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Constraining the contribution of Gamma-Ray Bursts to the high-energy diffuse neutrino flux with 10 years of ANTARES data

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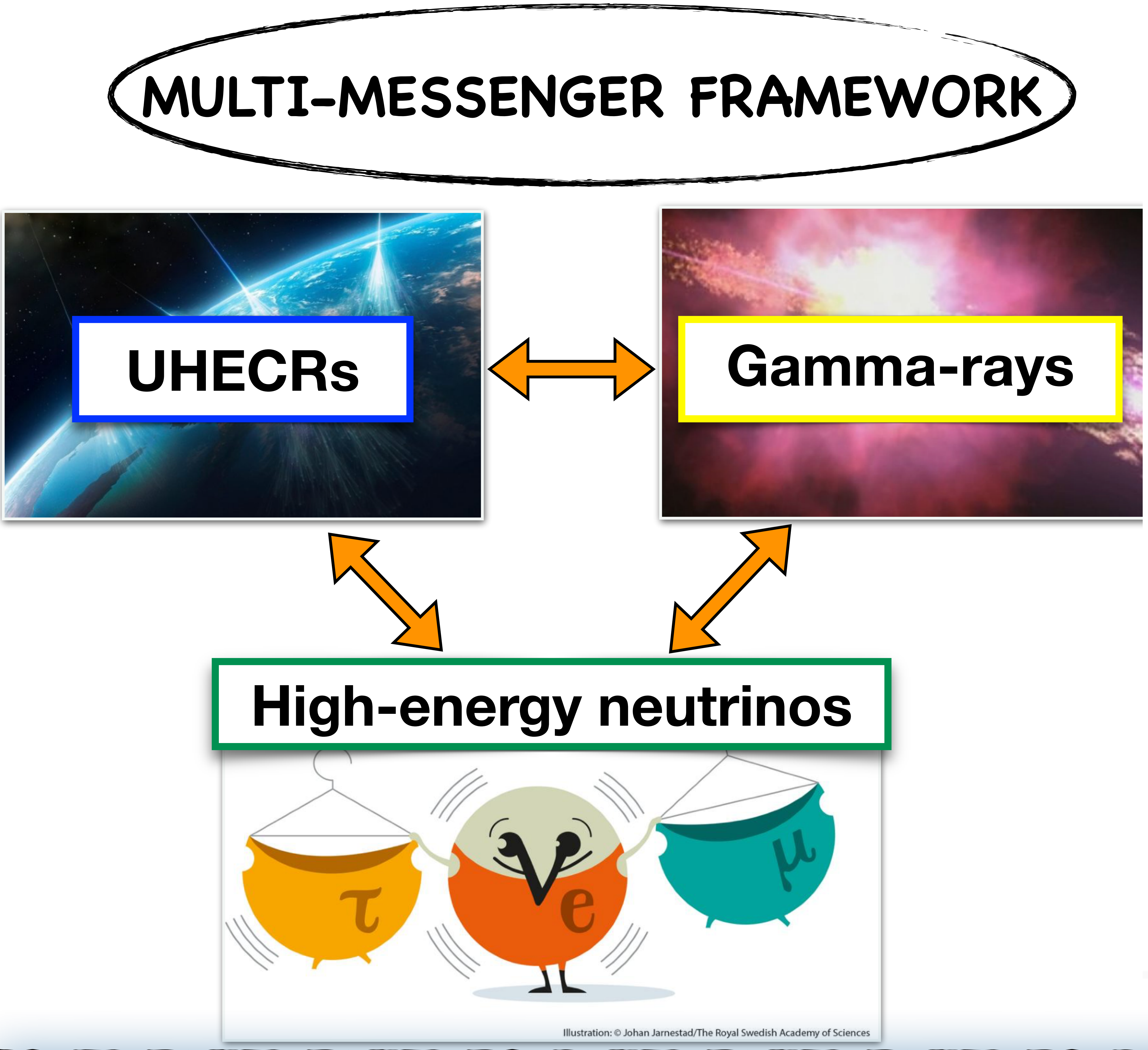
On behalf of the ANTARES Collaboration

Outline

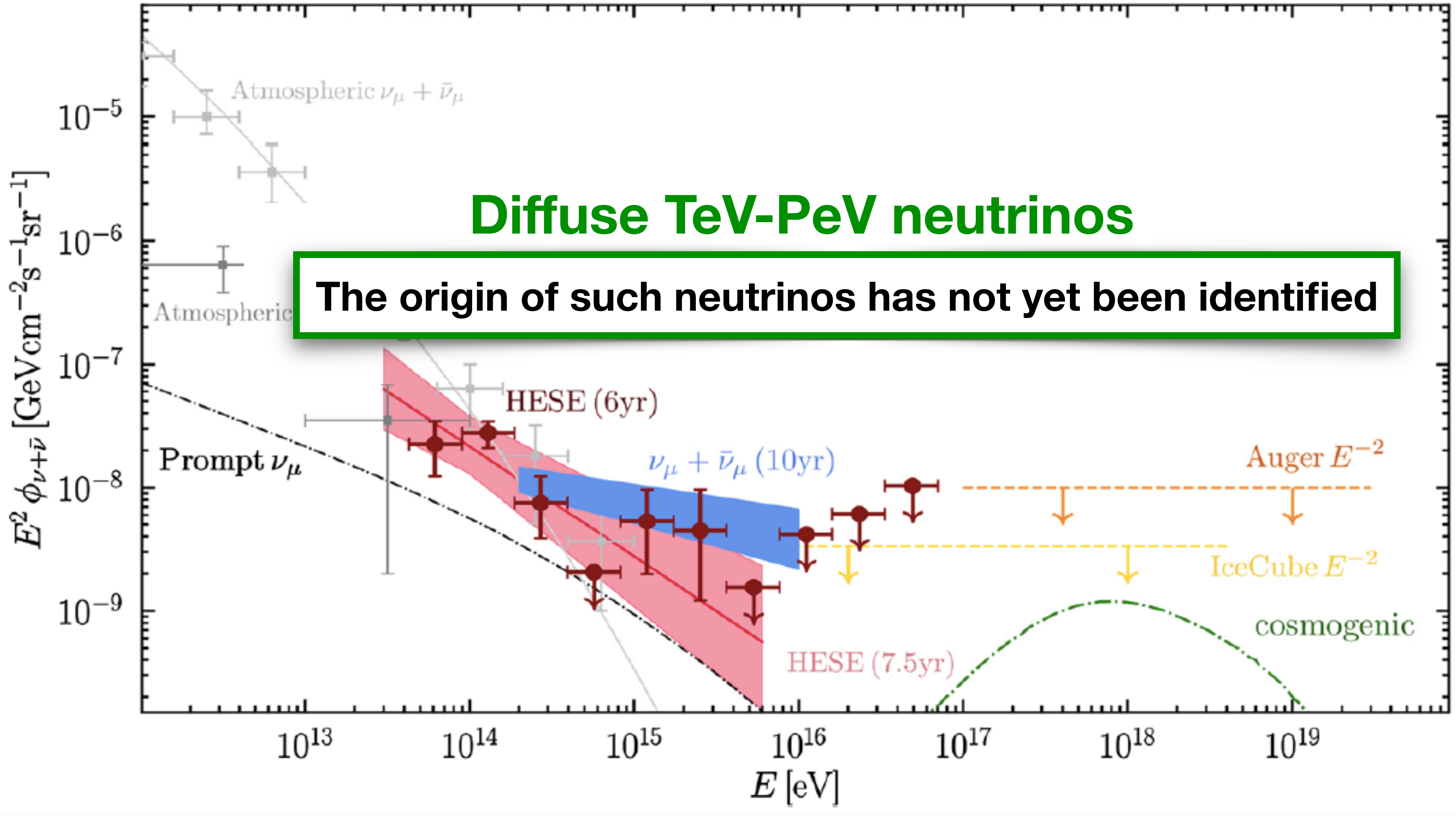
- Physics context of the work
- Gamma-Ray Bursts (GRBs) and neutrino production within the framework of the Internal Shock model;
- Expected stacked neutrino fluence by GRBs observable with ANTARES;
- Differences in modeling neutrino fluxes from GRBs with respect to previous analyses;
- Results and their interpretation in the light of the cosmic diffuse neutrino flux.

Physics context of the work

Need to explain the origin of the **diffuse astrophysical neutrino flux** observed by IceCube



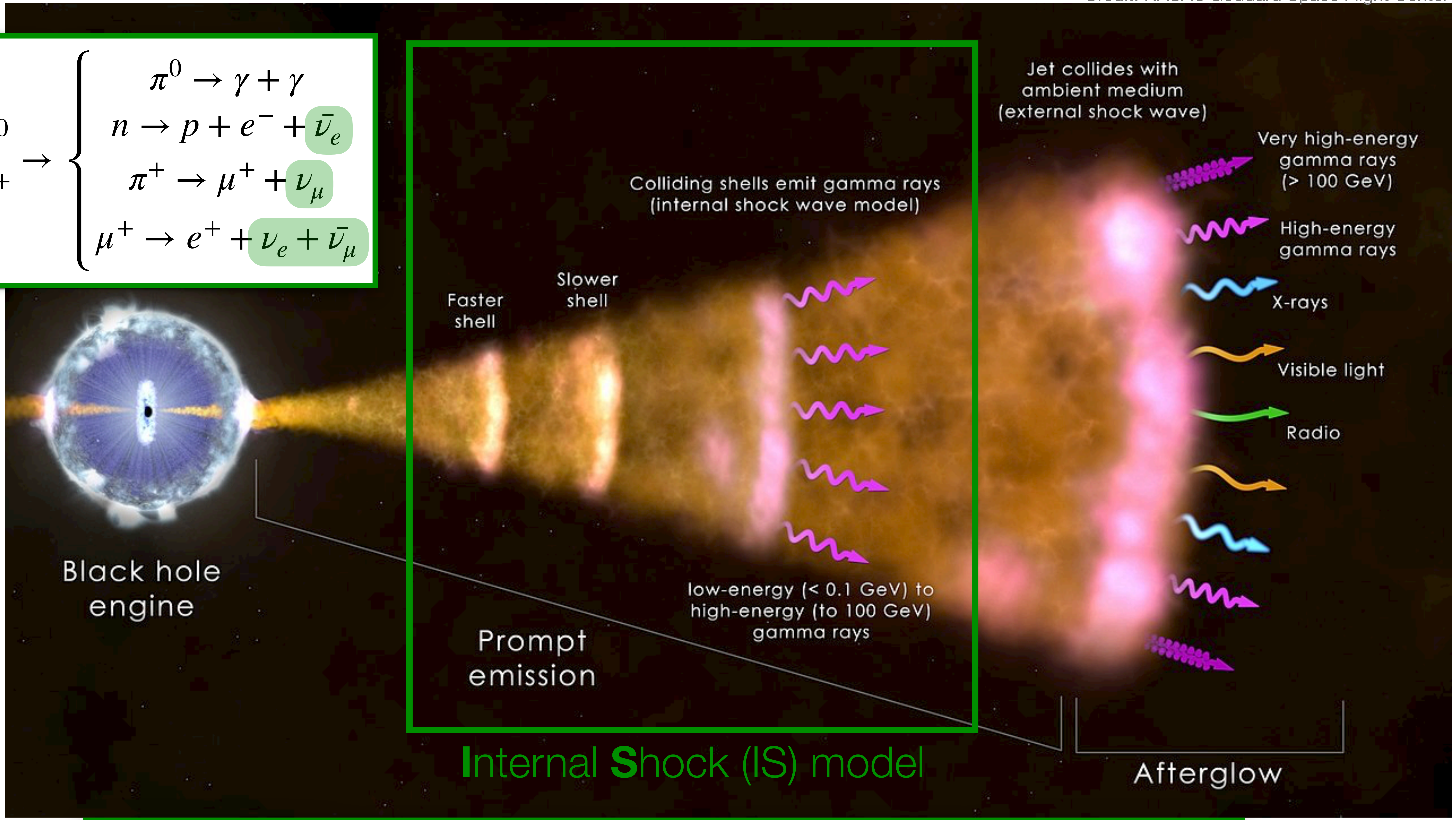
Credit by Kheirandish A., Astrophysics and Space Science, **365** 108 (2020)



Gamma-Ray Bursts: Fireball Model

Credit: NASA's Goddard Space Flight Center

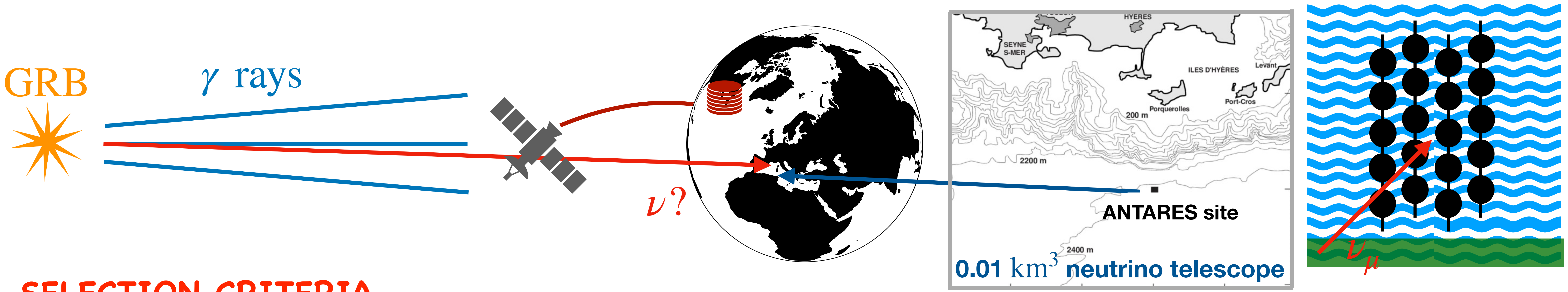
$$p + \gamma \to \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases} \to \begin{cases} \pi^0 \to \gamma + \gamma \\ n \to p + e^- + \bar{\nu}_e \\ \pi^+ \to \mu^+ + \nu_\mu \\ \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \end{cases}$$



Neutrino production expected during the prompt phase If GRBs are hadronic sources

Waxman & Bahcall 1997

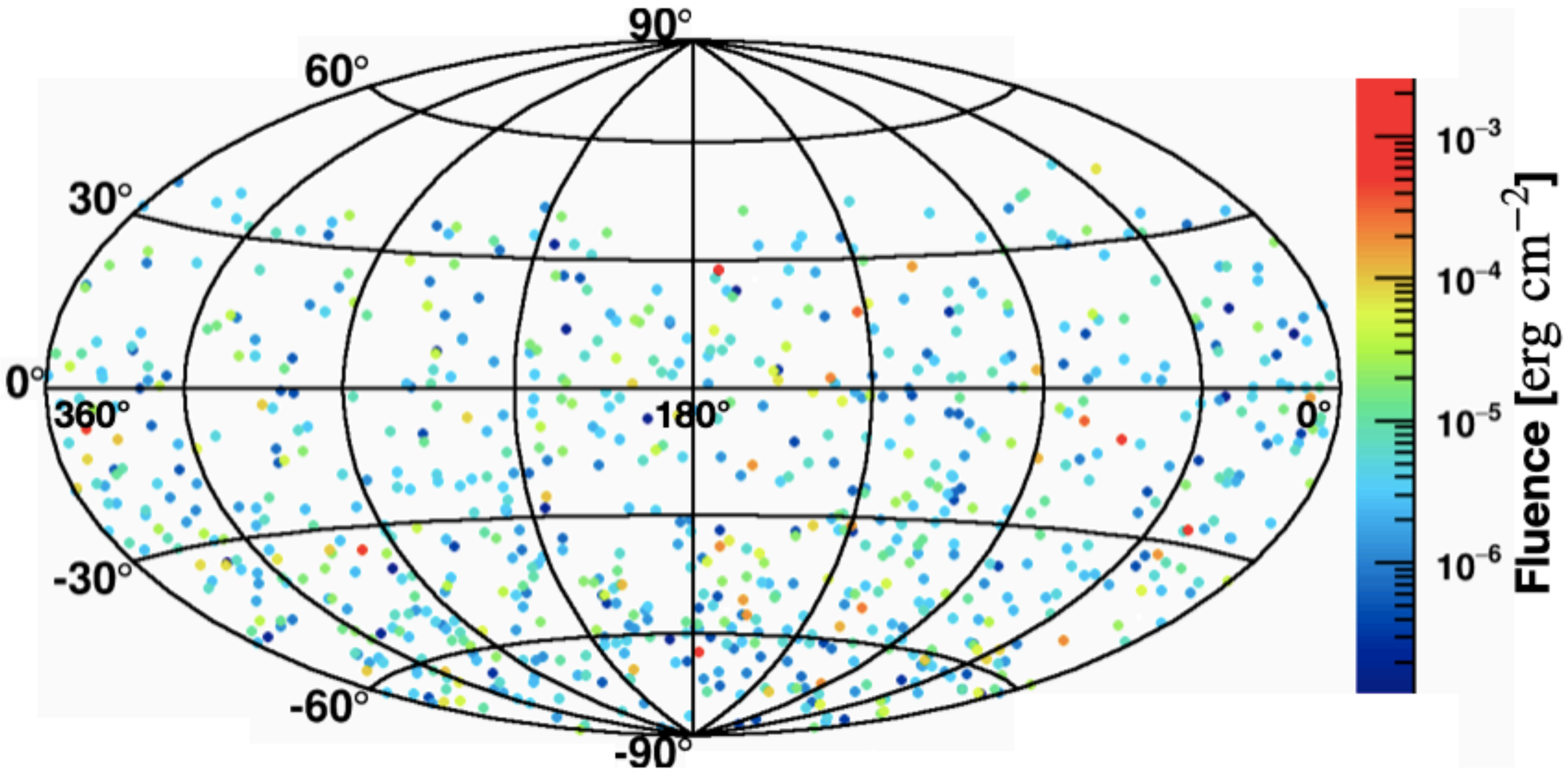
GRB search with ANTARES up-going ν_μ



10 years of ANTARES data

SELECTION CRITERIA

- **Long bursts** in **2007-2017** from Fermi (GBM + LAT), Swift (BAT + XRT + UVOT) catalogs and Konus-Wind GCN (https://gcn.gsfc.nasa.gov/gcn3_archive.html);
- Spectrum is measured;
- T90 (~ duration) is measured;
- Position is measured and satellite angular uncertainty is less than 10 degrees;
- **Below ANTARES horizon at trigger time**;
- ANTARES taking data.

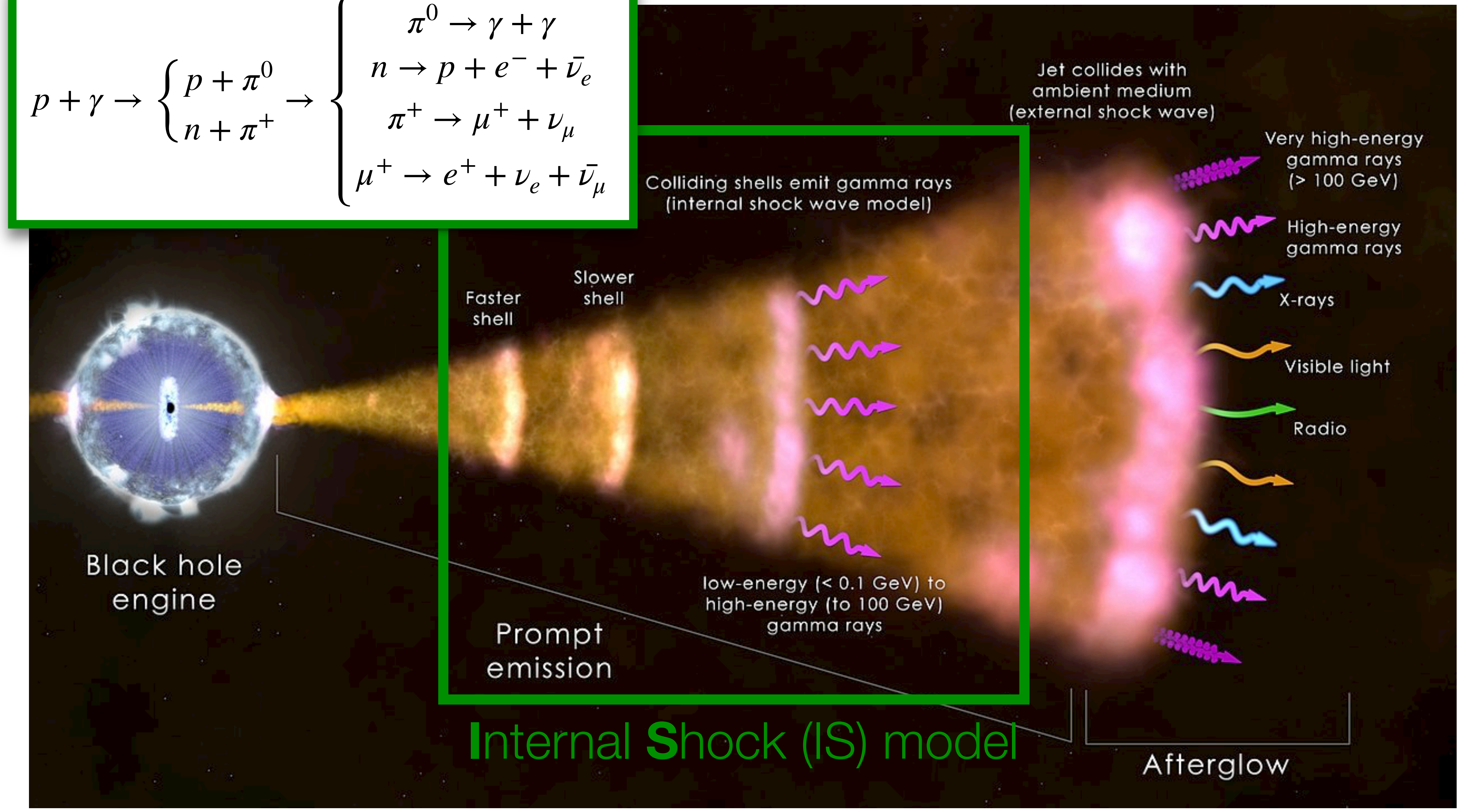


784 GRBs

ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

Neutrino-gamma relation in IS model

$$p+\gamma \rightarrow \begin{cases} p+\pi^0 \\ n+\pi^+ \end{cases} \rightarrow \begin{cases} \pi^0 \rightarrow \gamma+\gamma \\ n \rightarrow p+e^-+\bar{\nu}_e \\ \pi^+ \rightarrow \mu^+ + \nu_\mu \\ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \end{cases}$$



We want to know — Converted energy

$$\int_0^{+\infty} E_\nu F_\nu(E_\nu)dE_\nu = \frac{1}{8} f_p \left[1-(1-x_{p\rightarrow\pi})^{\frac{R}{\lambda_{p\gamma}}}\right] \int_{E_{min}}^{E_{max}} E_\gamma F_\gamma(E_\gamma)dE_\gamma$$

NEUTRINO FLUENCE

$$L_{\gamma,\text{iso}} = 4\pi d_L^2(z)\frac{F_\gamma}{T_{90}}$$

$$\frac{R}{\lambda_{p\gamma}} = \left(\frac{L_{\gamma,\text{iso}}}{10^{52}\text{erg/s}}\right)\left(\frac{10^{2.5}}{\Gamma}\right)^4\left(\frac{0.01\text{s}}{t_v}\right)\left(\frac{\text{MeV}}{E_{\text{peak}}}\right) = \tau_{p\gamma}$$

$< x_{p\rightarrow\pi} > = 0.2$ Average fraction of proton energy going into a pion per interaction

$f_p = 10$ Fraction of the total energy in protons compared to the total energy in electrons

BULK LORENTZ FACTOR — MINIMUM VARIABILITY TIMESCALE

Unknown parameters of the model (intrinsic source characteristics)

Large parameter variability from burst to burst

(NeuCosmA model)

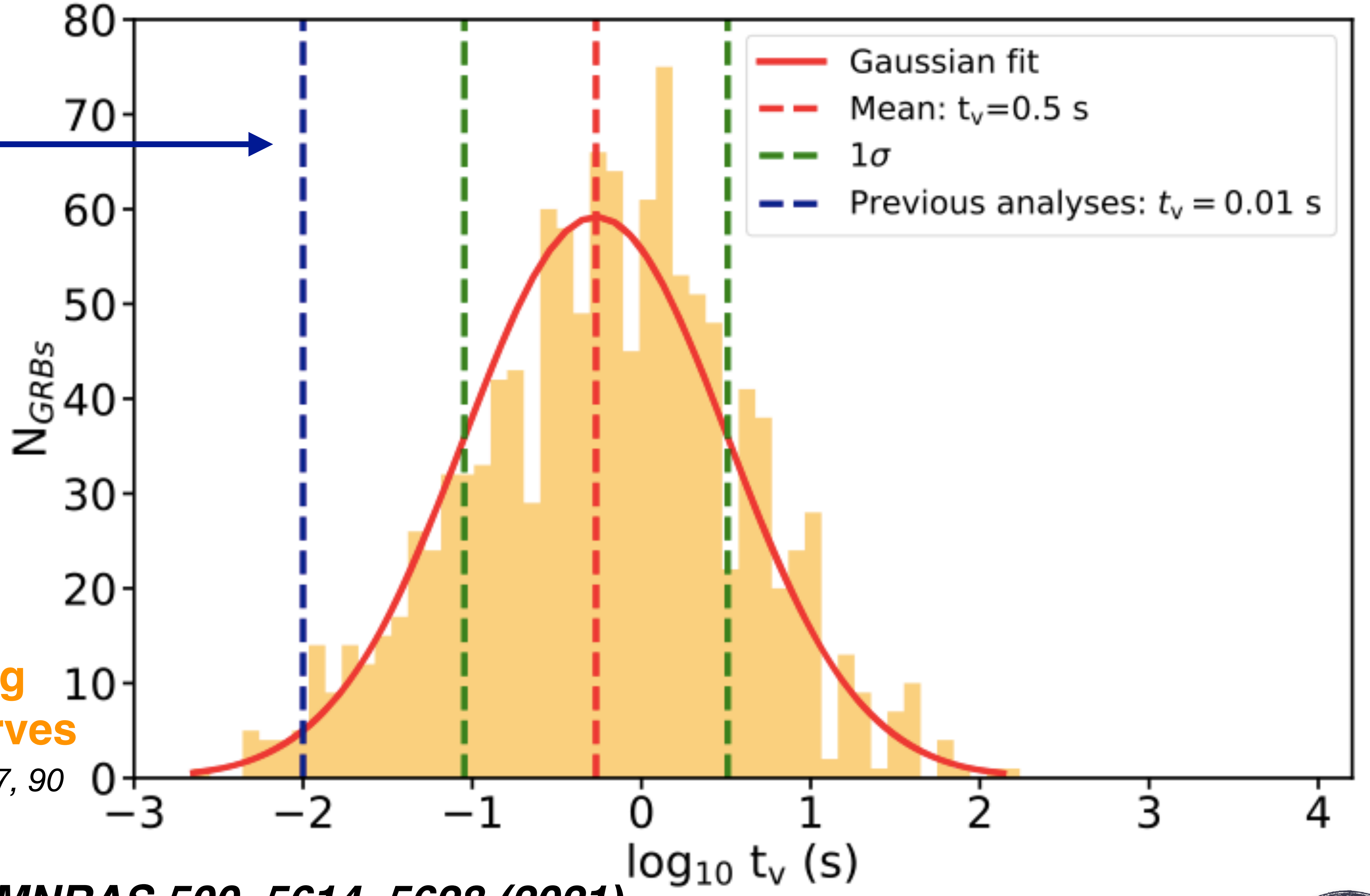
Hummer et al., Phys. Rev. Lett., 108, 231101, 2012

Parameter estimation: Minimum variability timescale t_v

$$\frac{R}{\lambda_{p\gamma}} = \left(\frac{L_{\gamma,\mathrm{iso}}}{10^{52}\mathrm{erg/s}}\right)\left(\frac{10^{2.5}}{\Gamma}\right)^4\left(\frac{0.01\mathrm{s}}{t_v}\right)\left(\frac{\mathrm{MeV}}{E_{\mathrm{peak}}}\right) = \tau_{p\gamma}$$

In the previous ANTARES analyses the minimum variability time scale was fixed at $t_v = 10$ ms

1000 random extractions for each GRB with unknown minimum variability timescale (~70% of the sample)



Values obtained from post-processing Fourier analysis on the burst lightcurves

Golkhou, V. Zach & Butler, Nathaniel R. 2014, ApJ, 787, 90
Golkhou, V. Zach, et al. 2015, ApJ, 811, 93

ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

Parameter estimation: Bulk Lorentz Factor Γ and redshift z

$$\frac{R}{\lambda_{p\gamma}} = \left(\frac{L_{\gamma,\mathrm{iso}}}{10^{52}\mathrm{erg/s}}\right)\left(\frac{10^{2.5}}{\Gamma}\right)^4\left(\frac{0.01\mathrm{s}}{t_\mathrm{v}}\right)\left(\frac{\mathrm{MeV}}{E_\mathrm{peak}}\right) = \tau_{p\gamma}$$

$L_{\gamma,\mathrm{iso}}$ - Γ correlation

$$\Gamma = 249\left(\frac{L_{\gamma,\mathrm{iso}}}{10^{52}\mathrm{erg/s}}\right)^{0.30}$$

Lu et al., ApJ, 751, 49, 2012
https://doi.org/ 10.1088/0004-637X/751/1/49

Knowing $L_{\gamma,\mathrm{iso}}$ we can infer Γ

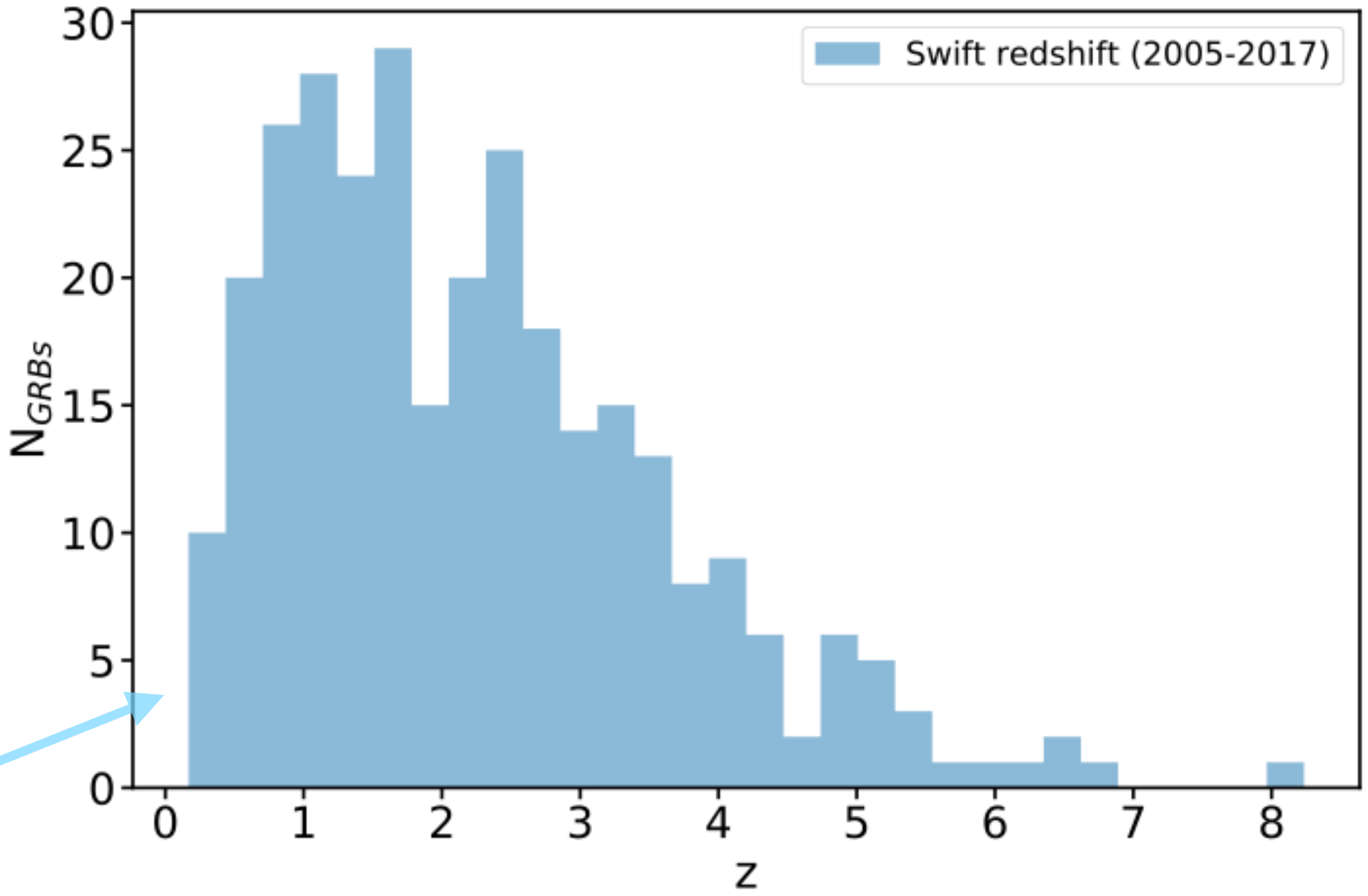
$$L_{\gamma,\mathrm{iso}}(z) = 4\pi d_L^2(z) F_\gamma T_{90}$$

measured (F_γ)

measured (T_{90})

To apply this correlation we need the redshift in order to evaluate the burst isotropic luminosity

1000 random extractions for each GRB with unknown redshift (~90% of the sample)



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Parameter estimation

$$\frac{R}{\lambda_{p\gamma}} = \left(\frac{L_{\gamma,\mathrm{iso}}}{10^{52}\mathrm{erg/s}}\right)\left(\frac{10^{2.5}}{\Gamma}\right)^4\left(\frac{0.01\mathrm{s}}{t_{\mathrm{var}}}\right)\left(\frac{\mathrm{MeV}}{E_{\mathrm{peak}}}\right) = \tau_{p\gamma}$$

L_{iso} - Γ correlation

$$\Gamma = 249\left(\frac{L_{\gamma,\mathrm{iso}}}{10^{52}\mathrm{erg/s}}\right)^{0.3}$$

Lu et al., ApJ, 751, 49, 2012

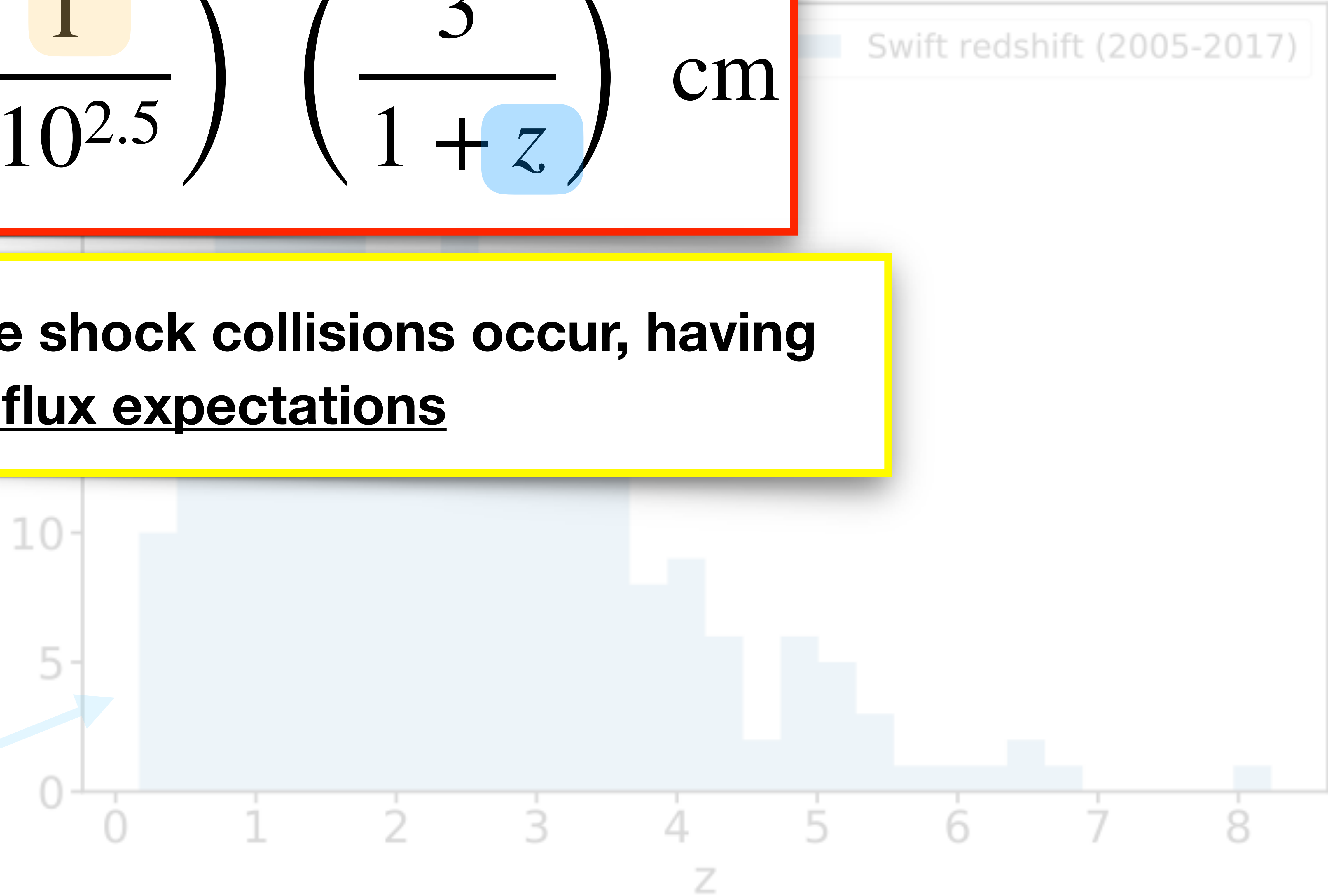
https://doi.org/10.1088/0004-637X

$$R_{\mathrm{is}} = 2\times 10^{13}\left(\frac{t_v}{0.01\ s}\right)\left(\frac{\Gamma}{10^{2.5}}\right)^2\left(\frac{3}{1+z}\right)\ \mathrm{cm}$$

z, t_v and Γ, set the radial distance where shock collisions occur, having large impact on neutrino flux expectations

To apply this correlation we need the redshift in order to evaluate the burst isotropic luminosity

1000 random extractions for each GRB with unknown redshift (~90% of the sample)



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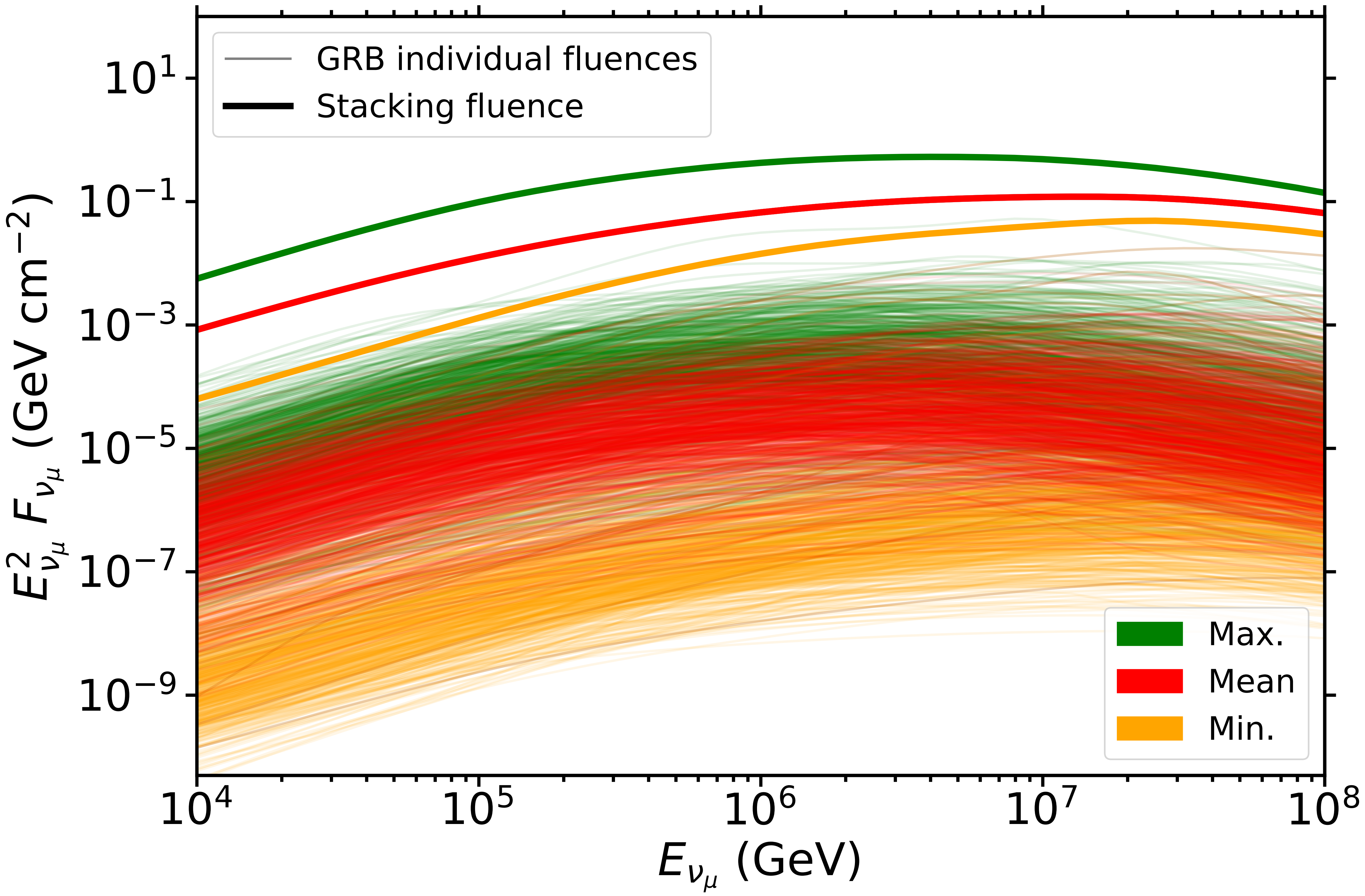
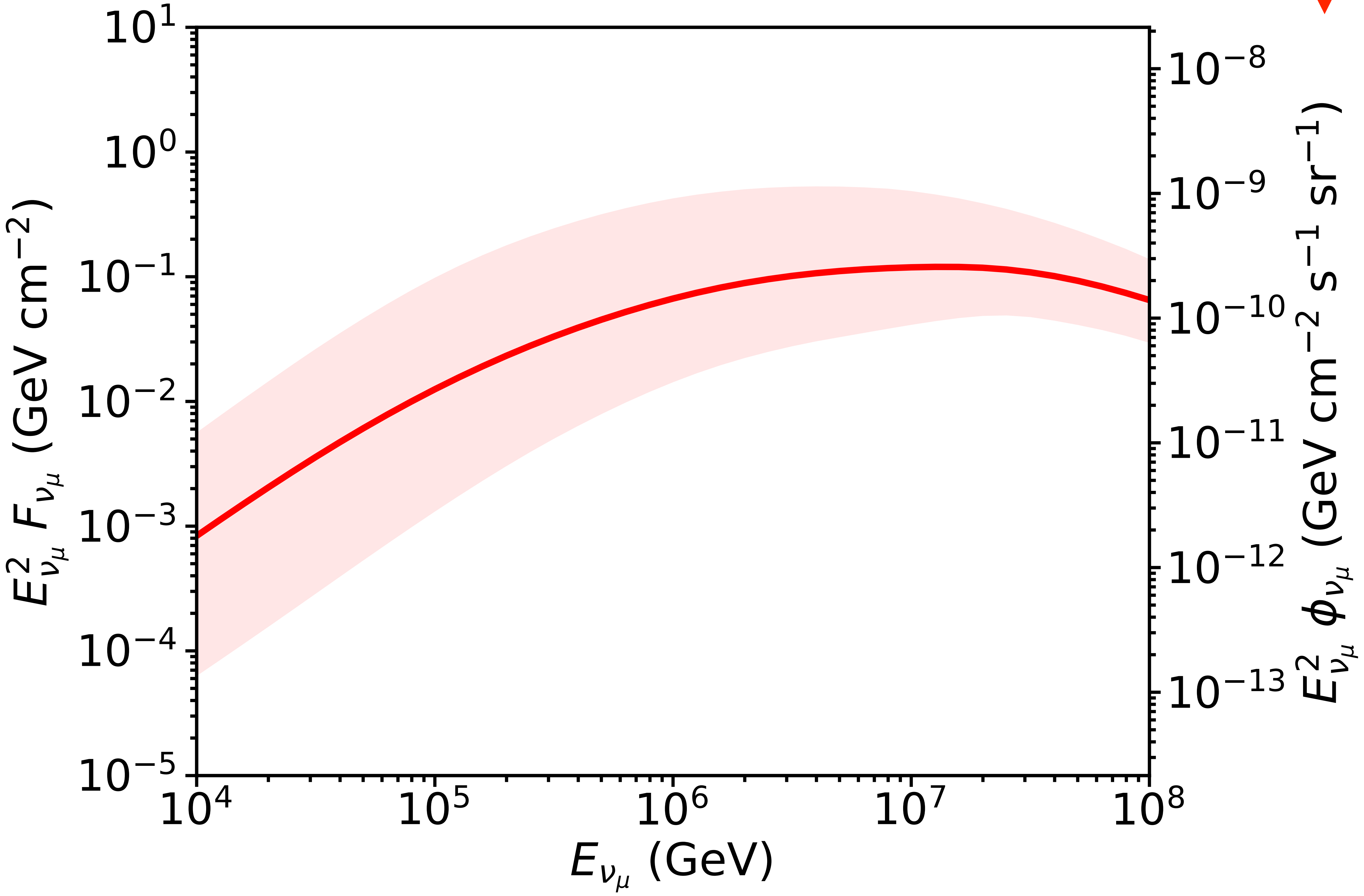
2007-2017 GRB stacked neutrino fluence (784 GRBs)

$$E^2_{\nu_\mu} F_{\nu_\mu} = \sum_{i=1}^{N_{\mathrm{GRB}}=784} (E^2_{\nu_\mu} F_{\nu_\mu})^i$$

$$E^2_{\nu_\mu} \phi_{\nu_\mu} = \sum_{i=1}^{N_{\mathrm{GRB}}} E^2_{\nu_\mu} F_{\nu_\mu} \frac{1}{4\pi} \frac{1}{N_{\mathrm{GRB}}} 667 \mathrm{yr}^{-1}$$

Diffuse neutrino flux



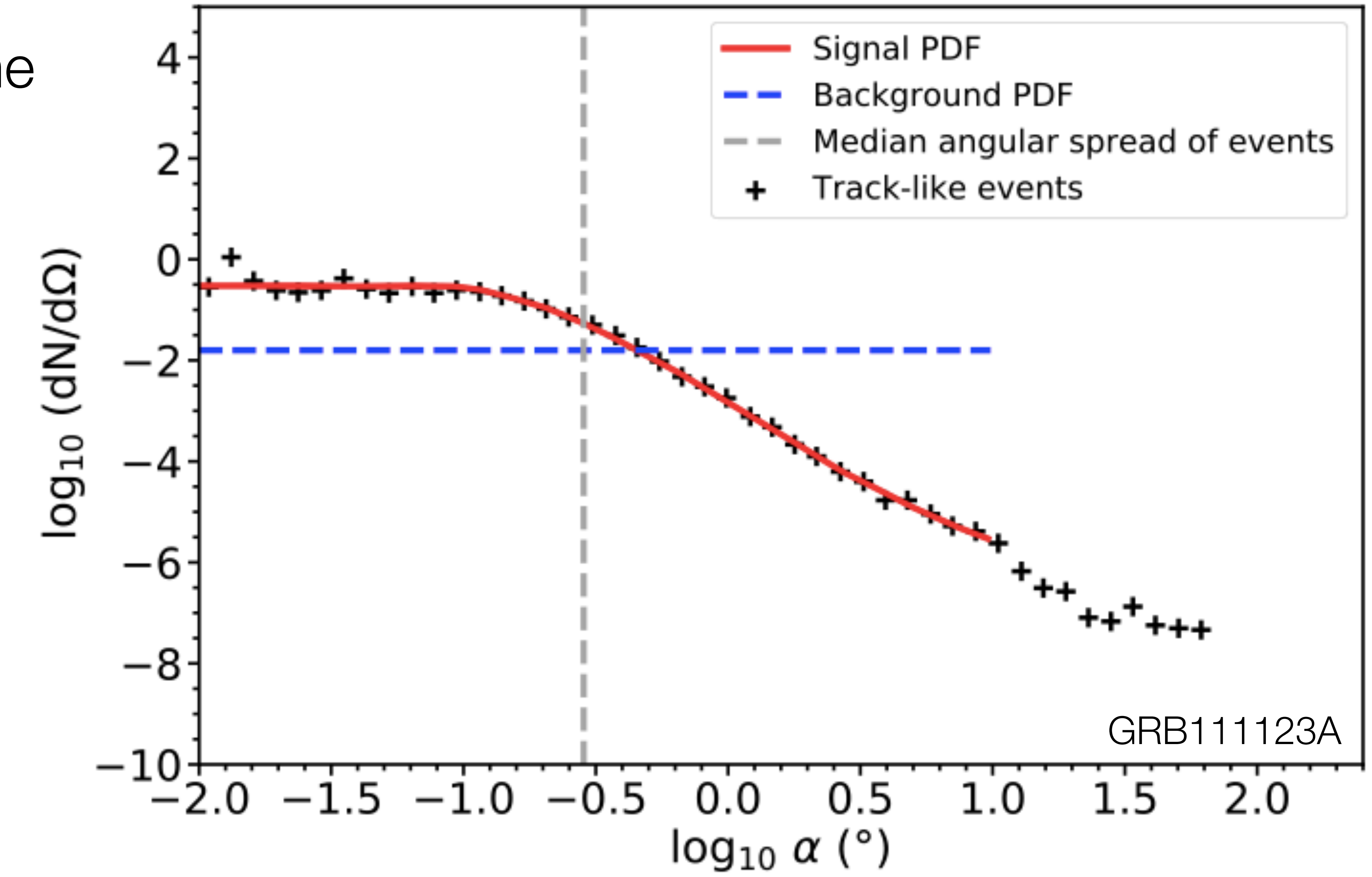


ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

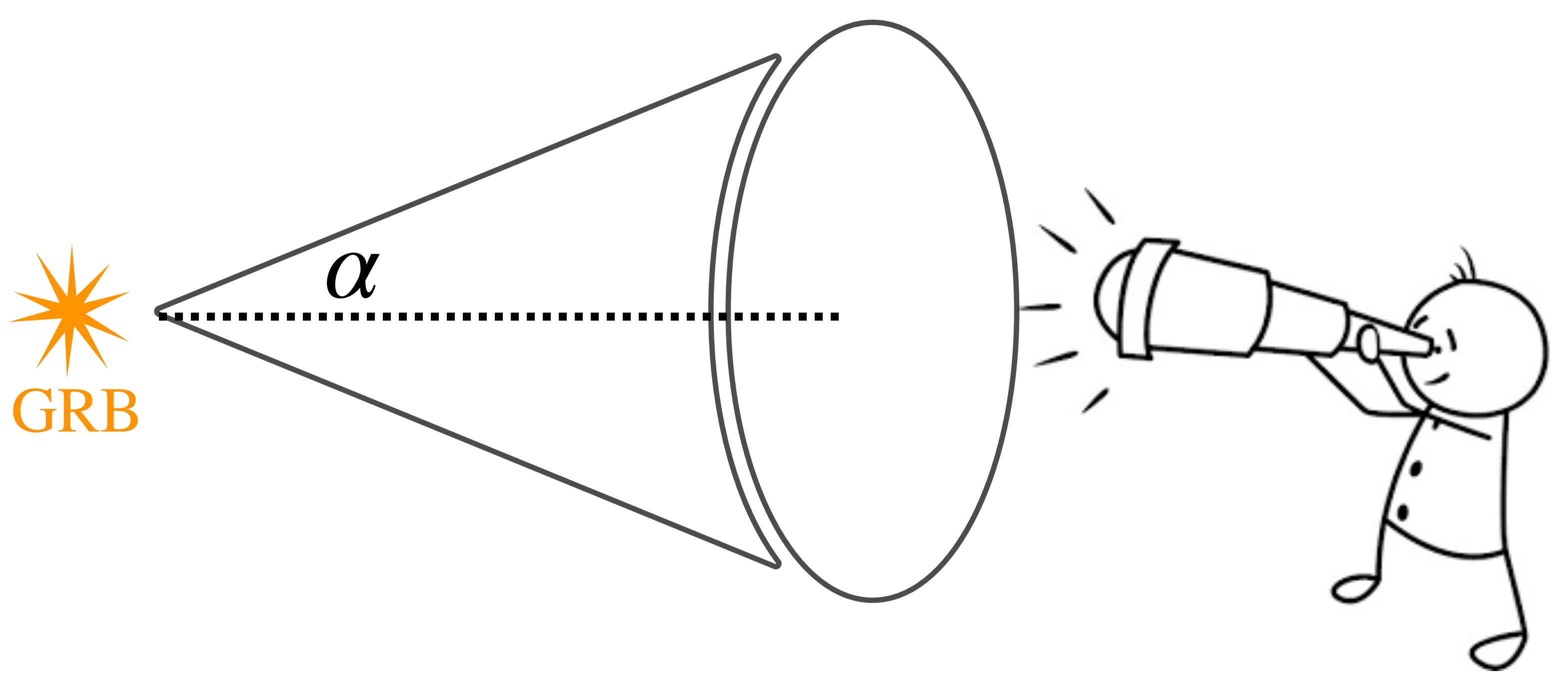
Signal simulation and background estimation

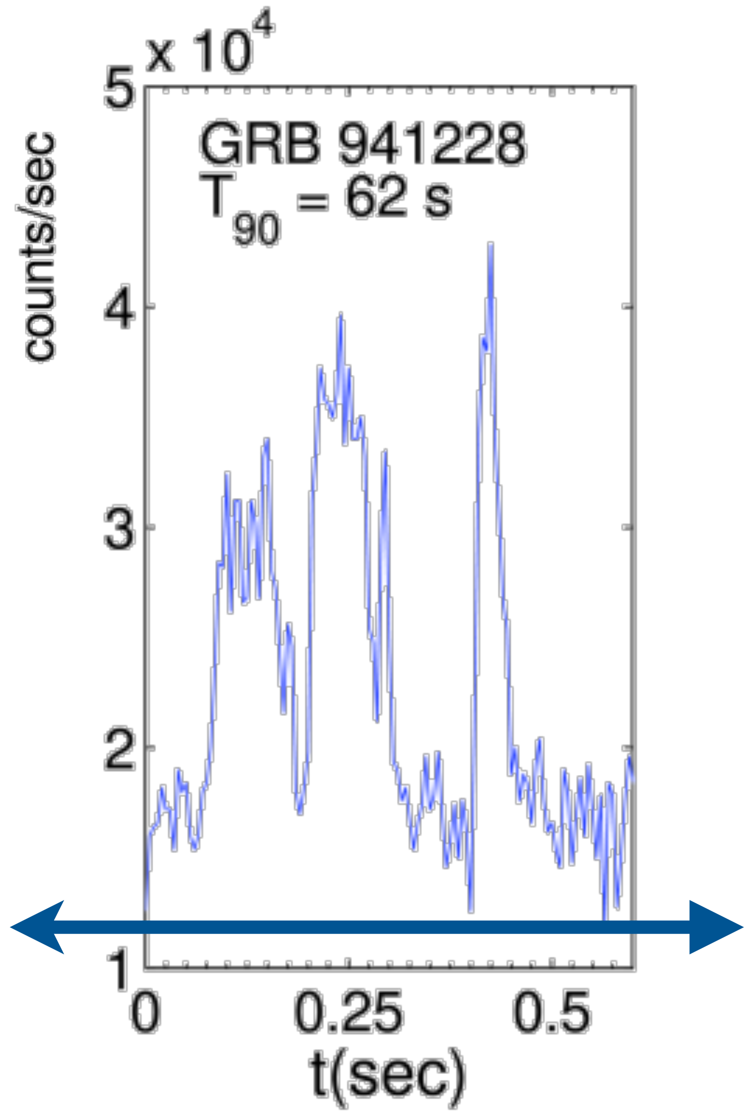
1. For each GRB, **signal MC simulations** were performed for the full statistics (2007-2017) accounting for detector performances where and when each burst has occurred as well as ANTARES pointing uncertainty

2. The expected number of **background** events associated to each GRB, at the GRB position, was evaluated directly **from data collected by ANTARES off source and off time** (2007-2017)



Angular window fixed at $\alpha = 10^{\circ}$ around satellite position





Search time window slightly extended than T_{90} (~ gamma-ray duration of the burst)

ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

Stacking search and optimization

ANTARES data were analyzed maximizing the discovery probability of the stacking sample through an **extended maximum likelihood strategy**

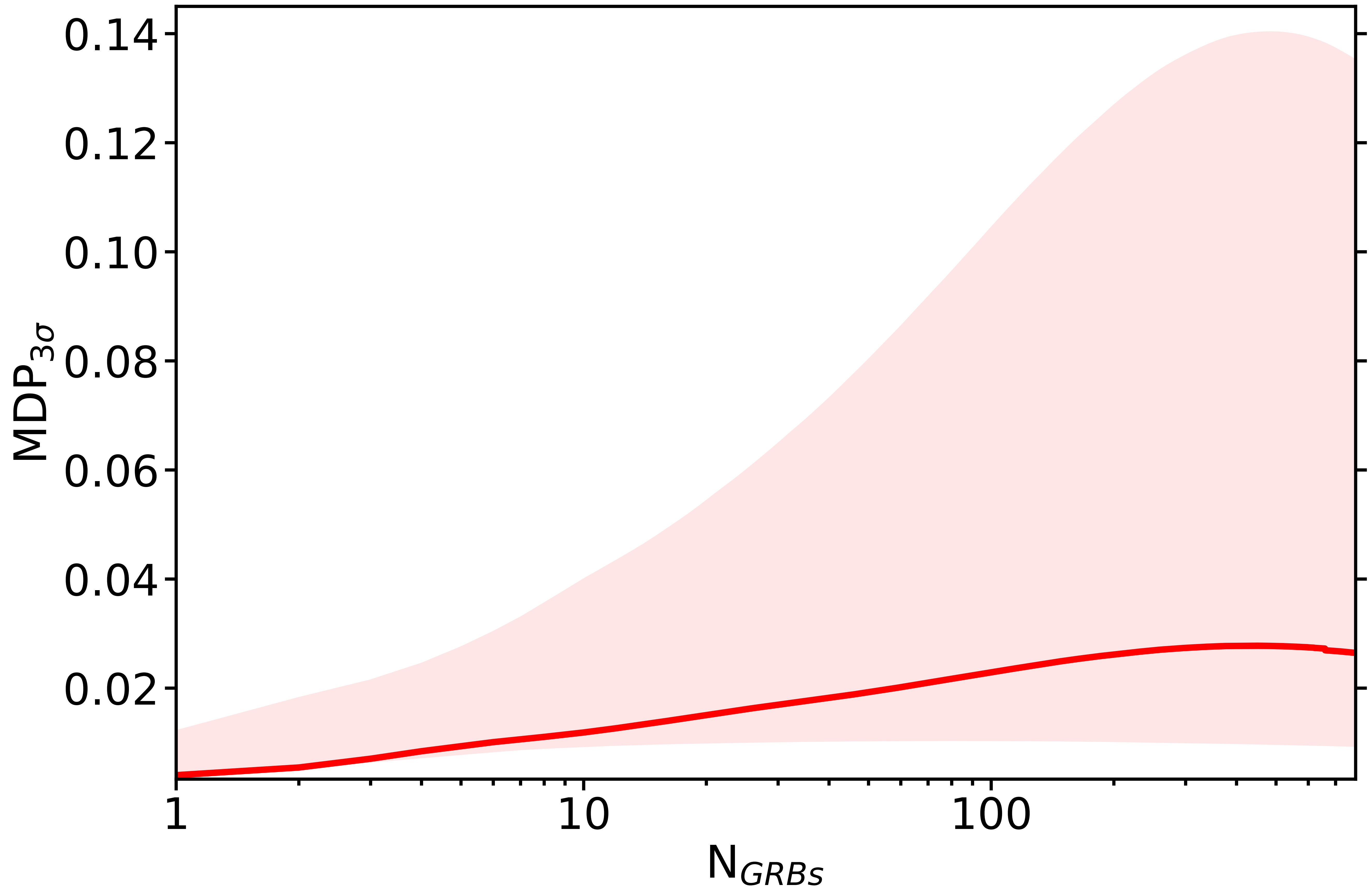
Barlow R., 1990, Nucl. Instr. Meth., A, 297, 496
Adrián-Martínez S. et al. (ANTARES Collaboration), 2013, A&A 559A

Several pseudo-experiments were performed (for different cuts) on the quality of track reconstruction

↓

The optimal cut is the one that maximizes the **M**odel **D**iscovery **P**otential (**MDP**) for the value of intensity signal predicted by NeuCosmA (model used to simulate the neutrino fluence expectation in each burst)

$$\mathrm{MDP}^p(\mathrm{N_{GRB}}) = 1 - \prod_{i=1}^{\mathrm{N_{GRB}}} (1 - \mathrm{MDP}_i^p)$$



ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

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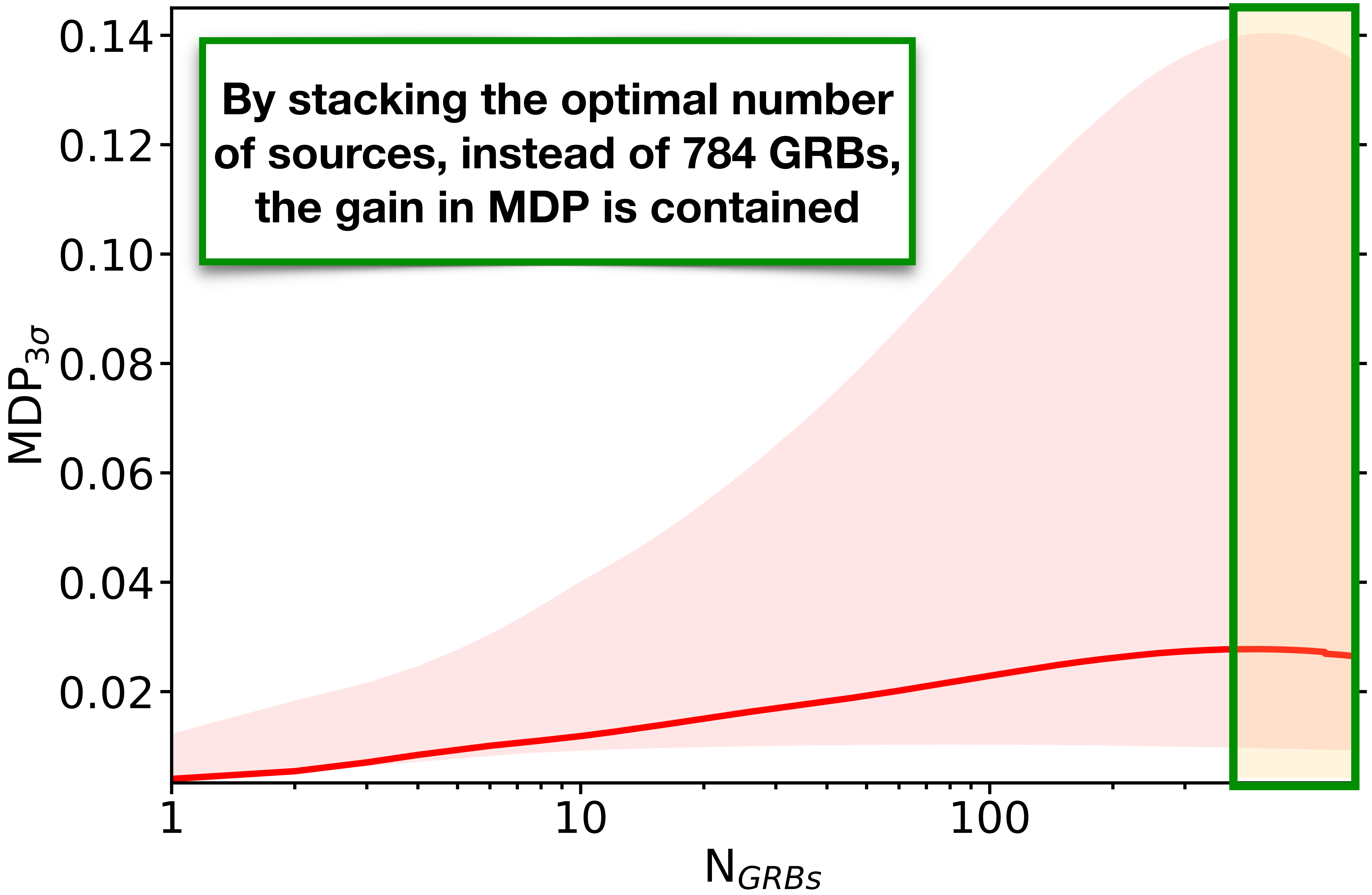
Barlow R., 1990, Nucl. Instr. Meth., A, 297, 496
Adrián-Martínez S. et al. (ANTARES Collaboration), 2013, A&A 559A

784 GRBs
for an equivalent lifetime of **T = 18.9 h** of data

The expected number of signal events from the total sample is:

$$n_s(N_{GRB} = 784) = 0.03^{+0.14}_{-0.02}$$



ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

Results: upper limit on stacked GRB neutrino fluence

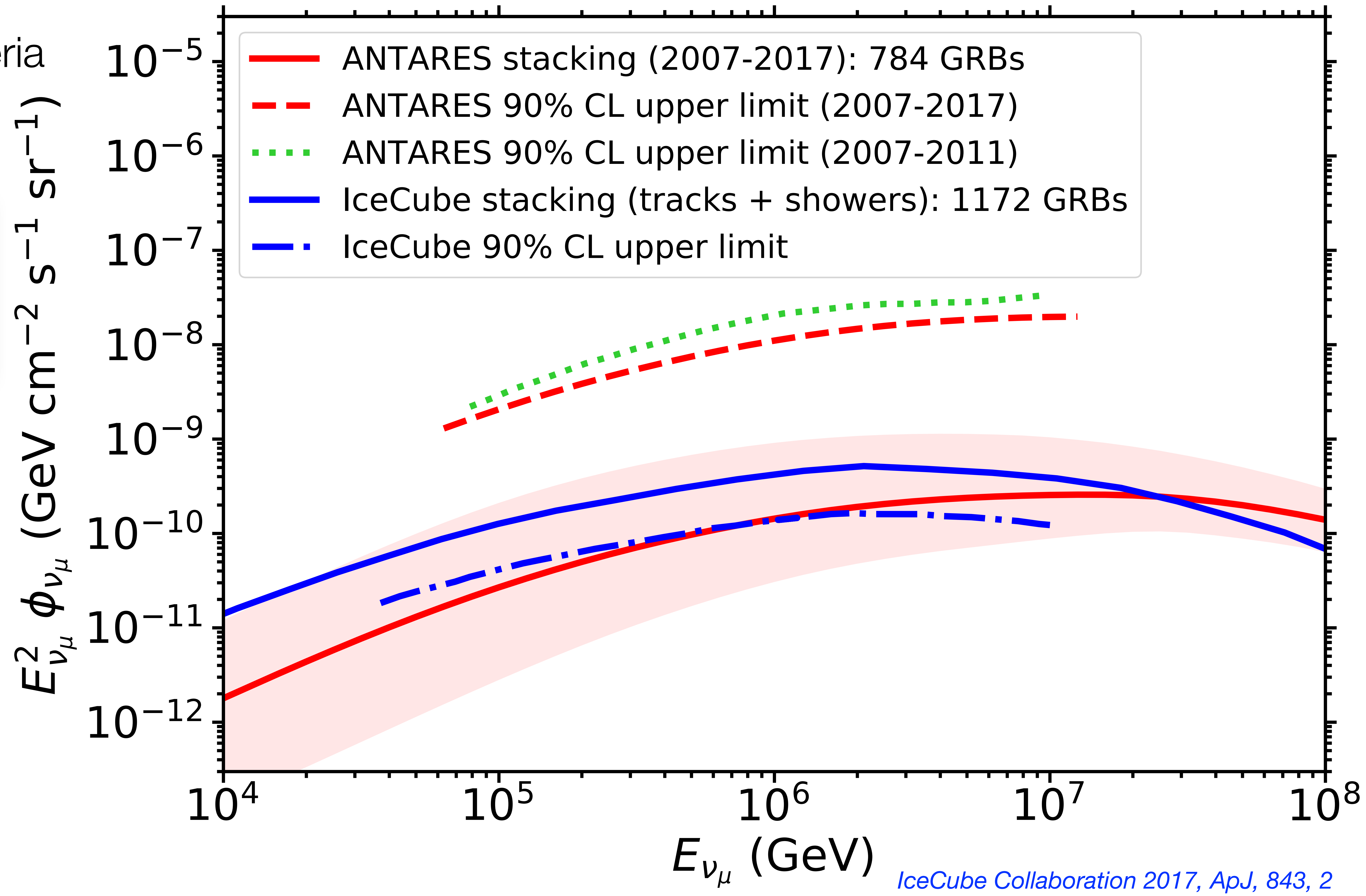
No neutrino events have passed the selection criteria defined by the optimization procedure

↓

NO neutrino events in ANTARES data found in spatial and temporal coincidence with the prompt phase of the GRB sample

90% C.L. upper limit on the estimated neutrino fluence:

$$\phi_{\nu_\mu}^{90\%} = \phi_{\nu_\mu}\frac{n^{90\%}}{n_s} = \phi_{\nu_\mu}\frac{2.3}{n_s} = \phi_{\nu_\mu}\cdot 77^{+226}_{-64}$$



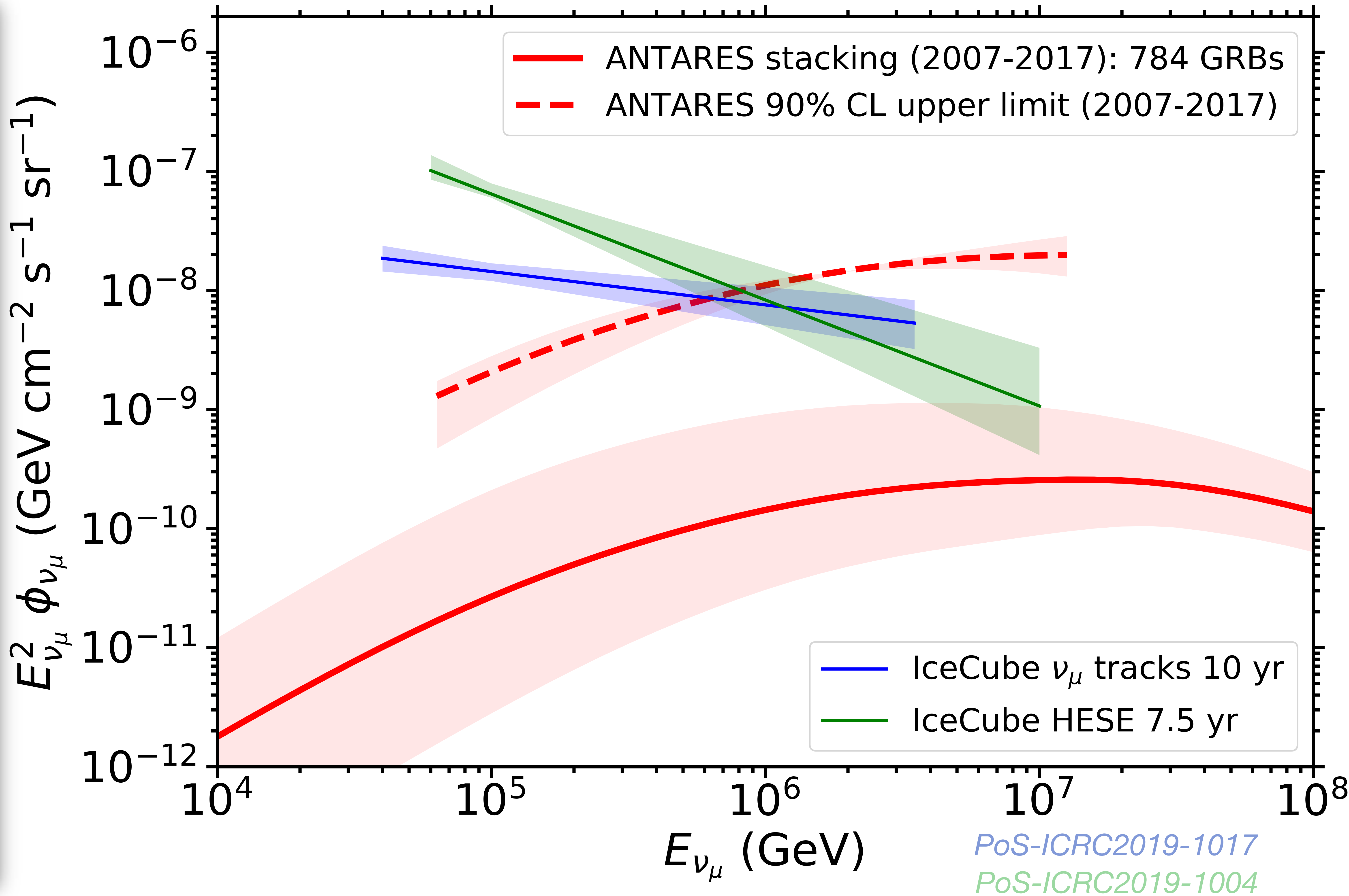
IceCube Collaboration 2017, ApJ, 843, 2

ANTARES Collaboration, 2013, A&A, 559, A9

ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

Results: constraining the HE diffuse neutrino flux

- For a sample size of 784 GRBs the level of systematic error around the 90% C.L. upper limits is of the order of (-70%, +30%)
- **GRBs are not the main contributors to the observed flux below ~ 1PeV,** within the NeuCosmA model framework with benchmark baryonic loading, $f_p = 10$
- **In the energy region where ANTARES is most sensitive (around 100 TeV), GRBs do not appear to contribute by more than 10%**



PoS-ICRC2019-1017
PoS-ICRC2019-1004

ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

Summary and Conclusions

- **10 years of ANTARES data** were analyzed searching for **coincident neutrinos and prompt gamma rays**;
- Uncertainties on expected neutrino fluxes (due to Γ, t_v and z) were evaluated with a **'physically-driven' model**;
- An **extended maximum likelihood analysis** was performed for each GRB. Per GRB optimization was realized and an uncertainty band around the stacked fluence (as well as around the number of expected signal events) from the IS model was calculated;
- Unblinded data were analyzed and no neutrino events passed the quality cuts set by the optimization procedure
  ⟹ **90% C.L. upper limit on the expected neutrino fluence from the stacked sample was derived**;
- ANTARES results indicates that **GRBs are not the main contributors to the observed flux** below ~1 PeV**,** within the framework of the classical IS model; in particular, the energy region where ANTARES is most sensitive (around 100 TeV), GRBs do not contribute by more than 10%;
- Other interesting classes of GRB sources (e.g. low-luminous GRBs, choked GRBs), not considered in this analysis, might potentially contribute to the observed diffuse astrophysical neutrino flux.