# Potential Neutrino Signals from Galactic $\gamma$-Ray Sources

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- TeV $\gamma$-Ray Sources as Potential $\nu$ Sources
- From $\gamma$-Rays to Neutrinos
- Rates in a $km^3$ Neutrino Telescope

# Introduction

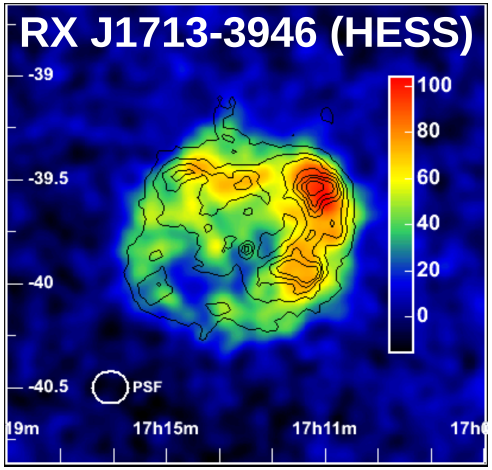
- Most of our galaxy surveyed by TeV $\gamma$-ray detectors
- Likely all bright Galactic TeV $\gamma$-ray sources identified
  $\Rightarrow$ neutrino source candidates

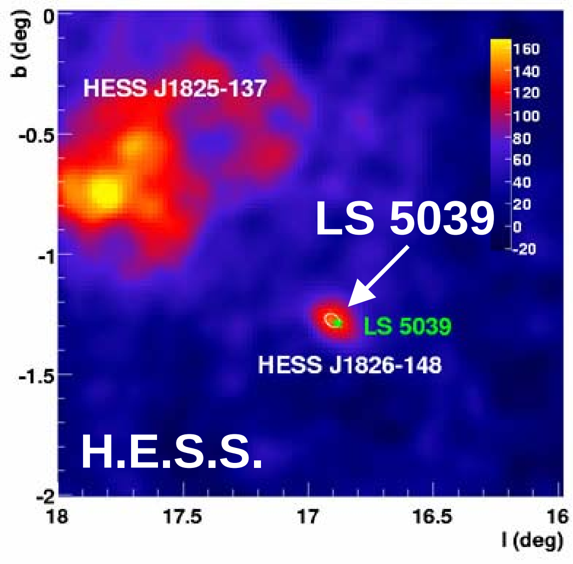
> - **How to derive neutrino flux from measured $\gamma$-ray flux?**
> - **What are the event rates in neutrino telescopes?**

# Galactic TeV γ-Ray Sources (I)

**7 Supernova Remnant (SNR) candidates**

- Detection of resolved γ-ray emission from shells
- RX J1713-3946 (H.E.S.S.) : Multiwavelength analysis points to hadronic origin



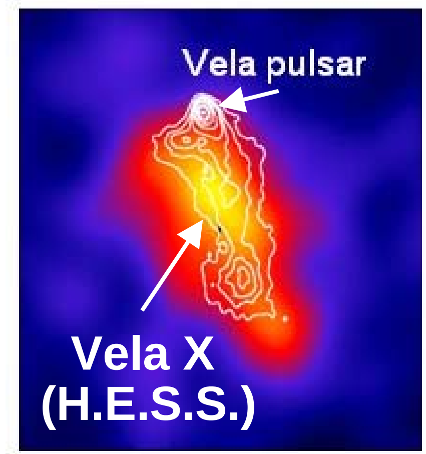

**3 Binary Systems**

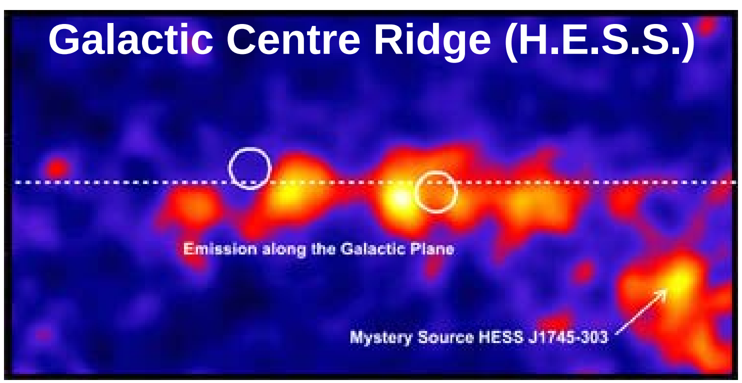
- Dense radiation fields
  ↳ rapid cooling of TeV electrons
  ⇒ hint to hadronic origin?
- Measured γ-ray flux weak but strong absorption
  ⇒ ν flux "enhanced" up to a factor 100 (LS 5039)
  (Aharonian et al., 2006, J.Phys.Conf.Series, 39, 408)

# Galactic TeV γ-Ray Sources (II)

**12 Pulsar Wind Nebula (PWN) candidates**

- Normally interpreted as inverse Compton up-scattering of CMBR photons by HE electrons
- But if significant fraction of nuclei in pulsar wind
  ⇒ Neutrinos
  (Horns et al., 2006, A&A, 451, L51)




**1 Diffuse Emission from CR Interactions**

Structure of TeV emission similar to radio emission in CS lines from molecular clouds

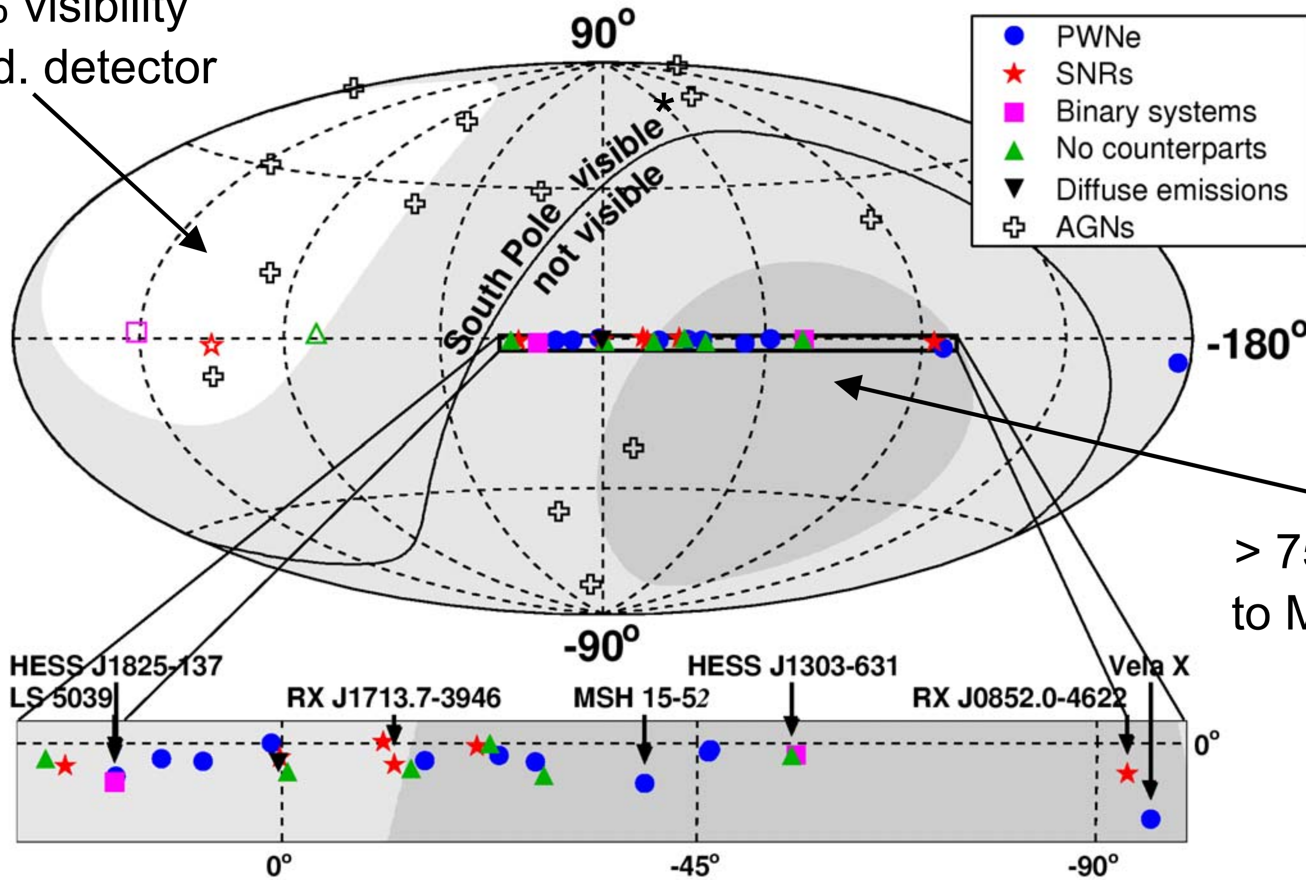
↳ interaction of accelerated protons

⇒ "guaranteed" TeV neutrino source

**7 Sources without good Counterpart at other Wavelengths**

# Sky Map of Known TeV γ-Ray Sources
## (Galactic coordinates)

< 25% visibility*
to Med. detector




> 75% visibility*
to Med. detector

* Visibilities for $E_{\nu}$ < 100 TeV

# From γ-Ray to Neutrino Flux (I)

**Hadronic neutrino and γ–ray production:**

$p + p \rightarrow \pi^0 + X$
$\hookrightarrow \gamma\,\gamma$

$p + p \rightarrow \pi^{\pm} + X$
$\hookrightarrow \mu + \nu_\mu$
$\hookrightarrow e + \nu_e + \nu_\mu$

Pion isospin symmetry $\Rightarrow (\gamma : \nu_e : \nu_\mu : \nu_\tau) \approx (1 : 2 : 1 : 0)$

Parameterisation of pion and secondary particle production (SIBYLL)
(Kelner et al., astro-ph/0606058)

Primary proton spectrum: $$\frac{\mathrm{d}N_p}{\mathrm{d}E_p} = k_p\, E_p^{-\alpha} \exp\left(-\frac{E_p}{\epsilon_p}\right)$$

$\Downarrow$

Neutrino / γ spectrum: $$\left(\frac{\mathrm{d}N}{\mathrm{d}E}\right)_{\gamma/\nu} = k_{\gamma/\nu}\, E_{\gamma/\nu}^{-\Gamma_{\gamma/\nu}} \exp\left(-\sqrt{\frac{E_{\gamma/\nu}}{\epsilon_{\gamma/\nu}}}\right)$$

# From γ-Ray to Neutrino Flux (II)

- **Assuming full neutrino mixing**

$$\left(\frac{\mathrm{d}N}{\mathrm{d}E}\right)^{\mathrm{Earth}}_{\nu_\mu} = \left(\left(\frac{\mathrm{d}N}{\mathrm{d}E}\right)^{\mathrm{src}}_{\nu_\mu} + \left(\frac{\mathrm{d}N}{\mathrm{d}E}\right)^{\mathrm{src}}_{\nu_e}\right) / 3$$

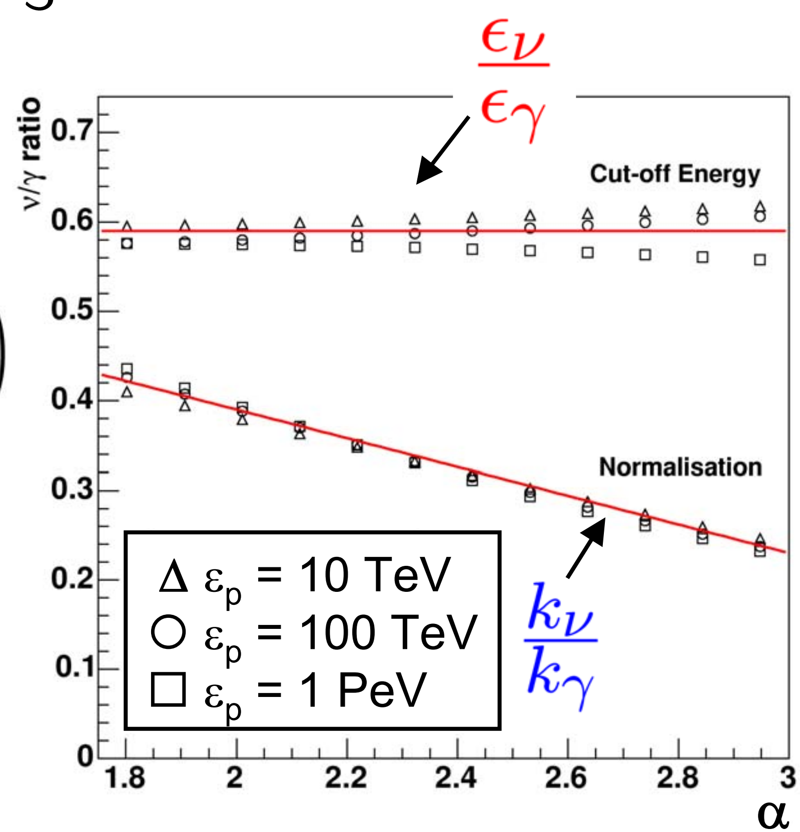
- **Relation γ / ν spectrum parameters (at Earth)**

$$\left(\frac{\mathrm{d}N}{\mathrm{d}E}\right)_{\gamma/\nu} = k_{\gamma/\nu}\, E_{\gamma/\nu}^{-\Gamma_{\gamma/\nu}} \exp\left(-\sqrt{\frac{E_{\gamma/\nu}}{\epsilon_{\gamma/\nu}}}\right)$$

**Norm:** $k_\nu \approx (0.71 - 0.16\alpha)\, k_\gamma$

**Index:** $\Gamma_\nu \approx \Gamma_\gamma \approx \alpha - 0.1$

**Cut-off:** $\epsilon_\nu \approx 0.59\epsilon_\gamma \approx \epsilon_p/40$

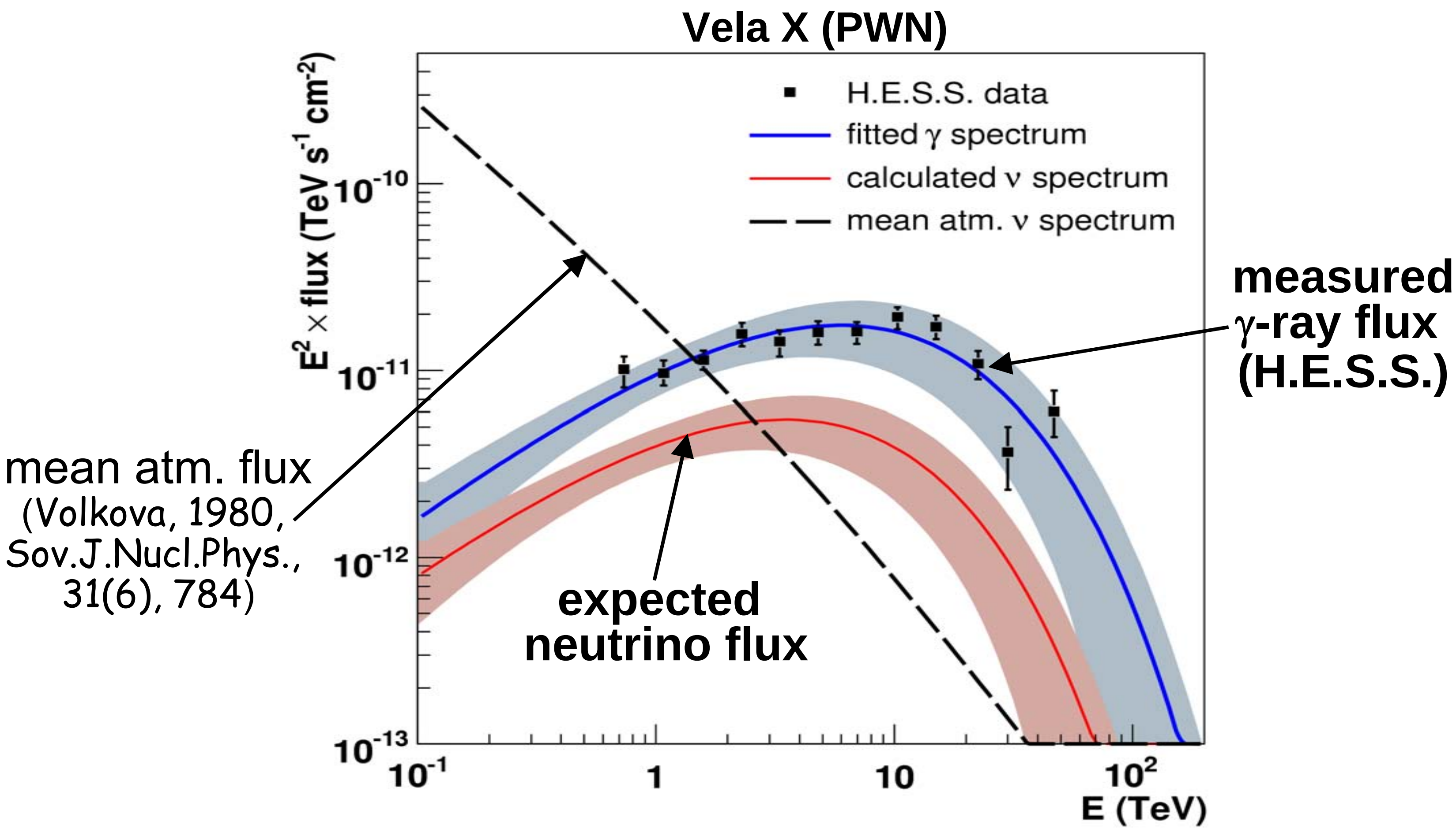


# Assumptions made for Calculations

1. No significant contributions from non-hadronic processes to $\gamma$ signal
2. Matter density low (no significant $\gamma$ absorption / $\pi^{\pm}$ decay before interaction)
3. Radiation density low (no significant $p\gamma$ interaction / $\gamma$ absorption)
4. Magnetic field low (muons decay without significant energy loss)
5. Size of emitting region large (full neutrino mixing)
6. *NN* interactions produce $\pi$ spectra similar to *pp*

- For all extended (H.E.S.S.) $\gamma$-ray sources conditions 1.– 6. likely valid (except condition 1. in several cases)
- For (point like) Binary Systems probable 2. (no significant $\gamma$ absorption) and 5. not true

# Neutrino and γ-Ray Spectra for Vela X

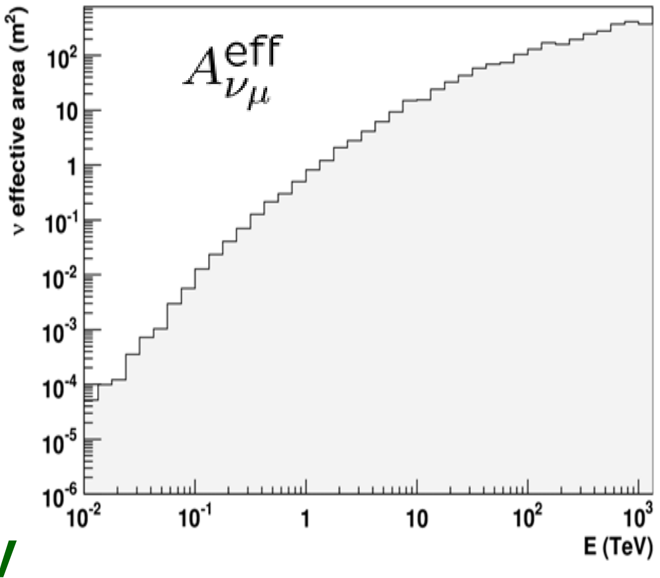



- 1 σ error bands include systematic errors (20% norm., 10% index & cut-off)

# Detector Simulation (KM3NeT)

**Location:** Mediterranean Sea
**Instrumented volume:** 1 km$^3$
**Angular resolution for muons:** $\sigma_{PSF} = 0.3^o$ ($E_\nu > 1$ TeV)

- **Event rate:** $\left(\frac{\mathrm{d}N_{\nu_\mu}}{\mathrm{d}t}\right)_{\mathrm{obs}} = \int \mathrm{d}E_{\nu_\mu}\, A^{\mathrm{eff}}_{\nu_\mu} \frac{\mathrm{d}N_{\nu_\mu}}{\mathrm{d}E_{\nu_\mu}}$



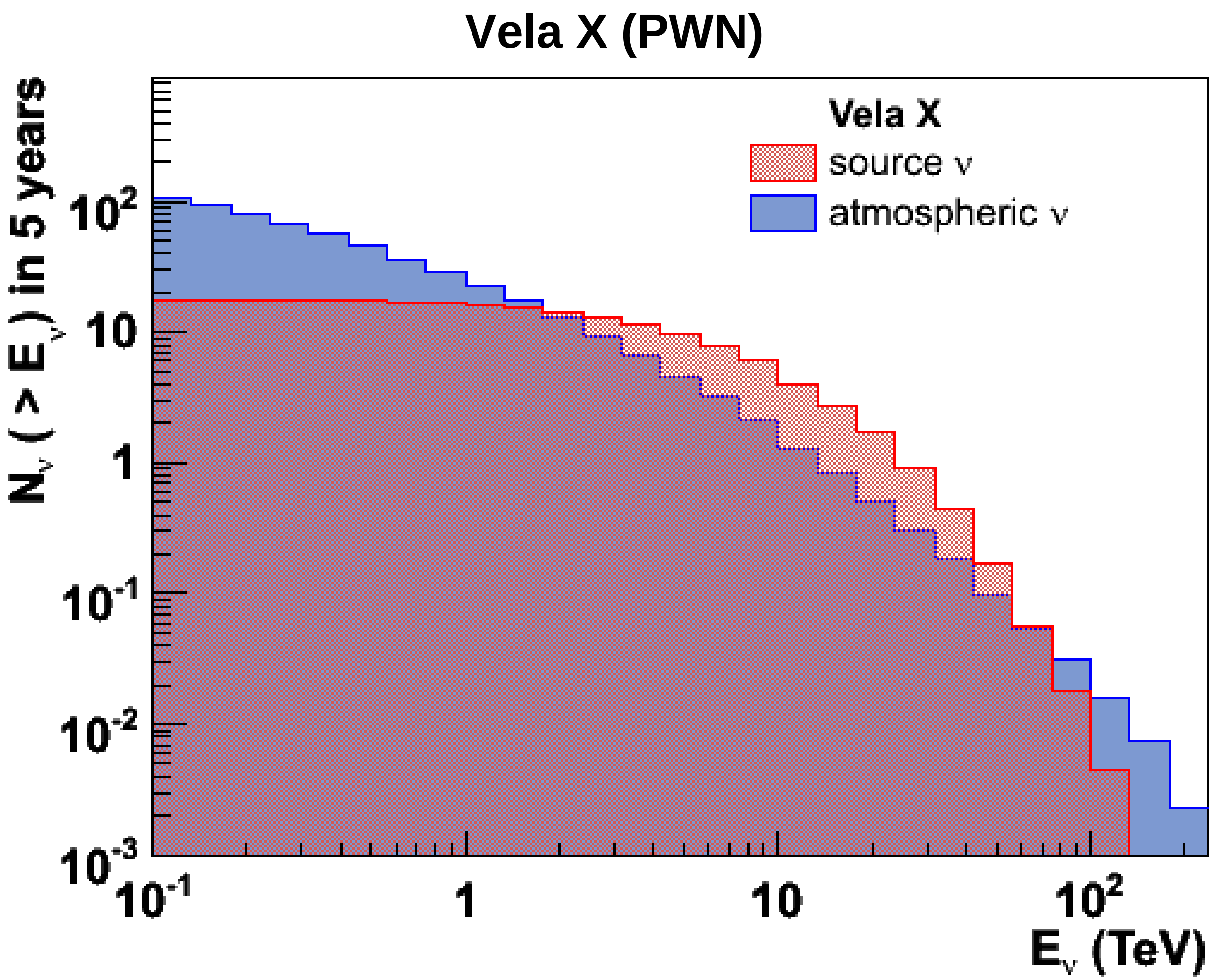

- $A^{\mathrm{eff}}_{\nu_\mu}$ **comprises** (full MC simulation)
  - ν attenuation in Earth
  - $\nu_\mu$ conversion to μ
  - μ detection efficiency

  (Kuch, astro-ph/0606507)

- **Neutrino spectrum cut-offs at few 10 TeV**
  ⇒ earth opaqueness not taken into account

- **Optimal search window** (flat background): $\theta_{\mathrm{opt}} \approx 1.6 \times \sqrt{\sigma^2_{\mathrm{PSF}} + \sigma^2_{\mathrm{src}}}$

# Neutrino Rates for Vela X in KM3NeT (1 km$^3$, 5 years)



# Neutrino Events from H.E.S.S. Sources

## Sources with observed cut-off

**KM3NeT (1 km$^3$, 5 years)**

| | Type | Ø [°] | $E_\nu$ > 1 TeV Src | $E_\nu$ > 1 TeV Bkg | $E_\nu$ > 5 TeV Src | $E_\nu$ > 5 TeV Bkg |
|---|---|---|---|---|---|---|
| Vela X | PWN | 0.8 | 9 – 23 | 23 | 5 – 15 | 4.6 |
| RX J1713.7–3946 | SNR | 1.3 | 7 – 14 | 41 | 2.6 – 6.7 | 8.2 |
| HESS J1825–137 | PWN | 0.3 | 5 – 10 | 9.3 | 2.2 – 5.2 | 1.8 |
| Crab Nebula | PWN | <0.1 | 4.0 – 7.6 | 5.2 | 1.1 – 2.7 | 1.1 |
| HESS J1303–631 | NCP | 0.3 | 0.8 – 2.3 | 11 | 0.1 – 0.5 | 2.1 |
| LS 5039* (INFC) | Binary | <0.1 | 0.3 – 0.7 | 2.5 | 0.1 – 0.3 | 0.5 |

**NCP: No counterpart at other wavelengths** ***no $\gamma$-ray absorption**

## 21 further H.E.S.S. sources investigated:

- All $\gamma$-ray spectra show no cut-offs (but limited statistics)
- Event numbers mostly below 1 – 2 in 5 years
- For more details: **preprint astro-ph/0607286**

# Summary

- Likely, strongest Galactic TeV $\gamma$-ray sources discovered
  $\Rightarrow$ neutrino source candidates
- Measured $\gamma$-ray spectra allow robust prediction of neutrino fluxes
- Simple relation between parameters of $\gamma$-ray and $\nu$ spectrum found
- Event rates in a 1 $km^3$ Mediterranean neutrino telescope (KM3NeT)
  - about 1 event per year from each of brightest sources ($E_\nu$ > 1 TeV)
  - about equal number of background and signal events