High Energy Neutrino Astronomy

The Neutrino Connections to Cosmic Ray Origins – Present & Future

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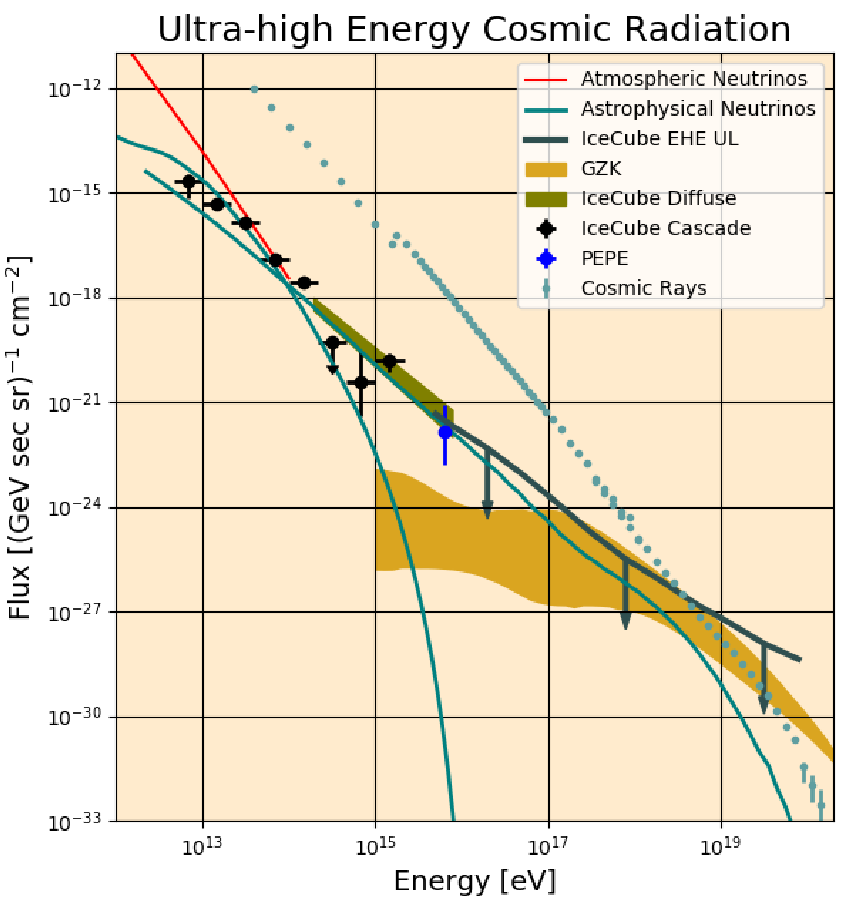
The Global Spectrum of the high-energy cosmic radiations



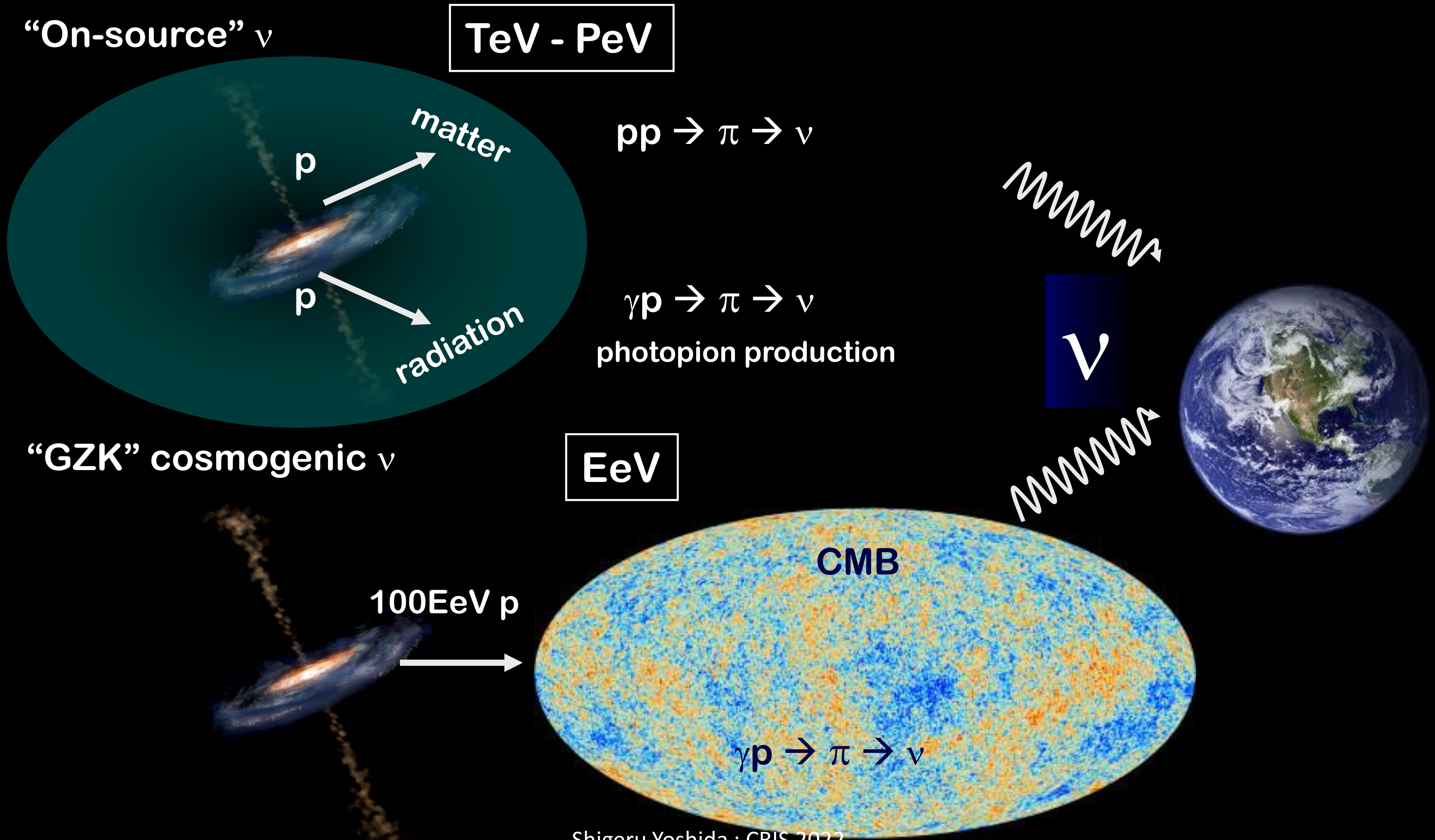
The (diffuse) cosmic background radiations

= the (nearly) isotropic radiations superposed from the numerous sources in the entire sky

- (UHE) Cosmic Rays
- **Neutrinos!**

(power law like) non-thermal spectrum extended from TeV to EeV and beyond

The Cosmic Neutrinos
Production Mechanisms



“On-source” ν

TeV - PeV

pp → π → ν

γp → π → ν

photopion production

“GZK” cosmogenic ν

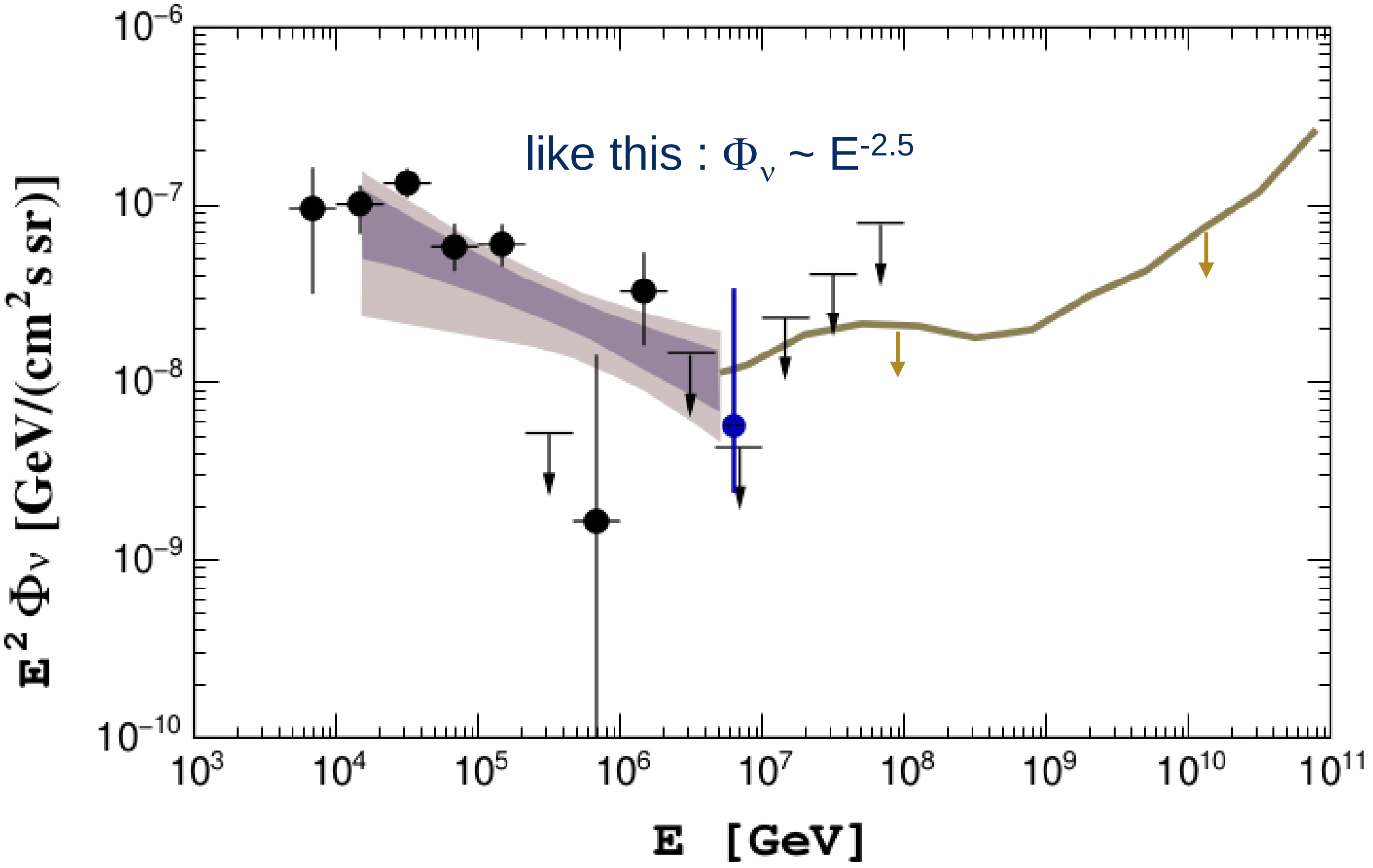
EeV

100EeV p

γp → π → ν

Our data today

A closer look – TeV-EeV range



like this : $\Phi_\nu \sim E^{-2.5}$

all 3-flavor sum flux

TeV PeV EeV

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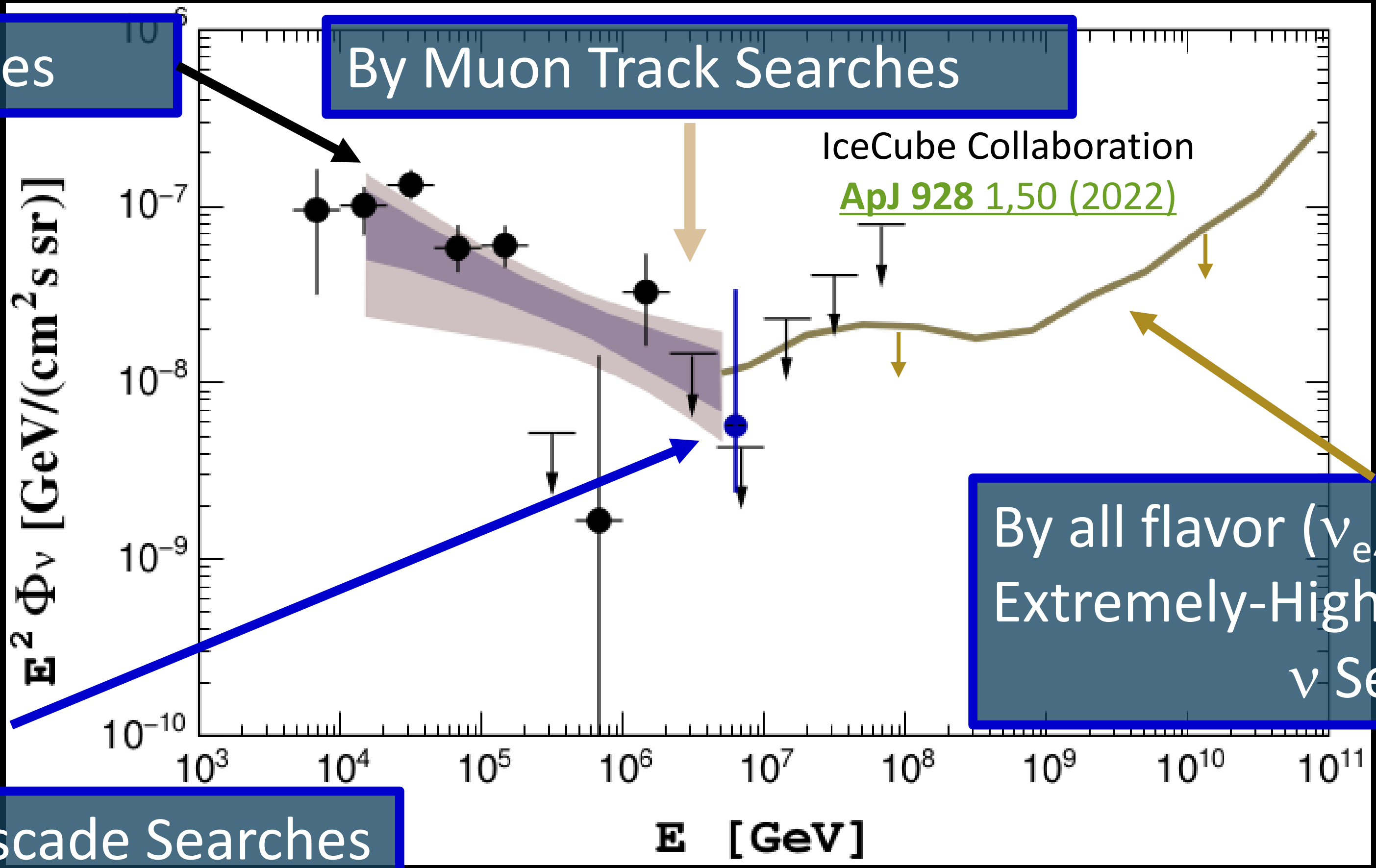

By Cascade Searches

IceCube Collaboration
PRL 125 121104 (2020)

By Muon Track Searches

IceCube Collaboration
ApJ 928 1,50 (2022)

By all flavor (ν_e, ν_μ, ν_τ) sensitive Extremely-High Energy (EHE) ν Searches

IceCube Collaboration
PRL 117 241101 (2016)
PRD 98 062003 (2018)

By Uncontained Cascade Searches

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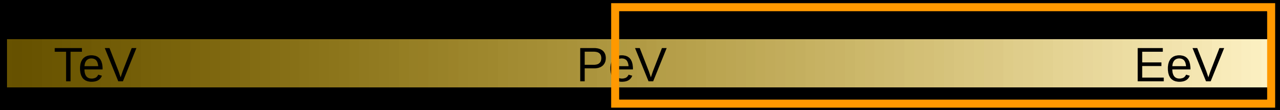
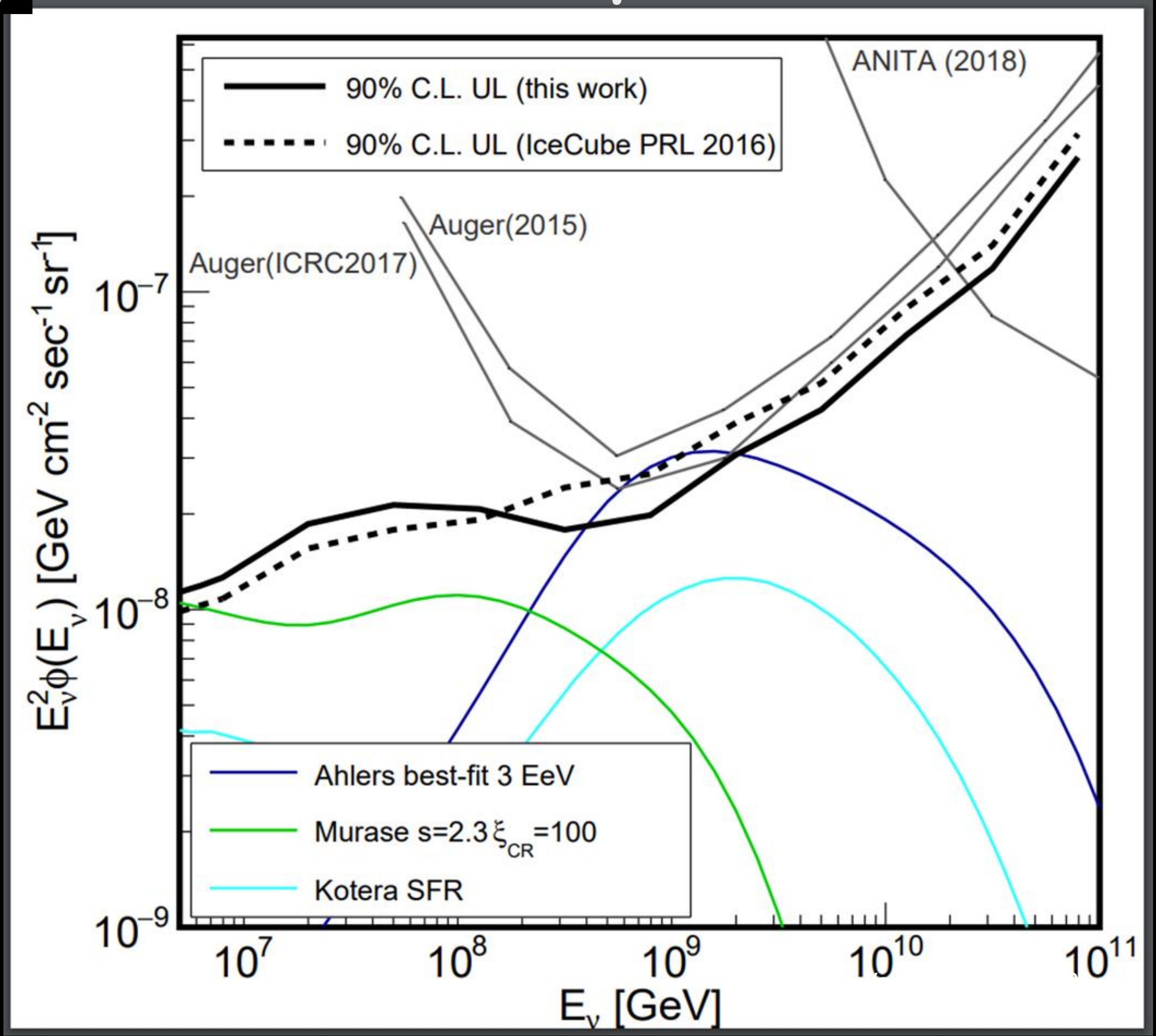
Nature 591 7849 220-224 (2021)



Model Independent Differential Limit



The obtained limit at 1 EeV

~ 2 x 10^{-8} GeV/cm^2 s sr

≈

Energy flux of UHECRs

IceCube Collaboration
PRD 98 062003 (2018)

GZK cosmogenic ν intensity @ 1EeV in the phase space of the emission history

Yoshida and Ishihara, PRD **85**, 063002 (2012)

$\rho \sim (1+z)^m$
$0<z<z_{max}$

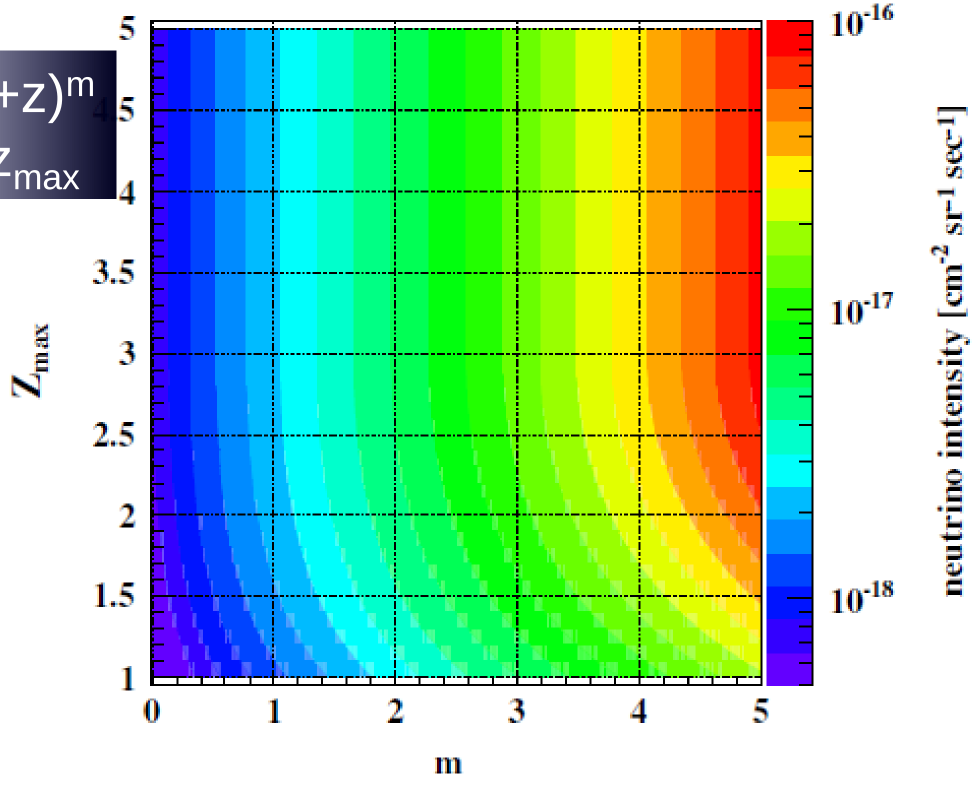


FIG. 2 (color online). Integral neutrino fluxes with energy above 1 EeV, J [cm^{-2} sec^{-1} sr^{-1}], on the plane of the source evolution parameters, m and z_{max}.

GZK ν flux $\phi = (m, z_{max})$

x IceCube Exposure

Event distribution
on plane of (E, cos(zenith))

↕

The *observed* event distribution

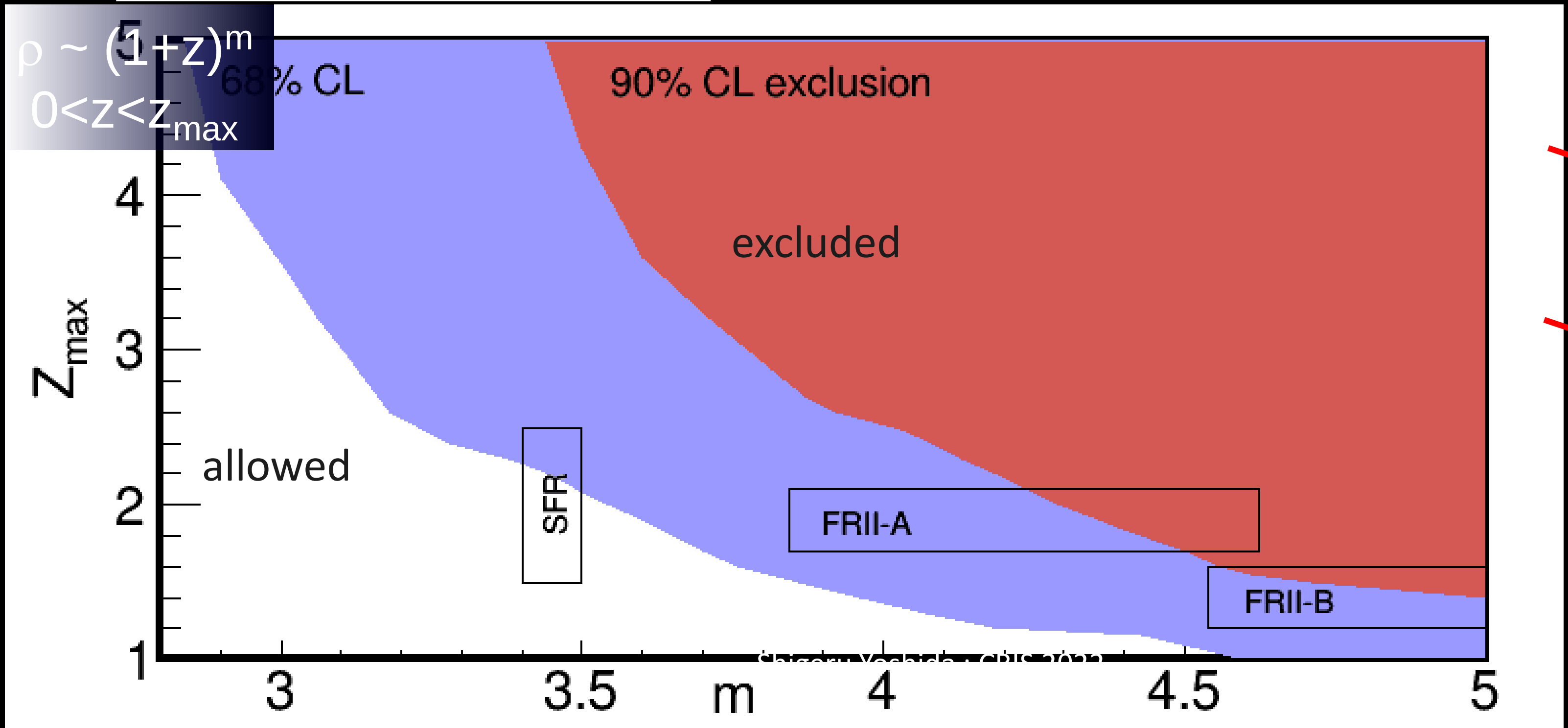
TeV PeV EeV

The Constraints on evolution (emission history) of UHE cosmic ray sources

IceCube Collaboration
Phys.Rev.Lett.**117** 241101(2016) erratum **119** 259902 (2017)

UHECR source
is cosmologically
LESS evolved

Any sources with evolution
compatible or stronger than
star formation rate are disfavored

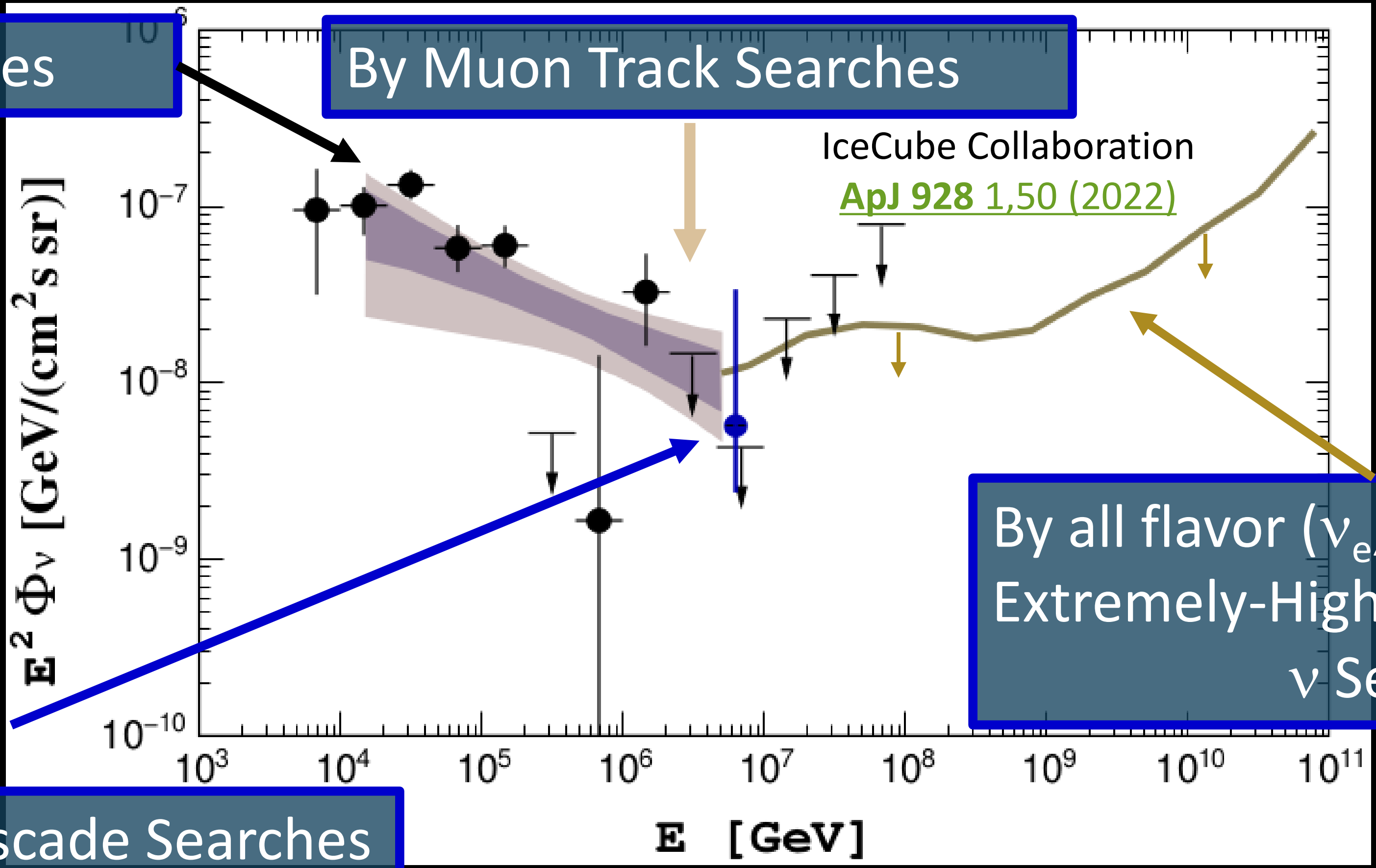

$\rho \sim (1+z)^m$
$0<z<z_{max}$

~~FRII (FSRQs)~~

~~GRBs~~

Our data today

A closer look – TeV-EeV range



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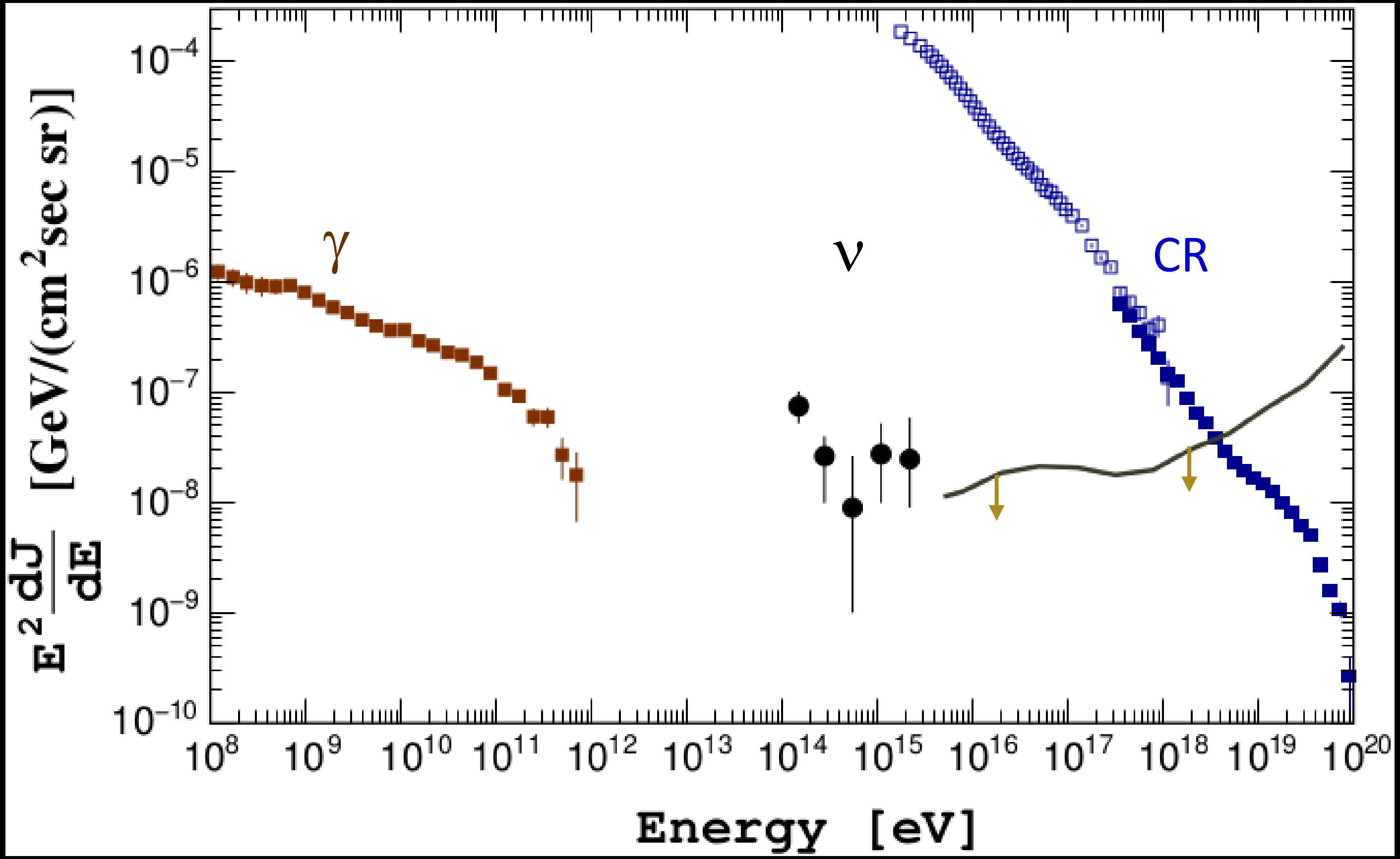
The energy fluxes in the multi-messengers



The bottom line

UHECR ~ Neutrinos!

~ 10^{-8} GeV cm^{-2} s^{-1} sr^{-1}

Why? By accident?

The energetics argument

Waxman & Bahcall (1998), Murase & Fukugita (2019) and more..

per source

neutrinos cosmic rays

$$\frac{d\dot{N}_\nu}{d\varepsilon_\nu} \approx \xi_\pi \tau_{p\gamma 0} \frac{1}{x_\pi y_\nu} \frac{d\dot{N}_{\rm CR}}{d\varepsilon_{\rm CR}}\left(\varepsilon_{\rm CR} = \frac{\varepsilon_\nu}{x_\pi y_\nu}\right)$$

pγ optical depth

charged pion multiplicity

energy flux

neutrinos cosmic rays

$$\varepsilon_\nu^2 \frac{d\dot{N}_\nu}{d\varepsilon_\nu} \approx \xi_\pi \tau_{p\gamma 0} x_\pi y_\nu \varepsilon_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{d\varepsilon_{\rm CR}}\left(\varepsilon_{\rm CR} = \frac{\varepsilon_\nu}{x_\pi y_\nu}\right)$$

$$n_0 \varepsilon_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{d\varepsilon_{\rm CR}} \approx 6 \times 10^{+43} \left(\frac{E_{\rm CR}^2 \Phi_{\rm CR}}{2 \times 10^{-8}\ \mathrm{GeV\ cm^{-2}\ sec^{-1}\ sr^{-1}}}\right) \left(\frac{ct_{\rm BH}}{2\mathrm{Gpc}}\right)^{-1} [\mathrm{erg\ Mpc^{-3}\ yr^{-1}}]$$

cosmic background energy flux

per source source evolution

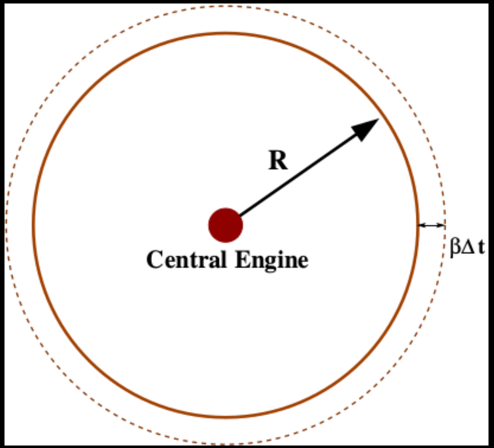
$$E_\nu^2 \Phi_\nu(E_\nu) = \frac{c}{4\pi} \int_0^{z_{\rm max}} \frac{dz}{1+z} \left|\frac{dt}{dz}\right| \left[\varepsilon_\nu^2 \frac{d\dot{N}_\nu}{d\varepsilon_\nu}(\varepsilon_\nu)\right] n_0 \psi(z),$$

$$\approx \frac{c}{4\pi} t_{\rm H} \left(\frac{1}{t_{\rm H}} \int \frac{dz}{1+z} \left|\frac{dt}{dz}\right| \psi(z)\right) \tau_{p\gamma 0} x_\pi \xi_\pi y_\nu n_0 \varepsilon_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{d\varepsilon_{\rm CR}}$$

$$\approx 4.5 \times 10^{-8} \left(\frac{\xi_z}{3}\right) \left(\frac{\tau_{p\gamma 0} x_\pi}{1}\right) \left(\frac{\xi_\pi y_\nu}{\frac{3}{8}}\right) \left(\frac{E_{\rm CR}^2 \Phi_{\rm CR}}{2 \times 10^{-8}\ \mathrm{GeV\ cm^{-2}\ sec^{-1}\ sr^{-1}}}\right) \left(\frac{ct_{\rm BH}}{2\mathrm{Gpc}}\right)^{-1} [\mathrm{GeV\ cm^{-2}\ sec^{-1}\ sr^{-1}}]$$

The **unified source** modeling

Yoshida & Murase PRD (2020)



$$L'_\gamma \approx L_\gamma/\Gamma^2$$

(co-moving) Luminosity of Photons that collides with protons

power-law index of photon spectrum

$$\tau_{p\gamma}(\varepsilon'_p) = \frac{2}{1+\alpha_\gamma}\frac{L'_{\gamma 0}}{4\pi R\Gamma c\varepsilon'_{\gamma 0}}\int ds\,\frac{\sigma_{p\gamma}(s)}{s-m_p^2}\left(\frac{\varepsilon'_p}{\tilde{\varepsilon}_{p0}{}'(s)}\right)^{\overset{\downarrow}{\alpha_\gamma}-1},$$

Optical depth to pγ interactions

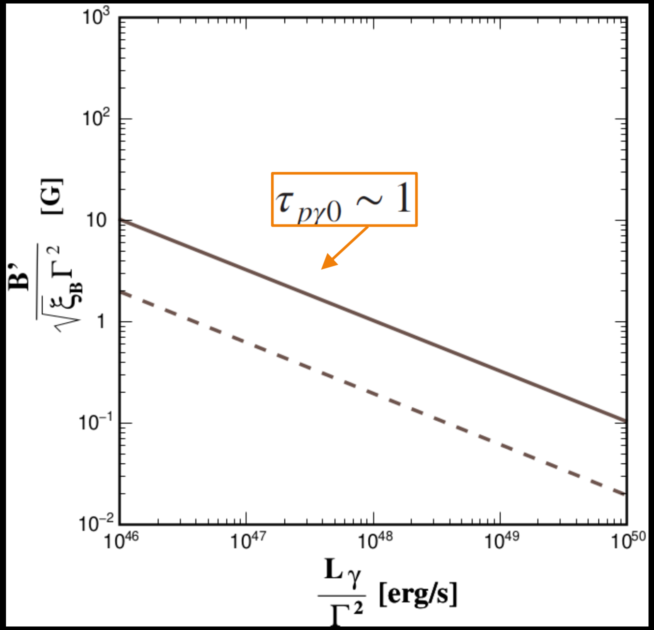
Specify the optical depth → R is determined
→ B-field strength is determined
by the equipartition principle

$$U'_{\rm B} = \xi_{\rm B}\frac{L'_\gamma}{4\pi R^2 c} = \xi_{\rm B}\frac{L_\gamma}{4\pi\Gamma^2 R^2 c},$$

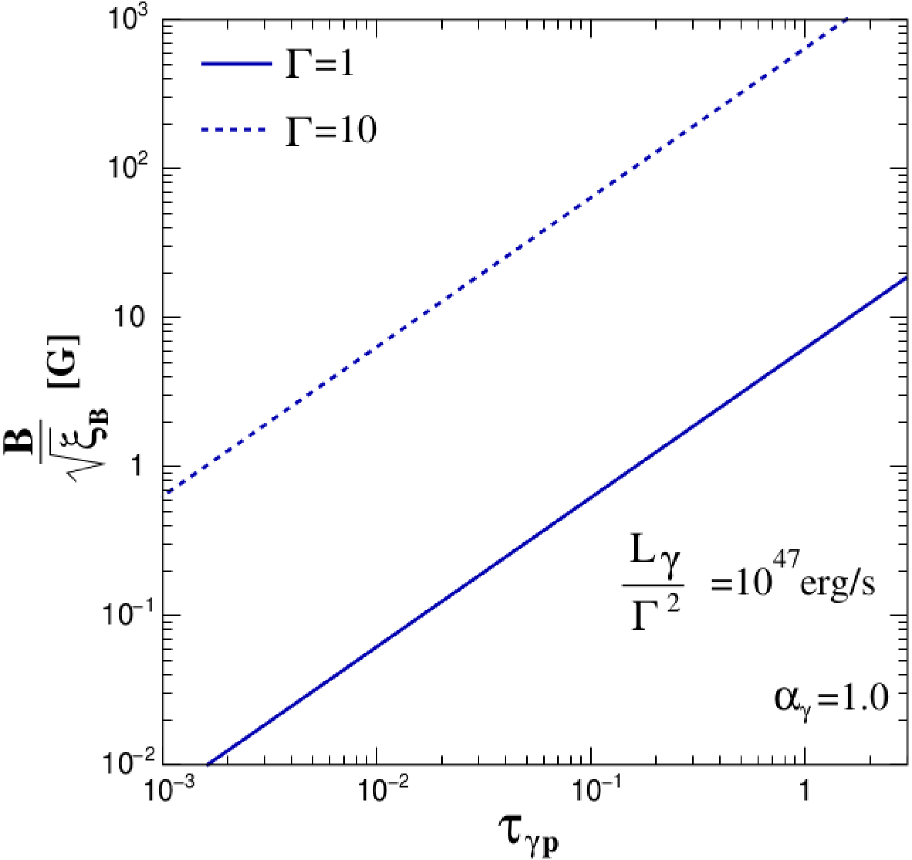
B-field equipartition parameter

$$\frac{B'/\Gamma^2}{\tau_{p\gamma 0}\sqrt{\xi_B/L'_\gamma}} = C(\alpha_\gamma, \tilde{\varepsilon}^{\Delta}_{p0})^{-1},$$

constant



neutrino production optical depth uniquely specifies the B-field



The **unified source** modeling

Requirements for being both UHECR and neutrino emitters

Acceleration Condition

acceleration time < dynamical time

$$L'_\gamma \geq \frac{1}{2}\xi_B^{-1} c\eta^2\beta^2 \left(\frac{\varepsilon_i^{\max}}{Ze}\right)^2$$
$$\simeq 1.7 \times 10^{45}\ \mathrm{erg/s}\,\xi_B^{-1}\eta^2\beta^2 \left(\frac{\varepsilon_i^{\max}}{Z10^{11}\ \mathrm{GeV}}\right)^2$$

Synchrotron Condition

acceleration time < cooling time

$$B' < \frac{A^4 6\pi e m_p^4 c^4}{Z^3 \sigma_T m_e^2} \frac{\Gamma^2}{(\varepsilon_i^{\max})^2}$$

Escape Condition

dynamical time < cooling time

$$B' < \frac{6\pi A^4 m_p^4 c^{9/2}}{Z^4 \sigma_T m_e^2 (2\xi_B L'_\gamma)^{1/2}} \frac{\Gamma^2}{\varepsilon_i^{\max}}$$

optical depth condition
= neutrino production power

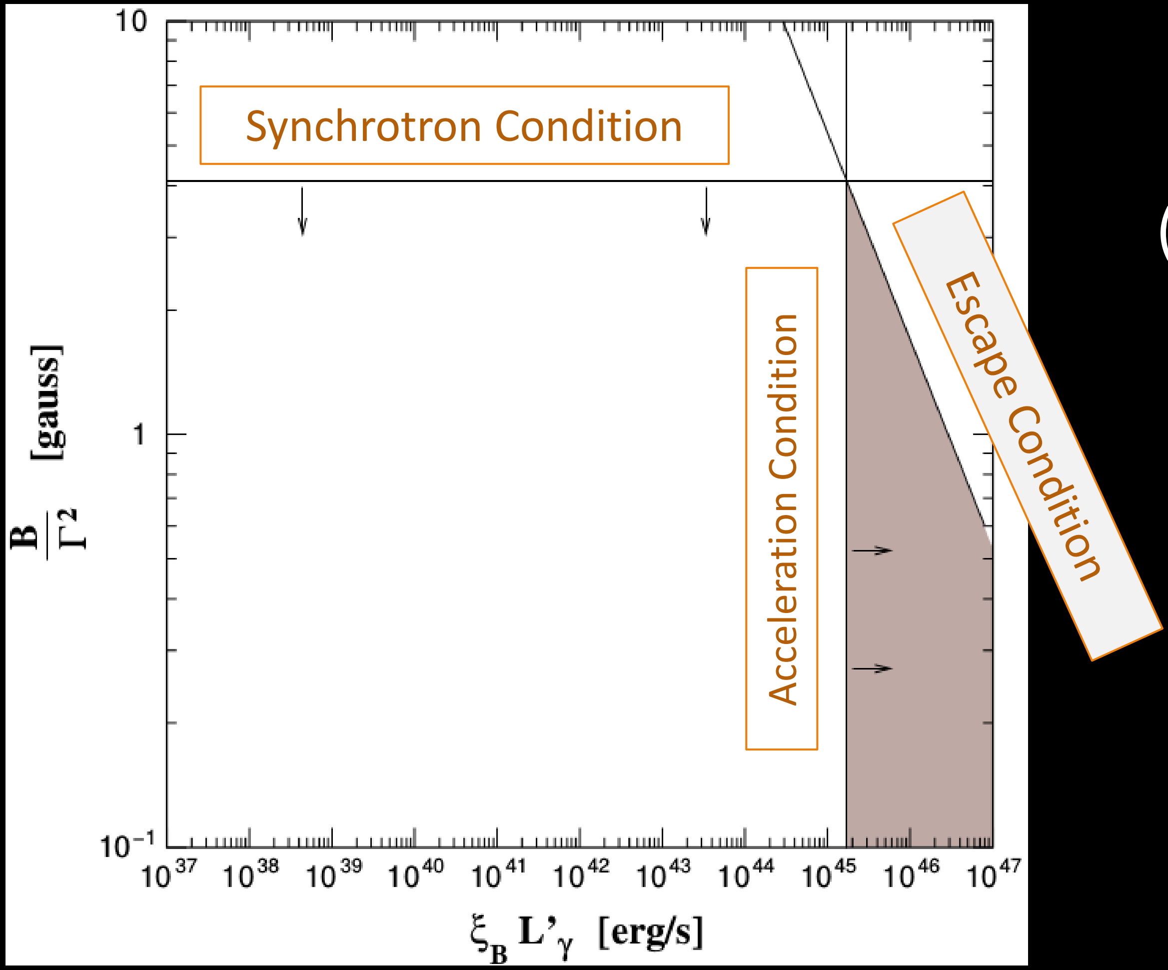
$$\tau_{p\gamma 0} < \frac{C(\alpha_\gamma, \tilde{\varepsilon}_{p0}^{\Delta}) 6\pi e m_p^4 c^4}{\sigma_T m_e^2} \frac{A^4}{Z^3} \left(\frac{L'^{1/2}_\gamma}{\xi_B^{1/2} (\varepsilon_i^{\max})^2}\right)$$

$$\tau_{p\gamma 0} < \frac{2}{1+\alpha_\gamma}\left(\int ds \frac{\sigma_{p\gamma}}{s - m_p^2}\right) \frac{3A^4 m_p^4 c^4 (L'_{\gamma 0}/L'_\gamma)}{4Z^4 \sigma_T m_e^2 (\varepsilon'_{\gamma 0}/\Gamma)} \frac{1}{\xi_B \varepsilon_i^{\max}}$$
$$\lesssim \boxed{6 \times 10^{-2}} \frac{2}{1+\alpha_\gamma} \xi_B^{-1} \left(\frac{A}{Z}\right)^4 \left(\frac{\varepsilon_i^{\max}}{10^{11}\ \mathrm{GeV}}\right)^{-1}$$

small! We may need $\xi_B \ll 1$ to compensate

Yoshida & Murase PRD (2020)

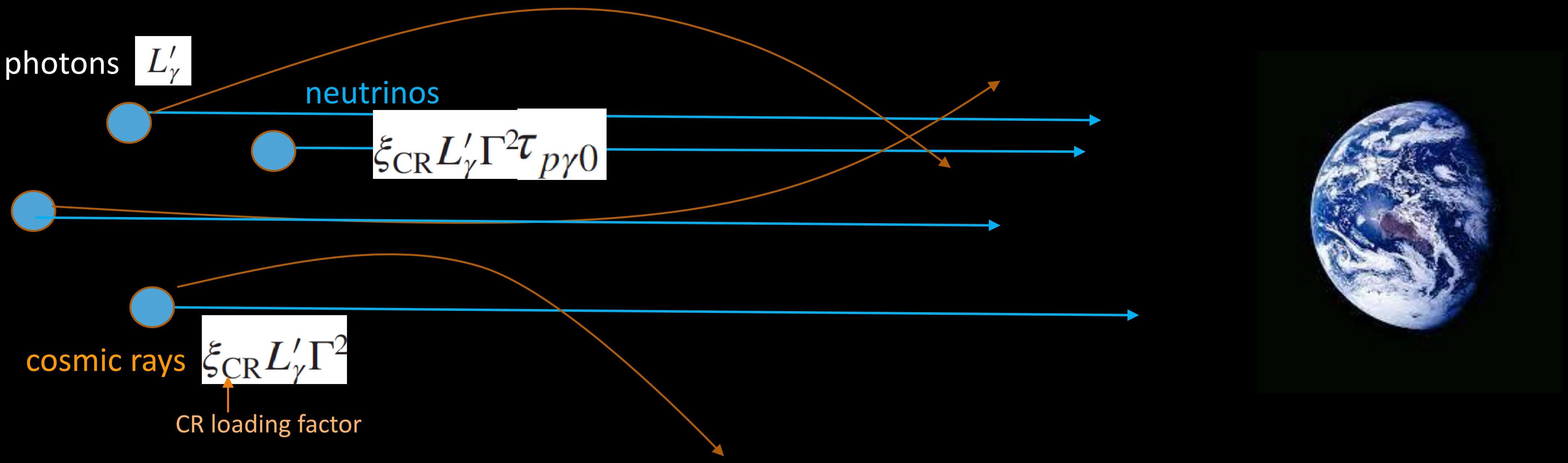
An example of constraints – B -field



(co-moving) B-field ~ $1\Gamma^2$ Gauss

(co-moving) source luminosity
~ 2 x 10^{45} ξ_B^{-1} Z^{-2} erg/s

The diffuse cosmic background fluxes from the unified sources



photons L'_γ

neutrinos $\xi_{\mathrm{CR}} L'_\gamma \Gamma^2 \tau_{p\gamma 0}$

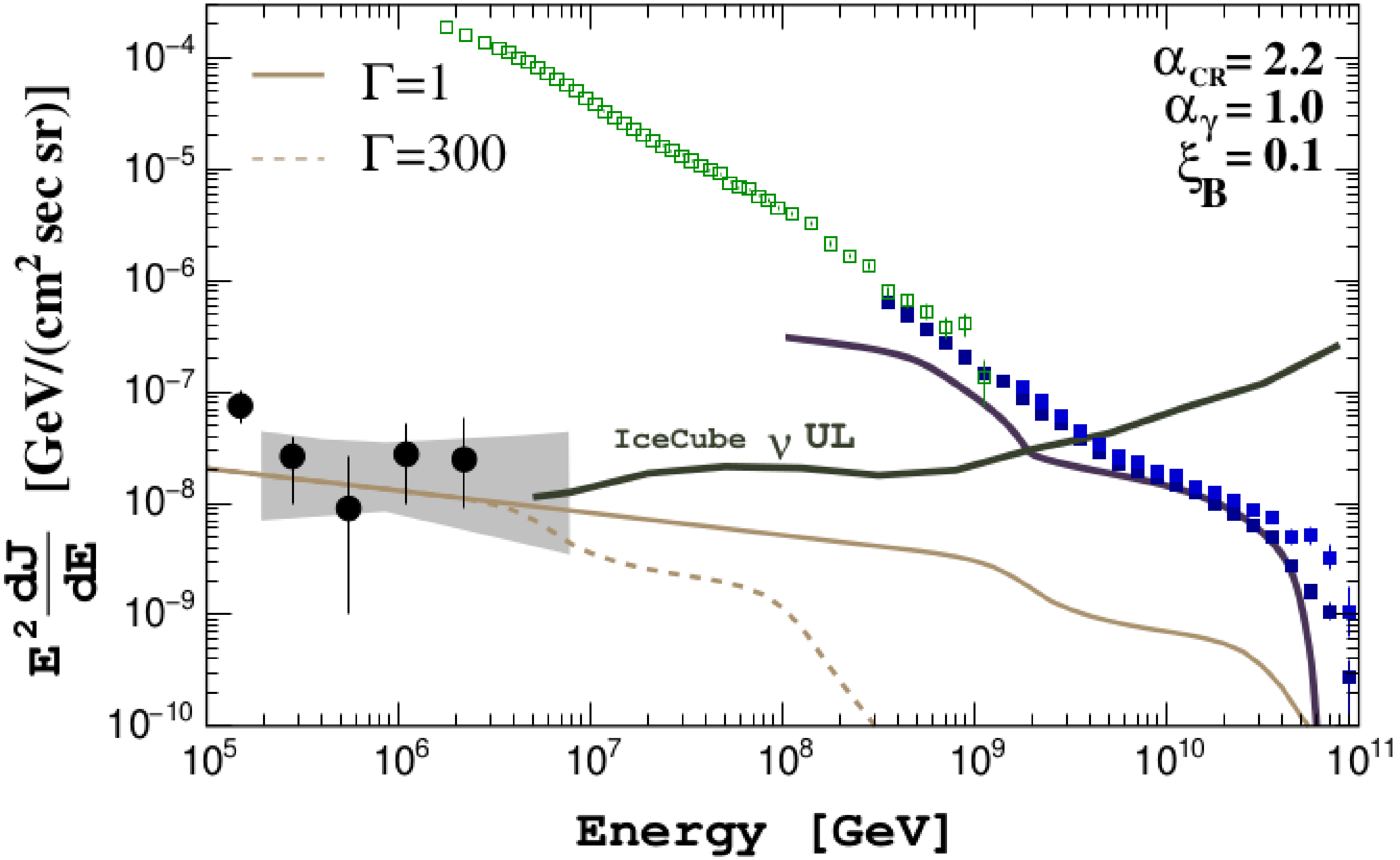
cosmic rays $\xi_{\mathrm{CR}} L'_\gamma \Gamma^2$

CR loading factor

boosted source density

$$\mathcal{N}_\Gamma \equiv n_0 \xi_{\mathrm{CR}} \Gamma^2 = \rho_0 \Delta T \xi_{\mathrm{CR}} \Gamma^2.$$

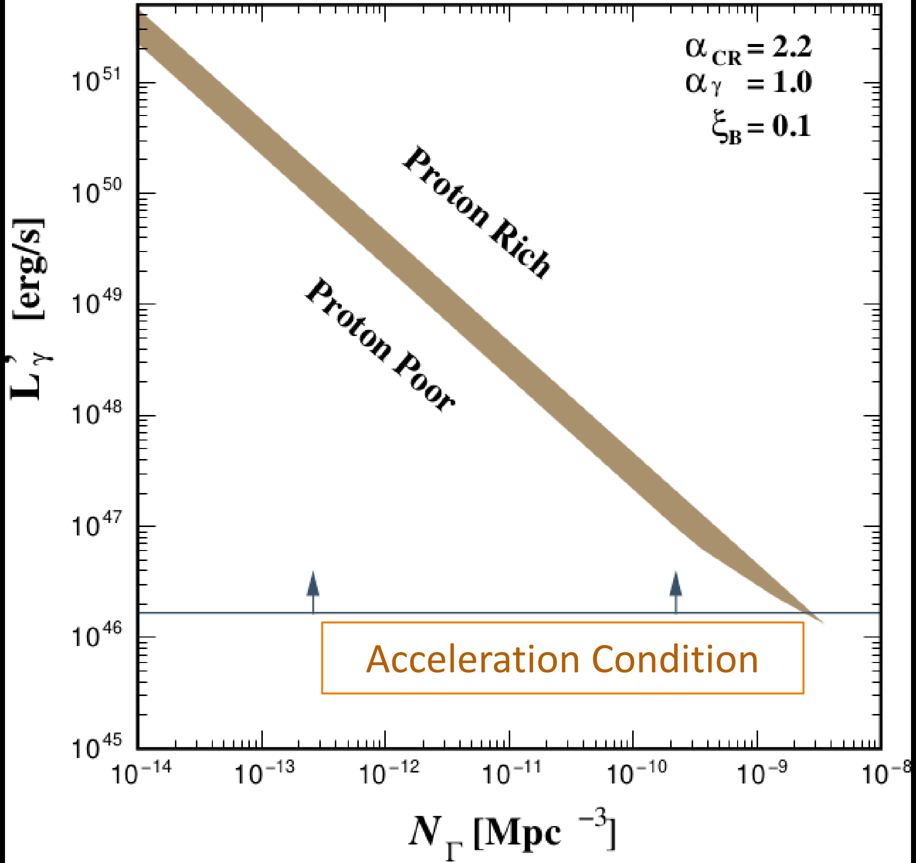
The fluxes from the **unified sources**



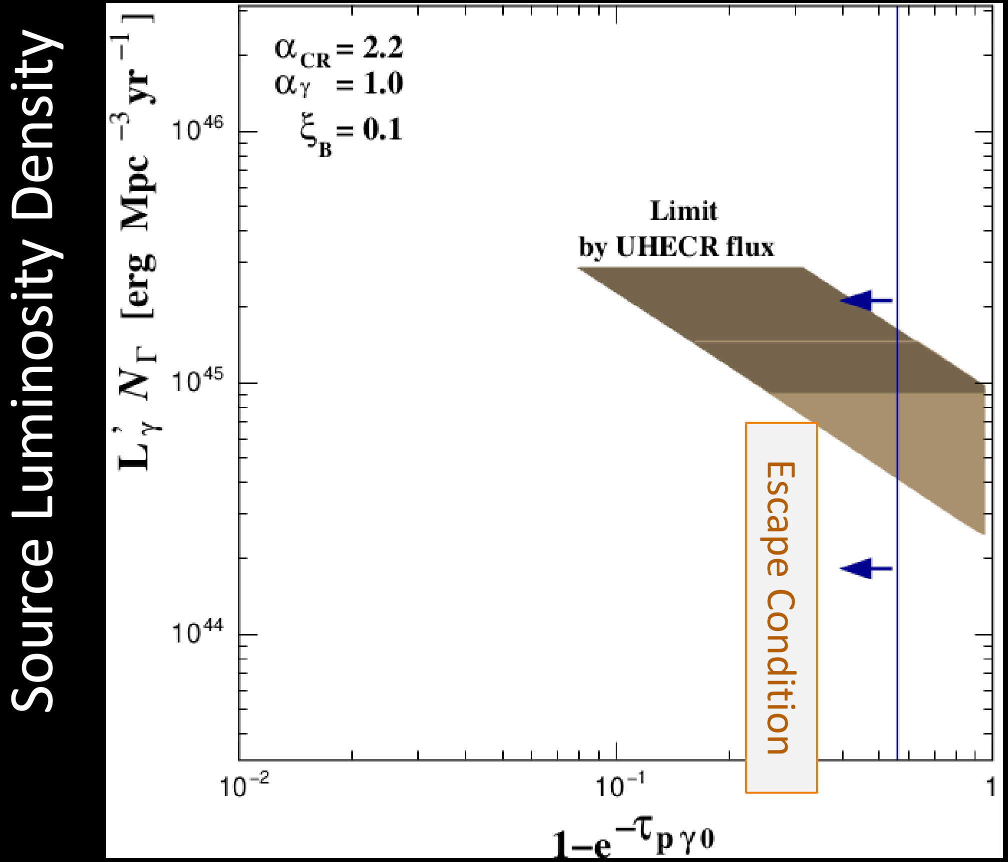
L'_γ	4.5 x 10^{46} erg/s
$\tau_{p\gamma 0}$	0.3
$\mathcal{N}_\Gamma$	1 x 10^{-9} Mpc^{-3}
ξ_B	0.1

Yoshida & Murase PRD (2020)

The allowed parameter space



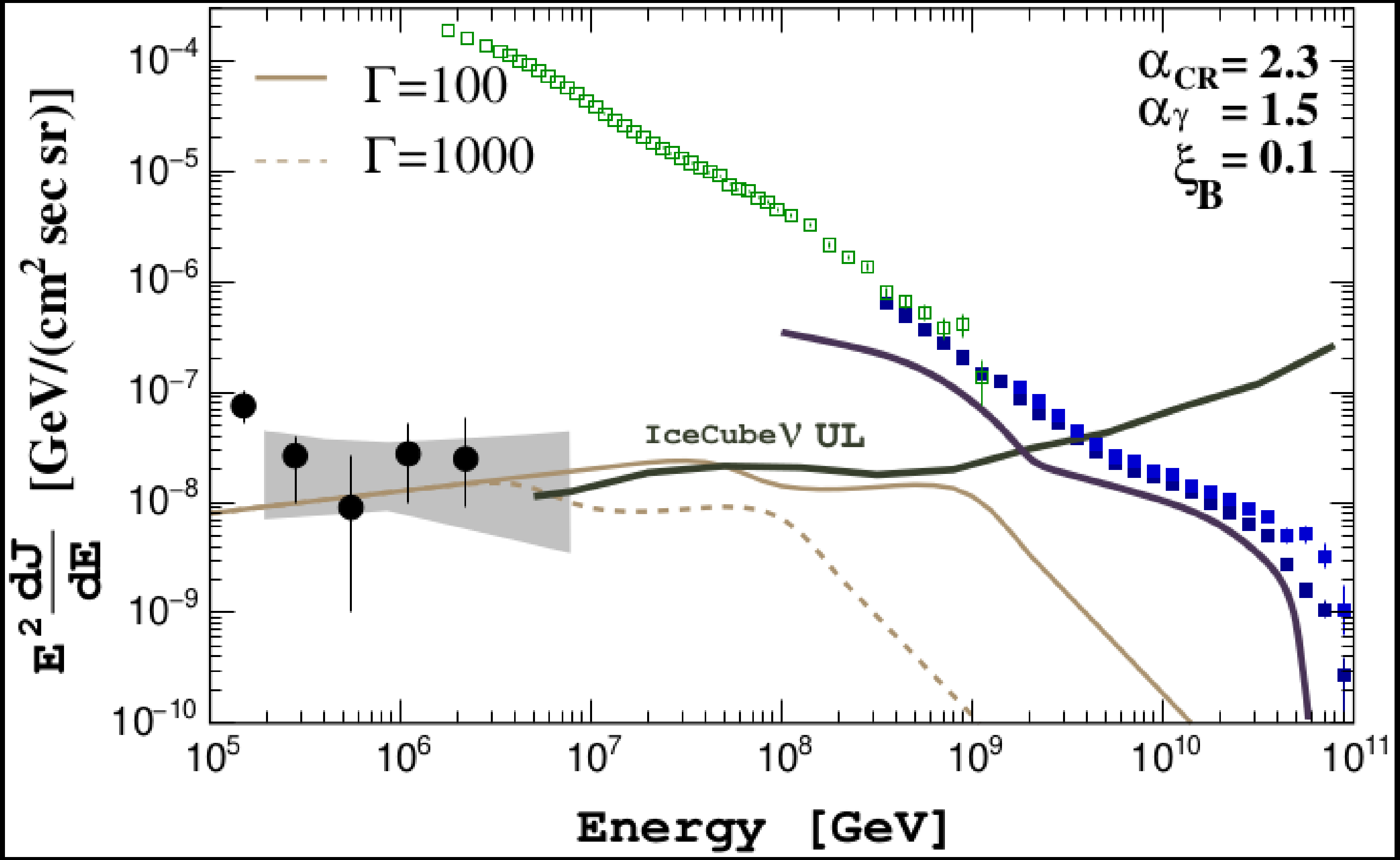
$$\mathcal{N}_\Gamma \equiv n_0 \xi_{\rm CR} \Gamma^2 = \rho_0 \Delta T \xi_{\rm CR} \Gamma^2.$$



$\xi_B < 0.5$ $\tau_{p\gamma} = [0.1, 1]$ Luminosity Density ~ 2 x 10^{45} erg/s

Yoshida & Murase PRD (2020)

The hard spectrum scenario

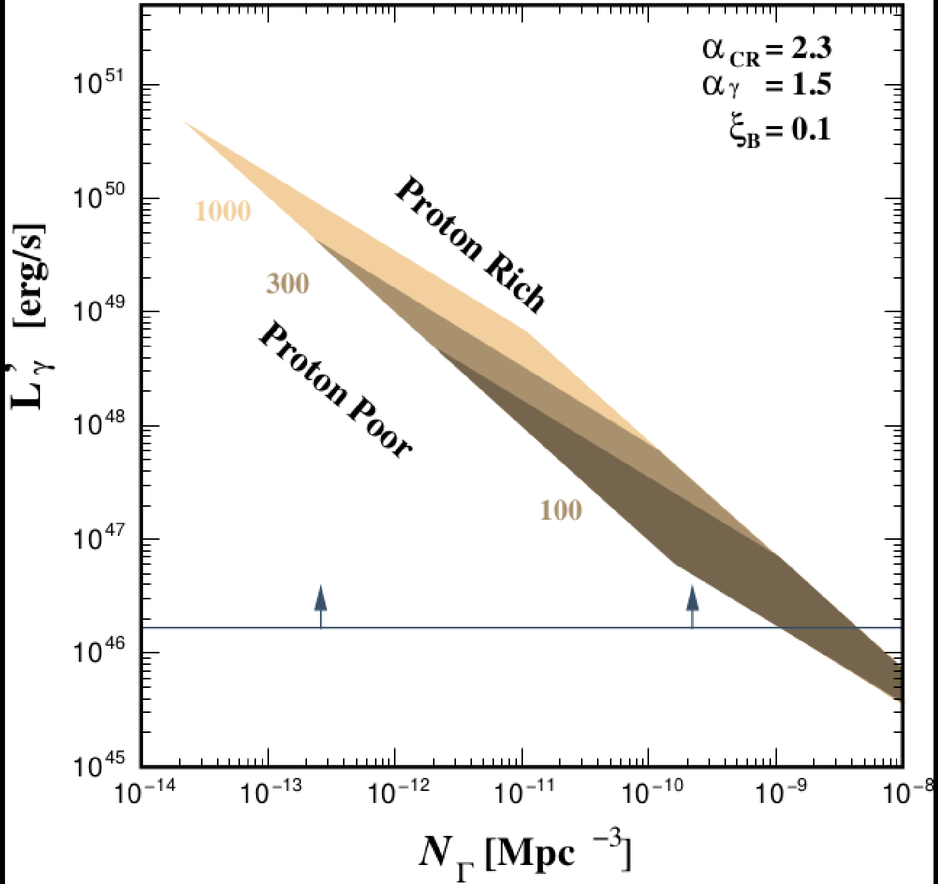


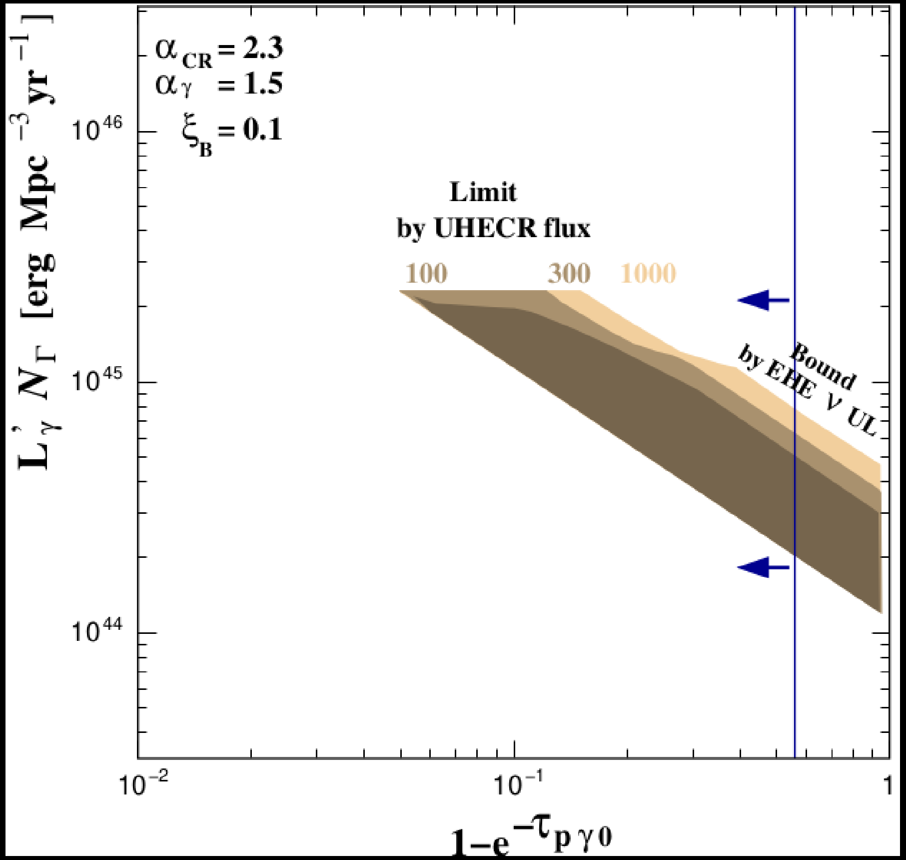
L'_γ	5.0 x 10^{46} erg/s
$\tau_{p\gamma 0}$	0.1
$\mathcal{N}_\Gamma$	1 x 10^{-9} Mpc^{-3}
ξ_B	0.1

$$\varepsilon_\nu^{\rm syn} \propto \sqrt{L'_\gamma}/(\Gamma \tau_{p\gamma 0})$$

The hard spectrum scenario

Require ultra-relativistic plasma flow, i.e., Γ >>1, to be consistent with IceCube EHE limit





$$\varepsilon_\nu^{\rm syn} \propto \sqrt{L'_\gamma}/(\Gamma \tau_{p\gamma 0})$$

Nuclei case : The unified sources emit nuclei

Nuclei must not be fully disintegrated – You would have seen only protons, otherwise

Nuclear Survival Condition

Murase & Beacom (2010)

photodisintegration
optical depth

$$\tau_{A\gamma}(\varepsilon_i^{\max}) \lesssim A,$$

connections
of photodisintegration
to photo-meson production pγ

$$\tau_{p\gamma 0} \approx \tau_{A\gamma}(\varepsilon_i^{\max}) \frac{\int ds \, \frac{\sigma_{p\gamma}(s)}{s-m_p^2}}{\int ds \, \frac{\sigma_{A\gamma}(s)}{s-m_A^2}} \left[\left(\frac{s_{\rm GDR} - m_A^2}{s_\Delta - m_p^2} \right) \left(\frac{\tilde{\varepsilon}_{p0}^{\Delta}}{\varepsilon_i^{\max}} \right) \right]^{\alpha_\gamma - 1}$$

More *severe* constraints on
the pγ optical depth

neutrino production power is more limited

Neutrino flux from nuclei

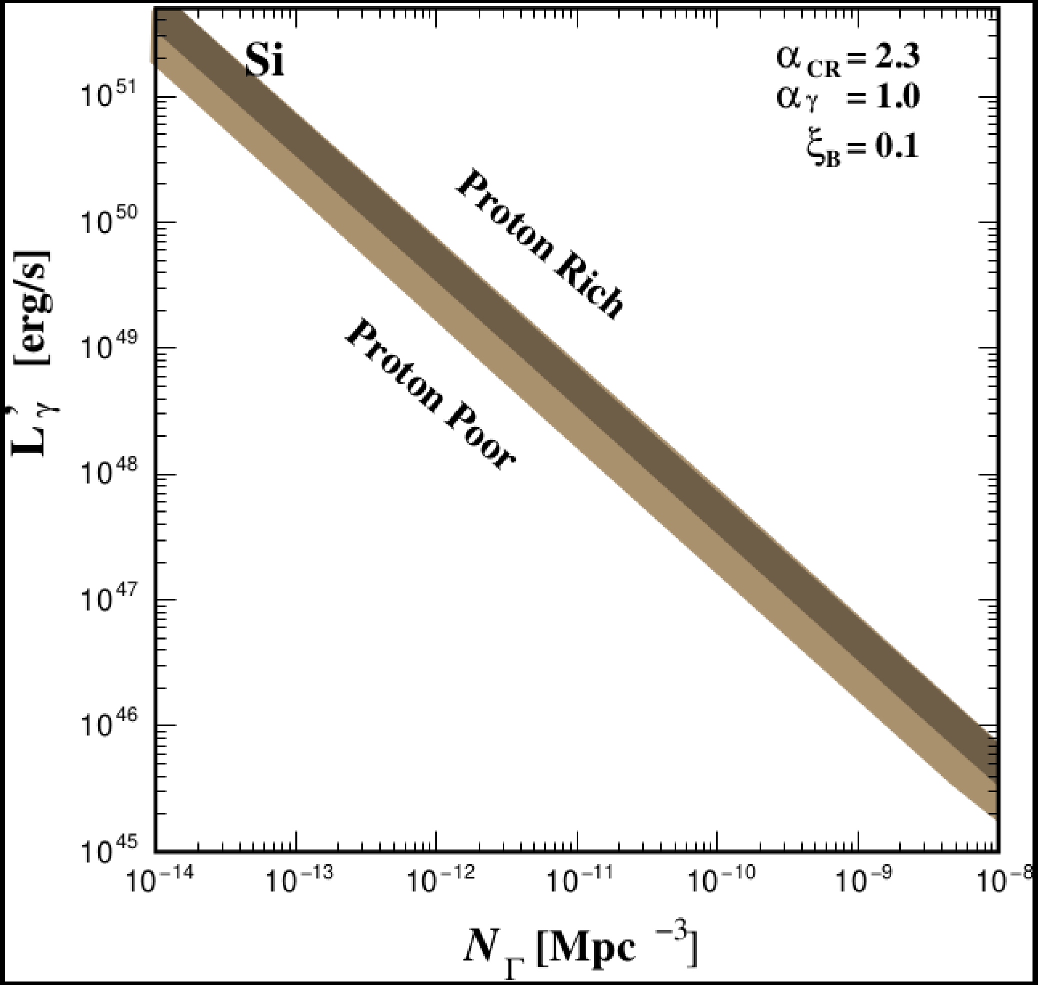
$$E_\nu^2 \frac{dJ_\nu}{dE_\nu} \approx \frac{3}{8} \kappa_{p\gamma} \tau_{p\gamma}[E_i/A] \kappa_{\rm dis} \tau_{A\gamma} E_i^2 \frac{dJ_{\rm CR}}{dE_i} + \frac{3}{8} \kappa_{\rm mes} \tau_{\rm mes}[E_i](1 - \kappa_{\rm dis}\tau_{A\gamma}) E_i^2 \frac{dJ_{\rm CR}}{dE_i}$$

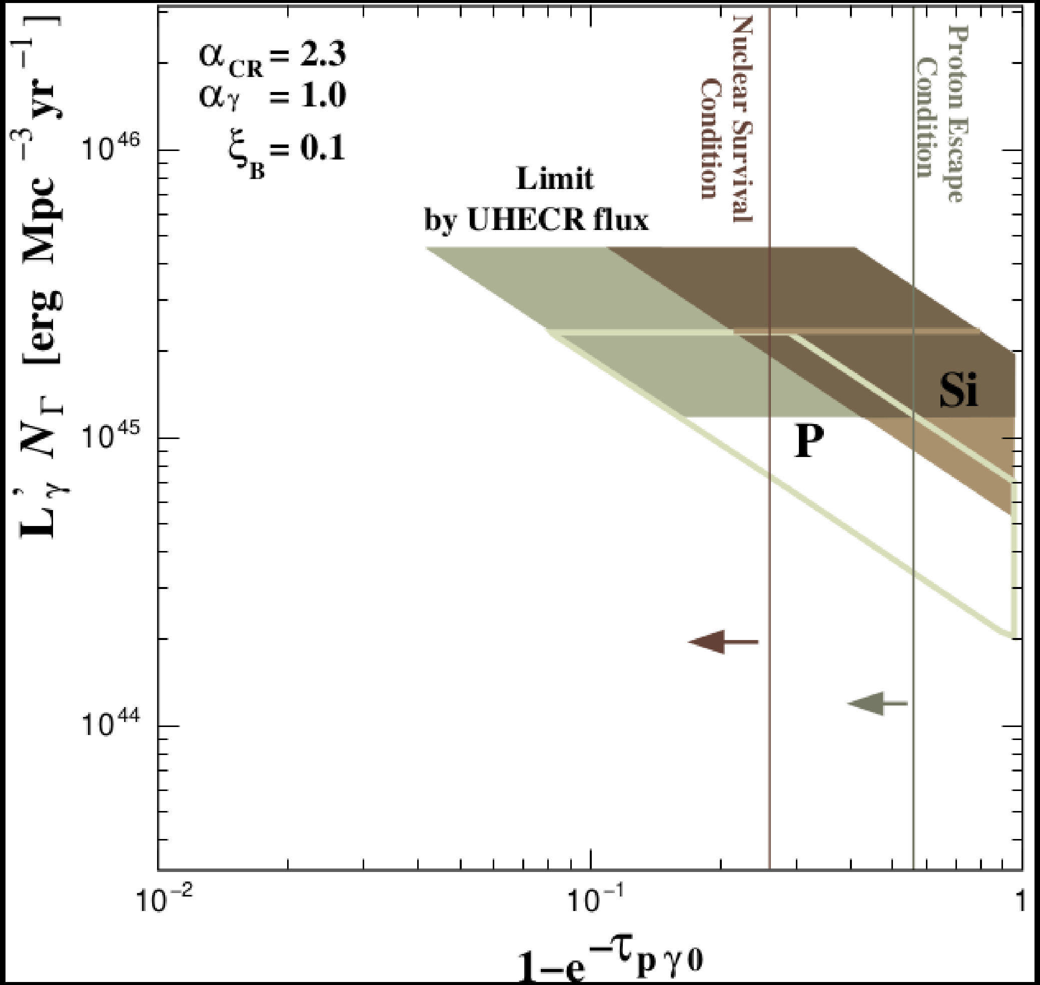
pγ for the secondary produced protons

photo-meson production on nuclei

Nuclei case : The unified sources emit nuclei

The only narrow parameter space is allowed!





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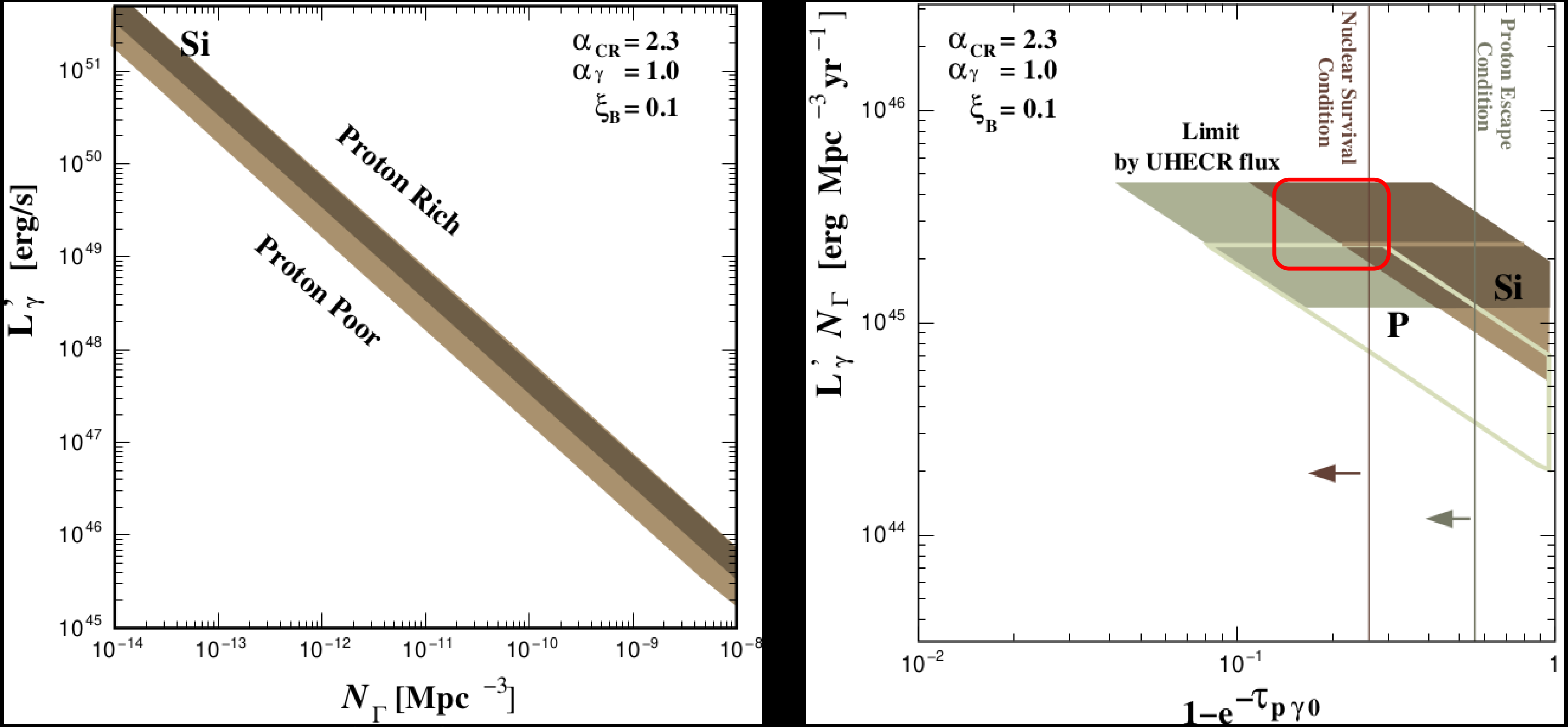


Yoshida & Murase PRD (2020)

The unified model – the parameter space is small

It means the model is testable by future observations!!

$0.1 < \tau_{p\gamma} < 0.6$

$\xi_B < 0.5$

(co-moving) source luminosity $L_\gamma' > 2 \times 10^{45}\ \xi_B^{-1}\ Z^{-2}$ erg/s

cosmic ray luminosity density $n_0\ L_\gamma'\xi_{CR}\ \Gamma^2 \sim 2 \times 10^{45}$ erg/Mpc^3 yr

$B' < 2.3\ \Gamma^2\ (L_\gamma'/10^{47}\ \mathrm{erg/s})^{-1/2}\ \xi_B^{-1/2}\ (A/56)^{-0.21}$ Gauss

(by the nuclear survival condition)

If spectrum harder than $E^{-1.8}$, then $\Gamma>20$ (relativistic scenario)

Yoshida & Murase PRD (2020)

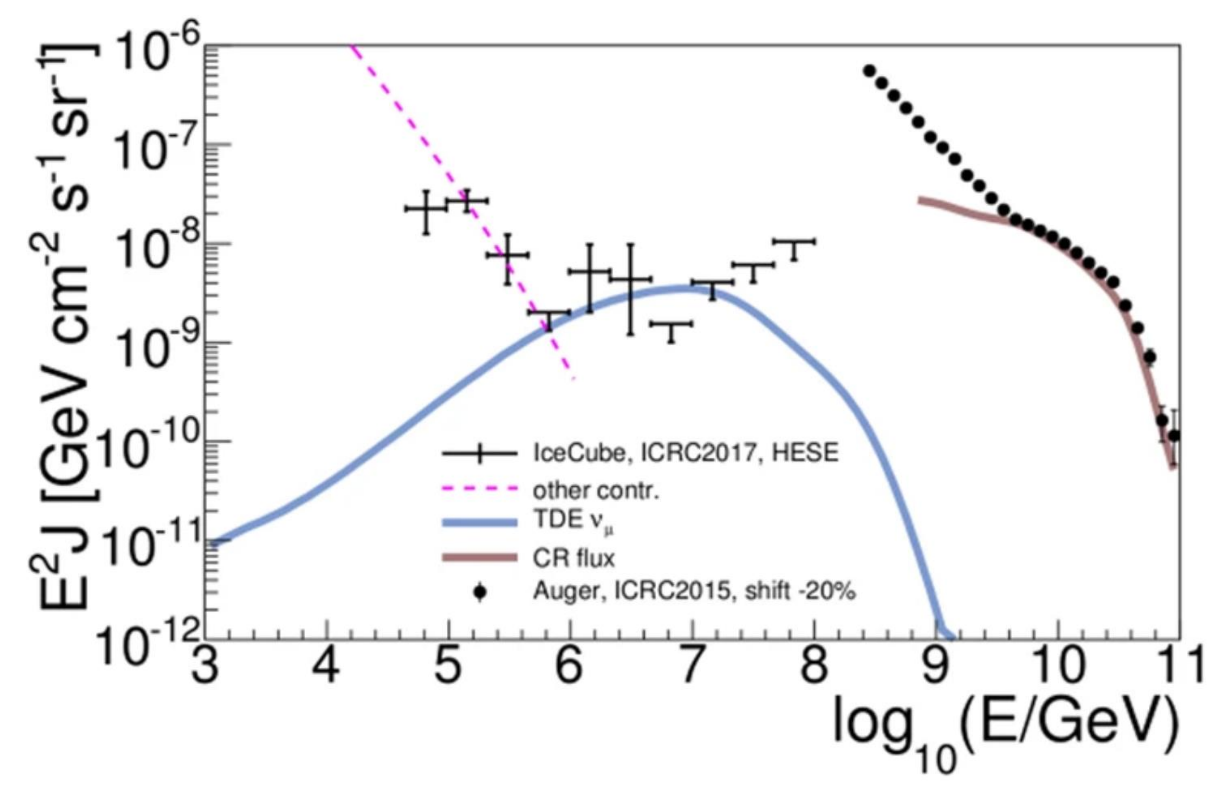
The unified scenario : an example

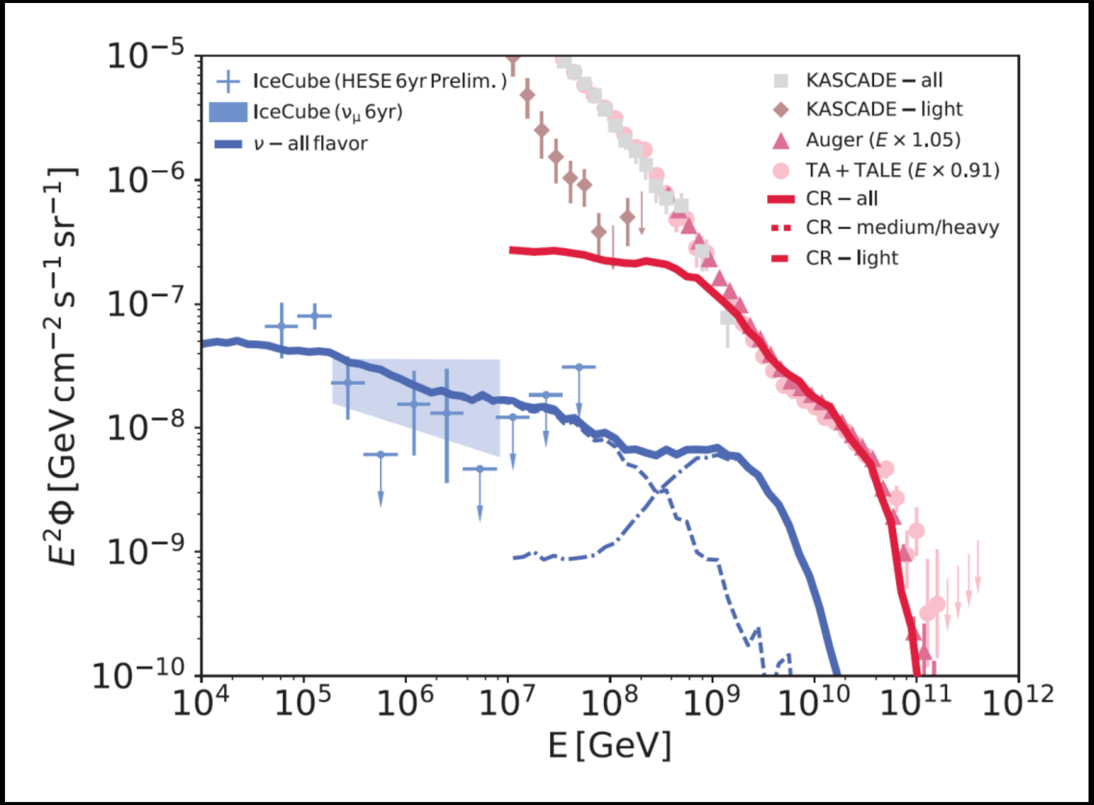
(low luminosity) TDE pγ

Biel, Boncioli, Lunaridini & Winter
Sci. Rep 8, 10828 (2018)

High Energy (10TeV-PeV) pp in clusters of galaxies

Fang & Murase
Nature Physics 14 196-198 (2018)

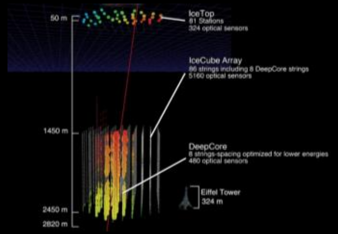




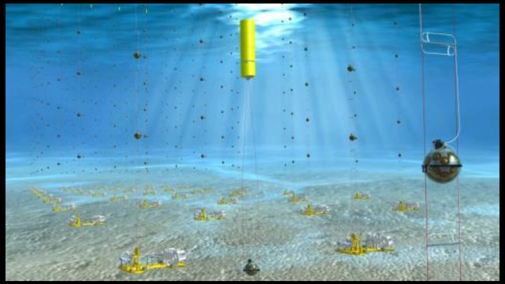
How can we find the unified sources?

low luminosity GRBs? Maybe.   low luminosity TDEs? Maybe.

Many of them are in fact **OPTICAL TRANSIENTS**



KM3NeT



follow up this neutrino alert! →

optical/NIR telescopes

The optical transient sky is too busy

~ 100 SNe are found in $z<2$ within 1 x 1 deg^2 sky patch!

We can’t tell which one out of ~100 SNe is the neutrino source!

These SNe are background, but a few of them could be signals

Type 1A – definitely *BACKGROUND*

core-collapse SNe, wind-driven SNe, low-luminosity GRBs

→ They can be ν sources, but may appear as Type Ibc or II

A difficult business

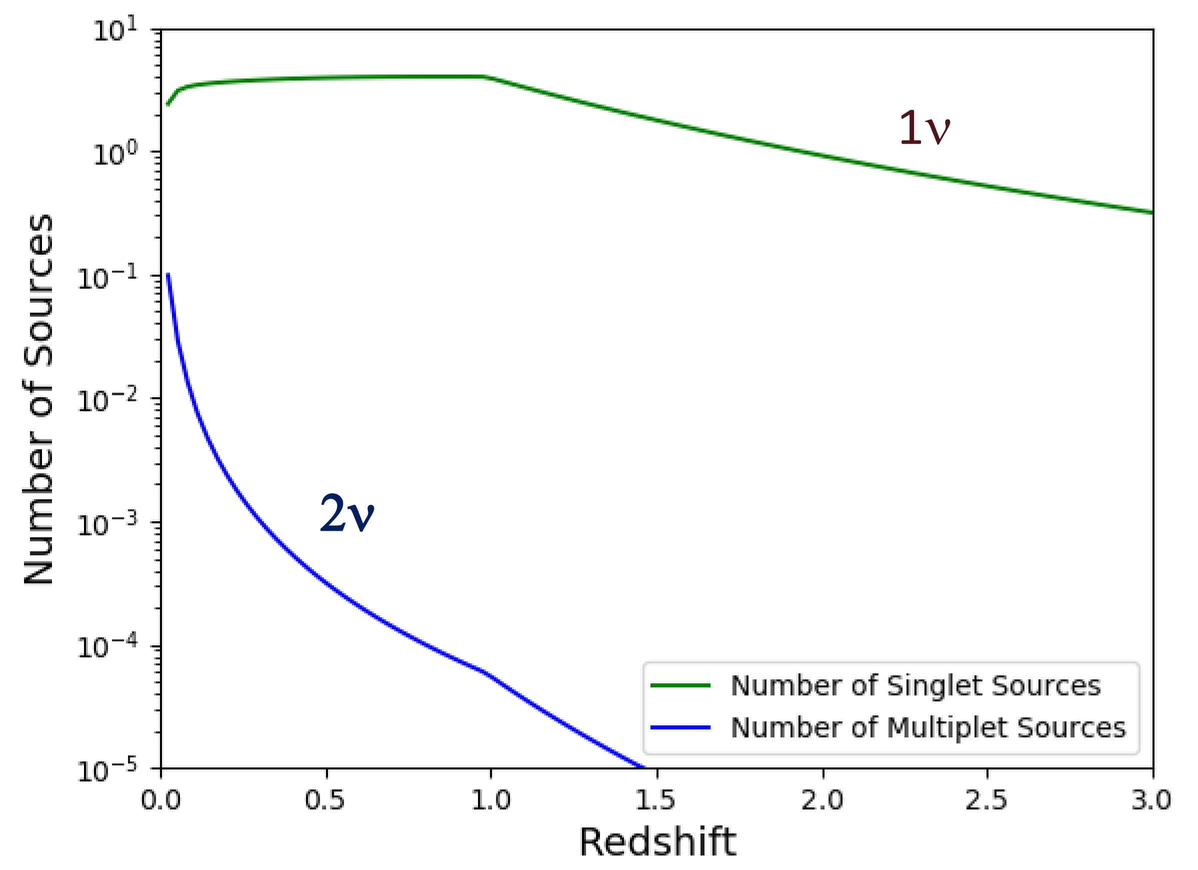
We need to filter out SNe but a few of them may be our sources

Demanding ν doublet detection

2 ν from the same direction within a time of ΔT (~ 30 days)

Example

$E_\nu = 3\times10^{49}$ erg $\rho_\nu = 3\times10^{-6}\ \mathrm{Mpc}^{-1}\ \mathrm{yr}^{-1}$



88% of sources to yield ν doublet detection are z<0.15

→ Limits the transient counterparts!

A pilot model

Yoshida+ Accepted for ApJ arXiv.2206.13719 (2022)

ν source modeling

$$\phi_{\rm PS} \equiv \frac{dN_\nu}{dAdtd\varepsilon_\nu} = \frac{1}{4\pi d_z^2}\frac{\kappa}{\varepsilon_0}\left(\frac{\varepsilon_\nu}{\varepsilon_0}\right)^{-\alpha_\nu} = \frac{1}{4\pi d_z^2}\frac{\kappa}{\varepsilon_0}\left(\frac{E_\nu(1+z)}{\varepsilon_0}\right)^{-\alpha_\nu}$$

$$\kappa = \frac{L_\nu}{\int d\varepsilon_\nu \left(\frac{\varepsilon_\nu}{\varepsilon_0}\right)^{-\alpha_\nu+1}}.$$

parameters to characterize transient sources

flare duration ΔT = 30 days

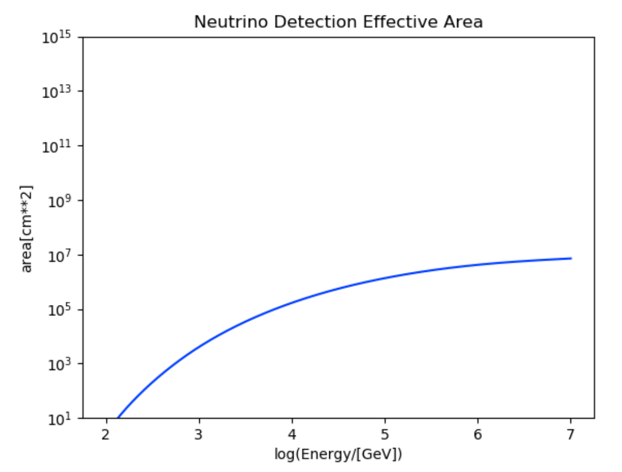
c.f. TDE~ month
CCSNe ~ 10 days

ε_0 = 100 TeV α_ν = 2.3

source luminosity $E_\nu = L_\nu \times \Delta T$ [erg]

flare rate ρ_ν [/Mpc3 yr]

detector modeling



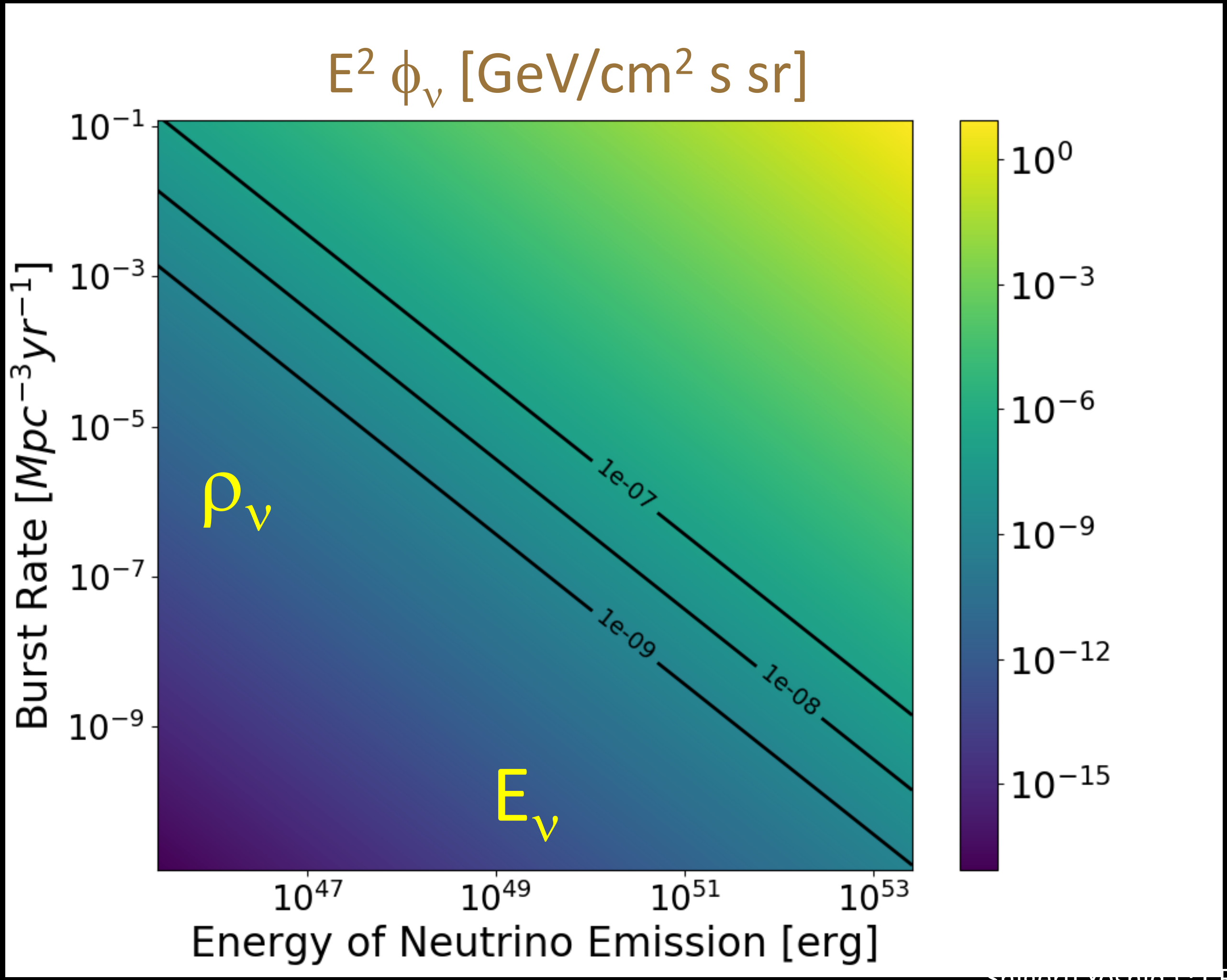
a la IceCube ~ 1km^3 detector

$\Delta\Omega$ = 1 x 1 deg^2
ΔT = 30 days

→ atmospheric ν background
~ 0.5 event

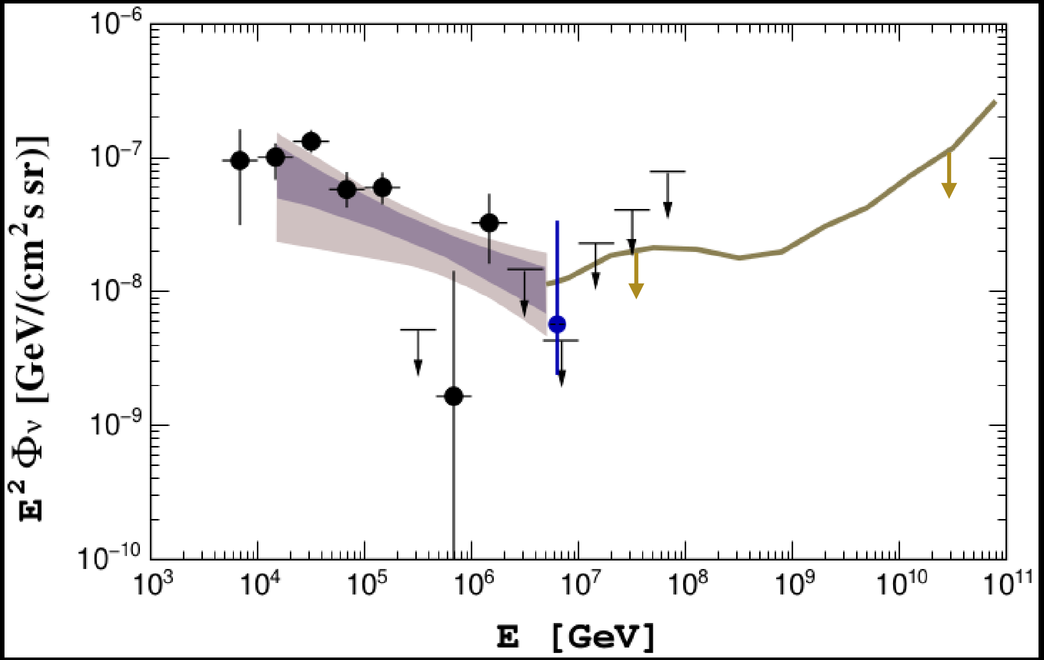
The parameter space

Self consistency – the sources should not overproduce the cosmic background flux



the isotropic "diffuse" flux measured by IceCube

$E^2 \phi_\nu = 10^{-8} \sim 10^{-7}$ GeV/cm^2 s sr



The parameter space

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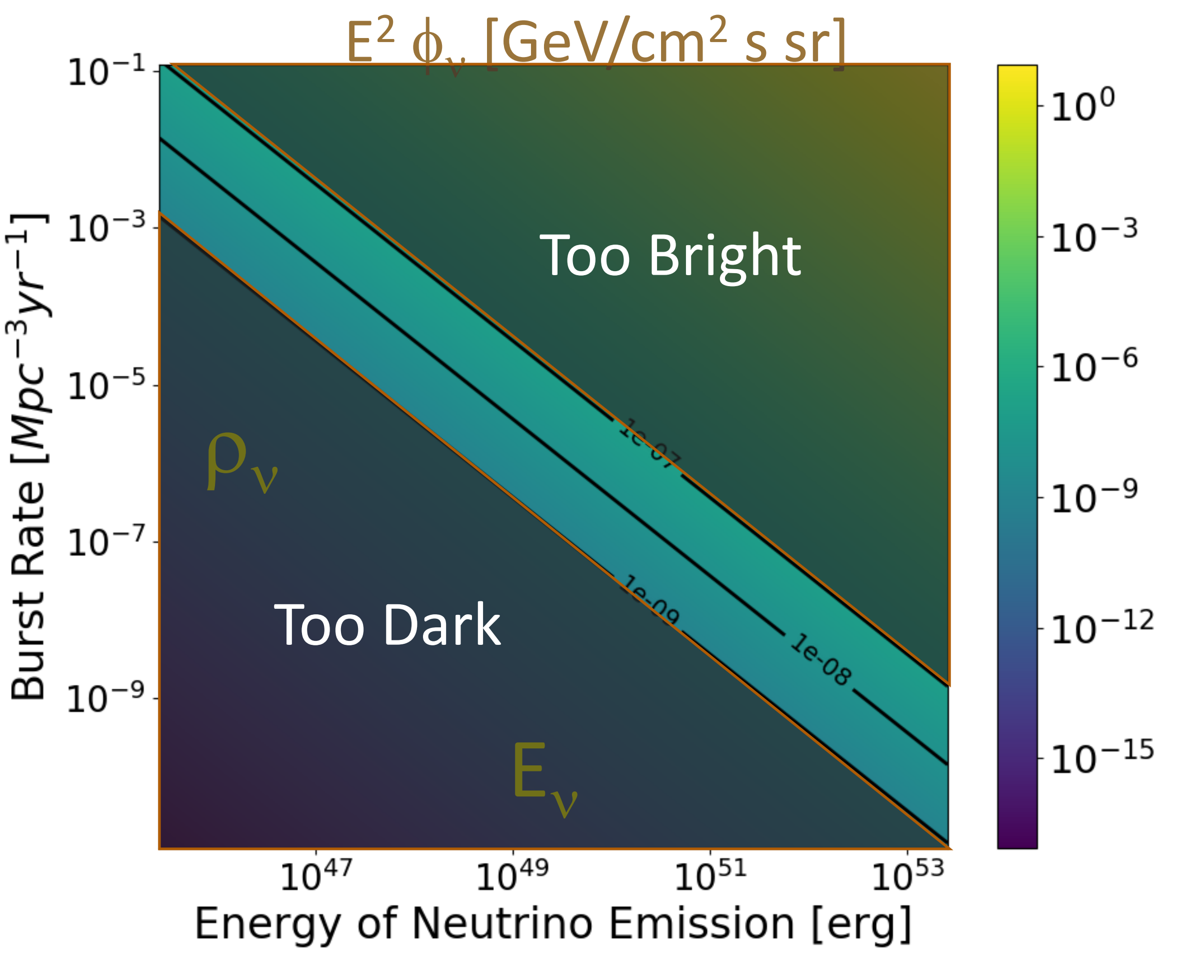
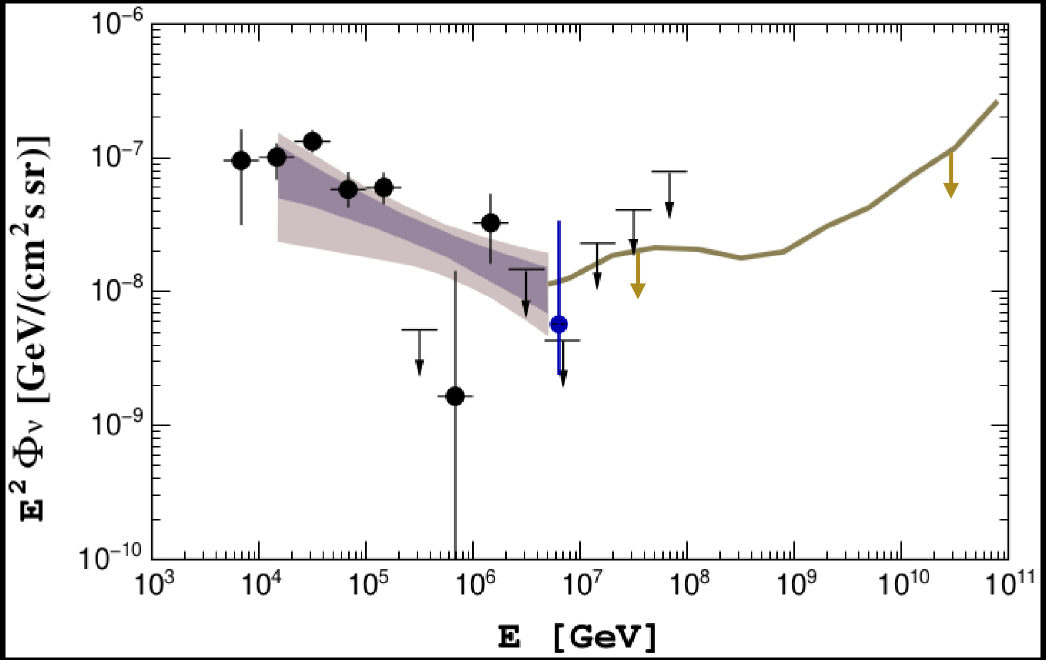
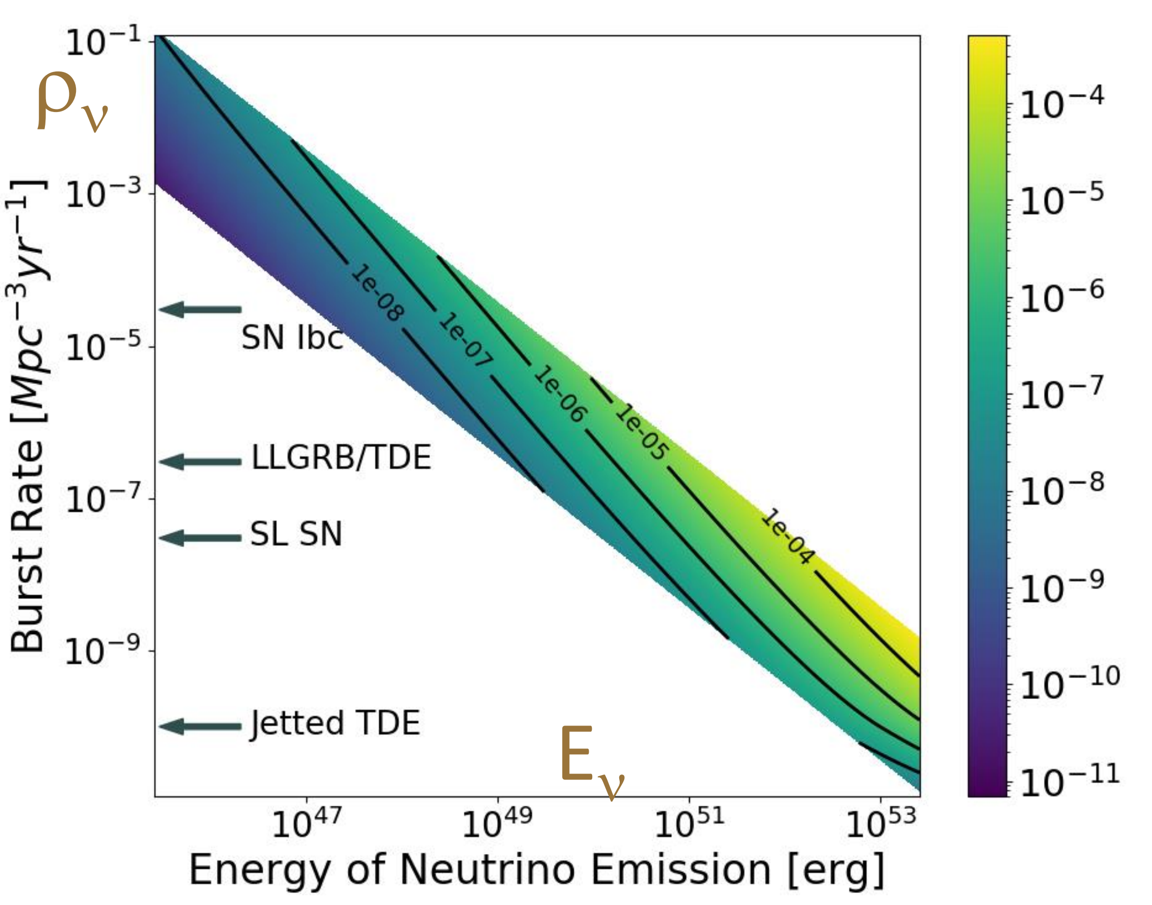


the isotropic “diffuse” flux measured by IceCube

$E^2\ \phi_\nu = 10^{-8} \sim 10^{-7}$ GeV/cm^2 s sr



Number of multiplet (doublet) sources



$$N^{\mathrm{M}}_{\mathrm{PS}} = \frac{\Delta\Omega}{4\pi}\int dV\, P_{\mathrm{p}}^{n=2}(\mu_{\mathrm{PS}})n_0(1+z)^3\psi(z).$$

$\Delta\Omega = 1 \times 1 \text{ deg}^2$

ΔT = 30 days

→ annual rate for 2π sky

$$\frac{2\pi\ 1yr}{\Delta\Omega\Delta T} N^M_{PS} = 2.4 * 10^5 N^M_{PS}$$

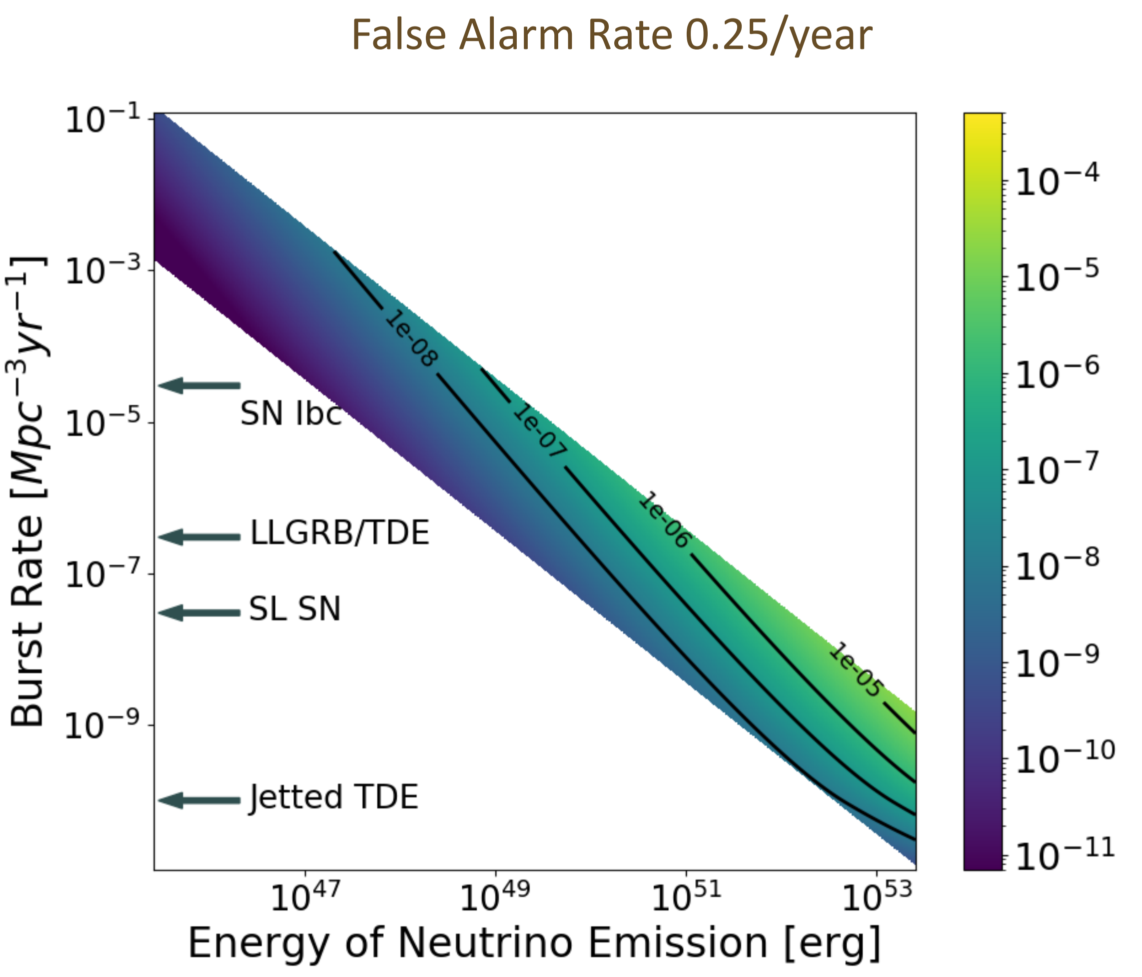
5-year sensitivity

$$N^M_{PS} > 10^{-6}$$

Number of multiplet (doublet) sources

Demanding more higher (> 100 TeV) doublet to filter out atmospheric ν background

$$N_{\rm PS}^{\rm M} = \frac{\Delta\Omega}{4\pi}\int dV\, P_{\rm p}^{n=2}(\mu_{\rm PS}) n_0 (1+z)^3 \psi(z).$$


False Alarm Rate 0.25/year

5-year sensitivity $N_{PS}^{M} > 10^{-6}$

Yoshida+ Accepted for ApJ arXiv.2206.13719 (2022)

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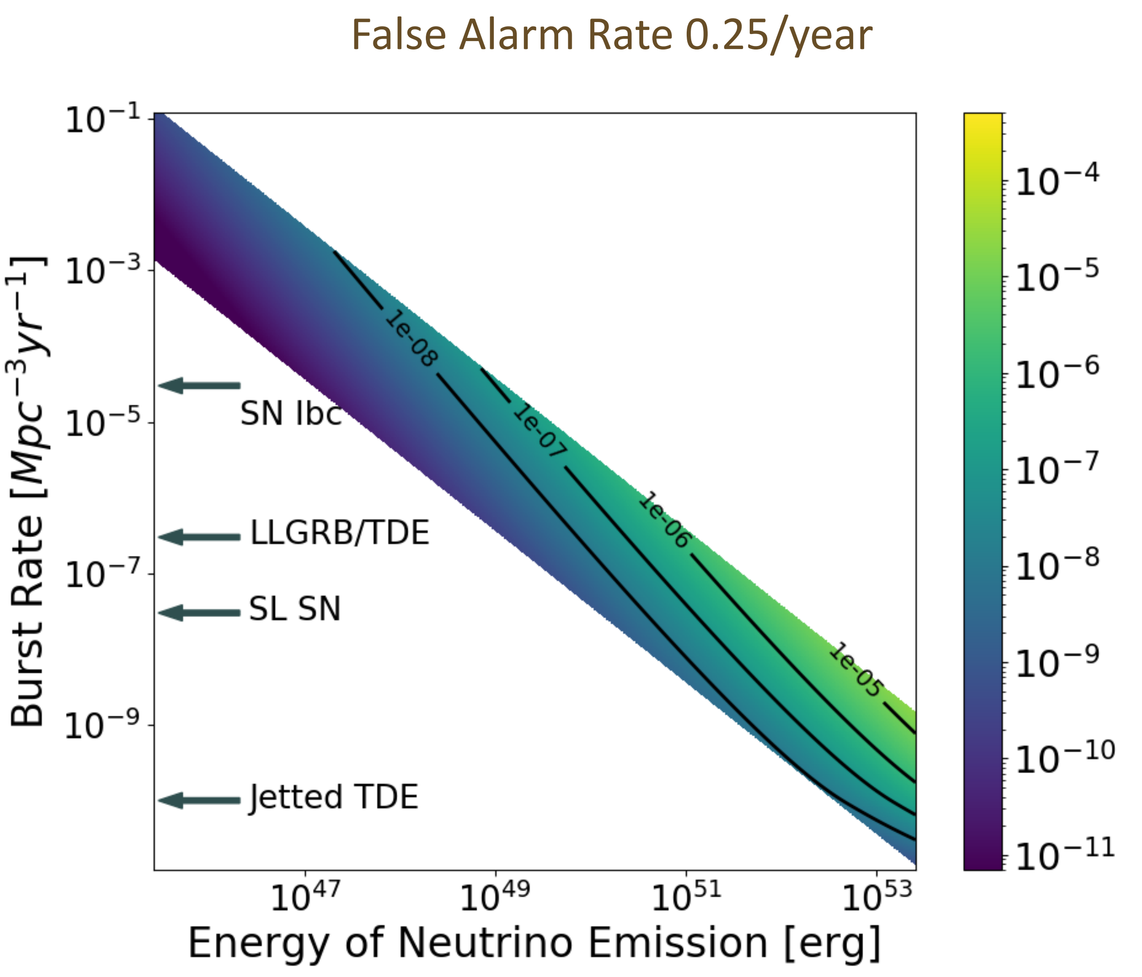

False Alarm Rate 0.25/year

5-year sensitivity $N^{M}_{PS} > 10^{-6}$

If we found no doublet by ~ 5 year observations

source classes with

$E_\nu > 5 \times 10^{51}$ erg, $\rho_\nu < 2 \times 10^{-8}$ Mpc^{-3} yr^{-1}

are rejected

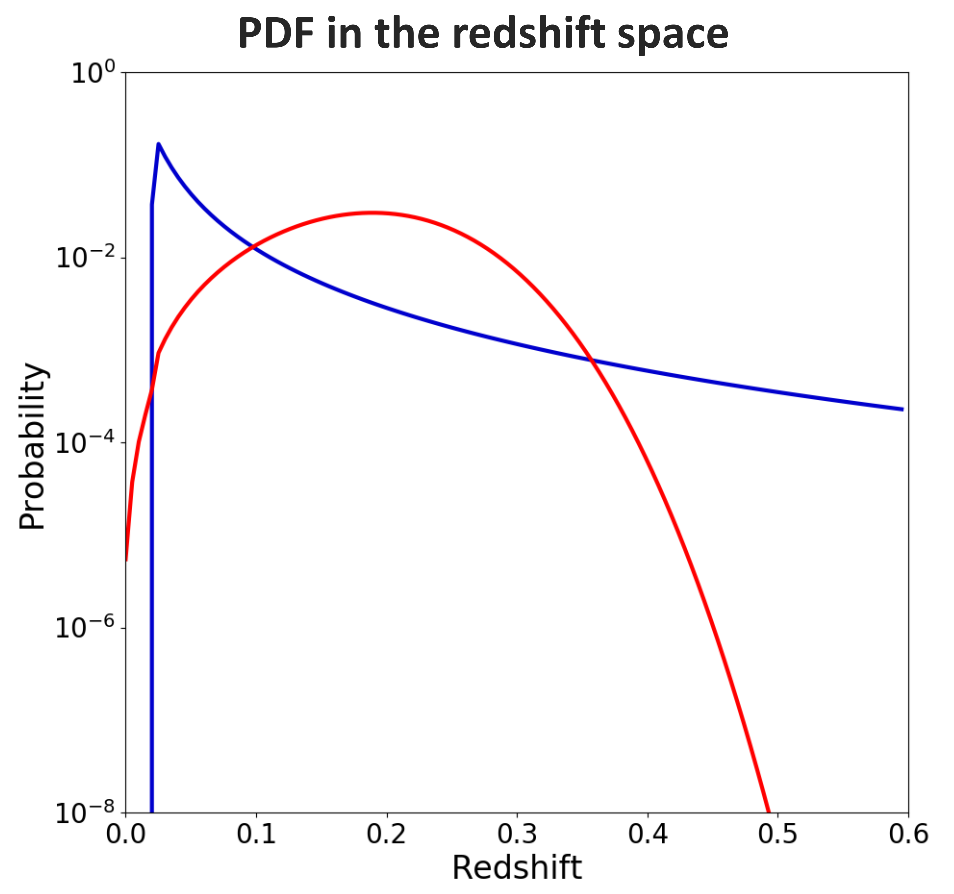
Super Luminous SNe and jetted TDEs are not the **unified sources**

Yoshida+ Accepted for ApJ arXiv.2206.13719 (2022)

If ν multiplet is detected, look for the optical counterpart

Identify the ν source

Test the hypothesis that the closest transient object is the ν doublet source



Select the closest (the smallest z) object found in the $\Delta\Omega$ =1 deg^2

🟦 Yes! It is the source to yield ν doublet detection

🟥 Nope. Unassociated SN tracing SFR-like evolution

Example:

Found a transient at z = 0.05

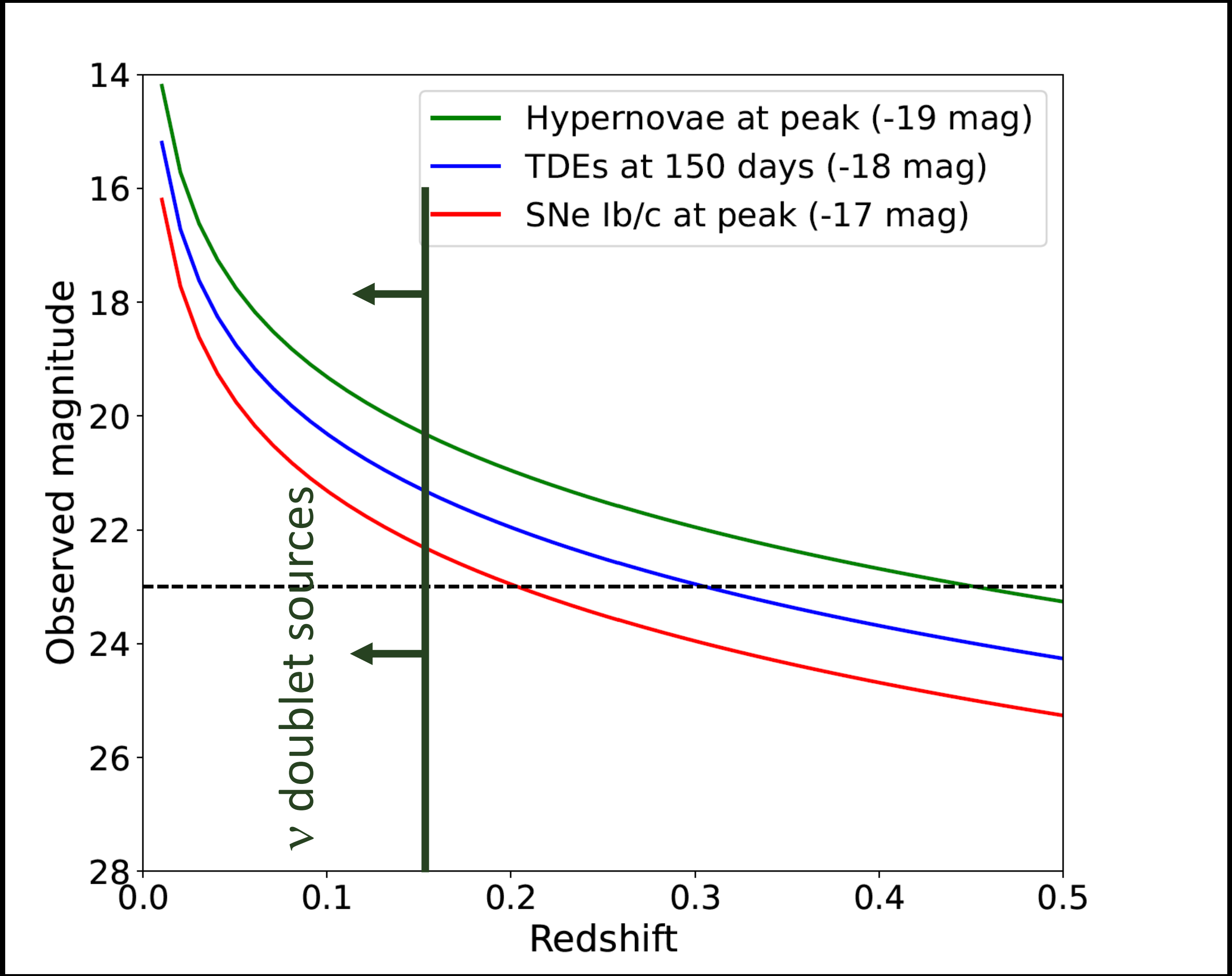
p-value to support 🟥 is 9×10^{-3}

(~ 2.4 σ rejection)

Focus on nearby (z<0.15) transients

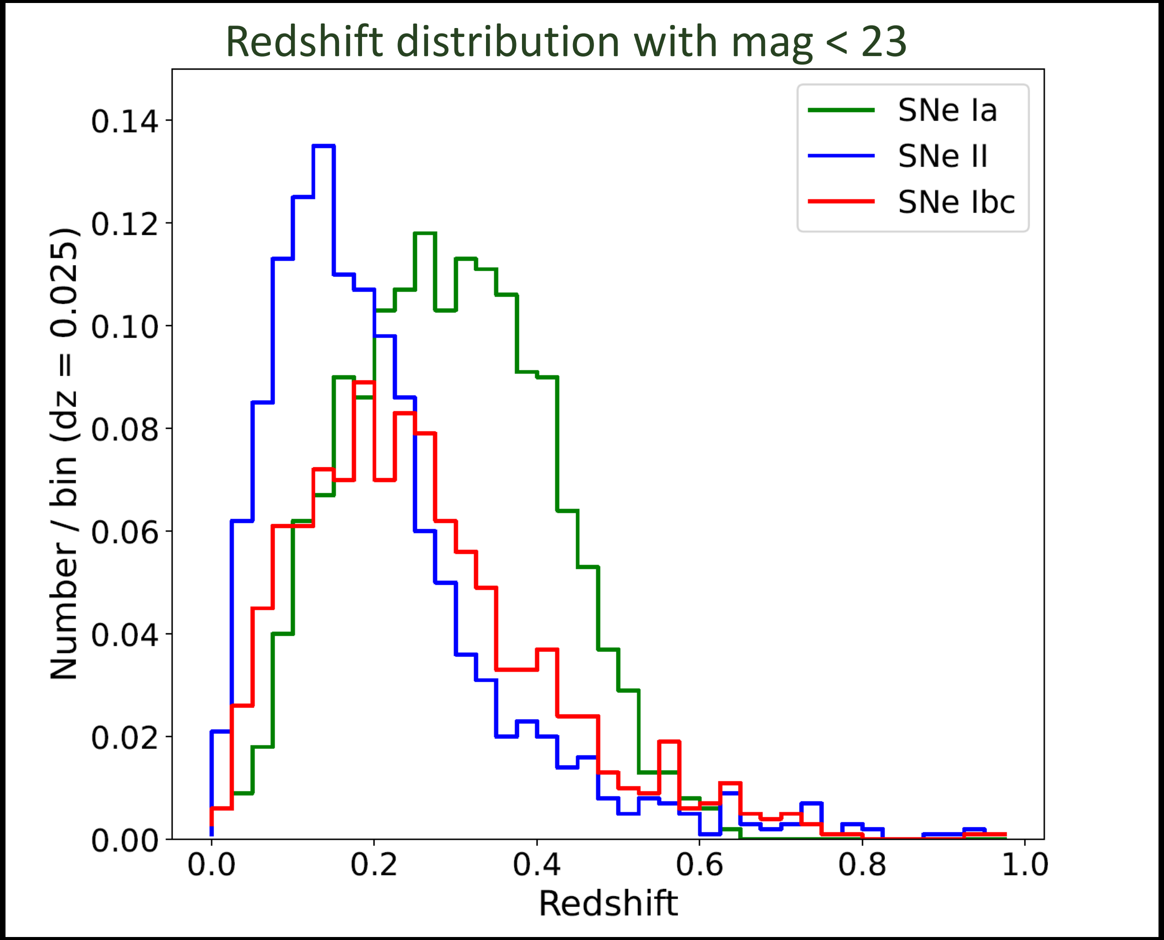
88 % of the sources to yield ν multiplet are z<0.15

Must be as bright as 23 magnitude → 4m class telescope



Optical Follow-ups

How many SNe < 23 magnitude are found in the redshift space?



Yoshida+ Accepted for ApJ arXiv.2206.13719 (2022)

Requiring as bright as 23 magnitude already filters out many distant SNe

Yet N for $\Delta\Omega = 1 \times 1 \text{ deg}^2$

Type Ia	~1.5 /$\Delta\Omega$
Type II	~1.3 /$\Delta\Omega$
Type Ibc	~1.1 /$\Delta\Omega$

~4 SNe are always found in your FOV

Which one out of 4 SNe is ν source?

1. Look at their redshift. Must be small

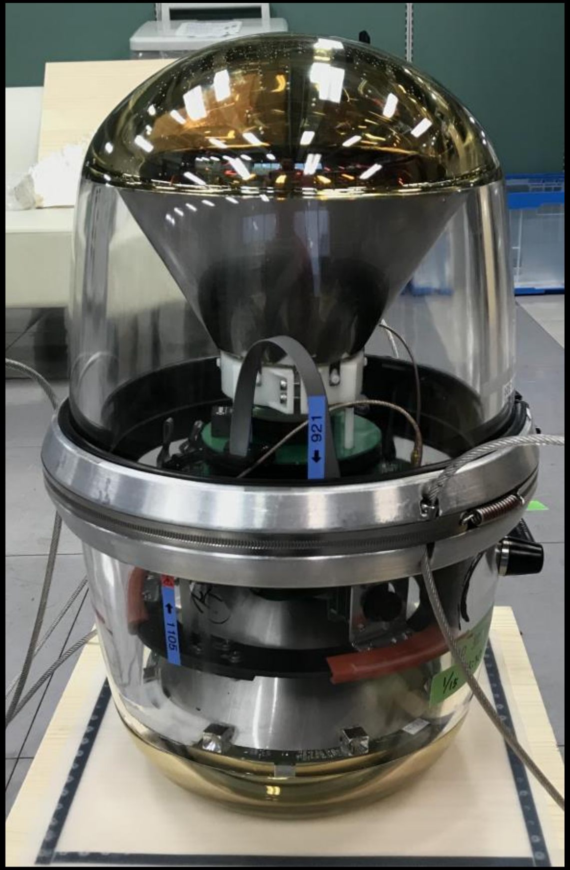
   e.g. if find it at z= 0.04, **2.7 σ** detection against the bg

2. photometric observations to measure light curve

   determine t_0

The in-ice Cherenkov detector

D-Egg



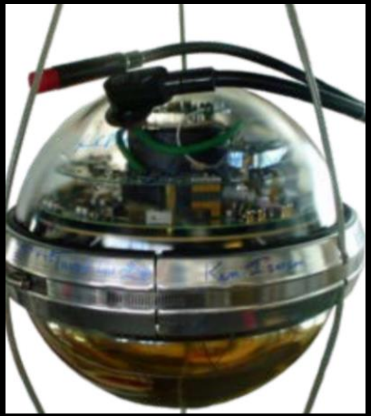
mDOM

The next generation Cherenkov detector modules **D-Egg**

developed and fabricated in Japan

278 pcs will be deployed in 2025/26

The DOM for the present IceCube

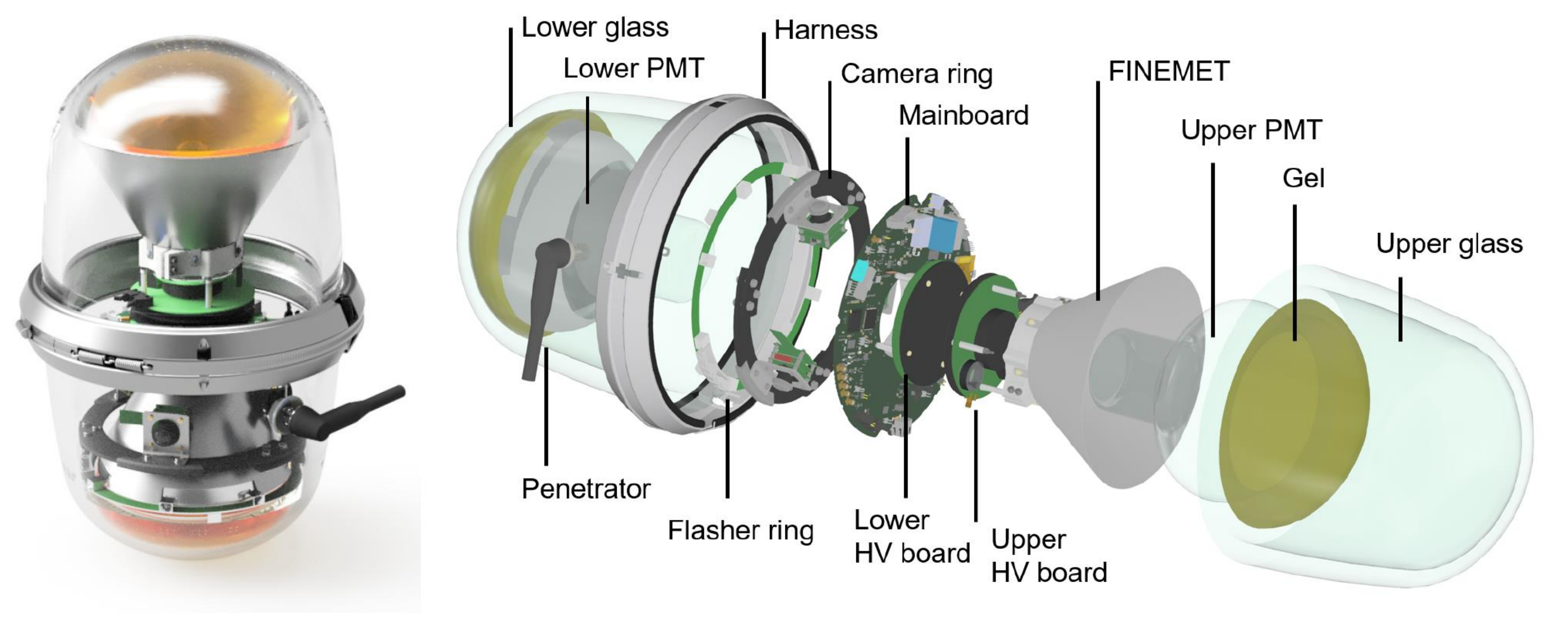


The D-Egg principle

optical sensors housed in an ellipsoid glass to reduce the hole diameter

diameter 30 cm → **5 cm reduction** from the IceCube DOM to save 15% in drill time and fuel consumption

two high-QE pmts enclosed in the vessel → A larger photon detection area (see the next slides)



The vessel : Challenging the ellipsoid shape

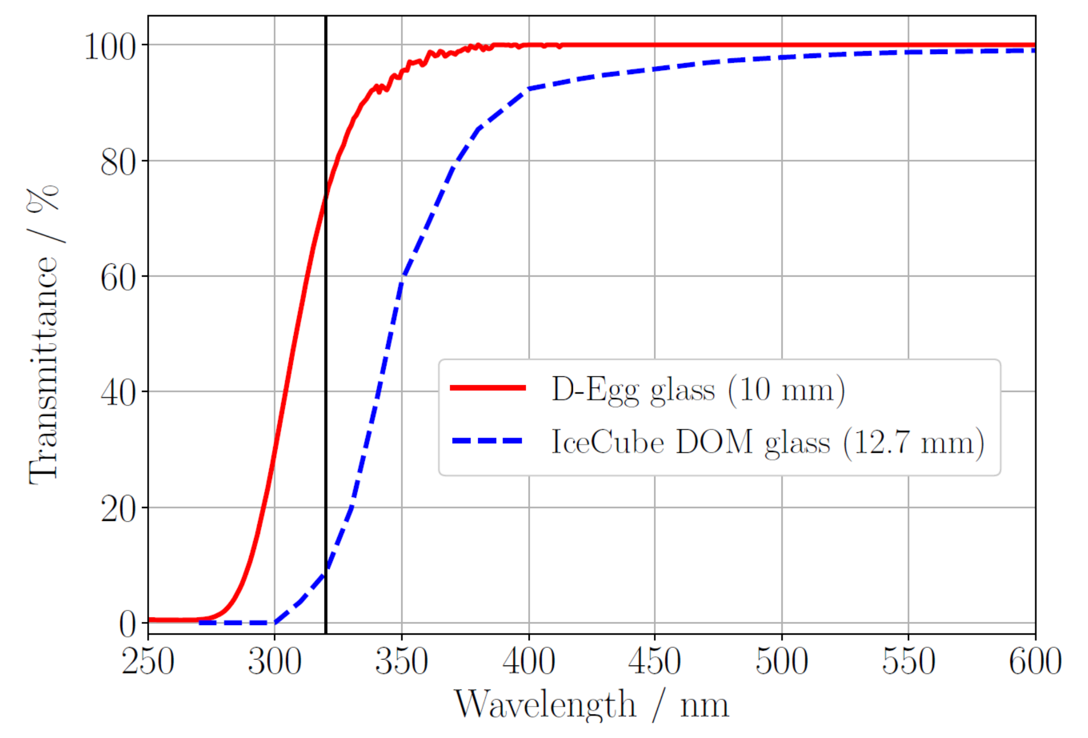
CHIBA UNIVERSITY

Thicker (20 mm thickness) at the equator for **mechanical strength**

Thinner (10 mm thickness) at the top and bottom surface for being **UV photon transparent**

Optimize the glass ion content (reduction of Fe_2O_3) to **enhance transmittance at $\lambda < 350$ nm**

The glass transmittance



pressure test up to 70 MPa in a hyperbaric chamber

The production dry run

built 320 pcs (2019-2021)

assemble, assemble, and assemble (and fight against the covid outbreak)

FAT – Final Acceptance Test

D-Eggs waiting for being tested

The bug freezer to house 16 eggs

Test

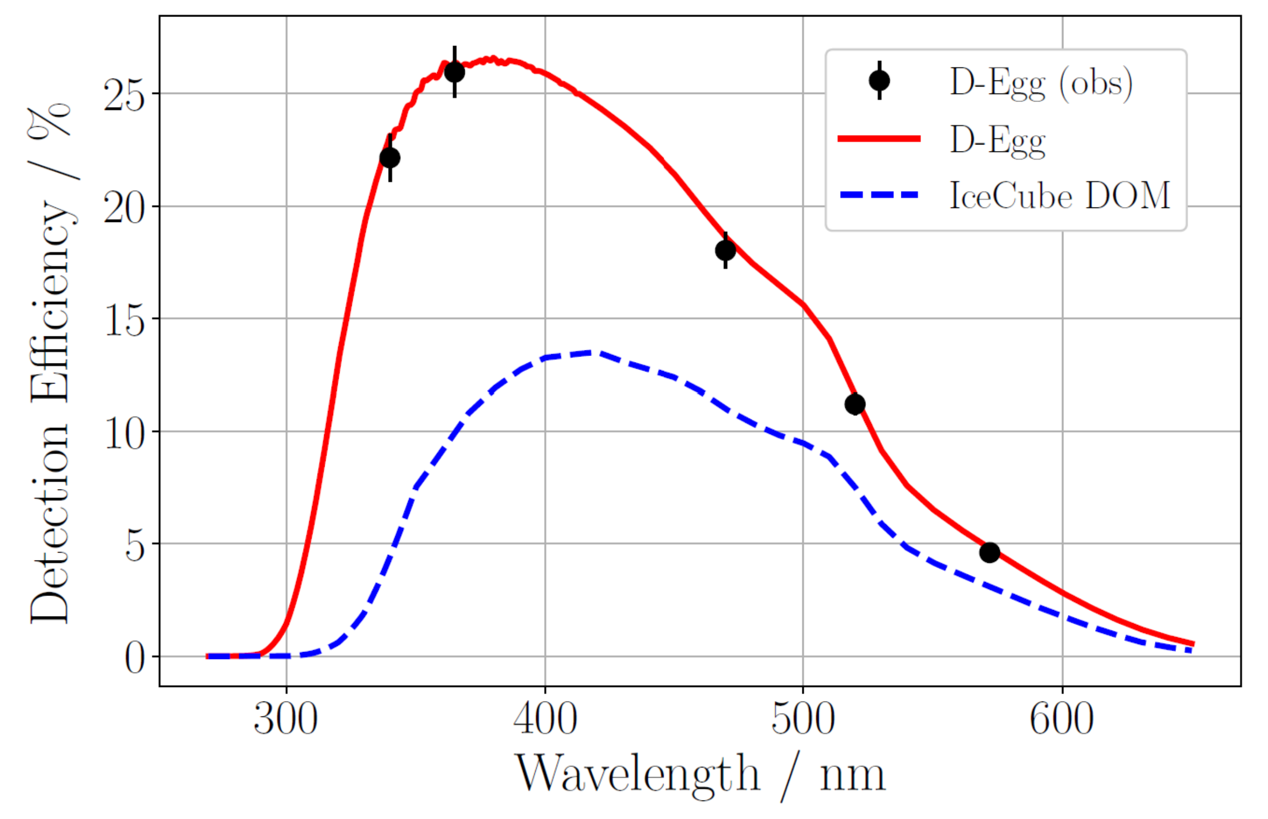
- Main board boot
- Data communication

Measure

- PMT Gain
- Charge resolution
- Transit time
- Linearity
- Dark rate
- Pulse feature extraction

at the various temperatures
from 20C to -40C

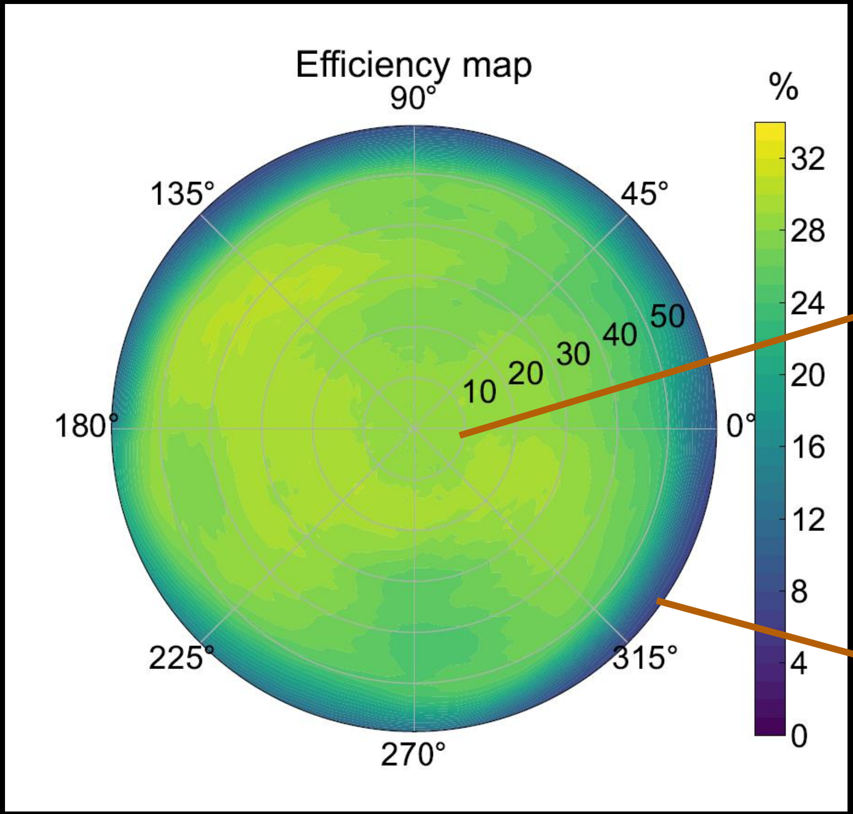
The improved photon detection efficiency

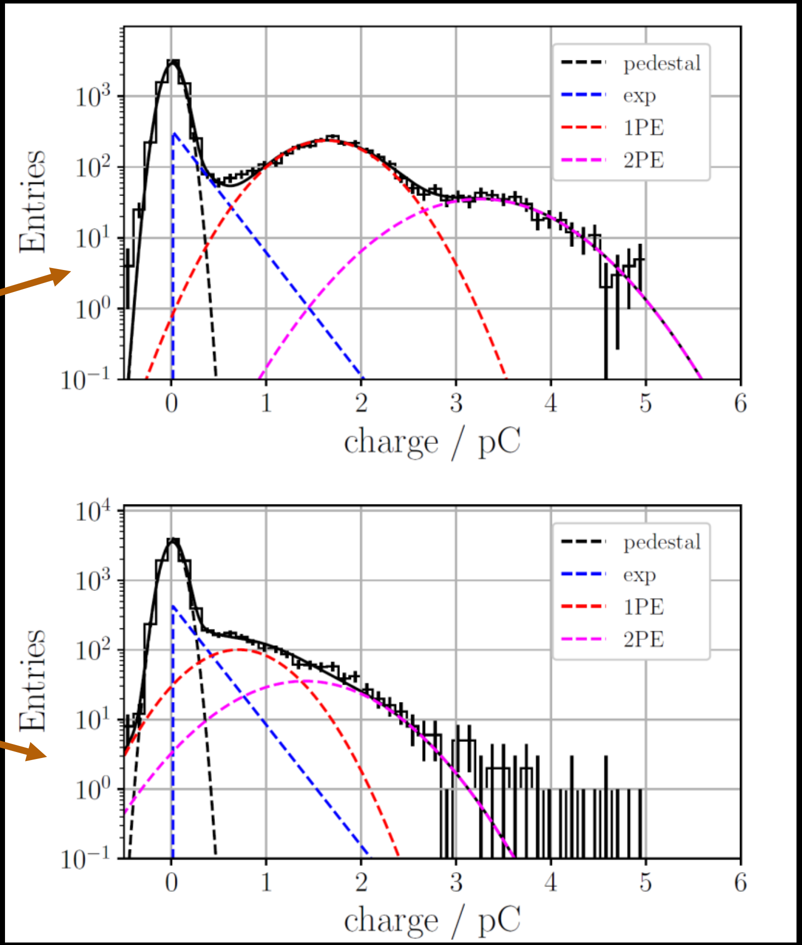


The PMT 2D detection efficiency distribution

8’ Hamamatsu R5912

implemented them into the detector MC



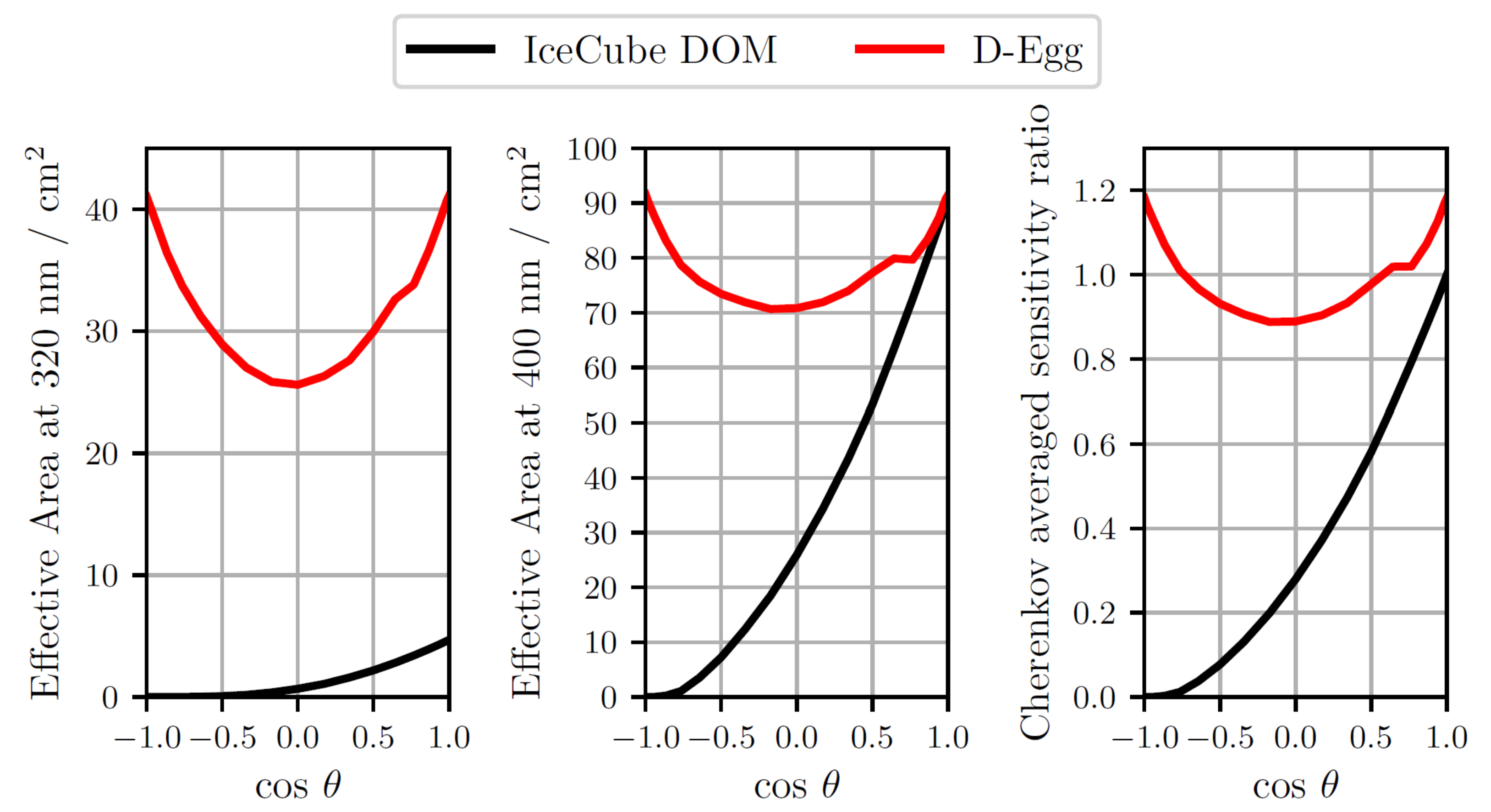


The effective detection area comparisons

320 nm

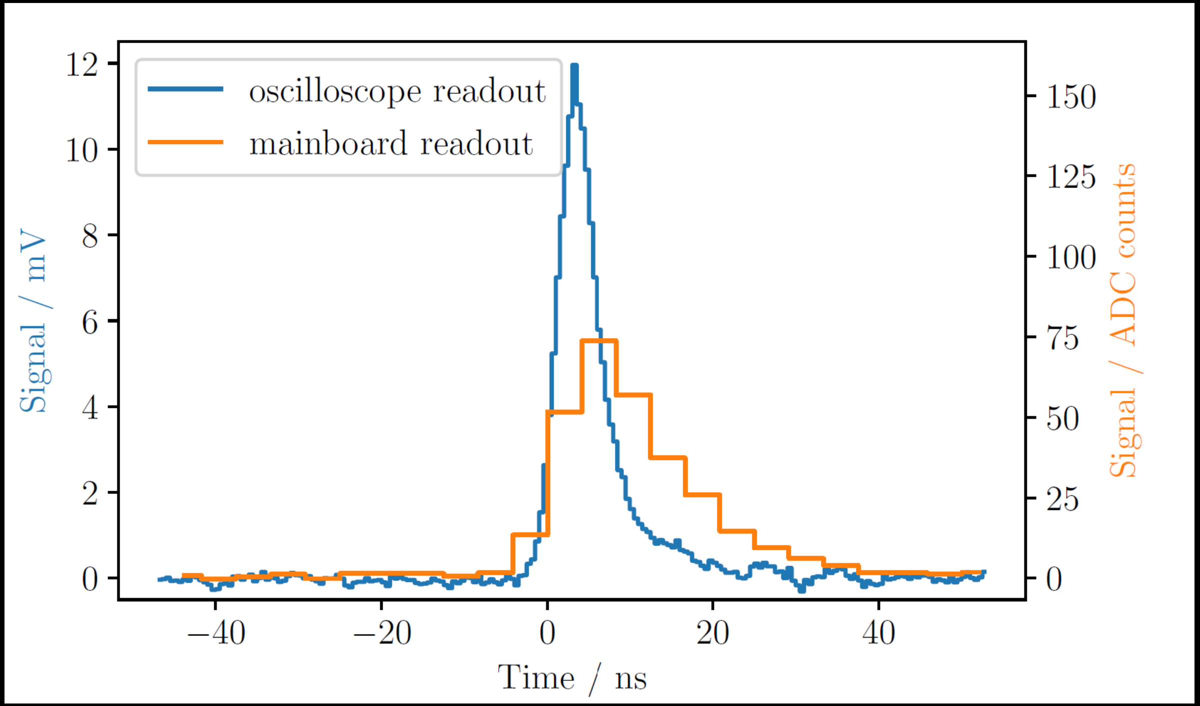
400 nm

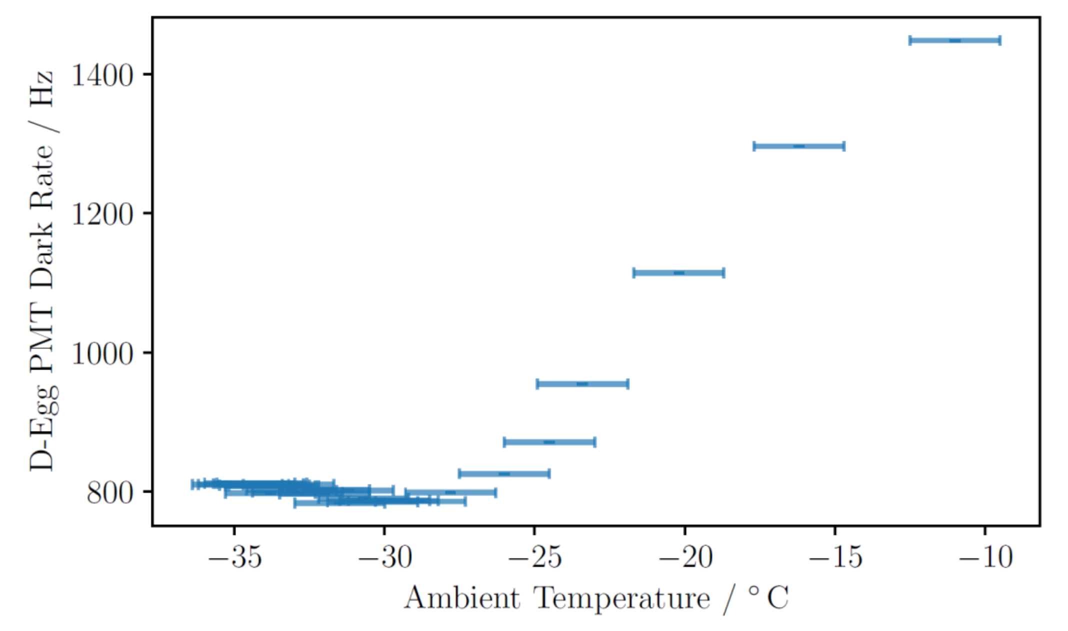
λ^{-2} weighted



1 D-Egg =
3 IceCube DOM

SPE pulse and Dark rate





Take-away Messages

- The UHECR – Neutrino Unified Model requires the narrow parameter space regarding the sources, their distributions and their evolutions, which is testable by the future observations

- Demanding the 100TeV neutrino multiplet with optical followup observations is a powerful approach to identify the unified sources

- The next generation in-ice Cherenkov optical sensors have been established, making a cost-efficient photon detector array technically feasible.
  Get ready for IceCube Upgrade in 2025