Roma International Conference on AstroParticle Physics 2022

Detection prospects for multi-GeV neutrinos from collisionally heated GRBs

A. Zegarelli, S. Celli, A. Capone, S. Gagliardini, S. Campion, I. Di Palma, Phys. Rev. D 105, 083023 (2022)

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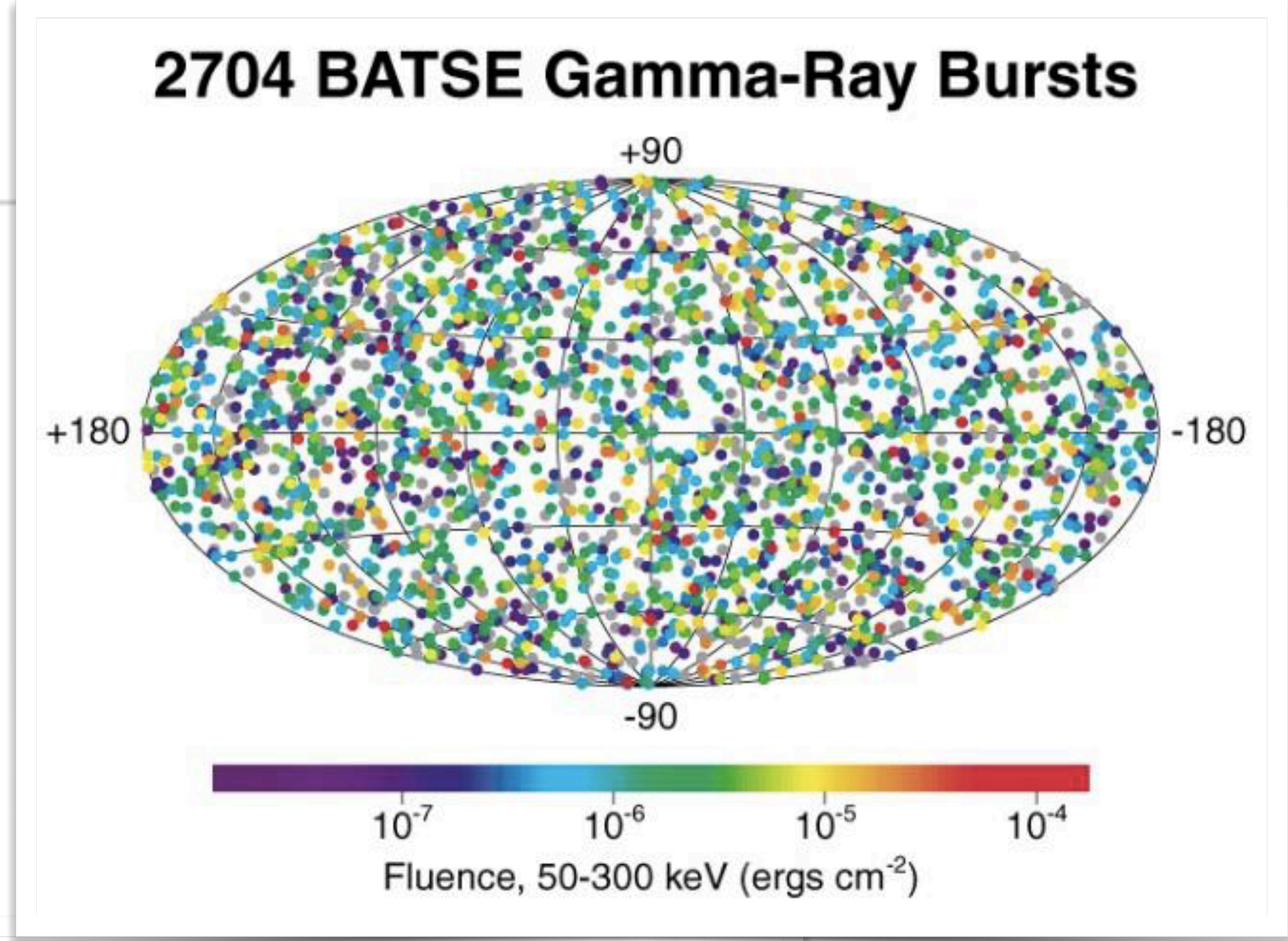
Outline

- Overview on Gamma-Ray Bursts (GRBs) and observed properties
- The *fireball model*
- Why GRBs are important in a multi-messenger context
- Typical GRB spectra: photospheric models vs internal shocks
- *Inelastic Collisional model* and multi-GeV neutrino production
- Detection prospects for low-energy neutrinos from the Inelastic Collisional model with KM3NeT and IceCube
    - Individual GRB
    - Stacking analysis
- Conclusions

Gamma-Ray Bursts (GRBs)

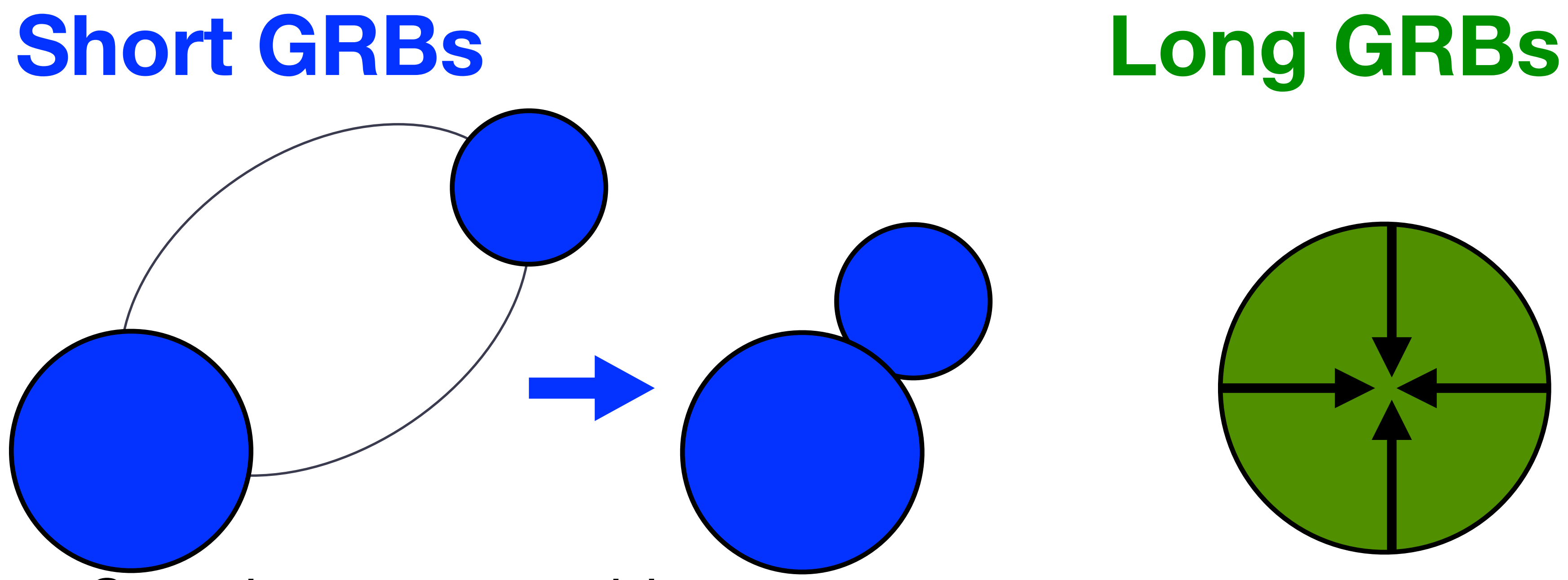
Public domain: https://heasarc.gsfc.nasa.gov/docs/cgro/cgro/batse_src.html



- Single, short-lived and irregular pulses of **gamma-ray radiation**
- The brightest electromagnetic events known to occur in the Universe

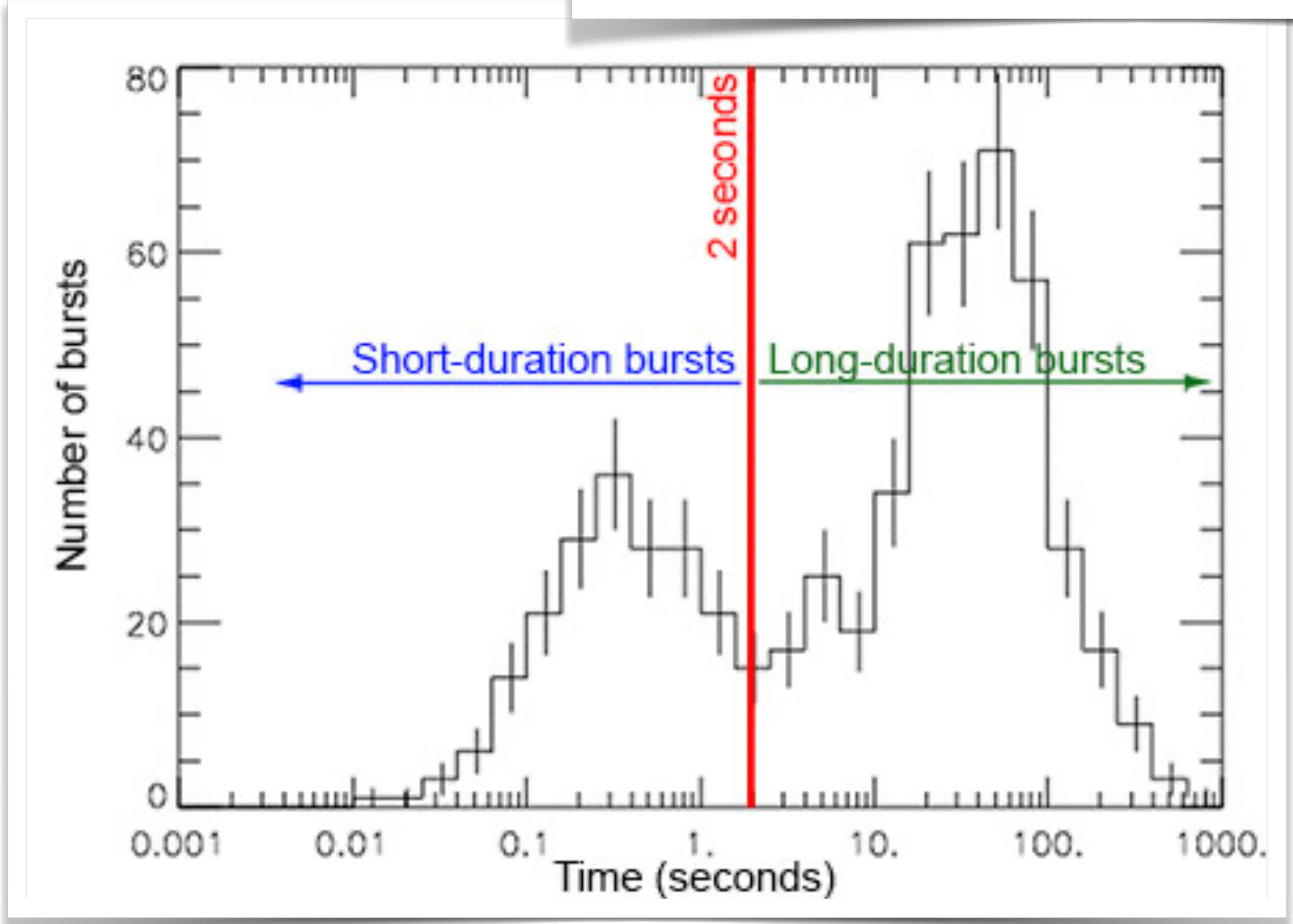
$$\boxed{L_{\gamma,\text{iso}} \sim 10^{54}\ \text{erg/s}}$$

- **Extragalactic** sources
- Short and Long GRBs, most likely related to different progenitors, exhibiting different temporal and spectral features



Stars in a compact binary system inspiral and merge

Collapse of a very massive star



Public domain: https://imagine.gsfc.nasa.gov/science/objects/bursts1.html

Basic framework: the *Fireball* model

GRBs in the multi-messenger framework: neutrino production

***pγ* interactions**

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

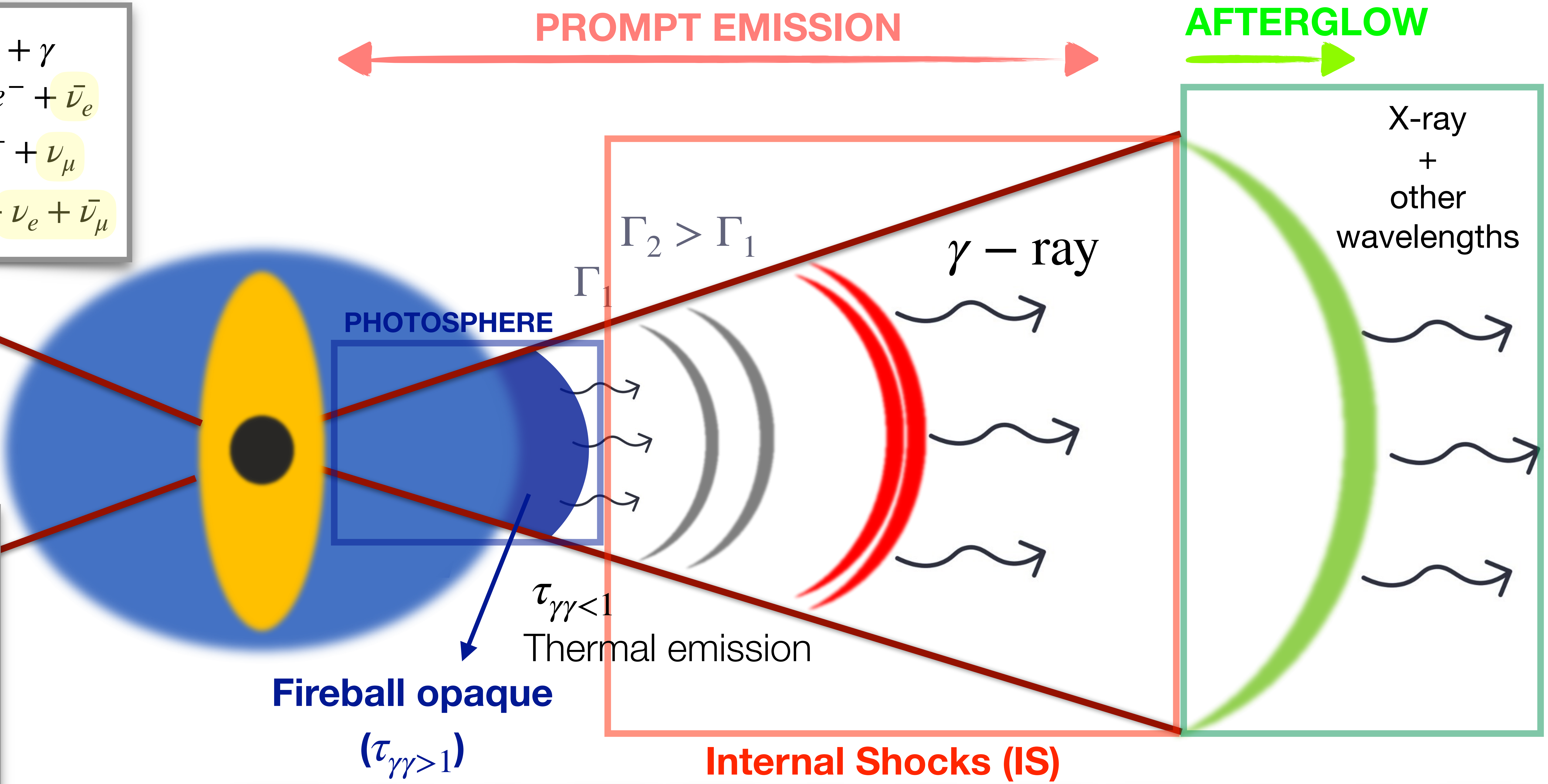
***pp/pn* collisions**

If the envelope is large enough

$$\begin{cases} p+p \rightarrow p+n+\pi^+ \\ p+n \rightarrow p+p+\pi^- \\ p+p \rightarrow p+p+\pi^0 \\ n+n \rightarrow p+n+\pi^- \end{cases}$$

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu \rightarrow e^\pm + \nu_e$$

$$\pi^0 \rightarrow 2\gamma \rightarrow e^\pm$$



GeV-TeV neutrinos — Meszaros & Waxman 2001

TeV-PeV neutrinos — Waxman & Bahcall 1997

PeV-EeV neutrinos — Waxman & Bahcall 2000

GRBs in the multi-messenger framework: neutrino production

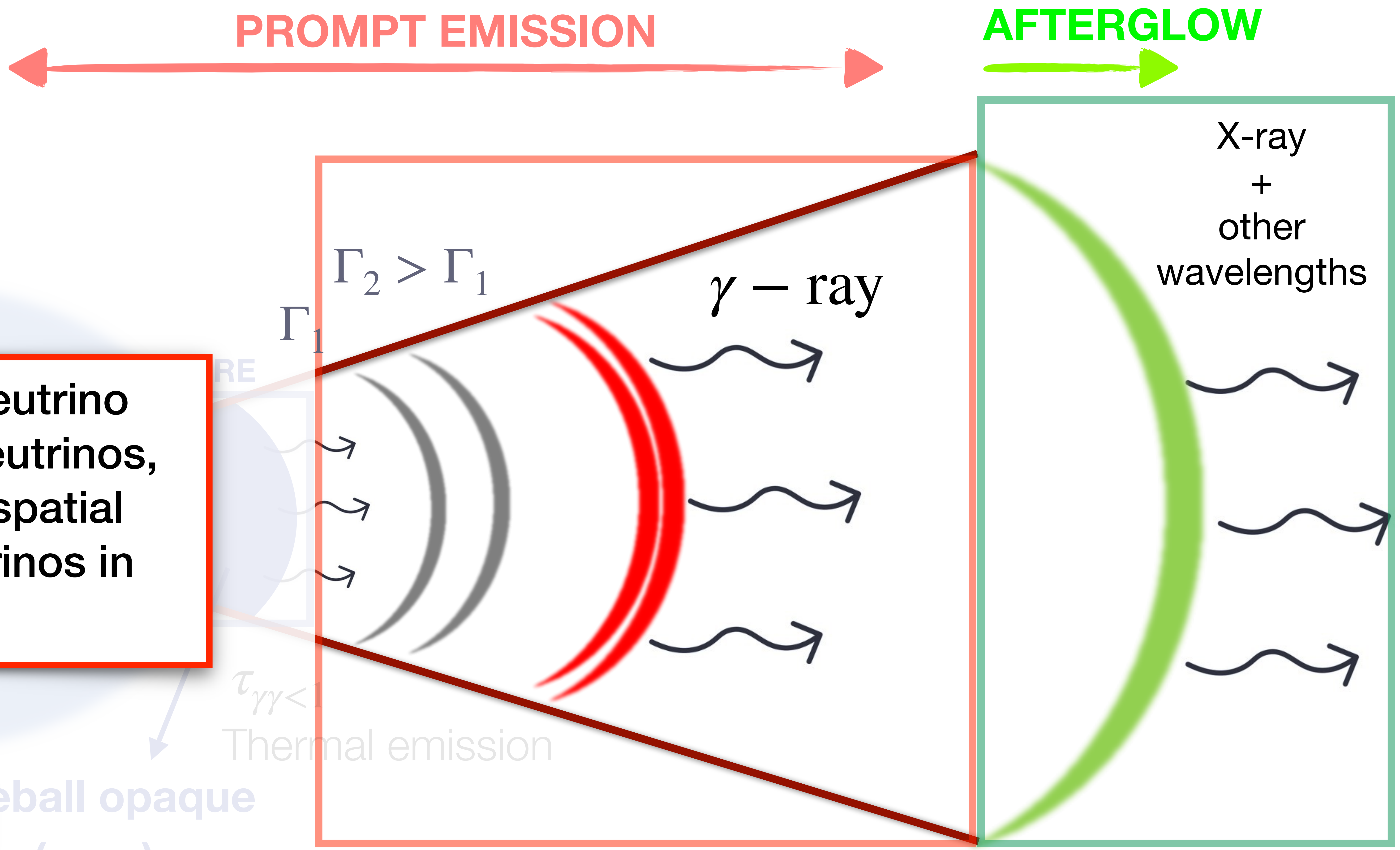
***pγ* interactions**

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

To date, the IceCube and ANTARES neutrino telescopes, sensitive to TeV and PeV neutrinos, have only searched for temporal and spatial associations between GRBs and neutrinos in the high-energy domain

Lack of $\gamma - \nu$ associations

The mechanism responsible for the GRB prompt emission is still unknown



Internal Shocks (IS)

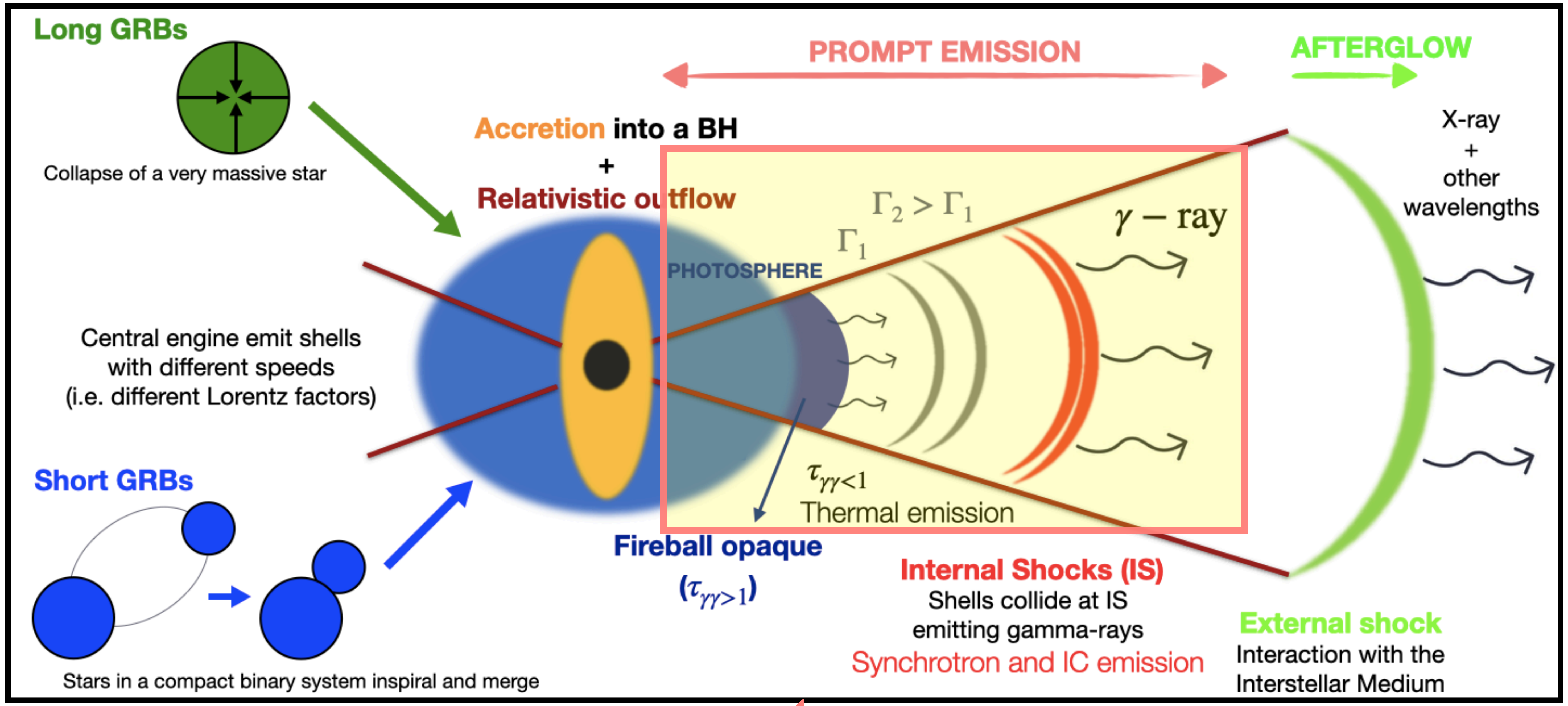
TeV-PeV neutrinos

Waxman & Bahcall 1997

PeV-EeV neutrinos

Waxman & Bahcall 2000

Typical GRB spectrum



GRB emissions
during prompt emission

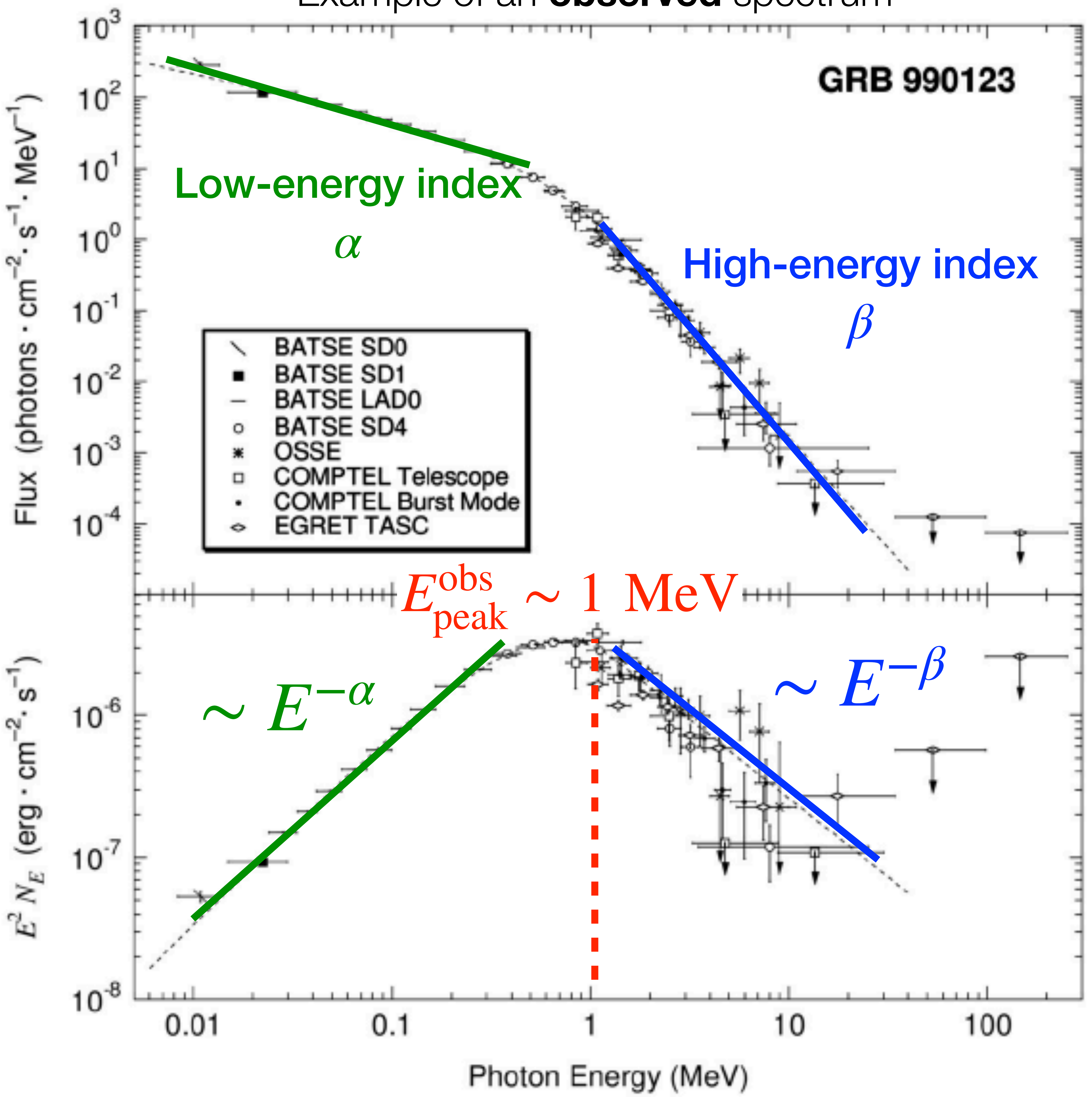
Non-thermal spectrum
Band function —> ~Broken power law

Typical energy indices

$< \alpha > \sim -1.0$

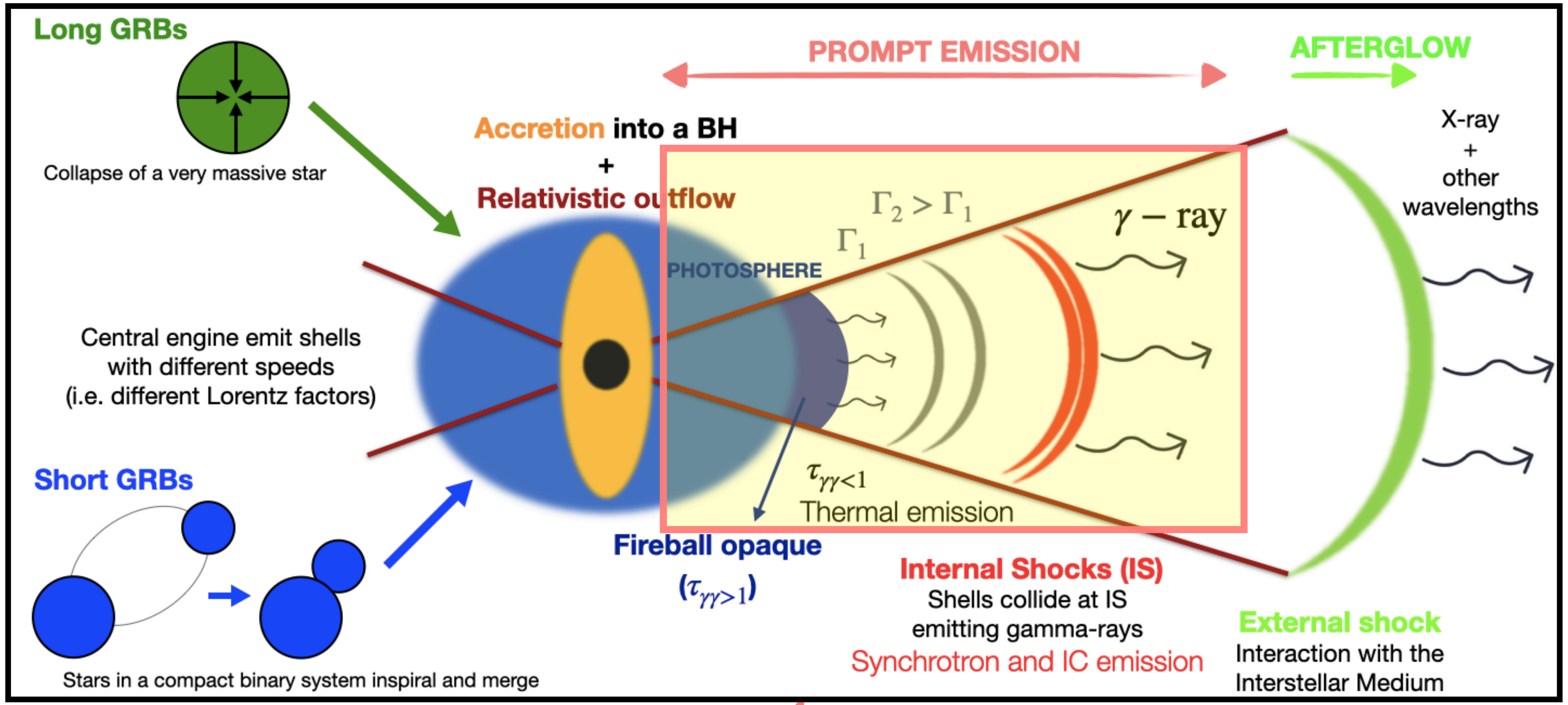
$< \beta > \sim -2.5$

Example of an **observed** spectrum

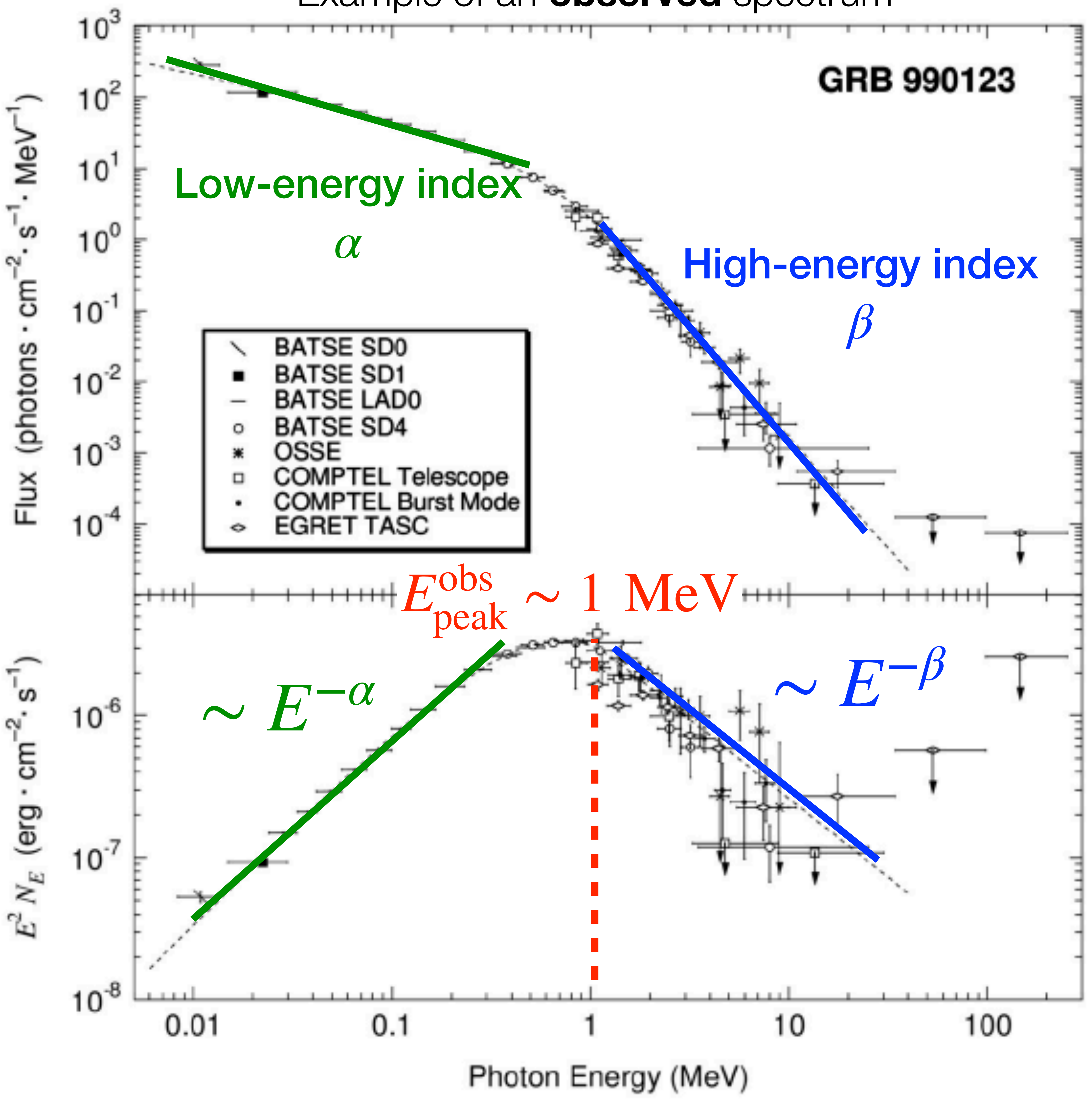


Briggs M. S., Band D. L., Kippen R. M., et al., ApJ524, 82-91, (1999)

Can the classical IS model explain the GRB spectrum?



Example of an **observed** spectrum



Briggs M. S., Band D. L., Kippen R. M., et al., ApJ524, 82-91, (1999)

The synchrotron model predicts GRB spectra with $\alpha \sim -1.5$, while the fitted values are often significantly harder

Typical energy indices

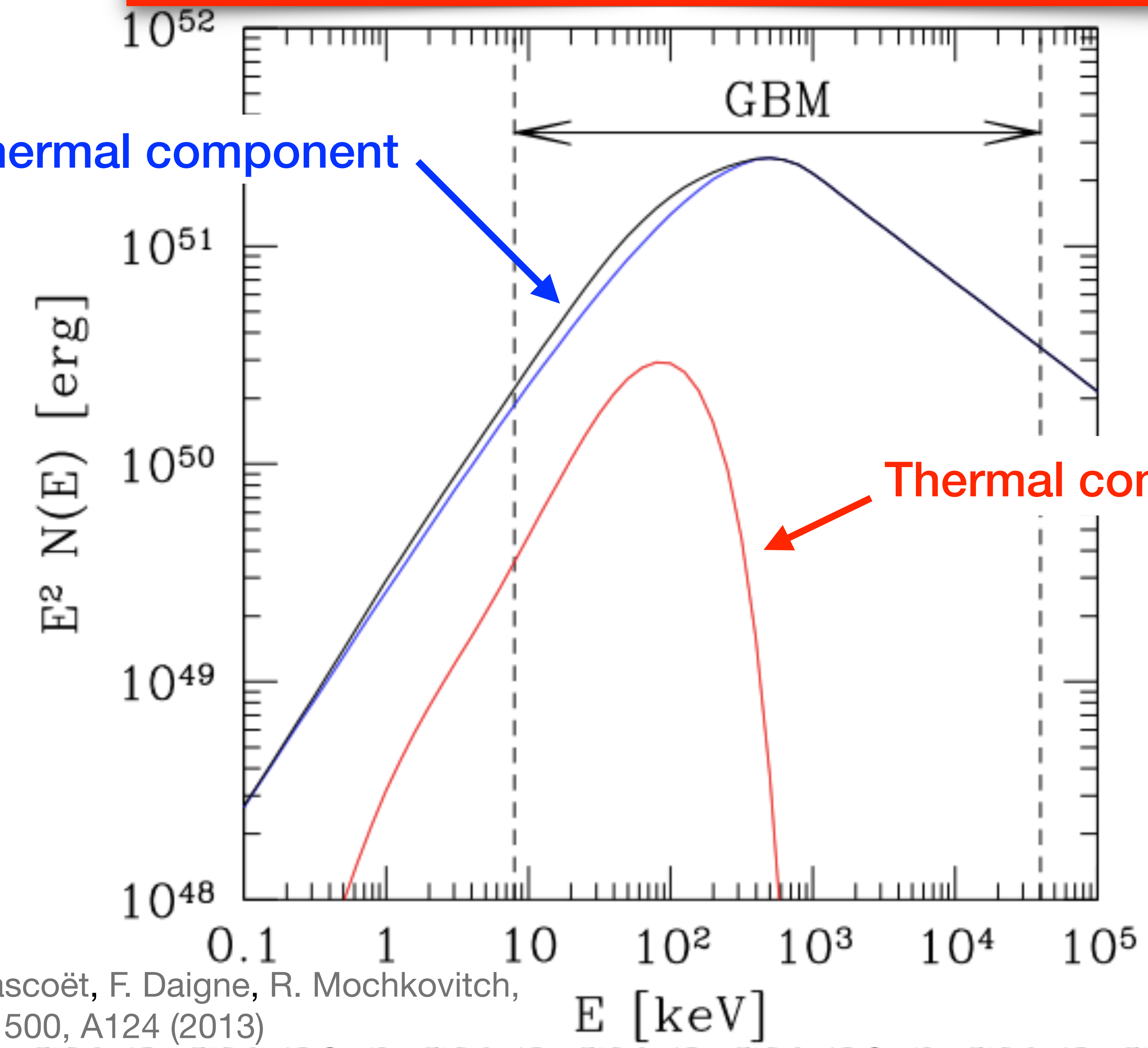
$<\alpha> \sim -1.0$

$<\beta> \sim -2.5$

GRB spectrum: thermal + non-thermal component

Total GRB spectrum
Sum of a thermal and a non-thermal component

Non-thermal component



R. Hascoët, F. Daigne, R. Mochkovitch, A&A, 500, A124 (2013)

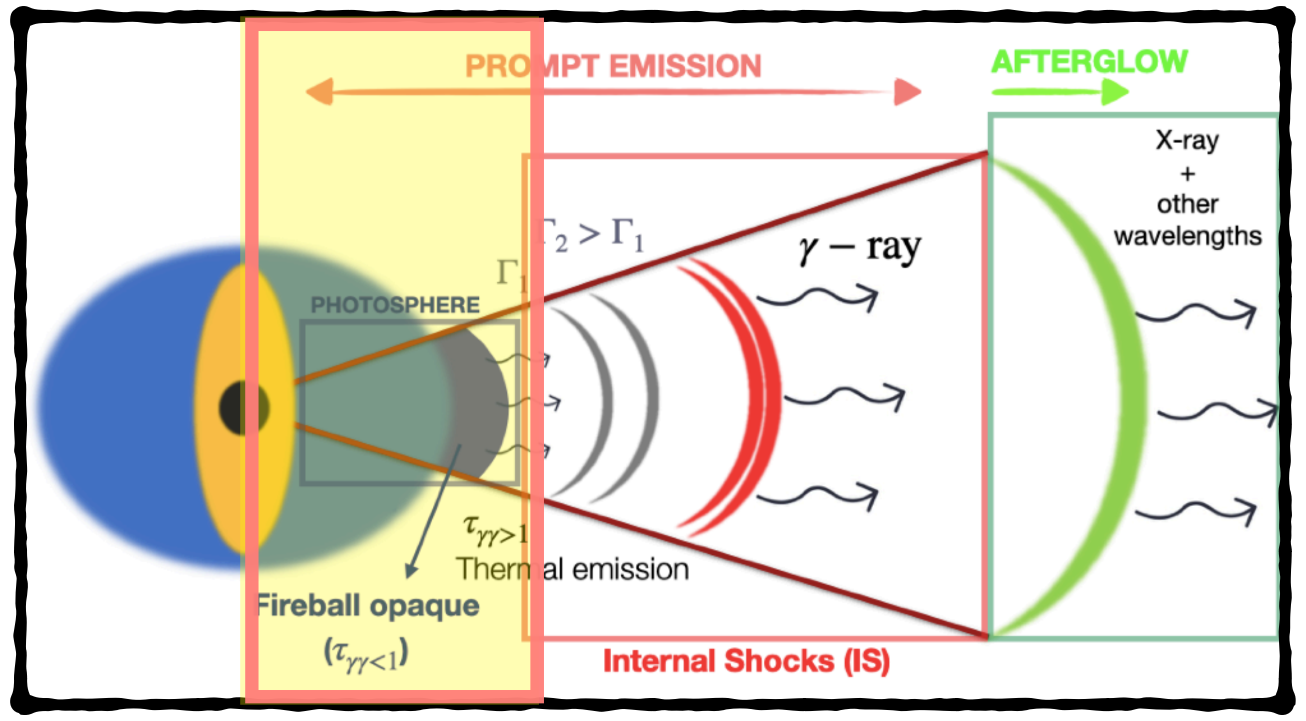
There are several GRBs whose time-resolved spectral analyses reveled an initial thermal component in its spectrum, then broadened into a Band-like one, e.g.

- GRB090902B A.A Abdo et al., ApJ 706, L138 (2009)
- GRB100724B S. Guiriec et al., ApJ 727, L33 (2011)
- GRB110721A S. Iyyani et al., MNRAS 433, 2739 (2013)

Thermal component —> natural consequence of the fireball model

Which is the process responsible of the non-thermal GRB emission?

The inelastic collisional model



Among the several models proposed to explain the prompt γ-ray emission, the so-called *inelastic collisional model* has been proposed some years ago

Sub-photospheric region

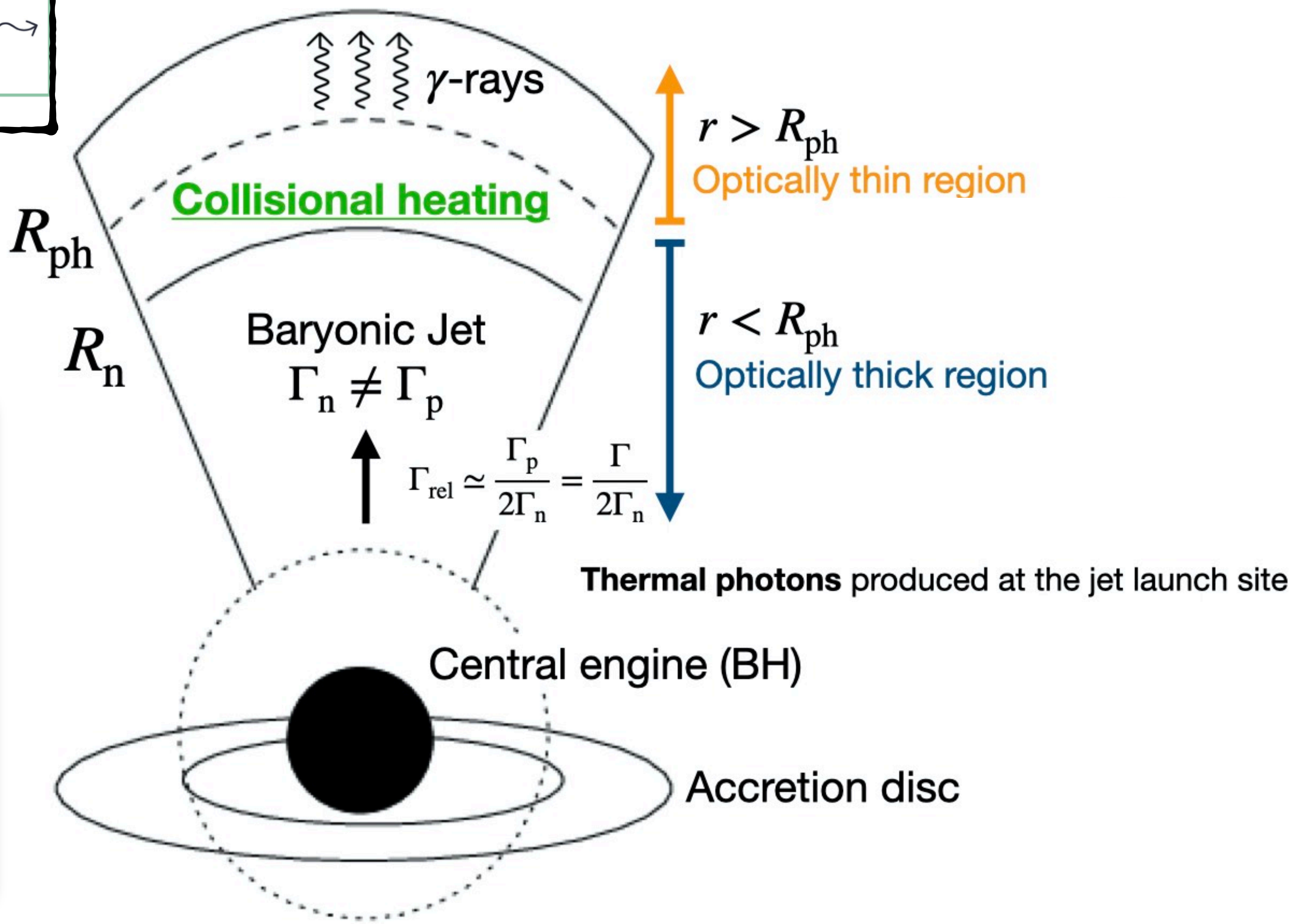
***pp/pn* collisions**

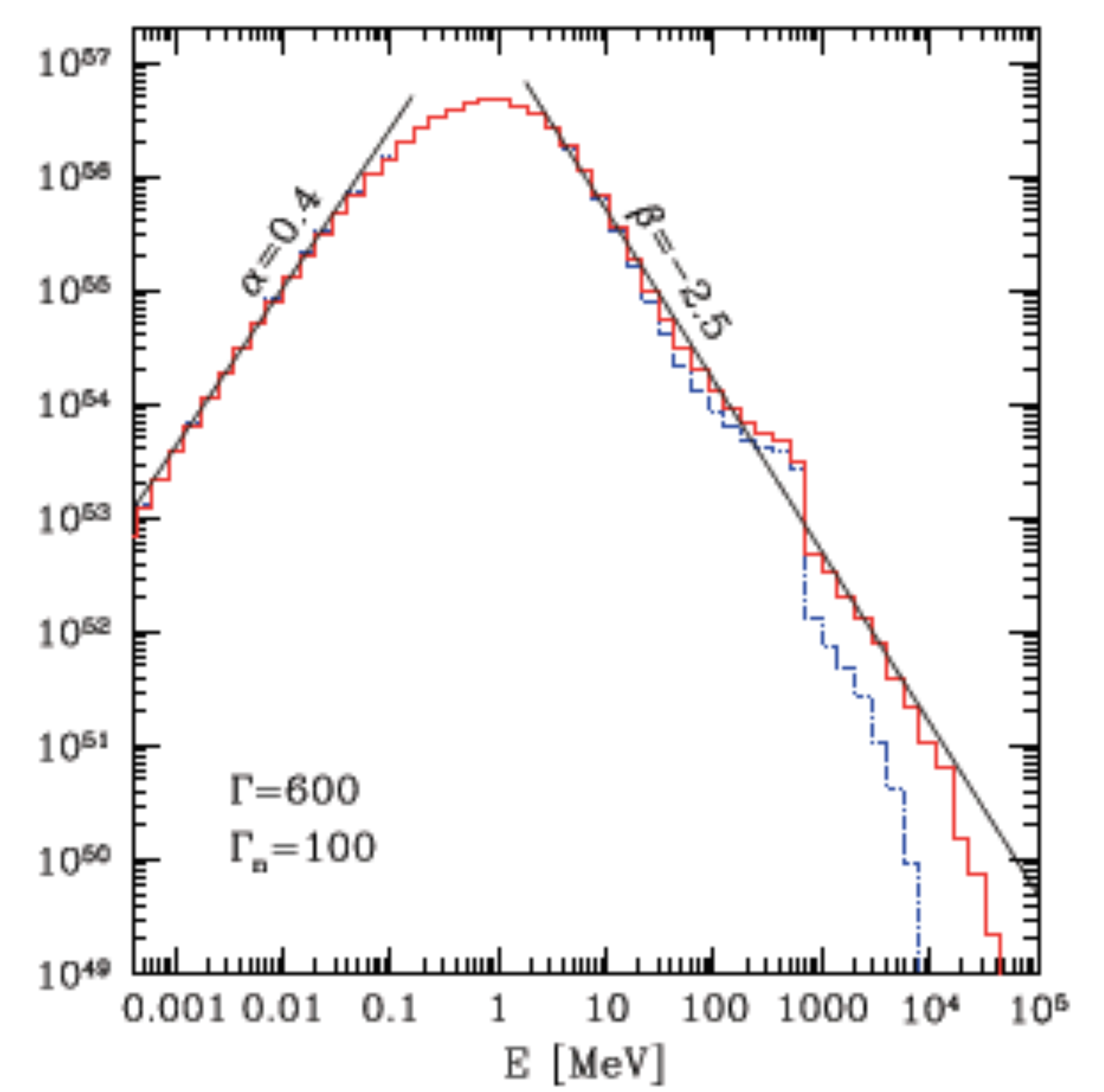
$$
\begin{cases}
p + p \to p + n + \pi^+ \\
p + n \to p + p + \pi^- \\
p + p \to p + p + \pi^0 \\
n + n \to p + n + \pi^-
\end{cases}
$$

$$\pi^\pm \to \mu^\pm + \nu_\mu \to e^\pm + \nu_e$$

$$\pi^0 \to 2\gamma \to e^\pm$$

GRB prompt emission

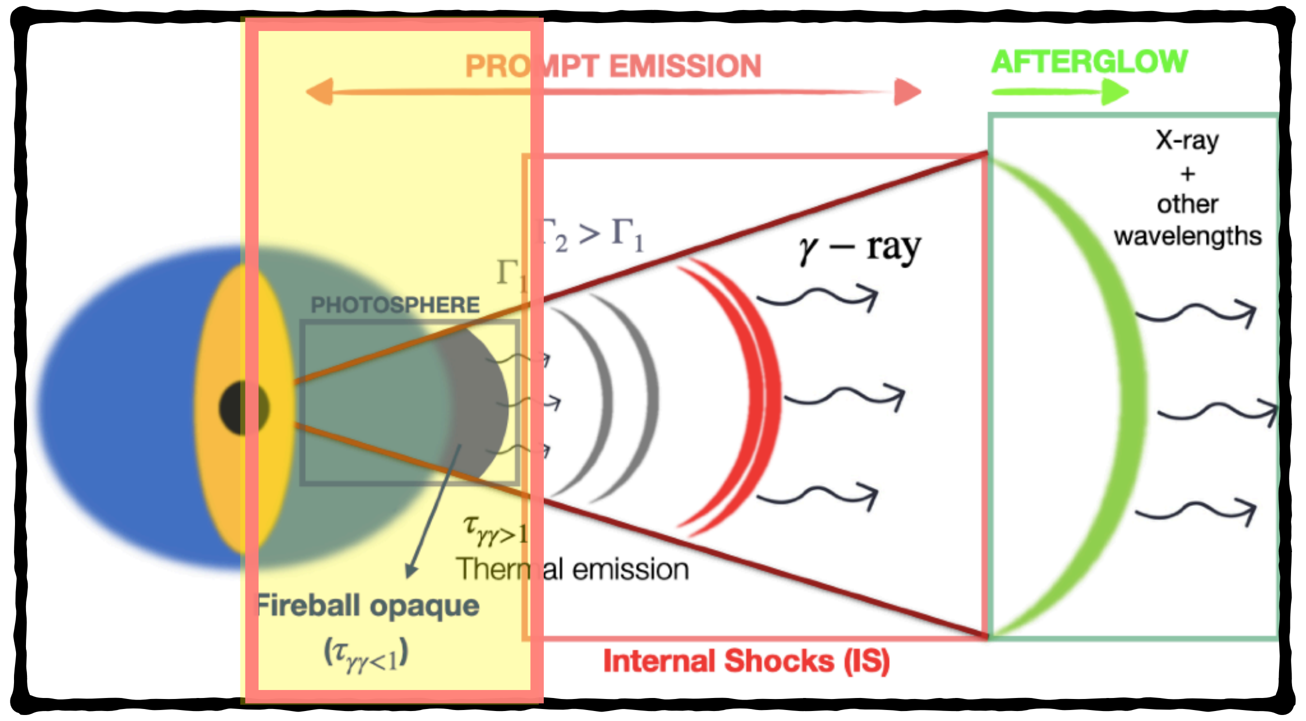




Belobodorov 2009

The non-thermal spectrum can be reproduced

The inelastic collisional model: multi-GeV neutrinos



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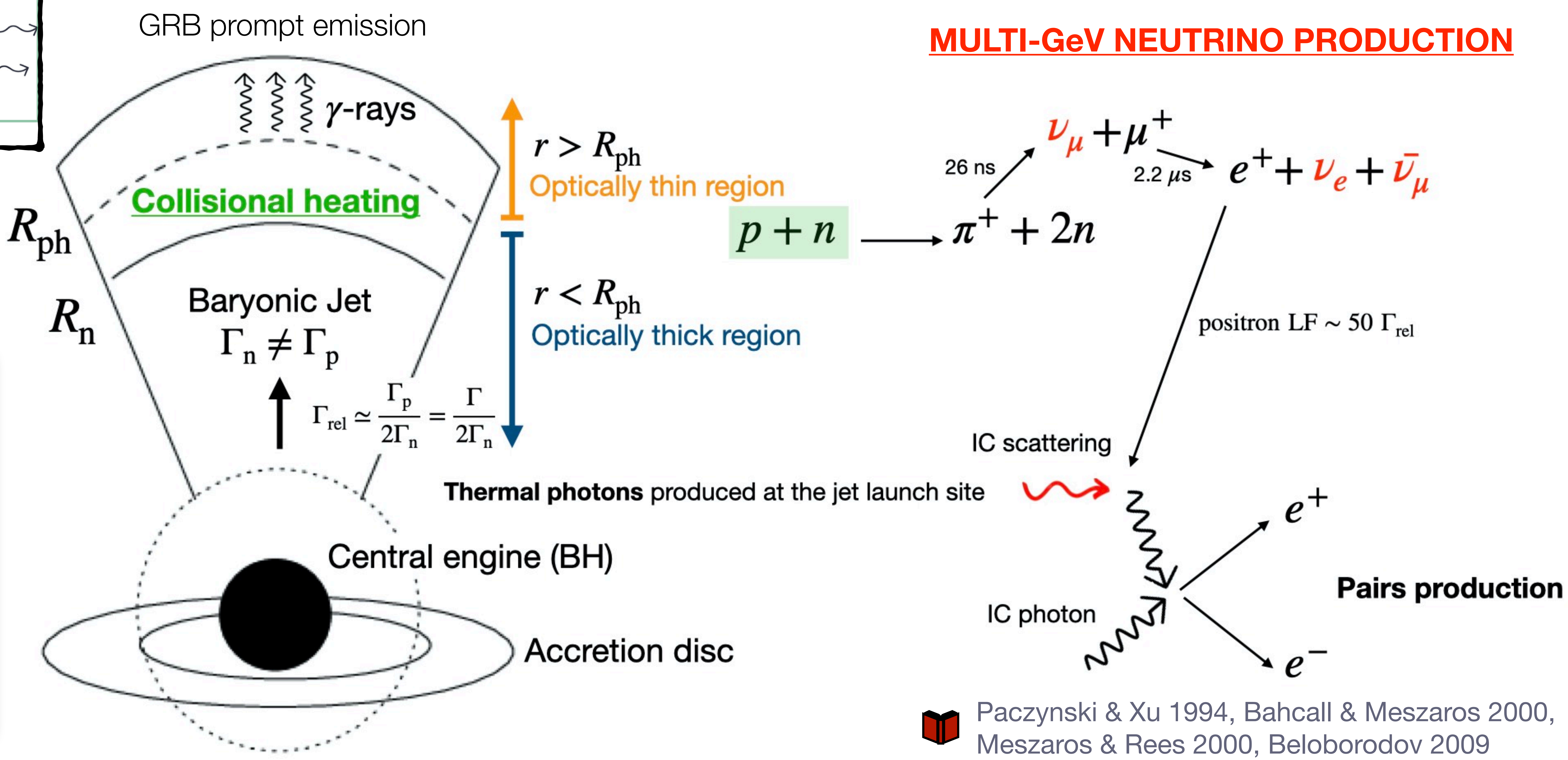
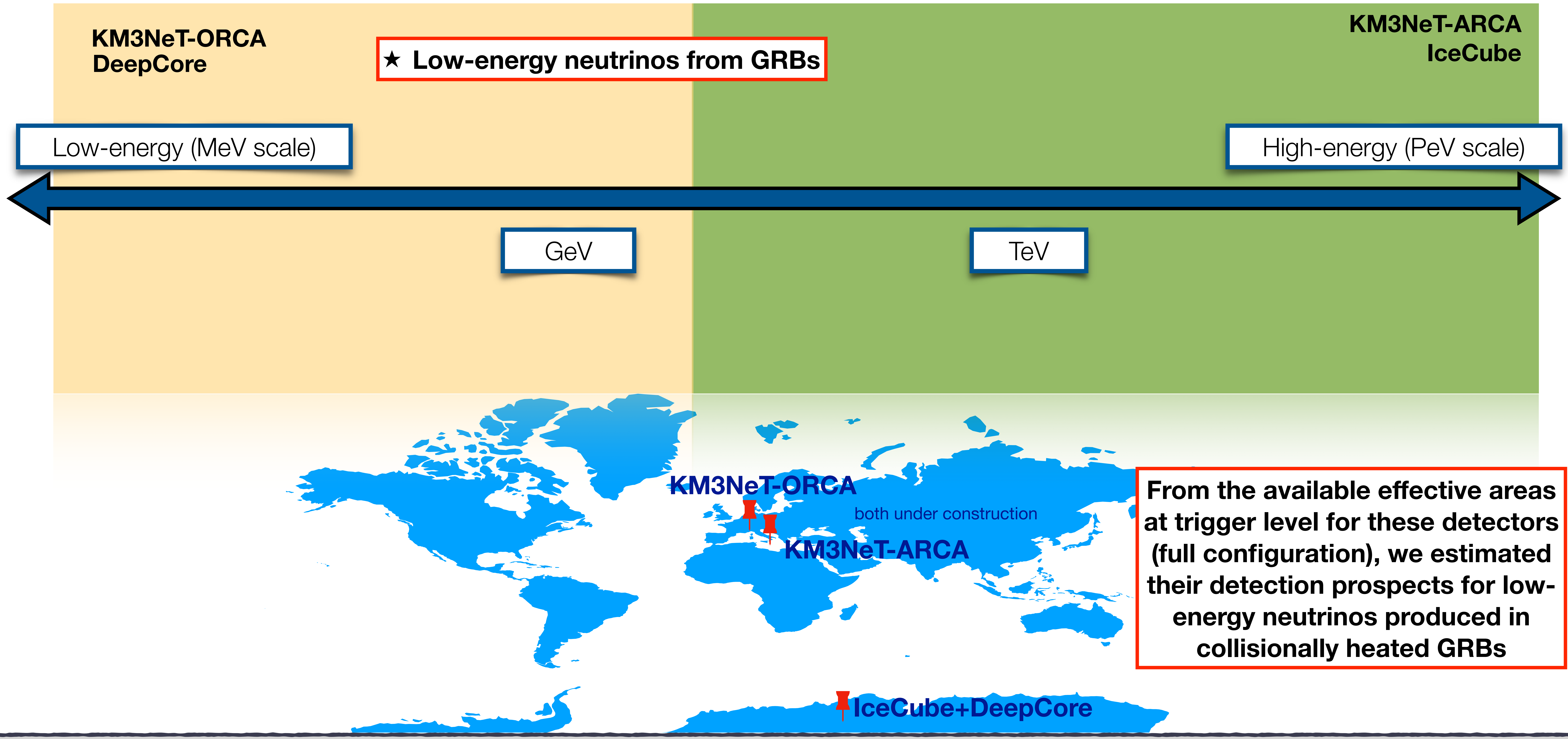


Paczynski & Xu 1994, Bahcall & Meszaros 2000, Meszaros & Rees 2000, Beloborodov 2009

Existing ‘low-E’ neutrino telescopes



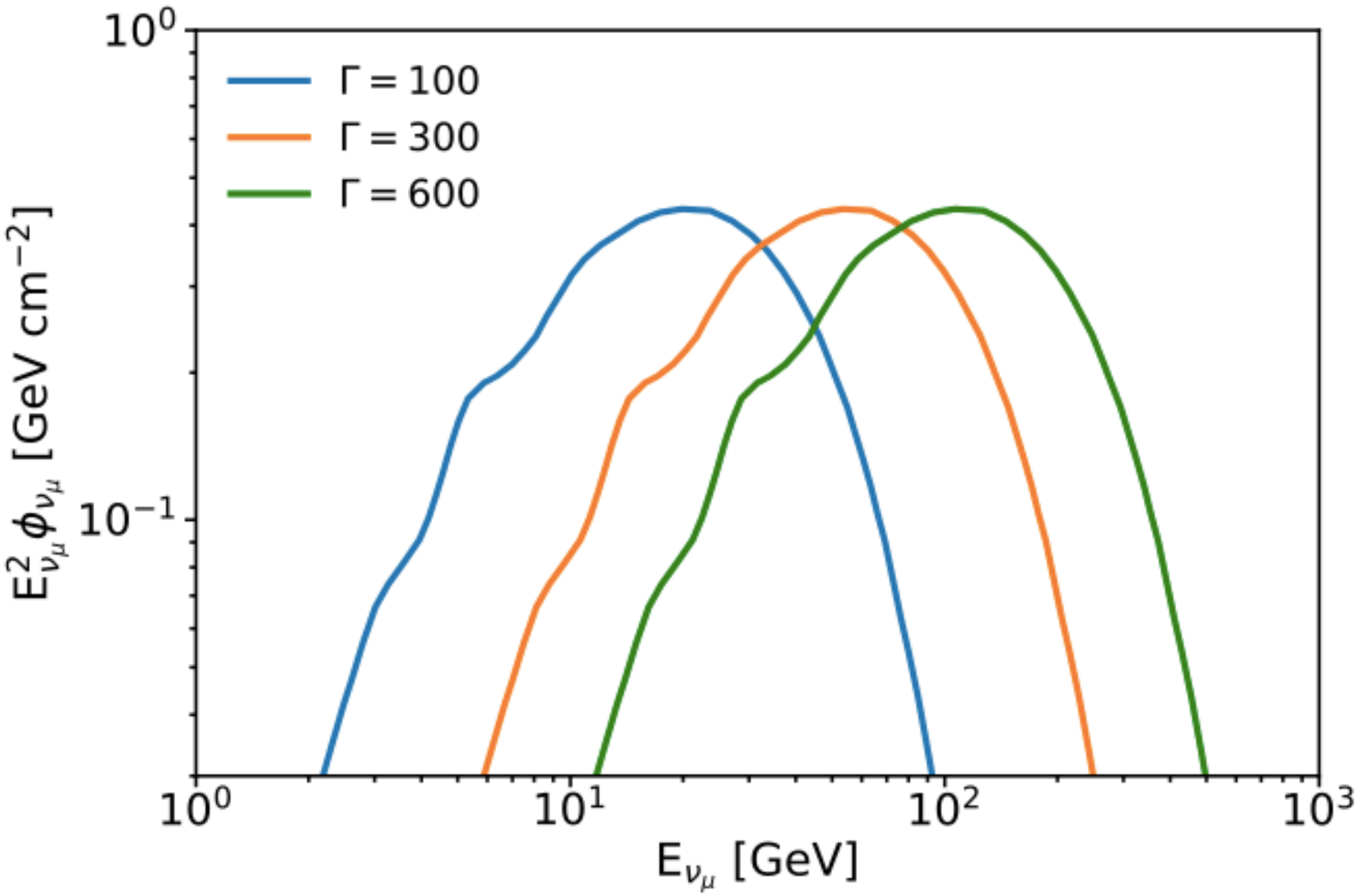
From the available effective areas at trigger level for these detectors (full configuration), we estimated their detection prospects for low-energy neutrinos produced in collisionally heated GRBs

Neutrino fluxes from collisionally heated GRBs

A. Zegarelli, S. Celli, A. Capone, S. Gagliardini, S. Campion, I. Di Palma, Phys. Rev. D 105, 083023 (2022)

ν_μ neutrino spectra produced in collisionally heated GRBs depend on several parameters:

- ★ The Lorentz factor of the jet, Γ
- ★ The relative Lorentz factor of the proton and neutron component, $\Gamma_{\rm rel}$
- ★ The ratio between the dissipated isotropic kinetic energy and the isotropic neutrino energy from inelastic nuclear collisions, $\xi_{\rm N}$
- ★ Since subphotospheric γ rays are responsible for the prompt emission, the neutrino emission is considered proportional to the observed γ-ray fluence



Flux observed at Earth for a source at redshift $z = 1$
$F_\gamma \sim 2 \times 10^{-3}$ erg cm^{-2}

Murase K. (2013), *Phys. Rev. Lett.* 111, 121102

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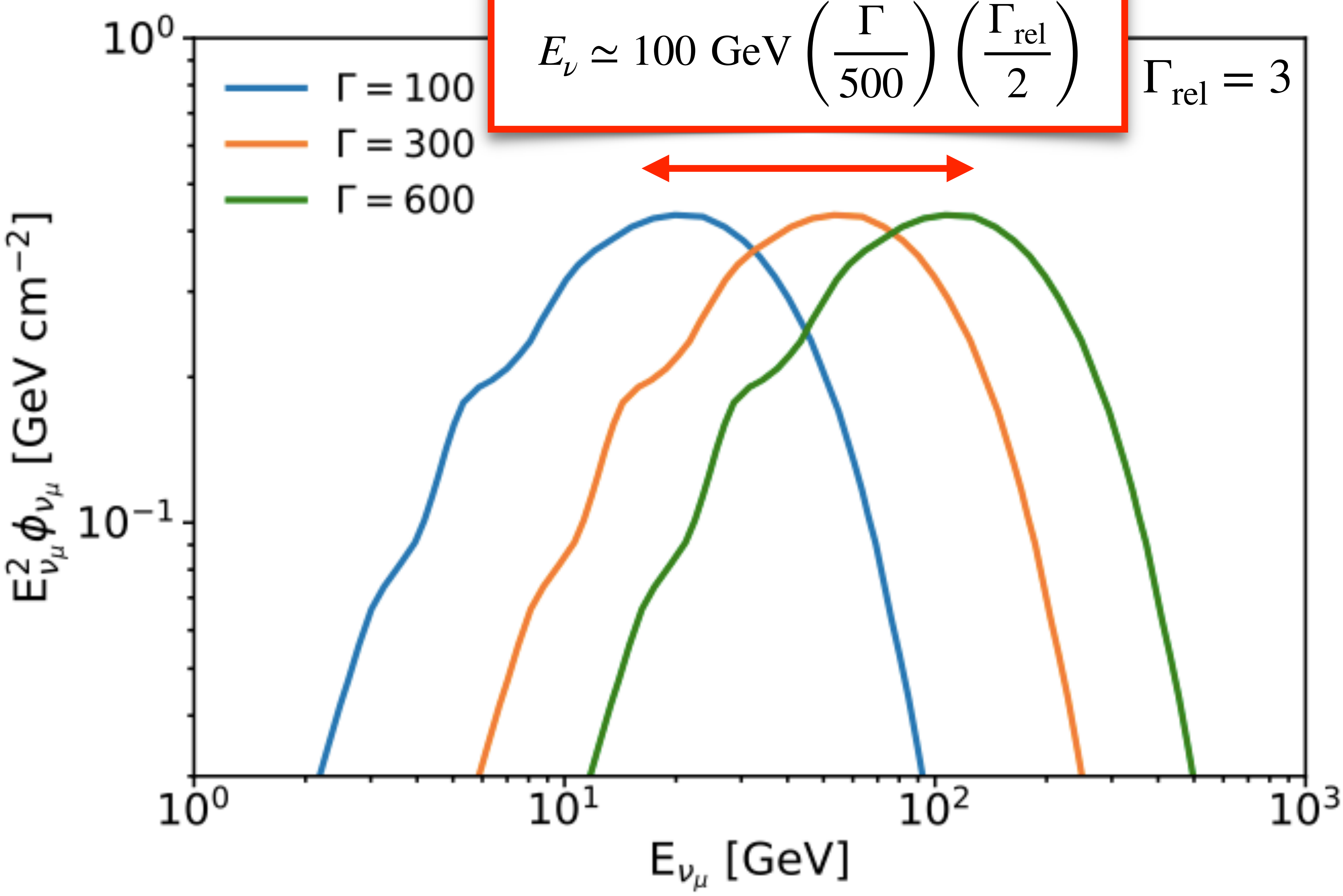
$$E_\nu \simeq 100\ \mathrm{GeV} \left(\frac{\Gamma}{500}\right)\left(\frac{\Gamma_{\rm rel}}{2}\right)$$

$\Gamma_{\rm rel} = 3$



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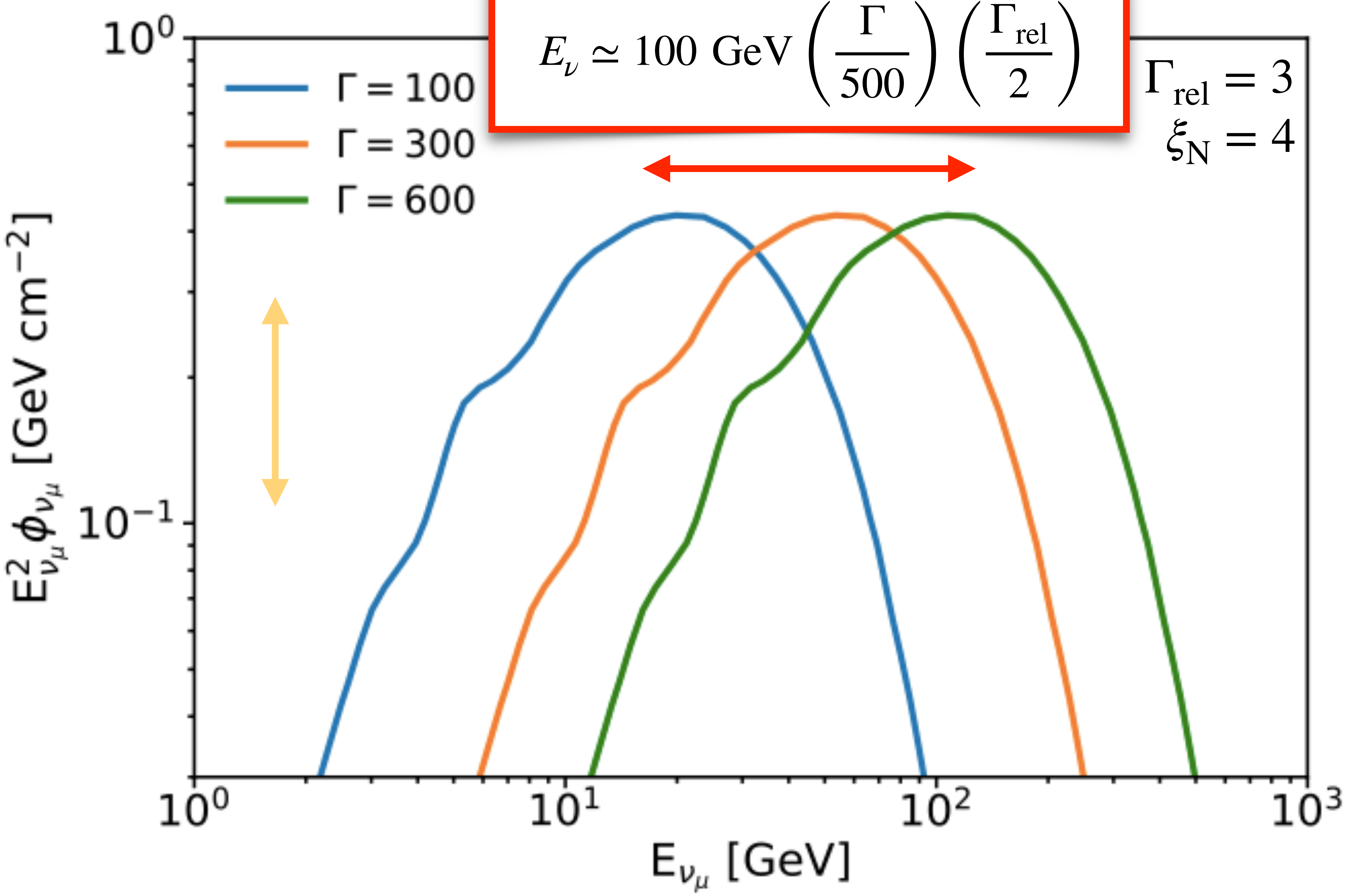
Normalization

$$F_\gamma \simeq E_\gamma^2 \phi_\gamma \sim E_{\nu_\mu}^2 \phi_{\nu_\mu}$$

Murase K. (2013), *Phys. Rev. Lett.* 111, 121102

$$E_\nu \simeq 100 \text{ GeV} \left(\frac{\Gamma}{500}\right)\left(\frac{\Gamma_{\rm rel}}{2}\right)$$



Flux observed at Earth for a source at redshift $z = 1$

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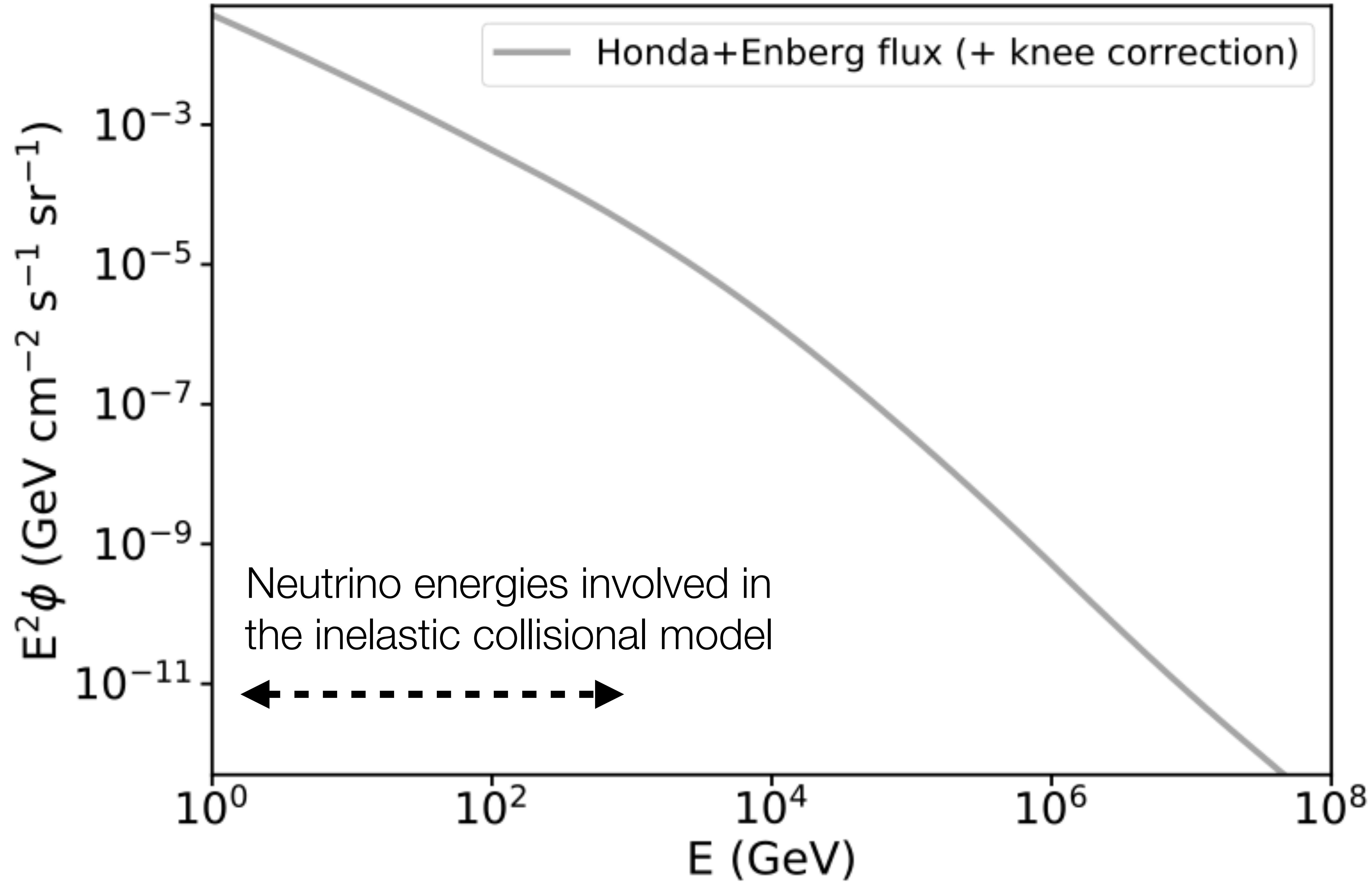
Background: atmospheric neutrino flux

A. Zegarelli, S. Celli, A. Capone, S. Gagliardini, S. Campion, I. Di Palma, Phys. Rev. D 105, 083023 (2022)

To limit the sever background in the sub-TeV region, only up-going neutrinos are considered

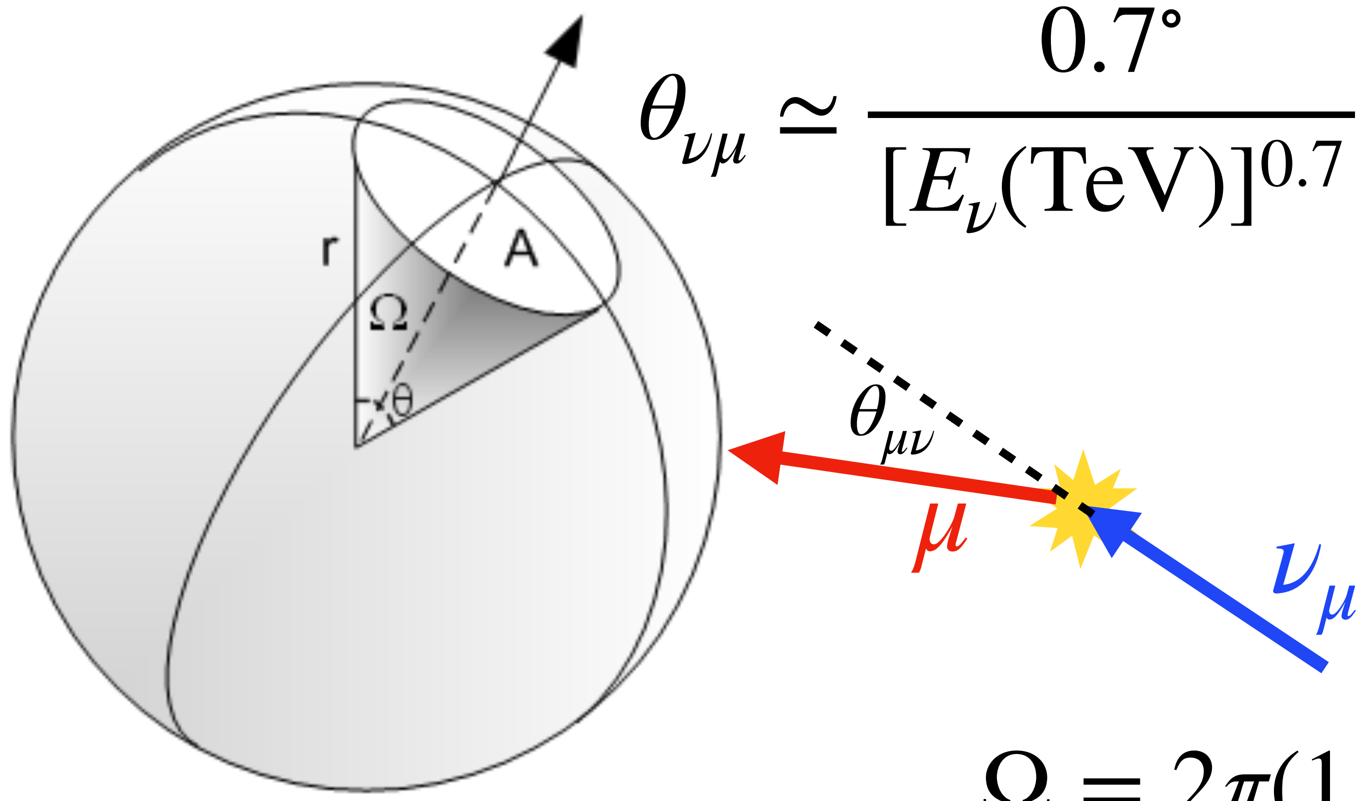


M. Honda et al., Phys. Rev. D 75 043006 (2007)
M. G. Artsen et al., Phys. Rev. D 89 062007 (2014)
R. Enberg et al., Phys. Rev. D 78 043005 (2008)

Temporal window

Estimation of the background within a time window slightly above extended than the prompt duration of the GRB $(T_{90} \pm 0.3T_{90})$

Angular window



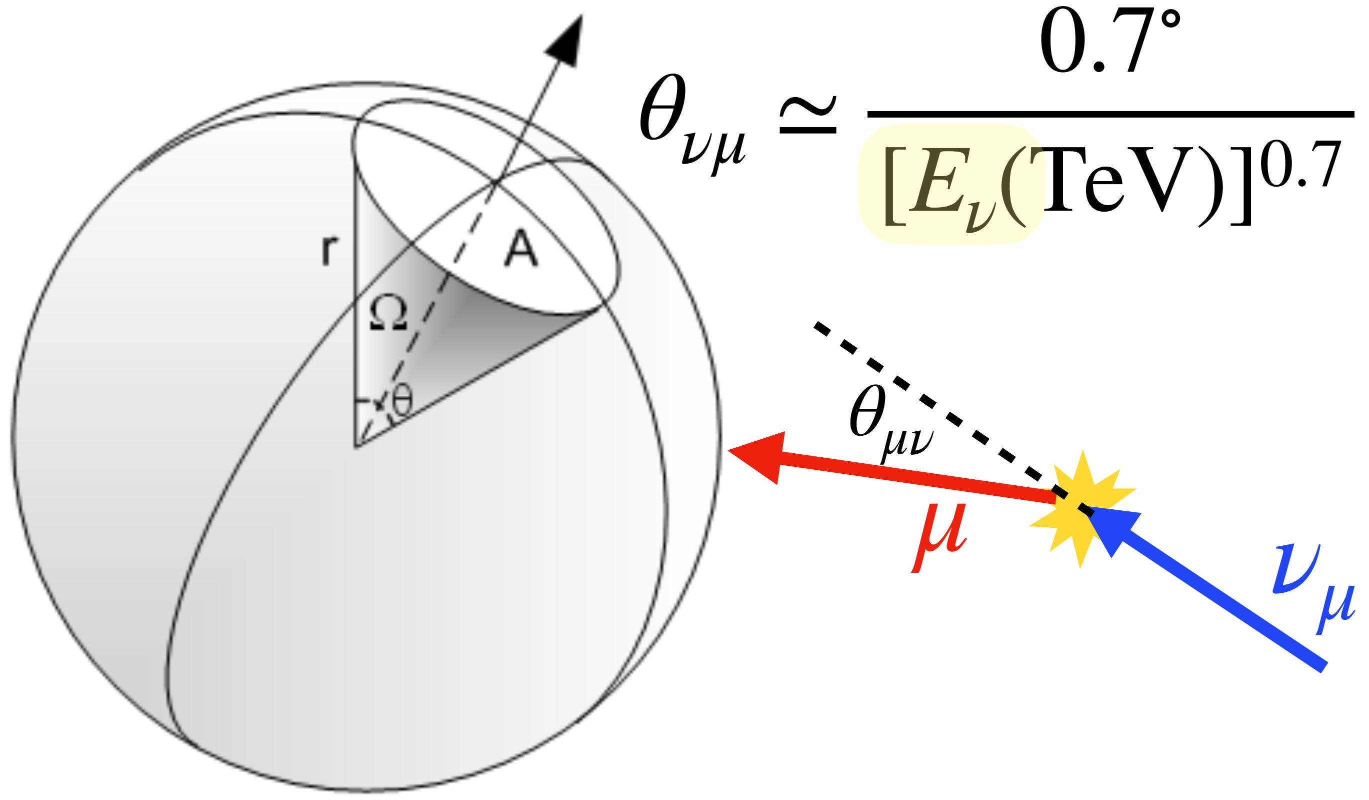
$$\theta_{\nu\mu} \simeq \frac{0.7^\circ}{[E_\nu(\mathrm{TeV})]^{0.7}}$$

$$\Omega = 2\pi(1 - \cos(\theta^*/2))$$
$$\theta^* = 3\theta_{\nu\mu}(\mathrm{E}_\nu)$$

Atmospheric neutrino flux in the up-going sky for each ν_s detector

A. Zegarelli, S. Celli, A. Capone, S. Gagliardini, S. Campion, I. Di Palma, Phys. Rev. D 105, 083023 (2022)

The kinematic angle between the incoming neutrino and the emerging muon is calculated at the energy $E^*_{\nu_\mu,\max}$ in which each neutrino telescope would observe the maximum number of neutrino given the model (i.e. for a given Γ)



$$\theta_{\nu\mu} \simeq \frac{0.7^\circ}{[E_\nu(\mathrm{TeV})]^{0.7}}$$

$$\Omega = 2\pi(1 - \cos(\theta^*/2))$$
$$\theta^* = 3\theta_{\nu\mu}(E_\nu)$$

	$\Gamma = 100$		$\Gamma = 300$		$\Gamma = 600$	
Detector	$E^*_{\nu_\mu,\max}$ [GeV]	θ^* [deg]	$E^*_{\nu_\mu,\max}$ [GeV]	θ^* [deg]	$E^*_{\nu_\mu,\max}$ [GeV]	θ^* [deg]
KM3NeT/ORCA	27	26	73	13	121	9
KM3NeT/ARCA	-	-	129	9	227	6
DeepCore	27	26	78	13	165	8
IceCube	-	-	156	8	258	5

Signal and background estimation

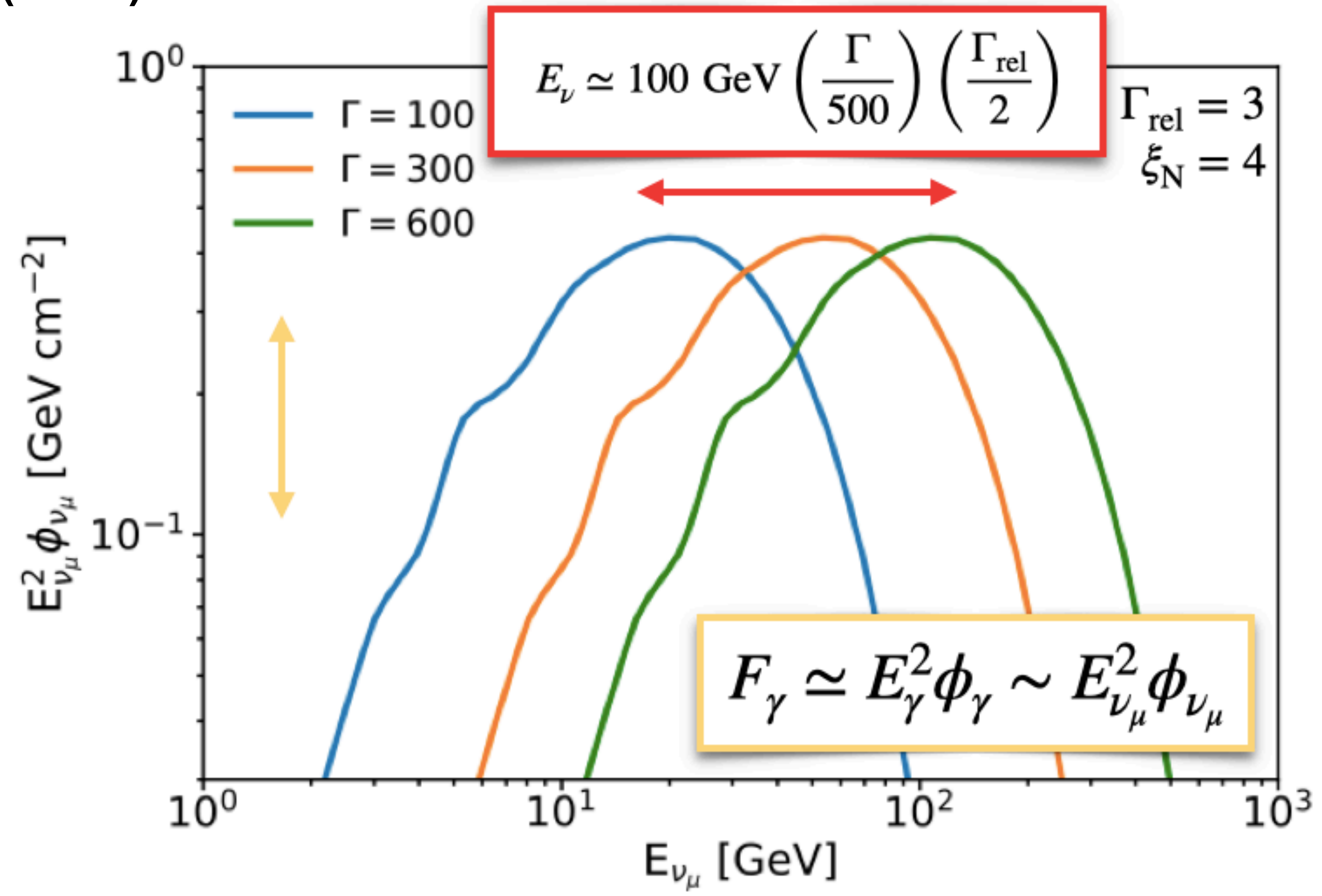
A. Zegarelli, S. Celli, A. Capone, S. Gagliardini, S. Campion, I. Di Palma, Phys. Rev. D 105, 083023 (2022)

For each GRB:

- Neutrino fluence calculated starting from F_γ (1 keV - 10 MeV);

$$F_\nu \propto \frac{1+z}{4\pi d_L^2(z)} \int dE \left(E \frac{dN}{dE} \right)_{\nu,s}$$

→ Number of expected signal events, n_s



Flux observed at Earth for a source at redshift $z = 1$
$F_\gamma \sim 2 \times 10^{-3}$ erg cm^{-2}

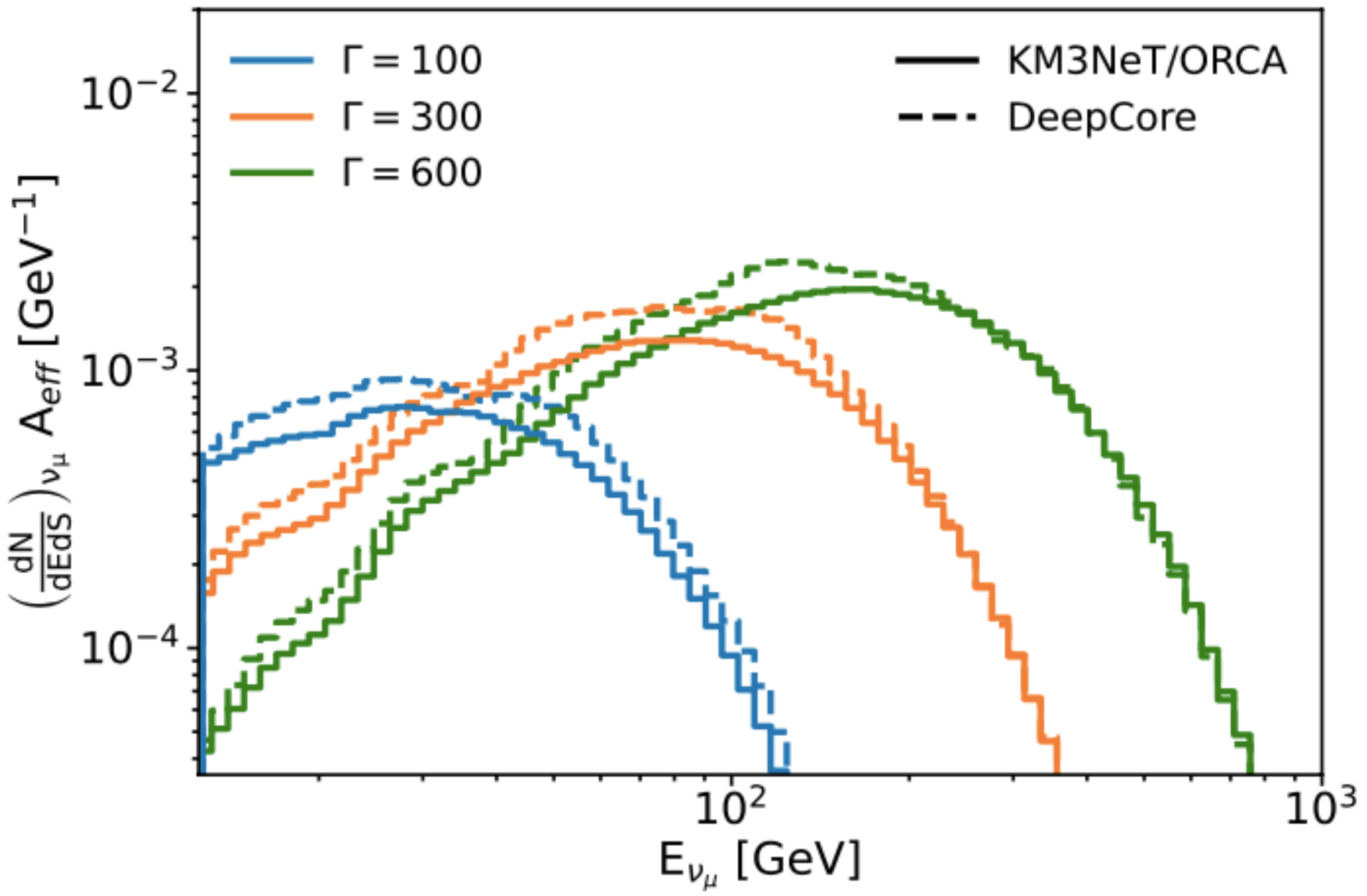
- Number of background events, n_b, calculated for each detector and for each Γ within the optimized solid angle Ω (see previous slide) and in $T_{90} \pm 0.3 T_{90}$

$$\boxed{N_{\nu_\mu}(E_{\nu_\mu}) = A_{eff}(E_{\nu_\mu}) \left(\frac{dN(E_{\nu_\mu})}{dE_{\nu_\mu} dS} \right) \Delta E_{\nu_\mu}}$$

Detection prospects from an individual extreme GRB

A. Zegarelli, S. Celli, A. Capone, S. Gagliardini, S. Campion, I. Di Palma, Phys. Rev. D 105, 083023 (2022)

Estimation of the number of neutrino events coming from a GRB with a fluence comparable to GRB130427A ($F_\gamma \sim 2 \times 10^{-3}$ erg cm^{-2}), which is the GRB with the highest fluence in the Fermi-GBM catalogue



Detector	n_s $\Gamma = 100$	$\Gamma = 300$	$\Gamma = 600$
KM3NeT/ORCA	4×10^{-2}	7×10^{-2}	1×10^{-1}
KM3NeT/ORCA+KM3NeT/ARCA	-	9×10^{-2}	2×10^{-1}
DeepCore	5×10^{-2}	9×10^{-2}	1×10^{-1}
DeepCore+IceCube	-	3×10^{-1}	8×10^{-1}

★ The number of ν_μ events from an individual GRB observable in ORCA/DeepCore and ORCA+ARCA/DeepCore+IceCube (combined analysis) is quite contained, even if the considered GRB is characterized by a very high fluence value

★ To allow an individual GRB to produce $n_s \geq 1$, it has to be characterized by $F_\gamma \geq 10^{-2}$ erg cm^{-2}, i.e. only nearby and very energetic GRBs. No such kind of GRBs has ever been observed so far

Stacking detection prospects: procedure

A. Zegarelli, S. Celli, A. Capone, S. Gagliardini, S. Campion, I. Di Palma, Phys. Rev. D 105, 083023 (2022)

A synthetic population of sources detectable in half-sky by gamma-ray satellites in **~5 years** has been built

$$N^{\text{half sky}}_{\text{short GRB}} \sim 75\ \text{yr}^{-1}, \quad N^{\text{half sky}}_{\text{long GRB}} \sim 175\ \text{yr}^{-1}$$

Such values were obtained from the Gamma-Ray Bursts Interplanetary Network (IPNGRB) database https://heasarc.gsfc. nasa.gov/w3browse/all/ipngrb.html.

- Random extraction of T_{90} and F_γ (10 keV-1000 keV) from observed distribution by Fermi GBM
- GRB accepted only if F_γ / T_{90} falls into the distribution obtained with the observed parameters

For the estimation of the neutrino flux, the gamma-ray fluence is then *k*-corrected —> F_γ (1 keV - 10 MeV)

Stacking detection prospects: results

Note: available detector areas at trigger level for each detector (full configuration) have been used.

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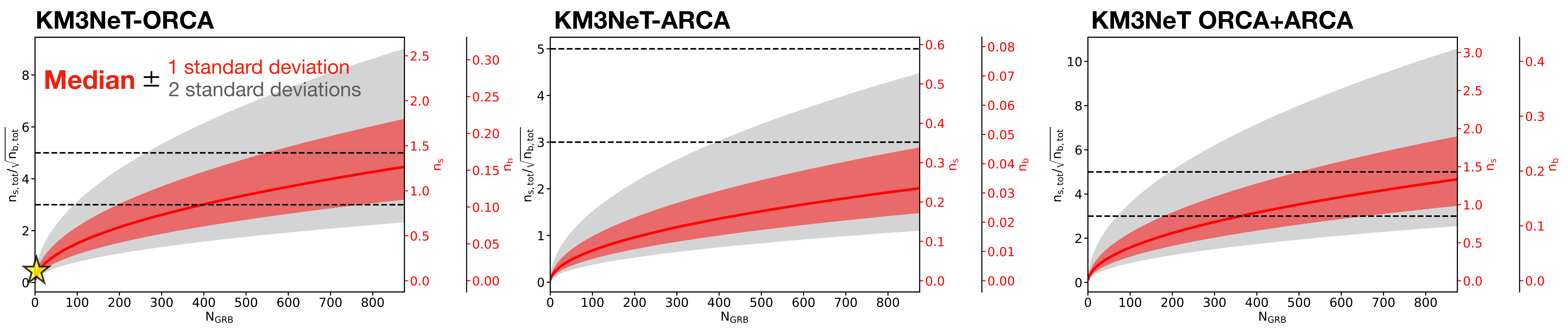
Long GRBs

$\Gamma = 300$



☆The first GRB is the one with the highest level of significance $\sigma = \frac{n_s}{\sqrt{n_b}}$

The others are added one by one choosing each time the GRB providing the maximum increase of the total level of significance $\sigma_{tot}(\mathrm{N}) = \frac{n_{\mathrm{s,tot}}}{\sqrt{n_{\mathrm{b,tot}}}} = \frac{\sum_{i=1}^{\mathrm{N}} n_{\mathrm{s,i}}}{\sqrt{\sum_{i=1}^{\mathrm{N}} n_{\mathrm{b,i}}}}$

The procedure was repeated 1000 times

Stacking detection prospects: results

Note: available detector areas at trigger level for each detector (full configuration) have been used.

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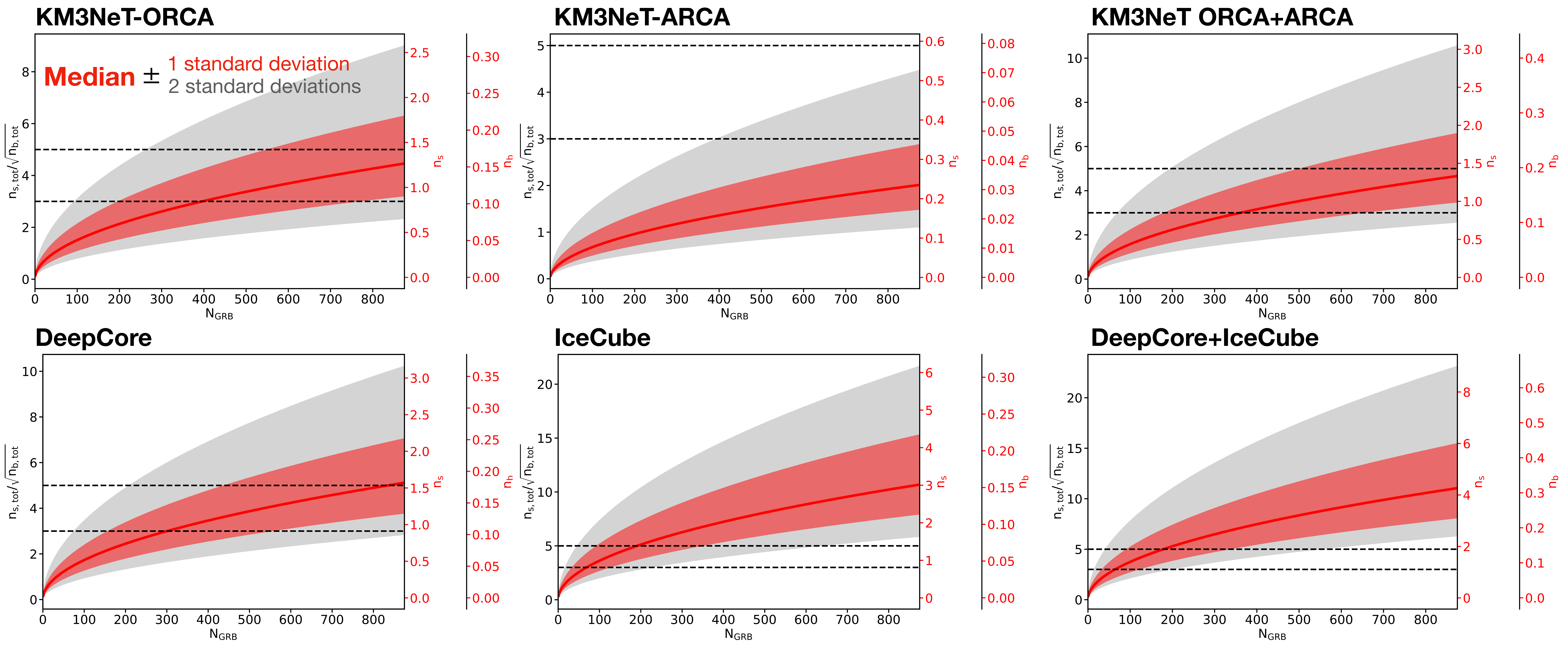

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Long GRBs

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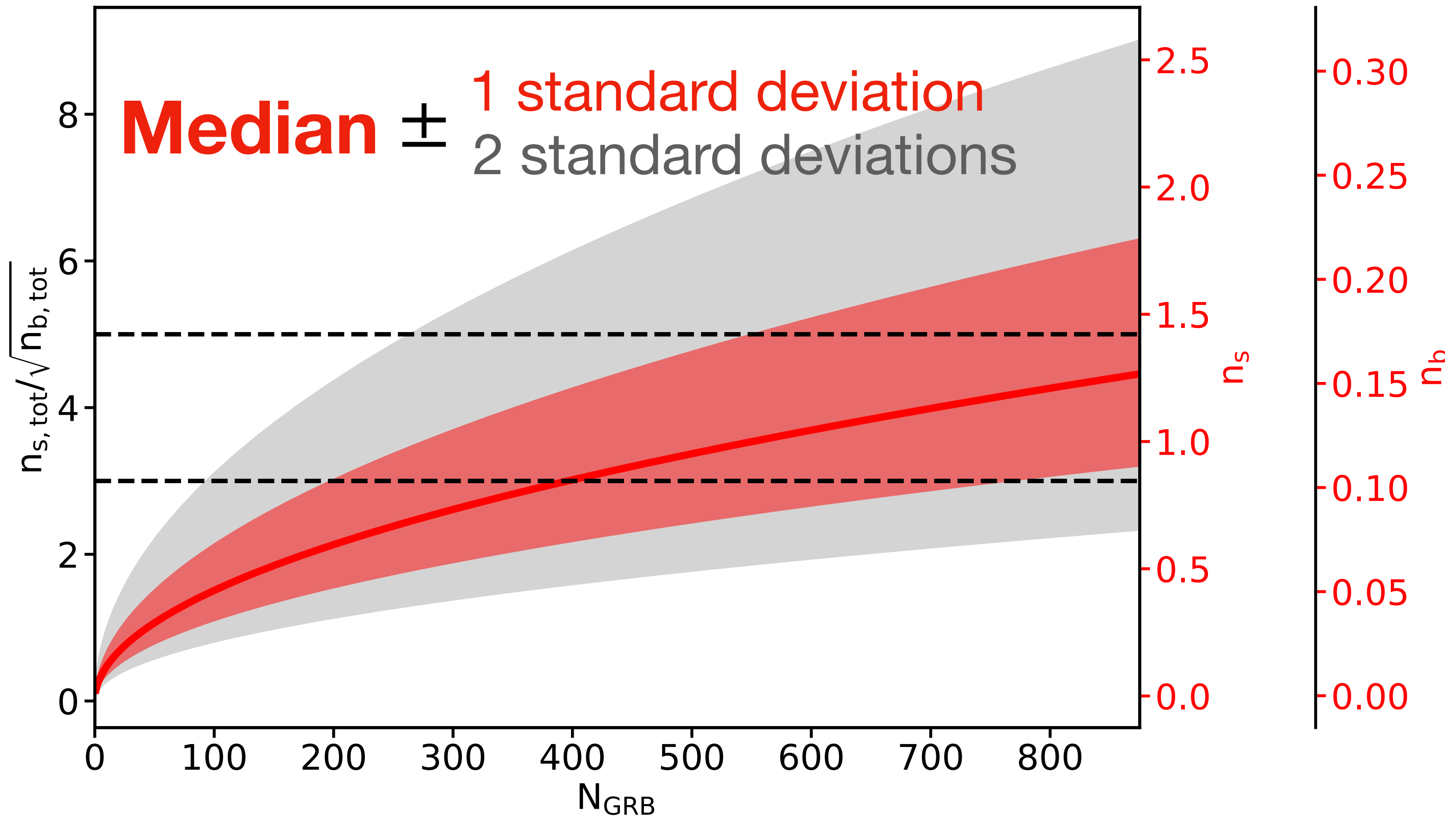
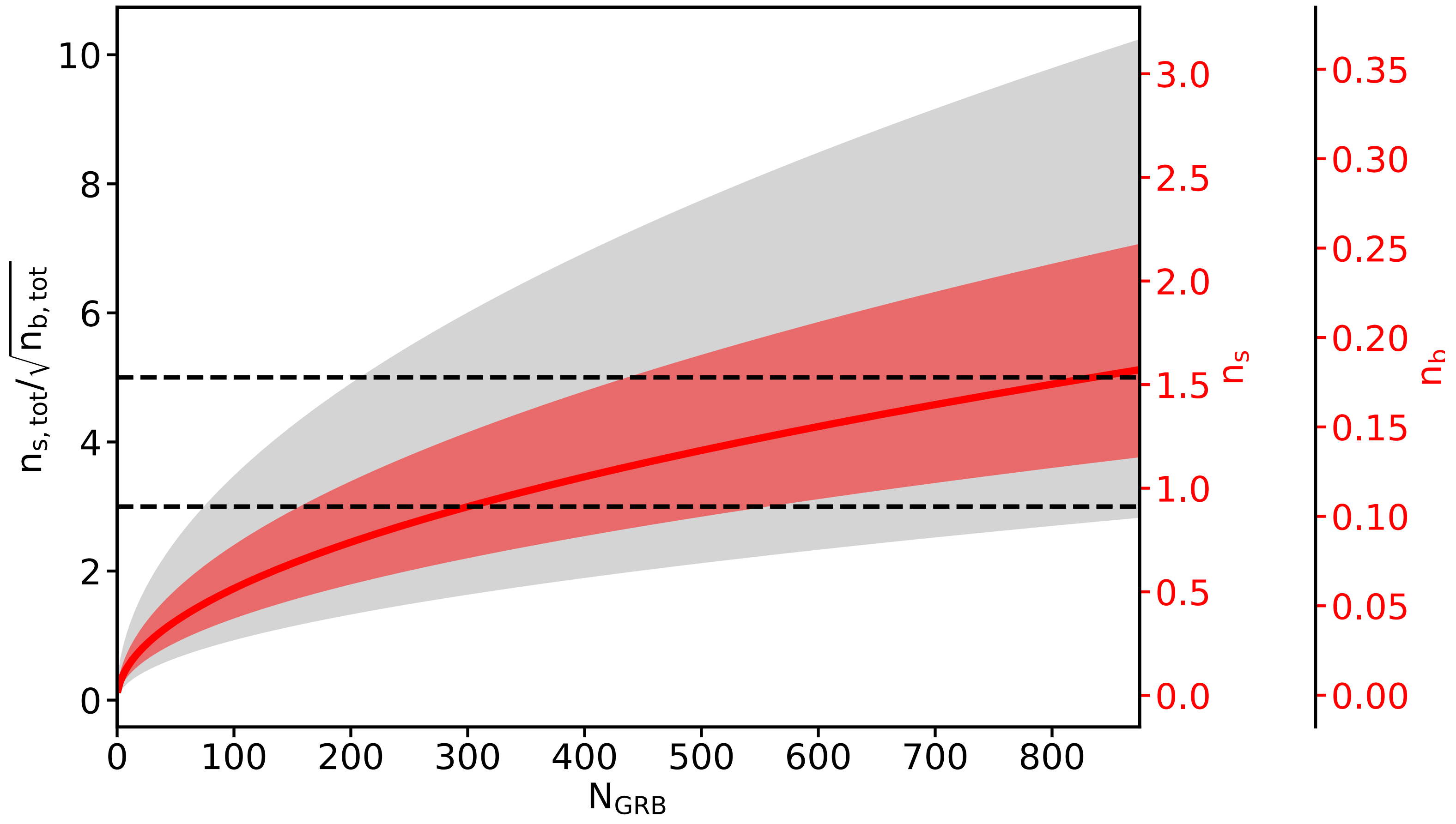
KM3NeT-ORCA

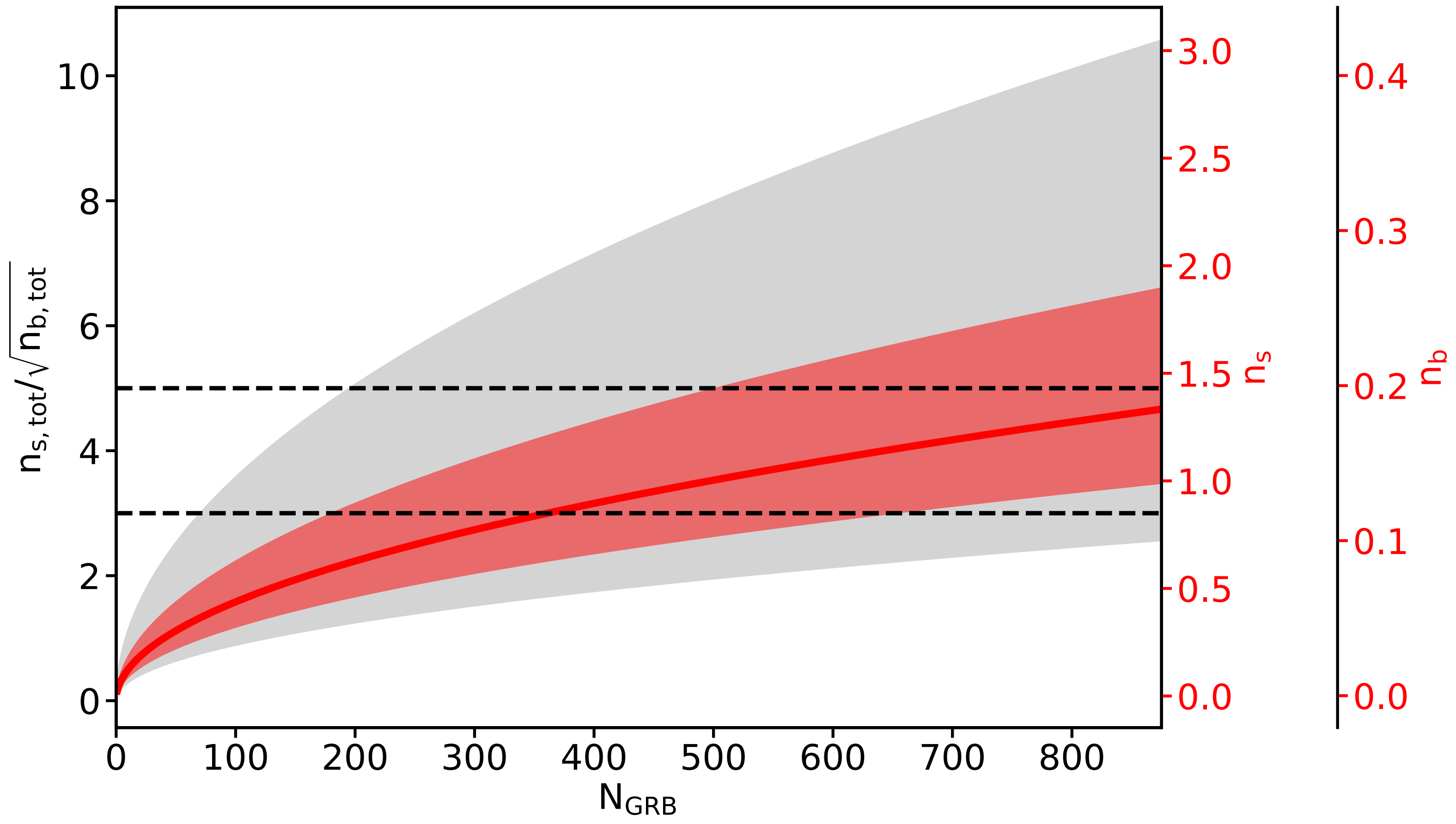


DeepCore

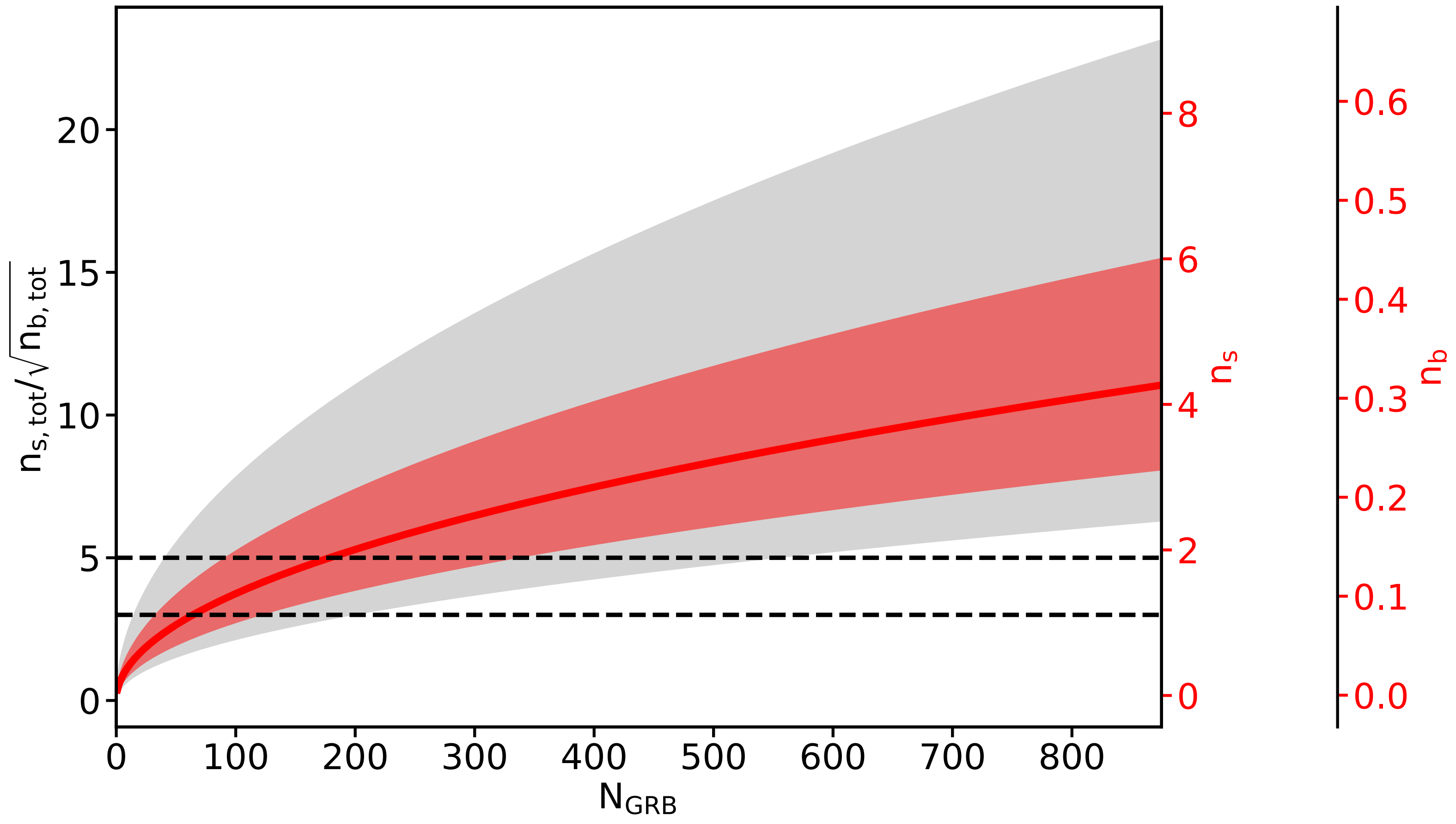


- ★ The detection is possible only if long GRBs are included in the search; short GRBs alone would not provide signal enough from this model to guarantee a detection, in spite of the particularly low background level;
- ★ There is a good chance to detect sub-TeV neutrinos after ~900 LGRBs;
- ★ Such a possibility is increased by integrating the low-energy detectors (ORCA and DeepCore) with the corresponding high-energy ones (ARCA and IceCube)

KM3NeT ORCA+ARCA



DeepCore+IceCube



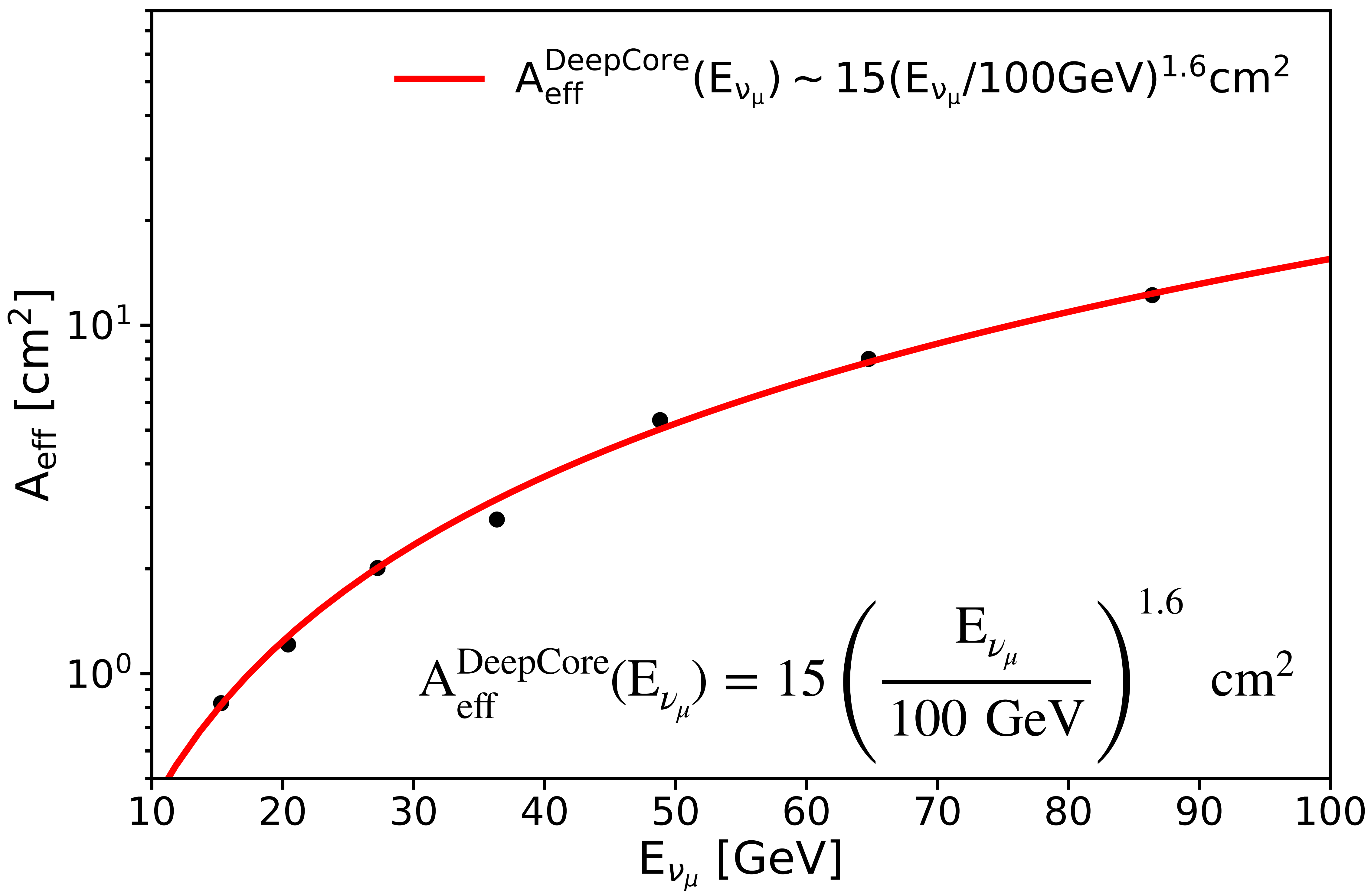
Summary and Conclusions

- The *inelastic collisional model* (*pn* collisions close to the photosphere of the GRB jet) is an alternative model for explaining the GRB prompt emission;
- This model involves lower neutrino energies with respect to photo-hadronic mechanisms so far investigated in the context of astrophysical neutrino data analyses;
- According to our results:
    - Short GRBs alone do not provide enough signal;
    - Concerning individual GRBs, we conclude that only nearby and very energetic GRBs (rare events) can produce at least one signal event in the available detectors;
    - By combining data collected both by low and high-energy detectors (DeepCore+IceCube and KM3NeT/ORCA+KM3NeT/ARCA, once completed) we would be able to explore the occurrence of inelastic collisions in GRB jets by means of a stacking analysis of up-going tracks with data collected in coincidence with ~900 LGRBs.

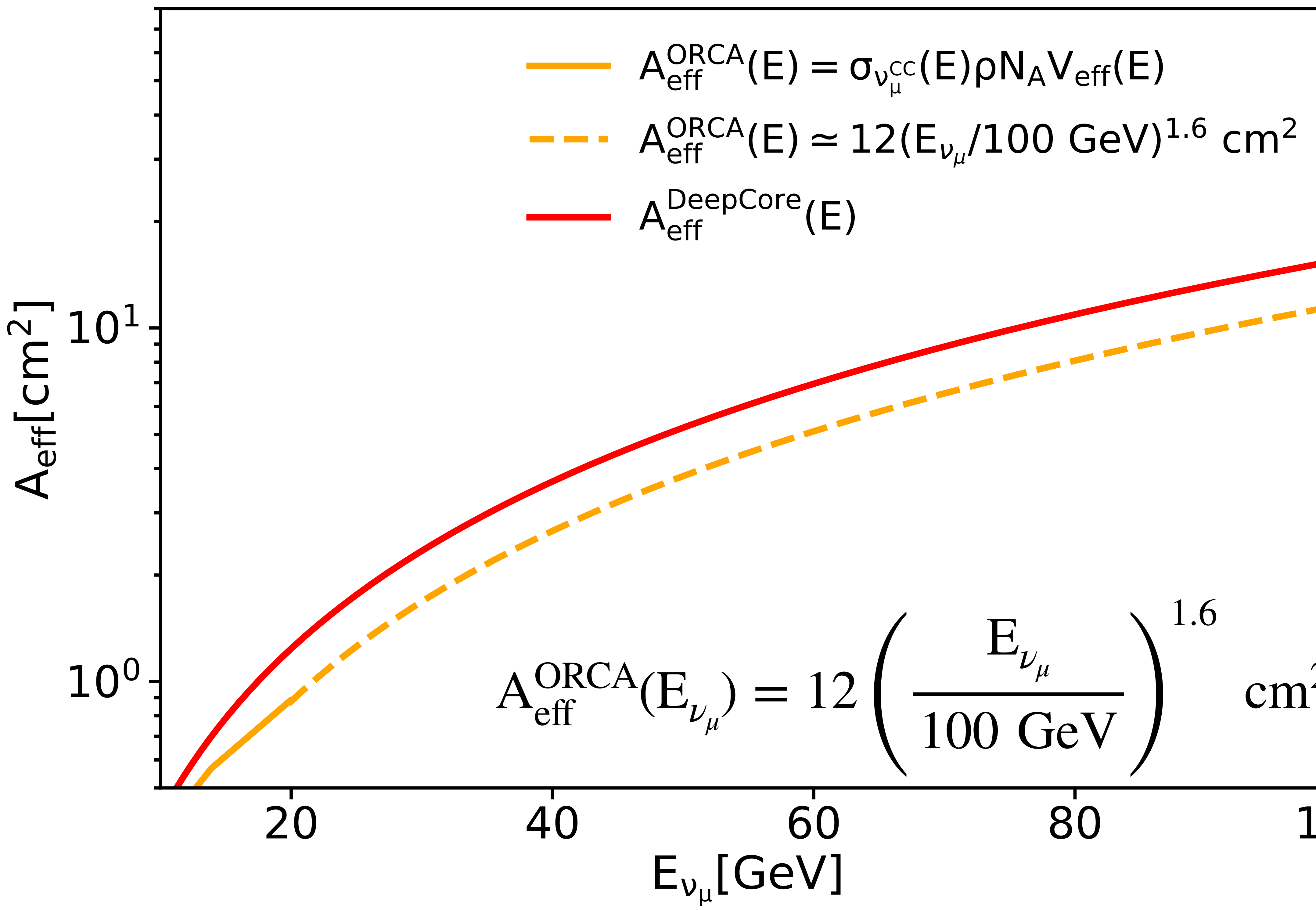
Backup slides

ORCA and DeepCore effective areas

A. Zegarelli, S. Celli, A. Capone, S. Gagliardini, S. Campion, I. Di Palma, Phys. Rev. D 105, 083023 (2022)



R. Abbasi et al., ApJ 35, 615 (2012)



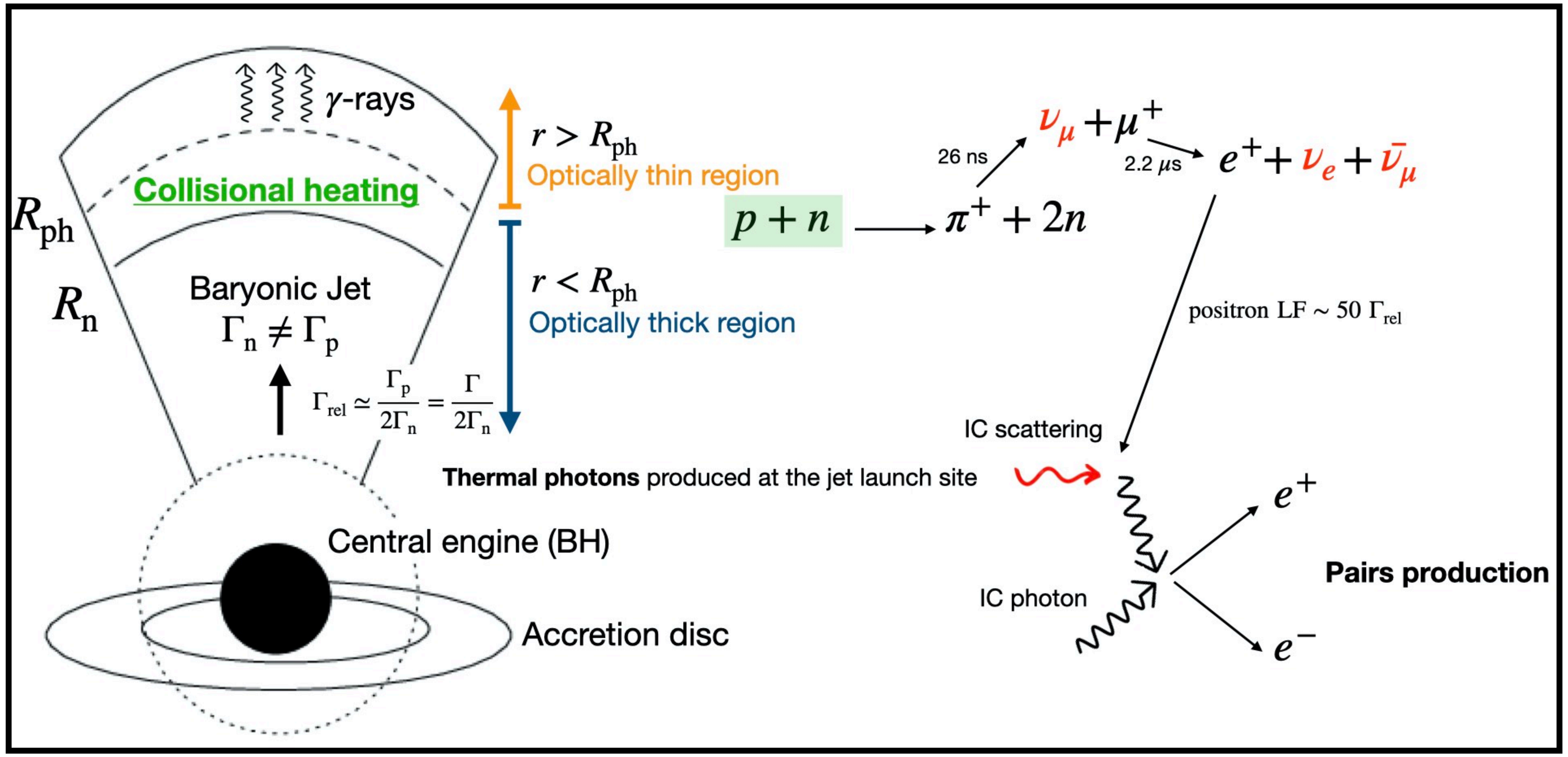
ORCA effective area from the its effective volume

A. Kouchner and J. Coelho, PoSICRC2017, 1027 (2017)

The effective area behaviour at higher energies than available has been extrapolated by using the same energy dependence as in DeepCore

Neutrino production at the source

A. Zegarelli, S. Celli, A. Capone, S. Gagliardini, S. Campion, I. Di Palma, Phys. Rev. D 105, 083023 (2022)



$$E_{\nu,s} = f_\nu E_{k,diss,s} = 1/2 E_{k,diss,s}$$

$$E_{\gamma,s} = f_{ad}(1 - f_\nu) E_{k,diss,s} \simeq \frac{f_{ad}}{2} E_{k,diss,s}$$

$$\frac{E_{\nu,s}}{E_{\gamma,s}} = \frac{E^{iso}_{\nu,s}}{E^{iso}_{\gamma,s}} = \frac{1}{f_{ad}}$$

Fraction of proton energy going into neutrinos via inelastic nuclear collisions

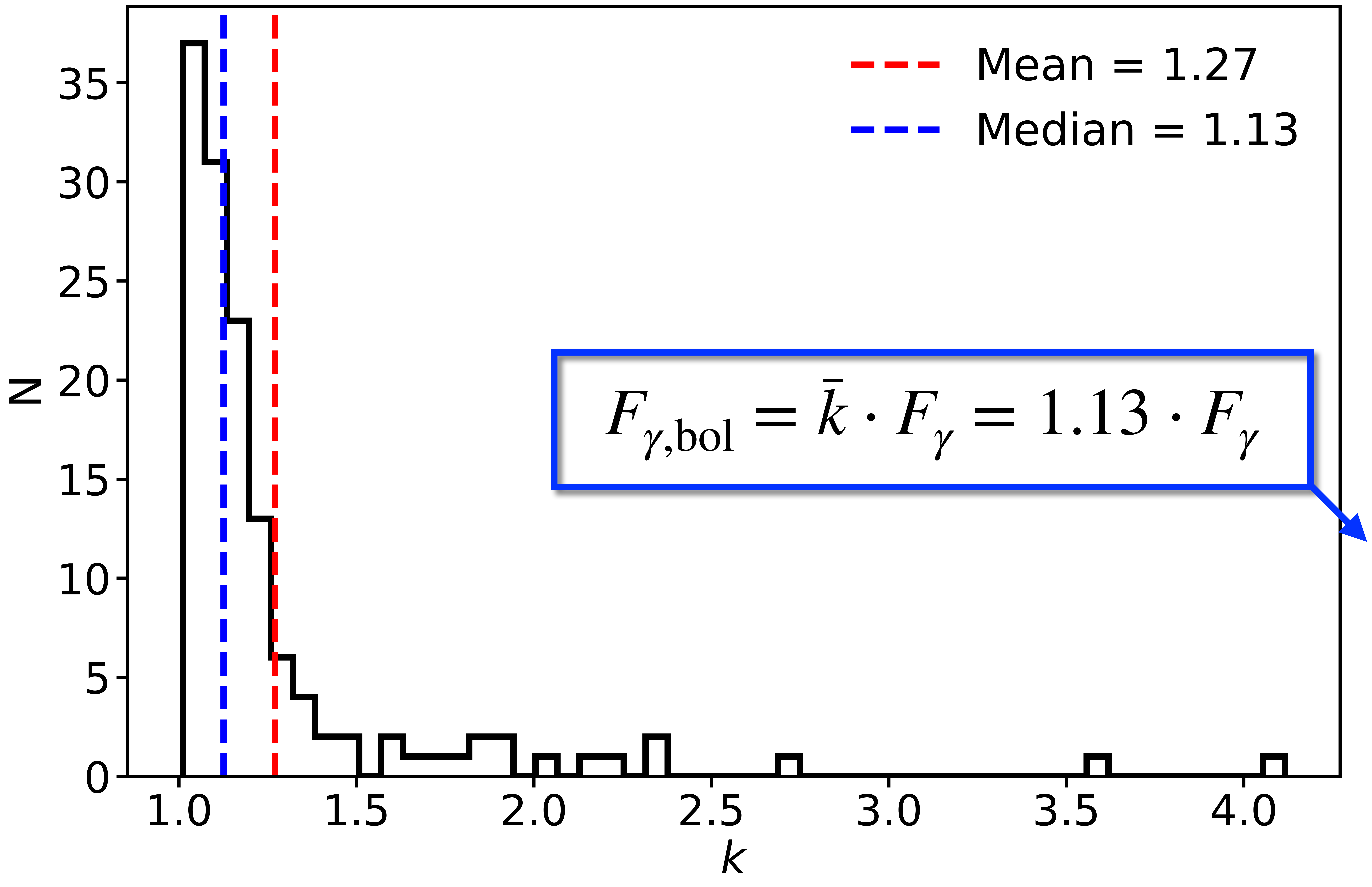
$$f_\nu \sim \frac{3}{4} \cdot f_{\pi^+} \sim \frac{3}{4} \cdot \frac{2}{3} = \frac{1}{2}$$

Assuming $f_{ad} = 0.5$:

$$\boxed{E^{iso}_{\nu,s} = 2E^{iso}_{\gamma,s} \rightarrow E^{iso}_{\nu_\mu + \bar{\nu}_\mu,s} \sim \frac{2}{3} E^{iso}_{\gamma,s}}$$

k-correction for γ-ray fluence

A. Zegarelli, S. Celli, A. Capone, S. Gagliardini, S. Campion, I. Di Palma, Phys. Rev. D 105, 083023 (2022)



$$F_{\gamma,\mathrm{bol}} = \bar{k} \cdot F_\gamma = 1.13 \cdot F_\gamma$$

k-correction values calculated on the GRB sample collected by *Fermi*-GBM during the first ten years of detector operation, including both LGRBs and SGRBs.

S. Poolakkil et al., ApJ 913, 60 (2021)

$$k = \frac{F_{\gamma,\mathrm{bol}}}{F_\gamma} = \frac{F_\gamma\left[\frac{E_1}{1+z}, \frac{E_2}{1+z}\right]}{F_\gamma\left[e_1, e_2\right]}$$

$$E_1 = 1\ \mathrm{keV},\ E_2 = 10\ \mathrm{MeV}$$
$$e_1 = 10\ \mathrm{keV},\ e_2 = 1000\ \mathrm{keV} \rightarrow \mathit{Fermi} - \mathrm{GBM}$$

This factor can be obtained in principle directly from gamma-ray spectra specifically for each GRB. However, we use a median k-correction for each GRB in our sample because:

- the shape of the gamma-ray spectrum does not enter additionally into our computations;
- most of GRB spectra can be described by the same functional form.

Angular windows around GRBs in the background evaluation

A. Zegarelli, S. Celli, A. Capone, S. Gagliardini, S. Campion, I. Di Palma, Phys. Rev. D 105, 083023 (2022)

Median angular resolutions of ν_μ charged current events for KM3NeT/ORCA (green) [W. Assal, D. Dornic, E. Le Guirriec, M. Lincetto, G. Vannoye, et al., PoS ICRC2021, 941 (2021)], KM3NeT/ARCA (red) [R. Muller, A. Heijboer, A. Garcia Soto, B. Caiffi, M. Sanguineti, et al., PoS ICRC2021, 1077 (2021)], DeepCore (orange), and IceCube (blue) [M. G. Aatsen et al., ApJ 835, 151 (2017)]. Note that the KM3NeT/ORCA angular resolution refers to a partial configuration with 6 strings, being the only available from the literature. The shaded grey region shows the interval among $\theta_{\nu\mu}$ and $3\theta_{\nu\mu}$, being $\theta_{\nu\mu}$ the kinematic angle between the incoming neutrino and the muon inside the detector. The vertical dashed lines indicate the energy values $E^*_{\nu_\mu,\max}$ at which each detector is expected to observe the highest number of muon neutrinos events.

Effects of some parameter uncertainties on neutrino fluences