Pulsar wind nebulae at very-high energies: issues and lessons

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With the support of

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Outline of the next few minutes

- A few specific points:
  - Impact of approximations onto the PWN solutions
  - Order parameters for the detectability of PWNe cannot be reduced to spin-down and distance
  - Self-Synchrotron domination, why Crab is the only one?
  - Are highly magnetized nebulae detectable at TeV?

Impact of approximations onto the PWN solutions

First approximation for a quick solution of the diff.-loss equation

- Diffusion-loss equation:

$$\frac{\partial N(\gamma,t)}{\partial t} = Q(\gamma,t) - \frac{\partial}{\partial \gamma}\left[\dot{\gamma}(\gamma,t) N(\gamma,t)\right] - \frac{N(\gamma,t)}{\tau(\gamma,t)}$$

Degeneracies in today's fit, leading to changes in time

- Diffusion-loss equation:

$$\frac{\partial N(\gamma,t)}{\partial t}=Q(\gamma,t)-\frac{\partial}{\partial\gamma}\left[\dot{\gamma}(\gamma,t)N(\gamma,t)\right]-\frac{N(\gamma,t)}{\tau(\gamma,t)}$$

In the collaboration's papers
usually no time-dependent model is used. Solutions can
and have been found to be very misleading.

For simplicity, escape, energy, and adiabatic losses as well as the time evolution of the magnetic field strength in the PWN are neglected, since the characteristic age of the pulsar is quite young. As reported by Nakamori et al. (2008), a single power-law electron spectrum does not reproduce the SED; hence the accumulated electron spectrum used here follows a broken power law with an exponential cutoff

$$\frac{dN_e}{dE}\propto\frac{(E/E_{br})^{-p_1}}{1+(E/E_{br})^{p_2-p_1}}\exp\left(-\frac{E}{E_{max}}\right), \qquad (3)$$

where E_{max}, E_{br}, p_1, and p_2 are the maximal energy, break energy, and the indices of the electron spectrum, respectively.

From Abdo et al. 2010

More involved analysis

- Diffusion-loss equation:

$$\frac{\partial N(\gamma,t)}{\partial t}=Q(\gamma,t)-\frac{\partial}{\partial\gamma}[\dot{\gamma}(\gamma,t)N(\gamma,t)]-\frac{N(\gamma,t)}{\tau(\gamma,t)}$$

e.g., Zhang et al. 2008 (TDE)

- Without energy losses, but escape

$$\frac{\partial N(\gamma,t)}{\partial t}=Q(\gamma,t)-\frac{N(\gamma,t)}{\tau(\gamma,t)}$$

Additional approximations:

- Consider just synchrotron and Bohm diffusion timescales

e.g. Tanaka et al. 2010, (ADE)

- Without escape, but energy losses

$$\frac{\partial N(\gamma,t)}{\partial t}=Q(\gamma,t)-\frac{\partial}{\partial\gamma}[\dot{\gamma}(\gamma,t)N(\gamma,t)]$$

Additional approximations:

- Do not consider Bremsstrahlung, IC (FIR & NIR)
- Max. energy of injection fixed
- Ballistic expansion for the PWN

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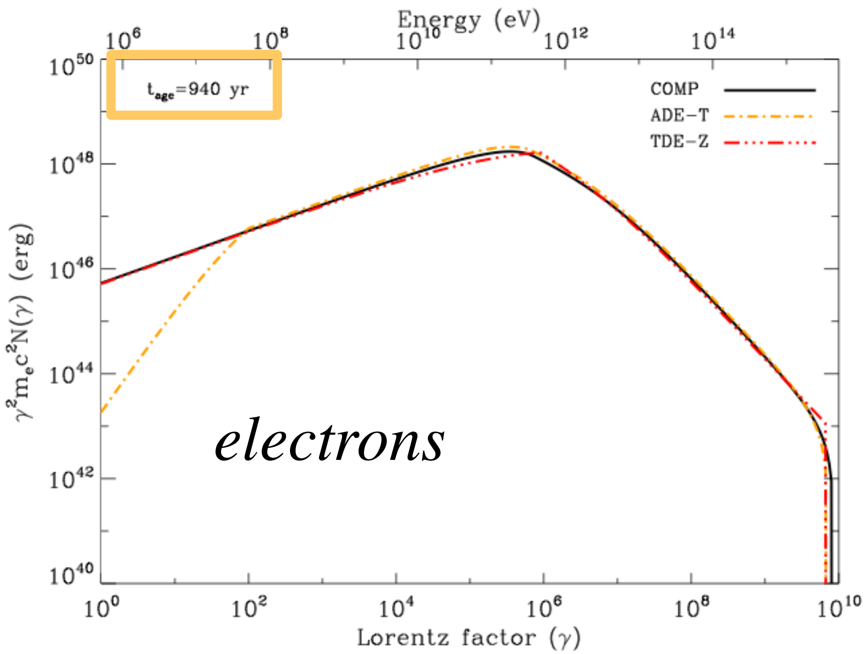
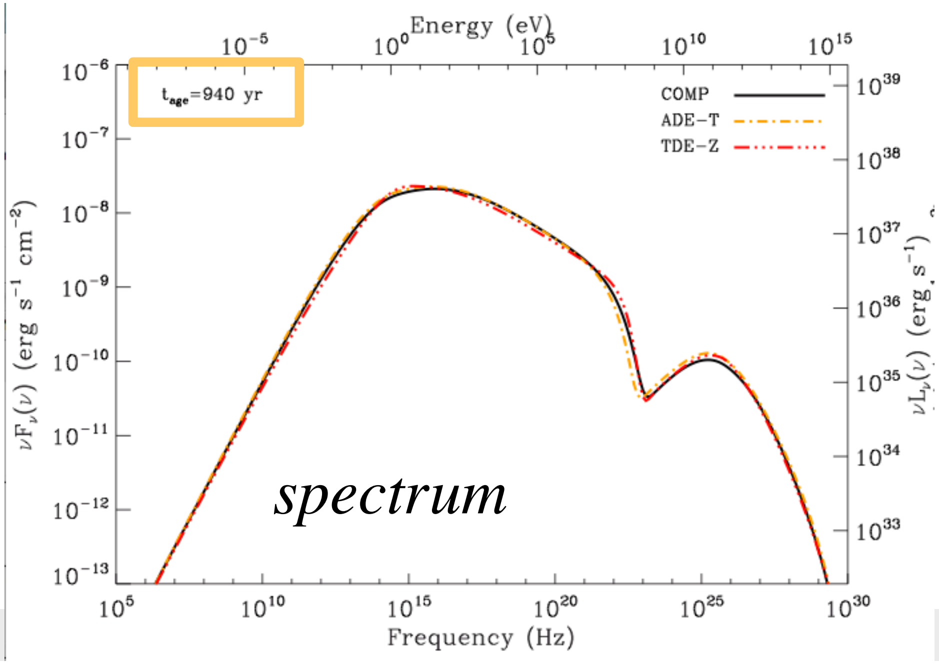
Take care of degeneracies in today's fit, leading to changes in time

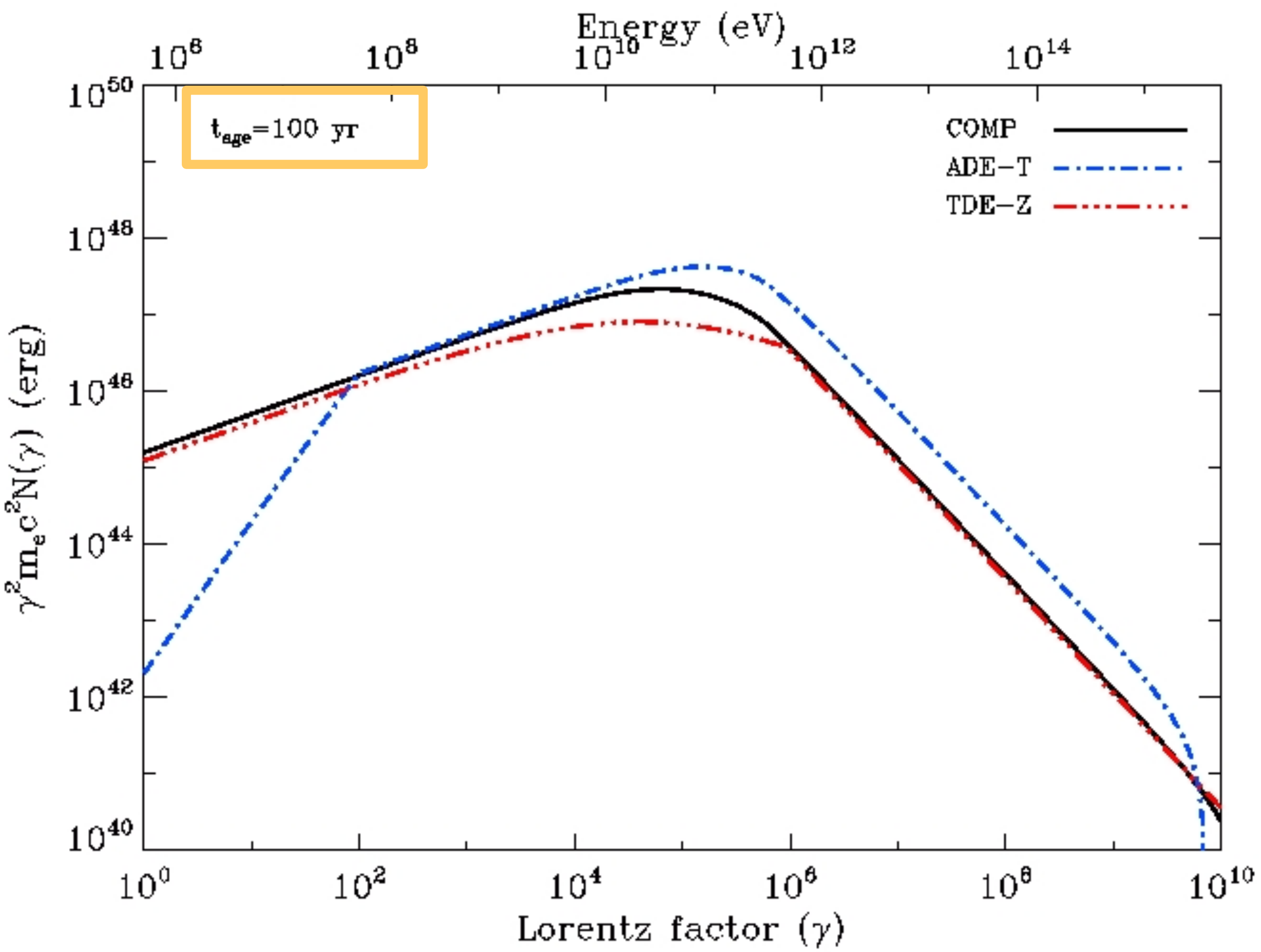




Symbol	Value	ADE-T	TDE-Z
$L(t_{age})$	4.5×10^{38}	...	2.5×10^{38}
$\gamma_{min}(t)$	1	10^2	...
$\gamma_{max}(t)$	7.9×10^9	7×10^9 (fixed)	6.5×10^9
γ_b	7×10^5	7×10^5	9×10^5
α_1	1.5	...	...
α_2	2.5	...	...
ε	1/3	...	...
L_0	3.1×10^{39}	...	1.7×10^{39}
$B(t_{age})$	87	...	83
η	0.012	0.006	0.015
R_{PWN}	2.1	1.7	1.9
T_{CMB}	2.73	...	...
w_{FIR}	0.25	...	...
T_{FIR}	70	0	...
w_{FIR}	0.5	0	...
T_{NIR}	5000	0	...
w_{NIR}	1	0	...
n_H	1	0	...

Good match for Crab @ normalization age;
but not so much for other PWN with no SSC domination

Look at it in a time-evolving setting: electron evolution



from Martin, DFT, Rea, MNRAS 2012

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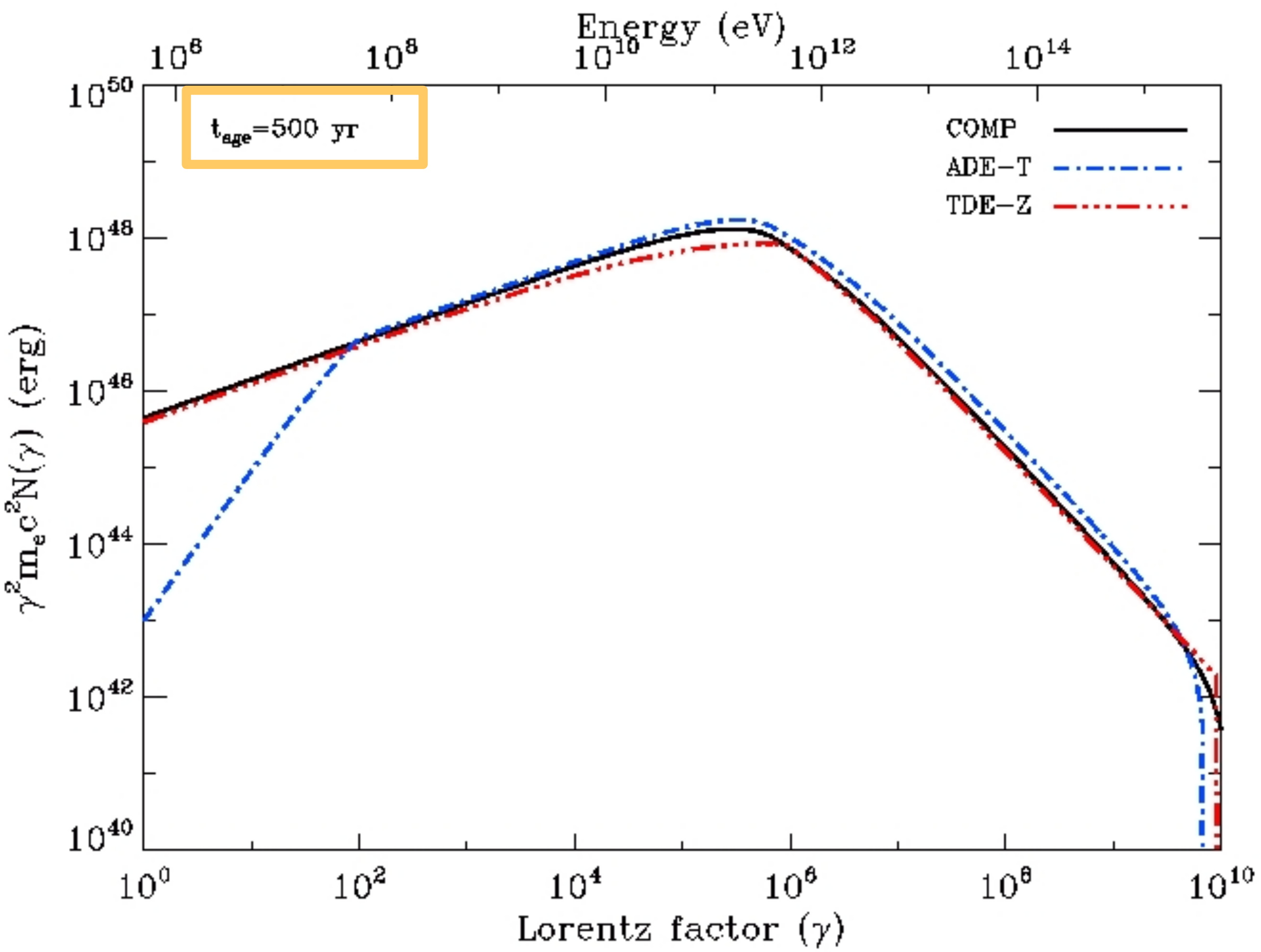

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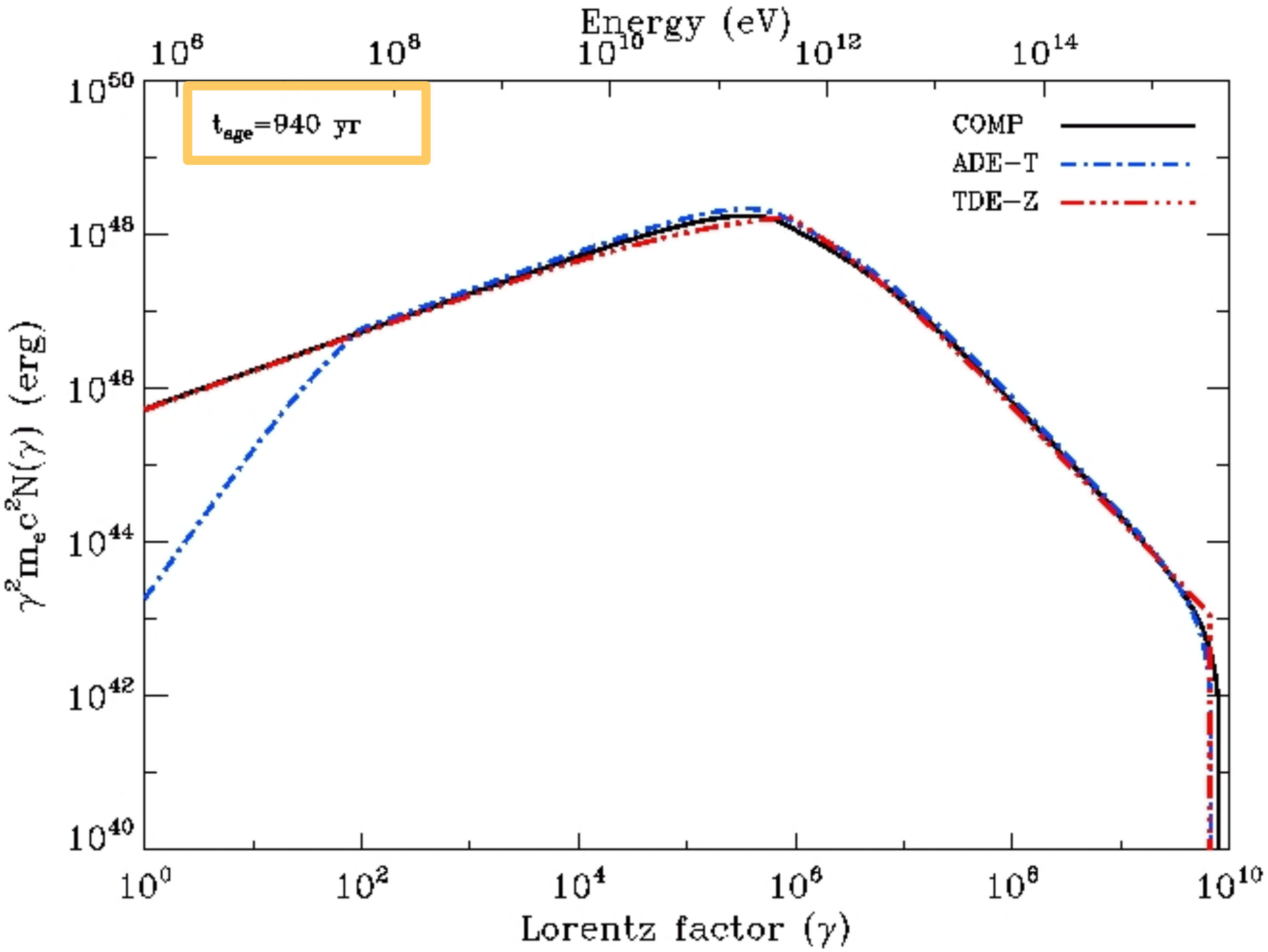

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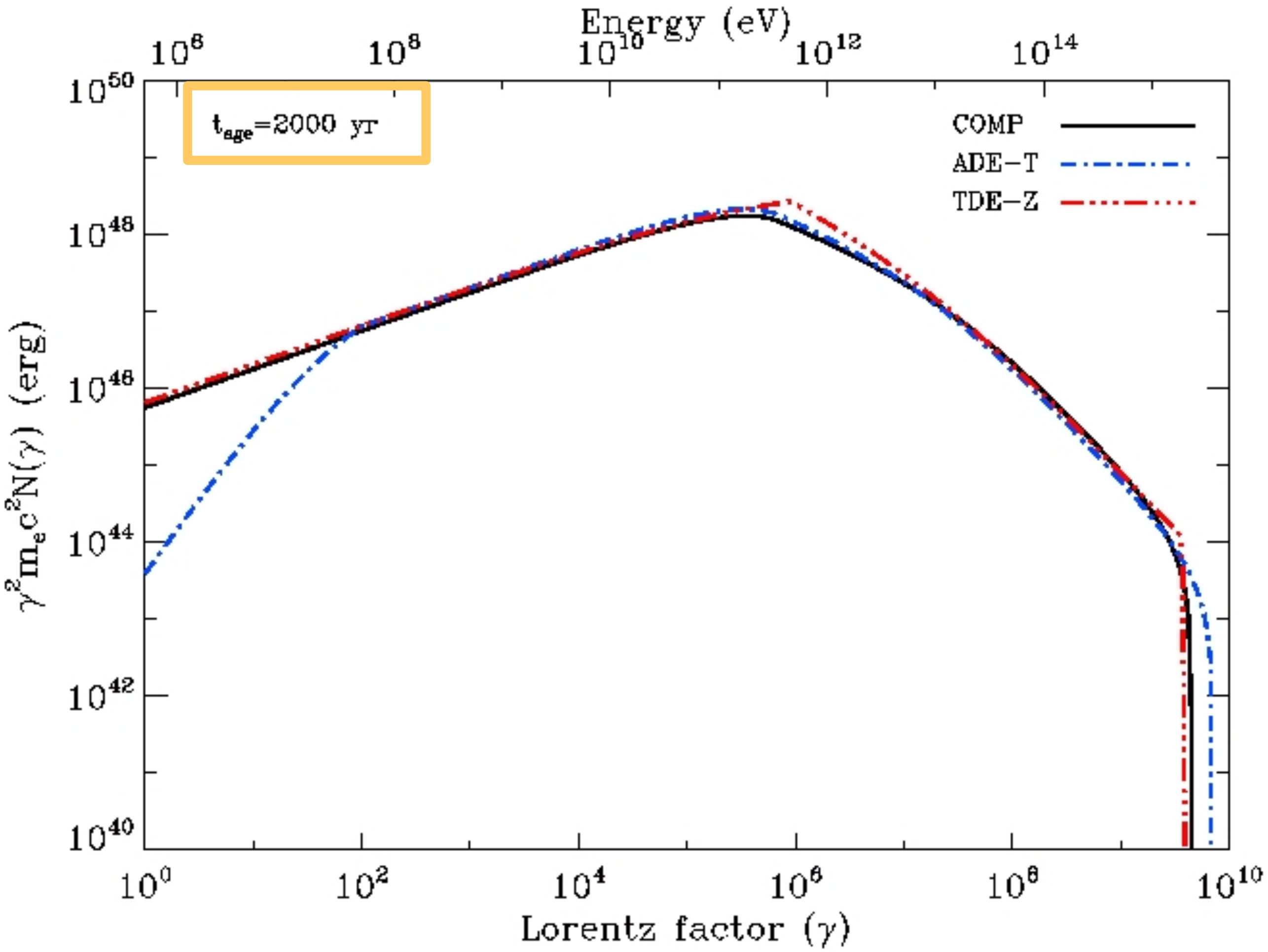

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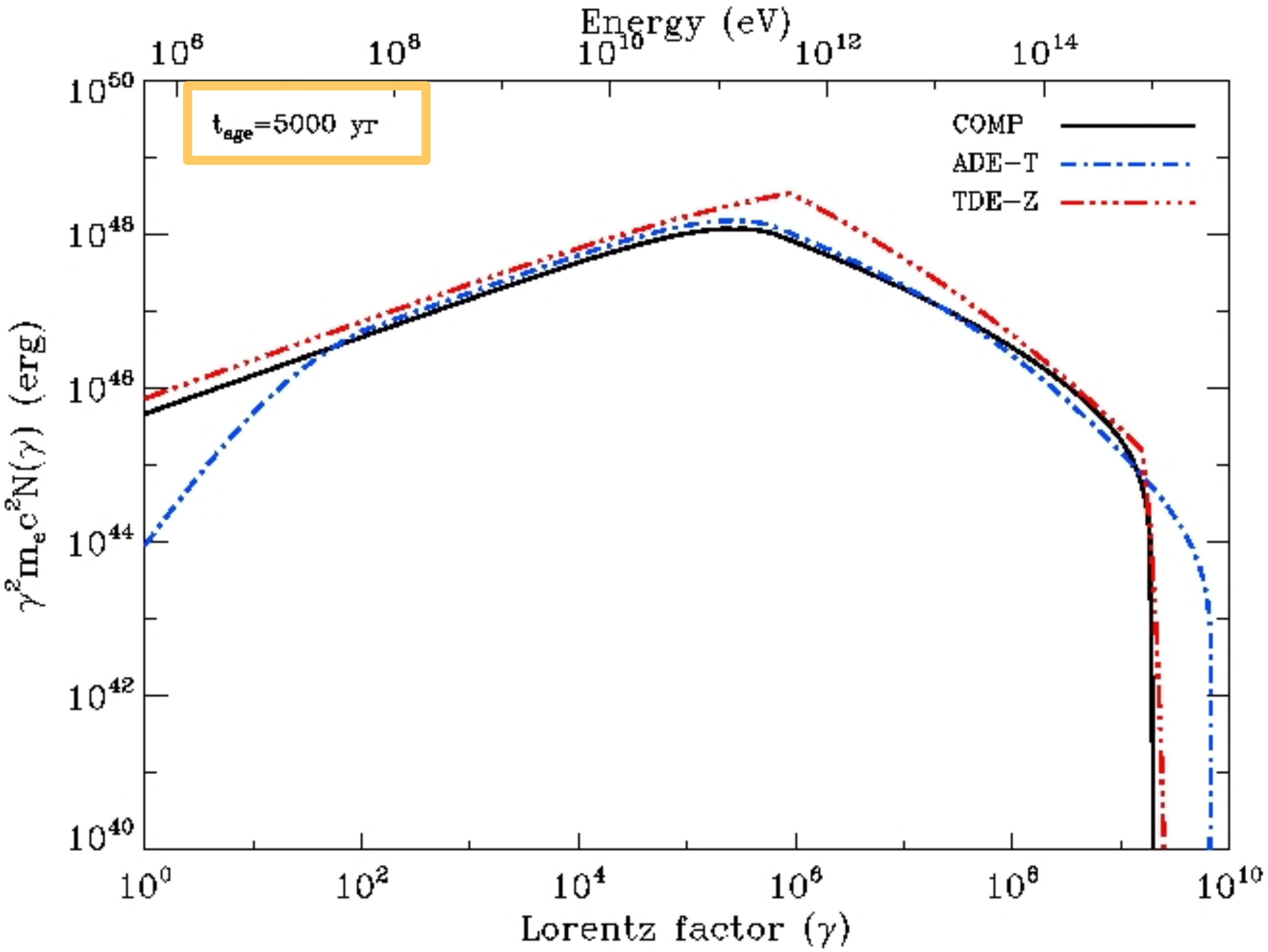

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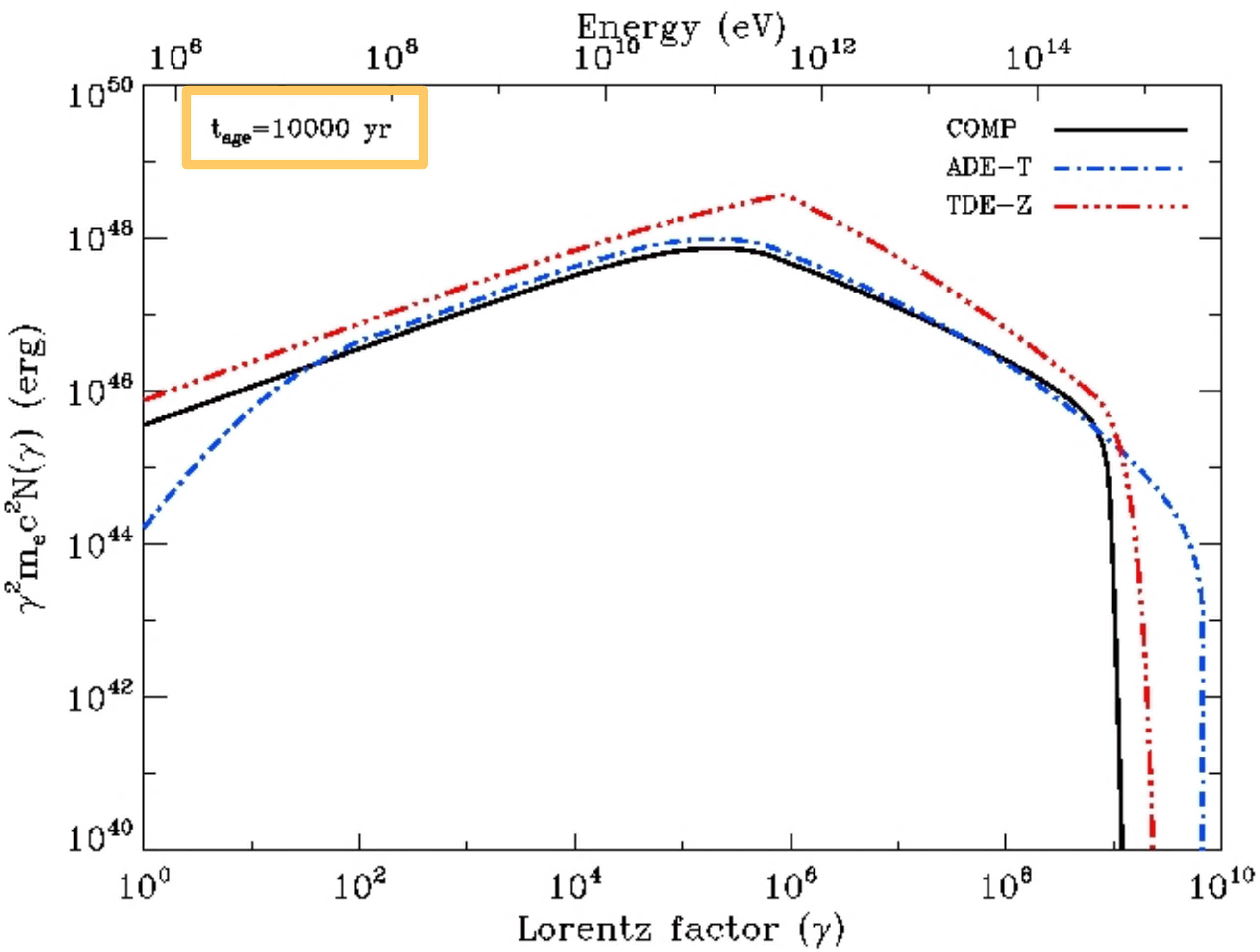
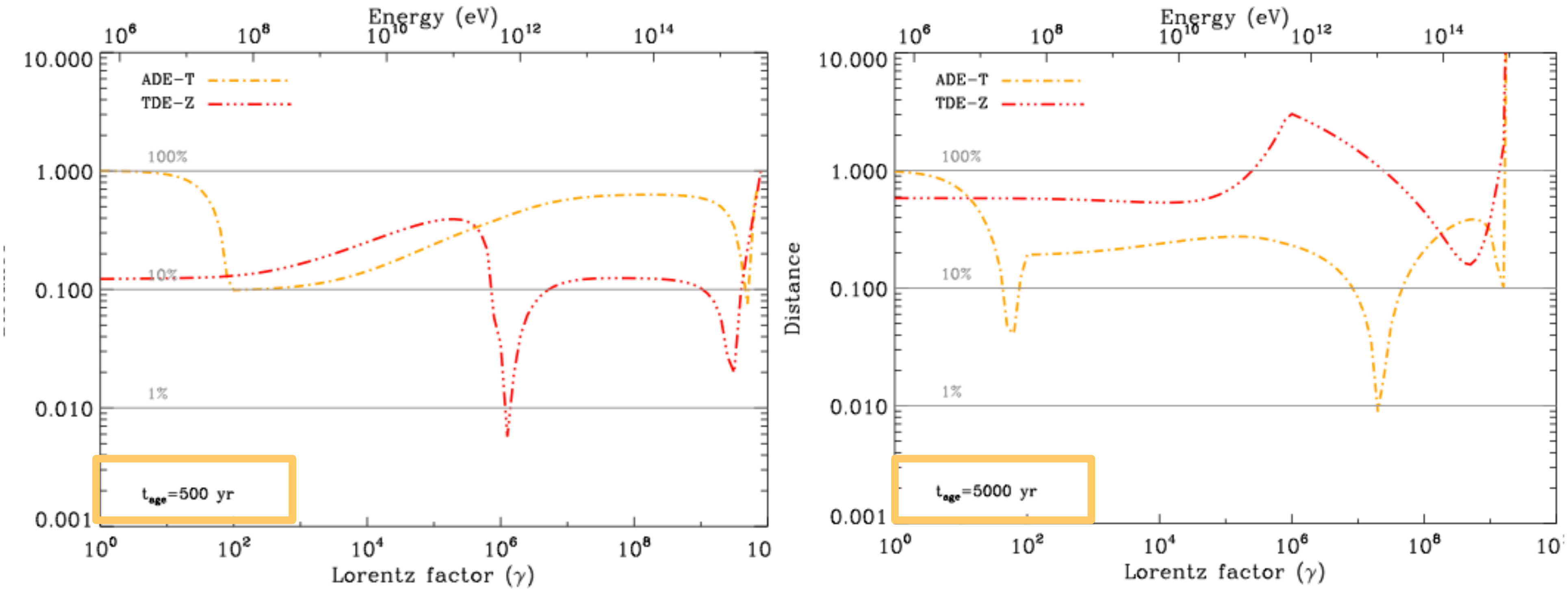


from Martin, DFT, Rea, MNRAS 2012

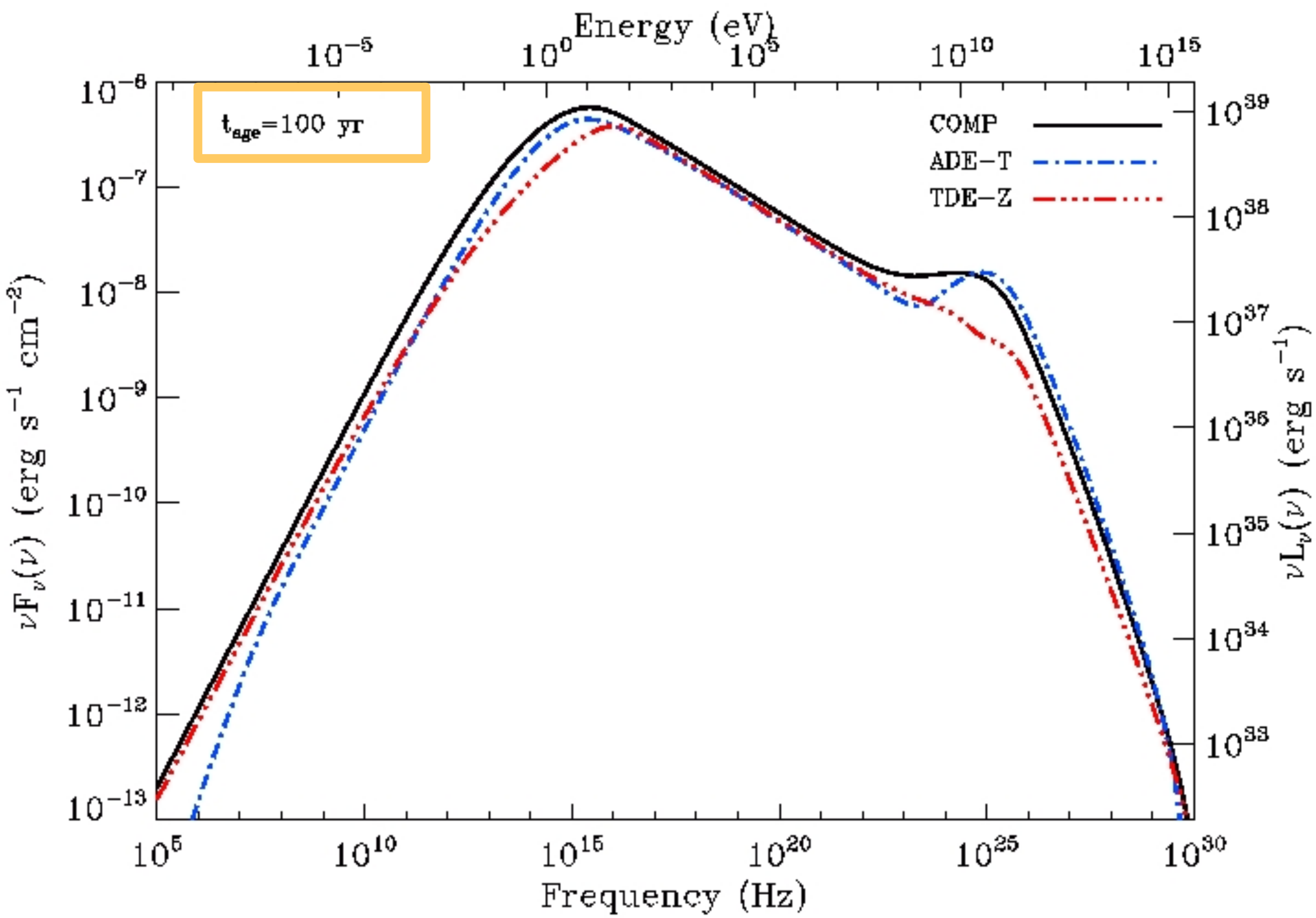
Relative distances for the electron population: btw 10 and 100%



Distance = | complete – approximate | / complete

distance times 100% is the percentile value of the deviation btw models

Look at it in a time-evolving setting: spectral evolution



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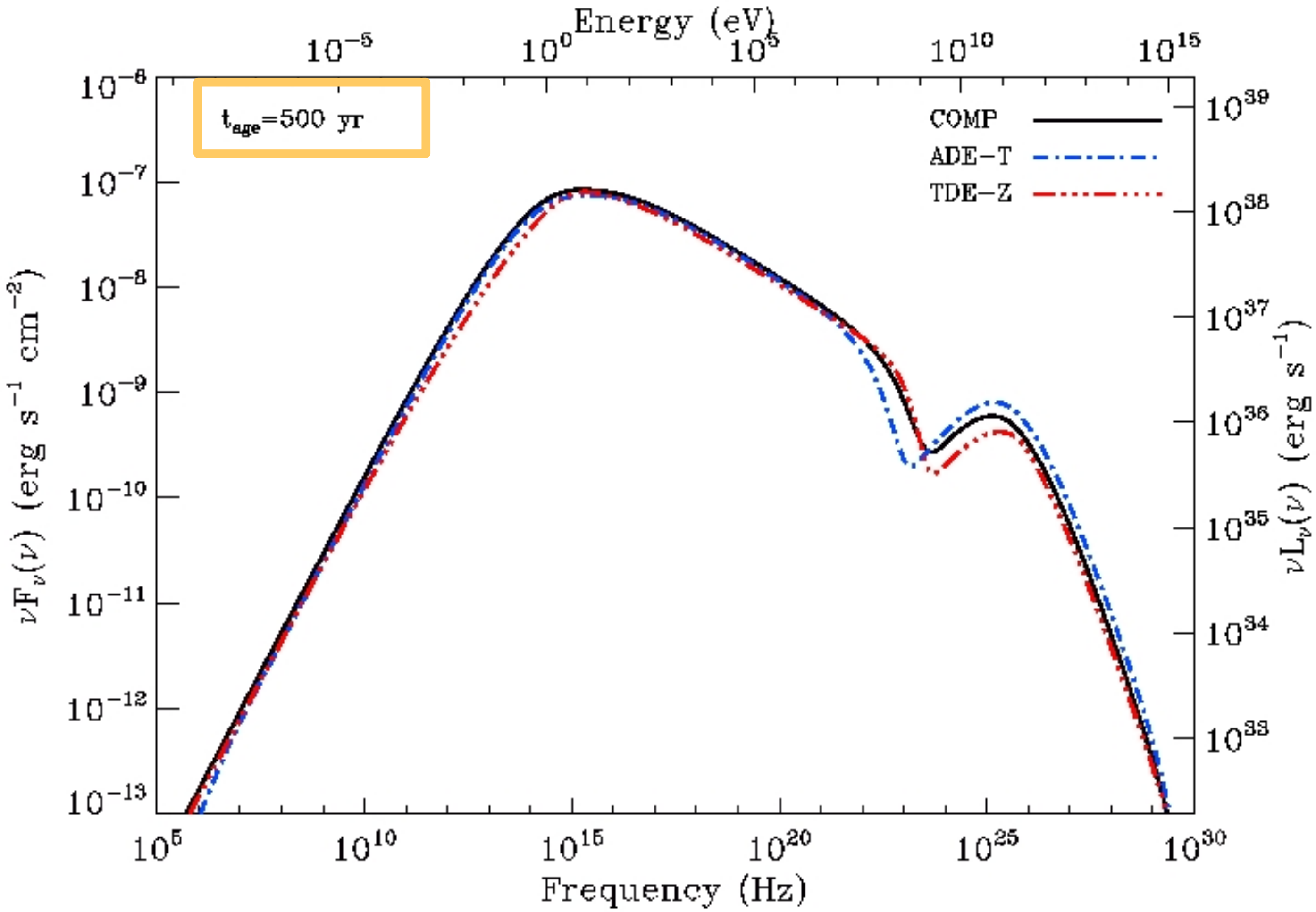

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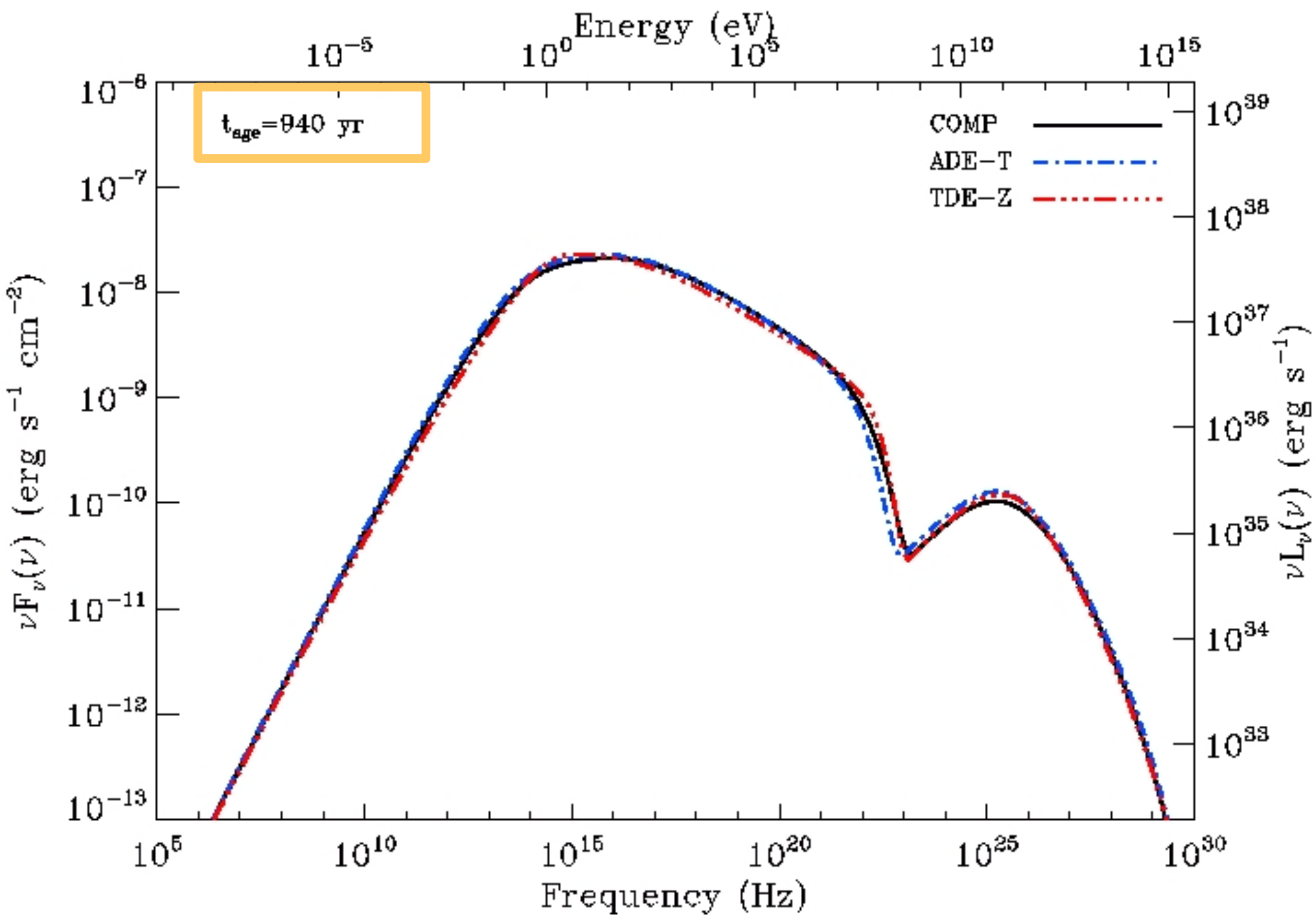

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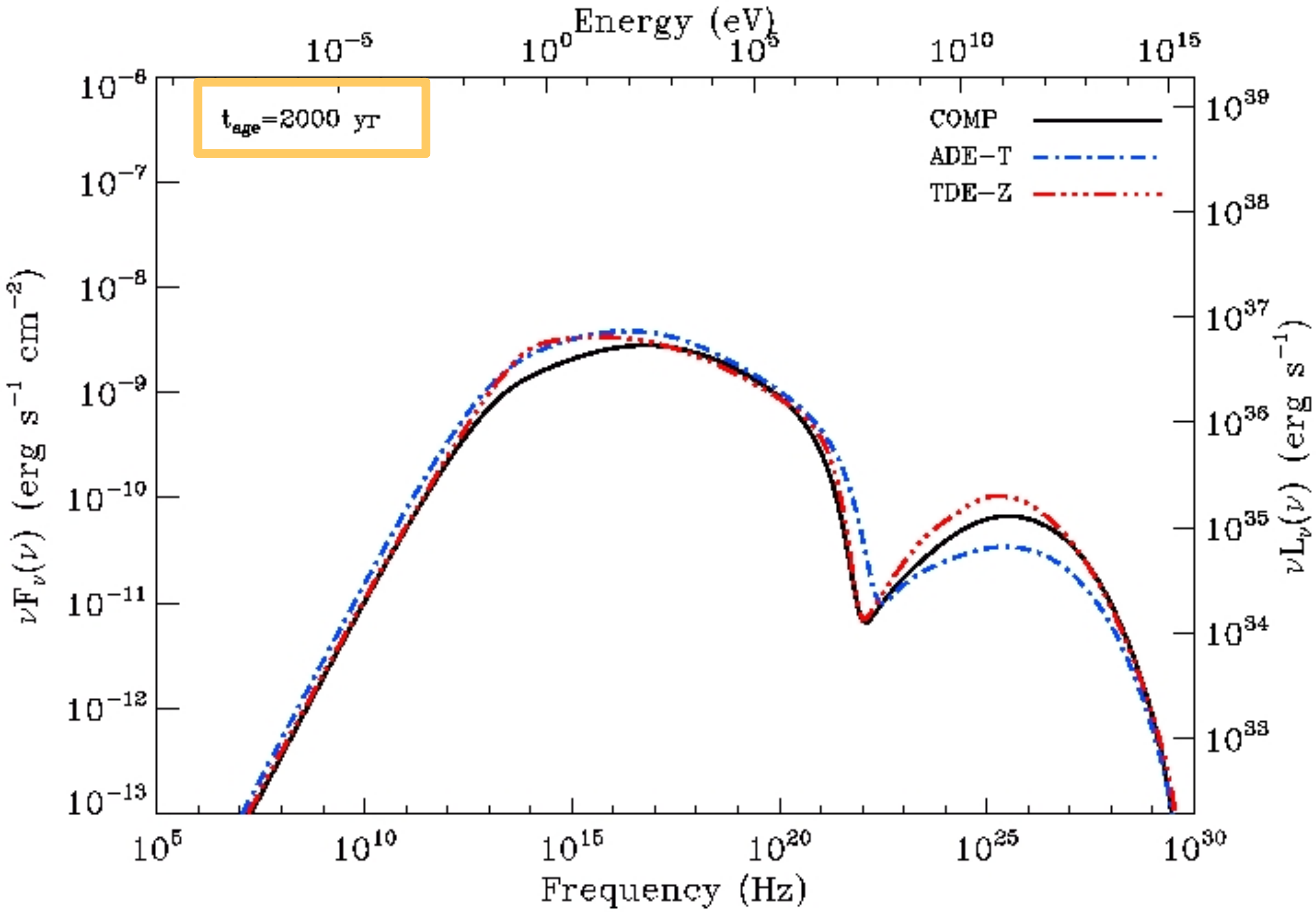

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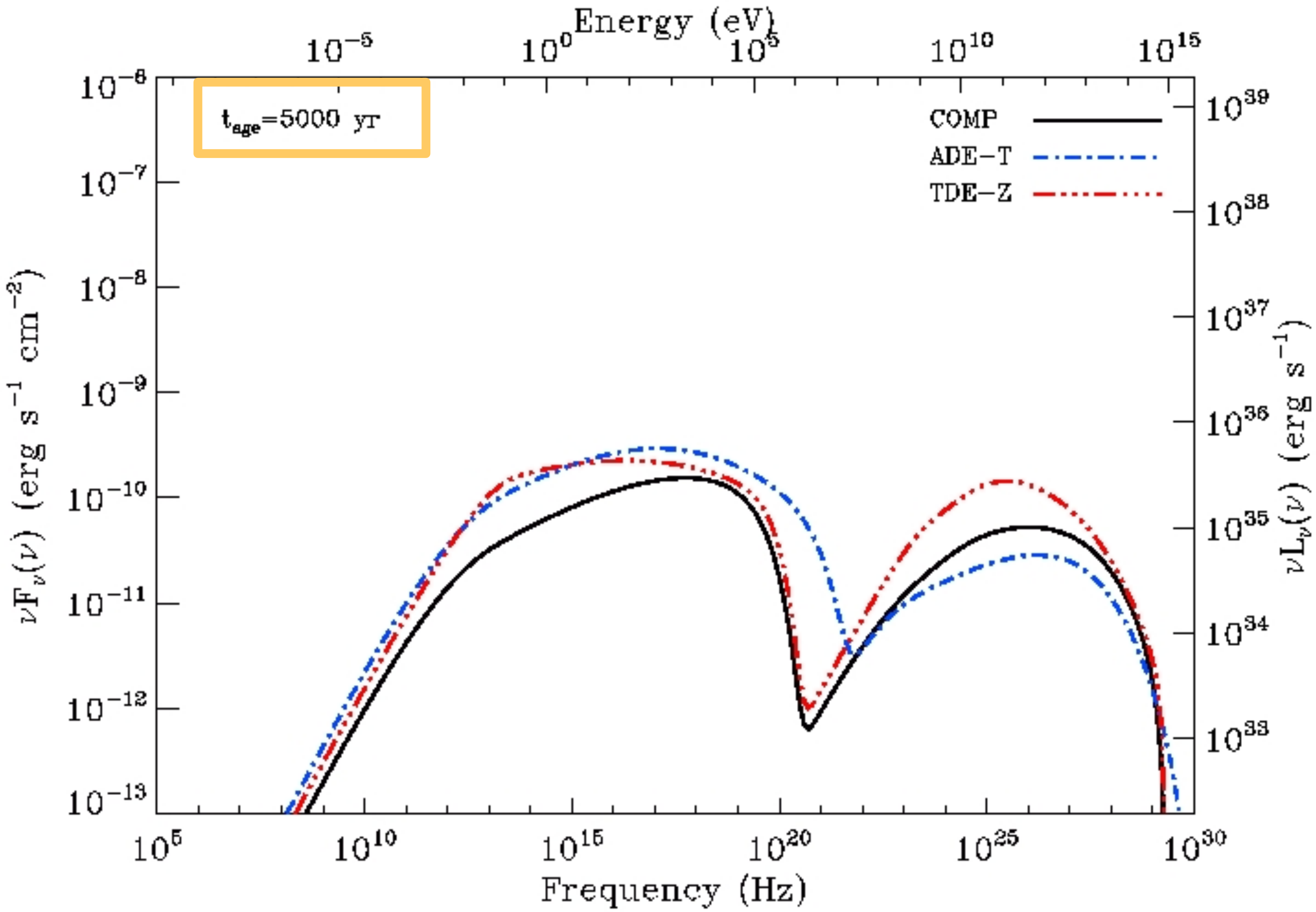

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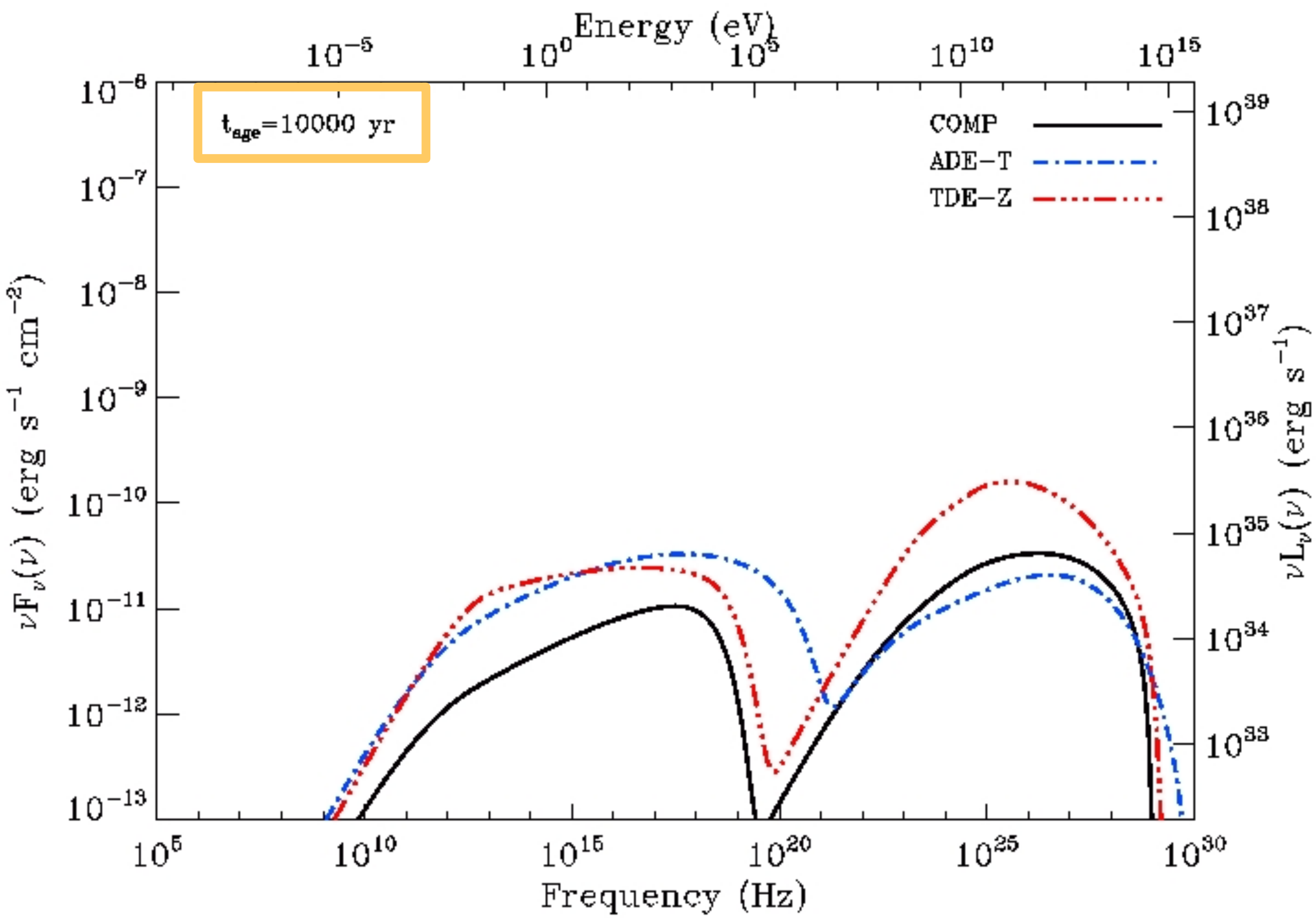
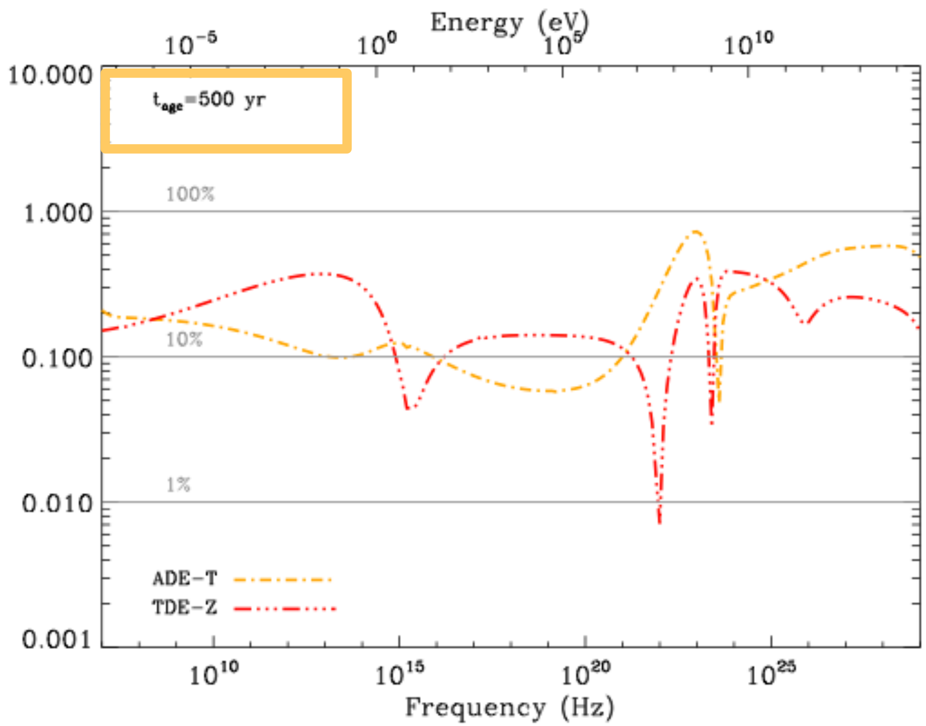
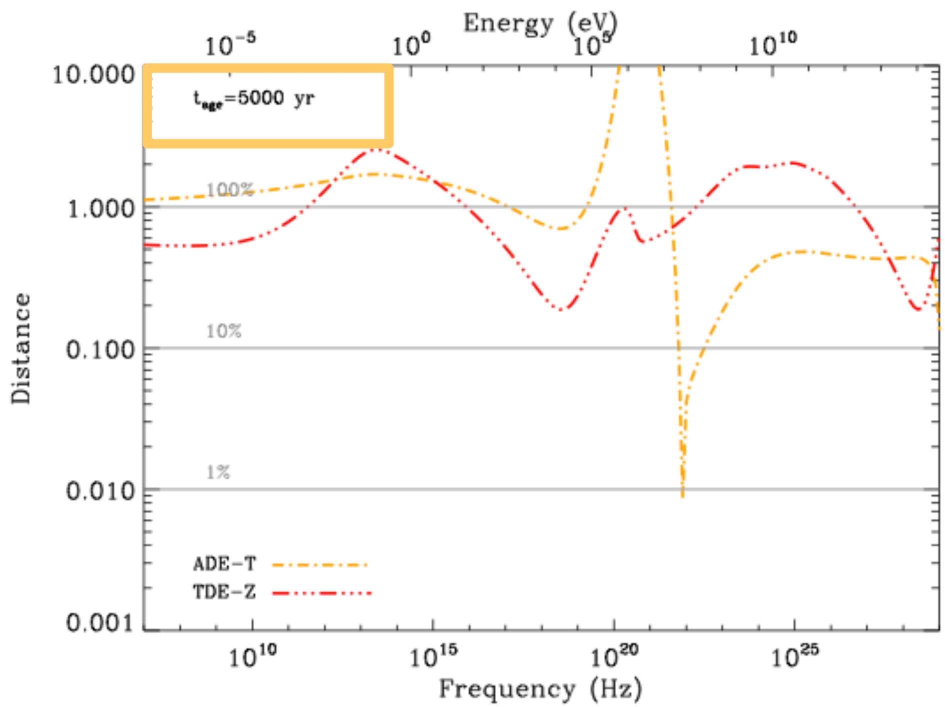


from Martin, DFT, Rea, MNRAS 2012

Relative distances for the SED: of the order of 100% or more





Distance = | complete – approximate | / complete

distance times 100% is the percentile value of the deviation btw models

from Martin, DFT, Rea, MNRAS 2012

Conclusion

- Take care of approximations, particularly when propagating time evolution or comparing results
  - They introduce unphysical changes in the spectral predictions.
- If time evolution or population studies are pursued there is a need of minimizing assumptions as much as possible, for these approximations introduce severe changes of predictions

from Martin, DFT, Rea, MNRAS 2012

Order parameters

Order parameters cannot be reduced just to spin-down / distance

Name J...	P s	$\dot{P}$ s s^{-1}	D kpc	τ yrs	B_d G	$\dot{E}$ erg s^{-1}	$\dot{E}/D^2$ erg s^{-1} kpc^{-2}	TeV Obs.?	TeV PWN?	T_τ^{Crab} yrs	$\dot{E}_{Crab}(T_\tau^{Crab})$ erg s^{-1}	CFP %
1808−2024 †	7.5559	5.49×10^{-10}	13.0	218	2.06×10^{15}	5.0×10^{34}	3.0×10^{32}	H	J1809-194/G11.0+0.08	...	...	...
1846−0258	0.3265	7.10×10^{-12}	5.8	728	4.88×10^{13}	8.1×10^{36}	2.4×10^{35}	H	Kes 75	238	1.6×10^{39}	0.5
1907+0919 †	5.1983	9.20×10^{-11}	...	895	7.00×10^{14}	2.6×10^{34}	...	H	J1908+063/G40.1-0.89	459	1.0×10^{39}	0.003
1714−3810 †	3.8249	5.88×10^{-11}	...	1030	4.80×10^{14}	4.1×10^{34}	...	H	J1718-385/CTB37A	638	7.2×10^{38}	0.006
0534+2200	0.0334	4.21×10^{-13}	2.0	1258	3.78×10^{12}	4.5×10^{38}	1.2×10^{38}	HMV	Crab Nebula	940	4.5×10^{38}	100
1550−5418	2.0698	2.32×10^{-11}	9.7	1410	2.22×10^{14}	1.0×10^{35}	1.1×10^{33}	H	...	1141	3.5×10^{38}	0.03
1513−5908	0.1512	1.53×10^{-12}	4.4	1560	1.54×10^{13}	1.7×10^{37}	9.0×10^{35}	H	J1514-281/MSH 15-52	1340	2.8×10^{38}	6
1119−6127	0.4079	4.02×10^{-12}	8.4	1610	4.10×10^{13}	2.3×10^{36}	3.3×10^{34}	H	J1119-6127/G292.1-0.54	1406	2.6×10^{38}	0.9
0540−6919	0.0504	4.79×10^{-13}	53.7	1670	4.98×10^{12}	1.5×10^{38}	5.1×10^{34}	H	...	1486	2.4×10^{38}	63
0525−6607	8.0470	6.50×10^{-11}	...	1960	7.32×10^{14}	4.9×10^{33}	...	...	...	1871	1.6×10^{38}	0.003
1048−5937	6.4520	3.81×10^{-11}	9.0	2680	5.02×10^{14}	5.6×10^{33}	6.9×10^{31}	H	...	2825	7.8×10^{37}	0.007
1124−5916	0.1354	7.52×10^{-13}	5.0	2850	1.02×10^{13}	1.2×10^{37}	4.8×10^{35}	H	...	3050	6.8×10^{37}	18
1930+1852	0.1368	7.50×10^{-13}	7.0	2890	1.03×10^{13}	1.2×10^{37}	2.4×10^{35}	V	J1930+188/G54.1+0.3	3103	6.6×10^{37}	18
1622−4950	4.3261	1.70×10^{-11}	9.1	4030	2.74×10^{14}	8.3×10^{33}	9.9×10^{31}	H	...	4614	3.0×10^{37}	0.03
1841−0456	11.7789	4.47×10^{-11}	9.6	4180	7.34×10^{14}	1.1×10^{33}	1.2×10^{31}	H	...	4813	2.8×10^{37}	0.004
1023−5746	0.1115	3.84×10^{-13}	8.0	4600	6.62×10^{12}	1.1×10^{37}	1.7×10^{35}	H	J1023+575	5370	2.2×10^{37}	50
1833−1034	0.0618	2.02×10^{-13}	4.10	4850	3.58×10^{12}	3.4×10^{37}	2.0×10^{36}	H	J1833-105/G21.5-0.9	5701	2.0×10^{37}	170
1838−0537	0.1457	4.72×10^{-13}	...	4890	8.39×10^{12}	6.0×10^{36}	...	H	...	5754	1.9×10^{37}	32
0537−6910	0.0161	5.18×10^{-14}	53.7	4930	9.25×10^{11}	4.9×10^{38}	1.7×10^{35}	H	N157B	5807	1.9×10^{37}	2579
1834−0845	2.4823	7.96×10^{-12}	...	4940	1.42×10^{14}	2.1×10^{34}	...	H	J1834-087/W41	5820	1.9×10^{37}	0.1
1747−2809	0.0521	1.55×10^{-13}	17.5	5310	2.88×10^{12}	4.3×10^{37}	1.4×10^{35}	H	J1747-281/G0.9+0.1	6311	1.6×10^{37}	269
0205+6449	0.0657	1.94×10^{-13}	3.2	5370	3.61×10^{12}	2.7×10^{37}	2.6×10^{36}	MV	...	6390	1.6×10^{37}	169
1813−1749	0.0446	1.26×10^{-13}	...	5600	2.41×10^{12}	5.6×10^{37}	...	H	J1813-178/G12.8-0.02	6695	1.4×10^{37}	400
0100−7211	8.0203	1.88×10^{-11}	62.4	6760	3.93×10^{14}	1.4×10^{33}	3.7×10^{29}	...	...	8233	9.1×10^{36}	0.02
1357−6429	0.1661	3.60×10^{-13}	4.1	7310	7.83×10^{12}	3.1×10^{36}	1.9×10^{35}	H	J1356-645/G309.9-2.51	8962	7.6×10^{36}	41
1614−5048	0.2316	4.94×10^{-13}	7.2	7420	1.08×10^{13}	1.6×10^{36}	3.0×10^{34}	H	...	9107	7.3×10^{36}	22
1734−3333	1.1693	2.28×10^{-12}	7.4	8130	5.22×10^{13}	5.6×10^{34}	1.0×10^{33}	H	...	10048	5.9×10^{36}	0.9
1617−5055	0.0693	1.35×10^{-13}	6.4	8130	3.10×10^{12}	1.6×10^{37}	3.8×10^{35}	H	J1616-508	10048	5.9×10^{36}	271
2022+3842	0.0242	4.32×10^{-14}	10.0	8910	1.04×10^{12}	1.2×10^{38}	1.2×10^{36}	...	...	11082	4.8×10^{36}	2500
1708−4009 †	11.0013	1.93×10^{-11}	3.8	9010	4.67×10^{14}	5.7×10^{32}	4.0×10^{31}	H	J1708-443/G343.1-2.69	11215	4.7×10^{36}	0.01

DFT et al. 2013, in preparation

The search of order parameters, in the form of 2 questions

- Why is Crab SSC-dominated and no other PWN we know of is?

- Why are the PWN that we see particle dominated? Is there any observational biases? Do we expect to map the whole phase space between particle and magnetic dominated nebula? At which sensitivity if so?

We see particle dominated nebulae

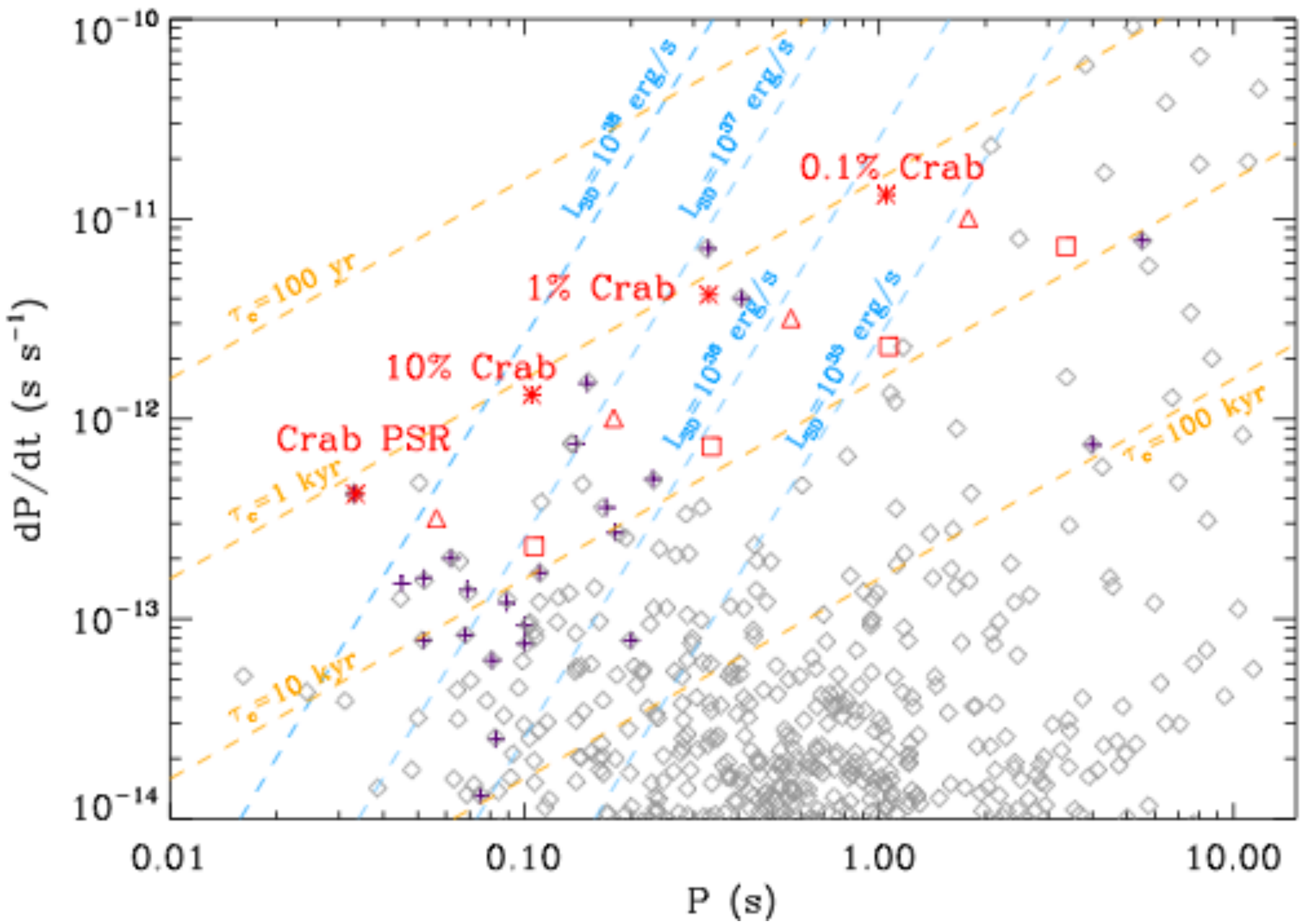
	Crab Nebula	G54.1+0.3 Model 1	... Model 2	G0.9+0.1 Model 1	... Model 2	G21.5−0.9 Model1
Pulsar & Ejecta						
$P(t_{age})$ (ms)	33.40	136	...	52.2	...	61.86
$\dot{P}(t_{age})$ (s s^{-1})	4.20×10^{-13}	7.51×10^{-13}	...	1.56×10^{-13}	...	2.02×10^{-13}
τ_c (yr)	1296	2871	...	5305	...	4860
$L(t_{age})$ (erg/s)	4.53×10^{38}	1.2×10^{37}	...	4.3×10^{-37}	...	3.37×10^{37}
n	2.509	3	...	3	...	3
t_{age} (yr)	940	1700	...	2000	3000	870
d (kpc)	2.0	6	...	8.5	13	4.7
τ_0 (yr)	730	1171	...	3305	2305	3985
L_0 (erg/s)	3.1×10^{39}	7.21×10^{37}	...	1.11×10^{38}	2.28×10^{38}	5×10^{37}
M_{ej} ($M_\odot$)	9.5	20	...	11	17	8
$R_{PWN}(t_{age})$ (pc)	2.1	1.4	...	2.5	3.8	0.9
Environment						
T_{FIR} (K)	70	70	40	70	...	70
w_{FIR} (eV/cm^3)	0.5	2.8	2.0	4	5	2
T_{NIR} (K)	5000	5000	4000	5000	...	5000
w_{NIR} (eV/cm^3)	1.0	0.5	0.5	35	40	2
n_H	1.0	10	10	1	...	0.1
Particles and field						
$\gamma_{max}(t_{age})$	7.9×10^9	7.5×10^8	5.3×10^8	1.3×10^9	1.9×10^9	2.4×10^9
γ_b	7×10^5	5×10^5	1.8×10^5	1.0×10^5	0.5×10^5	1.0×10^5
α_1	1.5	1.20	1.2	1.4	1.2	1.0
α_2	2.5	2.77	2.55	2.65	2.53	2.53
ϵ	0.2	0.3	...	0.2	...	0.2
$B(t_{age})$ (μG)	84	14	10	14	15	71
η	0.03	0.005	0.0025	0.01	0.02	0.04

DFT et al. 2013a, in preparation

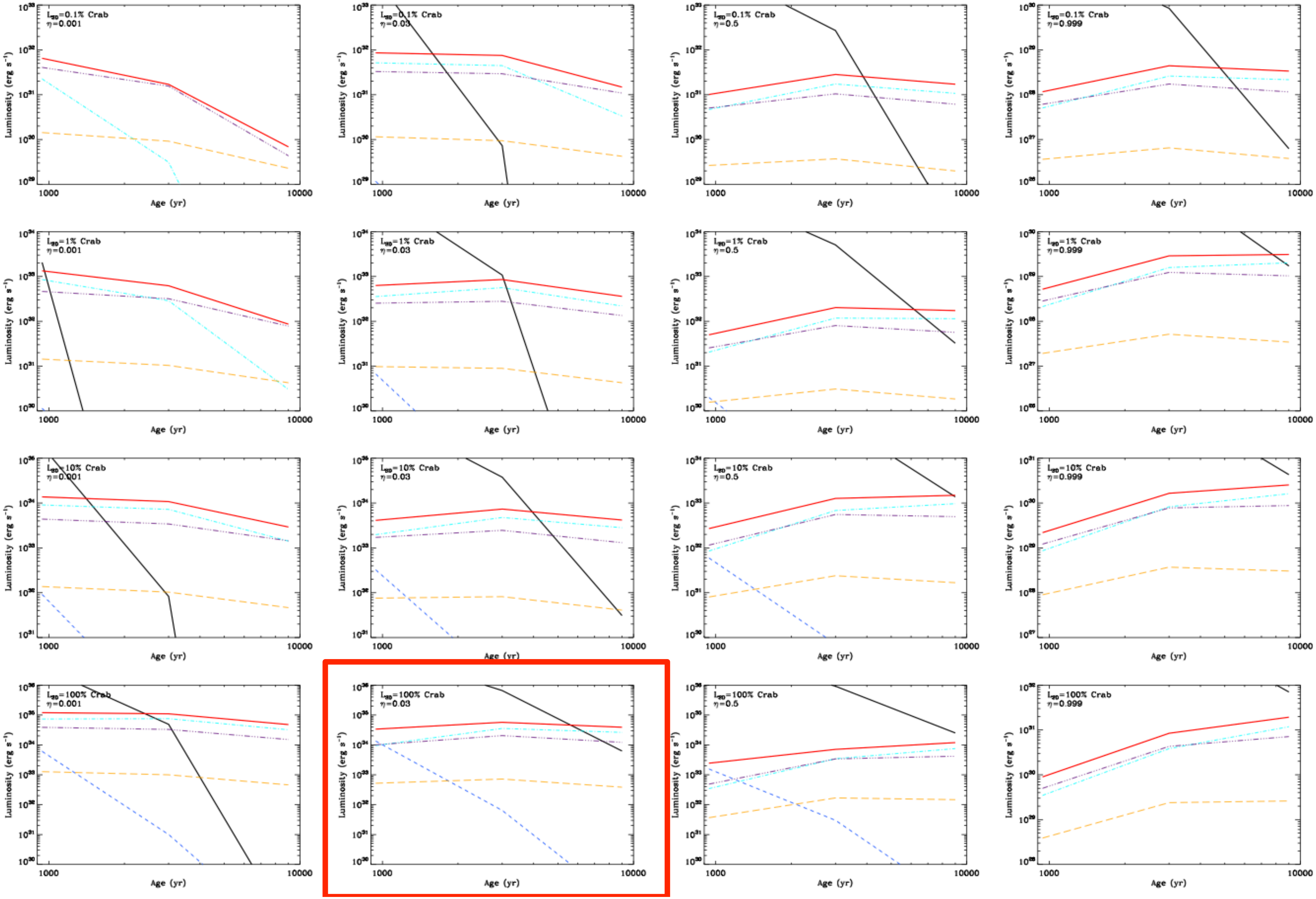
Method: 100 models of PWN to cover the phase space

- 4 fake pulsars (P and Pdot defined by fixing the spin-down power, the braking index, and the characteristic age –the latter two as in Crab)
- Mapping young pulsars (studied at different conditions)
- 8 values of magnetic fraction
- 3 ages: 940, 3000, and 9000 years
- 4 initial spin-down powers (100%, 10%, 1%, and 0.1% of Crab Nebula's)

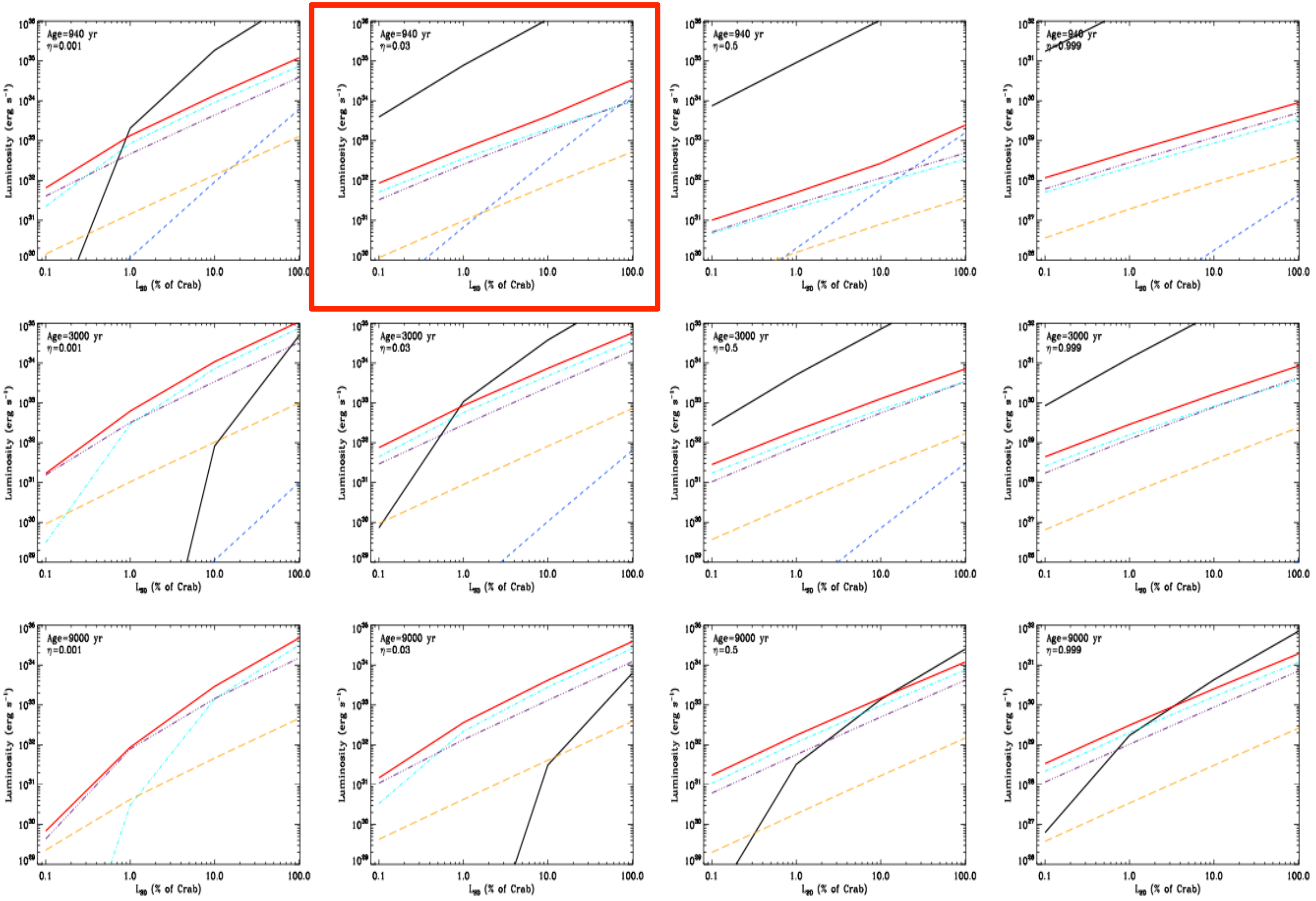
Method: 100 models of PWN to cover the phase space



Luminosities vs age



Luminosities vs spin down



Conclusion

Why is Crab SSC-dominated and no other PWN we know of is?

Because for SSC to dominate, or even to contribute significantly, the nebula has to be

- particle dominated,
- the spin-down has to be at least ~70% of the Crab
- the age has to be less than a few kyrs (2-3 kyrs).

No pulsar with these parameters is known.

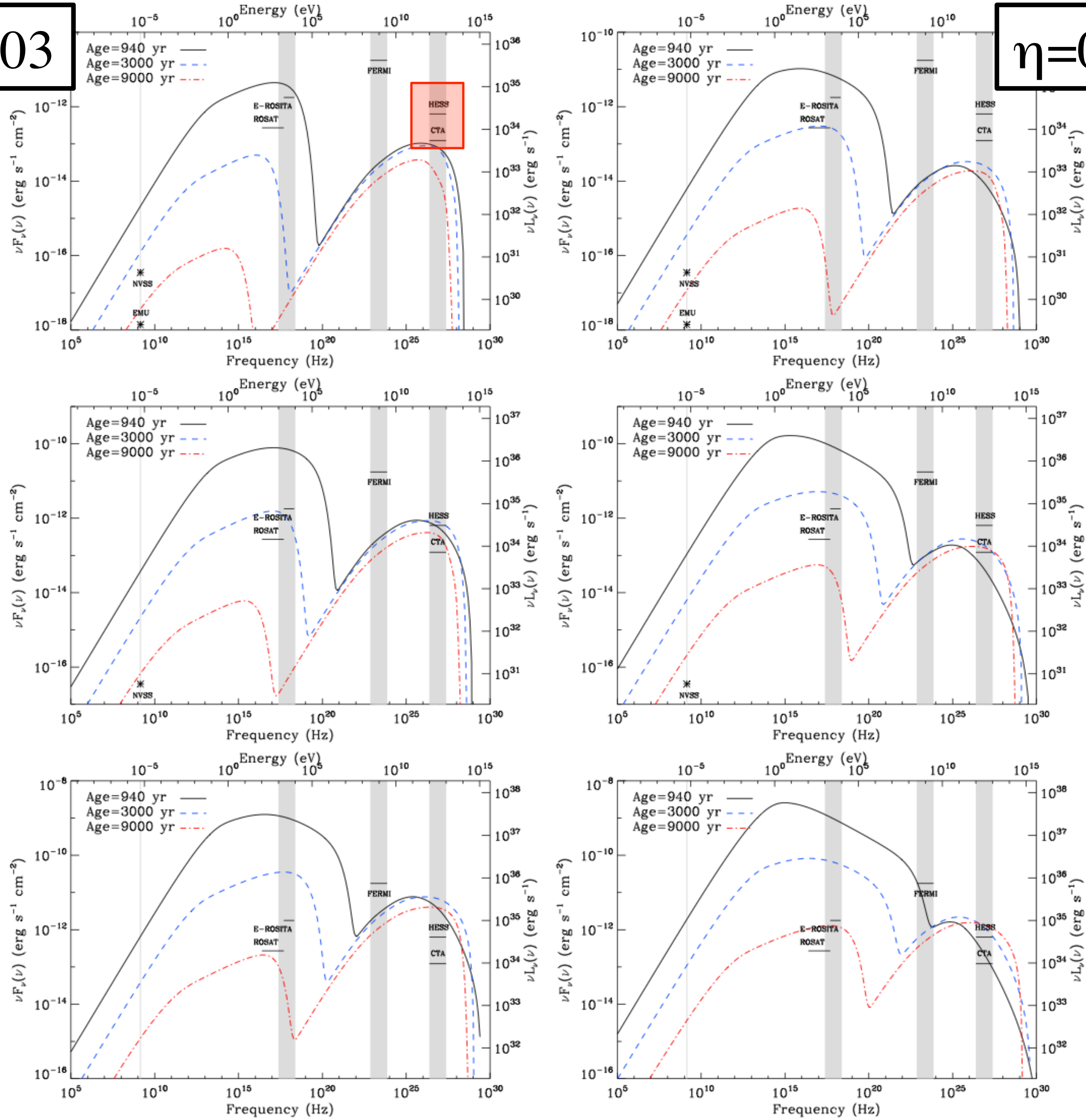
SED dependence with age / magnetic fraction

η=0.03 η=0.5

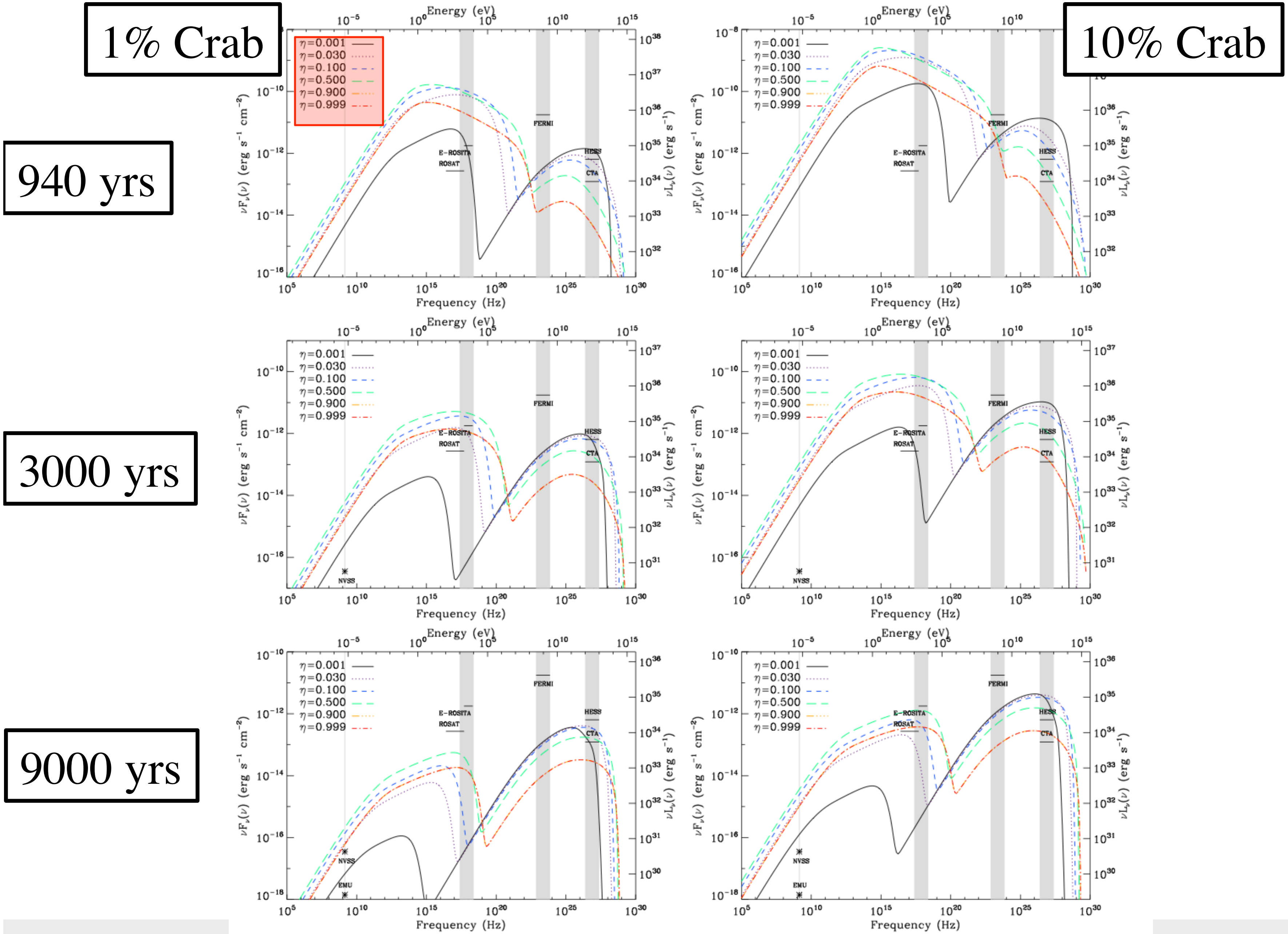
0.1% Crab

1% Crab

10% Crab

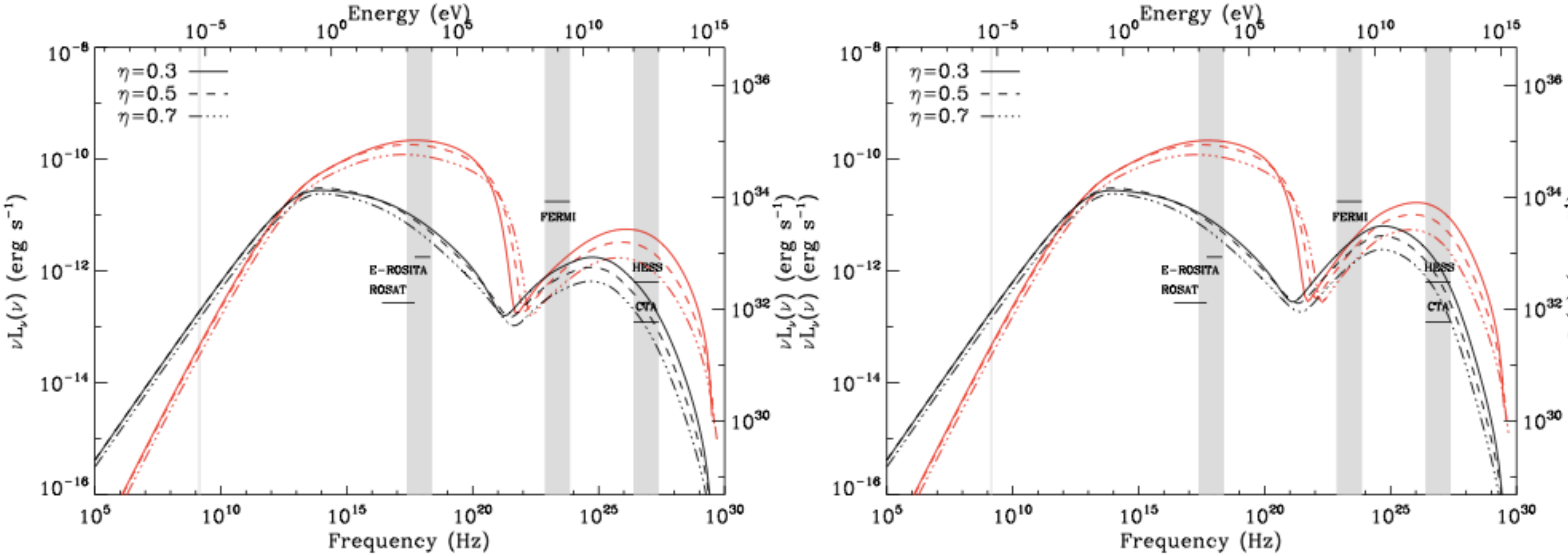


SED dependence with magnetic fraction



Answers against changes of ISRF target fields / injection

0.5 eV cm^{-3} | 3 eV cm^{-3}



SEDs for different magnetic fraction (as detailed in the legend) and different FIR photon density (0.5 eV cm^{-3} in the left panel, and 3 eV cm^{-3} in the right one) for a pulsar with 10% of Crab's energetics. In red, a hard spectrum of particles with $\alpha_1 = 1.2$, $\alpha_2 = 2.3$ is assumed, whereas the black curves stand for a steep case with $\alpha_1 = 1.7$, $\alpha_2 = 2.9$.

DFT et al. 2013, in preparation

Conclusion

Why are the PWN that we see particle dominated? Is there any observational biases? Do we expect to map the whole phase space between particle and magnetic dominated nebula? At which sensitivity if so?

We would not see any magnetic dominated nebula unless very energetic, with very hard spectrum, in a high FIR background.

We could barely see a nebula in equipartition if the spin-down is larger than or at least 10% of Crab, for nebulae of similar slope than Crab in the injection and living in normal backgrounds