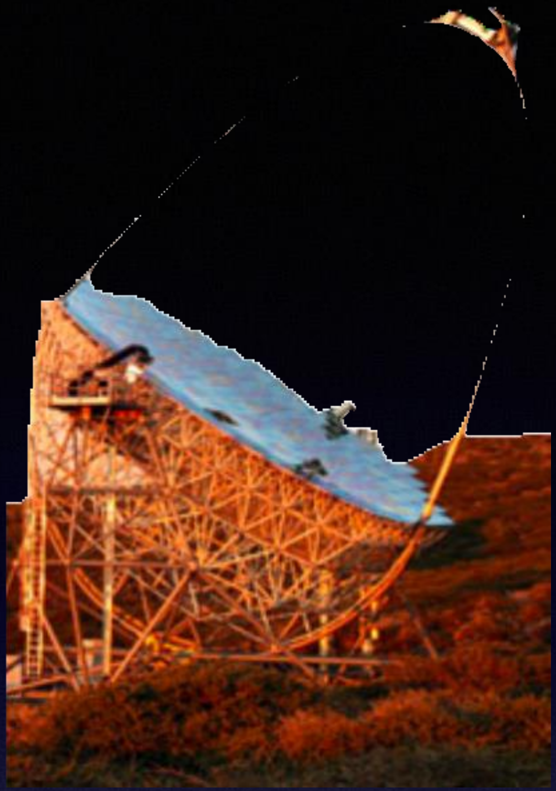

TeV emission - GRBs' 190114C

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Submitted to PRL, astro-ph/2209.01940

GRBV

Magic sub-TeV
Mirzoyan + 19

GCN 23701

MAGIC detects the GRB 190114C in the TeV energy domain

The MAGIC telescopes detected very-high-energy gamma-ray emission from GRB 190114C. The observation started about 50s after the Swift T0. The GRB data of MAGIC shows a clear excess of gamma-ray events with the significance >20 sigma in the first 20 min (starting at T0+50s) for energies >300GeV. The relatively high detection threshold is due to the large zenith angle of observations (~60 deg.) and the presence of partial moon. After the first bright flash the source is quickly fading.

The signal MAGIC saw

nature DOI: 10.1038/s41586-019-175(

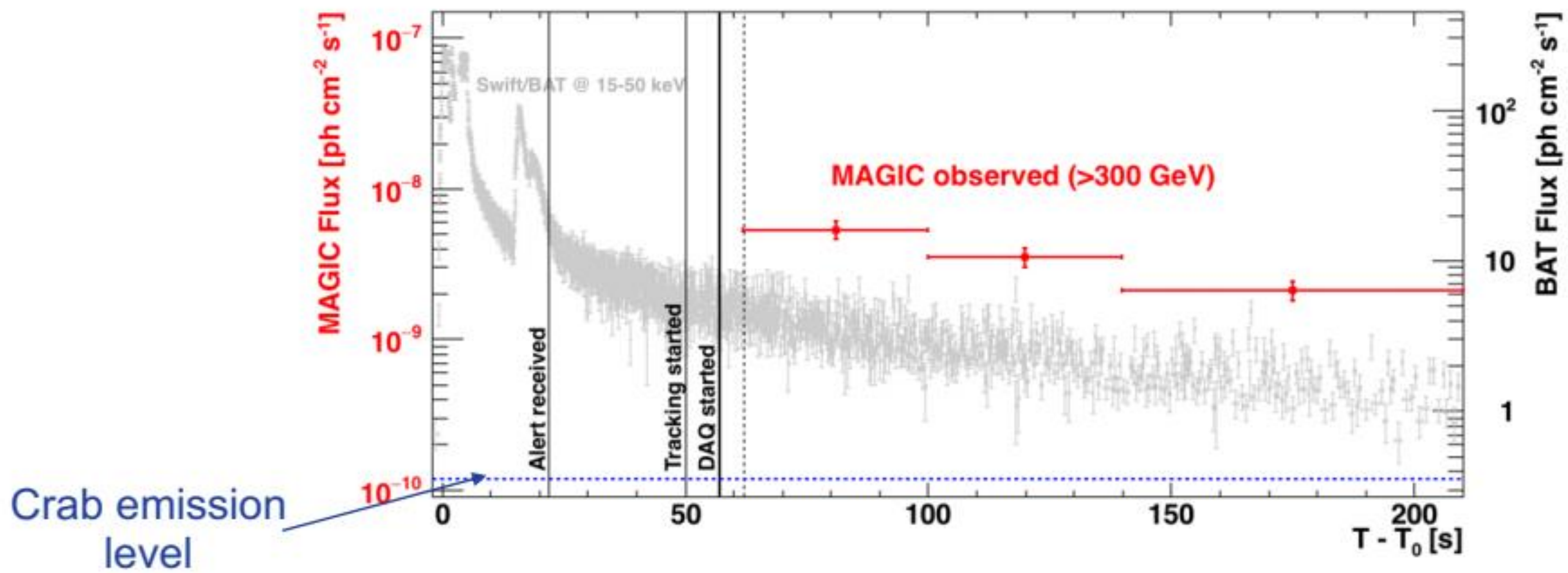
Article | Published: 20 November 2019

Teraelectronvolt emission the γ-ray burst GRB 190114

MAGIC Collaboration

Nature **575**, 455–458(2019) | Cite this article

4230 Accesses | **493** Altmetric | Metrics

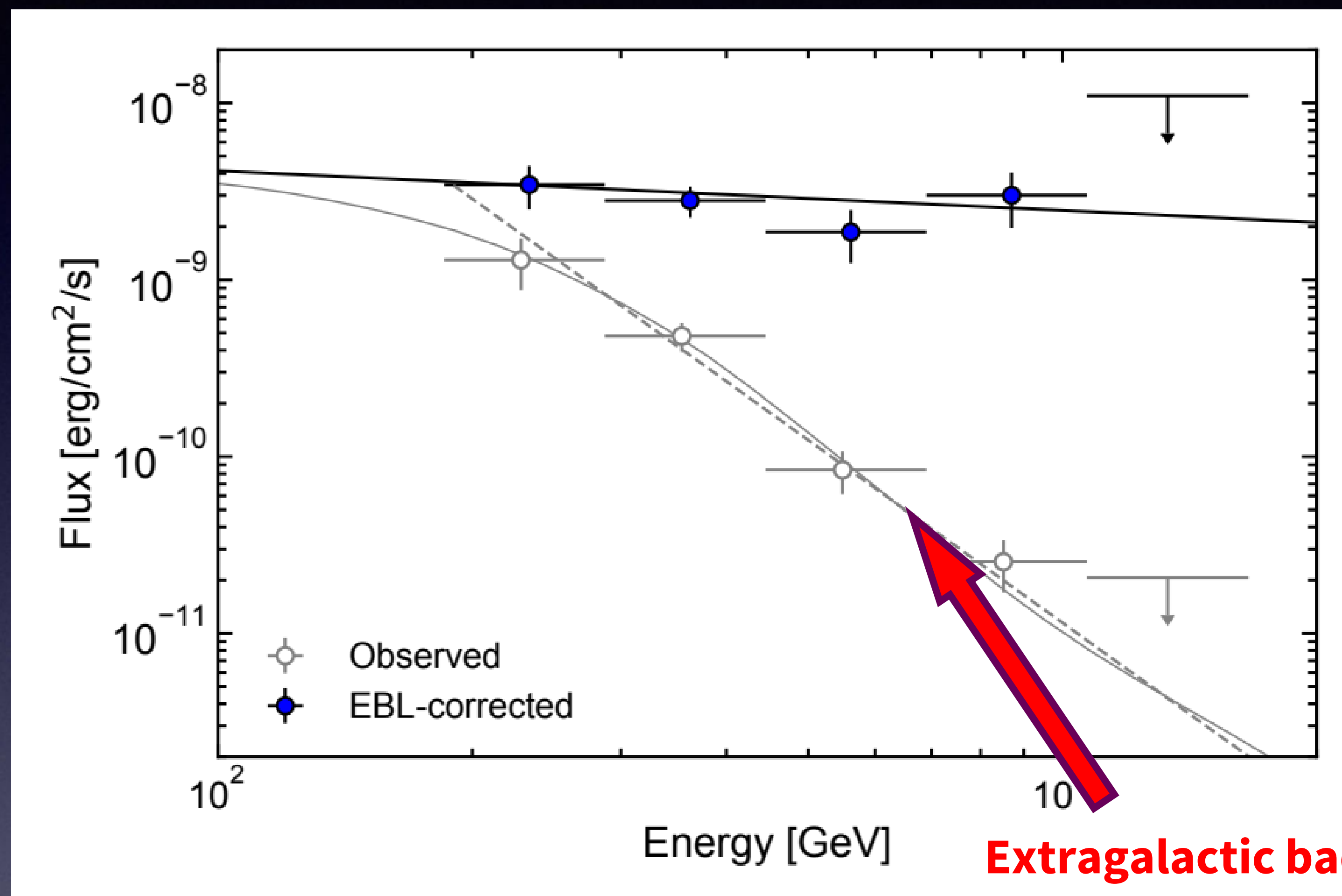


Abstract

Long-duration γ-ray bursts (GRBs) are the most luminous sources of electromagnetic radiation known in the Universe. They arise from outflows of plasma with velocities near the speed of light that are ejected by newly formed neutron stars or black holes (of stellar mass) at cosmological distances[1,2]. Prompt flashes of megaelectronvolt-energy γ-rays are followed by a longer-lasting afterglow emission in a wide range of energies

**In the first 30 seconds of observation,
GRB190114C was the brightest source to date at 0.3 TeV,
with flux about 100 times higher than from the Crab Nebula.**

Highest energy from a GRB
~1 TeV



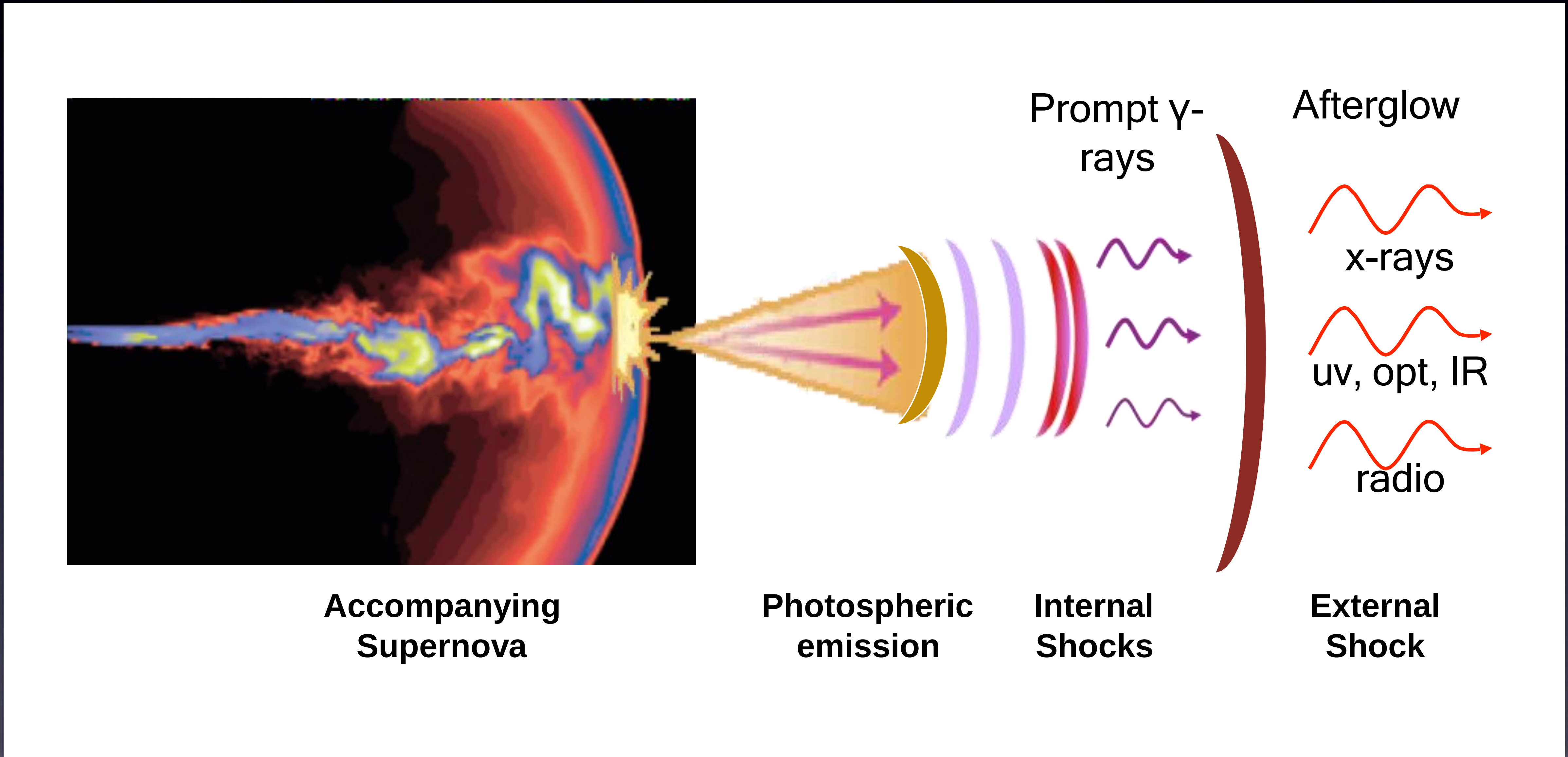
The spectrum from T0+68s – T0+2454s shows a roughly equal distribution of the power in the 0.2-1TeV band, without break or cutoff.
Energy flux emitted @ sub TeV about half of the one emitted in X-ray (between 60-2454s)

Observations

- $Z=0.4245$ (Some TeV absorption)
- $L_{peak}^{Iso} \simeq 1.6 \times 10^{53}$ erg/sec
- $E^{Iso} \simeq 3 \times 10^{53}$ erg
- $E_{TeV} \simeq 350$ GeV (peak below 200 GeV; flat* up to 1 TeV)
- Overlap time TeV (68 s after trigger) and prompt MeV emission (T90=115 s)
- Both prompt and afterglow scenario are possible

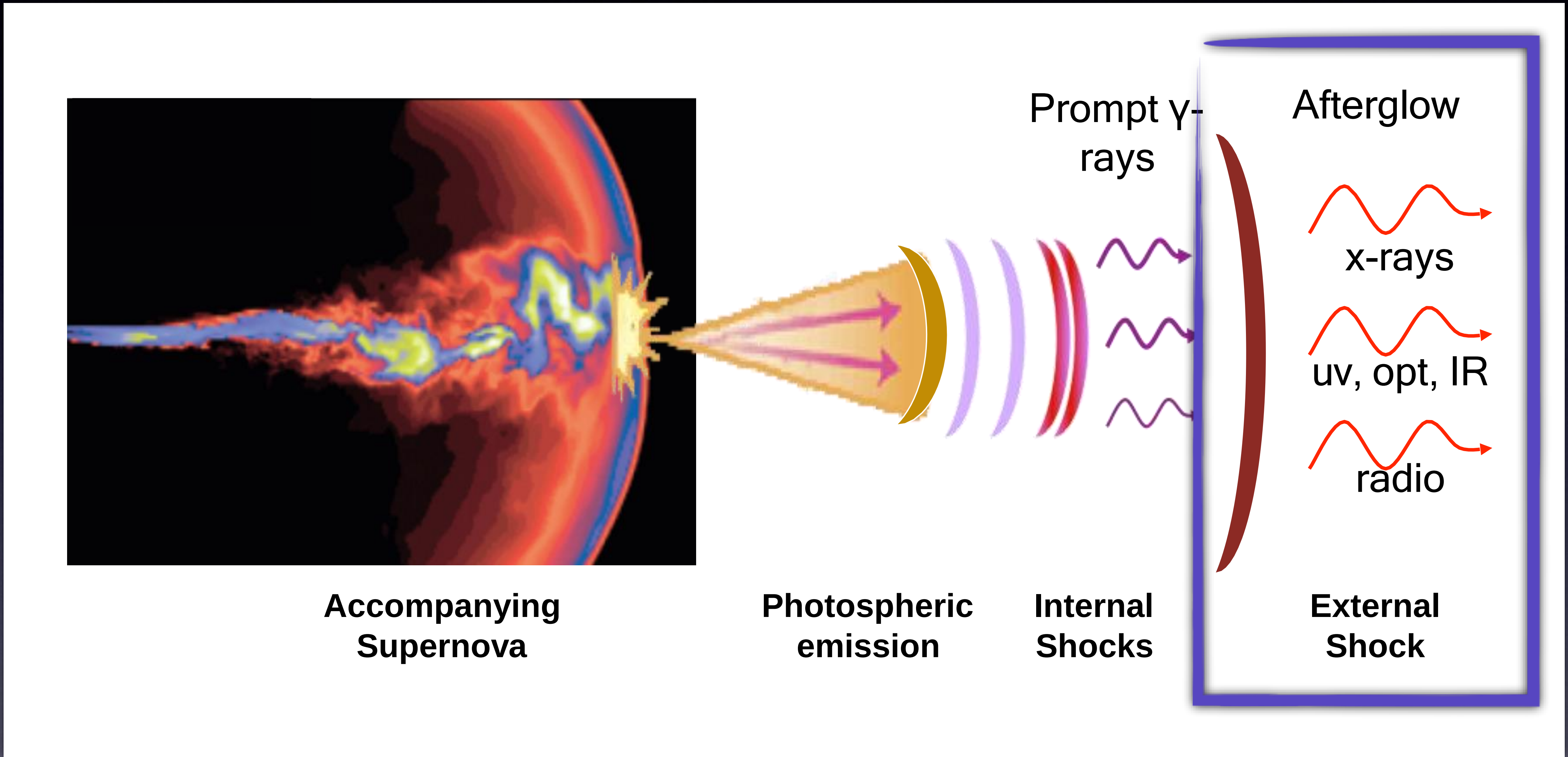
A Gamma-Ray Burst Model

Credit: Tsvi Piran



Numerous attempts to reveal the conditions within the emitting regions of the Afterglow - but usually degeneracy

A Gamma-Ray Burst Model

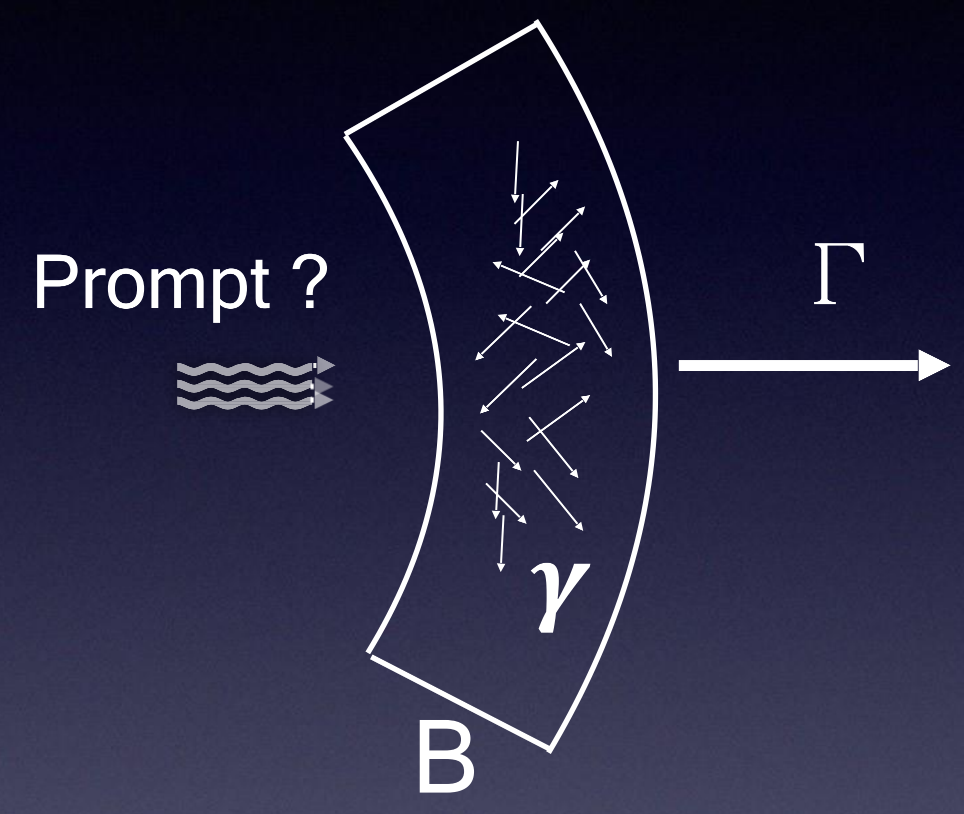


Numerous attempts to reveal the conditions within the emitting regions of the Afterglow - but usually degeneracy

The Model

- Energy dissipation occurs at shocks internally to the jet

- Single Zone scenario



Parameters: Lorentz Factor Γ, variability time t_{var}, **the fraction of the jet energy converted into magnetic energy ε_B, the fraction of the jet energy carried by the electrons ε_e .**

Origin of TeV? Leptonic?

Synchrotron burn-off limit
(Acc. time $\simeq$ cooling time)

- $E_{burn\text{-}off} = \Gamma m_e c^2 / \boldsymbol{\alpha} \simeq \Gamma 100$ MeV <u>too low</u>

  The energies detected by MAGIC are much above

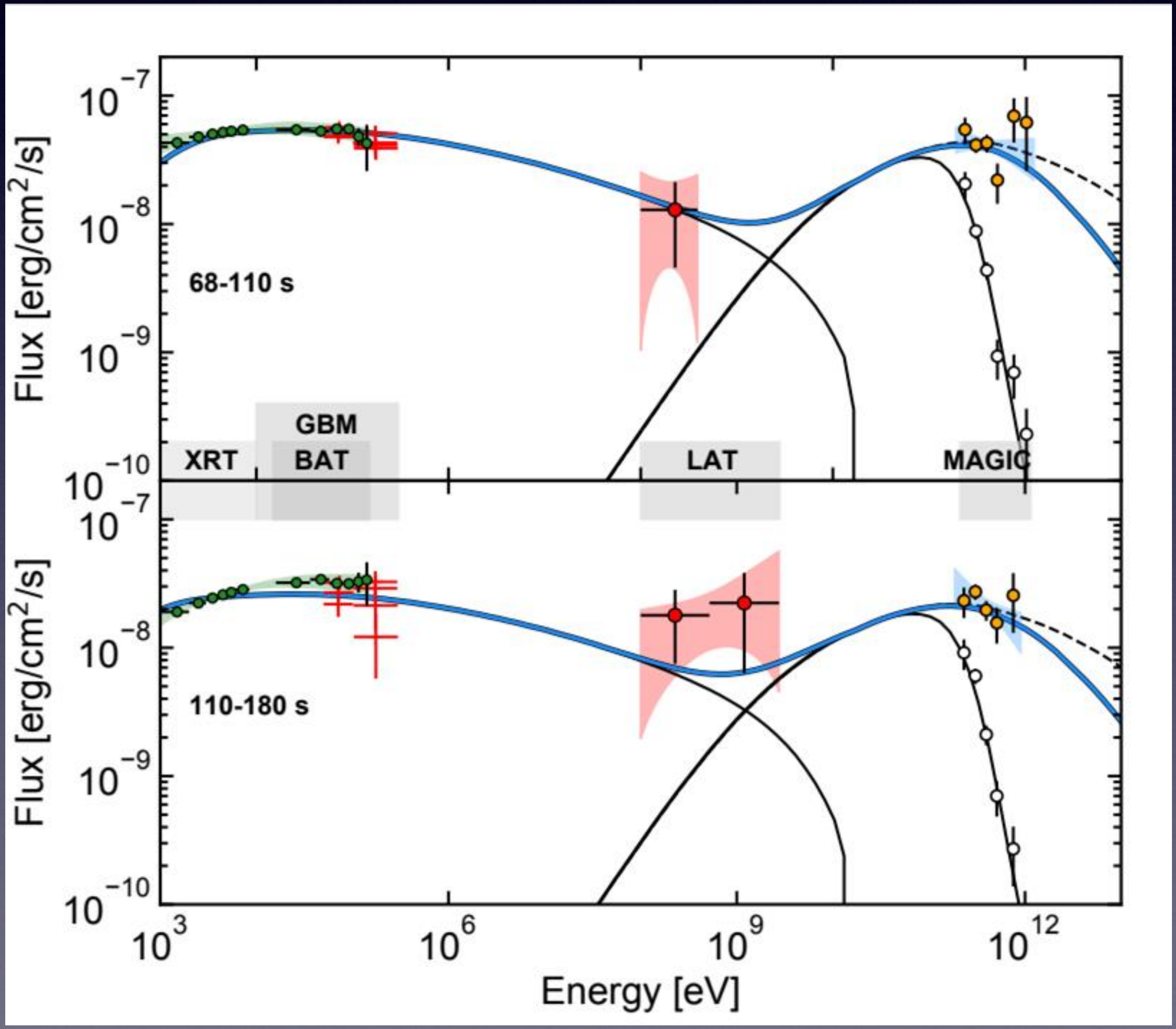
  the synchrotron burn off limit .

- Bypass burn-off limit: acceleration in a weak field and emission in a strong one (e.g. Kumar & Barniol-Duran 09) or "converter" acceleration.

- => Inverse Compton

Synchrotron Self-Compton

The extra component is generated by the synchrotron photons Compton up-scattered by the same electrons accelerated in the shocks.
To model the MAGIC data other 2 processes need to be considered: Klein-Nishina Effect (suppression of the highest energy photons) and photo-absorption (γ-γ absorption).



SSC also suggested in Derishev & Piran (2019), Wang et al. (2019), Fraija et al. (2019), Zhang et al. (2019)

Synchrotron Self-Compton: SSC

1. The model optimised for the very high energy data slightly over-predicts the optical and radio components.

2. While a model optimised for the low energies fails to predict the VHE data.

3. It may explain the TeV emission for the GRB parameters

Synchrotron Self-Compton: SSC

From the modelling the values of few physical parameters that describe the outflow can be derived.

- Isotropic energy in synchrotron component (68-110s): 1.5×10^{52} erg
- Isotropic energy in SSC component (68-110s): 6.0×10^{51} erg

→ Important fraction of energy in SSC, **missed up to now**

→ **no equipartition values!**

- Magnetic field at the shocks (t=100s) B= 0.5 -5 G

→ **Large amplification from the few μG of the stellar medium**

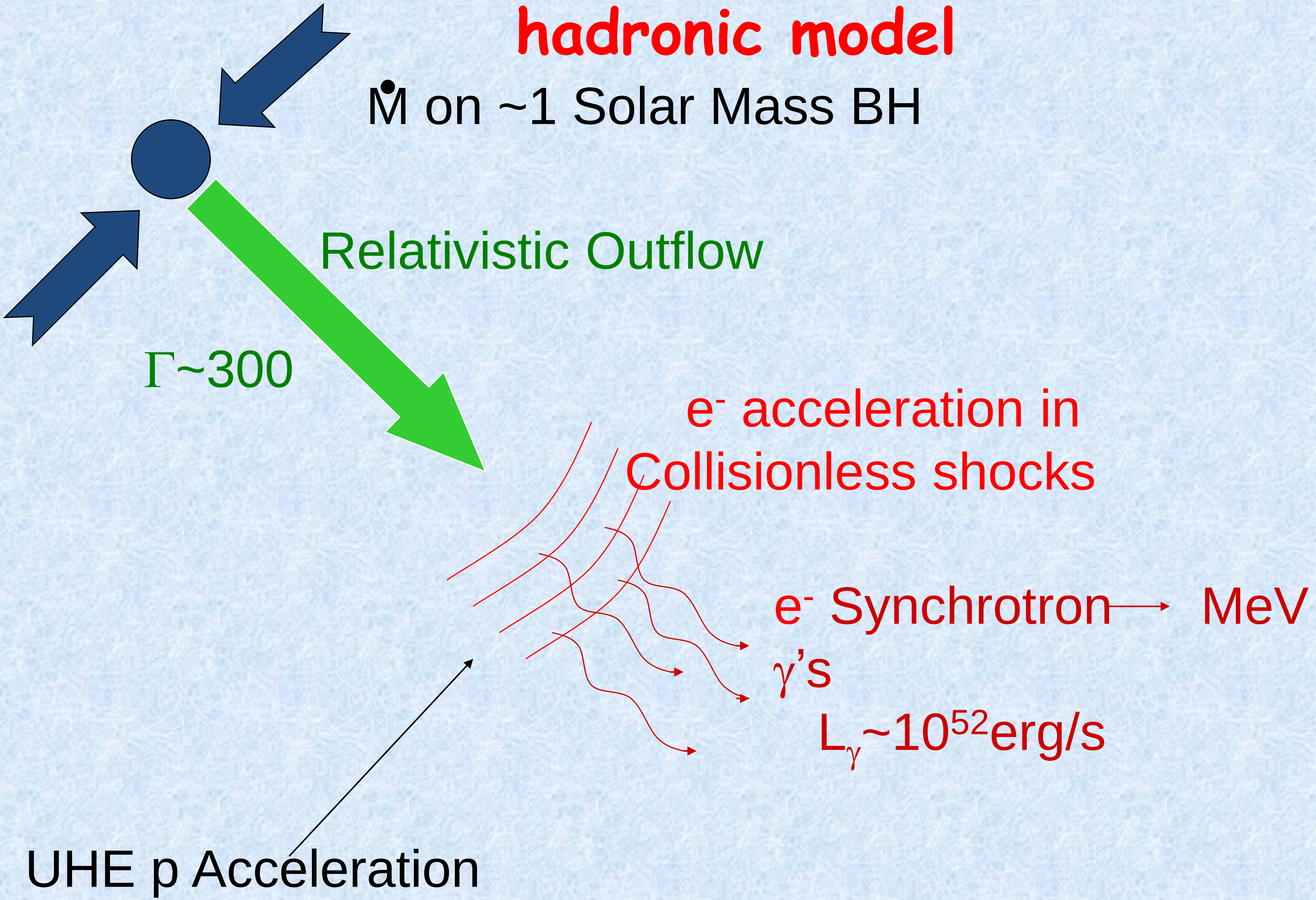
- Initial bulk Lorentz factor: $\Gamma_0 \sim 500$ (dependent on the medium density)

→ **Typical value for GRB**

- Isotropic kinetic energy of the blast wave: $E_k = 3 \times 10^{53}$ erg

→ **Typical value for GRB**

Gamma-ray Bursts as particle accelerators hadronic model



[Meszaros, ARA&A 02;
Waxman, Lecture Notes in Physics 598 (2003).]
]

Hadronic model for the TeV emission

Gagliardini, Celli, Guetta Zegarelli, Capone, Campion, DiPalma

Submitted to PRL, astro-ph/2209.01940

Head-on collision of MeV-photon and PeV-proton through photo-meson interaction in the internal shocks

- $p + \gamma \rightarrow \Delta^{+} \rightarrow \begin{cases} n + \pi^{+} & 1/3 \\ p + \pi^{0} & 2/3 \end{cases}$

$$\pi^{+} \rightarrow e^{+} + \nu_e + \nu_\mu + \bar{\nu}_\mu$$

$$\pi^{0} \rightarrow \gamma + \gamma$$

- Model parameters

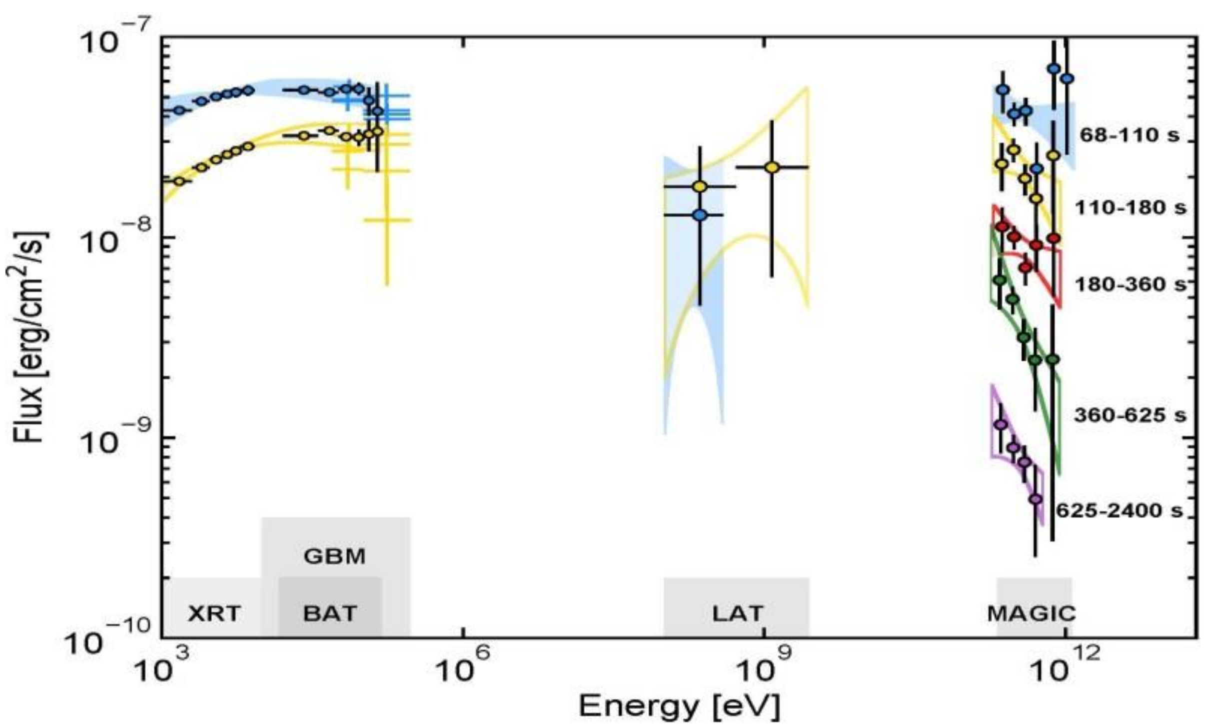
  - t_v - variability time
  - f_p - fraction of energy in protons
  - Γ - bulk Lorentz Factor

The fraction of the jet energy converted into magnetic energy $\varepsilon_{B=0.1}$, the fraction of the jet energy carried by the electrons $\varepsilon_{e=0.1}$ EQUIPARTITION!!

Montecarlo simulation

1. We have considered the photo-meson interaction and the spectra of secondary particles emerging from these interactions
2. we additionally simulated the electromagnetic absorption that gamma rays undergo in the IS shell.
3. The spectrum of escaping photons thus obtained has been compared to the intrinsic source spectrum derived by deconvolving MAGIC observations of GRB 190114C in the EBL
4. We get the best fit parameters of the model by comparing the predictions with the observations

MAGIC OBSERVATION



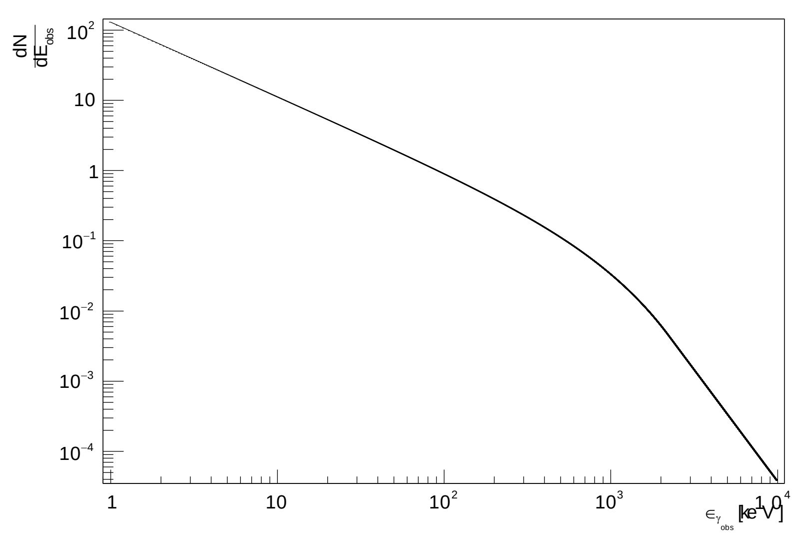
MAGIC observations in different time intervals [V. A. Acciari et al.]. Assuming that the high energy photons production can be attributed to the *prompt phase* of GRB, characterized by the parameter $T_{90} = 116s$, we decided to compare our simulated data with the first interval 68-110 s due to the overlap with the T_{90}.

MONTE CARLO SIMULATION astro-ph/2209.01940

Photo-meson interaction between:

- Accelerated proton ($\frac{dN_p}{dE_p} \propto E^{-2}$)
- Target photon, Band Function

$$p + \gamma_{target} \longrightarrow \Delta^{+} \longrightarrow \begin{cases} \mathbf{p} + \pi^0 \\ n + \pi^+ \end{cases}$$



$\alpha = -1.058$, $\beta = 3.18$,

$E_{peak} = 998.6$ keV in (0 -38.15) s

[*Fermi*-GBM Collab. (2019)]

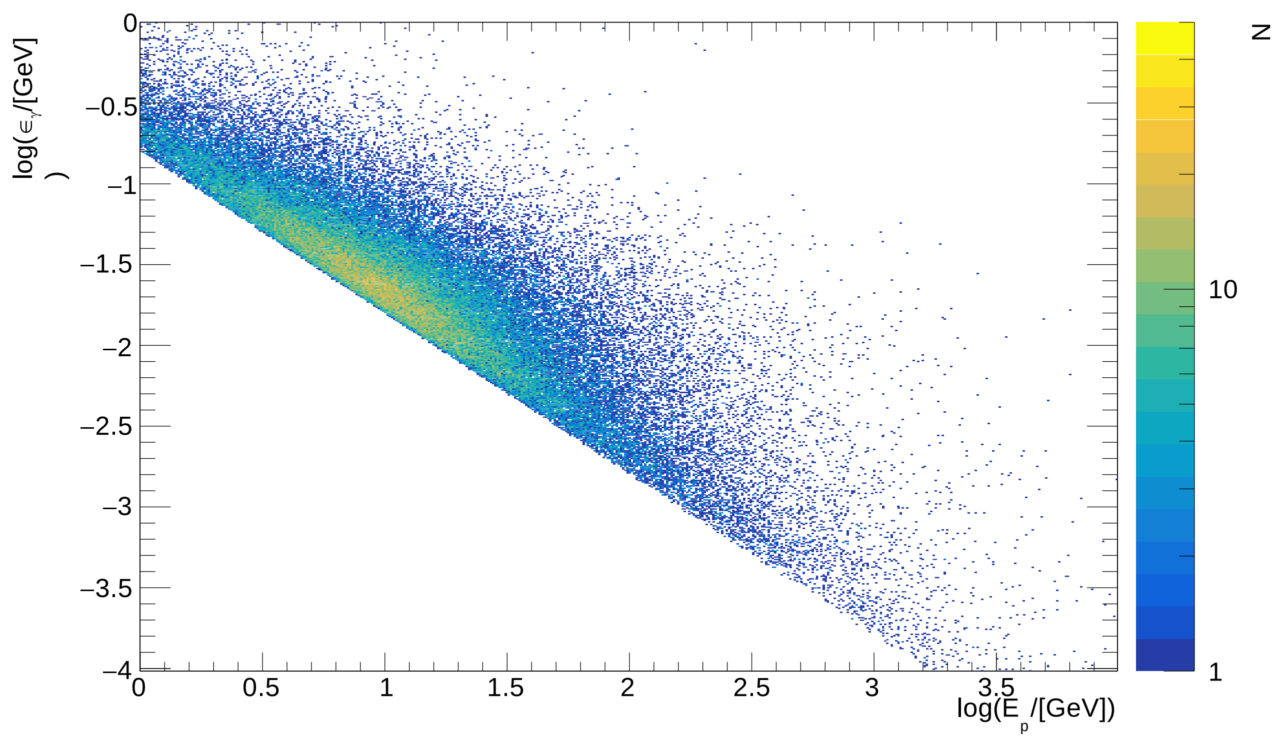


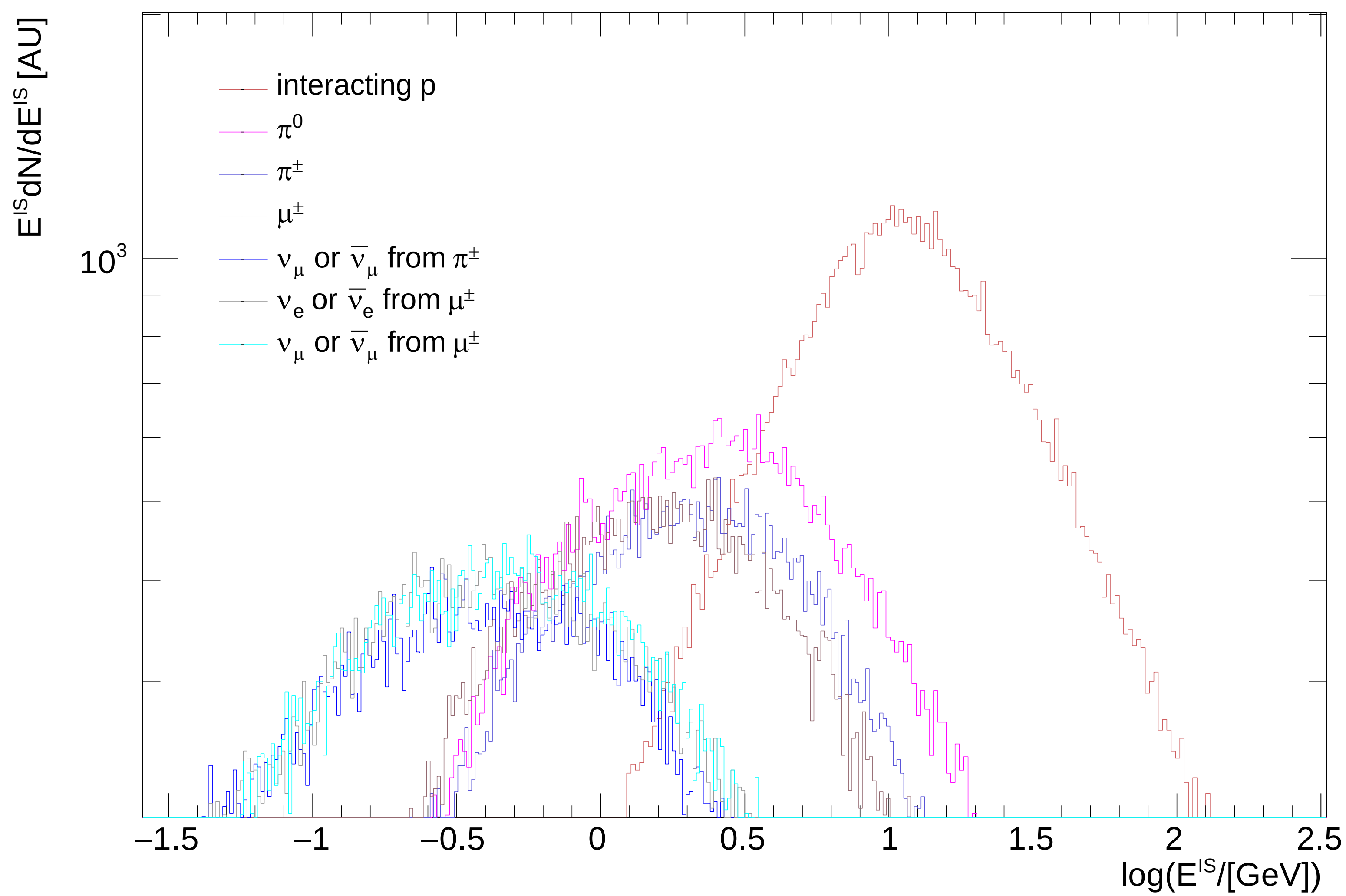
Figure: Distribution of simulated events exceeding the photo-meson threshold in the IS frame ($\Gamma = 100$ and $t_{\rm var} = 1$

MONTE CARLO SIMULATION: Setting parameters

We decided to consider **variability time** t_{var} and **Lorentz factor** Γ as a **free parameter**.The MC simulation has been run for different set of parameters, $t_{var} = 1, 3, 6$ ms, and Γ in the range 60-120 with a $\Delta\Gamma = 20$ for each t_{var} value.

- $T_{90} = 116$ s (50-300 keV)
- $F_{\gamma} = 3.99 \times 10^{-4}$ erg cm^{-2} (10-1000 keV)
- $E_{\rm iso} \simeq 3 \times 10^{53}$ erg
- $\alpha = -1.058$
- $\beta = -3.18$
- $E_peak = 998.6$

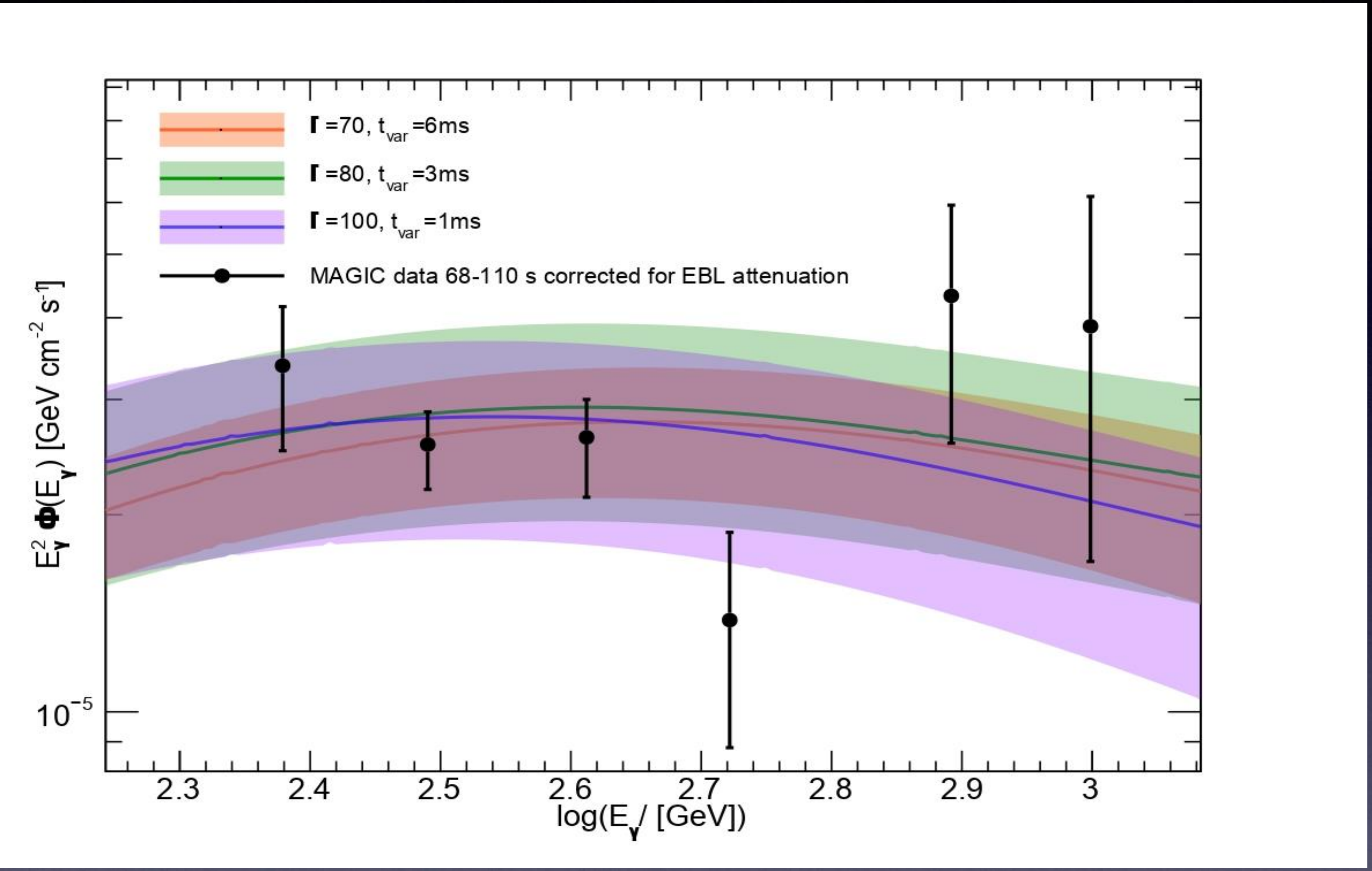
IS PARTICLES



$E^{IS}\frac{dN}{dE^{IS}}$ vs $log(E^{IS})$ of the simulated particles in the Internal Shock frame.
As known from
[E. Waxman and Bahcall]:

- E_π ' $\frac{1}{5}E_p$
- E_ν ' $\frac{1}{4}E_{\pi^\pm}$
- E_ν ' $\frac{1}{20}E_p$

Results: Photon spectrum



Comparison between the MAGIC EBL-deconvolved SED in the temporal interval 68-110 s , and the simulated photon SEDs arising from the π^0-decay, after accounting for internal gamma-ray absorption, for different parameter values, as indicated in the legend. **f_p ~ 0.9-1**

Neutrino flux from GRB 190114C

A direct proof of the hadronic origin of the observed TeV radiation might come from coincident neutrino observations.

$$\gamma + p \rightarrow n + \pi^{+} ; \quad \pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_{e} + \nu_{\mu} + \bar{\nu}_{\mu}$$

Both the ANTARES and IceCube Collaborations have searched for coincident neutrino-induced signals from the direction of GRB 190114C. No events were observed in extended time windows, covering both the prompt and the afterglow phase of the GRB, leading to upper limits on the expected neutrino fluence.

ANTARES: the 90% confidence level integrated limit 1.6 GeV/cm2

IceCube: the 90% confidence level integrated limit 0.44 GeV/cm2

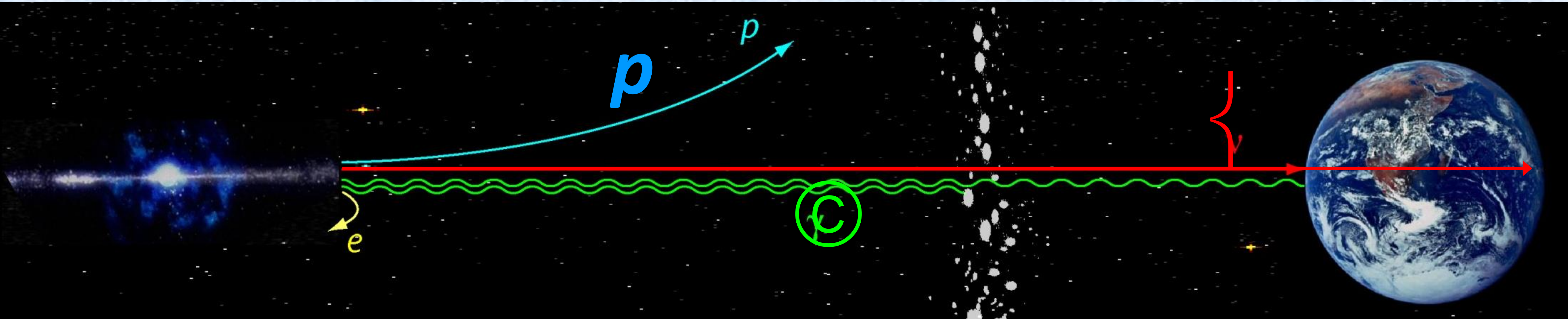
Cosmic neutrinos?

Why look for them?

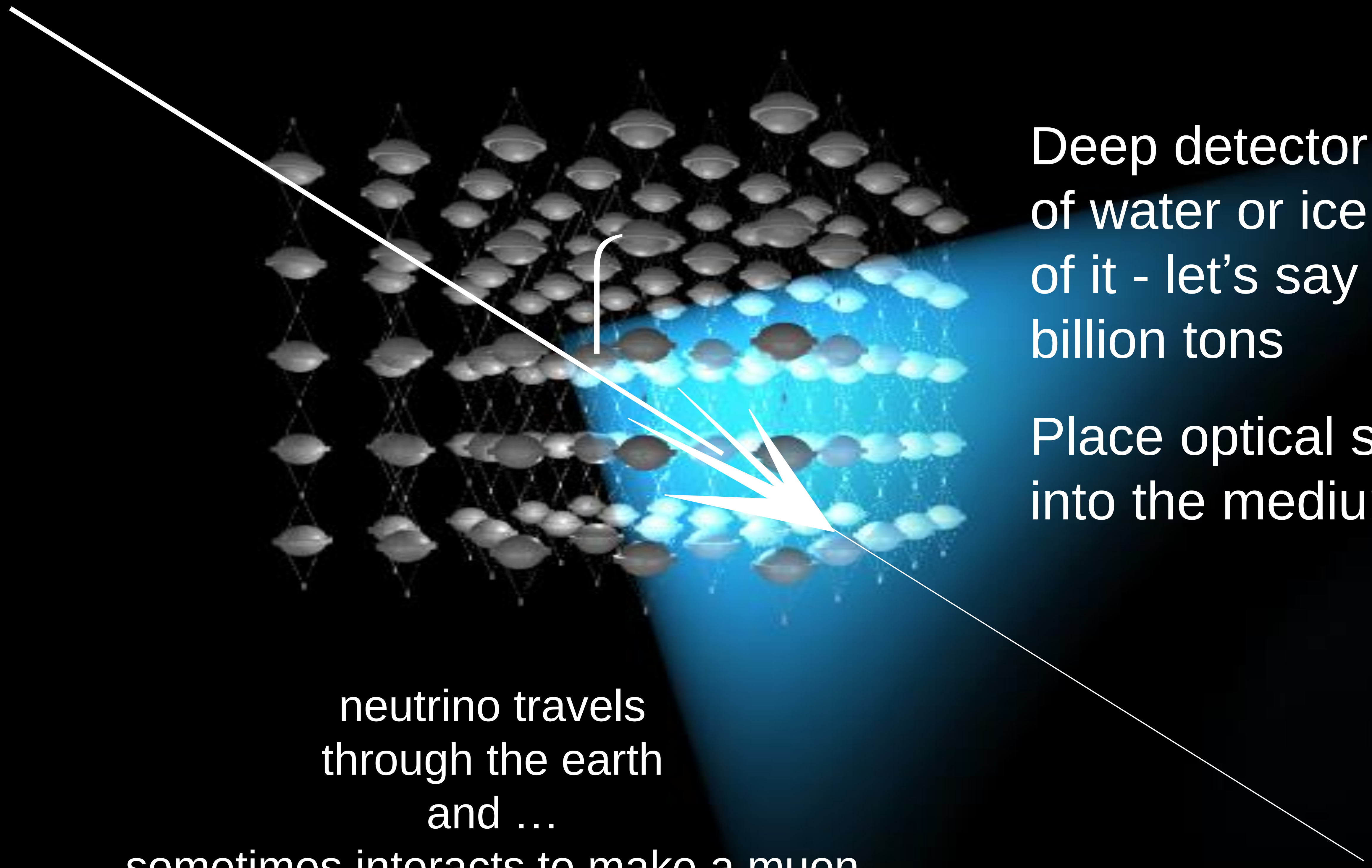
- They could tell us about the origin of high energy cosmic rays, which we know exist.
  - There are numerous ways how neutrinos can tell us about fundamental questions in nature: dark matter, supernova explosions,
  - Composition of astrophysical jets, physics of the source core

Can they reach us?

- High energy neutrinos will pass easily and undeflected through the Universe
  - That is **not** the case for other high energy particles: such as photons or other cosmic rays, eg protons.



How to catch them?
Detection principle

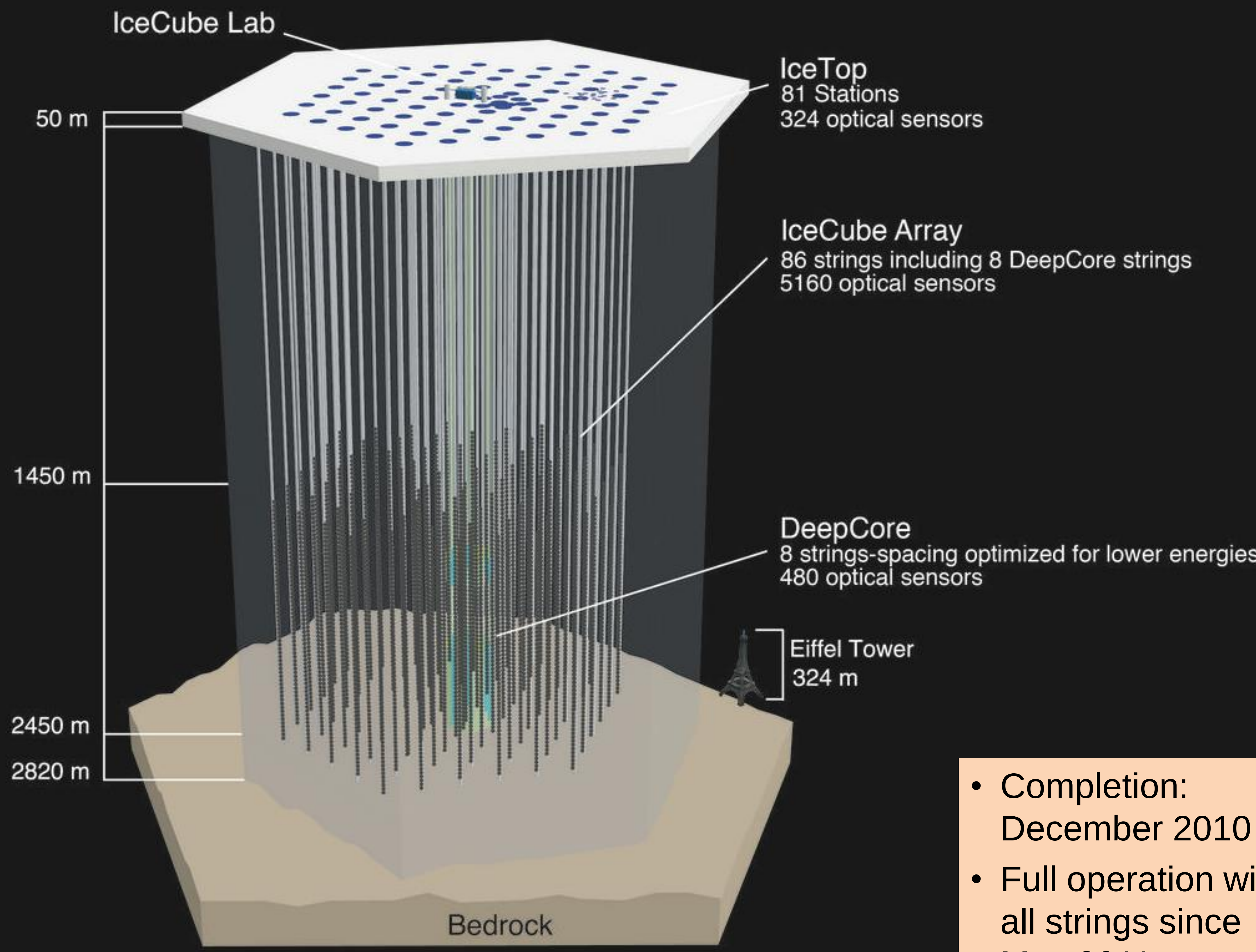


Deep detector made of water or ice – lots of it - let's say 1 billion tons

Place optical sensors into the medium

neutrino travels
through the earth
and …
sometimes interacts to make a muon
that travels through the detector

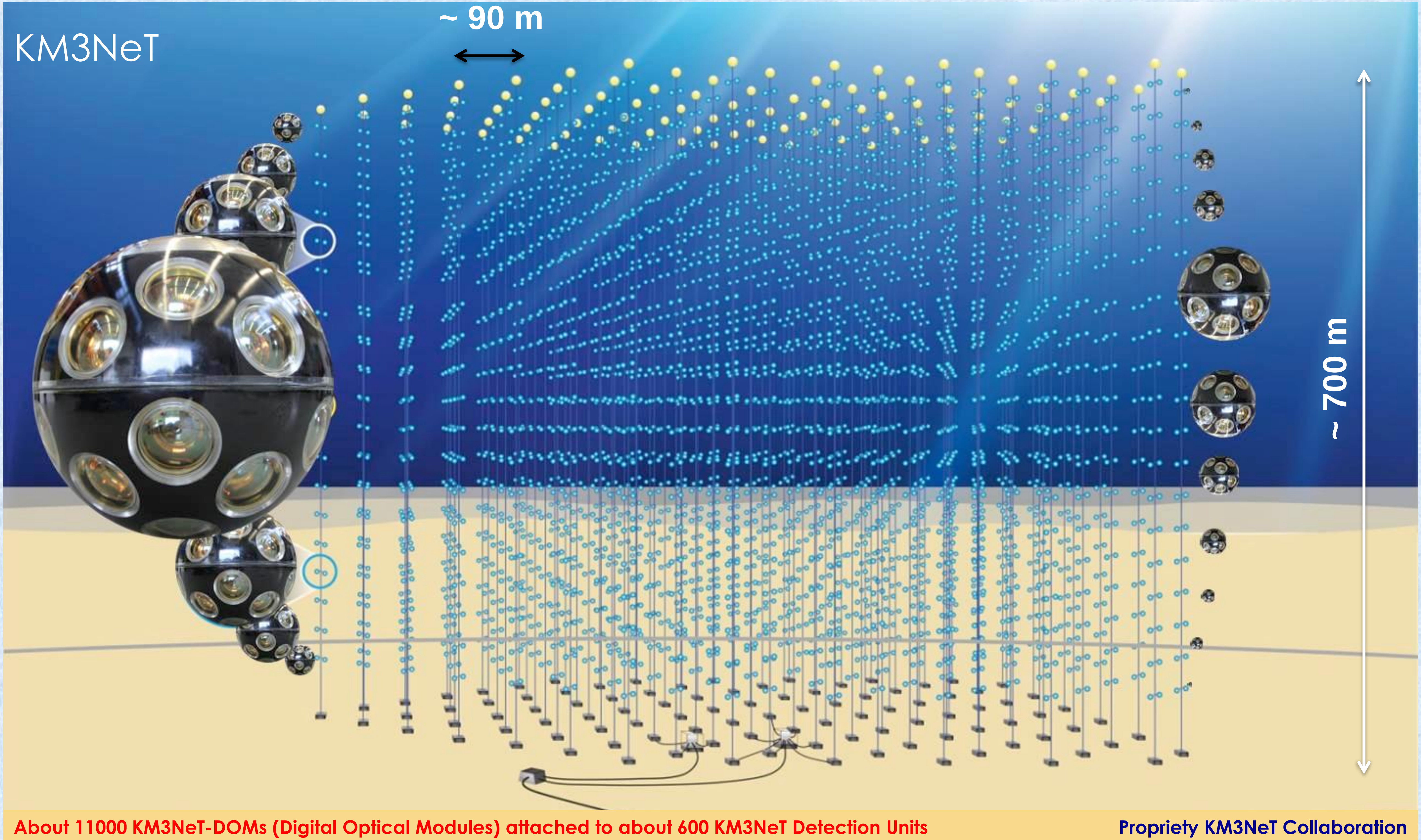
IceCube



- Completion: December 2010
- Full operation with all strings since May 2011.

The KM3NeT Detector

TDR : ISBN 978-90-6488-033-9 (2010)



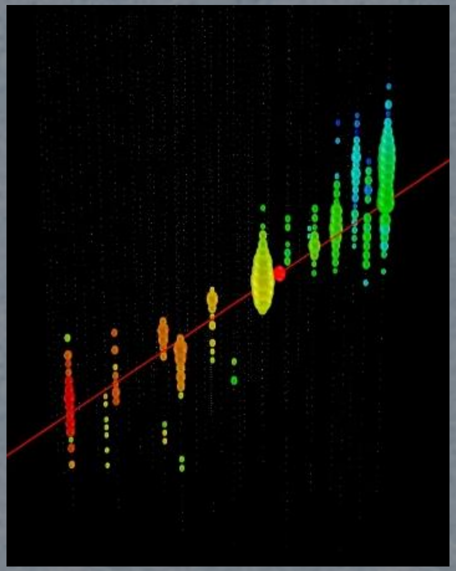
18 optical modules per detection unit
First optical module above seabed ~ 100m

Distance between optical modules ~ 36 m

Neutrino Event Signatures

time

CC Muon Neutrino

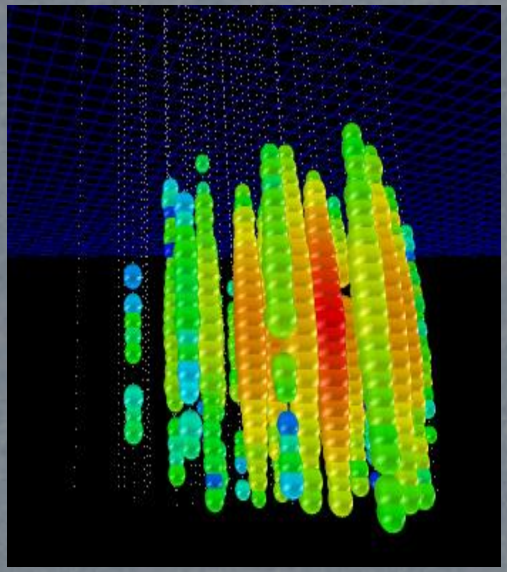


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 0.5° angular resolution

Neutral Current /Electron Neutrino



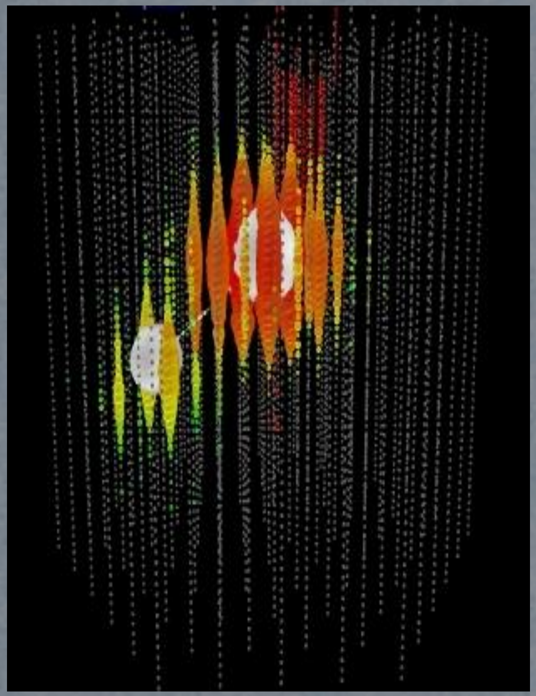
$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies $\gtrapprox$ 100 TeV)

CC Tau Neutrino

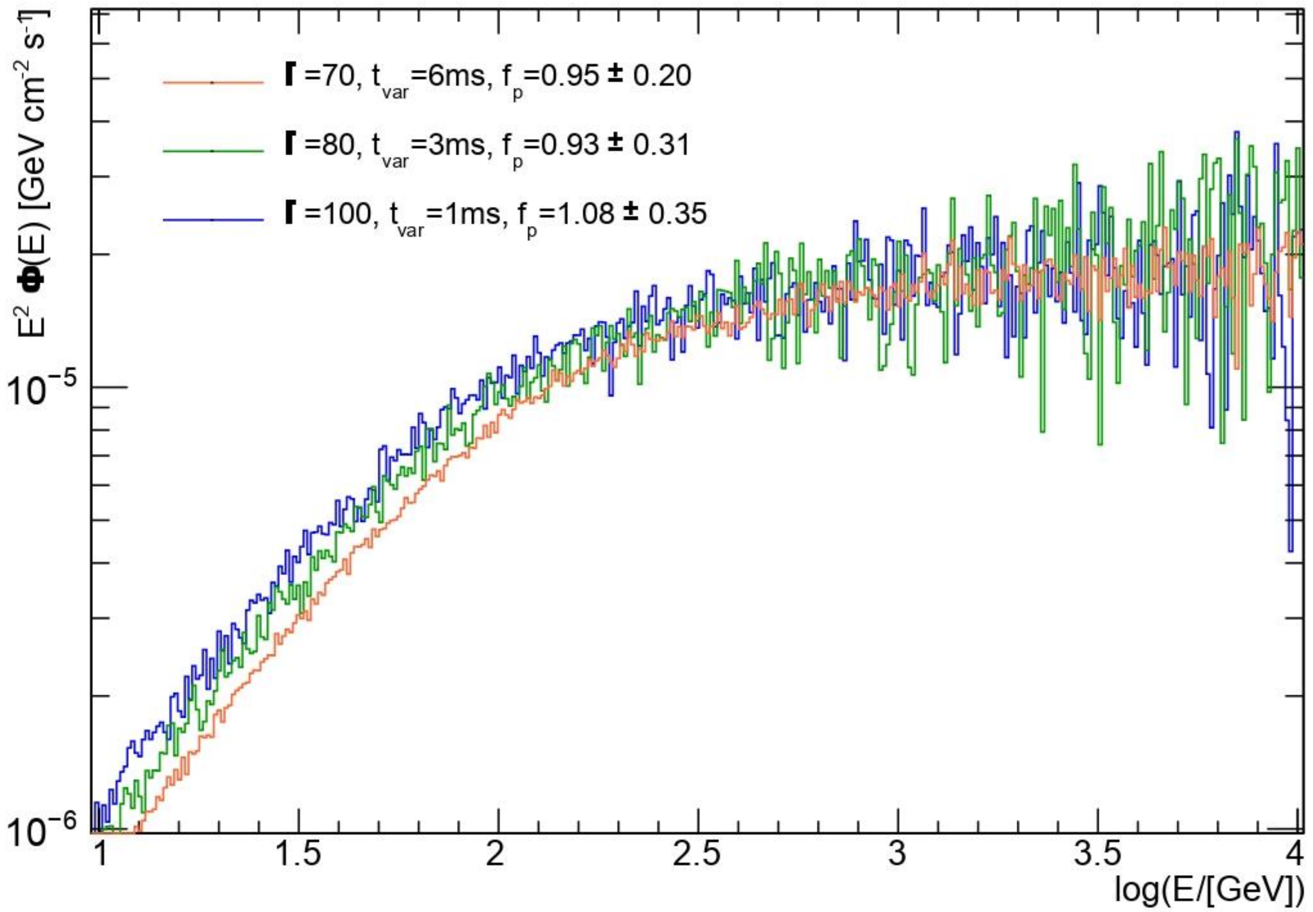


$$\nu_\tau + N \rightarrow \tau + X$$

“double-bang” and other signatures (simulation)

(not observed yet)

EXPECTED NEUTRINO EVENTS



Detector	Declination band	$N_{\rm events}$
ANTARES	$-45^o < \delta < 0^o$	1×10^{-3}
IceCube	$-30^o < \delta < 0^o$	2×10^{-2}
KM3NeT/ARCA	Mean	1×10^{-1}

Expected signal events induced by muon neutrino interactions during GRB 190114C, within different telescopes. The computations refer to instrument effective areas for the source declination (ANTARES [ANTARES Collab. (2012)], IceCube [IceCube Collab. (2014)], and KM3NeT [KM3NeT Collab. (2016)]).

Expected number of events from GRB 190114C

$$N_\nu = \int A_{eff}(E_\nu, \delta)(dN_\nu/dE_\nu)\, dE_\nu$$

Detector	Declination band	Nevents
ANTARES	$-45^{o} < \delta < 0^{o}$	1 × 10−3
IceCube	$-30^{o} < \delta < 0^{o}$	2 × 10−2
KM3NeT/ARCA	Mean	1 × 10−1

Conclusions leptonic model

- Basic parameters 👍
  👍

Conclusions leptonic model

- Basic parameters 👍
- Physical model
  Afterglow SSC with comparable values of Γ and **γ** 👍

Conclusions leptonic model SSC

- Basic parameters 👍
- Physical model
  Afterglow SSC with comparable values of Γ and **γ** 👍

But

- Slow cooling 👎
- $\varepsilon_B \ll \varepsilon_e$ 👎

Conclusions hadronic model

1. Confirmation of the hadronic origin of sub-TeV radiation might in principle
   arise from neutrino observations.

2. In the context of the parameters that better reproduce MAGIC data, however
   such a detection from GRB 190114C appears extremely unrealistic, as confirmed by the lack of spatial correlations in data from both the ANTARES abd IceCube neutrino telescopes

3. Hope for the future Km3Net and IceCube-Gen2 telescopes

Conclusions

1. Both leptonic and hadronic interpretations of the TeV data cannot be excluded

2. Extended studies about the entire sample of observed TeV GRBs are required to understand the physical mechanisms responsible for the TeV emission.

3. It is crucial to have a better characterization of the very-high-energy photon spectrum in the early stages of the GRB emission, which seems to be currently limited by the prompt response of imaging atmospheric Cherenkov telescopes in pointing.