Virtual Seminar on Multimessenger Astronomy II
at Technische Universität München
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Neutrinos from GRBs: can they account for the IceCube diffuse neutrino flux?

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Plan of the talk

- **Gamma-ray bursts** (GRBs): an introduction.

- GRB and ultra-high energy cosmic-ray (UHECR) connection: the **Waxman-Bahcall (WB) bound**.

- The **diffuse neutrino flux** observed by IceCube (IC).

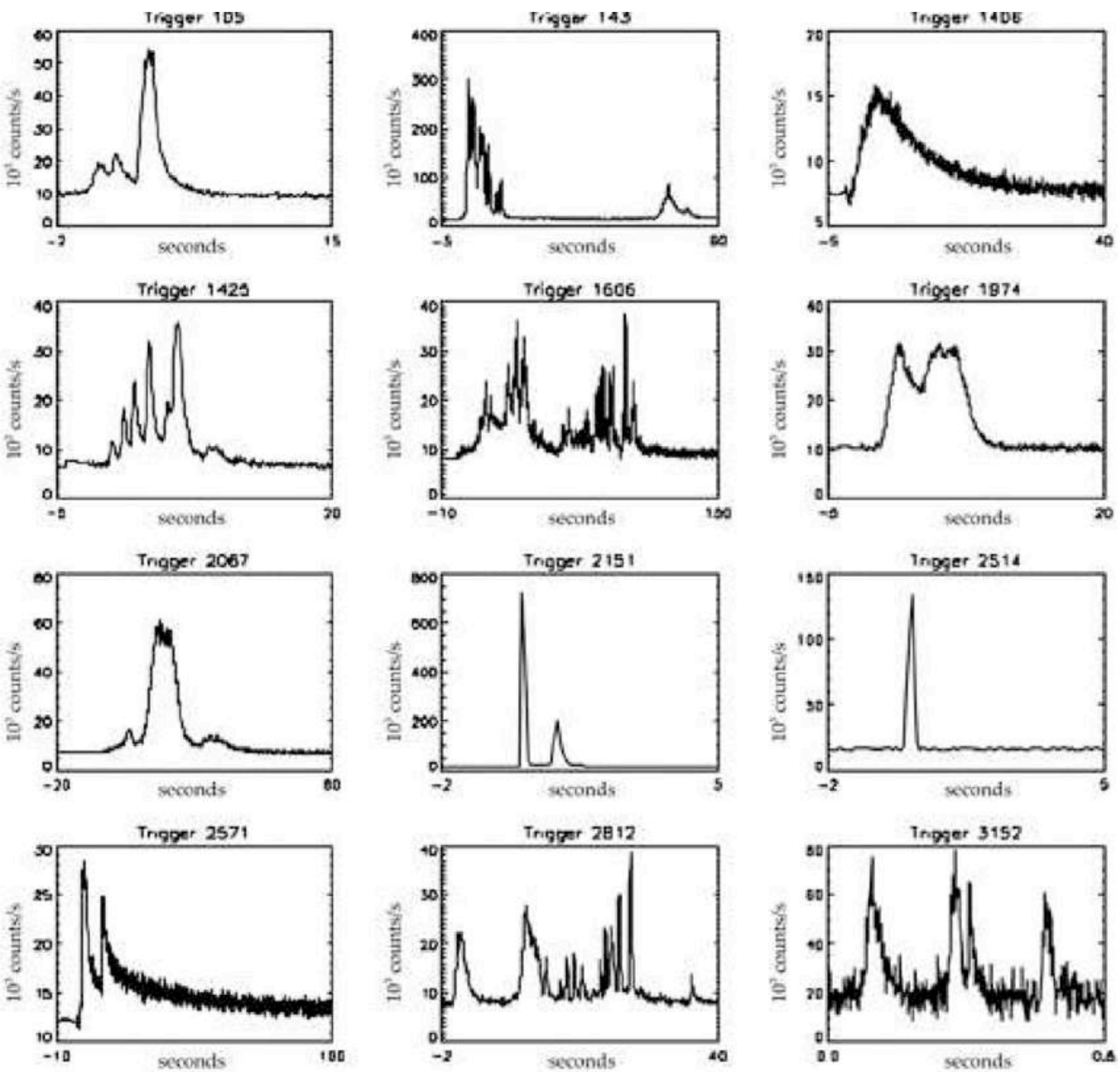
- ANTARES and IC **searches for neutrinos in coincidence with the prompt emission of GRBs**:
  - Individual source searches (bright GRBs);
  - Population searches (diffuse flux).

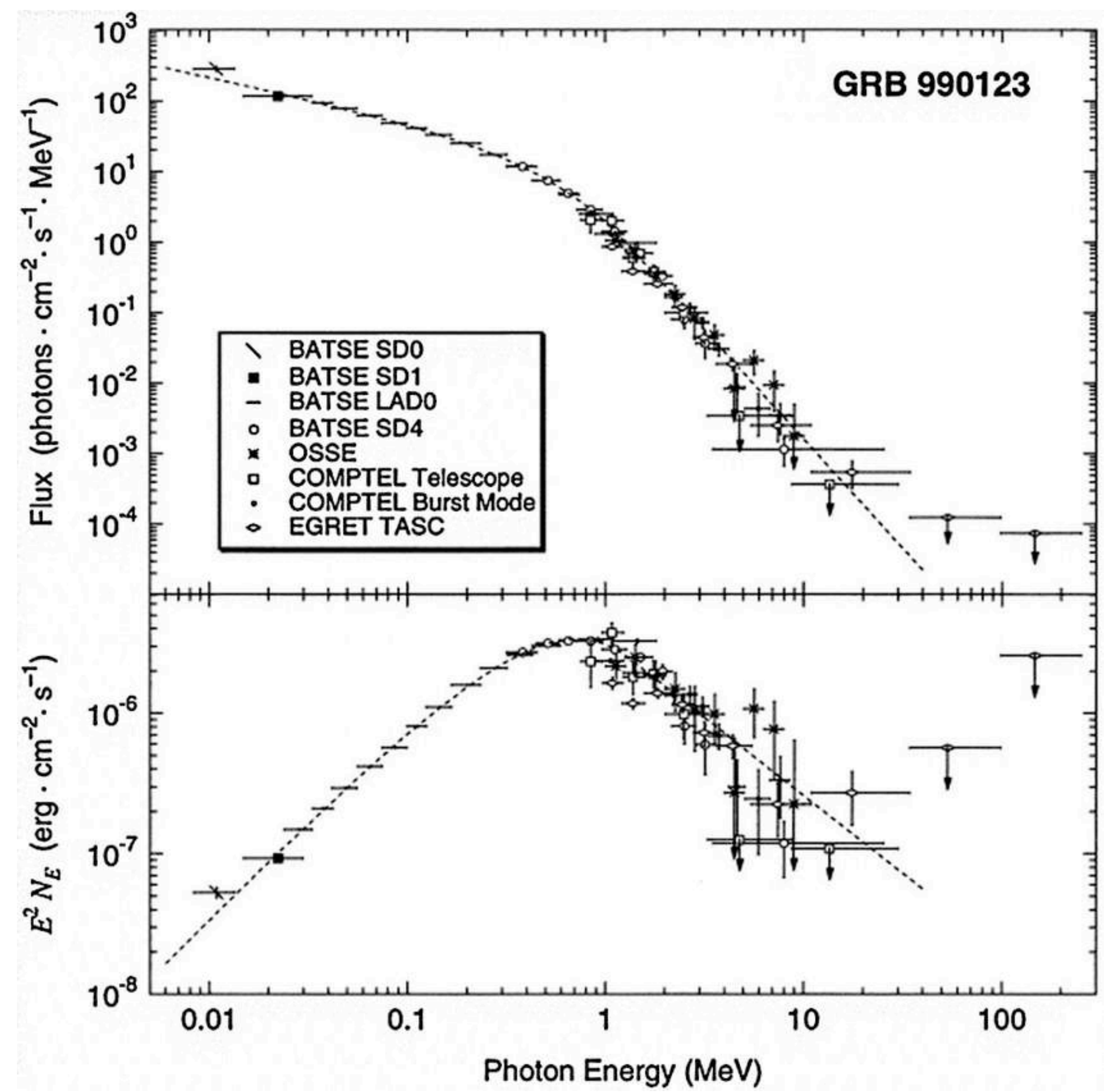
- Latest results: **TeV GRBs** and **chocked GRBs**.

Gamma-ray bursts

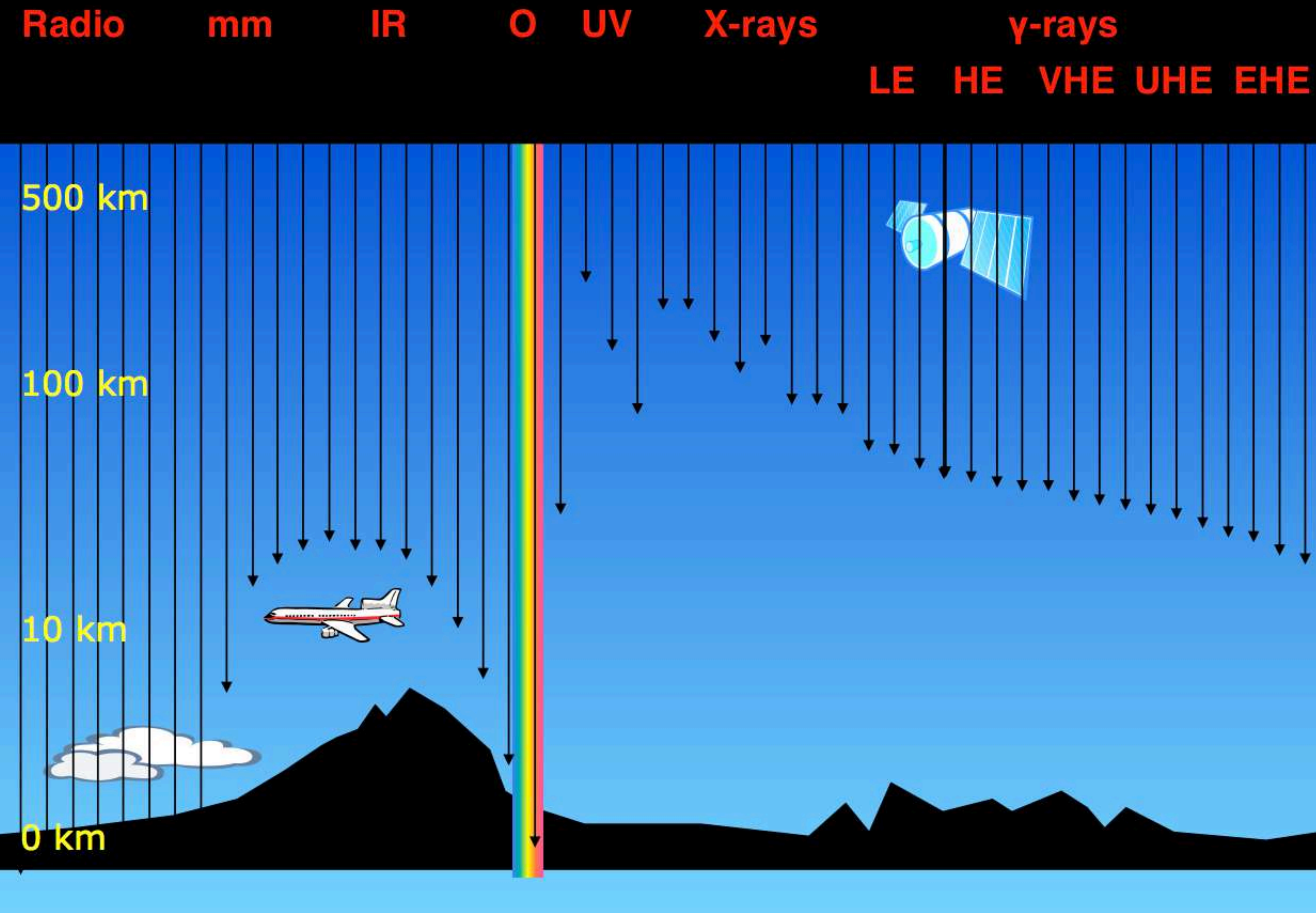
First serendipitous discovery in **1967** by the (US) Vela satellites, which were operating to ensure the Nuclear Test Ban Treaty was observed.

Klabesadel et al., ApJ 182 (**1973**)

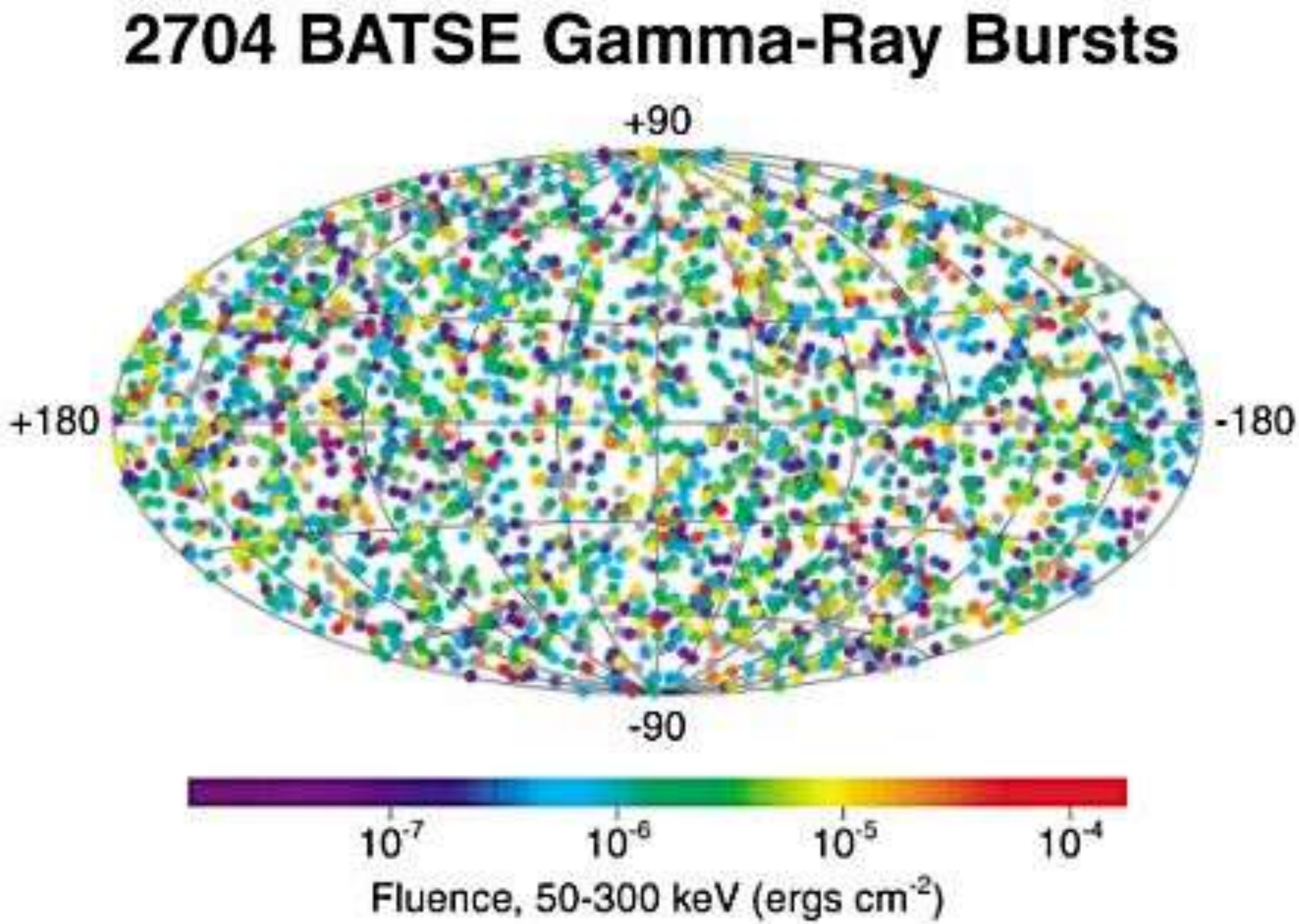




Transparency of the Earth's atmosphere for cosmic E-M radiation

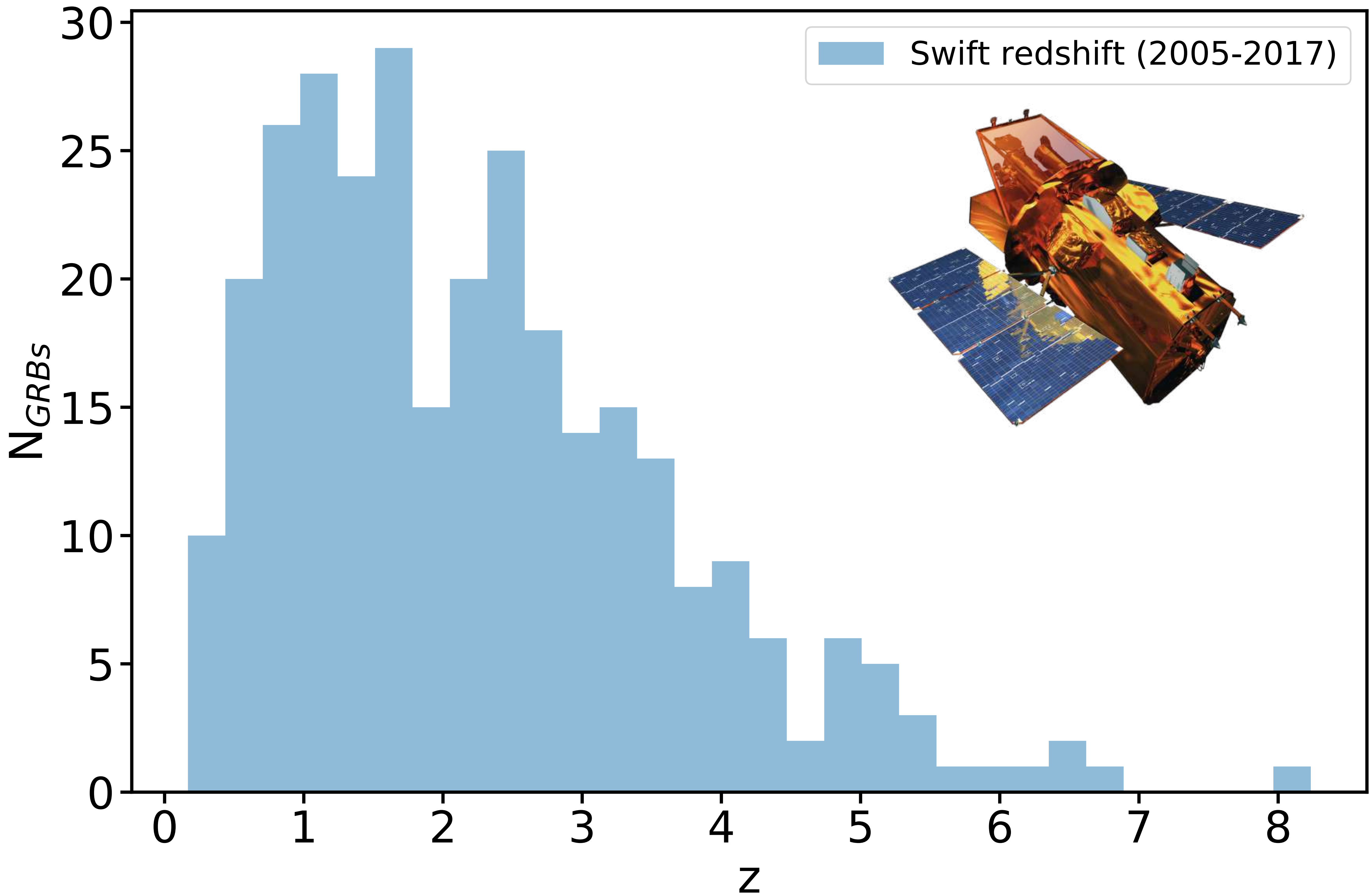


An isotropic sky distribution…



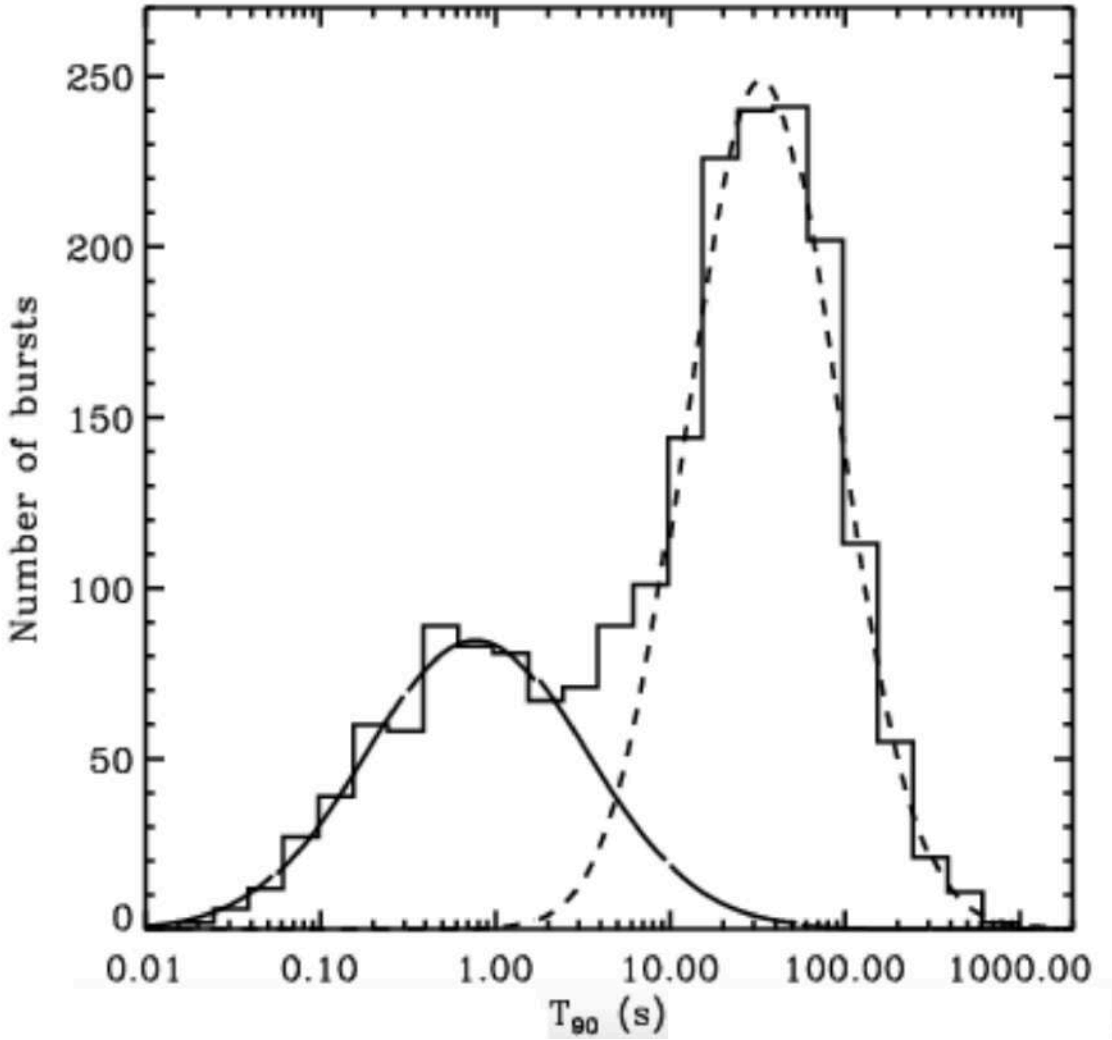
10 yrs data taking of the CGRO

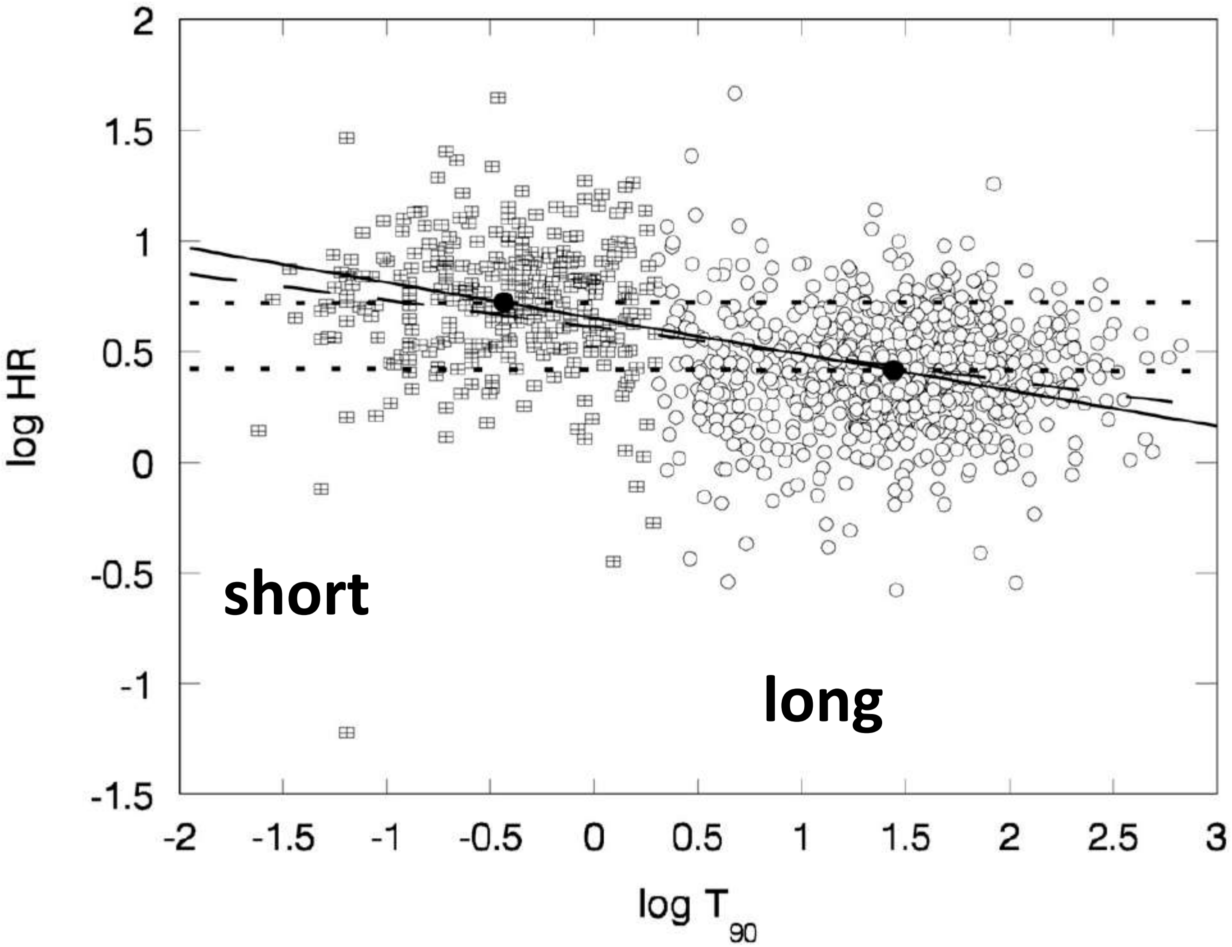
…namely extra-galactic sources



https://swift.gsfc.nasa.gov/archive/grb table/

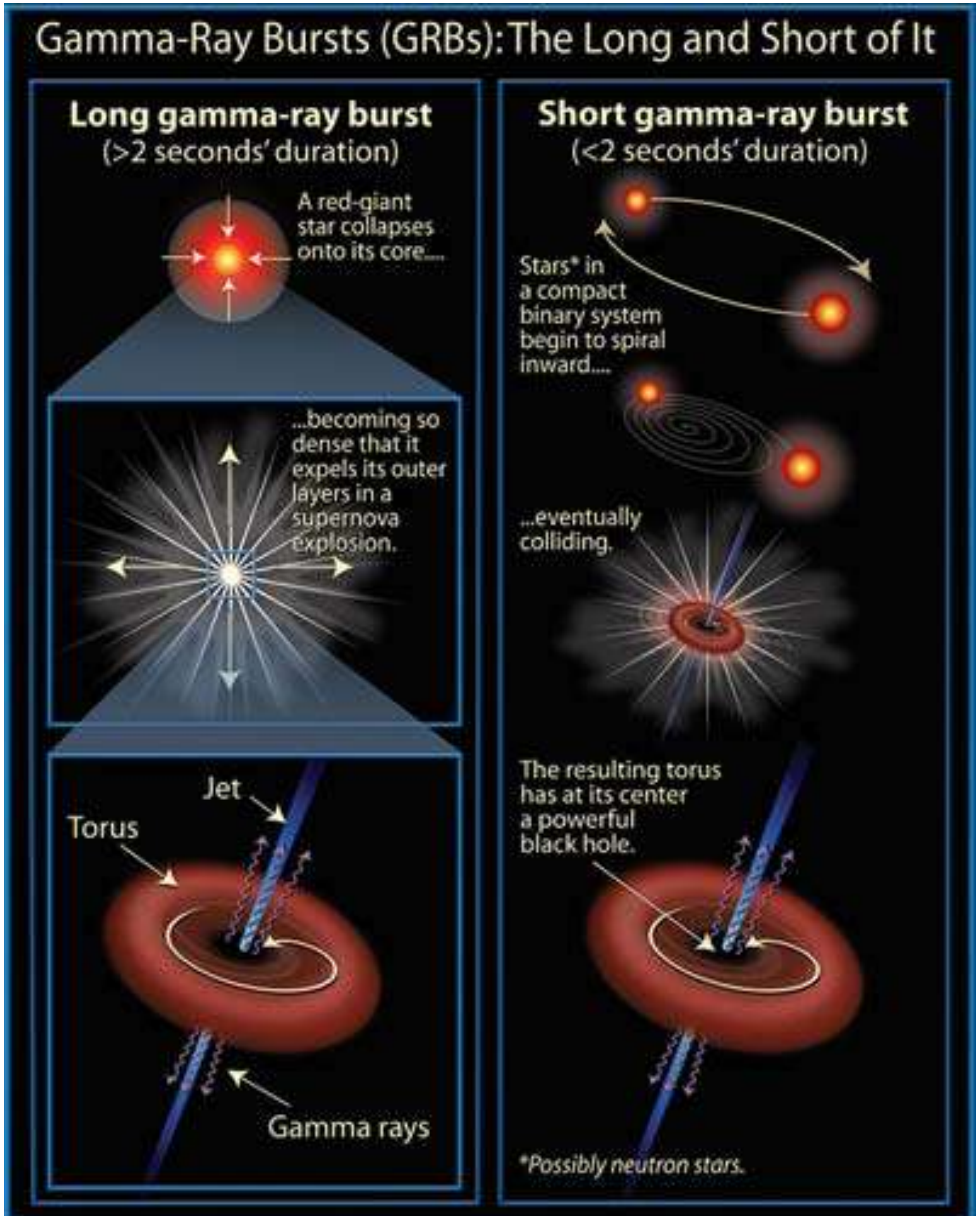
Gamma-ray bursts populations





$$\mathrm{HR} = \frac{F_{50-100\,\mathrm{keV}}}{F_{25-50\,\mathrm{keV}}}$$

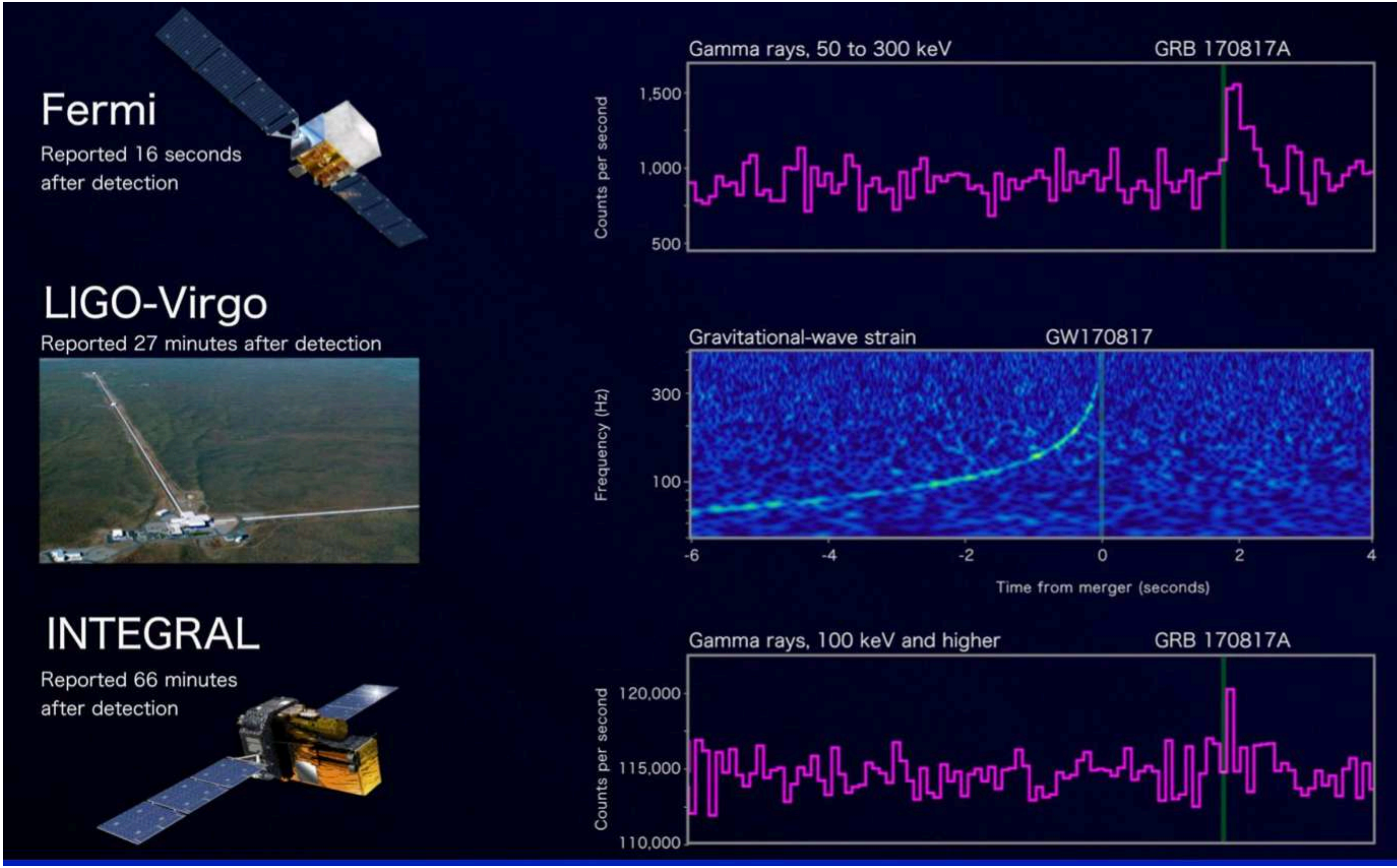
Gamma-ray bursts progenitors



- <u>Long GRBs:</u>
  soft emission
  CC SN progenitor

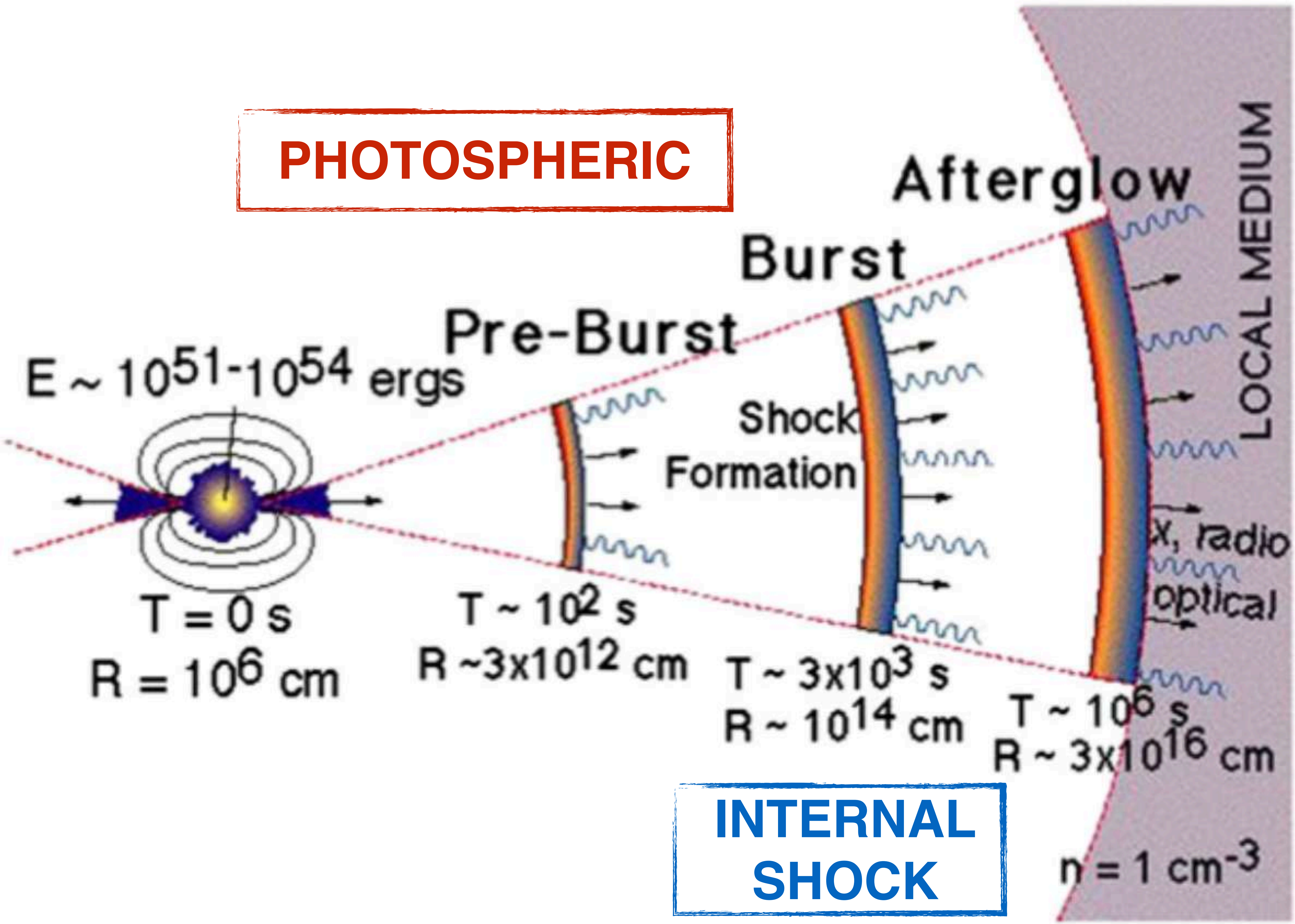
- <u>Short GRBs:</u>
  hard emission
  BNS progenitor

A breakthrough: GRB170817A - GW170817



Abbott et al., ApJ 848 (2017) L12

Gamma-ray bursts: the fireball model



Gamma-ray bursts: the compactness problem

The short variability time observed in GRB lightcurves (10 ms) indicate a size of the emitting region of

$$R \simeq c t_{\rm var} \simeq 3 \times 10^{8}\,{\rm cm}$$

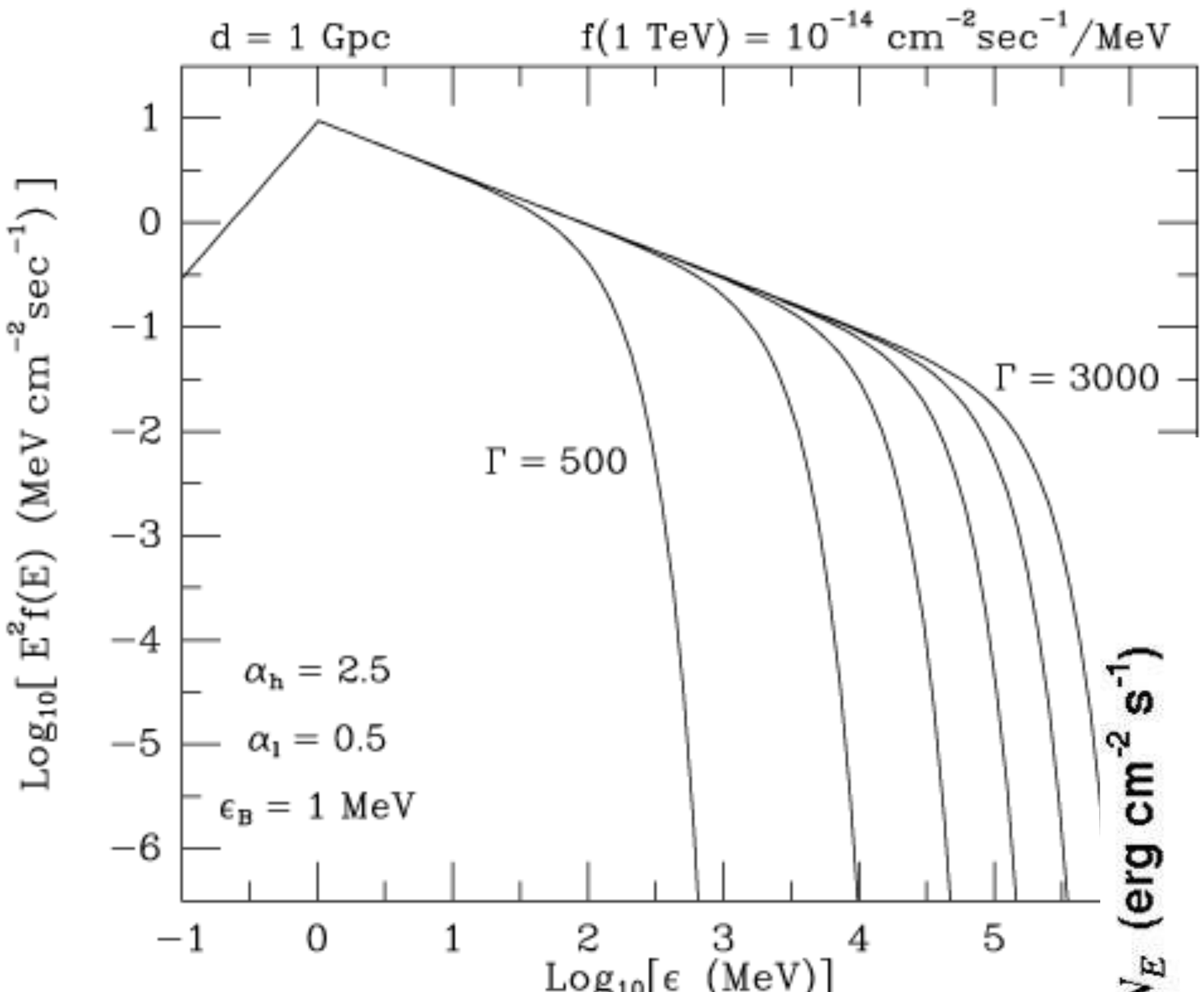
implying for the optical depth of γγ —> e⁺e⁻ a value of

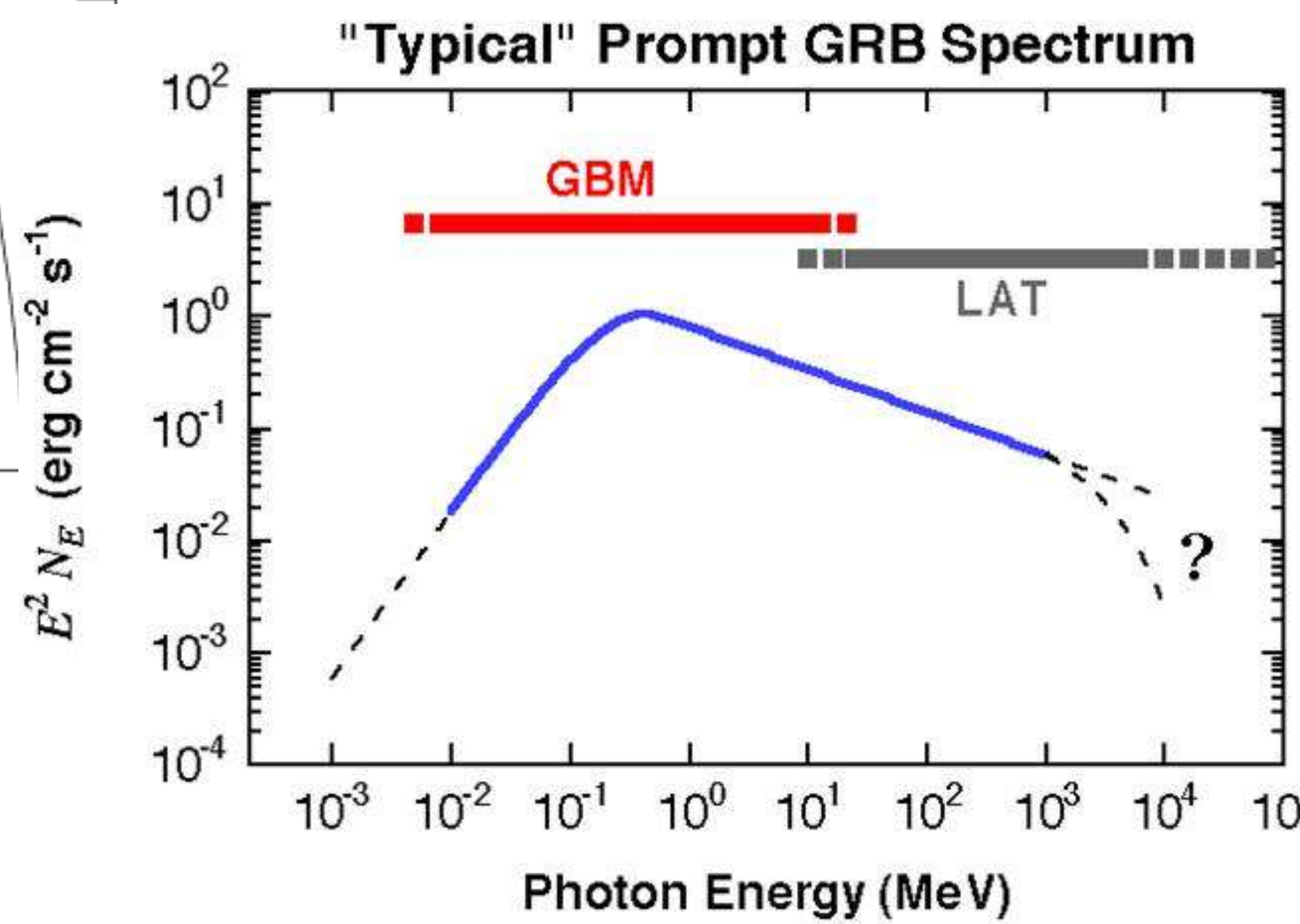
$$\tau_{\gamma\gamma} = \frac{f_{\rm ph}\sigma_{\rm T} F_\gamma d^2}{R^2 m_e c^2} \simeq 10^{12} f_{\rm ph} \left(\frac{F_\gamma}{10^{-6}\ {\rm erg/cm}^2}\right)\left(\frac{d}{3\ {\rm Gpc}}\right)^2\left(\frac{t_{\rm var}}{10\ {\rm ms}}\right)^{-2}$$

namely thick sources to gamma rays, except in the case of a relativistic jet (bulk Lorentz factor Γ), as

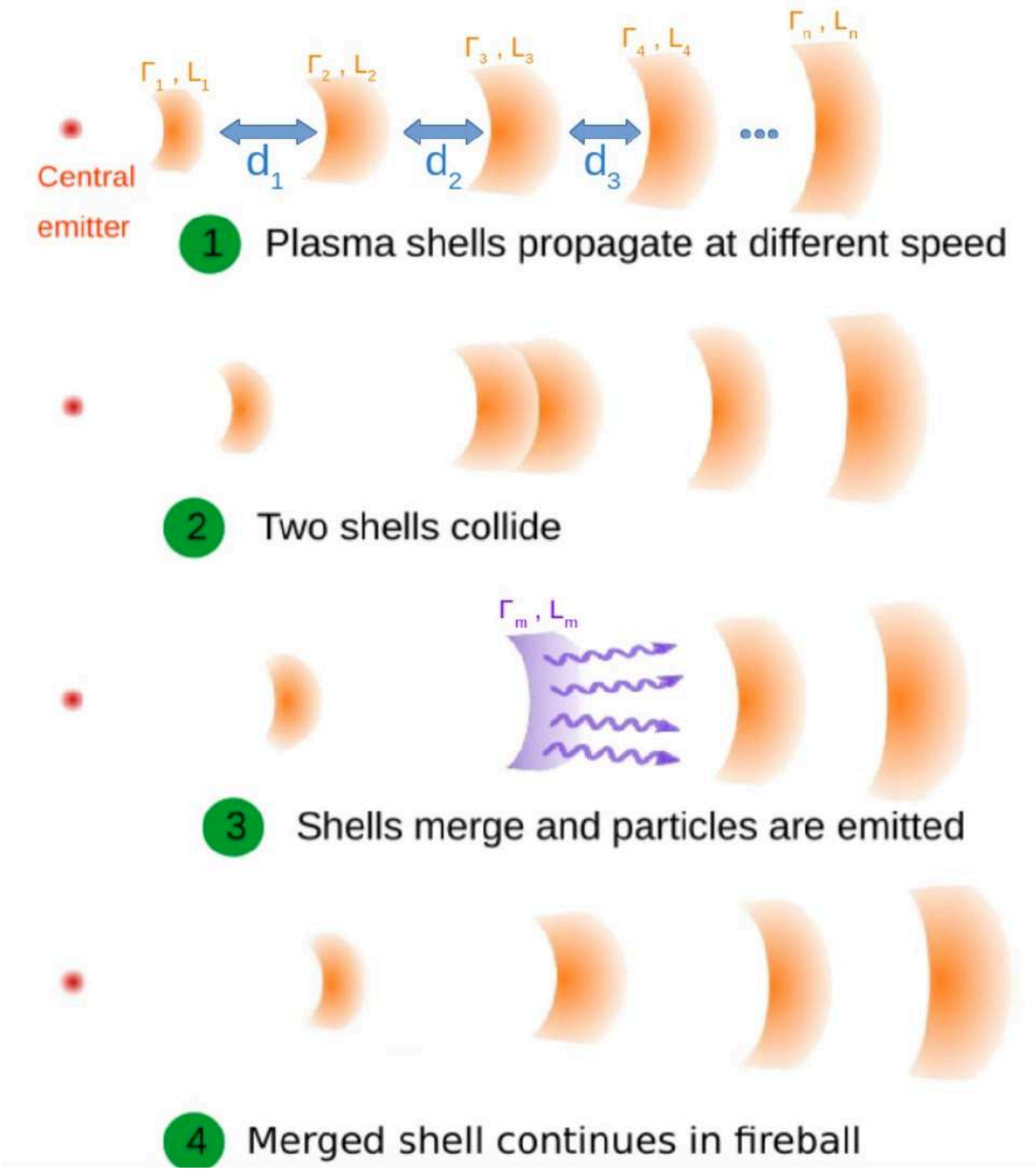
$$\tau_{\gamma\gamma} = \frac{f_{\rm ph}\sigma_{\rm T} F_\gamma d^2}{\Gamma^{2\alpha} R^2 m_e c^2} \simeq 10^{-3} f_{\rm ph} \left(\frac{\Gamma}{300}\right)^{4+2\alpha}\left(\frac{F_\gamma}{10^{-6}\ {\rm erg/cm}^2}\right)\left(\frac{d}{3\ {\rm Gpc}}\right)^2\left(\frac{t_{\rm var}}{10\ {\rm ms}}\right)^{-2}$$

Gamma-ray bursts: the compactness problem





Gamma-ray bursts: the internal shock scenario of the fireball model



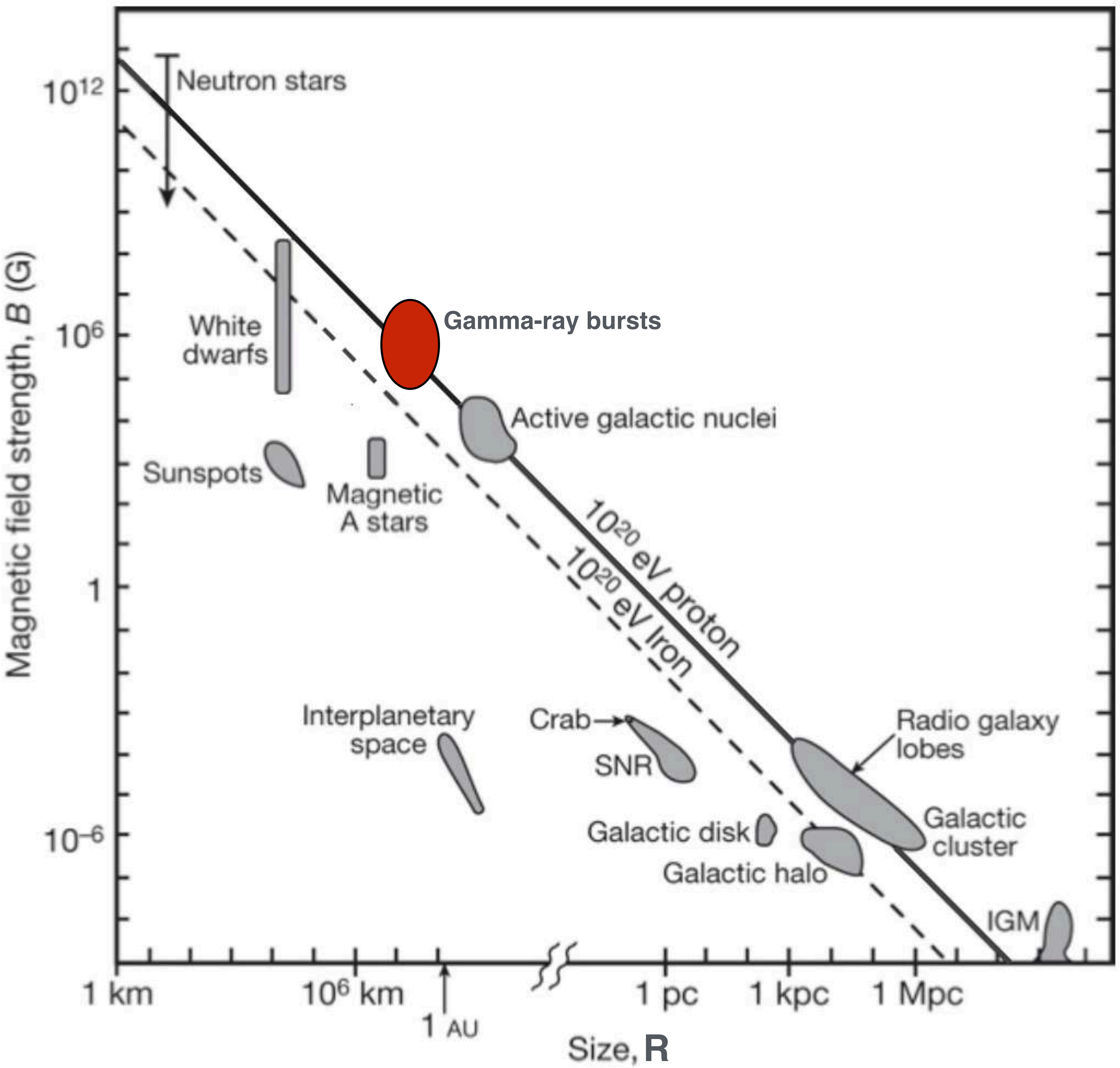
Acceleration mechanisms:
shock acceleration?
magnetic reconnection?
other?

Efficiency of particle acceleration?
energy equipartition among electrons and magnetic fields?

Hadronic acceleration?
can GRBs be the main sources of UHECRs?

Bustamante et al., Nature Comm. 6 (2015) 6783

The Hillas plot for CR sources



Particle confinement (aka Hillas) condition:

$$R > 2r_{\rm L}/\beta$$

size of accelerator

speed of scattering centers

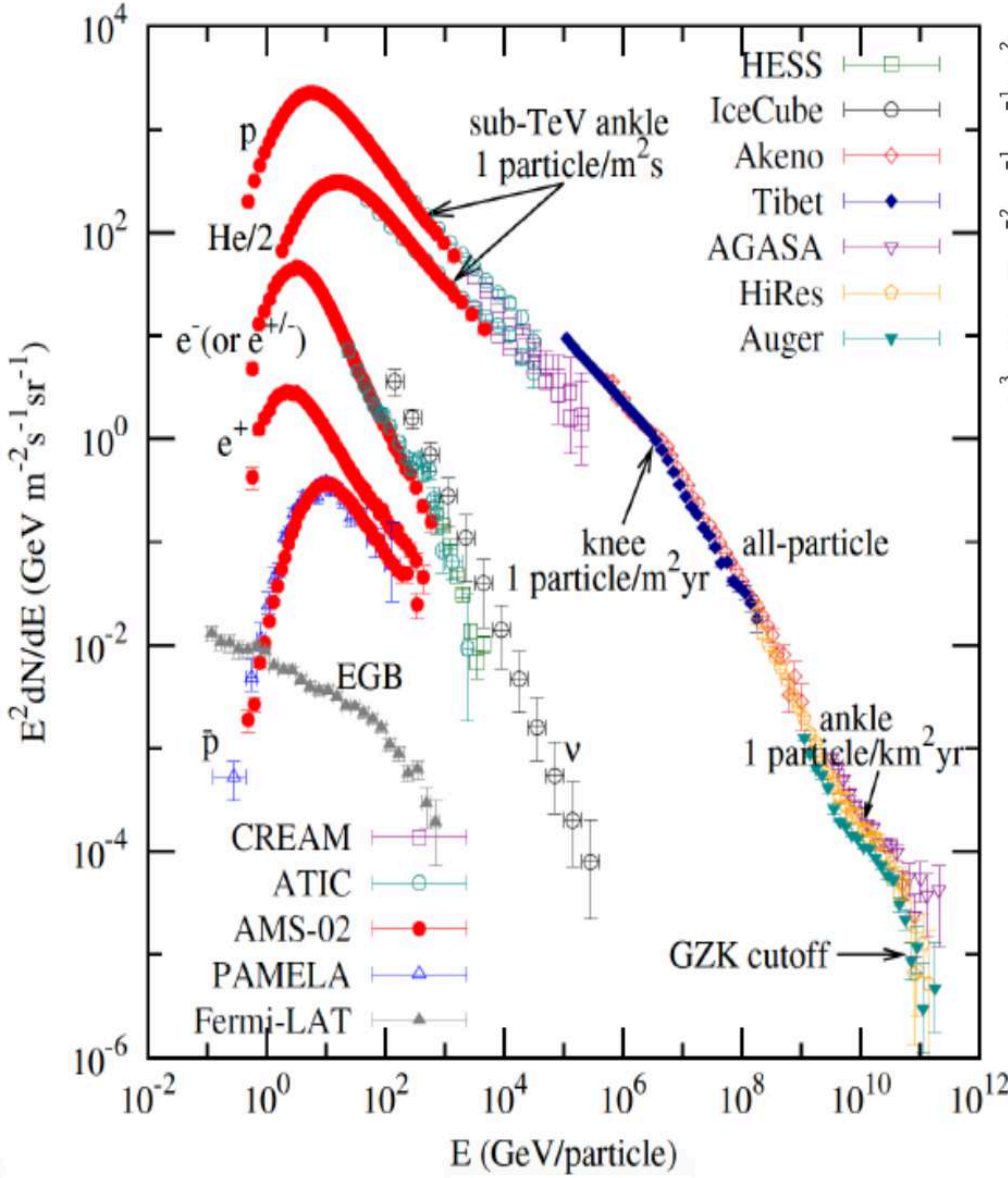
$$\longrightarrow E < 0.5 Z\beta B R$$

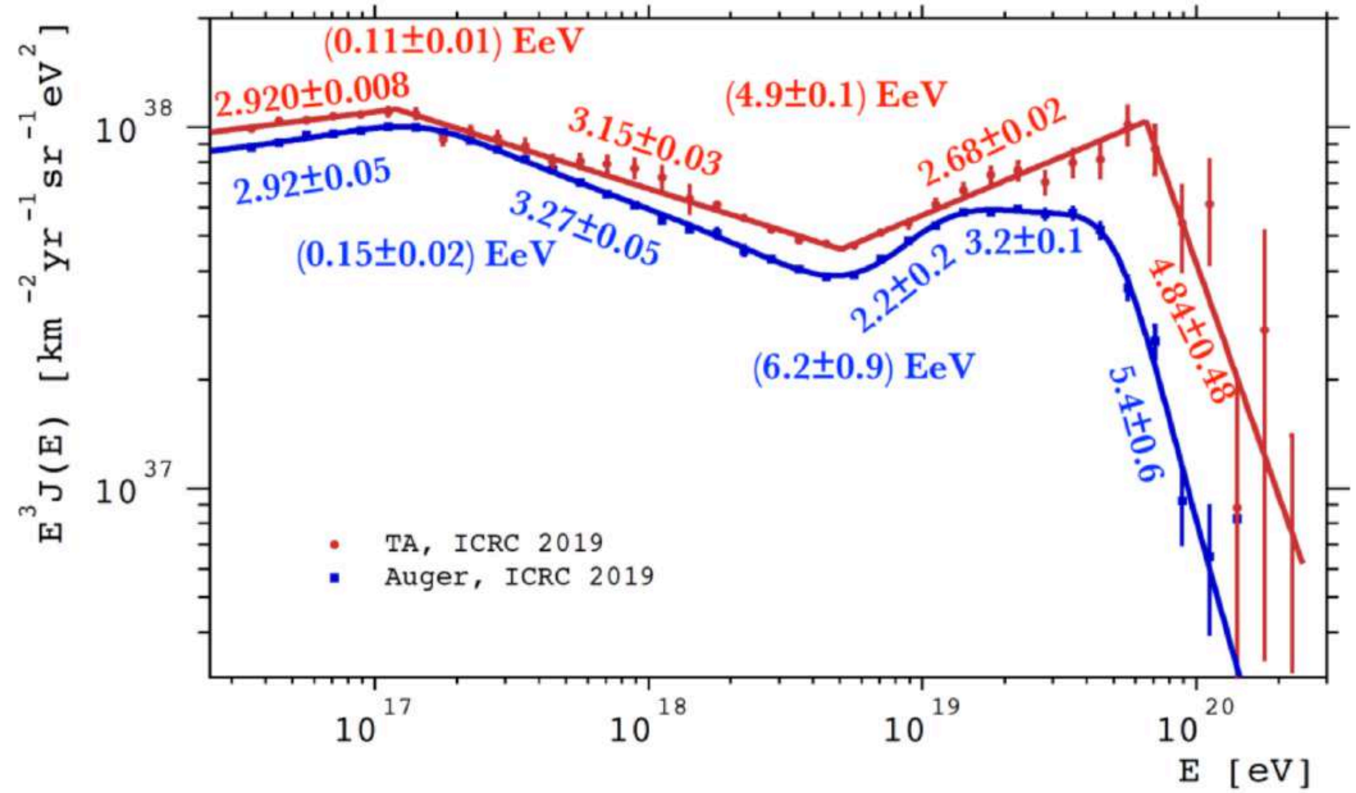
upstream magnetic field

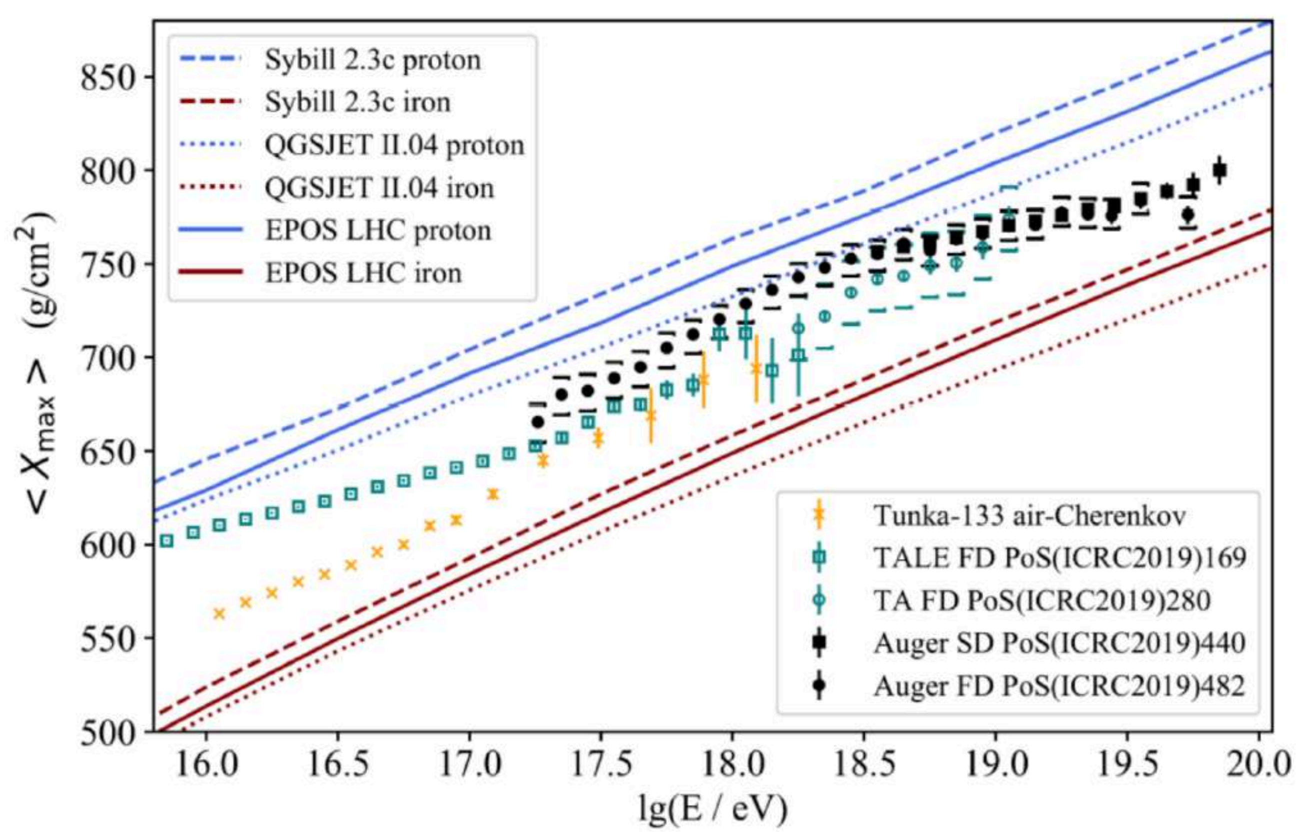
$$E_{\max} \simeq 10^{20}\,\mathrm{eV}\left(\frac{Z}{1}\right)\left(\frac{\beta}{1}\right)\left(\frac{B}{10^5\ \mathrm{G}}\right)\left(\frac{R}{10^8\ \mathrm{km}}\right)$$

Hillas, Ann. Rev. A&A 22 (1984) 425

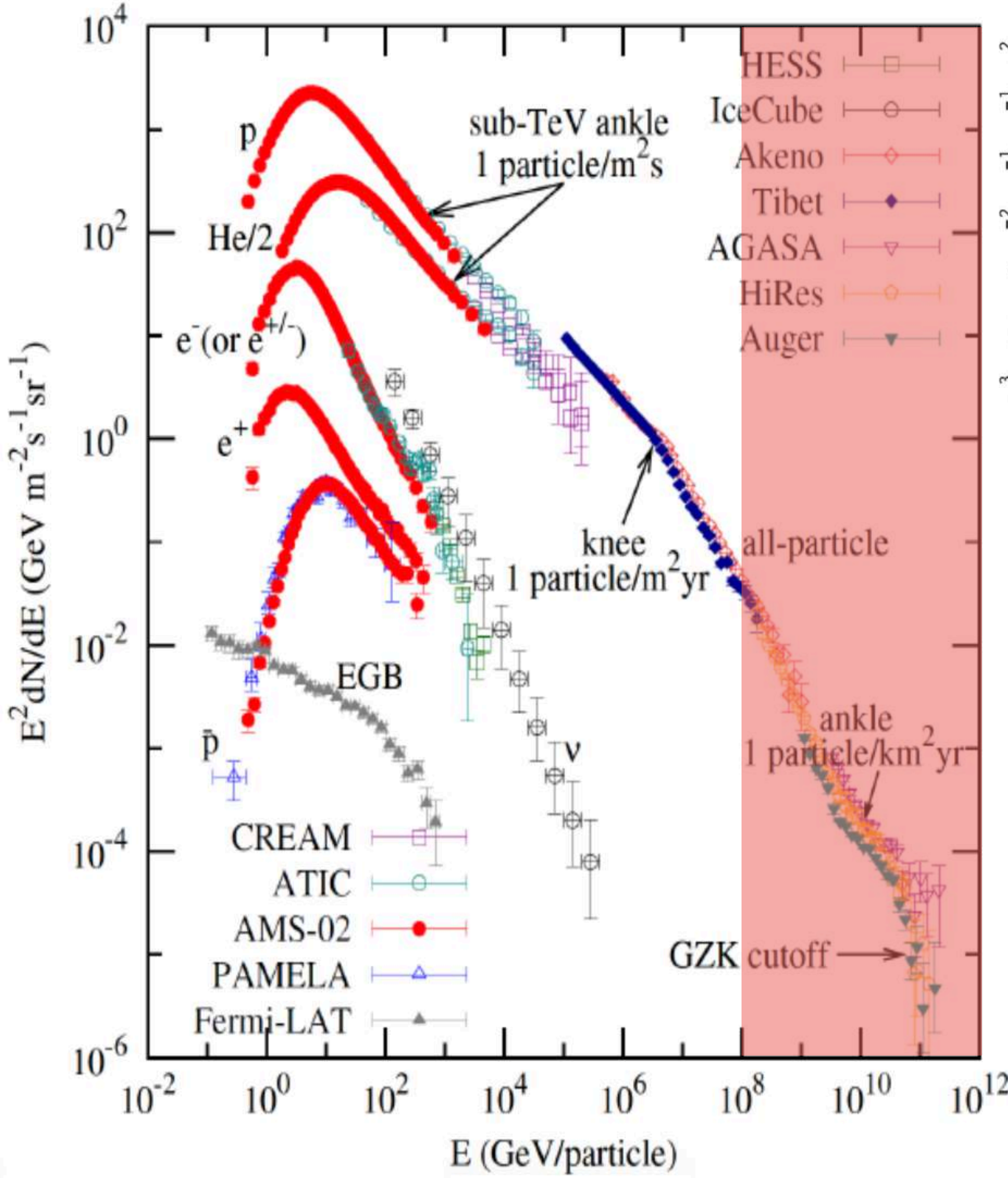
The all particle CR spectrum

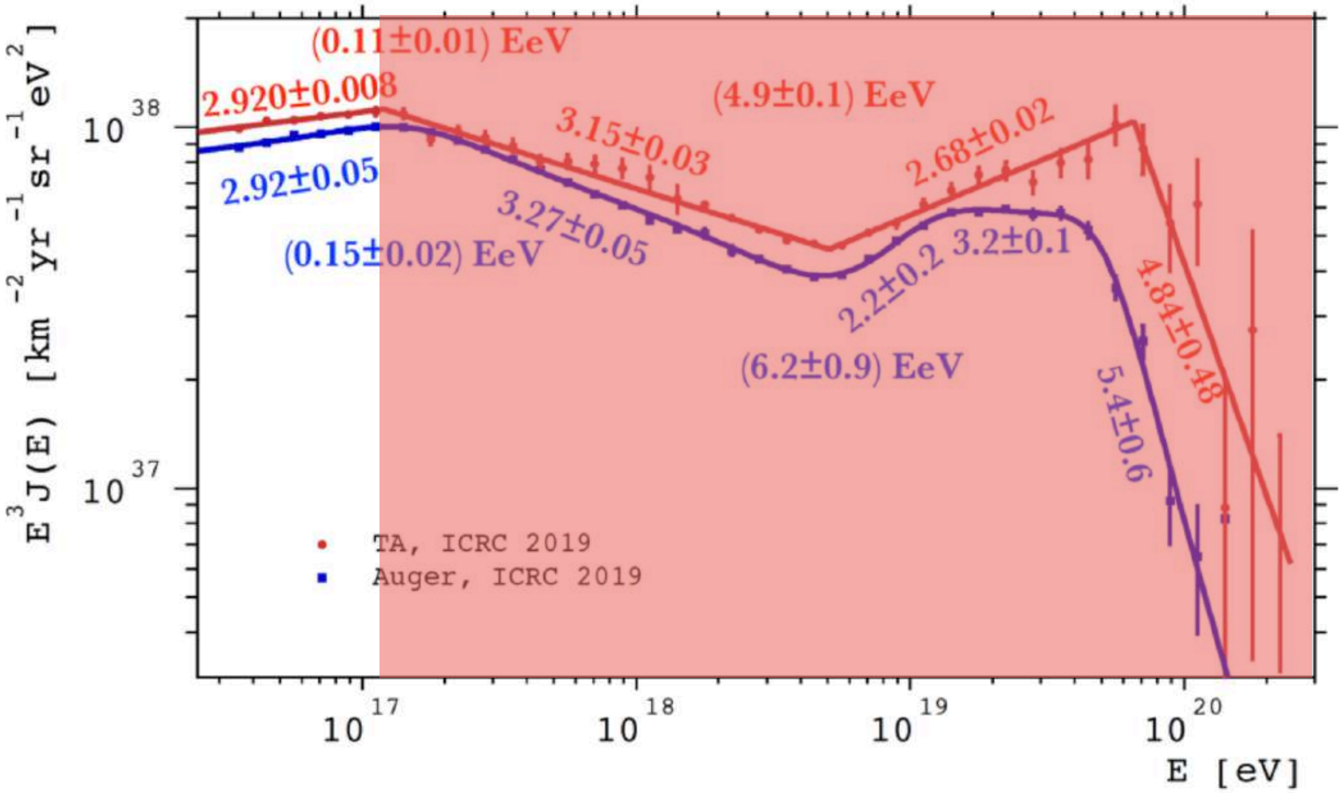


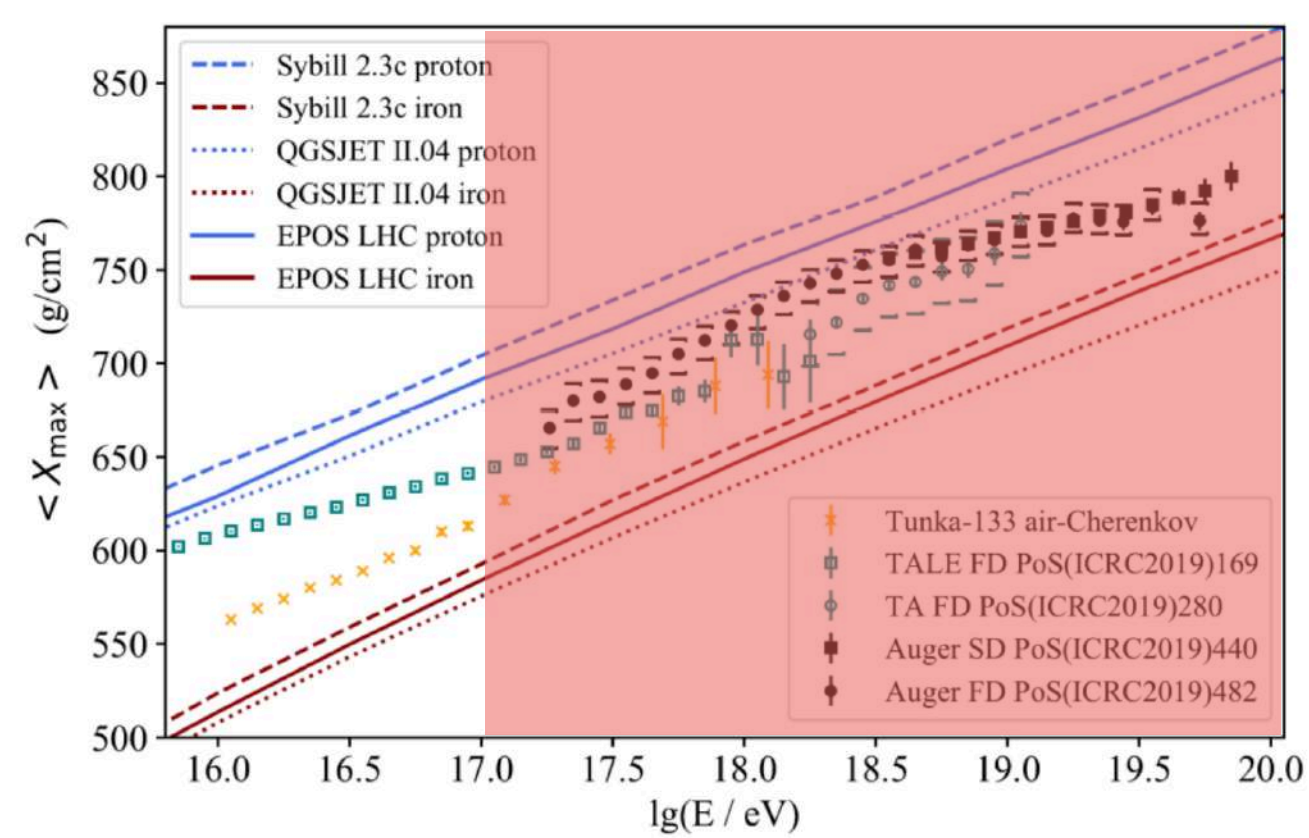




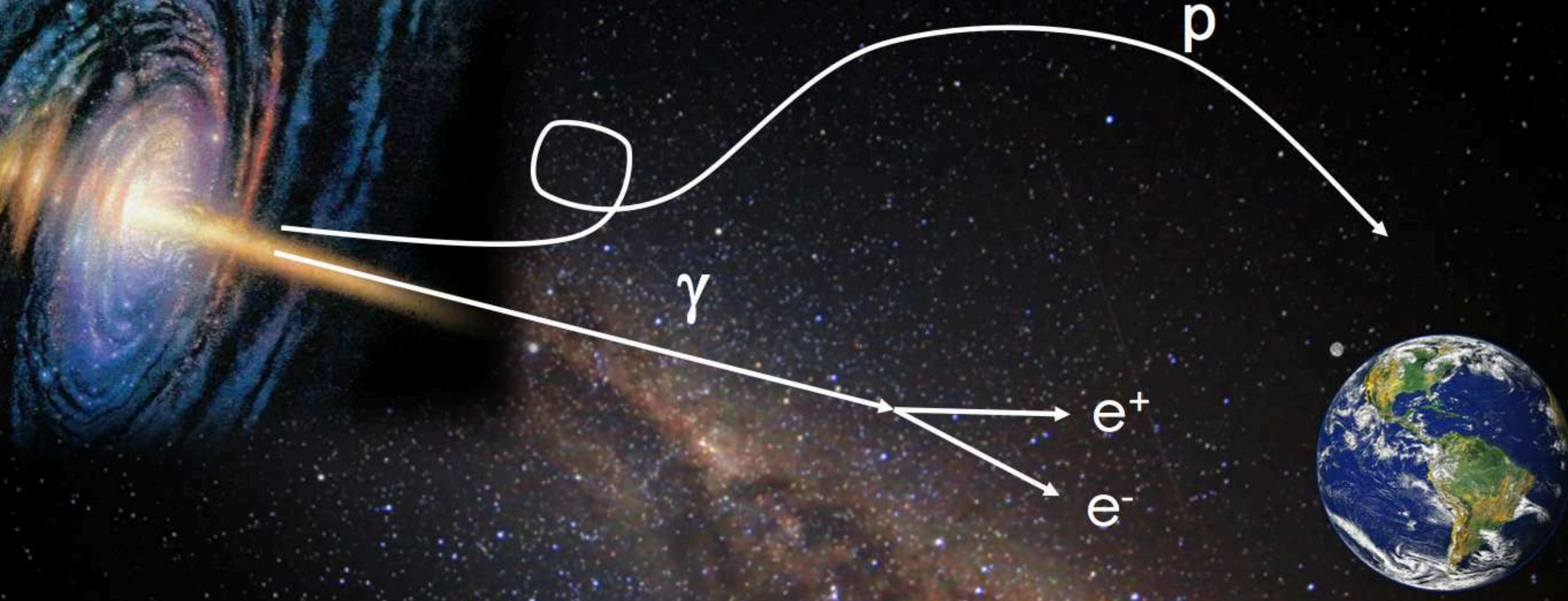
The all particle CR spectrum







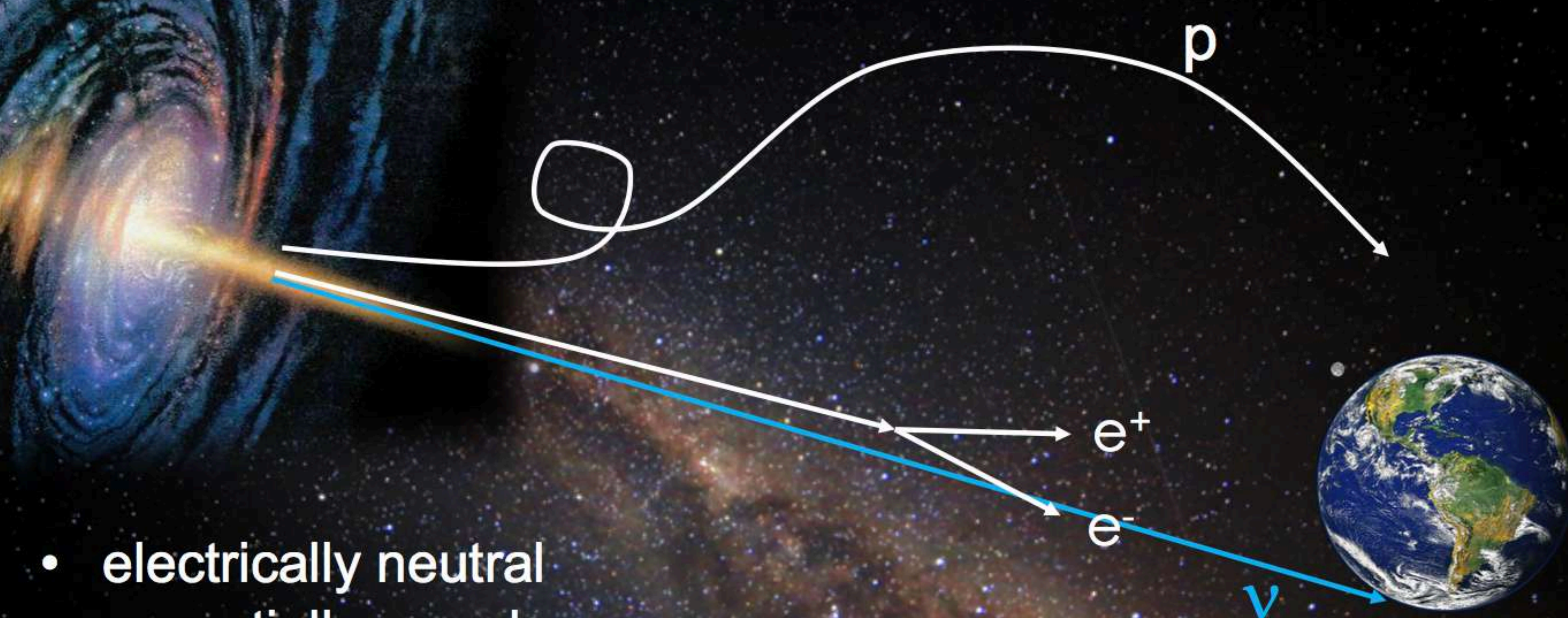
The opaque Universe



$$\gamma + \gamma_{CMB} \rightarrow e^{+} + e^{-}$$

PeV photons interact with microwave photons ($411/cm^3$) before reaching our telescopes

Neutrinos? Perfect Messenger



- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays

GRB and UHECR connection: the Waxman-Bahcall upper bound

UHECR observations indicate an emissivity of

$$E_{\rm CR}^2 \frac{dN_{\rm CR}}{dE_{\rm CR}} = \frac{\dot{\epsilon}_{\rm CR}^{[10^{19},10^{21}]}}{\ln(10^{21}/10^{19})} \simeq 10^{44} \text{ erg Mpc}^{-3}\text{yr}^{-1}$$

hence a maximum $\nu_\mu + \overline{\nu}_\mu$ intensity as arising from pγ (ϵ=1)

$$I_{\rm max} \simeq 0.25 \xi_Z t_H \frac{c}{4\pi} E_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}} \simeq 1.5 \times 10^{-8} \xi_Z \text{ GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

cosmological effects, O(1)

$$\longrightarrow E_{\nu_\mu}^2 \phi_\nu \equiv \frac{c}{4\pi} E_{\rm CR}^2 \frac{dN_{\nu_\mu}}{dE_\nu} = \frac{1}{2} \epsilon I_{\rm max} \simeq 10^{-8} \epsilon \xi_Z \text{ GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

Waxman & Bahcall, PRD 59 (1999) 023002

Hadronic acceleration in GRBs?

pγ collisions might be realized in the dense radiation field of the jet, if protons are accelerated

$$p + \gamma \xrightarrow{\Delta^+} \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

$$\pi^0 \longrightarrow \gamma + \gamma$$
$$n \longrightarrow p + e^- + \boxed{\overline{\nu}_e}$$
$$\pi^+ \longrightarrow \mu^+ + \boxed{\nu_\mu}$$
$$\mu^+ \longrightarrow e^+ + \boxed{\nu_e} + \boxed{\overline{\nu}_\mu}$$

At at high energies, the interaction proceeds through

$$p + \gamma \longrightarrow K^+ + \Lambda/\Sigma$$
$$K^+ \longrightarrow \mu^+ + \boxed{\nu_\mu}$$

$$\pi^- \longrightarrow \mu^- + \boxed{\overline{\nu}_\mu}$$
$$\mu^- \longrightarrow e^- + \boxed{\overline{\nu}_e} + \boxed{\nu_\mu}$$

$\longrightarrow$ **Neutrinos are smoking guns for hadronic processes**

$$E_\nu \simeq 0.05 E_p$$

Hadronic acceleration in GRBs?

The synchrotron dominated radiation field of the jet represents the photon target of pγ interaction. In a simplified scenario of **one-zone collision**, the optical depth reads as

$$\tau_{p\gamma} = 0.8 \left(\frac{\mathrm{R}}{10^{14}\mathrm{cm}}\right)^{-1} \left(\frac{\Gamma}{10^{2.5}}\right)^{-2} \left(\frac{\mathrm{E}_\gamma}{1\ \mathrm{MeV}}\right)^{-1} \left(\frac{\mathrm{L_{iso}}}{10^{52}\mathrm{erg/s}}\right)$$

If the collision takes place in the **photosphere**, then

$$\mathrm{R_{PH}} = \frac{\mathrm{L_{iso}}\sigma_T}{8\pi m_p c^3}\Gamma^{-3} \sim 10^{11} \left(\frac{\mathrm{L_{iso}}}{10^{52}\mathrm{erg/s}}\right) \left(\frac{\Gamma}{10^{2.5}}\right)^{-3} \mathrm{cm}$$

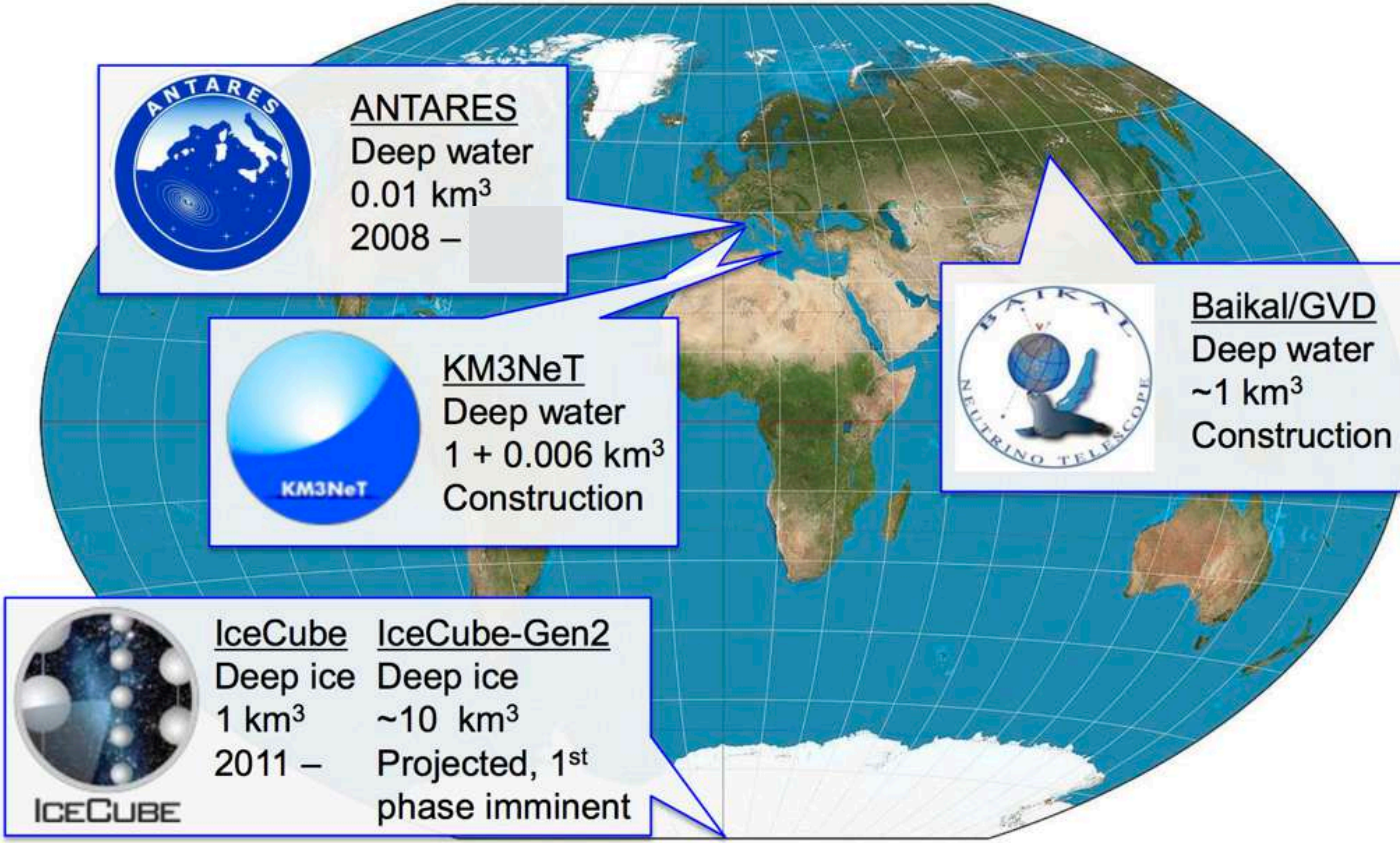
Zhang & Kumar, Phys. Rep. 561 (2015) 1

while in the **internal shock** scenario the dissipation radius is

$$\mathrm{R_{IS}} = \frac{c t_{\mathrm{var}}}{1+z}\Gamma^2 \sim 10^{13} \left(\frac{t_{\mathrm{var}}}{0.01\ \mathrm{s}}\right) \left(\frac{\Gamma}{10^{2.5}}\right)^{2} \left(\frac{1+2.15}{1+z}\right) \mathrm{cm}$$

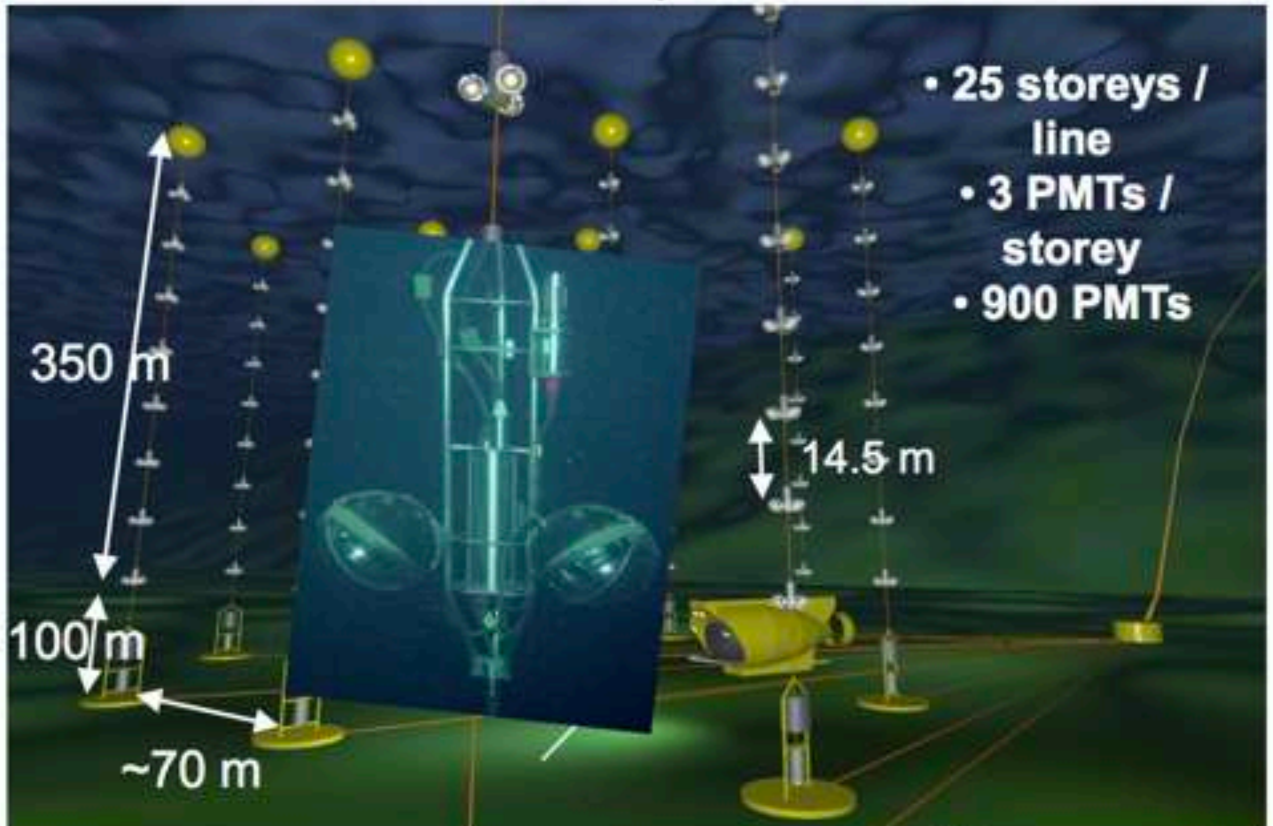
Guetta et al., Astropart. Phys. 20 (2004) 4

Operational neutrino telescopes

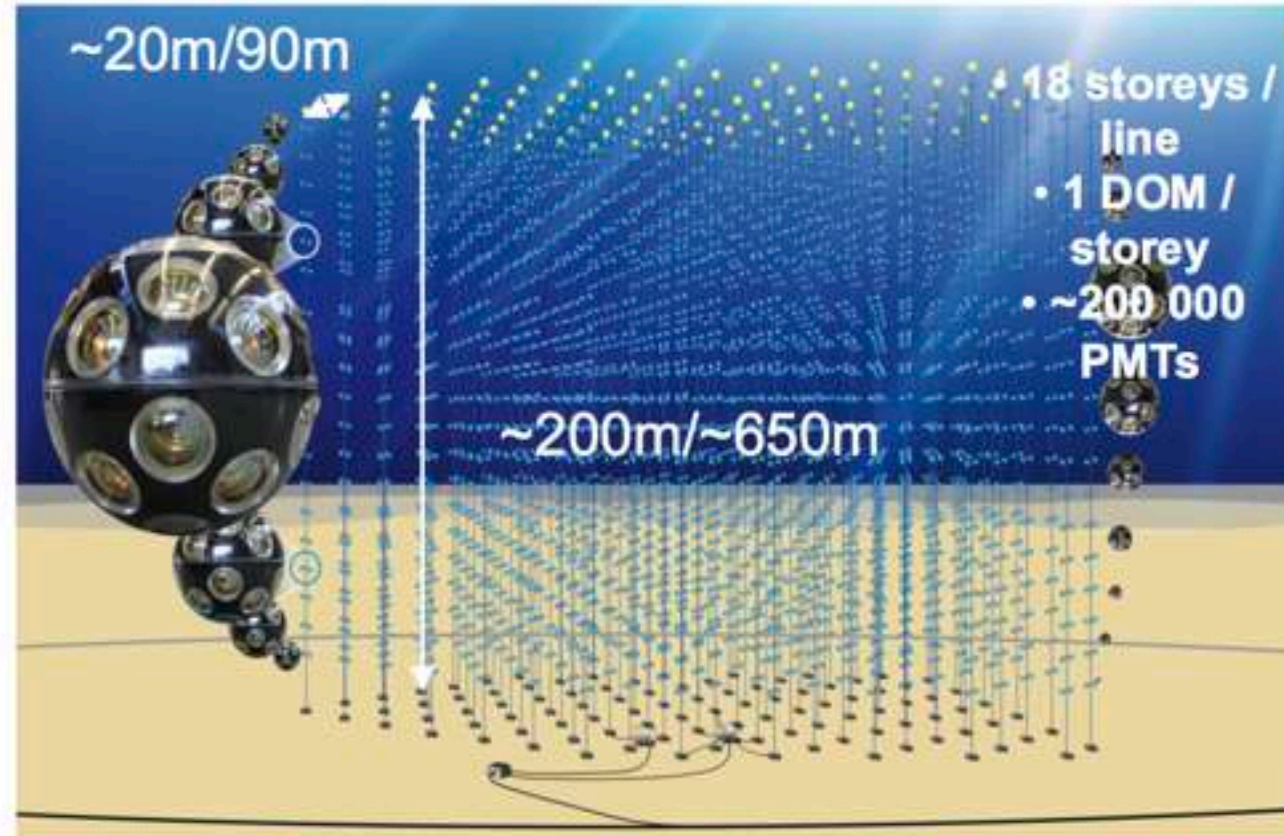


Mediterranean telescopes

ANTARES Complete since 2008



KM3NeT Under Construction



~10 Mton

12 lines

First Generation

First line since 10 years

$$\lambda_{\rm abs} = 60\,{\rm m}$$
$$\lambda_s = 270\,{\rm m}$$

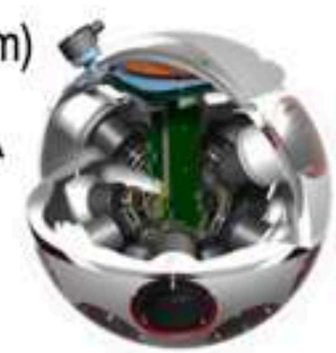
In water

230 ARCA + 115 ORCA lines New Generation

~1 Gton ~6 Mton

Same size (43cm)

Compact

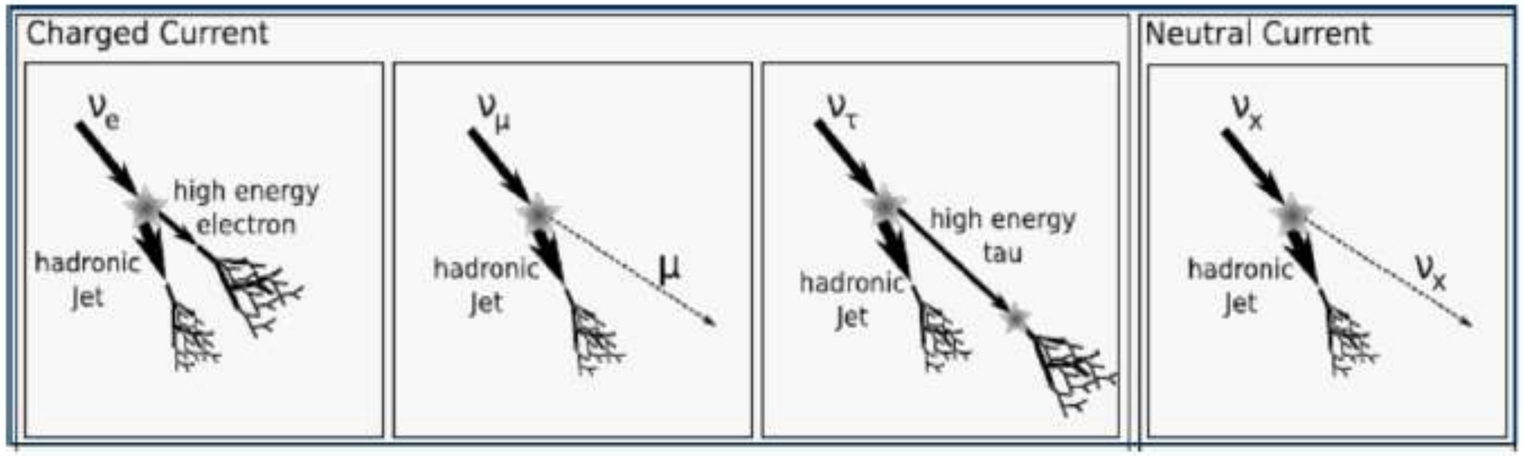


- DOM: 31 3" PMTs
- Digital photon counting
- Directional information
- Wide angle of view
- Cost reduction wrt ANTARES

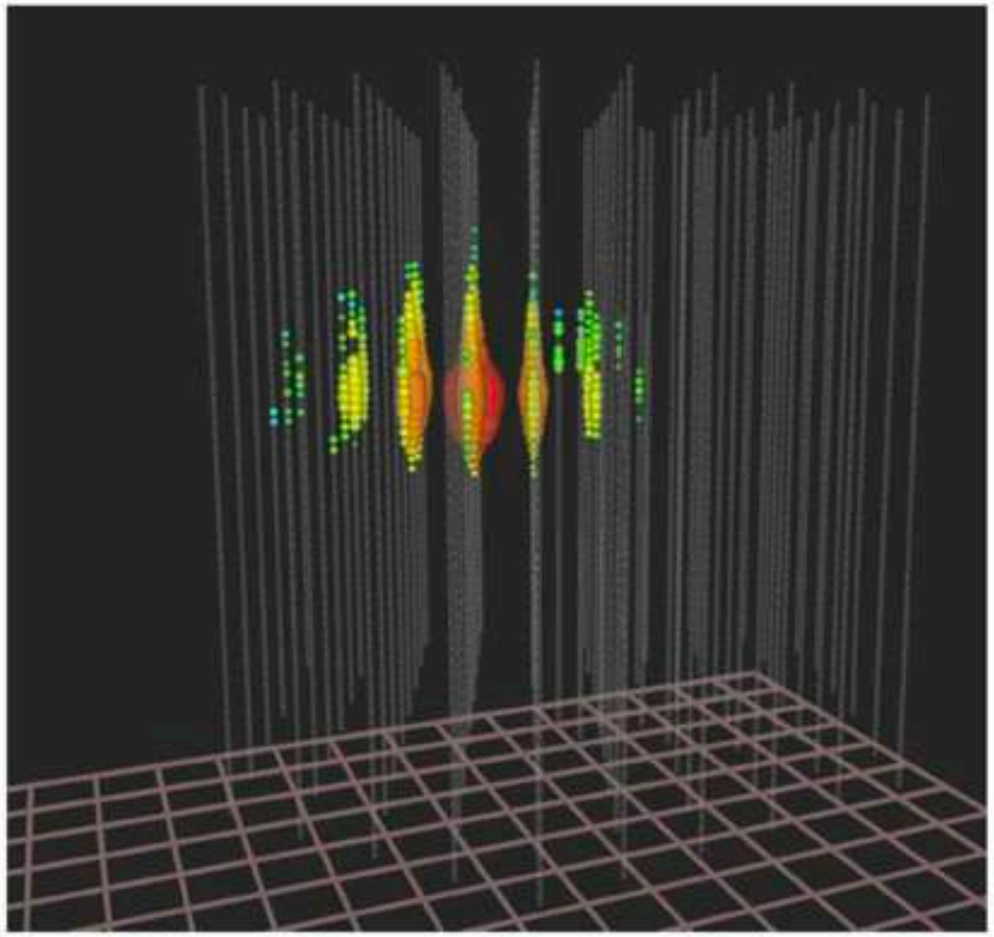
http://antares.in2p3.fr

http://www.km3net.org

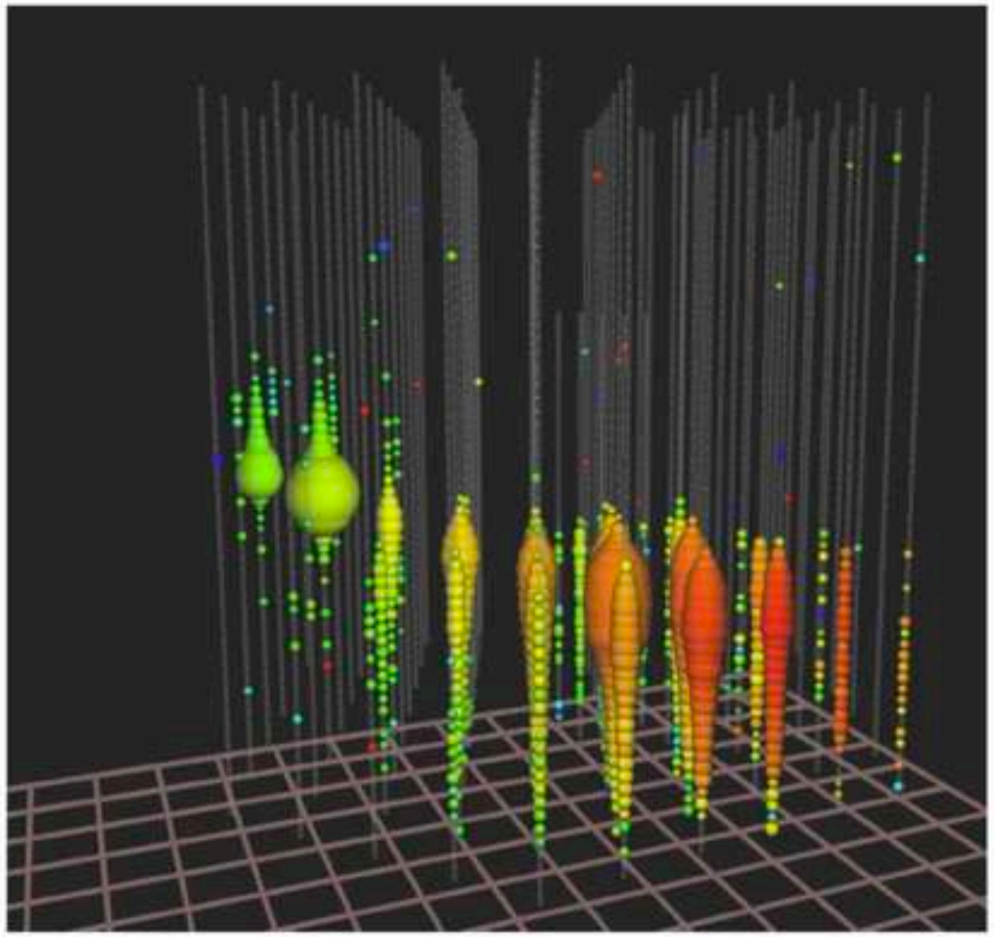
Neutrino event tolopologies



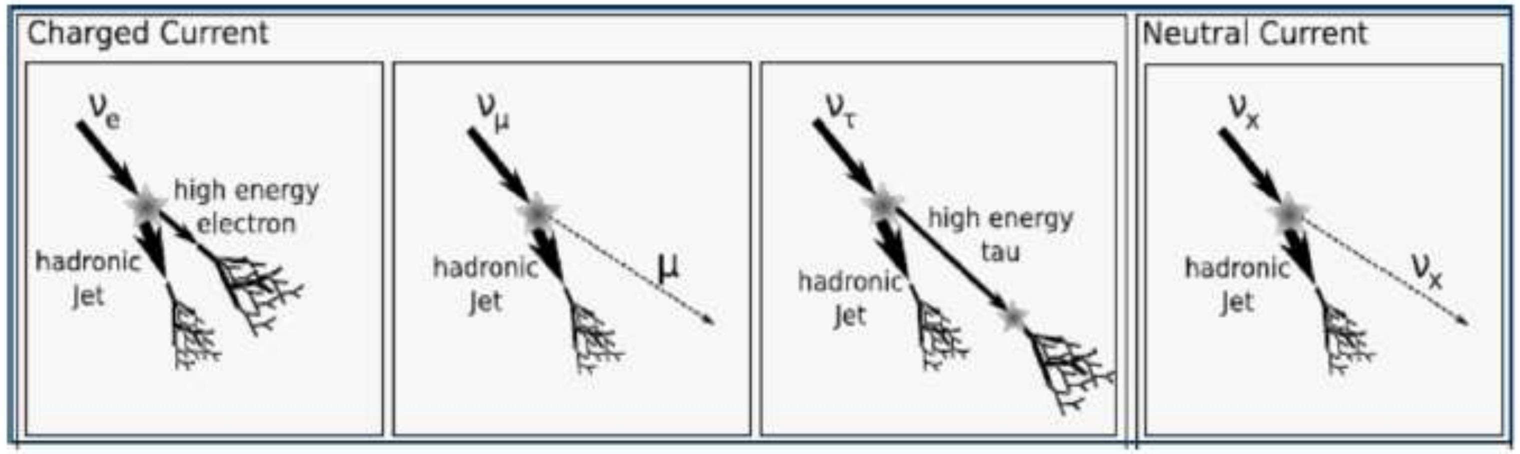
Isolated neutrinos interacting within the detector



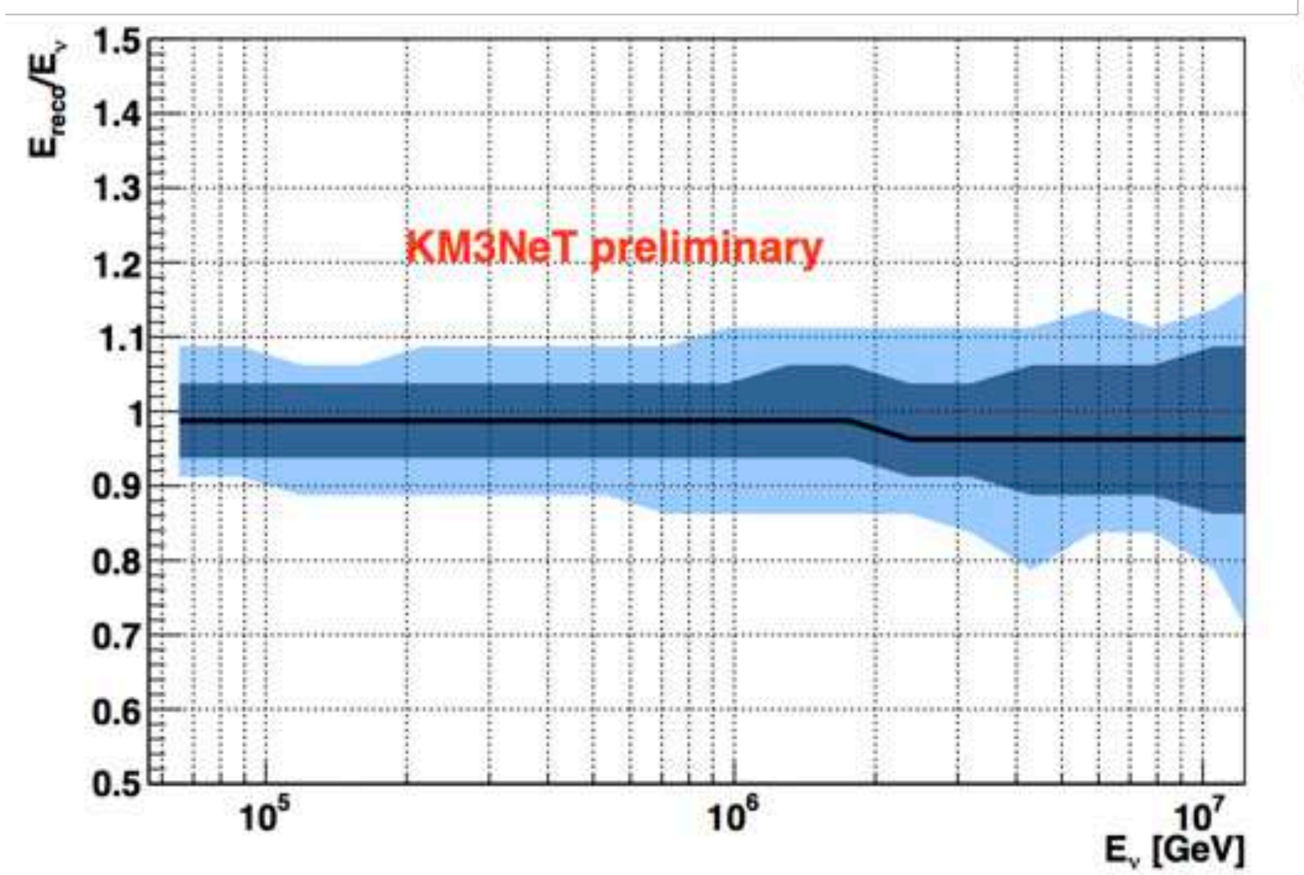
Upgoing muon tracks



Neutrino event tolopologies

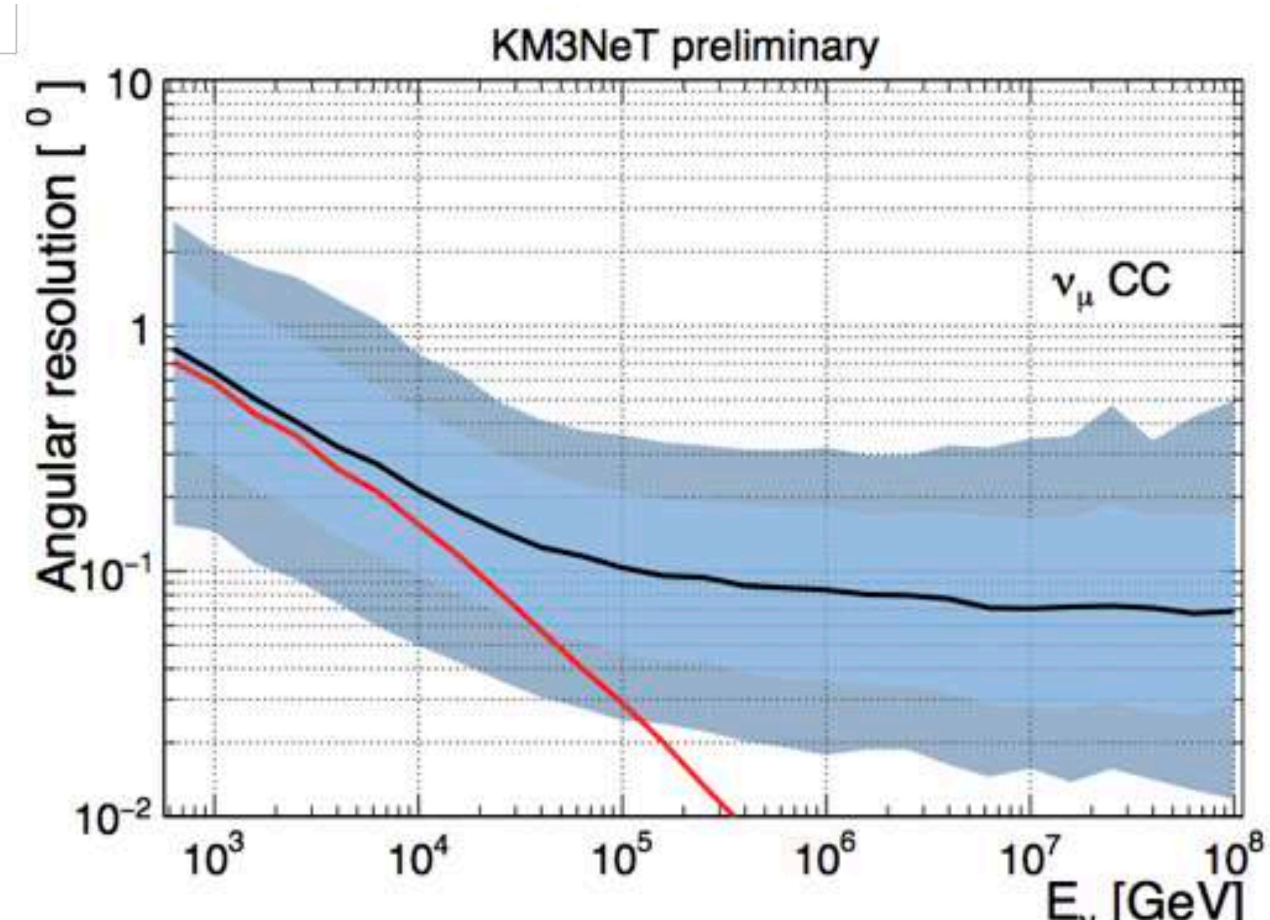


Isolated neutrinos interacting within the detector



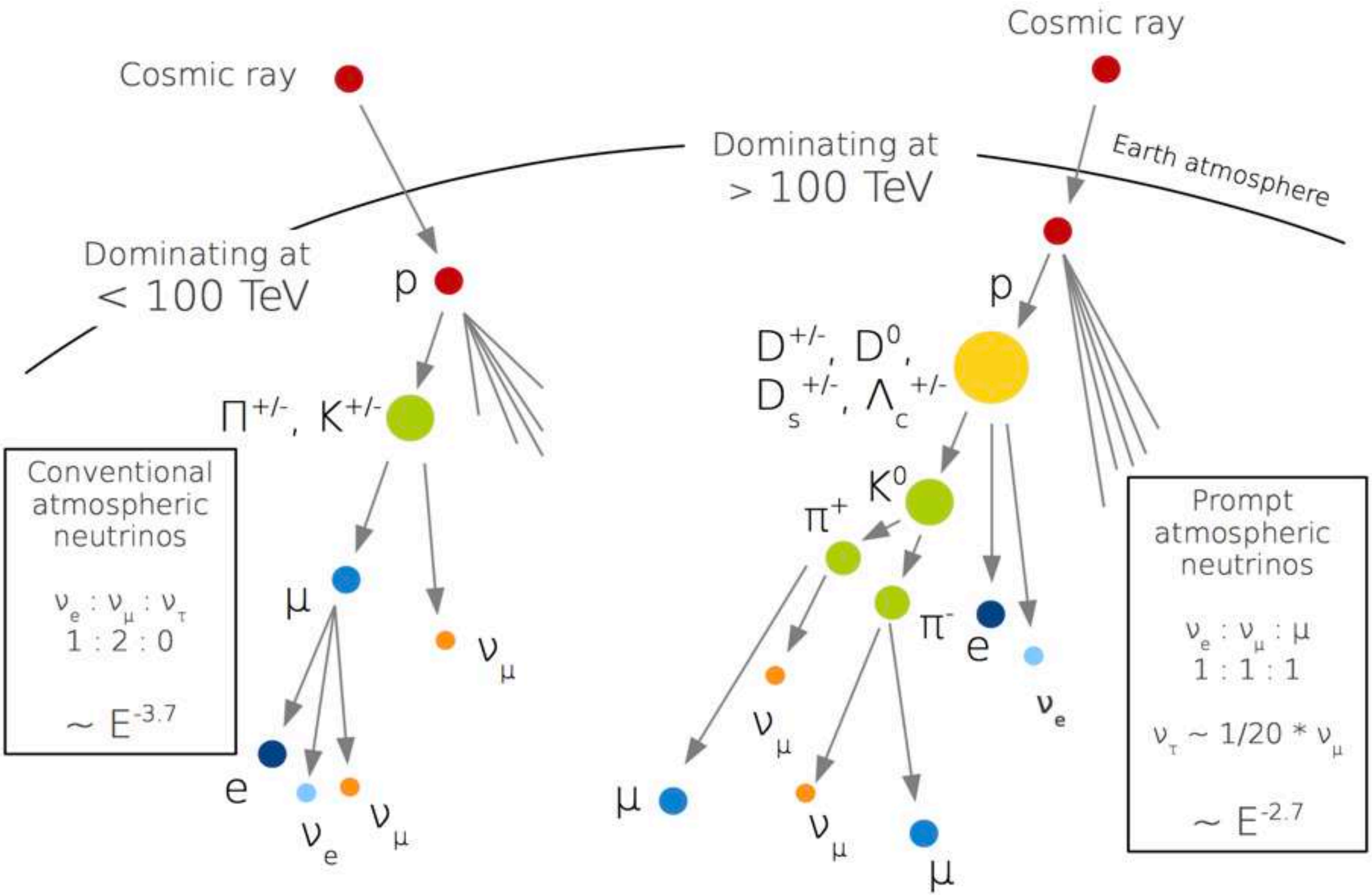
Calorimetry + all flavors

Upgoing muon tracks



Astronomy

Atmospheric neutrino background



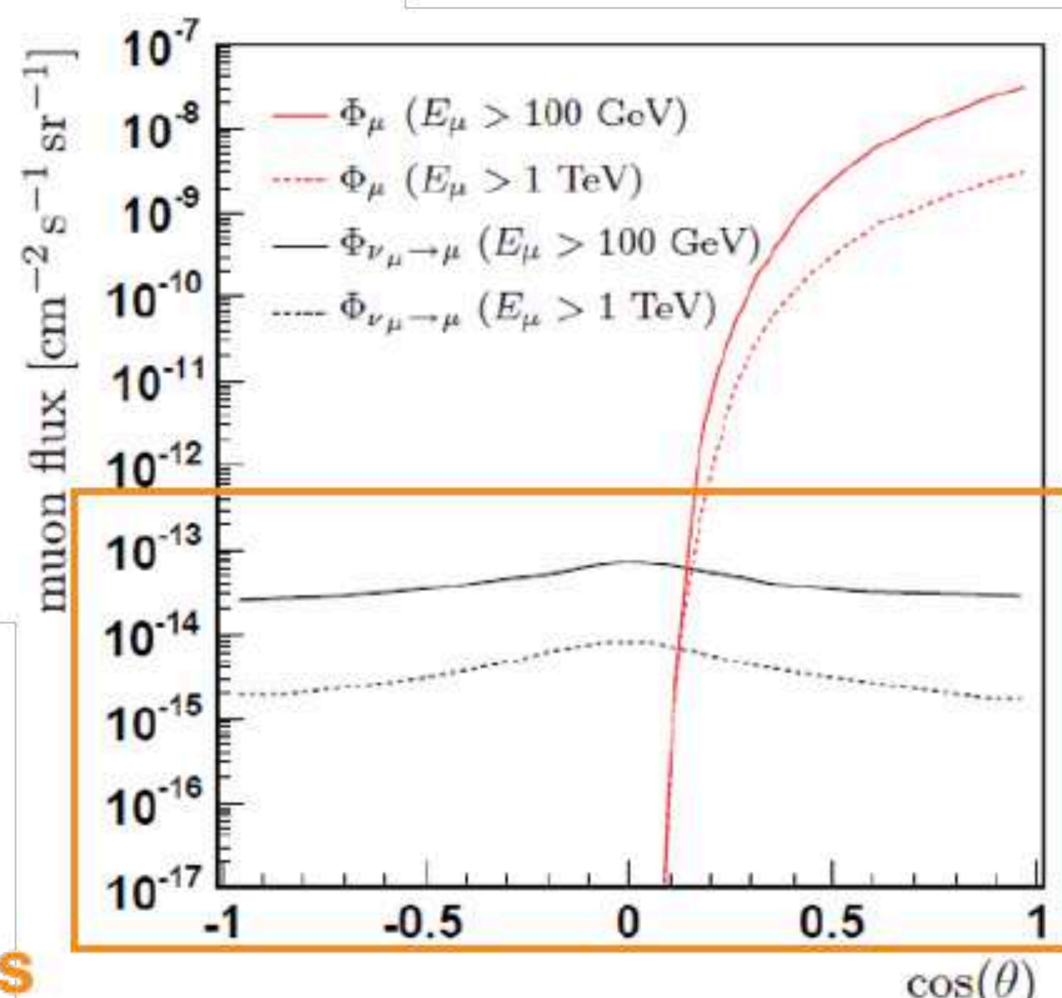
and atmospheric muon background

$$\boxed{\nu_\mu N \longrightarrow \mu X}$$

Search for neutrino induced events, mainly $\nu_\mu N \rightarrow \mu X$, up-going

Down-going μ from atm. showers
$\mu_{upgoing} / \mu_{atm} \sim 10^{-6}$ **at 3500m w.e. depth**
S/N $\sim 10^{-10}$

Up-going μ from neutrinos generated in atm. showers
S/N $\sim \nu_{astro} / \nu_{atm} \sim 10^{-4}$

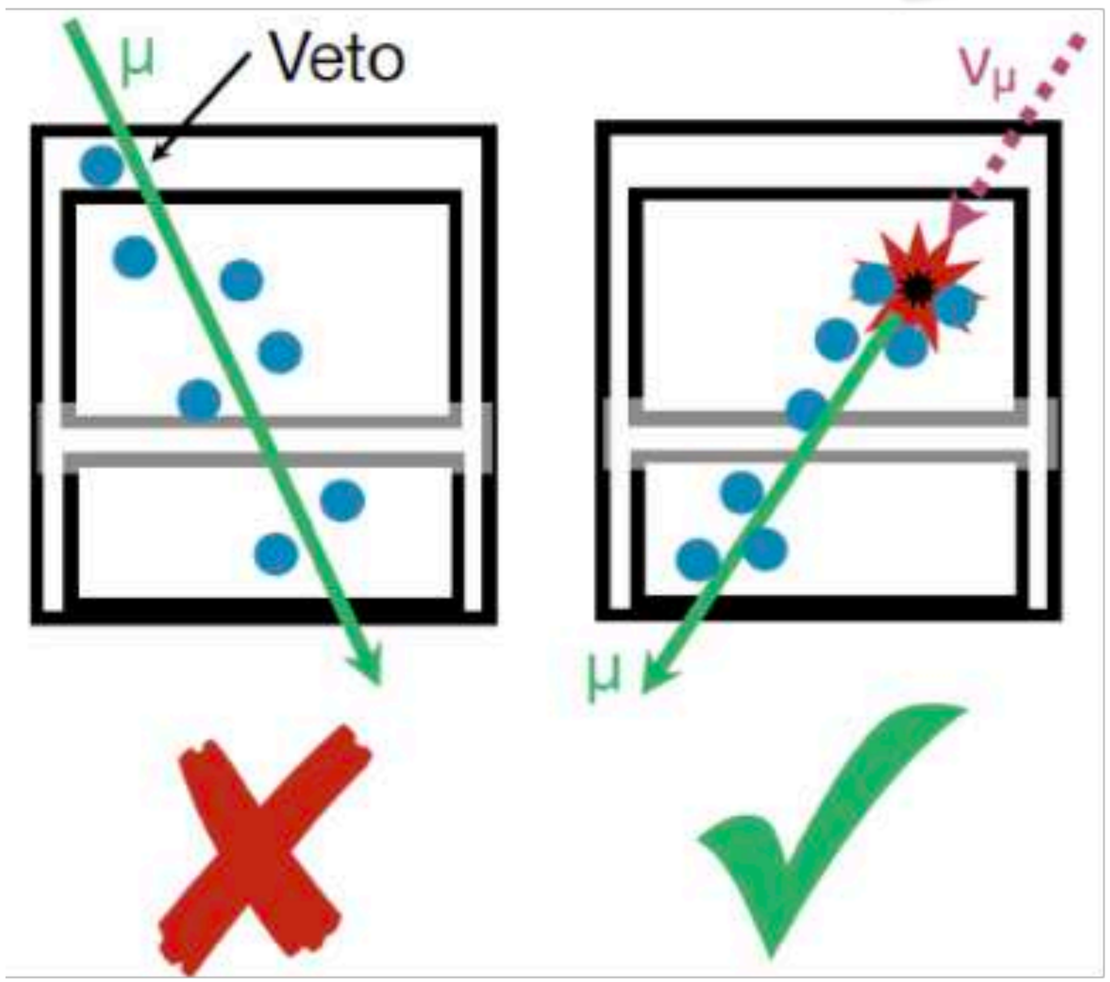


still some background from atmospheric neutrinos

The HESE event sample

"Vetoing the muon produced by the same parent meson decaying in the atmosphere"

$$\pi \longrightarrow \mu^{atmo} + \nu_\mu^{atmo}$$

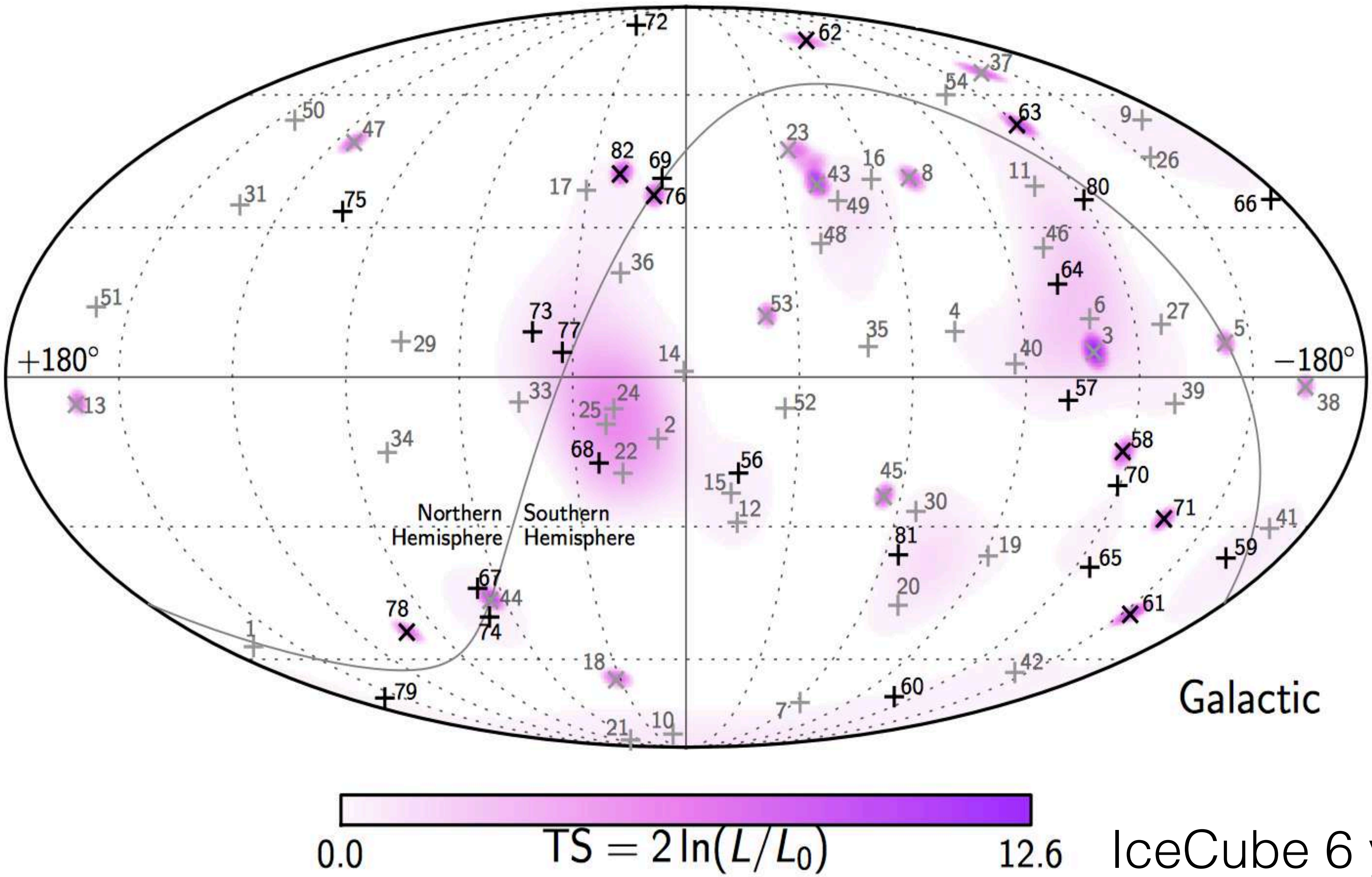


- Detects penetrating muons
- Reduced effective volume (400 MTon)
- Sensitive to all flavors
- Sensitive to the entire sky

Schonert et al., PRD 79 (2009) 4

$\boxed{E_\nu \sim 60 \text{ TeV}}$ in IceCube

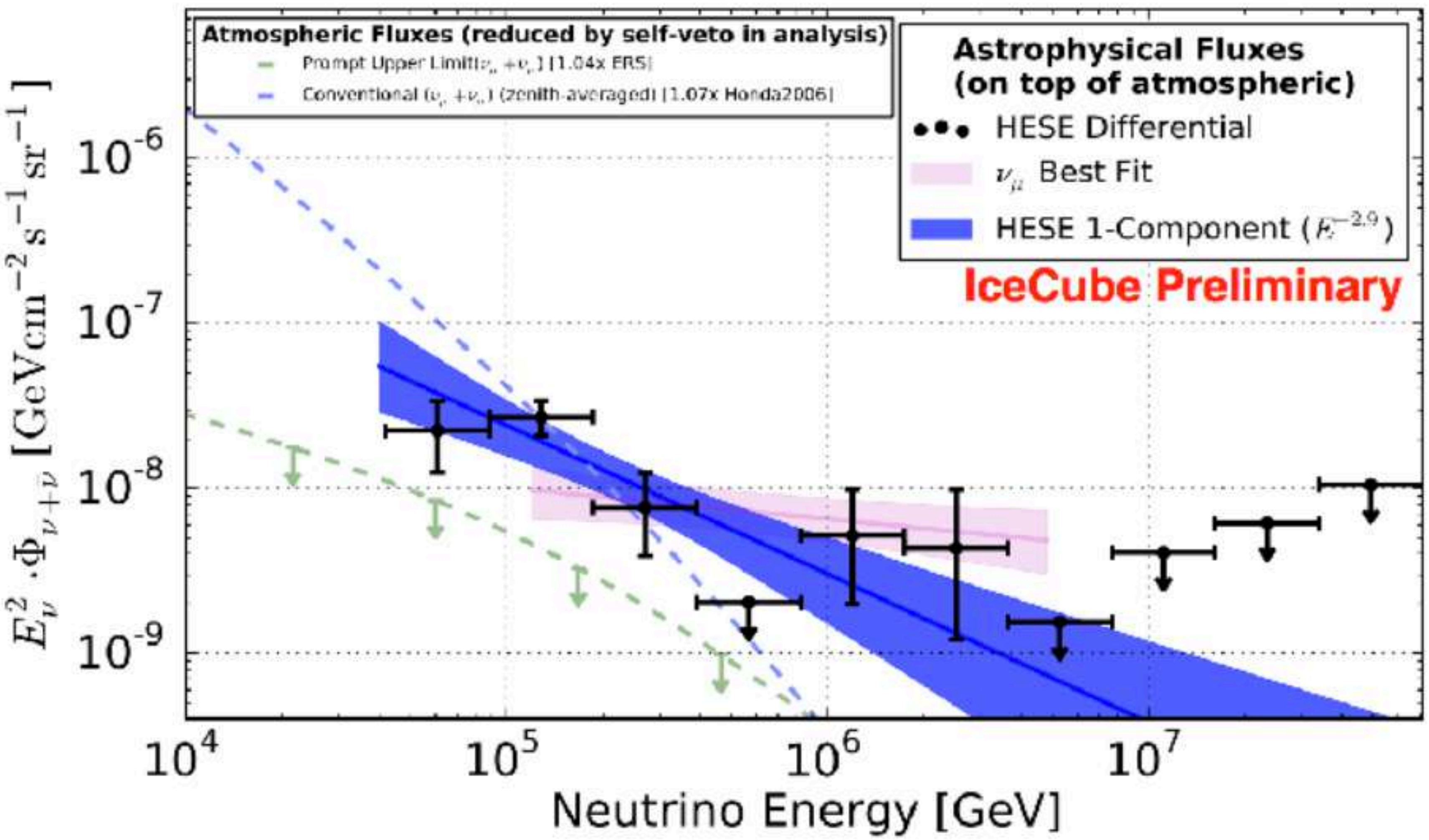
The era of neutrino astronomy



IceCube 6 yr map:
+ showers
x tracks

Kopper (IceCube Coll.), PoS ICRC (2017) 981

The era of neutrino astronomy



Tracks
119 TeV - 4.8 PeV
6.7σ

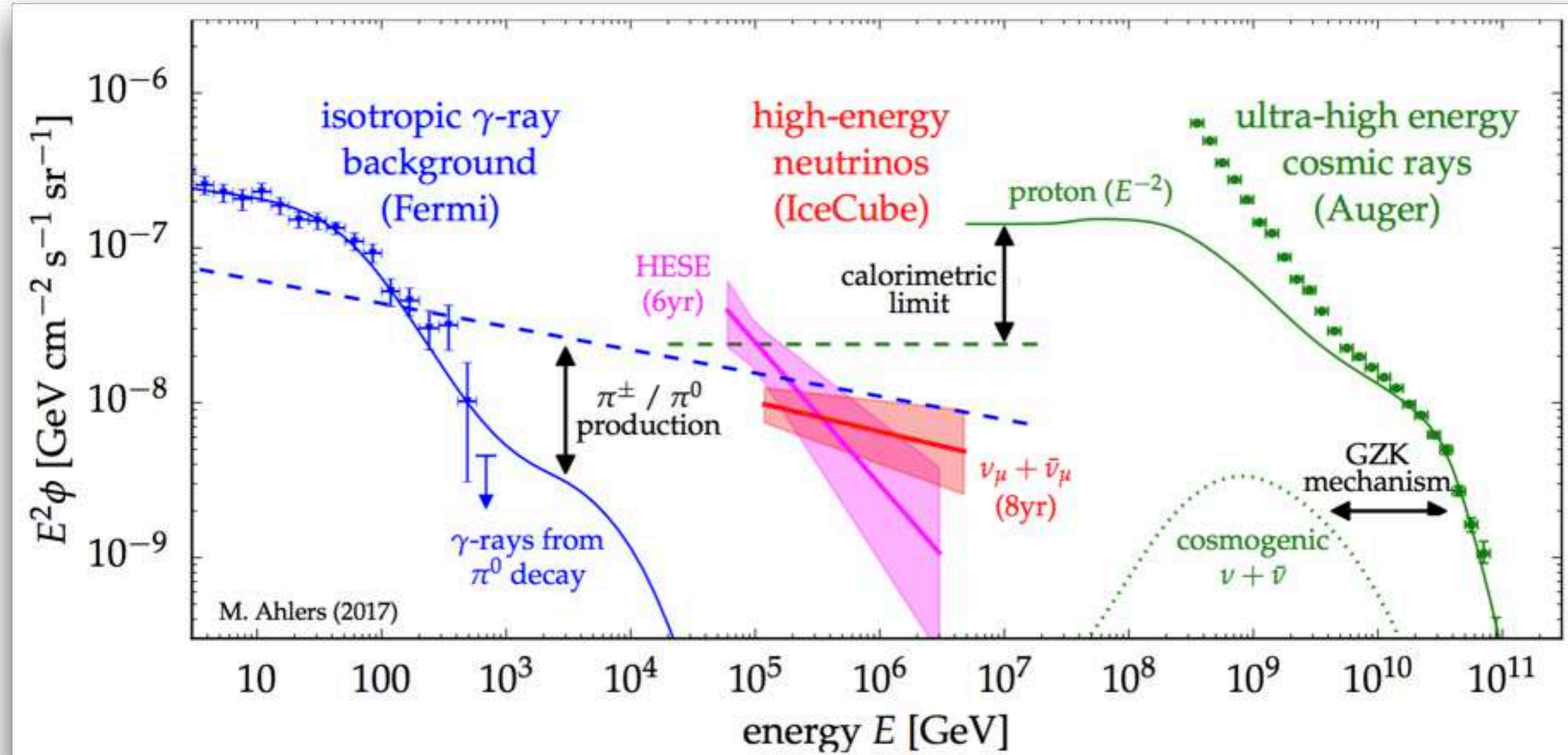
HESE
60 TeV - 10 PeV
8σ

$$\frac{d\phi}{dE}(\nu_\mu + \bar{\nu}_\mu) = (1.01^{+0.26}_{-0.23}) \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-2.19\pm0.10} \times 10^{-18} \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

$$\frac{d\phi}{dE}(\nu + \bar{\nu})_{\mathrm{HESE}} = (2.46 \pm 0.8) \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-2.92} \times 10^{-18} \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

Kopper (IceCube Coll.), PoS ICRC (2017) 981

in the multi-messenger context



EXTRAGALACTIC SOURCES APPEAR TODAY THE MOST REALISTIC CANDIDATES

Identification of ν-sources: open questions

SPECTRUM

- Is the IceCube flux an unbroken power law all the way up to 100 PeV? Is there a break or a cut-off?
- Is it a one-component flux?

COMPOSITION

- Has the IceCube flux an extra-galactic origin? Which sources contribute it the most? What is the connection with UHECR sources?
- What is the amount of Galactic component?

ANISOTROPY

- Is the IceCube flux truly isotropic?
- Why don't we see multiplets?

Identification of ν-sources: methods

Several strategies to look for ν-sources:

1. **Clustering** of neutrino events (all-sky scan);

2. **Catalog search**, i.e. at pre-defined sky positions, as indicated by MM studies (typically bright sources in EM wavelengths): e.g. population & stacking analyses;

3. **MM alerts** for extremely energetic events. So far, only this strategy has lead to positive results:
   → **TXS 0506+056** & IC170922A IceCube Coll. et al., Science 361 (2018)
   → **TDE AT2019dsg** & IC191001A R. Stein et al., arXiv:2005.05340

Catalog search: transient sources

- GRBs are promising neutrino candidate sources, given their **transient** nature.

- Background is integrated in a **limited time window**, which is defined by the T90, assuming coincident neutrino-photon emission during the prompt phase of the burst.

- Still, it is necessary to select sources **below the detector's horizon** at the occurrence of the transient event, as to reduce the huge atmospheric muon background.

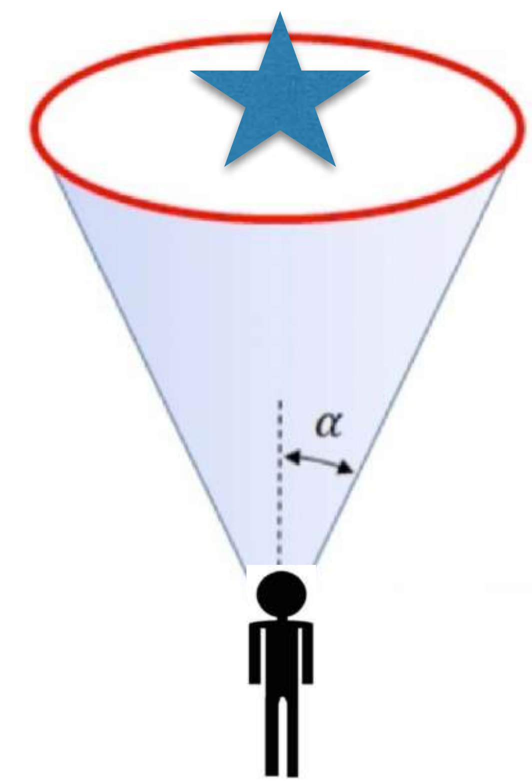
- Two **ANTARES** analyses are presented in the following:
  - promising **bright GRBs**;
  - **diffuse** search from the **GRB population in 2007-2017**.

Catalog search: transient sources

We look for **muon neutrinos** in **spatial and temporal coincidence** with the GRB occurrence:

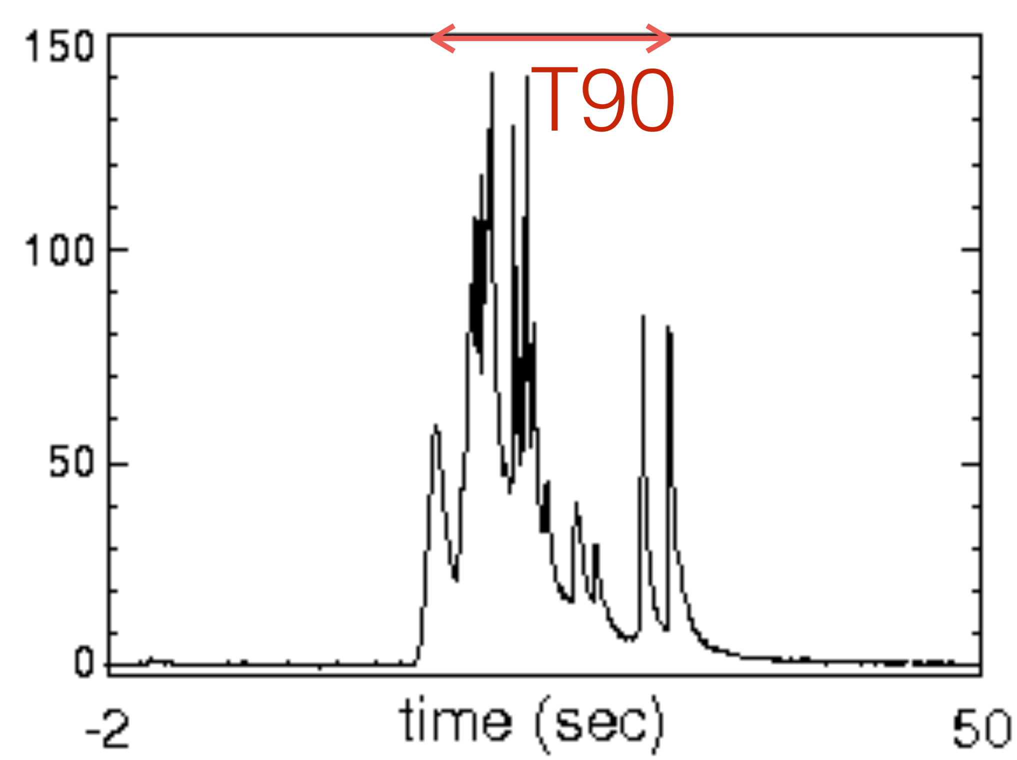
- Angular search window around source position:

$$\alpha = 10^{\circ}$$



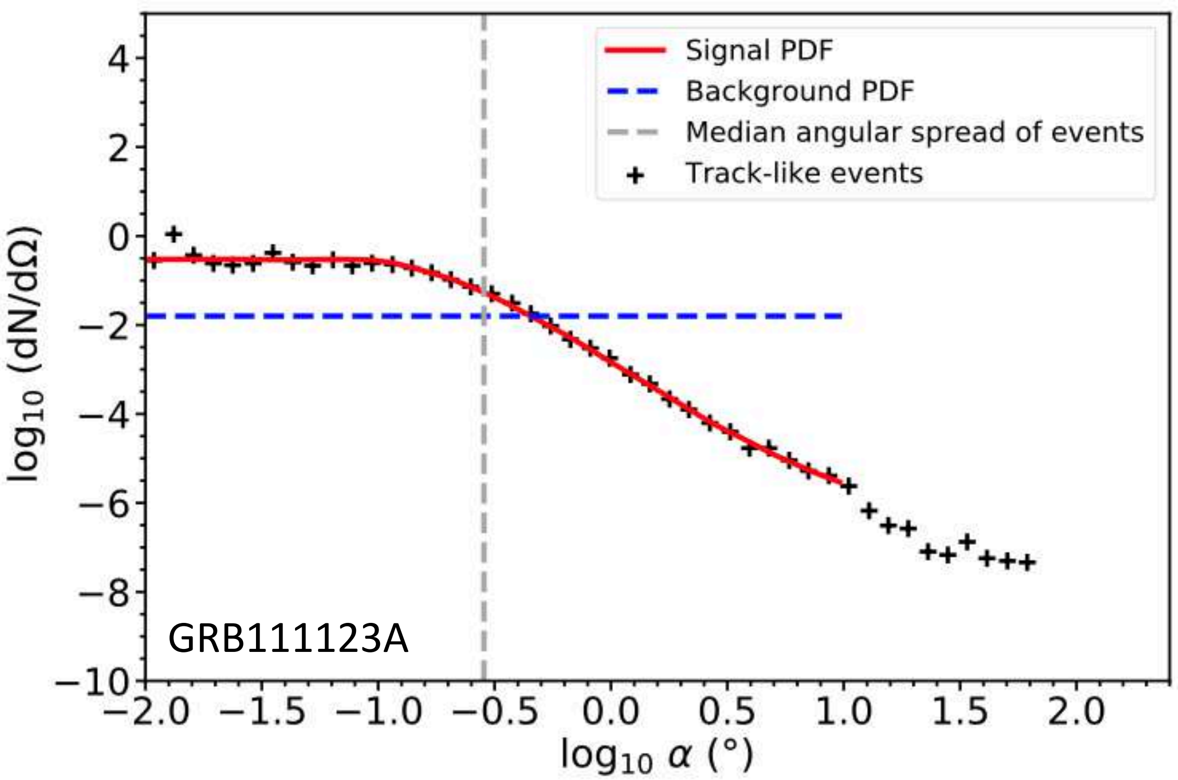
- Temporal search window around T0:

$$T_{\mathrm{search}} = T90 \pm 30\% T90 \pm 2\ \mathrm{s}$$



Catalog search: transient sources

- Discrimination between signal and background relies upon their different **spatial distribution**, which is obtained through ad-hoc **Monte Carlo simulations** of the detector's response:



The spatial PDF is centered in the source position, while the background is considered flat in the search cone angle.

Albert et al. [ANTARES Coll.], MNRAS 500 (2021) 4

- Optimization is performed individually for each GRB, based on an **extended maximum likelihood ratio**

$$Q = \max_{\mu'_s \in [0;n_{\mathrm{tot}}]} \left(\sum_{i=1}^{n_{\mathrm{tot}}} \log \frac{\mu'_s S(\alpha_i) + \mu_b B(\alpha_i)}{\mu_b B(\alpha_i)} - \mu'_s \right)$$

ANTARES search for ν from individual bright GRBs

- Source selection:
  - Measured gamma-ray fluence is $\mathbf{F_\gamma > 10^{-4}}$ **erg/cm²**;
  - Redshift of the progenitor is measured;
  - GRB observable in 2008-2013, from **below the ANTARES horizon** at T0.

⟶ **GRB080916C, GRB110918A, GRB130427A, GRB130505A**

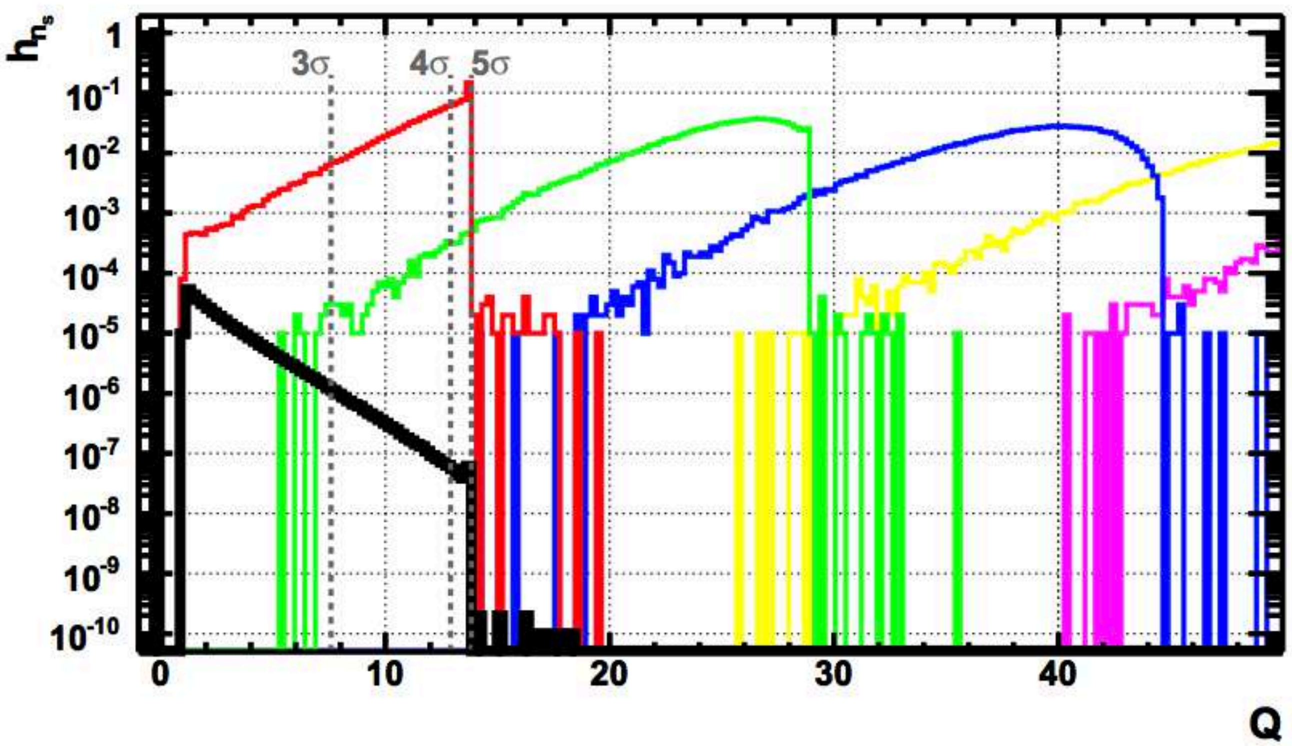
Adrian-Martinez et al. [ANTARES Coll.], MNRAS 469 (2017) 1

- Search optimization on individual GRBs: **pseudo-experiments** are run in order to optimize the **quality parameter** of the reconstructed track, as to yield the **maximum discovery potential** of the model (MDP)

$$MDP = P(Q \geq Q_p^{\mathrm{th}} | \mu_s) = \int_{Q_p^{\mathrm{th}}}^{\infty} P(Q|\mu_s) dQ = \sum_{n_s=0}^{\infty} P(n_s|\mu_s) \int_{Q_p^{\mathrm{th}}}^{\infty} h_{n_s}(Q) dQ$$

ANTARES search for ν from individual bright GRBs

GRB110918A



Distributions of the test statistics:

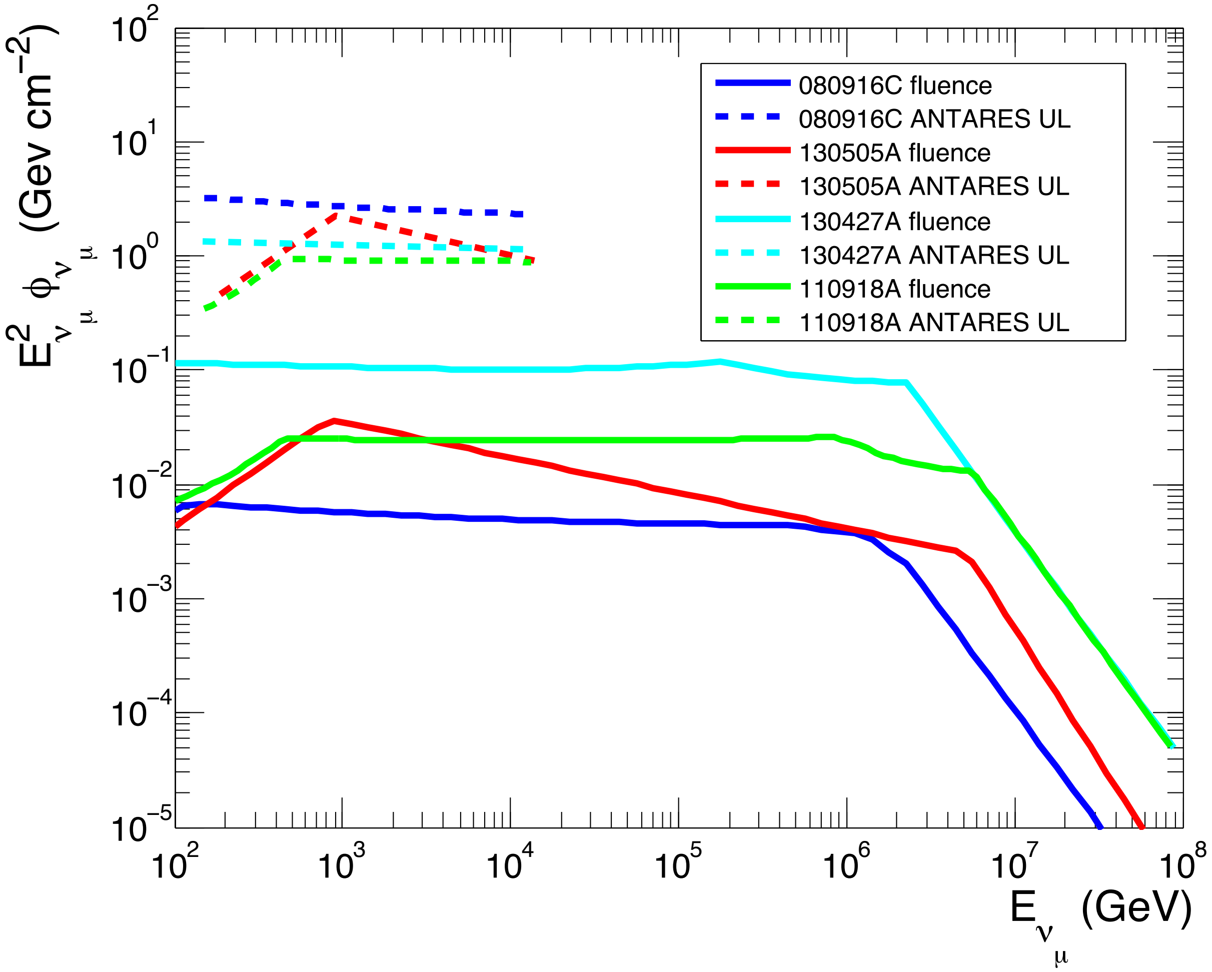
$h_0(Q)$ bkg only
$h_1(Q)$ 1 signal event + bkg
$h_2(Q)$ 2 signal events + bkg
$h_3(Q)$ 3 signal events + bkg

$$p = P(Q \geq Q_p^{\text{thres}} | \mu_b) = \int_{Q_p^{\text{thres}}}^{\infty} h_0(Q) dQ$$

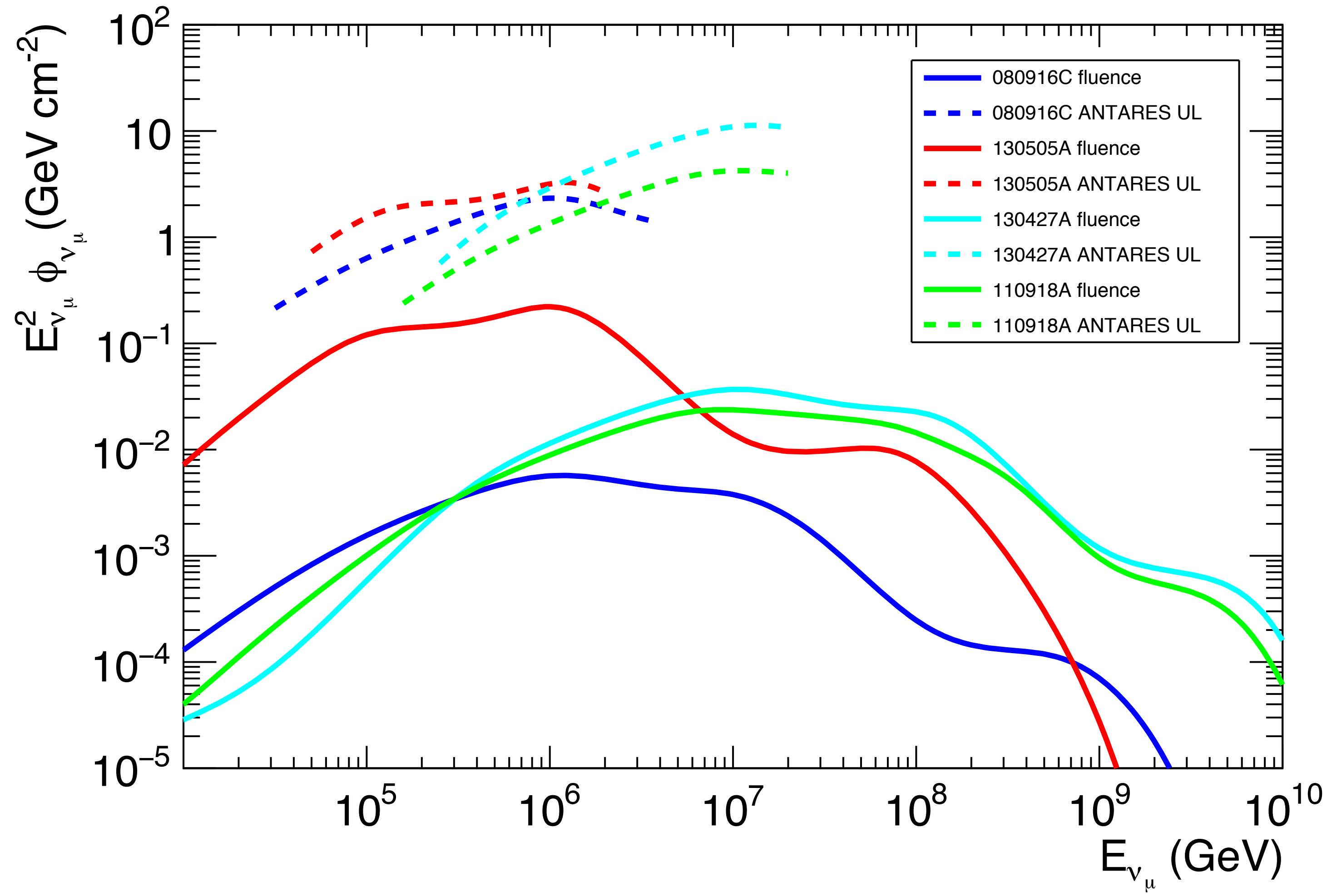
Adrian-Martinez et al. [ANTARES Coll.], A&A 559 (2013) A9

ANTARES search for ν from individual bright GRBs

PHOTOSPHERIC SCENARIO



INTERNAL SHOCK SCENARIO



Neutrino flux computation assuming $\mathbf{f_p=10}$ and $\mathbf{\Gamma=316}$:

PH analytical model from Zhang & Kumar, Phys. Rept. 561 (2015) 1

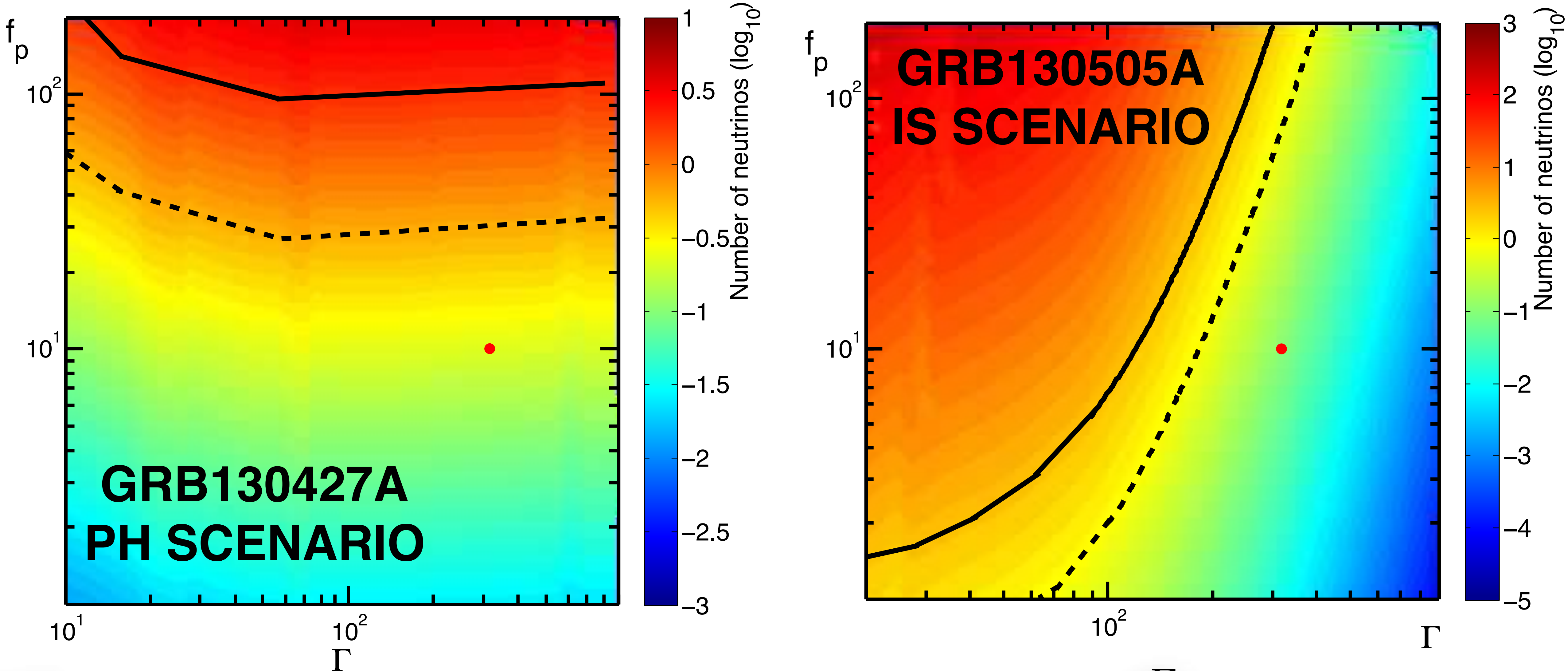
IS numerical model from Hummer et al., ApJ 721 (2010) 630 **(NeuCosmA)**

Data unblinding at optimal cuts results in **no neutrino detection**.

Adrian-Martinez et al. [ANTARES Coll.], MNRAS 469 (2017) 1

ANTARES search for ν from individual bright GRBs

For each GRB, the parameter space of the models was investigated:



$$\int_0^{\infty} E_\nu F_\nu(E_\nu)dE_\nu = \frac{1}{8} f_p [1-(1-\langle x_{p\to\pi}\rangle)^{\tau_{p\gamma}}] \int_{E_{\min}}^{E_{\max}} E_\gamma F_\gamma(E_\gamma)dE_\gamma$$

Adrian-Martinez et al. [ANTARES Coll.], MNRAS 469 (2017) 1

—— 90% CL - - - - - 50% CL

ANTARES diffuse search for ν from GRBs in 2007-2017

1. GRB selection for the years from 2007 to 2017

GRBs from Fermi, Swift, and Konus-Wind satisfying the following conditions are selected:

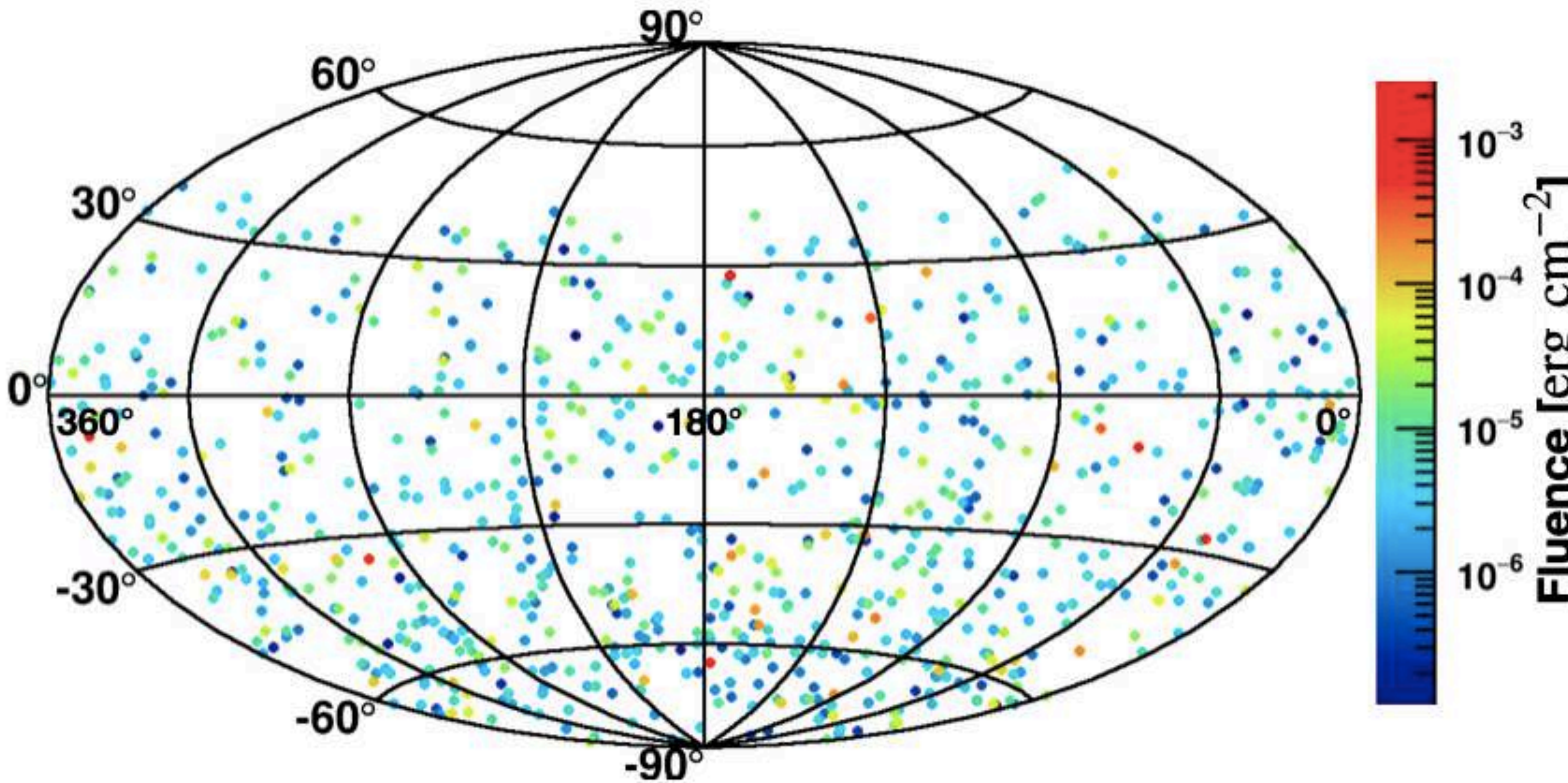
- T90 (~ duration) measured and > 2s (**long GRBs**);
- Gamma-ray spectrum is measured;
- Position measured and satellite angular uncertainty <10°;
- One among fluence and redshift is measured;
- **Below ANTARES horizon** at trigger time (up-going events);

$\longrightarrow$ **sample of 784 GRBs**

Albert et al. [ANTARES Coll.], MNRAS 500 (2021) 4

ANTARES diffuse search for ν from GRBs in 2007-2017

1. **GRB selection for the years from 2007 to 2017**



equatorial coordinates

Albert et al. [ANTARES Coll.], MNRAS 500 (2021) 4

ANTARES diffuse search for ν from GRBs in 2007-2017

2. Analysis features

- We explore the selected GRB sample by assuming the **one-zone internal shock** scenario of the fireball model.
- We investigate the **uncertainties** connected to the lack of knowledge of some model parameters **on neutrino expected flux**

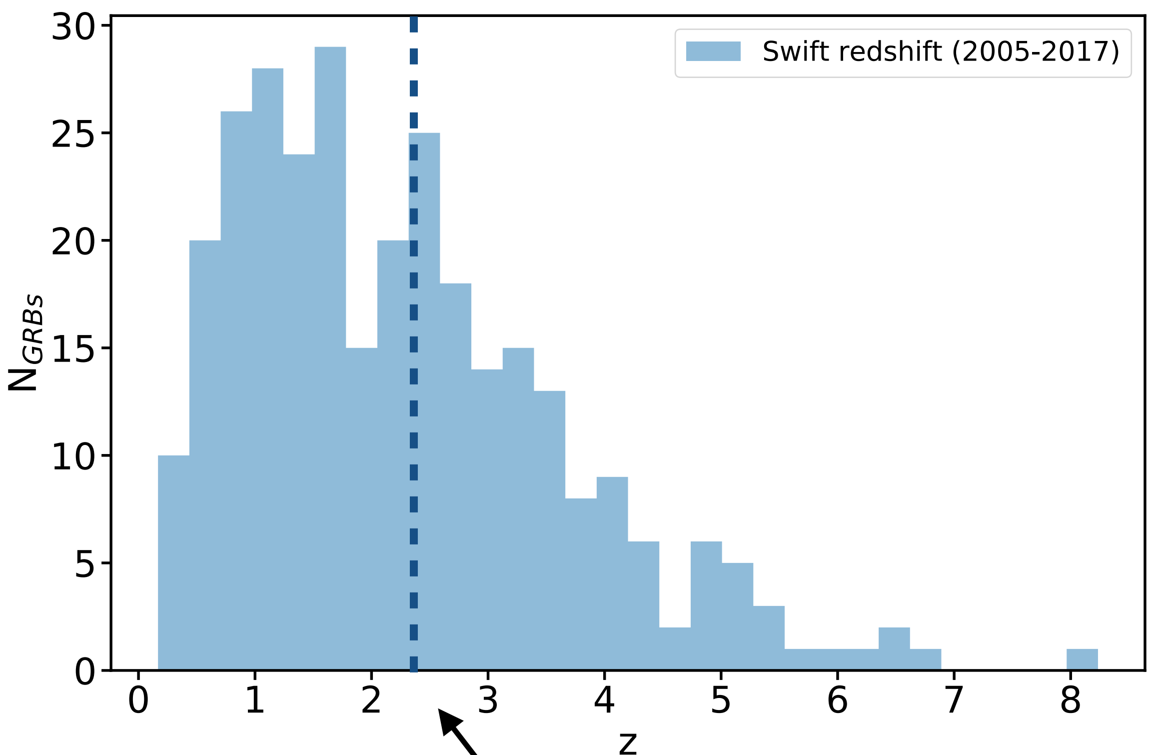
  - 89% of the sample has unknown **z**;
  - 68% of the sample has unknown $\mathbf{t_{var}}$;
  - **Γ** is unknown for the entire sample.

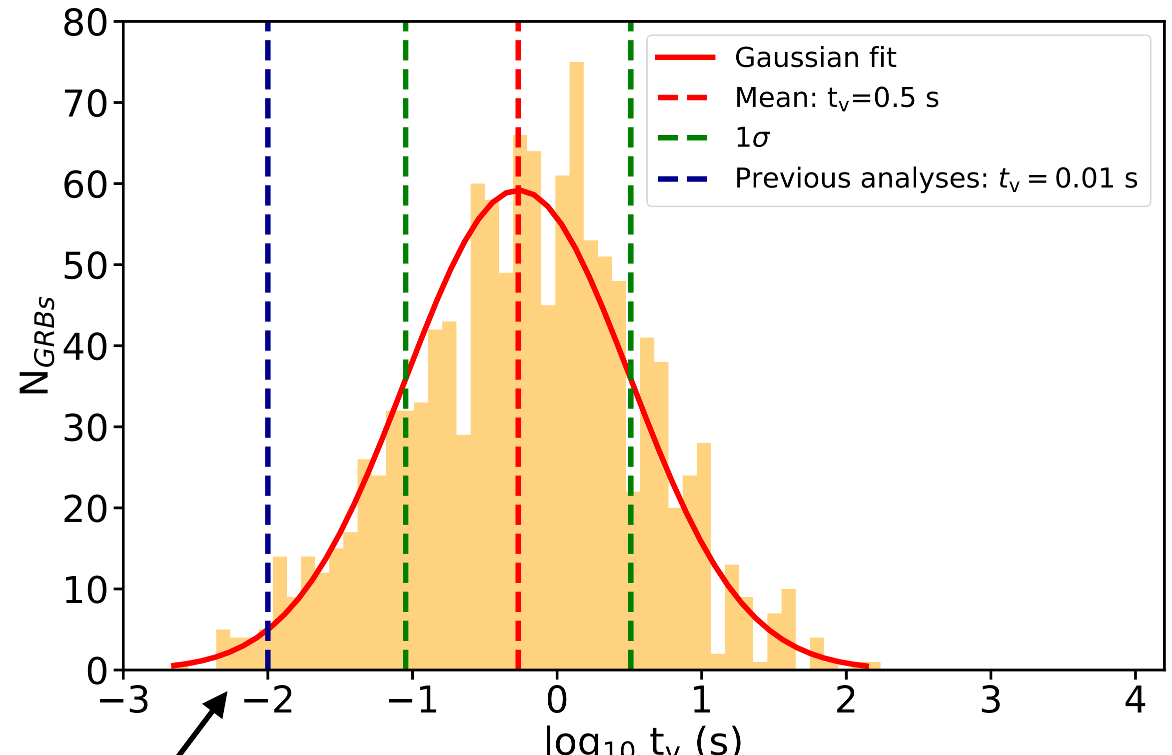
Instead of assuming a fixed value for these unknown, we randomly extract their values from distributions obtained by satellites with large statistics.

ANTARES diffuse search for ν from GRBs in 2007-2017

2. Analysis features

For each GRB of the sample, **1000 extractions** are realized:





https://swift.gsfc.nasa.gov/archive/grb table/

Golkhou et al., ApJ 787 (2014) 90

Golkhou et al., ApJ 811 (2015) 93

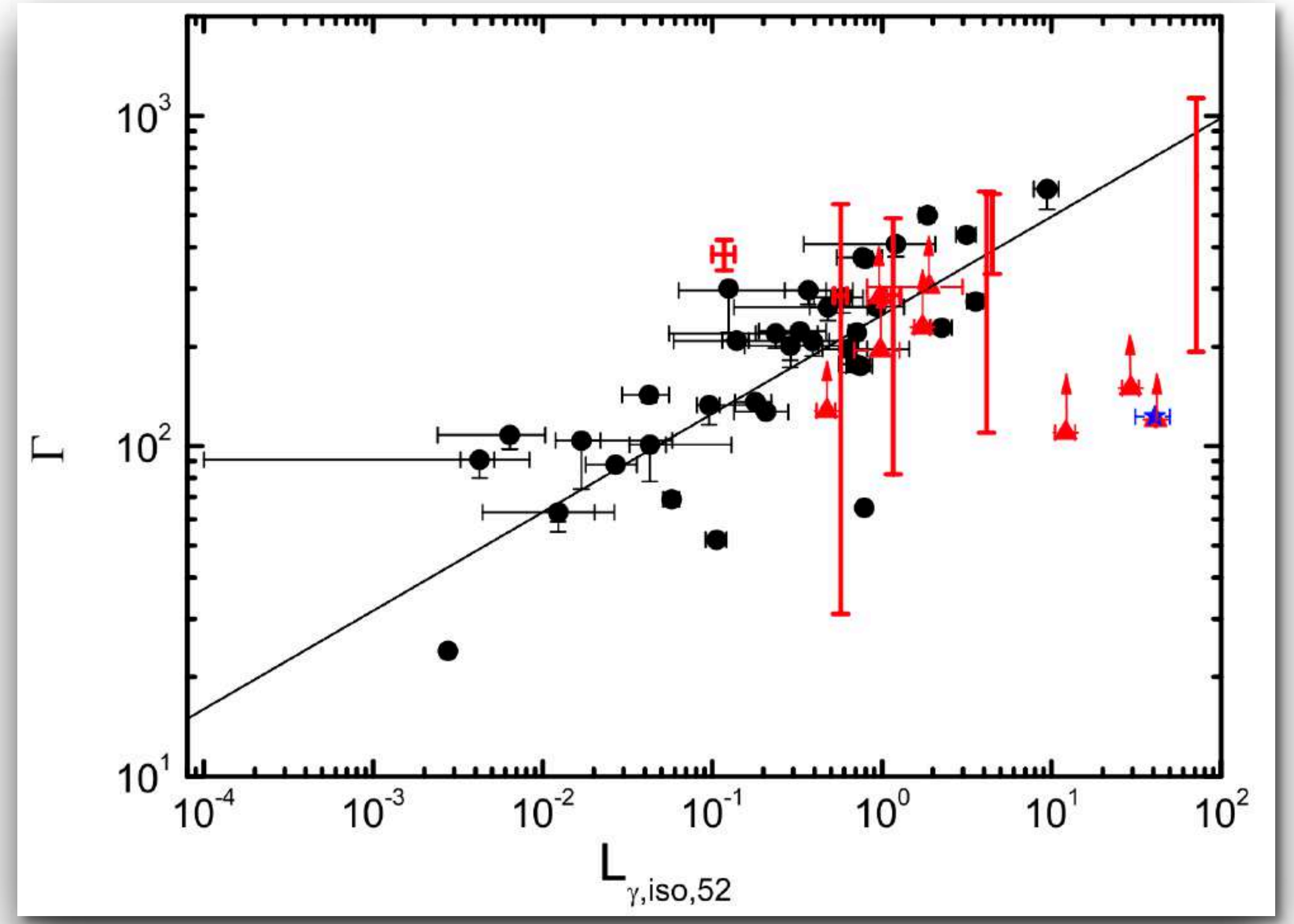
Sonbas et al., ApJ 805 (2015) 86

assumed in previous stacking analyses

ANTARES diffuse search for ν from GRBs in 2007-2017

2. Analysis features

From extracted redshift, Γ is derived thanks to correlation with L_{iso}:



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

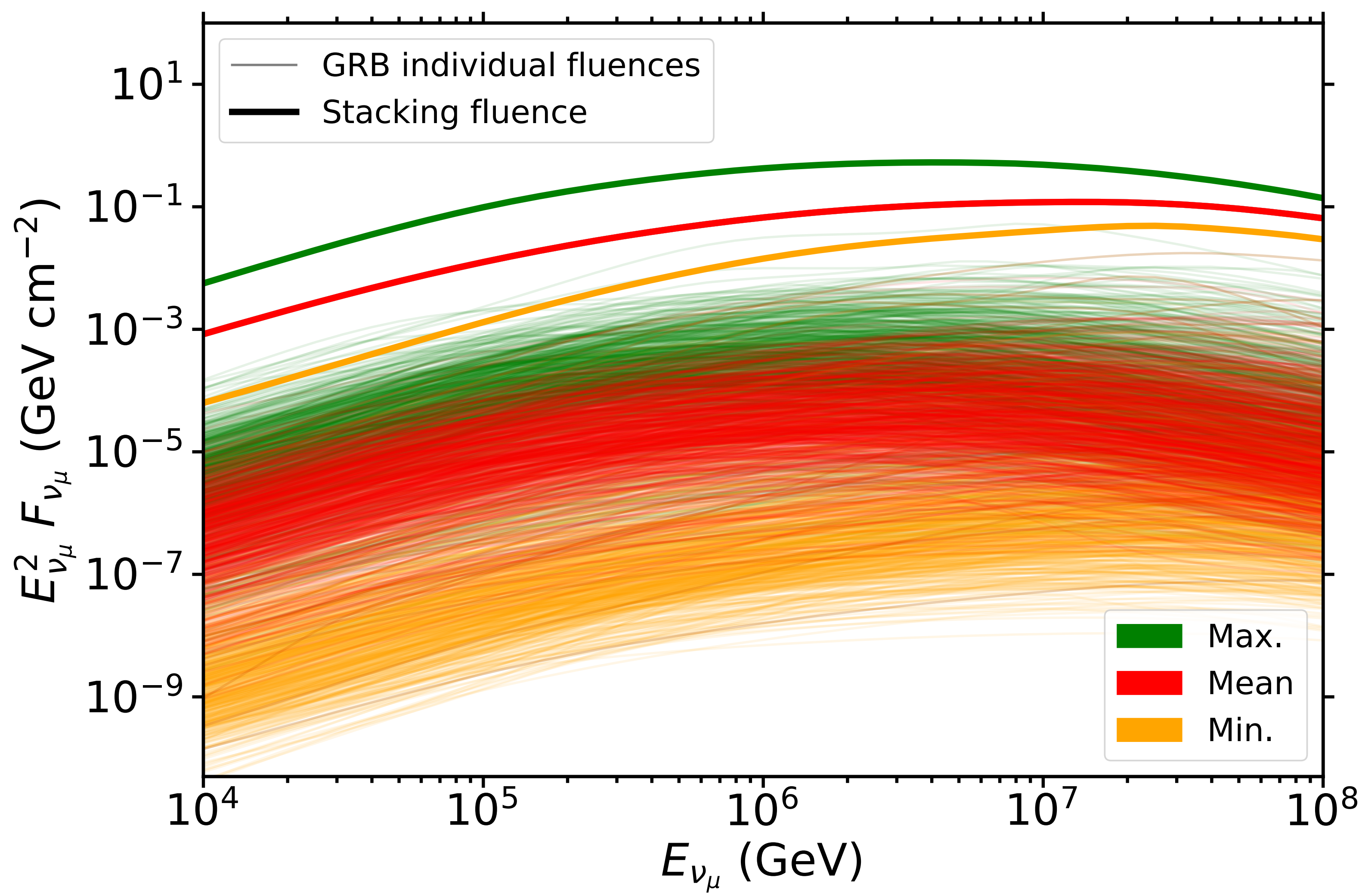
Lu al., ApJ 751 (2012) 49

→ for each GRB, we can compute $\langle E_\nu^2 F_\nu \rangle \pm 2\sigma$

ANTARES diffuse search for ν from GRBs in 2007-2017

2. Analysis features

$$\longrightarrow \langle E_\nu^2 F_\nu \rangle \pm 2\sigma$$



Albert et al. [ANTARES Coll.], MNRAS 500 (2021) 4

ANTARES diffuse search for ν from GRBs in 2007-2017

2. Analysis features

The **stacking** technique allows to derive the **GRB sub-sample** that is able to provide the highest discovery potential of the model. In order to do so, two strategies are possible:

x Introduce a weight factor according to ν flux: would highly depend on the signal modelling;

o Consider the **individual source contribution to the overall MDP**, while accounting for a trial factor in the definition of the p-value in order to have the same overall probability of false discovery:

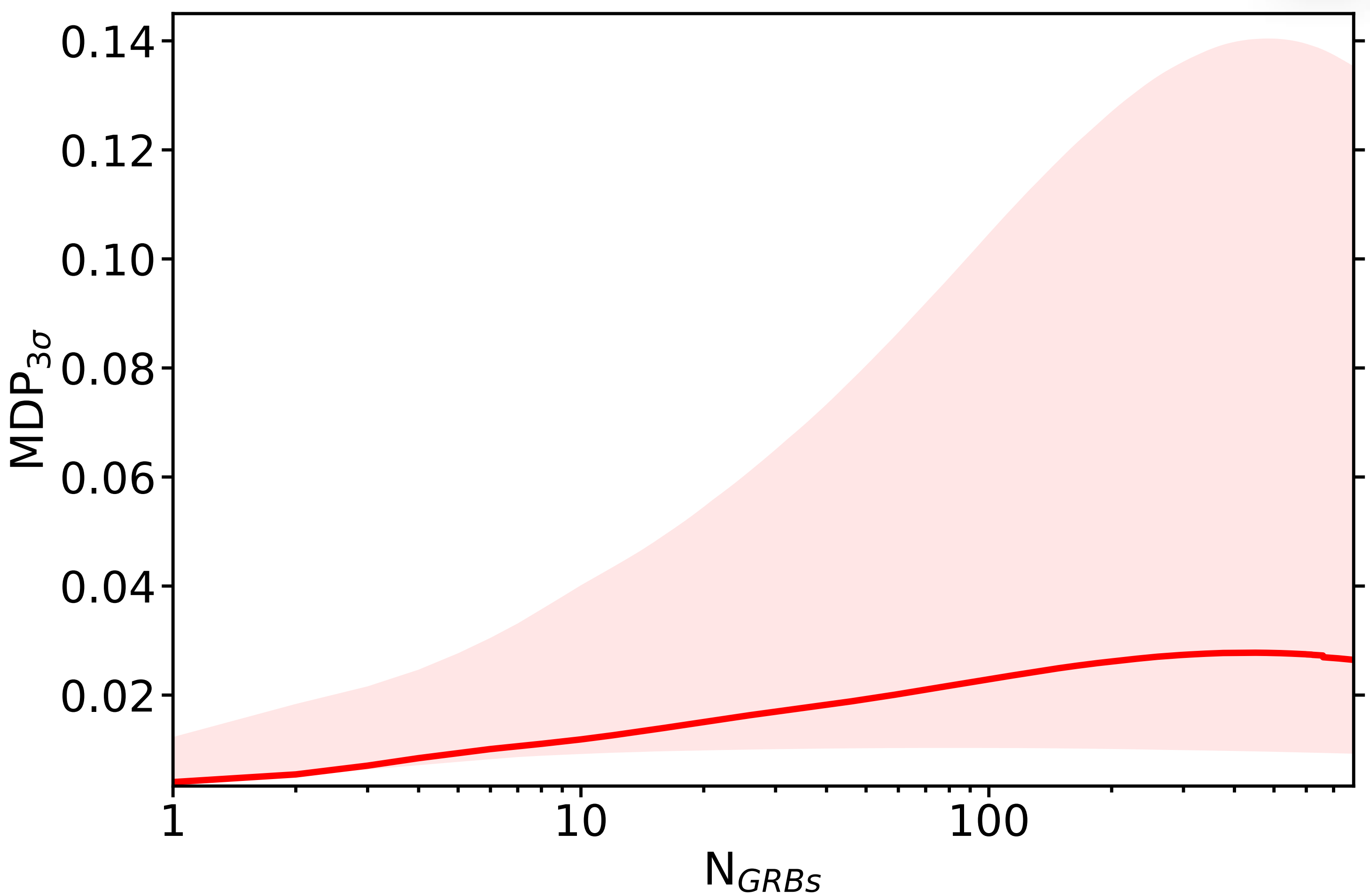
$$p = 1 - \sigma \longrightarrow p' = \frac{1 - \sigma}{TF}$$

ANTARES diffuse search for ν from GRBs in 2007-2017

2. Analysis features

The search is optimized in the **stacking MDP**:

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



Maximum values:

MDP(N=82)=0.010

MDP(N=430)=0.028

MDP(N=482)=0.14

Selecting entire sample:

MDP(N=784)=0.09

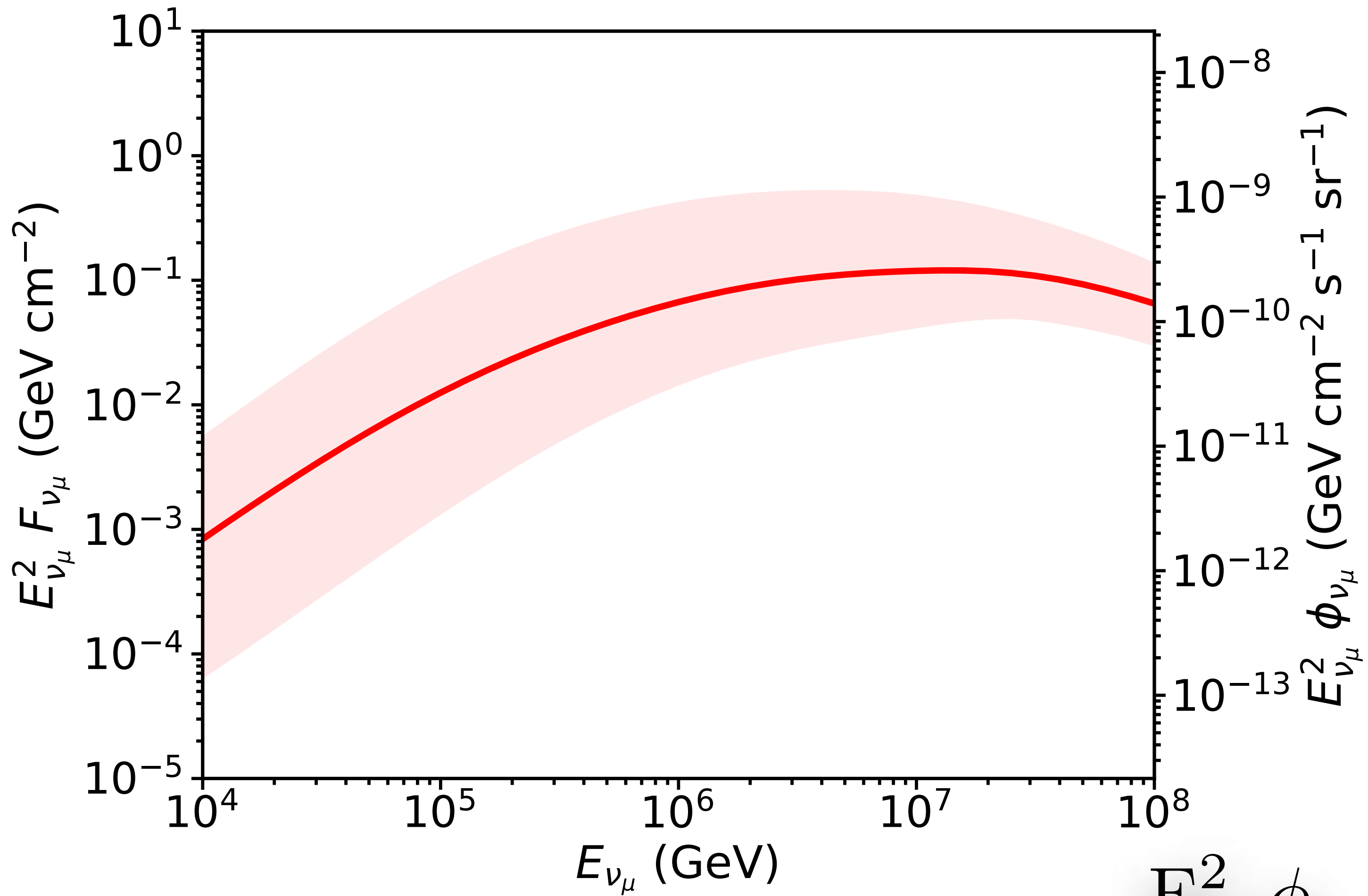
MDP(N=784)=0.027

MDP(N=784)=0.14

ANTARES diffuse search for ν from GRBs in 2007-2017

2. Analysis features

Hence, **stacking the entire GRB sample**, we obtain:



1. cumulative neutrino fluence:

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

2. stacking neutrino flux (quasi-diffuse):

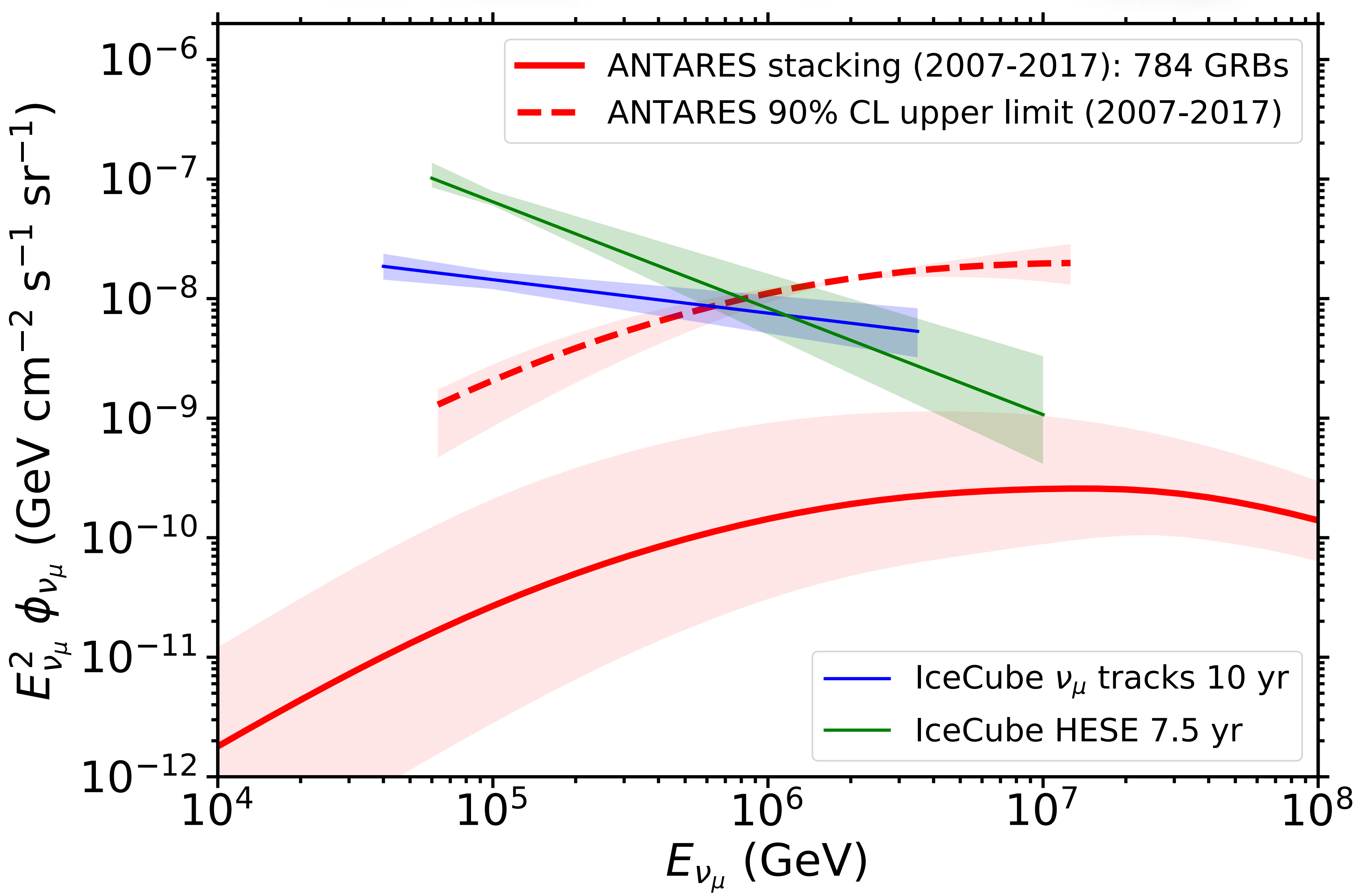
$$\mathrm{E}^2_{\nu_\mu}\phi_{\nu_\mu} = \sum_{i=1}^{\mathrm{N_{GRB}}} (E^2_{\nu_\mu}\mathrm{F}_{\nu_\mu})^i \frac{1}{4\pi}\frac{1}{\mathrm{N_{GRB}}} 667\mathrm{yr}^{-1}$$

Albert et al. [ANTARES Coll.], MNRAS 500 (2021) 4

ANTARES diffuse search for ν from GRBs in 2007-2017

After data unblinding, **no event** passed the selection criteria: hence, we derived an upper limit given the expected signal events

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



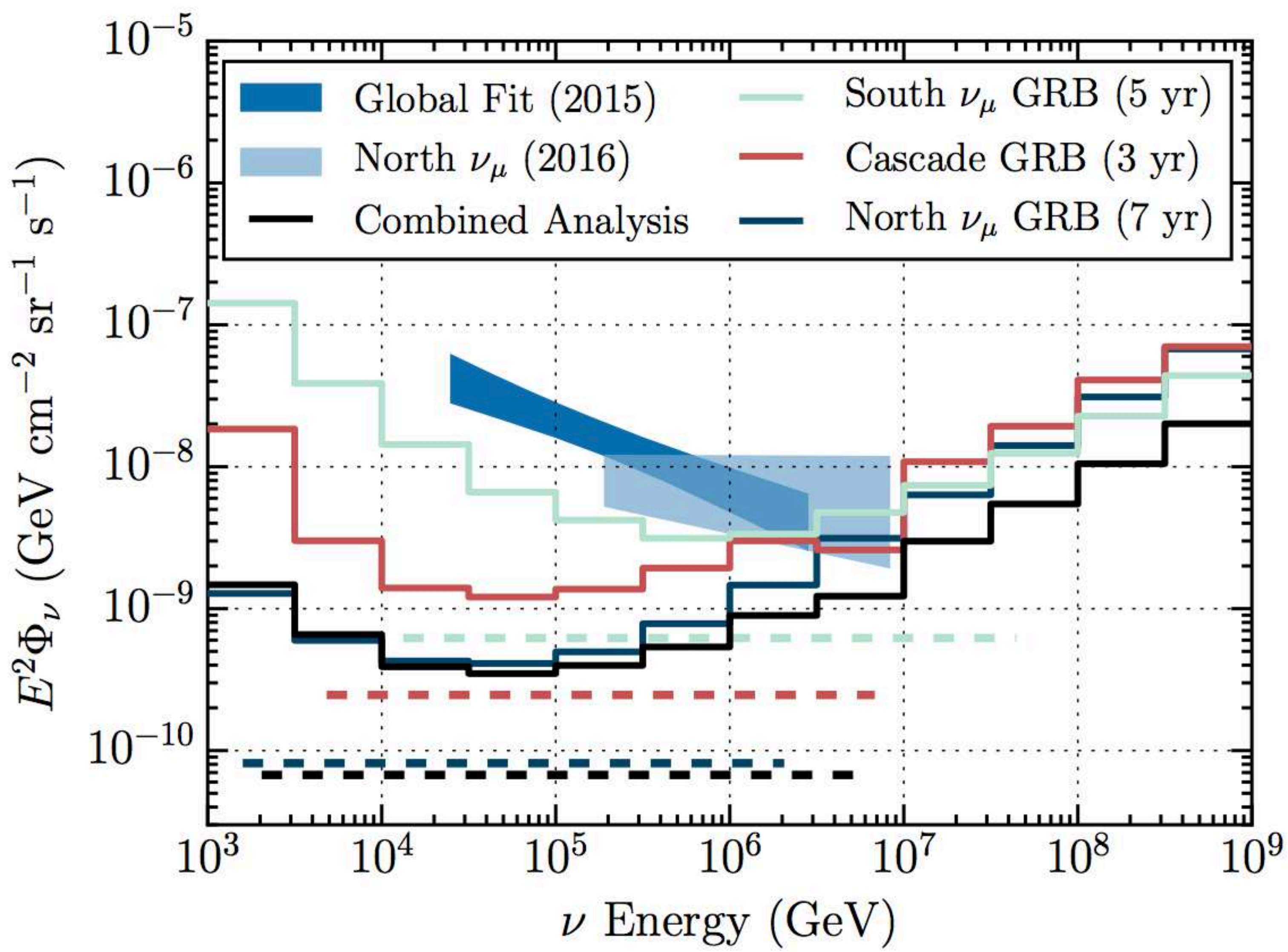
Albert et al. [ANTARES Coll.], MNRAS 500 (2021) 4

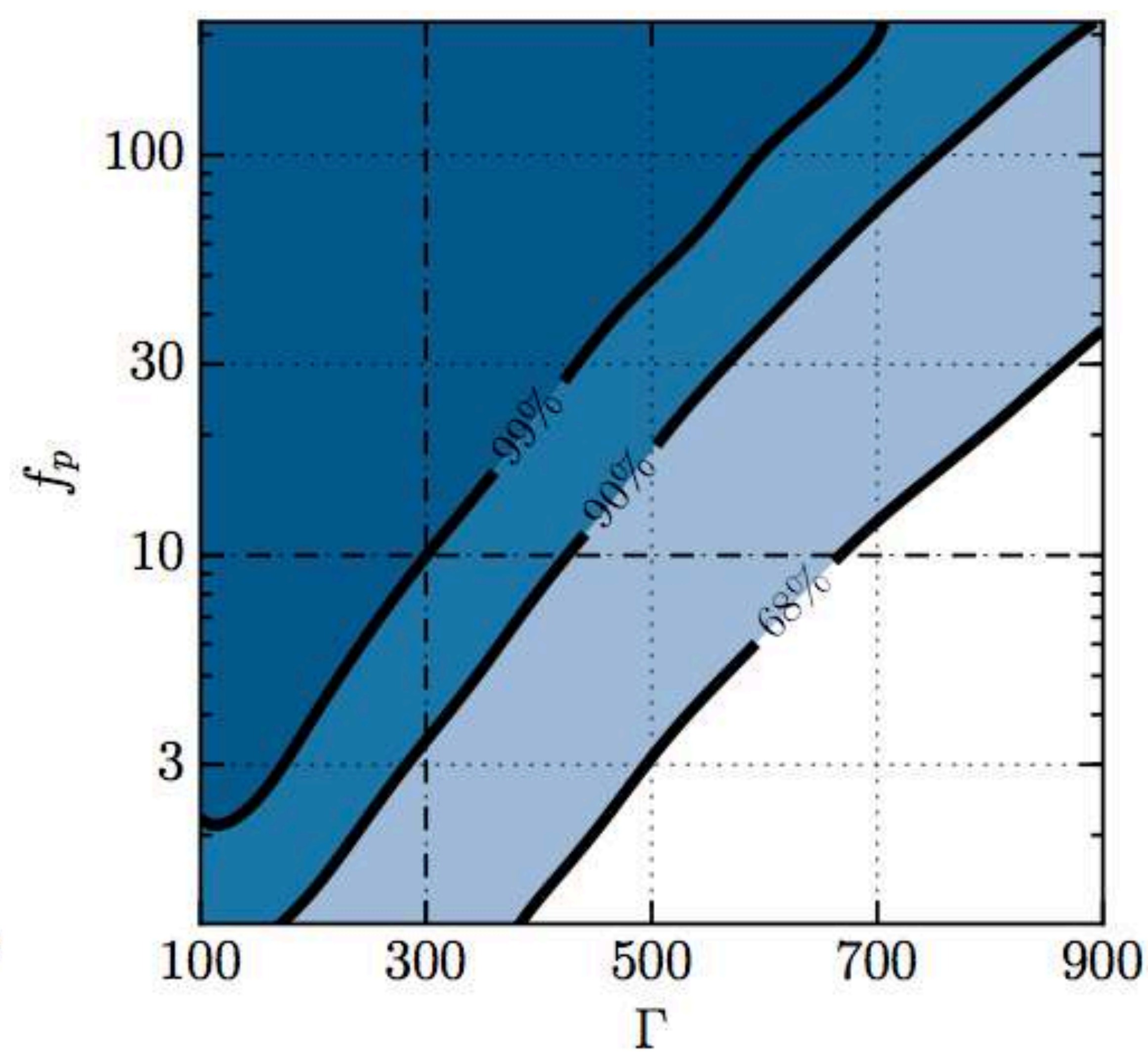
livetime=18.9 h

IceCube search for ν from GRBs

The latest IceCube search refers to:

- **All flavor** (tracks+cascades);
- **All sky** (upgoing+downgoing);
- Sample of **1172 GRBs**, looking for neutrino spatial and temporal coincidences with the prompt phase of gamma-ray emission.

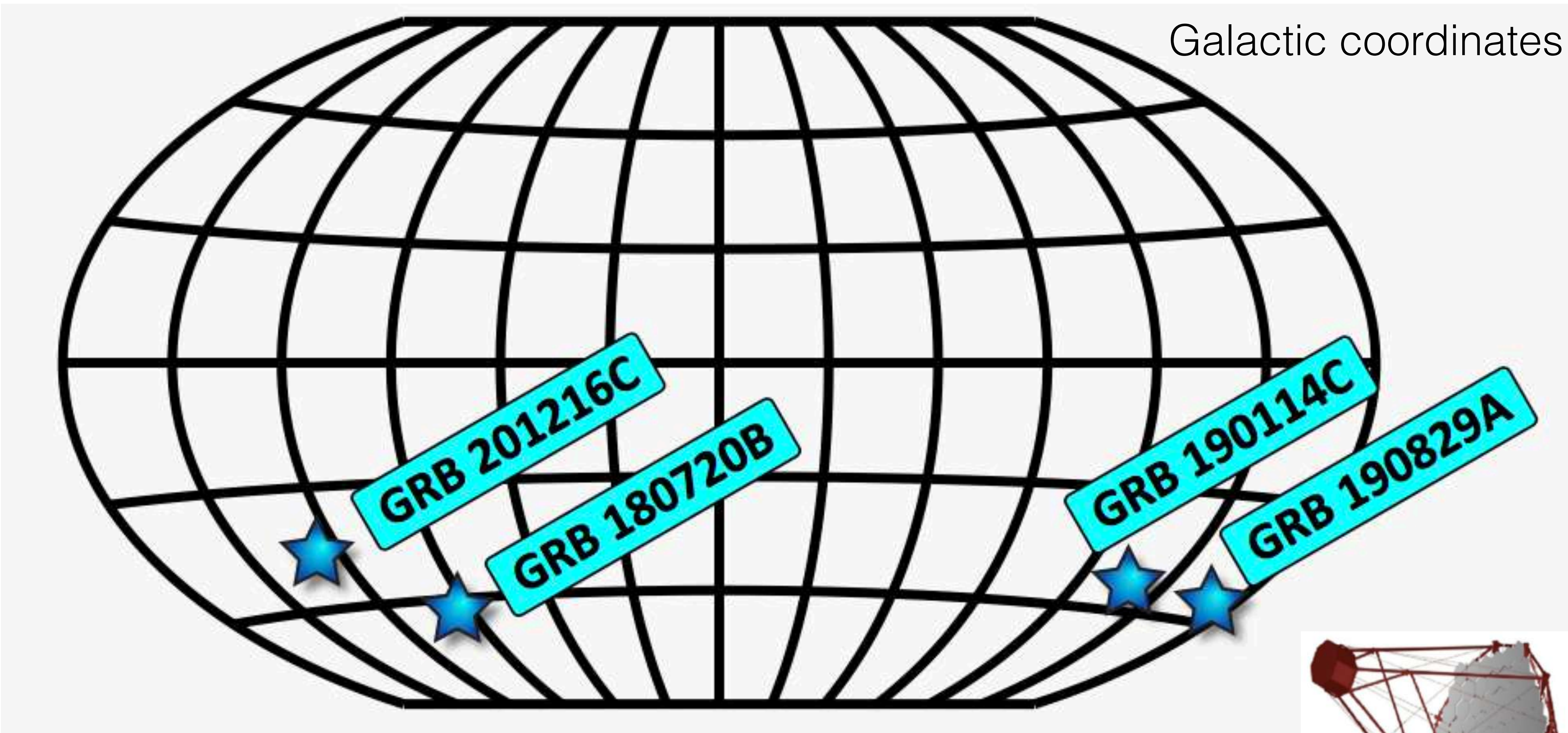




Aartsen et al. [IceCube Coll.], ApJ 843 (2016) 2

Latest results: TeV GRBs

A major advancement has been recently achieved with the detection of TeV emission from GRBs by **IACTs**:



http://tevcat2.uchicago.edu

ANTARES search for v from TeV GRBs

No neutrinos were observed in ANTARES in coincidence with the prompt and afterglow of the bursts:

- **Real time alert** with upgoing muon tracks GCN 25582 for GRB190829A
- Tailored **offline analysis** with tracks and cascades

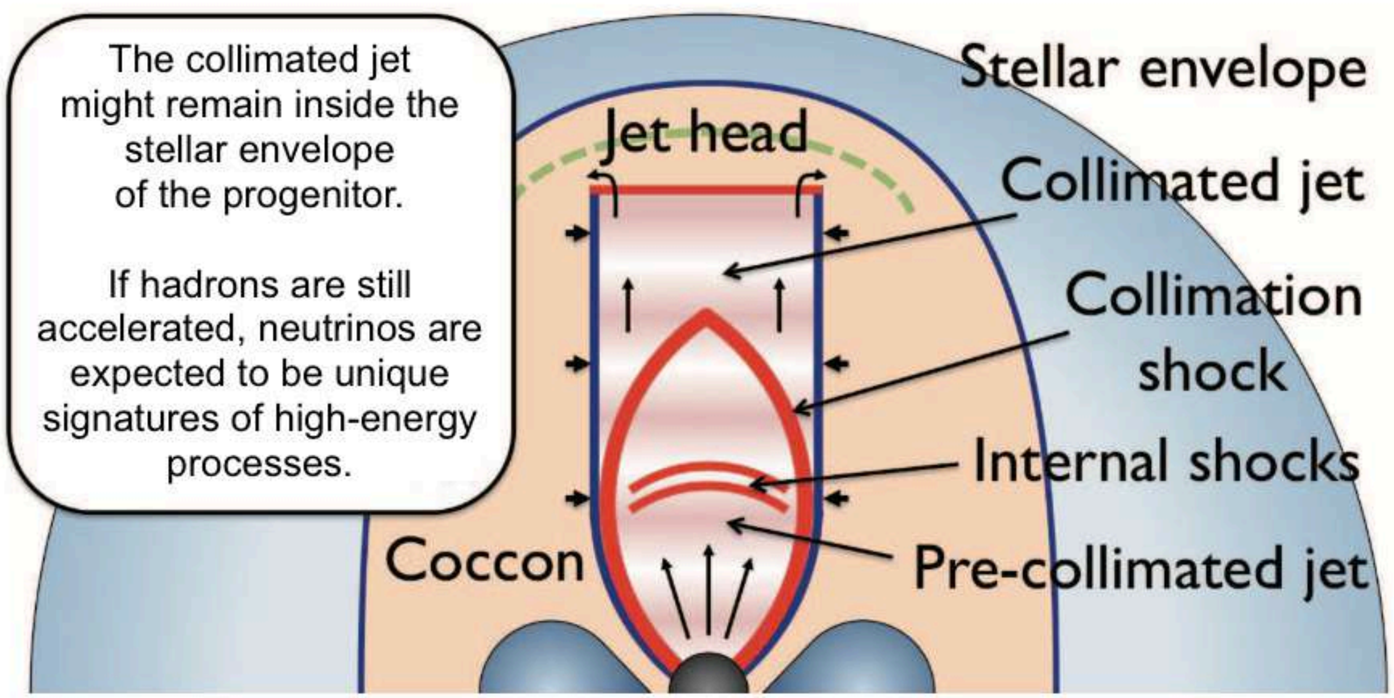
Event	$\delta t_{\mathrm{total}}$	δt_{up}	δt_{down}
GRB 180720B	12.1 h	7.7 h	4.4 h
GRB 190114C	2805 s	—	2805 s
GRB 190829A	8.1 h	2.85 h	5.25 h

Albert et al. [ANTARES Coll.], arXiv:2011.11411

	GRB 180720B	**GRB 190114C**	**GRB 190829A**
δt_{up}	$[T_0-350\ \mathrm{s}, T_0+7.6\ \mathrm{h}]$	-	$[T_0-350\ \mathrm{s}, T_0+2.85\ \mathrm{h}]$
$\phi_{0\ up}^{90\%}$ $(\mathrm{GeV{\cdot}cm^{-2}})$	$\lesssim 1.5$	-	$\lesssim 1.4$
δt_{down}	$[T_0+7.6\ \mathrm{h}, T_0+12.1\ \mathrm{h}]$	$[T_0-350\ \mathrm{s}, T_0+2454\ \mathrm{s}]$	$[T_0+2.85\ \mathrm{h}, T_0+8.1\ \mathrm{h}]$
$\phi_{0\ down}^{90\%}$ $(\mathrm{GeV{\cdot}cm^{-2}})$	$\lesssim 10$	$\lesssim 1.6$	$\lesssim 4$
$E_{5-95\%}^{\mathrm{up}}$	2.5 TeV – 4.0 PeV	-	2.5 TeV – 4.0 PeV
$E_{\nu,\mathrm{iso}}^{90\%}$ upgoing (erg)	$\lesssim 2\times10^{55}$	-	$\lesssim 2\times10^{53}$
$(\frac{f_\pi}{f_e})_{\mathrm{up}}$	$\lesssim 80$	-	$\lesssim 5\times10^4 - \lesssim 3\times10^3$
$E_{5-95\%}^{\mathrm{down}}$	20 TeV – 30 PeV	7 TeV – 20 PeV	15 TeV – 25 PeV
$E_{\nu,\mathrm{iso}}^{90\%}$ downgoing (erg)	$\lesssim 1\times10^{56}$	$\lesssim 8\times10^{54}$	$\lesssim 7\times10^{53}$
$(\frac{f_\pi}{f_e})_{\mathrm{down}}$	$\lesssim 600$	$\lesssim 2\times10^3$	$\lesssim 2\times10^5 - \lesssim 1\times10^4$
$E_{\gamma,\mathrm{iso}}$ (erg)	6×10^{53} [50; 300 keV]	2.5×10^{53} [1 keV; 10 MeV] 2×10^{52} [300 GeV; 1 TeV]	3×10^{50} [1 keV; 10 MeV] 2×10^{50} [50 keV; 300 keV]

Neutrinos from chocked GRBs

Unsuccessful GRBs might have **unique signatures in neutrinos**



K. Murase & K. Ioca, PRL 111 (2013) 121102

Thermalized photons in the reverse shock have typical temperatures of

$$kT_\gamma \simeq 741\,\mathrm{eV}\ \mathrm{L}_{\mathrm{iso},\,51}^{1/8}\,\epsilon_{\mathrm{e},\,-1}^{1/4}\,\mathrm{t}_{\mathrm{jet},\,2}^{-1/4}\,\rho_{\mathrm{H},-7}^{1/8}$$

From the forward shock region, they're energy reads as

$$E_{\gamma,\,\mathrm{IS}}^{\max} = \Gamma E_{\gamma,\,\mathrm{RS}}^{\max} \sim 210\,\mathrm{keV}$$

He et al., ApJ 856 (2018) 119

Neutrinos from chocked GRBs

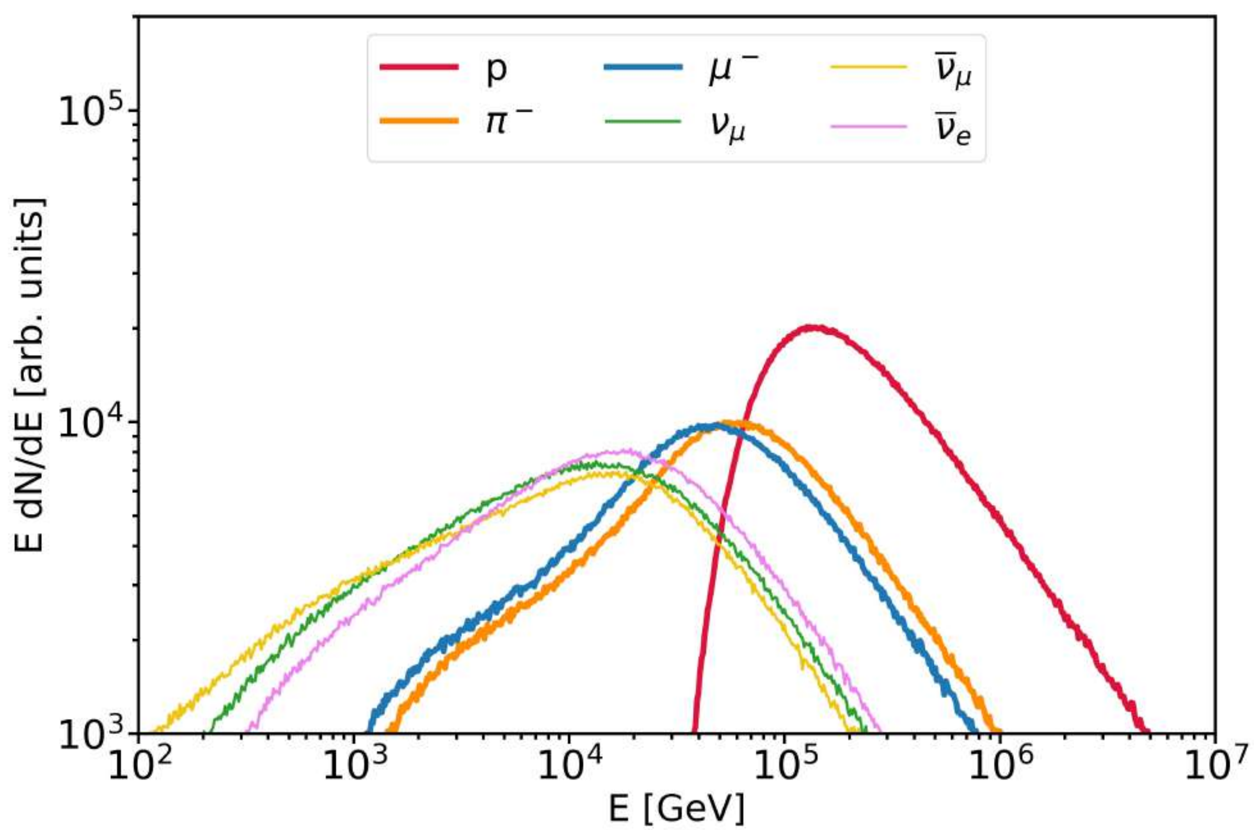
We performed a **Monte Carlo** simulation of pγ interactions with

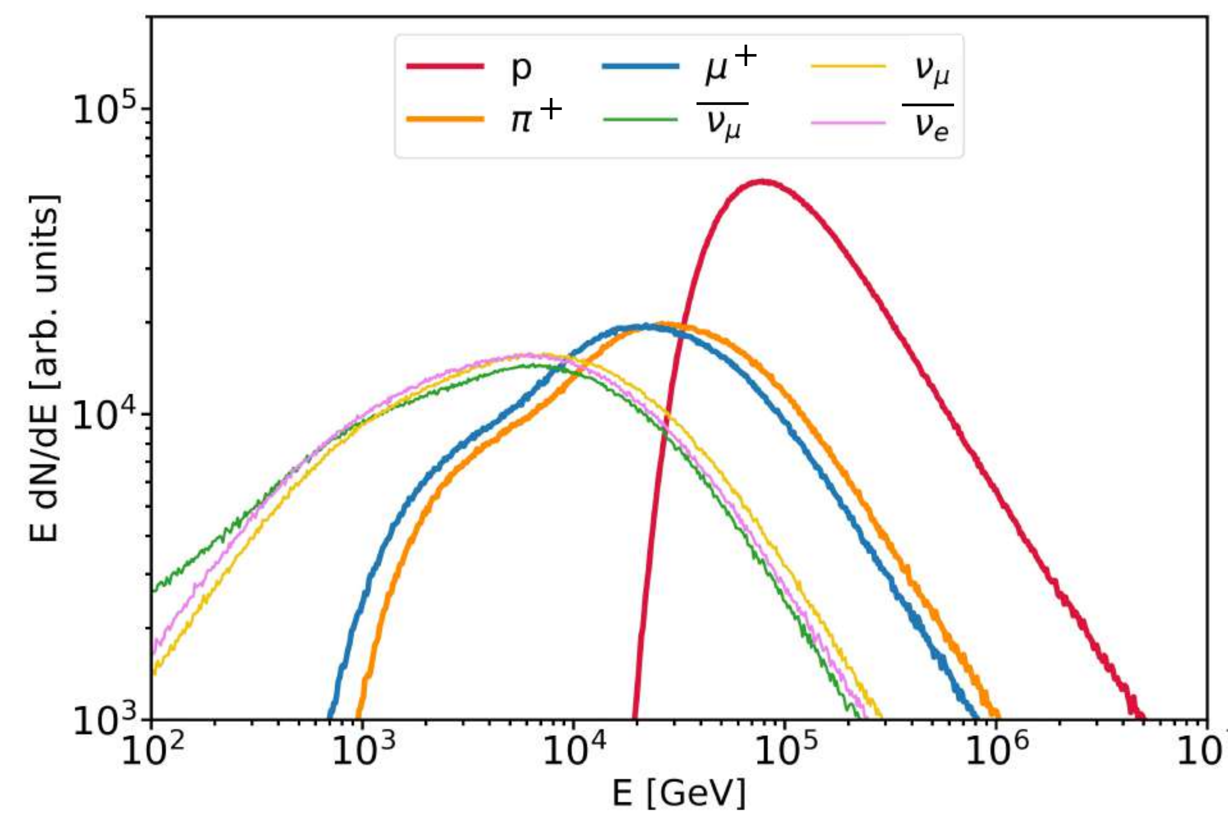
1. accelerated protons:

$$\frac{dN_p}{dE_p} = k_{\mathrm{MC}}\, E_p^{-2}$$

2. target photons

$$\frac{dN_\gamma}{dE_\gamma} = 2\sqrt{\frac{E_\gamma}{\pi}}\left(\frac{1}{kT_\gamma}\right)^{\frac{3}{2}} e^{-\frac{E_\gamma}{kT_\gamma}}$$

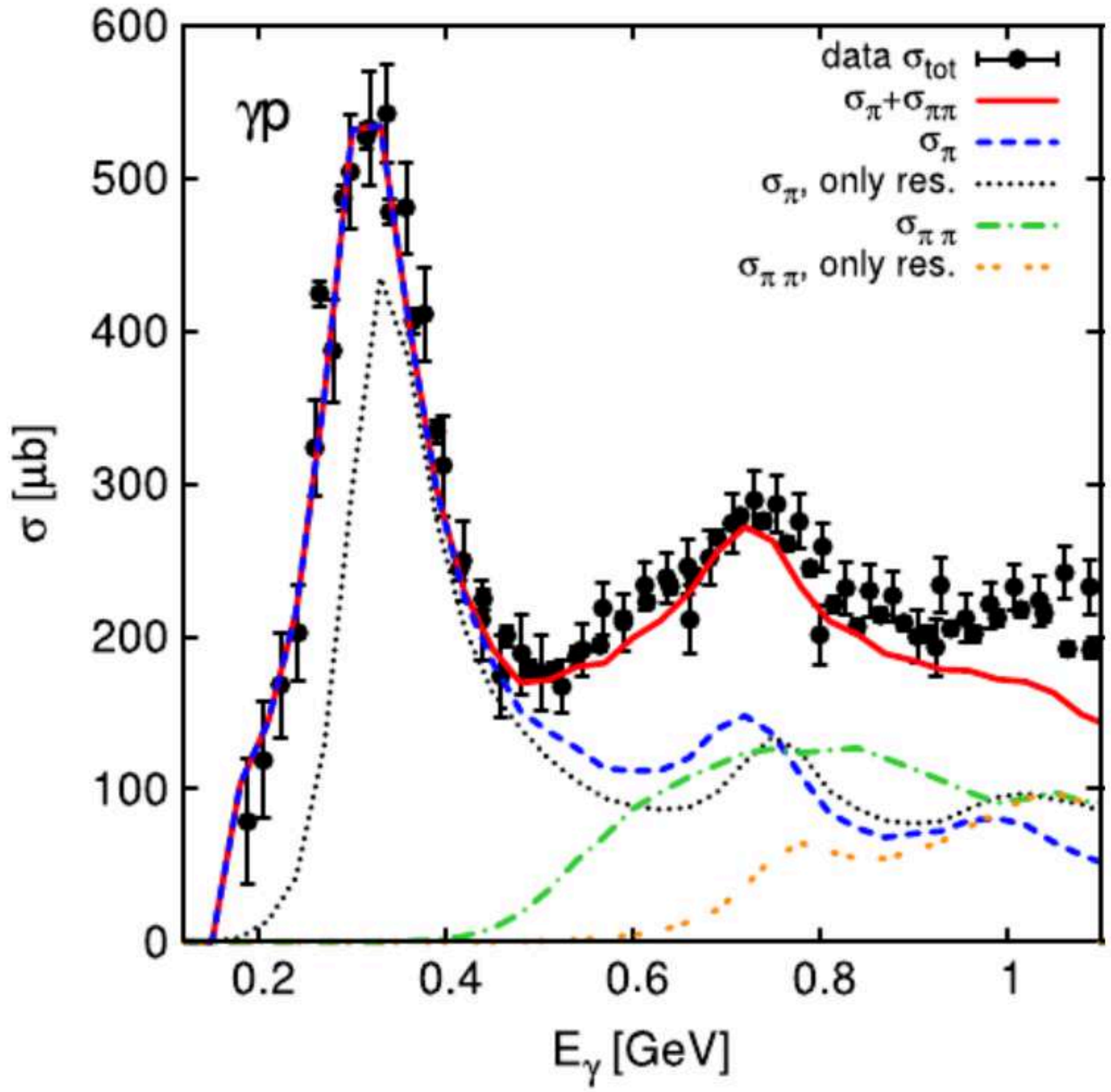


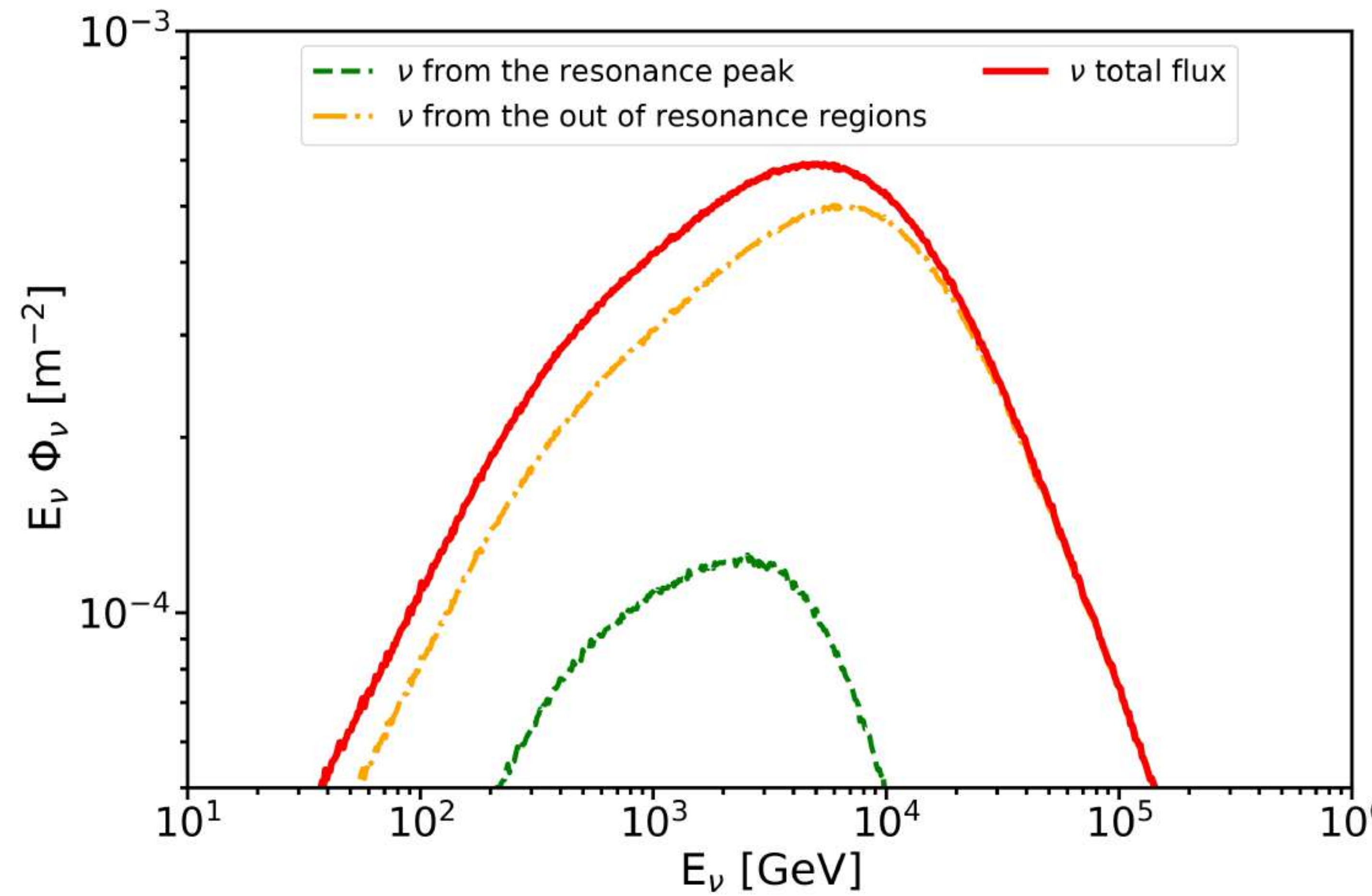


Fasano et al., arXiv:2021:03502

Neutrinos from chocked GRBs

studying both the region of the Δ^+ resonance, as well as the out-of-resonance region





Fasano et al., arXiv:2021:03502

$$p + \gamma \xrightarrow{\Delta^+} \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

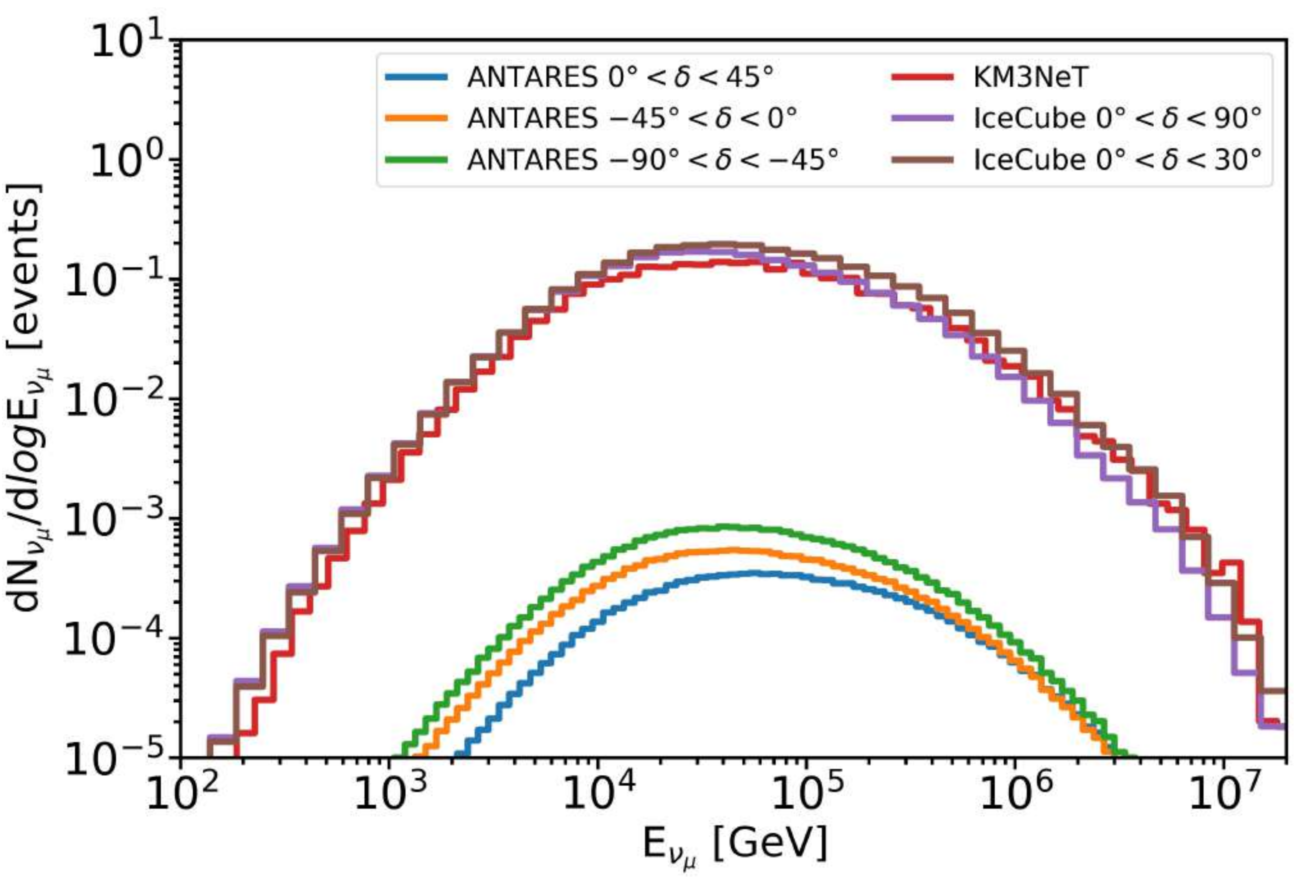
Neutrinos from chocked GRBs

1. EXPECTED EVENT RATES

$$k_{\rm MC}\int_{E_{\rm min}}^{E_{\rm max}} E_p \frac{dN_p}{dE_p} dE_p = E_{\rm iso} \longrightarrow \Phi^{\rm Earth}_{\nu_\mu} = k_{\rm MC}\,\frac{\Omega}{4\pi\, D(z)^2}\, F_{\nu_\mu}(E_{\nu_\mu})$$

Benchmark of the model:

z = 1, E_{iso} = 10^{53} erg, t_{jet} = 100 s, Γ = 100, Ω = 0.13 sr (α = 0.2 rad)



Detector	δ	$N_{\rm events}$
ANTARES	$0° < \delta < 45°$	0.011
	$-45° < \delta < 0°$	0.016
	$-90° < \delta < -45°$	0.025
KM3NeT	Mean δ	2.57
IceCube	$0° < \delta < 90°$	2.05
	$0° < \delta < 30°$	2.45

Fasano et al., arXiv:2021:03502

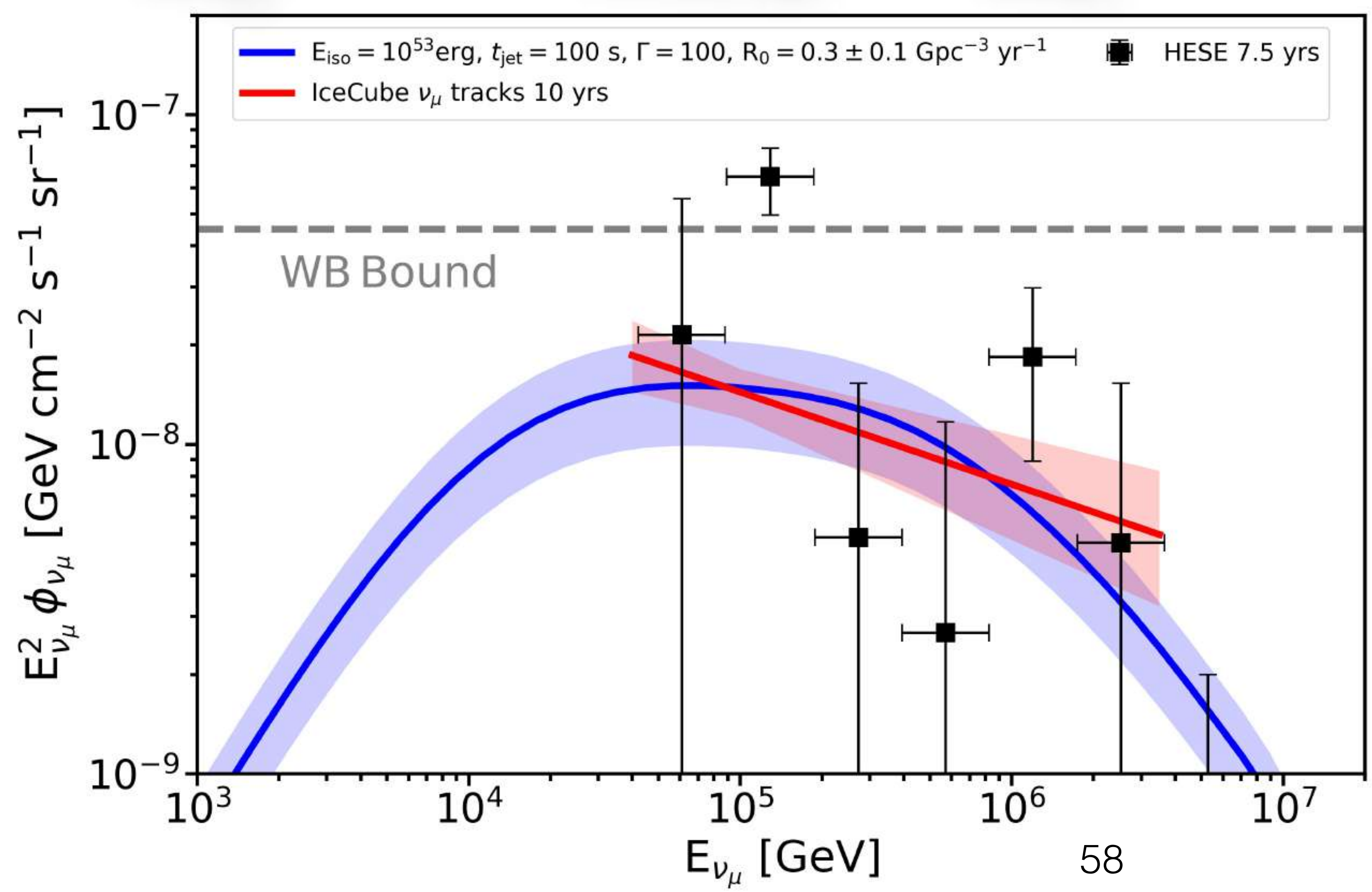
Neutrinos from chocked GRBs

2. CONTRIBUTION TO THE DIFFUSE NEUTRINO FLUX

Assuming chocked GRBs follow the SRF $\rho(z) = \dfrac{(1+z)^{2.7}}{1+[(1+z)/2.9]^{5.6}}$

Madau & Dickinson, Ann. Rev. A&A 52 (2014) 415

$$E_{\nu_\mu}^{\mathrm{obs}} \frac{dN_{\nu_\mu}}{dE_{\nu_\mu}^{\mathrm{obs}}}(E_{\nu_\mu}^{\mathrm{obs}}) = \frac{c}{4\pi H_0} \int_0^8 E_{\nu_\mu} \frac{dN_{\nu_\mu}}{dE_{\nu_\mu}}((1+z)E_{\nu_\mu}) \frac{\frac{\Omega}{4\pi} R_0 \rho(z) dz}{(1+z)\sqrt{\Omega_\Lambda + \Omega_{\mathrm{M}}(1+z)^3}}$$



Implying a local rate of chocked GRBs of

$$R_0 = (0.3 \pm 0.1)\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$$

consistent with standard GRBs

Fasano et al., arXiv:2021:03502

Conclusions

- The origin of IC neutrinos remains so far **elusive**, though overall a major contribution from EG sources appears preferable;
- **ANTARES** has performed neutrino searches from **4 bright GRBs** and from the **population of long GRBs** occurred in the years **2007-2017** through **upgoing muons in spatial and temporal coincidence** with the gamma-ray emission. No event satisfied the optimized cuts and limits were derived, as well as constraints in the parameter space of the models;
- **Upper limits** derived in the **stacking** search of ANTARES **disfavor GRBs as major contributors of the IC diffuse flux** (<10% below 100 TeV), consistently with IC results;
- **Choked GRBs** appear a viable alternative, possibly dominating the IC flux if their local rate is of the order of standard GRBs.

THANKS FOR YOUR KIND ATTENTION

SFB 1258 | Neutrinos Dark Matter Messengers