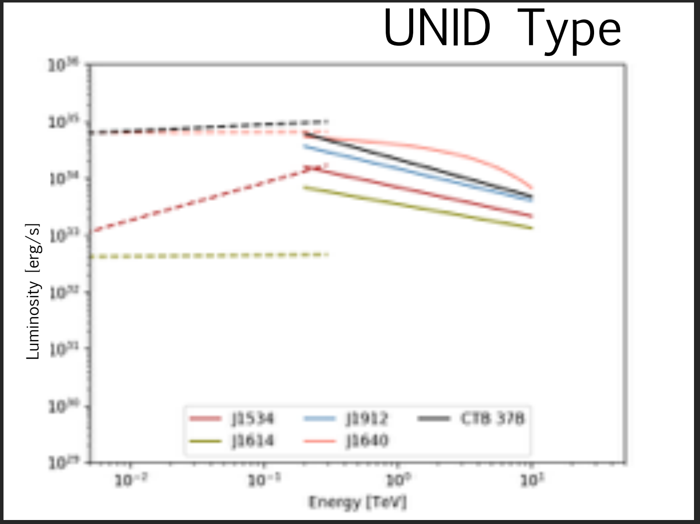
Young TeV SNRs

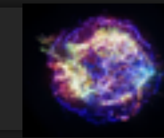






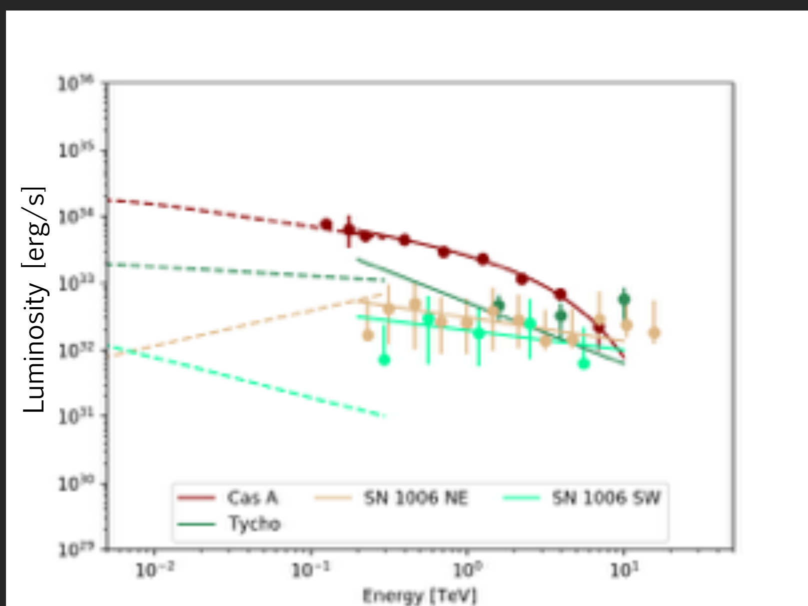


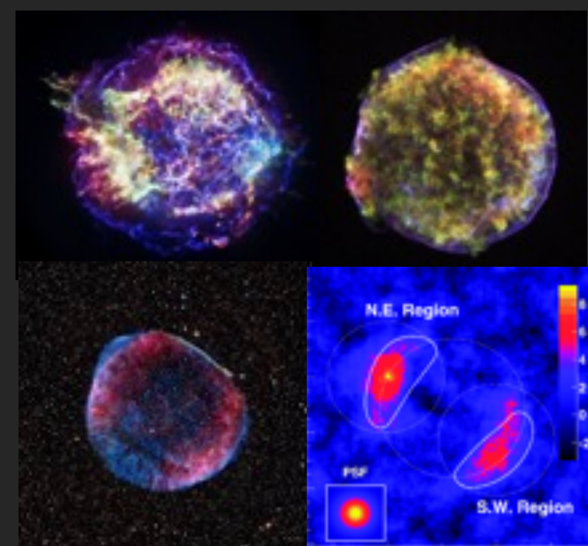


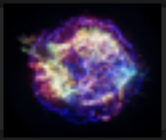


Best Candidates:

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







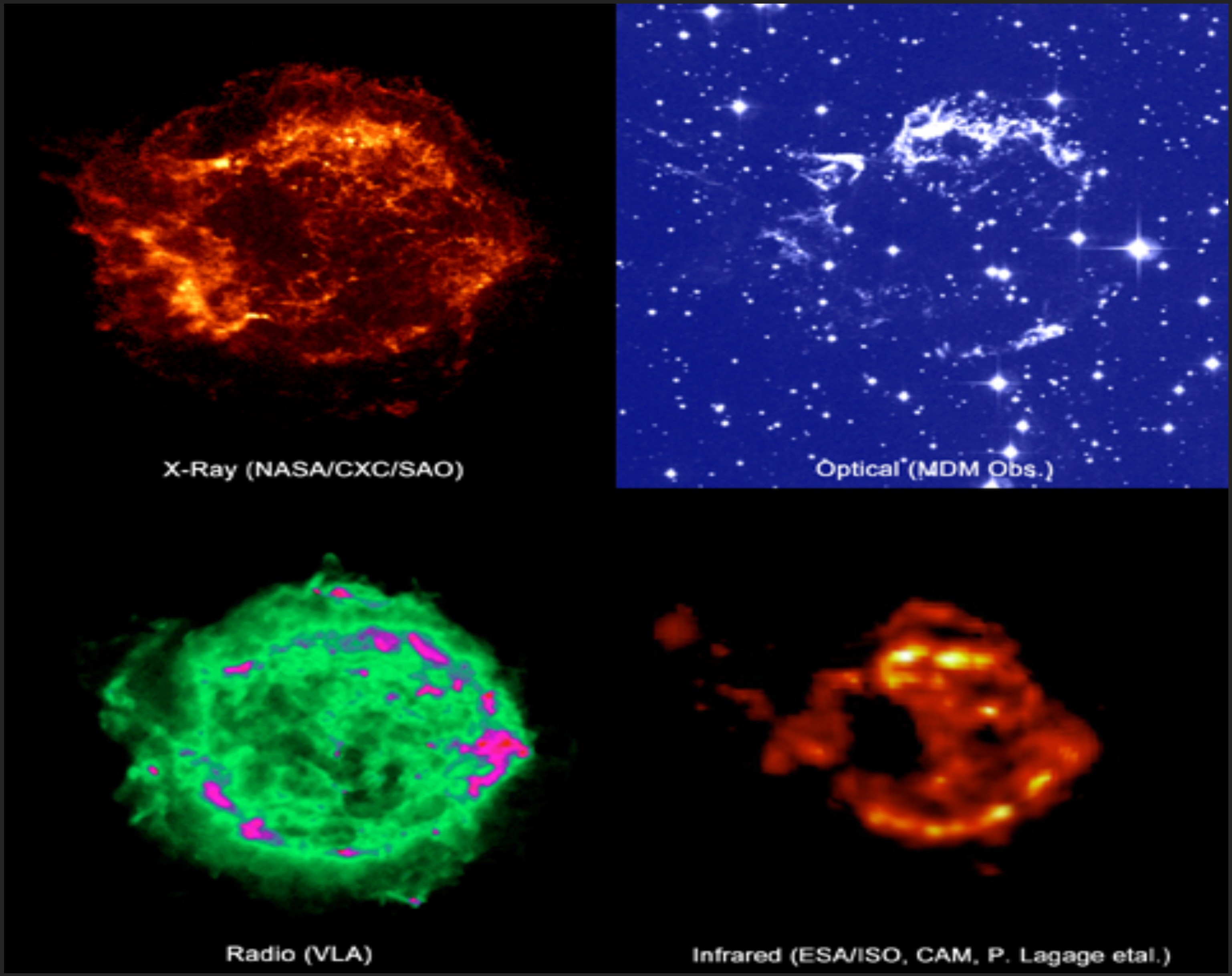
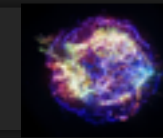


Image credit: NASA/CXC/SAO

Lastochkin et al. 1963; Medd & Ramana 1965; Allen & Barrett 1967; Parker 1968; Braude et al. 1969; Hales et al. 1995, Anderson et al. 1991, Gotthelf et al. 2001; Maeda et al. 2009; Grefenstette et al. 2015; Wang & Li 2016, Uchiyama & Aharonian 2008, Metzger et al 1986



Young shell, IIb SNR (330 yrs)
d ~ 3.4 kpc

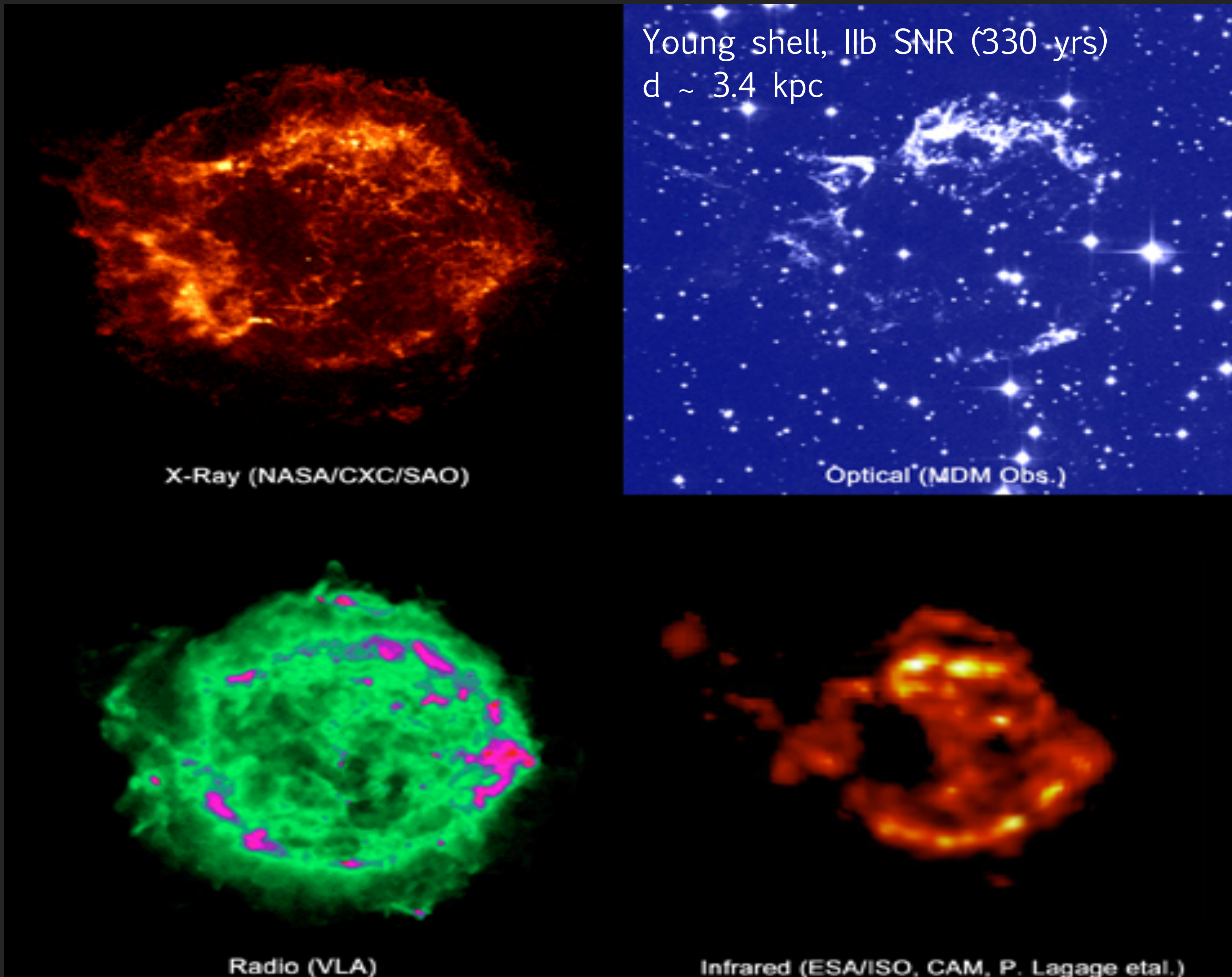


Image credit: NASA/CXC/SAO

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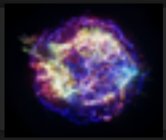
Cassiopeia A the Remnant



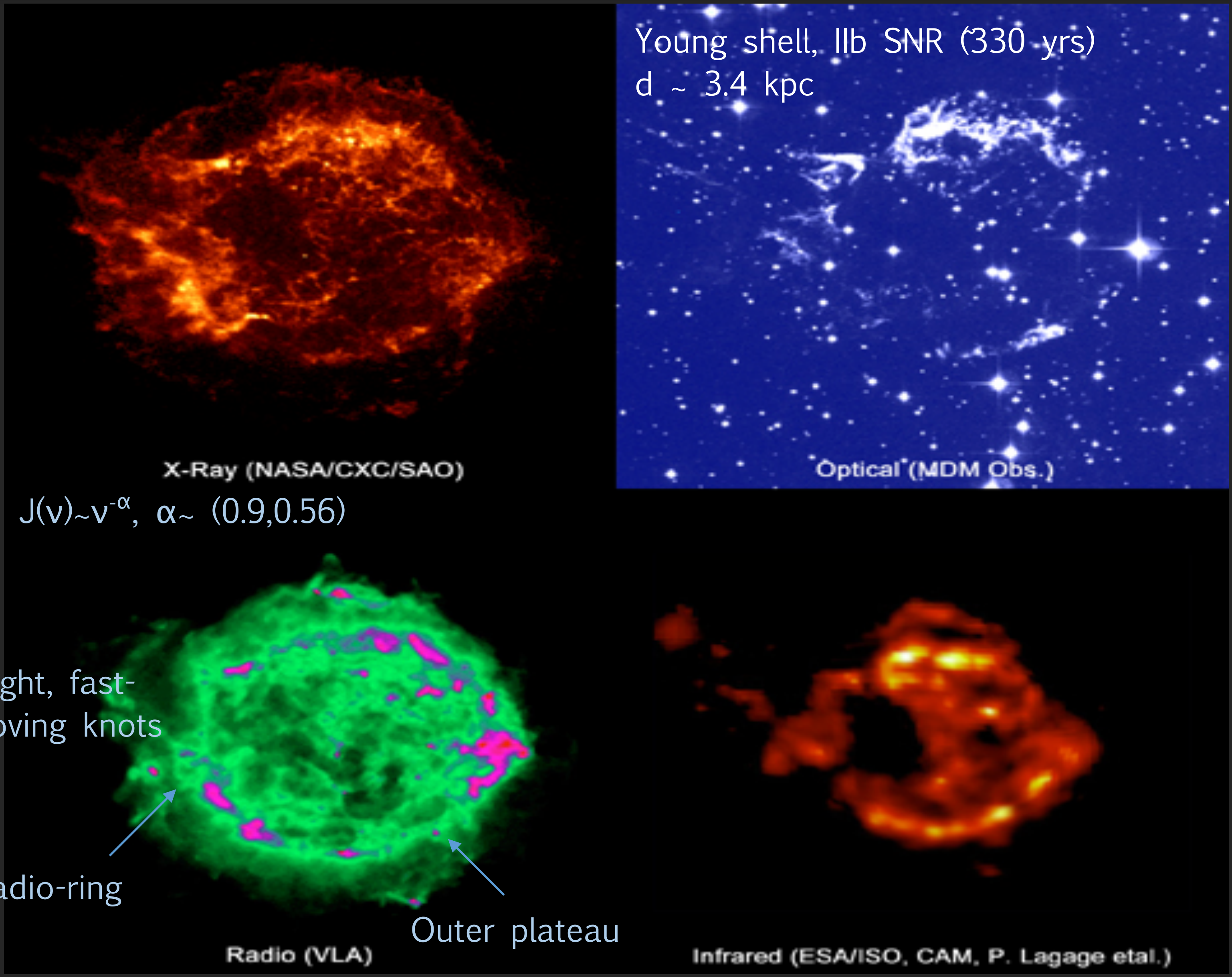


Image credit: NASA/CXC/SAO

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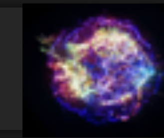

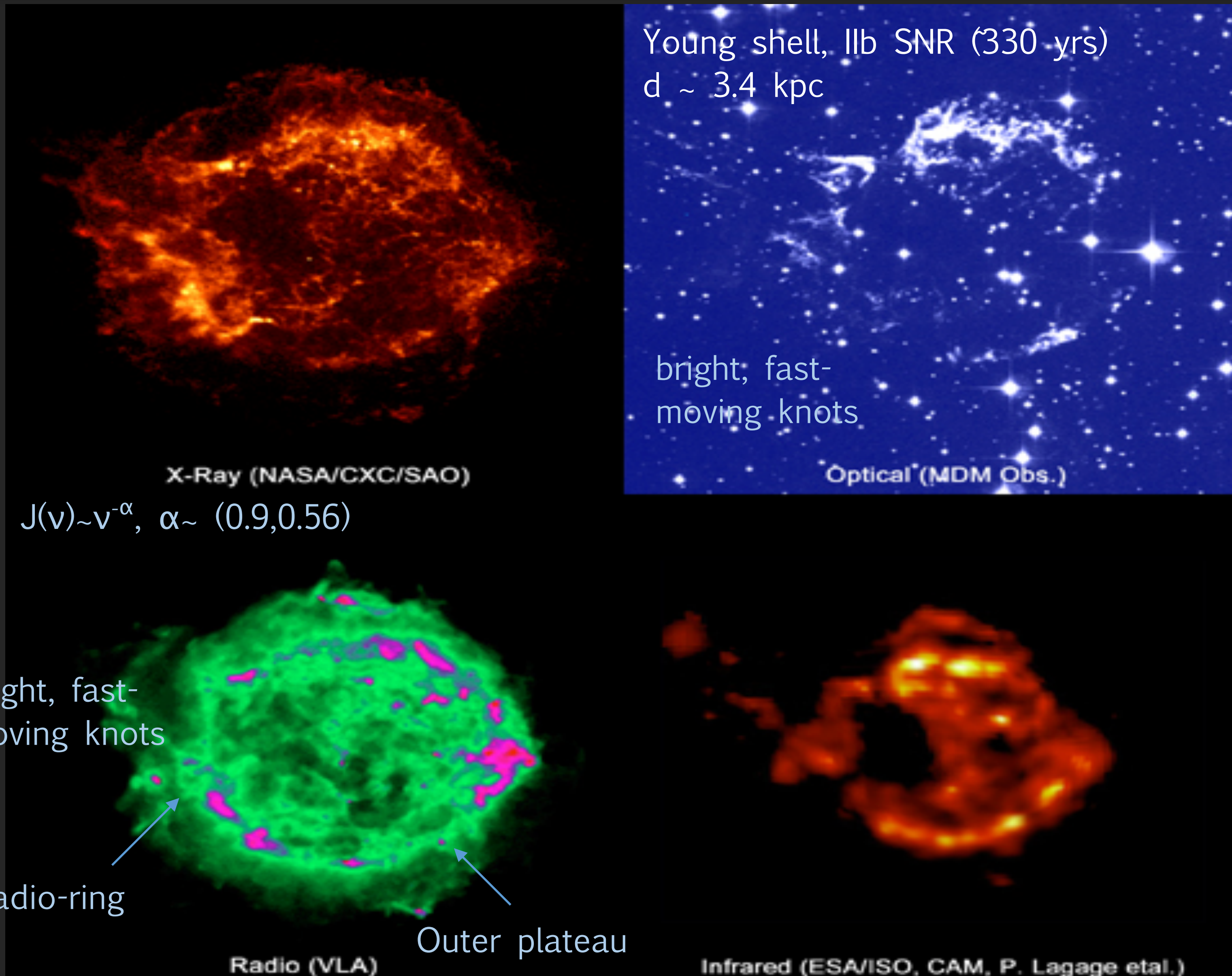

Image credit: NASA/CXC/SAO

Lastochkin et al. 1963; Medd & Ramana 1965; Allen & Barrett 1967; Parker 1968; Braude et al. 1969; Hales et al. 1995, Anderson et al. 1991, Gotthelf et al. 2001; Maeda et al. 2009; Grefenstette et al. 2015; Wang & Li 2016, Uchiyama & Aharonian 2008, Metzger et al 1986

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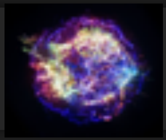

thermal (1-3 keV) ejecta
Non-thermal up to 100 keV
Above 15 keV dominated by knots and rim filaments
B ~ mG (year-scale variability)

Young shell, IIb SNR (330 yrs)
d ~ 3.4 kpc

$J(\nu) \sim \nu^{-\alpha}$, $\alpha \sim (0.9, 0.56)$

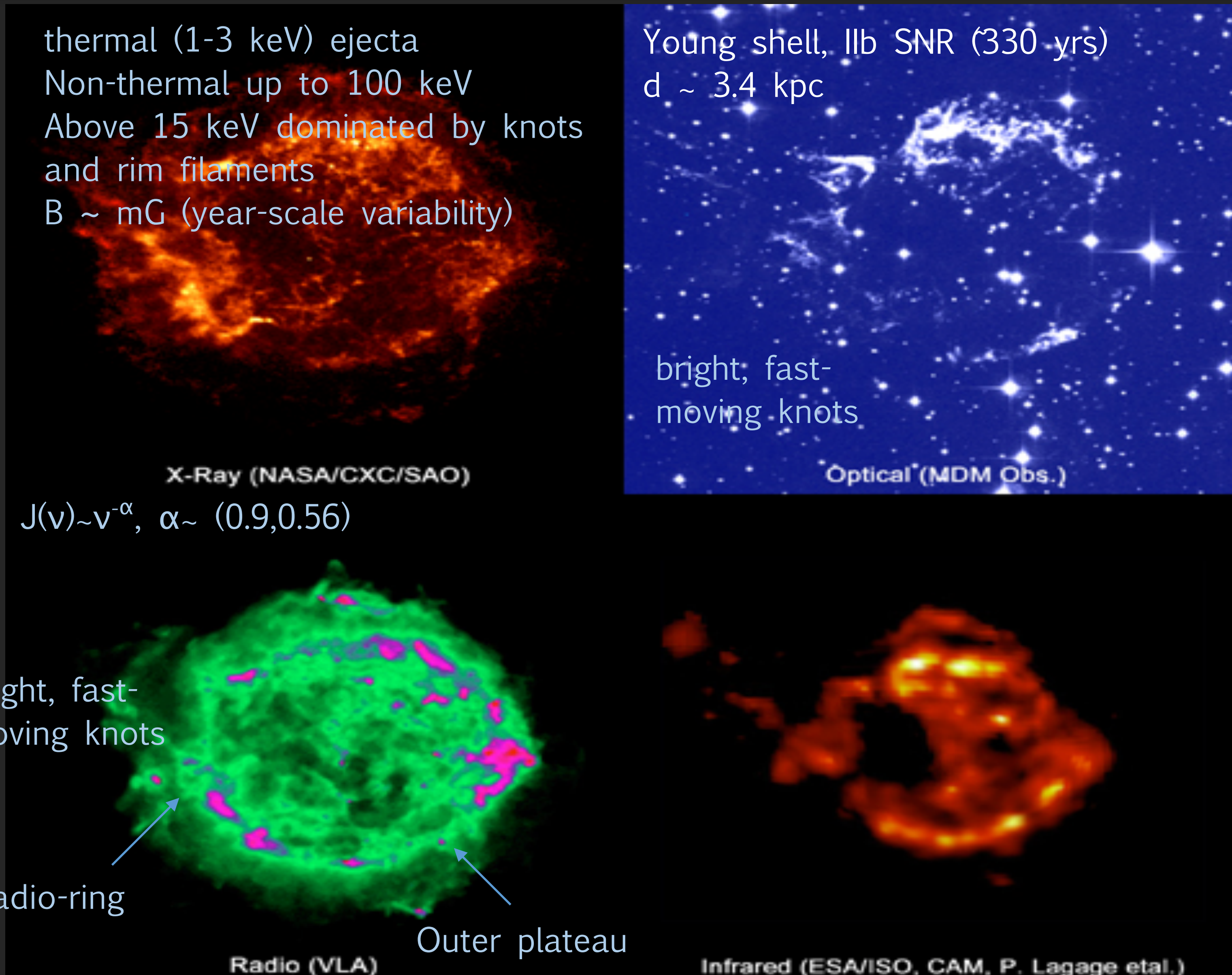

Image credit: NASA/CXC/SAO

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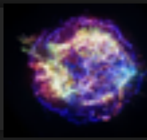


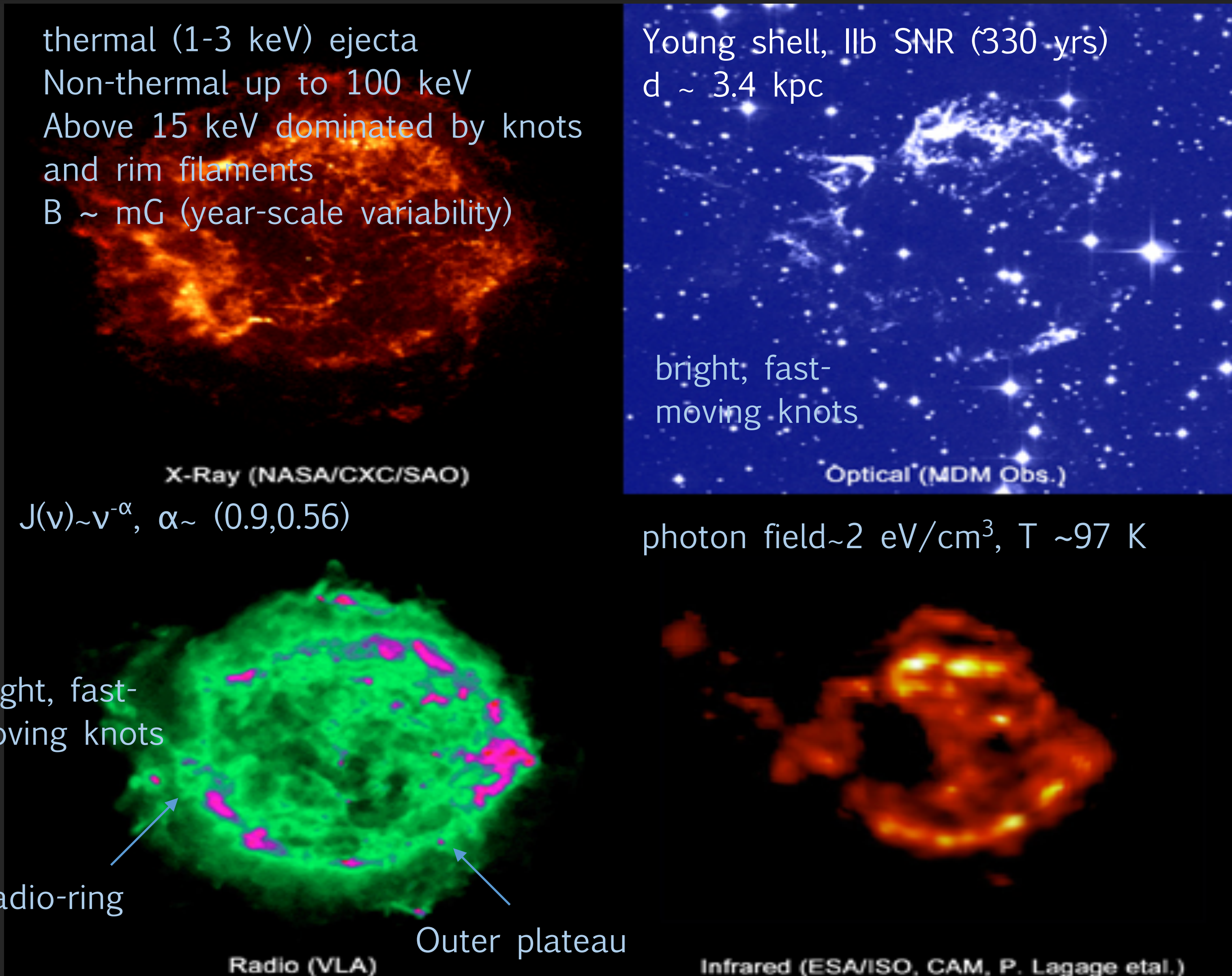
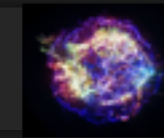


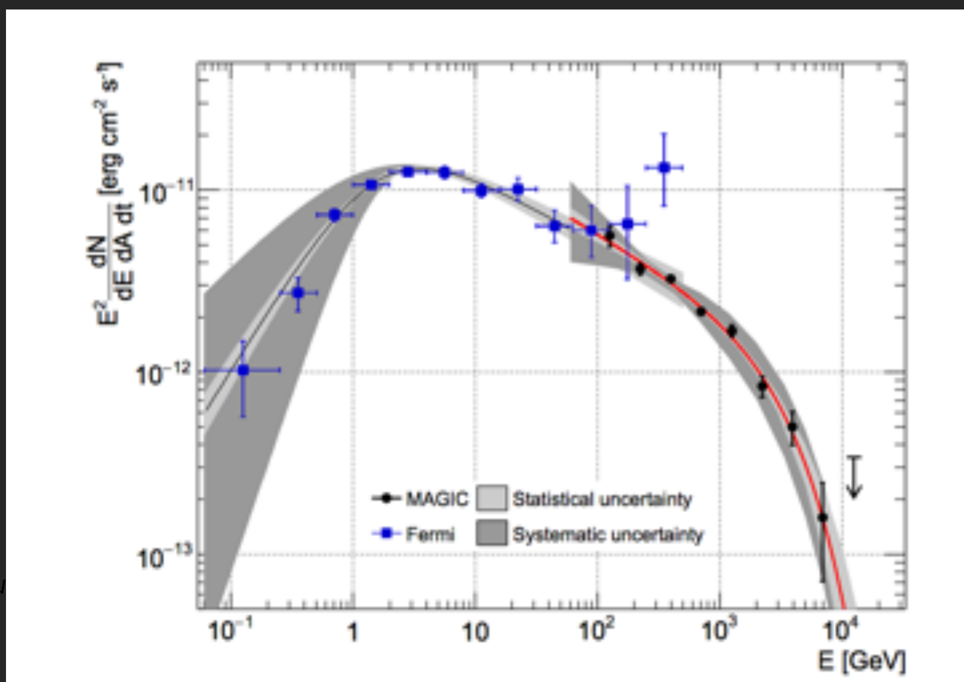
Image credit: NASA/CXC/SAO

Lastochkin et al. 1963; Medd & Ramana 1965; Allen & Barrett 1967; Parker 1968; Braude et al. 1969; Hales et al. 1995, Anderson et al. 1991, Gotthelf et al. 2001; Maeda et al. 2009; Grefenstette et al. 2015; Wang & Li 2016, Uchiyama & Aharonian 2008, Metzger et al 1986



At high energies:

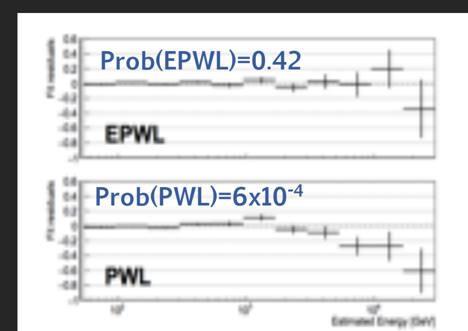
- point-like emission (angular size ~5')
- we observed with MAGIC for a total of 160h (2014-2016)
- energy turn-off at ~1.7 GeV, evidence of change of slope among GeV/TeV data



MAGIC Col. 2017

EPWL preferred over PWL with 4.6σ significance.

Ecut = 3.5 TeV

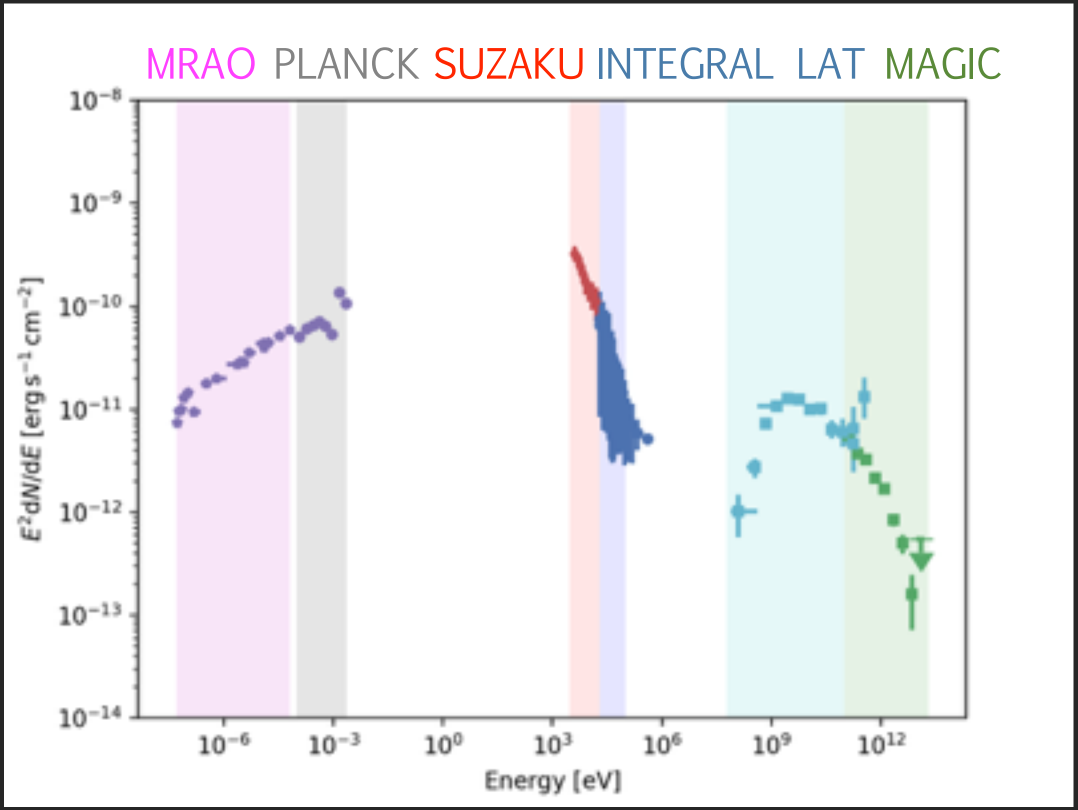


MAGIC Col. 2017

Spectral Energy Distribution

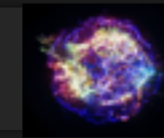
Zabalza 2015, Kafexhiu et al 2014, Aharonian et al 2010, Khangulyan et al 2014, Baring et al 1999, Laming & Hwang 2003, Lagage & Cesarsky 1983

Multi-Wavelength SED fit using Naima*
Parent population: electron/positrons described by a power-law function plus exponential cutoff



*https://github.com/zblz/naima

Spectral Energy Distribution



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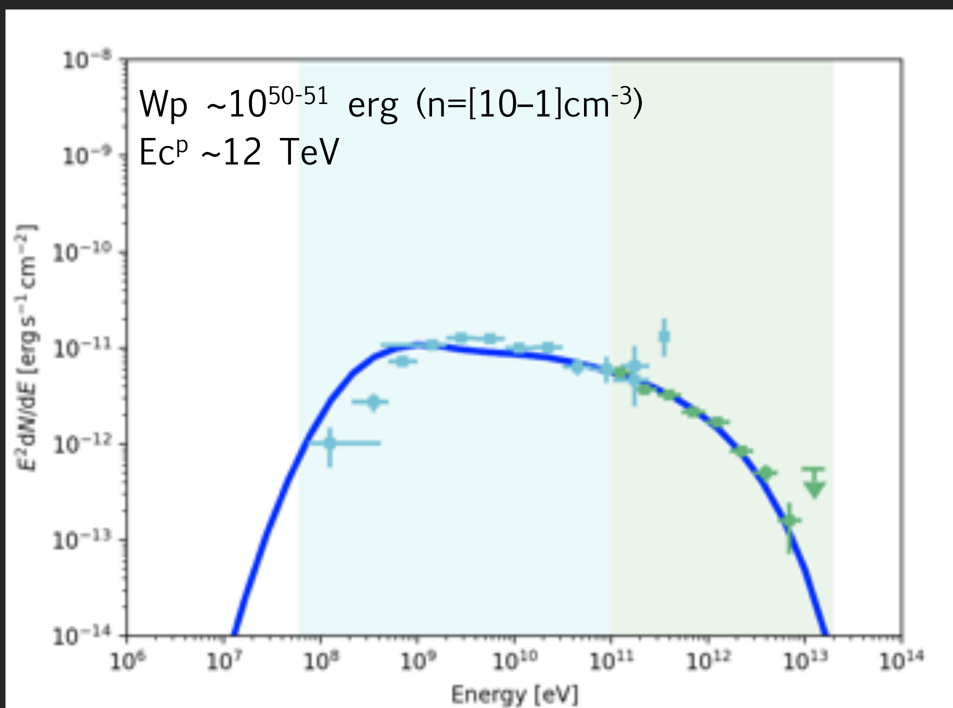


Proton-proton Interactions

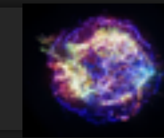
Np ~ 10 cm^{-3}, α ~ 2.21
E_c ~ 12 TeV
Wp(>1 TeV) ~ 5.1×10^{48} ($1/n/10cm^{-3}$)erg (0.2% of Esn (=2×10^{51} erg))
Wp(>100 MeV) ~ 9.9×10^{49}($1/n/10cm^{-3}$)erg

If hadronic: Extremely inefficient accelerator to very high energies! escape?

$$E_c^p \simeq 450\left(\frac{B}{1\ \mathrm{mG}}\right)\left(\frac{t_0}{100\ \mathrm{yr}}\right)\left(\frac{u_s}{3000\ \mathrm{km/s}}\right)^2\eta^{-1}\ \mathrm{TeV},$$

*https://github.com/zblz/naima

Spectral Energy Distribution



Multi-Wavelength SED fit using Naima*
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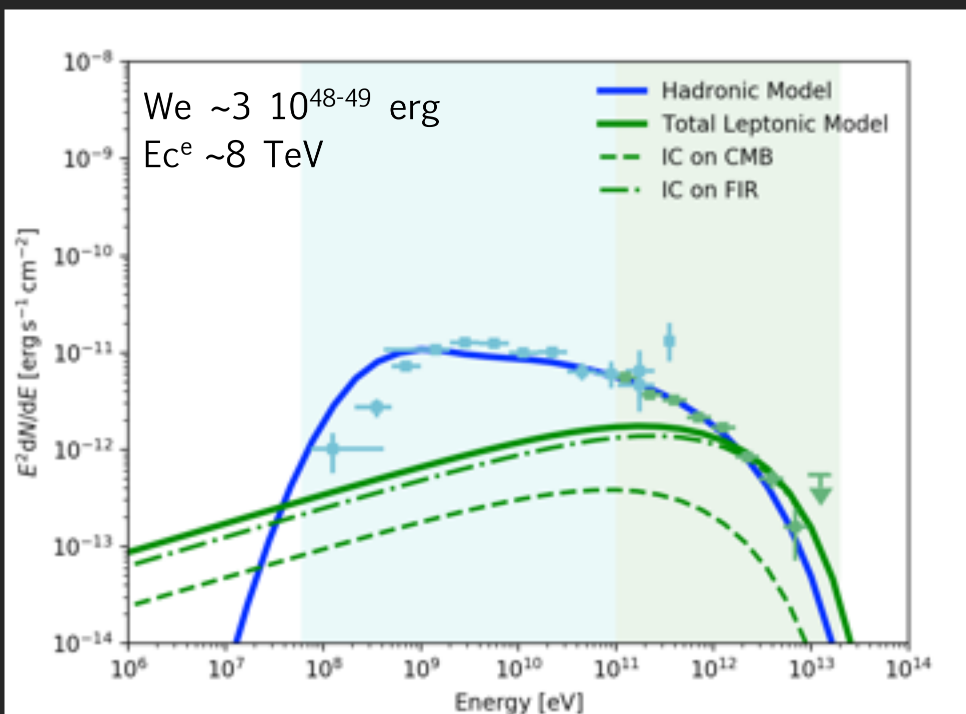
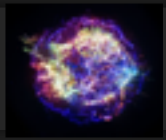


Inverse Compton

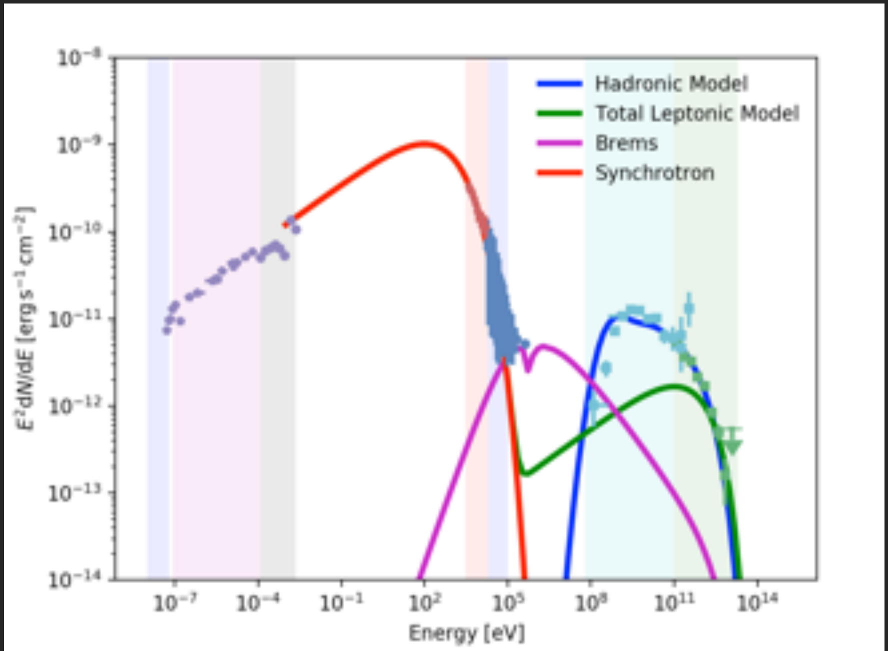
α ~ 2.54 (as in radio)
E_c ~ 8 TeV
N_e (1 TeV) ~ 2×10^{34} eV^{-1}
Photon Fields:
CMB & FIR (2.0 eV/cm3 at 100 keV)

*https://github.com/zblz/naima

Spectral Energy Distribution



Multi-Wavelength SED fit using Naima*
Parent population: electron/positrons described by a power-law function plus exponential cutoff



Inverse Compton & Synchrotron

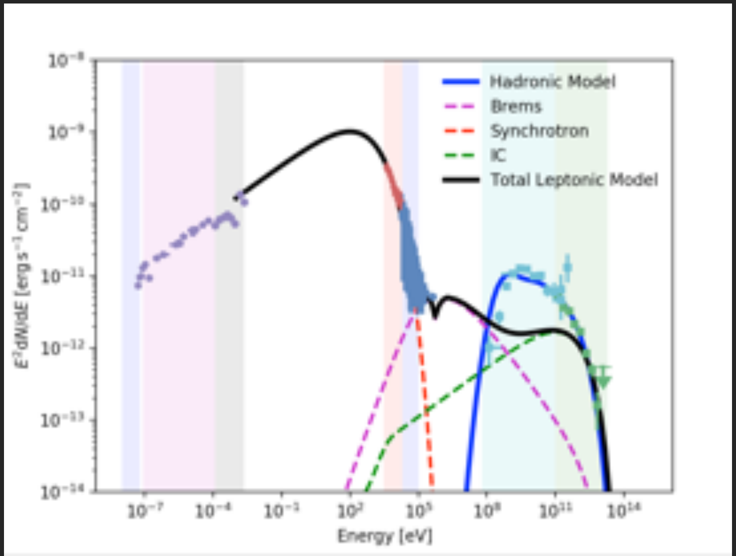
α ~ 2.54 (as in radio)
E_c ~ 8 TeV
N_e (1 TeV) ~ 2×10^{34} eV^{-1}
Photon Fields:
CMB & FIR (2.0 eV/cm3 at 100 keV)

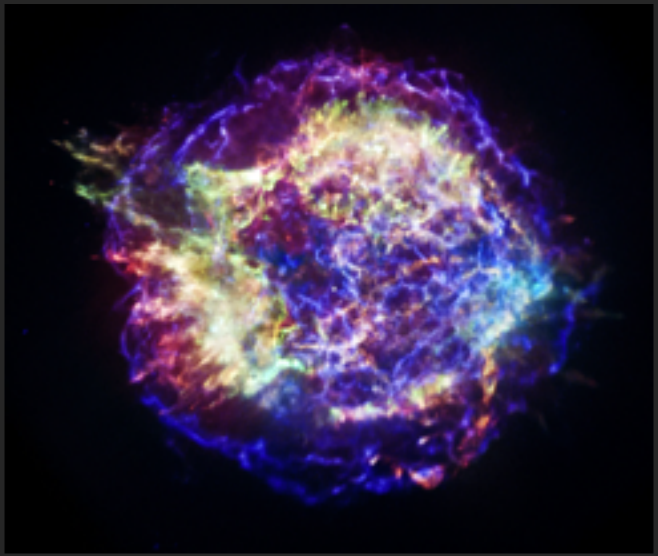
B ~180 uG (80-160 uG - Vink&Lamming)

Bremsstrahlung
(with completely ionised target gas with ISM abundances)
n_o < 1 cm^{-3}
(n_o=10 cm^{-3} for the shock circumstellar medium)

*https://github.com/zblz/naima

Spectral Energy Distribution





If leptonic:

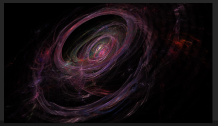
Relative low magnetic field in large photon field, possible in a thin, clumpy ejecta medium

If hadronic:

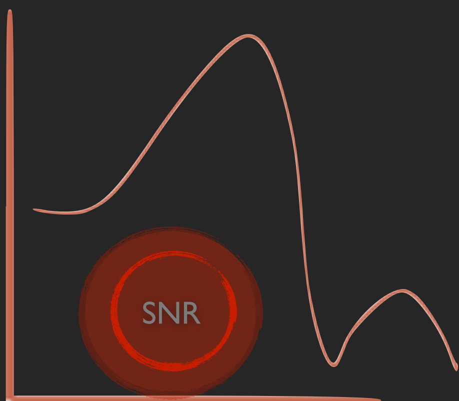
Moderate CR efficiency but very low maximum energy! E_{max}^{p} only 1.5 times larger than E_{max}^{e} (of course, higher B_{field} (~1mG) would imply lower - undetectable - IC)

We/Wp ~1/[100–1000] —> Compatible with the e/p ratio content

Where are the PeVatrons?

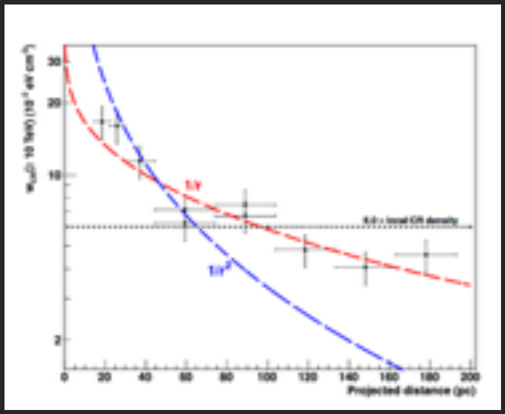


Hypothesis: PeV particles are accelerated at the beginning of Sedov phase (~200yrs), when the shock speed is high but the SNR is faint, then they escape
Look at the surroundings, or somewhere else?
GeV/TeV morphology: a good diagnosis tool to identify the origin of gamma-rays

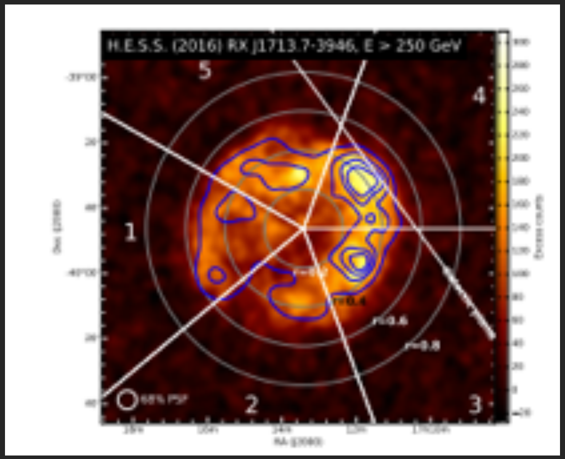


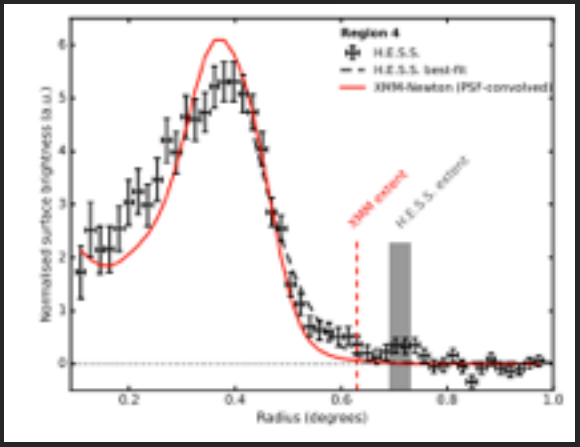
radial profile

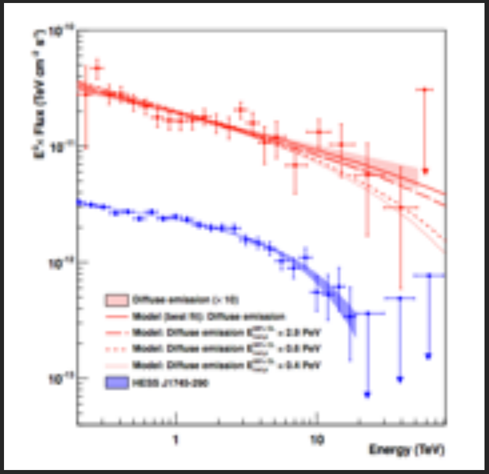
1/r profile is characteristic of a continuous injection spectrum + diffusive propagation of particles interacting with gas.



Galactic Center







HESS Col. 2016

HESS Col. 2016

Cosmic Rays Stellar Clusters

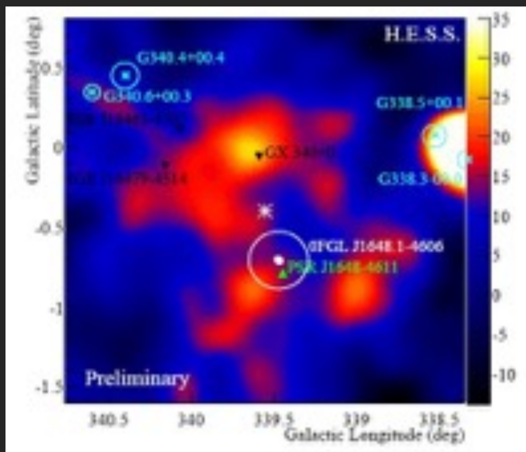
Other accelerators - Old massive Stars (wind-wind, clusters, collective effects)
Energy reservoir ~$10^{38\text{-}39}$ erg over ages of T≥10^6 years

Table 1. Properties of massive clusters in the Galaxy[a]

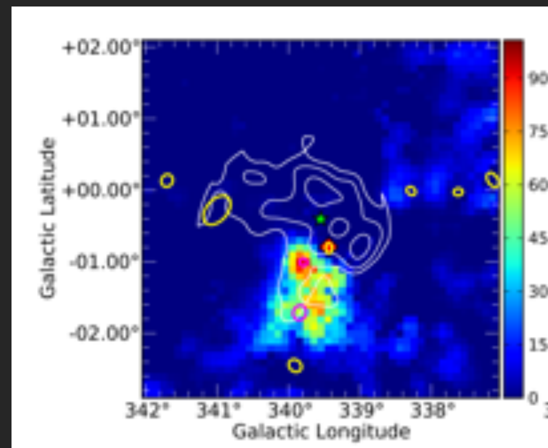
Cluster	Log(M) $M_\odot$	Radius pc	Log(ρ) $M_\odot$ pc^{-3}	Age Myr	Log(L) $L_\odot$	Log(Q) s^{-1}	OB	YSG	RSG	LBV	WN	WC
Westerlund 1[b]	4.7	1.0	4.1	4–6	...	...	...	6	4	2	16	8
RSGC2[c]	4.6	2.7	2.7	14–21	...	...	0	0	26	0	0	0
RSGC1[d]	4.5	1.3	3.5	10–14	...	...	1	1	14	0	0	0
Quintuplet[e]	4.3	1.0	3.2	4–6	7.5	50.9	100	0	1	2	6	13
Arches[f]	4.3	0.19	5.6	2–2.5	8.0	51.0	160	0	0	0	6	0
Center[g]	4.3	0.23	5.6	4–7	7.3	50.5	100	0	4	1	18	12
NGC 3603[h]	4.1	0.3	5.0	2–2.5	...	...	60	0	0	0	3	0
Trumpler 14[i]	4.0	0.5	4.3	<2	...	...	31	...	...	...	...	...
Westerlund 2[j]	4.0	0.8	3.7	1.5–2.5	...	...	...	...	...	...	2	...
Cl 1806-20[k]	3.8	0.8	3.5	4–6	...	...	5	0	...	1	2	2

Figer 2008

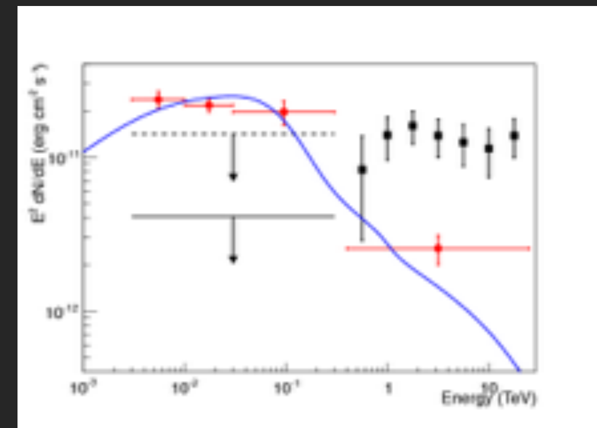
Westerlund 1:



HESS Col. 2011

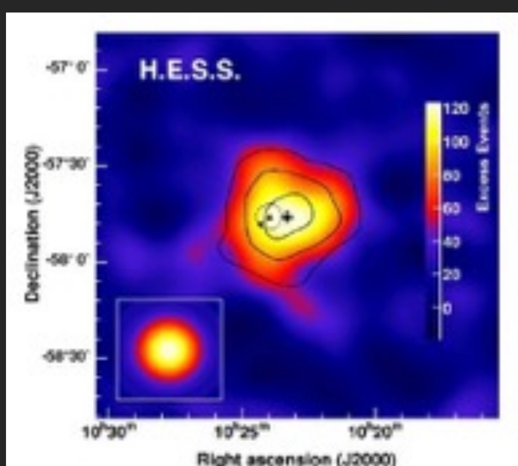


Ohm et al 2013

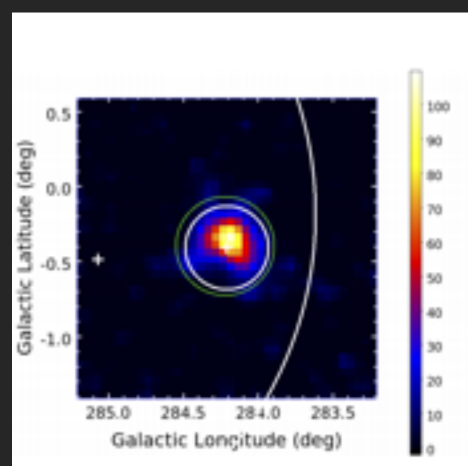


Ohm et al 2013

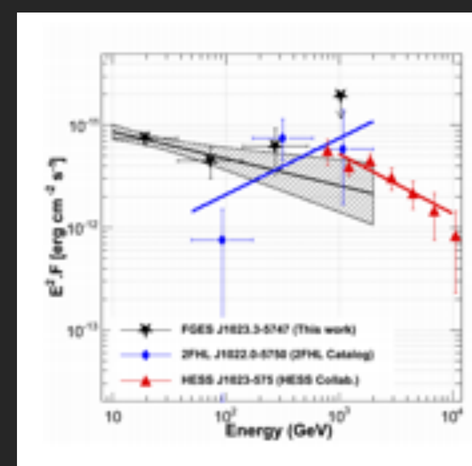
Westerlund 2:



HESS Col. 2010



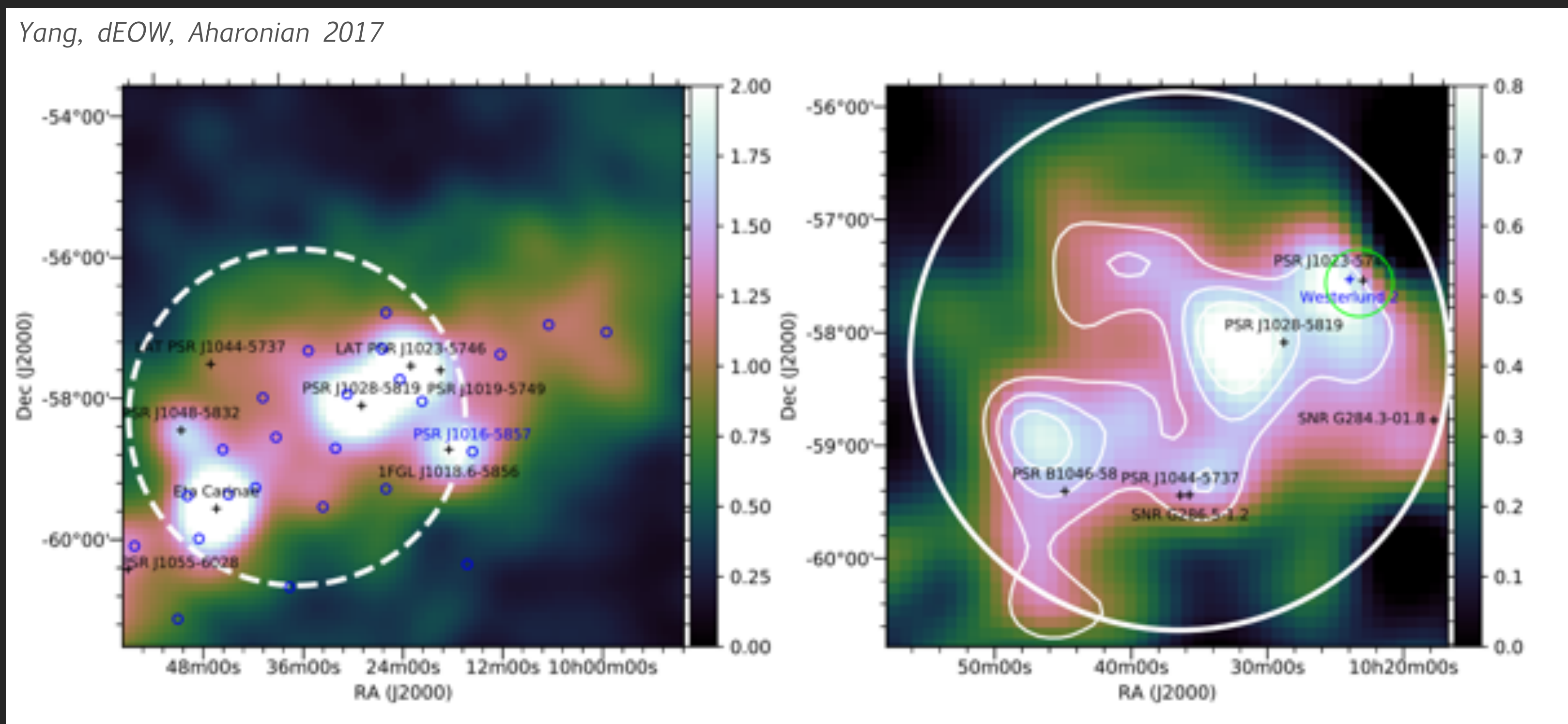
LAT Col. 2016



LAT Col. 2016

Westerlund 2:

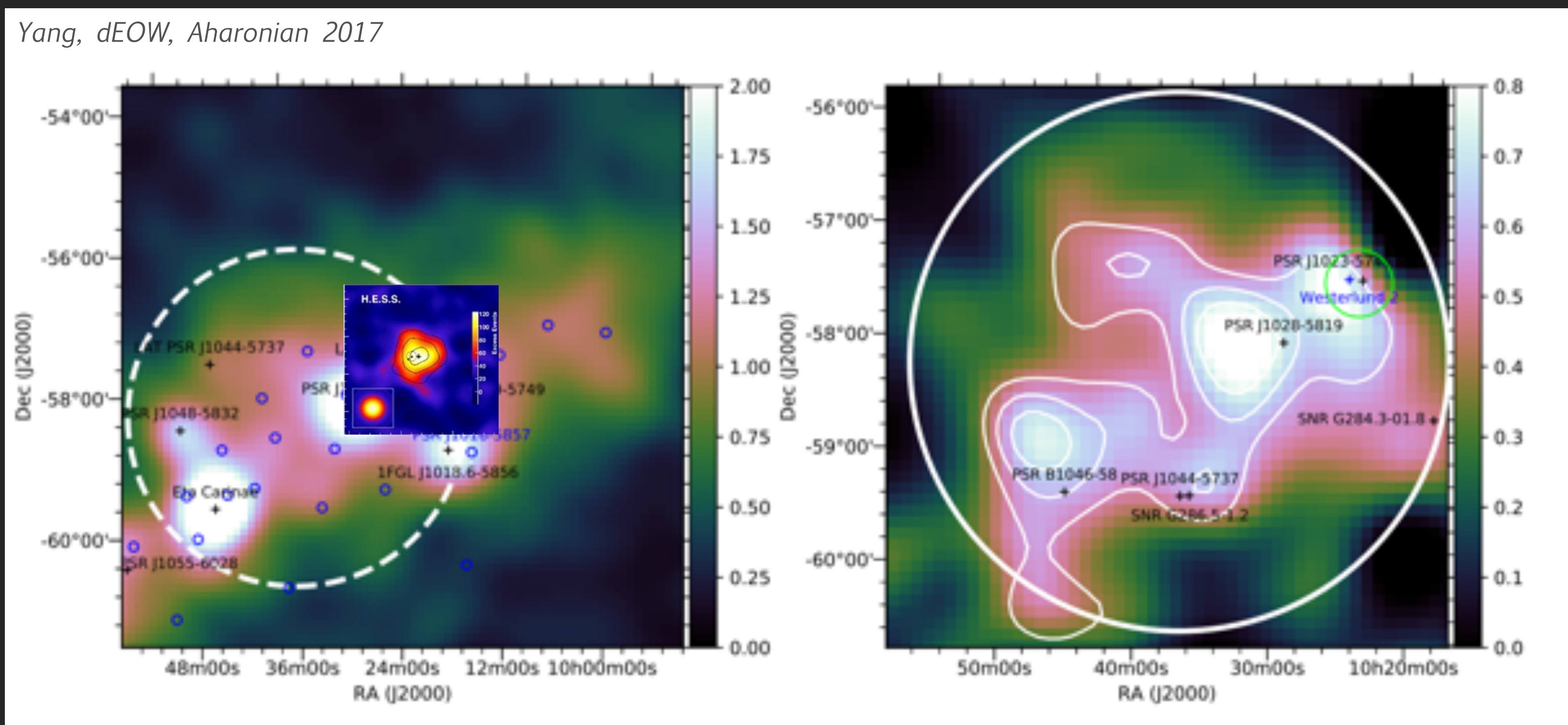
- A large single region is statistically preferred with a radius of 2.4deg, centred on $RA_{J2000} = (159.10 \pm 0.10)^{\circ}$, $DEC_{J2000} = (-58.50 \pm 0.10)^{\circ}$



Skymap >10 GeV after subtracting diffuse and identified sources

Westerlund 2:

- A large single region is statistically preferred with a radius of 2.4deg, centred on RA_{J2000} = (159.10±0.10)$^{\circ}$, DEC_{J2000} = (–58.50±0.10)$^{\circ}$



Yang, dEOW, Aharonian 2017

Skymap >10 GeV after subtracting diffuse and identified sources

Westerlund 2:

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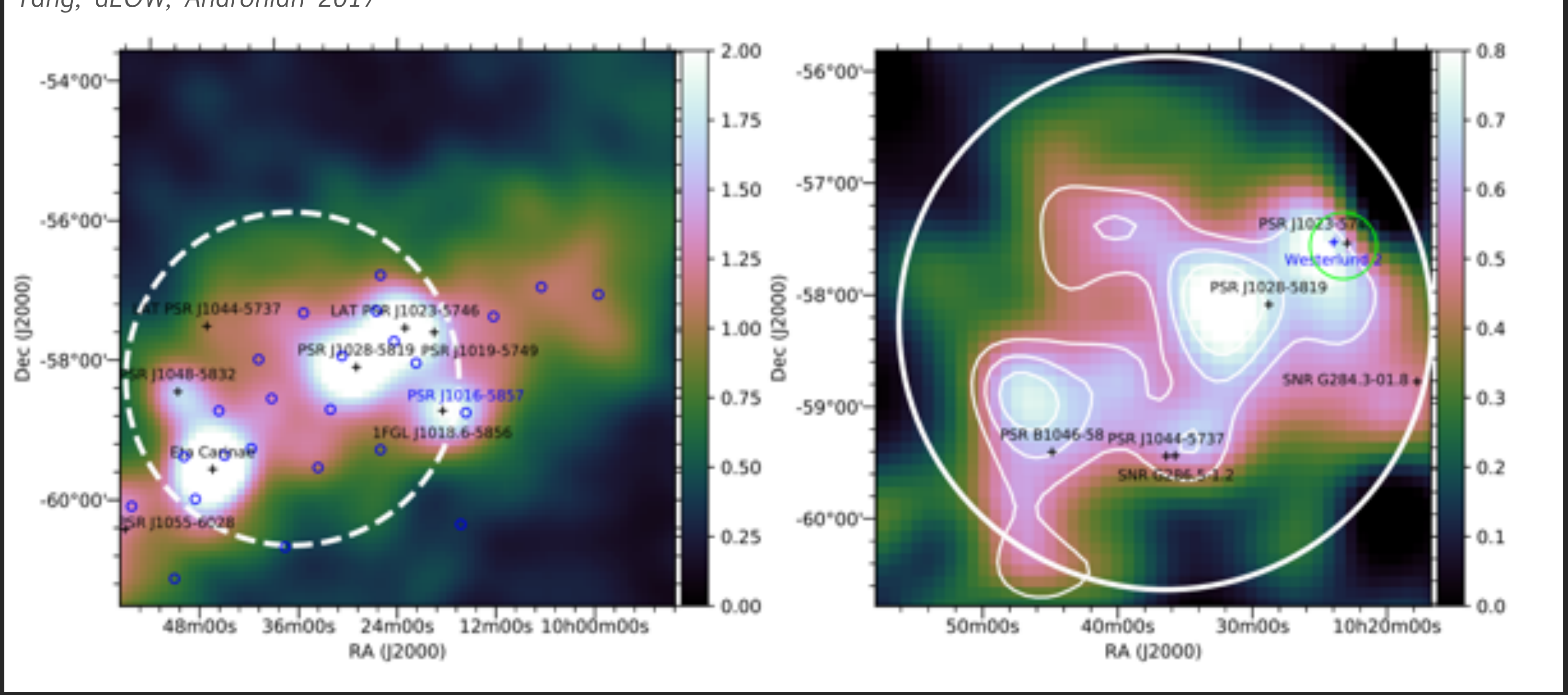
Yang, dEOW, Aharonian 2017

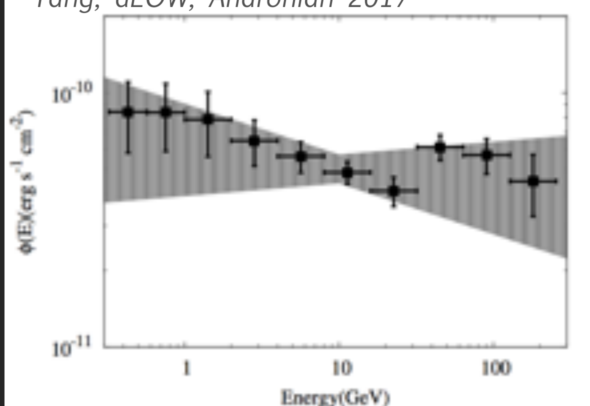


Skymap >10 GeV after subtracting diffuse and identified sources

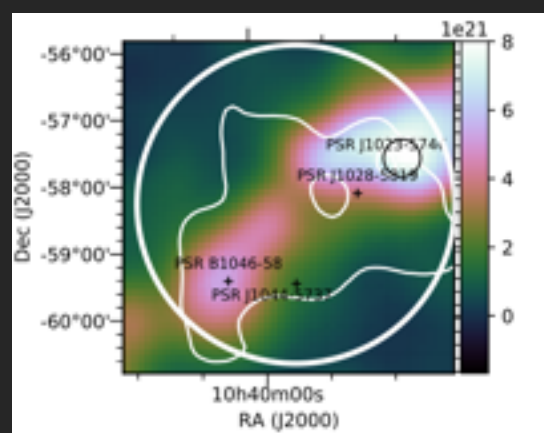
Westerlund 2:

- A large single region is statistically preferred with a radius of 2.4deg, centred on $RA_{J2000} = (159.10 \pm 0.10)^{\circ}$, $DEC_{J2000} = (-58.50 \pm 0.10)^{\circ}$
- $F\ (>100\ \mathrm{MeV}) = (4.2 \pm 0.2) \times 10^{-8} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ Index $= 2.02 \pm 0.11_{sta} \pm 0.1_{sys.}$
- $L = 10^{36}$ erg/s (d = 5 kpc)
- We evaluate the gas using Planck free-free (HII) and CfA (CO) maps in the [-11,21] km/s. Gas density: $7\ \mathrm{cm}^{-3} < n_{gas} < 25\ \mathrm{cm}^{-3}$

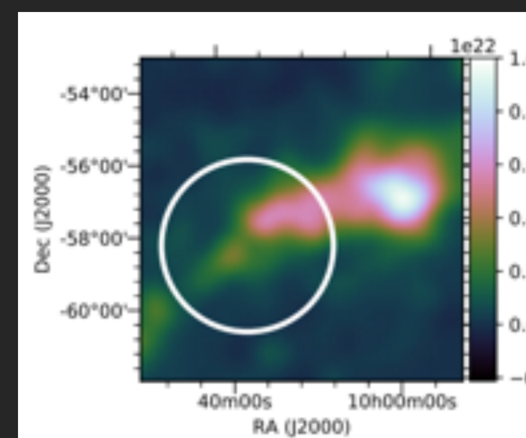
Yang, dEOW, Aharonian 2017



Total gas column derived from CO + HII



Total gas column derived from CO



Tracer	Gas Phase	Mass ($10^6\ M_\odot$)
2.6 mm line	H_2	1.8
free-free intensity ($n_e = 2\ \mathrm{cm}^{-3}$)	H II	1.0 / 5.5
free-free intensity ($n_e = 10\ \mathrm{cm}^{-3}$)	H II	0.2 / 1.1

Possible scenarios:

- **CRs continuously injected from Westerlund 2 stellar cluster**

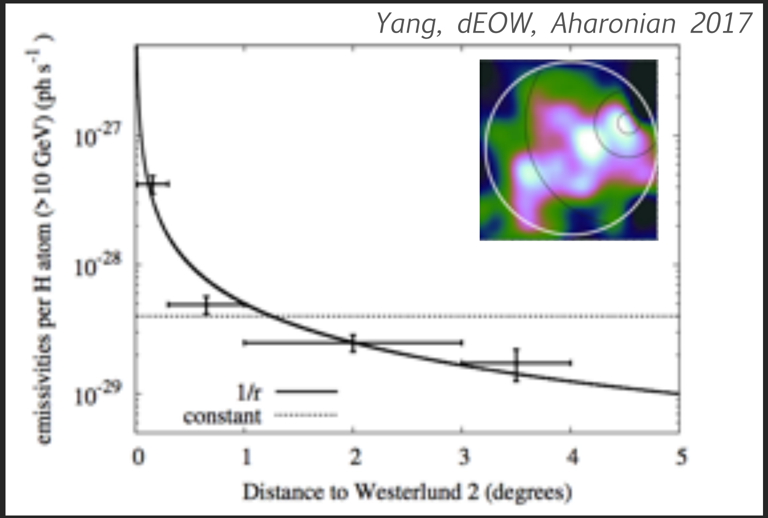
CR energy confined in the γ-ray production area **$(4\text{–}13)\times10^{49}$ erg.**
Total mechanical energy in the form of stellar wind 10^{51} erg (in 10^6 yrs)

If CRs diffusing away from Westerlund 2:

Aharonian & Atoyan 1996

$$\frac{n_{\rm emis}}{n_{\rm tot}} = \left(\frac{R}{r_{\rm diff}}\right)^2 = 0.1 \times \left(\frac{2\times10^6\ \rm years}{T}\right)\left(\frac{10^{28}\ \rm cm^2/s}{D}\right),$$

x10 more!!



(1/r): χ2/ndf=1.3
(cte): χ2/ndf=15.6

But we do not see a good correlation between gas and gamma-rays! different distances? missing gas?

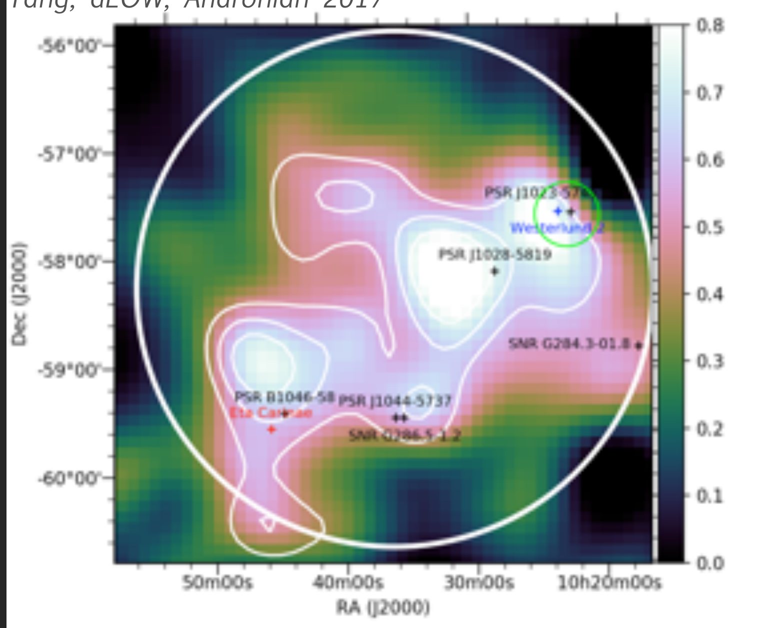
Possible scenarios:

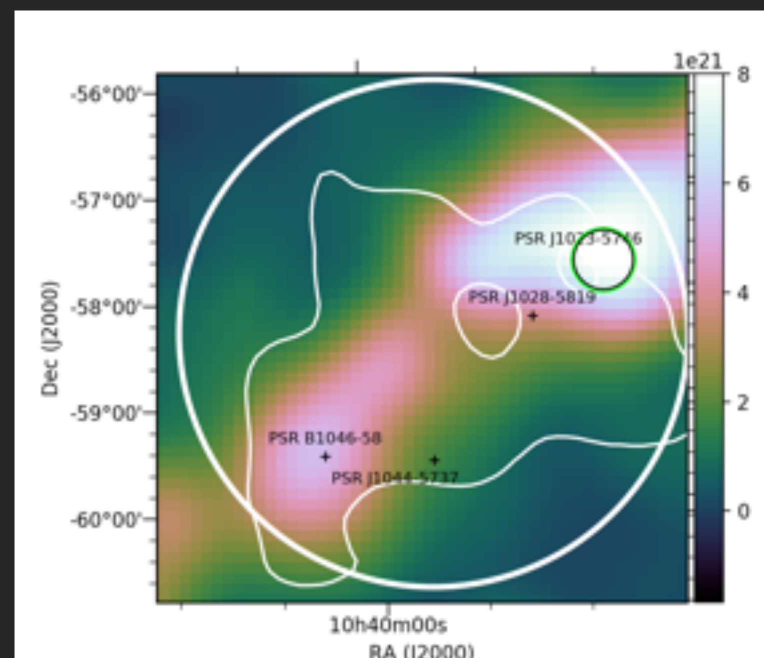
- **Other possible scenarios:**

The colliding binary Eta-Carina with similar radiation process (10^{37} erg/s in 10^{6} yrs)

Combination of low and high energy emission coming from TeV PWNe associated to energetic pulsars shinning in the GeV regime

Yang, dEOW, Aharonian 2017





Possible scenarios:

- **Other possible scenarios:**

The colliding binary Eta-Carina with similar radiation process (10^{37} erg/s in 10^{6} yrs)
Combination of low and high energy emission coming from TeV PWNe associated to energetic pulsars shinning in the GeV regime

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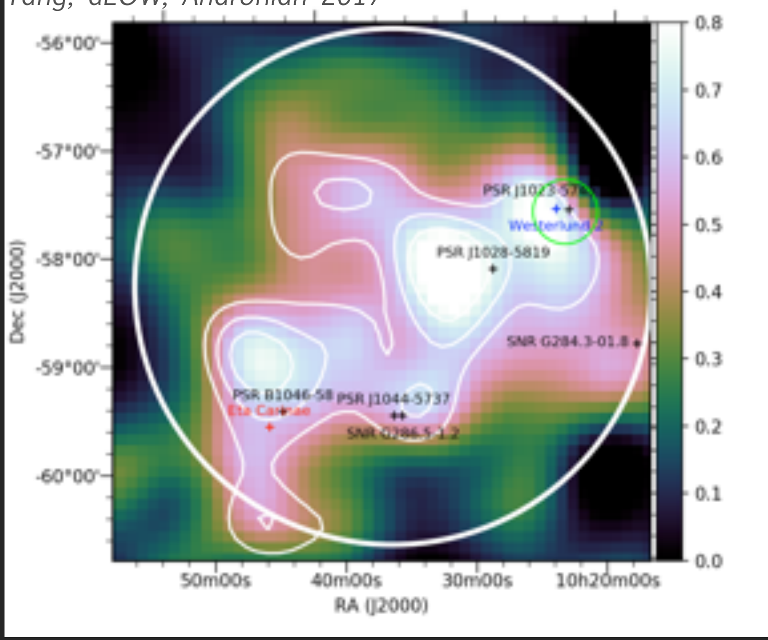

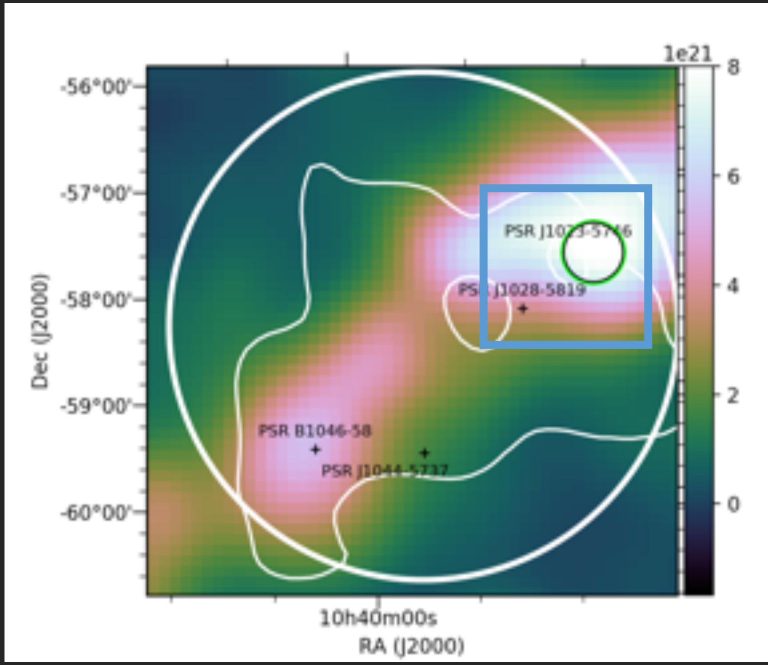

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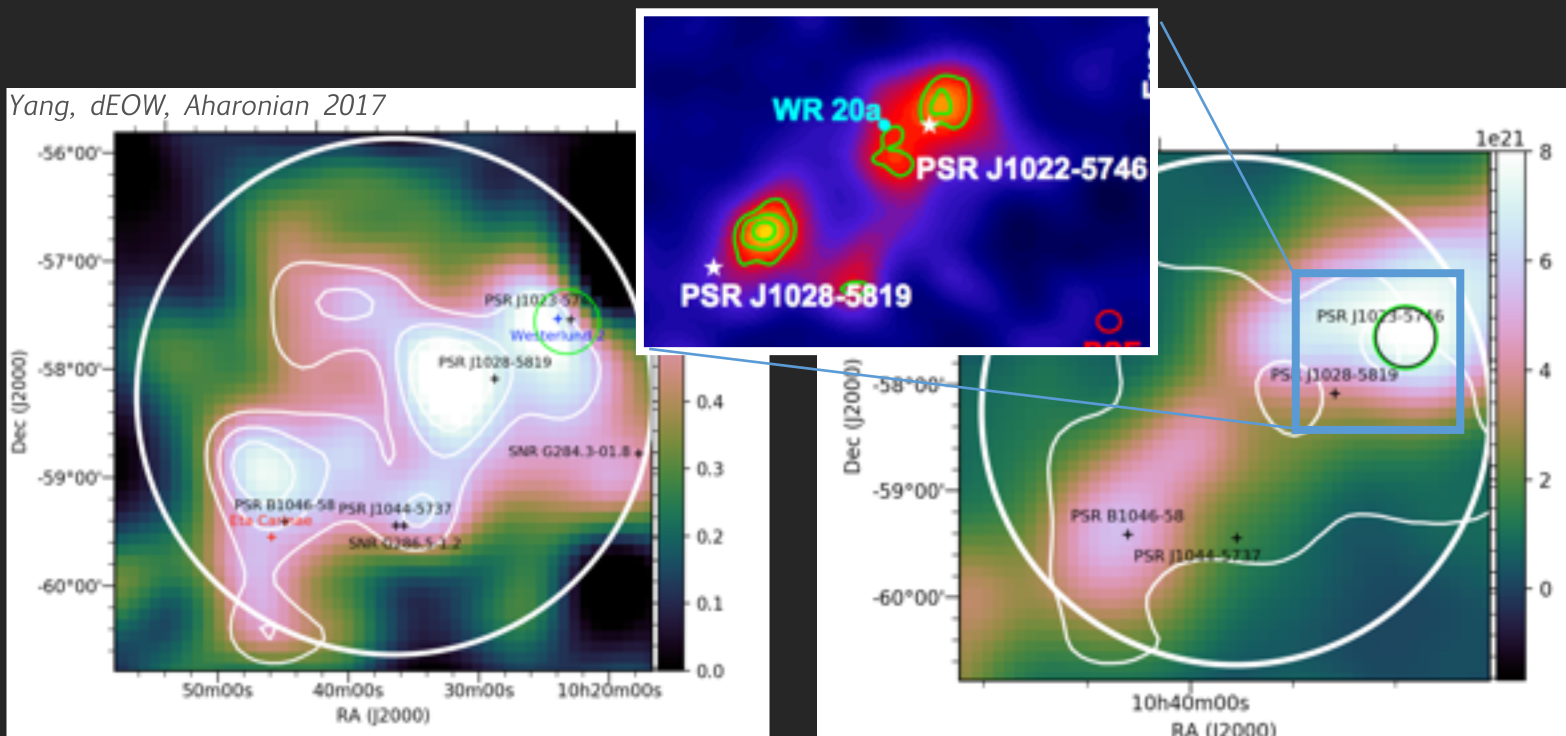

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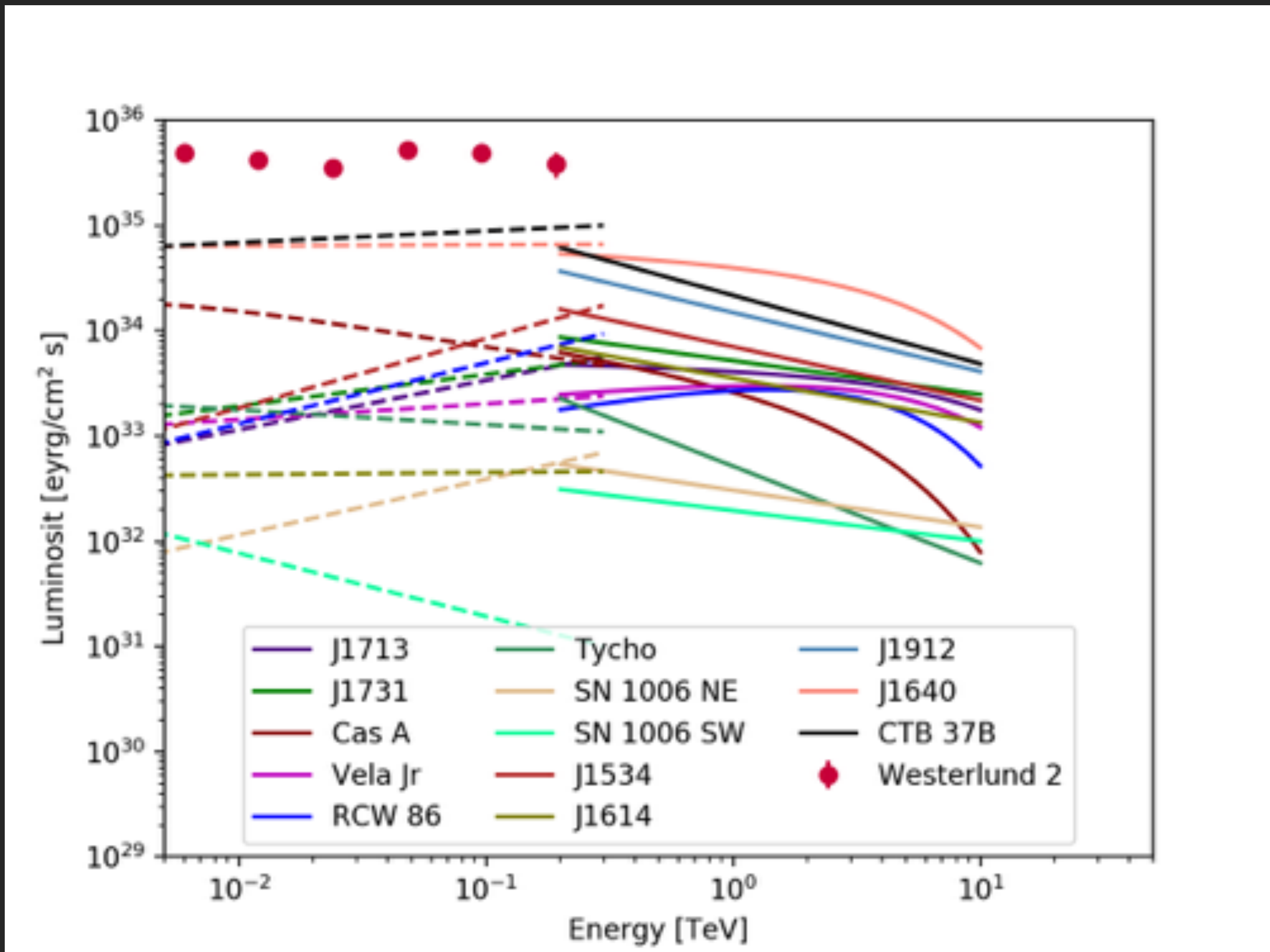
Fig. Westerlund 2 compared with young TeV SNRs



Summary

We obtain a good sample of SNRs at low and high energy, sampling the spectral energy distribution from a few ~100 MeV to a few~tens of TeV

The brightest TeV SNRs show an exponential cutoff at high energies

Observations of the best candidates (or the one with the more ‘hadron-like’ spectrum and higher magnetic field) also have resulted in measuring a energy turnover at a few TeV

Deep observations of Cassiopeia A provide evidences of a likely hadronic origin, but the acceleration energy reached does not exceed ~10 TeV - Escape?

We might be facing more than one type of accelerator - stellar clusters seems also to be contributing to the bulk of CRs - also at PeV energies?

Backups

Moon-light observations

Likelihood