GRAND:
Giant Radio Array for Neutrino Detection

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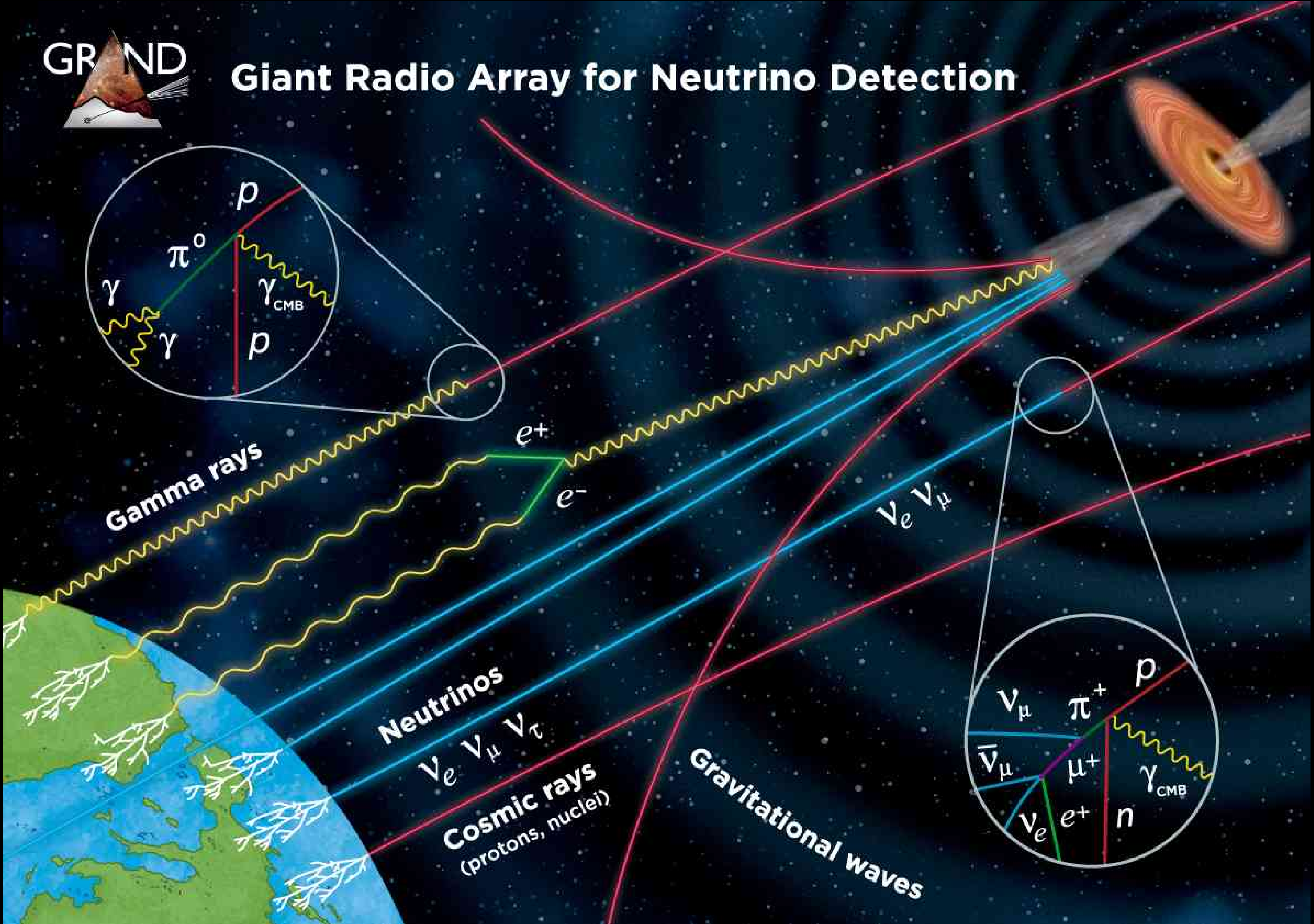
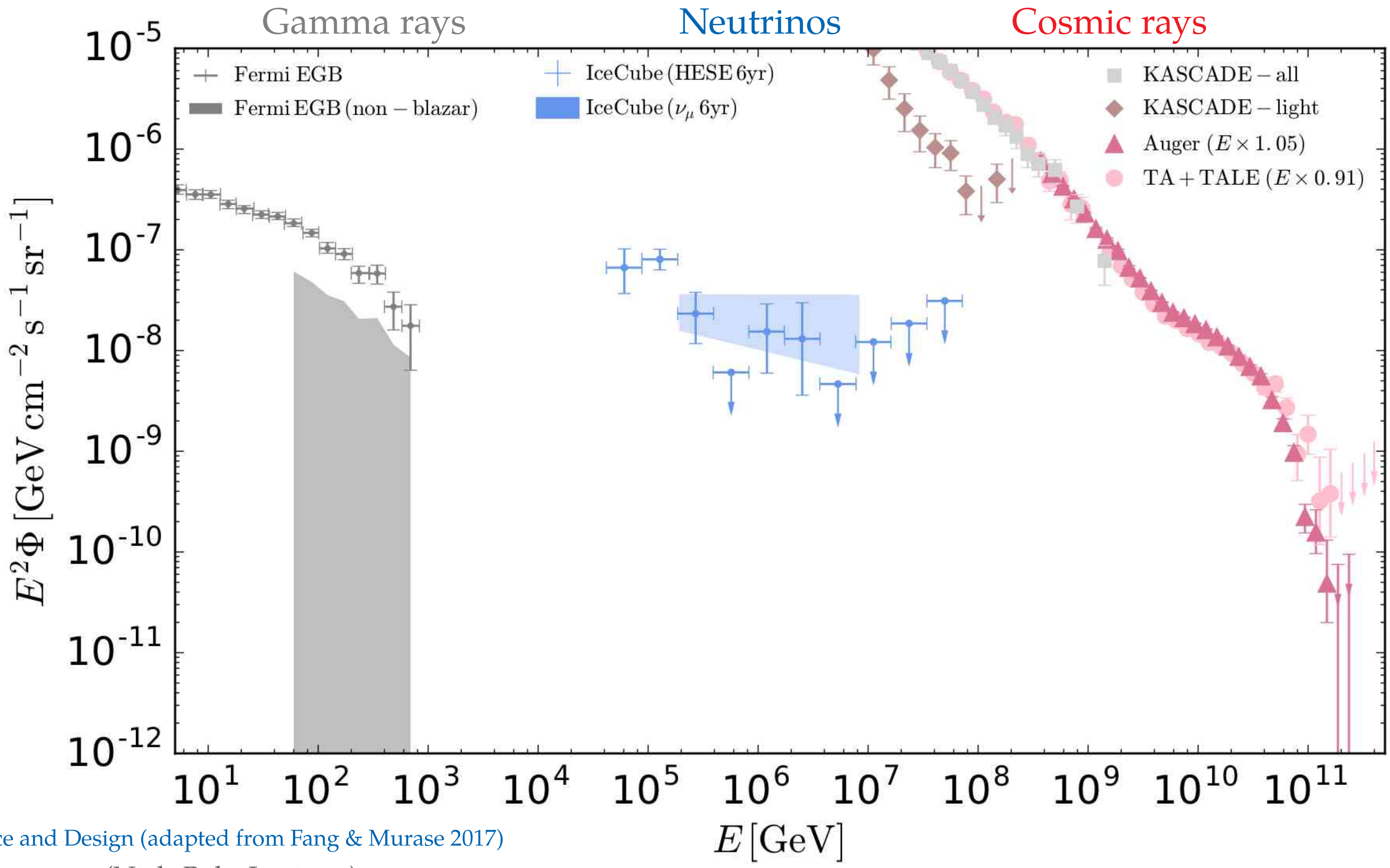
Niels Bohr Institute, University of Copenhagen

TeVPA
Berlin, August 28, 2018

UNIVERSITY OF COPENHAGEN


GRAND
Giant Radio Array for Neutrino Detection
p
π^0
γ
γ_{CMB}
γ
p
Gamma rays
e^+
e^-
$\nu_e \nu_\mu$
Neutrinos
$\nu_e \nu_\mu \nu_\tau$
Cosmic rays
(protons, nuclei)
Gravitational waves
ν_μ
π^+
p
$\bar{\nu}_\mu$
μ^+
γ_{CMB}
ν_e
e^+
n

Fluxes at Earth



GRAND: Science and Design (adapted from Fang & Murase 2017)

Quo vadis?

Recall the threshold condition for $p\gamma \to \pi\ (\to \nu)$:

$$E_p \cdot E_{\gamma_{\rm target}} = 0.2\ \mathrm{GeV}^2$$

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$E_\nu = E_p/20$

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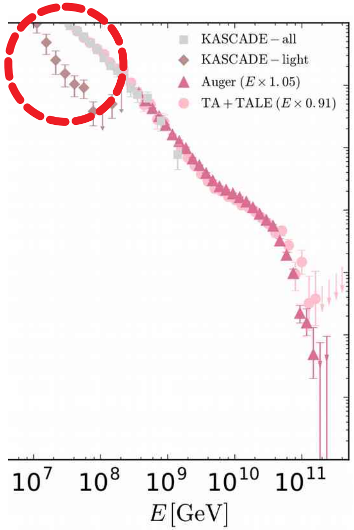
- Inside sources: Protons: $20 \cdot 10^6$ GeV; Photons: 10^{-8} GeV → Neutrinos: 10^6 GeV

Quo vadis?



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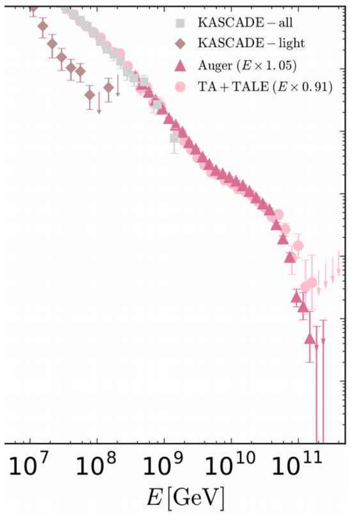

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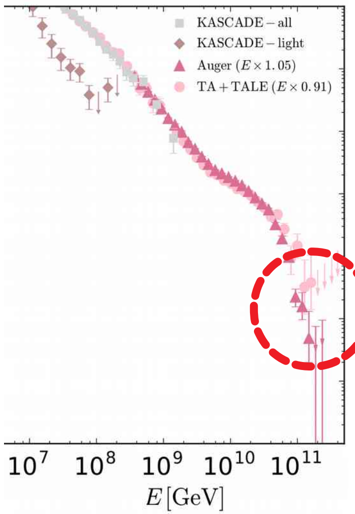

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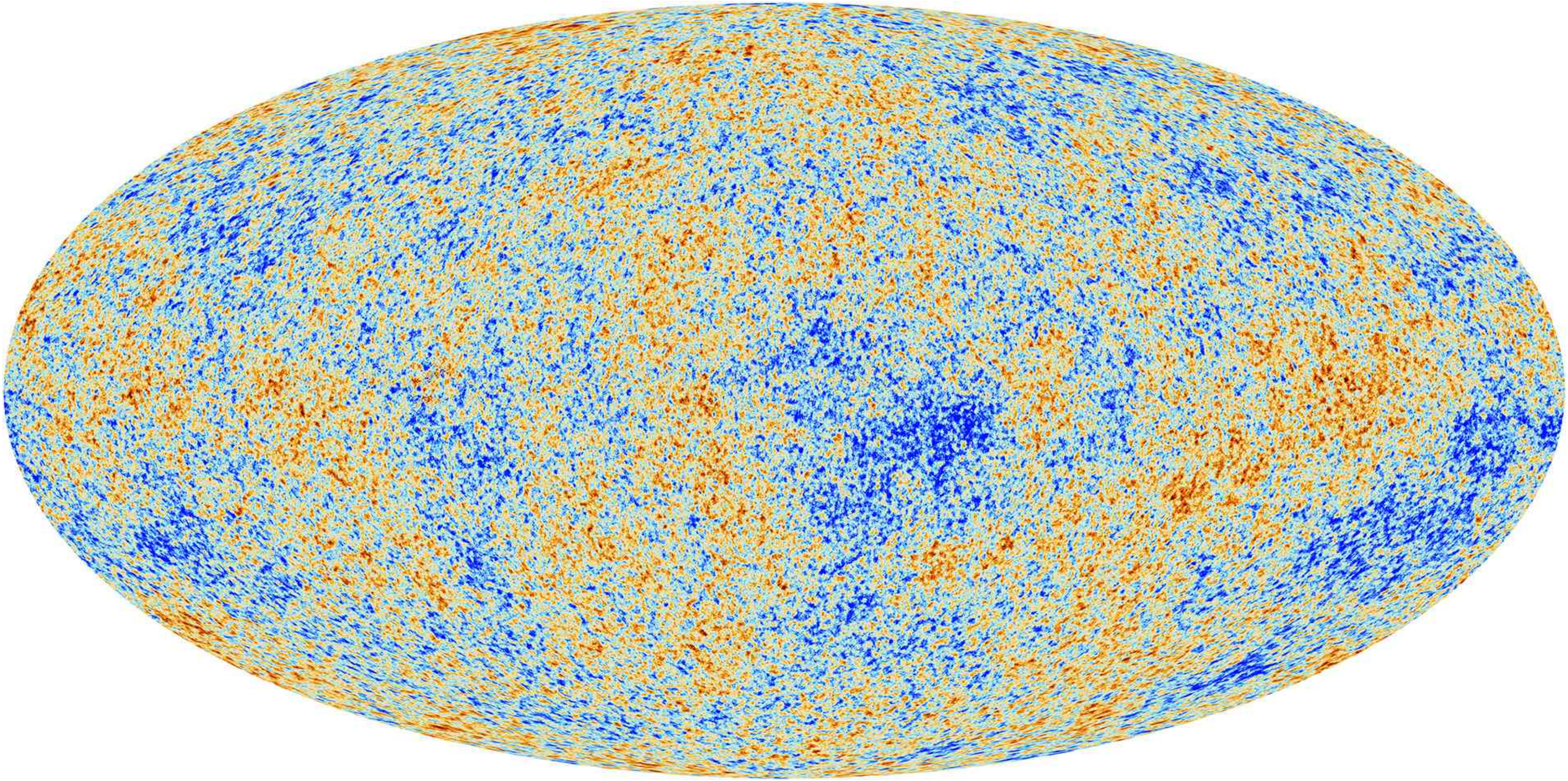

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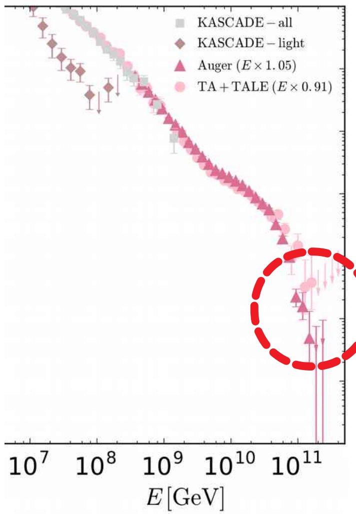

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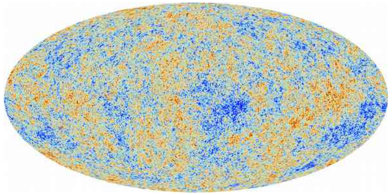
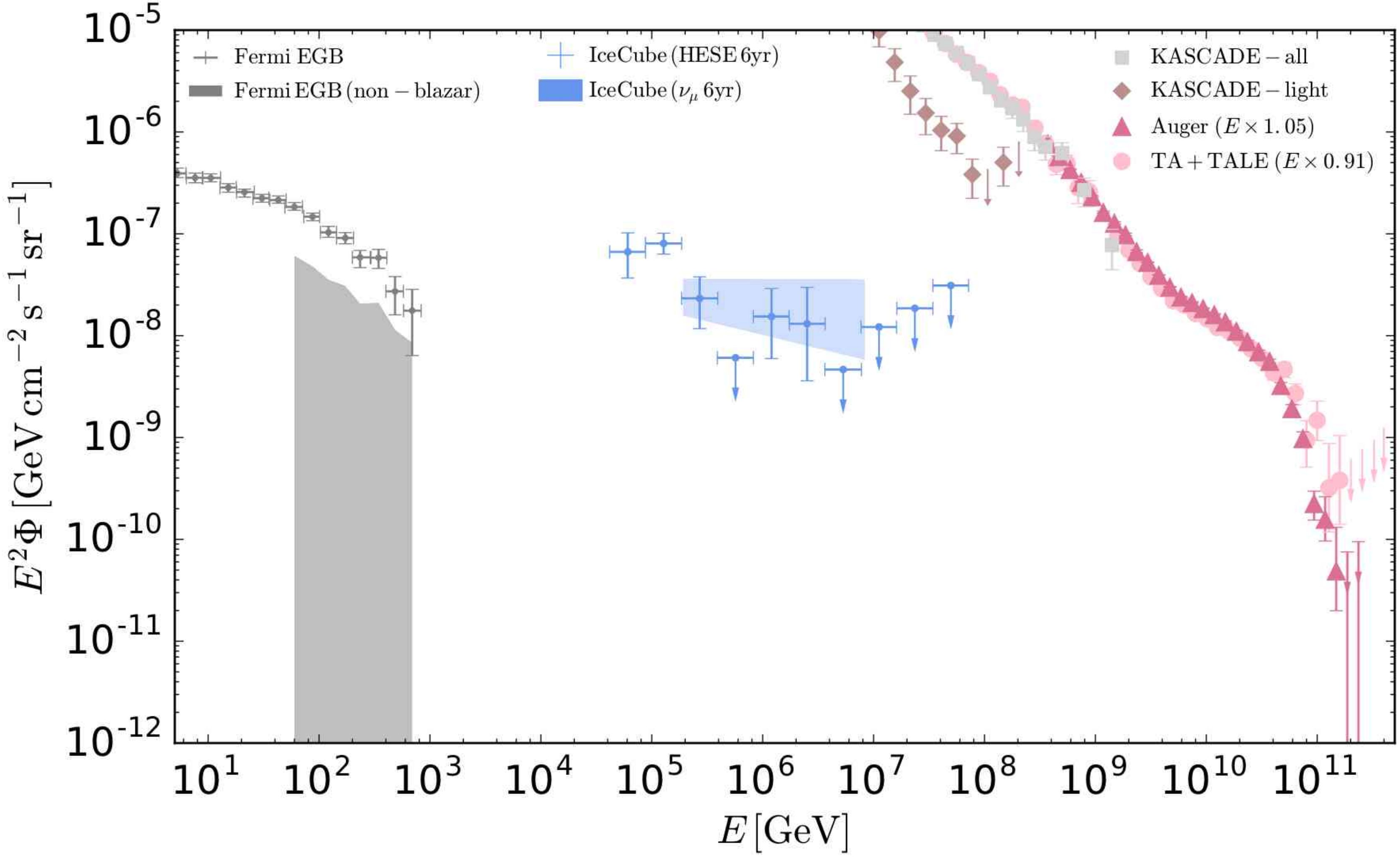
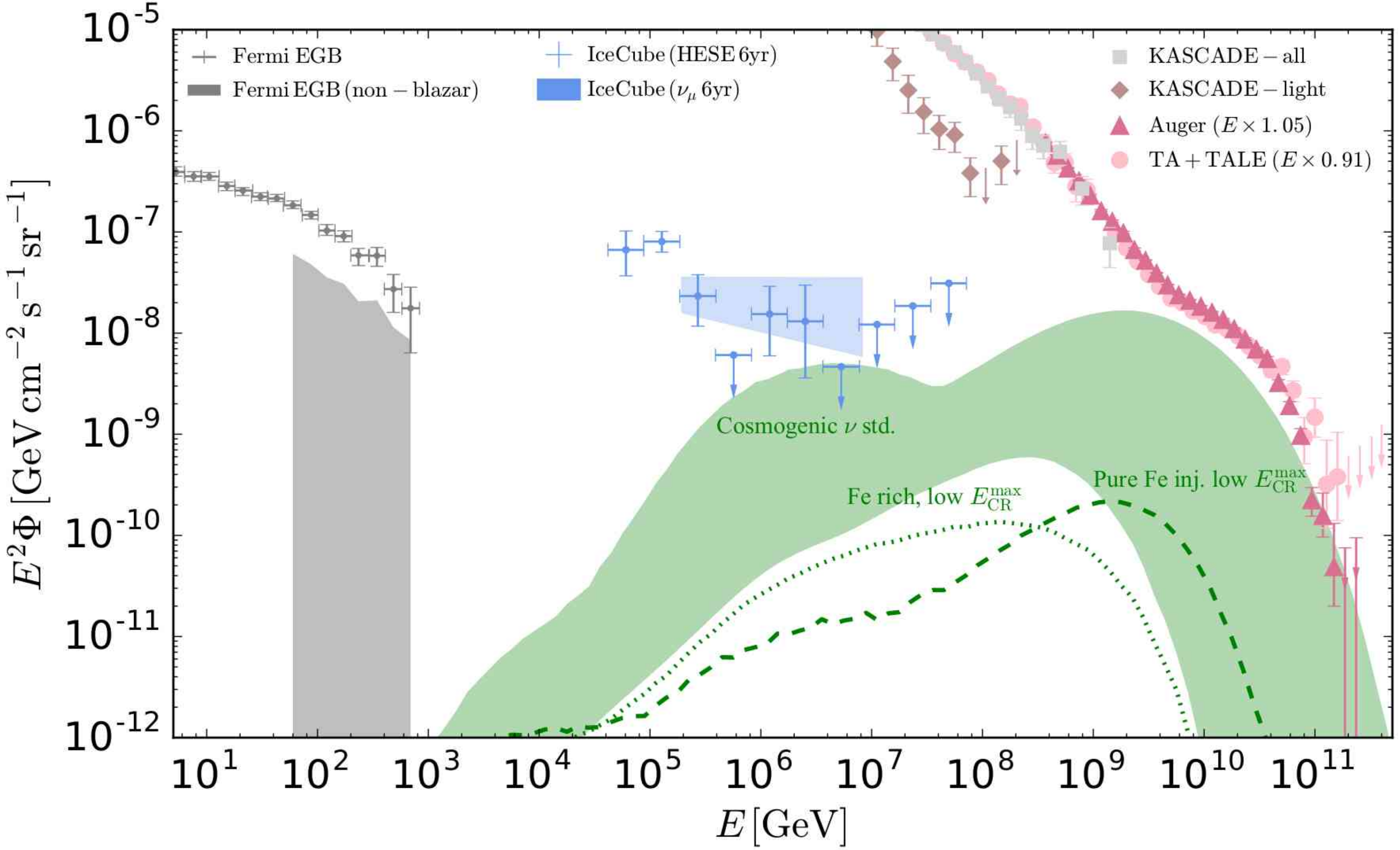




Fermi EGB
Fermi EGB (non − blazar)
IceCube (HESE 6yr)
IceCube (ν_μ 6yr)
KASCADE − all
KASCADE − light
Auger ($E \times 1.05$)
TA + TALE ($E \times 0.91$)
$E^2\Phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11}



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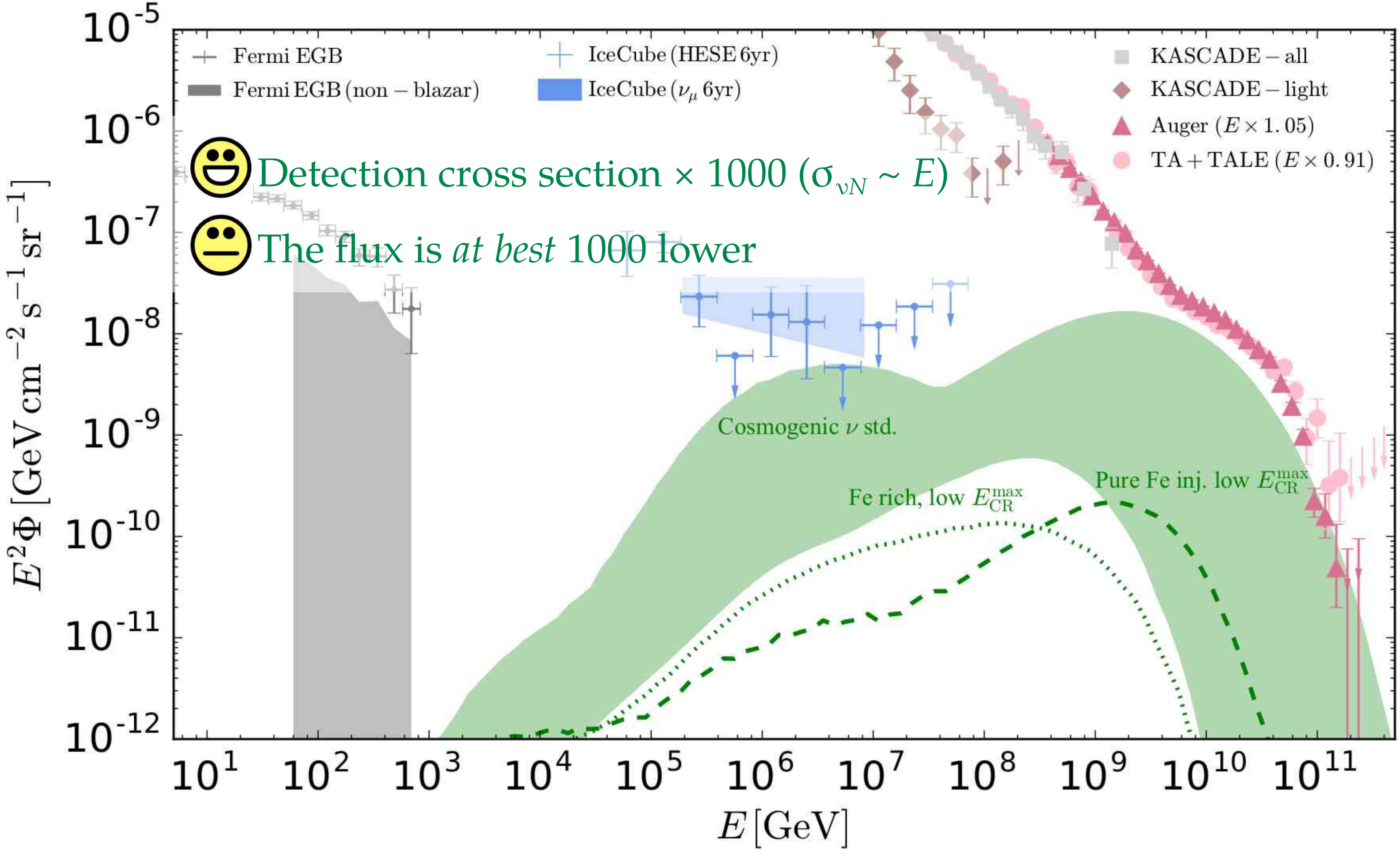
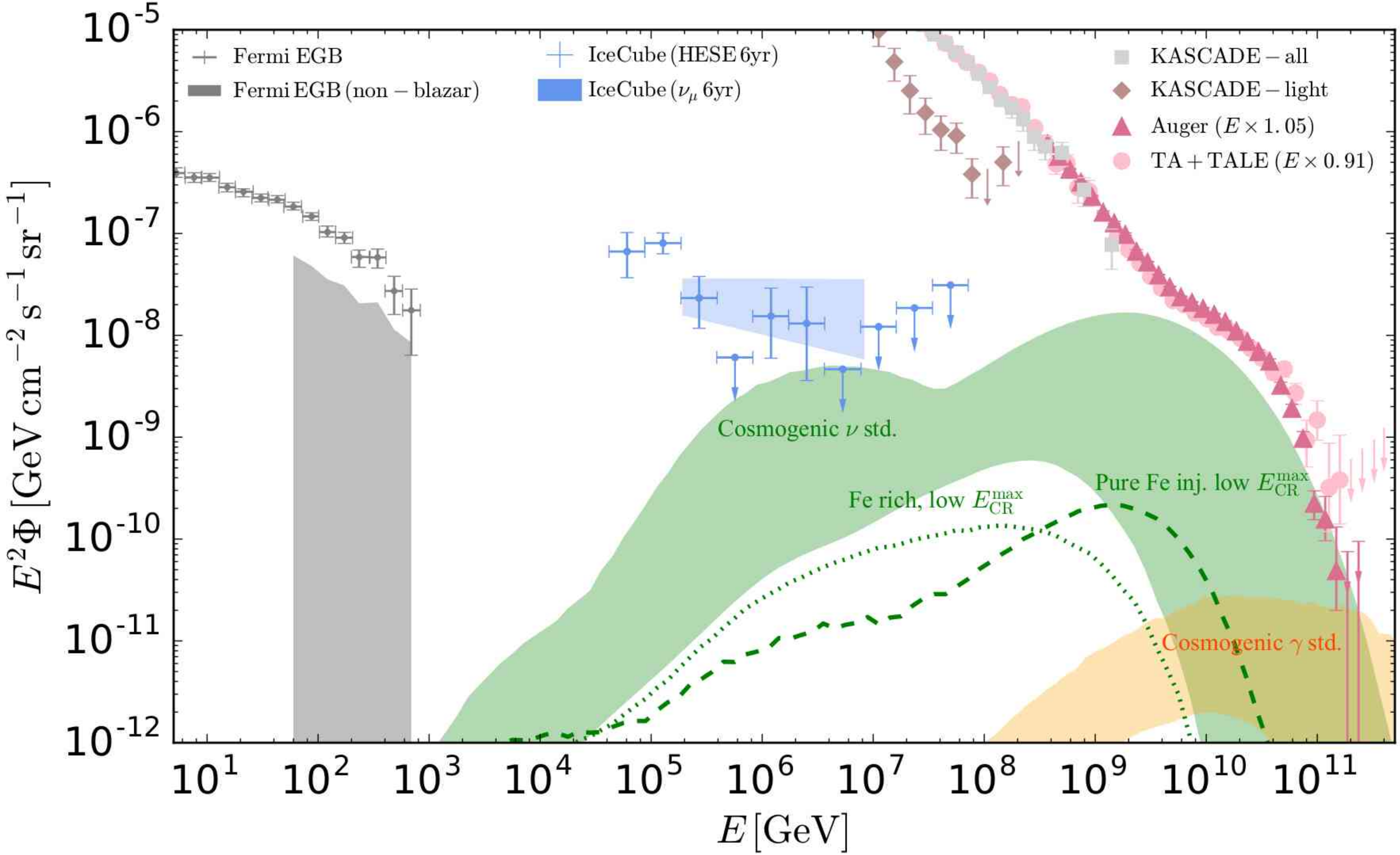
Cosmogenic ν std.
Fe rich, low $E_{\rm CR}^{\rm max}$
Pure Fe inj. low $E_{\rm CR}^{\rm max}$
$E^2\Phi\,[\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}]$
$E\,[\mathrm{GeV}]$
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11}

Detection cross section × 1000 ($\sigma_{\nu N} \sim E$)

The flux is *at best* 1000 lower

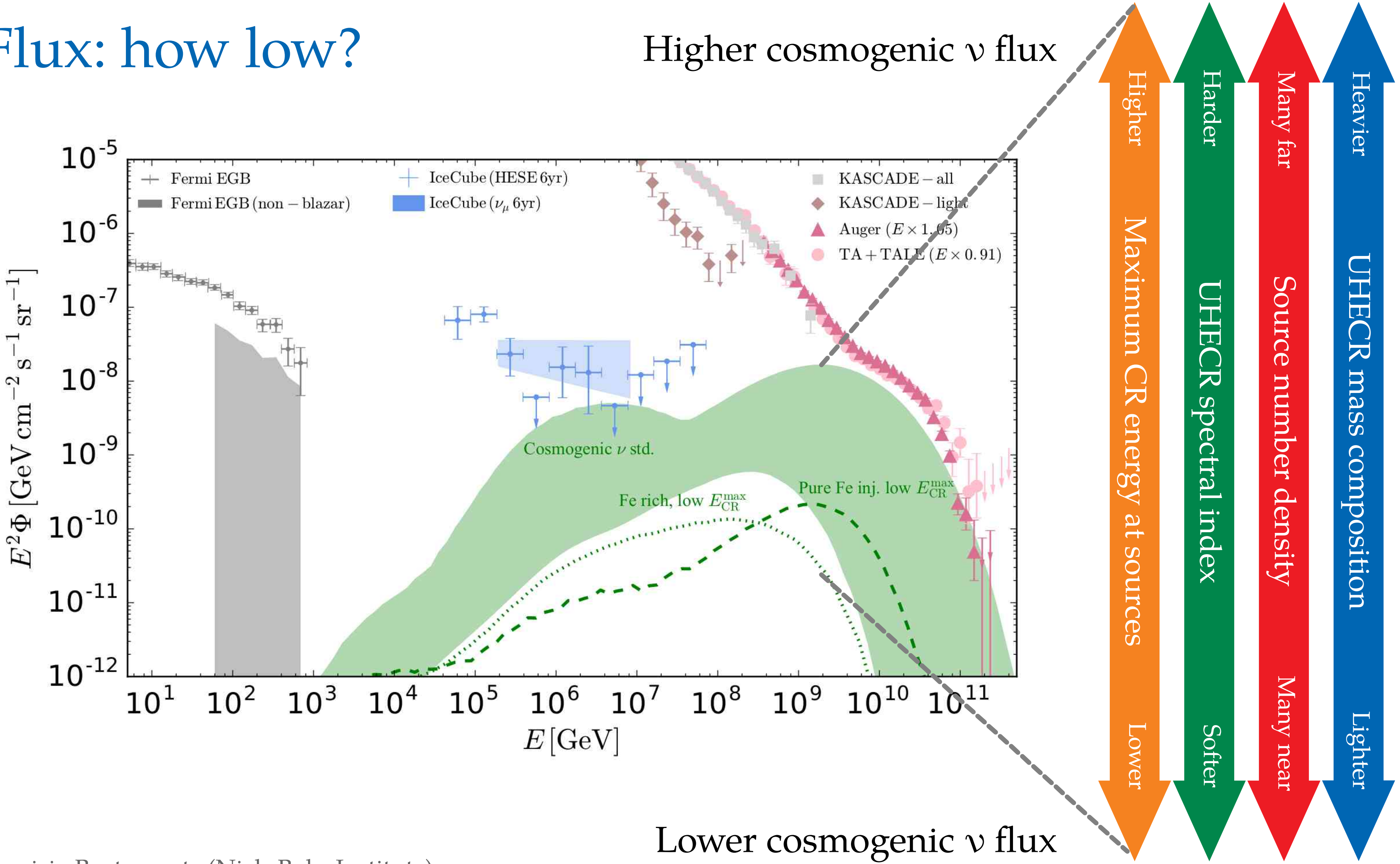




Fermi EGB
Fermi EGB (non – blazar)
IceCube (HESE 6yr)
IceCube (ν_μ 6yr)
KASCADE – all
KASCADE – light
Auger ($E \times 1.05$)
TA + TALE ($E \times 0.91$)
Cosmogenic ν std.
Fe rich, low $E_{\rm CR}^{\rm max}$
Pure Fe inj. low $E_{\rm CR}^{\rm max}$
Cosmogenic γ std.
$E^2\Phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]

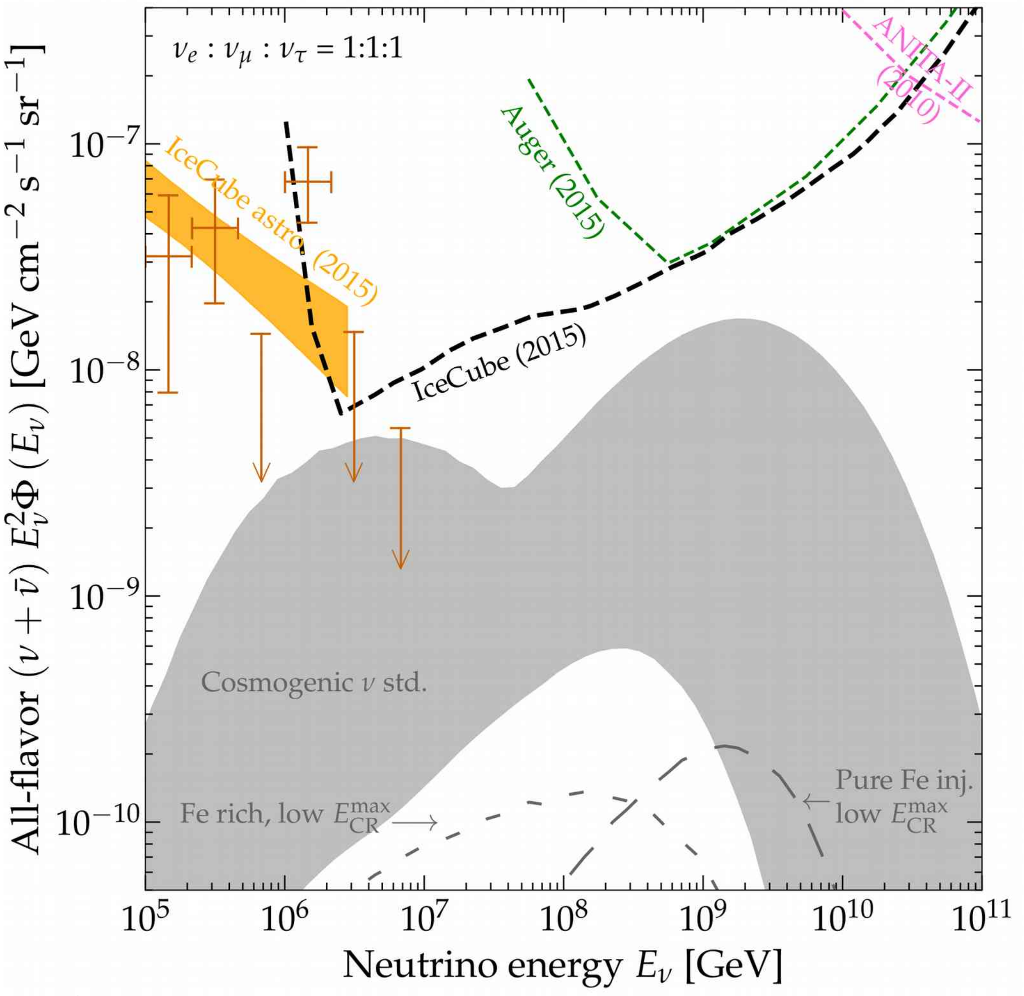
Flux: how low?

Higher cosmogenic ν flux

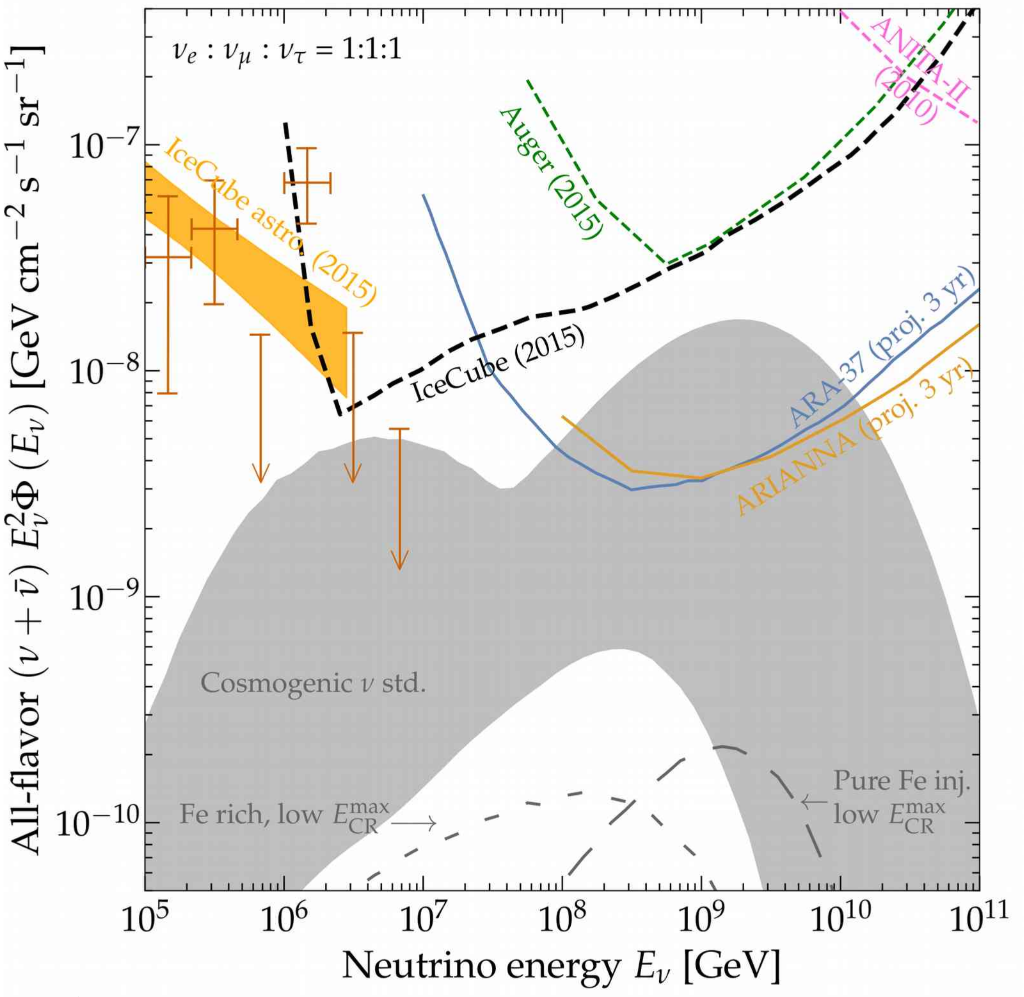


Lower cosmogenic ν flux

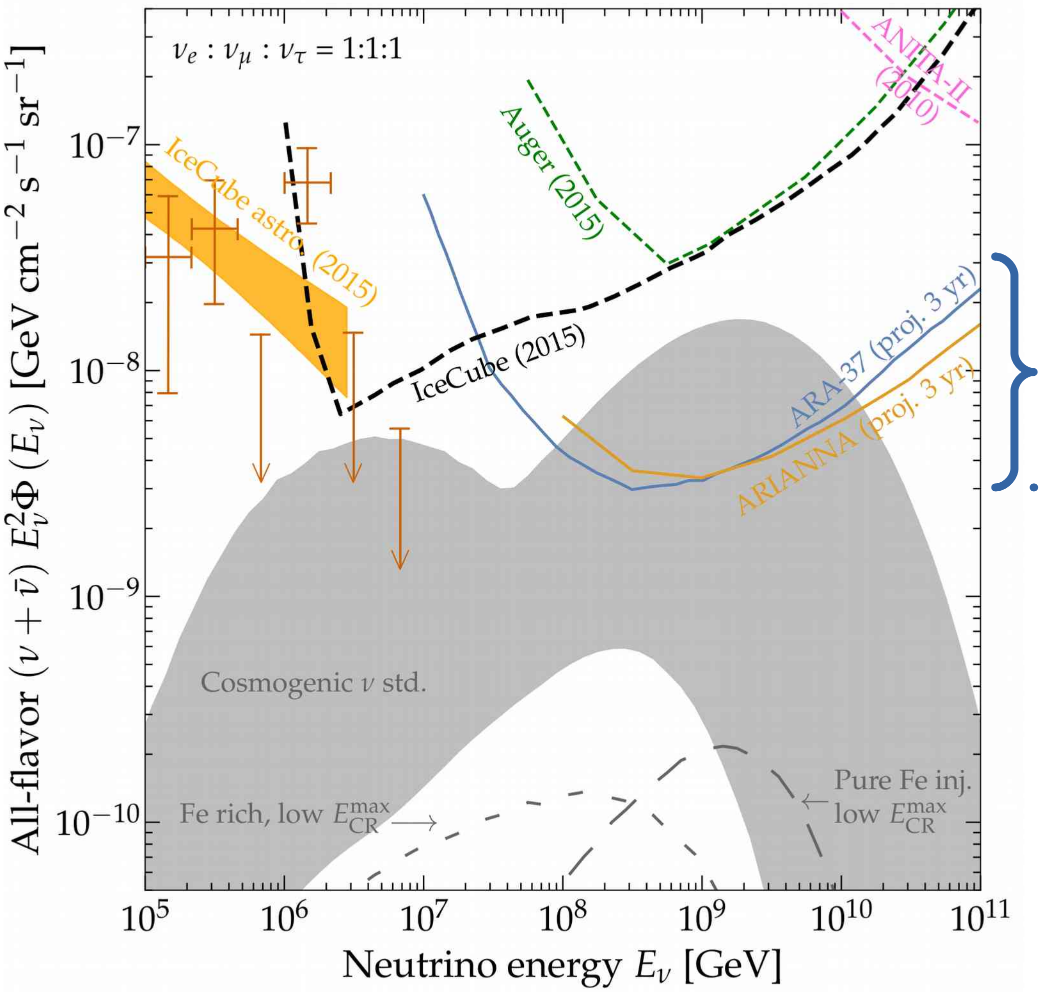
Cosmogenic fluxes



Cosmogenic fluxes

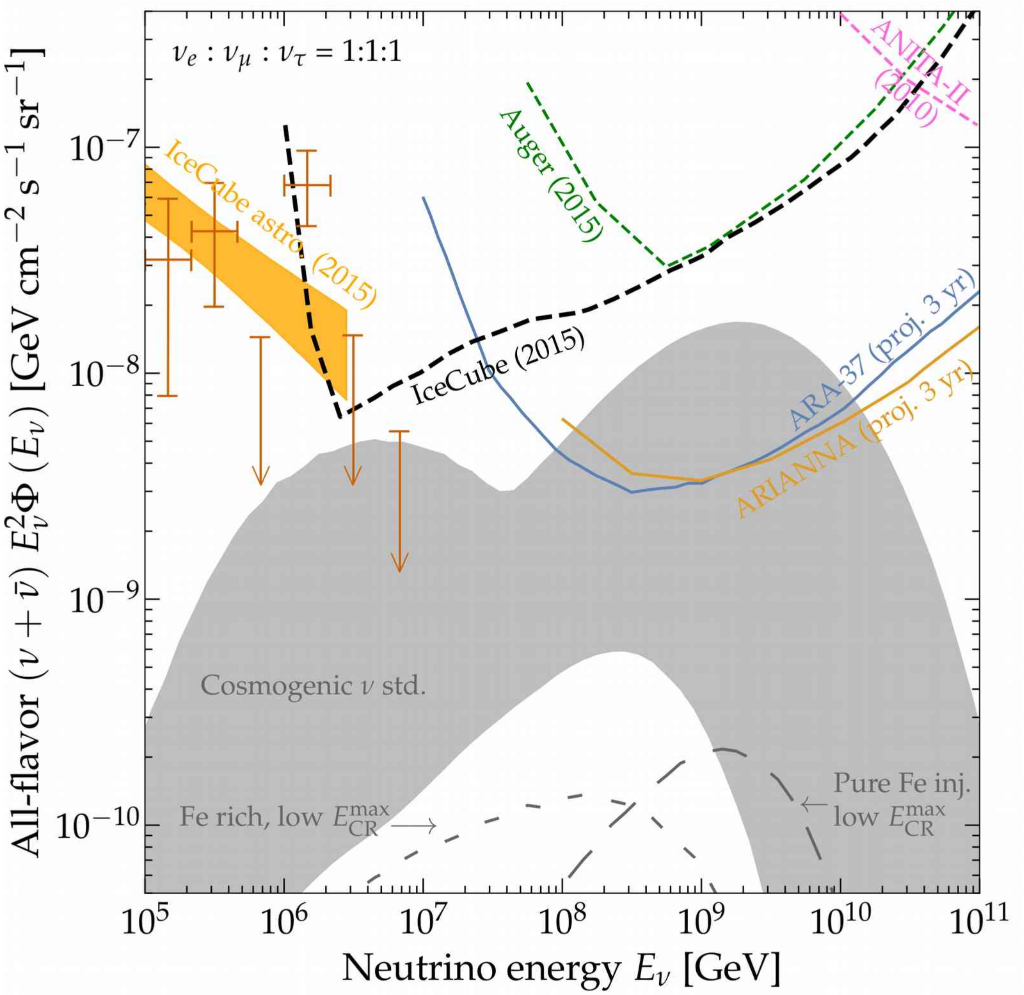


Cosmogenic fluxes

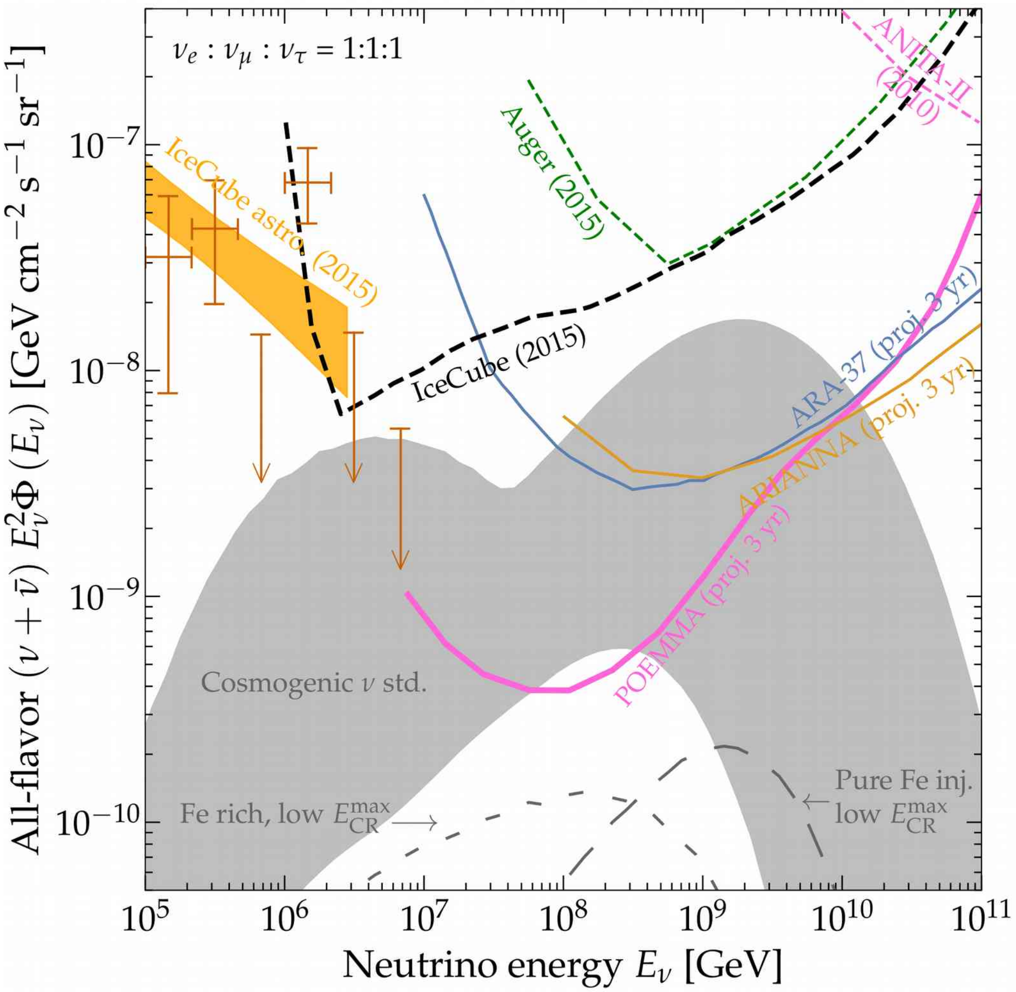


Possible future upgrades of ARA, ARIANNA

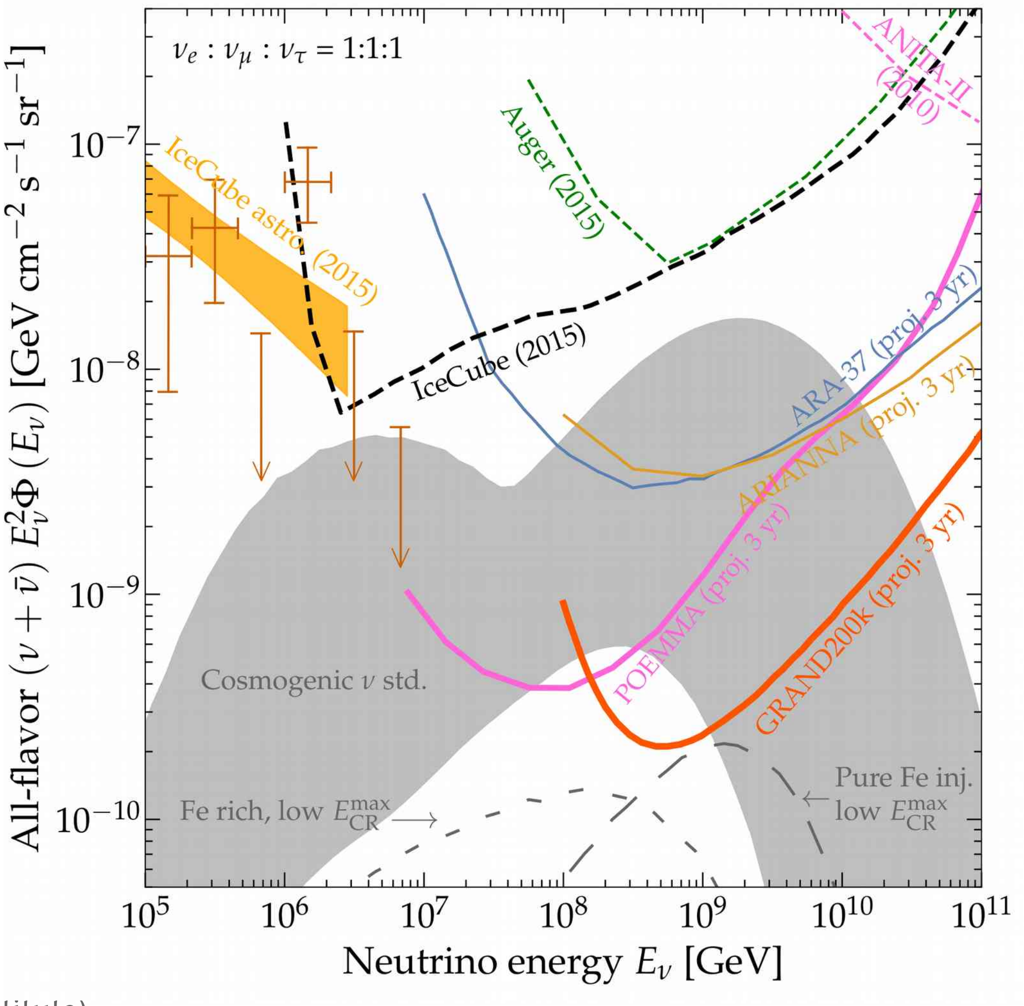
The way forward



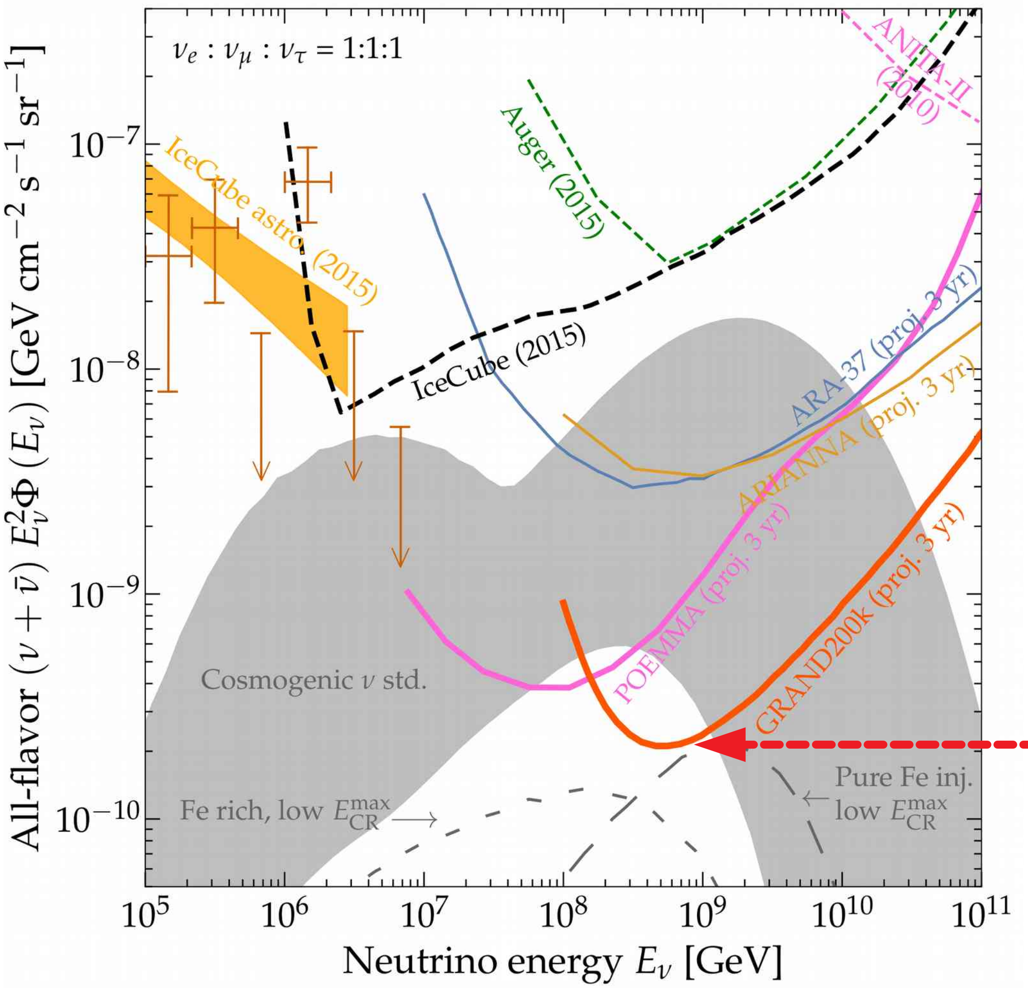
The way forward



The way forward

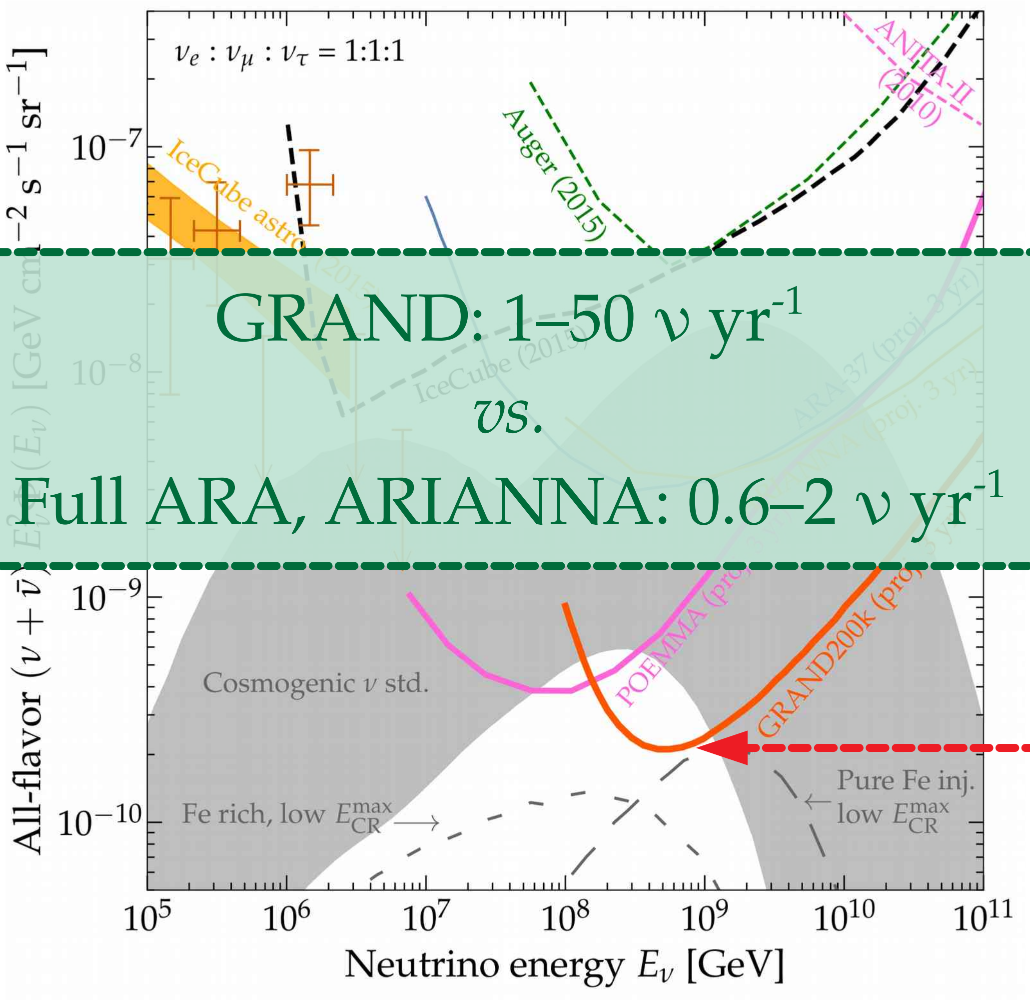


The way forward



GRAND will probe *very* low fluxes at ~10^9 GeV

The way forward



GRAND: 1–50 ν yr^{-1}

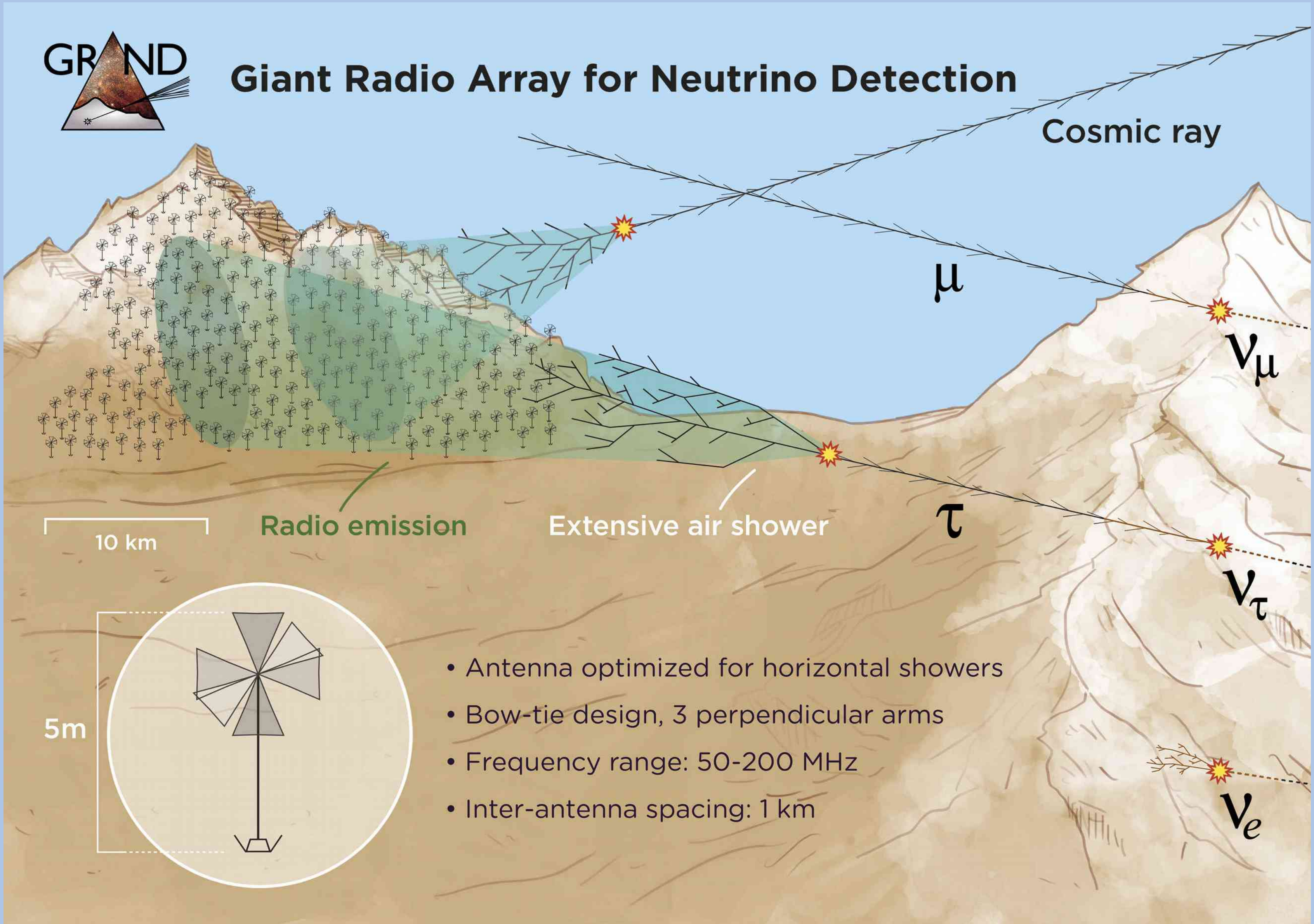
vs.

Full ARA, ARIANNA: 0.6–2 ν yr^{-1}

GRAND will probe *very* low fluxes at ~10^9 GeV

What is GRAND?

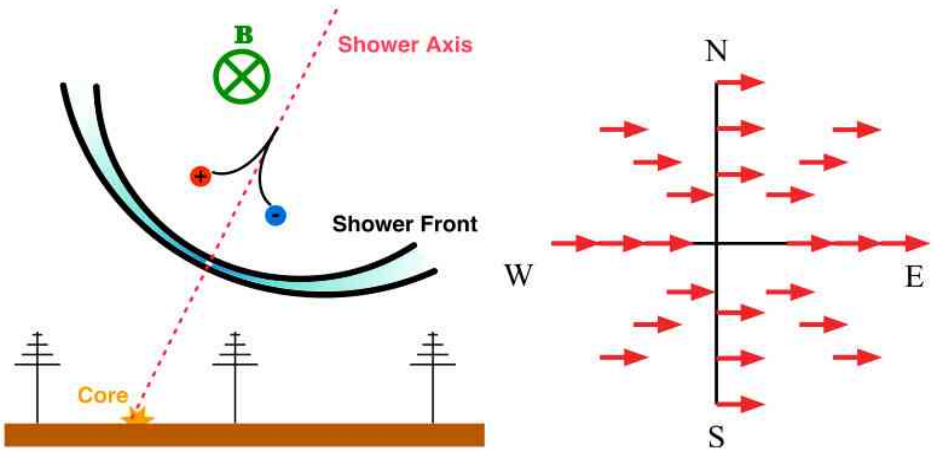
- Giant Radio Array for Neutrino Detection
- Radio-detection of extended air showers (EAS) from primaries of > 10^9 GeV
- Why radio?
  - Attenuation length in air: ~100 km
  - Easily scalable
  - Relatively affordable
- Final configuration: 200k antennas over 200 000 km^2
- Frequency band: 50–200 MHz



GRAND
Giant Radio Array for Neutrino Detection
Cosmic ray
μ
ν_μ
τ
ν_τ
ν_e
10 km
Radio emission
Extensive air shower
5m
• Antenna optimized for horizontal showers
• Bow-tie design, 3 perpendicular arms
• Frequency range: 50-200 MHz
• Inter-antenna spacing: 1 km

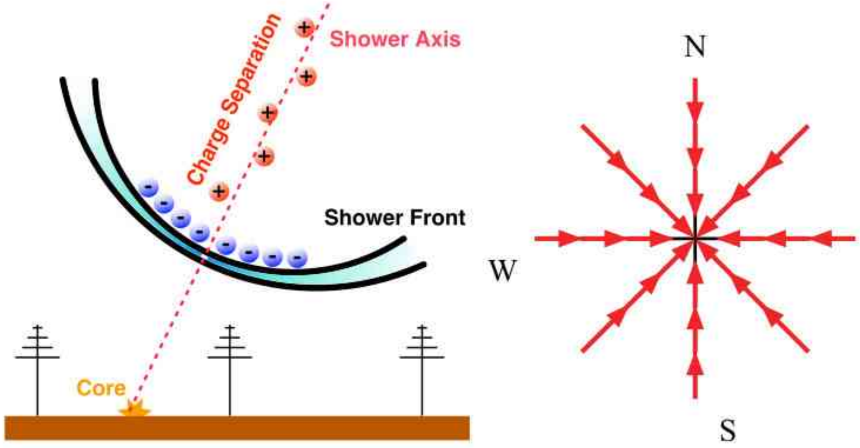
Radio emission: geomagnetic and Askaryan

Geomagnetic



- Time-varying transverse current
- Linearly polarized parallel to Lorentz force
- Dominant in air showers

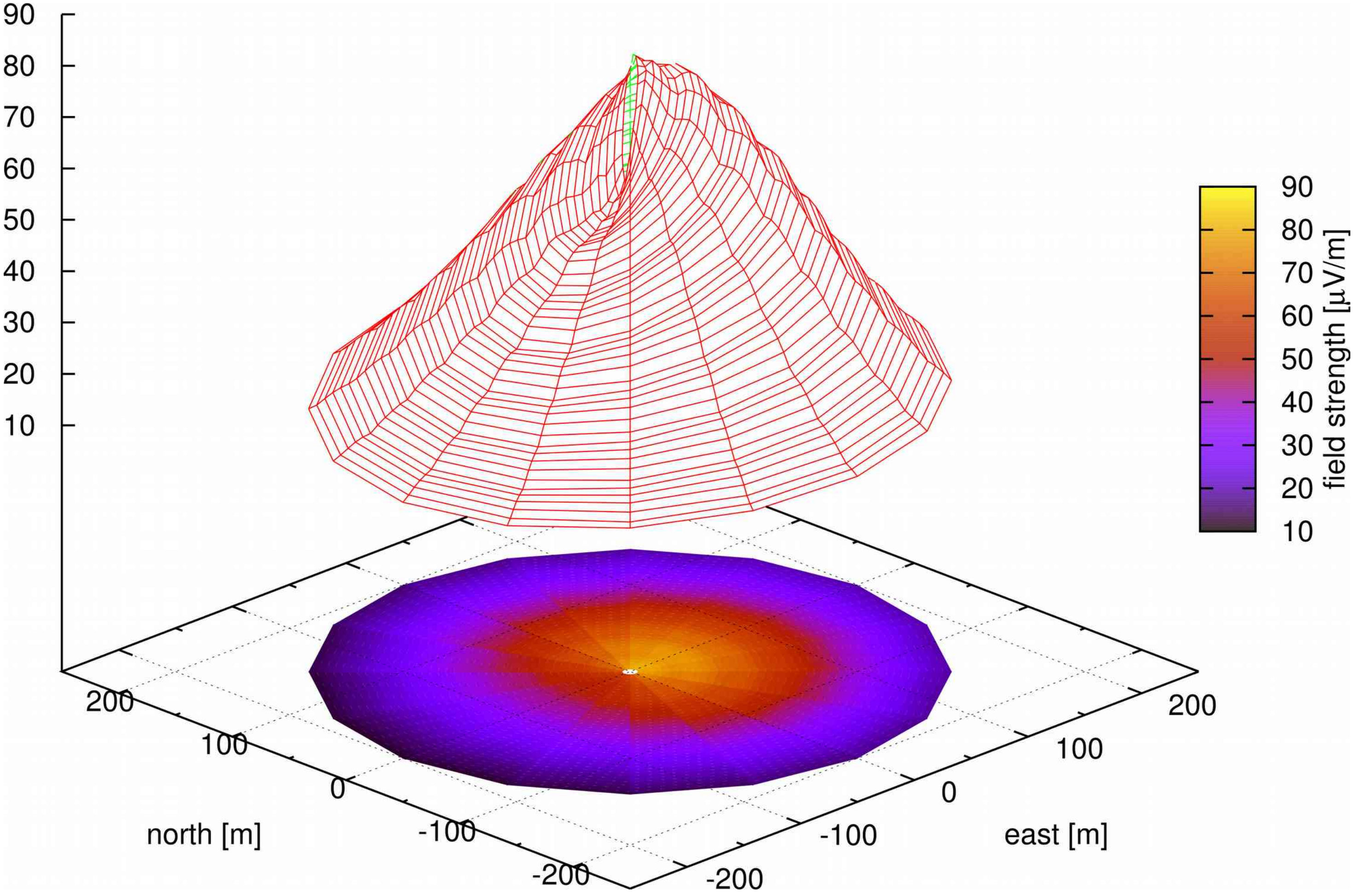
Askaryan



- Time-varying negative-charge ~20% excess
- Linearly polarized towards axis
- Sub-dominant in air showers

Figures by H. Schoorlemmer and K. D. de Vries

Radio emission: geomagnetic and Askaryan



COREAS simulation from Huege, Ludwig, James, *AIP Conf. Proc.* **1535**, 128 (2013)

BETPAQDALA DESERT
Lake Balqash
Lake Sasyqkol
Lake Alakol
Dzungarian (Junggar) Gate
MONGOLIAN ALTAI MTS.
BAYTAG BOGD MTS.
MONGOLIA
Karamay
Shu (Chu)
SHU-ILE MOUNTAINS
Ile
Karatal
QARATAU RANGE
Syr Darya
KAZAKHSTAN
ZHONGGHAR ALATAU RA.
Lake Aibi
JUNGGAR BASIN
BOROHORO MTS.
Ile Depression
Yining
Ürümqi
BOGDA MTS.
KARLIK MTS.
Zhambyl
Almaty
KYRGYZ ALA RA.
Bishkek
ILE ALATAU RA.
KÜNGOY ALA MTS.
KETPEN RA.
EREN HABIRGA MTS.
Turfan
-154
Turfan Depression
HAMI BASIN
TALAS ALATAU RA.
CHATKAL MTS.
Lake Ysyk
TESKEY ALA MTS.
SARY-JAZ MTS.
S H A N
HALIK MTS.
Lake Bosteng
KYRGYZSTAN
Tashkent
Naryn
FERGANA RA.
T I E N
Victory Peak 7439
Muzat Pass
KURUKTAG MTS.
BEI MTS.
UZBEK.
Namangan
FERGANA VALLEY
Khujand
KAKSHAAL RANGE
ATBASHI RA.
Tarim
Fergana
ALAI RA.
TRANS-ALAI RA.
TURKESTAN MTS.
ZERAVSHAN RA.
HISOR RANGE
Lenin Peak 7134
Hotan
TARIM BASIN
CHINA
Lop Nur
Kashgar
Yarkand
TAKLA MAKAN DESERT
TAJIKISTAN
PAMIRS
Imeni Ismail Samani Peak 7495
Mt. Kongur 7719
Qarqan
ALTUN
Yarkand
Qiemo
Pishan
Karakax
Keriya
Hotan
KUNLUN MTS.
K2 8611
Gasherbrum 8068
Mt. Keriya 7120
45°
40°
70°
75°
80°
85°
90°
95°
Elevation
metres
feet
3,000
9,843
2,000
6,562
1,000
3,281
500
1,640
200
656
0
0
Spot elevations in metres
Spot depth in metres
Intermittent streams
Glaciers
Salt flats
Sand areas
Swamps and marshes
0
100
200
300 mi
0
100
200
300
400
500 km
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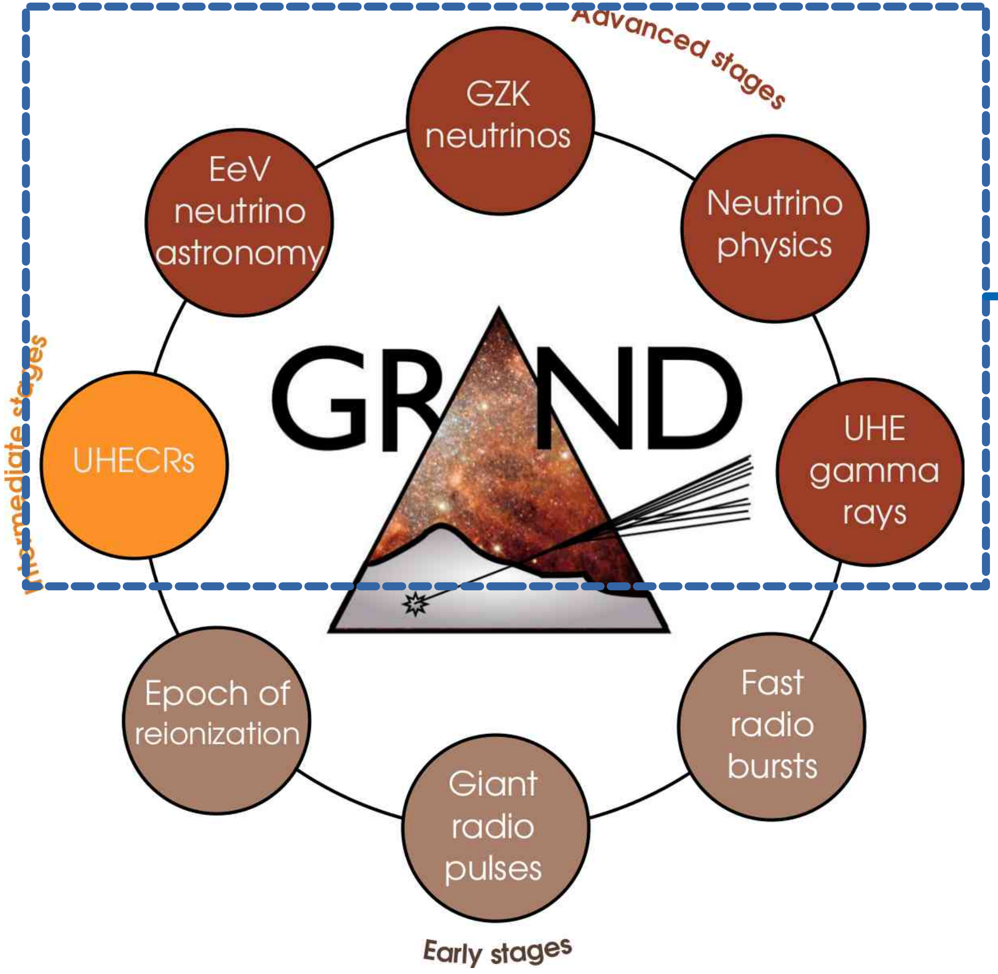
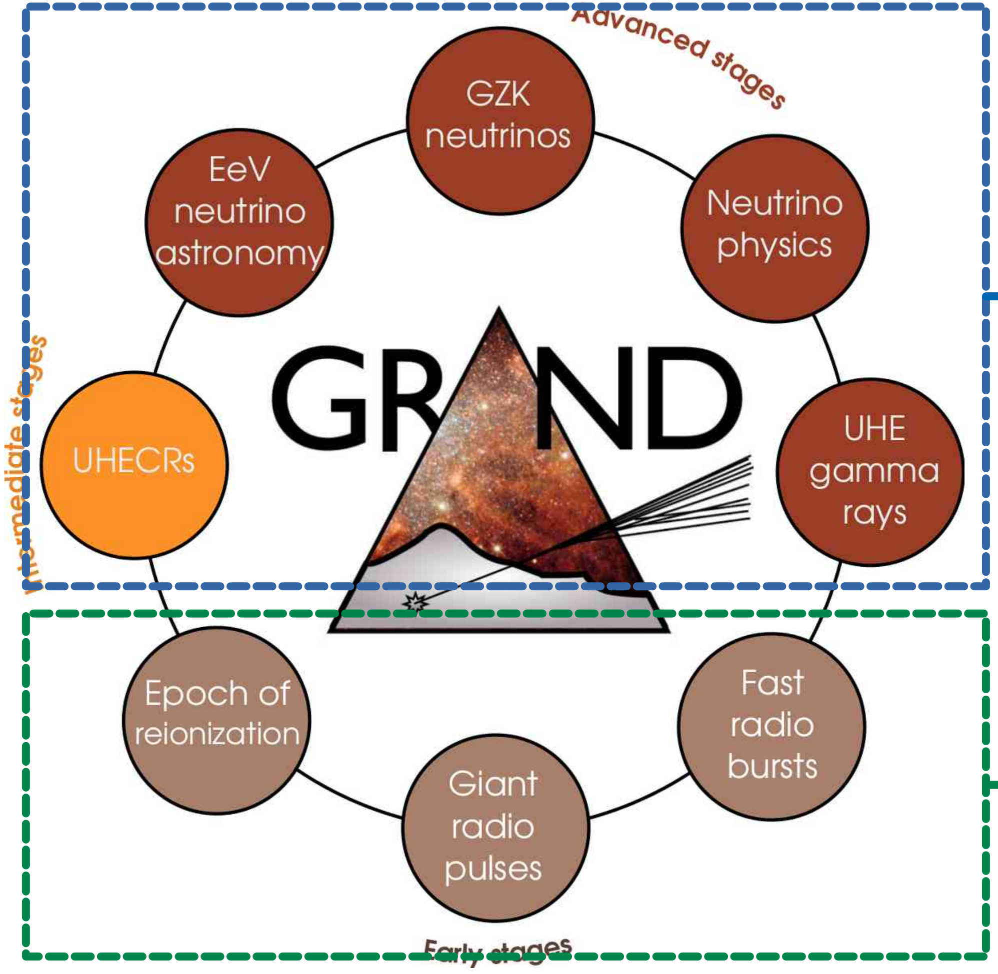
Advanced stages
GZK neutrinos
EeV neutrino astronomy
Neutrino physics
Intermediate stages
UHECRs
GRAND
UHE gamma rays
Epoch of reionization
Fast radio bursts
Giant radio pulses
Early stages



Main goal:

Finding the sources of UHECRs above 10^9 GeV



Main goal:

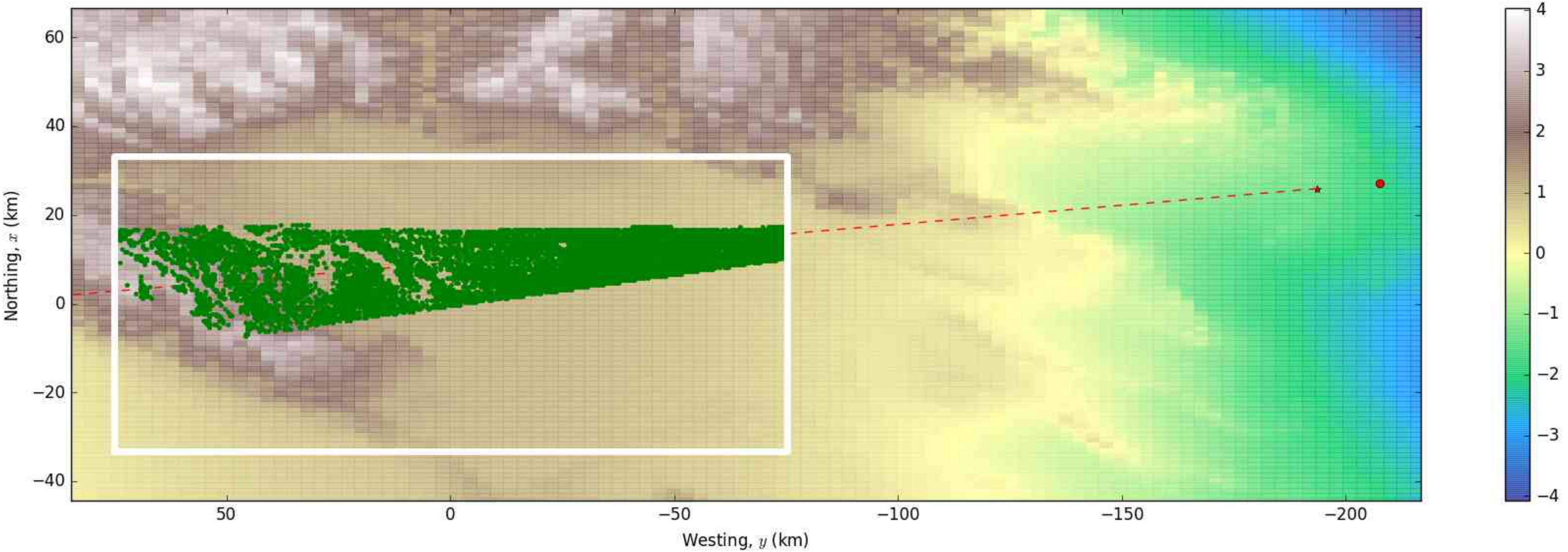
Finding the sources of UHECRs above 10^9 GeV

Secondary goal:

Radioastronomy and cosmology

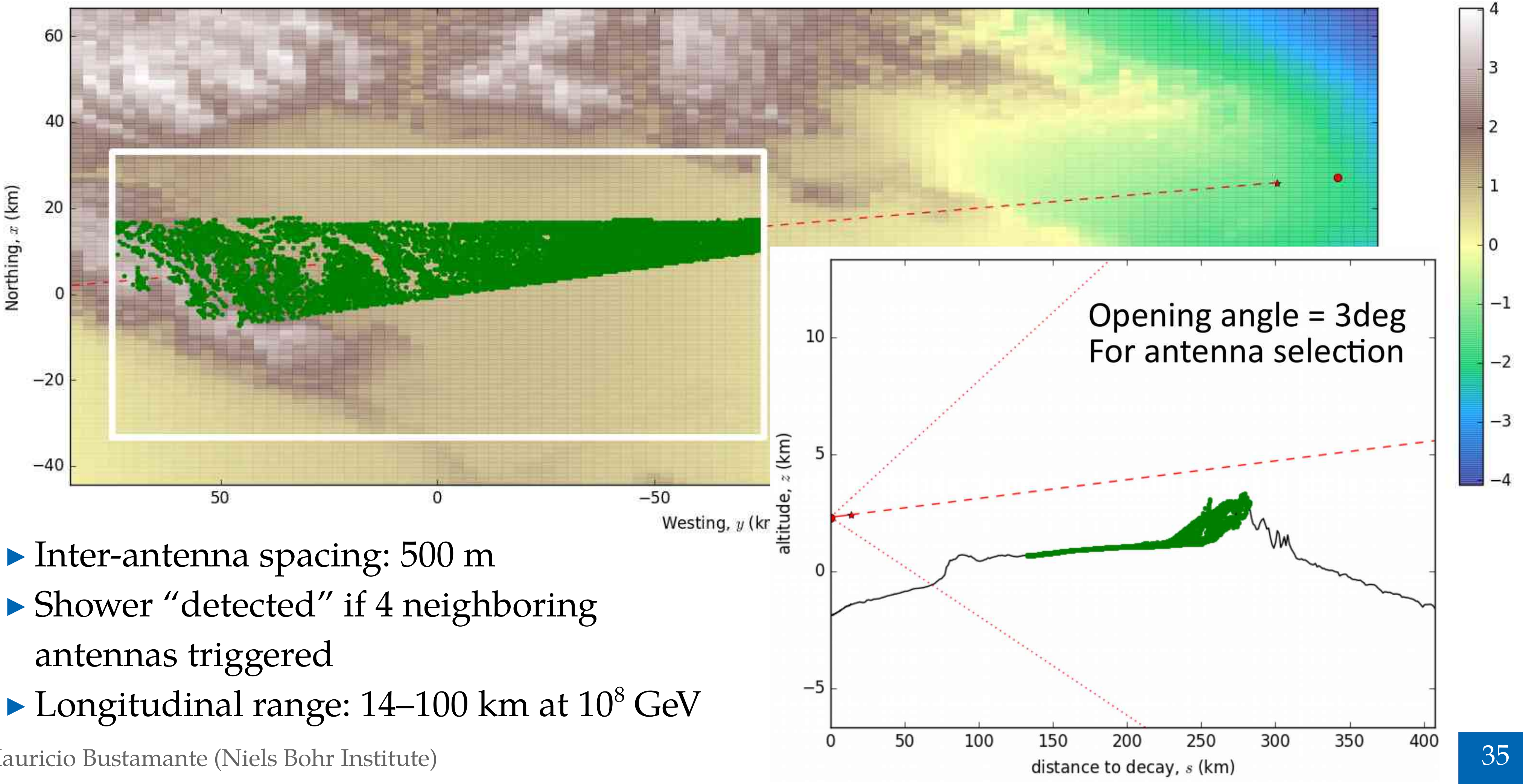
A simulated event

GRAND: Science and Design



- Inter-antenna spacing: 500 m
- Shower "detected" if 4 neighboring antennas triggered
- Longitudinal range: 14–100 km at 10^8 GeV

A simulated event



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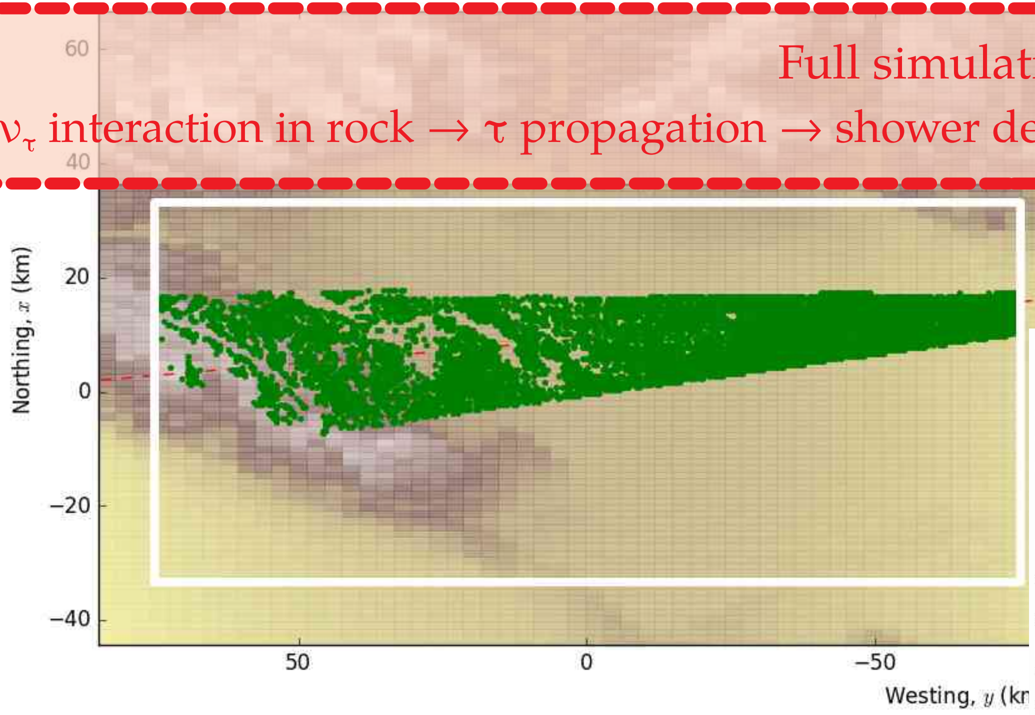
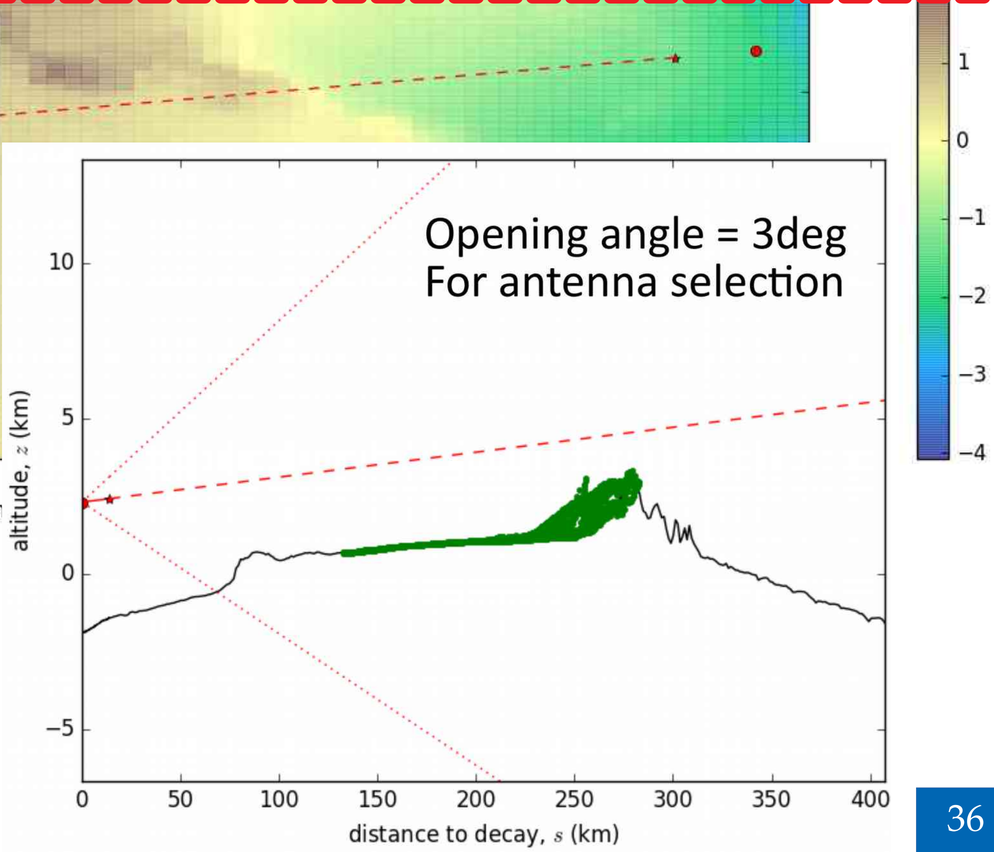
A simulated event

Full simulation chain:

ν_τ interaction in rock $\rightarrow$ τ propagation $\rightarrow$ shower development + radio emission $\rightarrow$ antenna response





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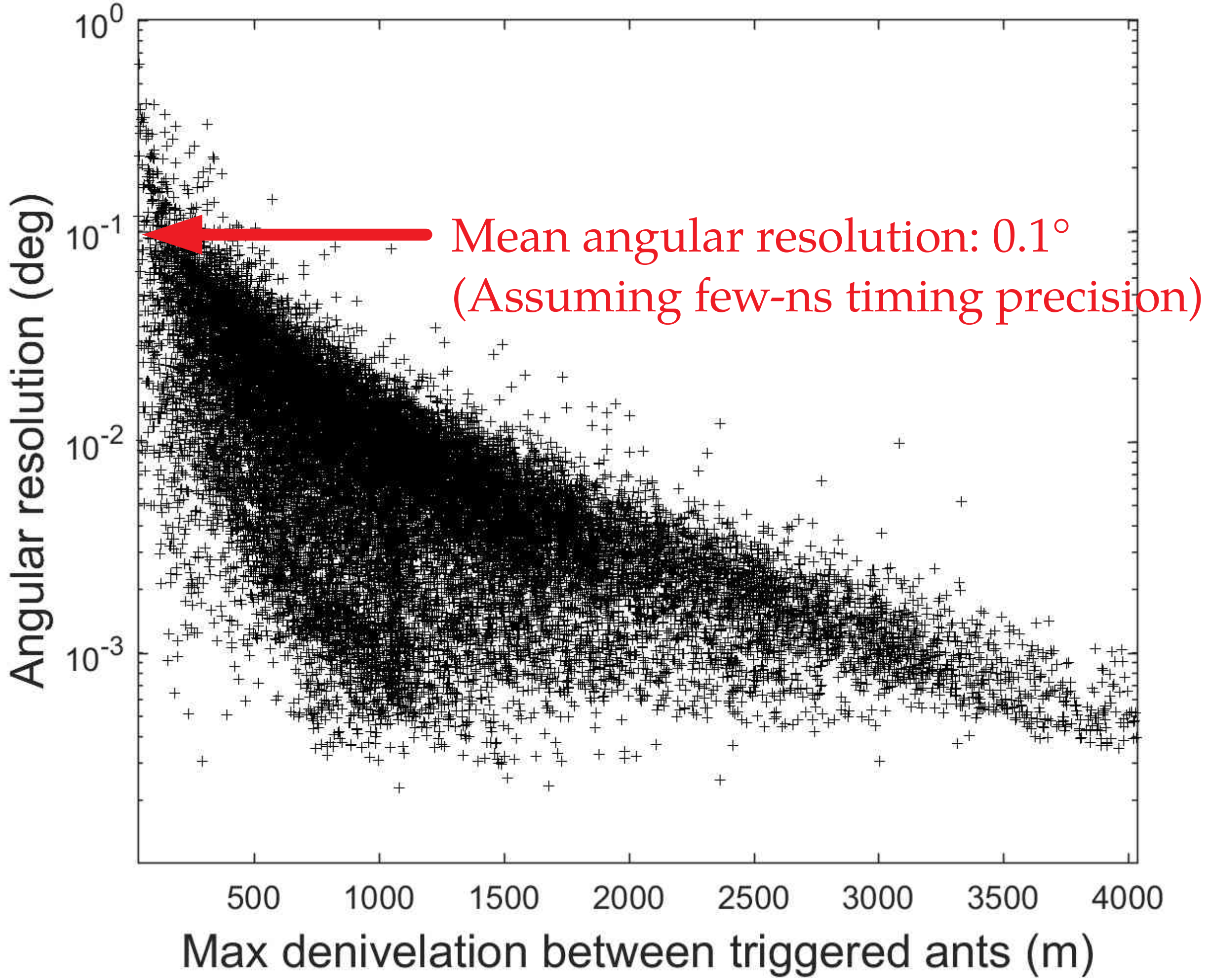
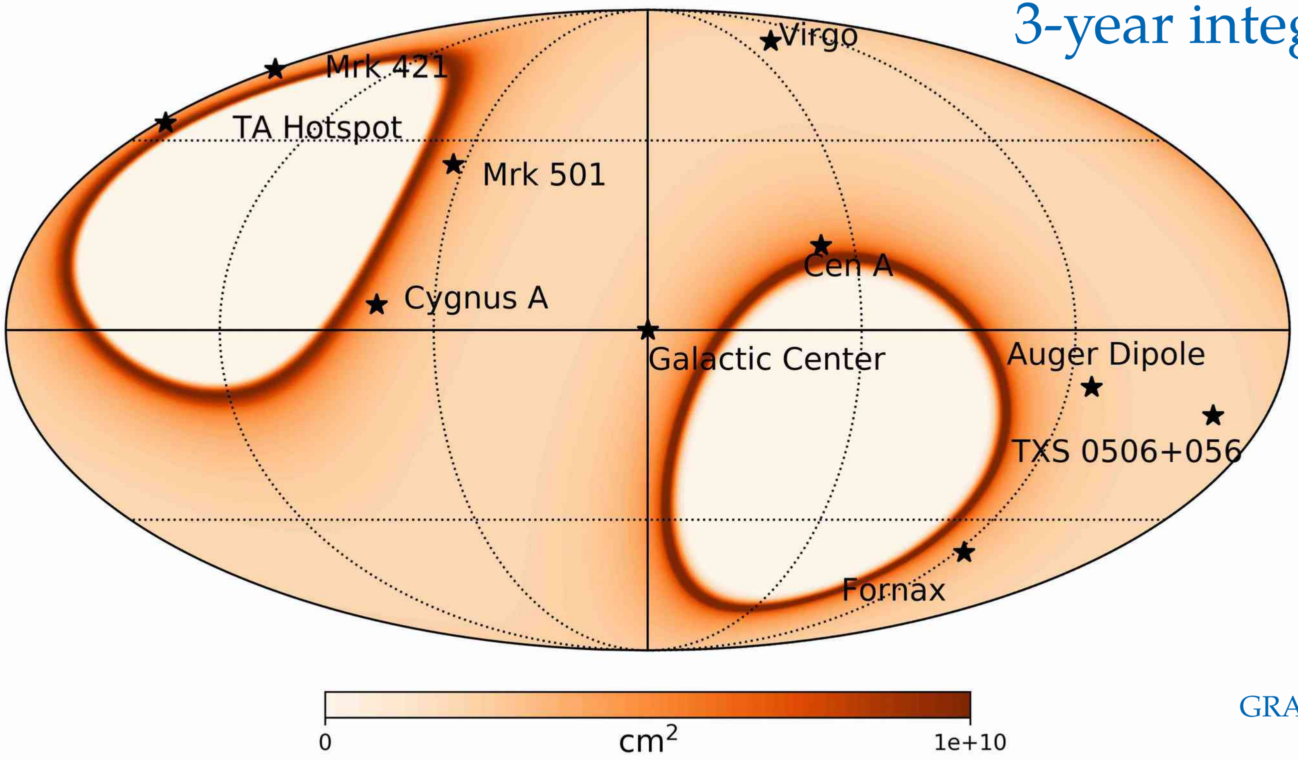
Angular resolution



Neutrino field of view

Earth-skimming ν_τ are detectable from ±3° off the horizon

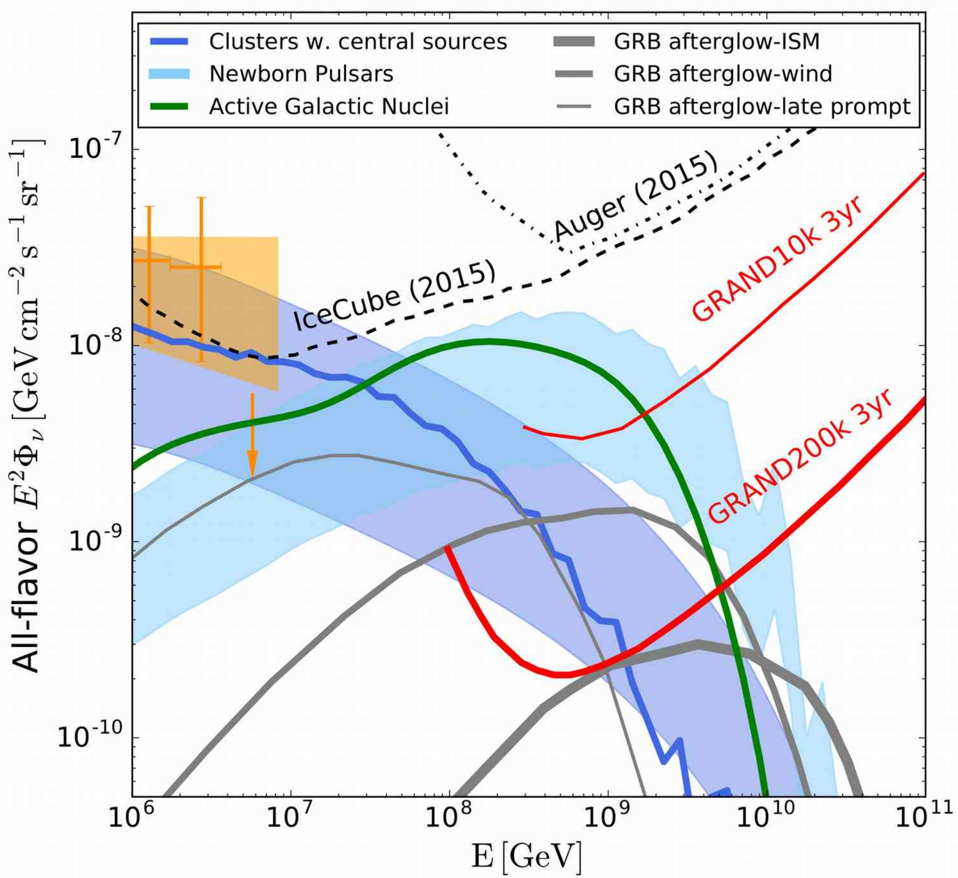


3-year integrated

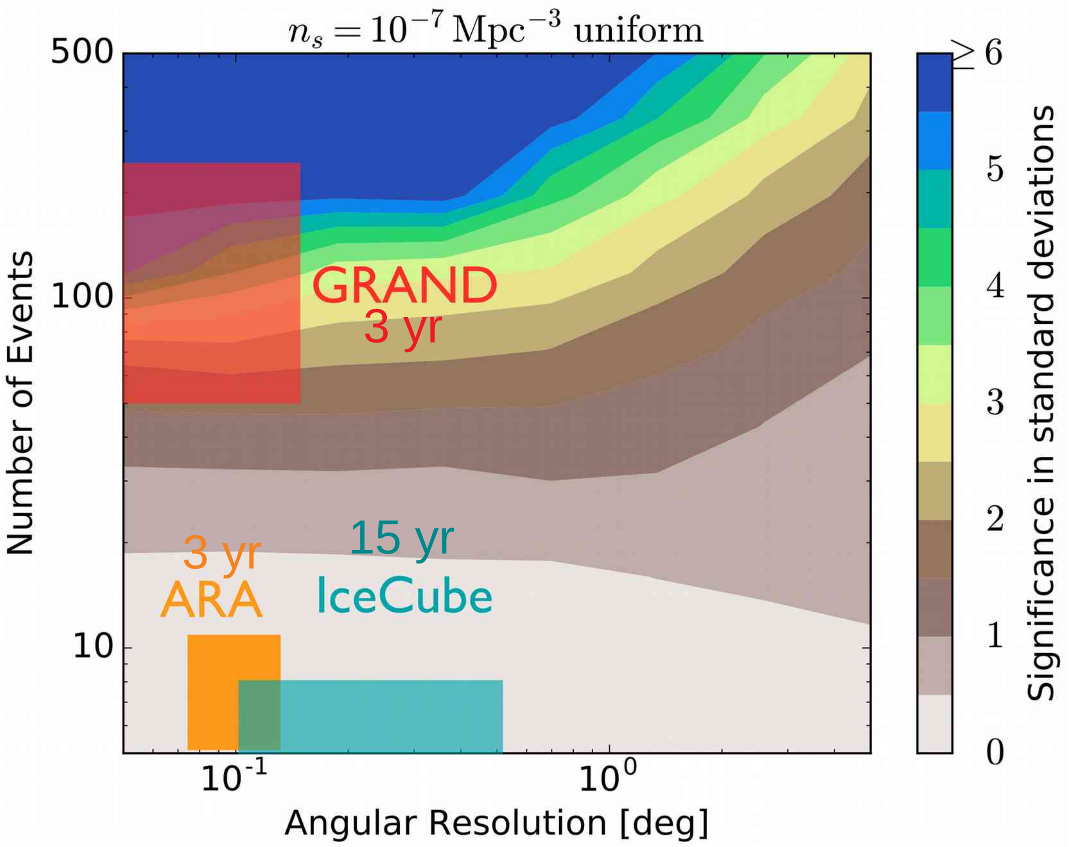
GRAND: Science and Design

Discovering source classes and point sources

Imprint of dominant class on diffuse flux:



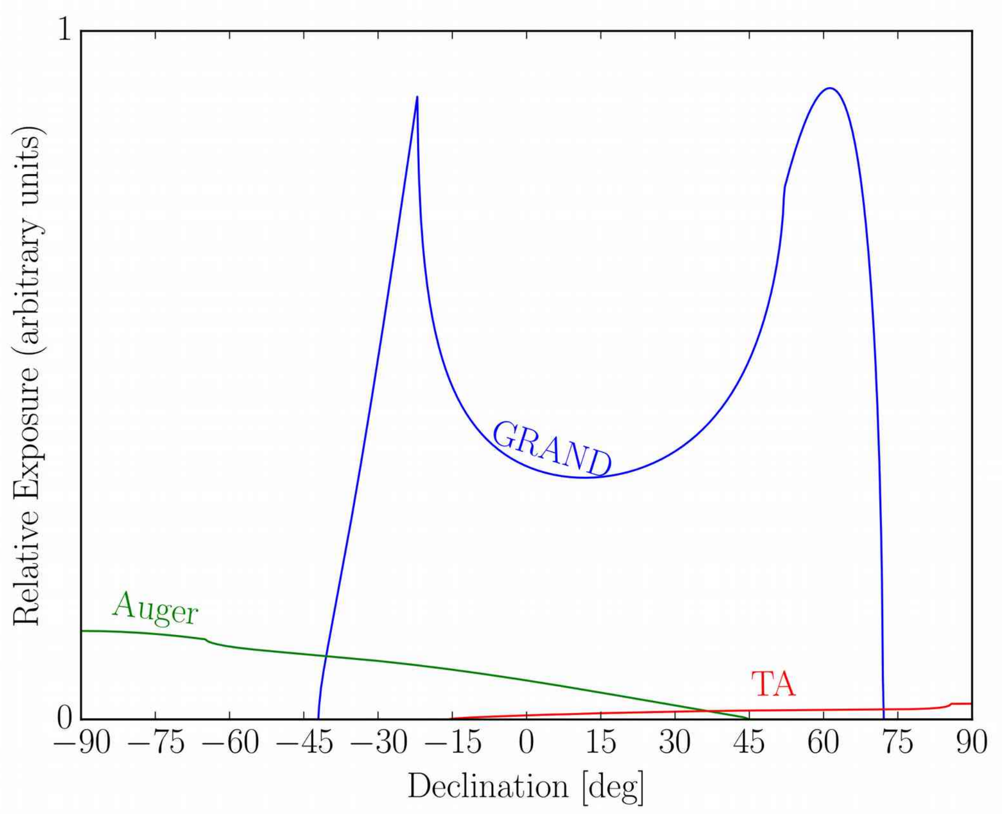
Discovery of point sources:

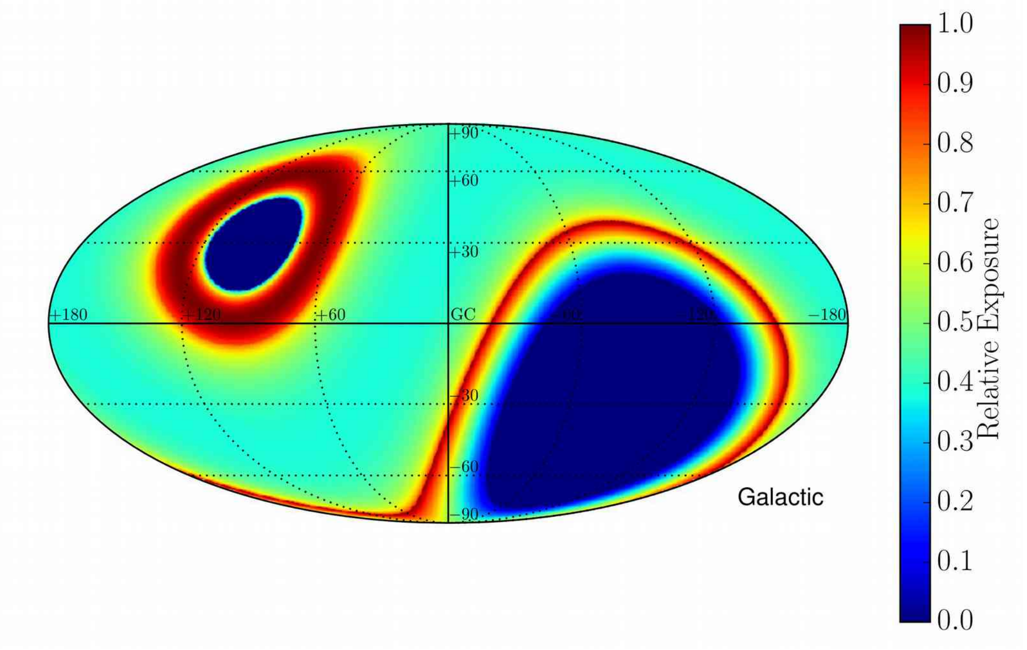


GRAND: Science and Design
See also Fang & Miller 2016

UHECR field of view

UHECRs are detectable from zenith angles of 65°–85°

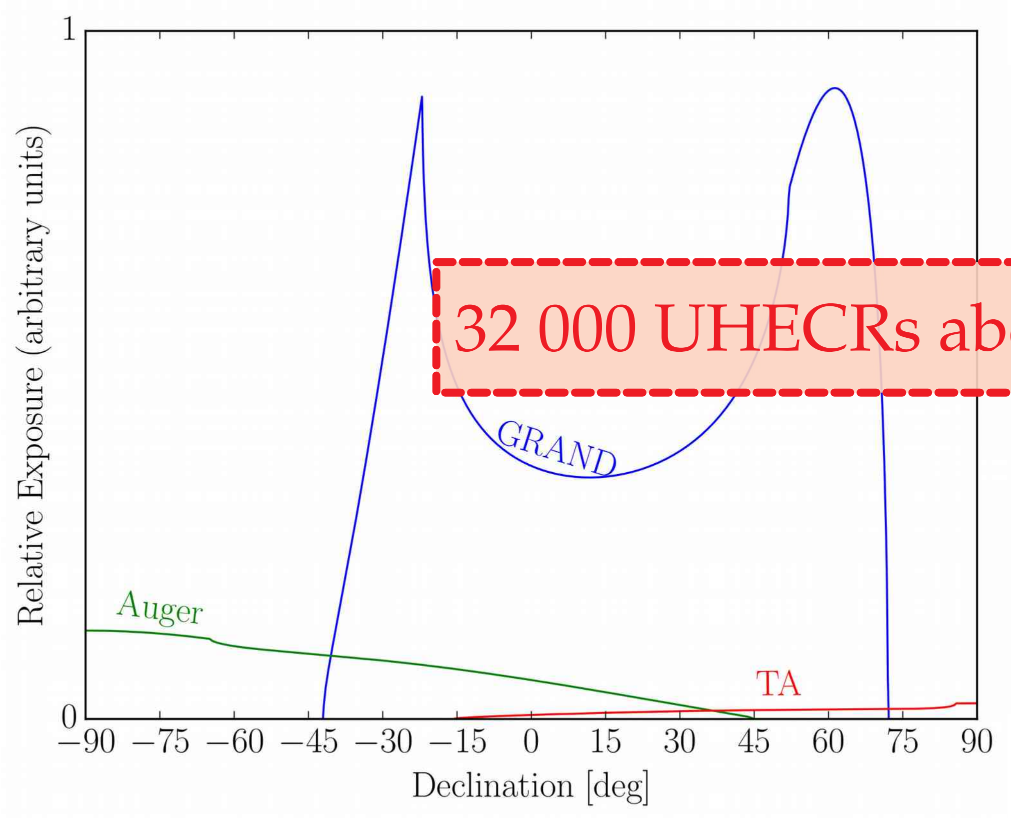


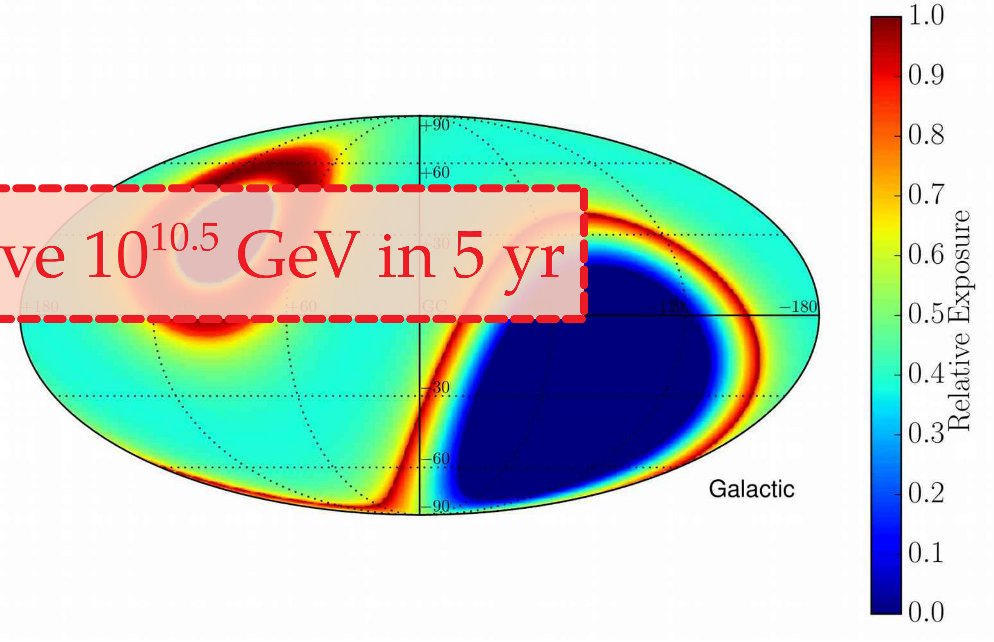


GRAND: Science and Design

UHECR field of view

UHECRs are detectable from zenith angles of 65°–85°





32 000 UHECRs above $10^{10.5}$ GeV in 5 yr

GRAND: Science and Design

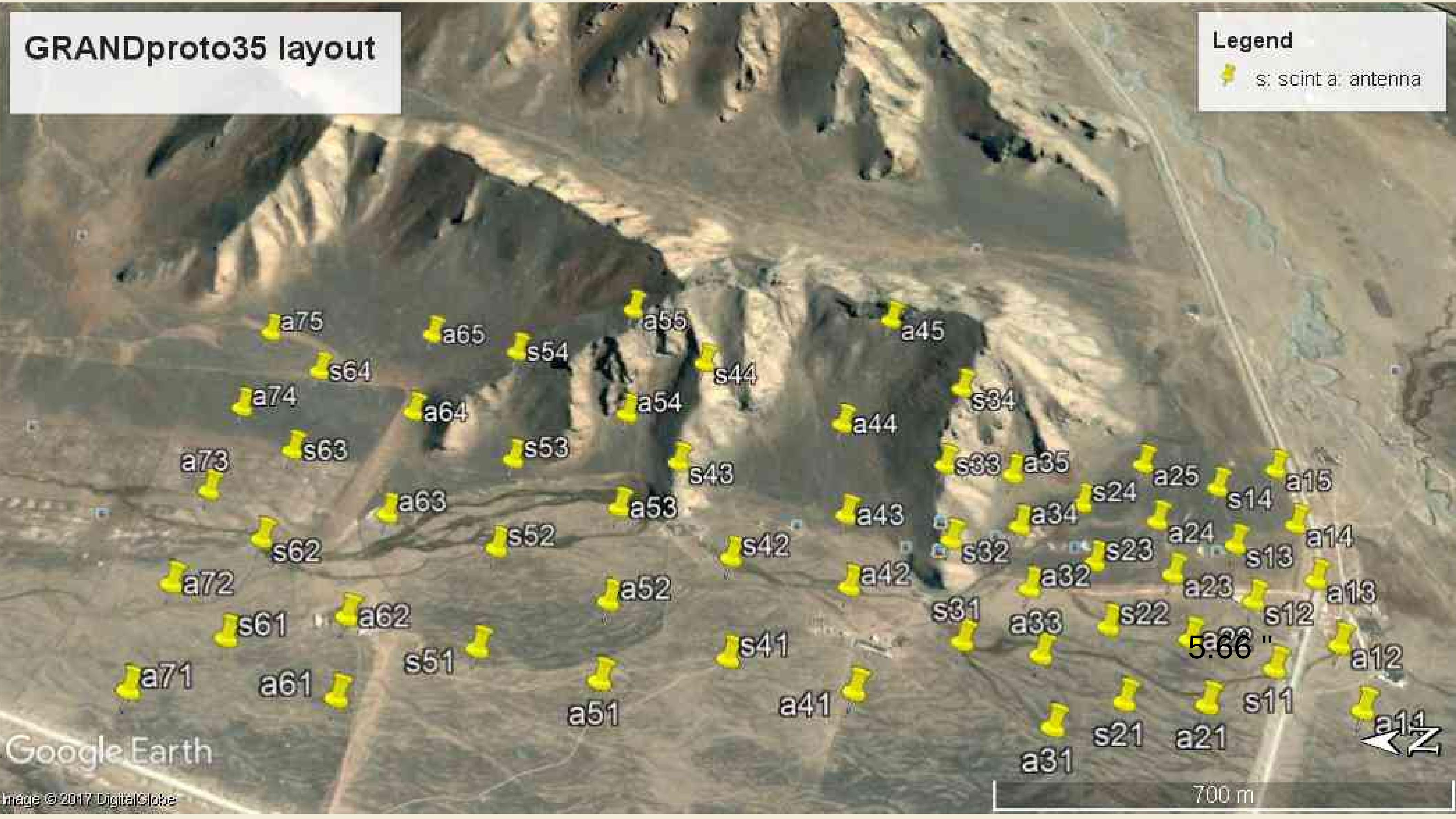
Current stage: GRANDProto35

- 35 antennas + 24 scintillators
- Built at LPNHE (France), shipped to NAOC (China)
- Deployment ongoing

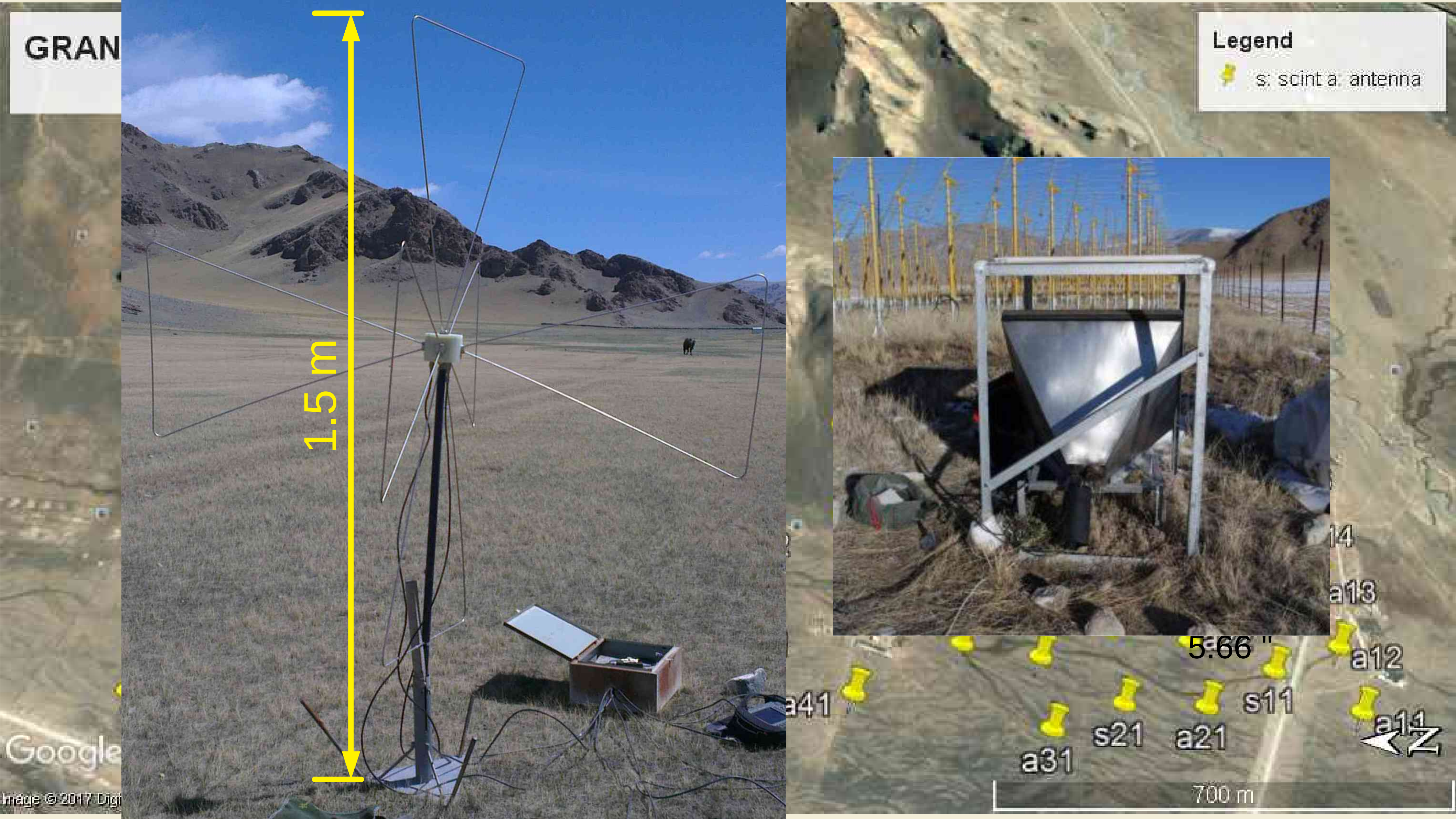
Goal:

Confirm self-triggered, autonomous radio-detection of EAS

- **Wanted:** >80% EAS detection efficiency
- **Wanted:** <10% false-positive rate



GRANDproto35 layout
Legend
s: scint a: antenna
a75
a65
a55
a45
s54
s64
s44
a74
a64
a54
s34
a44
a73
s63
s53
s43
s33
a35
a25
a15
s24
s14
a63
a53
a43
a34
a24
a14
s62
s52
s42
s32
s23
s13
a72
a52
a42
a32
a23
a13
s61
a62
s31
a33
s22
s12
a12
s51
s41
5.66 "
a71
a61
a51
a41
s21
a21
s11
a31
Google Earth
Image © 2017 DigitalGlobe
700 m


GRAN
1.5 m
Legend
s: scint a: antenna
a13
a12
a41
s11
s21
a21
a31
5.66 "
700 m
Google

Main challenge: Rejection of radio background

- Galactic radio background ($150\ \mu V \cdot m^{-1}$): known, easy to filter

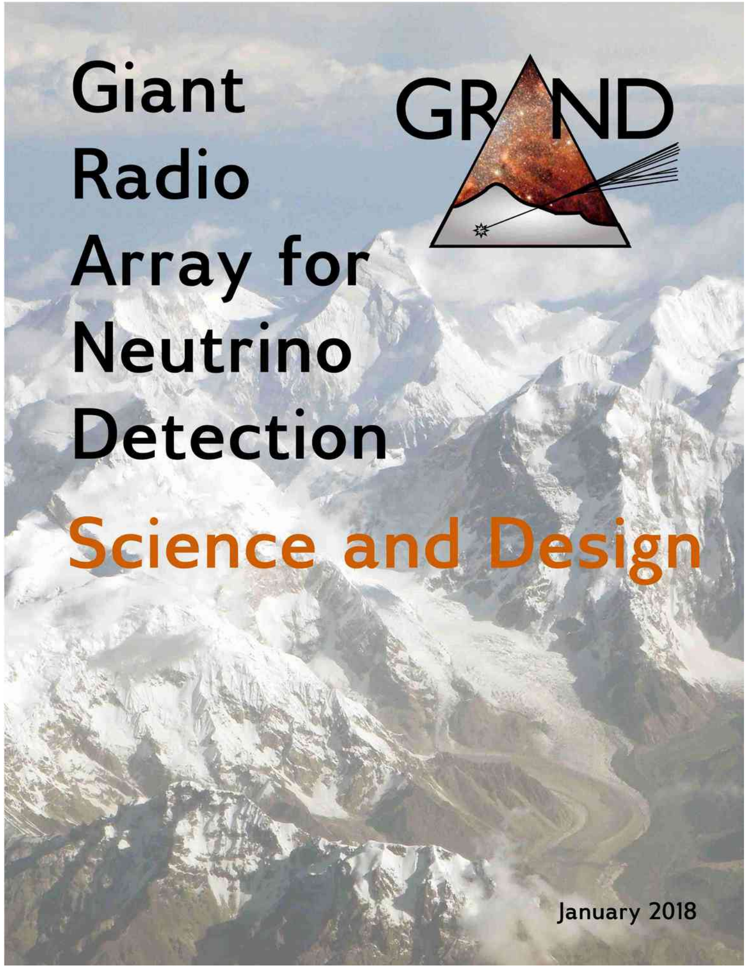
- Man-made radio background: unknown, high, challenging to filter

- Scaling up the background measured by TREND yields 10^8 events yr^{-1}
  $\mapsto$ We need a rejection factor of 10^9

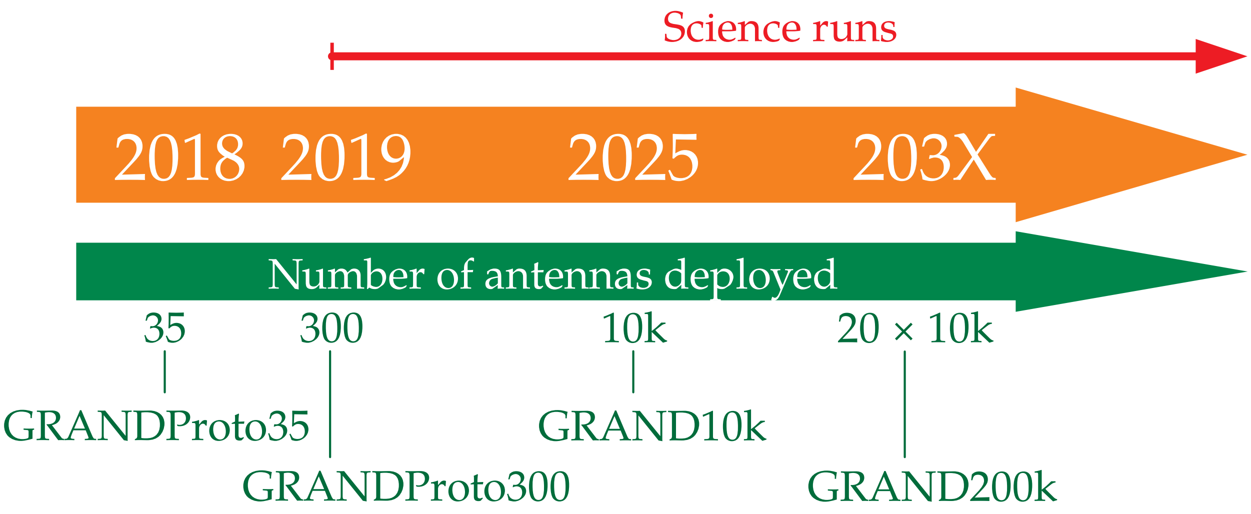
- How to remove the background?
  - Remove data in the direction of known sources
  - Filter based on antenna trigger pattern
  - Filter based on polarization

Under study

Status and future of GRAND



◀ GRAND white paper coming out later this year



Funding:

- GRANDProto35: funded
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Jaime Álvarez-Muñiz[1], Rafael Alves Batista[2,3], Julien Bolmont[4], Mauricio Bustamante[5,6,7,†], Washington Carvalho Jr.[8], Didier Charrier[9], Ismaël Cognard[10,11], Valentin Decoene[12], Peter B. Denton[5], Sijbrand De Jong[13,14], Krijn D. De Vries[15], Ralph Engel[16], Ke Fang[17,18], Chad Finley[19,20], QuanBu Gou[21], Junhua Gu[22], Claire Guépin[12], Hongbo Hu[21], Yan Huang[22], Kumiko Kotera[12,23,*], Sandra Le Coz[22], Jean-Philippe Lenain[4], Guoliang Lü[24], Olivier Martineau-Huynh[4,22,*], Miguel Mostafá[25,26,27], Fabrice Mottez[28], Kohta Murase[25,26,27], Valentin Niess[29], Foteini Oikonomou[30,25,26,27], Tanguy Pierog[16], Xiangli Qian[31], Bo Qin[22], Duan Ran[22], Nicolas Renault-Tinacci[12], Frank G. Schröder[32], Fabian Schüssler[33], Cyril Tasse[34], Charles Timmermans[13,14], Matías Tueros[35], Xiangping Wu[36,22,*], Philippe Zarka[37], Andreas Zech[28], Bing Theodore Zhang[38,39], Jianli Zhang[22], Yi Zhang[21], Qian Zheng[40,21], Anne Zilles[12]

GRANDProto35 | GRANDProto300 | GRAND10k | GRAND200k

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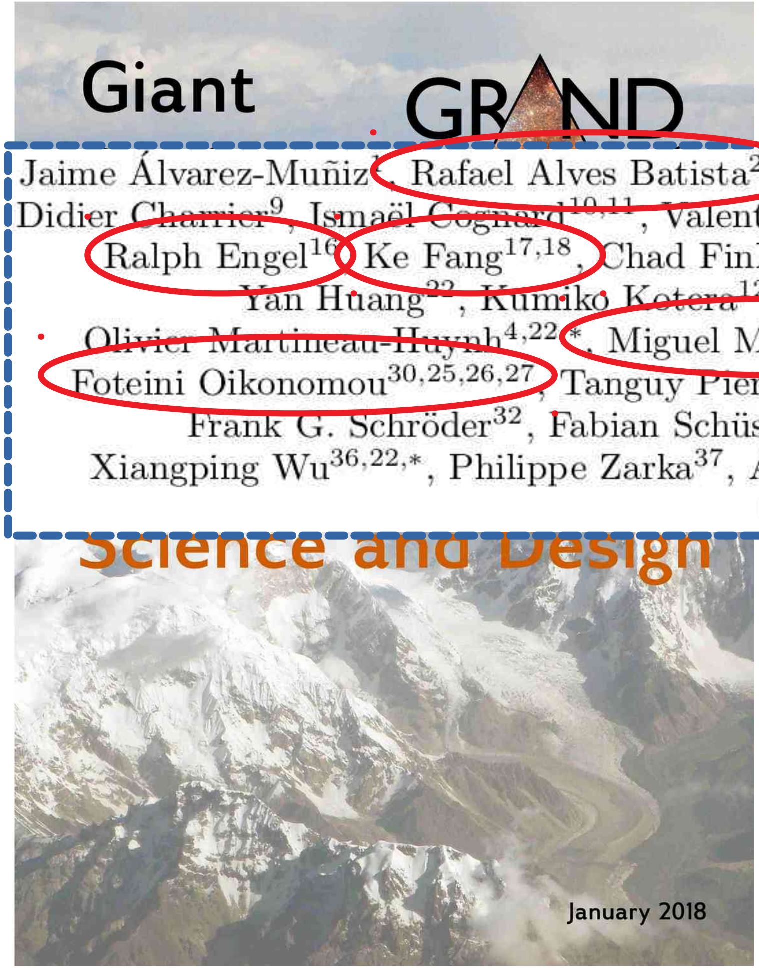

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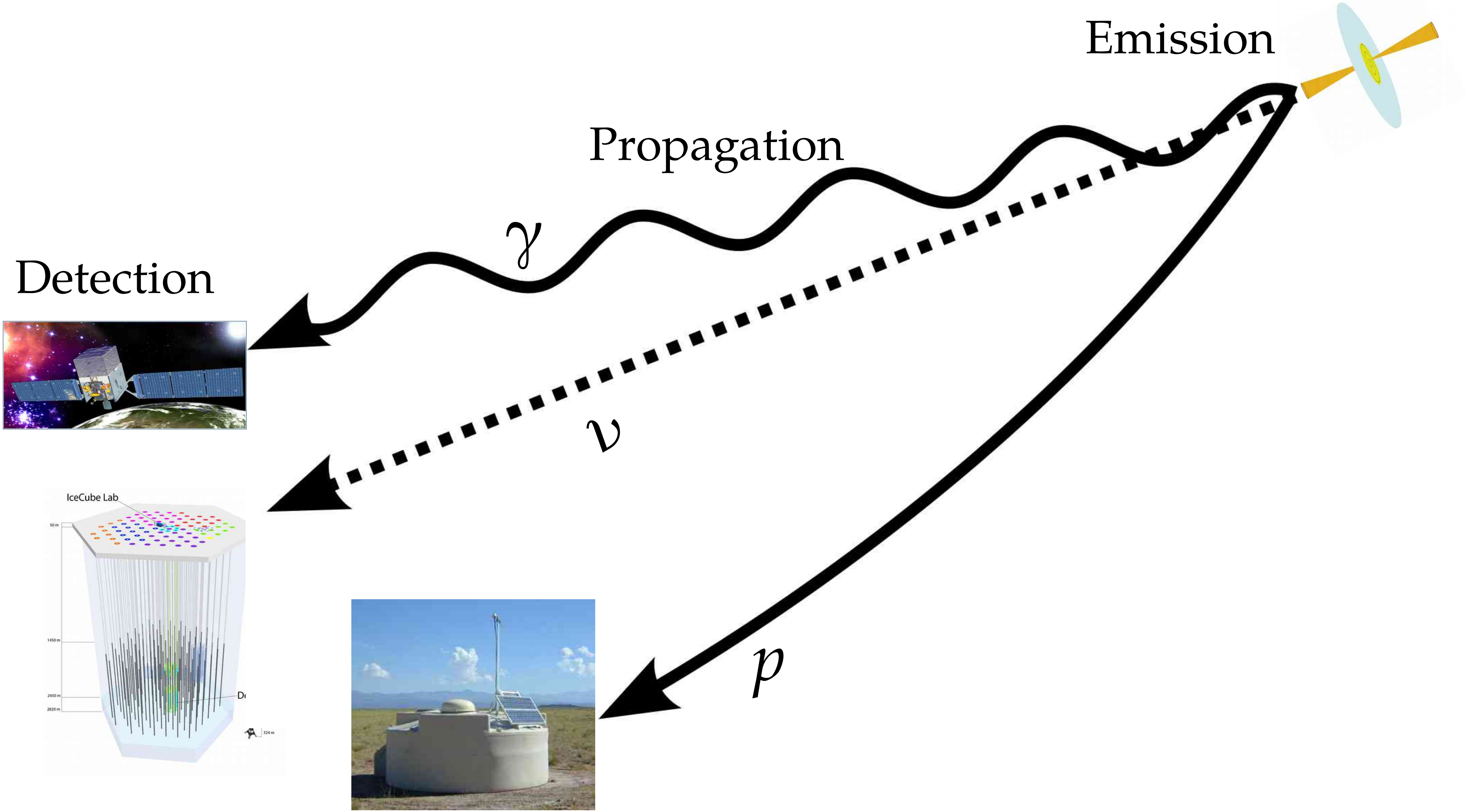
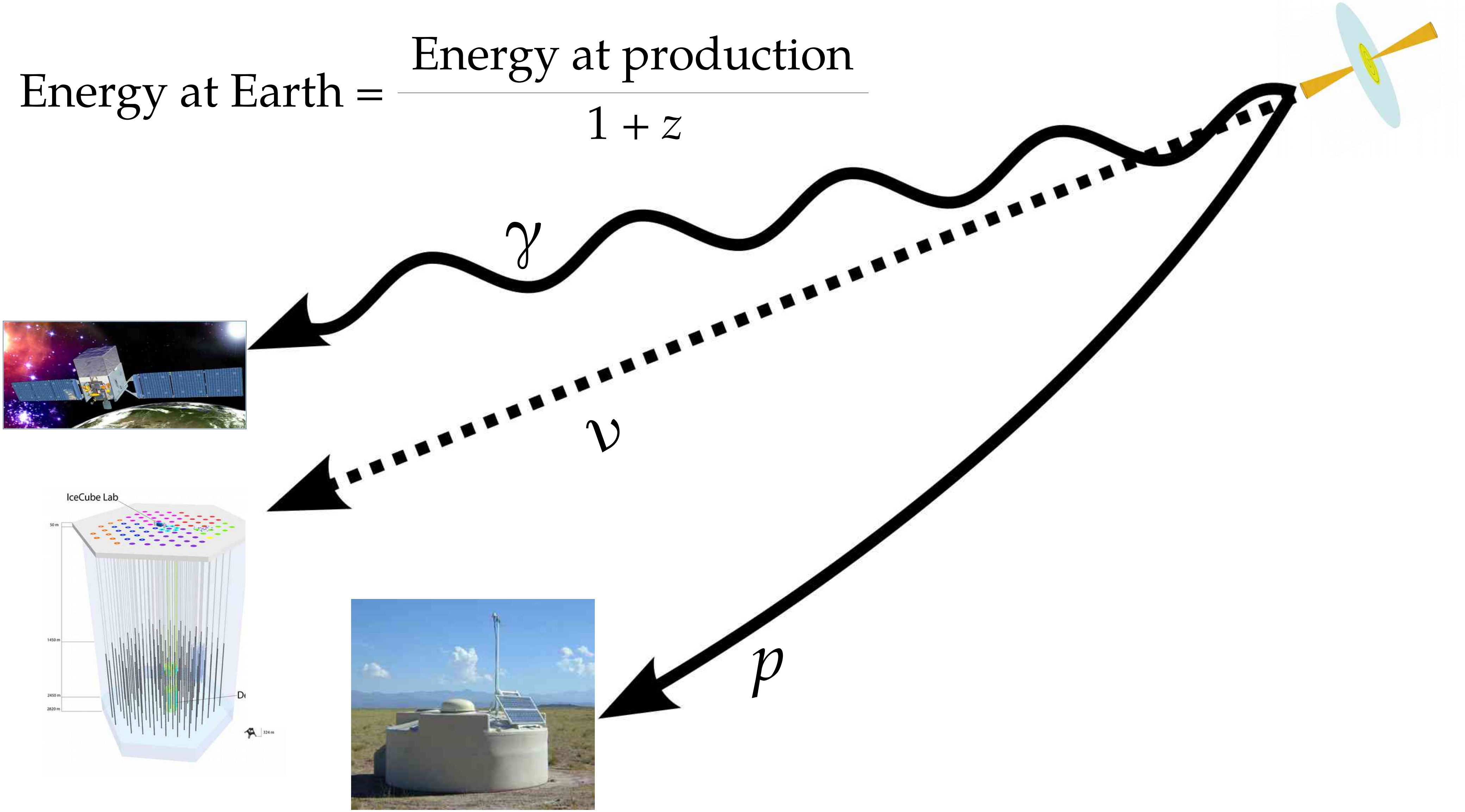
More information:

grand.cnrs.fr

Backup slides


Emission
Propagation
Detection
γ
ν
p
IceCube Lab

$$\text{Energy at Earth} = \frac{\text{Energy at production}}{1+z}$$



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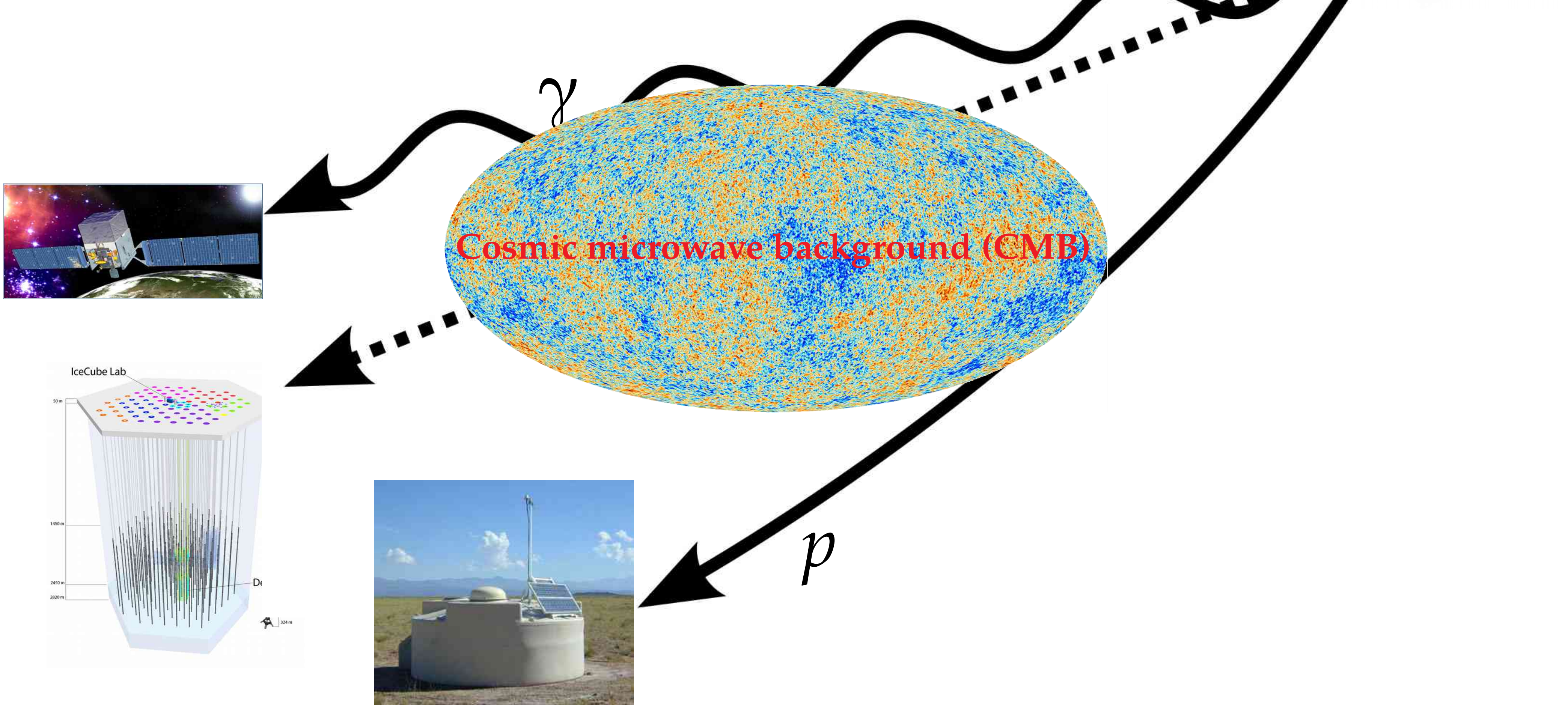
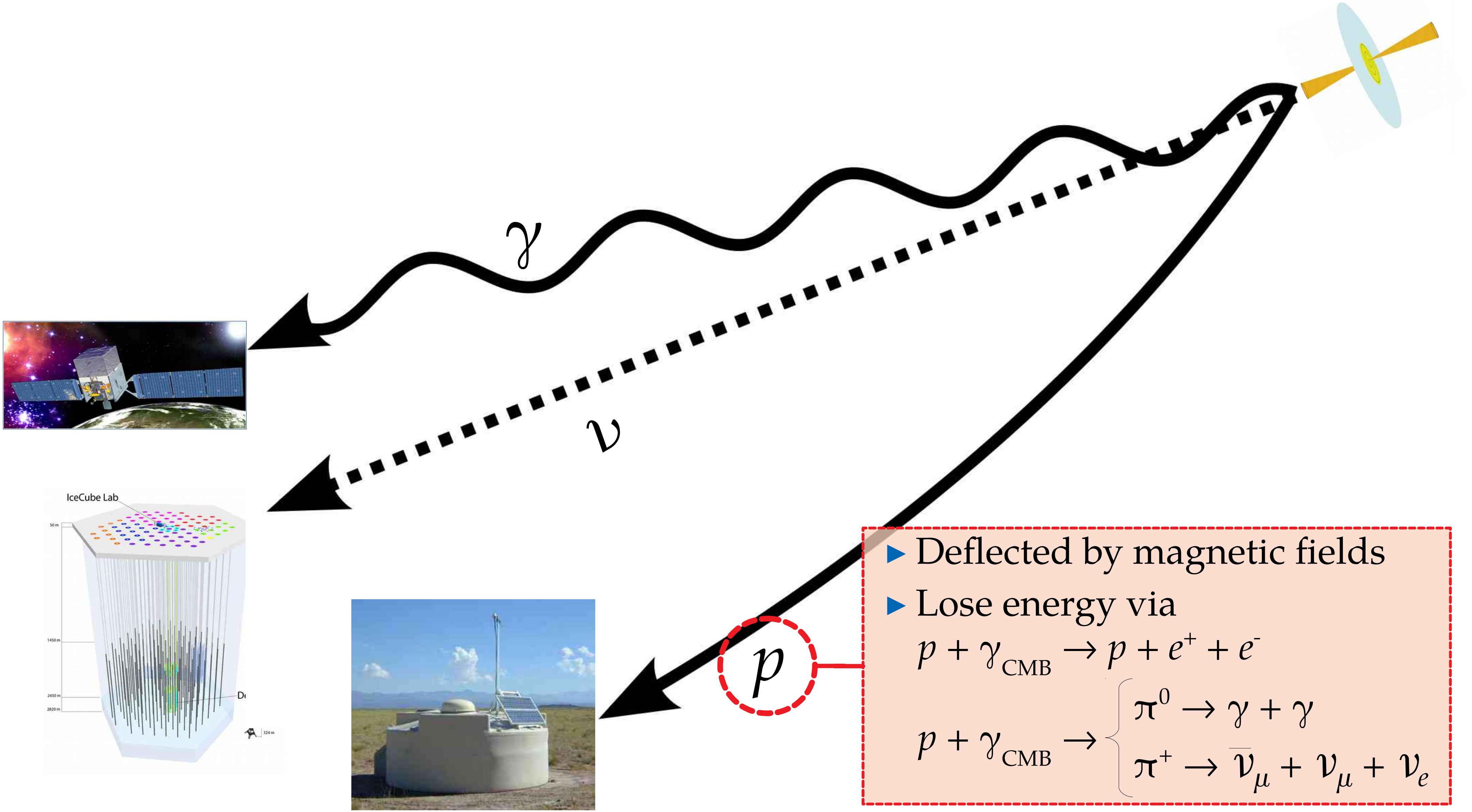
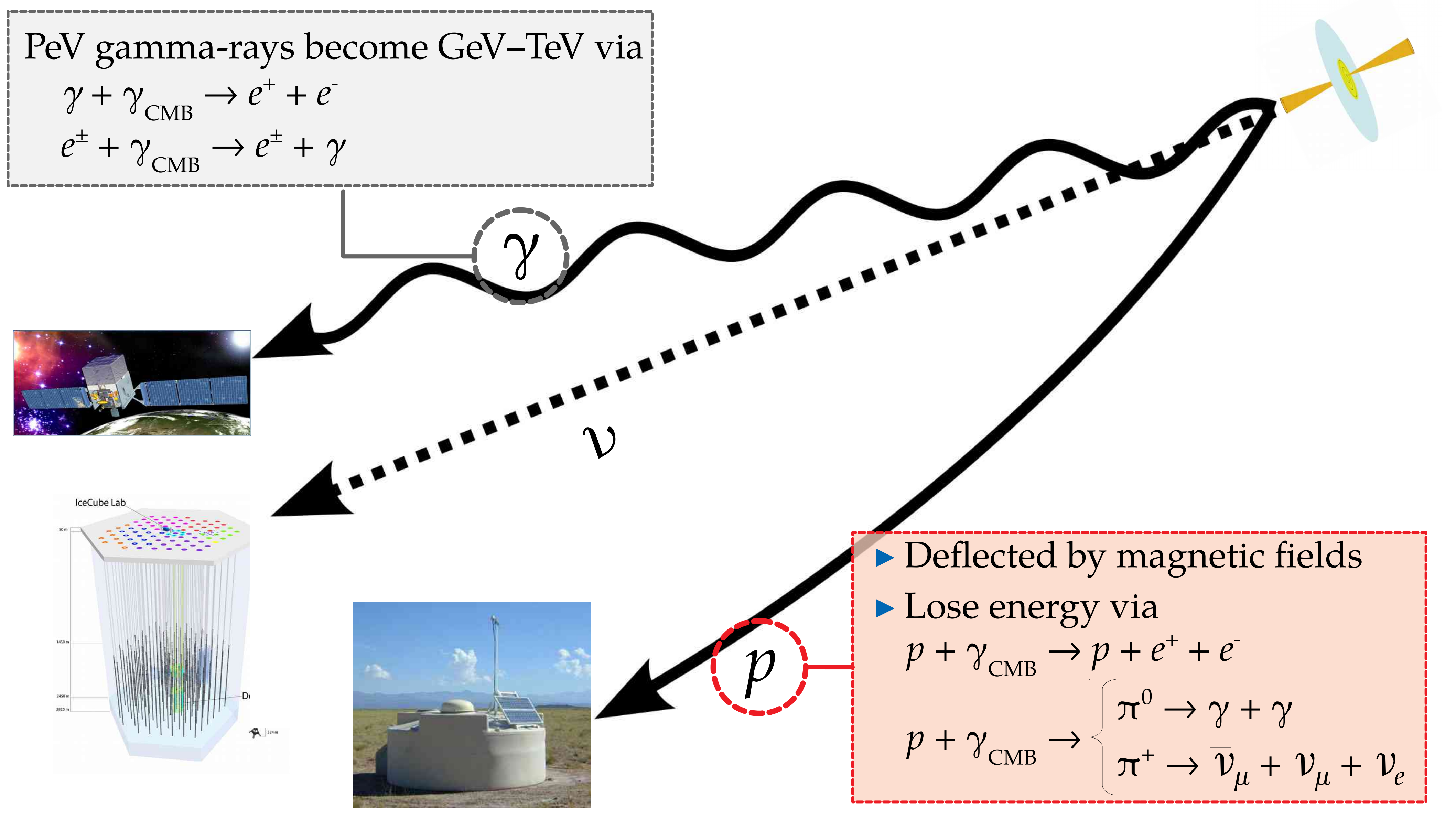



γ
ν
p
IceCube Lab
▸ Deflected by magnetic fields
▸ Lose energy via
$p + \gamma_{CMB} \rightarrow p + e^{+} + e^{-}$
$p + \gamma_{CMB} \rightarrow \begin{cases} \pi^{0} \rightarrow \gamma + \gamma \\ \pi^{+} \rightarrow \bar{\nu}_{\mu} + \nu_{\mu} + \nu_{e} \end{cases}$


PeV gamma-rays become GeV–TeV via
$\gamma + \gamma_{CMB} \rightarrow e^{+} + e^{-}$
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γ
ν
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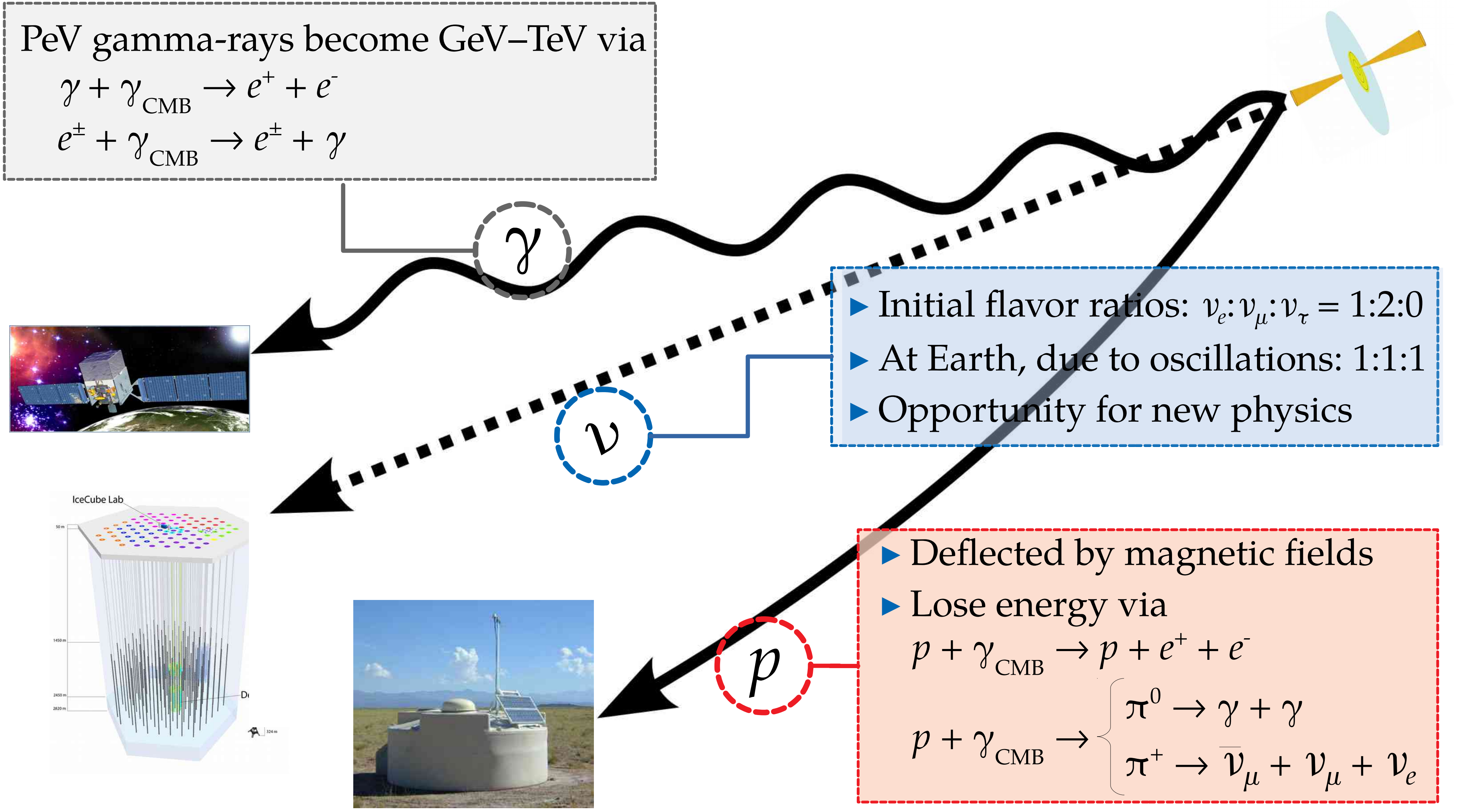


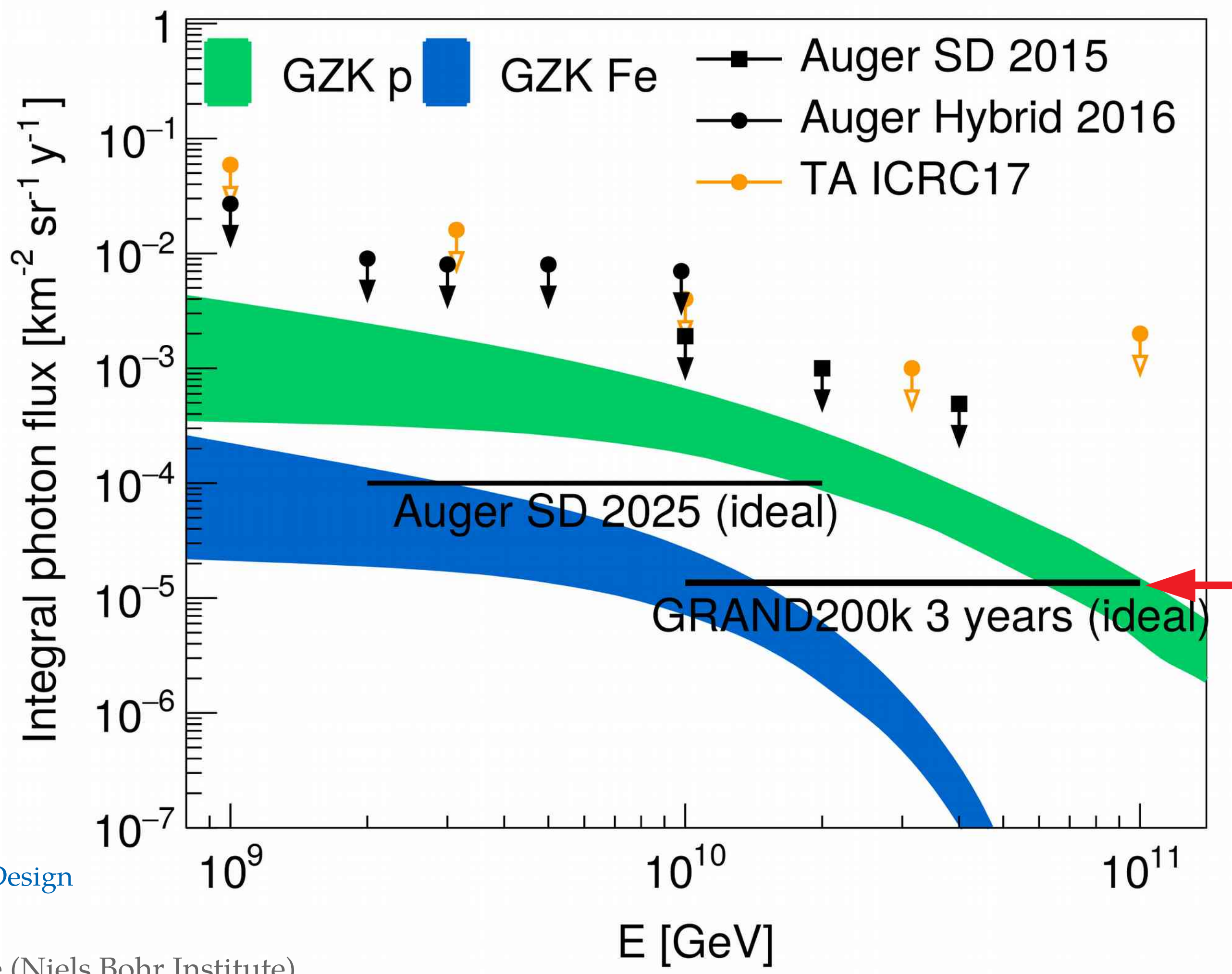
PeV gamma-rays become GeV–TeV via
$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
$e^\pm + \gamma_{CMB} \rightarrow e^\pm + \gamma$
γ
ν
Initial flavor ratios: $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$
At Earth, due to oscillations: 1:1:1
Opportunity for new physics
IceCube Lab
p
Deflected by magnetic fields
Lose energy via
$p + \gamma_{CMB} \rightarrow p + e^+ + e^-$
$p + \gamma_{CMB} \rightarrow \begin{cases} \pi^0 \rightarrow \gamma + \gamma \\ \pi^+ \rightarrow \bar{\nu}_\mu + \nu_\mu + \nu_e \end{cases}$

The GRAND roadmap

GRANDProto300

	GRANDProto35		GRAND10k	GRAND200k
	2018	2020	2025	203X
Goals	**Standalone** radio detection of EAS Very good **background rejection**	Standalone radio detection of **very inclined showers** (θ>65°) induced by high energy cosmic rays (>10^9 GeV)	First GRAND subarray, **sensitivity comparable to ARA/ARIANNA on similar time scale**, allowing potential 1st discovery of cosmogenic neutrinos	**First neutrino detection at 10^9 GeV even with pessimistic fluxes and/or neutrino astronomy**
Setup	35 radio antennas 21 scintillators 	• 300 Horizon Antennas over 300 km² • Fast DAQ • Solar pannels (day use) + WiFi data transfer • TBD: Array of surface muon detectors	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	160k€, fully funded by NAOC+IHEP, deployment 2018 @ Ulastai	1.3 M€ to be deployed in 2019	1500€ / detection unit	**Industrial scale allows to cut costs down: 500€/unit** **➔ 120M€ in total**

UHE gamma-ray reach

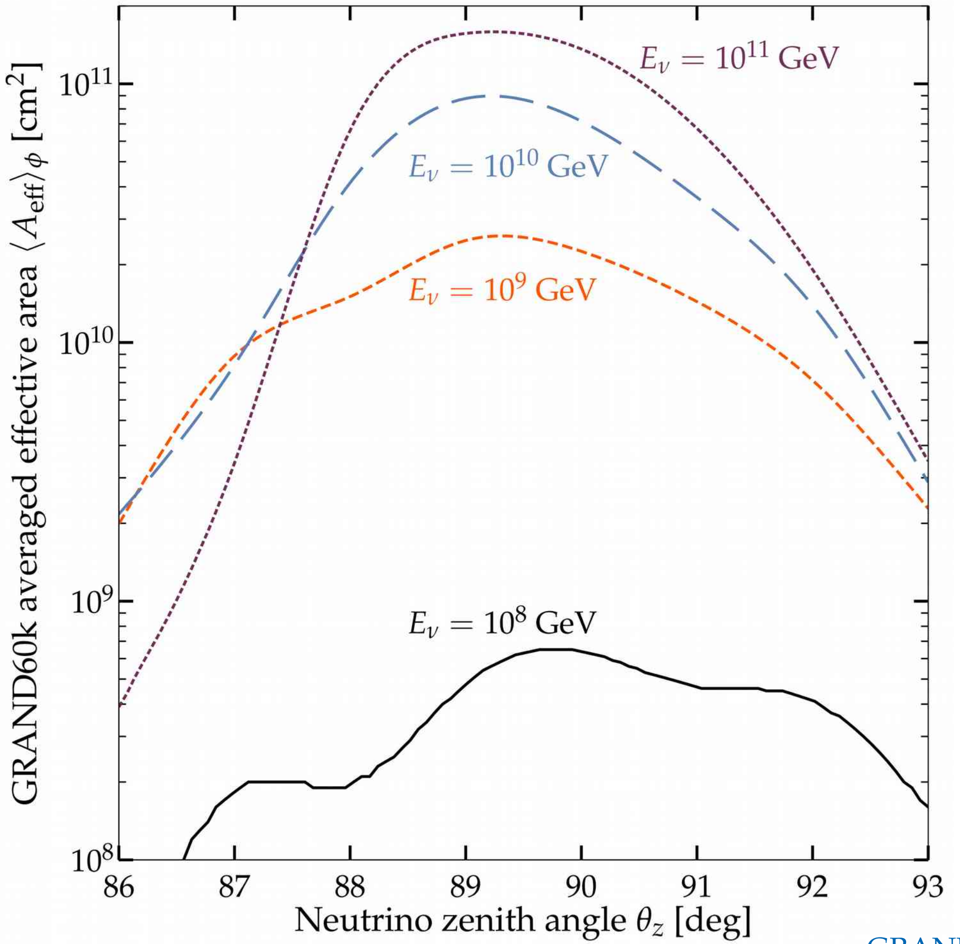


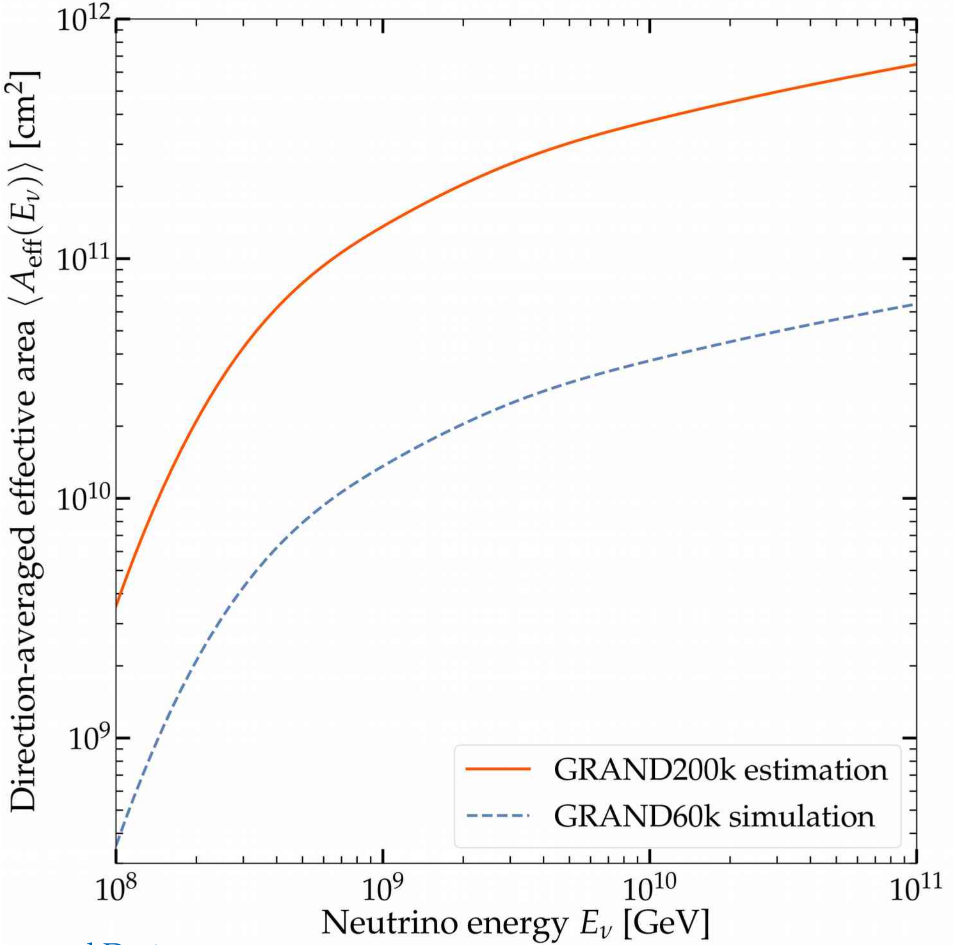
95% C.L., no background, E^{-2} spectrum

GRAND: Science and Design

Effective area

For the 60 000 km^2 simulation

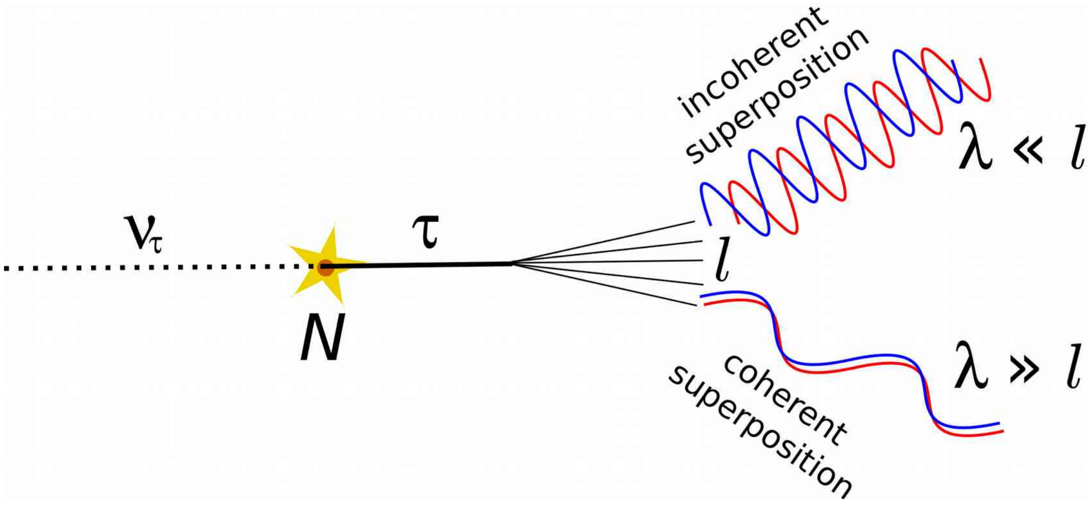




GRAND: Science and Design

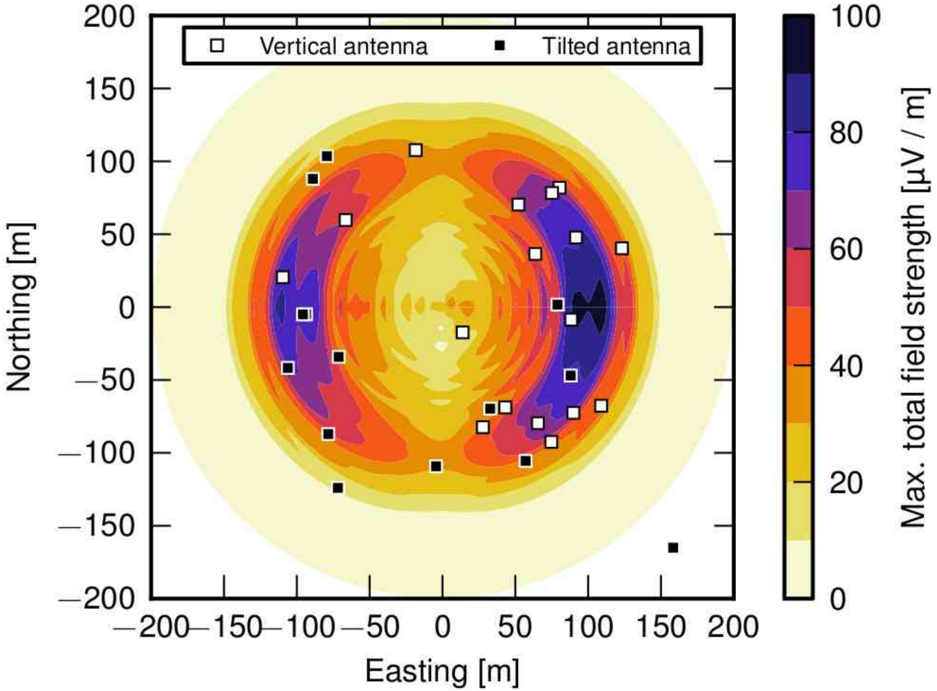
Coherent radio emission

- "Particle pancake": ~1 cm thick, few cm wide
- At radio wavelengths, emission adds coherently:



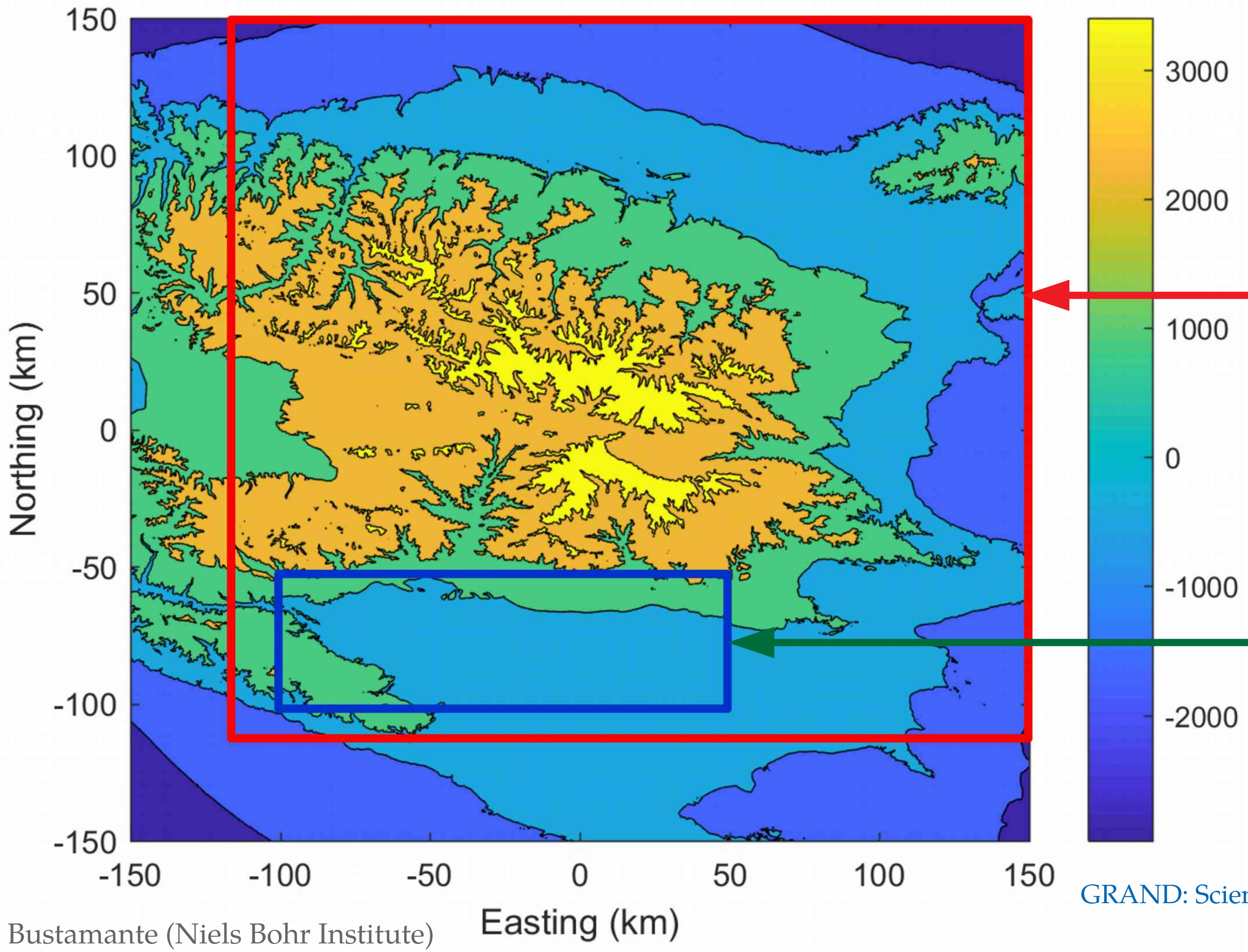
Cherenkov ring

Seen by CROME in 3.4–4.2 GHz band



F. Werner *et al.*, ICRC 2013

GRAND simulations



60 000 km^2 simulated area, Tian Shan mountains

7 500 km^2 hotspot (50% of downgoing events)

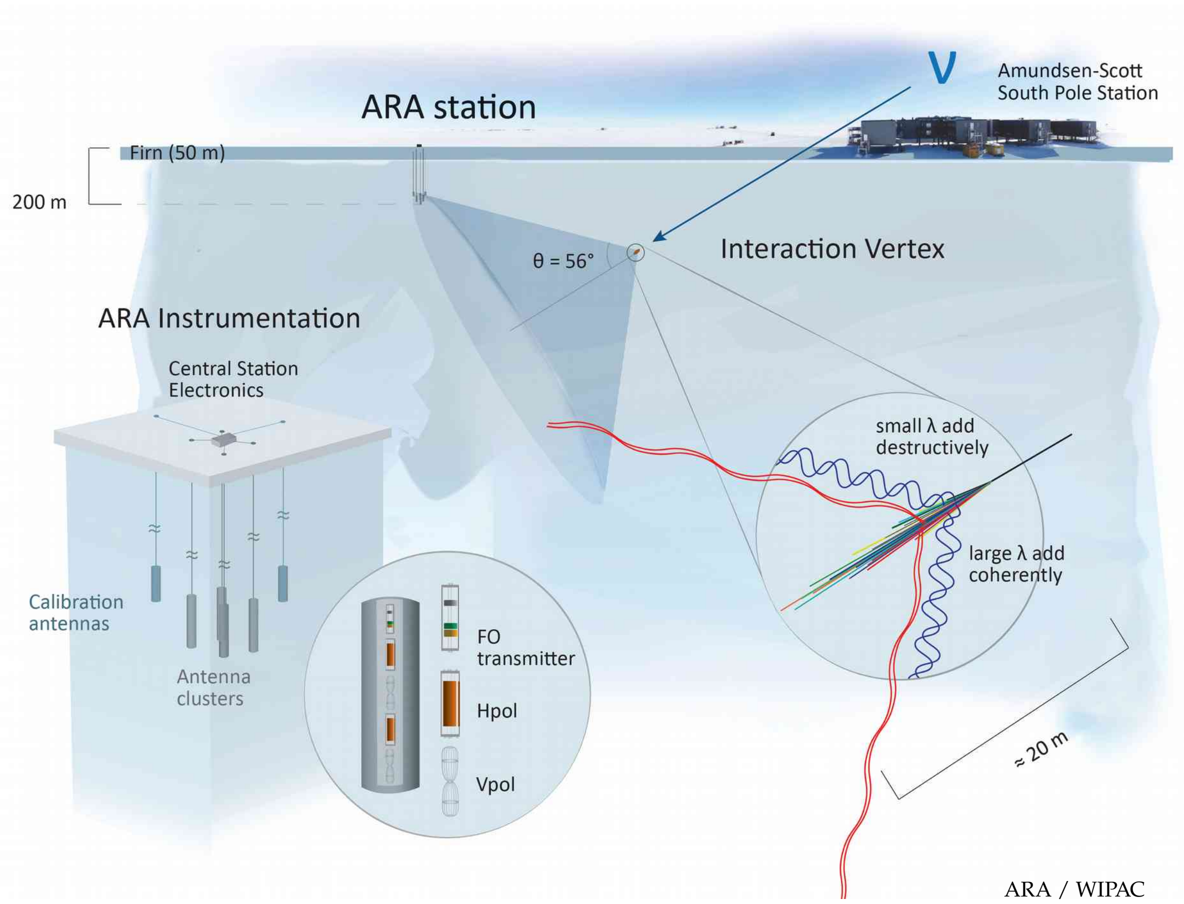
GRAND: Science and Design

Radio detection of UHE neutrinos

- Radio attenuation length in ice: few km (*vs.* 100 m for light)
- Larger monitored volume than IceCube
- ARA, ARIANNA: antennas buried in ice
- ANITA: antennas mounted on a balloon

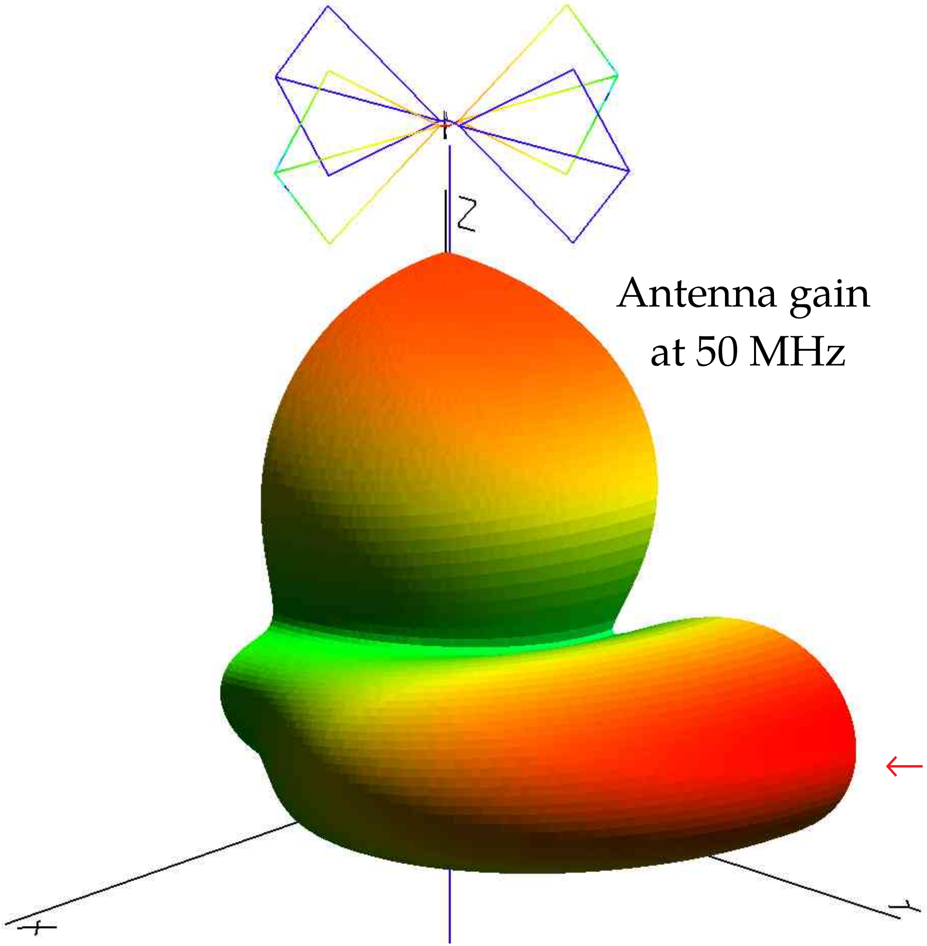
No ν detected yet

(But UHECRs detected regularly!)

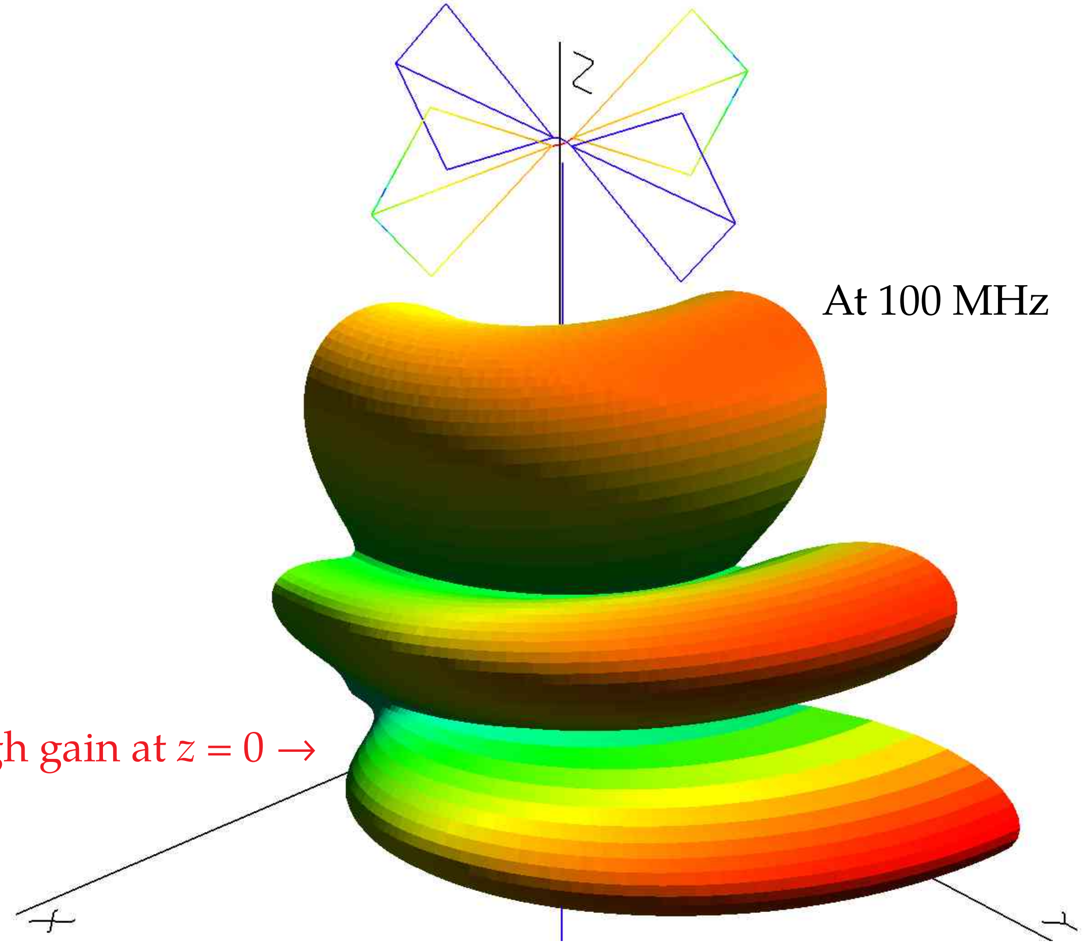


ARA / WIPAC

Antenna optimized for horizontal EAS



Antenna gain at 50 MHz



At 100 MHz

← High gain at $z = 0$ →

The multi-messenger connection

$$p + \gamma_{\text{target}} \to \Delta^+ \to \begin{cases} p + \pi^0, & \text{Br} = 2/3 \\ n + \pi^+, & \text{Br} = 1/3 \end{cases}$$

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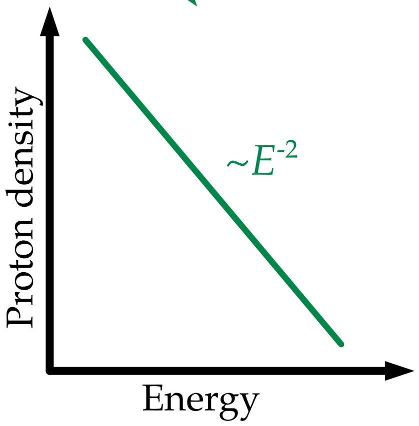

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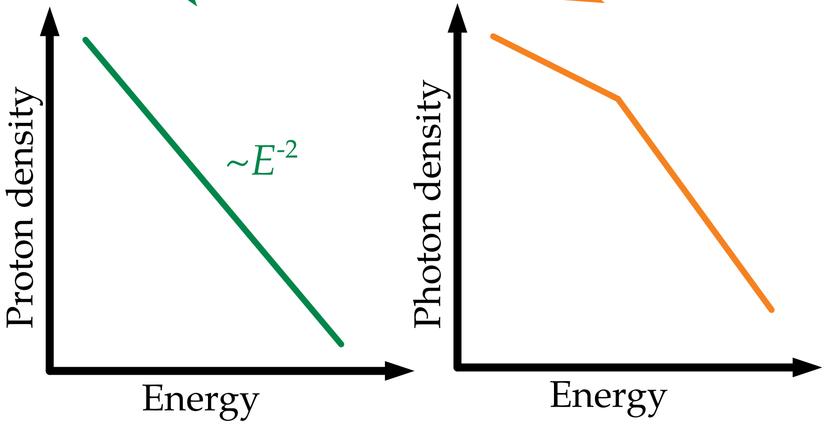

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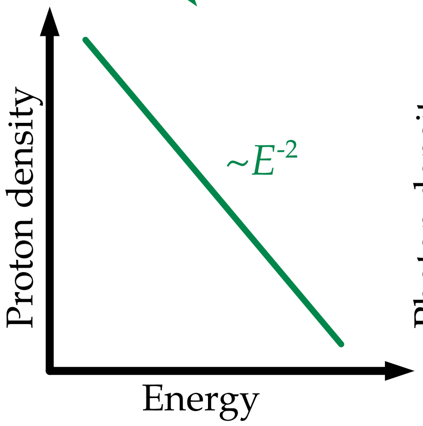

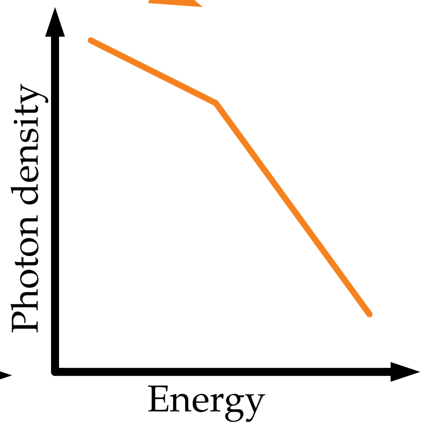

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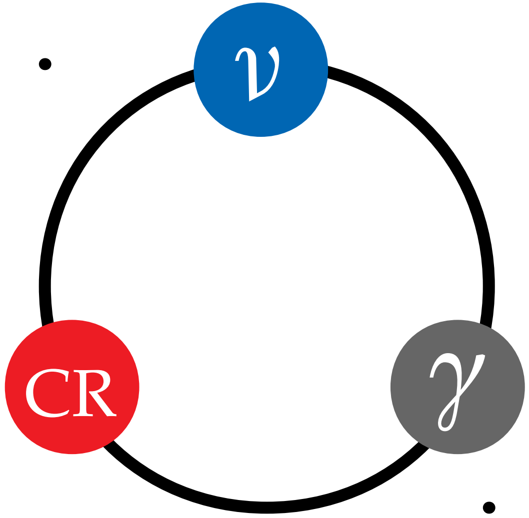

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 20

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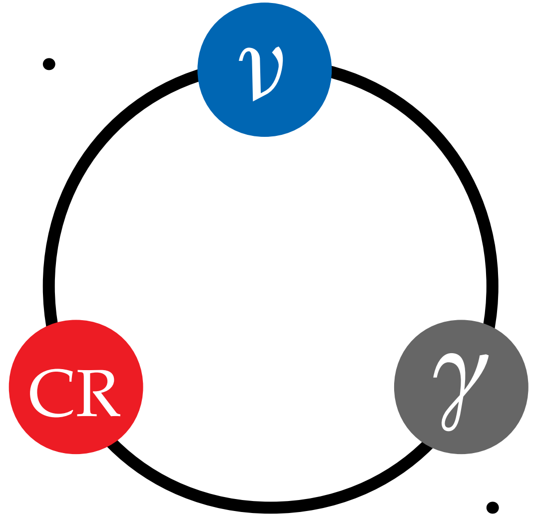

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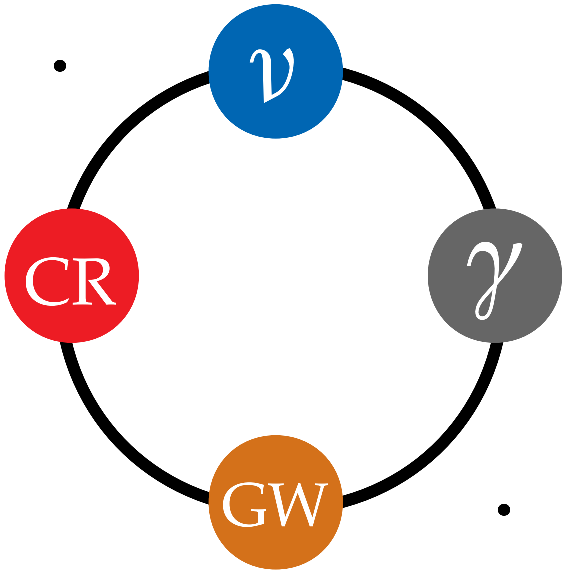

1 PeV — 20 PeV

Neutrino energy = Proton energy / 20

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Neutrinos – the ultimate smoking gun

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources			
Size of horizon			
Energy degradation			
Relative ease to detect			

Note: This is a simplified view

Neutrinos – the ultimate smoking gun

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources	Yes	Yes	No
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Neutrinos – the ultimate smoking gun

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources	Yes	Yes	No
Size of horizon	10 Mpc (at EeV)	Size of the Universe	100 Mpc (> 40 EeV)
Energy degradation			
Relative ease to detect			

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Note: This is a simplified view

Three strategies to reveal sources using TeV–PeV ν

Look at bright e.m. point sources

- **Examine single sources** → No evident single source, steady or transient
- **Stack several similar sources** → Ruled out gamma-ray bursts, blazars as dominant

Look for neutrino multiplets

- **Clustered in direction** → Placed generic limits on source number density and luminosity
- **Clustered in direction *and* time** → Used to trigger follow-ups by other detectors

Use the diffuse neutrino flux → Any population of candidate sources must account for all or part of it

GRANDProto300

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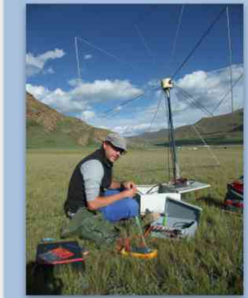
Setup	35 radio antennas 21 scintillators 	• 300 Horizon Antennas over 300 km² • Fast DAQ • Solar pannels (day use) + WiFi data transfer • TBD: Array of surface muon detectors	DAQ with discrete elements, but mature design for trigger, data transfer, consumption	200'000 antennas over 200'000 km² Hotspots could be in different continents
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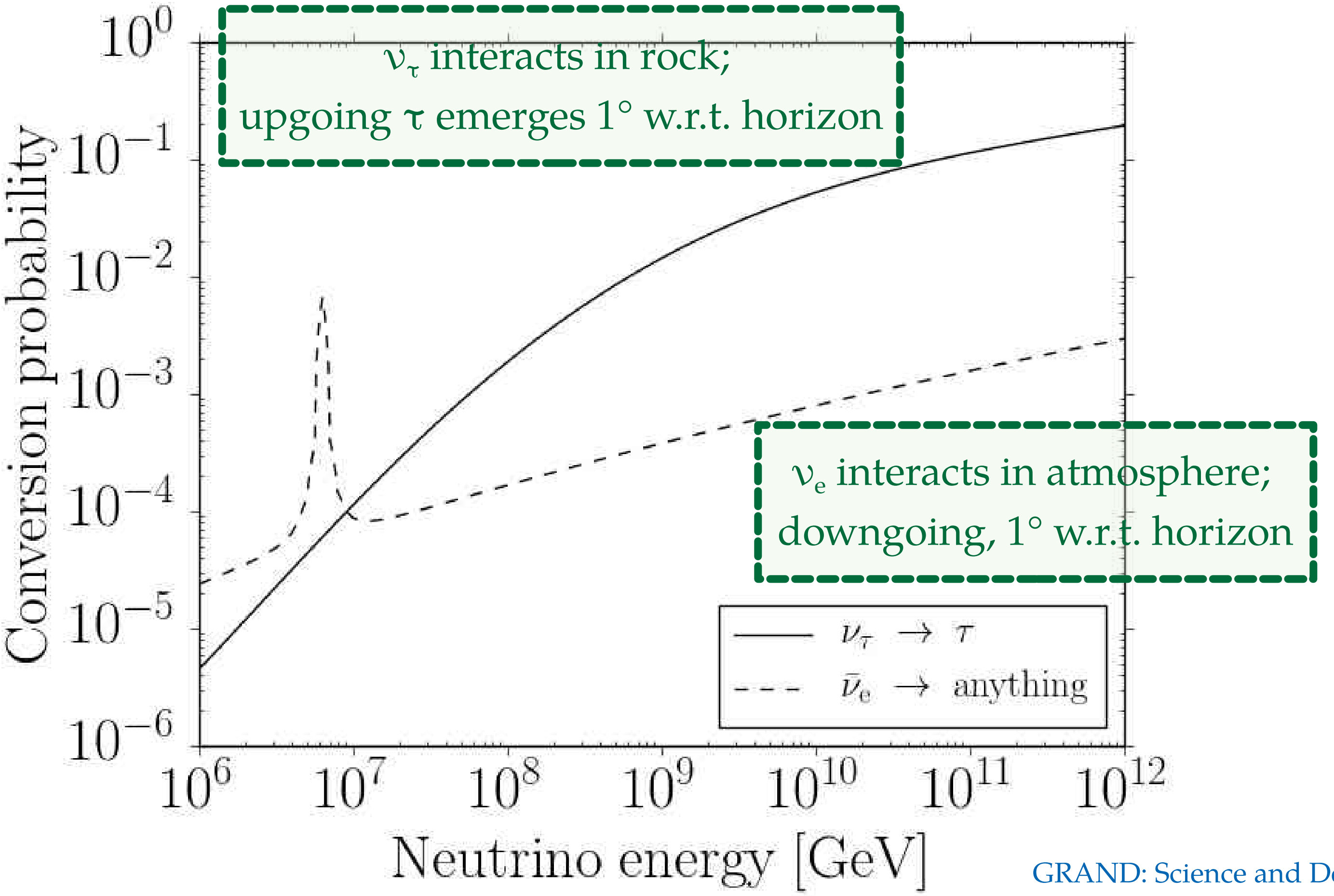
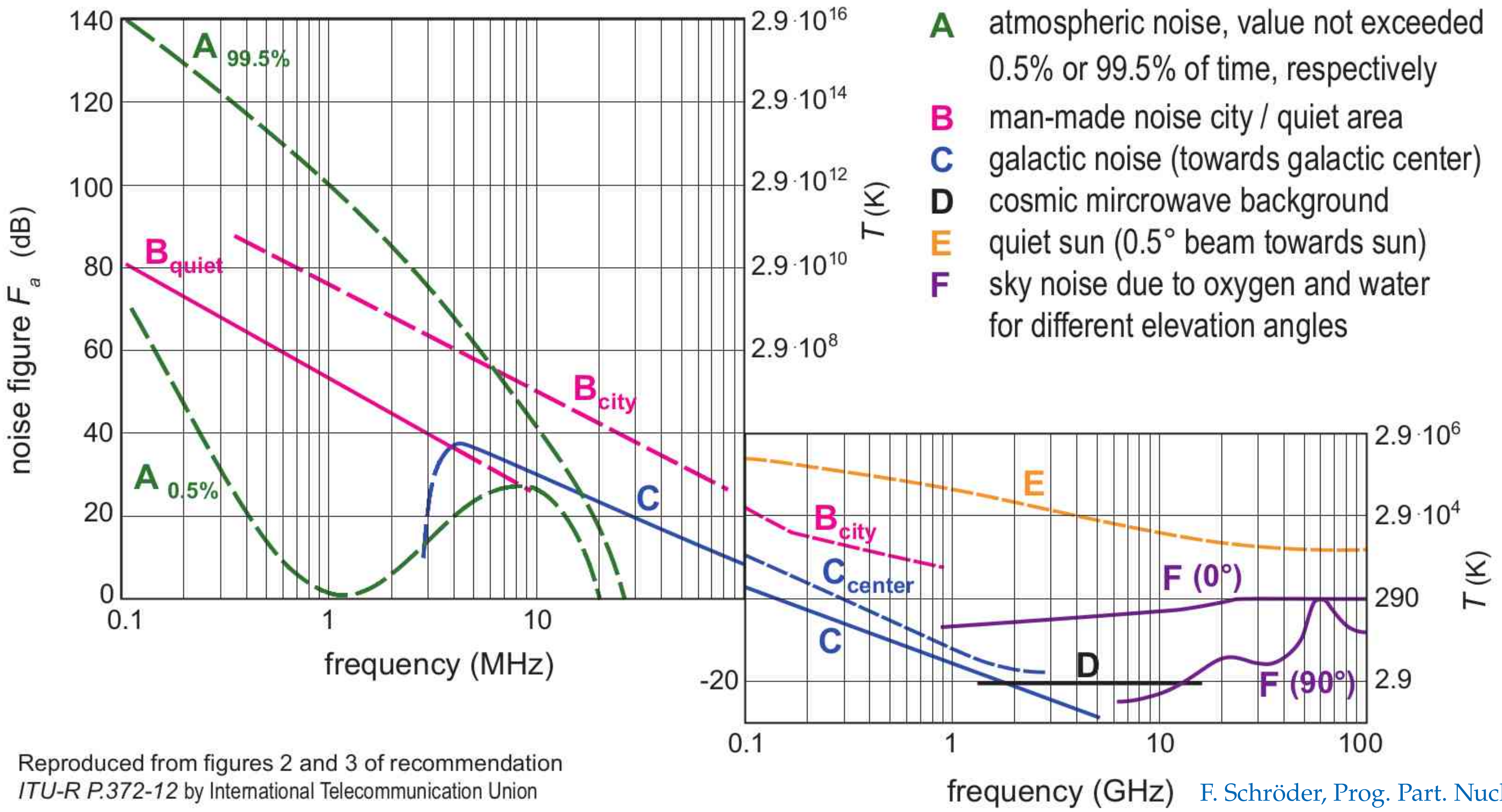
Conversion probability of neutrinos



GRAND: Science and Design

Radio noise



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F. Schröder, Prog. Part. Nucl. Phys. 2017