Search for Neutrinos from Gamma-Ray Bursts with the ANTARES Neutrino Telescope

Julia Schmid (ECAP, Erlangen)

GRBs in the Multi-messenger Era

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ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

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Search for ν_μ from GRB: late-2007 — 2011

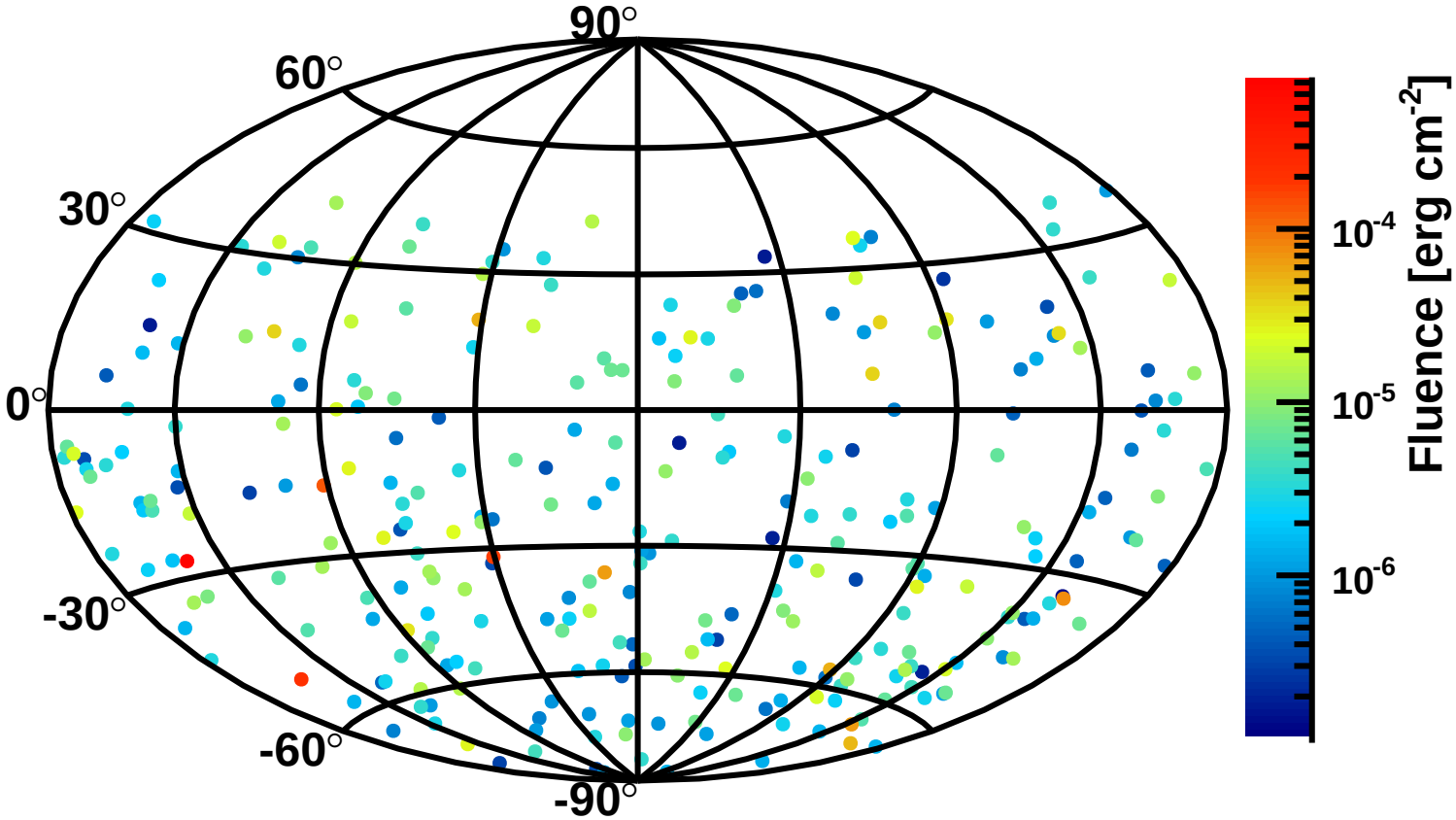
Overview:

- ANTARES data from Dec. 07, 2007 to Dec. 31, 2011
- 296 long GRBs, total $T_{\text{search}} = 6.6$ hours
- spatial Probability Density Functions (PDF):
  Background: extracted from data
  Signal: per–GRB Monte Carlo simulations

  (NeuCosmA model, Hümmer et al., 2010, $\rightarrow$ talk of M. Bustamante)
- Extended Maximum Likelihood Ratio search
- cut on reconstruction quality optimized per GRB
  $\longrightarrow$ **maximize model discovery potential $\mathcal{MDP}$ for 3σ**

$\longrightarrow$ A&A 559, A9 (2013)

Sky map of selected 296 GRBs: equatorial coordinates



Analysis in a Nutshell

background from real data $\longrightarrow \mathcal{B}(\alpha)$

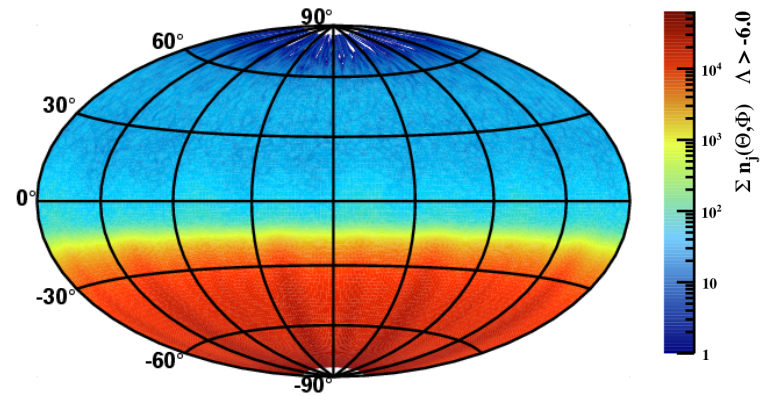
small rate of upgoing events ($\sim$ 4/day)

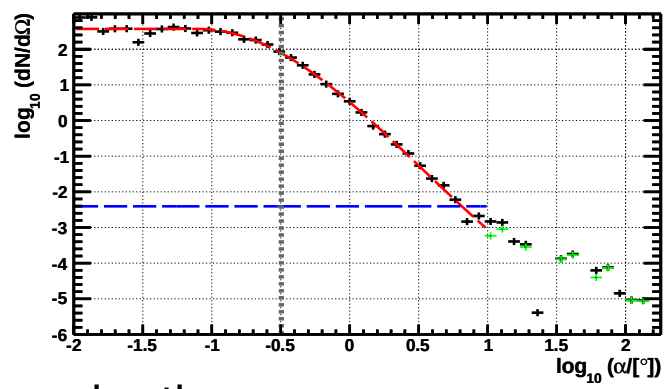
$\rightarrow$ average over whole data-taking period for GRB's coordinates Θ, Φ

$\rightarrow$ scale by time dependent factor $c(t)$ accounting for varying data-taking conditions

$$\mu_b(\Theta, \Phi) = \langle n(\Theta, \Phi) \rangle_{\text{late-07–11}} \cdot c(t)$$

simulation of GRB neutrinos $\longrightarrow \mathcal{S}(\alpha)$



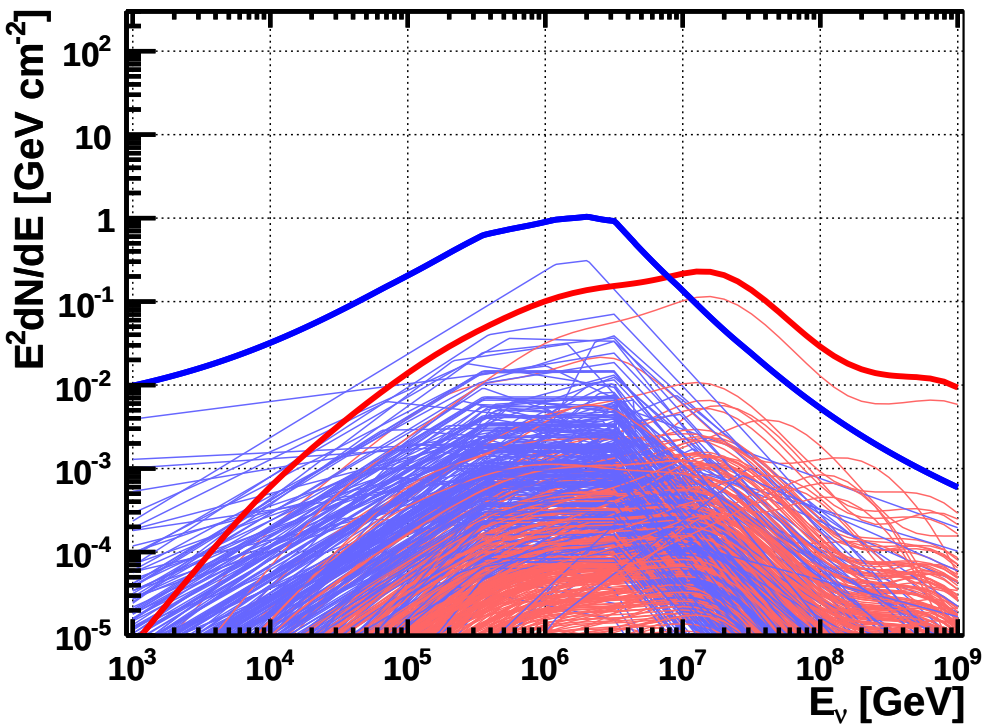


extended maximum likelihood ratio

$$Q = \max_{\mu'_s \in [0, n_{\text{tot}}]} \left(\sum_{i=1}^{n_{\text{tot}}} \log \frac{\mu'_s \cdot \mathcal{S}(\alpha) + \mu_b \cdot \mathcal{B}(\alpha)}{\mu_b \cdot \mathcal{B}(\alpha)} - (\mu'_s + \mu_b) \right)$$

Search for ν_μ from GRB: late-2007 — 2011 — Results

$\longrightarrow$ **no coincident ν_μ were found**



expected events: 0.48 (*Guetta*), 0.061 (*NeuCosmA* $\rightarrow$ talk of M. Bustamante)

$\longrightarrow$ A&A 559, A9 (2013)

Search for ν_μ from GRB: late-2007 — 2011 — Results

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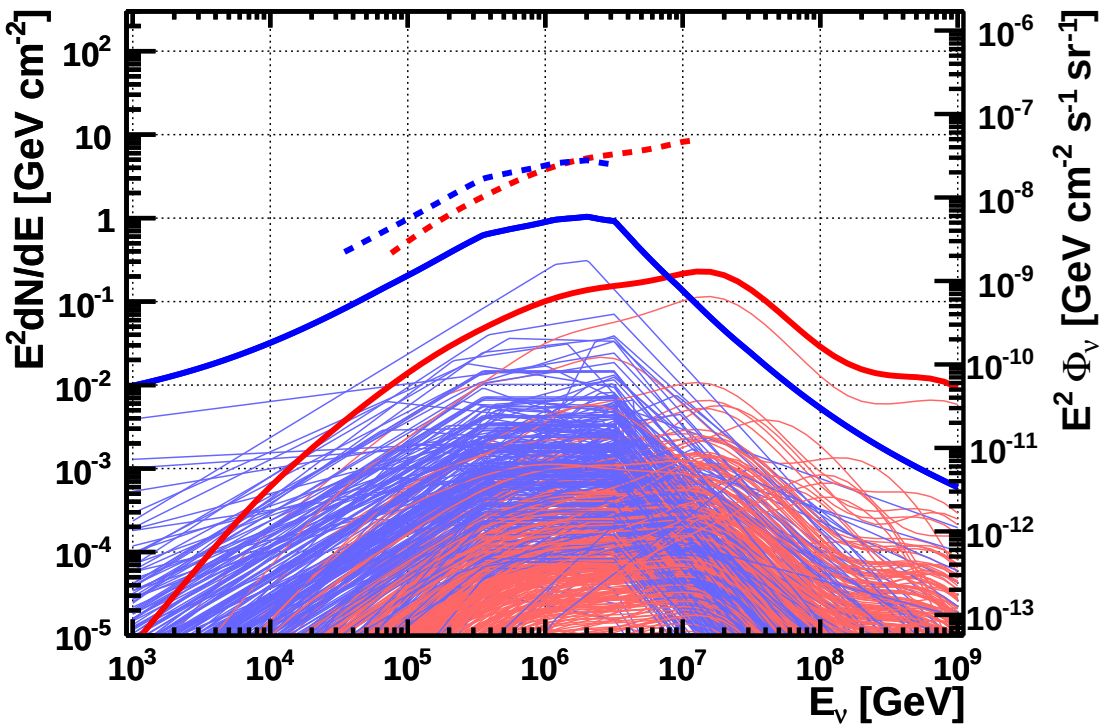

expected events: 0.48 (*Guetta*), 0.061 (*NeuCosmA* $\rightarrow$ talk of M. Bustamante) $\longrightarrow$ 90% C.L. limits (dashed)

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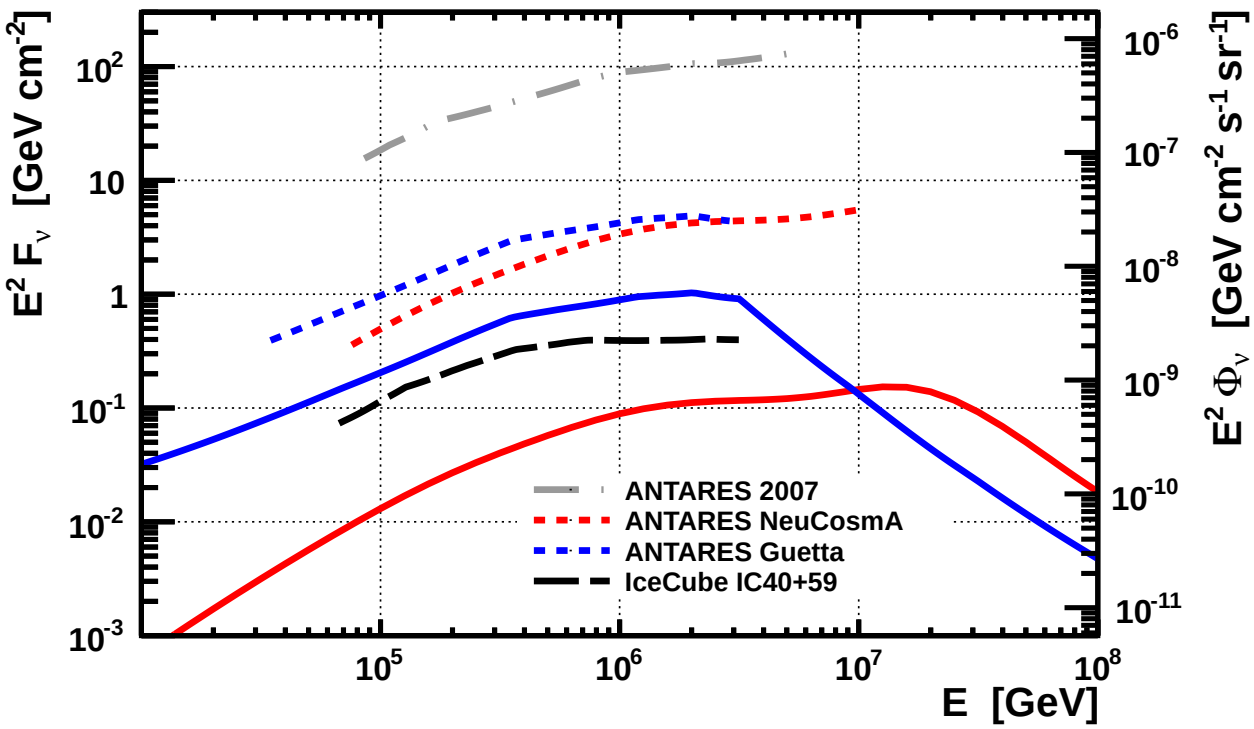
Search for ν_μ from GRB: late-2007 — 2011 — Results

$\longrightarrow$ **no coincident ν_μ were found**



expected events: 0.48 (*Guetta*), 0.061 (*NeuCosmA* $\rightarrow$ talk of M. Bustamante) $\longrightarrow$ 90% C.L. limits (dashed)
Grey: first ANTARES limit, 40 GRBs in 2007
Black: IceCube IC40+59 limit, 300 GRBs (Abbasi et al., 2012)

$\longrightarrow$ A&A 559, A9 (2013)

Dedicated search for ν_μ from GRB130427

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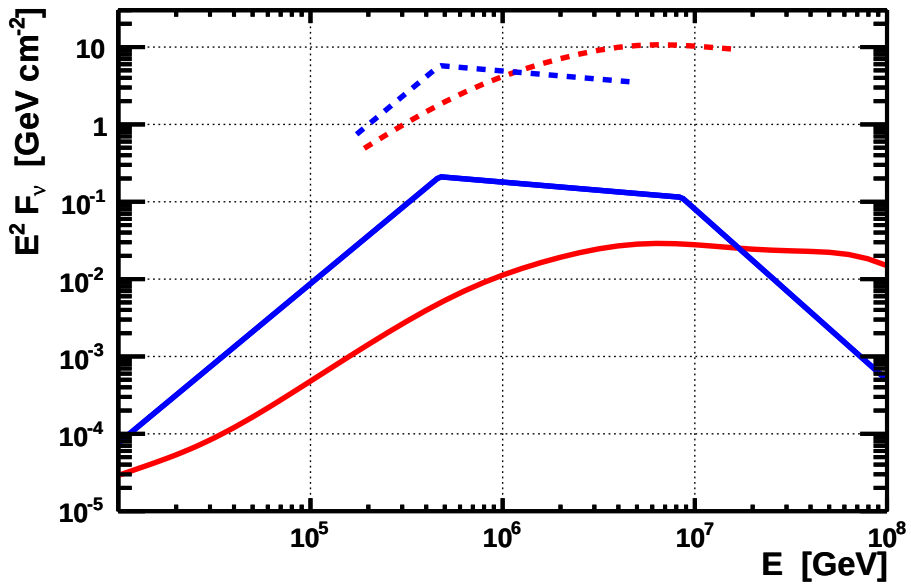
Dedicated search for ν_μ from GRB130427

$\longrightarrow$ expected signal events $6.2 \cdot 10^{-3}$ (NeuCosmA), $8.4 \cdot 10^{-2}$ (Guetta et al. (2004)) ,

$\longrightarrow$ background $1 \cdot 10^{-2}$

$\longrightarrow$ **no coincident ν_μ were found**



Stacked search for ν_μ associated with GRBs with extended Time Delays

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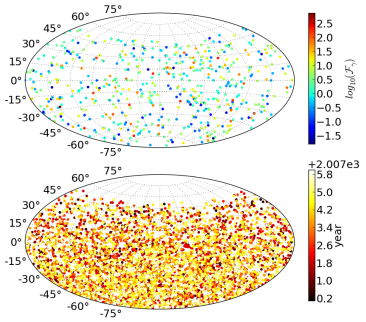
Stacked search for ν_μ associated with GRBs with extended Time Delays

Overview

- models, e.g.: neutrino precursors or afterglows of GRBs, Amelino-Camelia et al. (2013): possible delayed ν signal from GRBs due to Lorentz invariance violation (LIV) (Amelino-Camelia et al., 2013)
- GRB catalogue
- 5516 neutrino candidates from point-source search 07-12 (ANTARES Collaboration et al., 2014)

  $\rightarrow$ *search for spatial coincidences*
- collect time delay τ for each spatial coincidence

  $\rightarrow$ *investigate distribution of* τ



Analysis of time delays

for *spatial* coincident events $\longrightarrow$ create histograms of

- *generic:* time delay $\tau = t_{\nu\,\mathrm{event}} - t_{\mathrm{GRB}}$
  for $\sim 10\%$ of GRBs: redshift z known:
- *different emission times:* $\tau_z = \tau \cdot (1+z)$
- *LIV effects:*

$$\Delta t_{\mathrm{LIV}} = -(\pm 1) \cdot E / M_{\mathrm{LIV}} \cdot D(z) / c \tag{1}$$

$$\longrightarrow \quad \tau_{\mathrm{LIV}} = -\frac{\tau}{E_{\mathrm{est}} \cdot D(z)} \qquad \propto \pm \frac{E}{E_{\mathrm{est}}} \cdot \frac{1}{M_{\mathrm{LIV}} \cdot c} \tag{2}$$

$\rightarrow$ calculate *test statistics:*

- $\Psi = -10\left[\log_{10} n! + \sum_{k=1}^{m} n_k \log_{10} p_k - \log_{10} n_k!\right]$
  for τ, τ_z & τ_{LIV} ($\rightarrow$ see van Eijndhoven, 2008)
- ratio $n(\tau > 0) / n(\tau < 0)$

Pseudo Experiments: Test Statistics

for background:

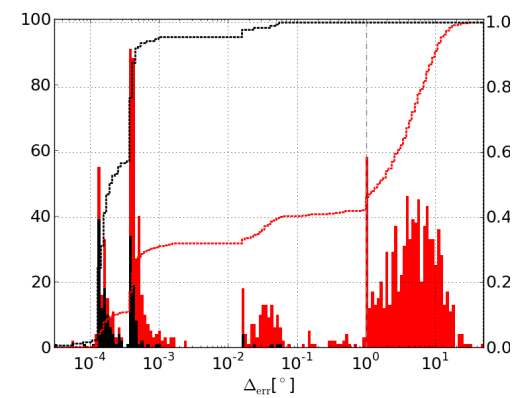
- randomize events' *right ascension & time*
- correlate GRBs and events

for signal:

- add 1 signal event at GRBs position with fixed time delay $\tau = x \cdot (1 + z)$ for a fraction of the GRBs

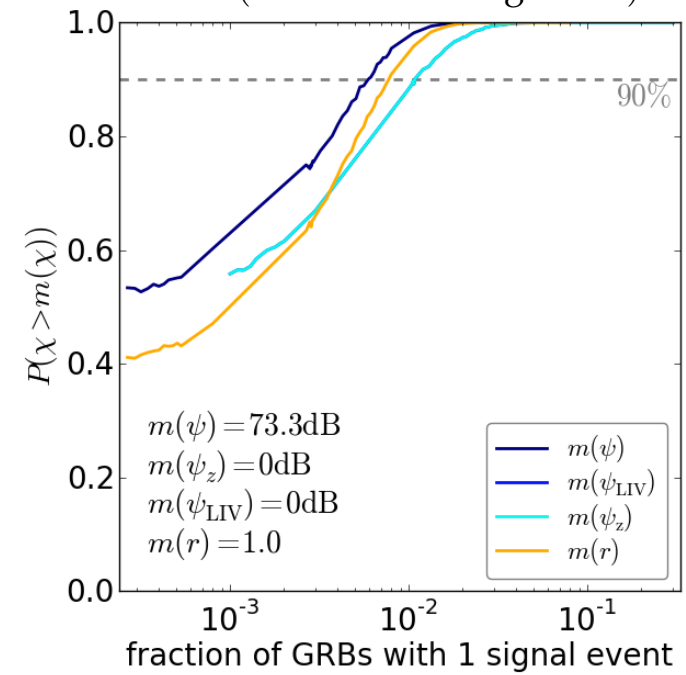
Analysis Inputs

- adjusted angular search cone δ_{max} with satellites' error boxes Δ_{err}
  minimum $\leftrightarrow$ ANTARES detector angular resolution
- maximum angular cone
  contribution of worst GRB $\leq 10\times$ contribution at minimum
  keeps almost $\sim 70\%$ of GRBs (563)
- maximum time delay τ_{max} to probe
  from maximal LIV-delay $\longrightarrow \tau_{\text{max}} = 40$d

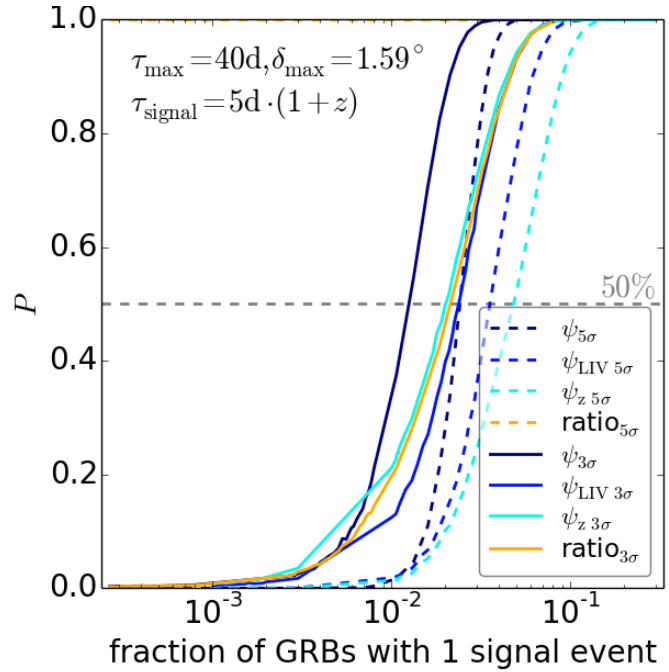


Sensitivity and Detection Power

Sensitivities: $P(>\text{median background})$



Efficiencies: $P(>\text{threshold } 3\sigma)$



With a 50% chance, we can identify a signal
in $\sim$ 1% of all GRBs at 3σ !
in $\sim$ 2% of all GRBs at 5σ!

Results

	all GRBs		GRBs /w z		
	n_{coinc}	ψ (dB)	n_{coinc}	ψ_{z} (dB)	ψ_{LIV} (dB)
median background	4.4	73.3	0.7	0	0
measurement	0	0	0	0	0
$P(\mathrm{bkg} > \mathrm{meas})$	98.7%	98.7%	48%	48.6%	48.6%

- measured under-fluctuation
- sensitivity was 0.6% of all GRBs

$P = 1.3\%$ of background!

Summary

- searches for **coincident GRB neutrinos** with ANTARES:
  full data 2007–2011 & dedicated GRB130427
- for the first time optimized for **2nd-generation numerical model**
  $\rightarrow$ **no excess over background found**
  $\rightarrow$ expected neutrinos from GRBs still **compatible with non–observation**
- search for **time-shifted neutrino signal** from GRBs (2007-2012 data)
  $\rightarrow$ no spatial coincident neutrino candidate with GRB sample in ± 40 days
  $\rightarrow$ observed **under-fluctuation wrt. background**
  with a sensitivity for a signal in 0.6% of all GRBs

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Bundesministerium
für Bildung
und Forschung

References

Search for Neutrinos from Gamma-Ray Bursts with the ANTARES Neutrino Telescope using 2008 to 2011 data: A&A 559, A9 (2013)
NeuCosmA simulations: P. Baerwald
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Swift: http://swift.gsfc.nasa.gov/docs/swift/archive/grb_table.html
GCN provided by *IceCube*: http://grbweb.icecube.wisc.edu

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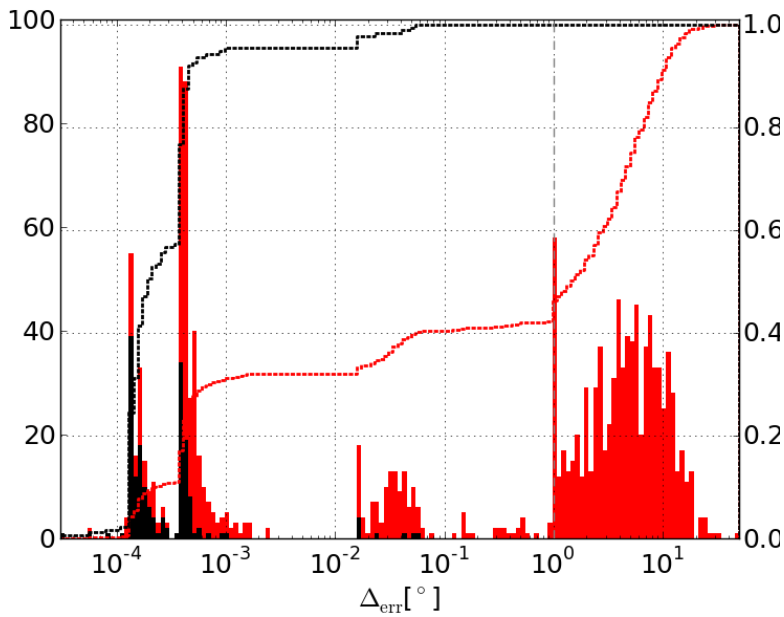
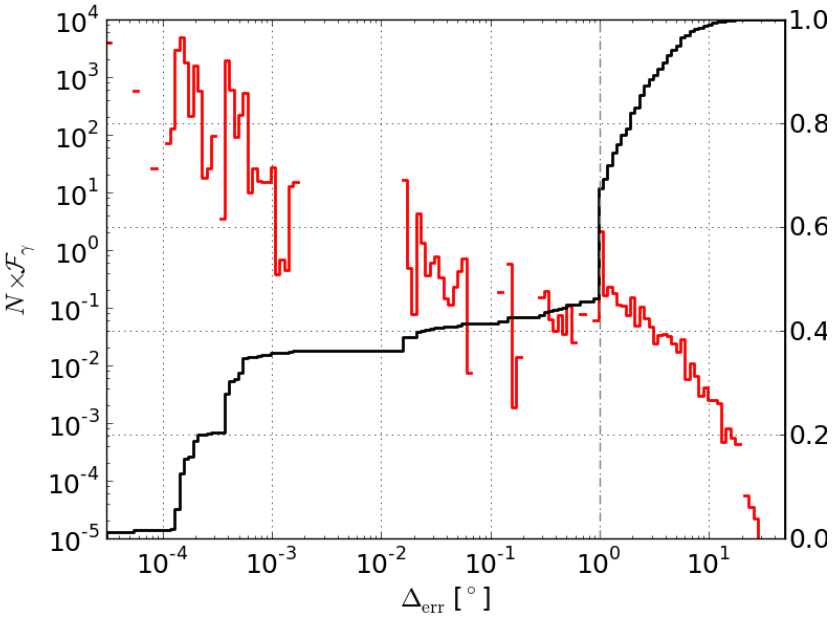
Backup

GRBs: Error Radius



red: all GRBs

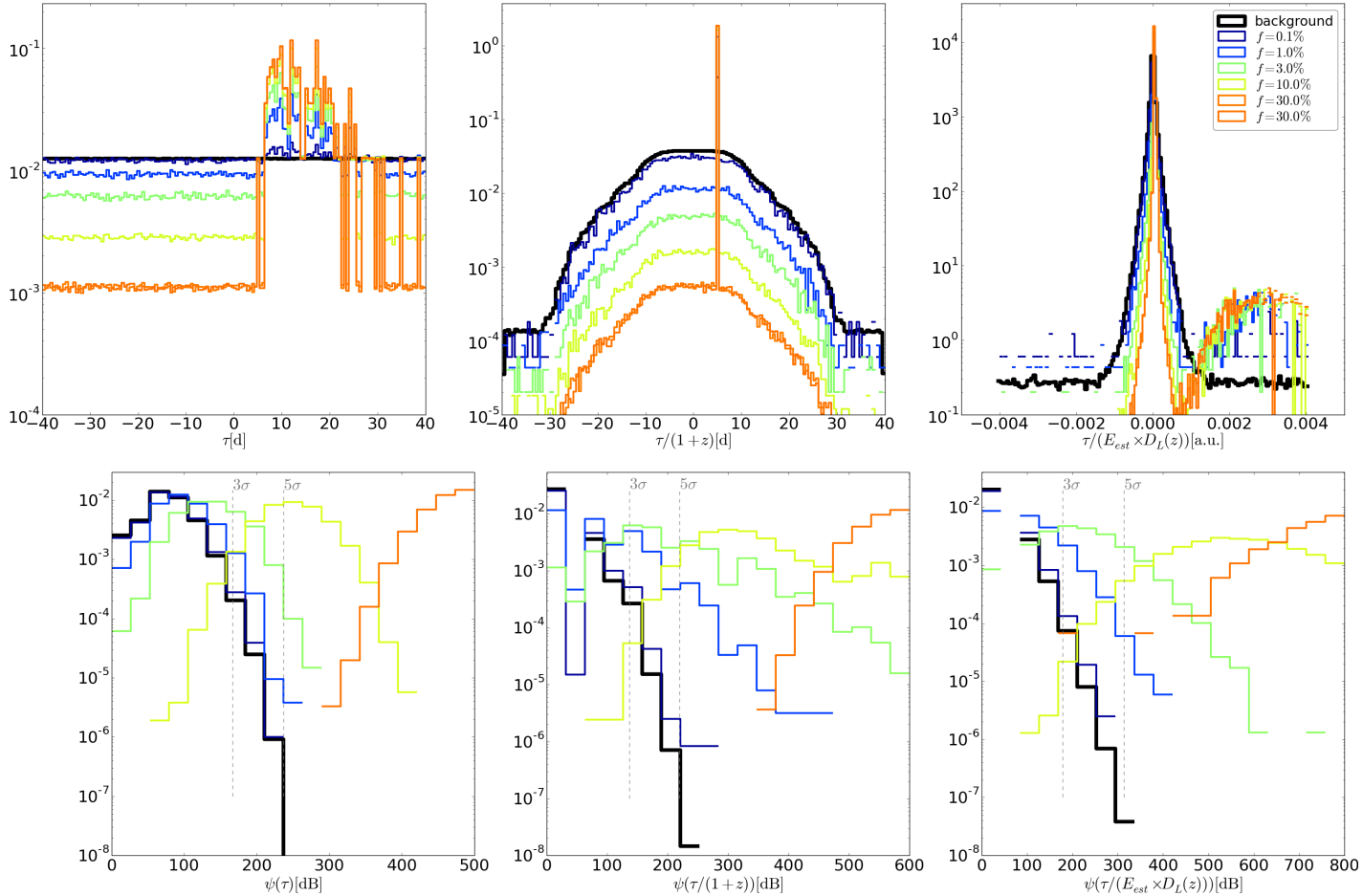
black: all GRBs w/ measured *z*



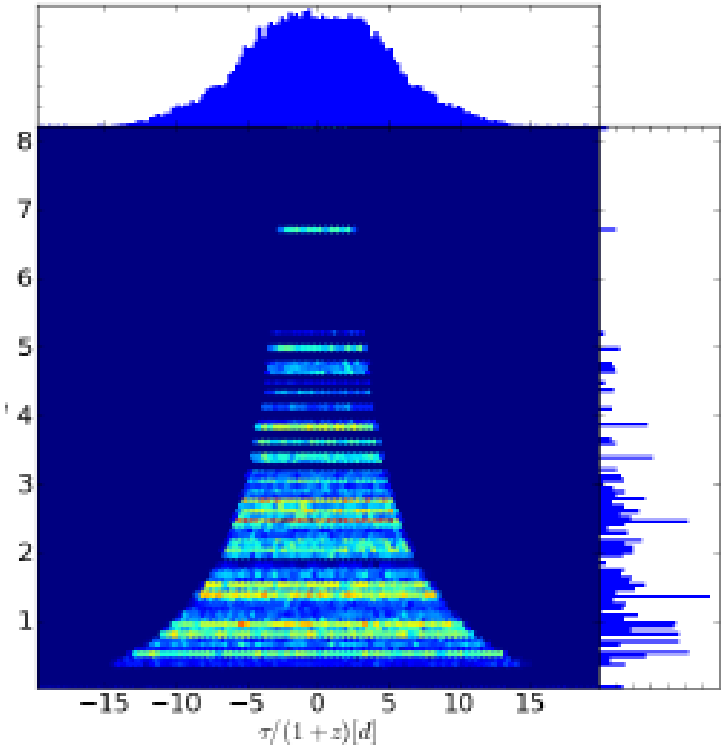
red: distribution of $N(\Delta_{\rm err}) \times F_\gamma$

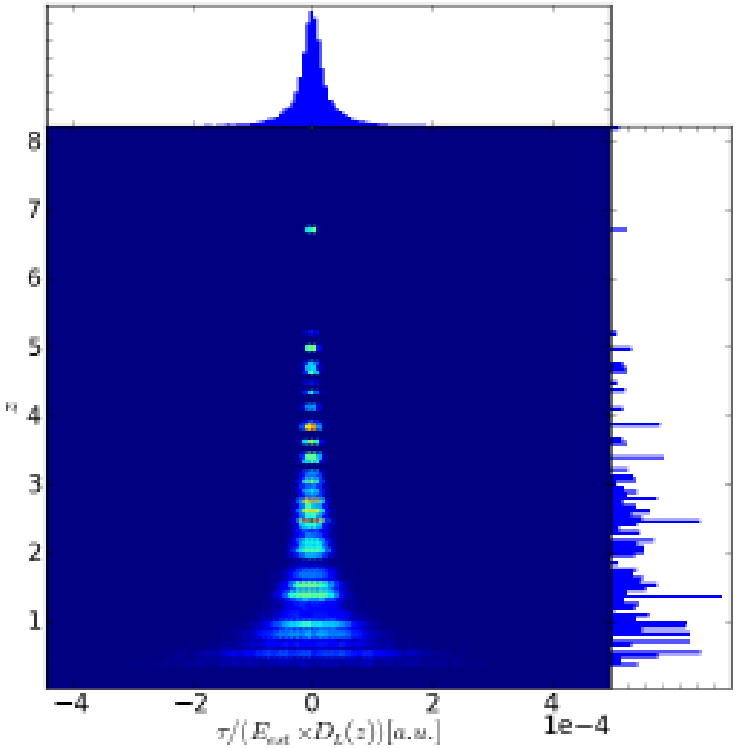
black: cumulative

Pseudo Experiments: Test Statistics

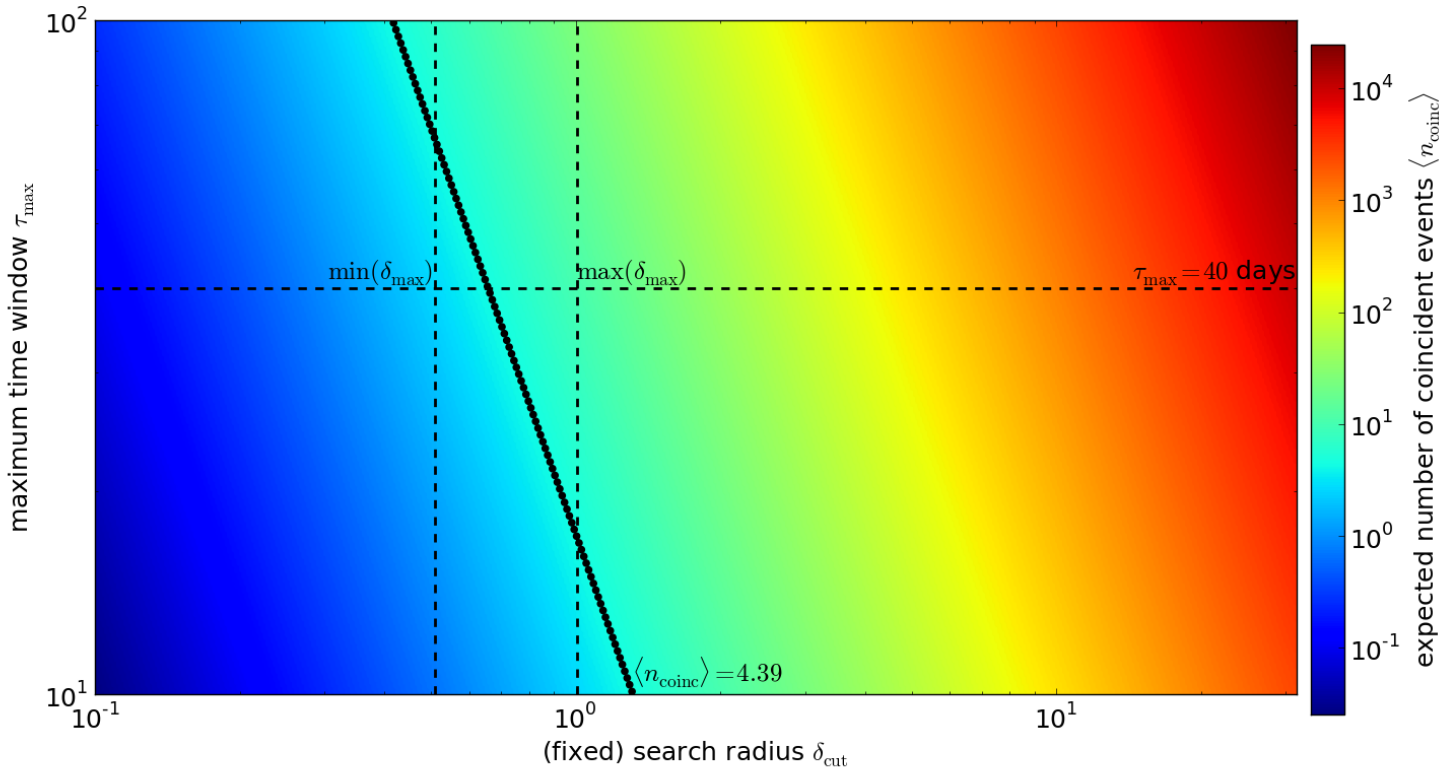


Pseudo Experiments: τ_z and τ_{LIV} vs. redshift z





Number of Coincidences – Expected



Average number of expected coincidences from randomized background

Number of Coincidences – Measured and Expected

τ_{cut} (d)	δ_{cut} (°)	n^{meas}_{coinc}	n^{exp}_{coinc}	$n^{meas}_{coinc,z}$	$n^{exp}_{coinc,z}$
40	0.4	0	1.3	0	0.4
40	0.7	0	4.4	0	1.2
40	1.0	2	10.1	0	2.7
40	2.0	32	40.6	9	10.8
40	5.0	235	253.5	59	67.5
40	10.0	981	1012.1	257	269.6
60	0.4	1	2.0	0	0.5
60	0.7	2	6.6	0	1.8
60	1.0	9	15.2	1	4.1
60	2.0	55	60.9	14	16.2
60	5.0	350	380.3	86	101.3
60	10.0	1489	1518.1	368	404.5
80	0.4	1	2.7	0	0.7
80	0.7	2	8.8	0	2.4
80	1.0	10	20.3	1	5.4
80	2.0	77	81.2	14	21.6
80	5.0	470	507.0	116	135.1
80	10.0	2028	2024.2	497	539.3
100	0.4	2	3.3	1	0.9
100	0.7	5	11.0	2	2.9
100	1.0	15	25.4	3	6.8
100	2.0	97	101.5	19	27.0
100	5.0	581	633.8	141	168.9
100	10.0	2489	2530.2	611	674.1

NB: underfluctuation in innermost $\pm$40days!

fixed δ_{cut}!

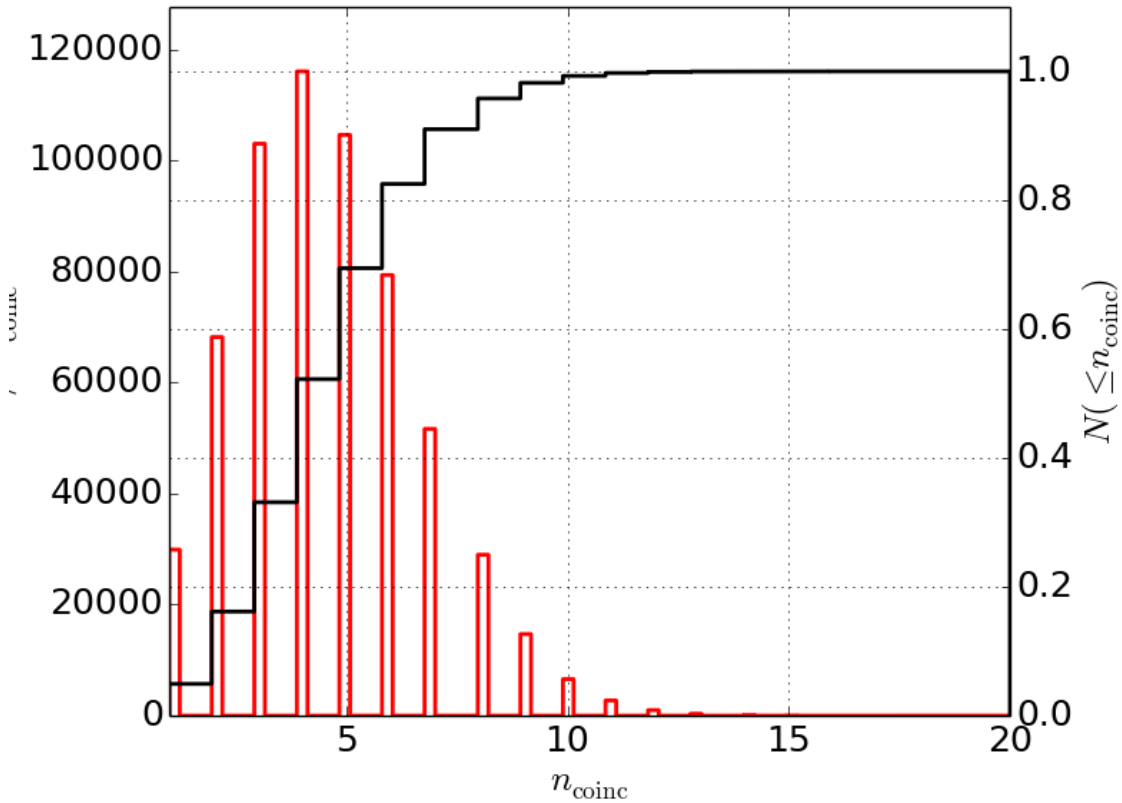
Artificially shifted GRB times

Δt_{GRB} (d)	$n_{\mathrm{coinc}}^{\mathrm{meas}}$	$n_{\mathrm{coinc}}^{\mathrm{meas},z}$
-700	1	0
-600	0	0
-500	1	0
-400	3	0
-350	2	0
-300	1	0
-250	1	0
-200	2	0
-150	1	1
-100	4	2
-50	4	1
0	0	0
50	1	1
100	1	1
150	2	1
200	0	0
250	1	1
300	2	2
350	4	1
400	4	1
500	1	1
600	0	0
700	3	0

NB: sample of GRBs not adjusted $\rightarrow$ move GRBs out of events' time windows

$\rightarrow$ less coincidences expected!

Number of coincidences for background-only PEs



Expected Number of GRB Neutrinos for KM3Net

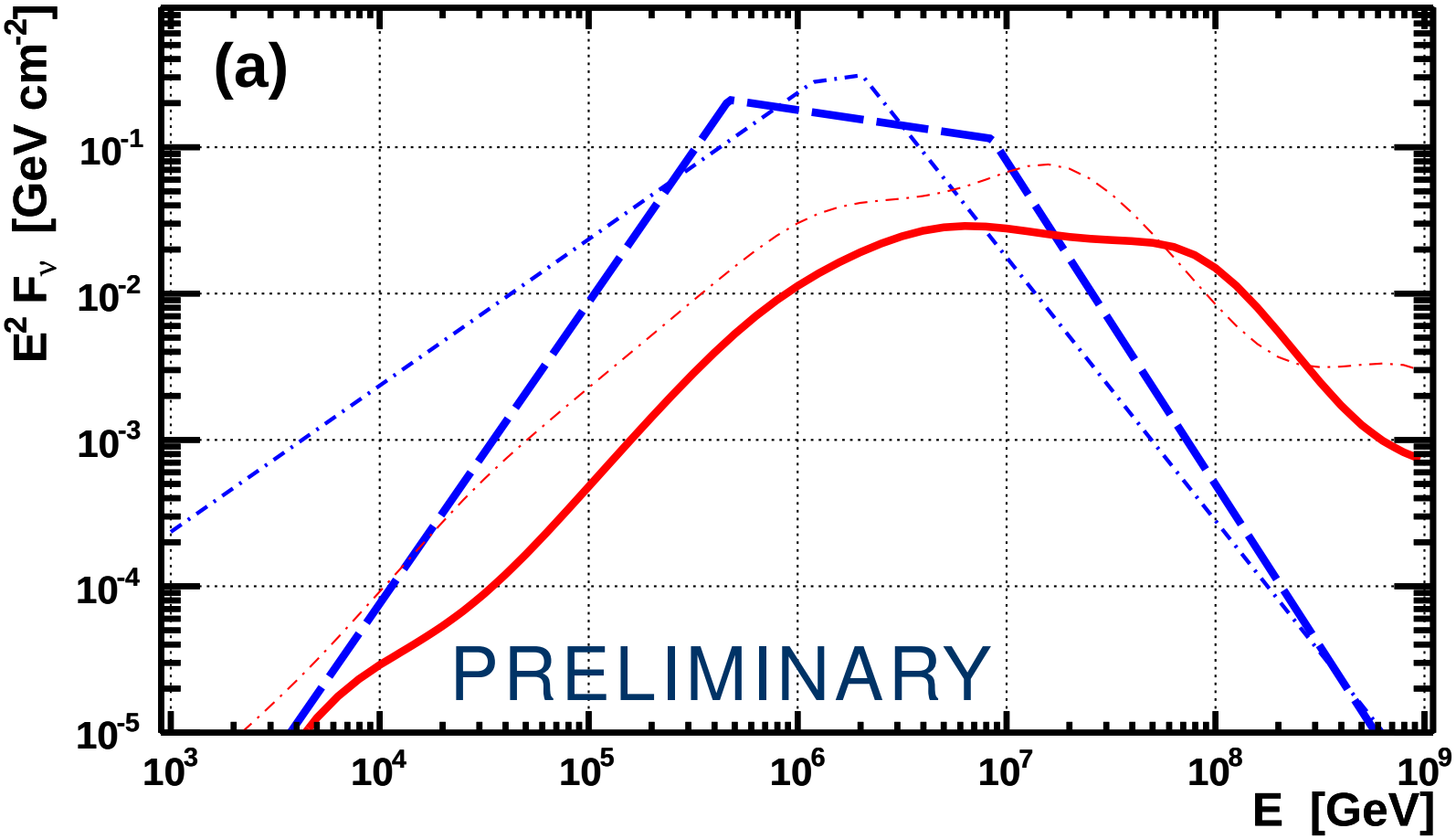
GRB	$\mathcal{F}_\gamma$ (10^{-6} erg/ cm^2)	T_{search} (s)	μ_s^{NeuCosmA}	μ_s^{Guetta}
11091889	750	73.376	1.0	6.1
all 296 GRBs late-07–10	3254.3	23785.7	3.4	36
13110886	36.5	23	0.2	0.7
13042732	2462	264.5	0.41	5.5

GRB Parameters for GRB130427

$ra = 173.14^\circ$	$dec = 27.70^\circ$	$\Delta_{\mathrm{err}} = 1\mathrm{arcsec}$
$\Theta = 108.31^\circ$	$\Phi = 101.66^\circ$	07:47:06 $\mathrm{UT}_{\mathrm{trigger}}$
$T_{90} = 138.242\,\mathrm{s}$	$T_{\mathrm{search}} = 264.5\,\mathrm{s}$	$z = 0.3399$
$\mathcal{F} = 0.002462\,\mathrm{erg\,cm^{-2}}$	$E_{\mathrm{min}} = 0.01\,\mathrm{MeV}$	$E_{\mathrm{max}} = 1\,\mathrm{MeV}$
$\alpha = 0.789$	$\beta = 3.06$	$E_{\mathrm{peak}} = 830\,\mathrm{keV}$

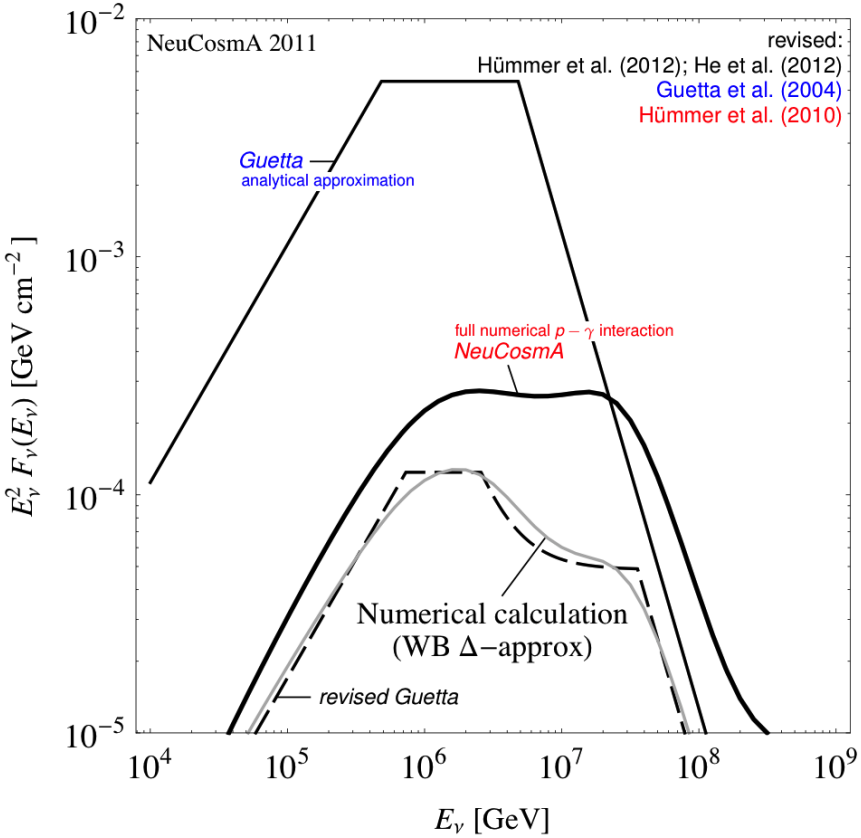
- coordinates: GCN 14450
  http://gcn.gsfc.nasa.gov/gcn3/14450.gcn3
- spectrum: Fermi GBM Catalog
  http://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html
- all GCN: http://gcn.gsfc.nasa.gov/other/130427A.gcn3
- IceCube non–detection: GCN 14520
  http://gcn.gsfc.nasa.gov/gcn3/14520.gcn3

GRB130427 vs. GRB110918 ν spectra



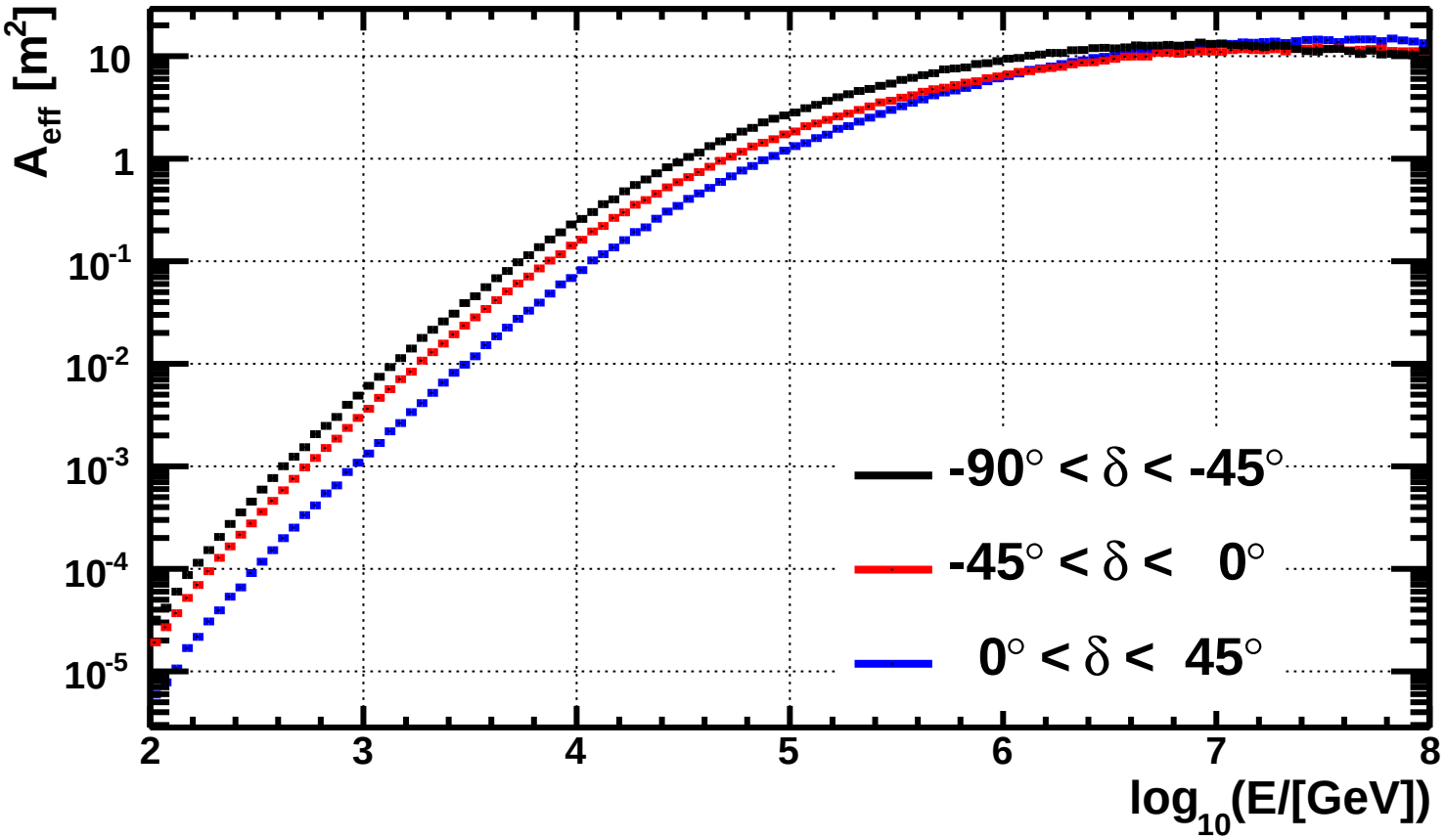
thick lines: GRB130427, thin lines: GRB110918

GRB models: Comparison



Guetta: Δ approximation, γ at break energy
Revised: full γ distribution, full Δ width, E loss of secondaries, E dependency of p mean free path, still Δ approximation
NeuCosmA: Monte Carlo simulations based on SOPHIA, full p–γ cross section, multi–π and K^+ production

Effective Area for muon neutrinos, late-2007 — 2011



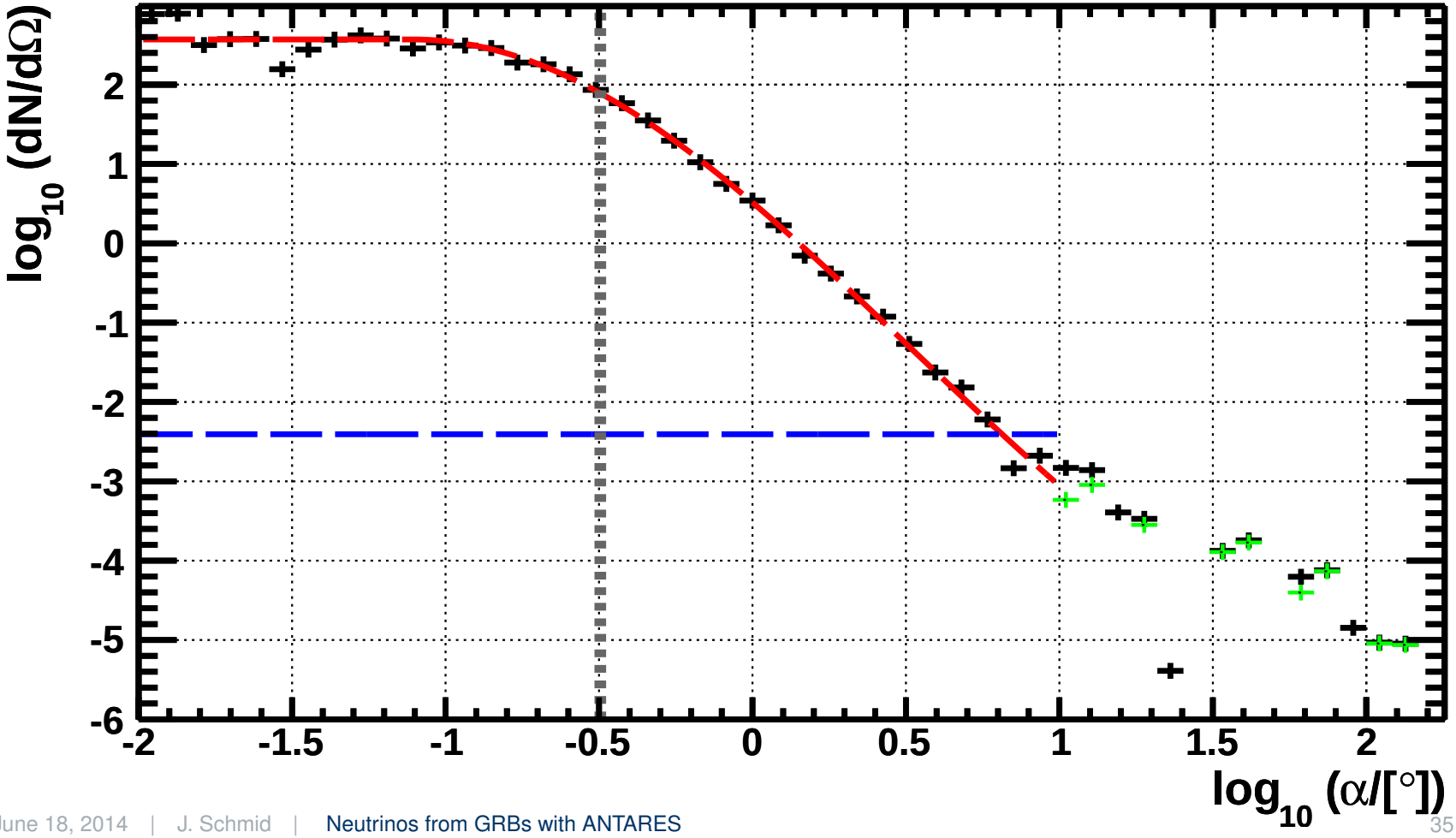
Background Calculation

$$\mu_b(\Theta, \Phi) = \langle \mu(\Theta, \Phi) \rangle_{\text{all runs}} \cdot c_i \cdot c_{\text{period}} \cdot 1.5$$

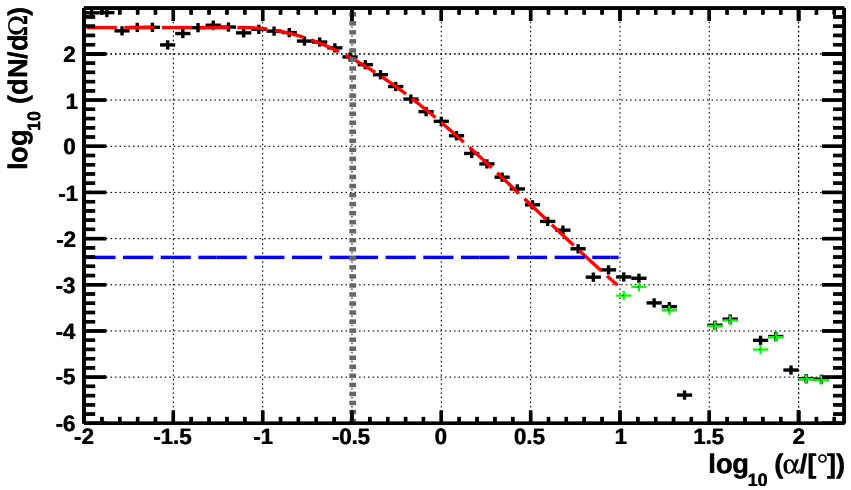
$$\text{with } c_i = \frac{[n_i]^{90\%}}{t_i} \frac{\sum_j t_j}{\sum_j n_j}$$

- $\langle \mu(\Theta, \Phi) \rangle_{\text{all runs}}$: average event rate
  max of average and central value of 10° cone around GRB position (Θ, Φ)
- c_i: correction factor for run i: ratio of event rate (all directions) in this run (i) to average event rate for all runs.
- c_{period}: correction for long periods with stable conditions $\sim 2 \ldots 3$ months
- 1.5: width of $n_{\text{est}} / n_{\text{meas}}$

Signal & Background PDFs (GRB110918)



Signal PDF fit



$$\log \frac{\mathrm{d}N(\delta)}{\mathrm{d}\Omega} = \begin{cases} A, & \text{if } \log\delta \leqslant \log\delta_0 \\ A - B \cdot \left(1 - \exp\left(\frac{-(\log\delta - \log\delta_0)^2}{2\sigma^2}\right)\right) & \text{if } \log\delta > \log\delta_0 \end{cases}$$

$$\mathcal{S}(\delta) = \frac{\mathrm{d}N(\delta)}{\mathrm{d}\delta} = \frac{\mathrm{d}\Omega}{\mathrm{d}\delta} \cdot \frac{\mathrm{d}N(\delta)}{\mathrm{d}\Omega} = 2\pi \sin(\delta) \cdot \frac{\mathrm{d}N(\delta)}{\mathrm{d}\Omega}$$

GRB Parameter Catalogue: late-2007 – 2011

condensated from

- *Fermi*[1]: best photon spectrum
- *Swift*[2]: best localization
- *grbweb*[3]: fill up missing parameters (Aguilar, 2011)

Default parameters:

$\alpha = 1$	$\beta = \alpha + 1$	$\epsilon_{\text{peak}} = 200\,\text{keV}$
$z = 2.15$	$L_{\text{iso}} = 10^{52}\,\text{erg/s}$	
$\Gamma = 316$	$\epsilon_e = 0.1$	$\epsilon_B = 0.1$
$f_e = 0.1$	$\langle x_{p\to\pi} \rangle = 0.2$	$t_{\text{var}} = 0.01\,\text{s}$

same as in Aguilar (2011)

[1] http://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html
[2] http://swift.gsfc.nasa.gov/docs/swift/archive/grb_table.html
[3] http://grbweb.icecube.wisc.edu

Selection of Gamma Ray Bursts: late-2007 – 2011

	(exclusion percentage)
• either spectrum or fluence measured	(3%)
• duration given	(2%)
• long GRBs	(15%)
• below ANTARES horizon	(47%)
• ANTARES taking physics data	(29%)
• whole GRB in data taking run & stable conditions	(19%)

1108 GRBs in total $\longrightarrow$ 296 GRBs in selected sample, $\sim$ 27%.

Model Discovery Probability

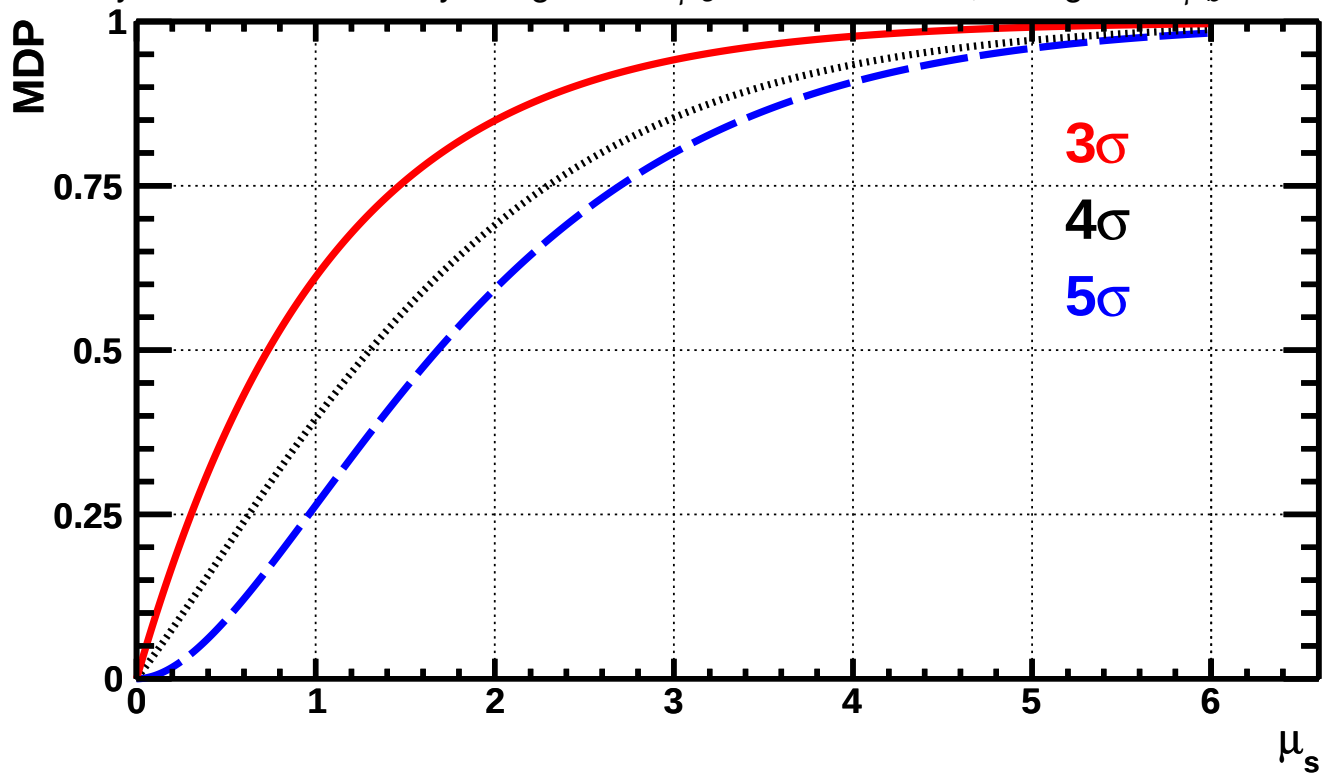
$$\mathcal{MDP} \equiv \sum_{n_s=0}^{\infty} \mathcal{P}(n_s|\mu_s) \cdot \int_{Q_p^{\text{thres}}}^{\infty} h_{n_s}(Q)$$

- n_s: injected signal events in pseudo experiment
- $\mathcal{P}(n_s|\mu_s)$: Poisson distribution for signal rate μ_s
- $h_{n_s}(Q)$: Distribution of Q–values for given n_s
- Q_p^{thres}: threshold value of Q for given significance

maximum of $\mathcal{MDP} \longrightarrow$ optimal quality cut

Results of Pseudo Experiments

probability to make a discovery at signal rate μ_s for GRB110918, background $\hat{\mu}_b = 3.7 \cdot 10^{-4}$



Reconstruction Quality Λ

$$\Lambda = \frac{\log \mathcal{L}_{\text{max}}}{N_{\text{hits}} - 5} + 0.1 \cdot (N_{\text{comp}} - 1) \tag{3}$$

with the maximum likelihood value $\mathcal{L}_{\text{max}}$
$N_{\text{hits}} - 5$: number of degrees of freedom of the fit
N_{comp}: how often the fit converged to the same track result

Final Analysis Parameters

Optimization results for the 10 most promising GRBs

GRB	Λ_{cut}	μ_{b}	$\mu_{\mathrm{s}}^{\mathrm{NeuCosmA}}$	$\mu_{\mathrm{s}}^{\mathrm{Guetta}}$	$\langle\alpha\rangle$ (°)	T_{search} (s)	σ_{tot}
11091889	-5.5	$3.7\cdot10^{-4}$	$3.5\cdot10^{-2}$	$1.7\cdot10^{-1}$	0.32	73.4	
08060725	-5.4	$5.5\cdot10^{-4}$	$6.5\cdot10^{-3}$	$1.4\cdot10^{-2}$	0.33	164.3	
11100892	-5.5	$3.6\cdot10^{-4}$	$2.2\cdot10^{-3}$	$2.6\cdot10^{-3}$	0.35	75.4	
10101417	-5.1	$4.1\cdot10^{-4}$	$1.2\cdot10^{-3}$	$1.7\cdot10^{-2}$	0.89	723.1	
10072809	-5.6	$2.0\cdot10^{-4}$	$9.6\cdot10^{-4}$	$1.4\cdot10^{-2}$	0.49	268.6	
09020174	-5.4	$5.4\cdot10^{-4}$	$7.0\cdot10^{-4}$	$2.4\cdot10^{-2}$	0.39	126.6	
11122048	-5.2	$1.4\cdot10^{-4}$	$6.2\cdot10^{-4}$	$1.2\cdot10^{-2}$	1.13	66.5	
09082967	-5.4	$1.7\cdot10^{-4}$	$3.9\cdot10^{-4}$	$5.7\cdot10^{-3}$	1.02	112.1	
11062215	-5.4	$1.7\cdot10^{-4}$	$4.3\cdot10^{-4}$	$9.5\cdot10^{-3}$	1.42	116.6	
08100914	-5.5	$1.3\cdot10^{-4}$	$3.5\cdot10^{-4}$	$1.9\cdot10^{-3}$	0.94	70.2	
all GRBs:							3σ
mean	-5.4	$1.7\cdot10^{-4}$	$2.0\cdot10^{-4}$	$1.6\cdot10^{-3}$	2.85	80.4	
sum		$5.1\cdot10^{-2}$	$6.1\cdot10^{-2}$	$4.8\cdot10^{-1}$		$2.4\cdot10^{4}$	

fixed $\beta \leq 1°$, reconstructed events $\leq 10°$ from GRB's coordinates

Analysis in Numbers: late-2007 – 2011

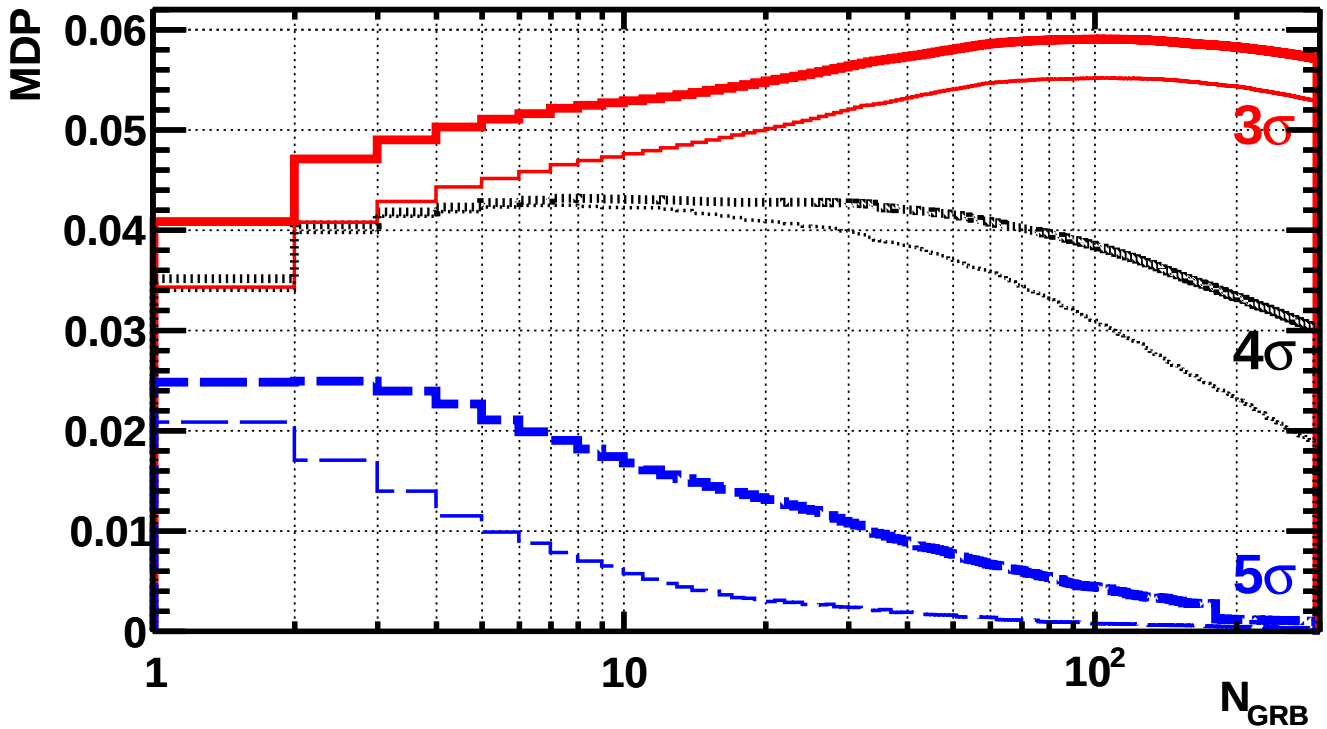
- Search radius $\delta_{\text{max}} = 10^{\circ}$

Simulations

Signal $\mathcal{S}(\delta)$
$4 \cdot 10^9$ ν_μ tracks
150 shower events

pseudo experiments
$1.1 \cdot 10^{10}$ background PEs
10^5 PEs for each n_s

Check for optimal Subsample N_{GRB}: late-2007 – 2011



thick: extended maximum likelihood method,
thin: binned analysis with fixed cuts $\Lambda > -5.5$, $\beta < 1^\circ$.