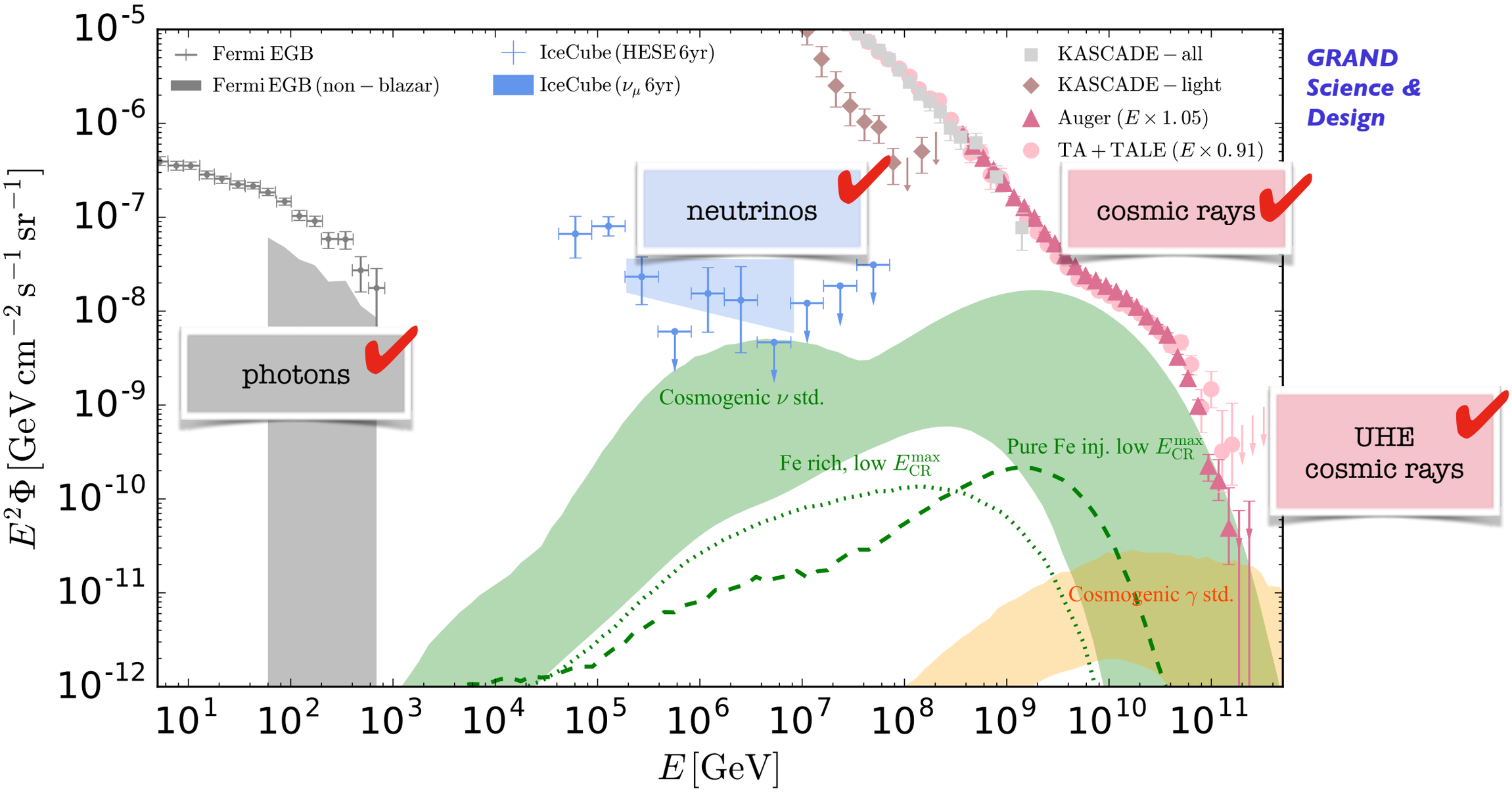

Giant Radio Array for
Neutrino Detection

# EeV neutrino astronomy and the GRAND project

Kumiko Kotera
*Institut d'Astrophysique de Paris*

Workshop on Non-Perturbative QCD - 18/06/2018

# The new multi-messenger era!

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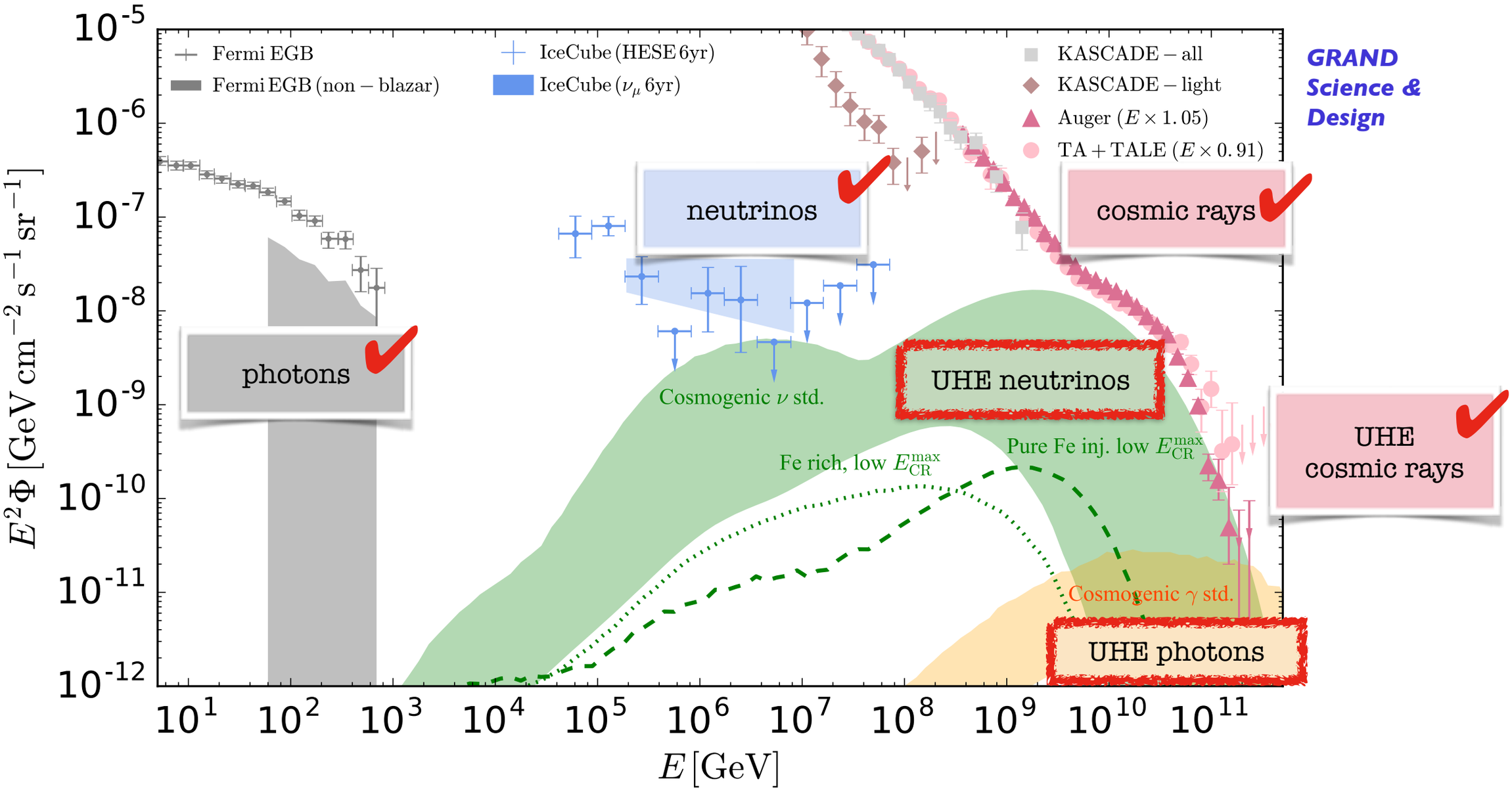


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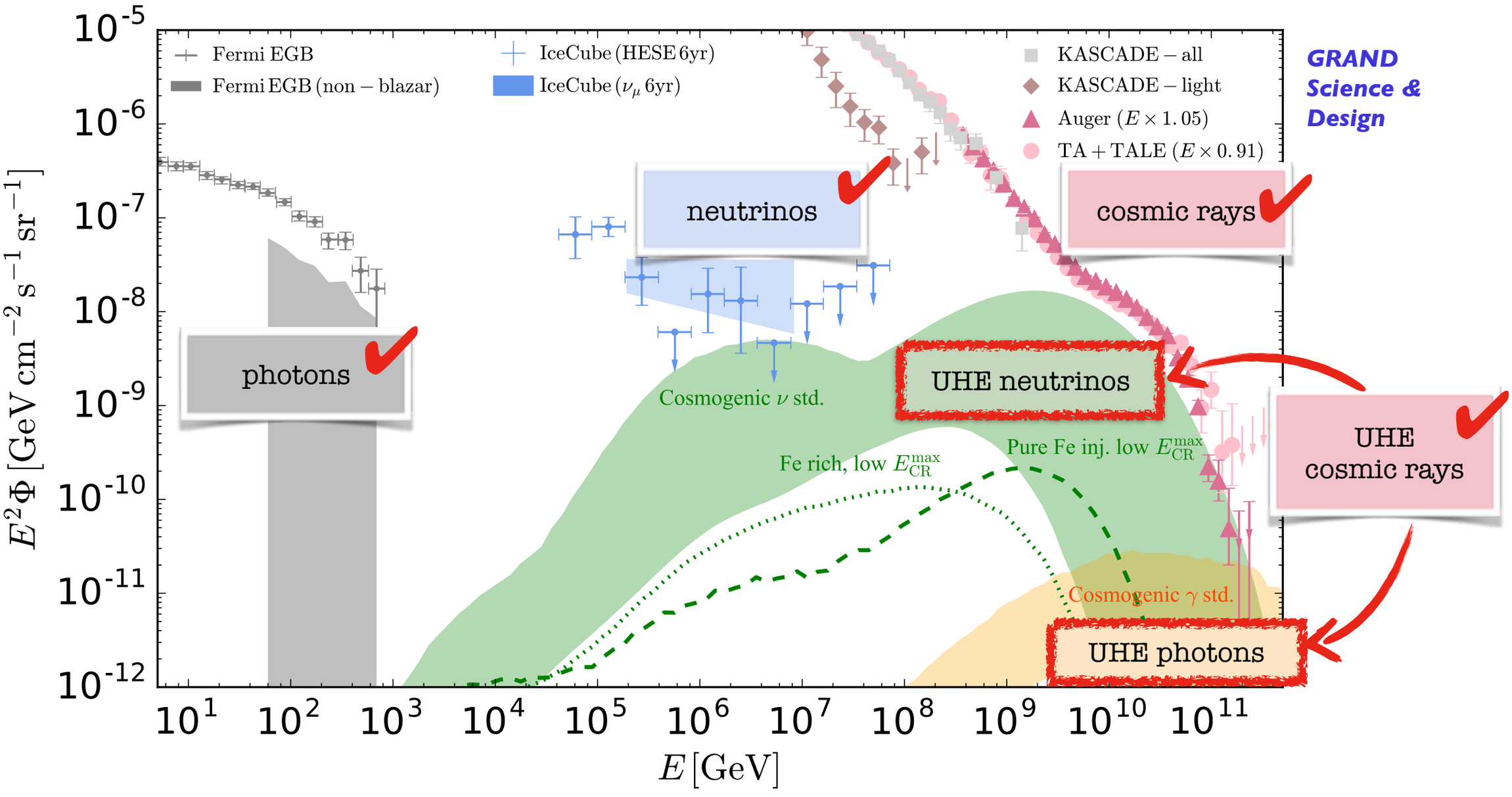


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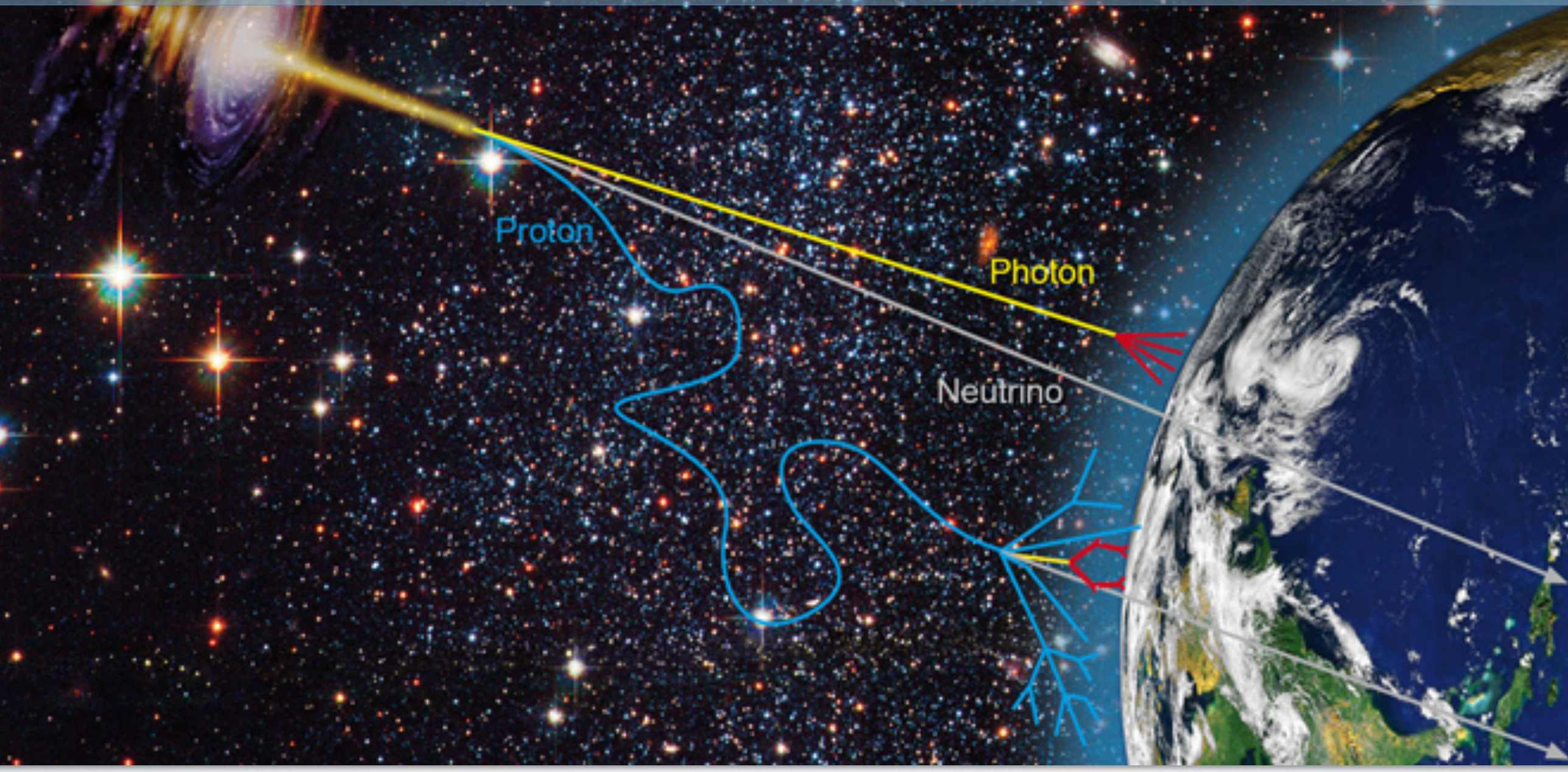
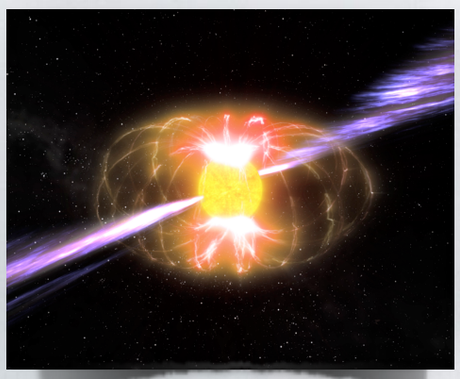
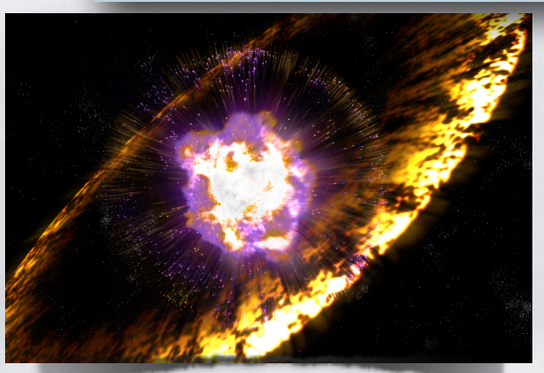
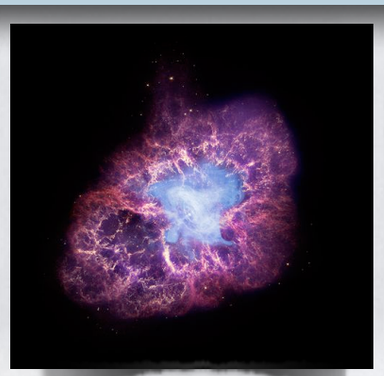
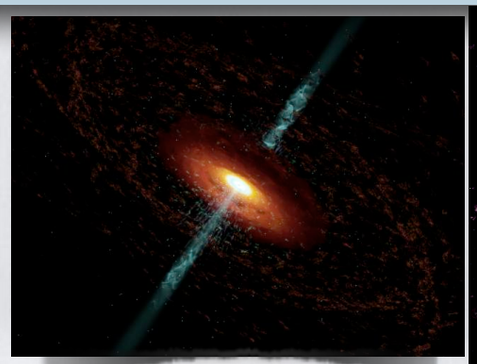
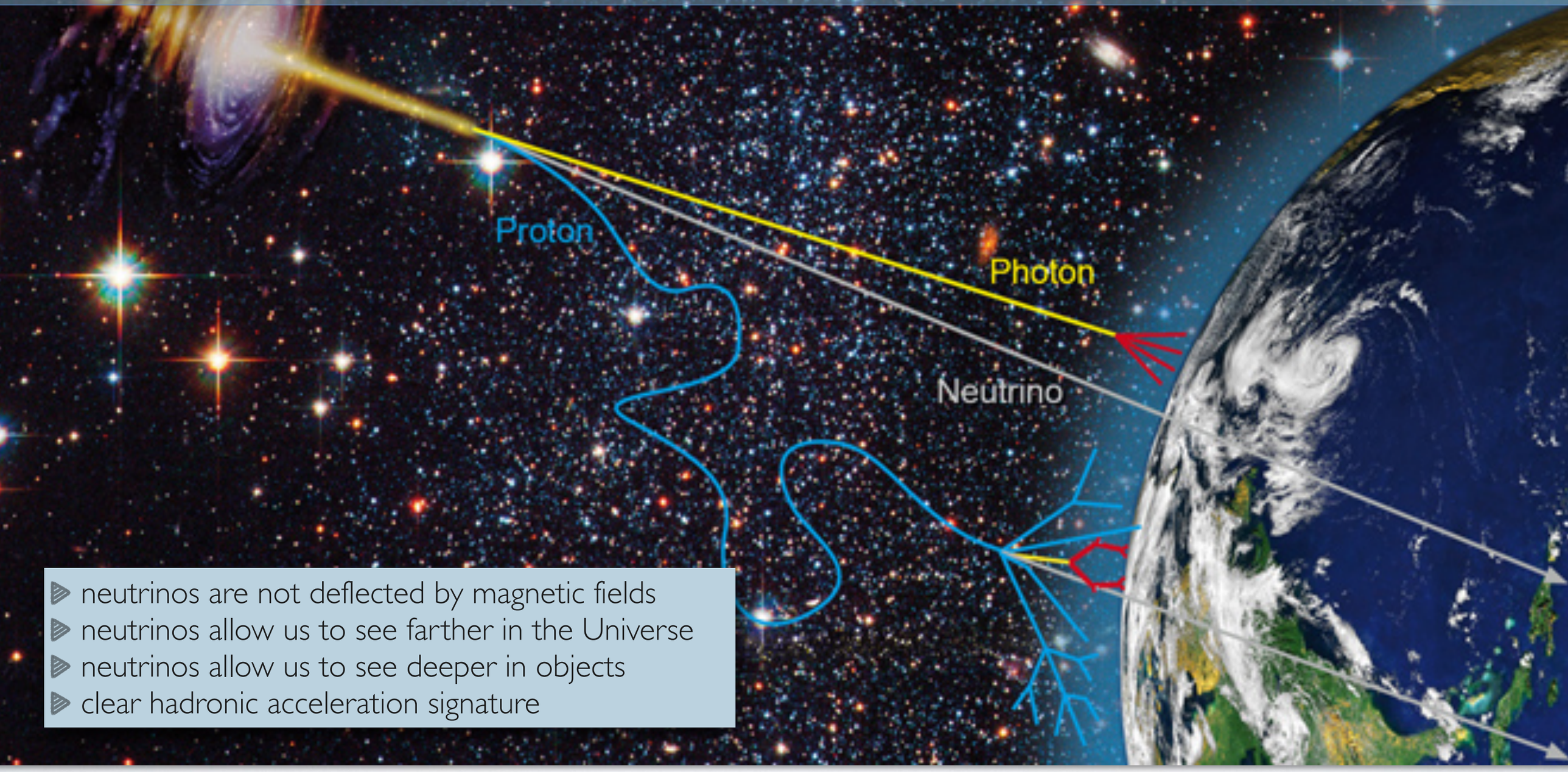
# Multi-messenger astronomy




- to probe the most powerful sources in the Universe

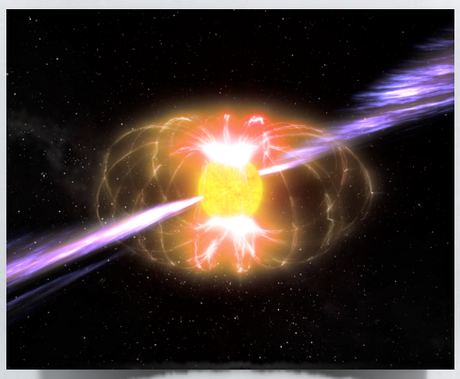
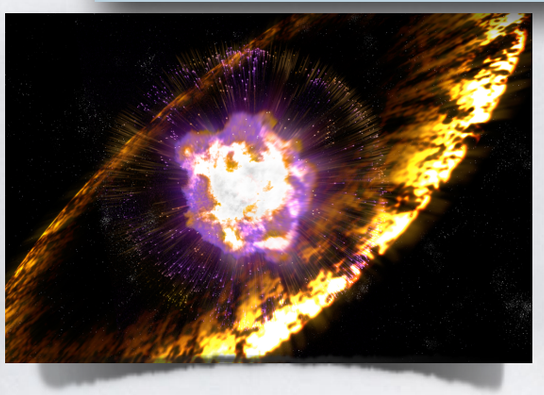
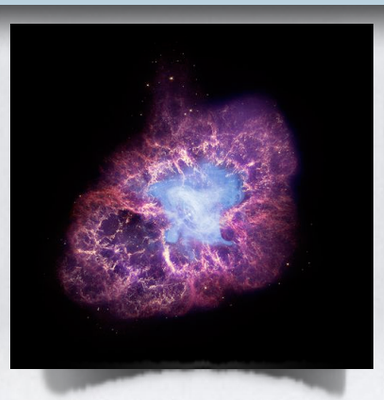
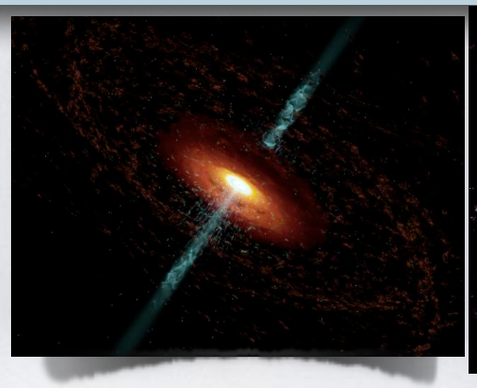
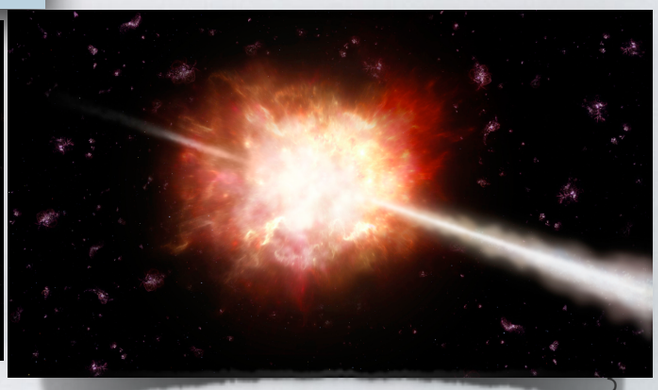






# Multi-messenger astronomy

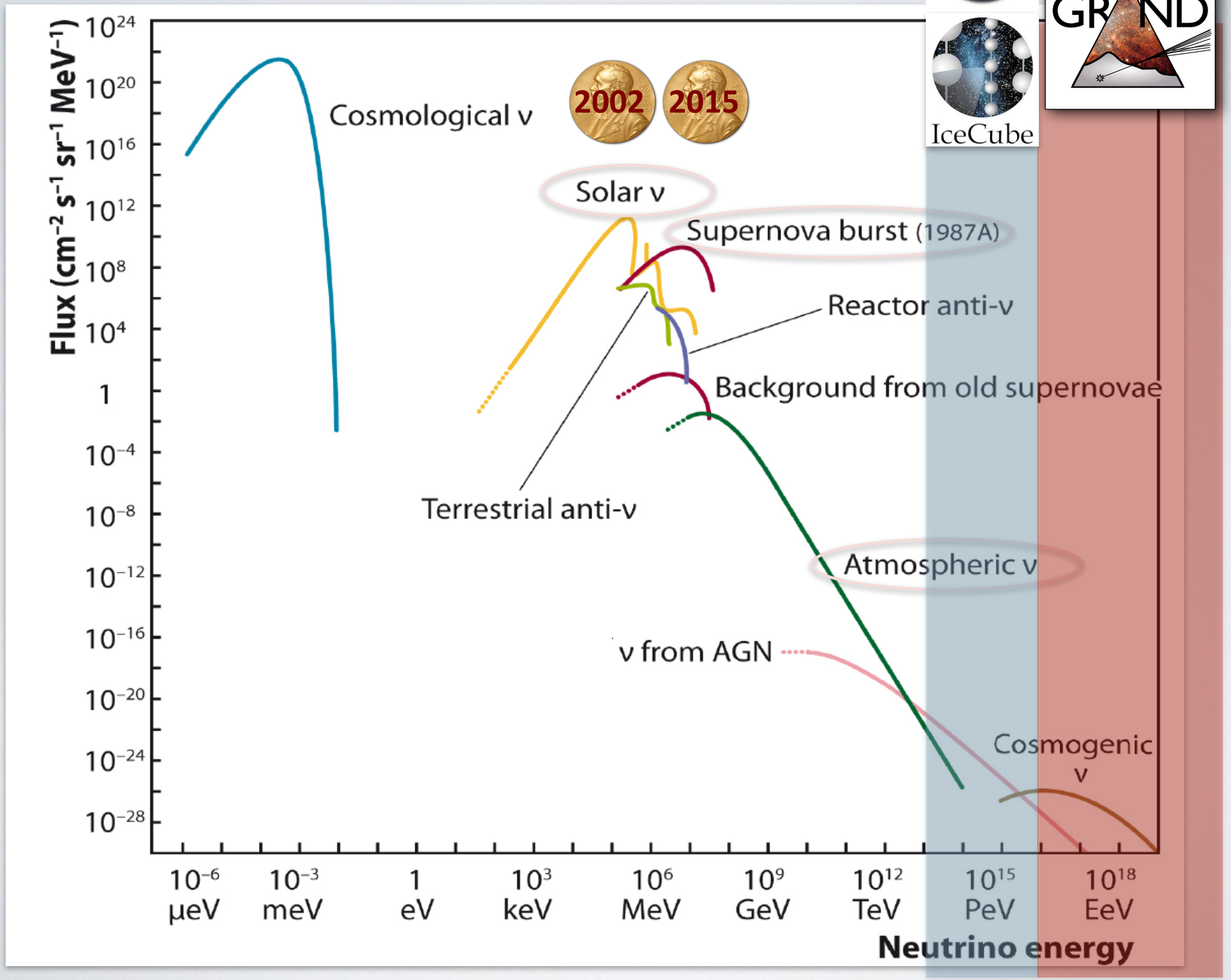



- neutrinos are not deflected by magnetic fields
- neutrinos allow us to see farther in the Universe
- neutrinos allow us to see deeper in objects
- clear hadronic acceleration signature

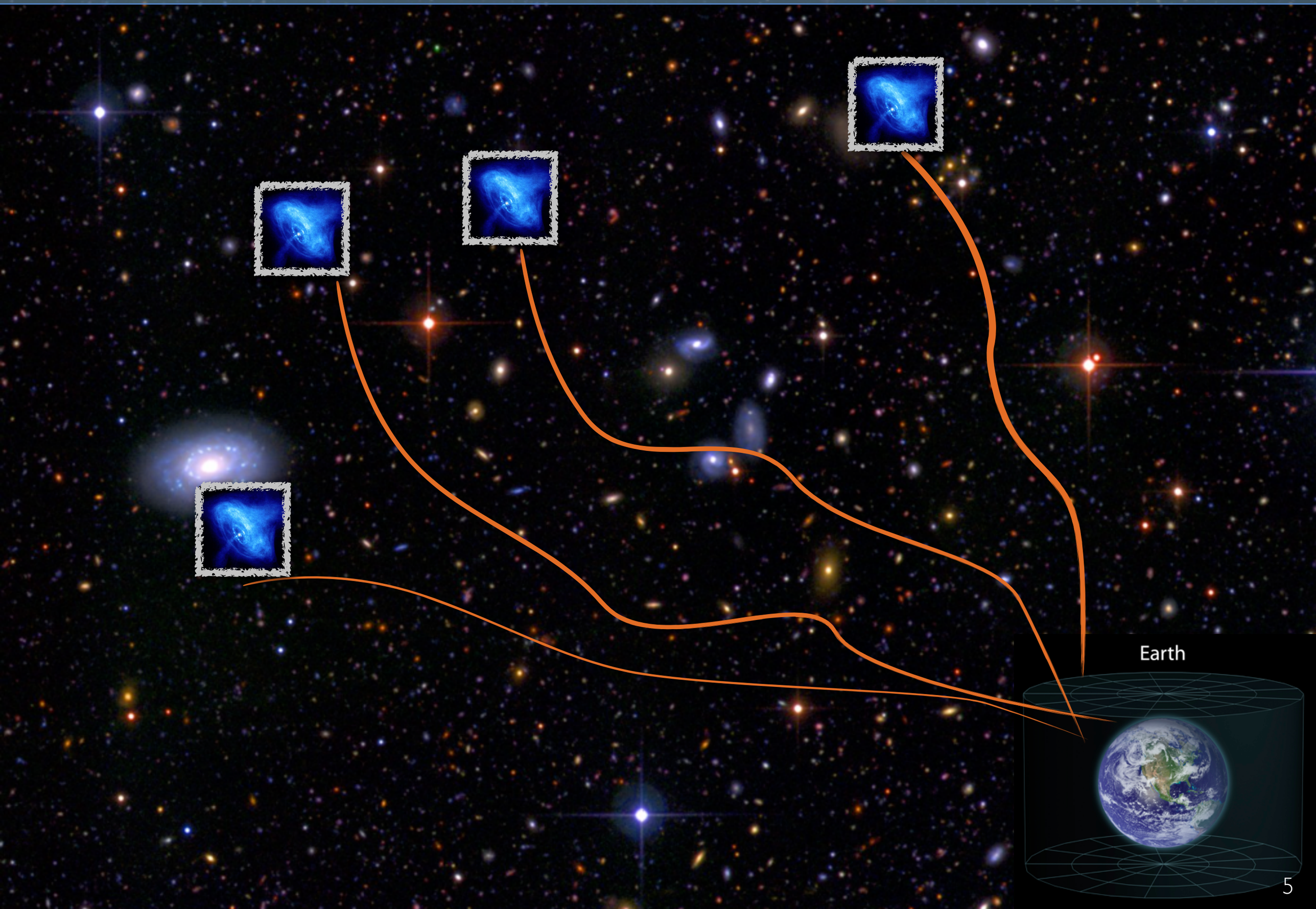
- to probe the most powerful sources in the Universe

# Neutrinos!


Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10²⁴
10²⁰
10¹⁶
10¹²
10⁸
10⁴
1
10⁻⁴
10⁻⁸
10⁻¹²
10⁻¹⁶
10⁻²⁰
10⁻²⁴
10⁻²⁸
Cosmological ν
2002
2015
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
10⁻⁶ μeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Neutrino energy

# Producing EeV neutrinos



# Producing EeV neutrinos

cosmic photon backgrounds

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

cosmogenic neutrinos

Earth

# Producing EeV neutrinos

photon/hadron backgrounds
in source environments

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neutrinos @sources

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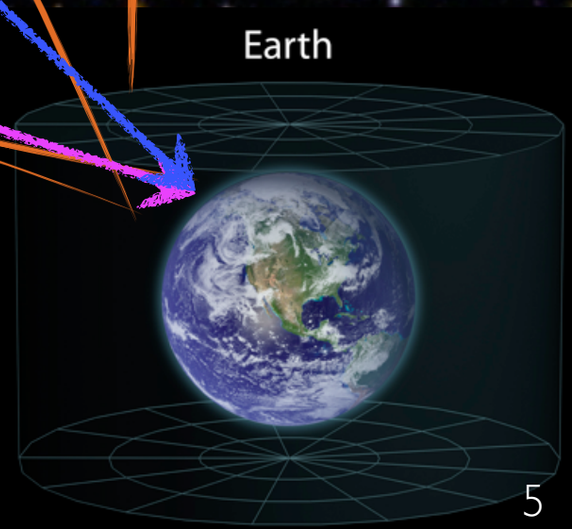

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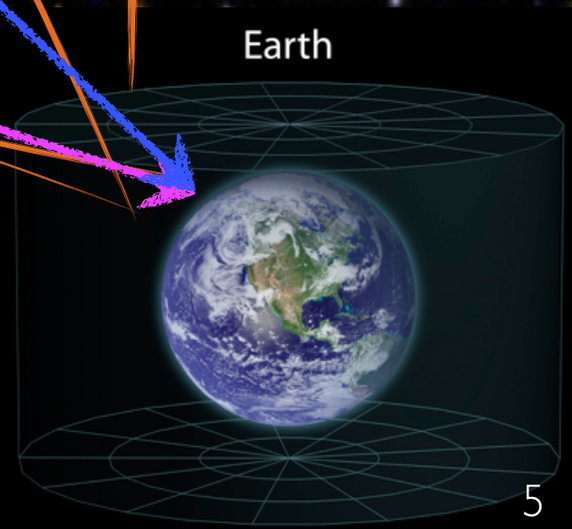


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- diffuse flux: integrate over all sources in the Universe
(source evolution history matters)

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- guaranteed

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neutrinos @sources

- likely very abundant

cosmic photon backgrounds

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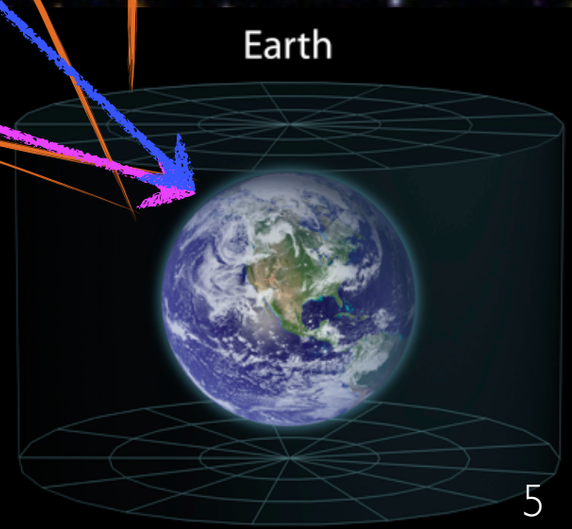


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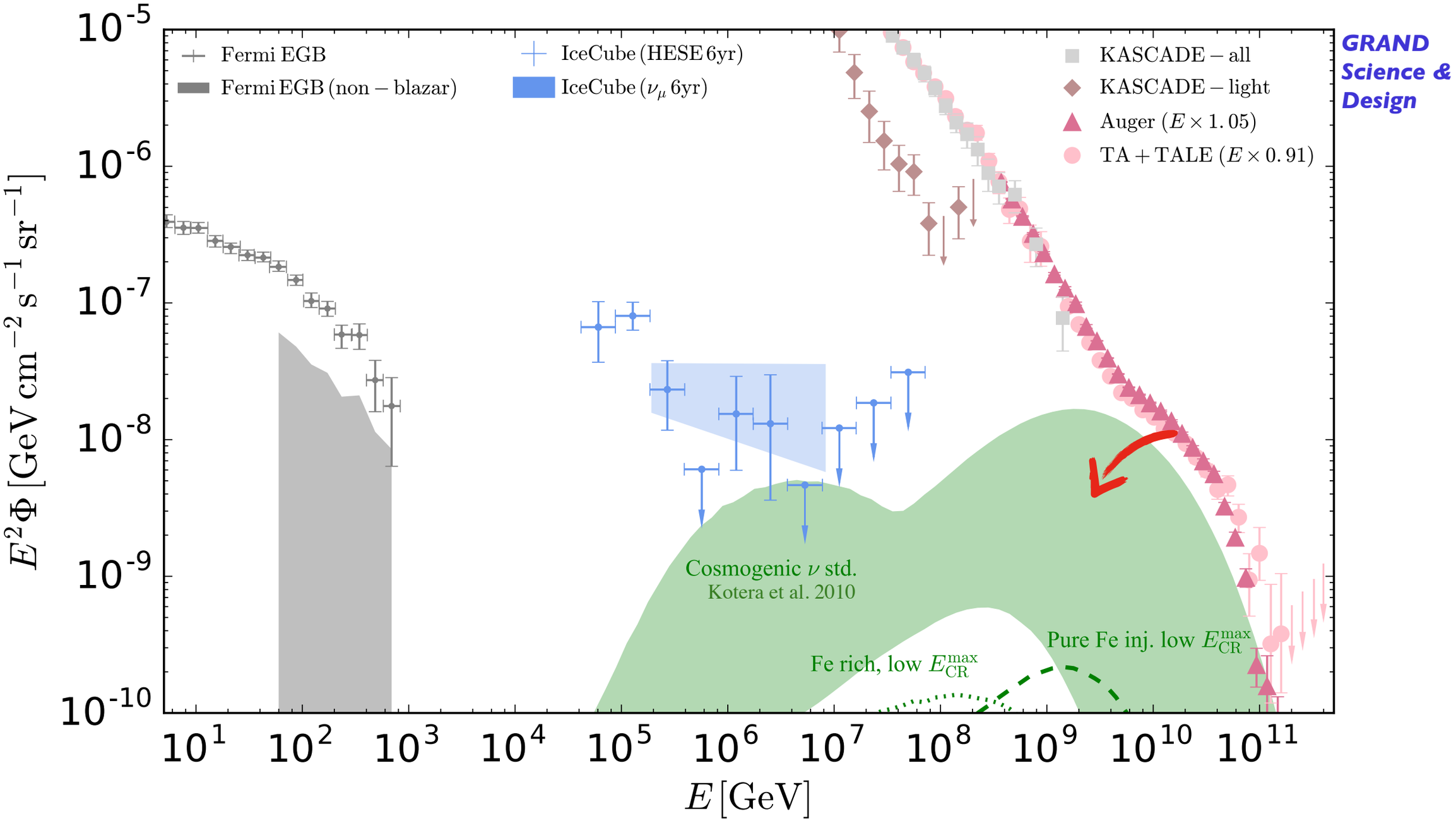


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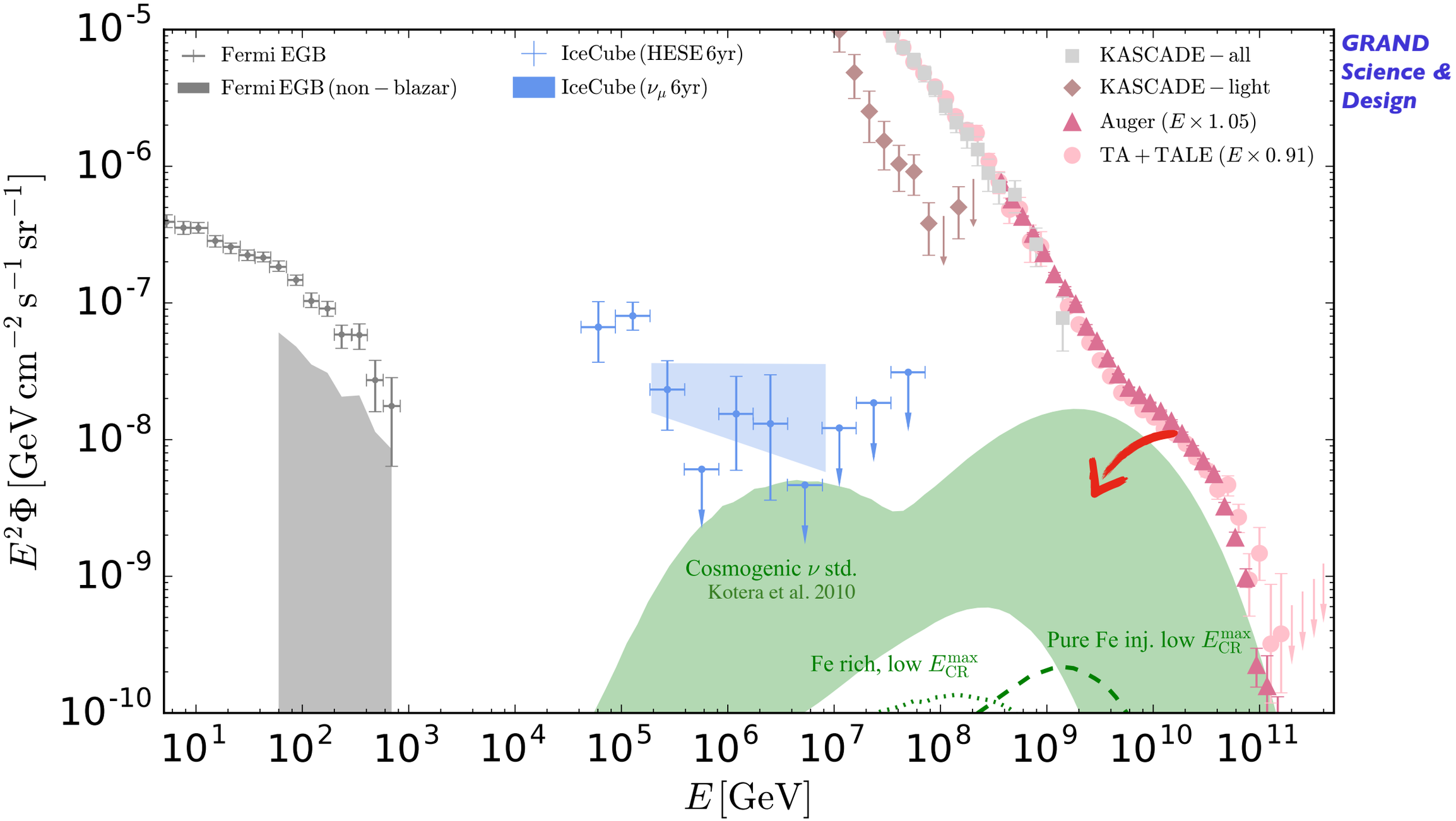


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cosmogenic neutrinos guaranteed
if sources of UHECRs
@cosmological distances

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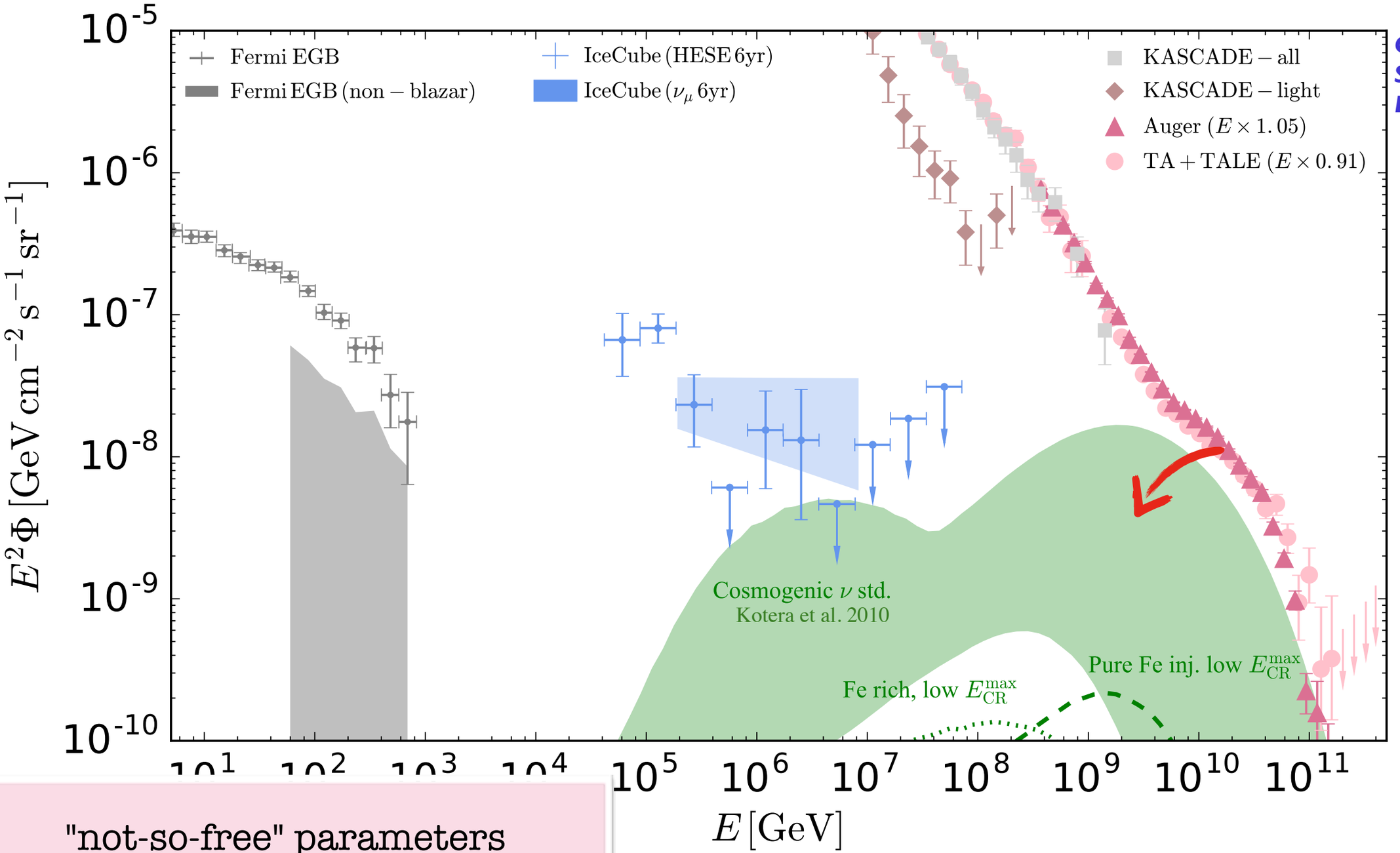


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## "not-so-free" parameters

- $A$ flux normalisation
- $\gamma$ injection spectral index
- $R_{\rm max}$ (max. rigidity ~ max. proton energy)
- composition
- source evolution history

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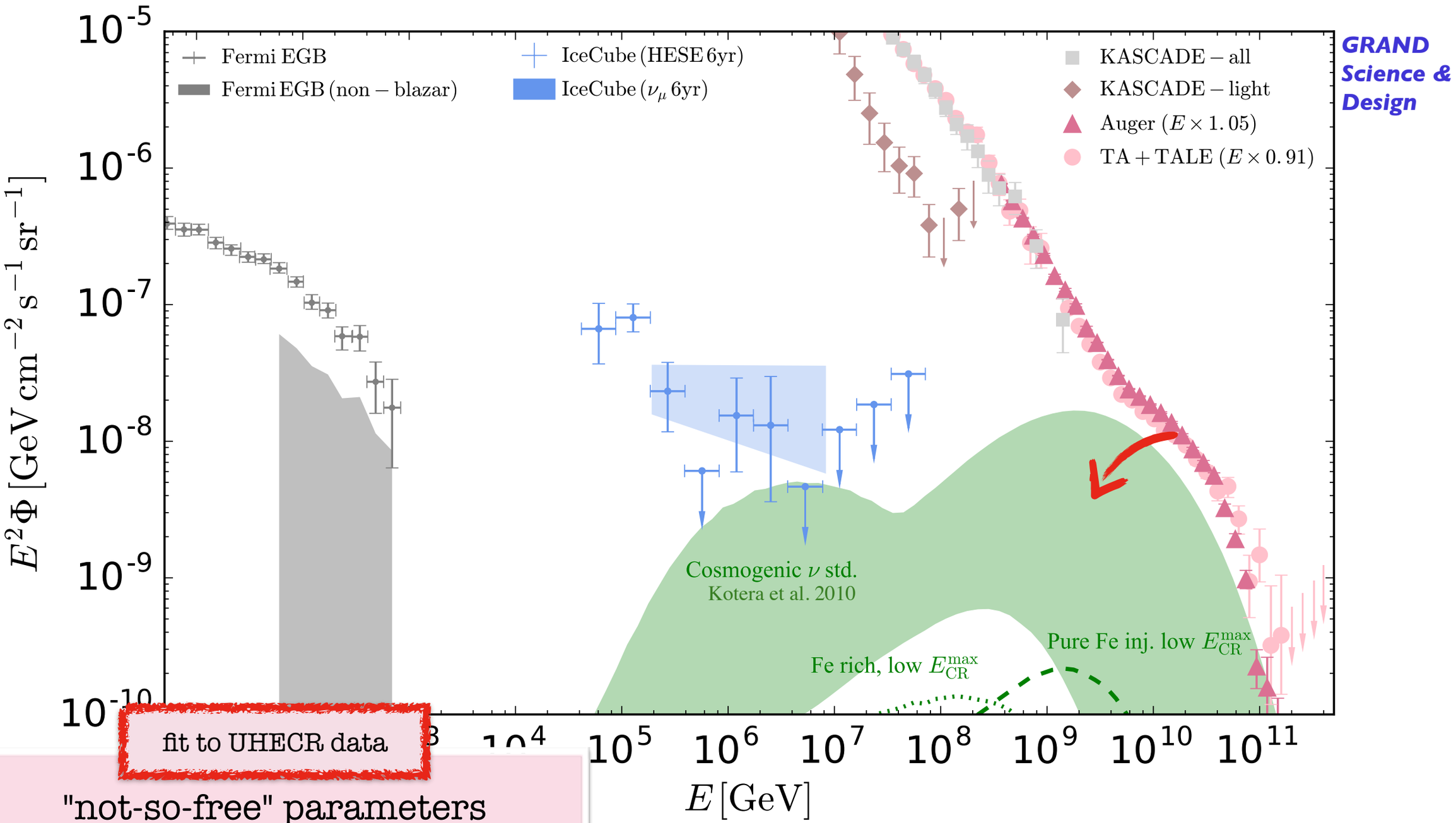


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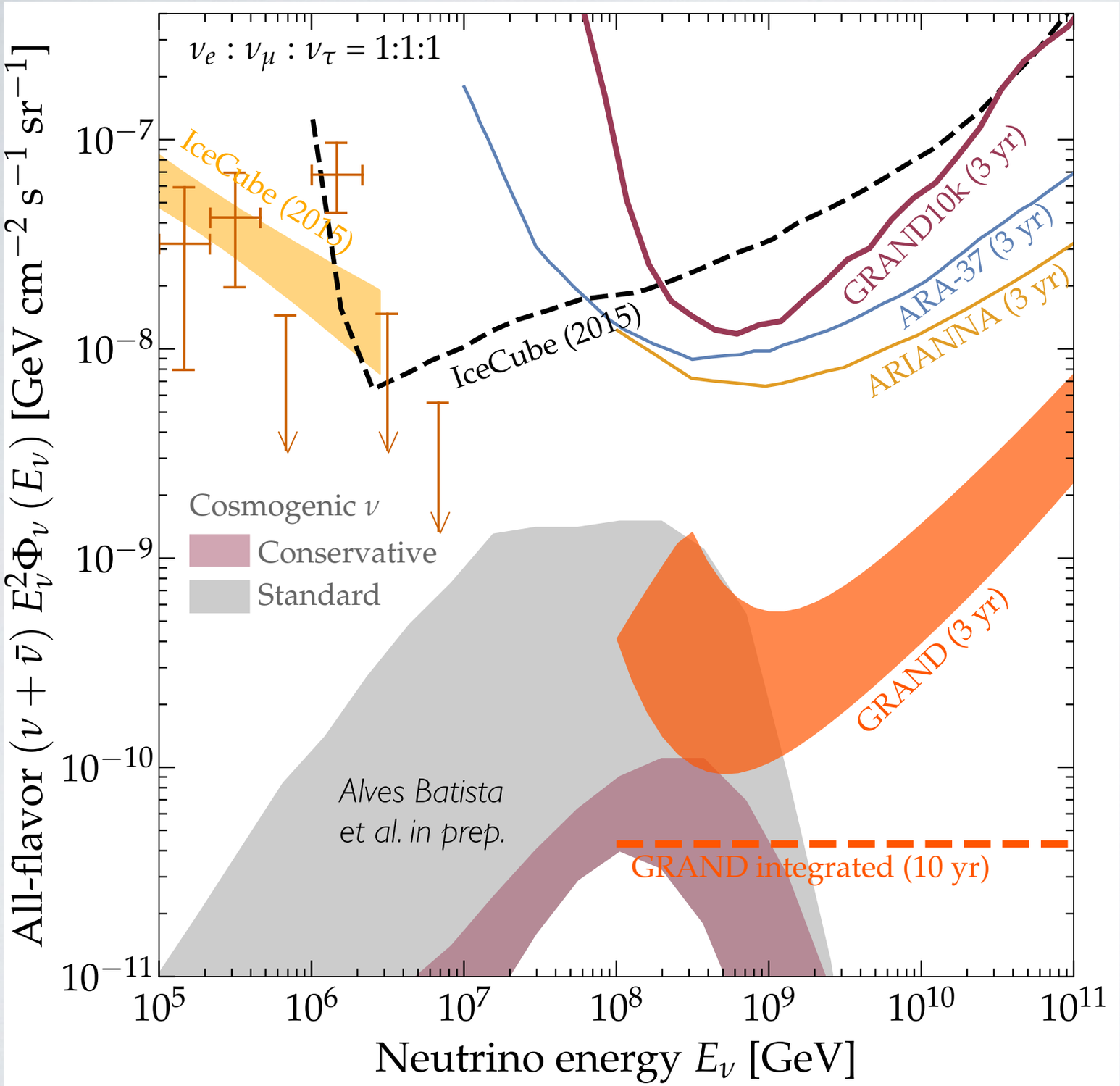
***Alves Batista, de Almeida, Lago, KK, in prep.***

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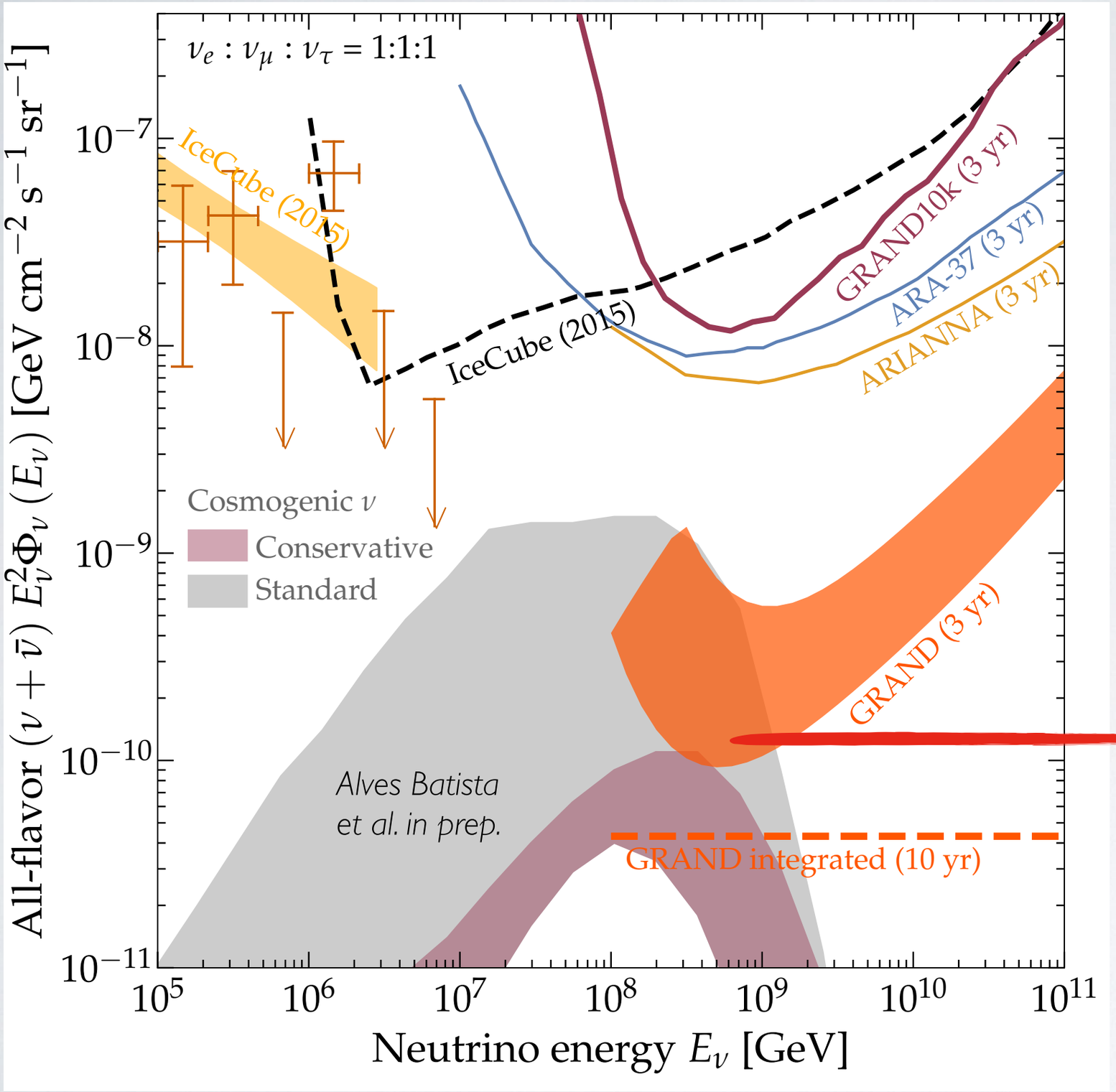




**EeV neutrinos guaranteed**
**if lucky: hundreds of events**

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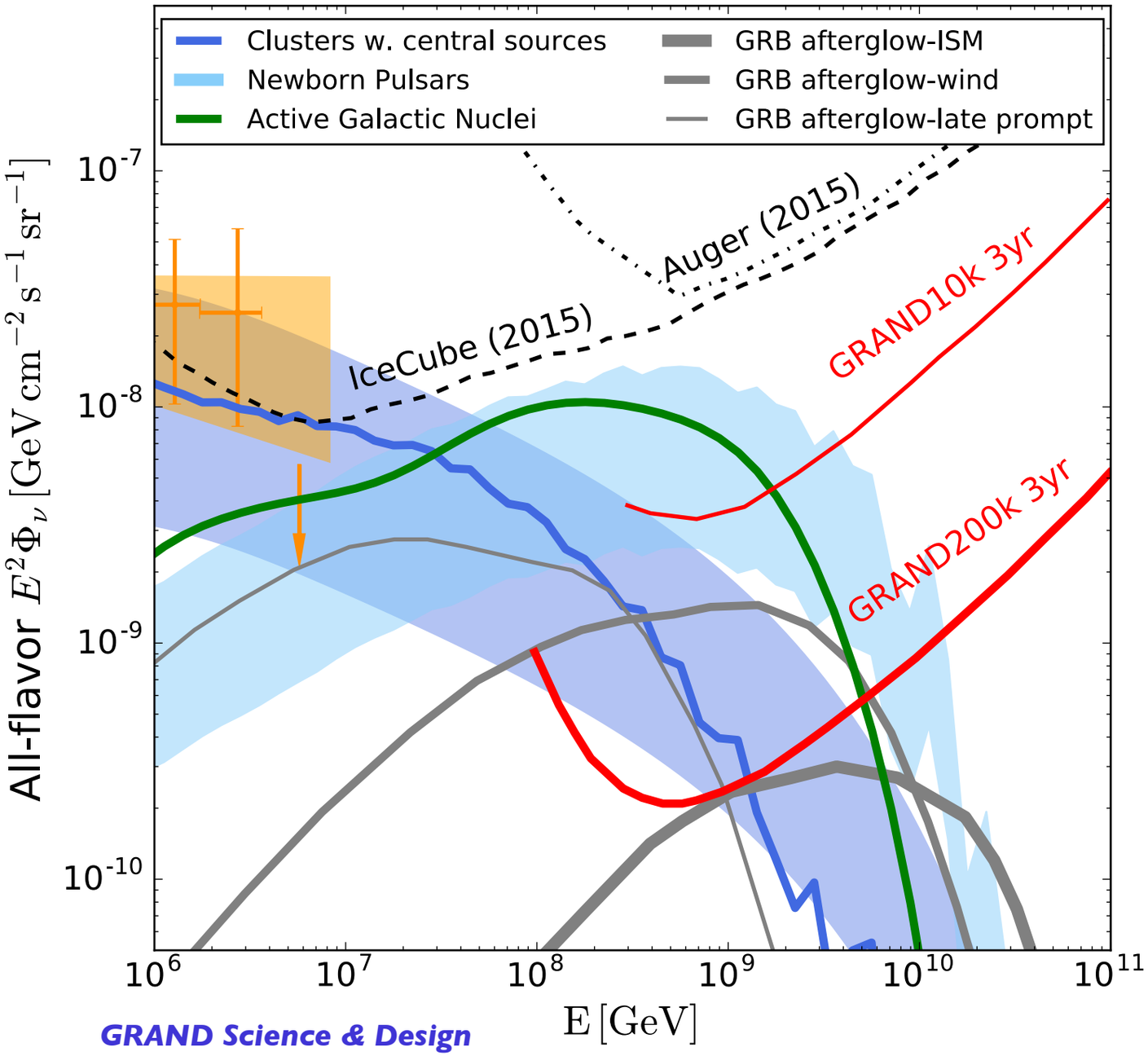
# Neutrinos produced at the source (diffuse flux)

Diffuse flux (integrated over the whole population)

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unique shapes for various sources (because of interaction backgrounds)

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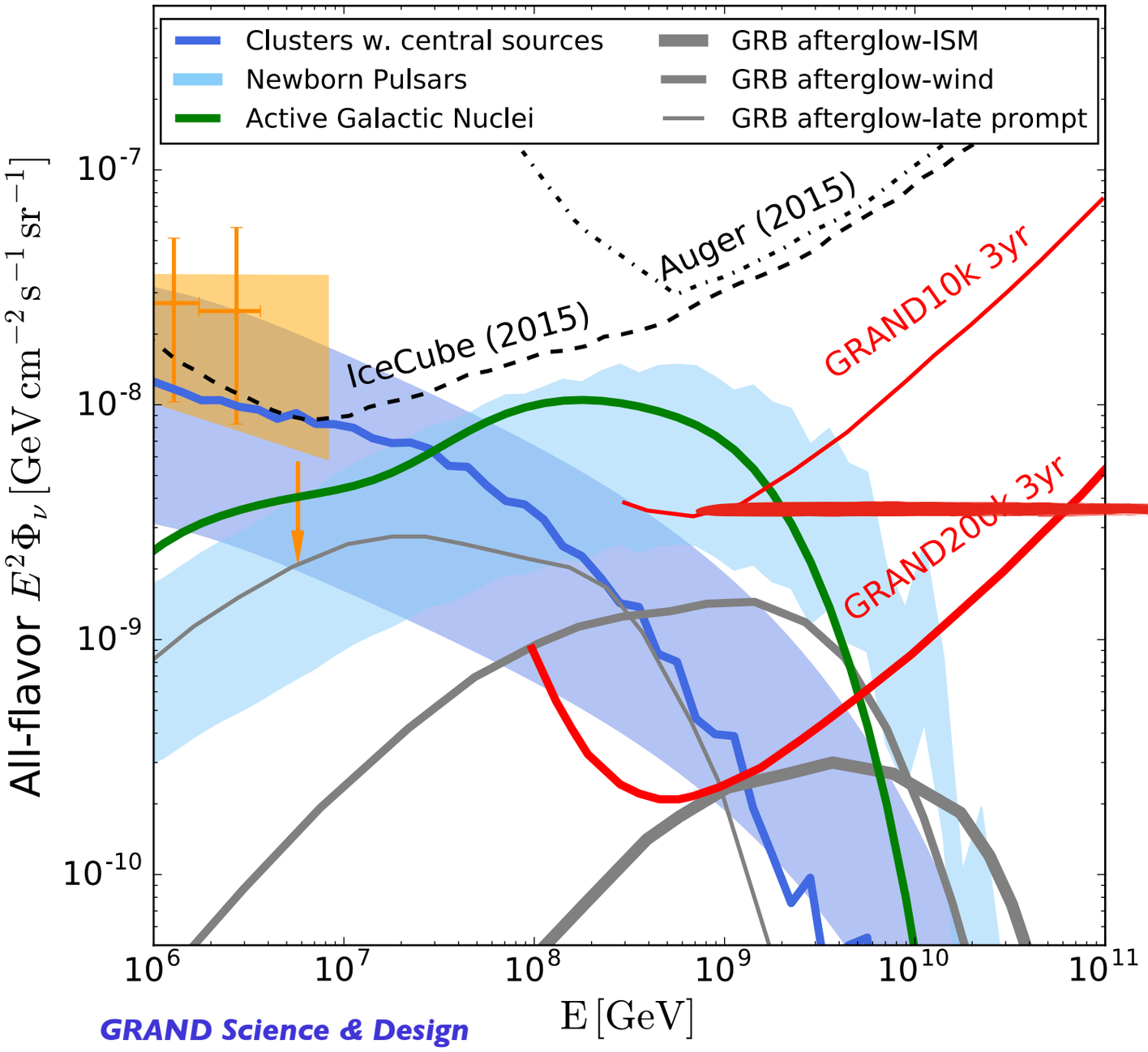


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GRAND 10k

ARIANNA

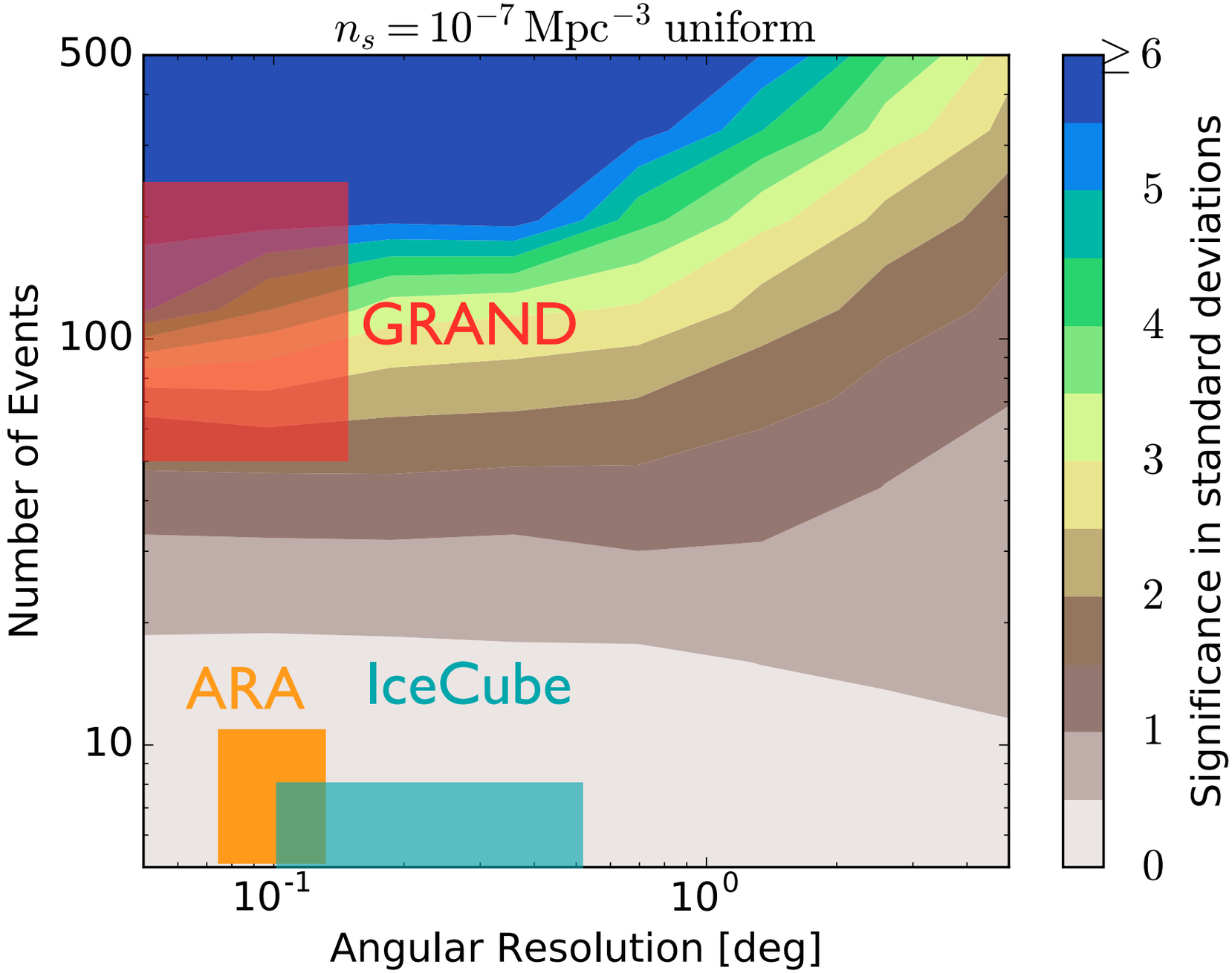
ASKARYAN RADIO ARRAY

**if lucky:**
**EeV source neutrinos**

unique shapes for various sources (because of interaction backgrounds)

# Can we detect very high-energy neutrino sources?

*Fang, KK, Murase, Miller, Oikonomou 2016*



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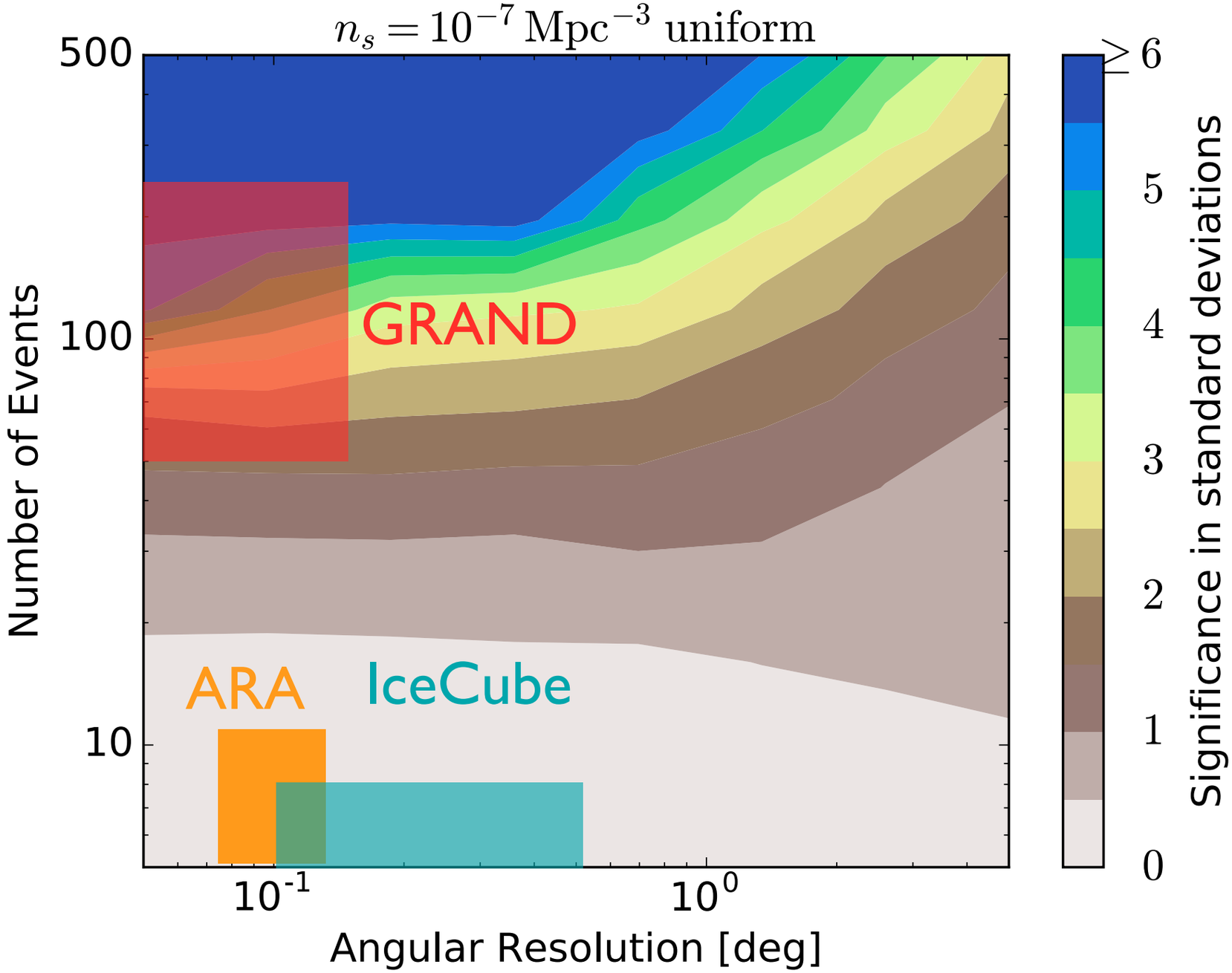


**YES if**

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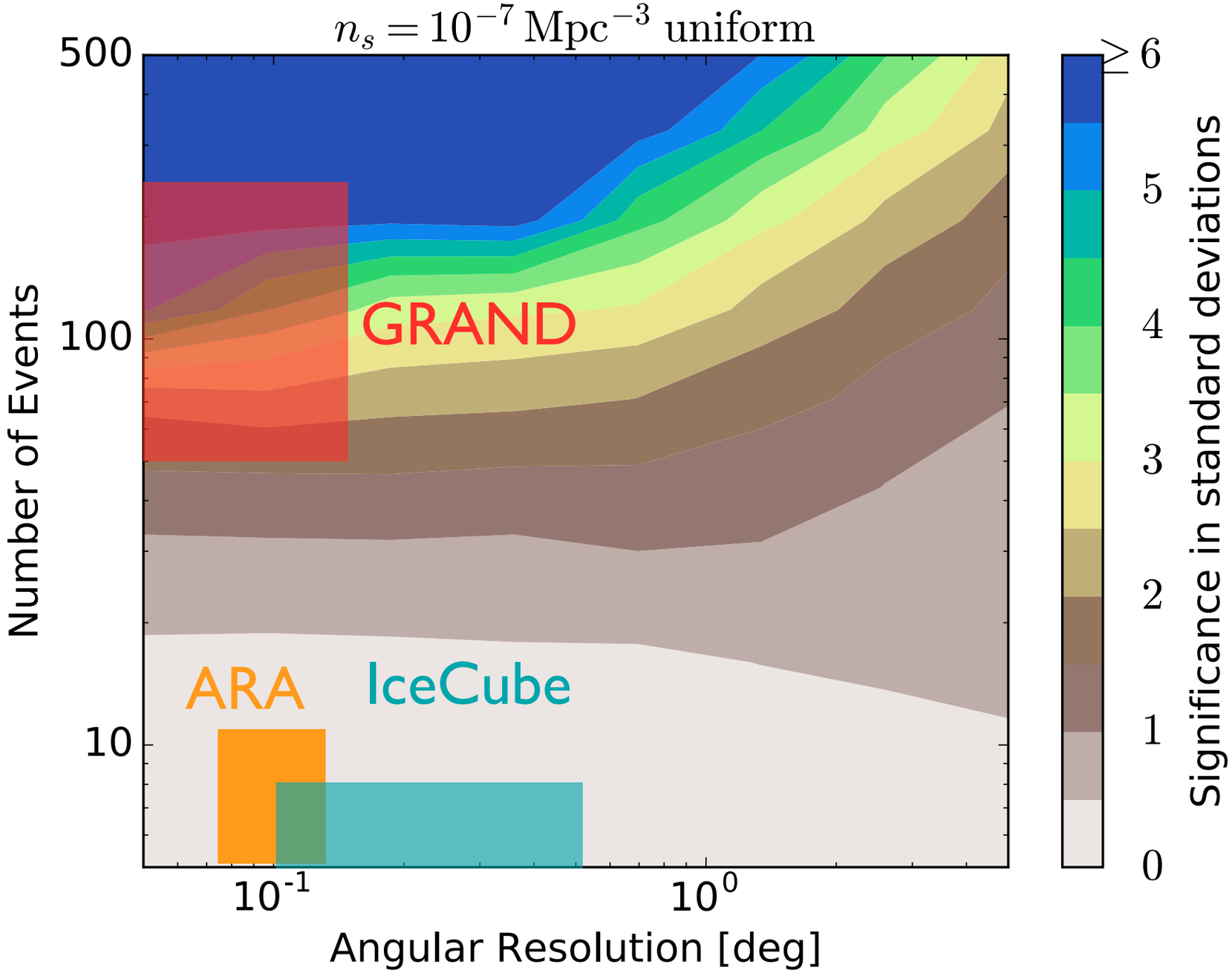


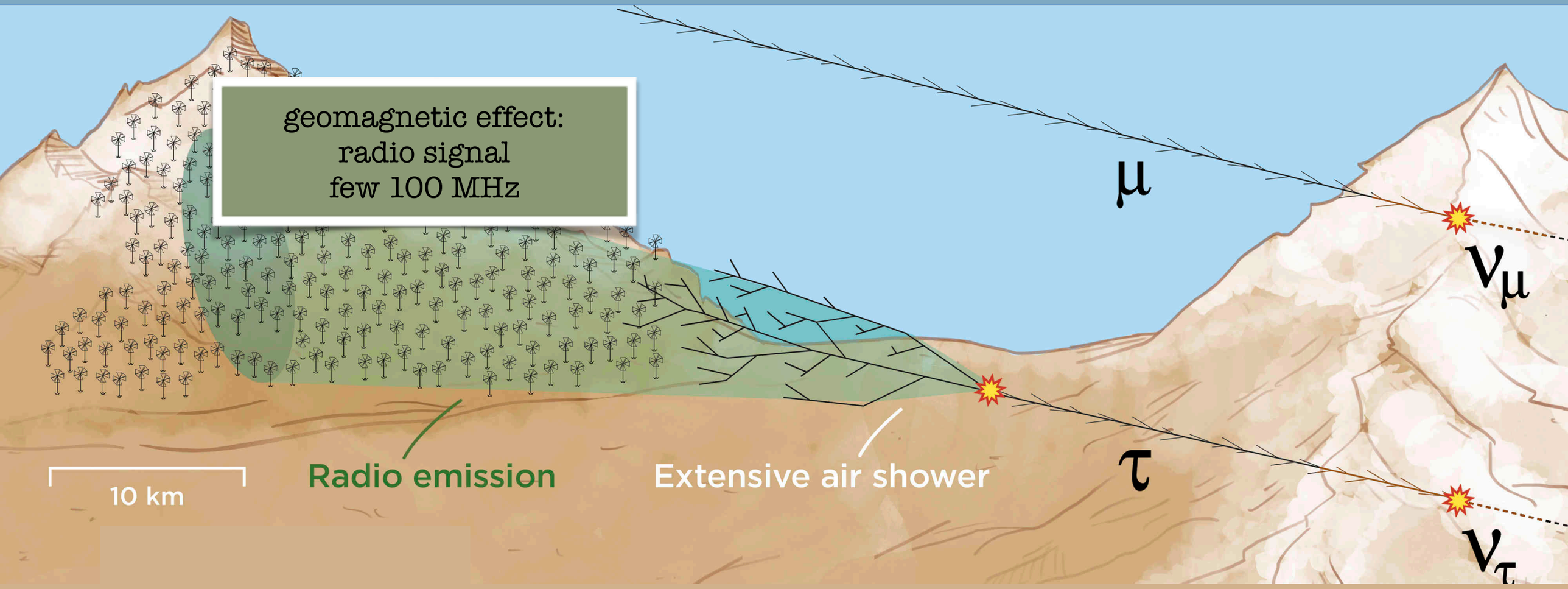

**YES if**

- good angular resolution (< fraction of degree)
- number of detected events > 100s

# The Giant Radio Array for Neutrino Detection

SF2A - 05/07/2017

# Radio-detection of high-energy neutrinos?



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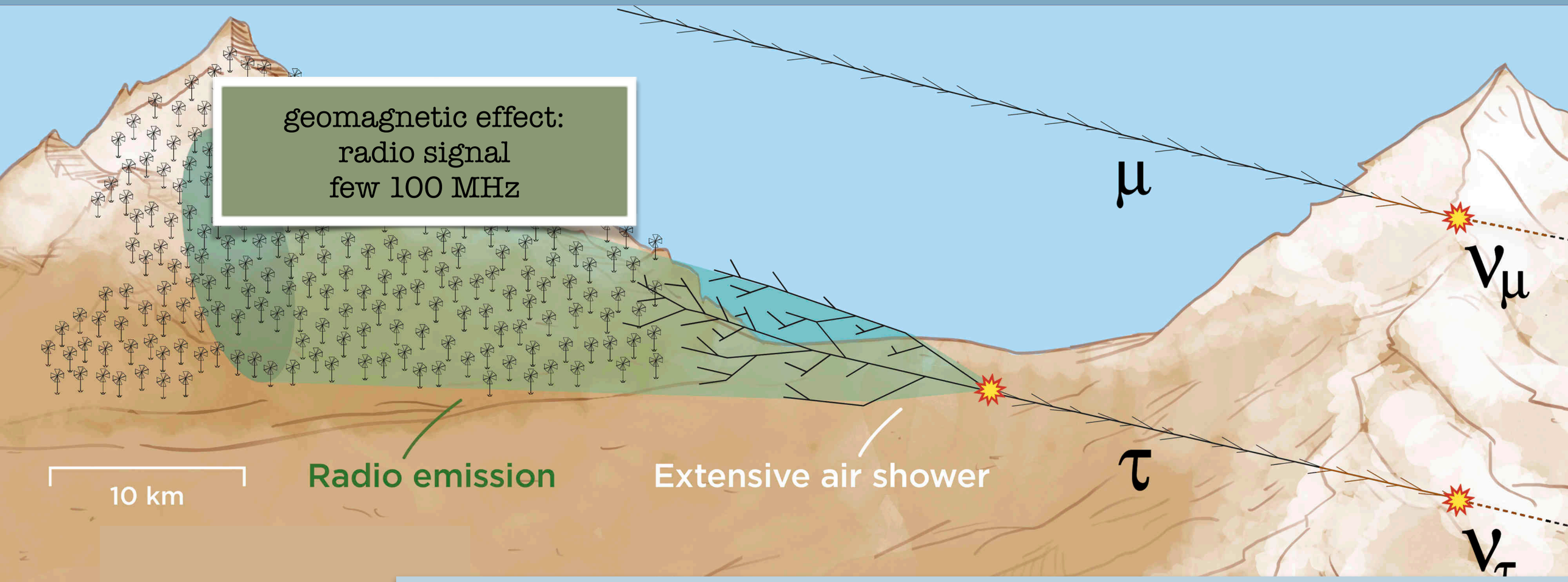


NEW! HOT! radio detection of astroparticles works!

*AERA Collaboration 2016a, b - LOFAR Collaboration 2016*

# Radio-detection of high-energy neutrinos?

geomagnetic effect:
radio signal
few 100 MHz

μ

$\nu_\mu$

τ

$\nu_\tau$

Radio emission

Extensive air shower

10 km

$X_{max}$

$\theta_c \sim 1^o$

~10 km

~400 m

vertical shower

dense array
needed

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>30km

inclined shower

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~30km

inclined shower

high-energy neutrinos well-suited for radio-detection

# Radio-detection of high-energy neutrinos?

**Radio antenna are probably the most basic HE particle detectors you can think of...**

- ➔ cheap + robust + easy to deploy & maintain
- ➔ perfect for giant arrays

LOFAR

# The GRAND Project

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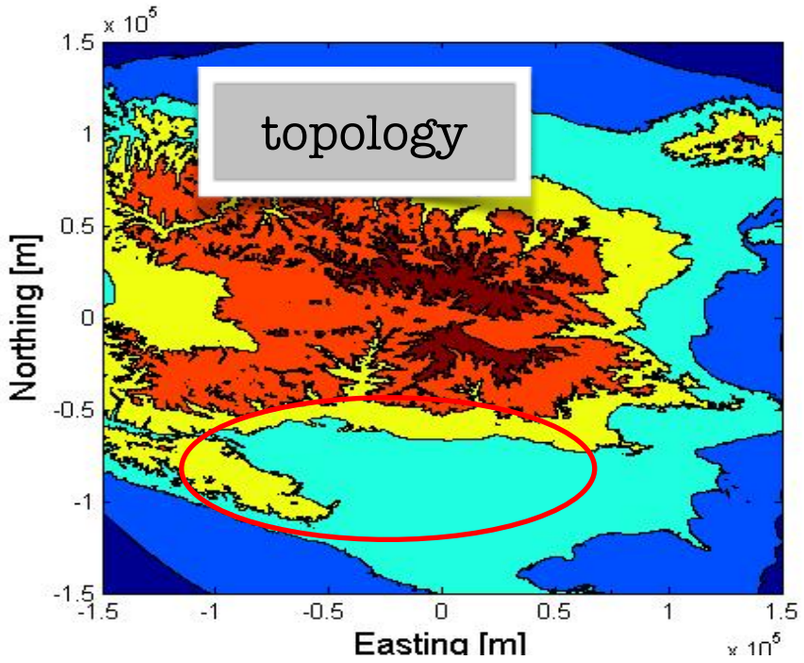
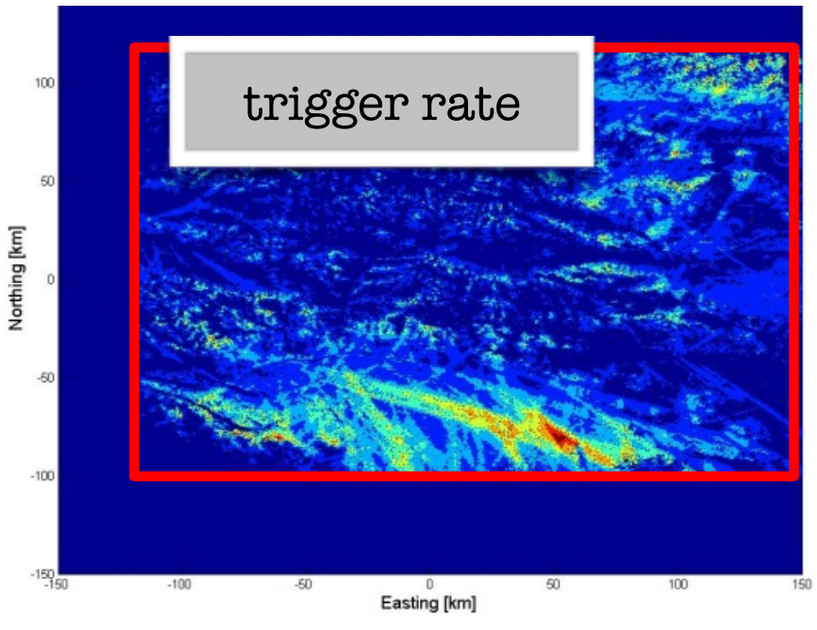
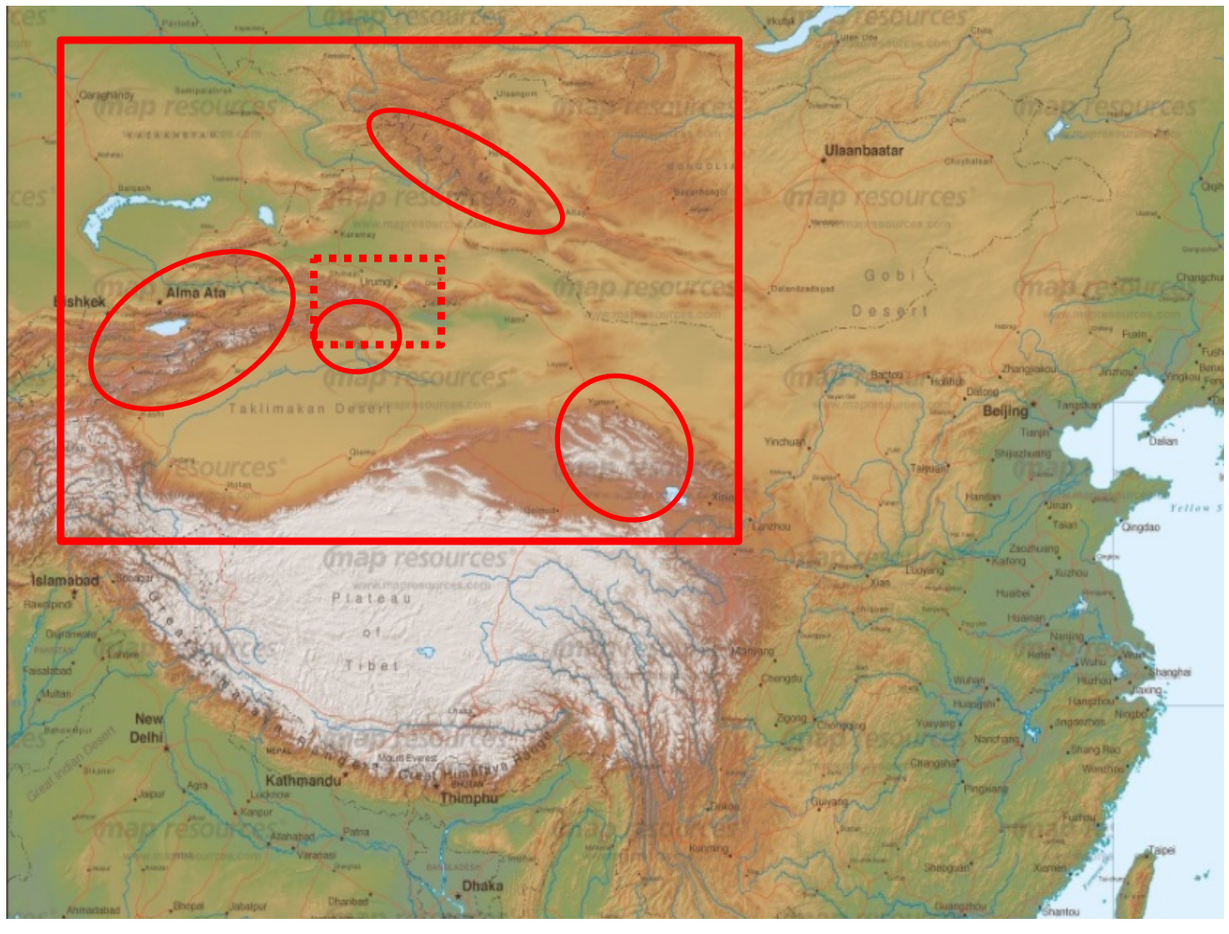
# Deployment in hotspots




Hotspot with favorable topology
⇒ enhanced detection rate!

- Target sensitivity: $\varphi_0 = 1.5 \times 10^{-11}$ GeV/cm²/sr/s
- Driver: go for **hotspots**! Then 200'000 km² may be enough to reach target sensitivity
- Giant simulation area (1'000'000 antennas over 1'000'000 km²? Full Earth?) to identify hotspots



# 47 collaborators
# main contributing institutes: NAOC, IAP, LPNHE, Radboud U., PennState

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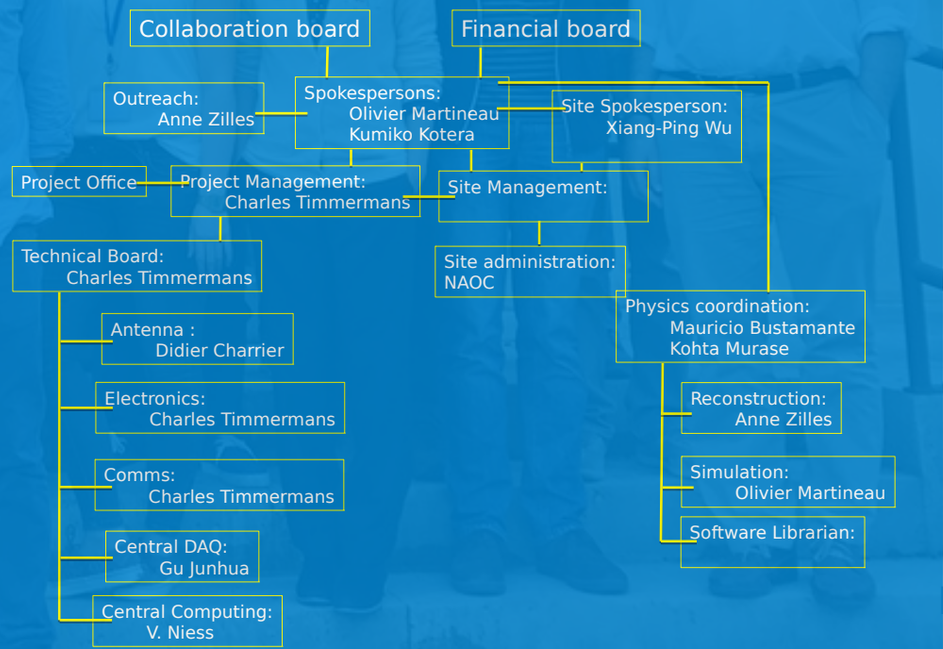
## GRAND organizational structure



# 47 collaborators
# main contributing institutes: NAOC, IAP, LPNHE, Radboud U., PennState

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France China Particle Physics Laboratory

Natural Science Foundation of China

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Chinese Academy of Science

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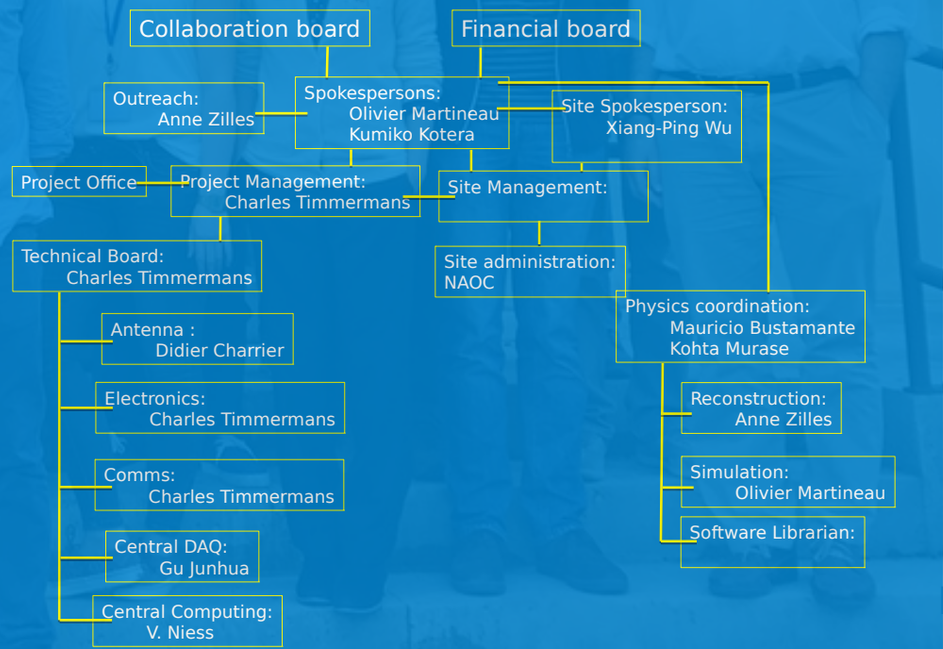


# GRAND Roadmap

GRANDproto300

GRANDproto35

GRAND10k

GRAND200k

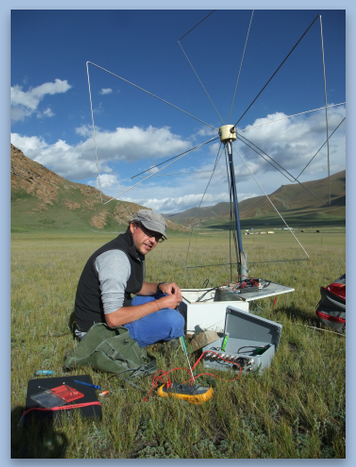
2017 2020 2025 203X

**Goals**

demonstrate that EAS can be detected on **standalone** radio array with high efficiency & very good **background rejection**

**Setup**

35 radio antennas
21 scintillators



**Budget & stage**

160kE, fully funded by NAOC+IHEP, deployment fall 2017 @ Ulastai

# GRAND Roadmap

GRANDproto300

GRANDproto35 | GRAND10k | GRAND200k

2017 — 2020 — 2025 — 203X

| | GRANDproto35 | GRANDproto300 |
|---|---|---|
| **Goals** | demonstrate that EAS can be detected on **standalone** radio array with high efficiency & very good **background rejection** | establish detection & identification by standalone radio array of **very inclined showers** ($\theta$>70°) induced by high energy cosmic rays (>$10^{18}$eV). Includes background rejection, EAS reconstruction, etc. |
| **Setup** | 35 radio antennas<br>21 scintillators<br>  | • 300 Horizon Antennas over 300 km²<br>• Fast DAQ (AERA+ GRANDproto35 analog stage)<br>• Solar pannels (day use) + WiFi data transfer |
| **Budget & stage** | 160kE, fully funded by NAOC+IHEP, deployment fall 2017 @ Ulastai | 1.3 ME (reasons to be optimistic for Chinese funding)<br>to be deployed in 2019 |

# GRAND Roadmap

GRANDproto300

GRANDproto35 | GRAND10k | GRAND200k

2017 — 2020 — 2025 — 203X

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| **Setup** | 35 radio antennas<br>21 scintillators<br>  | • 300 Horizon Antennas over 300 km²<br>• Fast DAQ (AERA+ GRANDproto35 analog stage)<br>• Solar pannels (day use) + WiFi data transfer | DAQ with discrete elements, but mature design<br>for trigger, data transfer, consumption |
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# GRAND Roadmap

GRANDproto300

GRANDproto35

GRAND10k

GRAND200k

2017 — 2020 — 2025 — 203X

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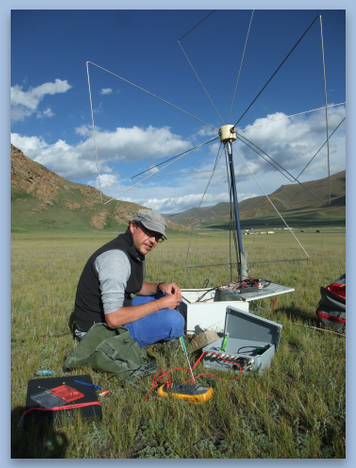
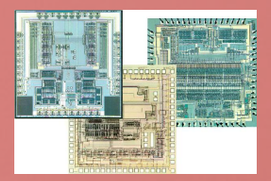
| **Setup** | 35 radio antennas<br>21 scintillators | • 300 Horizon Antennas over 300 km²<br>• Fast DAQ (AERA+ GRANDproto35 analog stage)<br>• Solar pannels (day use) + WiFi data transfer | DAQ with discrete elements, but mature design for trigger, data transfer, consumption | 200'000 antennas over 200'000 km² hotspots could be in different continents |
| **Budget & stage** | 160kE, fully funded by NAOC+IHEP, deployment fall 2017 @ Ulastai | 1.3 ME (reasons to be optimistic for Chinese funding)<br>to be deployed in 2019 | 1500€ / detection unit | **Industrial scale allows to cut costs down: 500€/unit**<br>**➔ 100M€ in total** |



**ASIC**

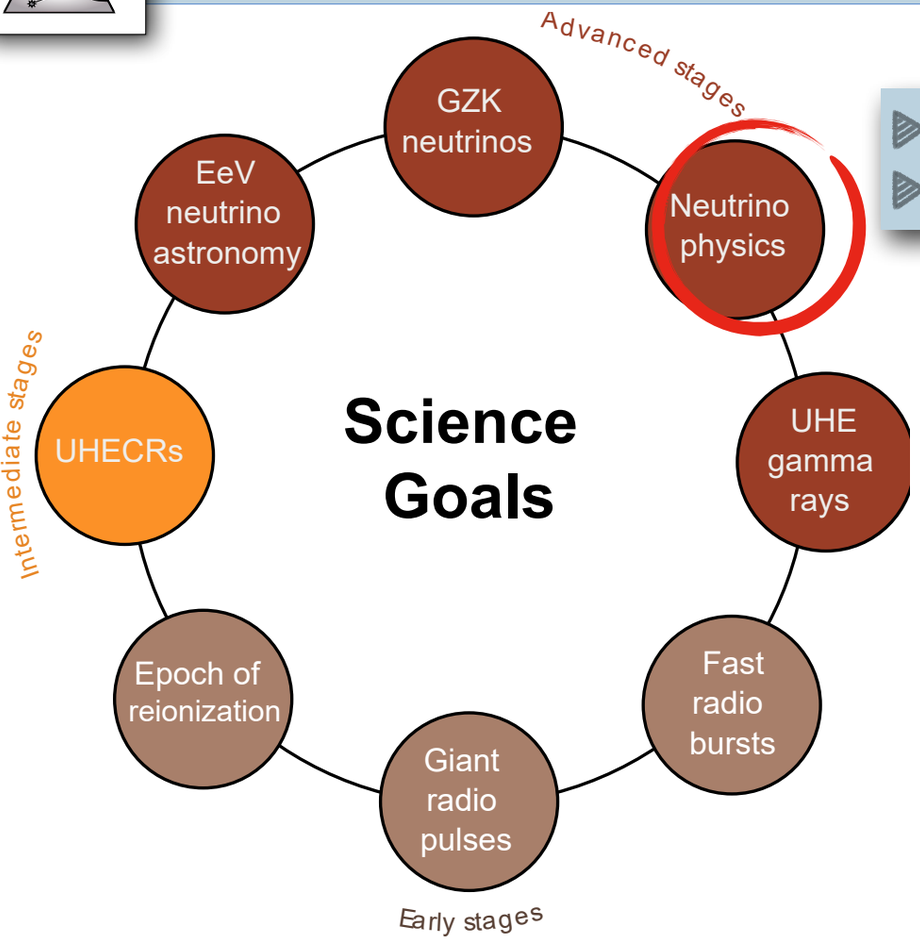


Cost ~10M$ ➔ few 10$/board

Consomption < 1W

Reliability ☺

# New Physics with GRAND




- the highest energies (PeV-EeV) - new physics effects grow with energy
- the longest baselines (Mpc-Gpc) - tiny new physics effects can accumulate

new physics effects scale as $\sim \kappa_n E^n L$

GRAND can probe

$$\kappa_n \sim 4 \cdot 10^{-50} (E/\mathrm{EeV})^{-n} (L/\mathrm{Gpc})^{-1} \ \mathrm{EeV}^{1-n}$$

- with atmospheric/solar neutrinos: $\kappa_0 \lesssim 10^{-32}\ \mathrm{EeV}$, $\kappa_1 \lesssim 10^{-33}$

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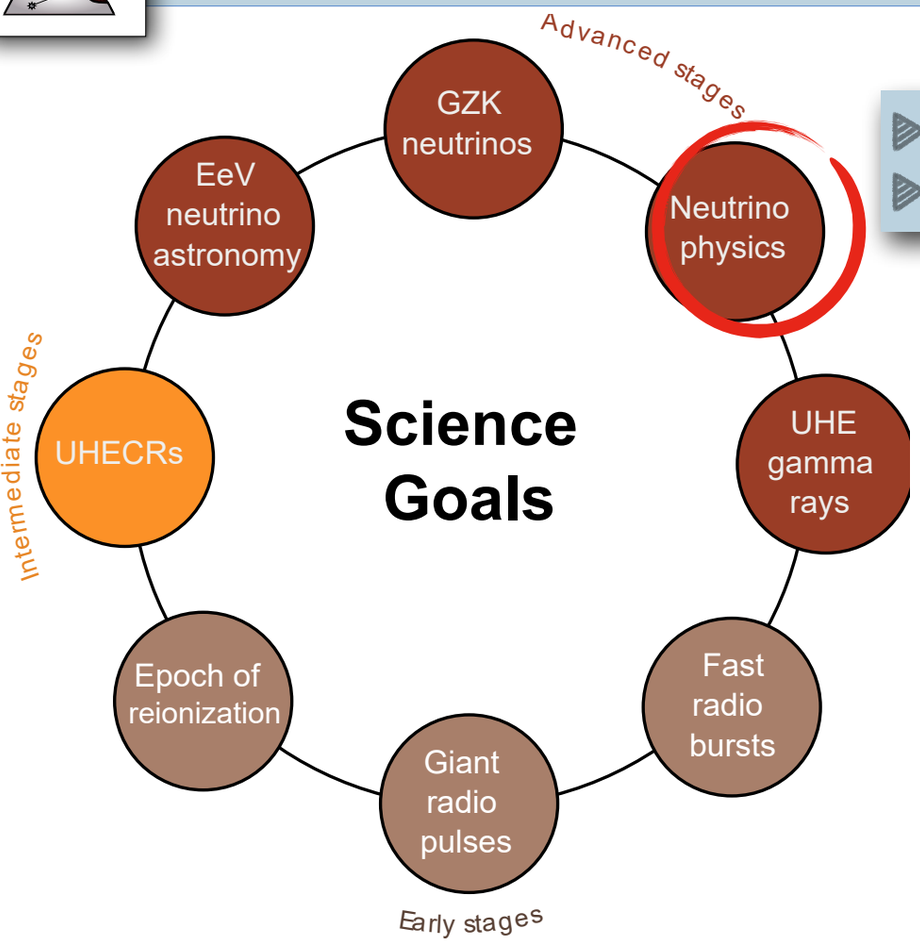


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- GRAND sensitive to tau neutrinos!

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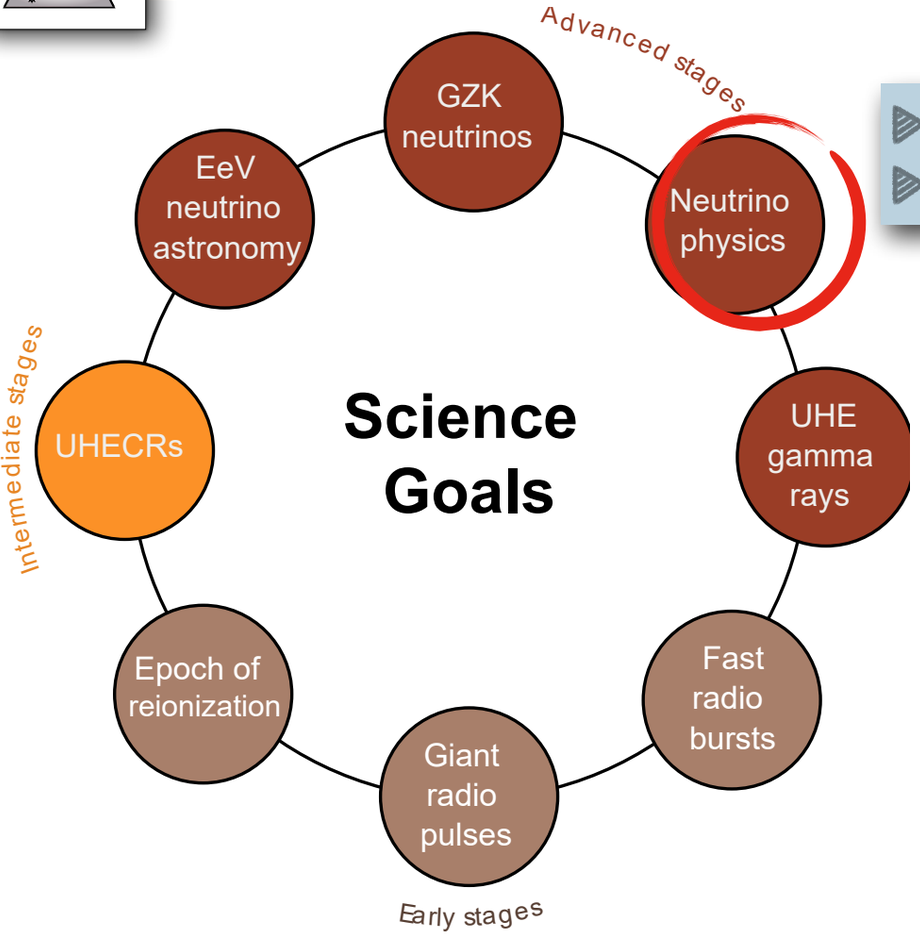


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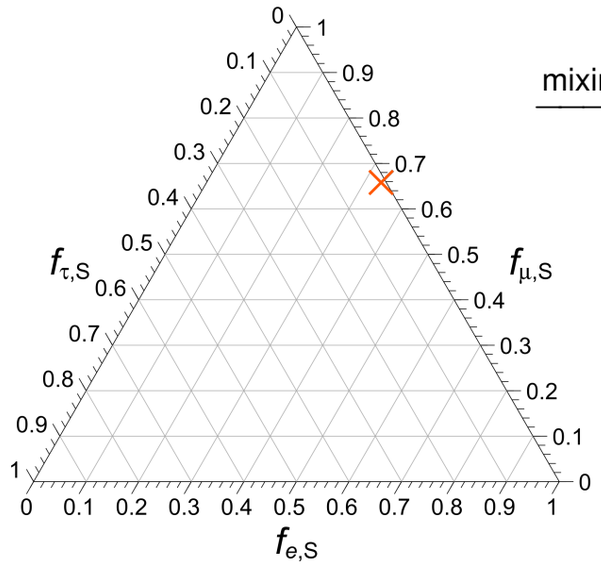
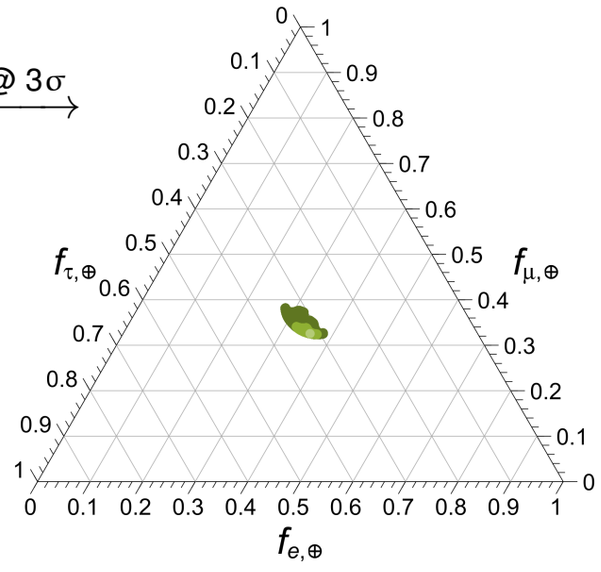
**flavors at source** $(1/3 : 2/3 : 0)_S$




mixing params. @ $3\sigma$

**flavors at Earth**




$p\gamma \to \Delta^+(1232) \to \pi^+ n$ $\quad \pi^+ \to \mu^+ \nu_\mu \to e^+ \nu_e \bar{\nu}_\mu \nu_\mu$

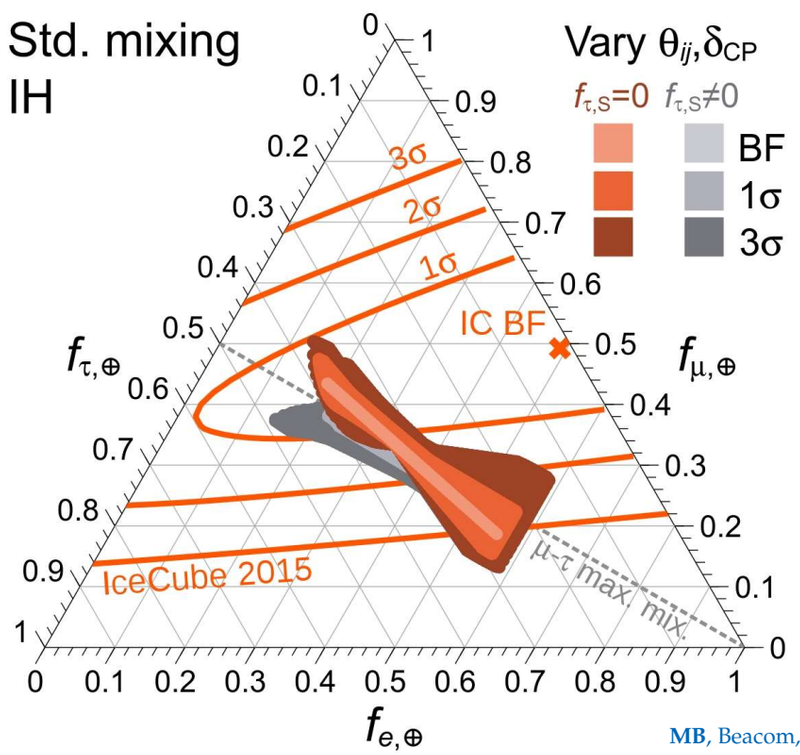
Flavor ratios at production: $(f_e : f_\mu : f_\tau)_S \approx (1/3 : 2/3 : 0)$

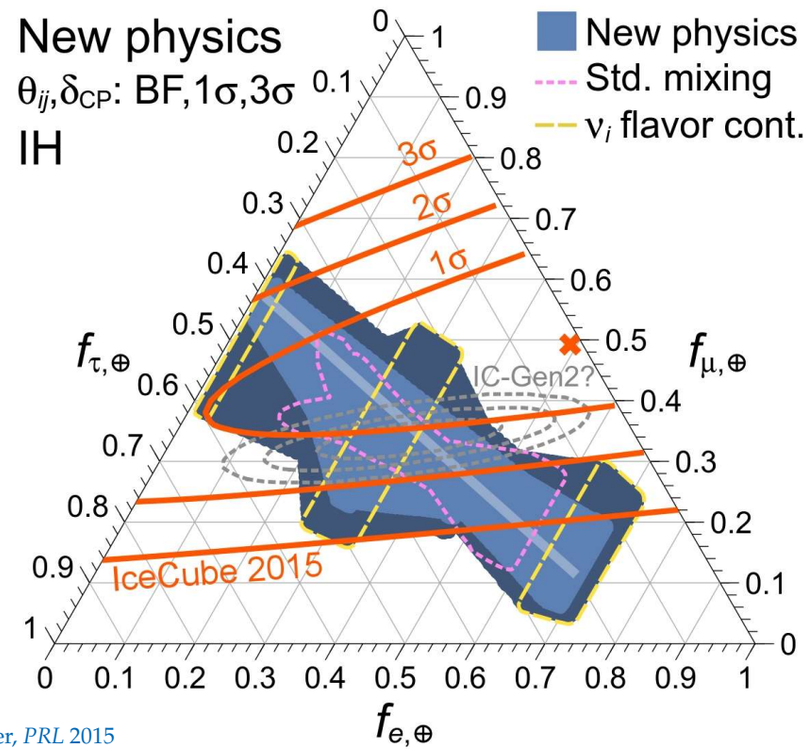
$f_{\tau,\oplus}$ outside [0.30,0.35] could imply new physics

*courtesy: M. Bustamante (GRAND Workshop 2017)*

# Neutrino Physics with flavor composition

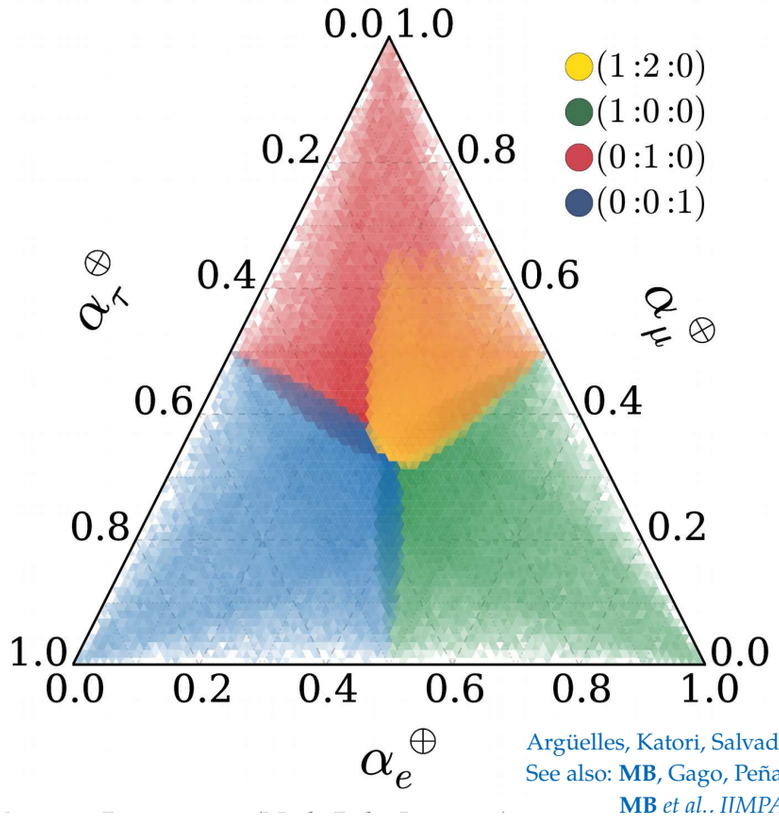
*courtesy: M. Bustamante (ISVHECRI 2018)*




**MB**, Beacom, Winter, *PRL* 2015

## Lorentz-invariance violation




Argüelles, Katori, Salvadó, *PRL* 2015
See also: **MB**, Gago, Peña-Garay, *JHEP* 2010
**MB** *et al.*, *IJMPA* 2009

# The ANITA mystery event

*courtesy: M. Bustamante (ISVHECRI 2018)*

- Two upgoing, unflipped-polarity showers:
  - ANITA-1 (2006): 20°±0.3° dec., 0.60±0.4 EeV
  - ANITA-3 (2014): 38°±0.3° dec., 0.56±0.2 EeV
- Estimated background rate: $< 10^{-2}$ events
- Were these showers due to $\nu_\tau$? *Unlikely*
- Optical depth to $\nu N$ interactions at EeV:

$$\frac{\text{Chord inside Earth}}{\text{Interaction length in Earth}} = \frac{7000\ \text{km}}{390\ \text{km}} = 18$$

- Flux is suppressed by $e^{-18} = 10^{-8}$

ANITA Collab., *PRL* 2016 + 1803.05088

- Transition radiation [Motloch *et al.*, *PRD* 2017]:
  - Refraction of radio waves at ice-air interface could make horizontal $\nu_\tau$ look upgoing
  - Assessment: Needs too large a diffuse flux of $\nu_\tau$, because transition radiation is a small effect
- Sterile neutrinos [Cherry & Shoemaker, 1802.01611; Huang, 1804.05362]:
  - Sterile neutrinos propagate in Earth, then convert $\nu_s \to \nu_\tau$
  - Assessment: Model predicts more (unseen) events at shallower angles
- Dark matter decay in Earth core [Anchordoqui *et al.*, 1803.11554]:
  - 480-PeV sterile right-handed $\nu_r$ in Earth core decays: $\nu_r \to$ Higgs + $\nu_\tau$
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Photo by Brian Hill/U. Hawaii-Manoa

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ANITA Collab., *PRL* 2016 + 1803.05088

**Problems with diffuse-flux interp.**

- Flux needs to be $10^8$ times larger
- No events seen closer to horizon

**Transient astrophysical event?**

- **ANITA-1 event:** none associated
- **ANITA-3 event:**
  - Type-Ia SN2014dz ($z$ = 0.017)
  - Within 1.9°, 5 hours before event
  - Probability of chance SN: $3 \times 10^{-3}$
  - $\nu$ luminosity must exceed bolometric luminosity of $4 \times 10^{42}$ erg s$^{-1}$

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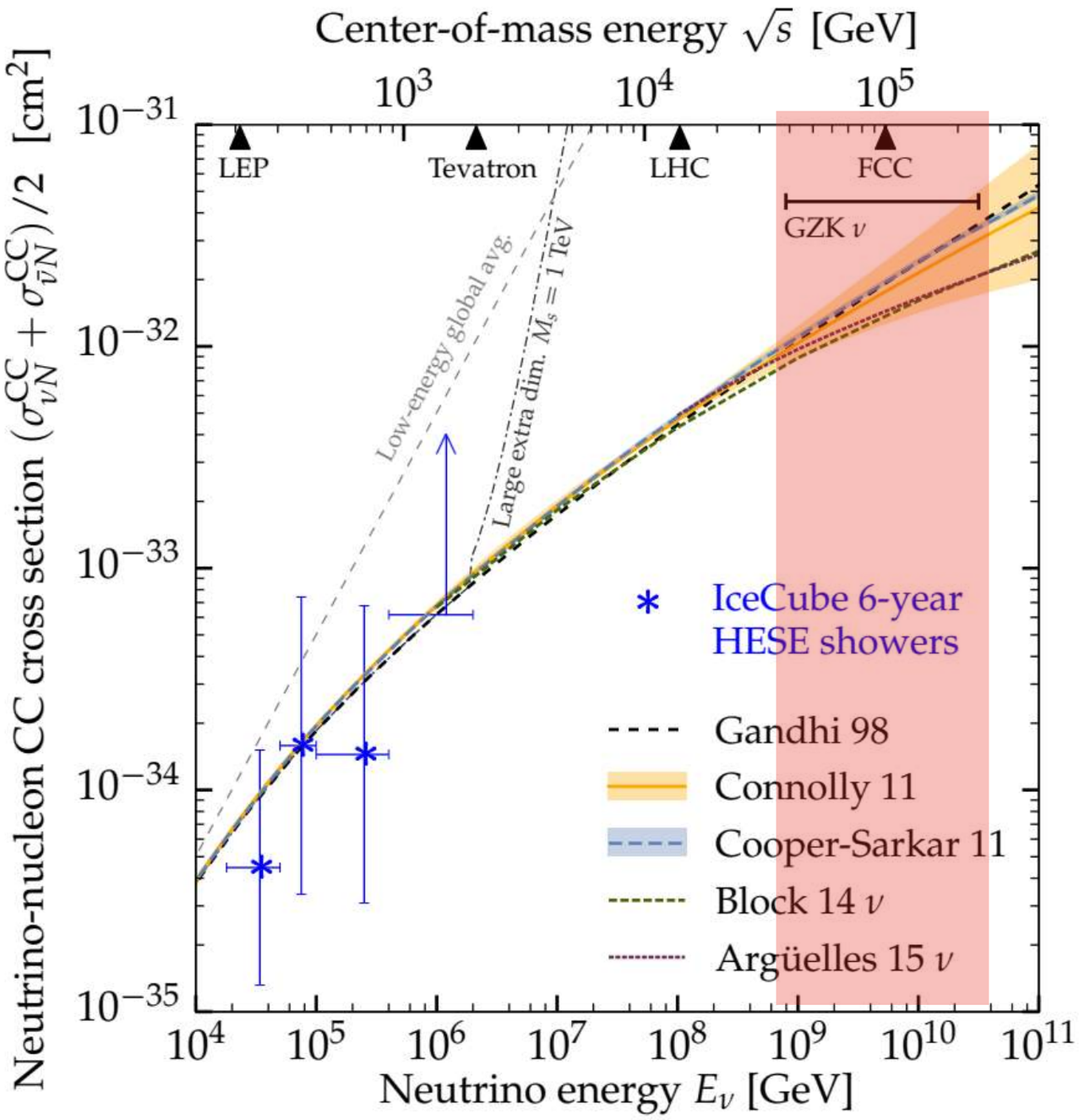
# Neutrino cross-section measurements




**MB** & Connolly, 1711.11043

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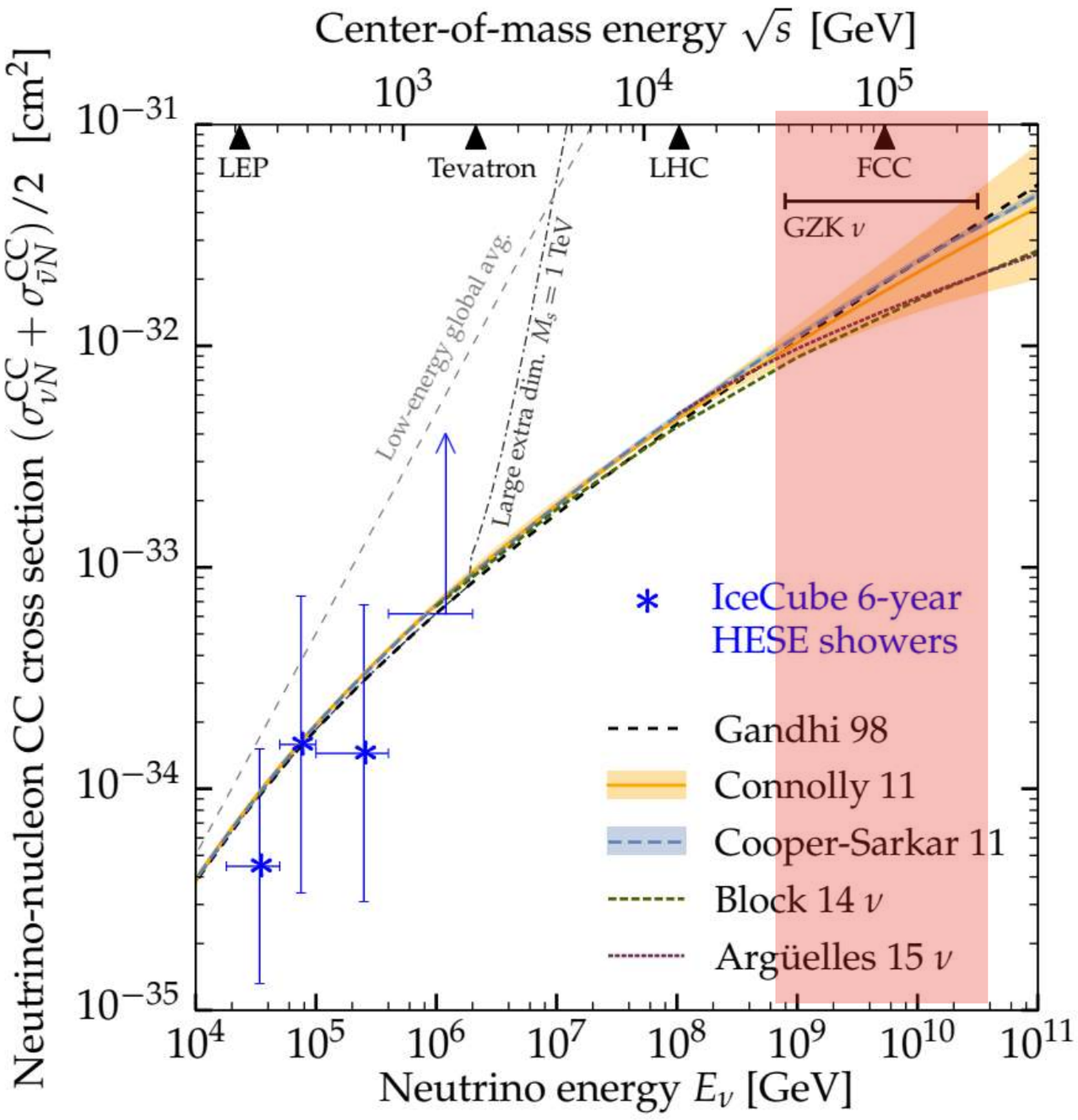


**MB** & Connolly, 1711.11043

With GRAND: specific measurements for tau neutrinos

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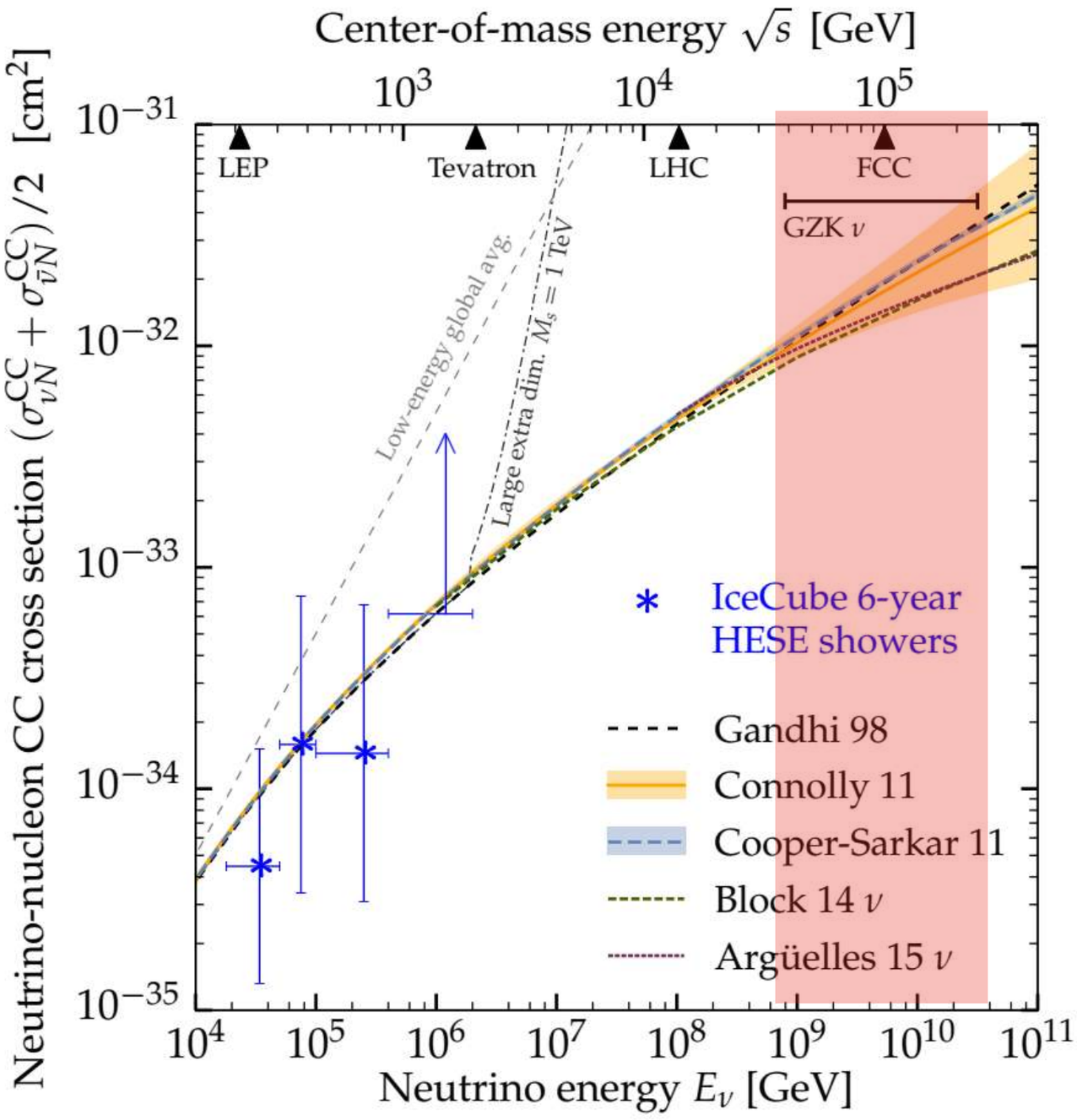
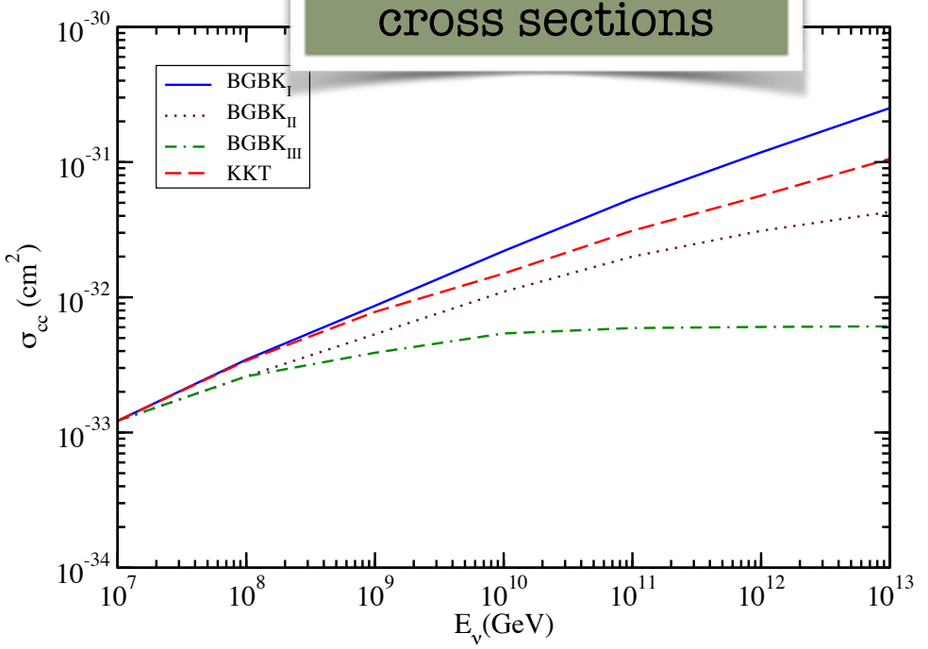



**MB** & Connolly, 1711.11043

neutrino-nucleon cross sections




Extreme gluon saturation @UHE for low Bjorken-x < $10^{-6}$

*Henley & Jalilian Marian (2006)*

▶ to explain ANITA events?

▶ With GRAND: specific measurements for tau neutrinos

# EeV Neutrino Astronomy

*May your GRAND* dreams come true!*

*Giant Radio Array for Neutrino Detection

*Kumiko Kotera - Institut d'Astrophysique de Paris - non-Perturbative QCD Workshop 2018*