Detecting Cosmic Accelerators with Neutrino Telescopes and GRB Results from IceCube

Alexander Kappes
NUSKY 2011
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Outline

• Some thoughts on the detectability of Galactic sources

• Extragalactic sources
  - Recent IceCube results on GRBs
  - IceCube follow-up programs
Sensitivity development

- SuperK
- ANTARES
- AMANDA
- IceCube 40
- IceCube 59
- IceCube 80 (predicted IC40)
- IceCube 40+59
- KM3NeT (predicted)

factor 1000 in 15 years
Development of flux predictions: An example

- Early predictions too optimistic (but correctly calculated!)
  (wrong $\gamma$-ray measurements, no $\nu$ oscillation, no cut-offs)

- Now expecting ($1 \text{ km}^3, E_\nu > 1 \text{ TeV}$): $1 \text{ – } 3 \text{ evt yr}^{-1}$
  (for pure hadronic acceleration)

Costantini & Vissani (2005)
Distefano (2006)
Kistler & Beacom (2006)
AK et al. (2007)
Morlino et al. (2009)
Most sensitive look at the (steady) neutrino sky

- Highest fluctuation: p-value = 0.67 after trials; in southern sky
- Data corresponds to almost 1 year IC86
  → if there is a source it takes quite long to become significant (improved angular resolution will help)
Trial factors in steady all-sky searches

• Difficult to see a (steady) source in the all sky search

• Trial factor for IC40+59: $3 \times 10^4$ ($4\sigma \rightarrow 0.5\sigma$) → pick the right sources

• What are the right sources?
### Galactic sources: Northern hemisphere

- **IceCube source list (IC40+59)**

<table>
<thead>
<tr>
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- **IceCube stacked searches (IC40)**

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**Remark:** extension taken into account

*periodic analyses?*

*IC40: CygX3 p-value 0.02 pretrial*

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“--” = negative fluctuation
# Galactic sources: Northern hemisphere

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## IceCube stacked searches (IC40)

- Milagro 17 srcs: 0.32
- Milagro 6 SNR: 0.02 (posteriori)

Unblinding for IC40+59 soon

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Up to now, all suspects have good alibis (high p-value)!

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*periodic analyses? (IC40: CygX3 p-value 0.02 pretrial)*

"--" = negative fluctuation
Galactic sources: Southern hemisphere

- IceCube sensitive to energies > 1 PeV (not likely Galactic origin)

- ANTARES 2007-08:
  - 14 sources (RXJ1713, Vela Junior, Gal.Center, LS5039 . . .)
  - Best p-value: 0.07 (GX339, posttrial)
  - Significant sensitivity improvement expected in next years but discovery unlikely
Galactic sources: Southern hemisphere

KM3NeT would open new possibilities . . .

Example RX J1713:
- Neutrino flux from gamma-ray flux (purely hadronic)
- Simulation of extended source (flat disk)
- Full Monte Carlo simulation of detector response (signal and background)
- Detection possible in 5-10 years
Galactic sources

. . . but currently, IceCube is in the driving seat!

- Are we looking at the wrong sources?
- How large are the potential sources?
- Are the individual fluxes too small?
  → Do we have to use more stacking?
  Which sources?
Galactic sources

- Do we concentrate too much on high-energy gamma-ray sources?
  - IACTs do have problem with extended sources
  - and are most sensitive at lower energies
- Francis: look at star forming regions!

\[ \text{Milagro, HAWC} \]
Galactic sources

- Do we concentrate too much on high-energy gamma-ray sources?
  - IACTs do have problem with extended sources and are most sensitive at lower energies
- Francis: look at star forming regions!

→ Cygnus region not very cooperative up to now
Are the Galactic sources still active?

Possible (depressing) alternative scenario?

• Source (e.g. Central black hole) produced cosmic rays $10^7$ years ago during “short” period

• Cosmic rays stored in Galactic magnetic field

• Neutrinos have escaped Galaxy a long time ago
  → neutrinos “only” from CR interaction with Molecular clouds uncorrelated with CR sources
Extragalactic sources

- A lot of potential sources are variable → already single large flare might be detectable
- But flux predictions only order of magnitude

- Most extreme “variable” sources:
  
  **Gamma-ray bursts**
Neutrinos from GRBs

Smoking gun evidence for hadronic acceleration → sources of UHECR
GRBs with IceCube

- GCN-satellite triggered searches
  - Very low background → 1 event can be significant!

- Individual modeling of neutrino fluxes (fireball model)
- Measured parameters:
  - $\gamma$ spectrum, (redshift)
- Average parameters: $\Gamma_{\text{jet}}$ (316), $t_{\text{var}}$ (10 (1) ms), $L_{\text{iso}}$ ($10^{52}$ (51) erg), $\varepsilon_B$ (0.1), $\varepsilon_e$ (0.1), $f_{\text{e/p}}$ (0.1)

IC59: 98 bursts in northern sky
Prompt GRB analyses: Some technical details

- Events after quality cuts (BDT) → Likelihood function
  \[ \ln (L) = -n_s - n_b + \sum_i \ln \left( n_s S_i(\vec{x}) + n_b B_i(\vec{x}) \right) \]

- Background PDF accordingly (flat time PDF; azimuthal assym. included)

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- Final likelihood ratio \((L(n_s) / L(0))\):
  \[ \ln (R) = -n_s + \sum_{i=1}^{N} \ln \left( n_s S_i \frac{1}{n_b B_i} + 1 \right) \]
**GRBs: Limits on prompt emission**

- 1.9 events needed for $\geq 5\sigma$ (50% cases)
- IC59: No signal-like events found (expected 5.8)
  → limit (90% CL) factor 2 below model

- Combination with upper limits from IC40
  → limit factor 5 below model
GRBs: Model independent search

Approach for “arbitrary” time scales:

- Start with search in small window and increase it consecutively
- Trial factor taken into account
- IceCube 40+59: No signal found

Limits $E^{-2} \nu_\mu$ (90%CL; IC 40+59, preliminary)
GRBs and UHECRs

• Up to now no hint for neutrinos from GRBs
• Diffuse IC40 limit starts to disfavor GRBs as major sources of UHECR (see M. Ahlers’ talk)

• But GRBs could still be neutrino sources!

Ahlers et al. 2011
Extragalactic sources

• Other searches:
  - **AGNs** → IC40+59: best p-value = 0.14 (PKS 1454-354 pretrial)
  - **Starburst galaxies** → IC40 (127 srcs): limit 60×model flux (p-value = 1)
  - **Galaxy clusters** → IC40 (5 clusters): limit 6×model flux (p-value = 0.78)

• Alternative: Trigger other instruments (IACTs, optical telescopes, X-ray satellites . . .)
Optical follow-up

- IceCube multiplets trigger optical follow-up
  - angular window 4°
  - time window 100 s
  - 20–30 false alerts yr⁻¹

- Delay neutrino detection → start of optical observations: < 5 min
  (was 6.5–8 hours for <IC79)
ROTSE telescope network

- Fully robotic
- 24 hour (almost) all sky coverage
- Large field of view (1.85° × 1.85°)
Observational program

- **Prompt observation (first night):**
  Search for fast decreasing GRB afterglow
  - $30 \times 60$ s exposures

- **Follow-up observations (24 following nights):**
  Slowly rising supernova light-curve
  - $8 \times 60$ s exposures every night
  (>12 days: every second night)
Image processing

- Automatic candidate selection
- Test of algorithms with simulated SN light-curve
  (SN light-curve model by P. Nugent (SN1999ex))

- System successfully running since end of 2008
Optical follow up: Results

• **Data set:** Dec 2008 to Dec 2009; 17 alerts with ROTSE observations → 0 SNe observed (0.04 accidental detections expected)

• **Model for neutrino spectrum:**
  “Slow jet” model (Ando, Beacom 2005)
  
  **Parameters:**
  - density of SNe with jets \( \rho \)
  - jet energy \( E_{\text{jet}} \)
  - jet boost factor \( \Gamma \)
Swift follow up

- Motivation for X-ray observations: GRB afterglow / GRB and SNe shock breakout
- Similar to optical follow up (triggered by multiplets)
- Delay until start of Swift observation: ~5 min
- XRT field of view: 0.4°
  → Tiled observation

- Program running since Feb. 2011
Summary

• Detectability of (steady) Galactic sources:
  - all-sky map shows no hint of a signal
    → a signal might take long to emerge
  - source list becomes more and more important
    → look for new tracers of potential neutrino-production sites

• GRB results from IceCube
  - Combined IC40+59 limit now factor 5 below fireball predictions
    → IceCube starts to seriously constrain fireball model
  - Follow-up program very promising extension to IceCube
    → first upper limits on “slow jets” in SNe from optical follow up