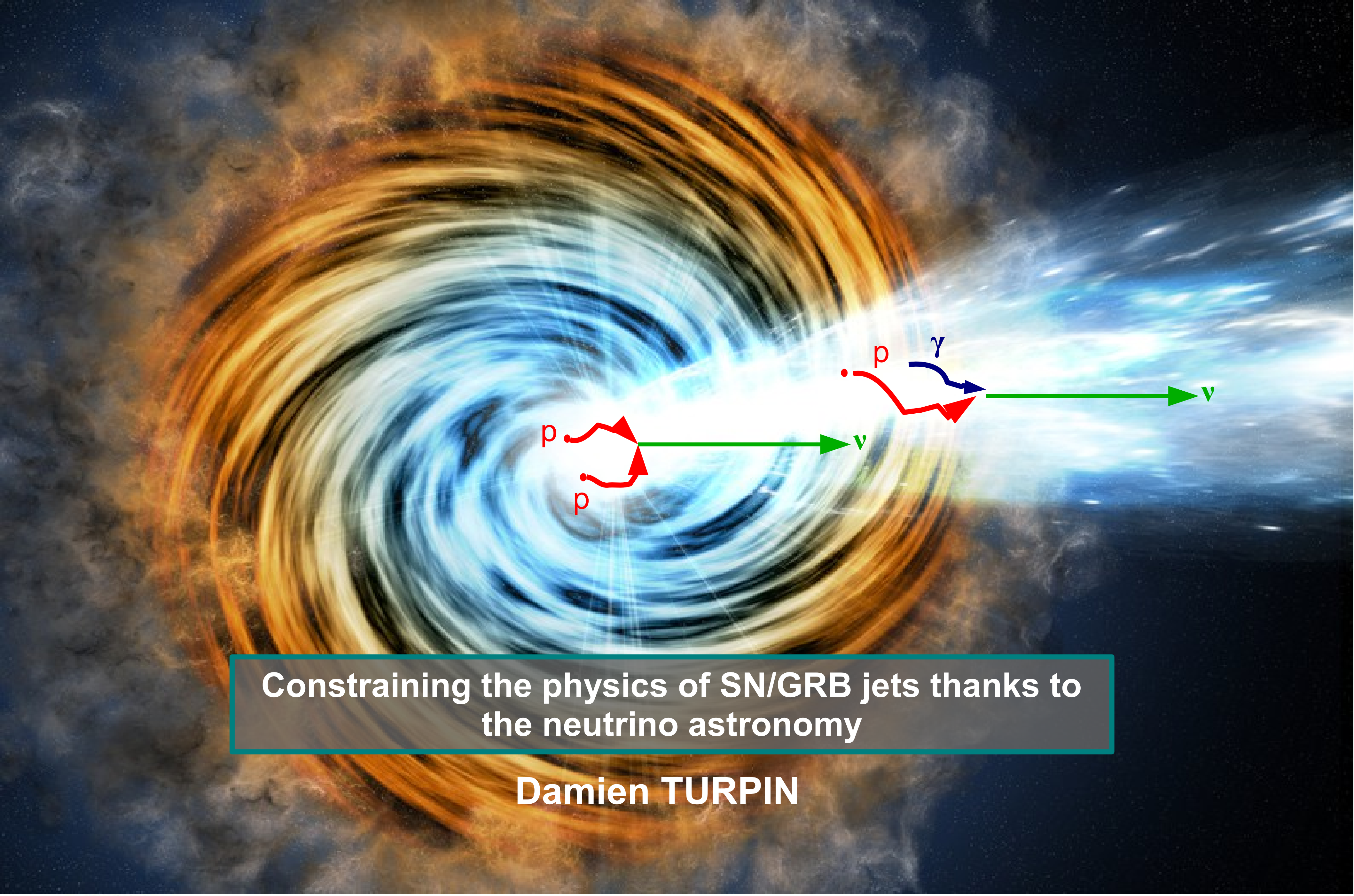


Constraining the physics of SN/GRB jets thanks to the neutrino astronomy

Damien TURPIN

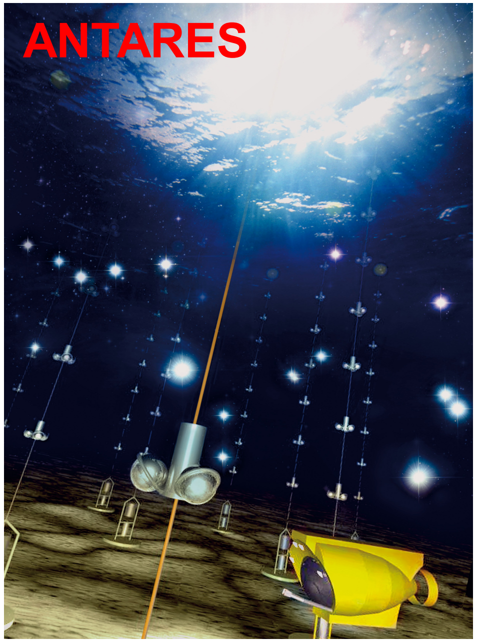
OCEVU
Origines, Constituants et EVolution de l'Univers

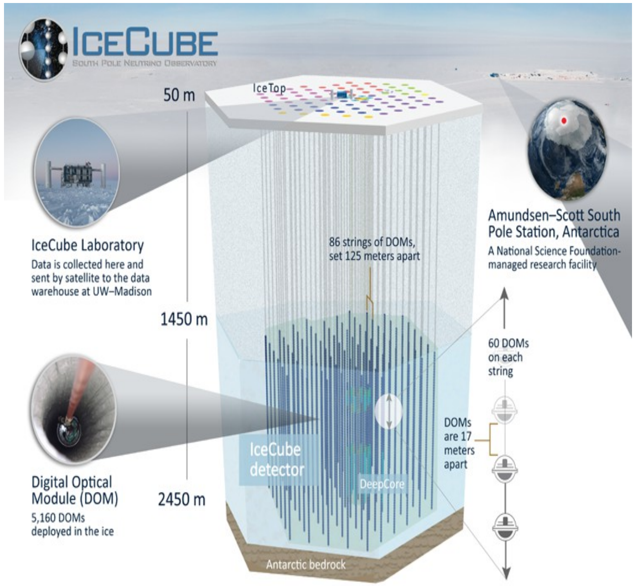
OCEVU astroparticle workshop : The physics of relativistic outflow

TOULOUSE 2016, March 22-24

irap
astrophysique & planétologie

HEN astronomy : our motivations





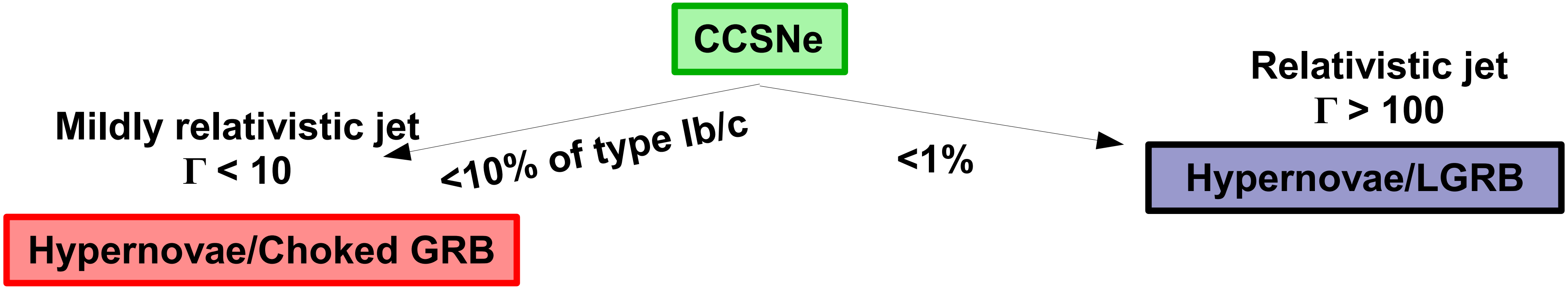
1/ Detection of a high energy neutrino signal from a cosmic accelerator

direct association with UHECR sources

So far no neutrino detection in coincidence with any SN/GRB

2/ Constraints on the hadronic models associated to the most promising astrophysical objects

SN/LGRB connection



CCSNe

Mildly relativistic jet
$\Gamma < 10$

<10% of type Ib/c

Hypernovae/Choked GRB

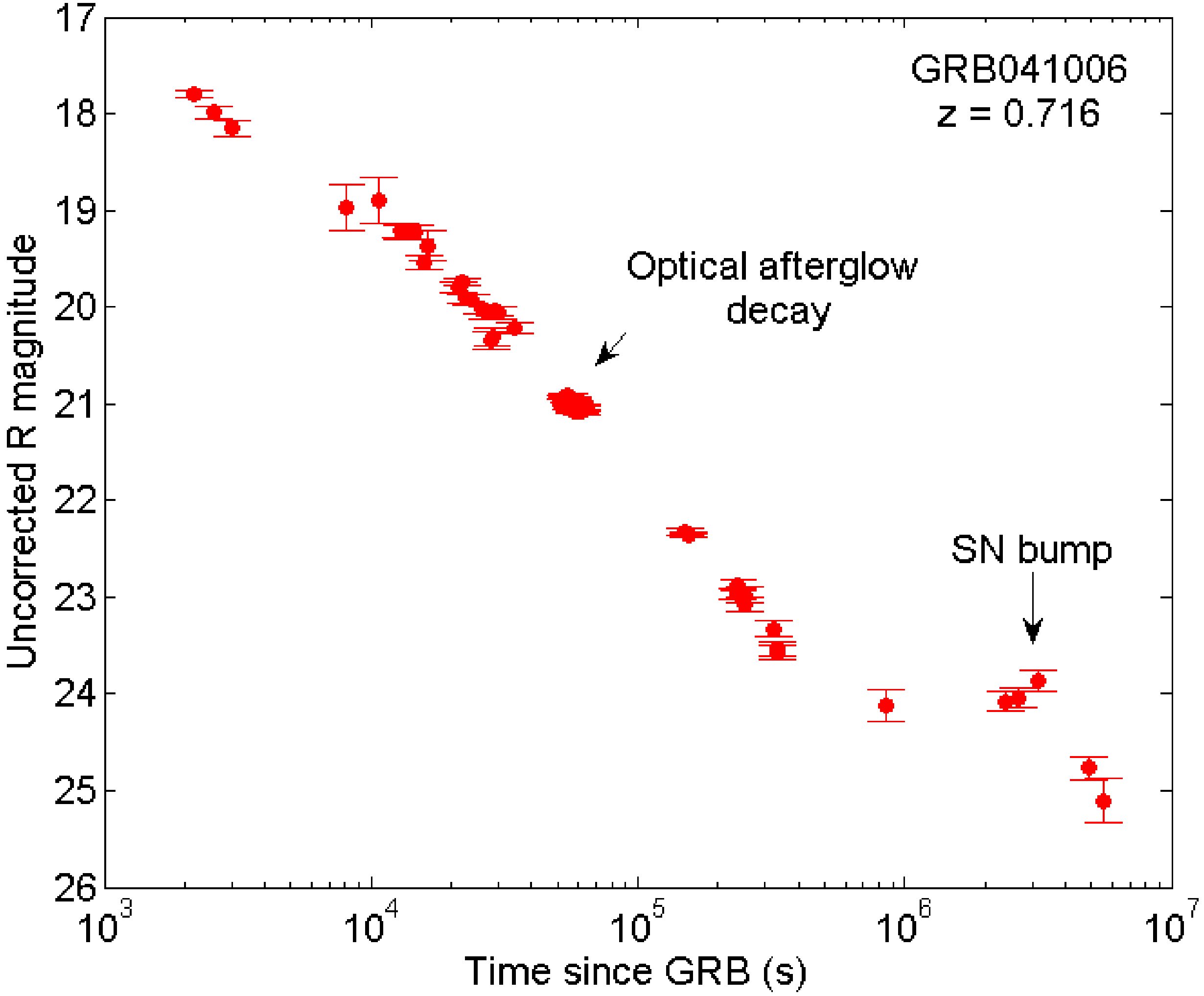
<1%

Relativistic jet
$\Gamma > 100$

Hypernovae/LGRB

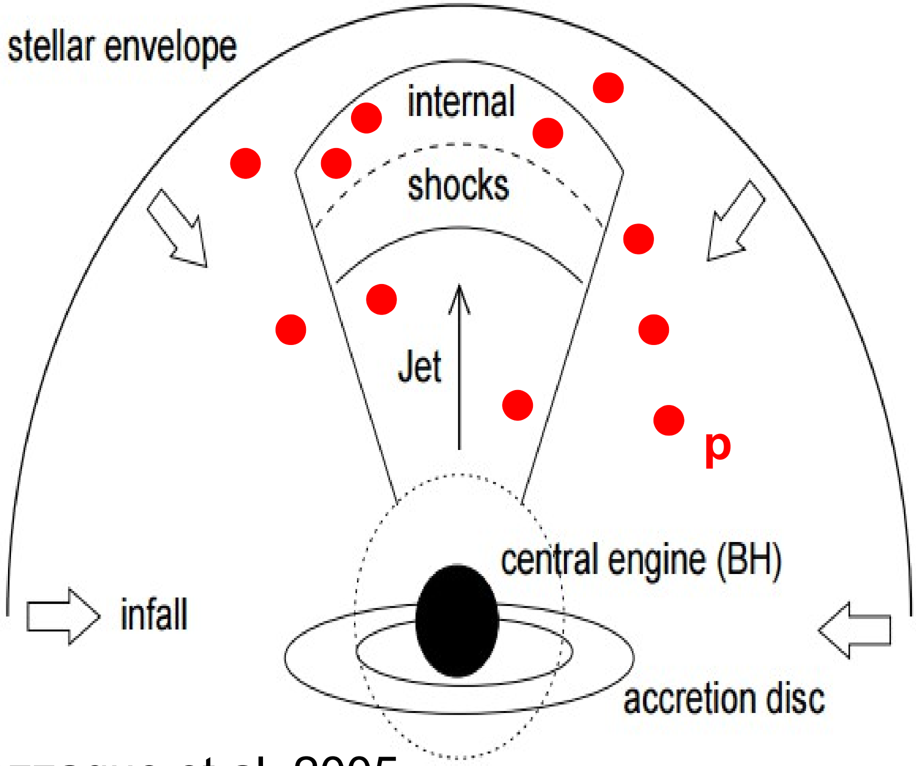
Razzaque et al. 2005
Ando&Beacom 2005

A rising SN LC 25 days after GRB041006



2 different environements

SN/Choked GRB

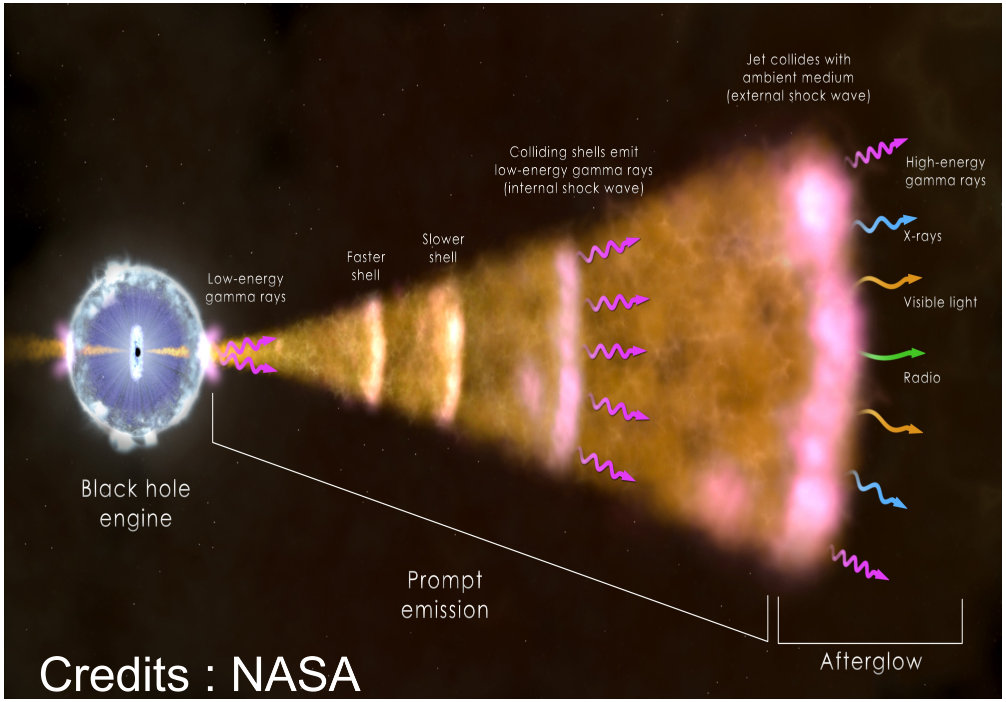


Razzaque et al. 2005

Jet burried in a dense and
baryon-rich medium
« Dirty and heavy jet »

The jet is **optically thick**

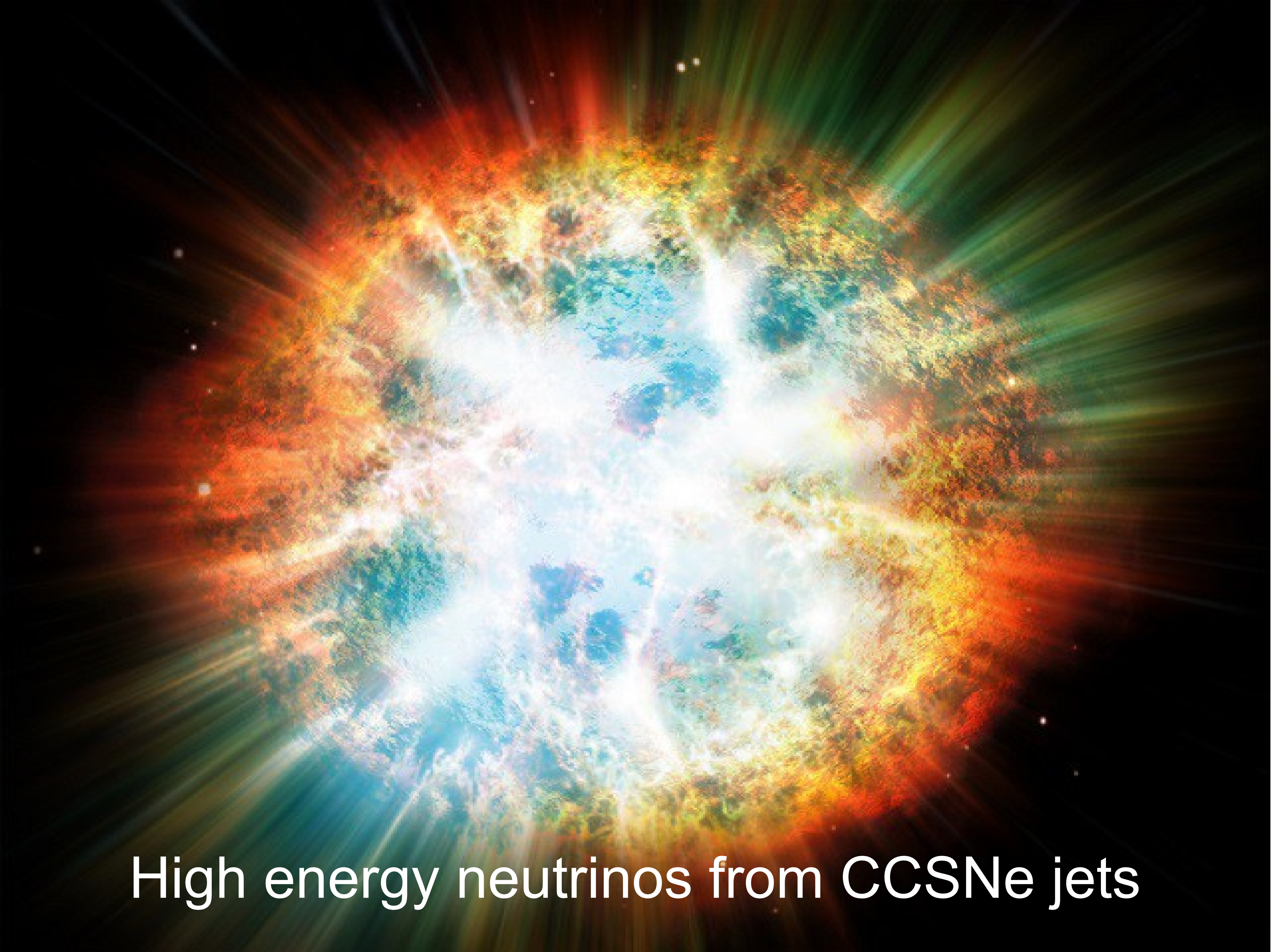
L-GRB



Credits : NASA

Jet expulsed in the **ISM medium** far away from the central engine. The baryon density of the jet is **« low » at high radius**

The jet is **optically thin**



High energy neutrinos from CCSNe jets

Hadronic processes in SN mildly relativistic jets

Ando&Beacom model : arXiv:astro-ph/0502521

pp interaction (baryon rich medium)

100GeV-10TeV regime

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

$$\big\downarrow$$

$\langle x_{p\rightarrow\pi} \rangle$ ~ 20%

$$p + p \rightarrow K^{+/-} \rightarrow \mu^{+/-} + \nu_\mu$$
$$\rightarrow e^{+/-} + \nu_e + \bar{\nu}_\mu$$

HEN spectra for a CCSNe located at 10 Mpc

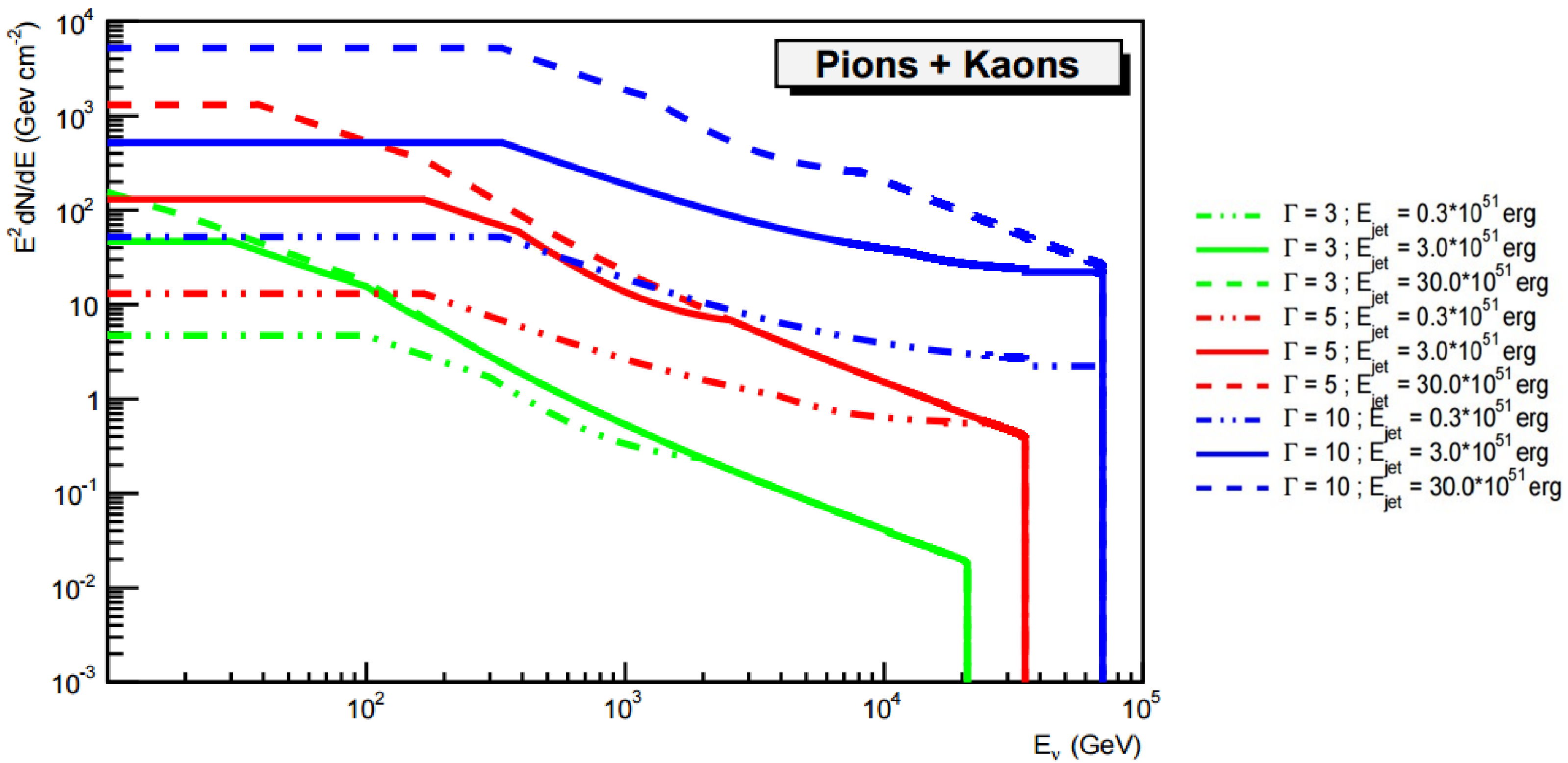
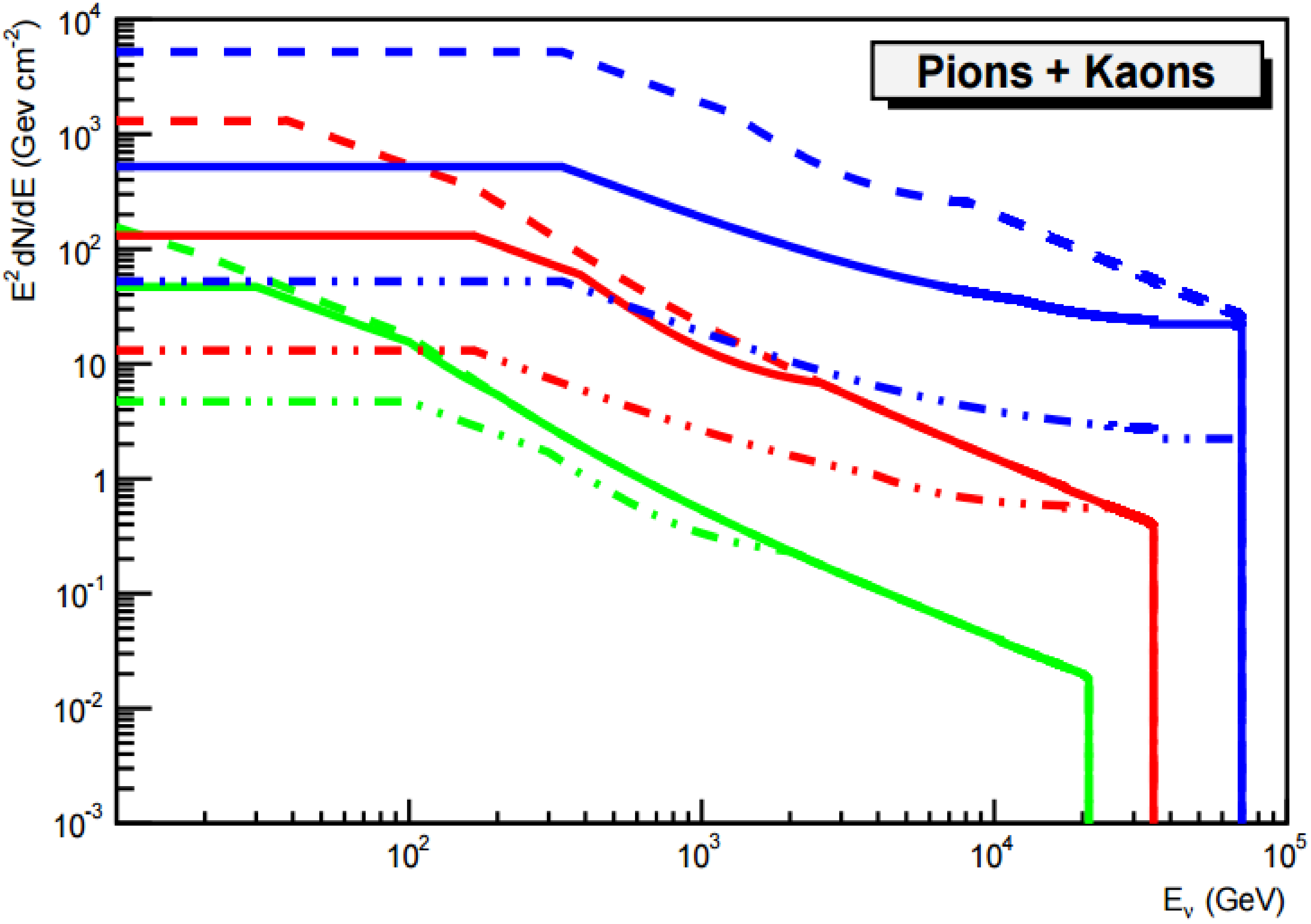


Fig. from A.Mathieu
PhD 2015

The Ando&Beacom model

(A&B2005 : arXiv:astro-ph/0502521)



Normalisation

$$E_{k,0}^{jet} = 3\times 10^{51}\, erg$$

$$\Gamma_0 = 3$$

$$F_\nu \propto \frac{E_k^{jet}}{E_{k,0}^{jet}} \times \left(\frac{\Gamma}{\Gamma_0}\right)^2$$

Energy breaks

$$E_{\nu,1} \propto \left(\frac{E_k^{jet}}{E_{k,0}^{jet}}\right)^{-1} \times \left(\frac{\Gamma}{\Gamma_0}\right)^5$$

$$E_{\nu,2} \propto \frac{\Gamma}{\Gamma_0}$$

$$E_{\nu,3}^{cutoff} \propto \frac{\Gamma}{\Gamma_0}$$

Parameter scan and exclusion limits

Step 1 : We produce a set of neutrino spectra with Γ = [1-10] and E_k^{jet} = [3.10^{49} – 3.10^{53}] erg

Step 2 : For each simulated spectrum we compute the expected number of neutrino detected by the neutrino detector, $\mathbf{N_\nu}$

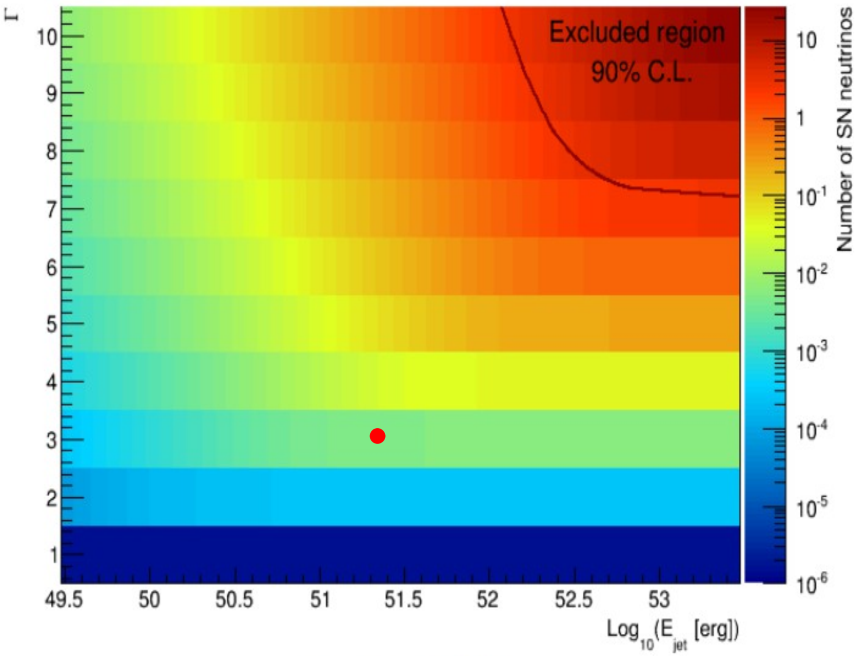
$$N_\nu^{\rm exp}(\Gamma, E_{\rm jet}) = \int_{E_{\nu,\rm min}}^{E_{\nu,\rm max}} \left(\frac{dN}{dE_\nu}\right)_{\rm AB05} \times A_{\rm eff}(E_\nu) dE_\nu$$

Neutrino $\mathbf{F_\nu}$ spectrum

Effective area of the neutrino detector

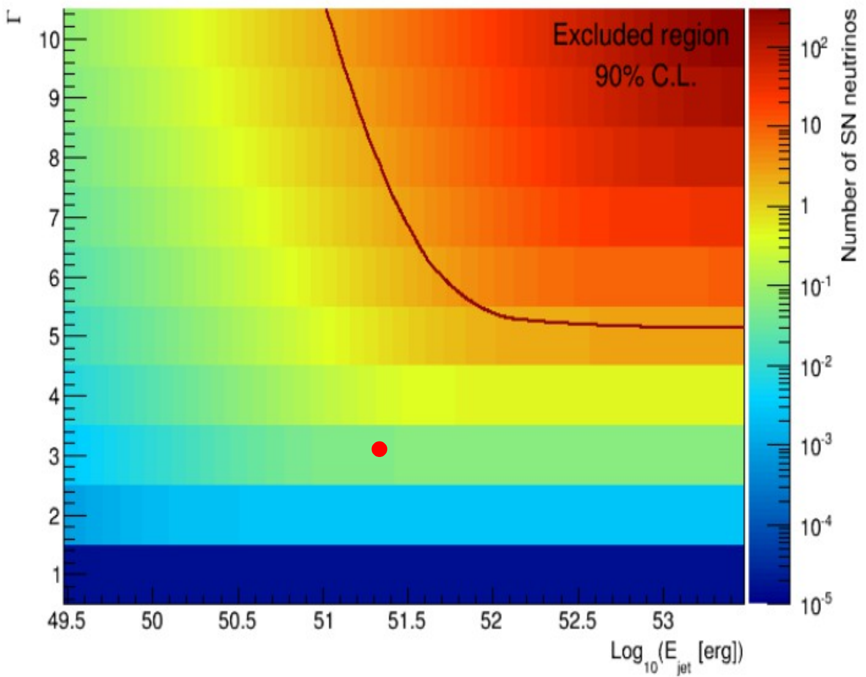
Step 3 : Assuming a Poisson distribution for the detected neutrino, the probability of detecting at least 1 neutrino given $\mathbf{N_\nu}$ **= 2.3 is 90%. Models that exhibit more than 2.3 neutrino are therefore excluded at 90% C.L**

Constraints on E_{jet} & Γ (ANTARES)

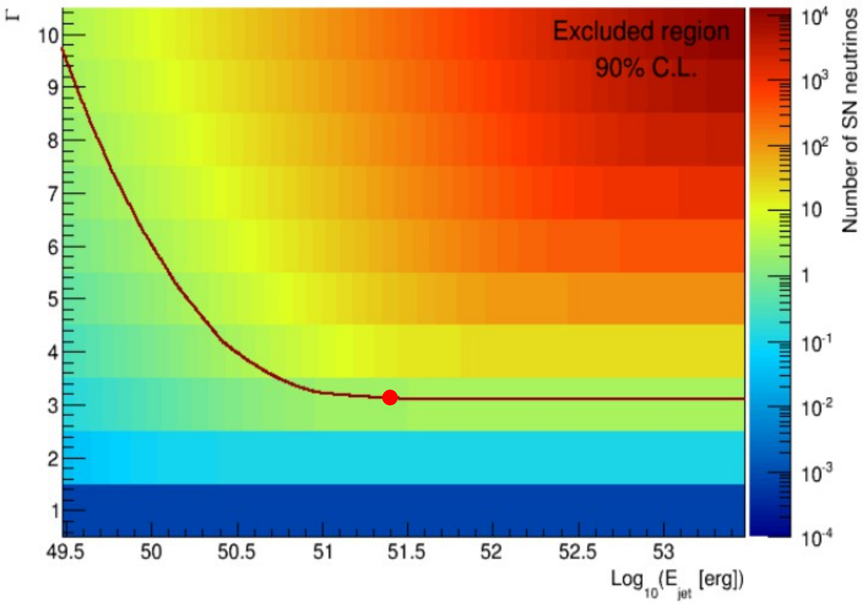


(a) $d = 10$ Mpc.

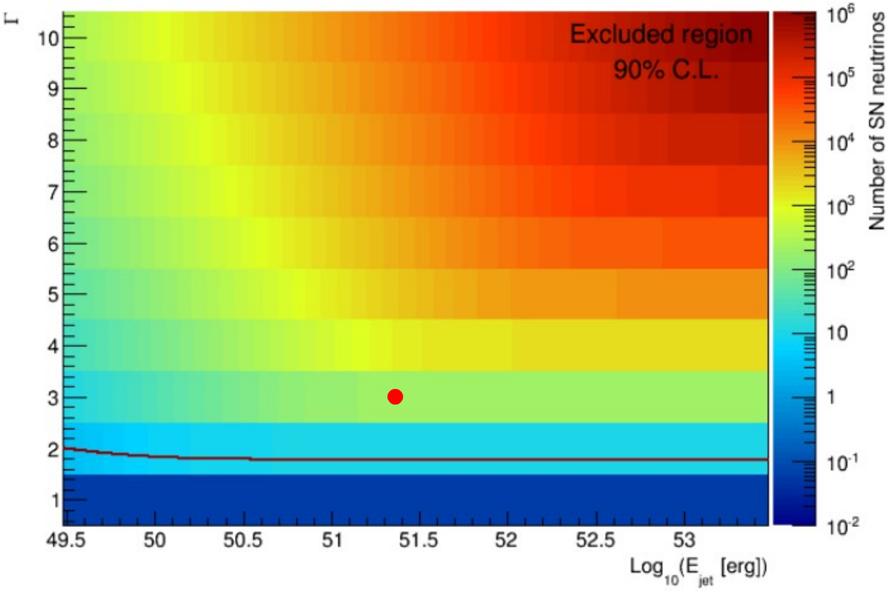
PRELIMINARY



(b) $d = 3$ Mpc.



(c) $d = 460$ kpc.

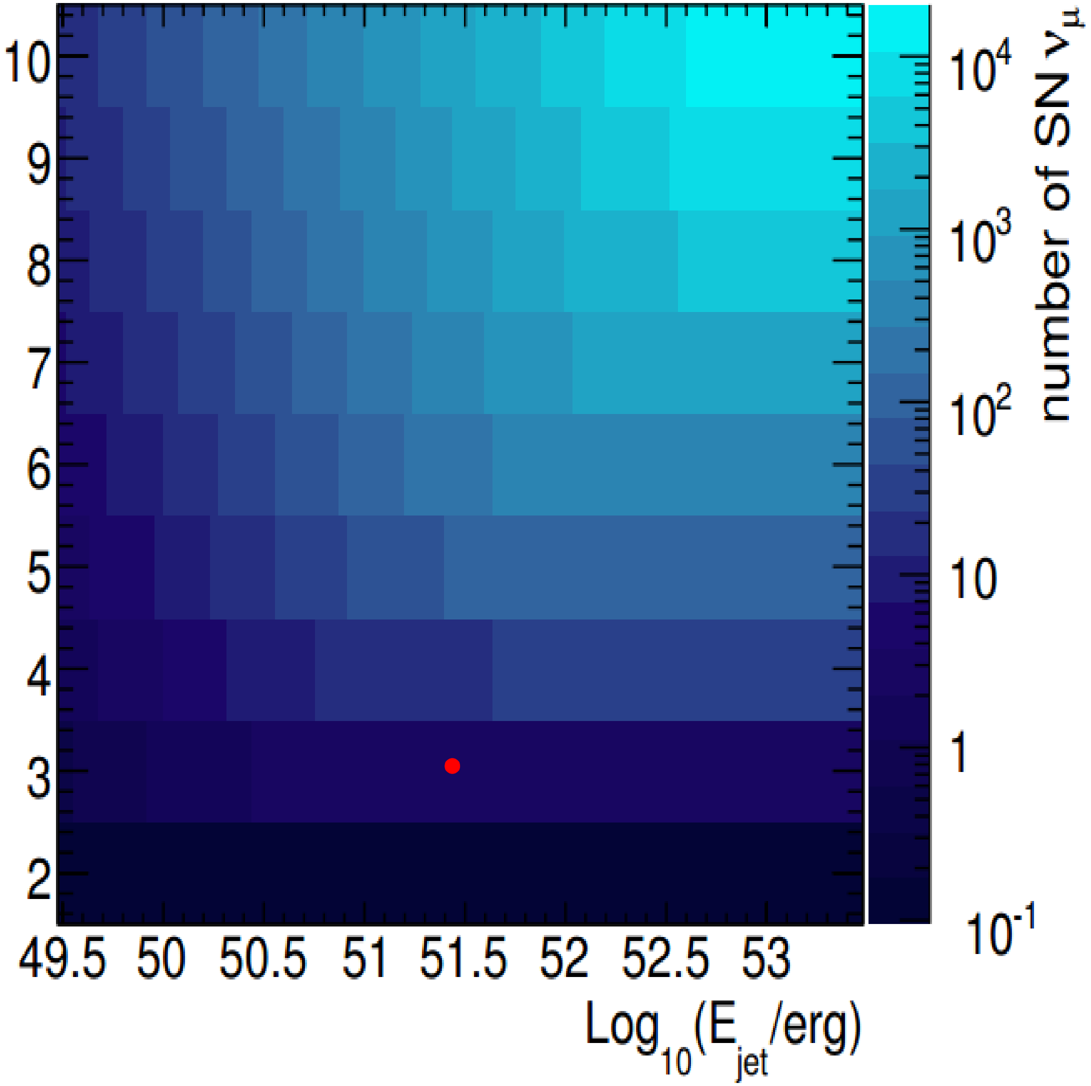


(d) $d = 50$ kpc.

Constraints on E_{jet} & Γ (IC/KM3NeT)

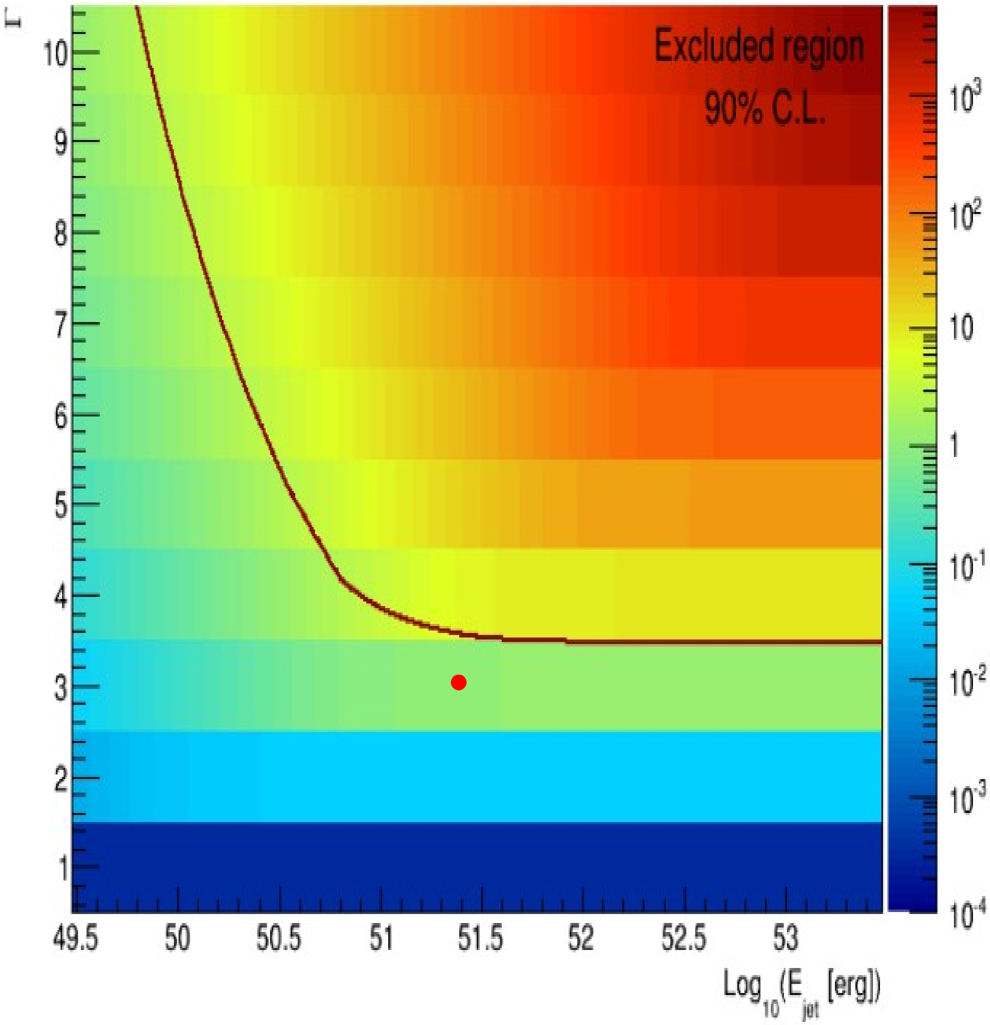
for a CCSNe at 10Mpc

Ice Cube (59 strings)



Abbasi et al. 2012

KM3NeT (Preliminary)

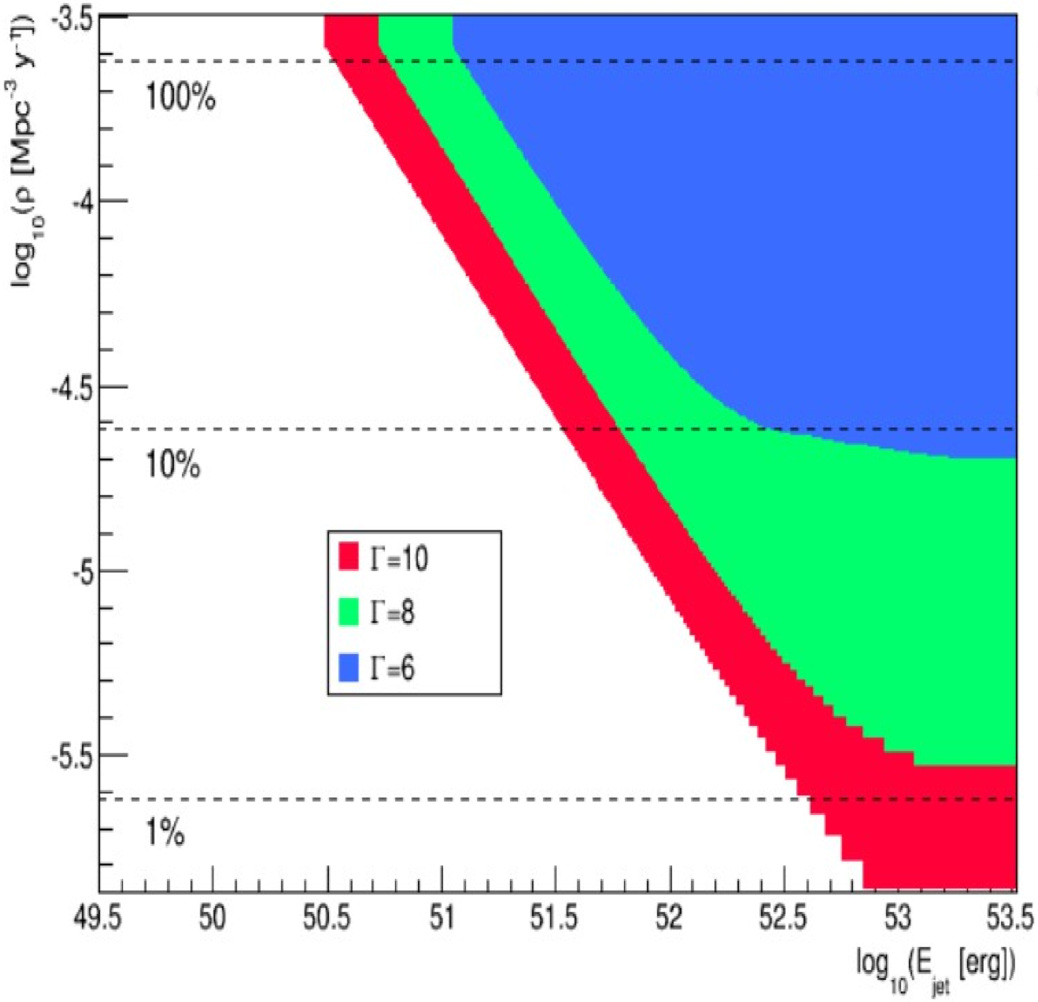


PRELIMINARY

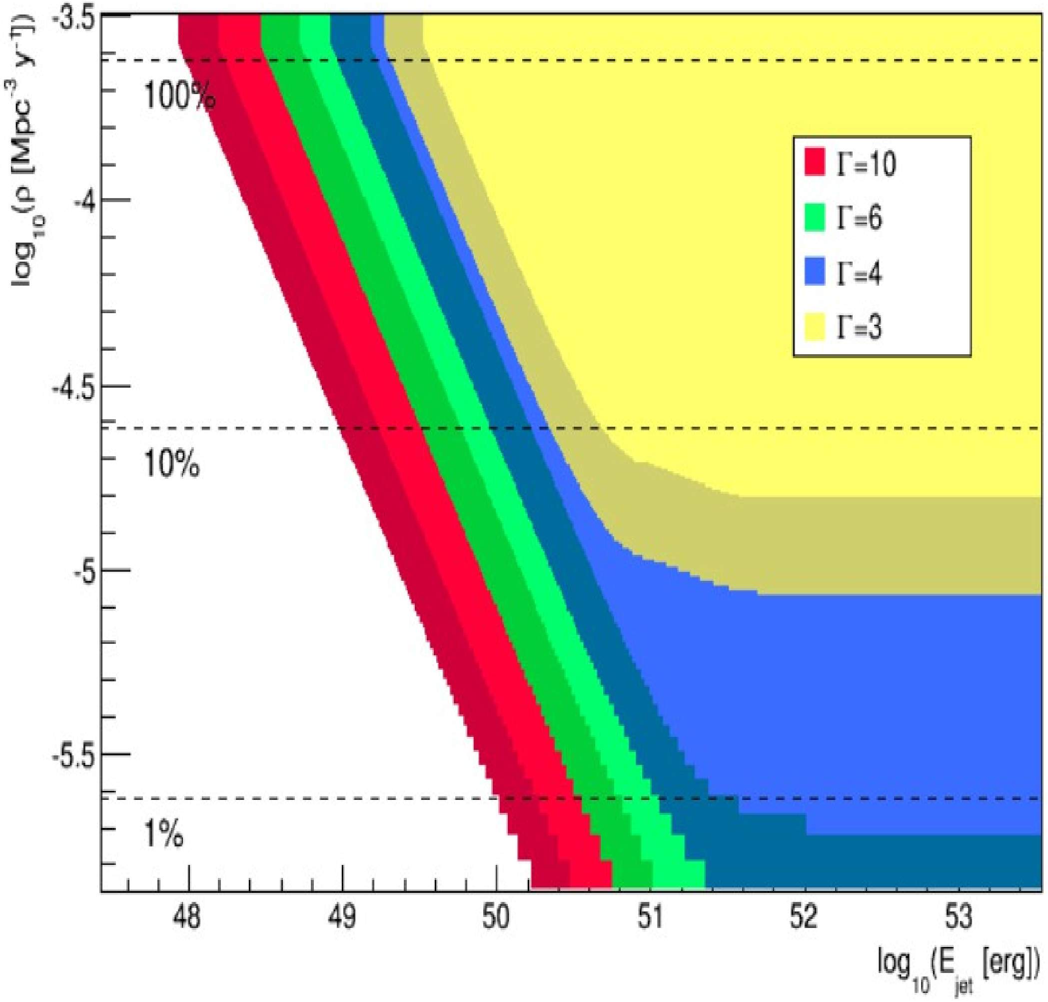
Limits on the rate of CCSNe with jet ρ

PRELIMINARY

ANTARES



KM3NeT



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Fraction of CCSNe with jets relative to an assumed CCSNe rate of 2.4.10^{-4} yr^{-1} .Mpc^{-3}
→ 1 CCSNe/year within 10Mpc Schiminovich, et al. 2005, Ando et al. 2005

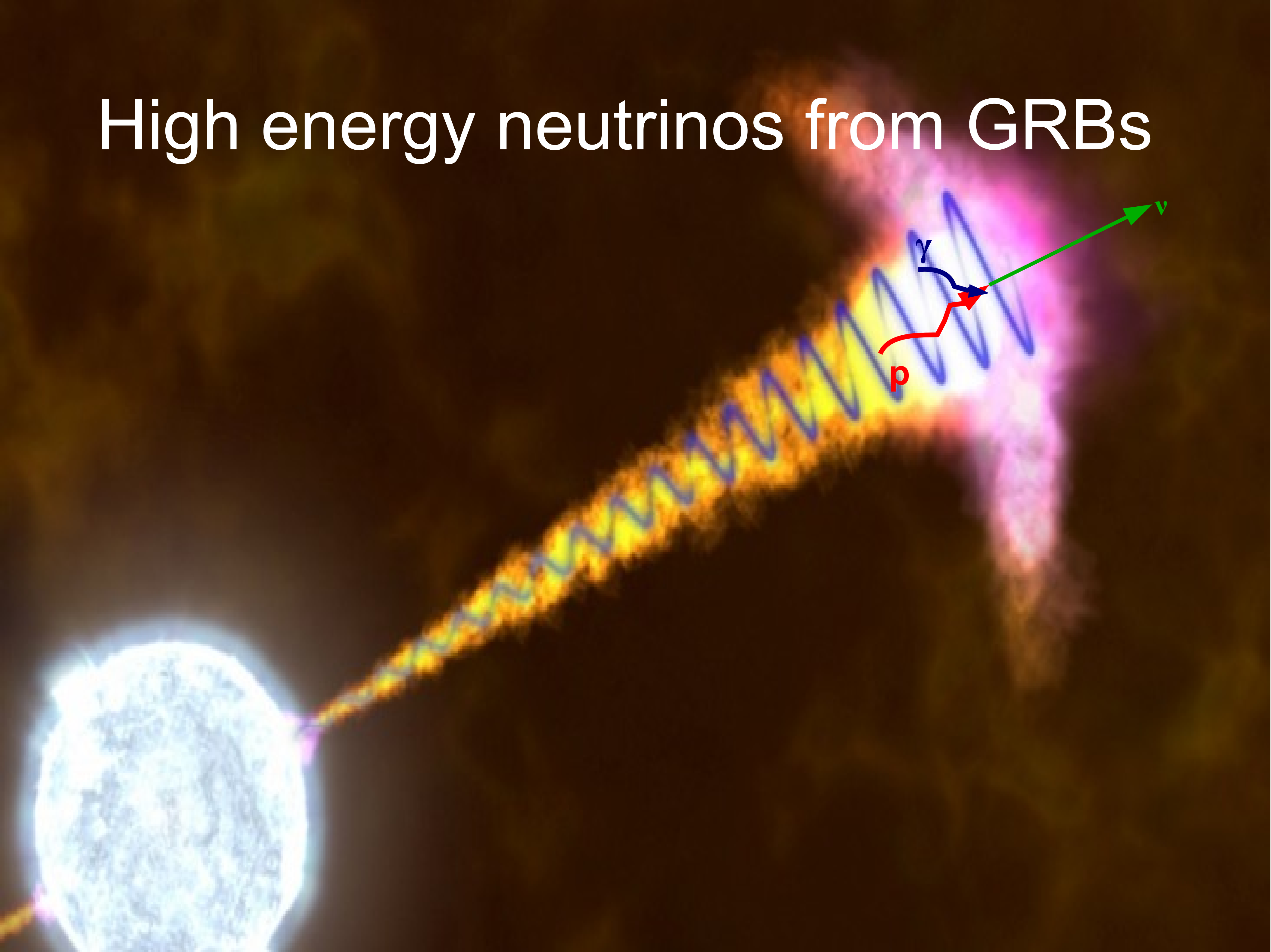
Conclusion CCSNe

No 100GeV -10 TeV neutrinos discovered yet from CCSNe

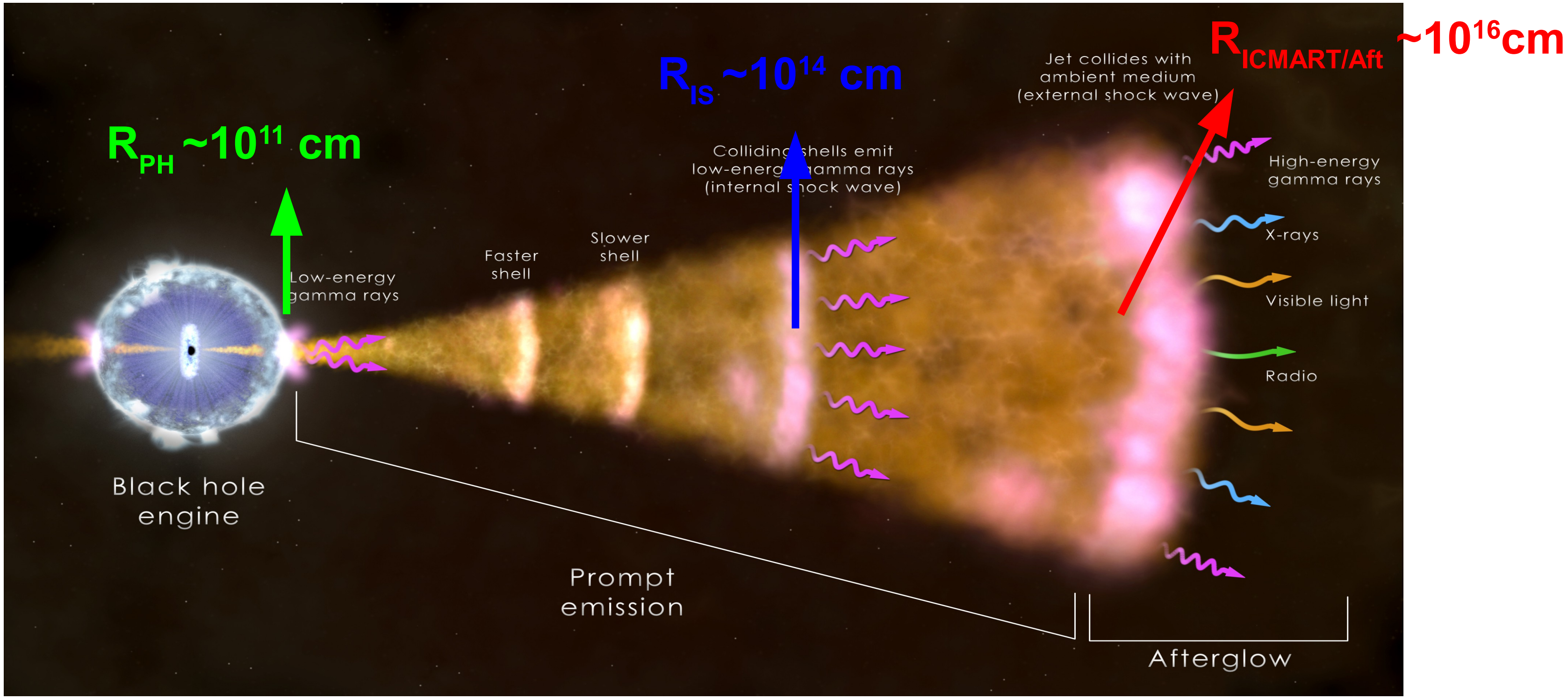
ANTARES is able to exclude a large region of the $E_{jet} - \Gamma$ plane for CCSNe at d<1Mpc. The ANTARES horizon limit is ~52Mpc. The non detection of GeV neutrinos from SN1987A (d= 51.4 kpc) by Kamiokande-II suggest no jet from this CCSNe

Larger neutrino detector such as **IceCube** and **KM3NeT** are able to (almost) rule out the presence of a jet in CCSNe located at d<10Mpc

High energy neutrinos from GRBs



Hadronic processes in GRB relativistic jets



pγ interaction (γ-ray photon rich medium)

100TeV-PeV regime

$$p + \gamma \xrightarrow{\Delta^+} \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases} \rightarrow \langle x_{p\rightarrow\pi} \rangle \sim 20\%$$

$$\pi^0 \longrightarrow \gamma + \gamma$$

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

$$\mu^+ \longrightarrow e^+ + \boxed{\nu_e + \overline{\nu}_\mu}$$

$$n \longrightarrow p^+ + e^- \boxed{+ \overline{\nu}_e} .$$

EeV regime

$$p + \gamma \longrightarrow K^+ + \Lambda/\Sigma$$

$$K^+ \longrightarrow \mu^+ \boxed{+ \nu_\mu}$$

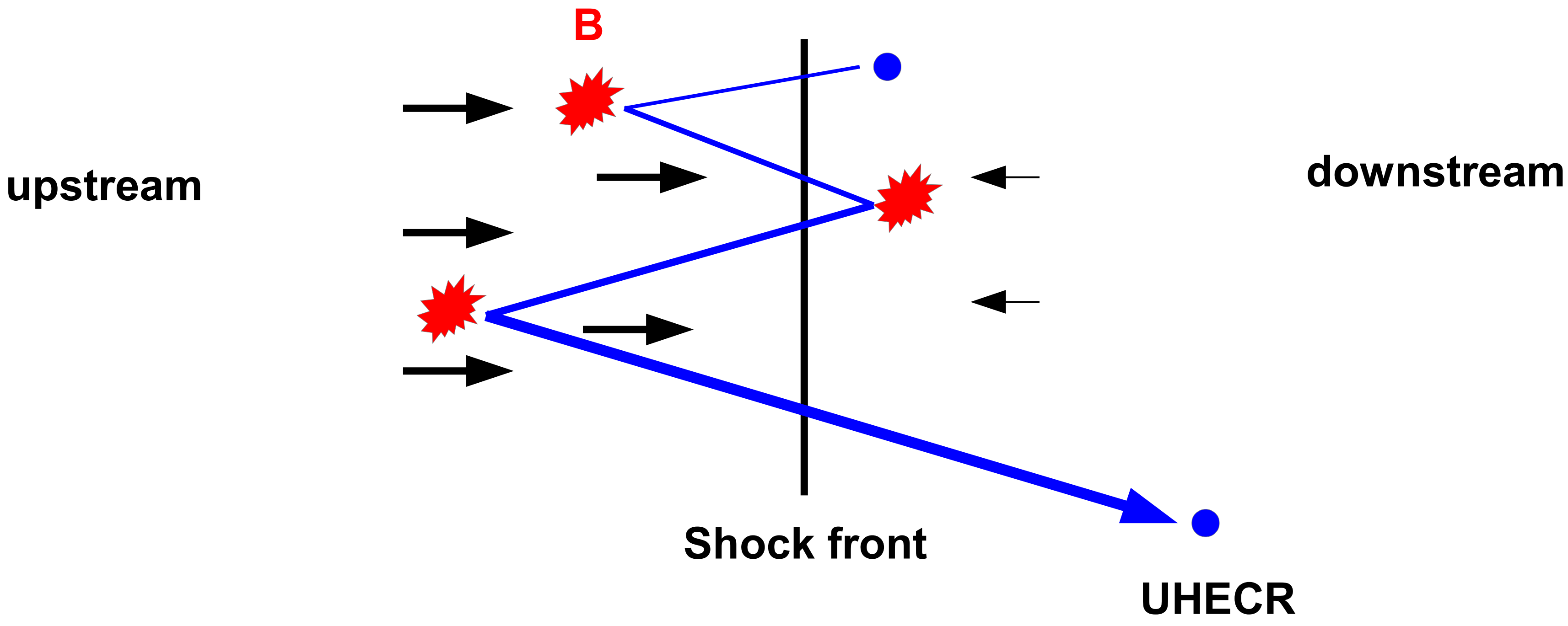
$$\pi^- \longrightarrow \mu^- \boxed{+ \overline{\nu}_\mu}$$

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

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

Particle acceleration in (mildly) relativistic shocks

1st order Fermi process at the shock front



The energy distribution of the jet energy at the shock radius

$$E = \varepsilon_p E + \varepsilon_e E + \varepsilon_B E + \gamma$$

Internal energy of the jet

baryons

electrons

Magnetic field

High energy neutrino spectrum : the main ingredients

		Standard values
Proton spectrum	$N(E) \sim E^{-p}$ *where* $p \sim 2$	**–**
Photon spectrum (**Band/SBPL/CPL/PL**)	α / β / *Epeak* / F_γ	**-1 / -2 / 200 keV/ 10^{-5} erg.cm^{-2} [1keV-10 MeV]**
GRB temporal characteristics	T_{90} / t_{min} *(only for IS)*	**50 s / 0.01 s**
Composition of the jet and its dynamics **UNKNOWN**	$f_p=\frac{\varepsilon_p}{\varepsilon_e}$ / ε_e / ε_B & Γ	**10 / 0.1 / 0.1 / 316**
Distance/redshift	z	**2.15** **(0.5 for SGRB)**

GRB neutrino model : double broken power laws

Normalisation

$$\int_0^{\infty} E_\nu dE_\nu F_\nu(E_\nu) = \boxed{\frac{f_p}{8}} \times \left(1-(1-\chi_{p\pi})^{\boxed{\tau_{p\gamma}}}\right) \int_{1\mathrm{keV}}^{10\mathrm{MeV}} E_\gamma dE_\gamma F_\gamma(E_\gamma)$$

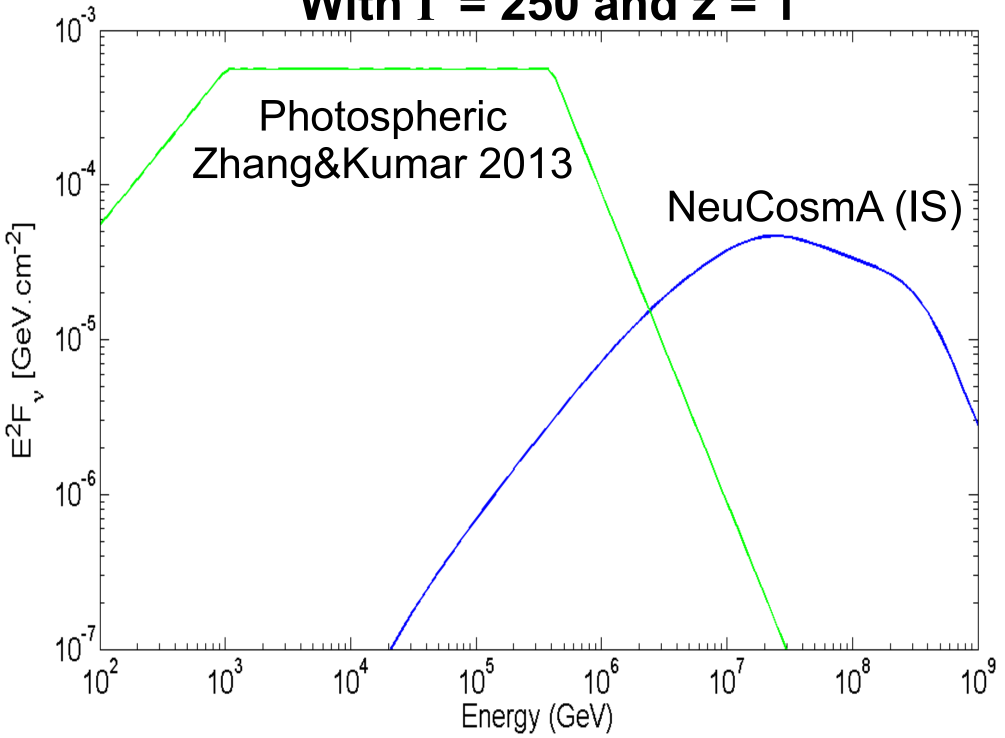
where $\tau_{p\gamma} \propto L_{iso} \times \boxed{\Gamma^{-2} \times R^{-1}} \times E_{peak}^{-1}$

$R_{IS} = c\Gamma^2 t_{min}/(1+z)$

$R_{PH} \propto L_{iso} \times \Gamma^{-3}$

$\blacktriangleright \quad \dfrac{R_{IS}}{R_{PH}} \sim 1000$

Neutrino spectrum for a « standard » GRB
With Γ = 250 and z = 1



Energy breaks

$$E_{\nu,1} \propto (1+z)^{-2} \times \boxed{\Gamma^2} \times E_{peak}^{-1}$$

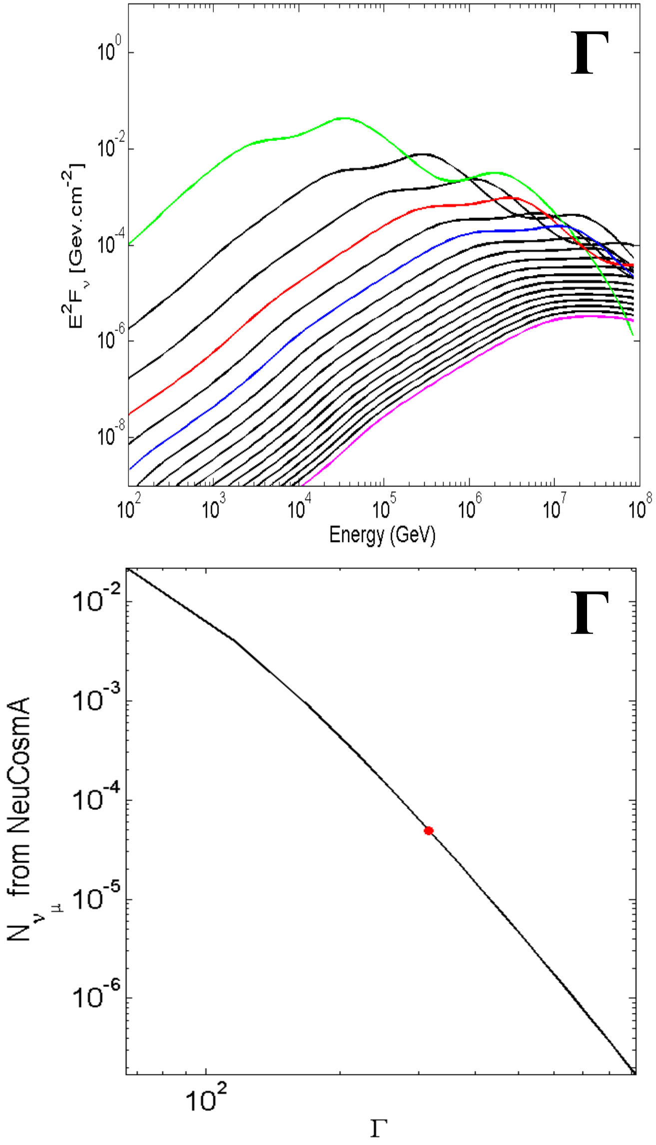
$$E_{\nu,2} \propto (1+z)^{-1} \times \boxed{\sqrt{\frac{\varepsilon_e}{\varepsilon_B}}} \times \sqrt{L_{iso}} \times \boxed{\Gamma^2 \times R}$$

NeuCosmA model

Hümmer et al. 2010
Hümmer et al. 2012

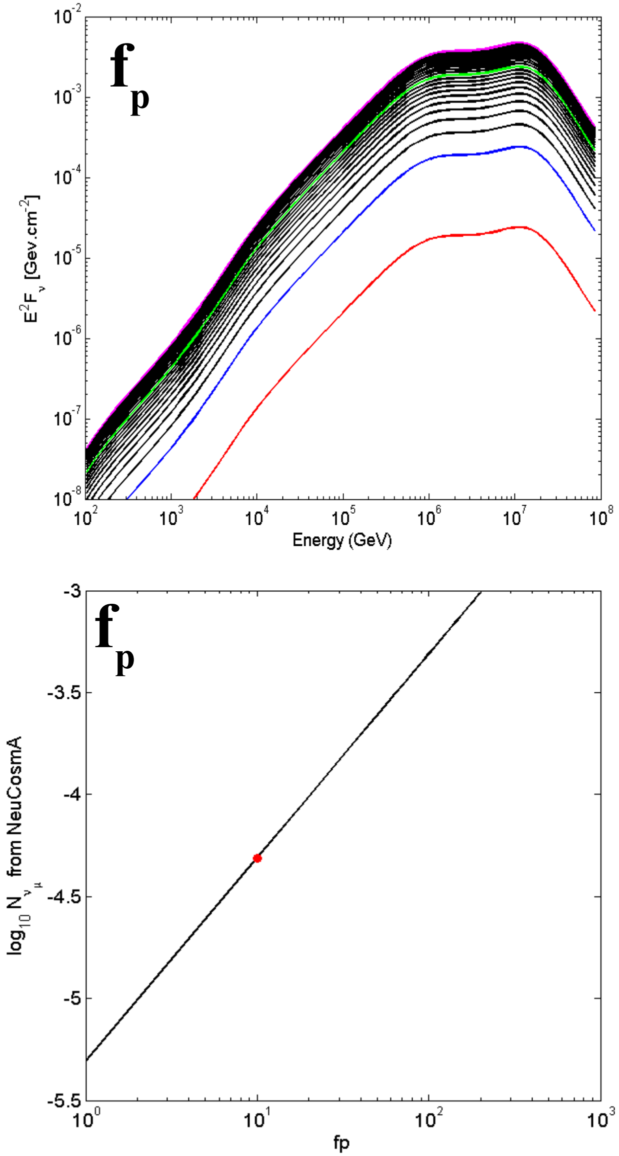
Impact of f_p / Γ and $\varepsilon_e/\varepsilon_B$ on the prompt IS neutrino spectrum

60 → 900



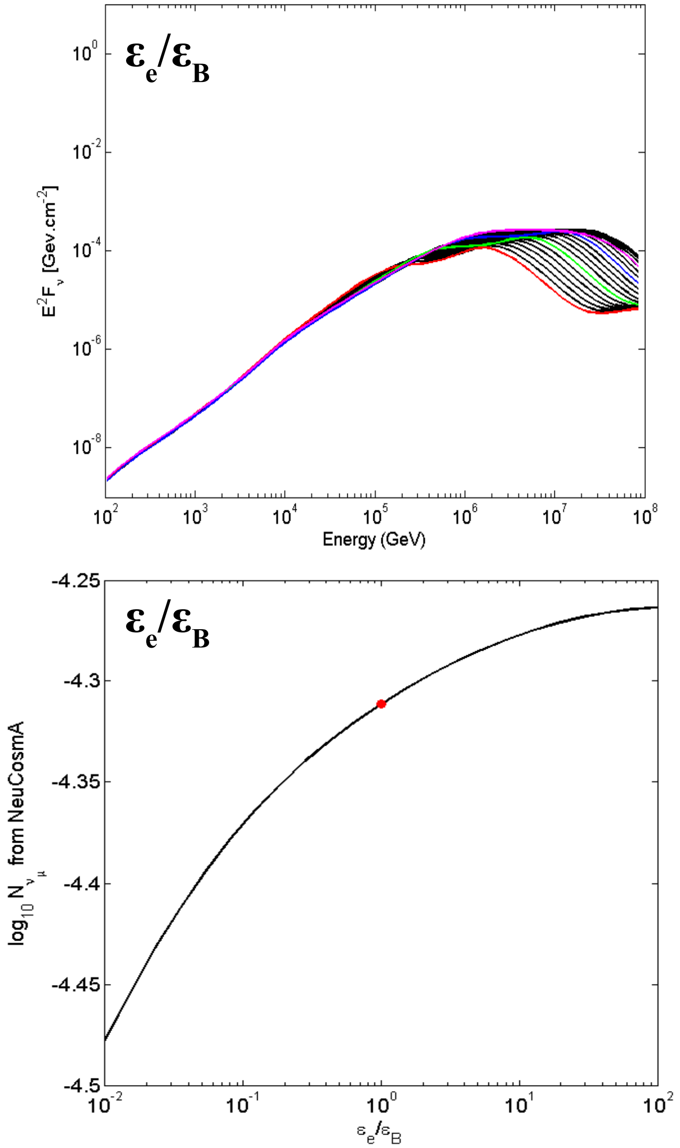
~5 orders of magnitude on the neutrino expectations

1 → 200



~2 orders of magnitude on the neutrino expectations

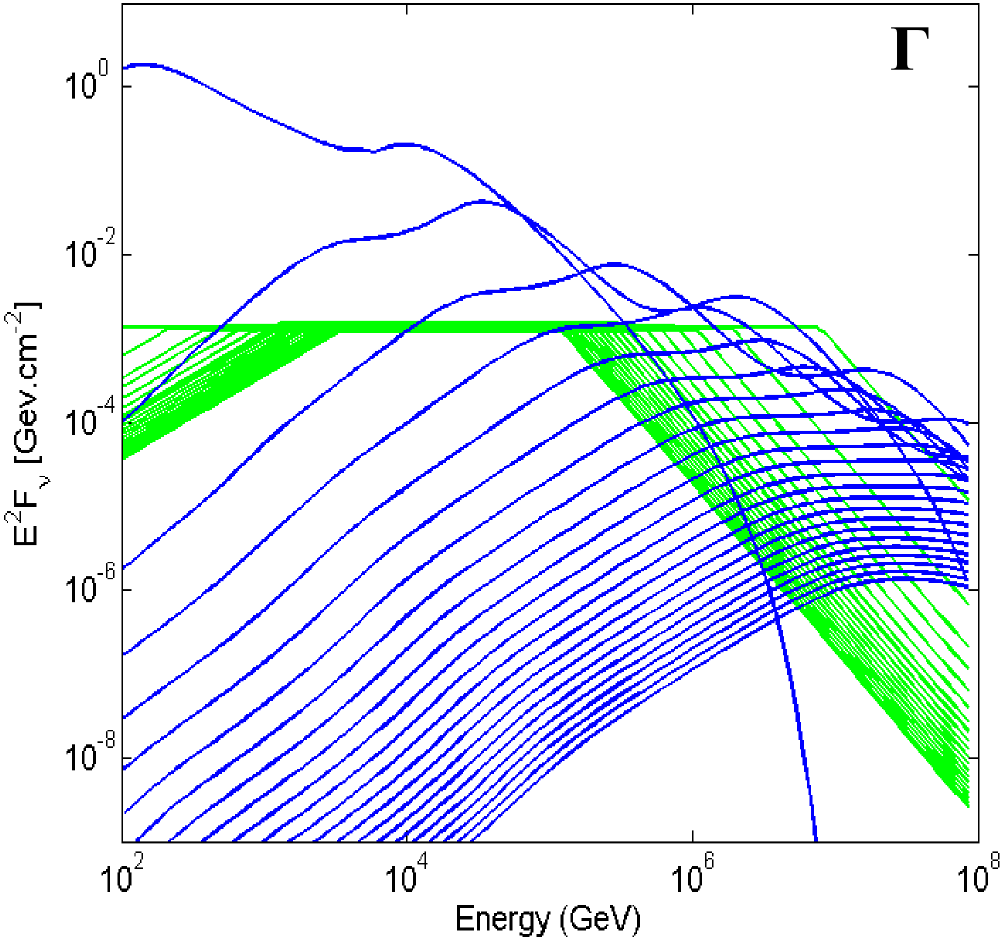
0.01 → 100



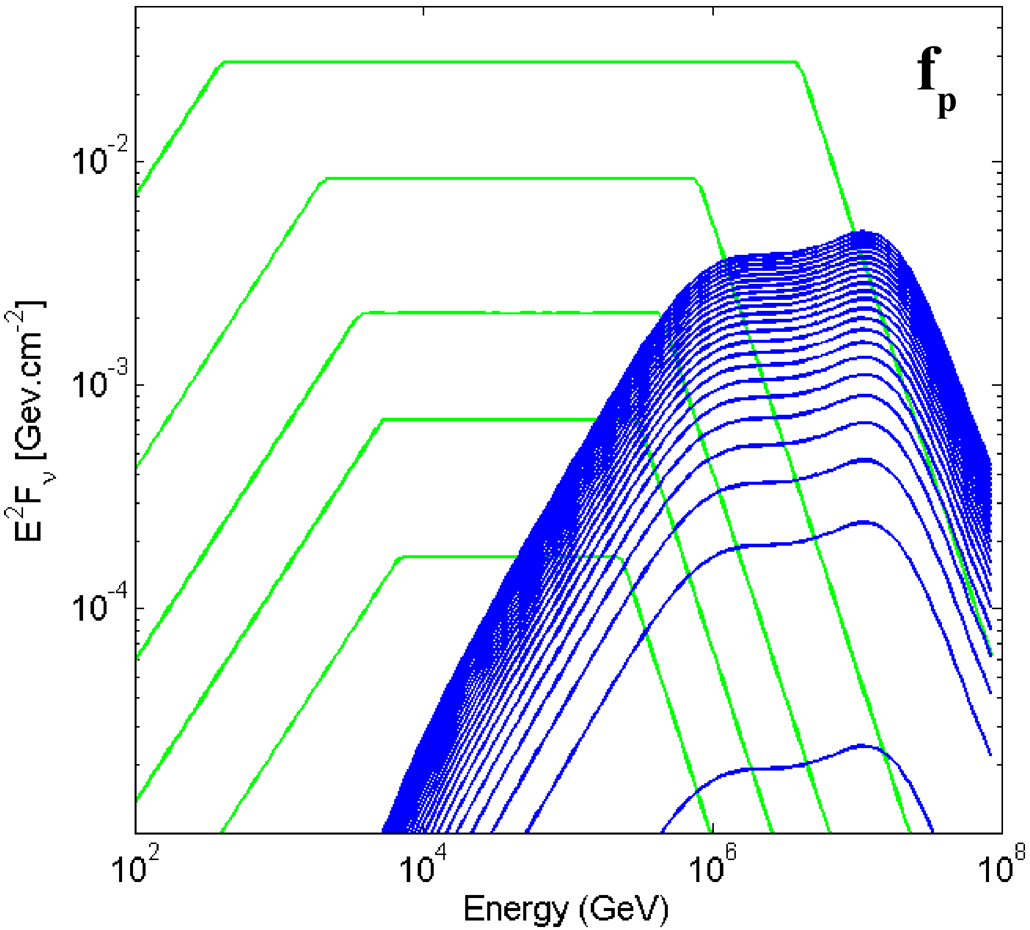
Negligible impact on the neutrino expectations

Impact of f_p / Γ on the prompt PH neutrino spectrum

50 → 850



1 → 200



🟩 PH

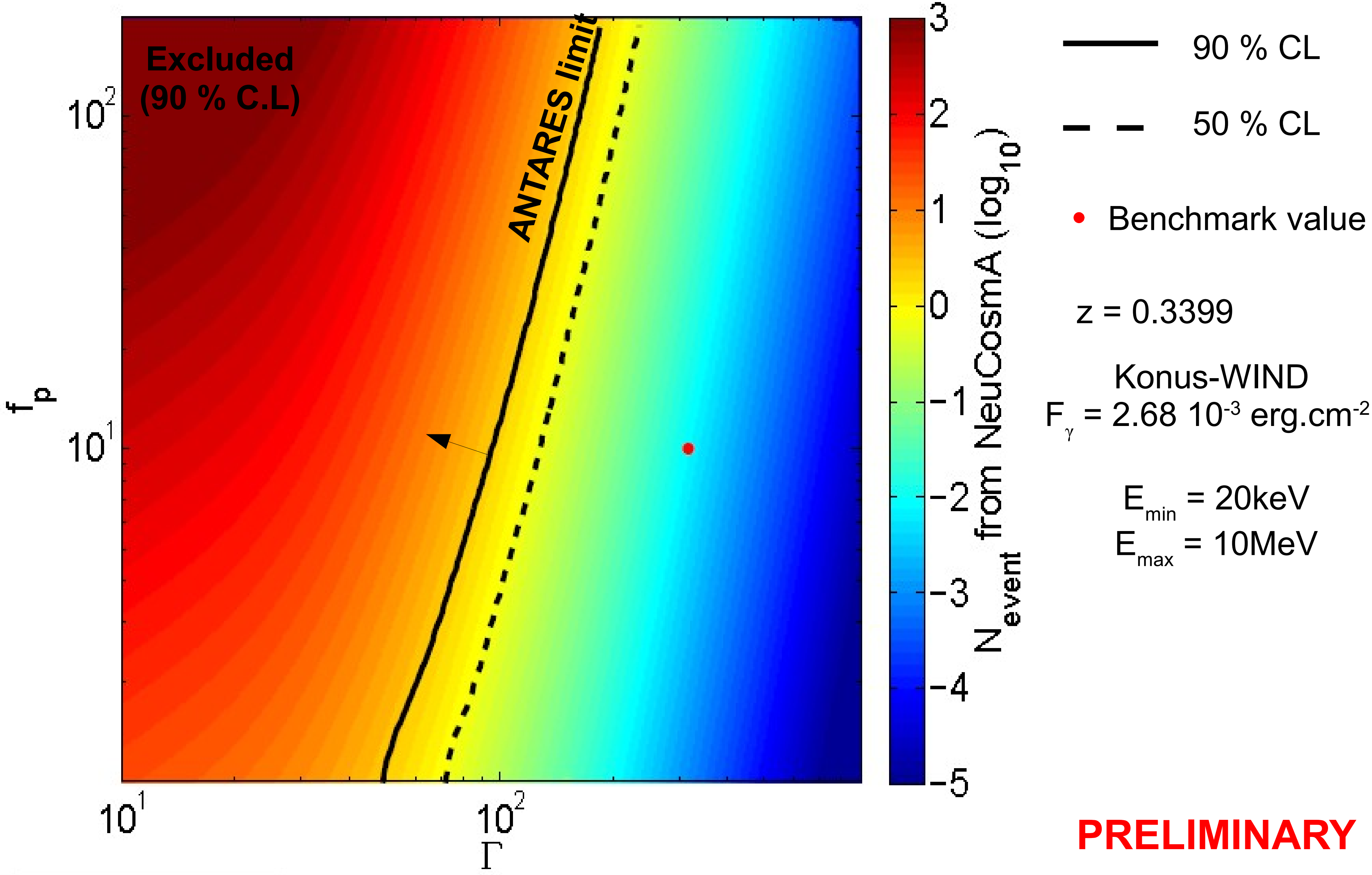
🟦 NeuCosmA (IS)

Few impact

~2 orders of magnitude on the neutrino expectations

Constraints on the most fluent GRB GRB130427A

Constraints on the physics of GRB **internal shocks**



z = 0.3399

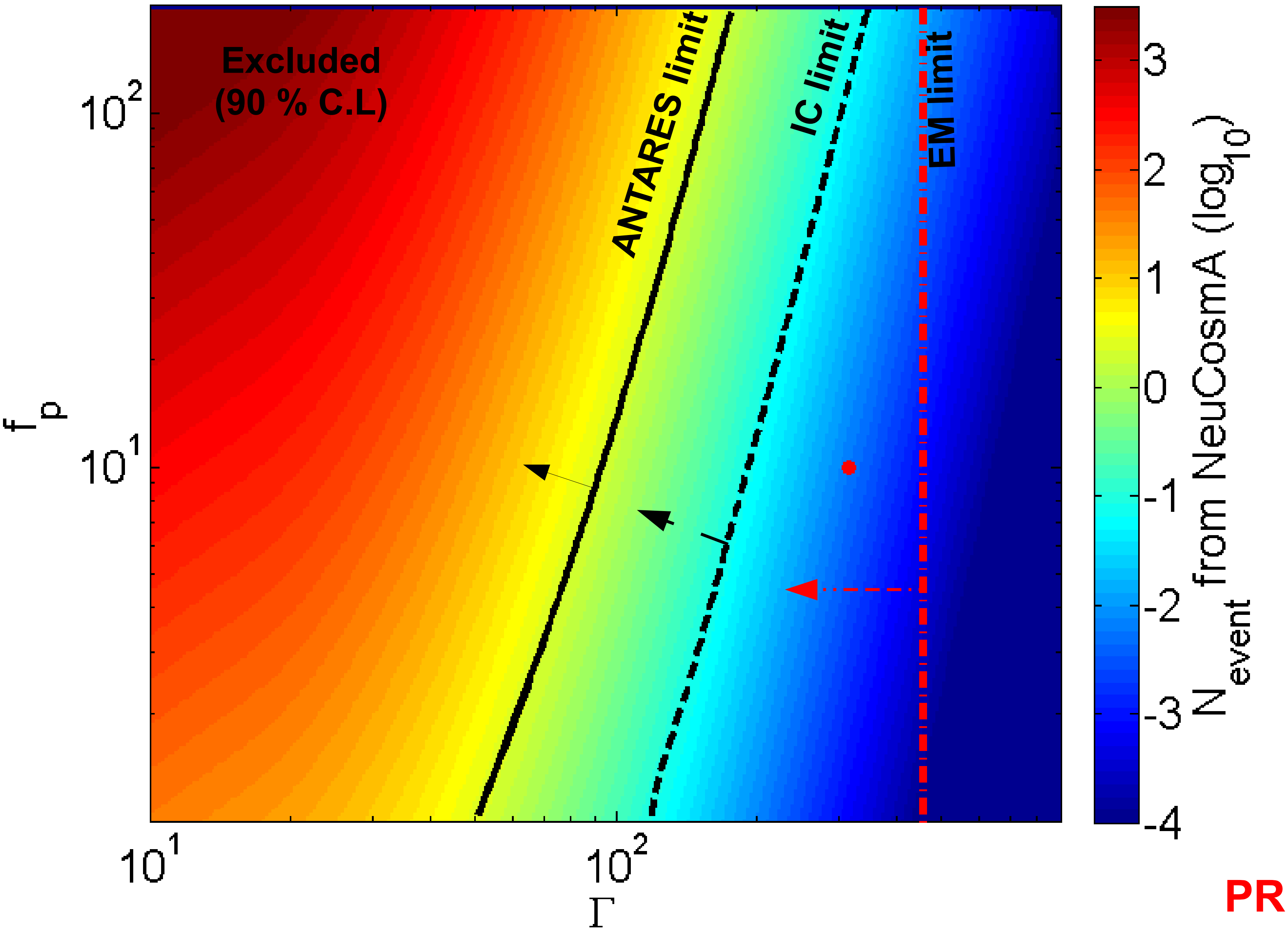
Konus-WIND
$F_\gamma = 2.68\ 10^{-3}\ \mathrm{erg.cm^{-2}}$

E_{min} = 20keV
E_{max} = 10MeV

PRELIMINARY

Constraints on the most fluent GRB GRB130427A

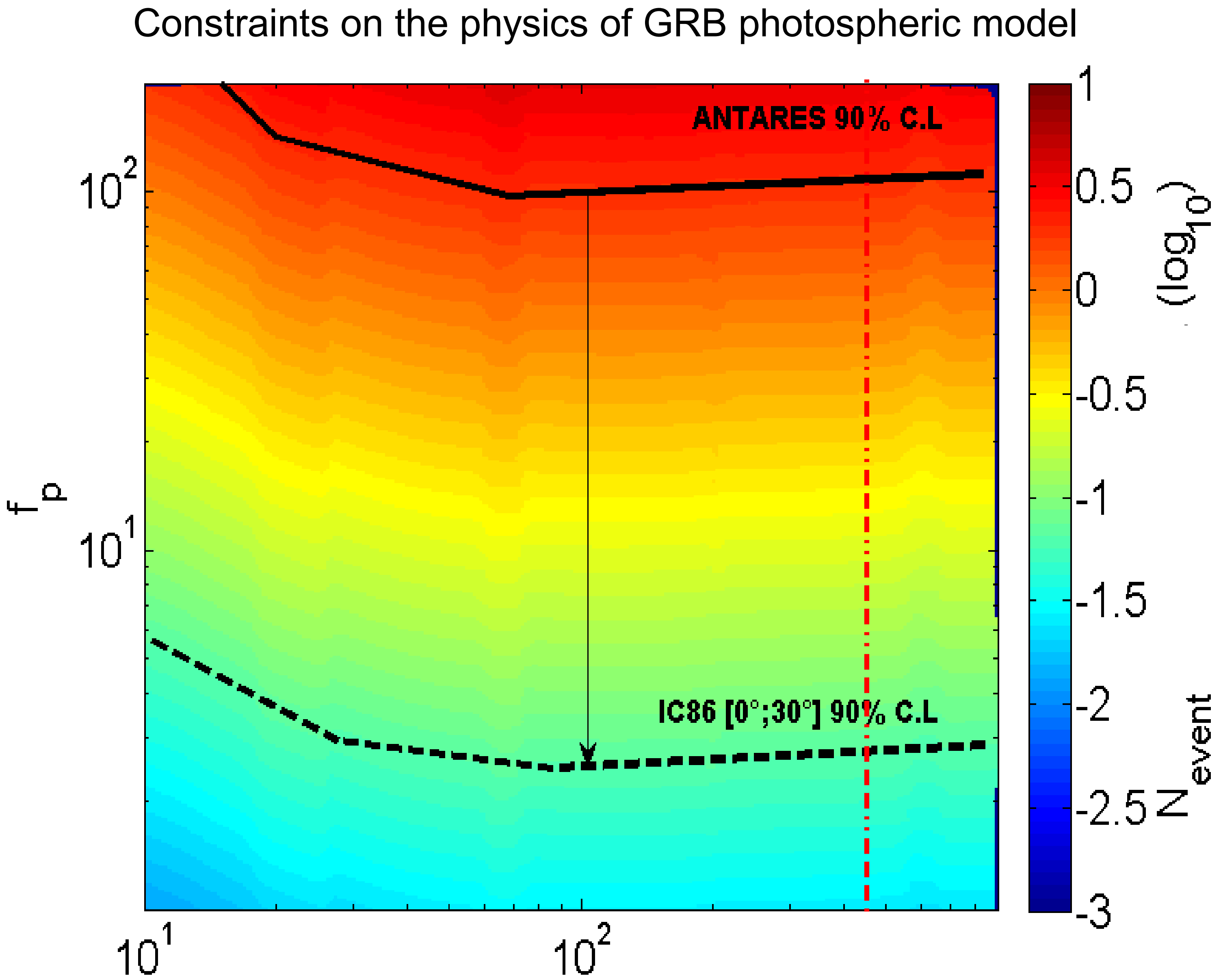
Constraints on the physics of GRB internal shocks



EM limit from Hascoët et al 2015

PRELIMINARY

Constraints on the most fluent GRB GRB130427A



IC almost rules out the photospheric model for this GRB

See also Gao et al. 2013

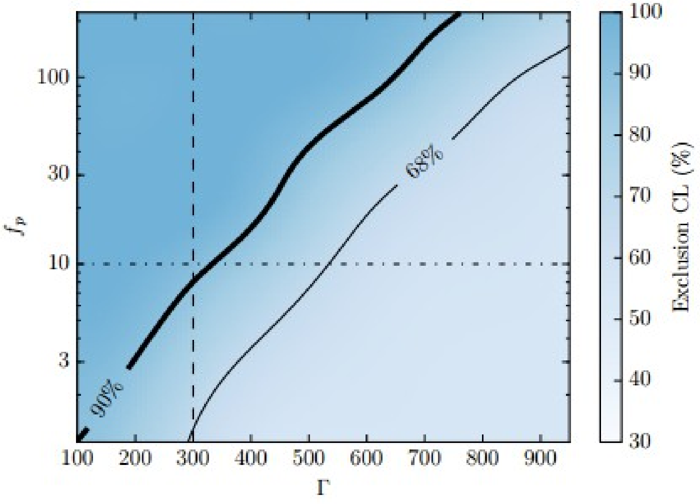
PRELIMINARY

Constraints from a large population of GRBs

Combined IC analysis of 3 years of data (all sky) using shower-like event (ν_e, ν_μ, ν_τ) and 4 years of Northern hemisphere track-like events (ν_μ)

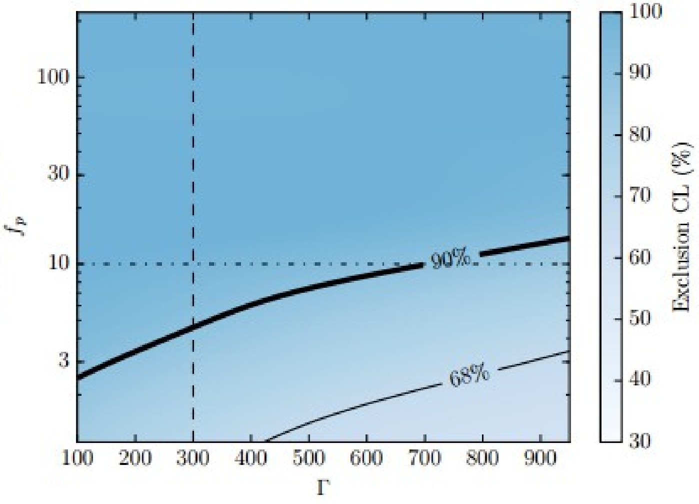
807 stacked GRBs

IS model



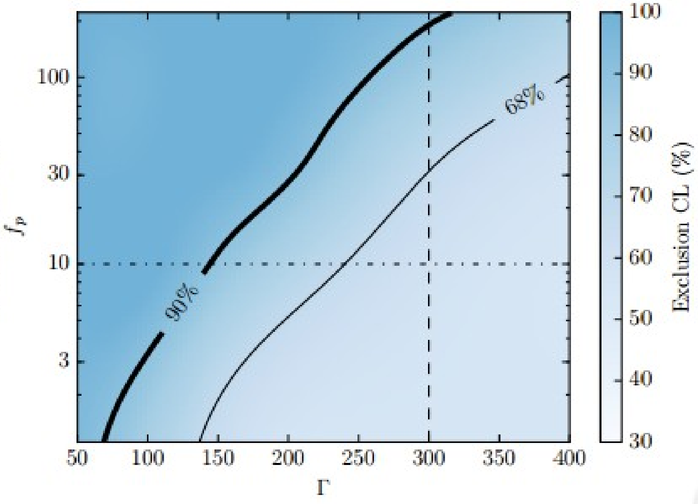
modestly constrained

PH model



Almost ruled out

ICMART model



Poorly constrained

IceCube Coll. 2016

ArXiv :1601.06484

Conclusion GRB

No TeV-PeV neutrino events yet detected from any GRBs by ANTARES or IceCube

The photospheric neutrino flux is already deeply constrained by the ANTARES/IceCube data.
Very low baryonic loading factor is asssumed for these kind of model
f_p <10 (and f_p <2-3 for GRB130427A)

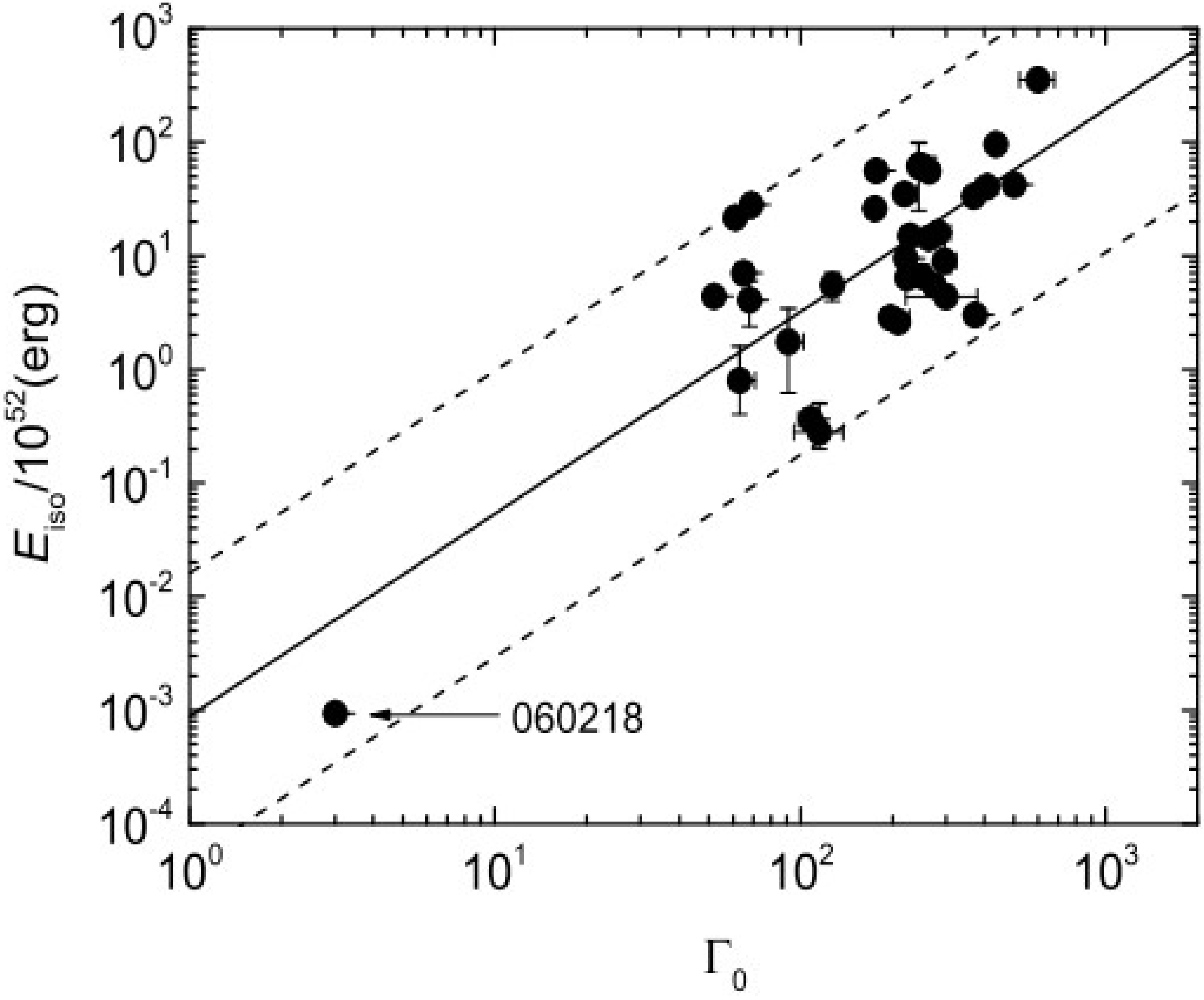
The Internal shock predictions start to be challenged by the IceCube detector placing restrictive limits on f_p for Γ <600-700 for large population of GRBs
(f_p <100 for Γ >300 for GRB-like 130427A)

Stacking analysis has to be interpreted carefully since there are a lot of unknowns :
Γ
z
F_γ
Gamma-ray spectral parameters badly constrained
Correlation between parameters

Are energetic GRBs the best candidate for a neutrino detection ?

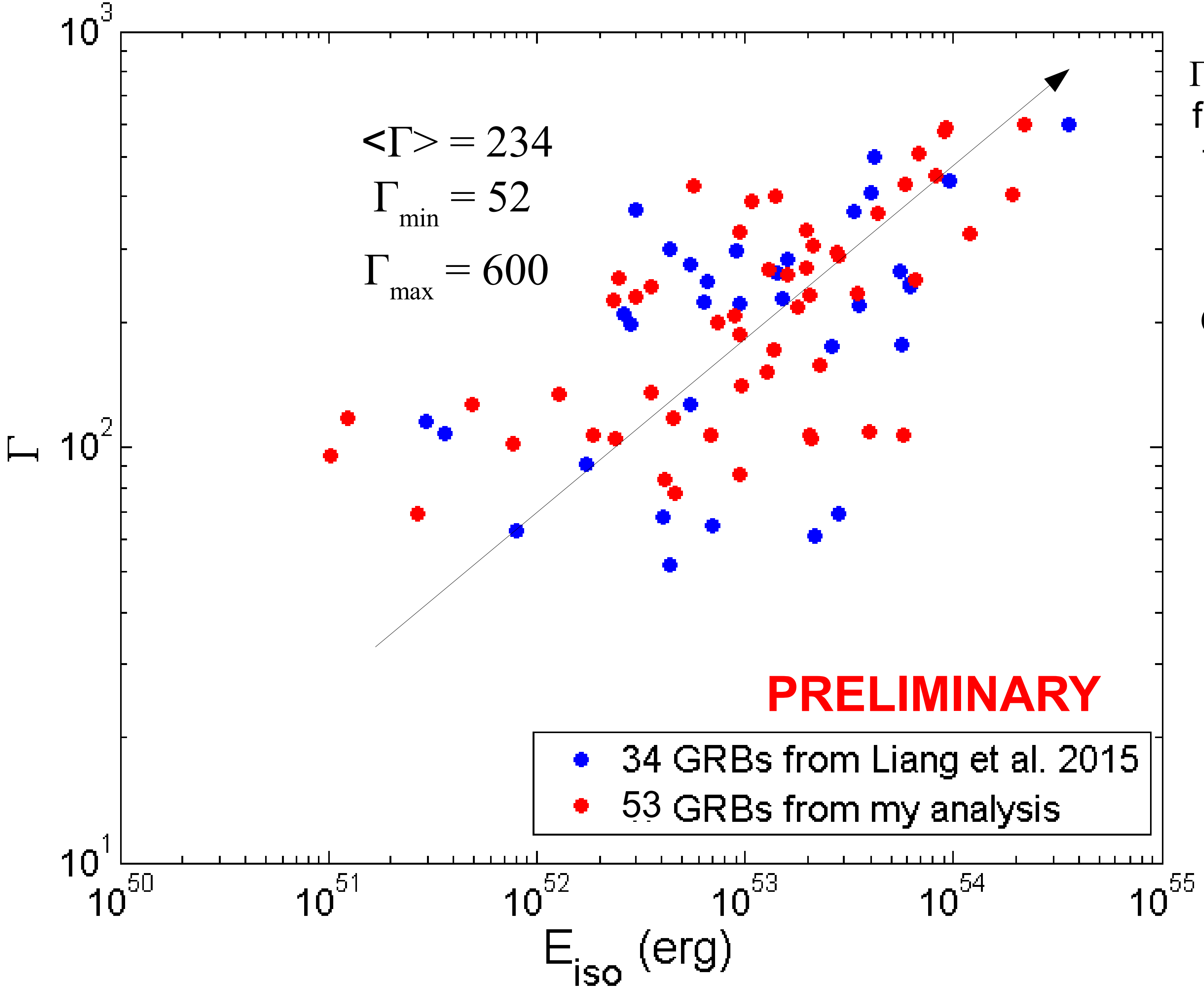
Detectable GRBs by ANTARES/KM3NeT

$E_{iso} - \Gamma$ correlation



Liang et al. 2015

E_{iso} – Γ correlation



Γ has been estimated from the peak time of the optical afterglow

Sari&Piran1999
Molinari2007
Ghirlanda et al 2012

Would we be able to detect one of those GRBs with ANTARES/KM3NeT ?

A detailed simulation of a GRB population emitting HEN
(NeuCosmA model used)

1/ Simulation of 10000 GRBs with Γ [10-900], Eiso [10^{50}-10^{56}] erg. Spectral and T_{90} parameters taken from the Fermi-GBM catalog (Gruber et al. 2014, von Kienlin et al. 2014).
f_p = 10 and t_{min} = 0.01 s

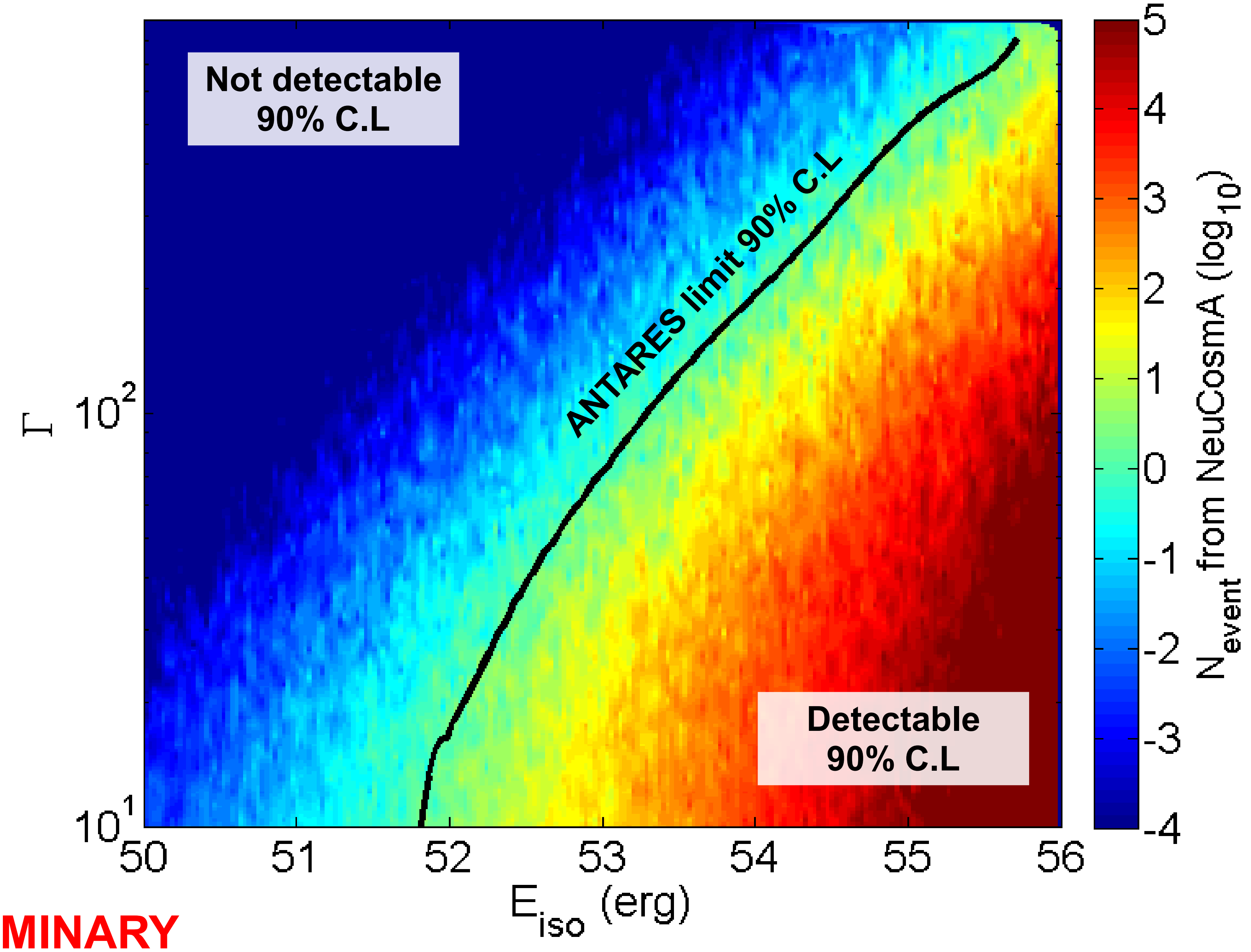
2/ Assuming a redshift, we can estimate the gamma-ray fluence, $F\gamma$

3/ We compute the NeuCosmA spectrum for each simulated bursts

4/ According to the ANTARES A_{eff} (2007-2011 with δ[-90°;-45°]) or expected KM3NeT A_{eff} we compute the # of neutrino events and exclude GRBs that exhibit more than N_ν=2.3.

The detection limit is thus set at 90% C.L

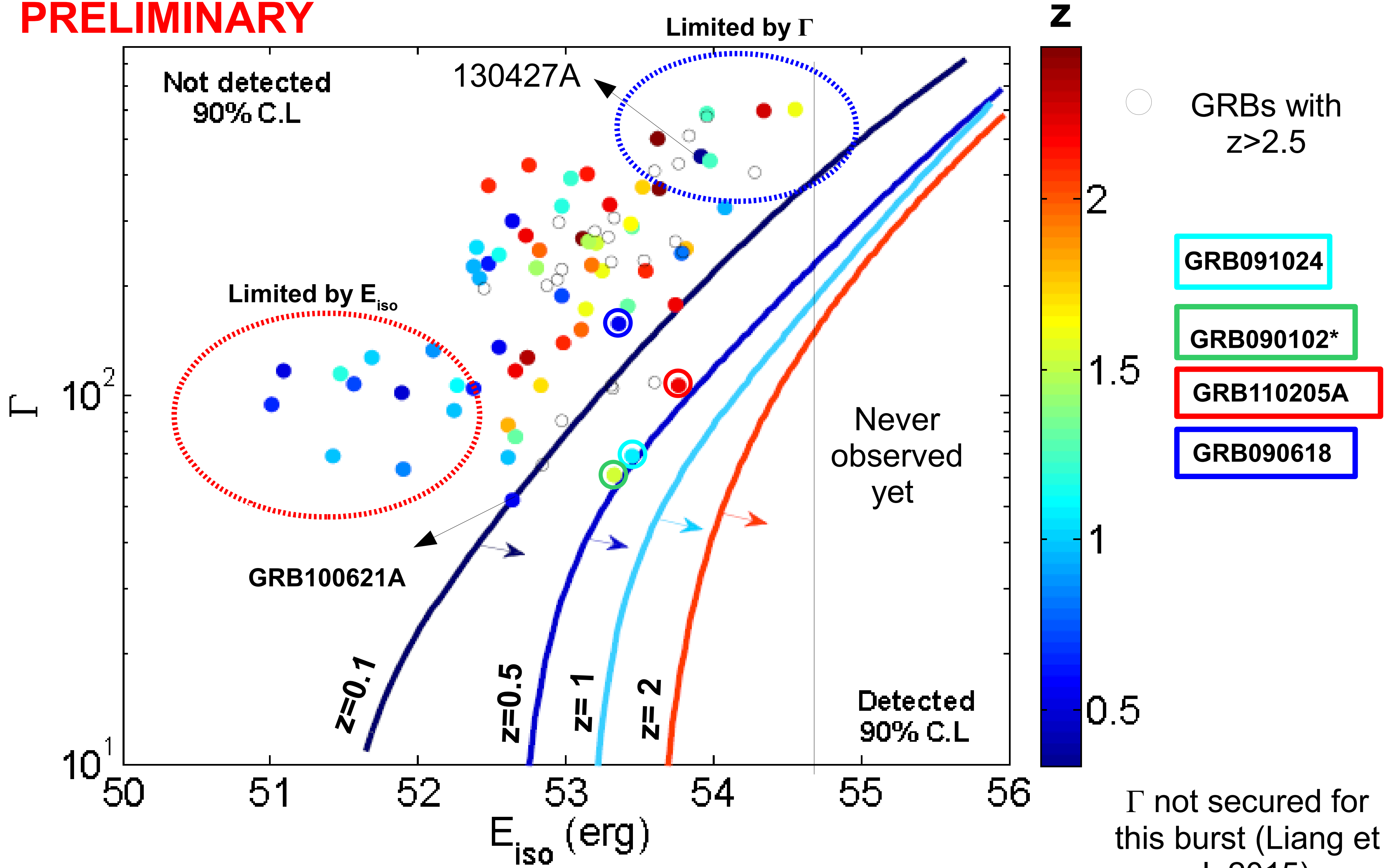
For GRBs located at z = 0.1



PRELIMINARY

z limits ANTARES [-90°;-45°] + GRB population

PRELIMINARY

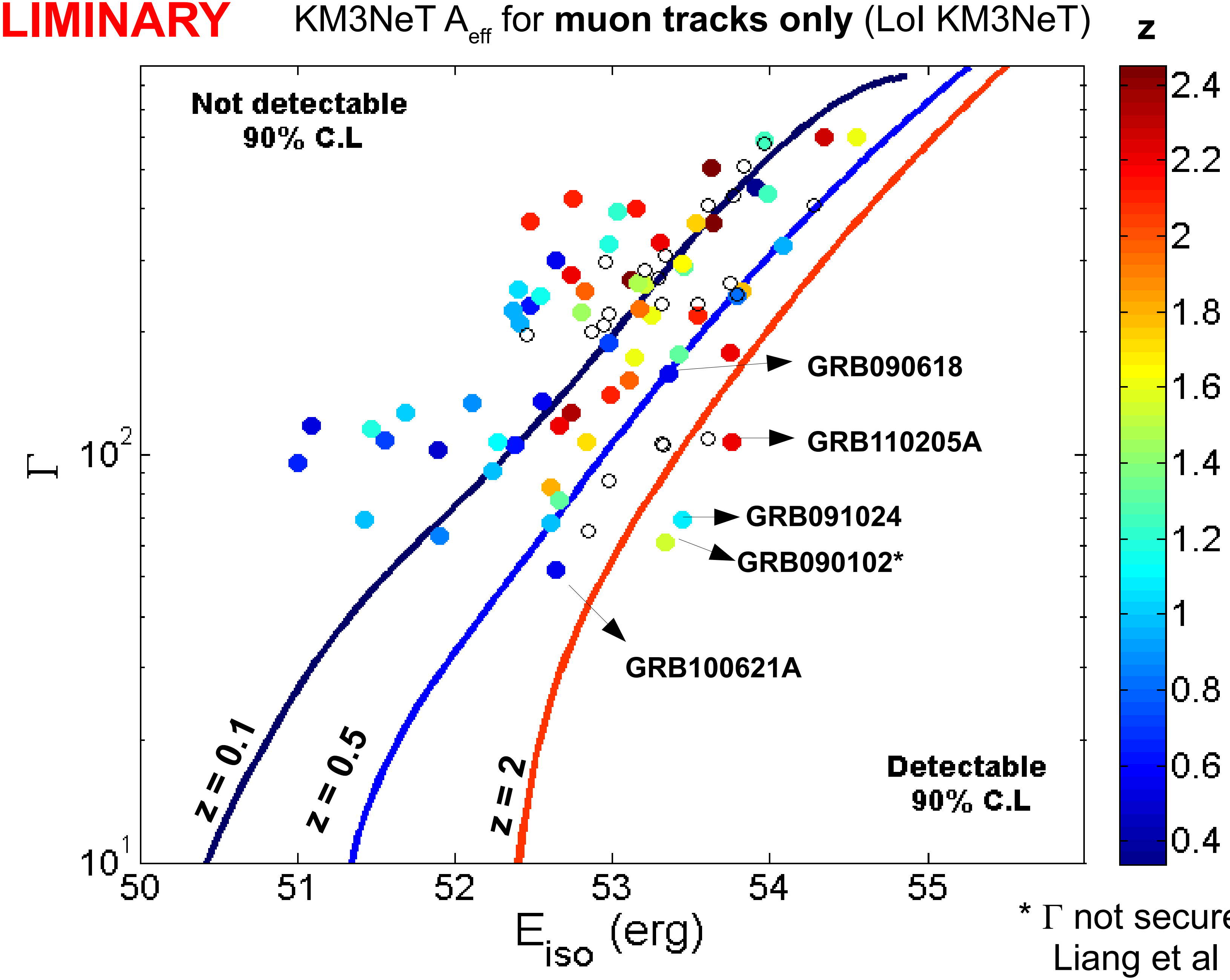


* Γ not secured for this burst (Liang et al. 2015)

The future with KM3NeT

PRELIMINARY

KM3NeT A_{eff} for **muon tracks only** (LoI KM3NeT)



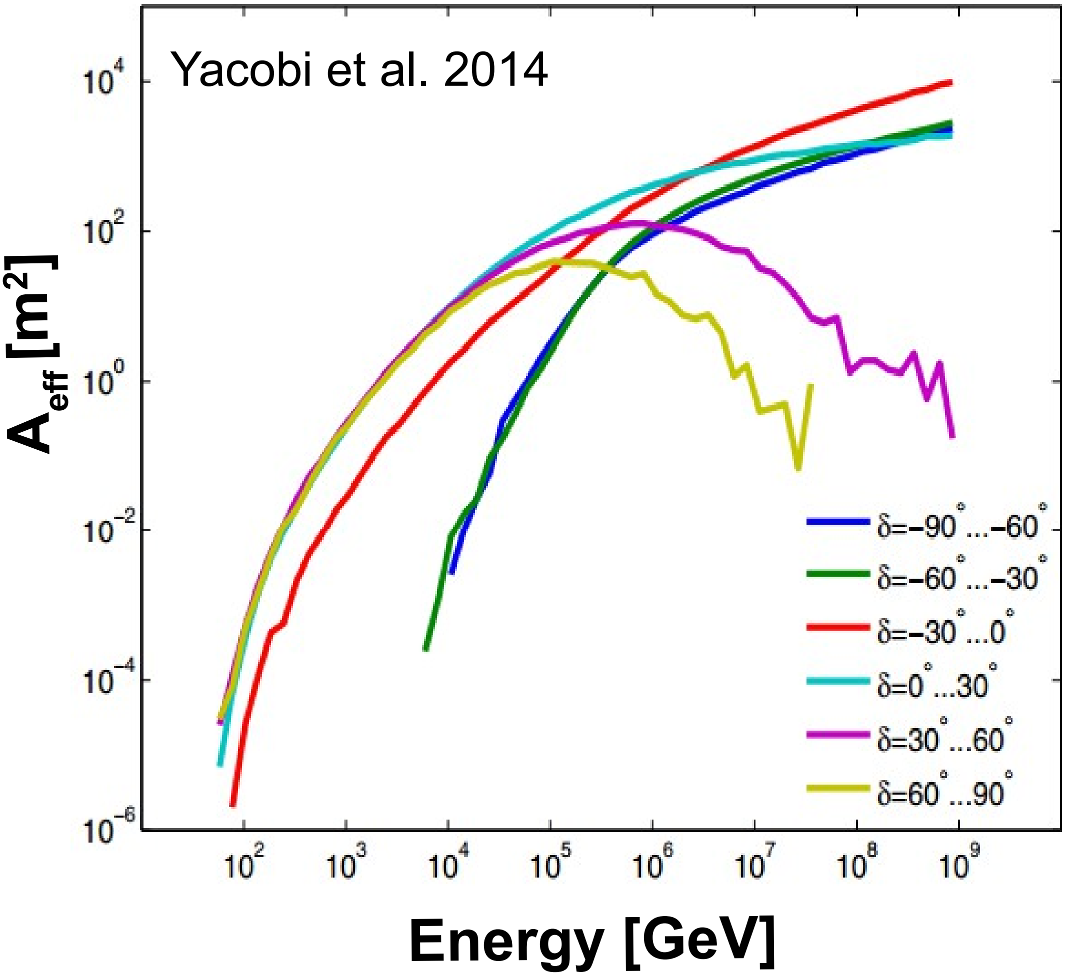
* Γ not secured (from Liang et al 2015)

Back up

IceCube/ANTARES A_{eff}

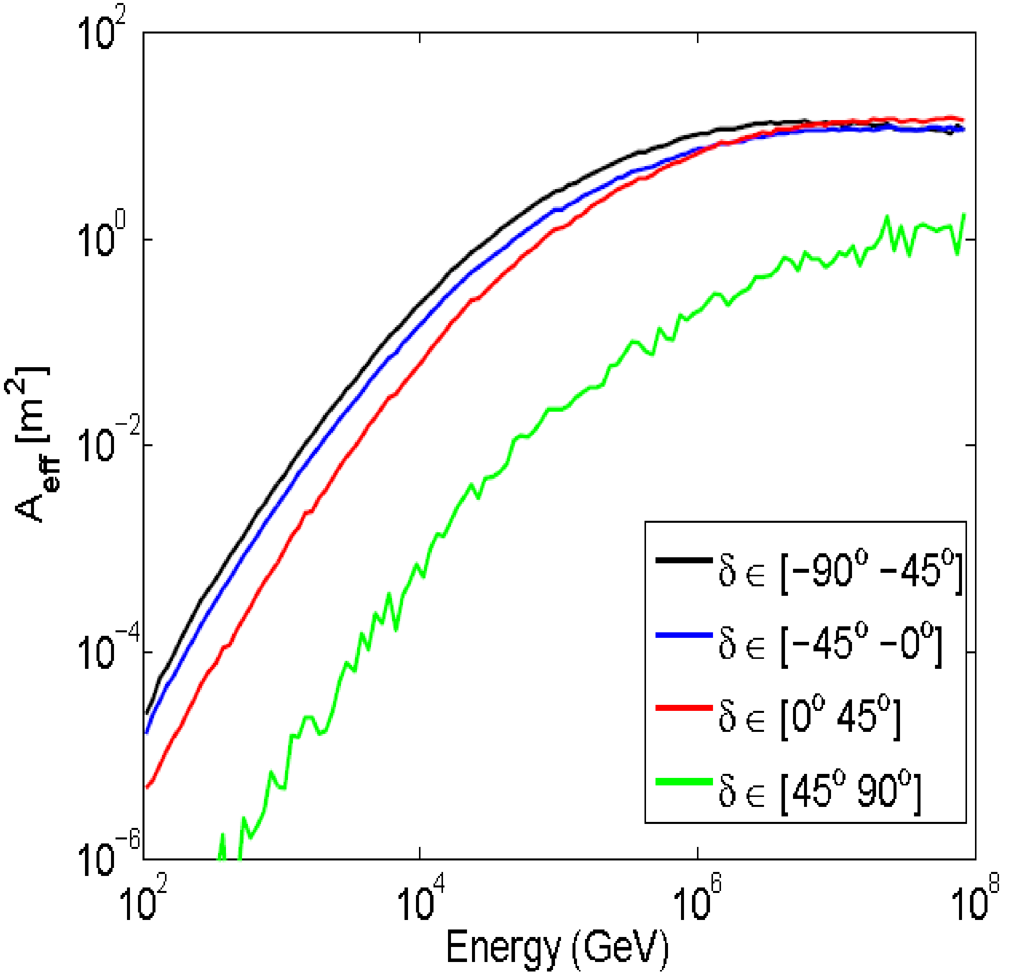
IC86

Better than ANTARES for δ [-30°;90°]

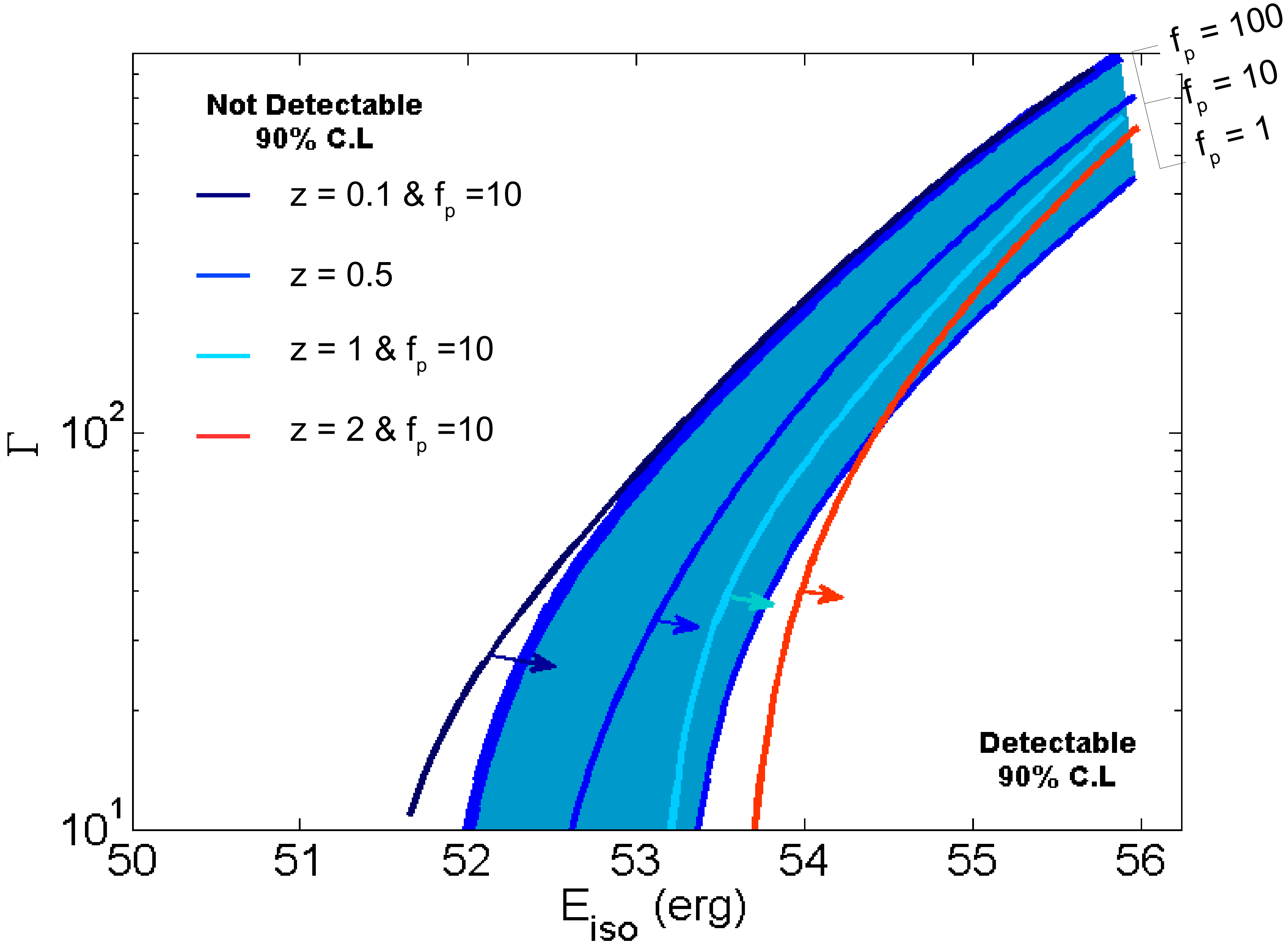


ANTARES [2007-2011]

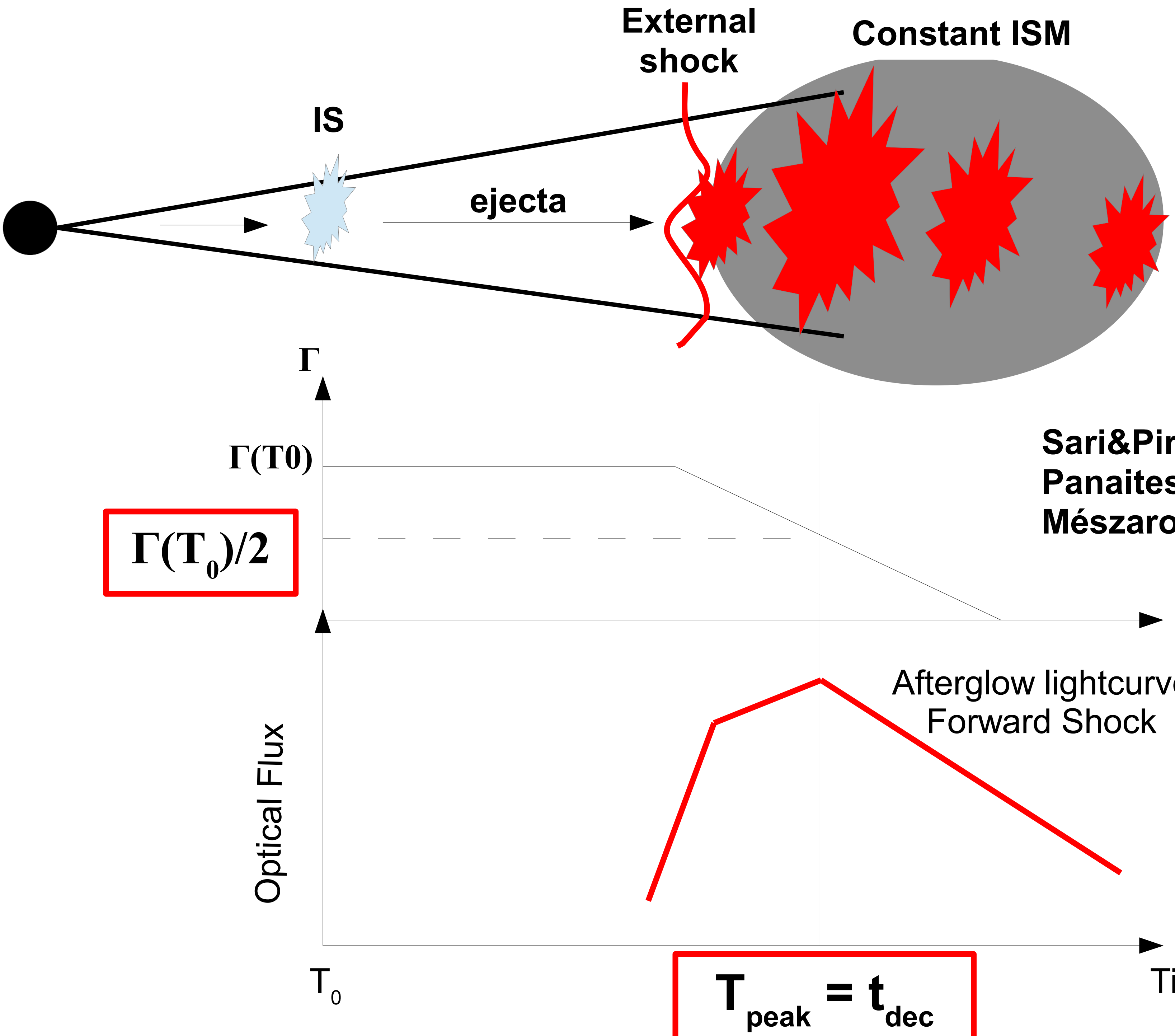
Better than IC86 for δ [-30°;-90°]
below E_ν~ 100 TeV



Impact of f_p in the $E_{iso} - \Gamma$ plane



Connecting Γ with the peak of the optical afterglow



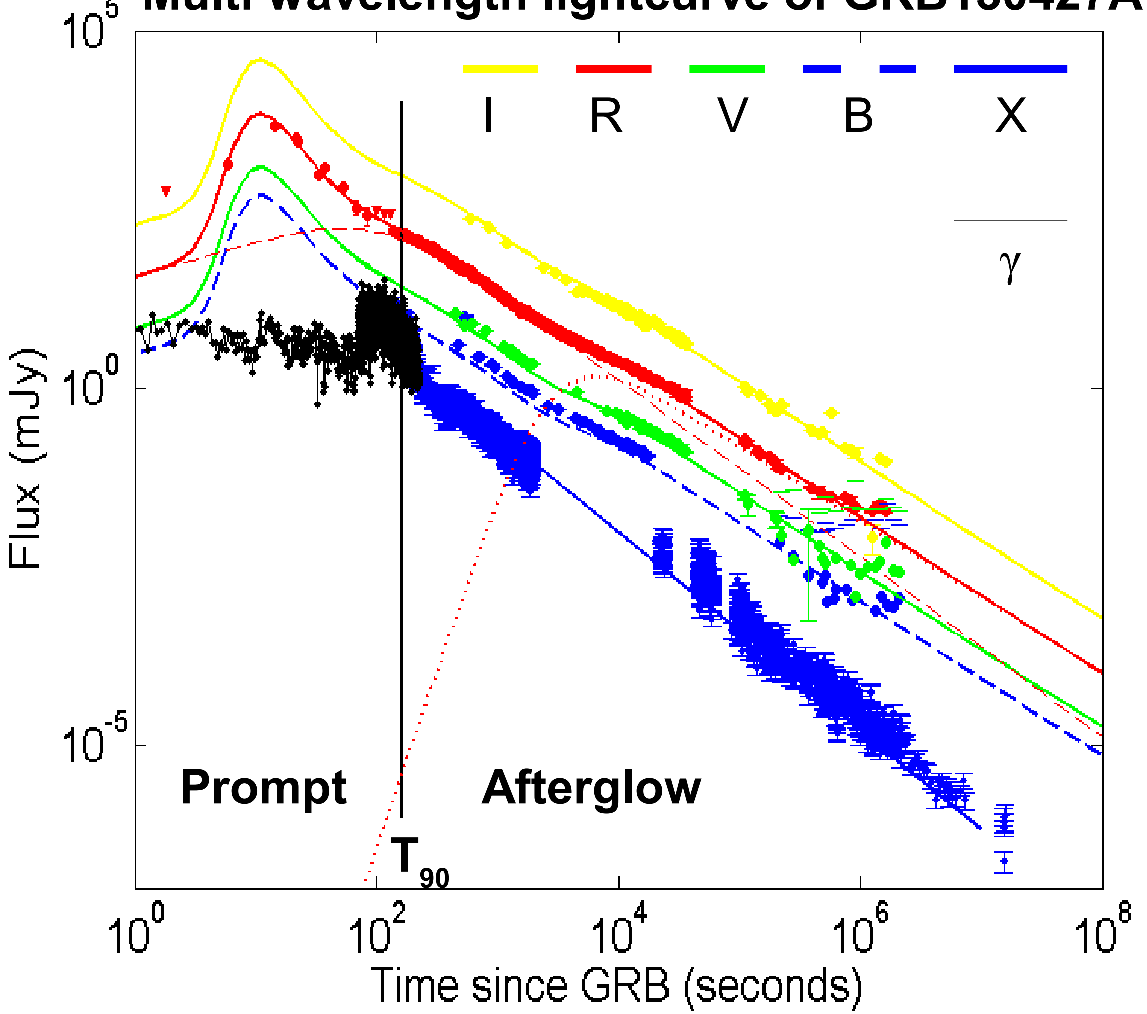
Sari&Piran 1999;
Panaitescu & Kumar 2000
Mészaros 2006

$$\Gamma(T_{peak}) \sim \frac{\Gamma_0}{2} = [\frac{3E_{iso}(1+z)^3}{32\pi n m_p c^5 \eta T_{peak}^3}]^{1/8}$$

Sari&Piran 1999
Molinari et al. 2007

Note that a refined expression for $\Gamma = f(T_{peak})$ has been reported in Ghirlanda et al. 2012. Results are quite similar.

Multi wavelength lightcurve of GRB130427A



Fit a standard afterglow model to R-band optical data

Best fit gives :
T_{peak} = 108 s
n = 0.53 part.cm^{-3}
η = 0.40

$\Gamma(T_{peak}) \sim 225$
$\Gamma_0 \sim 450$

In very good agreement with Hascoet et al. 2015 and references there in