Search for Neutrinos from Gamma-Ray Bursts with ANTARES

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for the ANTARES Collaboration
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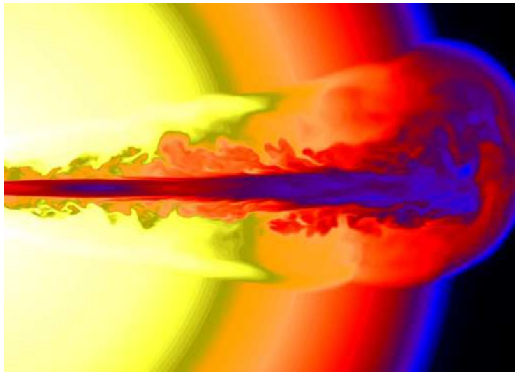
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
NATURWISSENSCHAFTLICHE FAKULTÄT

Why Gamma Ray Bursts?

Gamma Ray Bursts

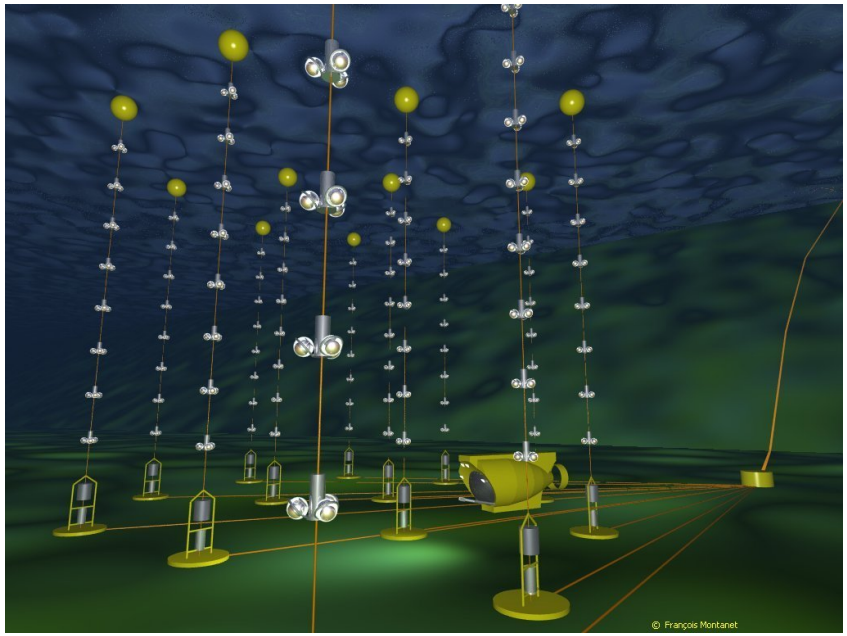
- intense flashes of γ radiation
- 2 classes: short ($\lesssim$2s) & **long** ($\gtrsim$2s) GRBs
- fast rotating Wolf-Rayet stars $\rightarrow$SN 1 b/c $\rightarrow$jet $\rightarrow$shock fronts
- Fermi-accelerated e^- $\rightarrow$Synchroton & inverse Compton $\rightarrow\gamma$–Rays
- may **also accelerate** p^+ in shocks $\rightarrow$**neutrino signal**
  $p^+ + \gamma \rightsquigarrow \pi^+ \longrightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \overline{\nu}_\mu + \nu_\mu$
- Short & defined position $\rightarrow$ **low background**

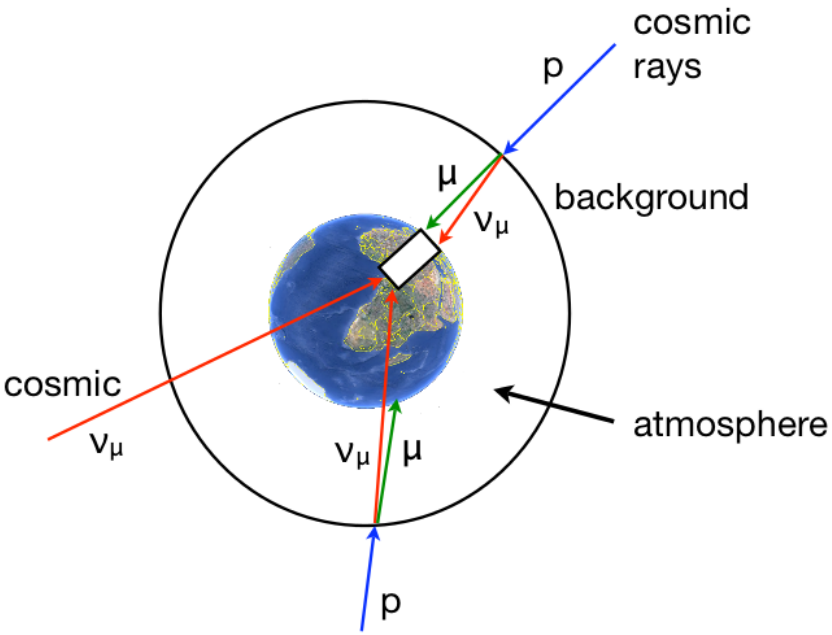


unambiguous proof of hadronic acceleration

GRB $\longleftrightarrow$ UHECR?

Reminder: The ANTARES detector





12 lines with 885 photo multiplier tubes, taking data since 2007

ANTARES overview → see talk of T. Eberl

First search for ν_μ from GRBs: 2007

- ANTARES construction phase:
  5 detection lines
  January 27 to December 7, 2007
- 40 long GRBs, total $T_{\text{search}} = 0.5$ hours
- binned search:
  $T_{\text{search}} = T_{90} \pm 5\%$
  reconstructed events $\leq 2^\circ$ around GRB
  fixed reconstruction quality cuts $\beta \leq 1^\circ$ & $\Lambda \geq -5.5$

$\rightarrow$ expected **Background:** $1.24 \cdot 10^{-4}$ events

$\rightarrow$ expected **Signal:** $1.7 \cdot 10^{-3}$ events

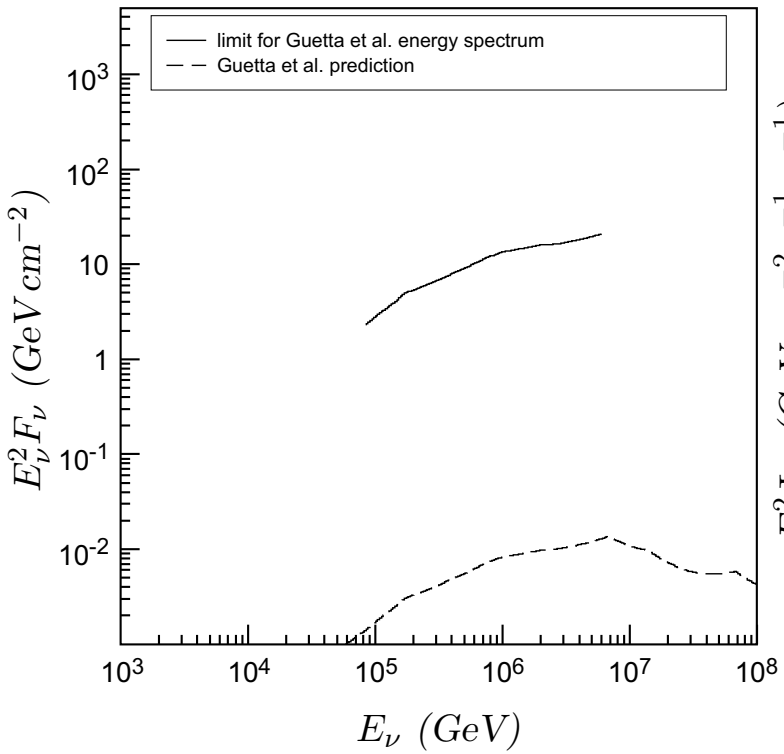
(analytical model by Guetta et al., 2004)

$\longrightarrow$**no coincident ν_μ event found!**

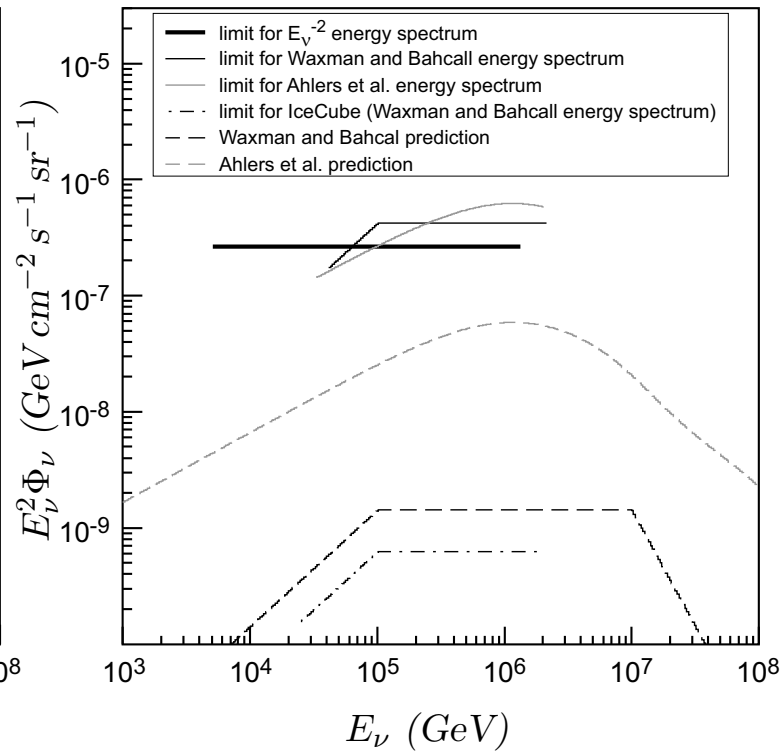
(Adrián-Martínez et al., 2013a, JCAP03(2013)006)

First search for ν_μ from GRBs: 2007

limit on Guetta et al. (2004) model



quasi–diffuse limit



(Adrián-Martínez et al., 2013a, JCAP03(2013)006)

Search for ν_μ from GRB: late-2007 — 2011

Overview:

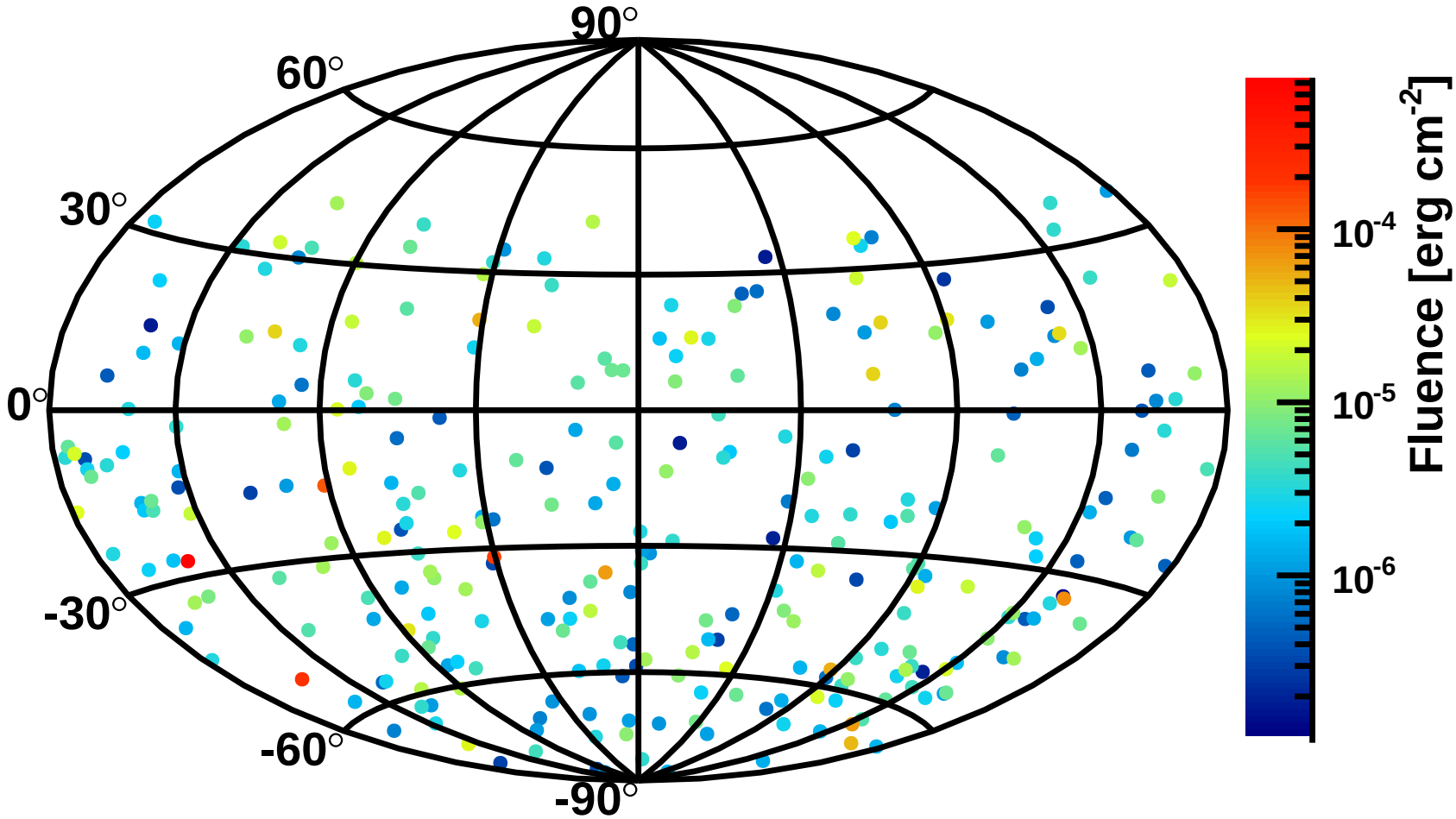
- 9 – 12 detection lines
  December 07, 2007 to December 31, 2011
- 296 long GRBs, total $T_{\text{search}} = 6.6$ hours
- parameters from *Fermi*, *Swift* & *grbweb* (Aguilar, 2011)
- **Signal**: per–GRB Monte Carlo simulations

(NeuCosmA model, Hümmer et al., 2010)

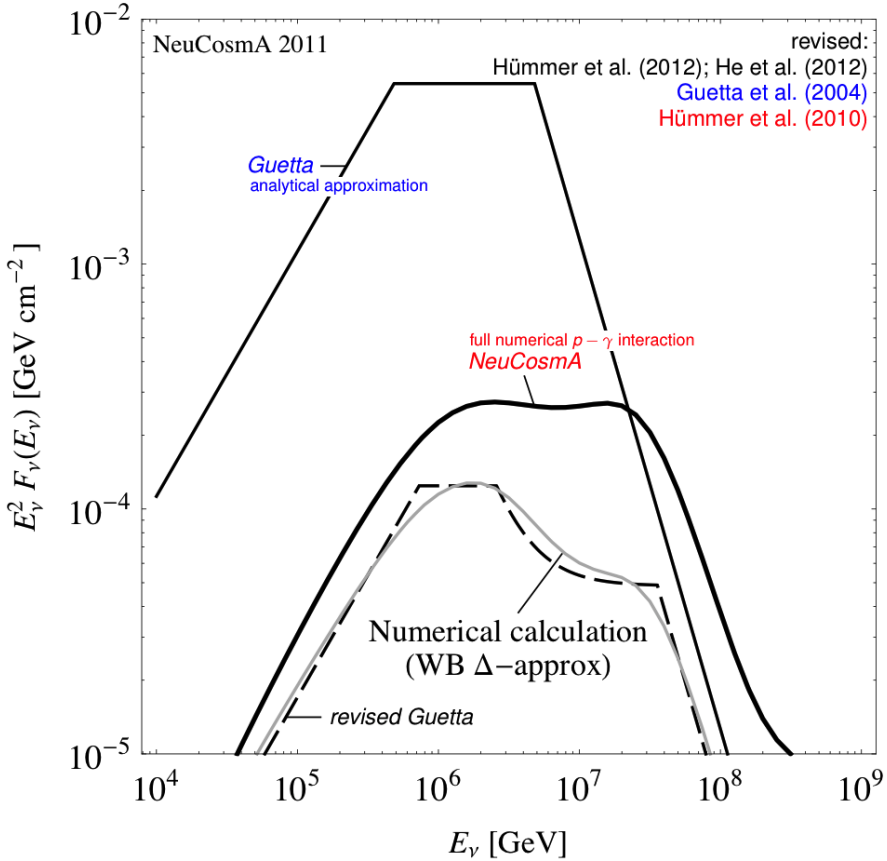
- **Background**: extracted from data
- Extended Maximum Likelihood search
- reconstruction quality cut Λ optimised per GRB
  $\longrightarrow$ **maximise model discovery potential** $\mathcal{MDP}$

(Adrián-Martínez et al., 2013b, arXiv:1307.0304, *submitted to A&A*)

Sky map of selected 296 GRBs



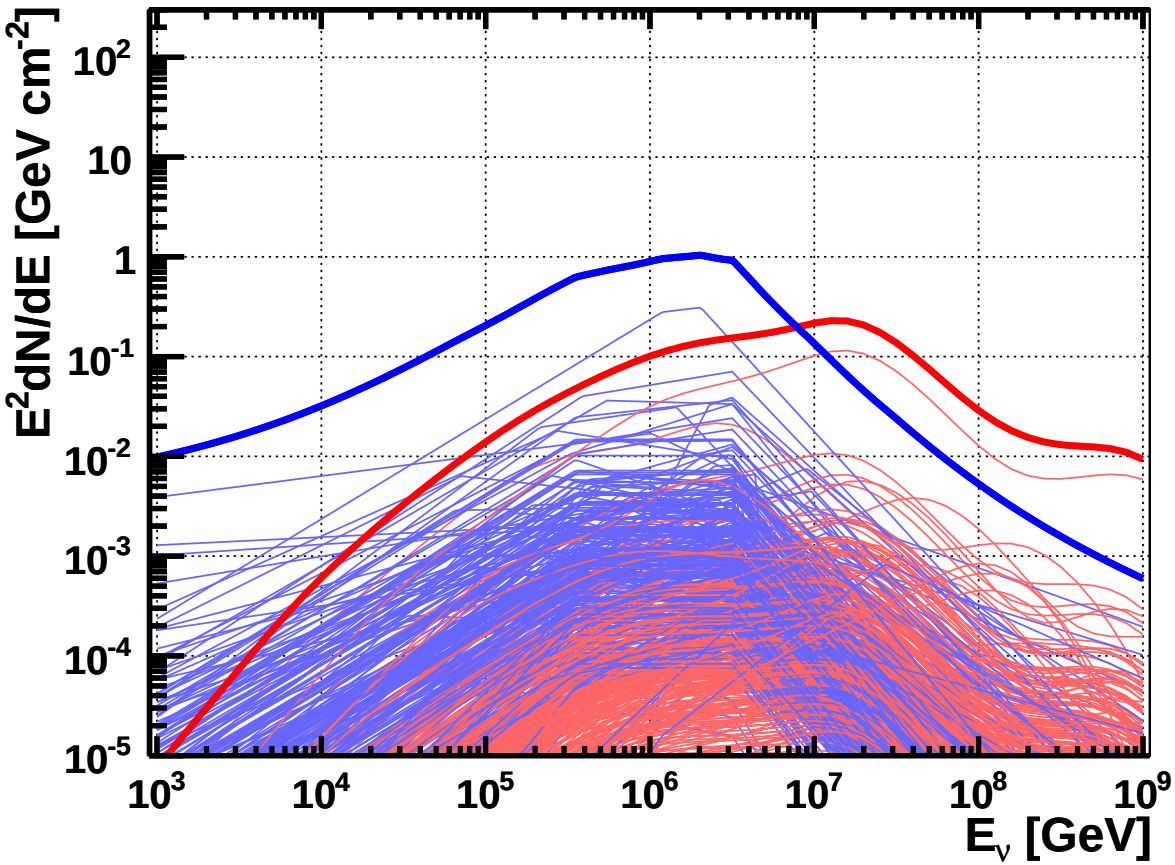
Neutrino Emission from Gamma-Ray Bursts: Models



Hümmer et al. (2012)

⟶see talk of M. Bustamante

Expected Neutrino Fluences

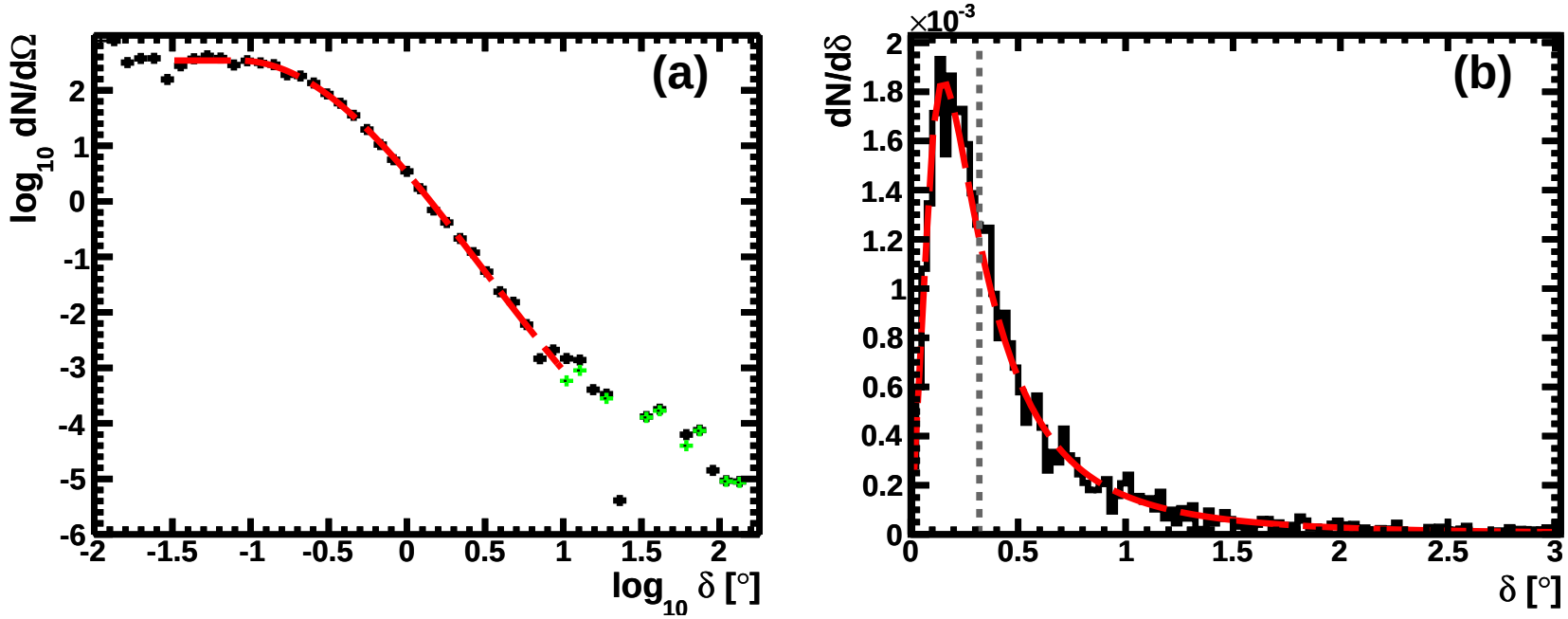


NeuCosmA and *Guetta* spectra

thick: sum of the 296 individual spectra

Generation of Signal Distribution

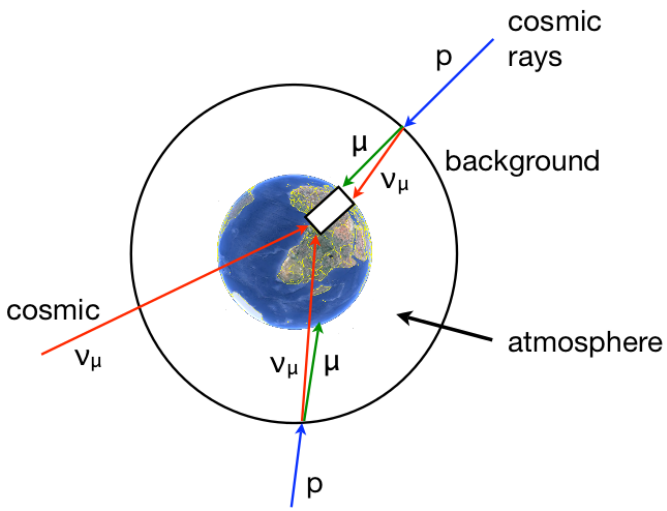
Monte Carlo Simulation $\rightarrow$ Reconstruction
$\rightarrow$ Point Spread Function $\mathcal{S}(\delta) = \mathrm{d}N/\mathrm{d}\delta$



$\longrightarrow$ median angular resolution: 0.32°
$\longrightarrow$ expected number of events: 0.035

Background estimation from Data

small rate of upgoing events ($\sim$ 4/day)
$\rightarrow$ average over late-2007 – 2011
for GRB's coordinates Θ, Φ
$\rightarrow$ scale by $c(t)$



$$\mu_b(\Theta, \Phi) = \langle n(\Theta, \Phi) \rangle_{\text{late-07–11}} \cdot c(t)$$
$$\longrightarrow \mathcal{B}(\delta) = \mu_b \cdot 2\pi \sin(\delta)$$

background components: atmospheric ν and misreconstructed atmospheric μ from Cosmic Rays

Extended Maximum Likelihood

- Pseudo–Experiments (*PE*) generated
  from background distribution $\mathcal{B}(\delta)$
  with $n_s = 1, 2, 3, \ldots$ signal events injected from $\mathcal{S}(\delta)$
- test function

$$Q = \max_{\mu_s \in [0, n_{\text{tot}}]} \sum_{i=1}^{n_{\text{tot}}} \log \frac{\mu_s \cdot \mathcal{S}(\delta_i) + \hat{\mu}_b \cdot \mathcal{B}(\delta_i)}{\hat{\mu}_b \cdot \mathcal{B}(\delta_i)} - (\mu_s + \hat{\mu}_b)$$

  a priori knowledge of background rate $\hat{\mu}_{\text{b}}$

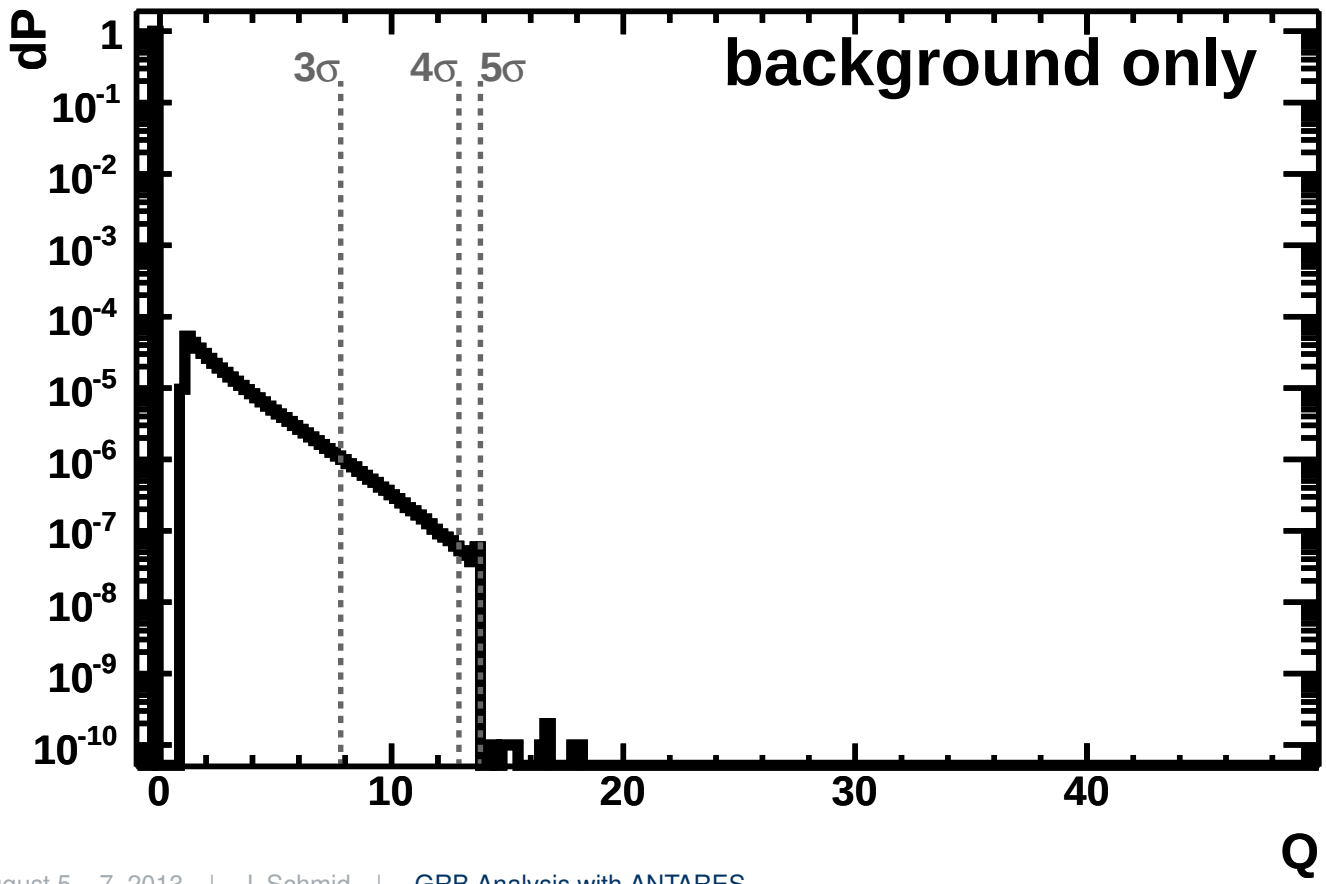
$\rightarrow$ calculate Q for each *PE*

$\rightarrow$ model discovery potential $\mathcal{MDP}$ for each Λ_{cut}

$\Rightarrow$ find optimal quality cut Λ_{cut}

Results of Pseudo Experiments

probability distributions of Q for GRB110918, background $\hat{\mu}_b = 3.7 \cdot 10^{-4}$



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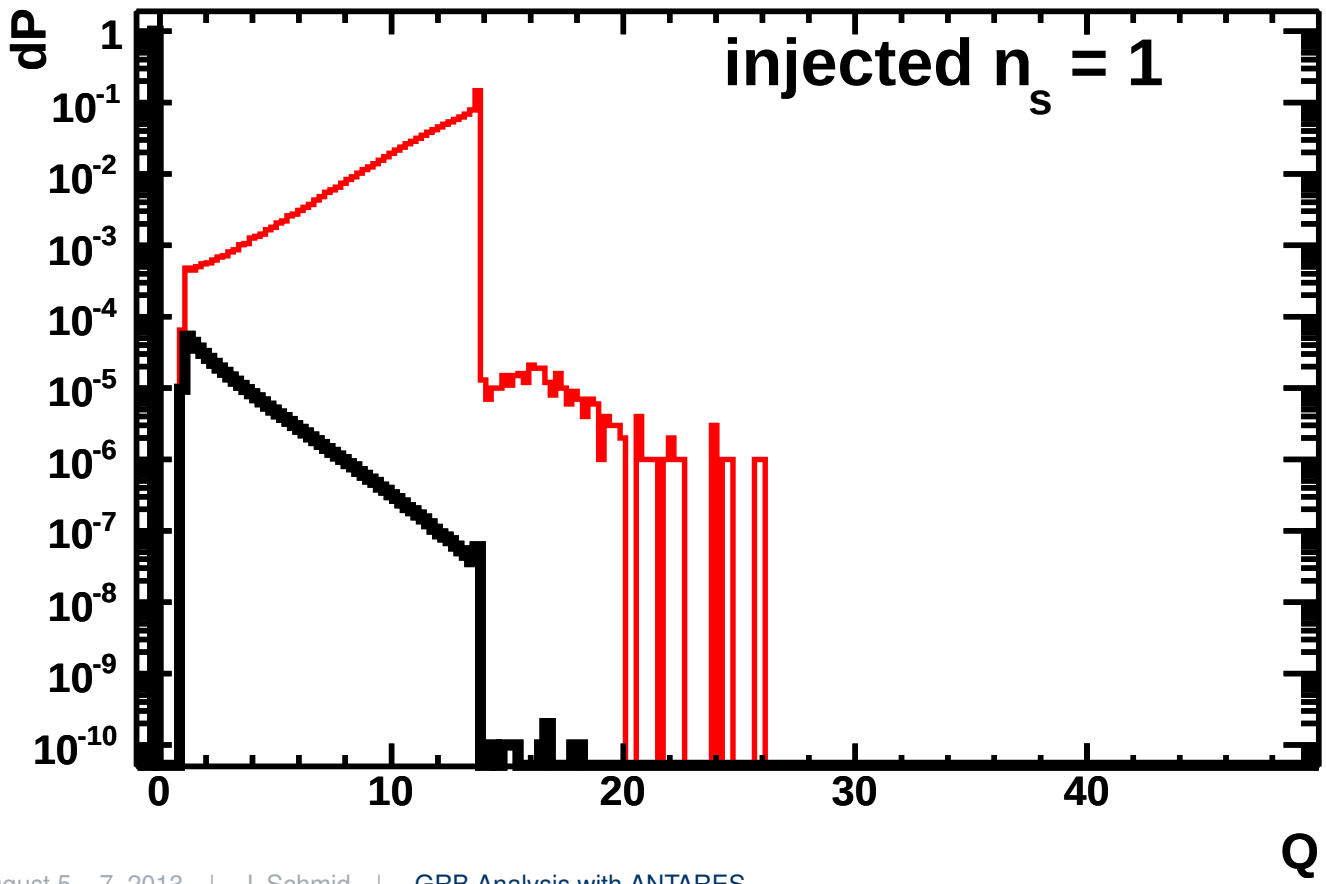

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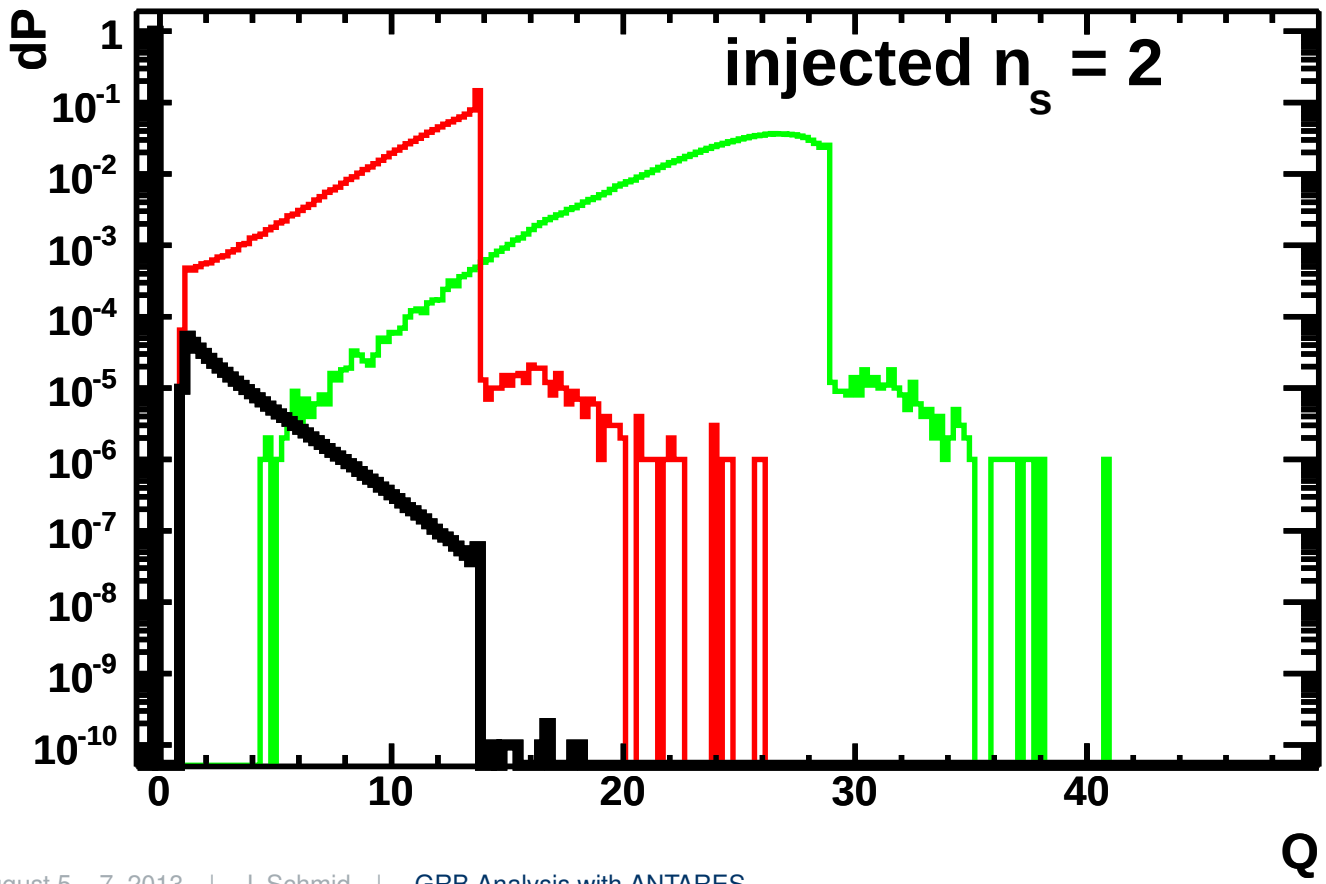

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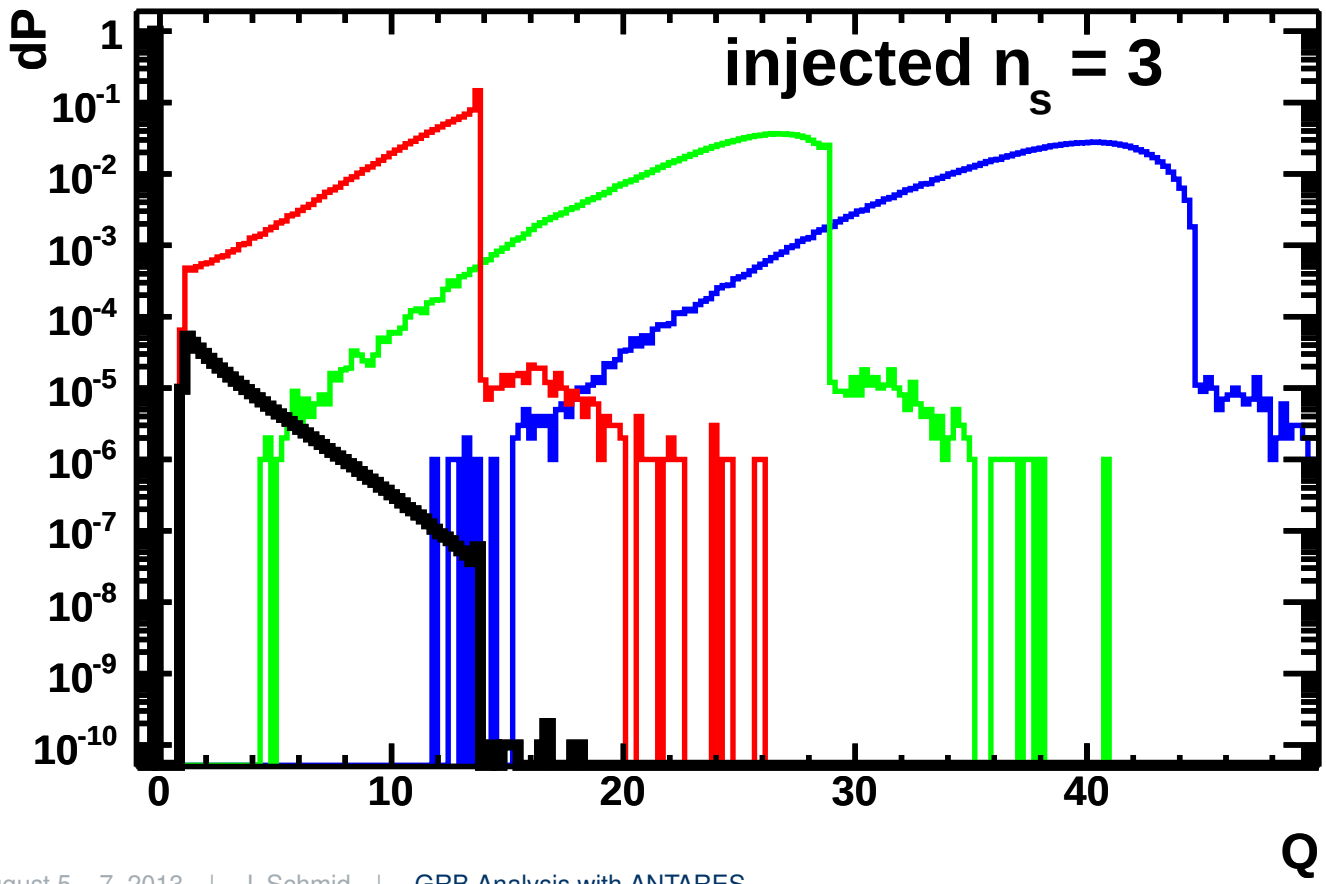

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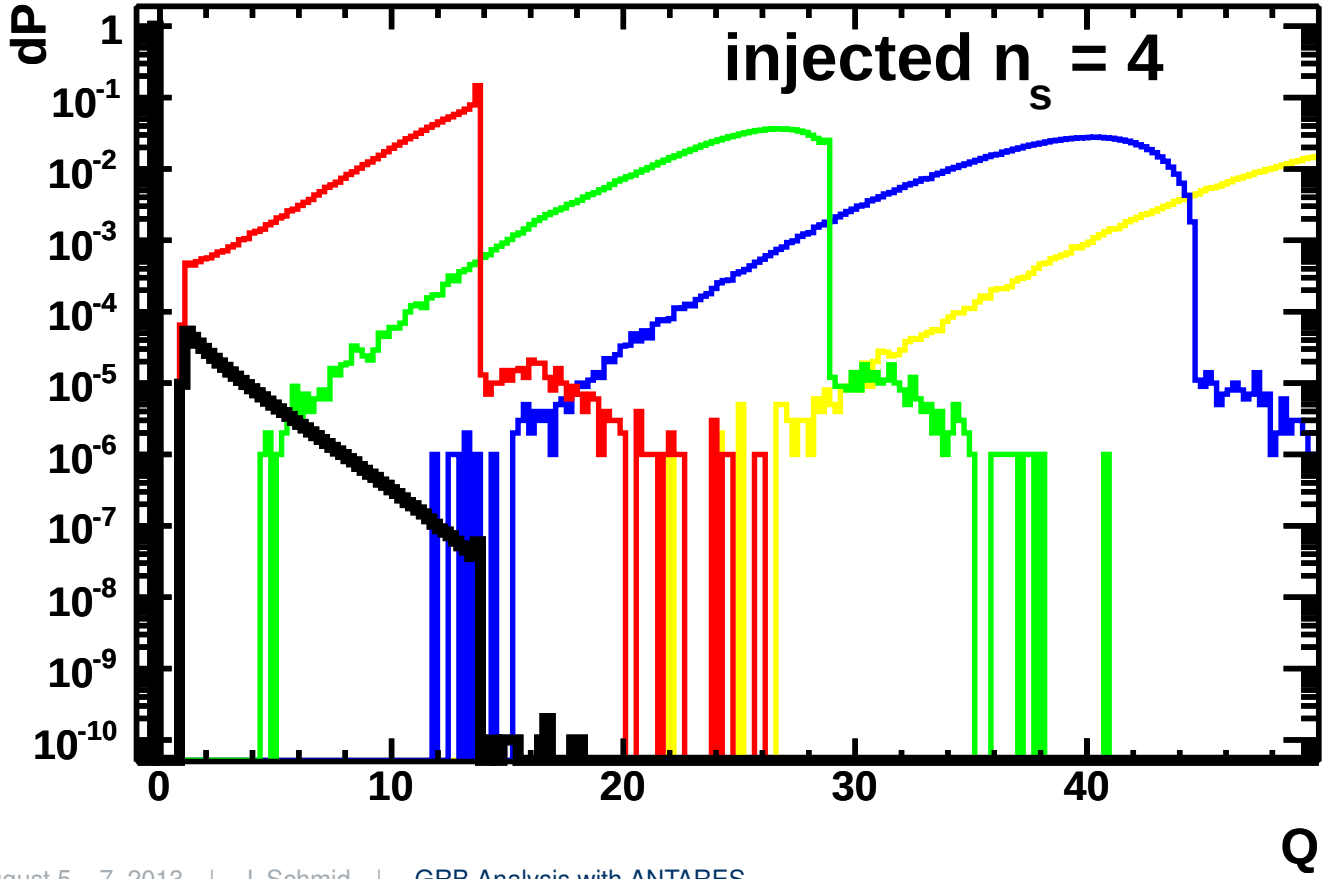

Results of Pseudo Experiments

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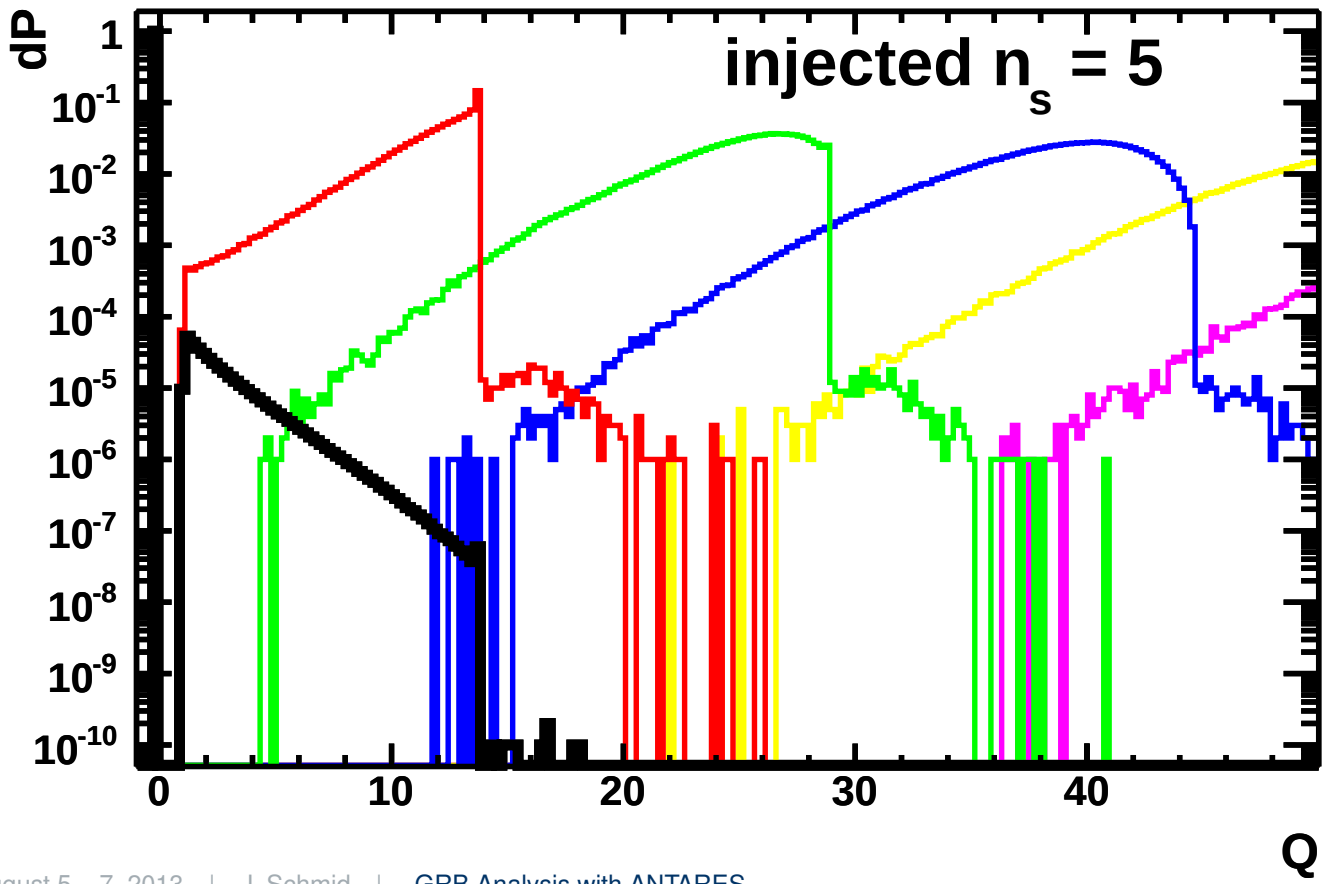
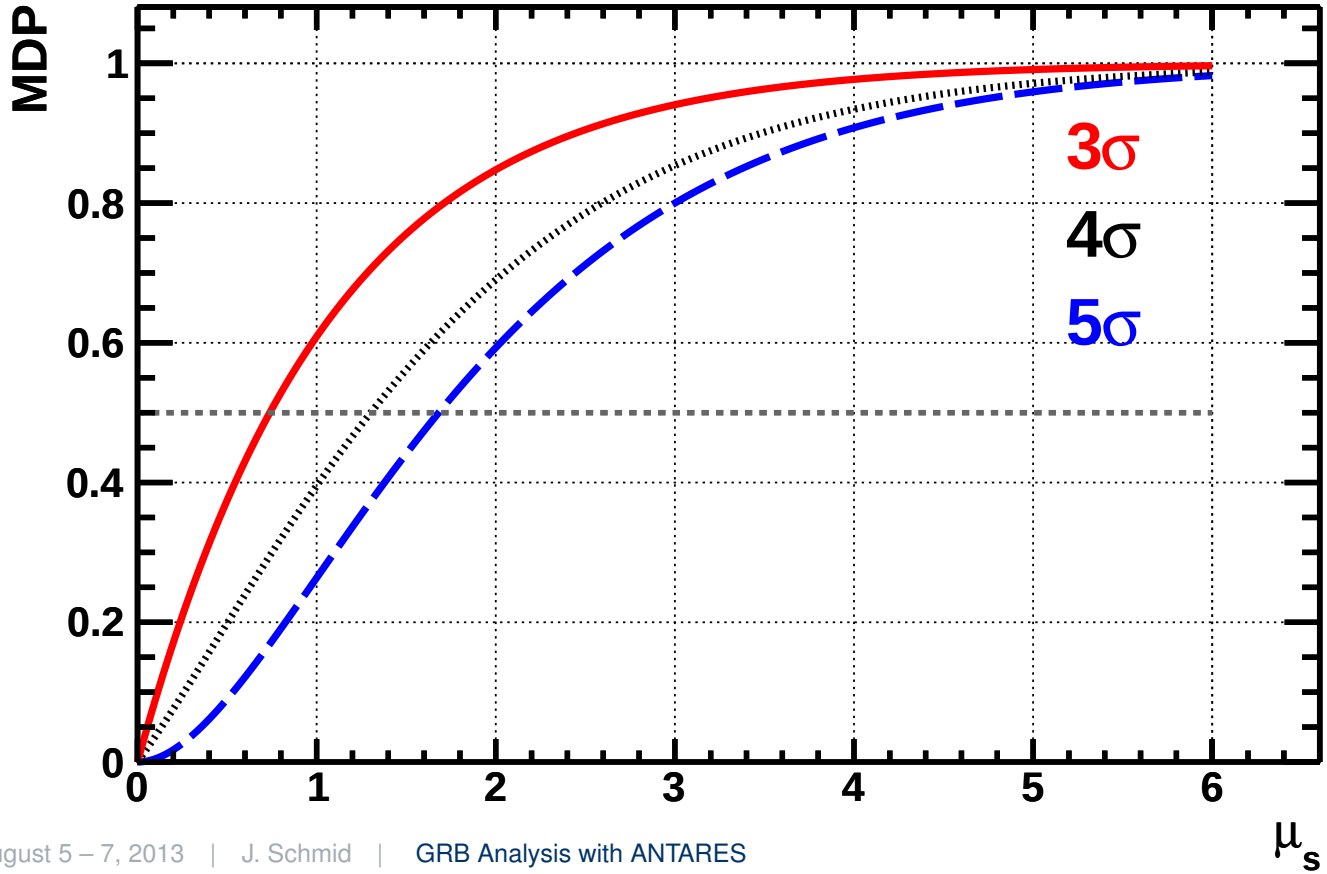


Results of Pseudo Experiments

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



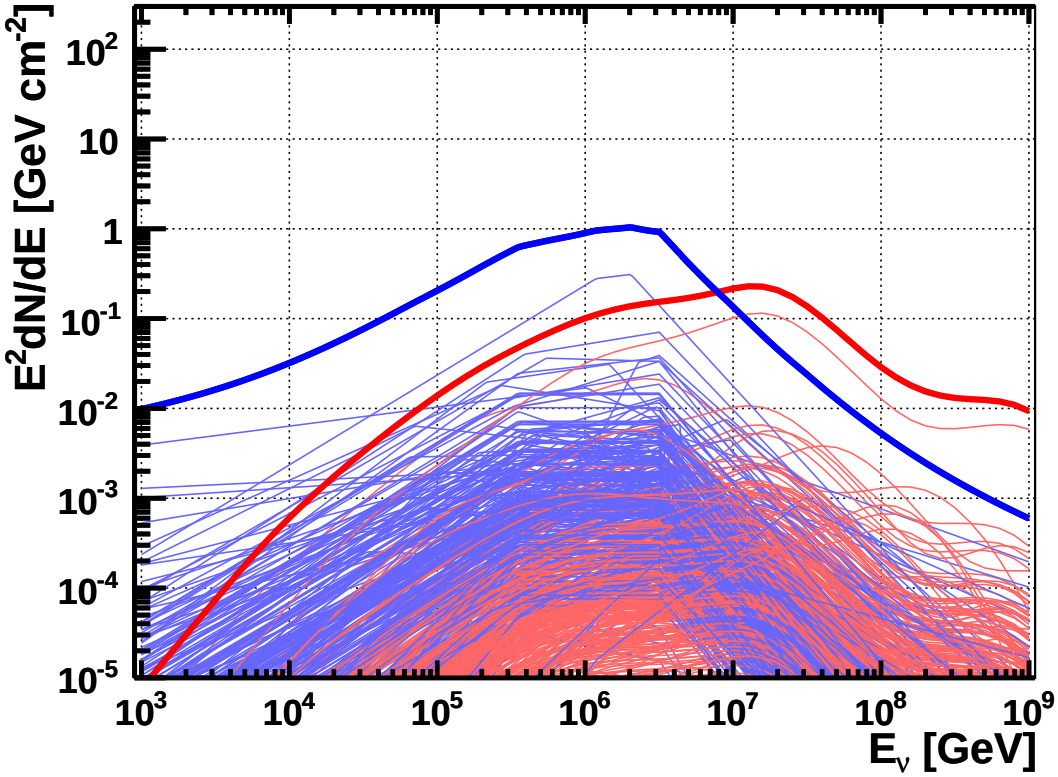
Final Analysis Parameters

Optimisation 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		$5.1\cdot10^{-2}$	$6.1\cdot10^{-2}$	$4.8\cdot10^{-1}$		$2.4\cdot10^{4}$	

Results

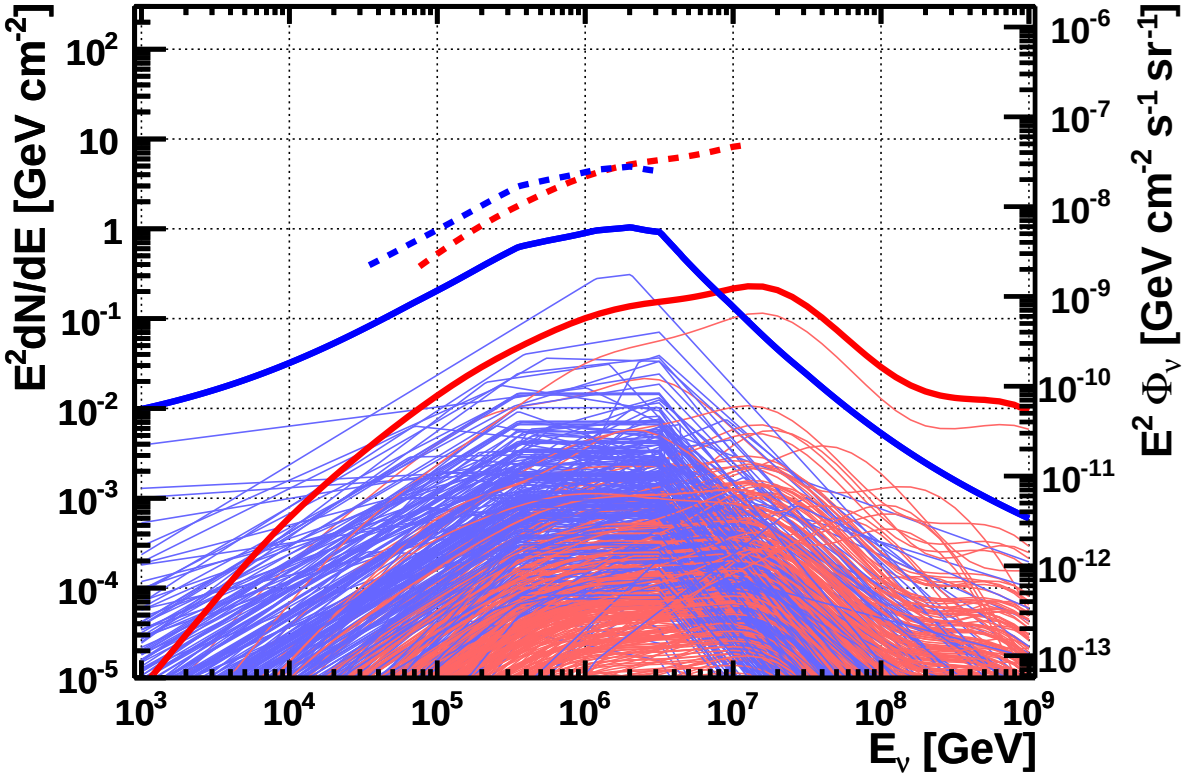
No event found in stacked GRB search windows!



expected events: 0.48 (*Guetta*), 0.061 (*NeuCosmA*)

Results

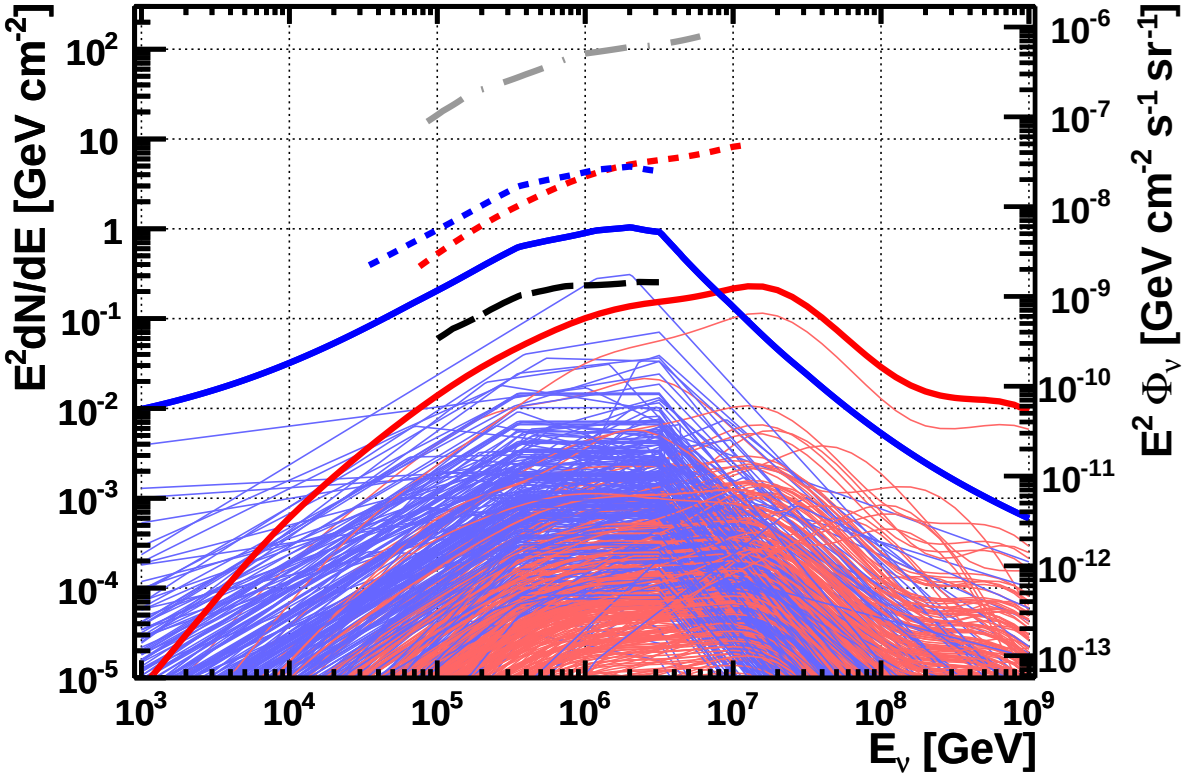
No event found in stacked GRB search windows!



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

Results

No event found in stacked GRB search windows!



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

Grey: first ANTARES limit, 40 GRBs in 2007

Black: IceCube IC40+59 limit, 300 GRBs (Abbasi et al., 2012)

Summary

- 2 GRB searches with ANTARES:
  2007 (construction phase) & late-07 – 2011 (full detector)
  $\rightarrow$no excess over background found
- put most stringent limits on Southern Hemisphere bursts
- for the first time optimised for numerical *NeuCosmA* model
  $\rightarrow$predicted fluxes $\sim$ 10 lower than analytical models
  $\rightarrow$expected neutrinos from GRBs still compatible with non–observation!

$\Rightarrow$ **Current & future neutrino telescopes may soon probe numerical GRB neutrino emission models**

GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung

References

Abbasi R., Abdou Y., Abu-Zayyad T., et al., 2012, Nat 484, 351

Adrián-Martínez S., Albert A., Al Samarai I., et al., 2013a, JCAP 2013, 006

Adrián-Martínez S., Albert A., Al Samarai I., et al., 2013b, ArXiv e-prints

Aguilar J.A., 2011, In: IUPAP (ed.) ICRC, Vol. 8. Proceedings of the 32nd International Cosmic Ray Conference, Institute of High Energy Physics, Beijing, p. 232

Guetta D., Hooper D., Alvarez-Muñiz J., et al., 2004, Astropart. Phys. 20, 429

Hümmer S., Baerwald P., Winter W., 2012, Phys. Rev. Lett. 108, 231101

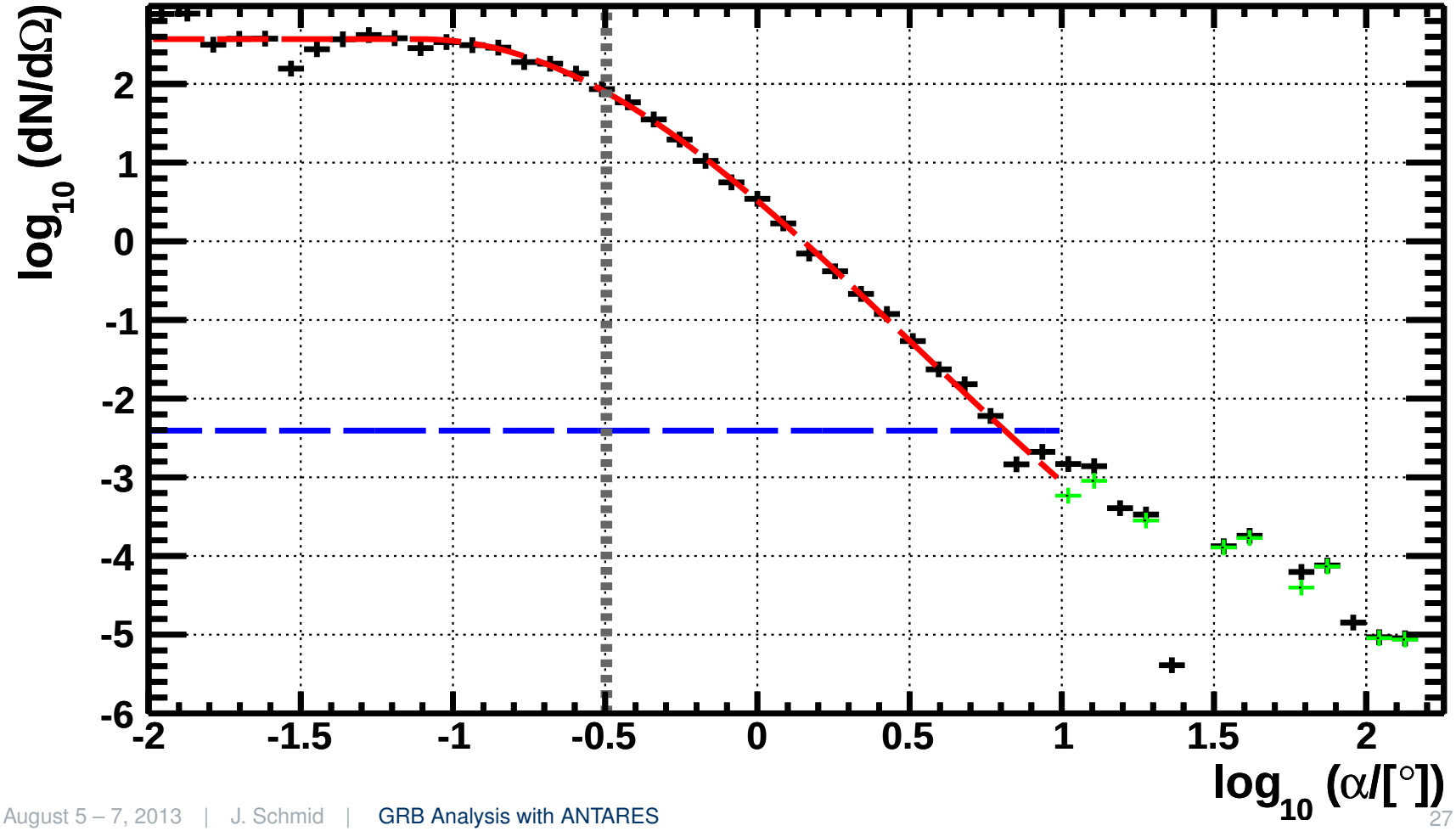
Hümmer S., Rüger M., Spanier F., Winter W., 2010, ApJ 721, 630

NeuCosmA simulations: P. Baerwald
Fermi: http://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html
Swift: http://swift.gsfc.nasa.gov/docs/swift/archive/grb_table.html

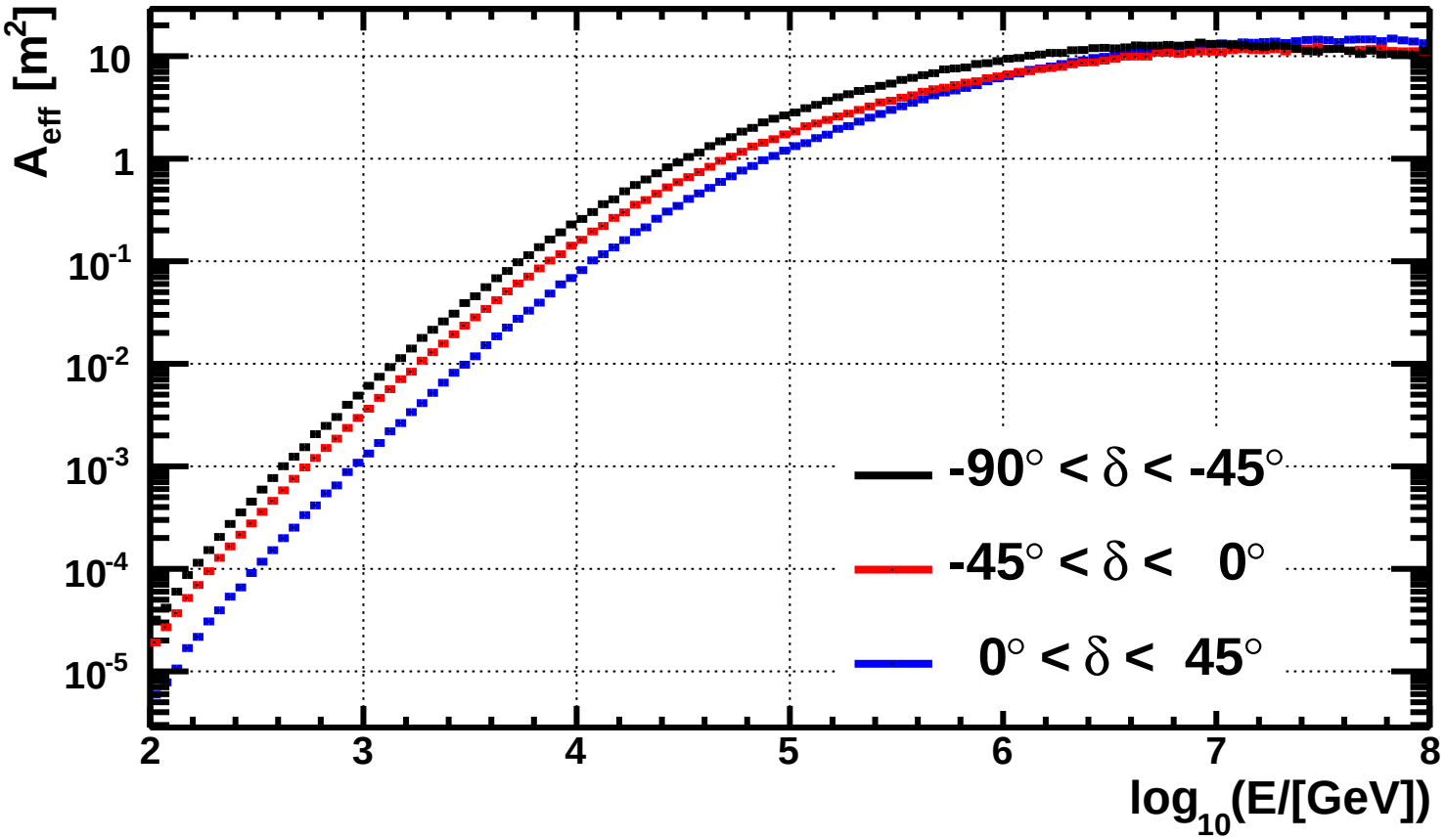
GCN provided by *IceCube*: http://grbweb.icecube.wisc.edu

Backup

Signal & Background PDFs



Effective Area for muon neutrinos, late-2007 – 2011



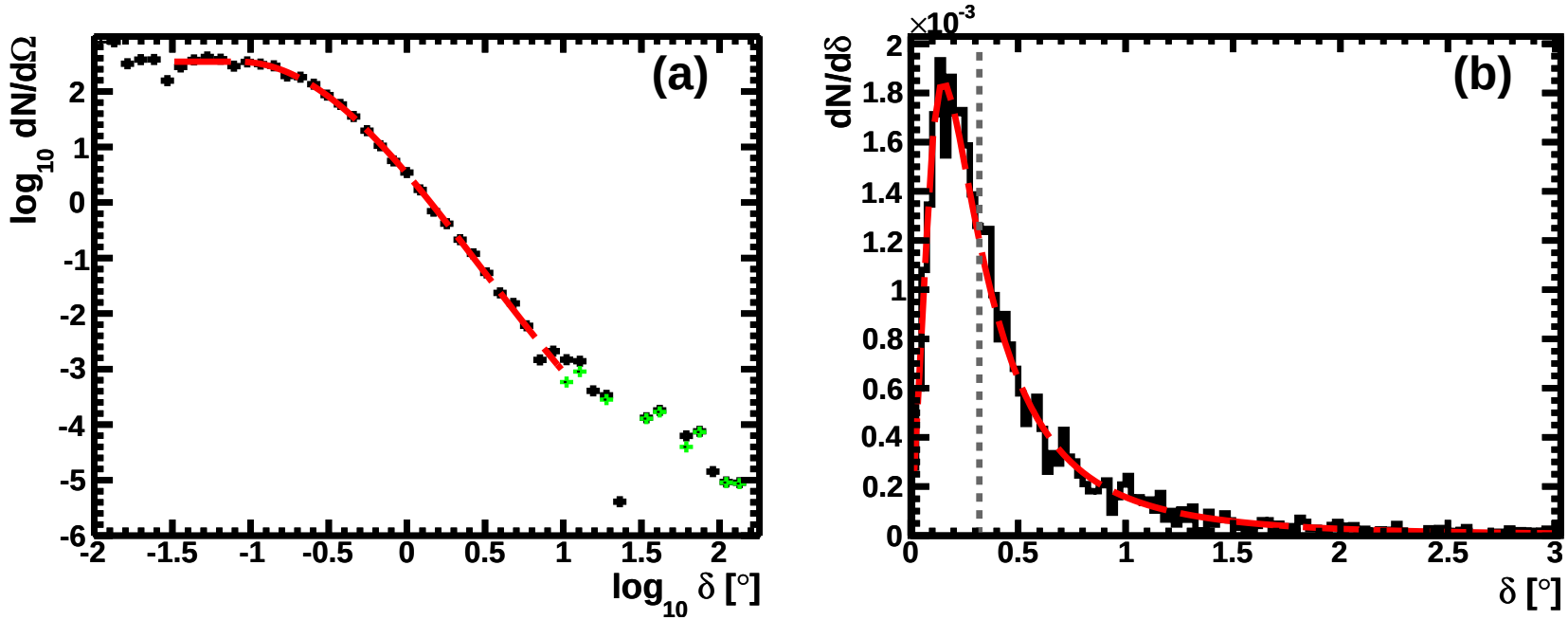
Background Calculation

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

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

- $n(\Theta, \Phi)$: max of average and central value of 10° cone around GRB position (Θ, Φ)
- c_i: correction factor for run i, ratio of events in this run and average events in this run
- c_{period}: correction for long periods with stable conditions
- 1.5: width of $n_{\text{est}} / n_{\text{meas}}$

Signal PSF 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

condensated from

- *Fermi*: best photon spectrum
- *Swift*: best localisation
- *grbweb*: 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)

Selection of Gamma Ray Bursts

(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%.

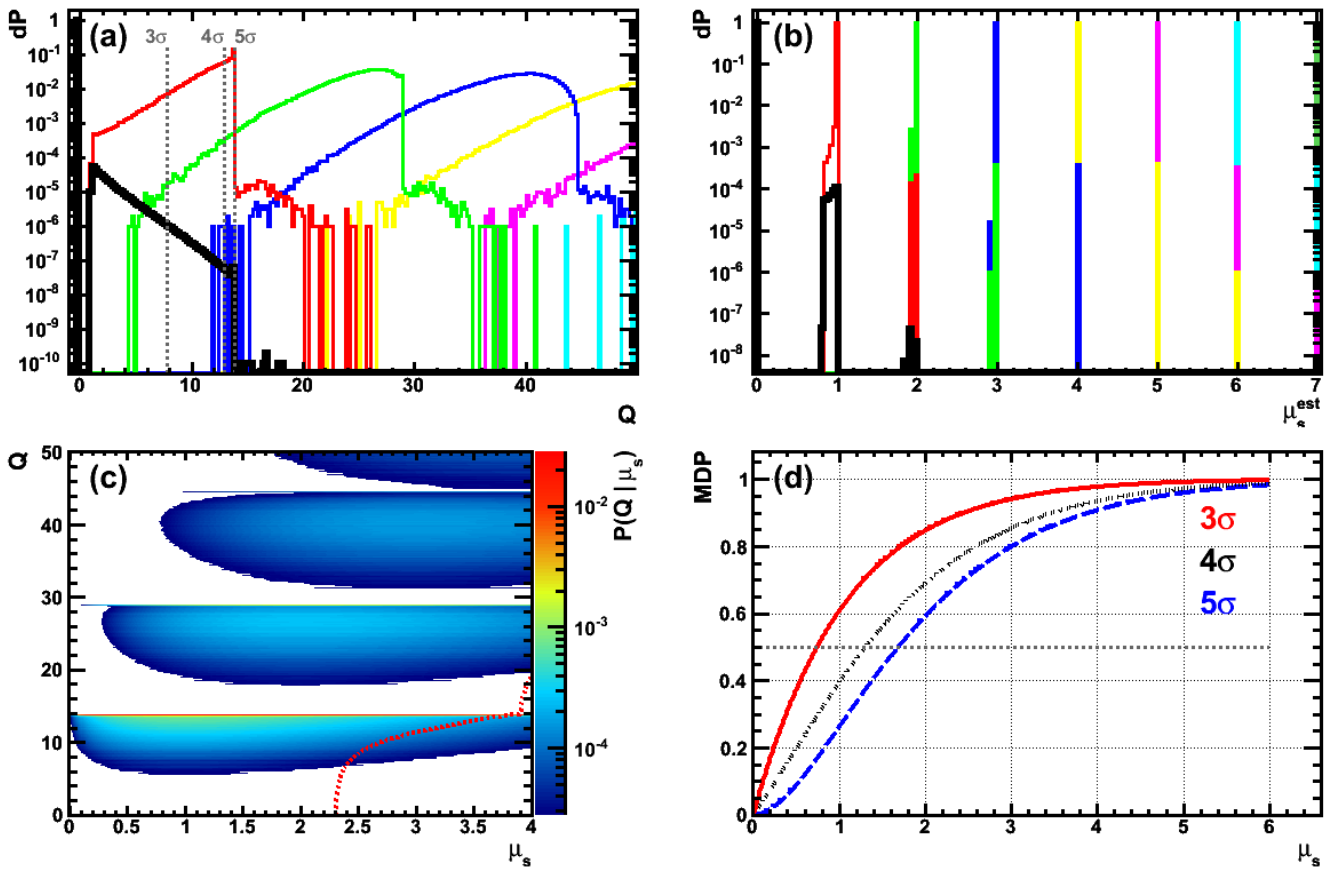
Model Discovery Probability

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

- 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

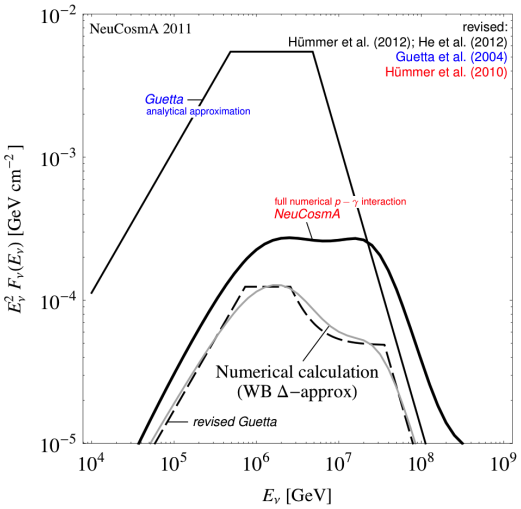
maximum of $\mathcal{MDP} \longrightarrow$ optimal quality cut

Results of Pseudo Experiments



distributions of Q and μ_s^{est} for n_s =0, 1, 2, 3,. . . injected signal events
Model Discovery Probabilities and probability of Q–values versus μ_s.

GRB models: Comparison



revision: full γ distribution, full Δ width, E loss of secondaries, E dependenc of p mean free path, still Δ approximation

numerical *NeuCosmA*: Monte Carlo simulations based on SOPHIA, full p–γ cross section, multi–π and K^+ production

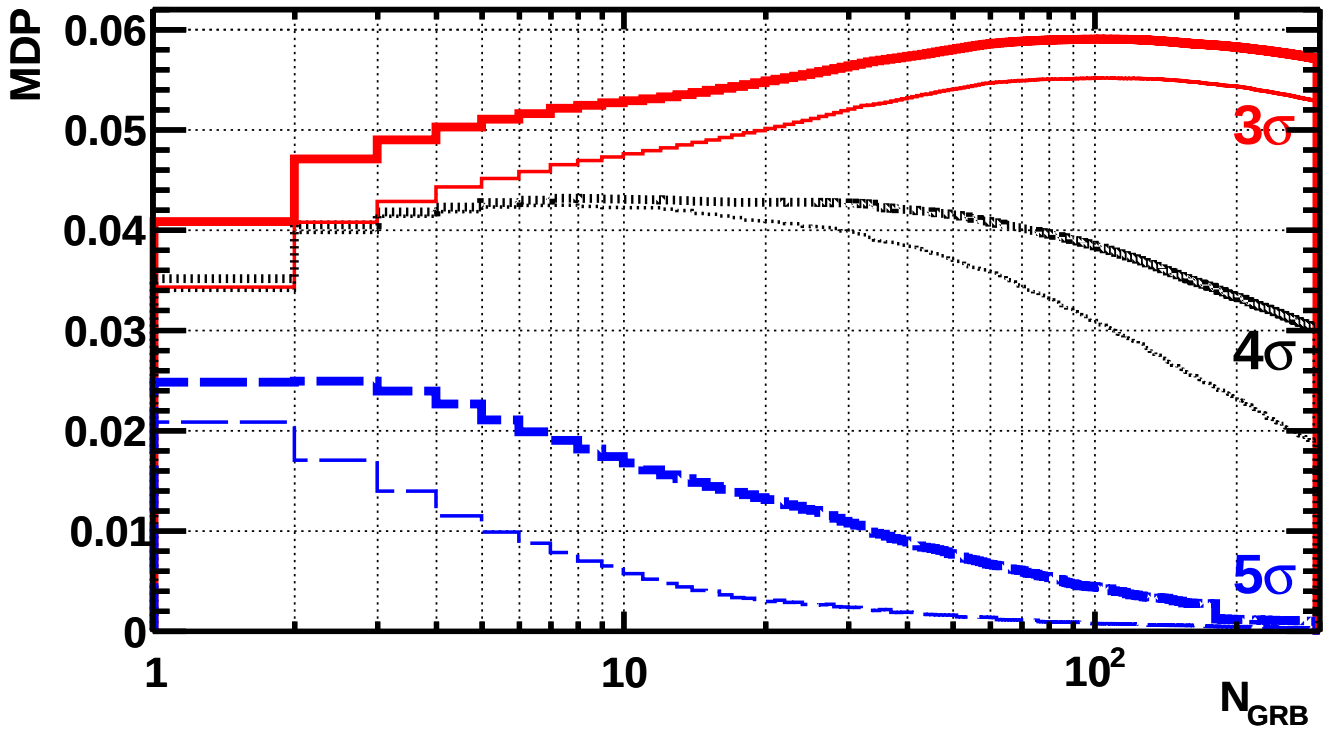
Analysis in Numbers

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

Simulations

Signal $\mathcal{S}(\delta)$	pseudo experiments
$4 \cdot 10^9$ ν_μ tracks	10^{10} background PEs
150 shower events	10^5 PEs for each n_s

Check for optimal Subsample N_{GRB}



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