High-energy neutrinos from Galactic sources

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Outline

• Introduction to neutrino astronomy
• Potential Galactic neutrino sources
• Expected fluxes and event rates
• The mystery of the missing PeVatrons
• Prospects for detection of Galactic neutrino sources
The Milkyway in different light

Optical

Laustsen et al. Photomosaic

1608
The Milkyway in different light

Radio Continuum
2.4–2.7 GHz Bonn & Parkes
1930’s

Optical
Laustsen et al. Photomosaic
1608
### The Milkyway in different light

<table>
<thead>
<tr>
<th>Waveband</th>
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<th>Instrument/Method</th>
<th>Date</th>
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1930’s: First observation of the Milky Way in the radio continuum.
1964: Detection of the Milky Way in the microwave region.
1960’s: Observation of the Milky Way in the infrared region.
1989: Observation of the Milky Way in the gamma ray region.
20??: Detection of the Milky Way in the TeV neutrino region.
Cosmic-rays

- Spectrum measured over 12 orders of magnitude in energy
- Power law spectrum (non-thermal)
- Consists of particles
- Sources still active

Sources still unknown!
High-energy particle production

Accelerator (source)
- Shock fronts (Fermi acceleration)
- Objects with strong magnetic fields (pulsars, magnetars)

Beam dump (secondary particle production)
- Interaction with photon and matter near the source
- Protons: pion decay

\[ p + p(\gamma) \rightarrow \pi^\pm + X \]

\[ \mu + \nu_\mu \]

\[ e + \nu_\mu + \nu_e \]

- Electrons: inverse Compton-scattering of photons

\[ e + \gamma \rightarrow e + \gamma \text{ (TeV)} \]
Potential Galactic neutrino sources

Classes of TeV γ-ray sources:
- 8 SNRs
- 12 PWNe
- 4 Binaries
- 4 Others
- 20 Unidentified
Source candidates

supernova remnants
(SN1006, optical, radio, X-ray)

pulsars
(Crab pulsar, optical, X-ray)

micro-quasars
(artist’s view)

star-forming regions
(Cygnus region, optical)
SNR: RX J1713.7–3946

Fermi acceleration:
- energy gain after each crossing of shock front
- repetitive process
- yields power law

Moon

Age ~1000 years

SNR: RX J1713.7–3946

Interstellar gas

Shock front

Rest system

Interstellar gas

Shocked gas

1.3˚
Fermi acceleration:

- energy gain after each crossing of shock front
- repetitive process
- yields power law

SNR: RX J1713.7–3946

Age ~1000 years

Moon

E<sup>2</sup> flux (TeV s<sup>-1</sup> cm<sup>-2</sup>)

Shock front

rest system
interstellar gas

rest system
shocked gas

shocked gas
interstellar gas
RX J1713: History of neutrino rate predictions

• Early predictions too optimistic
  (wrong γ-ray measurements, no ν oscillation, no cut-offs)

• Now expecting (1 km$^3$, $E_\nu > 1$ TeV): 1 – 3 evt yr$^{-1}$

• Source size important: $\varnothing = 1.3^\circ \rightarrow N_{bkg} \approx 8$

Costantini & Vissani (2005)
Distefano (2006)
Kistler & Beacom (2006)
Kappes et al. (2007)
Morlino et al. (2009)
RX J1713: Impact of High Energy Cut-Offs

- Effective area increases rapidly with energy
  → high energy cut-offs have large impact on event rates

$E_{ν} > 1$ TeV: $2.1$ evt yr$^{-1}$ (cut-off) → $3.6$ evt yr$^{-1}$ (no cut-off)
Binary Systems

- Potentially large $\gamma$-ray absorption
  $\rightarrow$ Neutrino flux much higher than expected

- LS 5039:
  - Evts in km$^3$ detector (> 1 TeV)
    (Kappes et al. (2007))
    INFC: 0.3 – 0.7 yr$^{-1}$
    SUPC: 0.1 – 0.3 yr$^{-1}$
  - Up to 100 times higher !
    (Aharonian et al. (2006))
  - Point-like source ($\varnothing \approx 0.1^\circ$)

\[ \text{HESS } \gamma\text{-ray spectra (2006)} \]
Pulsar wind nebulae

• PWNe generally expected to accelerate electrons
  ... but maybe significant fraction of nuclei
  in pulsar wind !?
  (e.g. Horn et al. (2006))

• Example Vela X:
  1 – 5 evts yr$^{-1}$ (km$^3$; > 1 TeV)
  (Kistler & Beacom (2006), Kappes et al. (2007))
Molecular clouds

• Interaction of cosmic rays with molecular clouds

• TeV γ-ray emission follows matter density

• Galactic Centre region: guarantied neutrino source . . .

. . . but rather weak (< 1 evt yr\(^{-1}\))
The missing PeVatrons

• No $\gamma$ rays above few 10 TeV (“knee” corresponds to ~300 TeV)

• “Direct” $\gamma$-rays maybe only in first few hundred years

• Detection by observing secondary $\nu$’s or $\gamma$-rays from clouds near sources
PeVatron candidates

Part of Galactic plane in $\gamma$-rays @ 12 TeV (Milagro)

- If PeVatrons, sources detectable with IceCube
- Energy resolution important

![Image showing PeVatron candidates with regions labeled C1, C2, MGRO J2019+37, MGRO J1852+01, and MGRO J1908+06.]

![Graph showing analysis with stacked sources featuring IceCube data with significance levels for 5 years and 10 years.]
Sky coverage of neutrino telescopes

Visibility South Pole (IceCube)
- 100%
- 0%

Visibility Mediterranean (Antares, KM3NeT)
- > 75%
- 25% – 75%
- < 25%

TeV γ-ray sources
- Galactic
- extra-Galactic
Point-source sensitivities

90% CL sensitivity for $E^{-2}$ spectra (preliminary)

Detectability of individual sources depends on many details:

- Cut-off energy
- Source size
- Energy resolution (Lower energy cuts improves Signal/Bckg ratio)
Gamma-ray dark sources

Neutrinos open a new window to the universe . . .
Conclusions

• Neutrino telescopes open new window to our galaxy and beyond (complete picture requires multi-messenger approach)

• Galactic high-energy neutrino sources must exist but up to now no source of high-energy neutrino emission identified

• km$^3$-class detectors (IceCube, KM3NeT) will enter discovery region - several good source candidates - will likely detect cosmic neutrinos within next years - detection significance depends on source-specific details

• Expect surprises!