# New physics and Ultra-High-Energy Neutrinos

## Crossing the desert - Signatures of New Physics in the Universe

Steffen Hallmann
DESY Zeuthen, 11/06/2021

# New physics and ultra-high-energy (UHE) neutrinos

## Agenda

**Flux & Detection**

- UHE neutrino fluxes, and ways to detect them
- Askaryan radio signal & detectors

**Interaction physics at extreme energies**

- Standard model neutrino - nucleon cross sections at UHE
- neutrino event signatures at UHE

**What surprises may new physics bring us? What have we seen so far?**

- Ways to look for new physics at UHE and IceCube measurements at the highest energies

Three (there are more!) possibilities:
→ Earth absorption
→ event signatures
→ neutrino flavor ratio

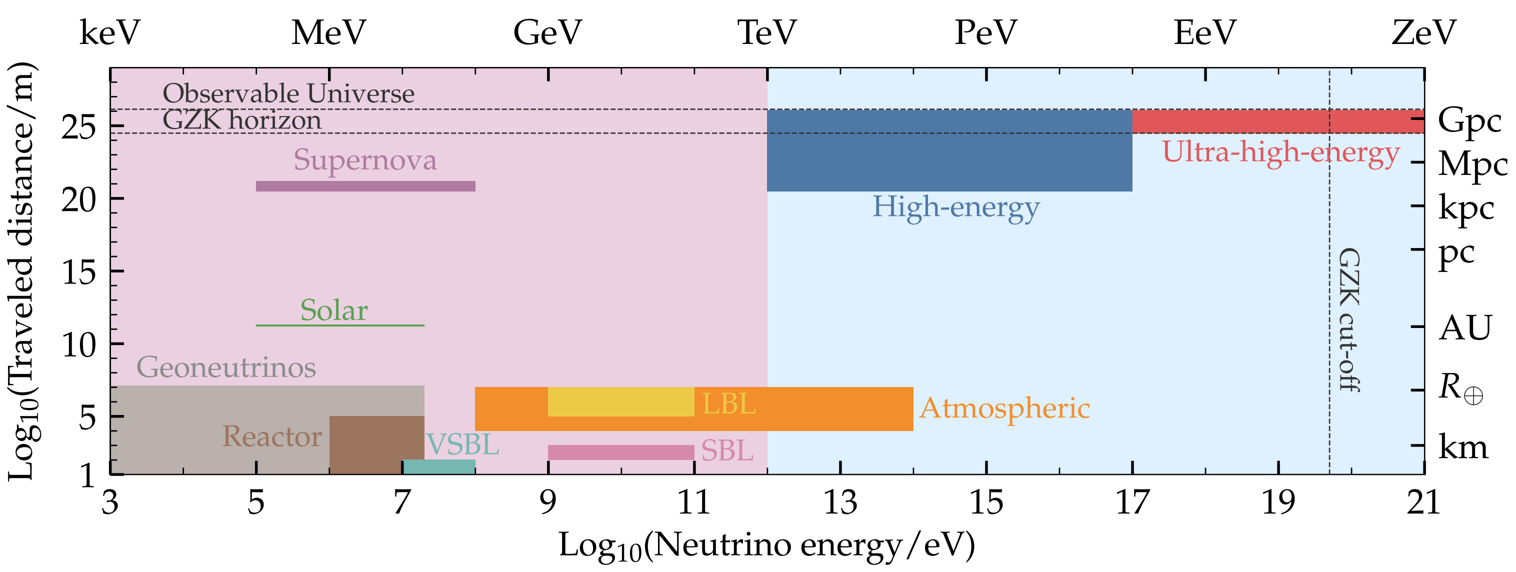
**What is ultra-high-energy?**

**Which fluxes do we expect?**

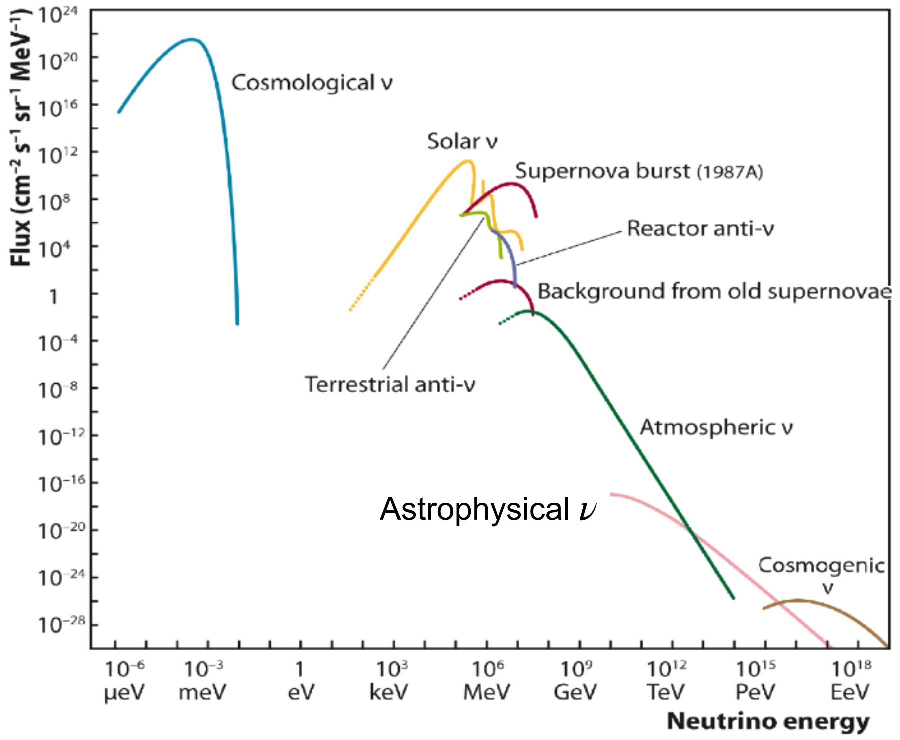
**How can we detect them?**

# Ultra-high-energy (UHE) neutrinos

IceCube-Gen2 Whitepaper




Katz, Spiering, Prog.Part.Nucl.Phys. 67 (2012) 651-704



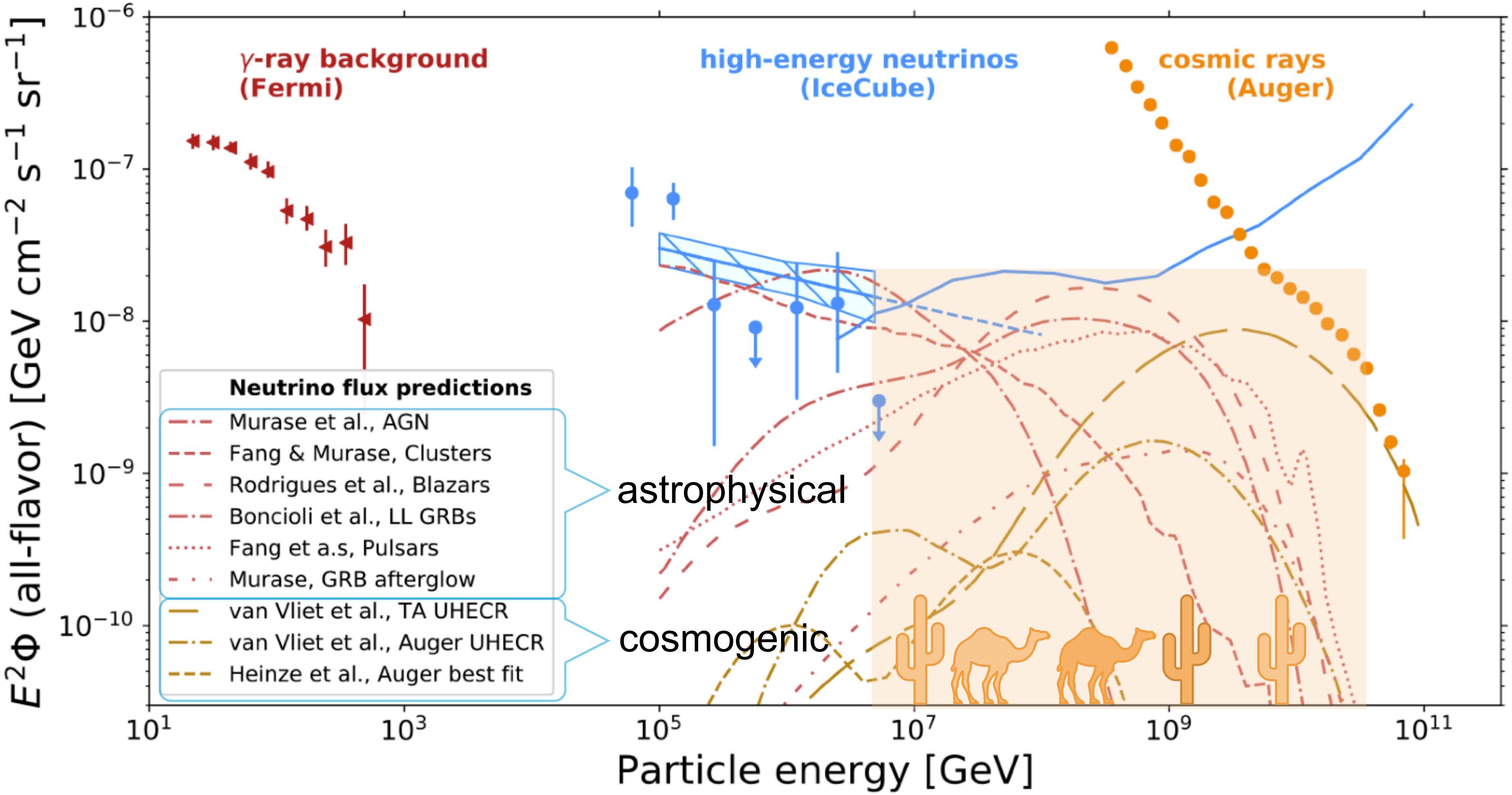

For this lecture:

ultra-high-energy = energies beyond ~10 PeV

Astrophysical neutrinos
Cosmogenic neutrinos

**+ new physics?**

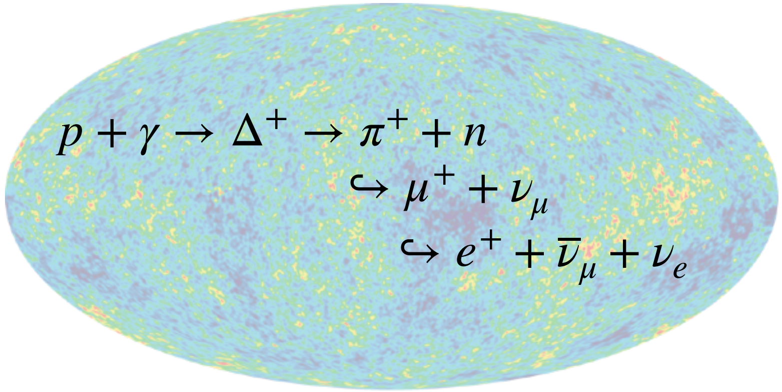
# Predicted neutrino fluxes (without “new physics”)



# The GZK effect: Why are we confident there are UHE neutrinos?

**GZK effect:**

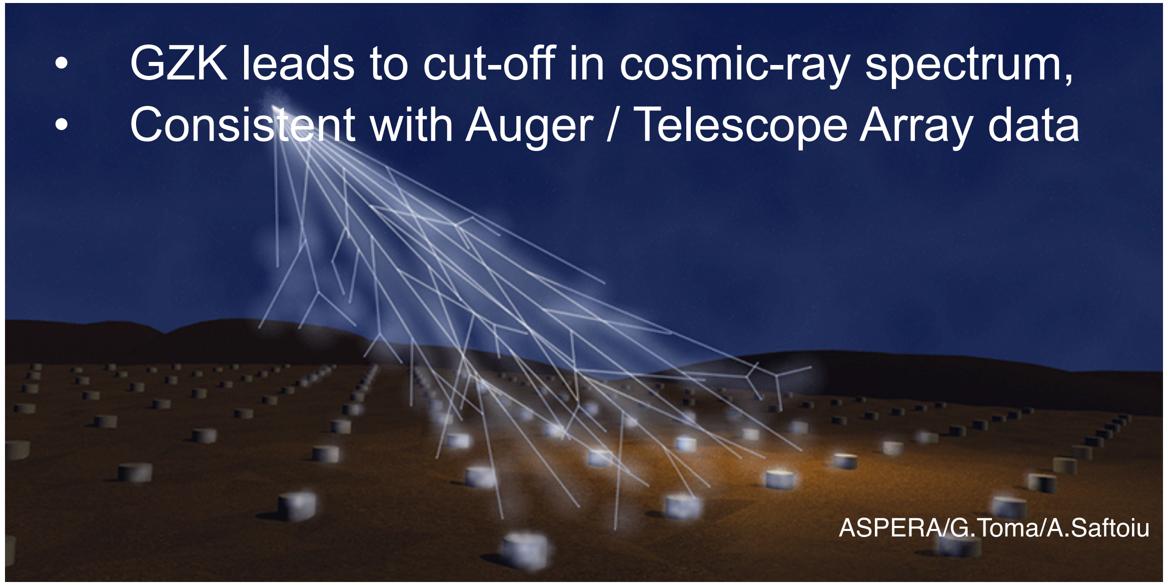
- Above ~$10^{19.5}$ eV, cosmic ray protons will interact with photons in the cosmic microwave background and produce neutrinos

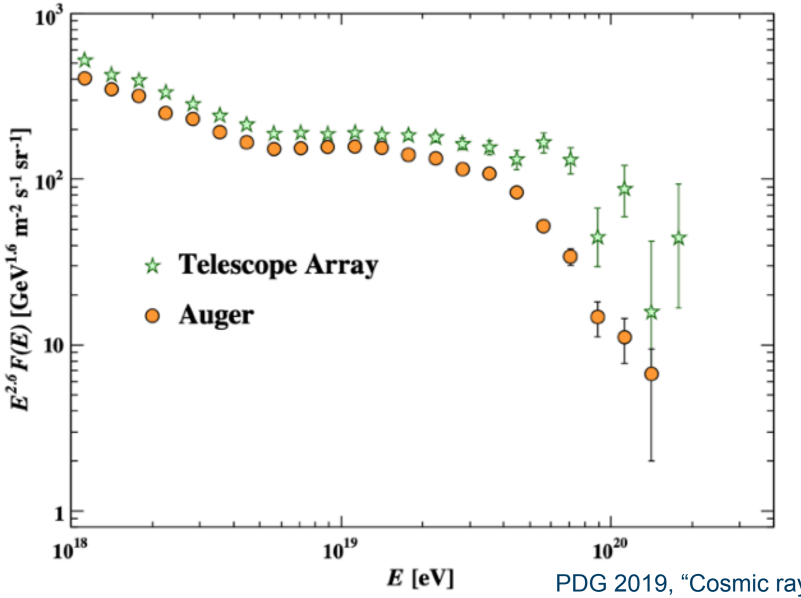


$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

- **Guaranteed flux of cosmogenic neutrinos. How large?**
- Strong dependence on spectrum and proton fraction (proton? iron (56 nucleons)?) of cosmic rays

- GZK leads to cut-off in cosmic-ray spectrum,
- Consistent with Auger / Telescope Array data

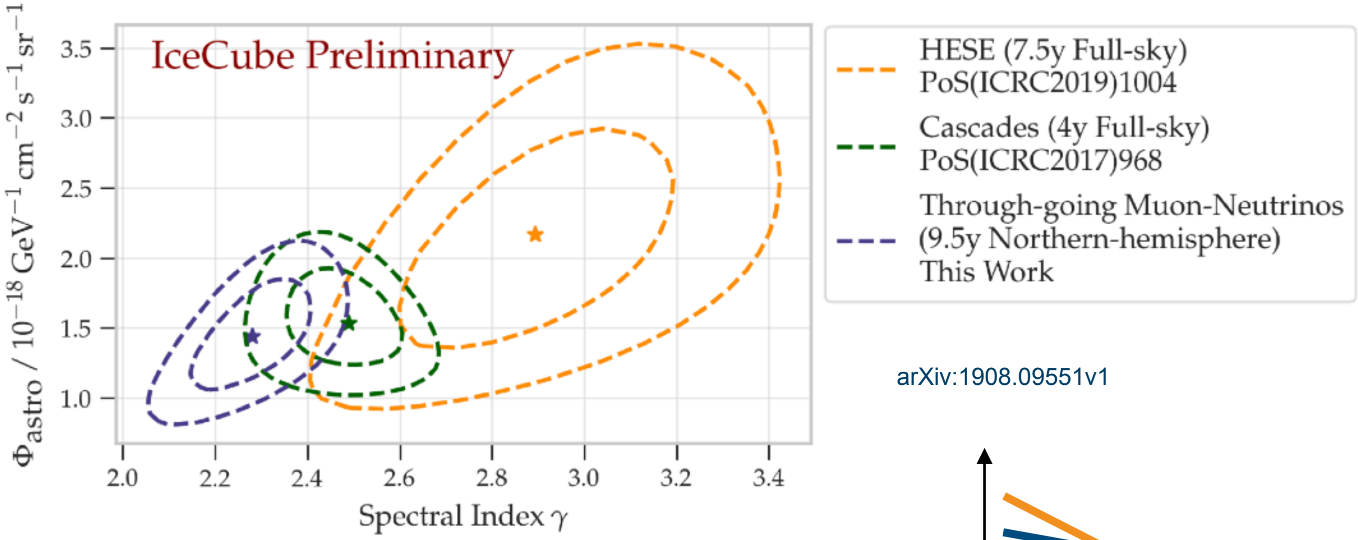


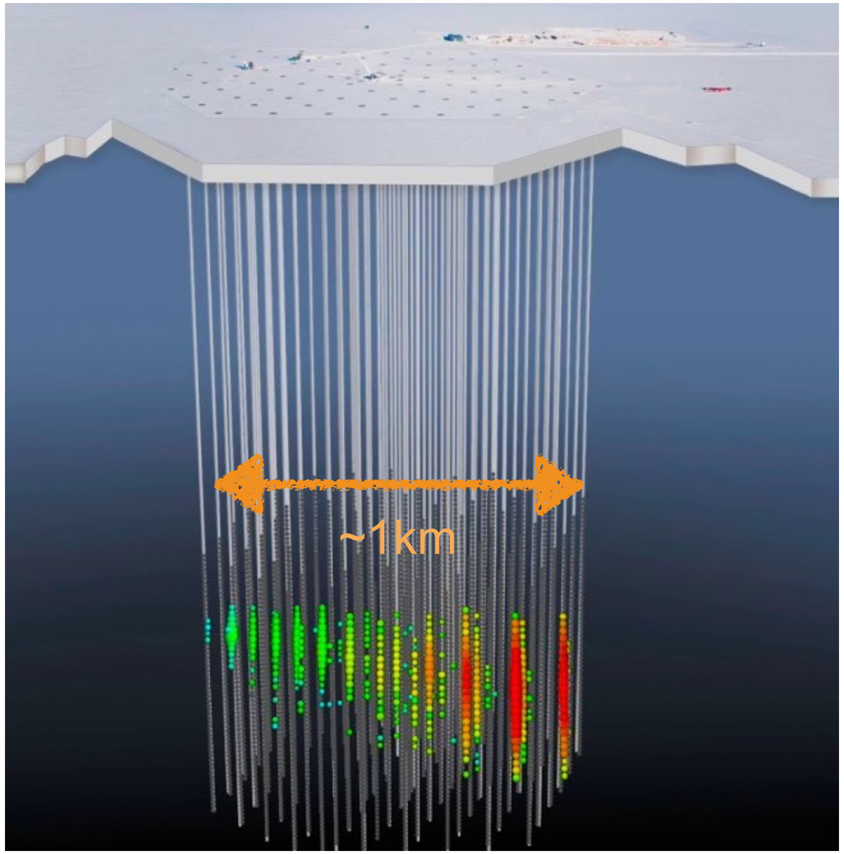

PDG 2019, “Cosmic rays”

# Astrophysical neutrinos

- IceCube has measured the presence of a diffuse astrophysical neutrino flux
- Flux present up to ~PeV energies, spectral index ~$E^{-2.5\ (-2\ldots-3)}$

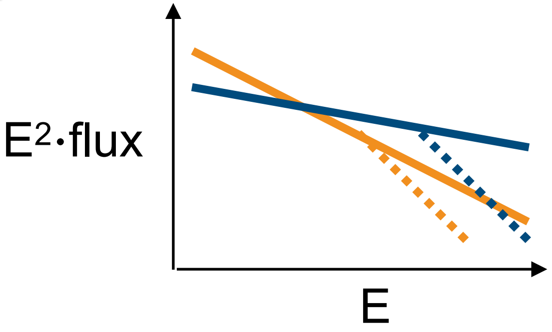



arXiv:1908.09551v1




IceCube/NSF

- Unclear: Continuation of the spectrum?



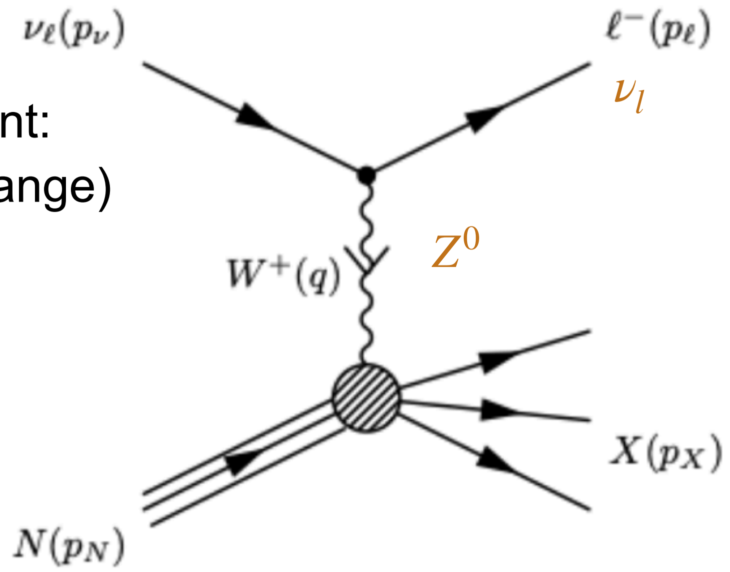

- (only) first likely point source candidates identified through multimessenger observations:
  Flaring blazars, Tidal distruption events

# Astrophysical neutrinos - Optical detection

- Optical Cherenkov detection method advanced; and successful !
- Several telescopes online: IceCube (ice), ANTARES, KM3NeT (sea), Baikal-GVD (lake),…

- Interactions:

charged current:
(via $W^{\pm}$ exchange)



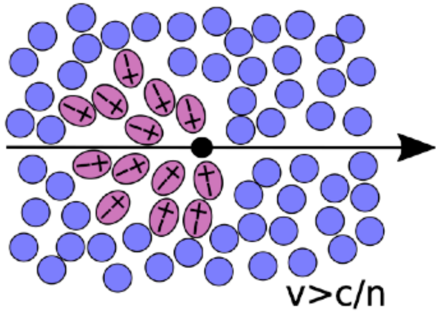

+ equivalent neutral current
(via $Z^0$ exchange)

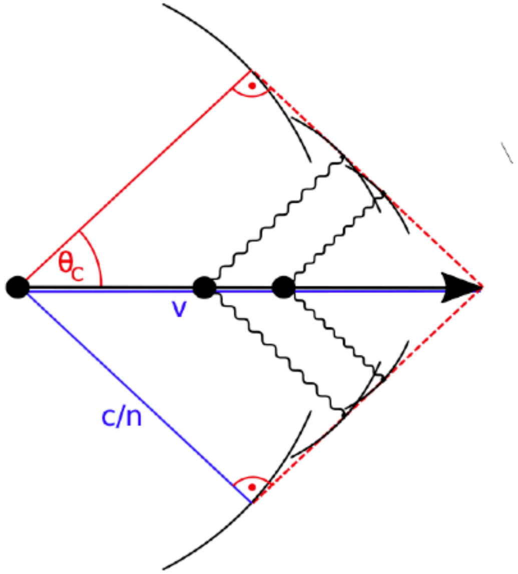
hadronic shower

Giunti, Kim, "Fundamentals of Neutrino Physics and Astrophysics"

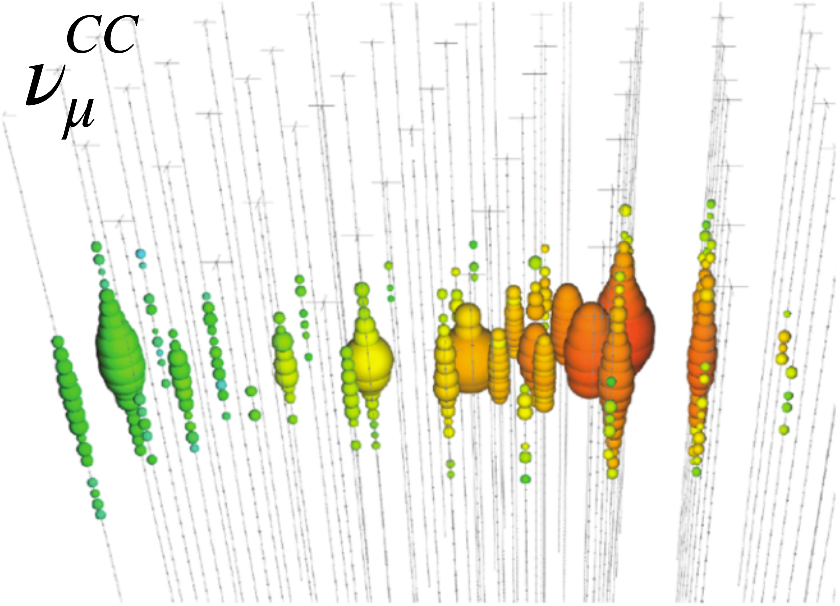
# Astrophysical neutrinos - Optical detection

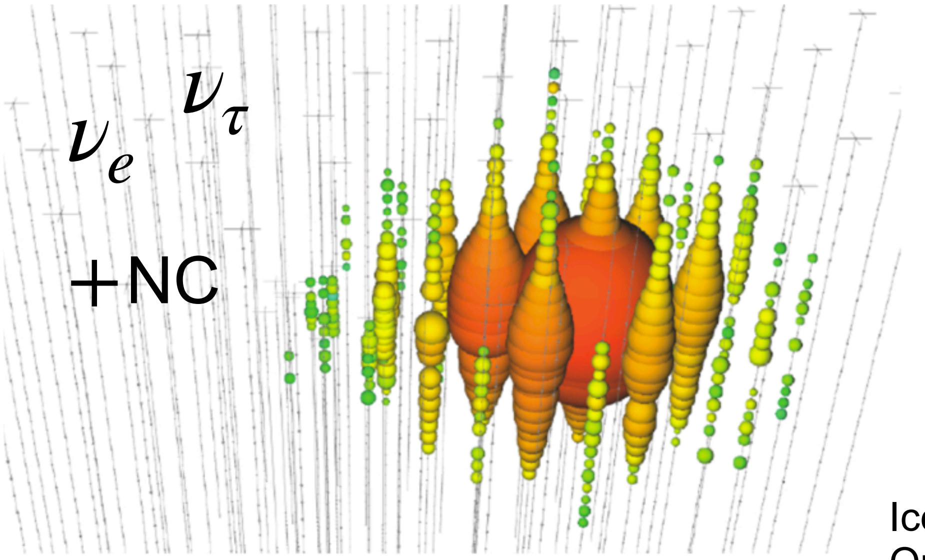
- Relativistic & charged particles induce visible Cherenkov light

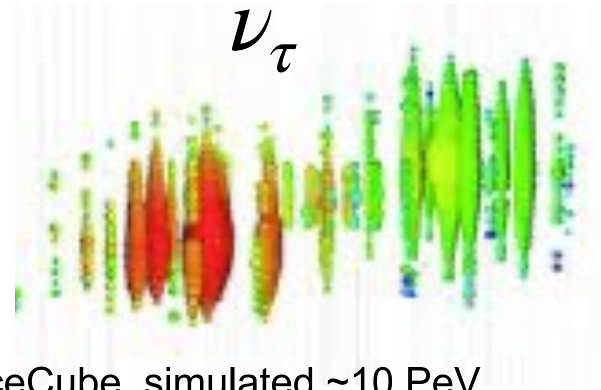



- Display of events detected in IceCube:



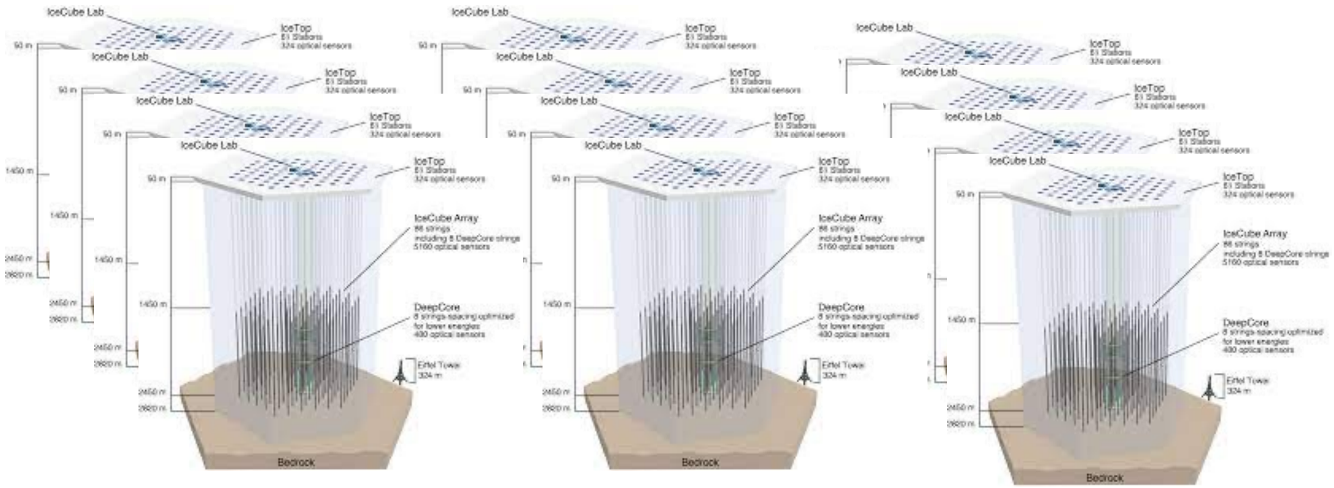




IceCube, simulated ~10 PeV
Or KM3NeT: http://www.cherenkov.nl

# Astrophysical neutrinos - Optical detection

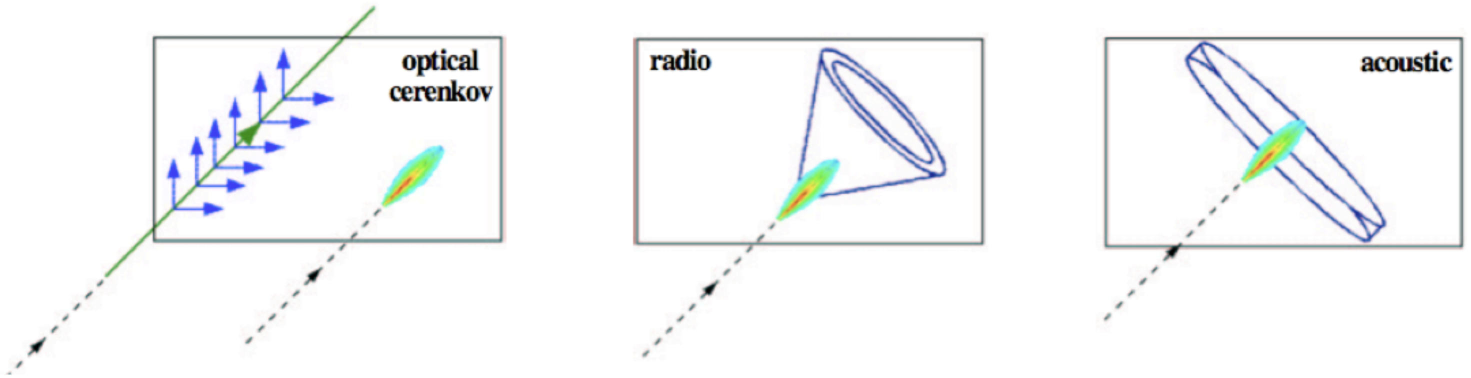
But: Visible light has ~50-100m attenuation length in ice/water




Scaling the ice/water Cherenkov technology to measure cosmogenic neutrinos is not cost-effective

Are there other options?

# Detection methods for UHE neutrinos




| | Optical Cherenkov | Radio | Acoustic |
|---|---|---|---|
| **Medium** | Ice / water | Ice / air / (salt / moon) | Water / (ice / salt) |
| **Threshold energy** | ~1 GeV | ~10 PeV | ~$10^4$ PeV |
| **Energy dependence** | $\propto E_\mu$ ; $\propto E_{\text{cascade}}$ | $\propto E_\nu^2$ | $\propto E_\nu^2$ |
| **Effective volume** | $\propto E_\nu$ ; $\sim$ fixed | $\propto E_\nu^3$ | $\propto E_\nu^{2...3}$ |
| **Signal attenuation length** | ~50-100m | ~1km | ~10km |

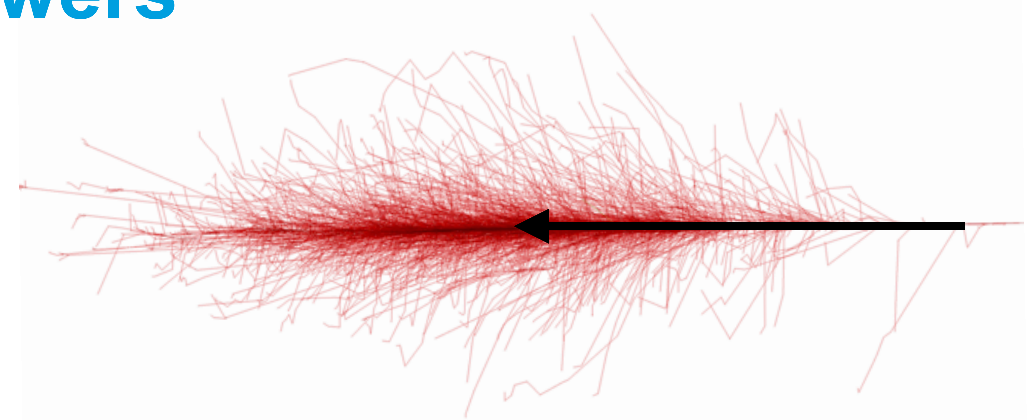
# Radio neutrino detection: Askaryan emission

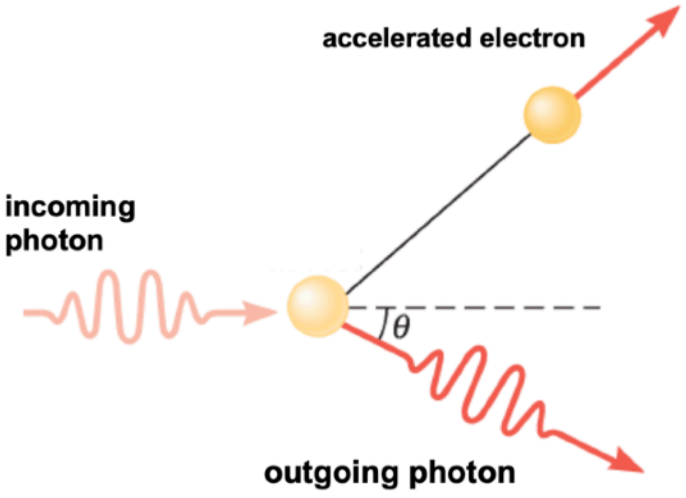
# Current/Planned detectors

# Radio emission from particle showers

## Askaryan

- Many high energy $\gamma$, $e^-$, $e^+$ in a shower
- In the medium (ice/air): only electrons
- shower particles interact with particles in the ice/air






+ positrons may annihilate

Figures credit: H. Schoorlemmer and K. D. de Vries

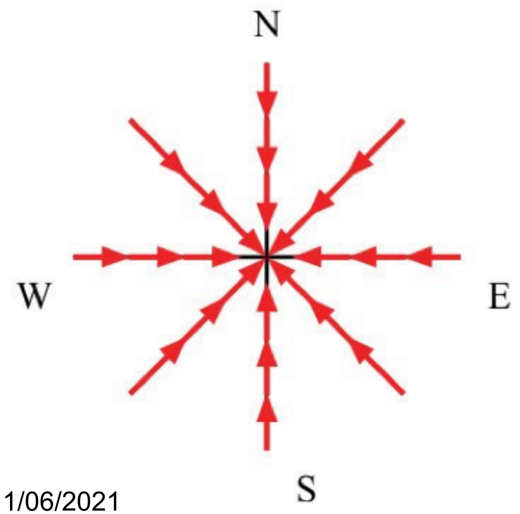
# Radio emission from particle showers

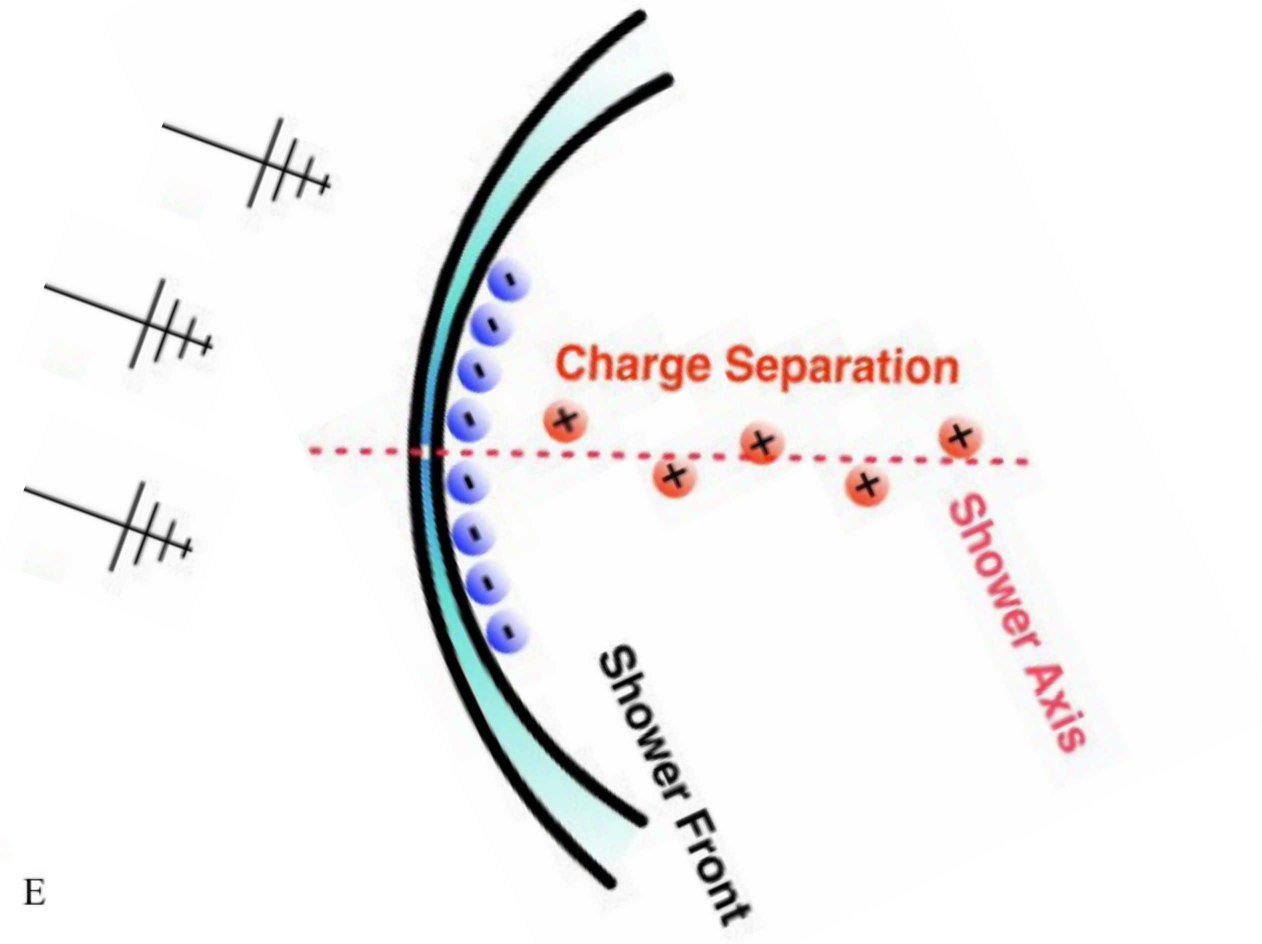
## Askaryan

- Time varying negative charge excess (~20%)

- Radio emission in MHz — GHz range
- Constructive interference @ Cherenkov angle

- Polarised towards shower axis



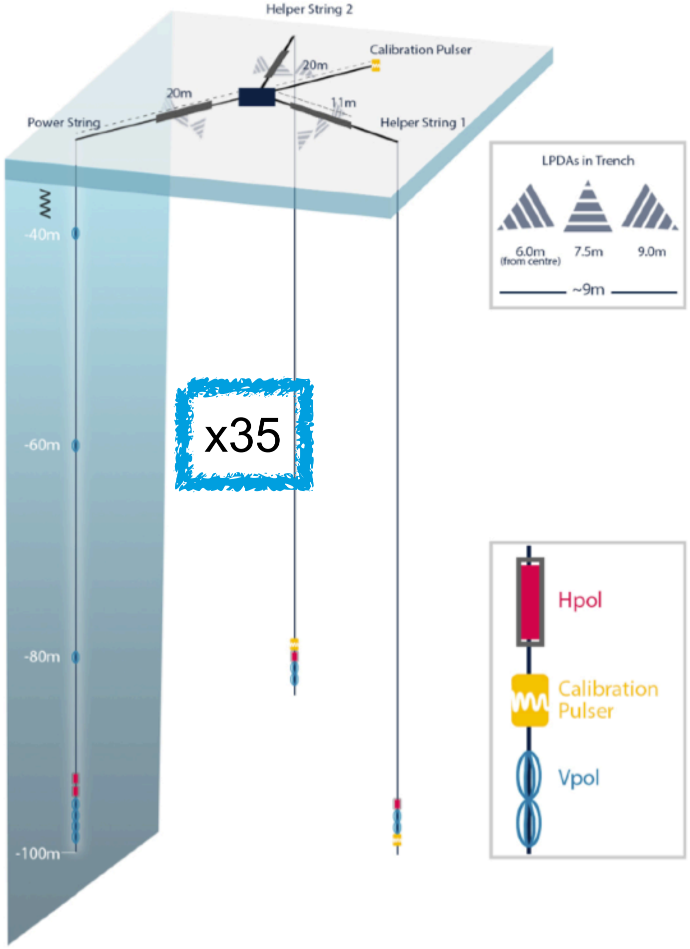

Figures credit: H. Schoorlemmer and K. D. de Vries

# Radio detection of UHE neutrinos in ice

- Radio attenuation length in ice: few km
- Radio-quiet environment: Antarctica, Greenland

- **No neutrinos detected yet**
- But: ultra-high energy cosmic-ray air showers detected regularly

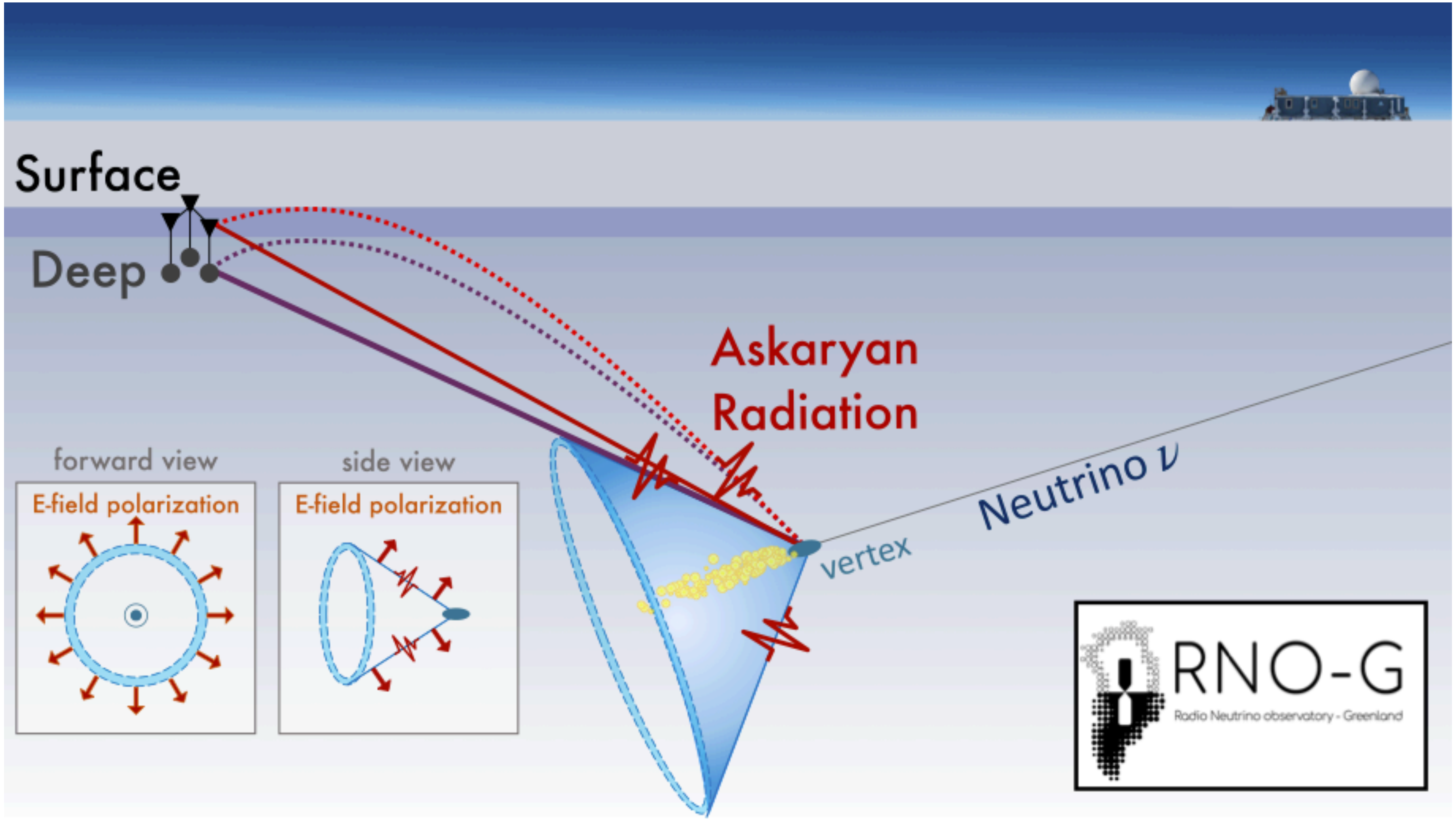
- in ice:
  - operational: ARA, ARIANNA
  - **under construction: RNO-G** ~50km$^2$
  - future: IceCube-Gen2 Radio ~500km$^2$




*JINST* 16 (2021) 03, P03025

*Credit: Uzair Latif*

# Askaryan detection methods: “in-ice”




*JINST* 16 (2021) 03, P03025

# Detection methods: Balloon

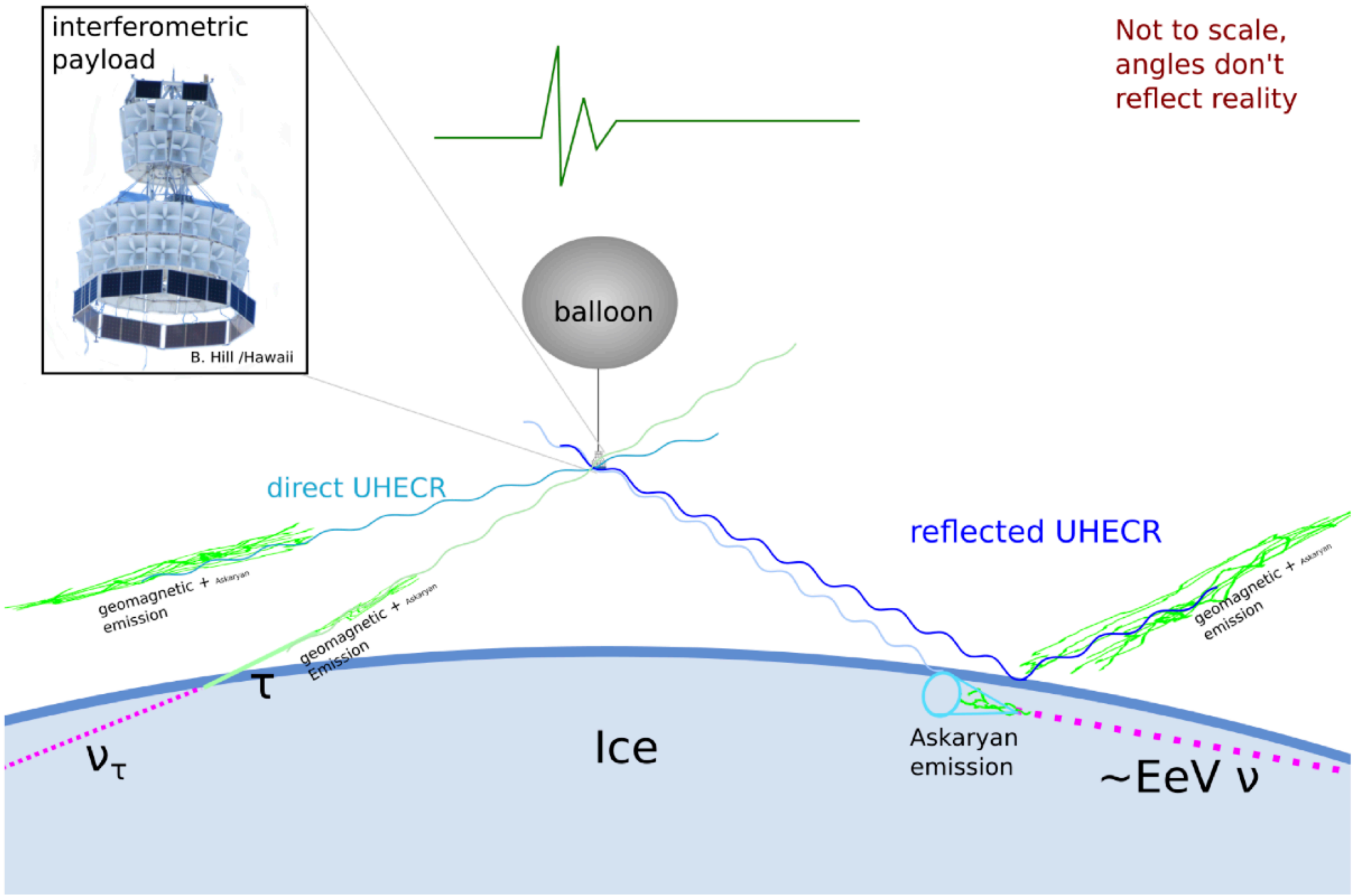
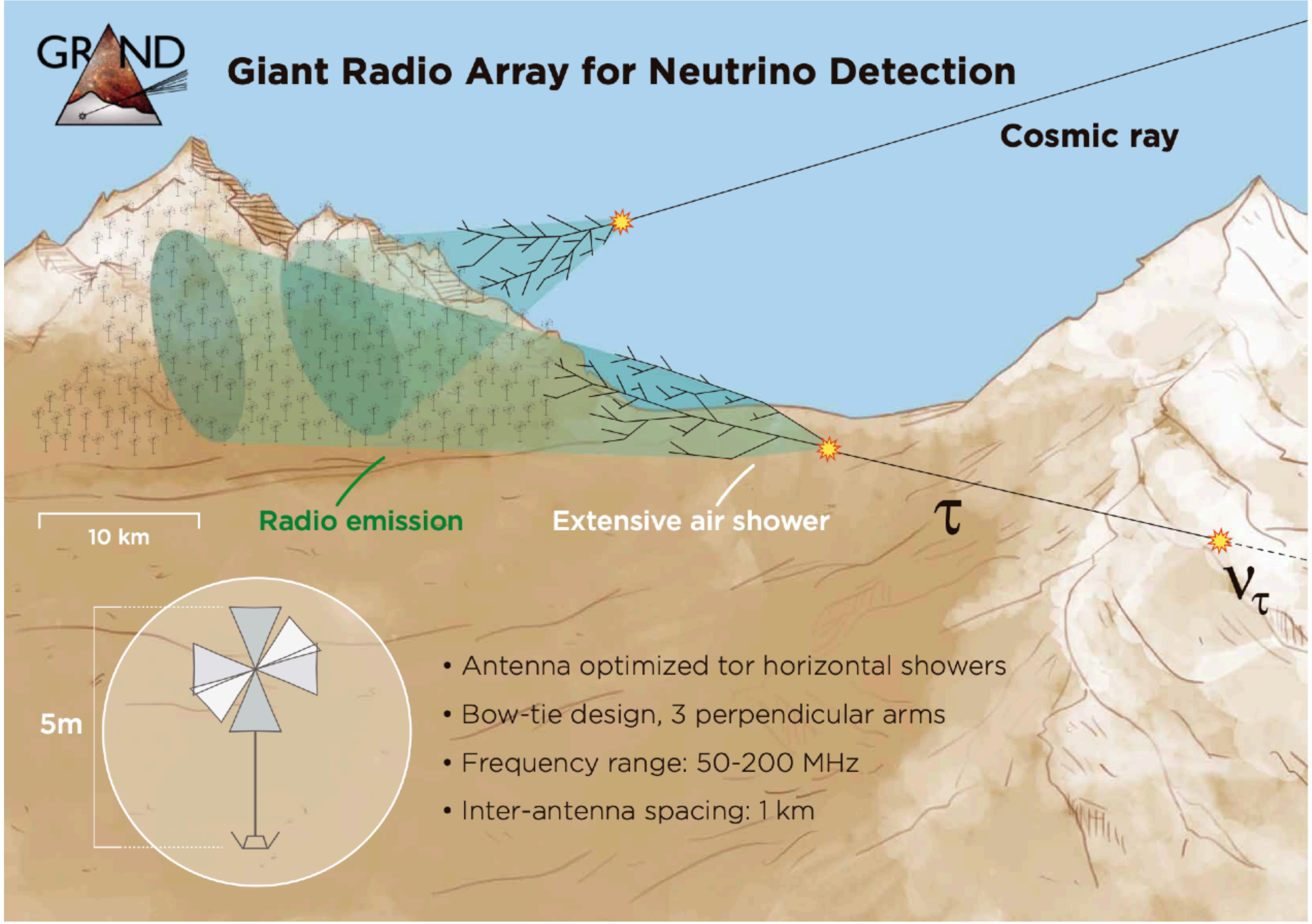



Image credits: Cosmin Deaconu

ANITA IV (Wikipedia Image)

# Detection methods: GRAND surface array

Plan to instrument large mountain areas with antennas



a) How does the $\nu N$ cross section behave at UHE?

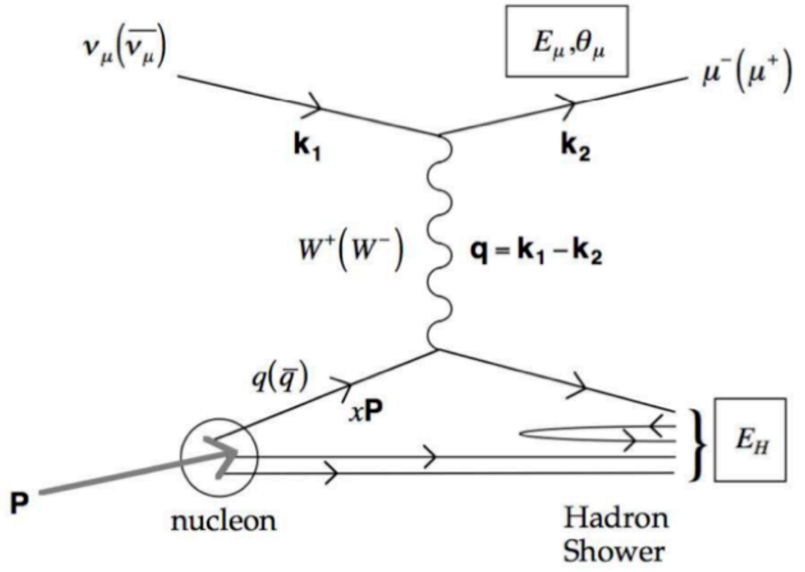
b) Can we distinguish neutrino flavours at UHE?

We need this to think about:
How can new physics show up in a) or b)?

Formaggio, Zeller, *Rev.Mod.Phys.* 84 (2012) 1307-1341

# Deep inelastic scattering

Neutrinos only interact weakly!




$$s = (p_\nu + P)^2 \quad \text{(center of mass energy)}$$

$$Q^2 = -q^2 = (p_\nu - k_\mu)^2 \quad (4 - \text{momentum transfer})$$

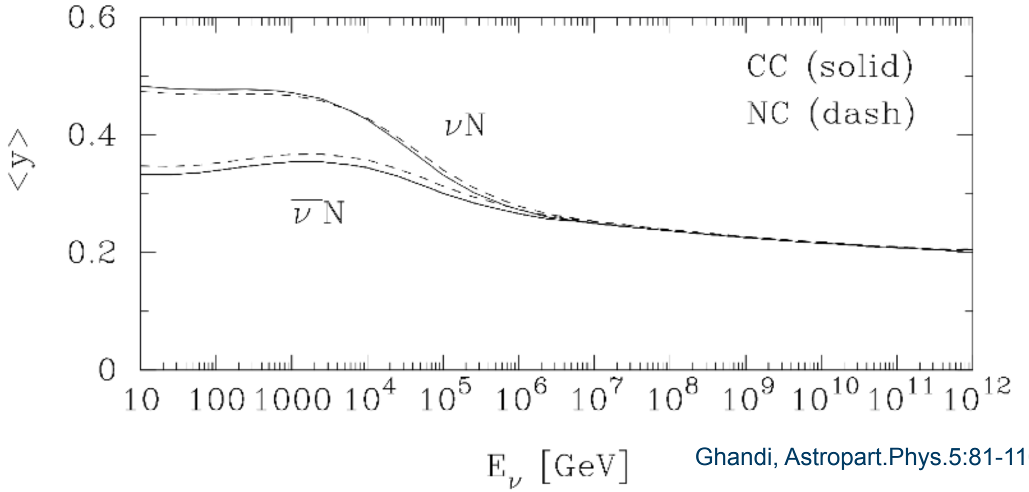
$$x = \frac{Q^2}{2P \cdot q} \quad \text{(Bjorken scaling variable)}$$

Target portion of struck nucleus

$$y = \frac{P \cdot q}{P \cdot p_\nu} \quad \text{(inelasticity)}$$

Fraction of energy going into hadron shower

$$\langle y \rangle \approx 20\,\%$$

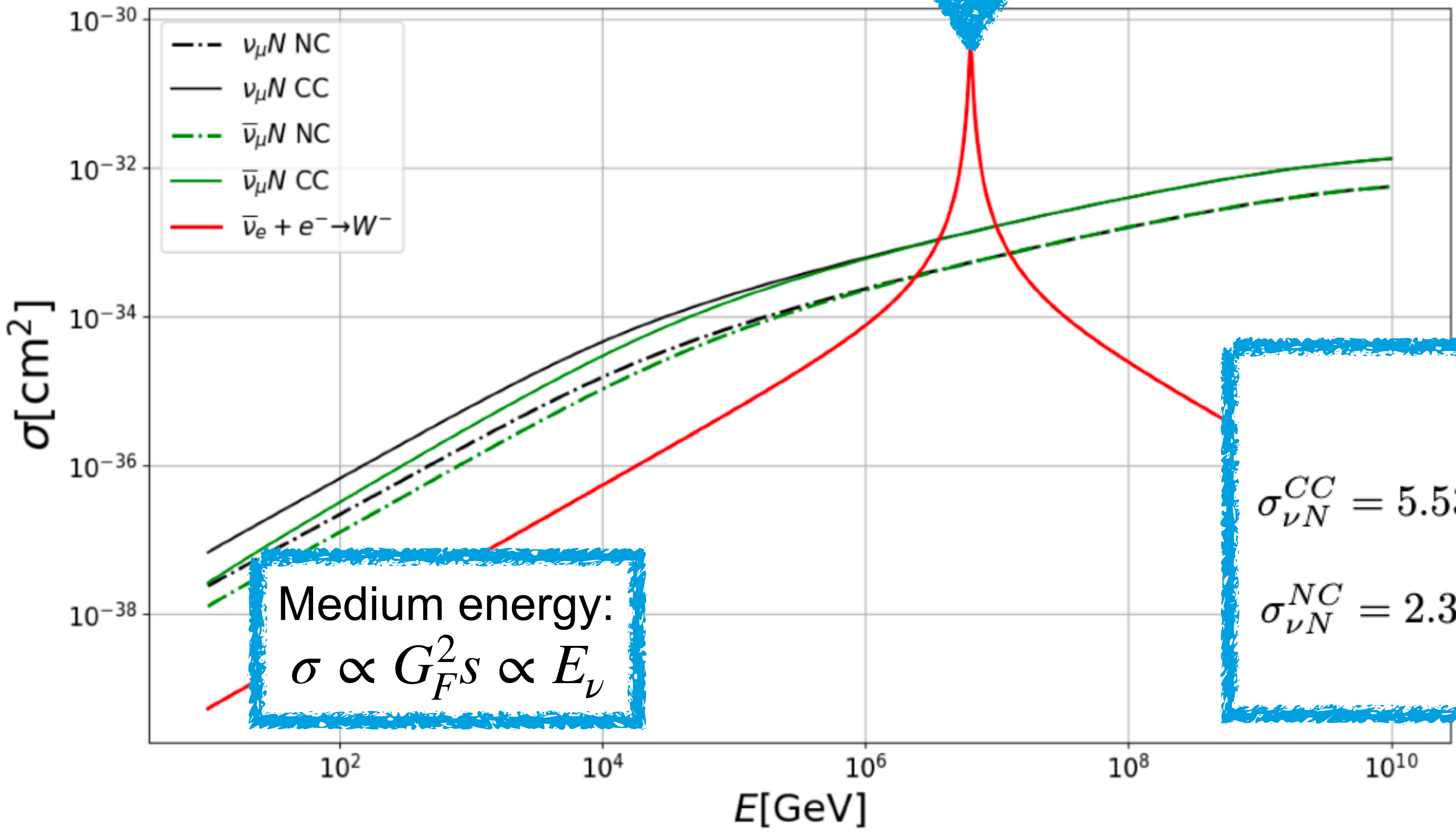



Ghandi, Astropart.Phys.5:81-110,1996

# Neutrino cross section

Glashow resonance

Symmetry **2021**, 13(3), 377




Medium energy:

$$\sigma \propto G_F^2 s \propto E_\nu$$

UHE:

$$\alpha \simeq 0.363$$

$$\sigma_{\nu N}^{CC} = 5.53 \times 10^{-36} \text{ cm}^2 \left(\frac{E_\nu}{1 \text{ GeV}}\right)^\alpha,$$

$$\sigma_{\nu N}^{NC} = 2.31 \times 10^{-36} \text{ cm}^2 \left(\frac{E_\nu}{1 \text{ GeV}}\right)^\alpha,$$

Ghandi, Astropart.Phys.5:81-110,1996

Cross section features at UHE:

- ~identical for $\overline{\nu}$ and $\nu$
- no longer grows linearly with energy

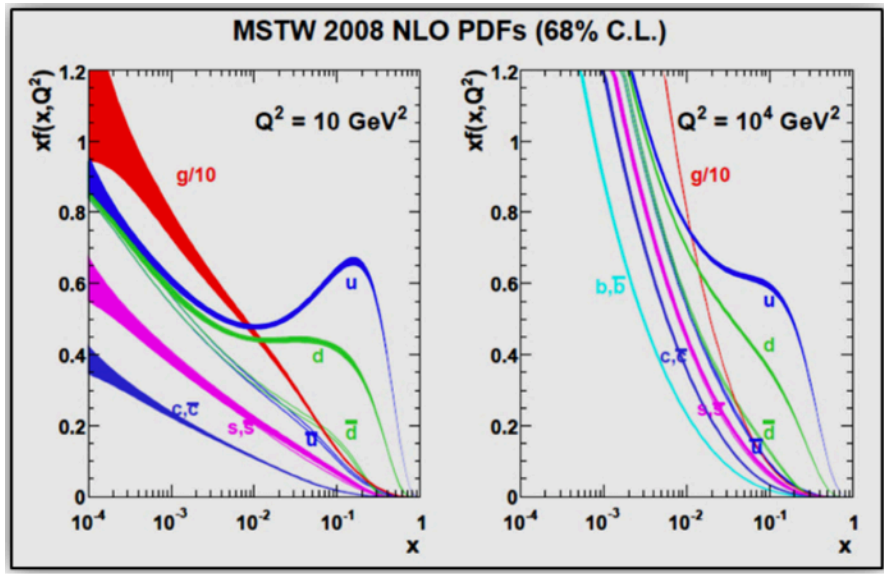
# Neutrino - nucleon cross section

$$\frac{d^2\sigma}{dxdy} = \frac{2G_F^2 M E_\nu}{\pi}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2\left[xq(x,Q^2) + x\bar{q}(x,Q^2)(1-y)^2\right]$$

W boson propagator

Quark distribution functions

$M_W \approx 80\,GeV$




@ medium energy: $\sigma \propto G_F^2 s \propto E_\nu$

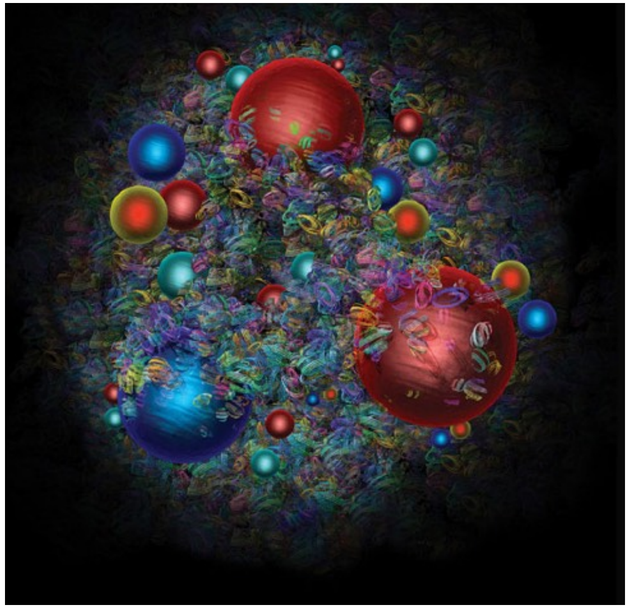
@ High energy:

- Propagation term no longer dominated by W mass

$$Q^2 \rightarrow M_W^2$$

$$x_{\min} = M_W^2/2m_N E_\nu$$

- Interaction with "sea": $(1-y)^2$ suppression less pronounced

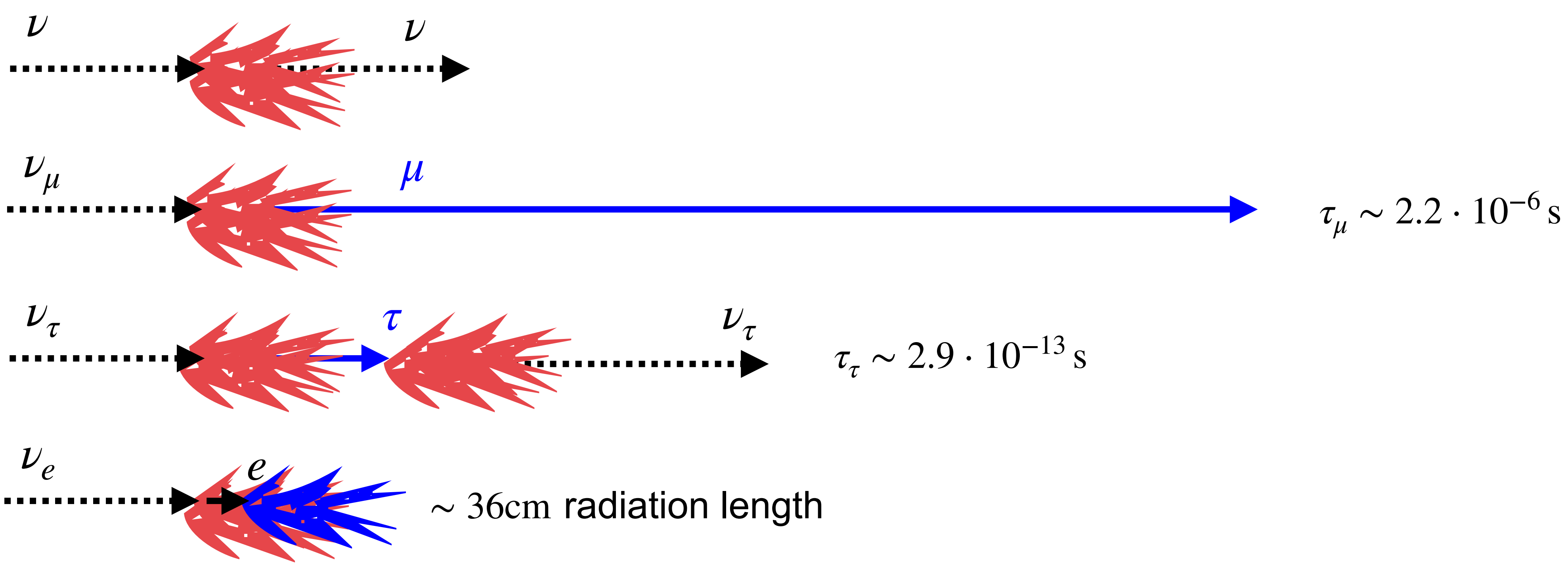


DANIEL DOMINGUEZ/CERN

Formaggio, Zeller, *Rev.Mod.Phys.* 84 (2012) 1307-1341

# Event signatures in neutrino telescopes

- Showers, tracks, and “double bangs” have all been observed in optical Cherenkov telescopes




- Differences in the signatures need to be exploited to get flavour sensitivity

Additional signatures at UHE?

# Muon energy loss

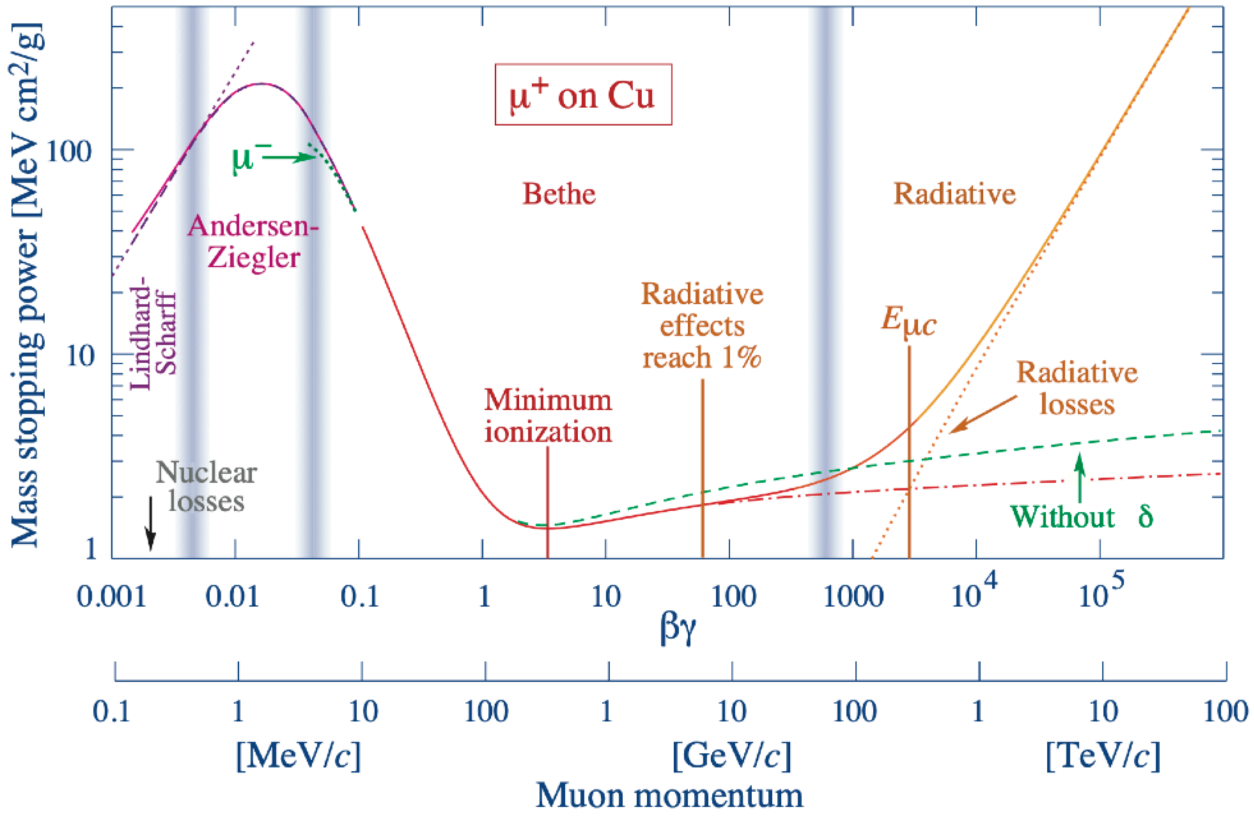
- Muon: long lifetime $\tau_\mu \sim 2.2\,\mu s$

- Optical Cherenkov detectors:

  long muon track with continuous energy loss during propagation

  + additional **radiative** losses from
    - **pair production**
    - **bremsstrahlung**
    - (nuclear interactions)

PDG 2019

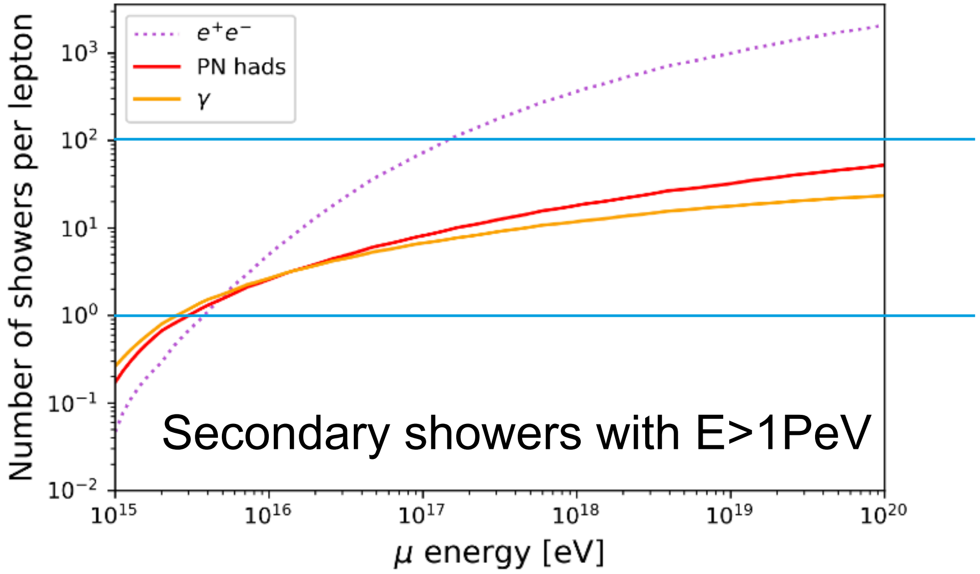



- At UHE: muons and taus at some point will also produce secondary showers which become visible in also in radio detectors

# Secondary radio showers in from muons and taus

Recall: <y>~0.2, i.e. 80% of energy transferred to the muon/tau

García-Fernández et al, Phys. Rev. D 102, 083011 (2020)




100

On average 1 secondary shower that might be visible in radio

Similar for tau: several >PeV showers at UHE possible
+ showers from tau decay
+ unique radio signal: tau might reach the atmosphere and decay

# Landau-Pomeranchuk-Migdal (LPM) effect

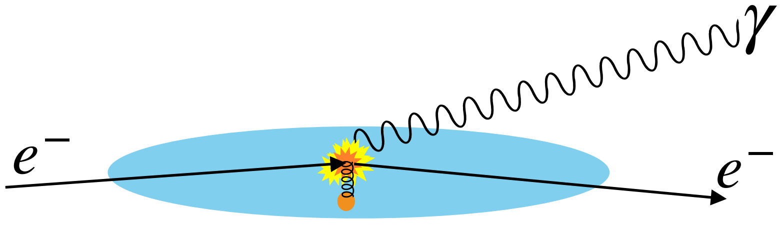
- Bremsstrahlung:
  Longitudinal momentum transfer to a given scattering center is small (~k/E(E-k))

- **Uncertainty principle:**
  Interaction is spread over comparatively long distance, the formation length $L_f \sim$ E(E-k)/k

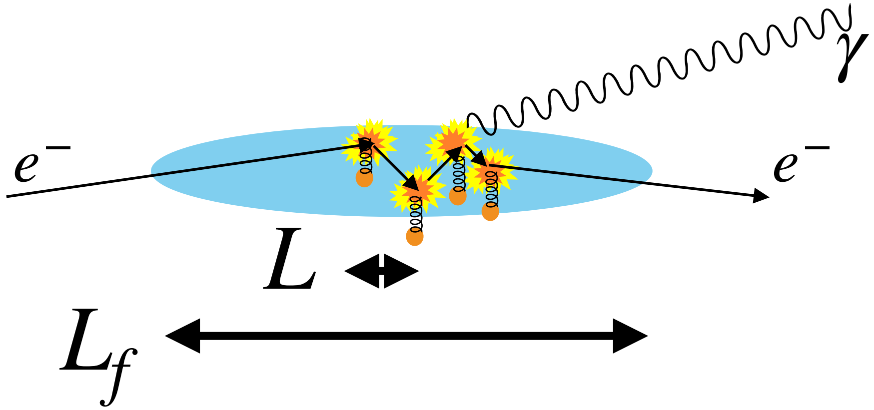
- $L \lesssim L_f$: quantum mechanical interference between amplitudes from different scattering centers

- Interference usually destructive

→ Decrease of cross-sections for bremsstrahlung & pair production at UHE (or high matter densities)

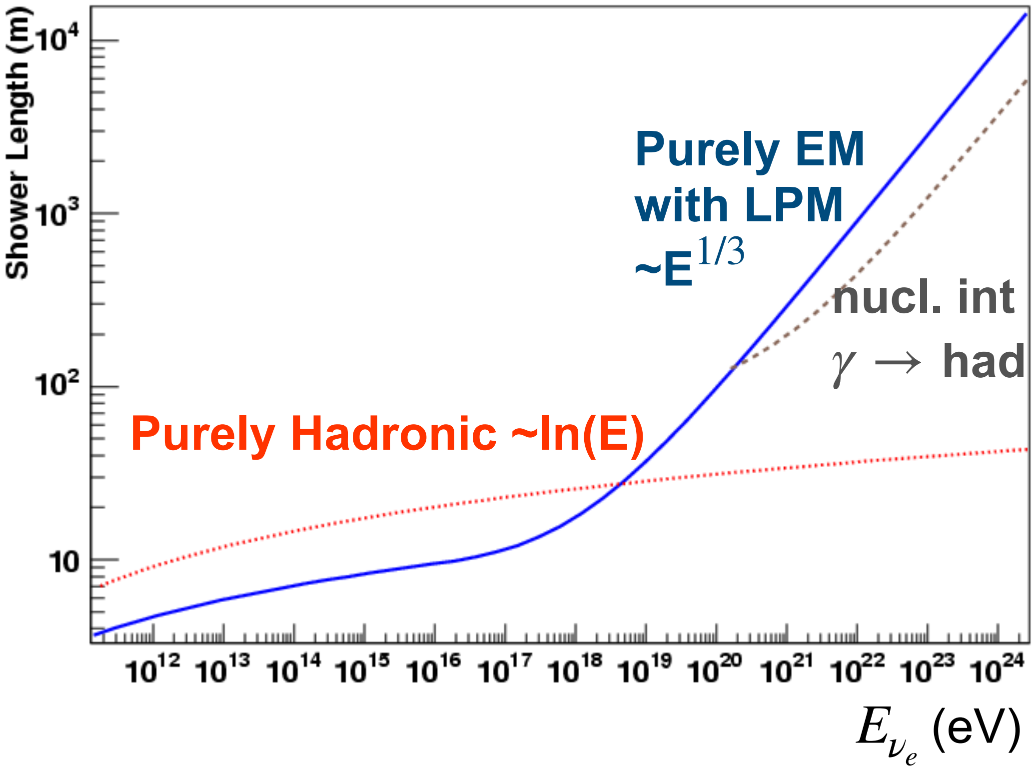



formation length $L_f$




1953: Lev Landau, Isaak Pomeranchuk
1956: Arkady Migdal: proper QM treatment

# Landau-Pomeranchuk-Migdal (LPM) effect

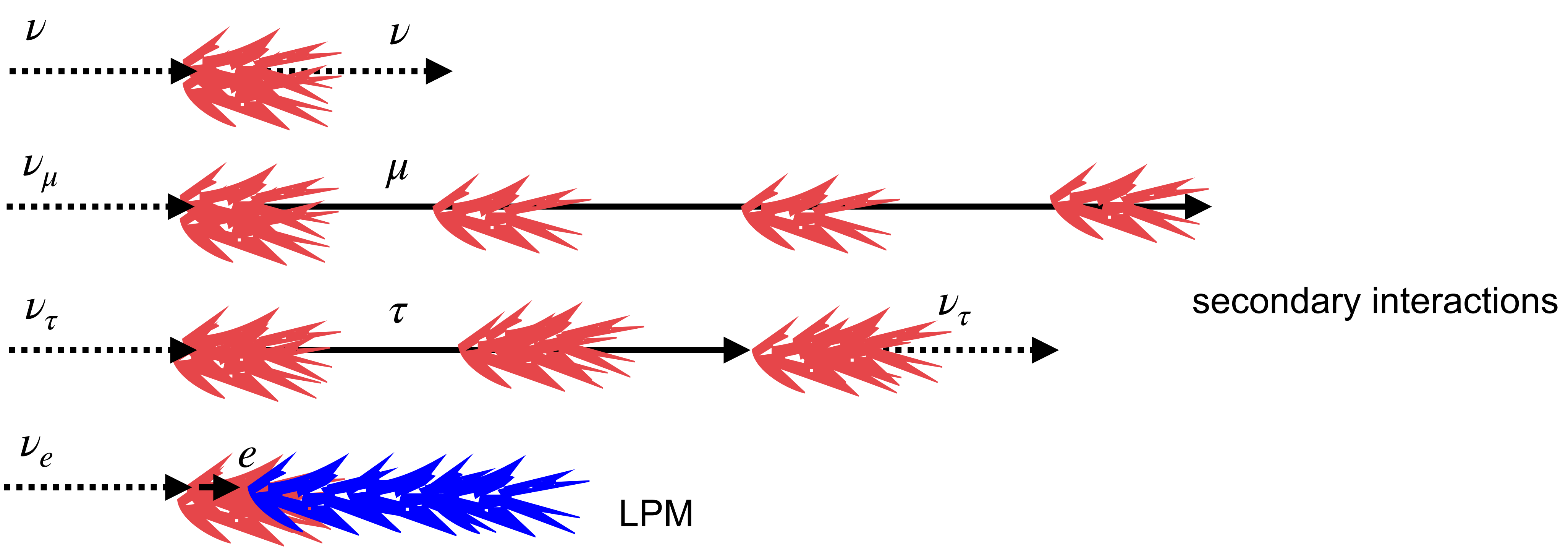



→ Longer, lower multiplicity showers

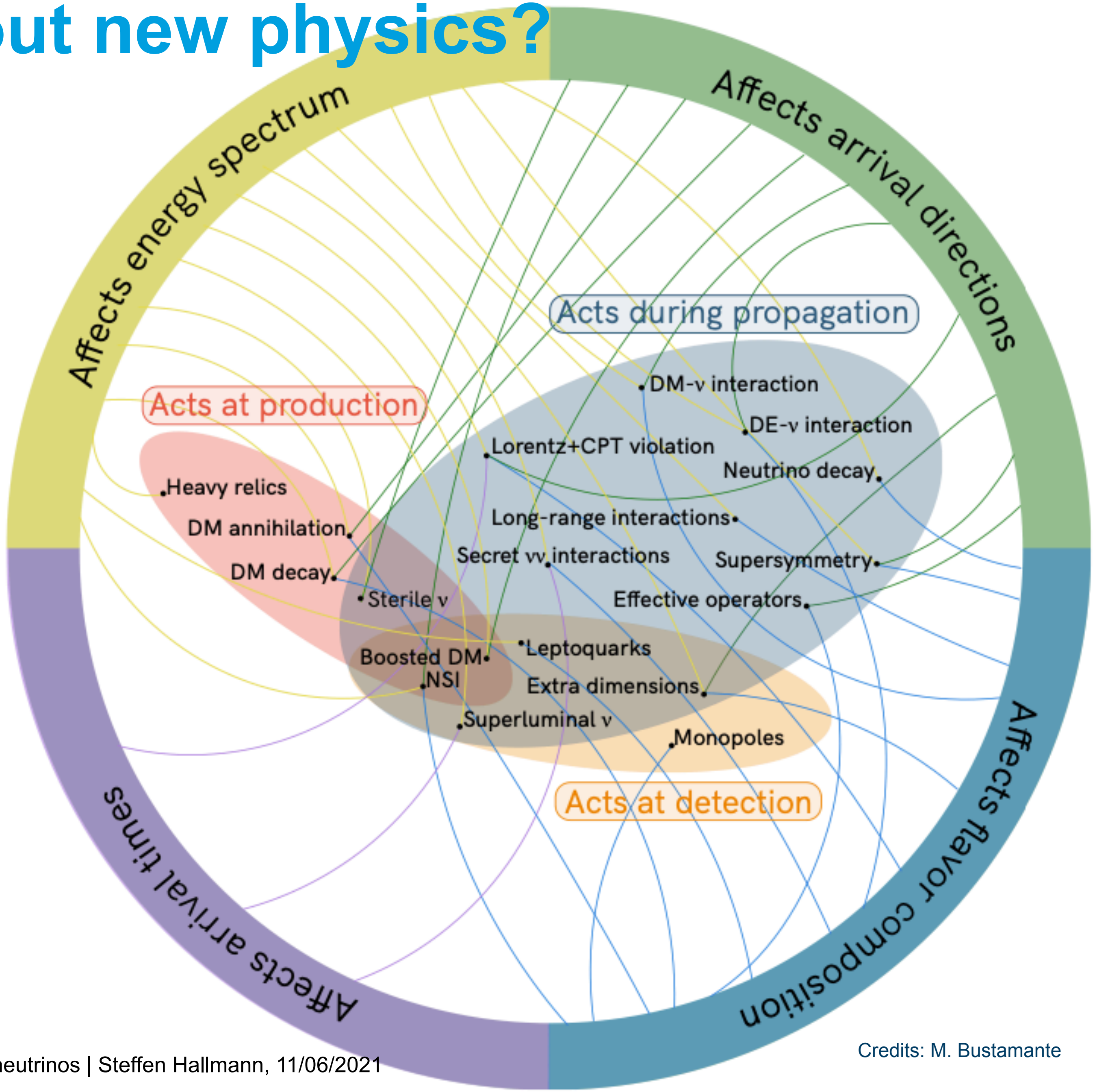
+ Bremsstrahlung:
  cross-section suppressed for low energy photons
+ Pair production:
  central part of differential cross-section suppressed
  (less likely produce e+ e- with similar energy)

→ Askaryan emission profile more peaked around the Cherenkov angle

# UHE event signatures in radio telescopes

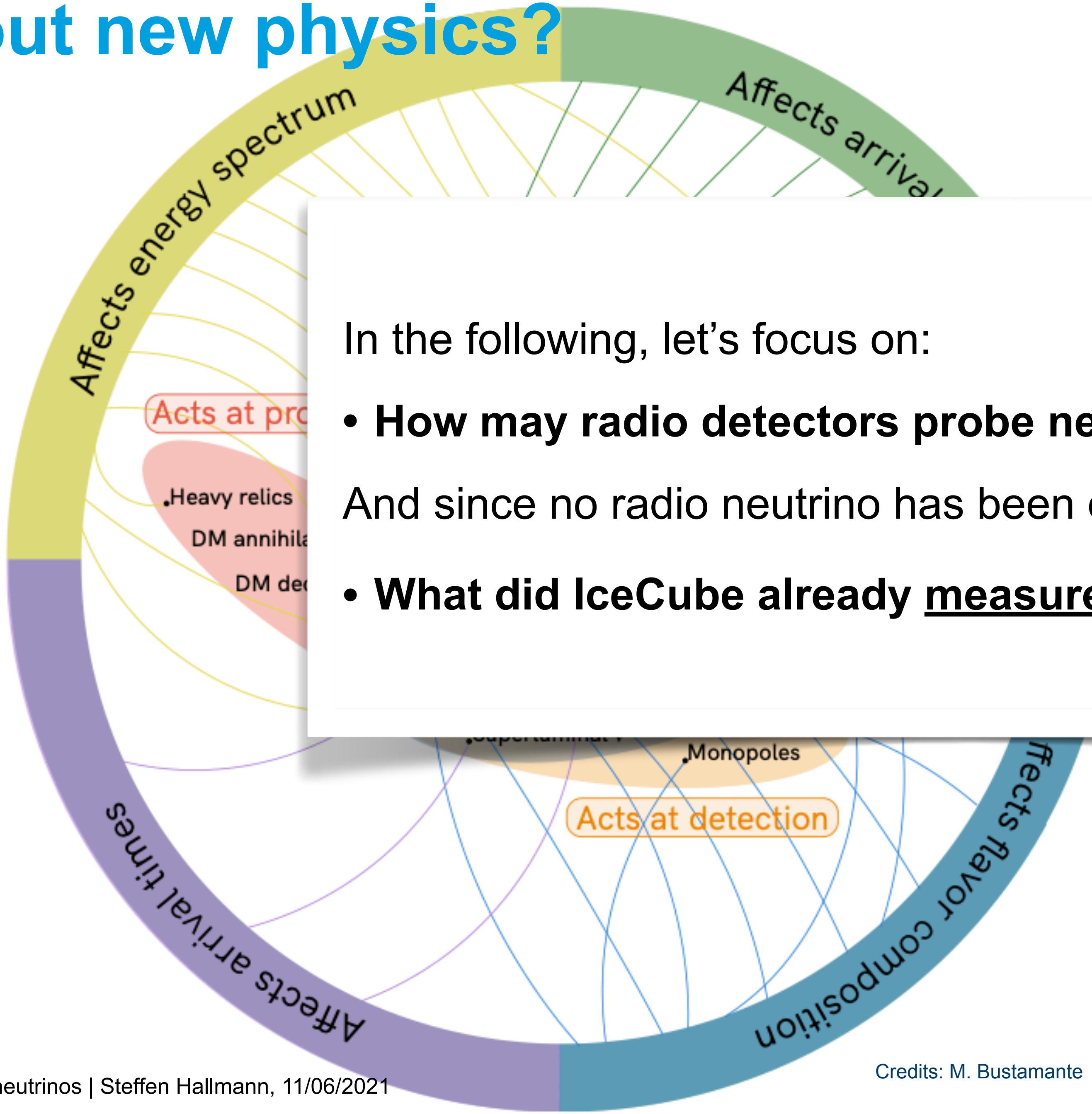


# What about new physics?




Credits: M. Bustamante

# What about new physics?




In the following, let's focus on:

- **How may radio detectors probe new physics at UHE?**

And since no radio neutrino has been detected yet:

- **What did IceCube already <u>measure</u> up to $\lesssim$ PeV?**

Credits: M. Bustamante

# New physics signatures

How does new physics affect cross sections?

Can new physics have unique event signatures?

Can new physics affect the $\nu$ flavour composition?

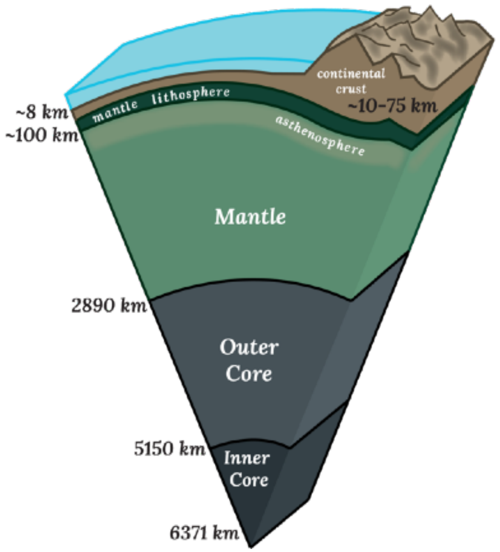
# New physics signatures

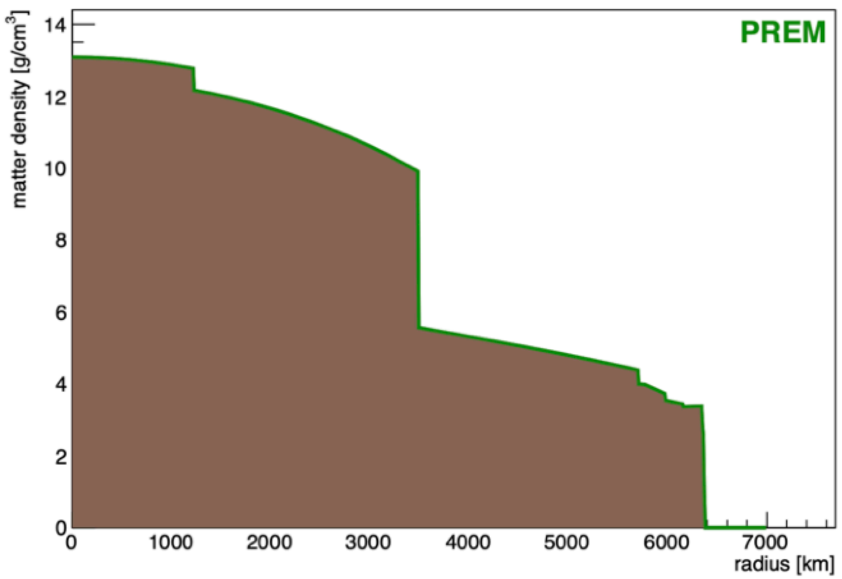
**How does new physics affect cross sections?**

Can new physics have unique event signatures?

Can new physics affect the $\nu$ flavour composition?

# Earth matter profile




A.M. Dziewonski, D.L. Anderson, "Preliminary Reference Earth Model" Phys.Earth Planet.Interiors 25 (1981) 297-356

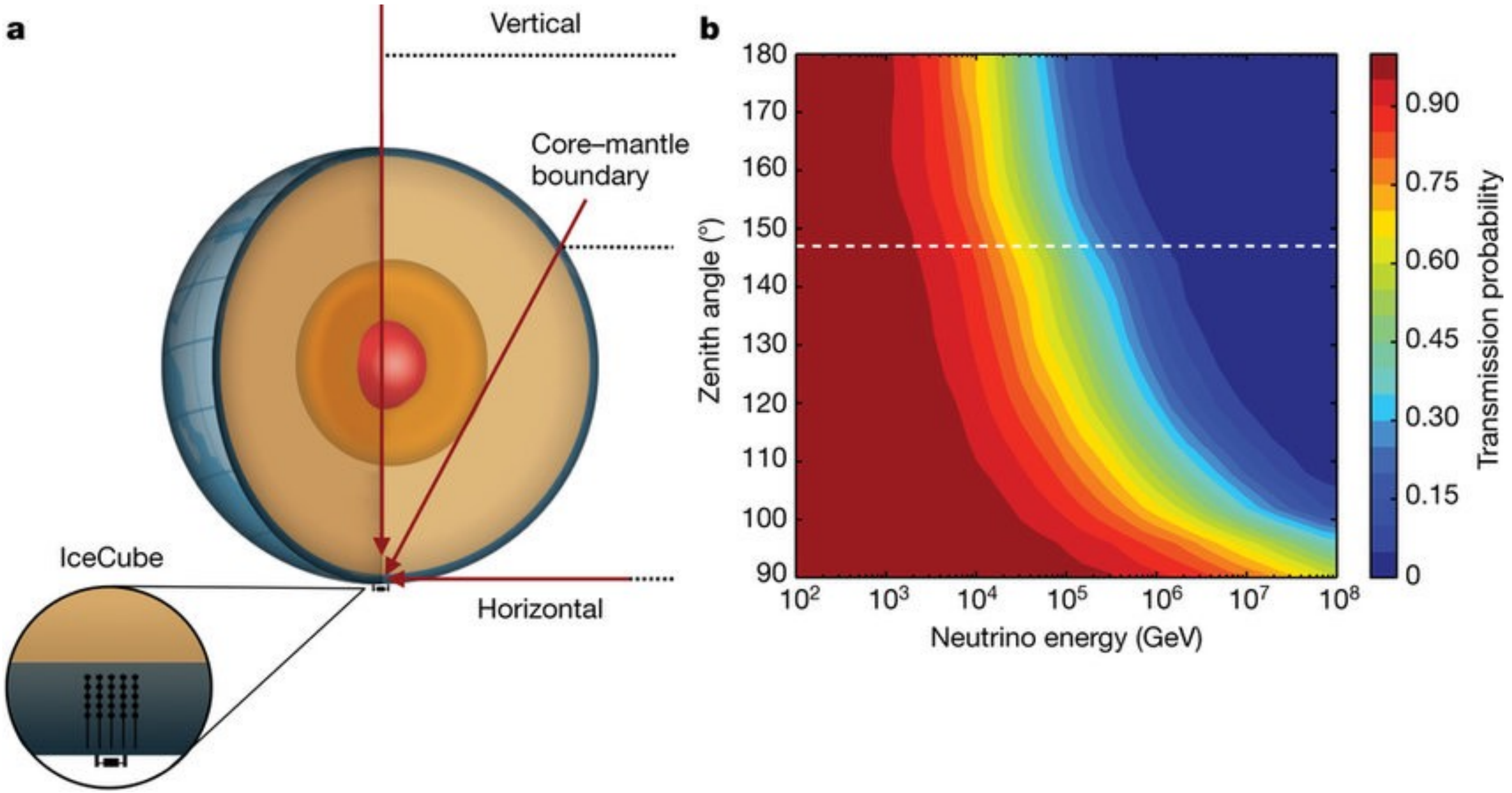
- Neutrino interaction length: $L_{int} = 1/(\rho_N \cdot \sigma)$, exponential attenuation: ~$e^{-d/L_{\rm int}}$
- Interaction length of neutrinos crossing the mantle?

$$m_N \approx 1.67 \times 10^{-24}\,\text{g}, \quad \rho \approx 3\,\text{g/cm}^3, \quad \sigma_{\nu N}(10^{18}\,\text{eV}) \approx 10^{-32}\,\text{cm}^2$$

A: 500 km

UHE neutrinos only arrive up to a couple of degrees below the horizon

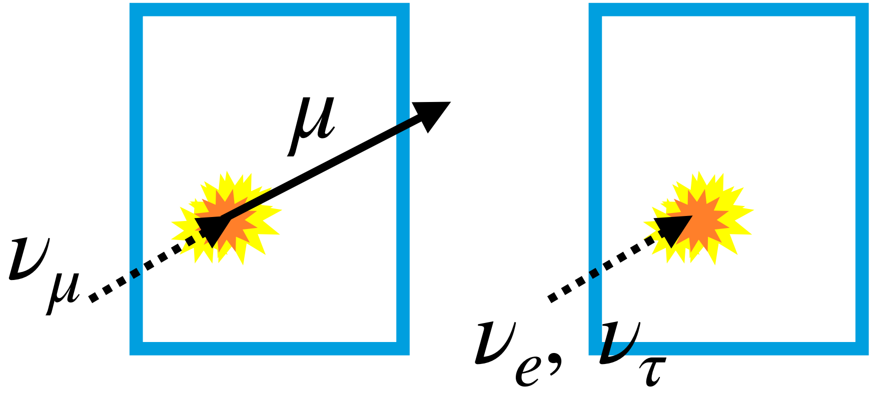
# Neutrino Earth absorption




→ Significant absorption above 10 TeV for neutrinos crossing the earth

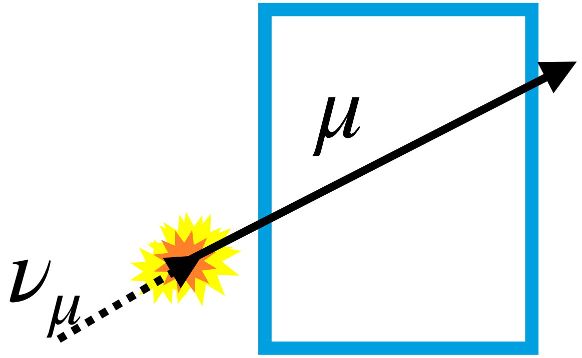
# Cross section measurements with IceCube:

Two approaches:




Interaction inside detector

Accurate measurement of $E_\nu$,
But: limited statistics (~100)




Interaction outside detector

Measure only $E_\mu \quad (< E_\nu)$,
But: High statistics (~$10^4$)

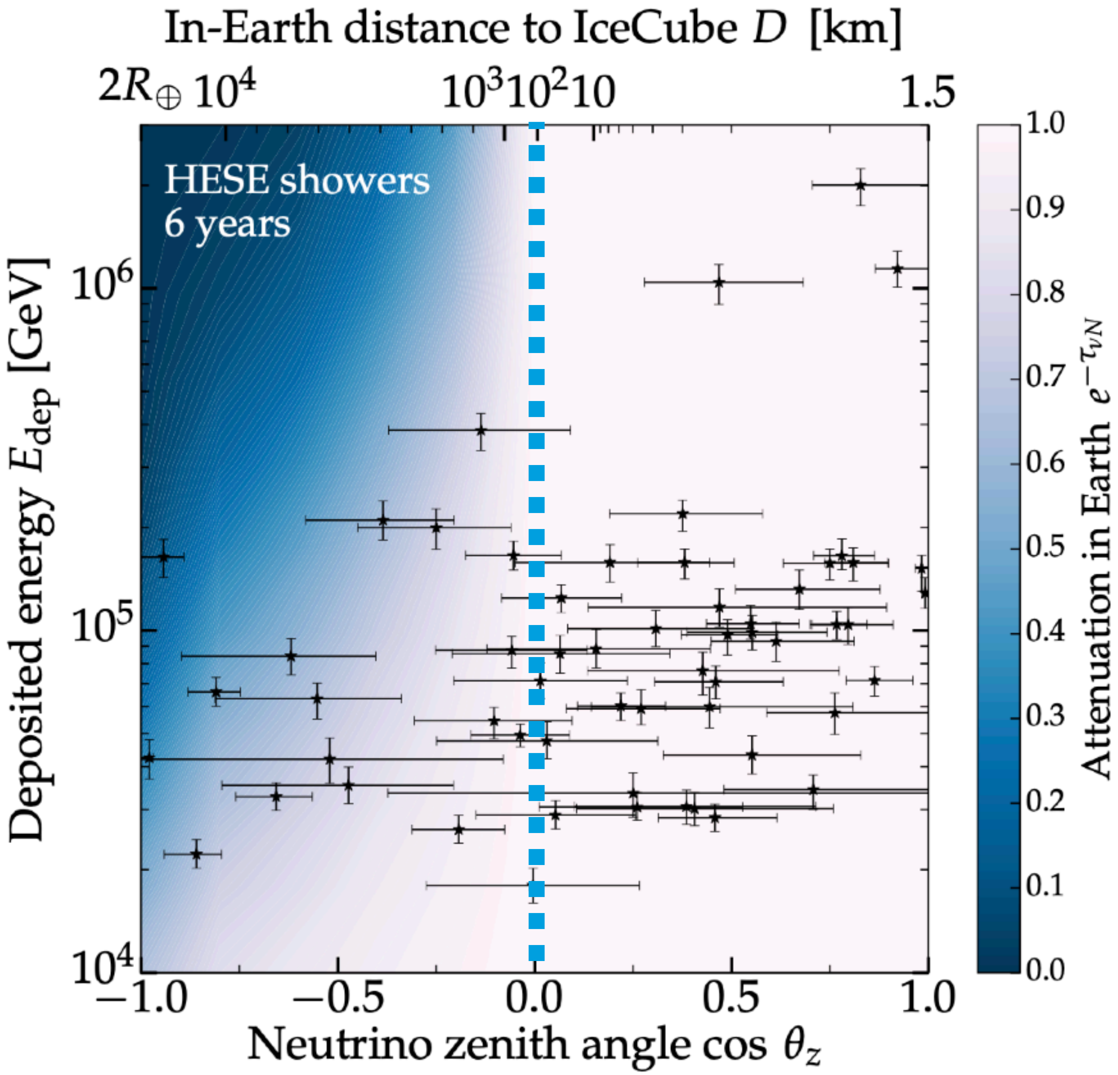
# IceCube cross section from "showers"

- Neutrinos from above are unabsorbed, constrain flux × cross-section

$$N_d \sim \Phi \cdot \sigma_{\nu N}$$

- Neutrinos crossing Earth feel absorption

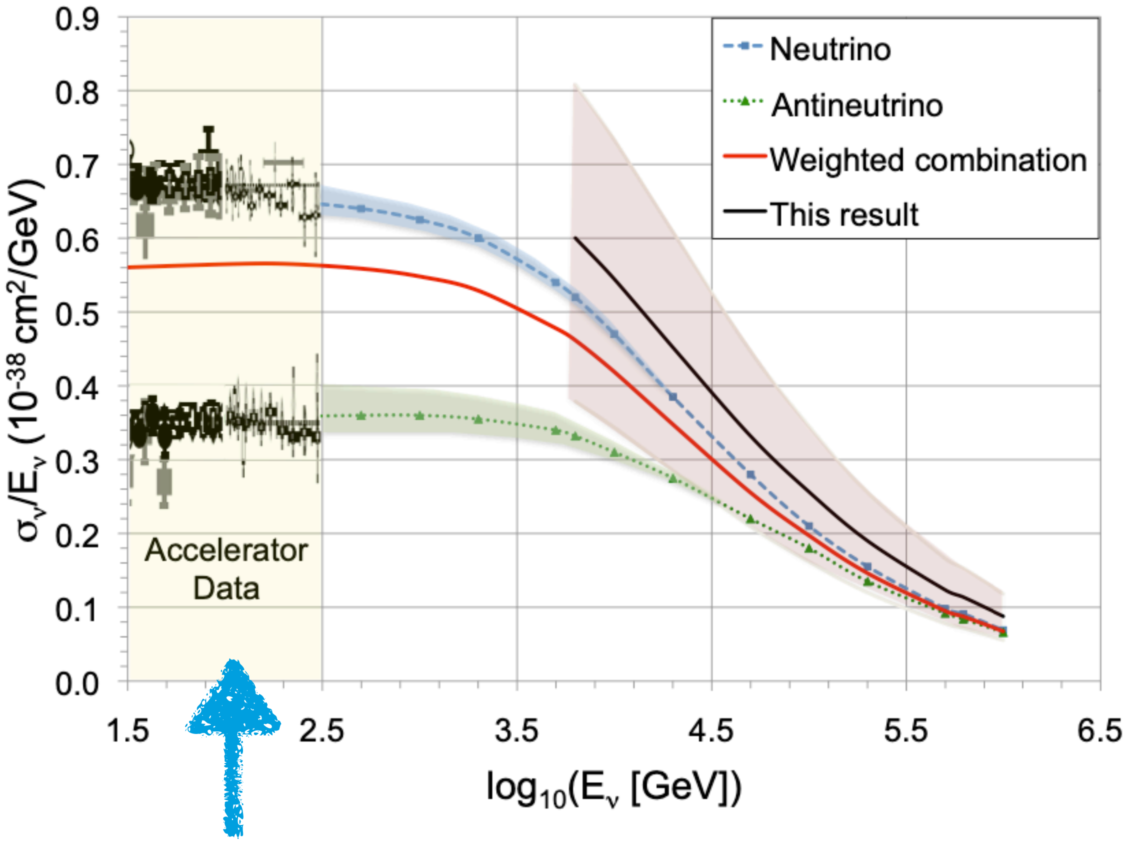
$$N_u \sim N_d \cdot e^{-\tau} \sim N_d \cdot e^{-L\sigma_{\nu N} n_N}$$



# IceCube cross section from "tracks"

IceCube, Nature 551 (2017) 596-600

- For tracks, statistics is much higher (~$10^4$),
- Need to derive probability density for $E_\nu$ from the measured $E_\mu$
- Fit cross section normalisation to the event distribution: ~1.3 , consistent with expectation



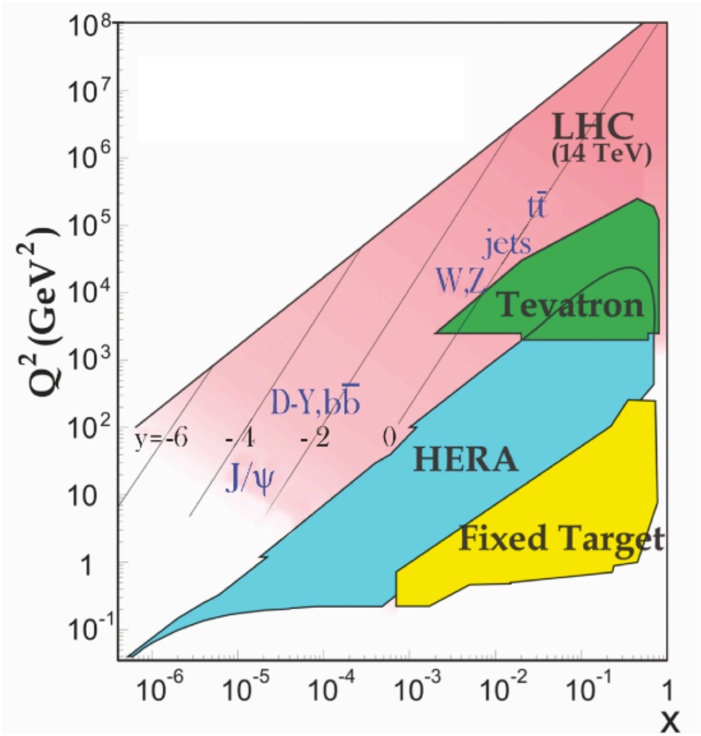

$\sigma \propto E$

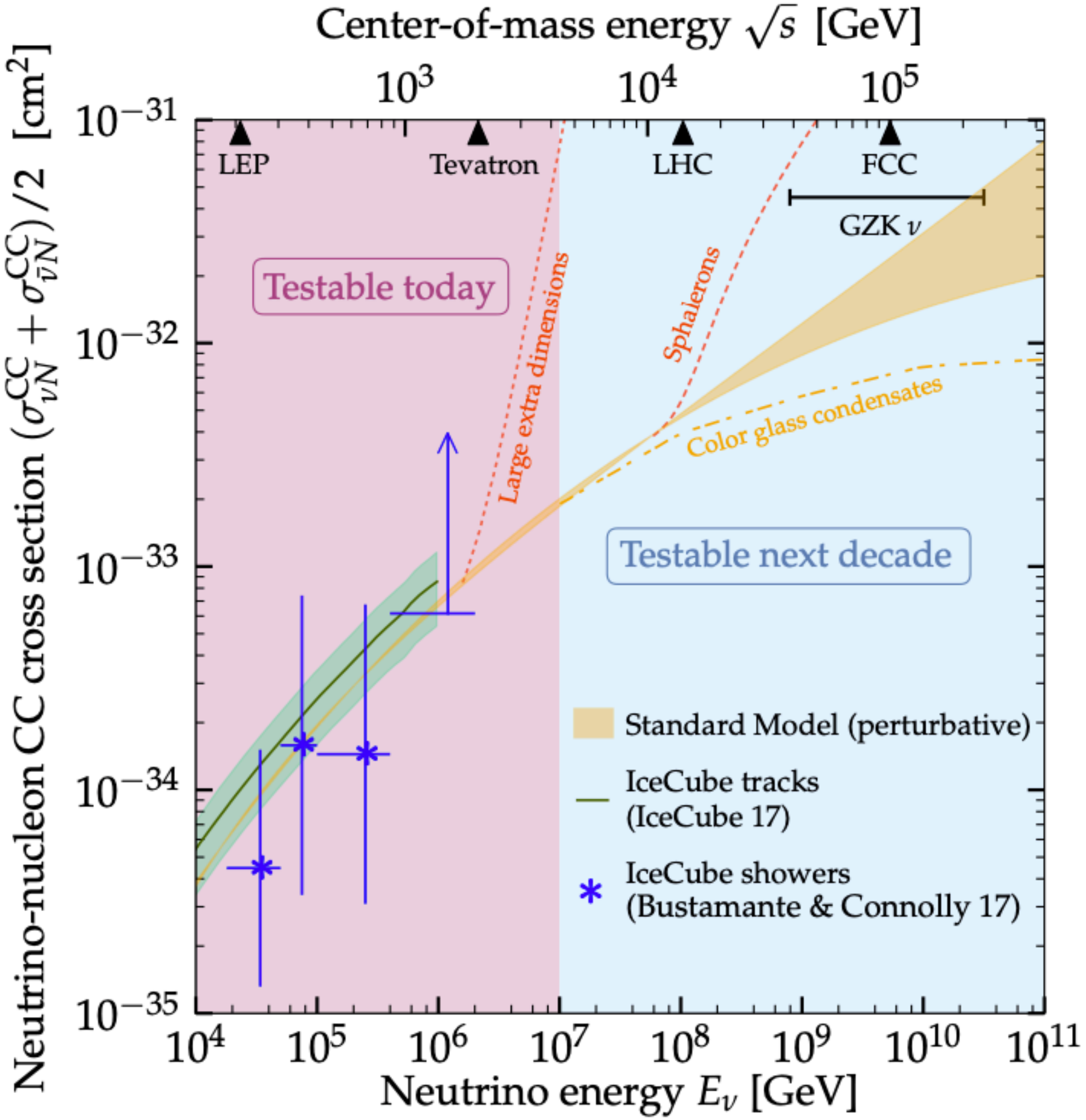


Note: Recently, also all flavour cross section measurement: 2011.03560

# What about new physics?

- Cross sections measured up to ~ PeV
- Above $10^7$ GeV:
  - probe nucleon structure at $x \lesssim 10^{-5}$
  - not accessible at accelerators

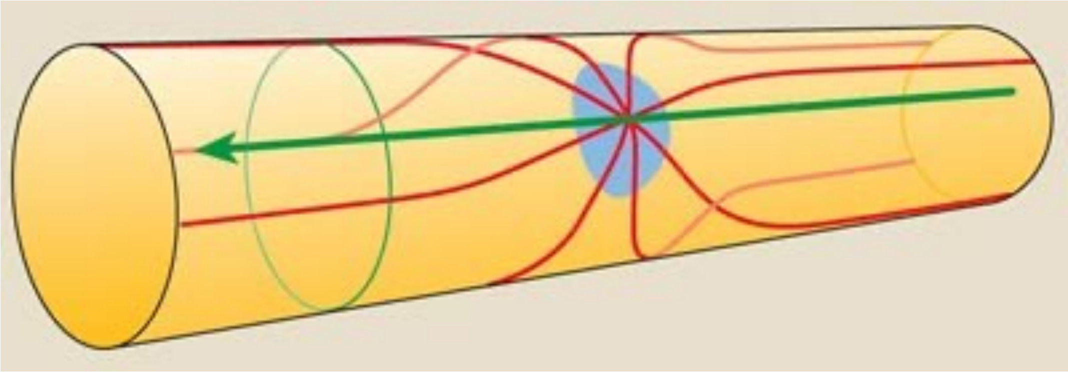


# Example: Mini black holes & Large Extra Dimensions

Models with large extra dimensions (LEDs)

- SM confined 3+1 dimensional **brane**
- **+ bulk** dimensions (only feel gravity)



Allows for production of mini black holes (mass M*) in interactions at sufficiently high energy

- Current collider constraints: M* $\gtrsim$ 3-25 TeV (depending on number of extra dimensions)

- 1 extra dimension ruled out (would imply solar system scale modifications to Newtonian gravity)

eg.: Kanti, Int.J.Mod.Phys.A19:4899-4951,2004, arXiv:hep-ph/0402168

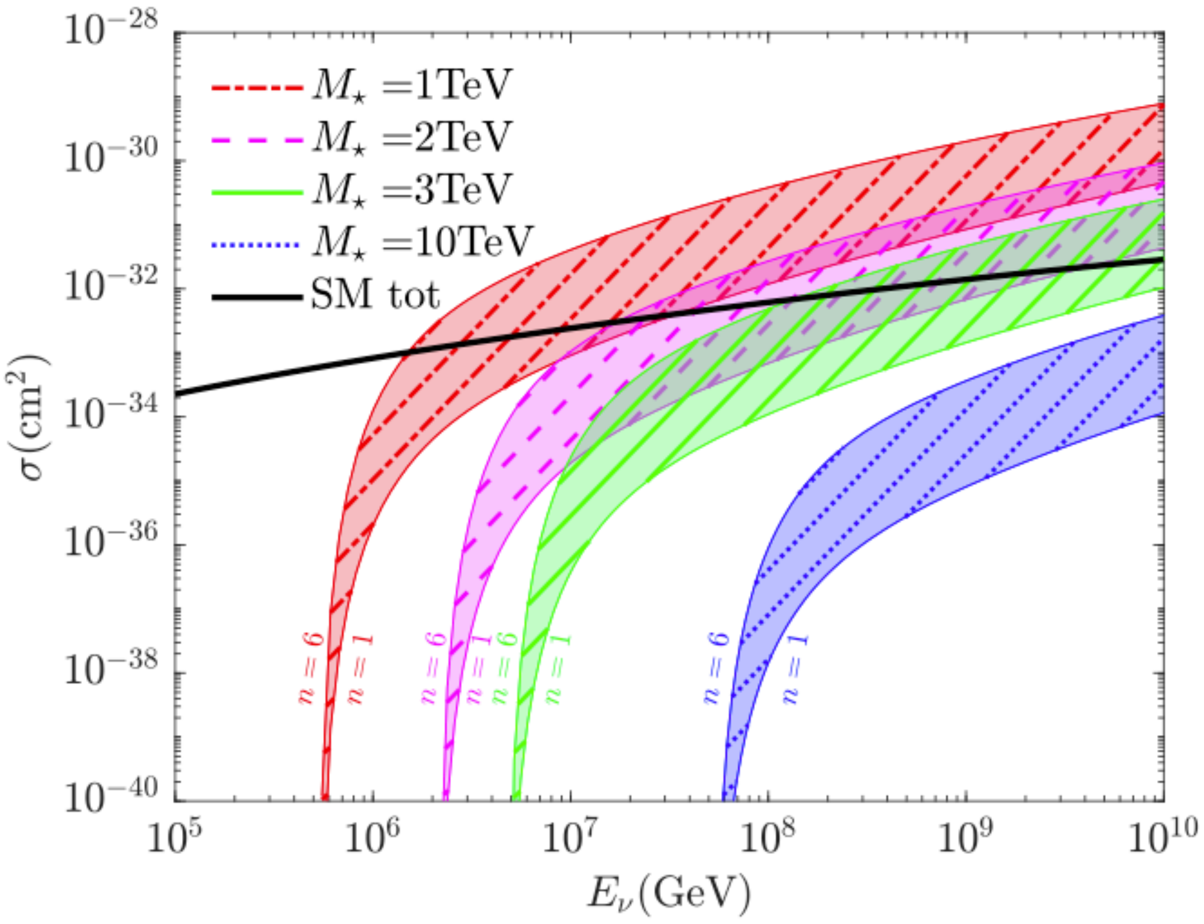
# Example: Microscopic black holes & Large Extra Dimensions

Q: At which neutrino energy can M* ~ 3 TeV be produced?

A: Center-of-mass energy in fixed-target collision:

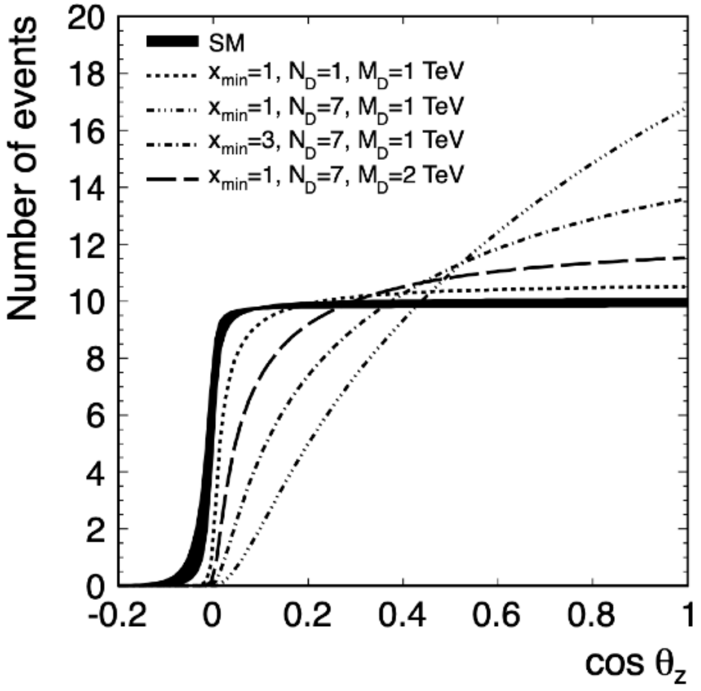
$$M^* \approx \sqrt{2E_\nu \cdot x m_p}$$

$$E_\nu \gtrsim 4.5 \times 10^6 \text{ GeV}$$

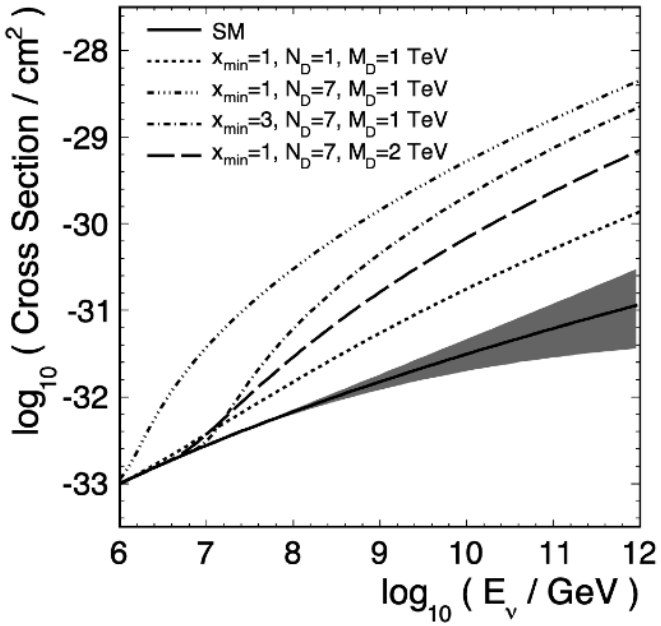


# Event distribution at UHE

- At ultra-high energies:
  - We will not see many events from more than few degree below horizon
  - But: already some absorption for neutrinos from above horizon:




Zenith distribution normalised to 100 detected events/model




Connolly, Thorne, Waters, Phys.Rev.D83:113009 (2011)

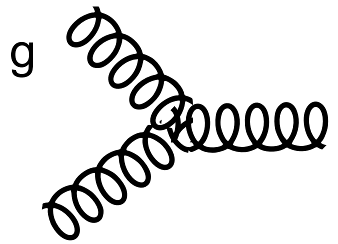
- Need sufficient statistics (>O(50) events?) to make such a measurement

- Similarly, for other new physics models: new physics / particles typically <u>increase</u> the cross section (e.g. also sphalerons have a predicted $M_{sph}$~10 TeV & large cross section)

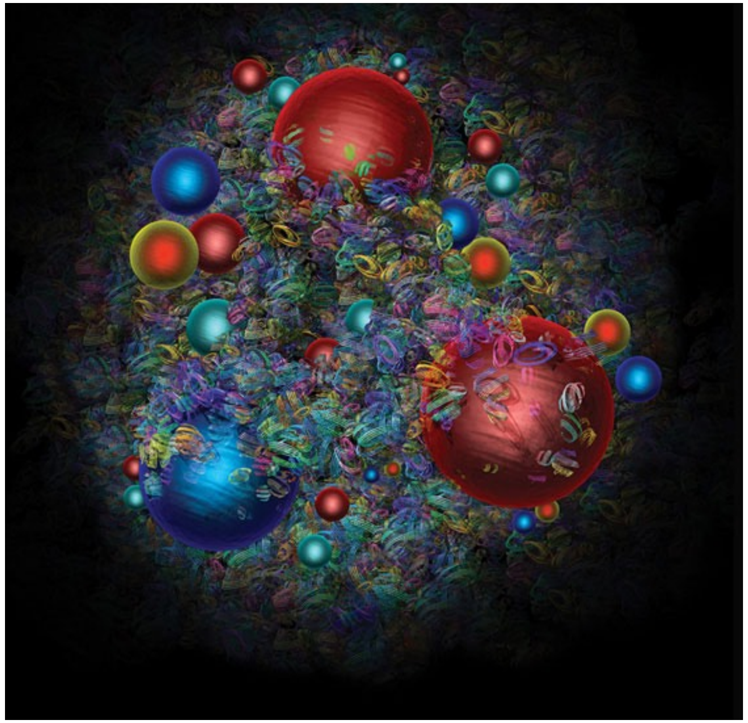
# The cross section might also be lower… Color glass condensate

- With in UHE interactions, smaller and smaller Bjorken x are probed
- Gluon density rises indefinitely in extrapolations towards low x

- At some point: non-perturbative effects must become relevant




…and the gluon density will saturate



DANIEL DOMINGUEZ/CERN

New phase of QCD has been postulated: Colour Glass Condensate

This could strongly suppress cross section!

# New physics signatures

How does new physics affect cross sections?

**Can new physics have unique event signatures?**

Can new physics affect the $\nu$ flavour composition?

# Back to our previous new physics example

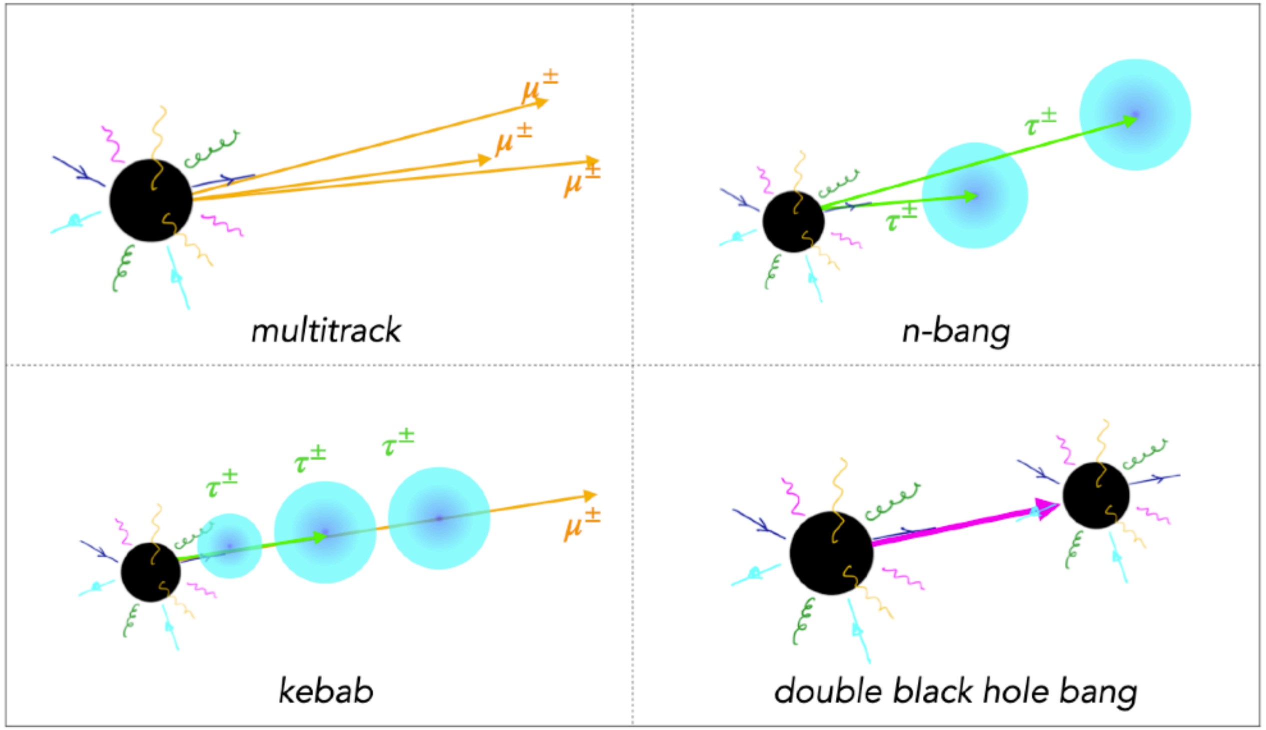
## Mini black holes & Large Extra Dimensions

- When massive (~ 1-10 TeV) particles decay, they will produce several O(10) decay particles

  → these initiate particle showers, each carrying a fraction of the energy

- Rest mass allows to draw decay particles from the entire Standard Model (and beyond?) i.e. no restriction to light particles

  → this may produce unique signatures:

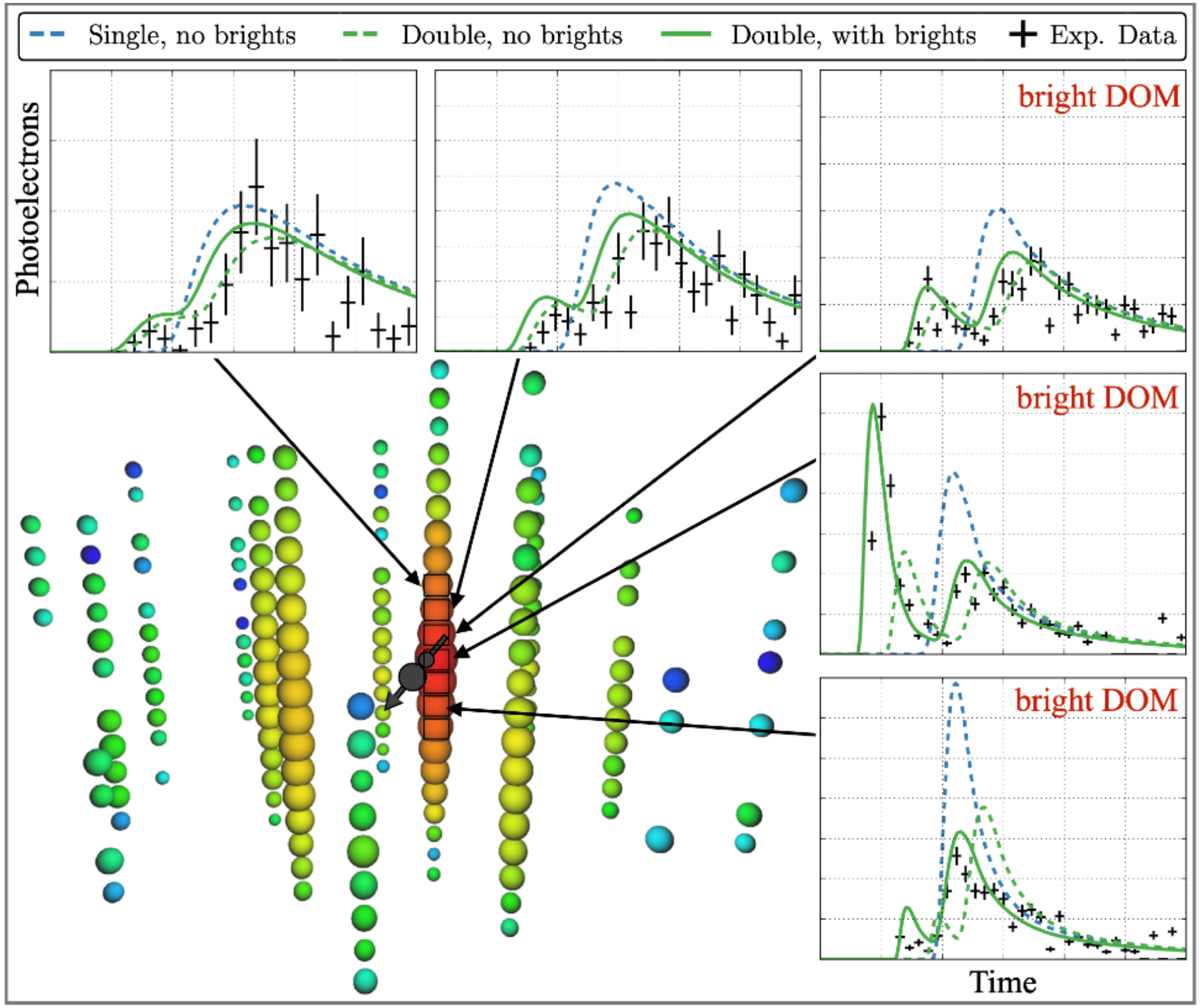



i.e. in principle, can be constrained by

- Hadronic vs. Electromagnetic showers
- Identification of secondary showers
- Measurement of inelasticity

… how does IceCube measure this?

# Double-bang signatures measured by IceCube



# New physics signatures

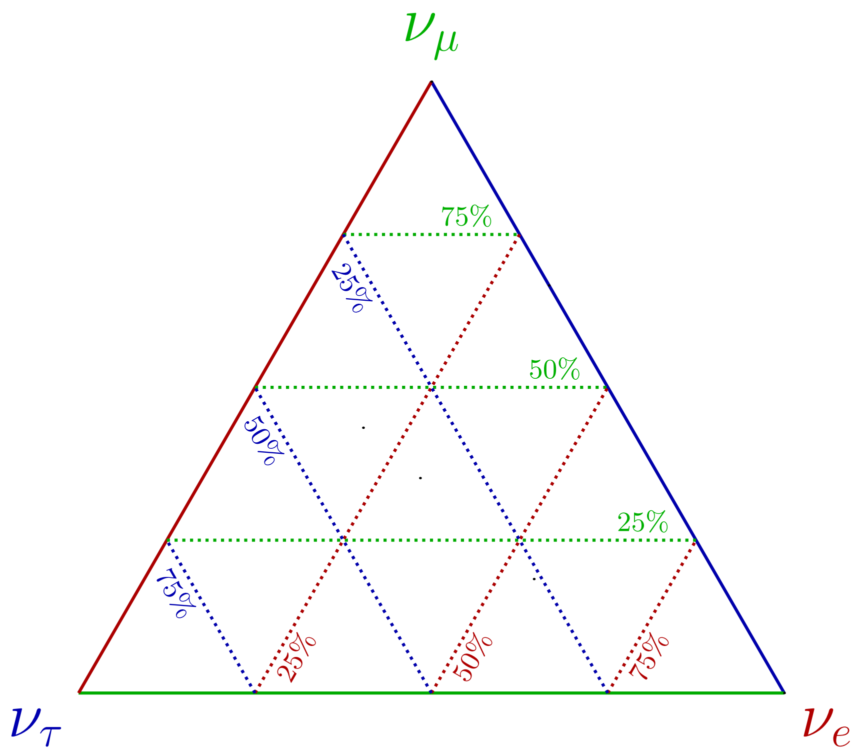
How does new physics affect cross sections?

Can new physics have unique event signatures?

**Can new physics affect the $\nu$ flavour composition?**

# Flavour composition at the source

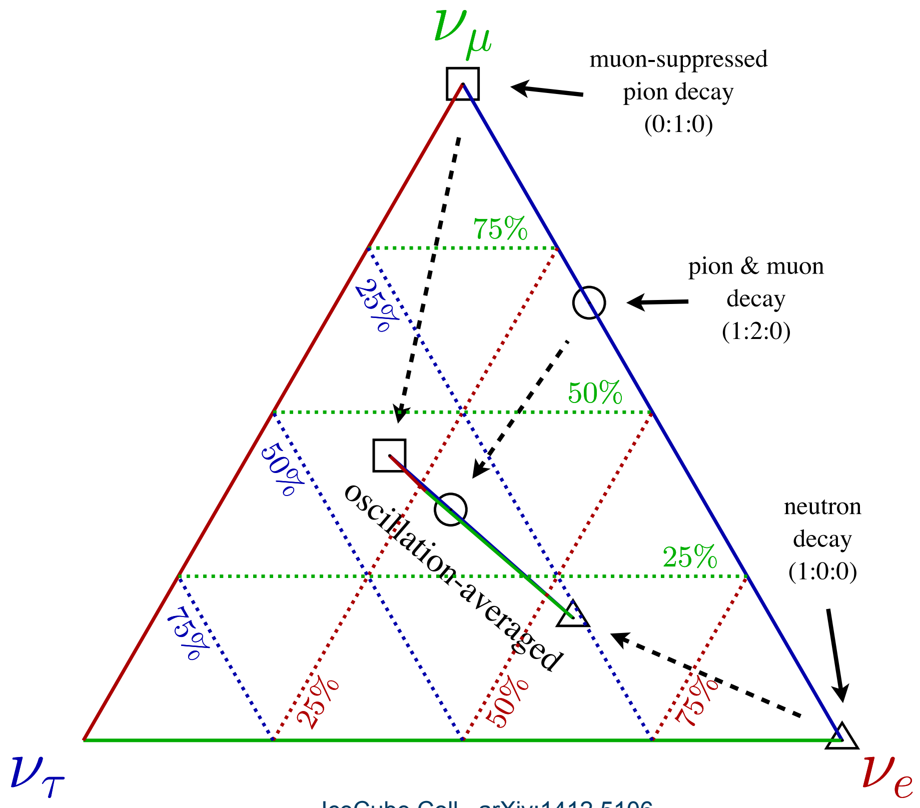
- Source scenarios:
  - (Photo)hadronic interactions → pion decay & muon decay: $(\nu_e : \nu_\mu : \nu_\tau)$ = (1:2:0)
  - if muons suppressed (dense media): $(\nu_e : \nu_\mu : \nu_\tau)$ = (0:1:0)
  - Neutron decay: $(\nu_e : \nu_\mu : \nu_\tau)$ = (1:0:0)
  - … and more exotic…




IceCube Coll., arXiv:1412.5106

- Composition of flavours often displayed in the "flavour triangle" (sometimes called: ternary plot)
- Each point in the triangle corresponds to a ratio $(\nu_e : \nu_\mu : \nu_\tau)$
- By default: analyses assume $(\nu_e : \nu_\mu : \nu_\tau)$ = (1:1:1) @ Earth … Q: Why?

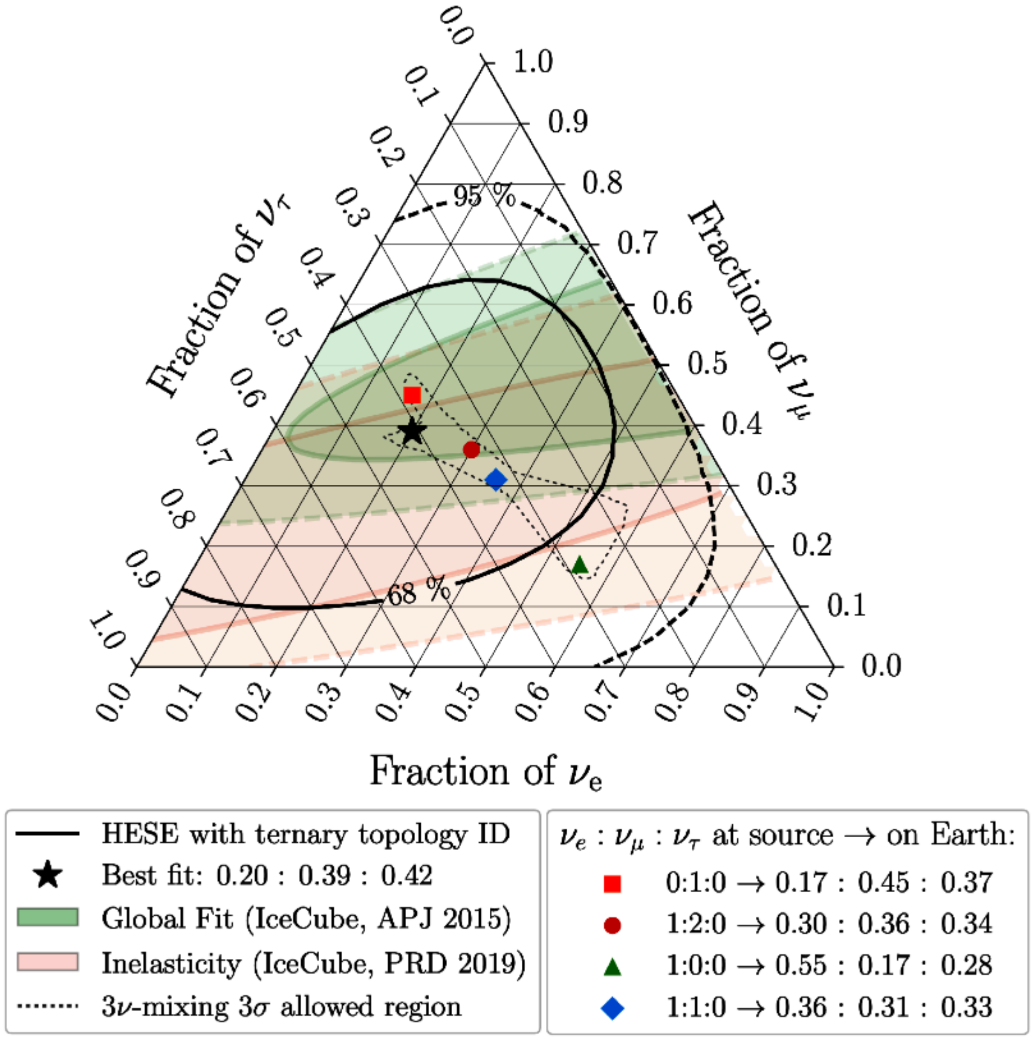
# Flavour composition at Earth




IceCube Coll., arXiv:1412.5106

# IceCube flavour composition at Earth

- Recent IceCube measurement including tau double-bangs:




IceCube Coll., arXiv:2011.03561v1

- Consistent with expectation for $3\nu$ oscillations
- Tau's still not clearly separated at ~ PeV:

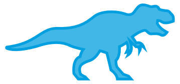
  → error largest in $\nu_\tau$ direction

  … Identification of all flavours is mandatory for accurate measurement

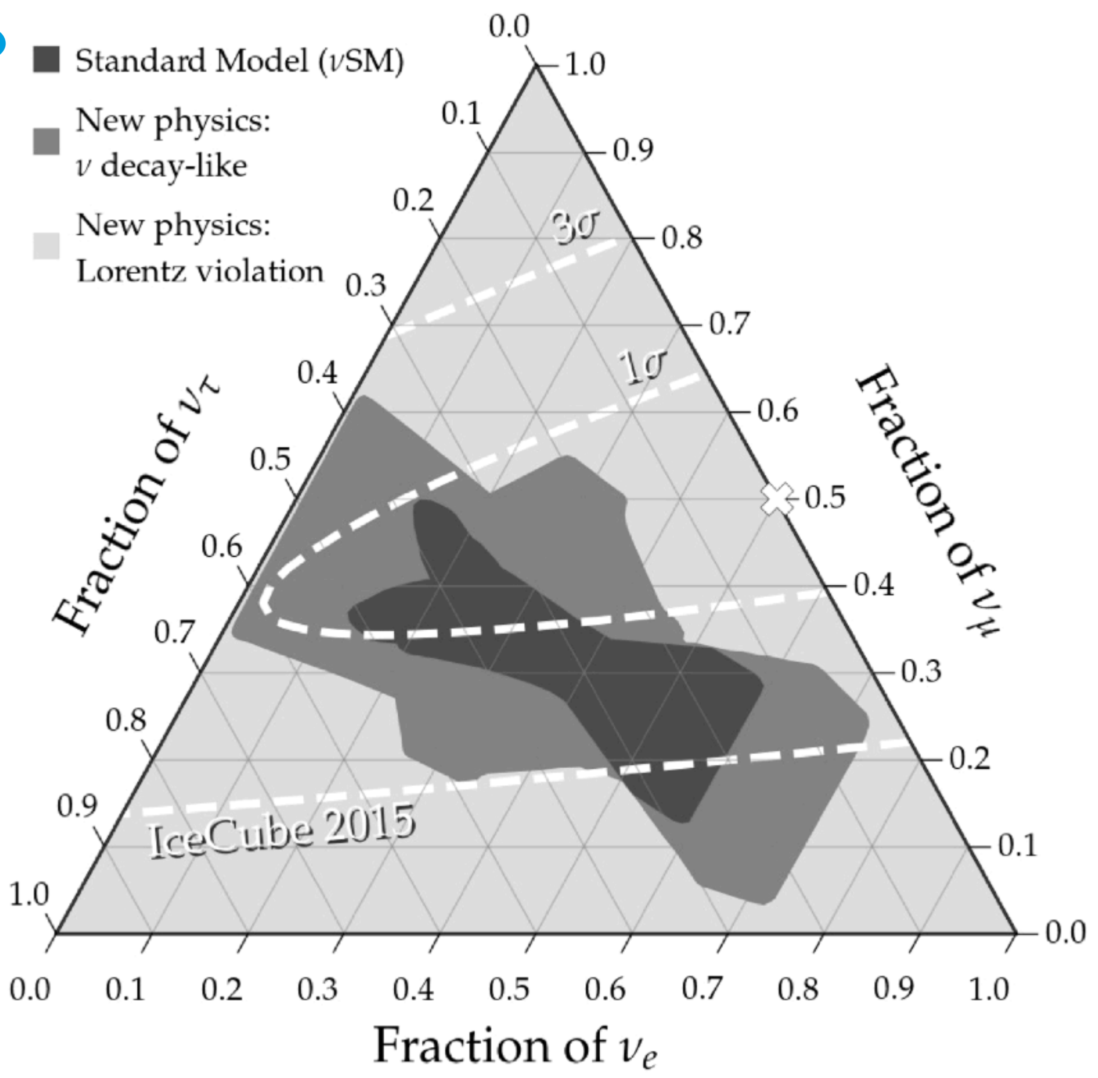
# New physics in the flavour triangle?

- Standard oscillations cover
  ~ 10% of the allowed parameter space
- Neutrino decay (extends modestly around
  SM allowed region)

more exotic theories may lie anywhere on the plane



Measuring neutrino flavour composition gives sensitivity to
- physics at the source, and
- new physics active during propagation




Ackermann et al., Astro2020 Survey (1903.04333)

# New physics and ultra-high-energy (UHE) neutrinos

## Some reminders…

GZK & astrophysical

attenuation length

Flux & Detection

Askaryan emission

Bjorken x and y

Interaction physics at extreme energies

secondary showers

LPM effect

Earth absorption

What surprises may new physics bring us?
What have we seen so far?

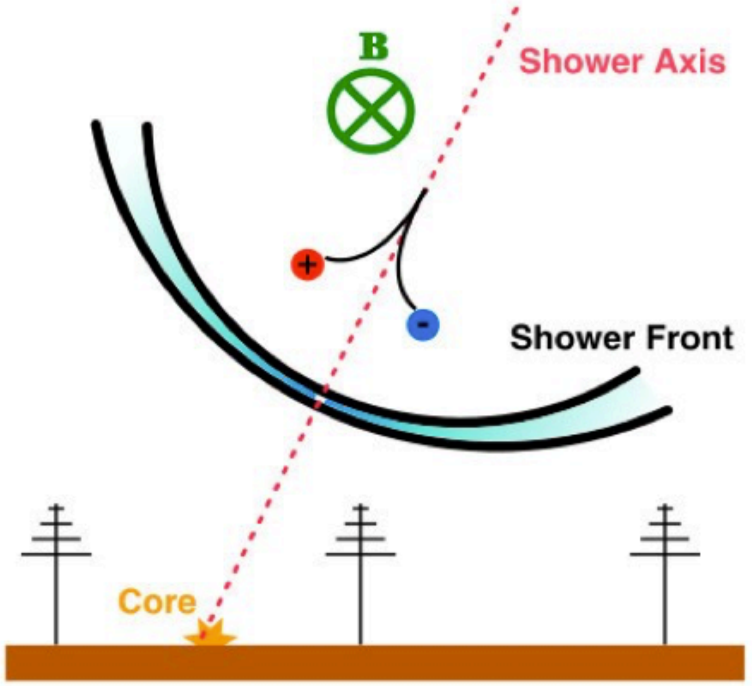
event signatures

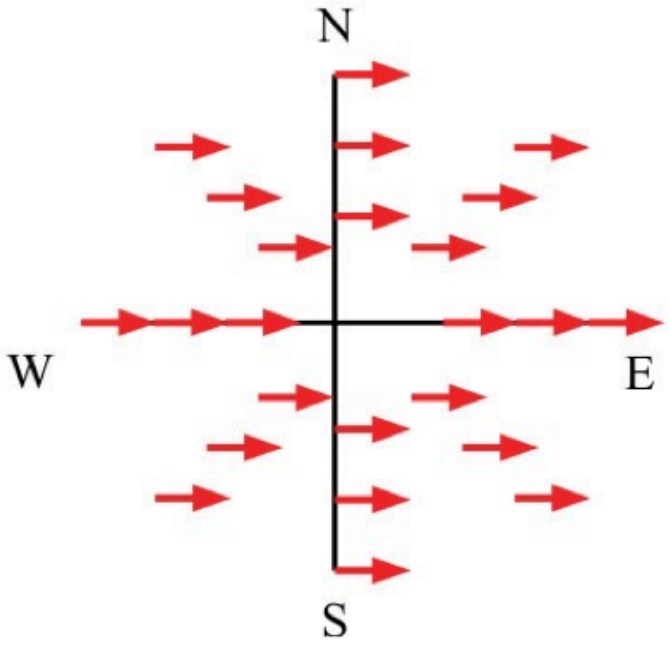
flavour triangle

# Backup

# + radio emission in air

## Geomagnetic



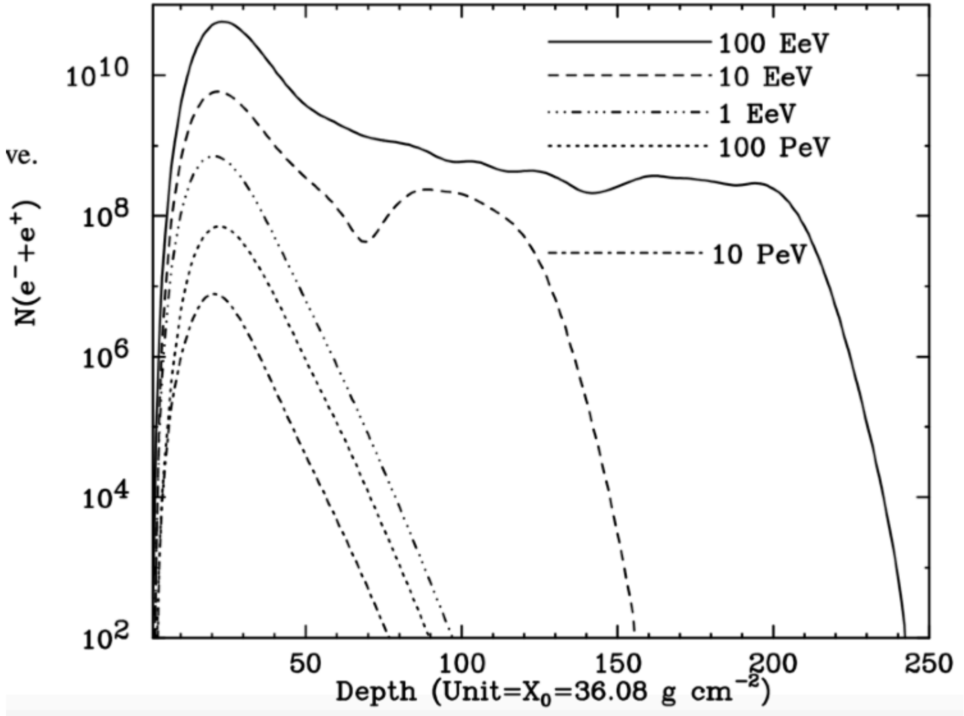

- Time varying transverse current
- Linearly polarised parallel to Lorentz force
- Dominant in air showers

Figures credit: H. Schoorlemmer and K. D. de Vries

# LPM also in hadronic showers?

- Average longitudinal shower profile from neutrinos interacting in the ice:

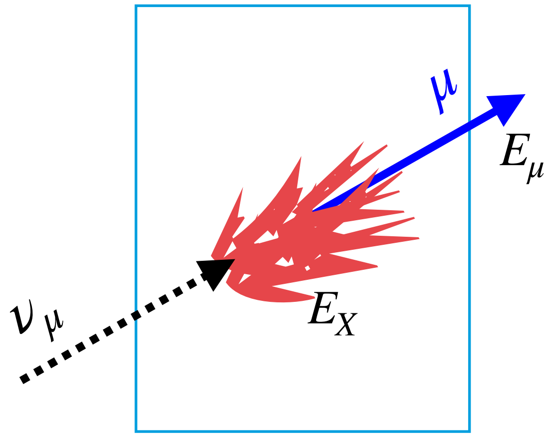
J. Alvares-Muñiz, E.Zas arXiv:astro-ph//9906347 (ICRC1999)




- Standard shower profile up to ~1EeV
- At higher energies: Tails from electromagnetic decays of resonances generated early in the shower

# Inelasticity (=Bjorken y) measured by IceCube

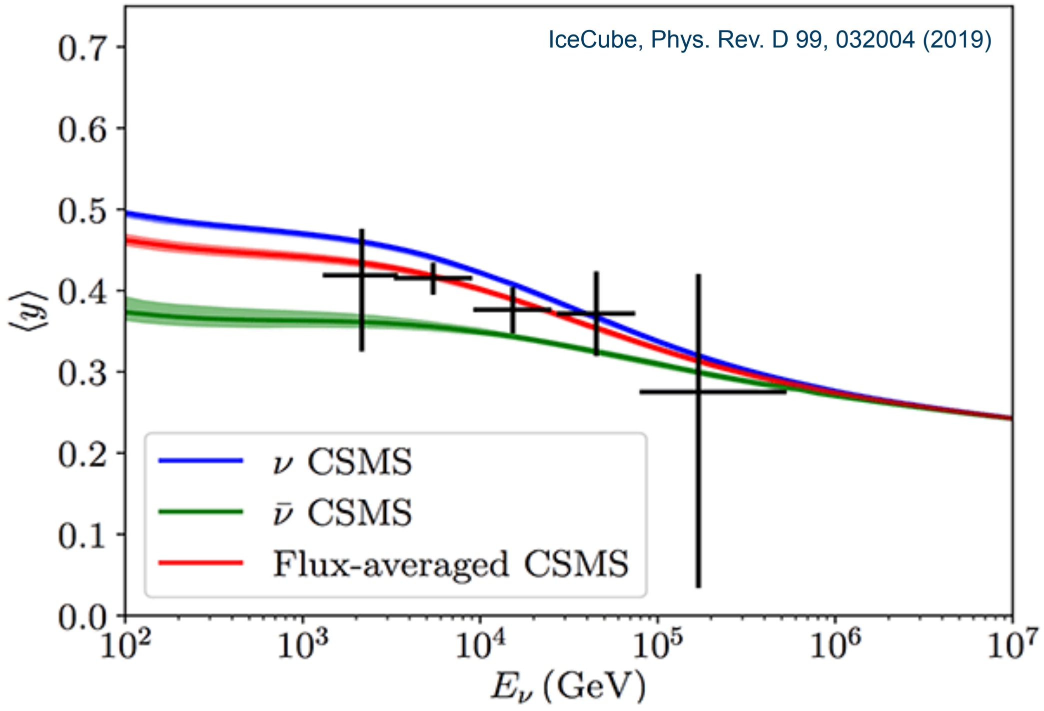
For $\nu_\mu$ charged current events, interacting inside the detector




energy of the hadronic shower + muon energy is seen

Can use this to determine

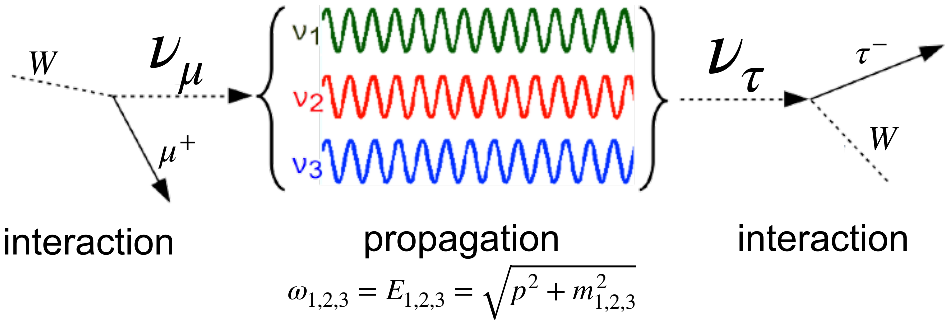
$$y = \frac{E_X}{E_X + E_\mu}$$




IceCube's event sample agrees with the Standard Model expectation!

# Flavour composition at Earth

- A: Flavour oscillation!




flavour eigenstates $\nu_{e,\mu,\tau}$

superposition of

mass eigenstates $\nu_{1,2,3}$

## Formula for 2 flavours: $\theta,\ \Delta m^2$

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\cdot\sin^2\left(1.27\Delta m^2\,[\mathrm{eV}]^2\cdot\frac{L\,[\mathrm{km}]}{E\,[\mathrm{GeV}]}\right)$$