21st International Conference on General Relativity and Gravitation
Columbia University, New York

IceCube and GRB neutrinos propagating in quantum spacetime

Niccoló Loret

Institut Ruđer Bošković

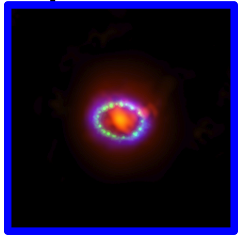
Based on arXiv:1605.00496

With *Giovanni Amelino-Camelia, Leonardo Barcaroli, Giacomo D'Amico and Giacomo Rosati*

Setting bounds on Quantum Gravity with astrophysical observations

- Strong bounds on photons' dispersion relation
  see exempli gratia arXiv:0908.1832

- Very weak limits on neutrino deformation parameters
  (low energy neutrinos from SN1987A)



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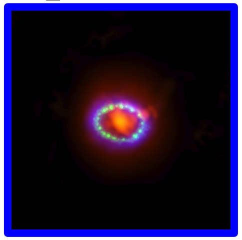
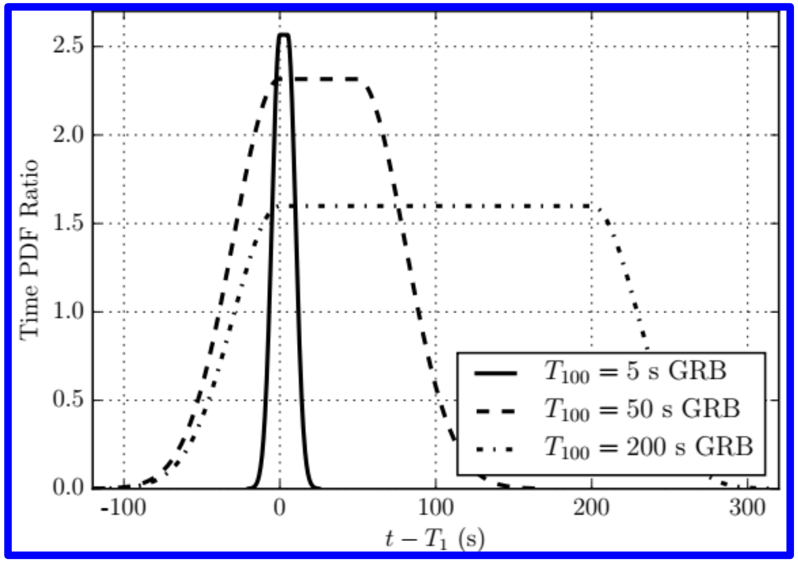


- No conclusive detection of GRB neutrinos, contradicting some influential predictions
  IceCube collaboration:
  arXiv:1601.06484v1



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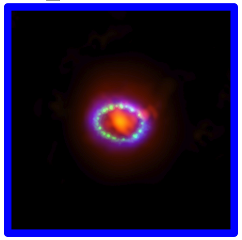

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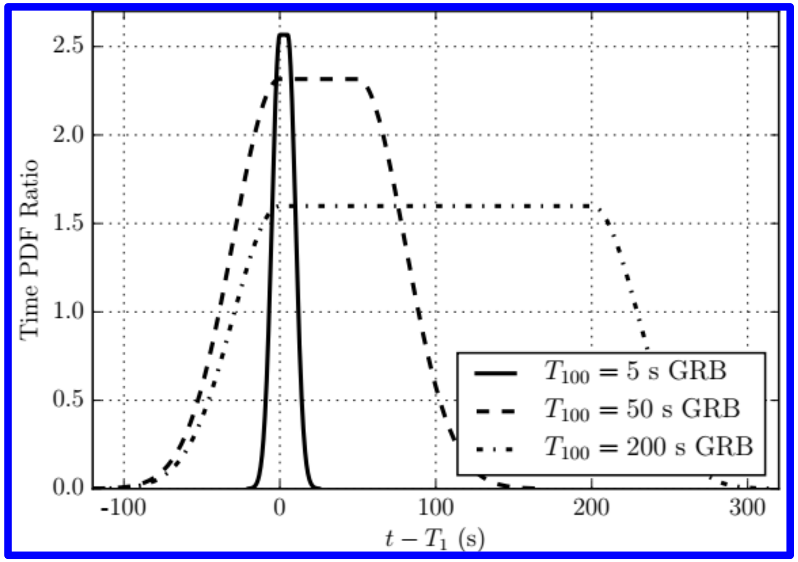

- **No tests on Quantum Gravity effects on neutrino propagation !!**

Theoretical framework

Alfaro, Morales-Técotl, Urrutia
arXiv:gr-qc/9909079v2

$$H^{(1)} := \int d^3x \frac{E_i{}^a}{2\sqrt{det(g)}} \left(i\pi^T \tau_i \mathcal{D}_a \xi + c.c.\right)$$

$$\boxed{v_\pm(\bar{p}) = \frac{\partial E_\pm(p,\mathcal{L})}{\partial p}\Big|_{p=\bar{p},\ \mathcal{L}=1/\bar{p}} = 1 - \frac{m^2}{2\bar{p}^2} + \kappa_1(\ell_P\ \bar{p}) \mp \kappa_7 \frac{(\ell_P\ \bar{p})^2}{2}}$$

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Myers, Pospelov
arXiv:hep-ph/0301124v2

$$\mathcal{L}_f = \frac{1}{M_{\rm Pl}} \bar{\Psi}\left(\eta_1 \not{n} + \eta_2 \not{n}\gamma_5\right)(n\cdot\partial)^2 \Psi$$

$$\boxed{\left(E^2 - |\vec{p}|^2 - m^2 - \frac{2|\vec{p}|^3}{M_{\rm Pl}}(\eta_1 + \eta_2\gamma_5)\right)\Psi = 0 \qquad \eta_{R,L} = \eta_1 \pm \eta_2}$$

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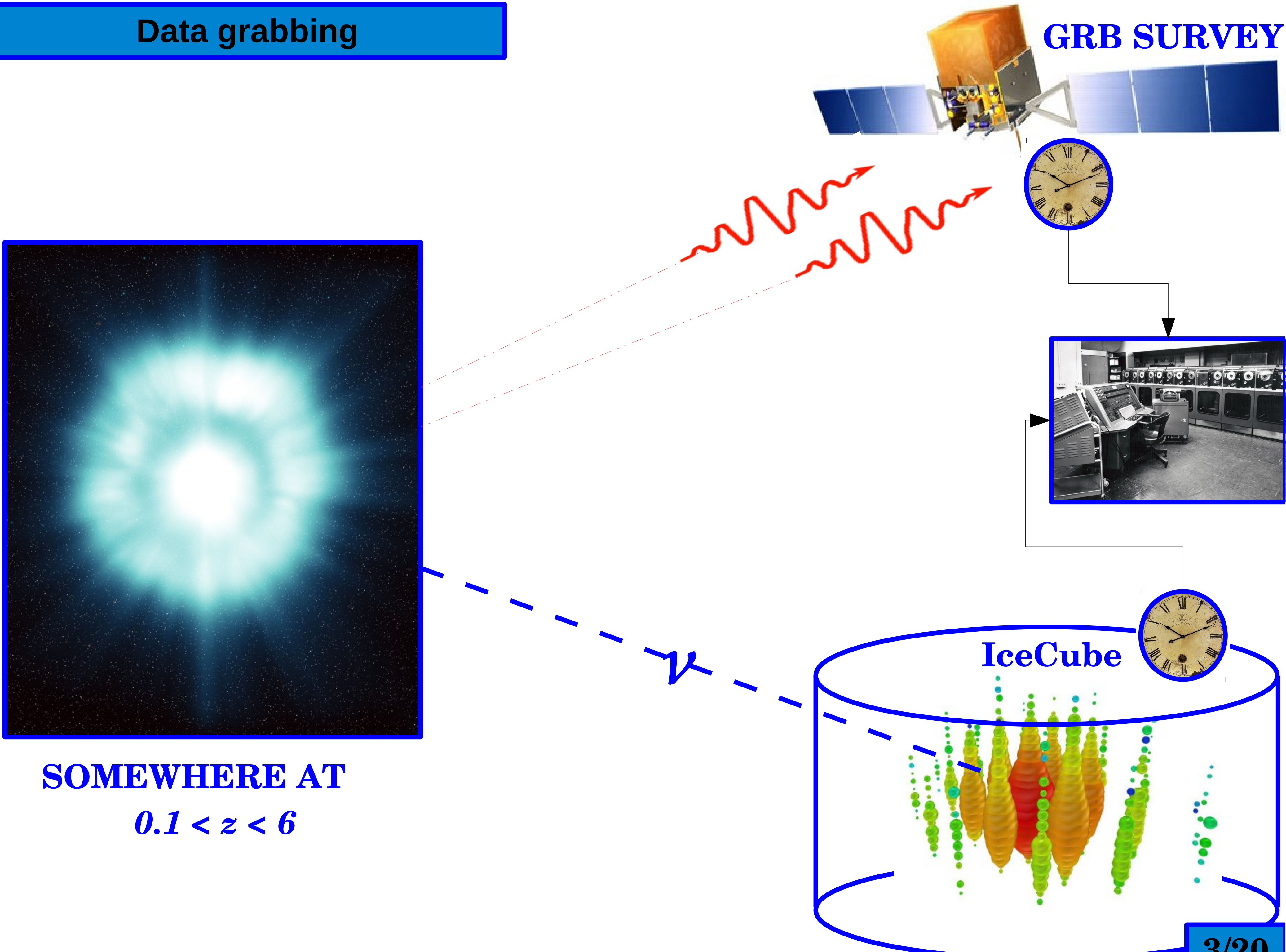
Stecker, Scully, Liberati, Mattingly
arXiv:1411.5889v3

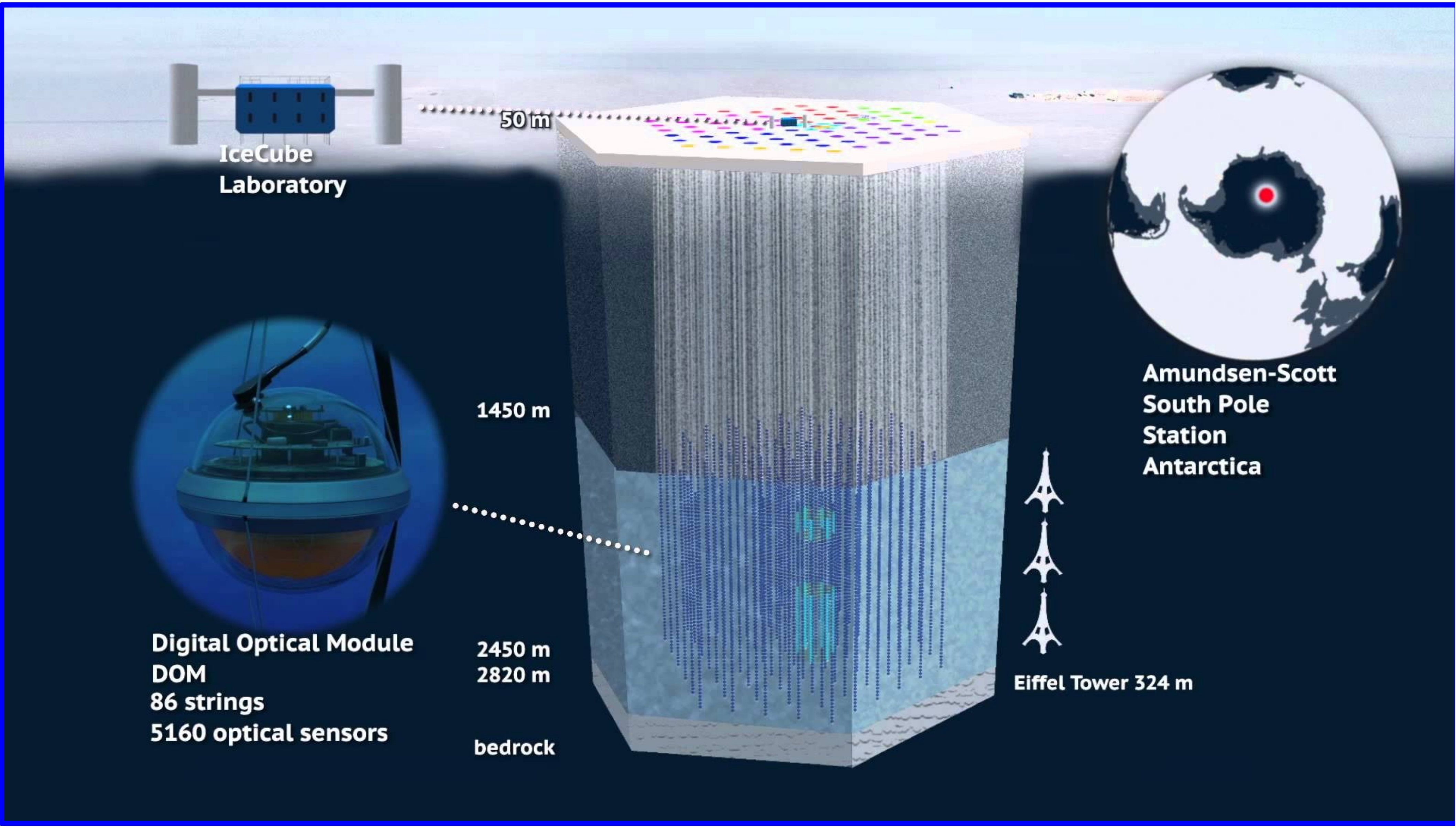
$$\Delta\mathcal{L}_f = \partial_i \Psi^* \epsilon \partial^i \Psi$$

$$\boxed{\frac{\partial E}{\partial|\vec{p}|} = \frac{|\vec{p}|}{\sqrt{|\vec{p}|^2 + m^2 v_{MAV}^2}} v_{MAV} \qquad v_{I,MAV} \equiv 1 + \delta_I}$$

Data grabbing



IceCube neutrino observatory



Particles propagating from cosmological distance

We focus on the class of scenarios whose predictions for energy (E) dependence of Δt can all be described in terms of

SYSTEMATIC **FUZZY**

$$\Delta t = \eta_X \frac{E}{M_P} D(z) \pm \delta_X \frac{E}{M_P} D(z)$$

The distance they come acros depends on the redshift as

$$D(z) = \int_0^z d\zeta \frac{(1+\zeta)}{H_0\sqrt{\Omega_\Lambda + (1+\zeta)^3\Omega_m}}$$

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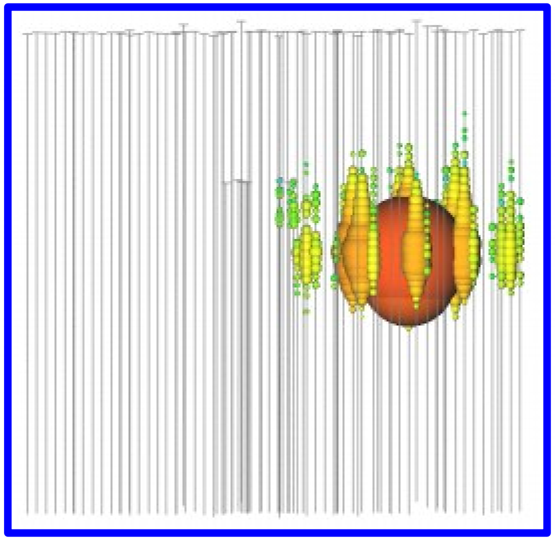
Observable t*

$$\boxed{\Delta t^* \equiv \Delta t \frac{D(1)}{D(z)} \qquad \Delta t^* = \eta_X \frac{E}{M_P} D(1) \pm \delta_X \frac{E}{M_P} D(1)}$$

Data selection

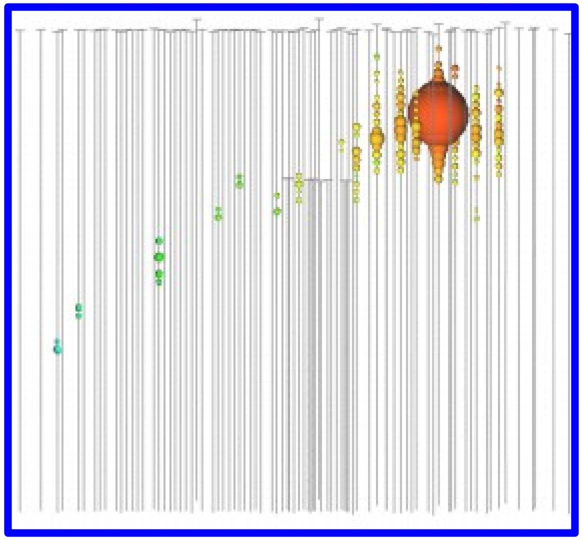
SHOWER EVENTS



Generated mostly by ν_e

- Higher energy
- Higher significance
- Worst angular discrimination

TRACK EVENTS



Generated by ν_μ

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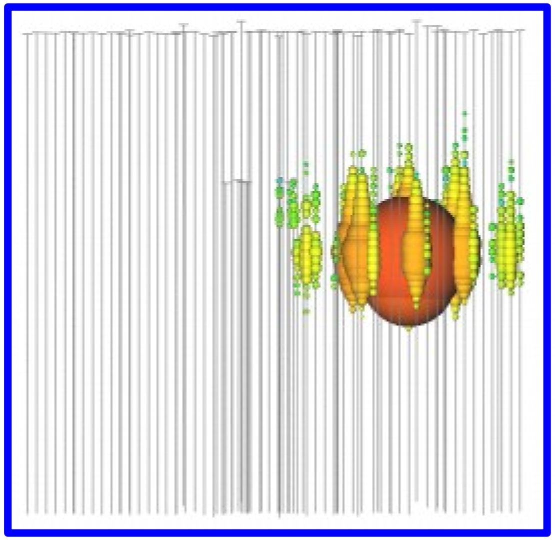
- Lower bound on neutrino energy
- Good angular discrimination

Data selection

SHOWER EVENTS



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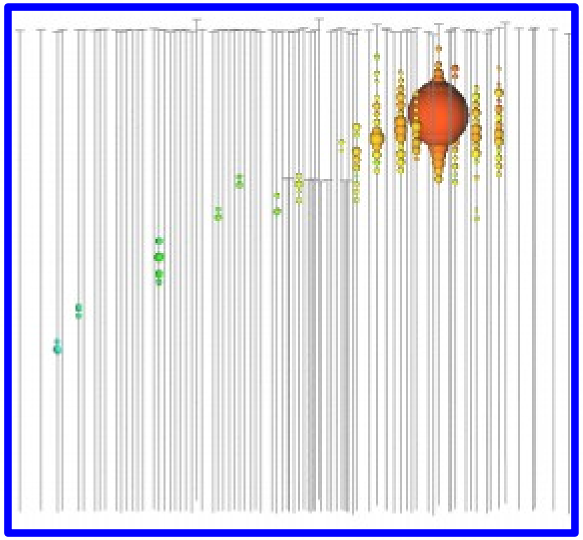

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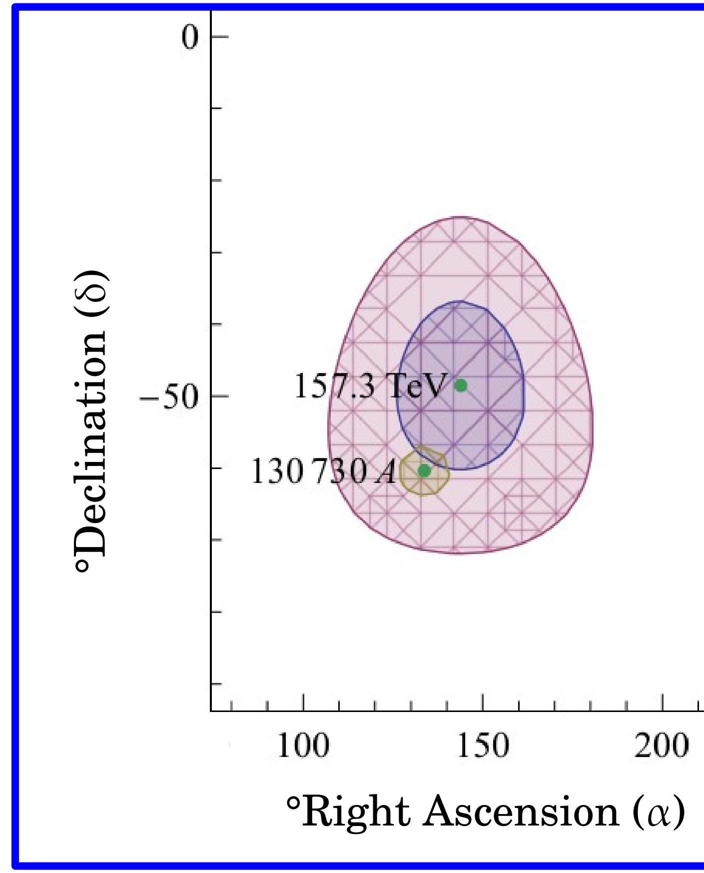
No tracks, at least for now...

Angular selection



Probability density function

$$PDF(\nu, GRB) = \frac{1}{2\pi\sigma^2} e^{-\frac{\psi^2(\vec{x}_\nu, \vec{x}_{GRB})}{2\sigma^2}}$$

Angular distance in the sky

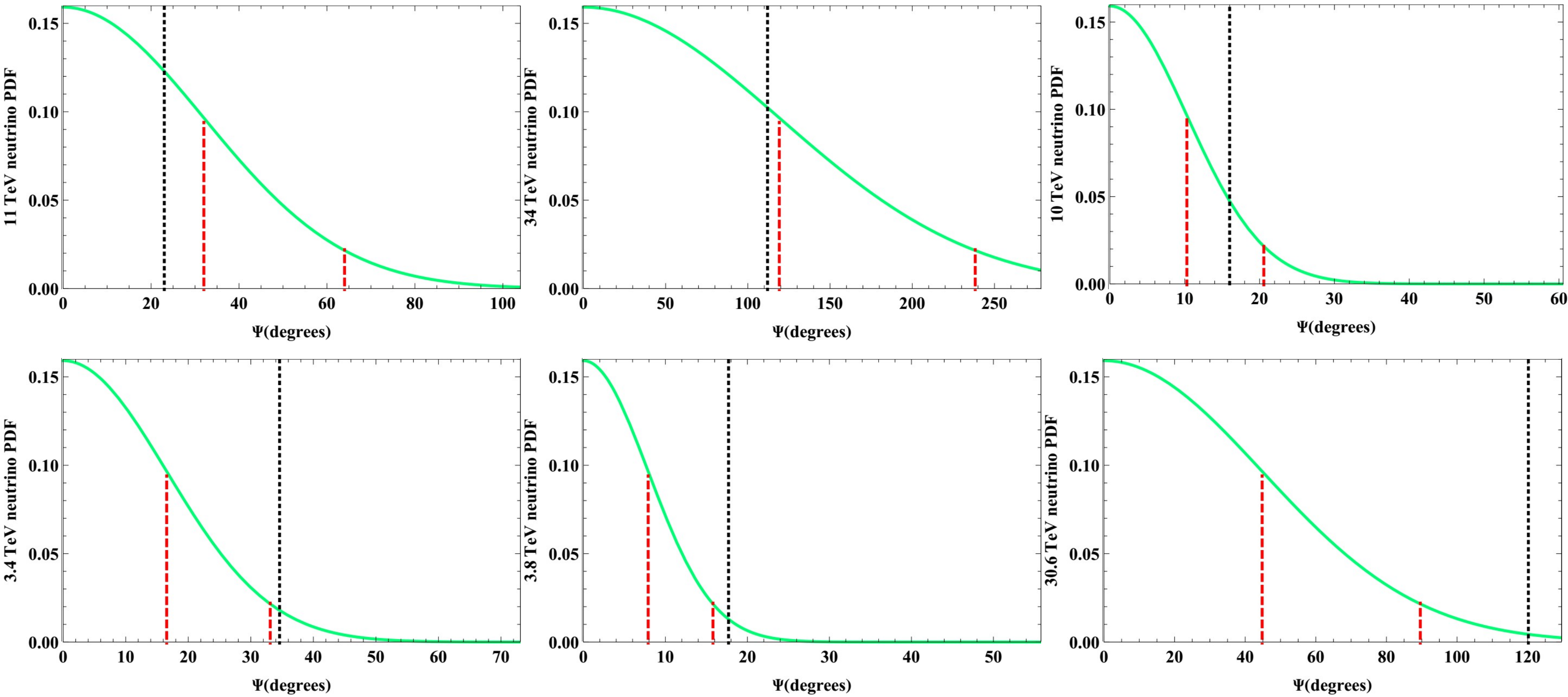
$$\psi^2(\vec{x}_\nu, \vec{x}_{GRB}) = \arccos\left(\cos(\delta_\nu)\cos(\delta_{GRB})\cos(\alpha_\nu - \alpha_{GRB}) + \sin(\delta_\nu)\sin(\delta_{GRB})\right)$$

Angular uncertainty

$$\sigma = \sqrt{\sigma_{GRB}^2 + \sigma_\nu^2}$$

IceCube PDF

IceCube collaboration:
arXiv:1601.06484v1



Ice Cube sygnal-like probability:

$$\mathcal{S}(\overrightarrow{x_i}) = P_{\rm s}^{\rm Time}(t_i) \times P_{\rm s}^{\rm Space}(\overrightarrow{r_i}) \times P_{\rm s}^{\rm Energy}(E_i)$$

IceCube PDF

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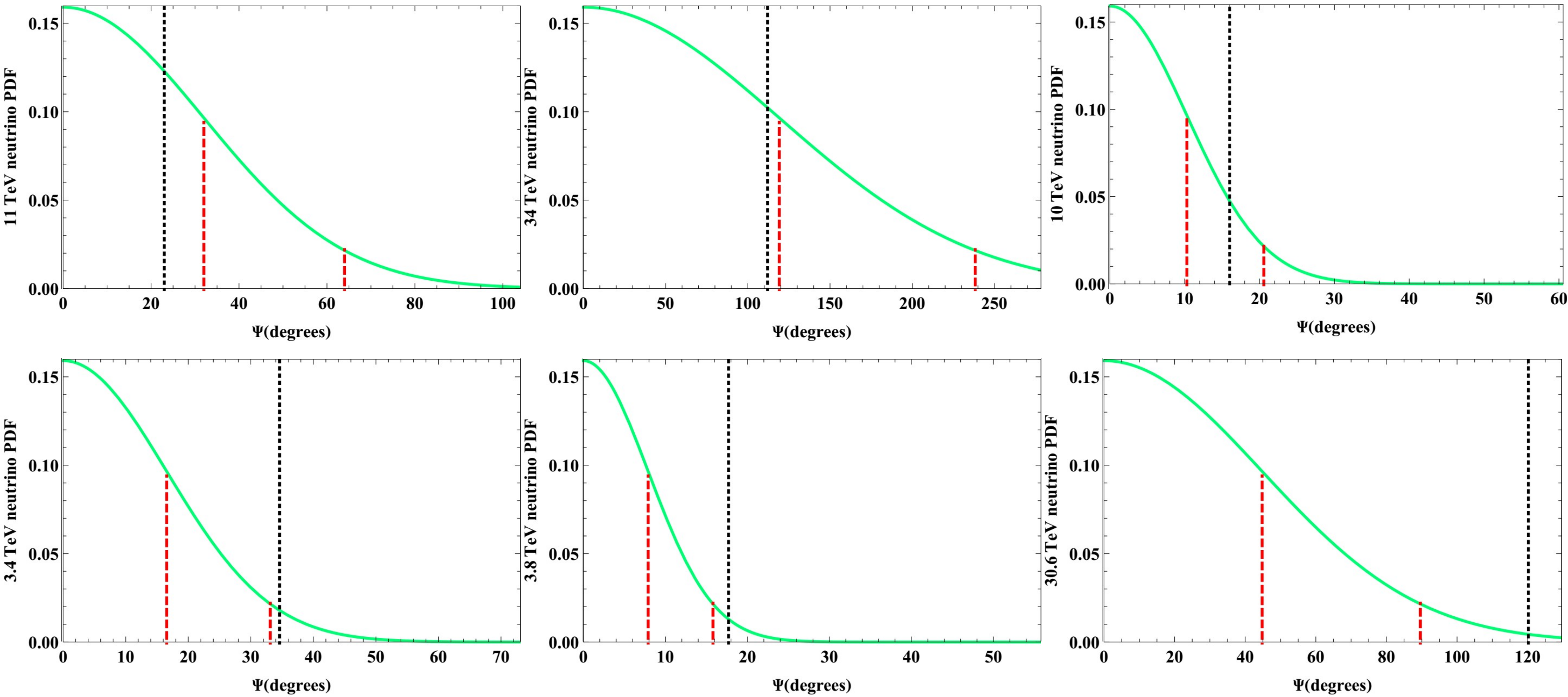
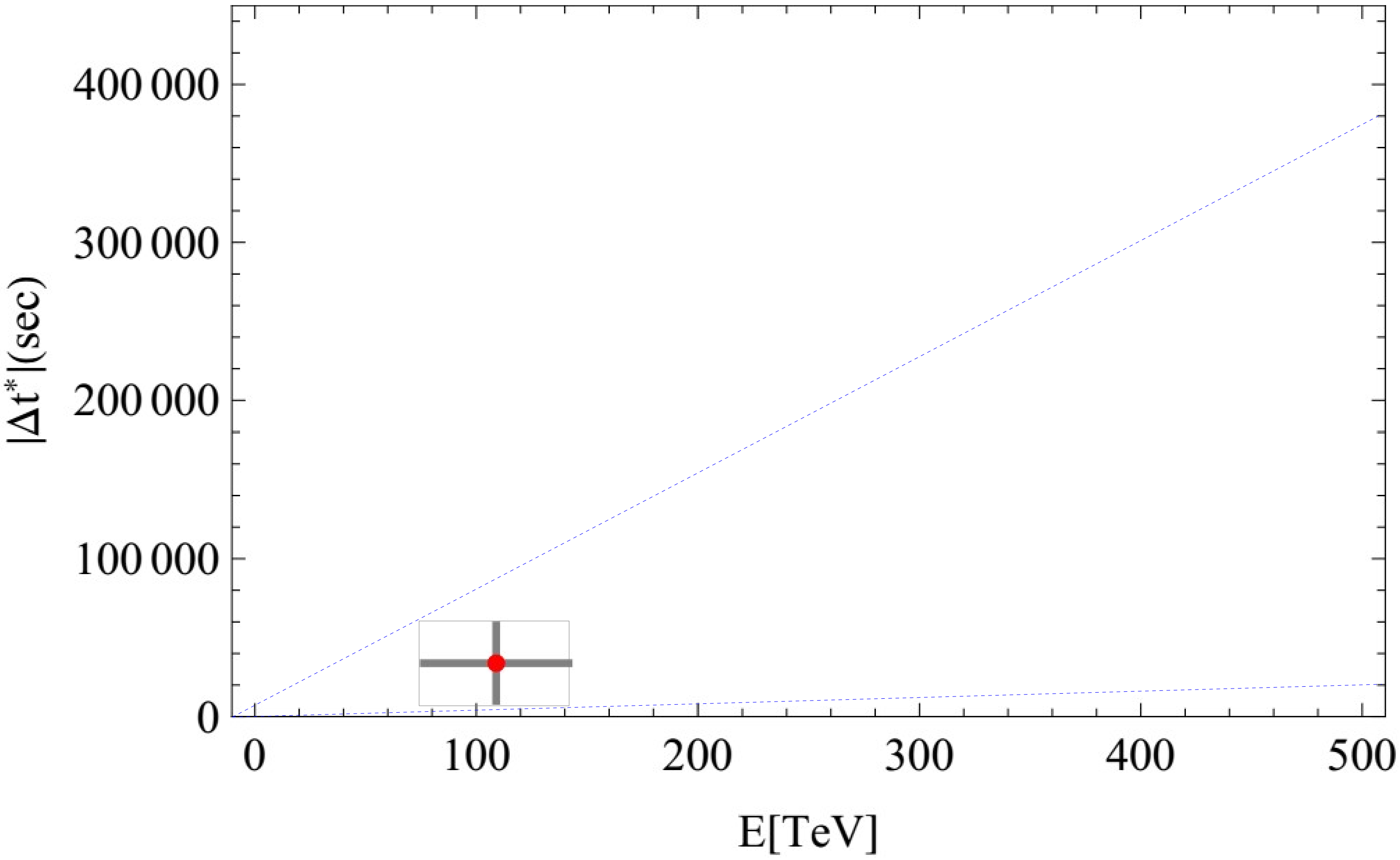


Ice Cube sygnal-like probability: $\boxed{\mathcal{S}(\overrightarrow{x_i}) = P_{\mathrm{s}}^{\mathrm{Time}}(t_i) \times P_{\mathrm{s}}^{\mathrm{Space}}(\overrightarrow{r_i}) \times P_{\mathrm{s}}^{\mathrm{Energy}}(E_i)}$

We set our angular threshold to: $\boxed{2\,\sigma}$

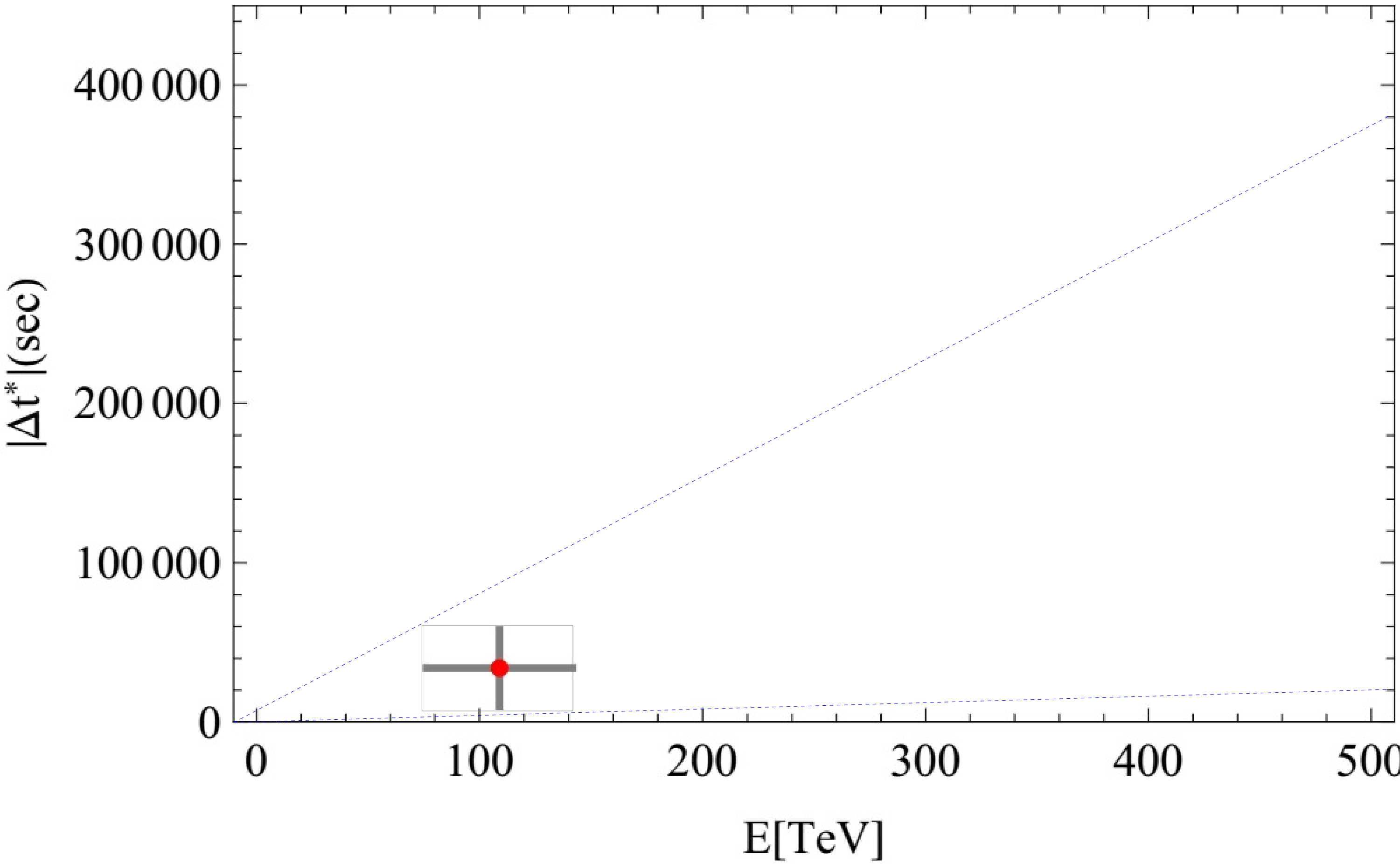
This will let some noise in, but we'll discuss about it later

Time and energy window



We use the 109 TeV neutrino studied in [Amelino-Camelia, Guetta, Piran arXiv:1303.1826] as a prior to inspire a choice of the temporal window.

Time and energy window



60 TeV< E < 500 TeV

-3 days < Δt < +3 days

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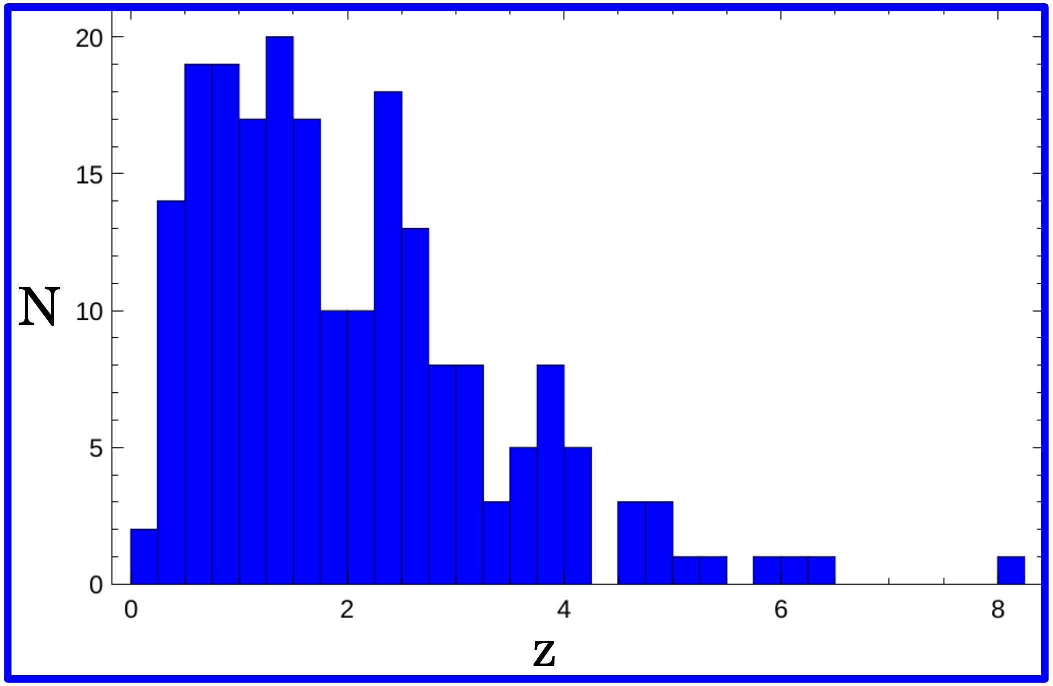
Our dataset

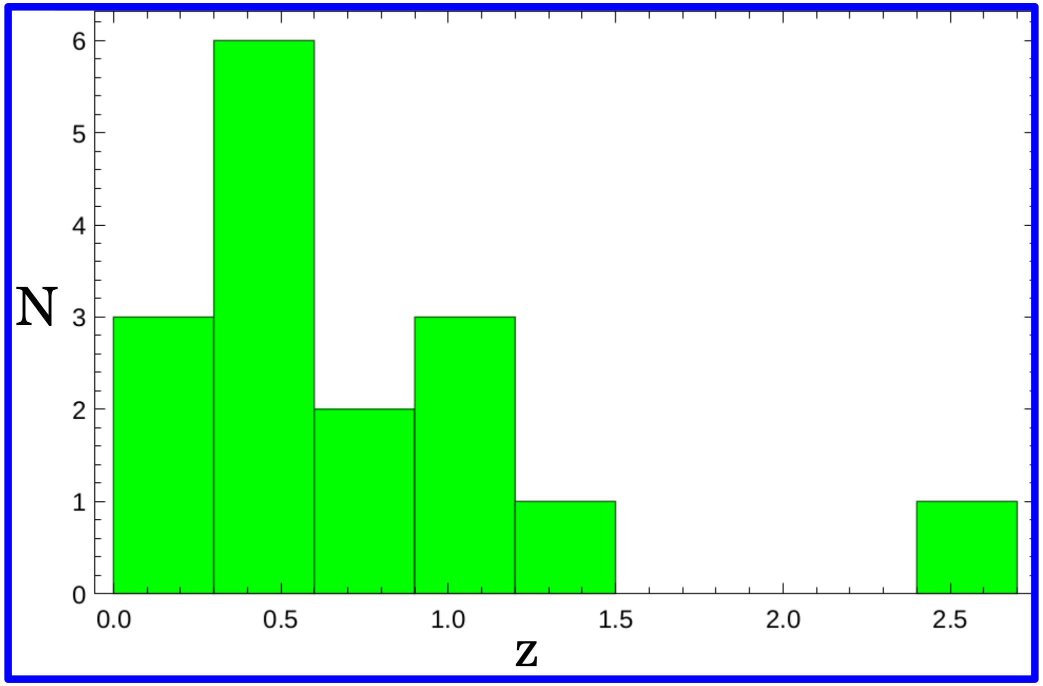
	E[TeV]	GRB	z	Δt^* [s]	
IC9	63.2	110503A	1.613	50227	*
IC19	71.5	111229A	1.3805	53512	*
IC42	76.3	131117A 131118A 131119A	4.042 1.497 * ?	5620 -98694 -146475	*
IC11	88.4	110531A	1.497 *	124338	*
IC12	104.1	110625B	1.497 *	108061	*
IC2	117.0	100604A 100605A 100606A	? 1.497 * ?	10372 -75921 -135456	*
IC40	157.3	130730A	1.497 *	-120641	*
IC26	210.0	120219A 120224B	1.497 * ?	153815 -117619	*
IC33	384.7	121023A	0.6 *	-289371	*

GRB distribution

LONG GRB



SHORT GRB

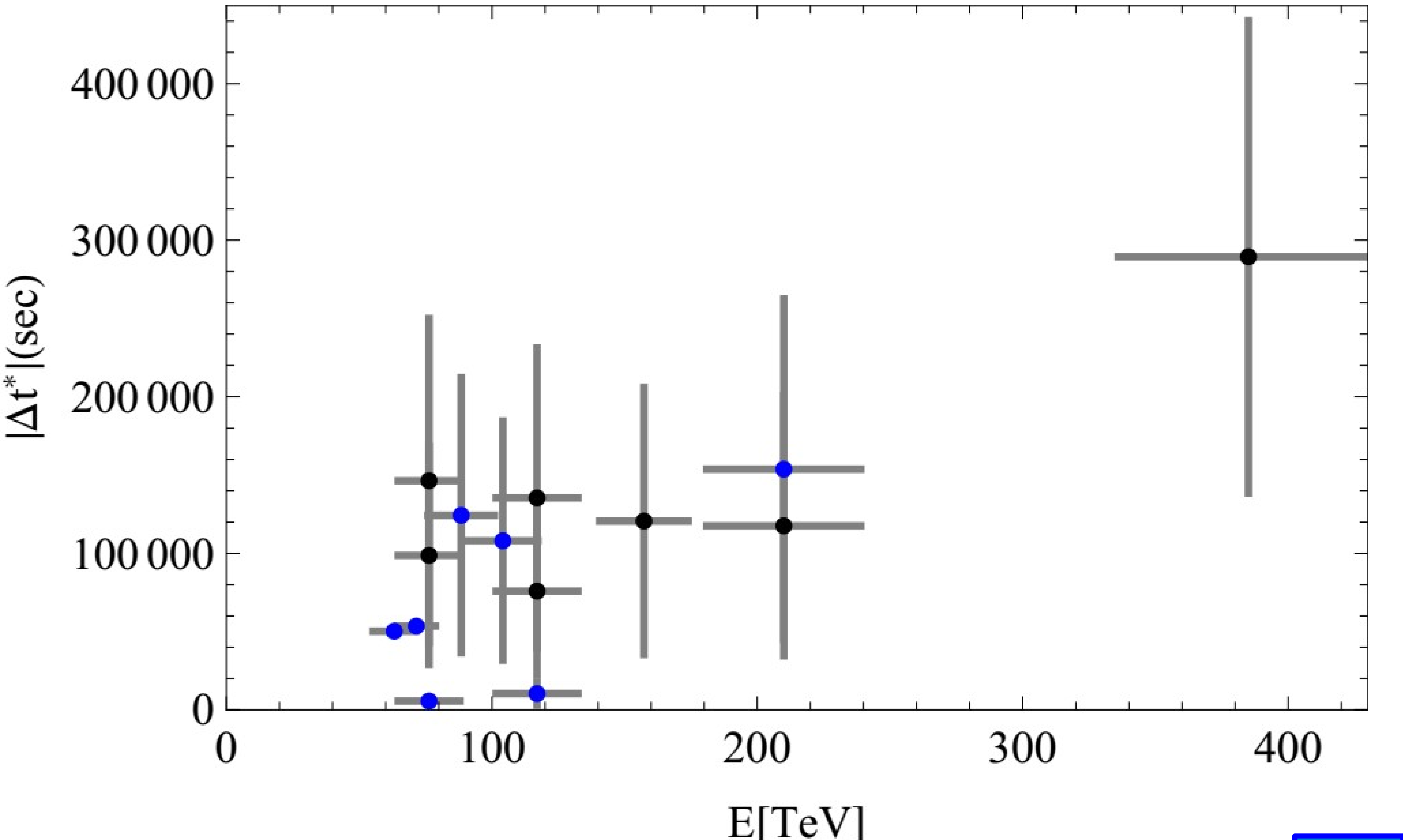


- The long-GRB distribution contains the 68% of the sample within an interval of ~1 around z~1.5.

- The average of the measured redshifts (1.497) for the long GRBs in our sample, could be a reasonably good estimate of the redshifts of the other long GRBs.

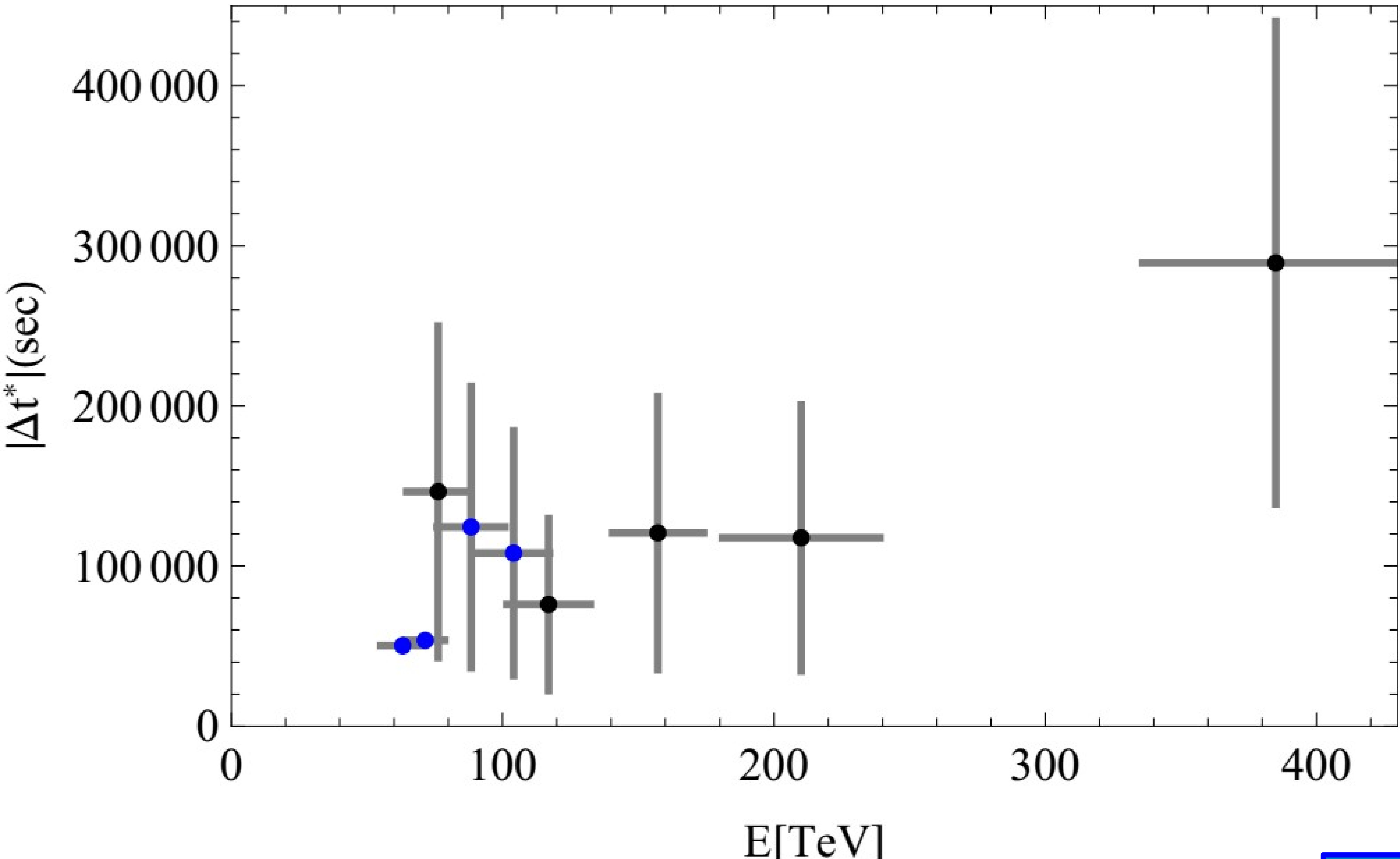
- The short-GRB distribution contains the 68% of the sample within an interval of ~0.4 around z~0.6.

Our dataset

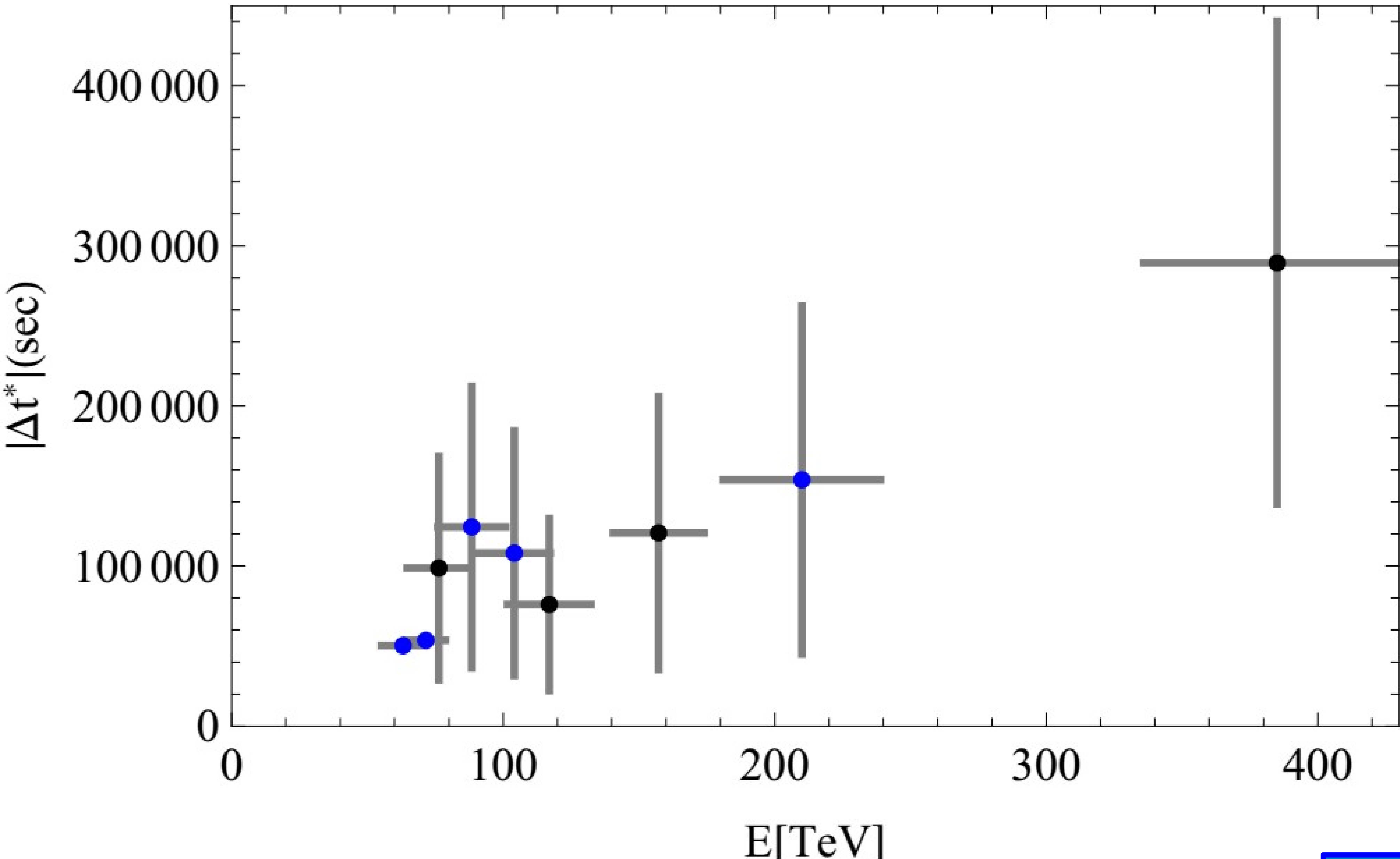


400 000
300 000
200 000
100 000
0
$|\Delta t^*|$(sec)
0
100
200
300
400
E[TeV]

By smaller angular distance



By best correlation



Fals alarm probability

CORRELATION **FALSE ALARM PROBABILITY**

BEST CORRELATION SELECTION

	$z_{long} = \bar{z}$	$z_{long} = 2$
$z_{short} = 0.5$	0.958	0.953
$z_{short} = 0.6$	**0.951**	0.960
$z_{short} = 0.7$	0.941	0.964

	$z_{long} = \bar{z}$	$z_{long} = 2$
$z_{short} = 0.5$	0.03 %	0.04 %
$z_{short} = 0.6$	**0.03 %**	0.02 %
$z_{short} = 0.7$	0.04 %	0.01 %

WORST CORRELATION SELECTION

	$z_{long} = \bar{z}$	$z_{long} = 2$
$z_{short} = 0.5$	0.844	0.869
$z_{short} = 0.6$	**0.803**	0.849
$z_{short} = 0.7$	0.751	0.822

	$z_{long} = \bar{z}$	$z_{long} = 2$
$z_{short} = 0.5$	0.7 %	0.6 %
$z_{short} = 0.6$	**1.0 %**	0.6 %
$z_{short} = 0.7$	1.5 %	0.8 %

Fals alarm probability

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MINIMIZATION OF ψ/σ

CORRELATION: ~ 0.86

FALSE ALARM PROBABILITY: ~ 0.12%

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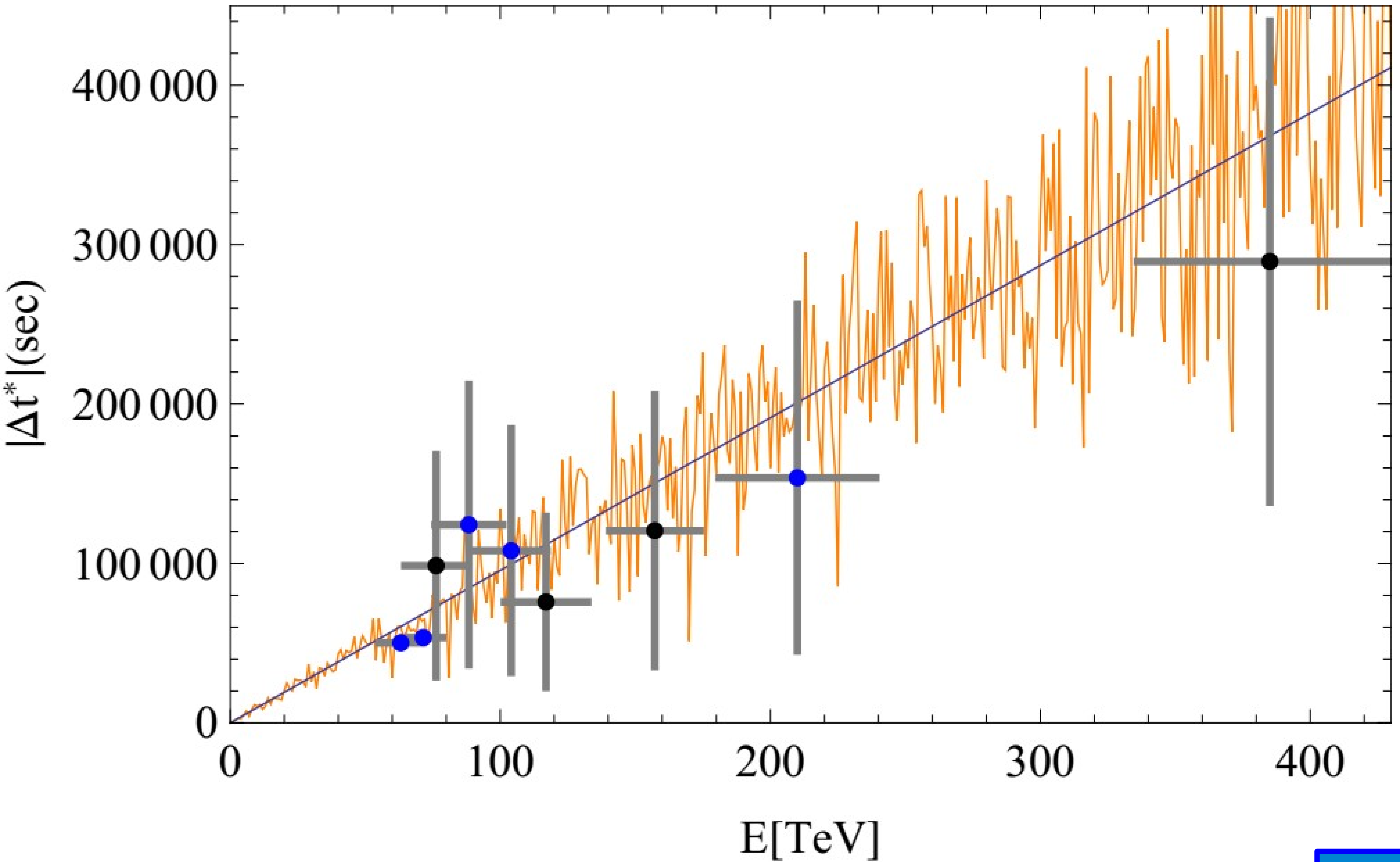
Toward estimating model parameters

$\eta_- = -\eta_+ \qquad \delta_- = \delta_+$

$\boxed{|\eta_+| = 23 \pm 2,\ \delta_+ = 4.7 \pm 1.5}$

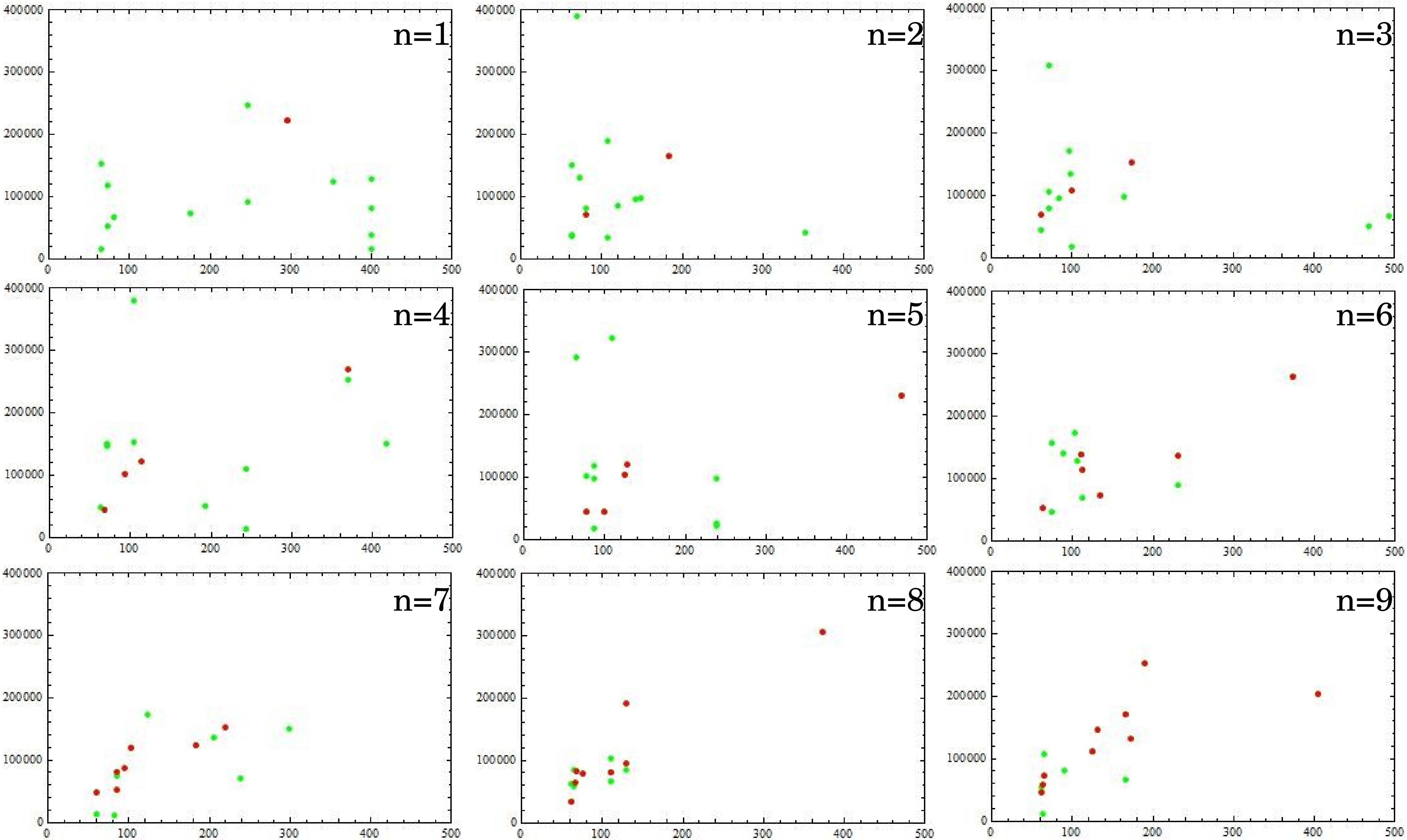


NOISE

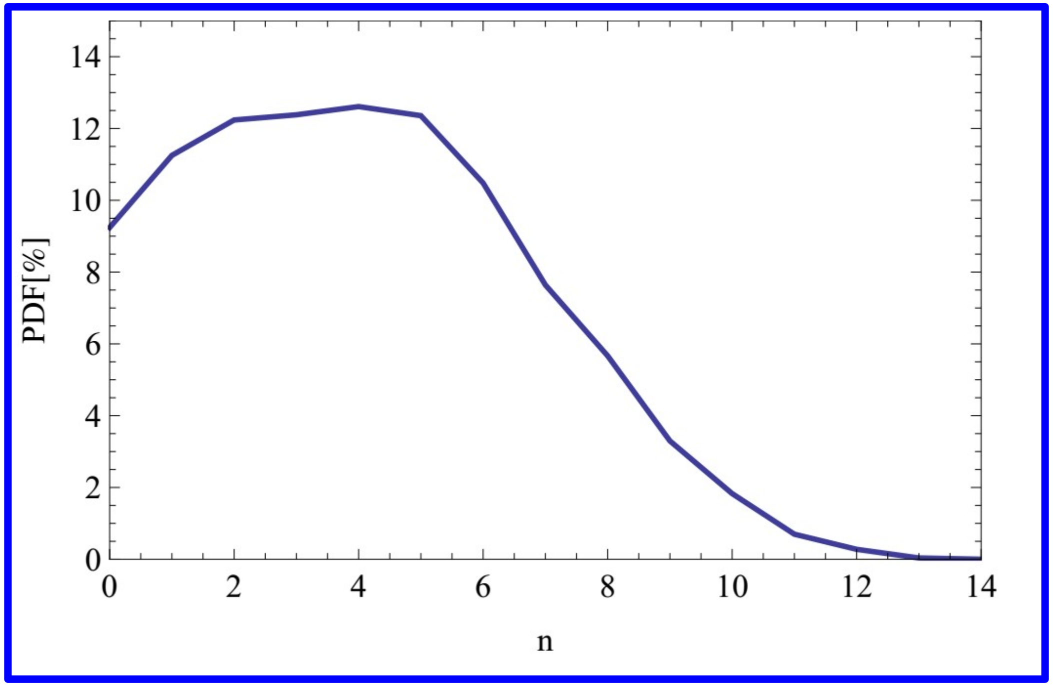
Let's generate 14 points

n → Model

21-n → Random



14 points Probability Density Functions



Probability Density Function to obtain
14 points from 21 events, with

n points from the model

N-n random neutrino-GRB pair

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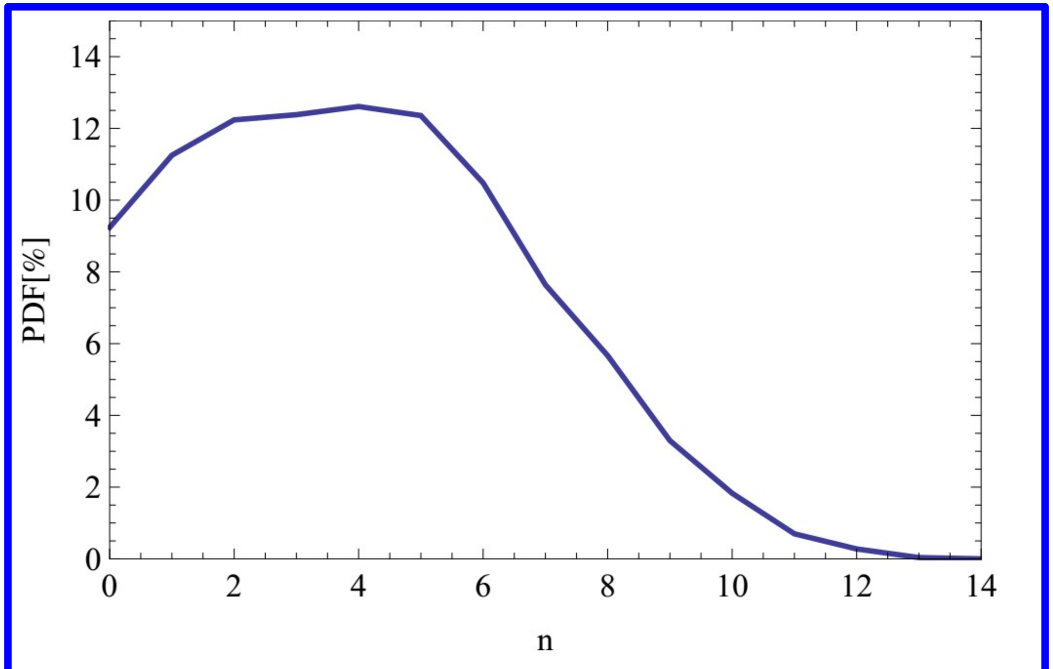

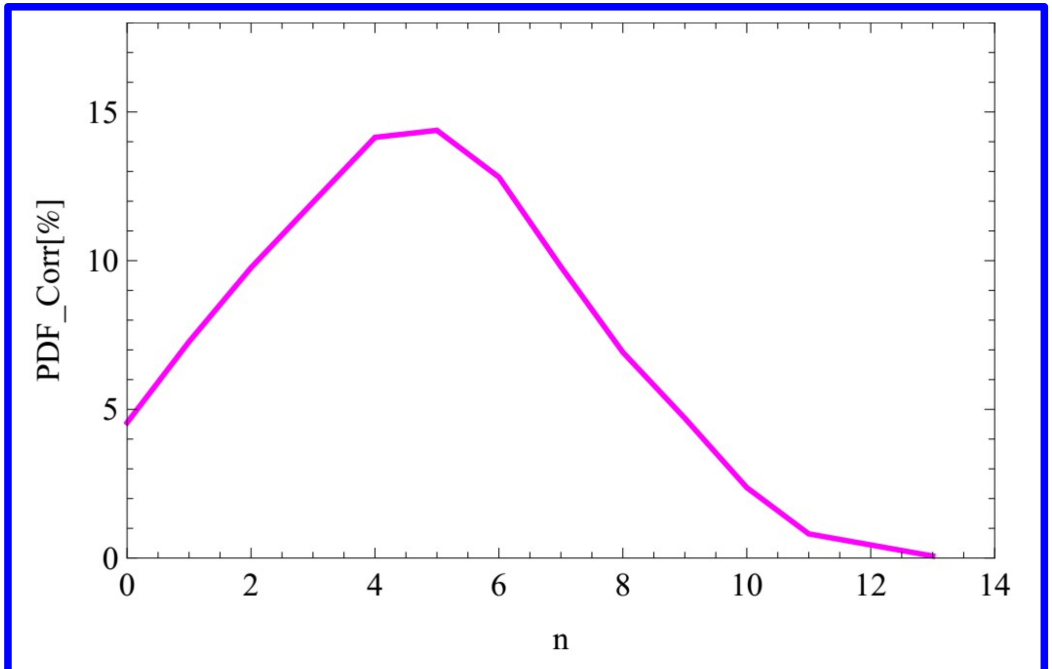

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With correlation > 0.8

Conclusions

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WE NEED MORE DATA