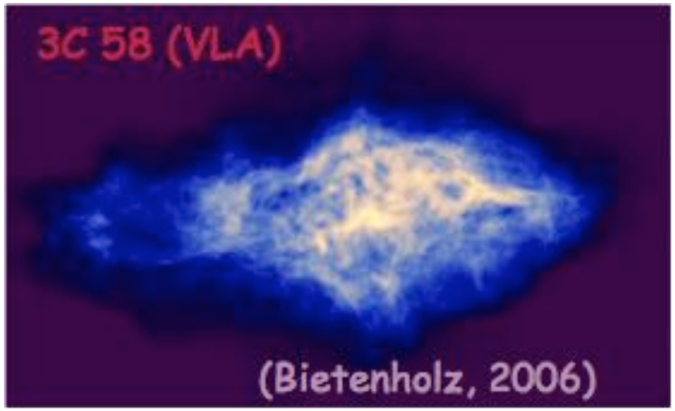
HIGH ENERGY NEUTRINOS FROM PULSAR WIND NEBULAE

Dafne Guetta
INAF-Osservatorio Astrofisico di Roma
BRAUDE-Israel

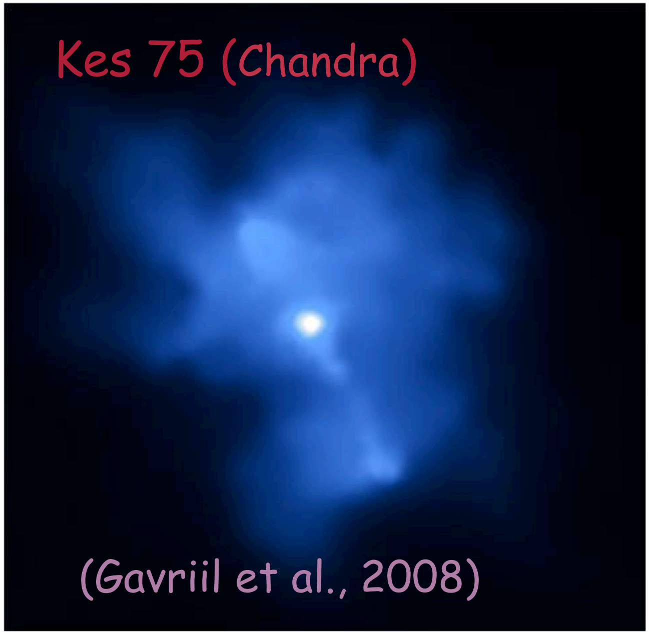
Collaborators: Irene Di Palma, Elena Amato

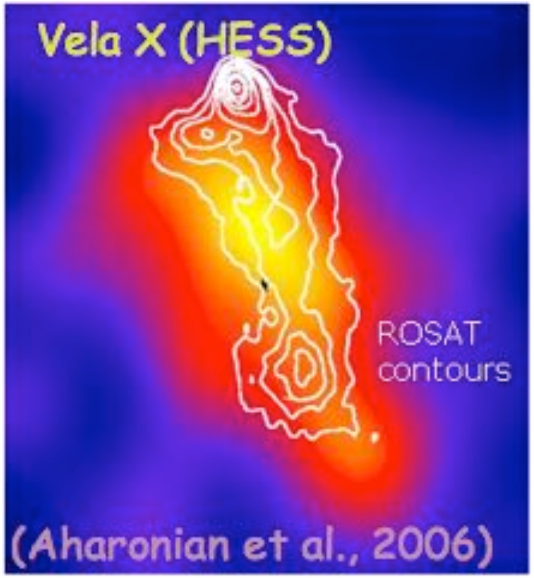
PULSAR WIND NEBULAE AT A GLANCE



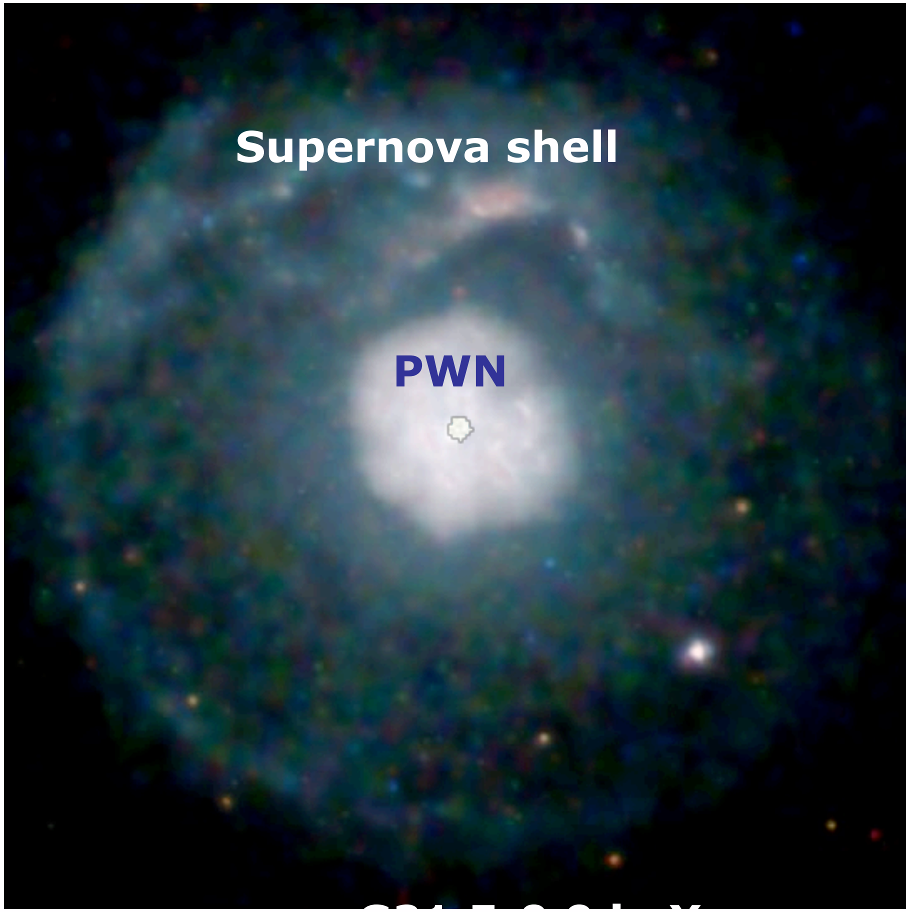
PLERIONS:

✓SUPERNOVA REMNANTS WITH A CENTER FILLED MORPHOLOGY
✓FLAT RADIO SPECTRUM (α_R<0.5)
✓VERY BROAD NON-THERMAL EMISSION SPECTRUM (FROM RADIO TO MULTI-TEV γ-RAYS)





Pulsar Wind Nebulae



WHY PWNe ARE INTERESTING

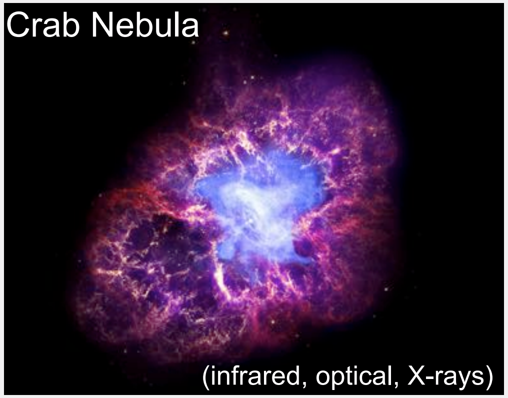
- **PULSAR PHYSICS:** THEY ENCLOSE MOST OF THE PULSAR SPIN-DOWN ENERGY

- **CLOSE AND BRIGHT:** BEST-SUITED LABORATORIES FOR THE PHYSICS OF RELATIVISTIC ASTROPHYSICAL PLASMAS

- **PARTICLE ACCELERATION** AT THE HIGHEST SPEED SHOCKS IN NATURE ($10^4<\Gamma<10^7$)

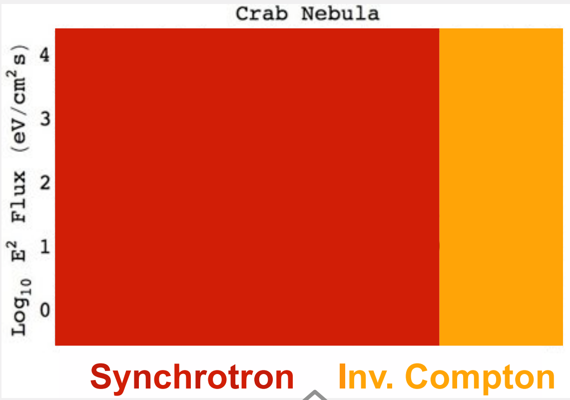
- **COSMIC RAYS:** ONLY SOURCES SHOWING DIRECT EVIDENCE FOR PEV PARTICLES

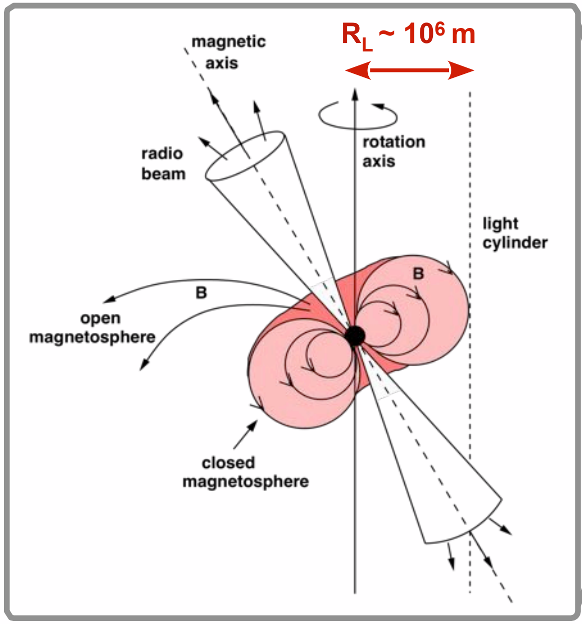
Pulsar wind nebulae: synopsis

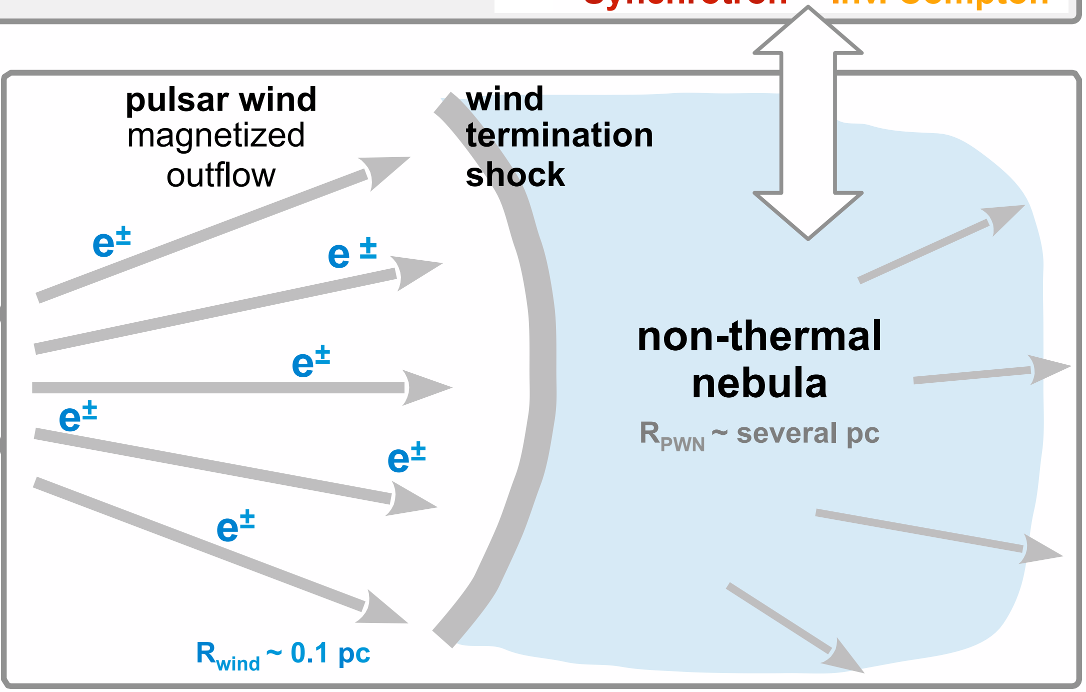


"A bubble of shocked relativistic particles, produced when a pulsar's relativistic wind interacts with its environment"

(Gaensler & Slane 2006)







MAIN OPEN QUESTIONS

WE KNOW THAT:

THESE ARE THE MOST EFFICIENT ACCELERATORS OBSERVED IN NATURE AND ACCELERATION TAKES PLACE IN THE MOST HOSTILE ENVIRONMENT (termination shock

relativistic)

WE DO NOT KNOW:

WHAT THE ACCELERATION MECHANISM(S) IS (ARE)

POSSIBILITIES DEPEND ON:

- COMPOSITION (IONS? MULT.?)
- MAGNETIZATION ($\sigma = B^2/4\pi n \Gamma m c^2$)

IN PRINCIPLE BOTH DEPEND ON WHERE PARTICLE ACCELERATION EXACTLY OCCURS

HOW TO GET CONSTRAINTS?

DETAILED DYNAMICAL AND RADIATION MODELING

Hadronic component if present dominate the energy content of the wind -> Neutrino detection...

Hadrons may be responsible of the particle acceleration mechanism in PWN

RESONANT CYCLOTRON ABSORPTION IN ION DOPED OUTFLOW in the relativistic termination shock:

- MAGNETIZATION IS NOT VERY IMPORTANT
- REQUIRES IONS DOMINANCE
- PARTICLE SPECTRUM AND EFFICIENCY DEPEND ON FRACTION OF ENERGY CARRIED BY IONS (Hoshino et al 92, Amato & Arons 06, Stockem et al 12)
- HADRONS SHOULD CARRY MOST OF THE OUTFLOW ENERGY
- HADRONS MAY PRODUCE PIONS THAT DECAY IN TeV PHOTONS AND TeV NEUTRINOS

Nebular leptonic emission

Interaction of high energy leptons with the ambient magnetic field and with the radio and IR background is thought to be the origin of the nebular emission from radio wavelengths-X-ray to the TeV band.

Synchrotron+Inverse Compton

Problems with pure leptonic interpretation of the TeV emission

Requirements:

✓Outcome: power-law with α~2.2 for optical/X-rays α~1.5 for radio

✓Maximum energy: for Crab ~few x 10^{15} eV (close to the available potential drop at the PSR)

✓Efficiency: for Crab ~10-20% of total L_{sd}

Signatures of relativistic protons

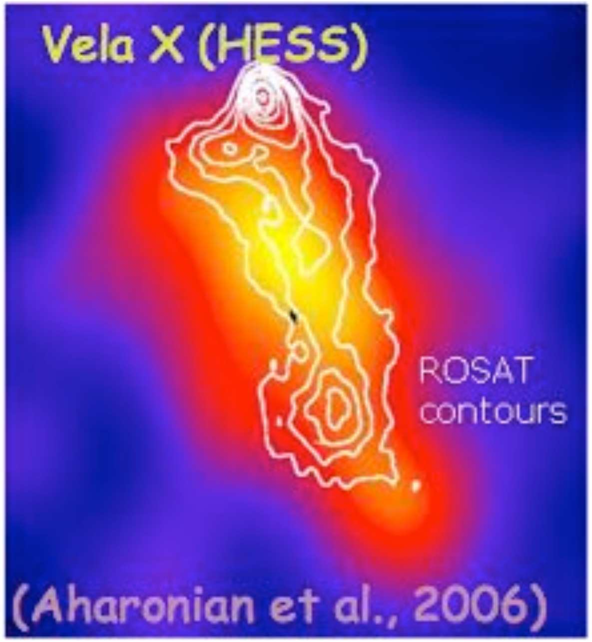
If protons are there, they might reveal themselves through

π-production (Bednarek 02; Amato et al 03)

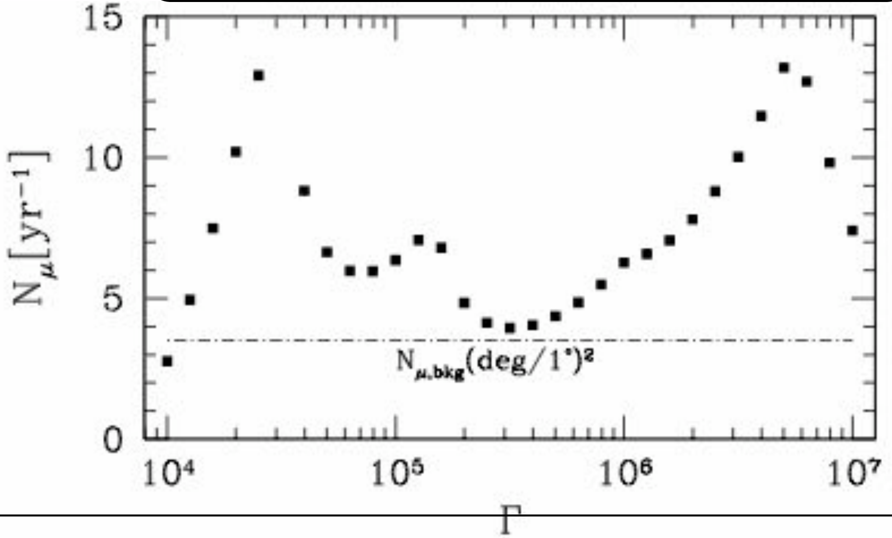
$\pi^0 \rightarrow \gamma$-rays ← $L_\pi = f_\pi L_p$ → $\pi^\pm \rightarrow e^\pm\ \nu$

Fluxes of all secondaries depend on U_i/U_{tot}, Γ and target density

π^0 γ-rays in Vela?
(Horns et al 06)
But see also LaMassa et al 08



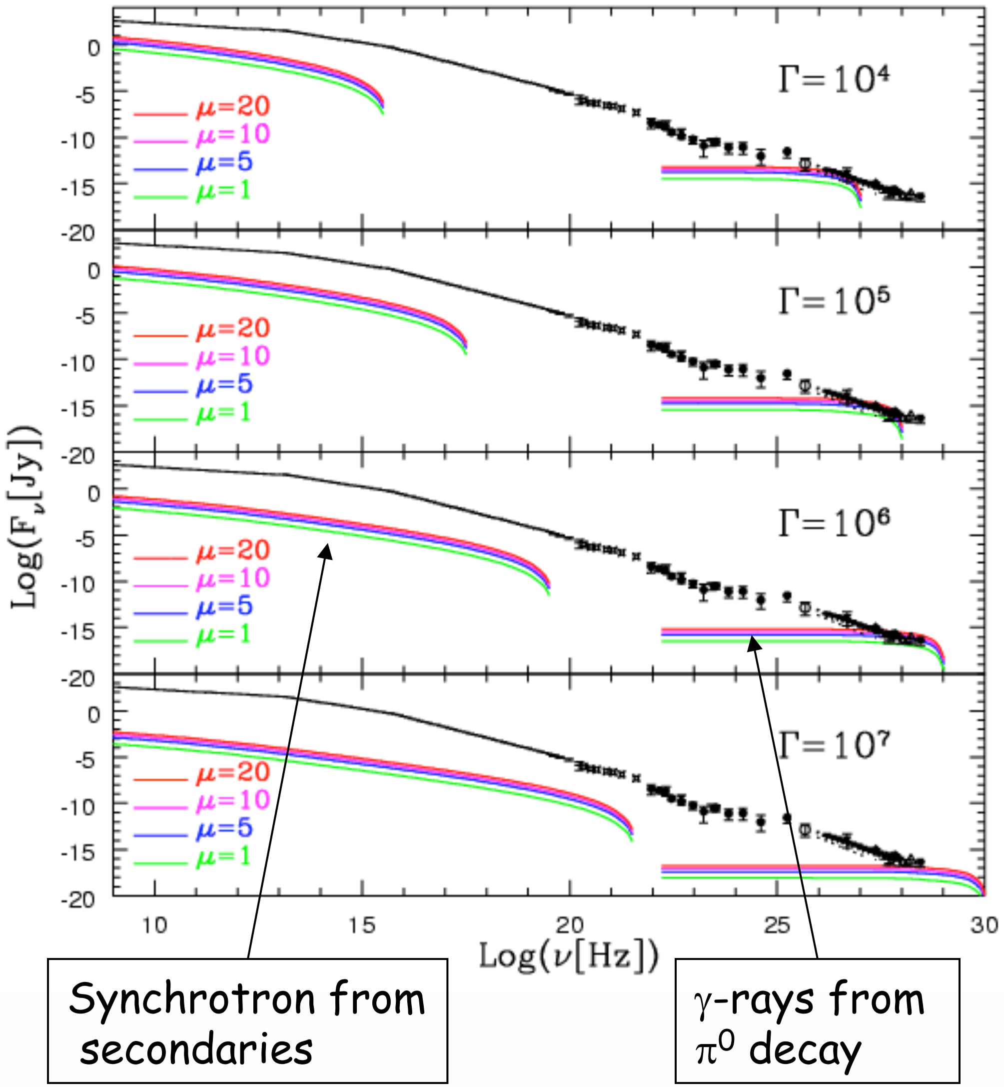
Most direct signature would be ν detection

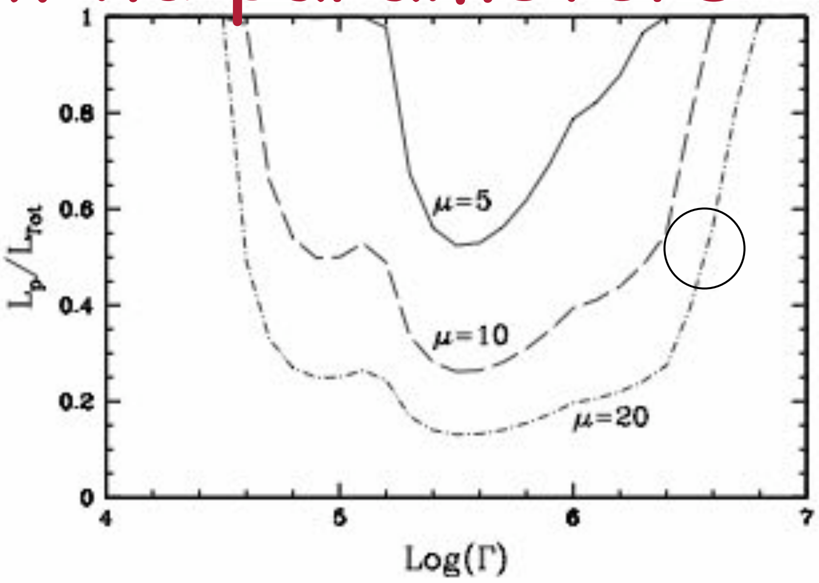


Calculations show that for Crab signal above the background if M_{ej}>8 M_{sun} Guetta & Amato 2003

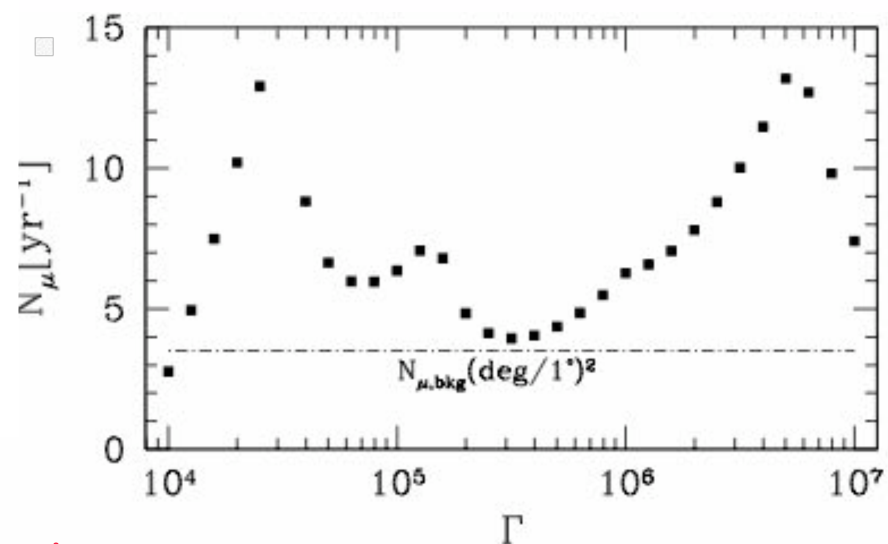
Constraints on Crab wind parameters

$$L_p = L_B = L_{e^{\pm}} = (1/3)L_0$$





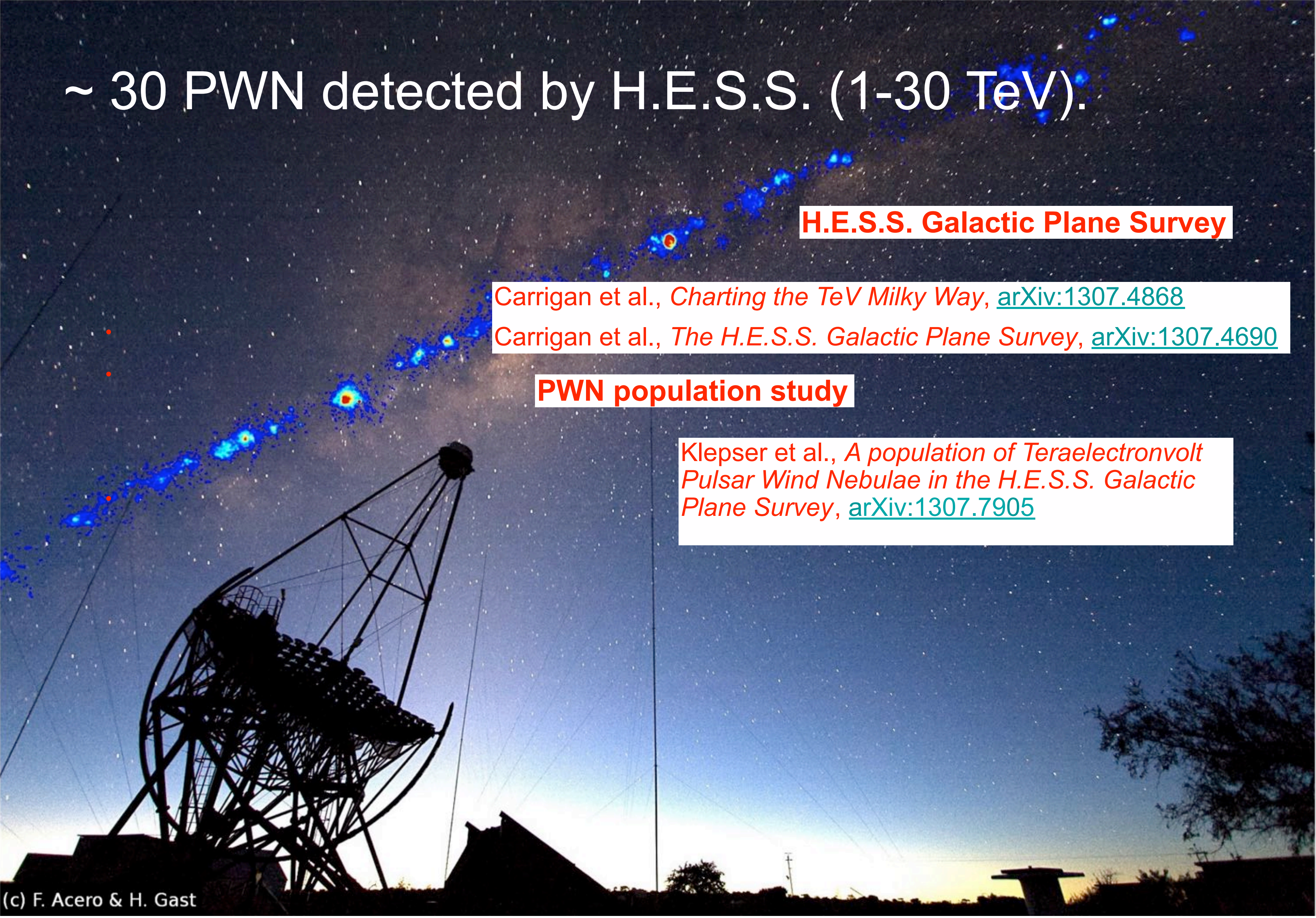
(Amato et al 03)



OLD CALCULATION!

Guetta & Amato 2003 FOR ICECUBE!

~ 30 PWN detected by H.E.S.S. (1-30 TeV).



H.E.S.S. Galactic Plane Survey

Carrigan et al., *Charting the TeV Milky Way*, arXiv:1307.4868

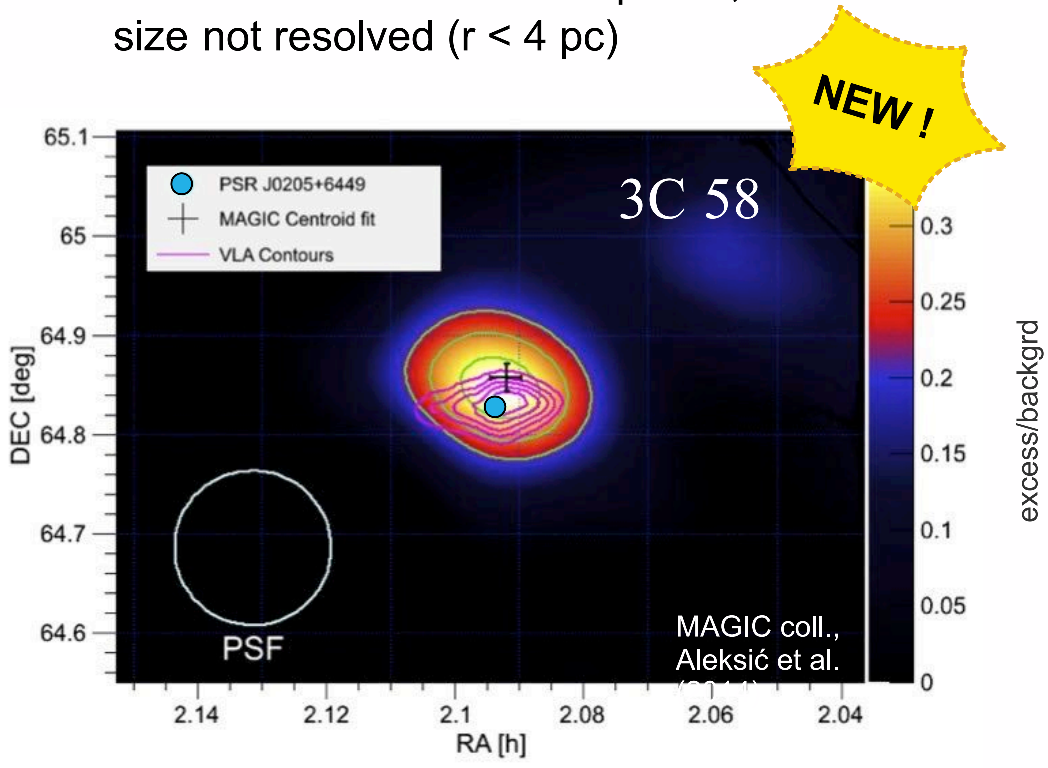
Carrigan et al., *The H.E.S.S. Galactic Plane Survey*, arXiv:1307.4690

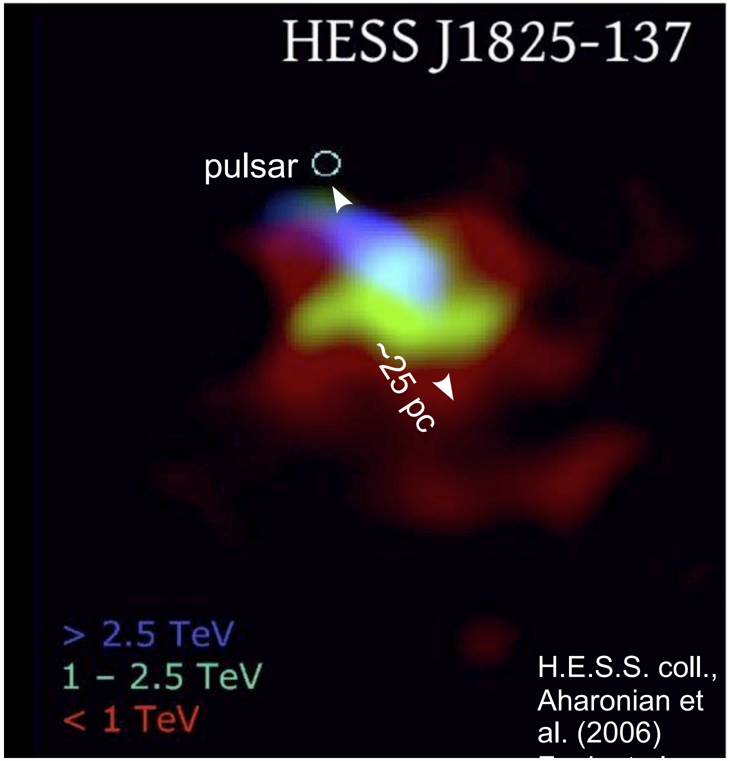
PWN population study

Klepser et al., *A population of Teraelectronvolt Pulsar Wind Nebulae in the H.E.S.S. Galactic Plane Survey*, arXiv:1307.7905

Pulsar wind nebulae in TeV γ rays

- Weakest TeV PWN ever detected:
  $L_{>1TeV}$ ~0.65% Crab, **~10^{-5} $\dot{E}$**
- Probably **young** (τ_c~5 kyr)
- TeV source coincides with pulsar, size not resolved (r < 4 pc)





- **Middle-aged** (τ_c~21 kyr, r~35 pc)
- “Crushed” shape (asymmetry, displacement)
- Synchr. burn-off of high-E particles

TeV emission and implication

TeV emission may be due ICS of the CMB, IR, FIR, background radiation by high energy leptons whose synchrotron emission is responsible of the X-ray emission

Problem: TeV flux so large that in order to interpret it as ICS one need to invoke a very weak magnetic field in the nebula much below the equipartition value or a largely enhanced radio-IR background.

Solution: Part of the emission may be hadronic!!

$$\frac{dN_\gamma}{dE_\gamma} = N_0 \left(\frac{E_\gamma}{TeV}\right)^{-\varepsilon}$$

spectral index

photon flux at 1 TeV

PWN detected at TeV

(Di Palma, Guetta & Amato in prep.)

Source Name	δ [°]	$N_0 \times 10^{11}$ [$\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$]	spectral index	reference
Crab	22.0145	2.8	-2.6	[13]
Vela	-45.17643	1.37	-1.4	[14]
G343.1-2.3	-44.26667	0.23	-2.5	[15]
MSH15-52	-59.1575	1.67	-2.27	[16]
G54.1+0.3	18.86667	0.075	-2.39	[17]
G0.9+0.1	-28.15	0.084	-2.4	[18]
G21.5-0.9	-10.58333	0.046	-2.08	[19]
Kes75	2.983333	0.062	-2.26	[19]
J1356-645	-64.5	0.27	-2.2	[20]
CTA1	72.98361	0.102	-2.2	[21]
J1023-575	-57.79	0.45	-2.53	[22]
J1616-508	-50.9	0.67	-2.35	[23]
J1640-465	-46.53	0.3	-2.42	[23]
J1834-087	-8.76	0.26	-2.45	[23]
J1841-055	-5.55	0.128	-2.4	[24]
J1813-178	-17.84	0.77	-2.09	[23]
J1632-478	-47.82	0.53	-2.12	[23]
J1458-608	-60.87722	0.21	-2.8	[26]
J1420-607	-60.76	0.35	-2.17	[27]
J1809-193	-19.3	0.46	-2.2	[28]
J1418-609	-60.97528	0.26	-2.22	[27]
J1825-137	-13.83889	0.198	-2.38	[29]
J1831-098	-9.9	0.11	-2.1	[30]
J1303-631	-63.1775	0.59	-2.44	[31]
N 157B	-69.16583	0.13	-2.8	[32]
J1837-069	-6.95	0.5	-2.27	[23]
J1912+101	+10.15167	0.35	-2.7	[33]
J1708-443	-44.33333	0.42	-2.0	[15]

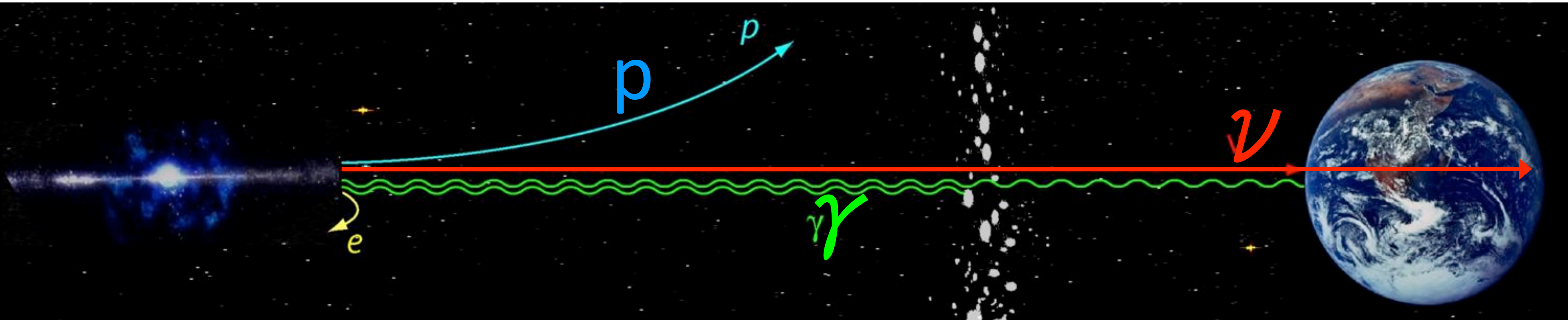
Smoking gun hadrons: neutrinos

Why look for them?

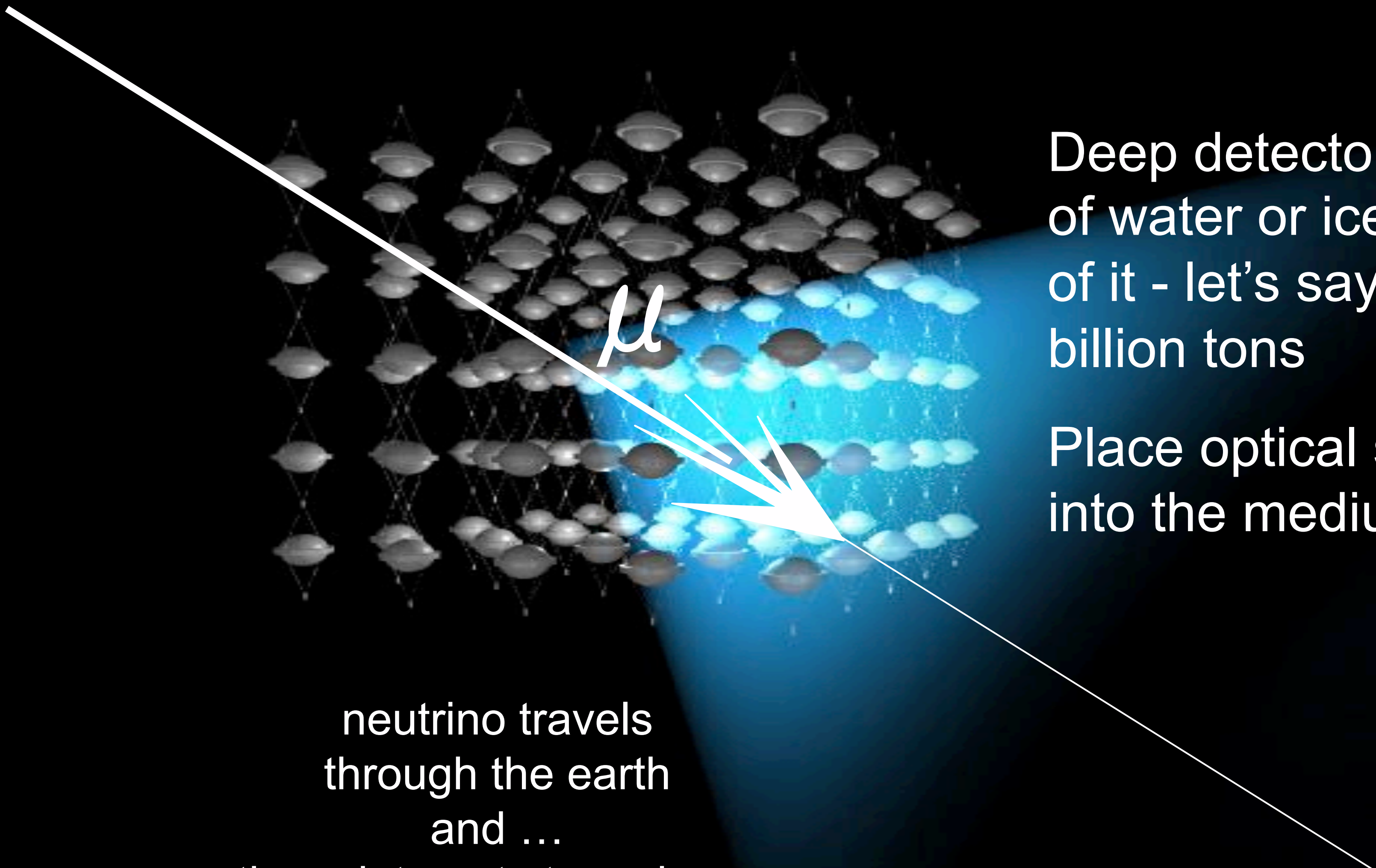
- They could tell us about the origin of high energy cosmic rays, which we know exist.
  - There are numerous ways how neutrinos can tell us about fundamental questions in nature: dark matter, supernova explosions,
  - Composition of astrophysical jets, physics of the source core

Can they reach us?

- High energy neutrinos will pass easily and undeflected through the Universe
  - That is **not** the case for other high energy particles: such as photons or other cosmic rays, eg protons.



How to catch them?
Detection principle



Deep detector made of water or ice – lots of it - let's say 1 billion tons

Place optical sensors into the medium

neutrino travels
through the earth
and …
sometimes interacts to make a muon
that travels through the detector

Neutrino fluence estimate

(Di Palma, Guetta & Amato in prep.)

- We assume that all the TeV emission is hadronic. Pions may be produced by photo-meson interaction or p-p collisions (most likely Guetta & Amato 2003).
- Number of expected neutrino events from PWN in a neutrino telescope

$$N = \int_{1\,TeV}^{100\,TeV} 2T \frac{dN_\gamma}{dE_\gamma} A(E_\nu, \delta)\, dE_\nu\, d\delta$$

T = 1 year

TeV spectrum

Effective Area

Background neutrinos

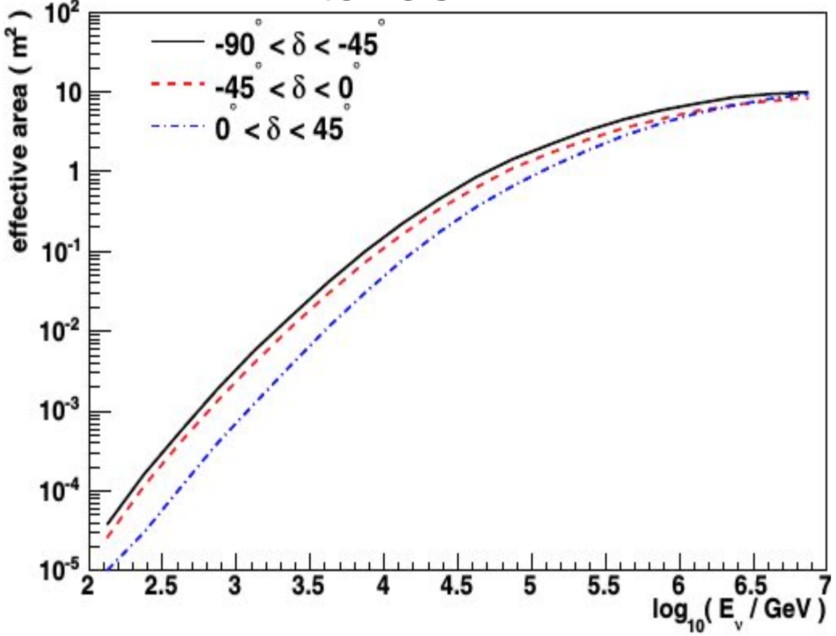
$$BG = \int_{1\,TeV}^{100\,TeV} 2T \frac{d\phi_\nu}{dE_\gamma d\Omega} A(E_\nu, \delta)\, dE_\nu\, d\delta\, d\Omega$$

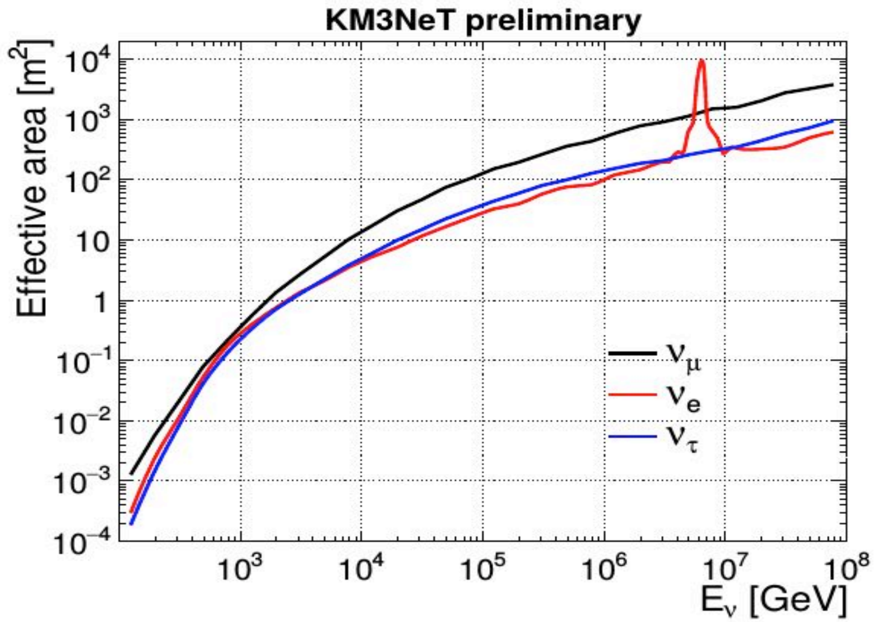
Atmospheric neutrino flux estimated
For Antares, KM3NeT and IceCube

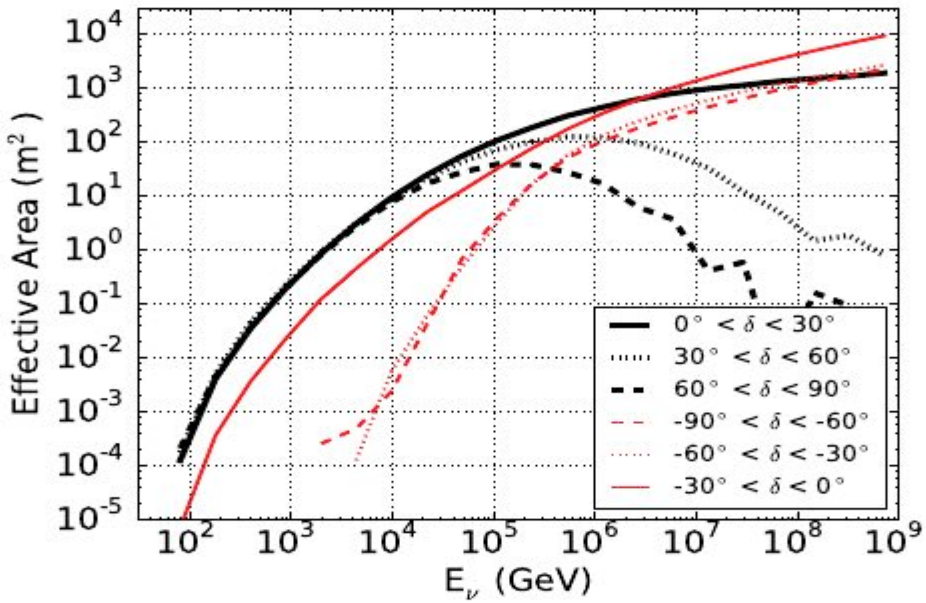
For KM3NeT the BG value are the same for each source
$BG\nu_\mu$=9.65, $BG\nu_e$=4.63, $BG\nu_\tau$=4.64

Effective Areas

Antares







Icecube

Neutrino Events (Di Palma, Guetta & Amato in prep.)

Name	IceCube N	IceCube BG	ANTARES N	ANTARES BG
Crab	13.09	0.04	0.07	0.02
Vela	0.02	3.1e-07	0.17	0.06
G343.1-2.3	1.8e-3	3.1e-07	0.02	0.04
MSH15-52	9.0e-3	3.2e-07	0.12	0.06
G54.1+0.3	0.54	0.04	3.3e-3	0.02
G0.9+0.1	0.10	5.6e-3	7.8e-3	0.04
G21.5-0.9	0.13	5.6e-3	9.6e-3	0.04
Kes75	0.60	0.04	3.8e-3	0.02
J1356-645	8.4e-3	3.7e-06	0.05	0.06
CTA1	0.89	0.04	0.02	0.06
J1023-575	3.2e-3	3.2e-07	0.04	0.06
J1616-508	9.3e-3	3.2e-07	0.09	0.06
J1640-465	3.2e-3	3.2e-07	0.04	0.06
J1834-087	0.28	5.6e-3	0.02	0.04
J1841-055	1.53	5.64e-3	0.12	0.04
J1813-178	20.63	5.6e-3	1.56	0.04
J1632-478	0.018	3.2e-07	0.13	0.06
J1458-608	6.9e-4	3.7e-06	0.01	0.06
J1420-607	0.01	3.7e-06	0.07	0.06
J1809-193	0.9	5.6e-3	0.07	0.04
J1418-609	7.5e-3	3.7e-06	0.05	0.06
J1825-137	2.5	5.6e-3	0.19	0.04
J1831-098	0.29	5.6e-3	0.02	0.04
J1303-631	7.4e-3	3.7e-06	0.07	0.06
N 157B	4.3e-4	3.7e-06	7.3e-3	0.06
J1837-069	0.836	5.6e-3	0.06	0.04
J1912+101	1.366	0.04	7.4e-3	0.02
J1708-443	0.02	3.2e-07	0.11	0.04

Name	KM3Net/ARCA N_{ν_μ}	N_{ν_e}	N_{ν_τ}
Crab	25.29	8.51	9.46
Vela	17.89	5.65	6.44
G343.1-2.3	2.48	0.81	0.91
MSH15-52	12.41	4.05	4.56
G54.1+0.3	0.99	0.31	0.36
G0.9+0.1	1.09	0.35	0.39
G21.5-0.9	1.21	0.34	0.41
Kes75	1.08	0.33	0.38
J1356-645	5.37	1.59	1.86
CTA1	2.03	0.60	0.70
J1023-575	4.60	1.51	1.70
J1616-508	9.67	3.00	3.45
J1640-465	3.77	1.11	1.36
J1834-087	3.08	0.99	1.12
J1841-055	16.72	5.28	6.02
J1813-178	197.84	56.26	67.12
J1632-478	12.68	3.64	4.33
J1458-608	1.38	0.49	0.53
J1420-607	7.46	2.18	2.57
J1809-193	9.157	2.70	3.17
J1418-609	4.95	1.47	1.72
J1825-137	26.91	8.44	9.64
J1831-098	2.76	0.79	0.94
J1303-631	7.13	2.28	2.59
N 157B	0.85	0.30	0.33
J1837-069	8.54	2.58	2.99
J1912+101	2.68	0.93	1.02
J1708-443	13.46	3.72	4.50

Equipartition field and ICS field for the most km3net promising sources

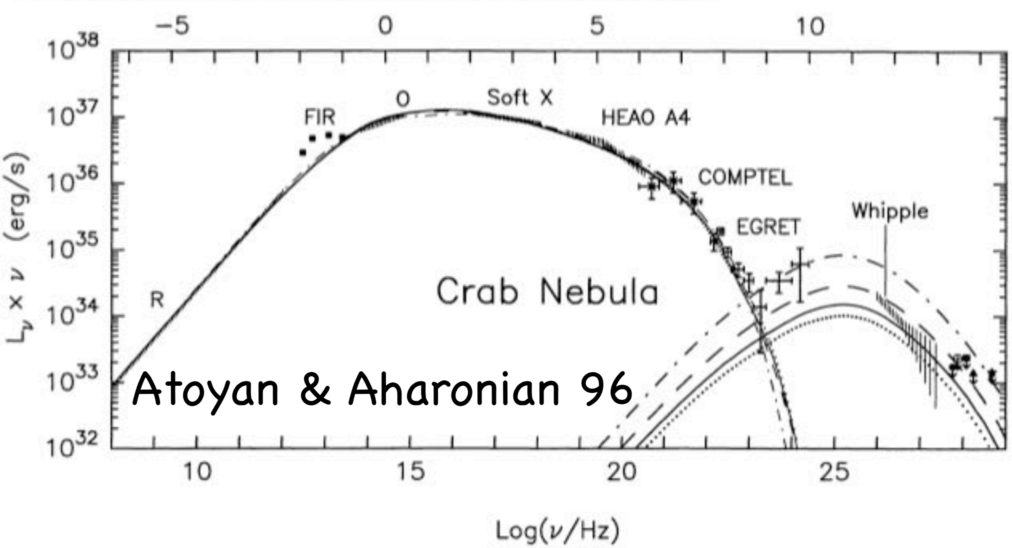
Source Name	L_X [10^{35} erg/s]	ϵ_1 [keV]	ϵ_2 [keV]	α_X	$R_{\rm PWN}$ [pc]	$B_{\rm eq}$ μG	$B_{\rm ICS}$ μG
Crab	200	0.5	8	1.12	1.2	200	150
Vela	1.3×10^{-3}	0.5	8	0.4	0.1	25	5
MSH15-52	0.4	0.5	8	0.65	4.5	20 20	15 17

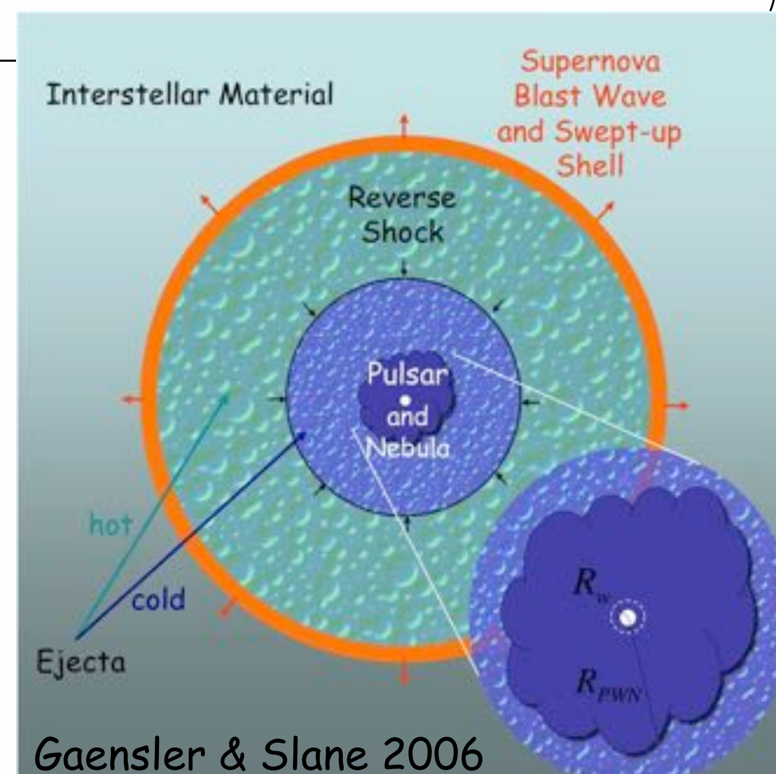
Out from equipartition TeV emission may be hadronic or enhanced IR background

THE CRAB NEBULA

(WHERE WE HAVE LEARNT MOST OF WHAT WE KNOW)

SYNCHROTRON AND ICS RADIATION BY **RELATIVISTIC PARTICLES** γ-ray spectrum well accounted for within a pure leptonic scenario. However hadrons may be energetically dominant in the Crab pulsar wind. Only test of hadrons is neutrinos!

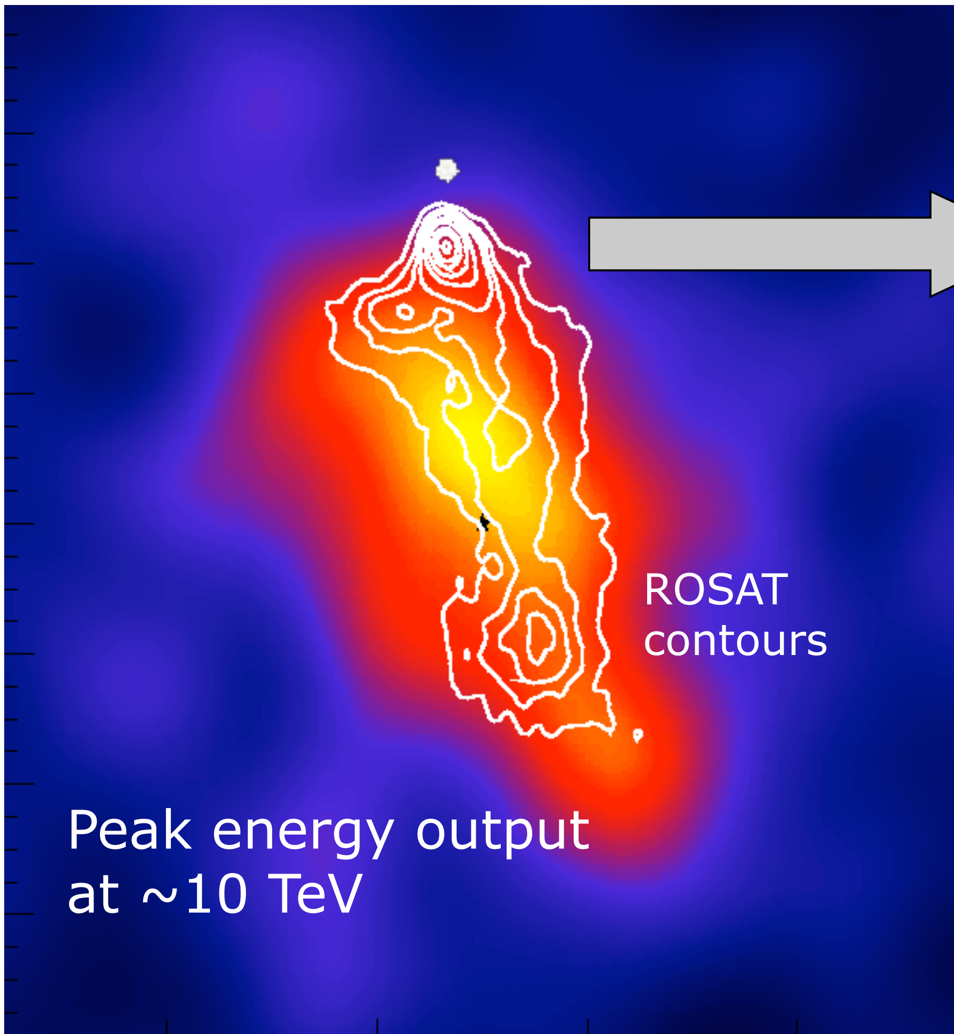


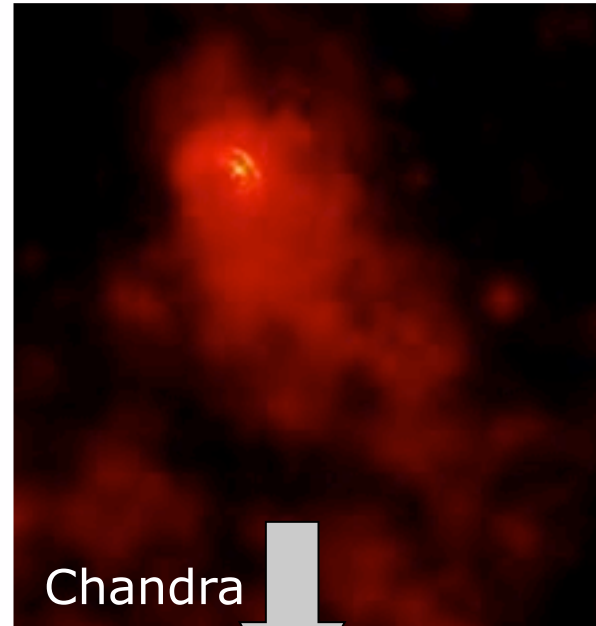


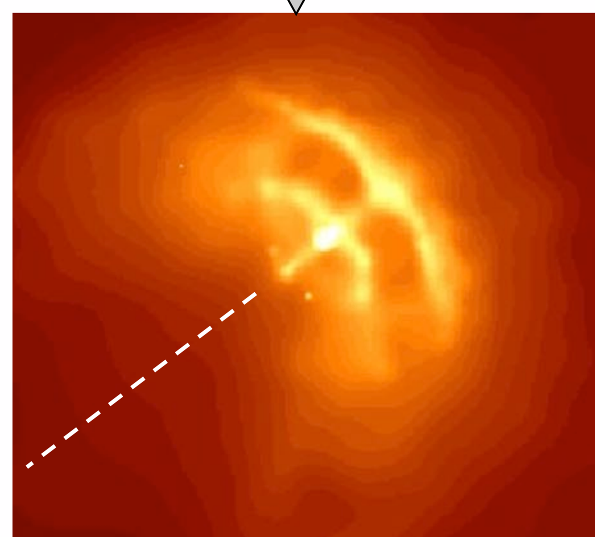
Vela-X

Old complex system where emission from PWN not easy to disentangle from other contributions. Presence of hadrons likely as the ICS B-field lower than the equipartition value or higher IR local background!!

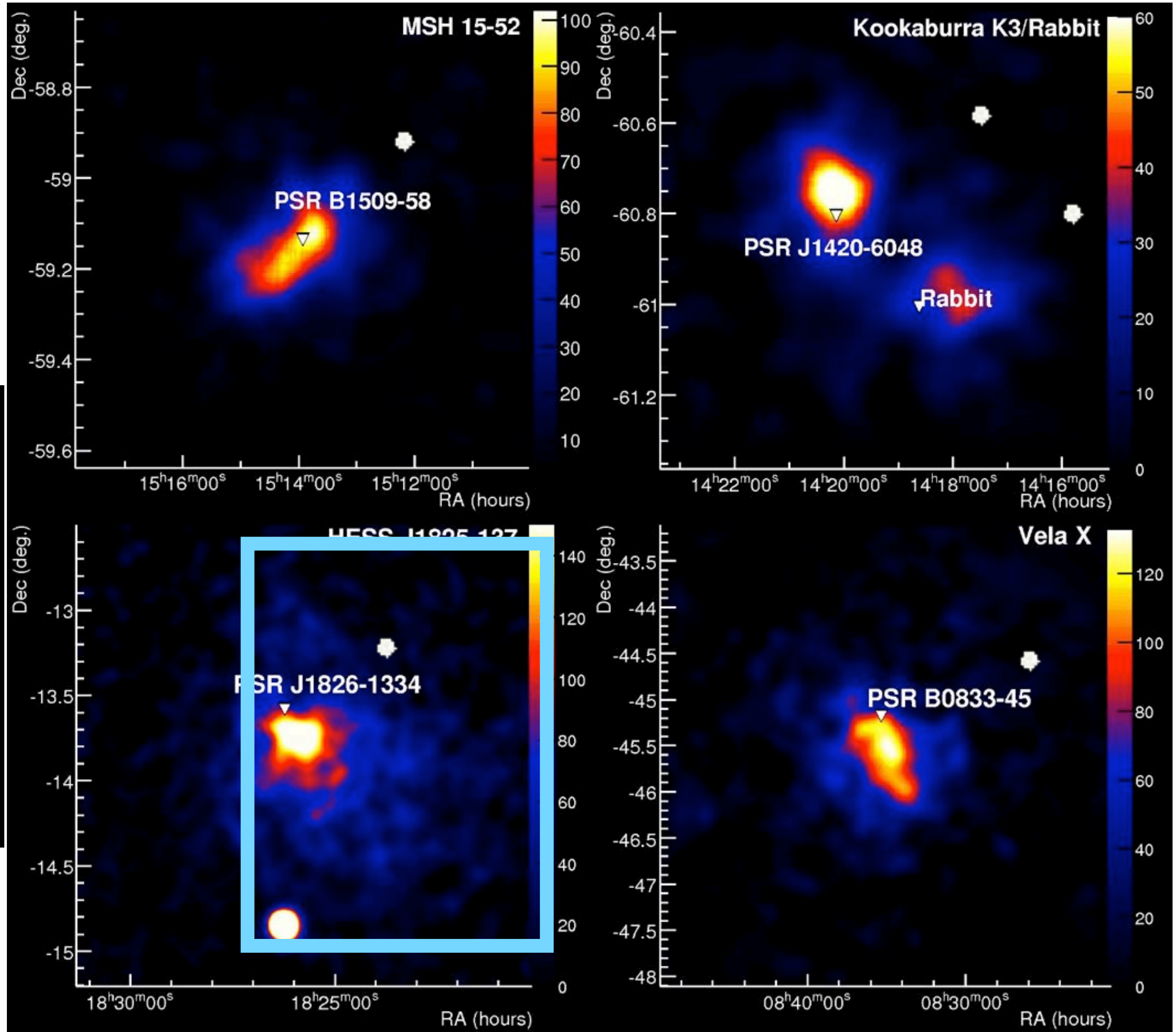
Detected By AGILE







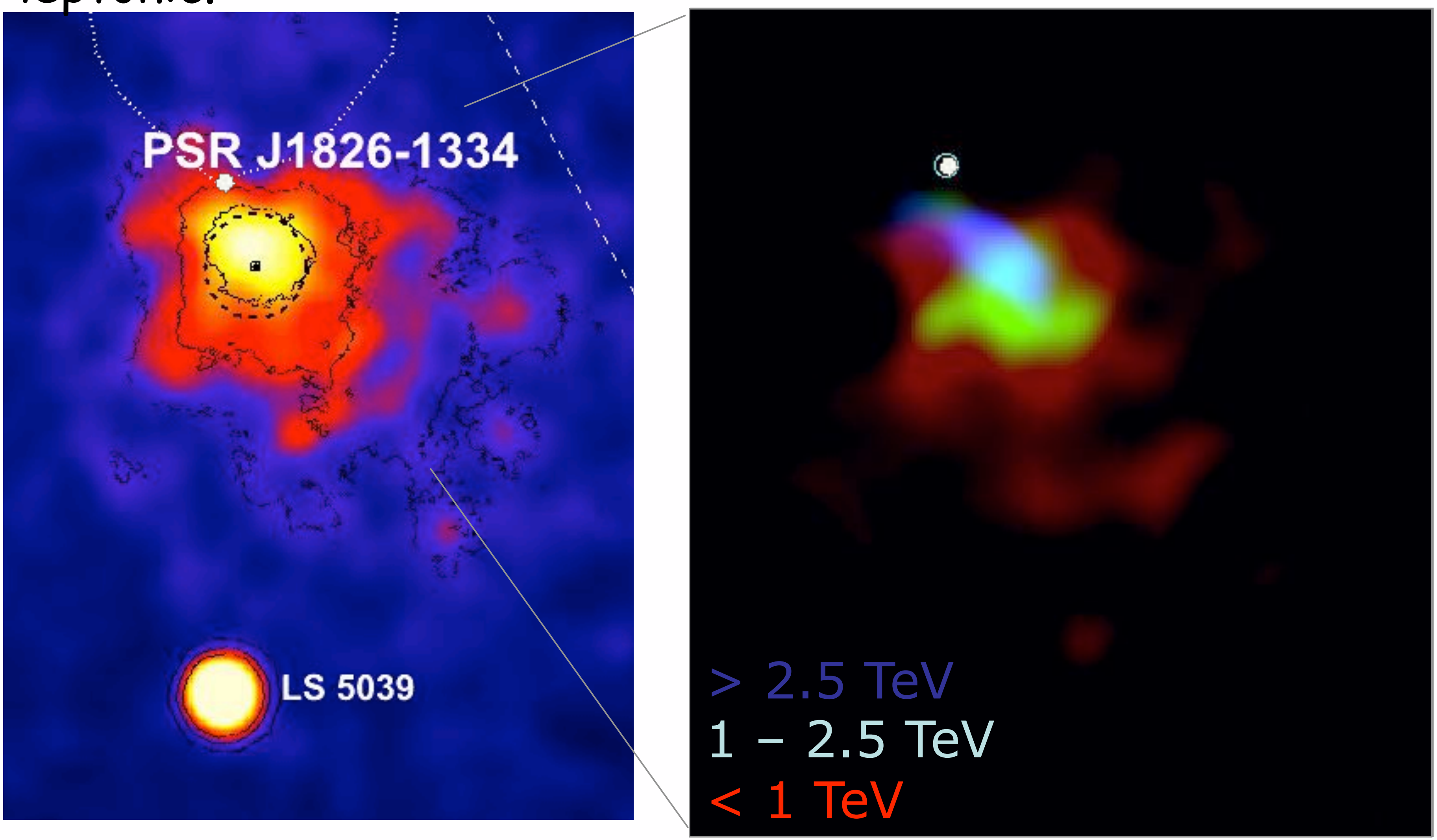
MSH15-52: nebula produced by one of the youngest and most energetic pulsar known. The energy to put in relativistic protons to explain the TeV exceeds the energy of the pulsar. However part may be hadronic.



γ-ray sources are

- extended O(10 pc)
- displaced from pulsar

J1825-137: Detected by HESS and Fermi, old PWN displaced from its parent pulsar position. B-field similar to equipartition again emission may be interpreted as purely leptonic.



Other promising sources for KM3NeT

- J1841-055: TeV source discovered in the HESS galactic plane survey. Detected by Fermi Very extended source, not clear from where the TeV emission come: need multiwavelenght survey
- J1813-178: Current spectra modeling explain the TeV emission as due to ICS with the target photon field contributed by CMB, IR and FIR background. The resulting magnetic field ~equipartition so emission may be purely leptonic.

IceCube should have detected this source

SUMMARY AND CONCLUSIONS

Acceleration process

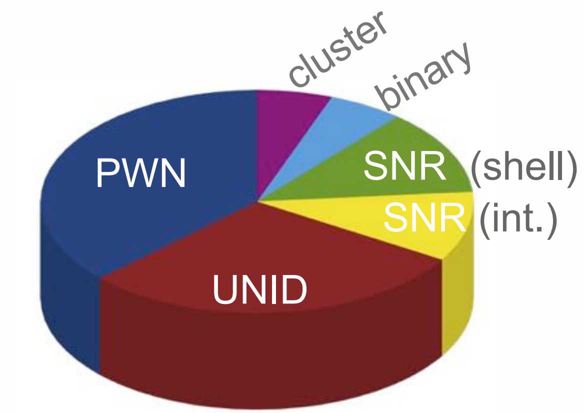
- PWNe ARE THE MOST EFFICIENT ACCELERATORS SEEN IN NATURE BUT PARTICLE ACCELERATION IN A VERY HOSTILE SETTING
- UNDERSTANDING THE ACCELERATION PHYSICS REQUIRES PINNING DOWN THE PLASMA PROPERTIES
- DETAILED DYNAMICS AND RADIATION MODELING ALLOWS TO SET LOWER LIMIT ON WIND MAGNETIZATION

⇒PRESENCE OF HADRONS SEEMS NECESSARY TO EXPLAIN THE ACCELERATION AT RELATIVISTIC TERMINATION SHOCK

Emission mechanism

- ~30 PWN were detected at TeV, CTA several hundreds. Most of the emission from radio-X-ray to TeV may be interpreted as purely sync +ICS however presence of hadrons NOT EXCLUDED and necessary for some PWN (Vela)

Summary & outlook



Composition of Gal. TeV sources
tevcat.uchicago.edu

- VHE γ-rays allow to study most powerful particle accelerators in the Galaxy these may be HE neutrino sources

PWN population: biggest (& rather diverse) Galactic source class

- Many UNID sources might be ageing PWNe
- Modeling: need better understanding of evolved PWNe …

… in particular for the leap ahead with CTA

Conclusions II

- We estimated the neutrino flux from the PWNs detected by HESS at TeV under the hypothesis that all the TeV emission is due to p-p scattering
- IceCube should have detected J1813-178 (~20 events expected) constraints can be put.
- For several PWNs more events expected in Antares than IceCube.
- KM3NeT better suited than IceCube to detect several neutrinos from several sources. It will confirm or disprove the hadronic emission.
- KM3NeT will provide the strongest constraints on the hadronic component of PWNs
- Positive detection of neutrinos with E>TeV will provide a final answer on the origin of TeV emission and confirm the hypothesis that protons may be accelerated up to tens TeV in these objects