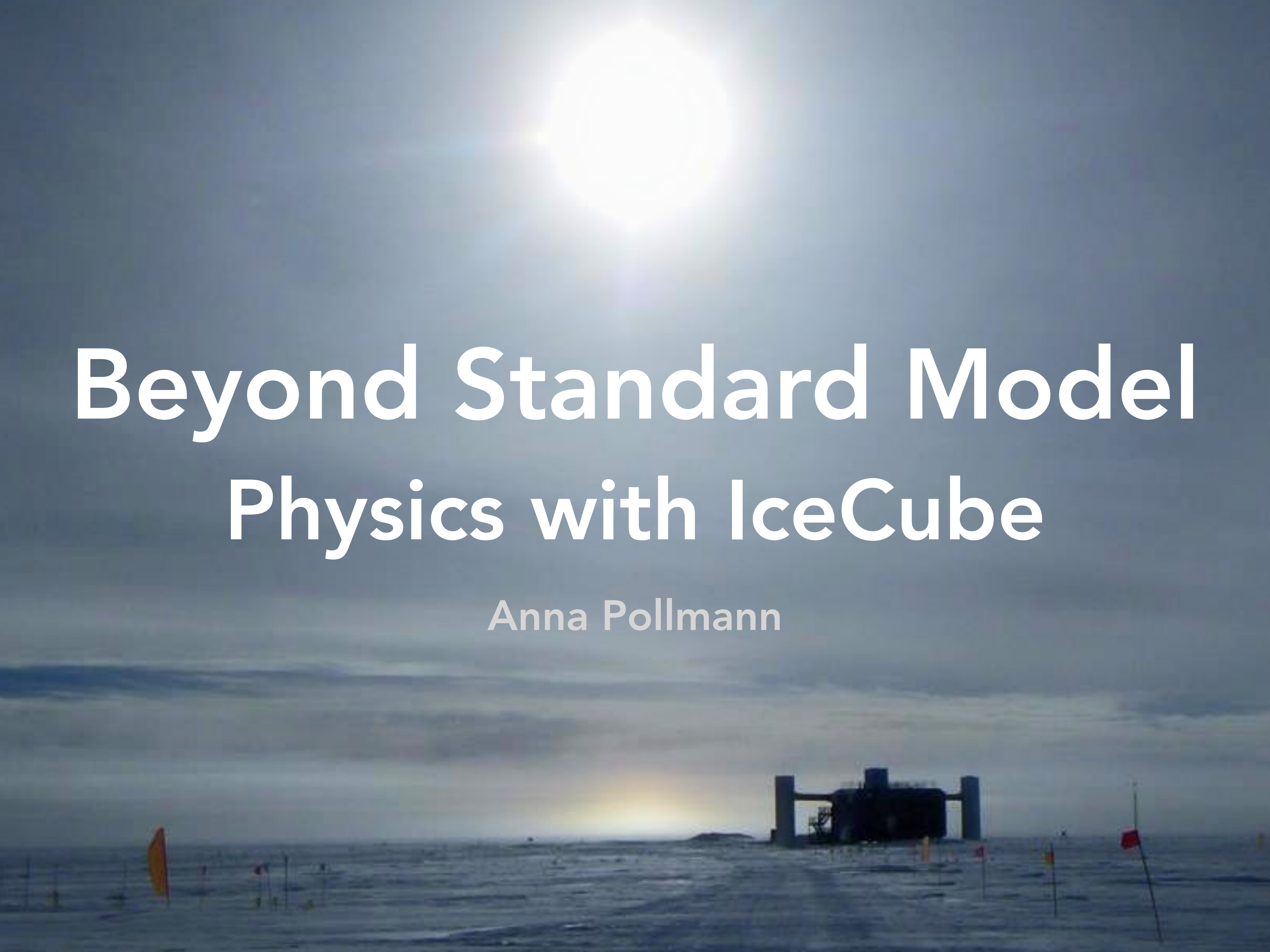
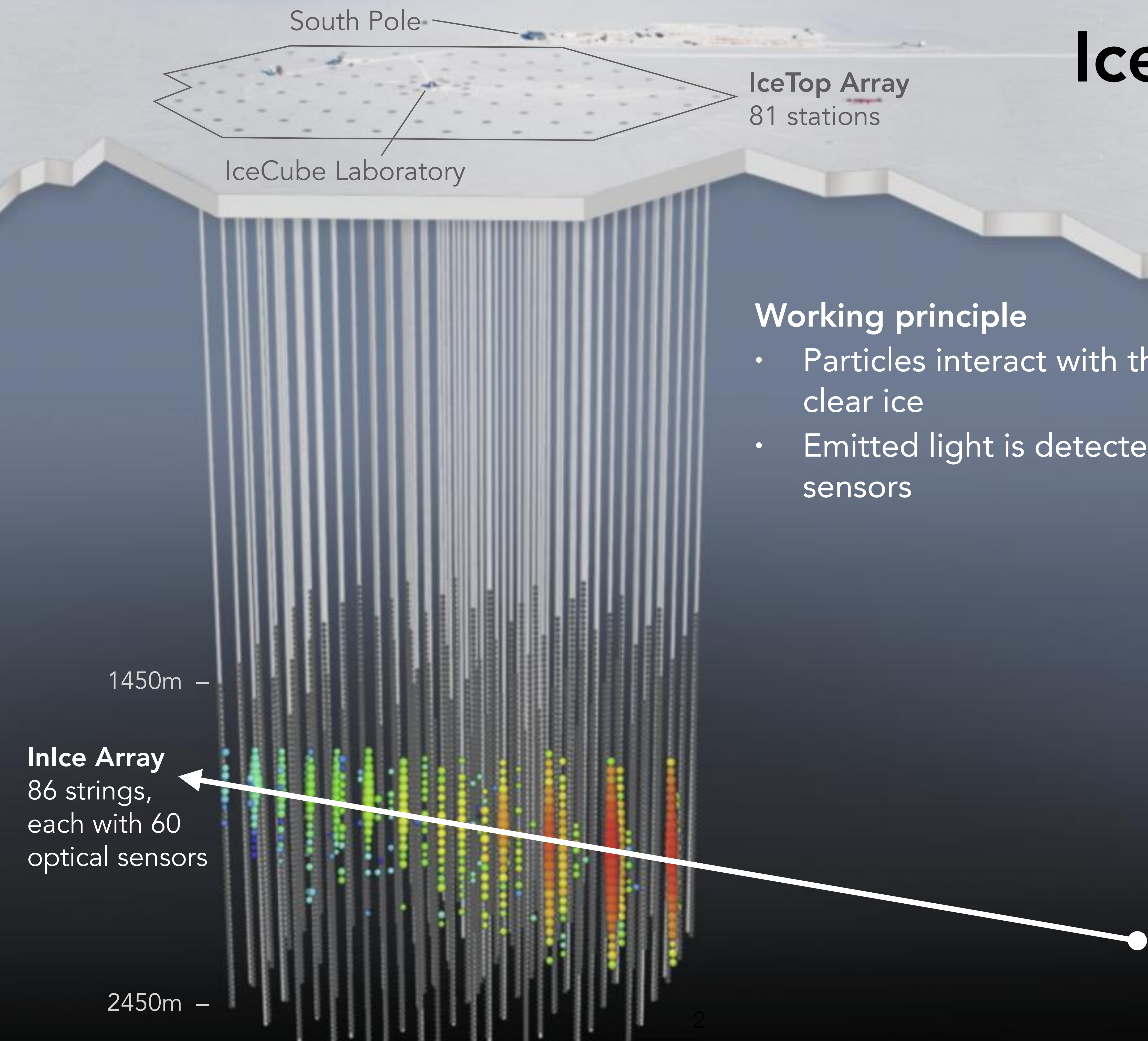


Beyond Standard Model Physics with IceCube

Anna Pollmann

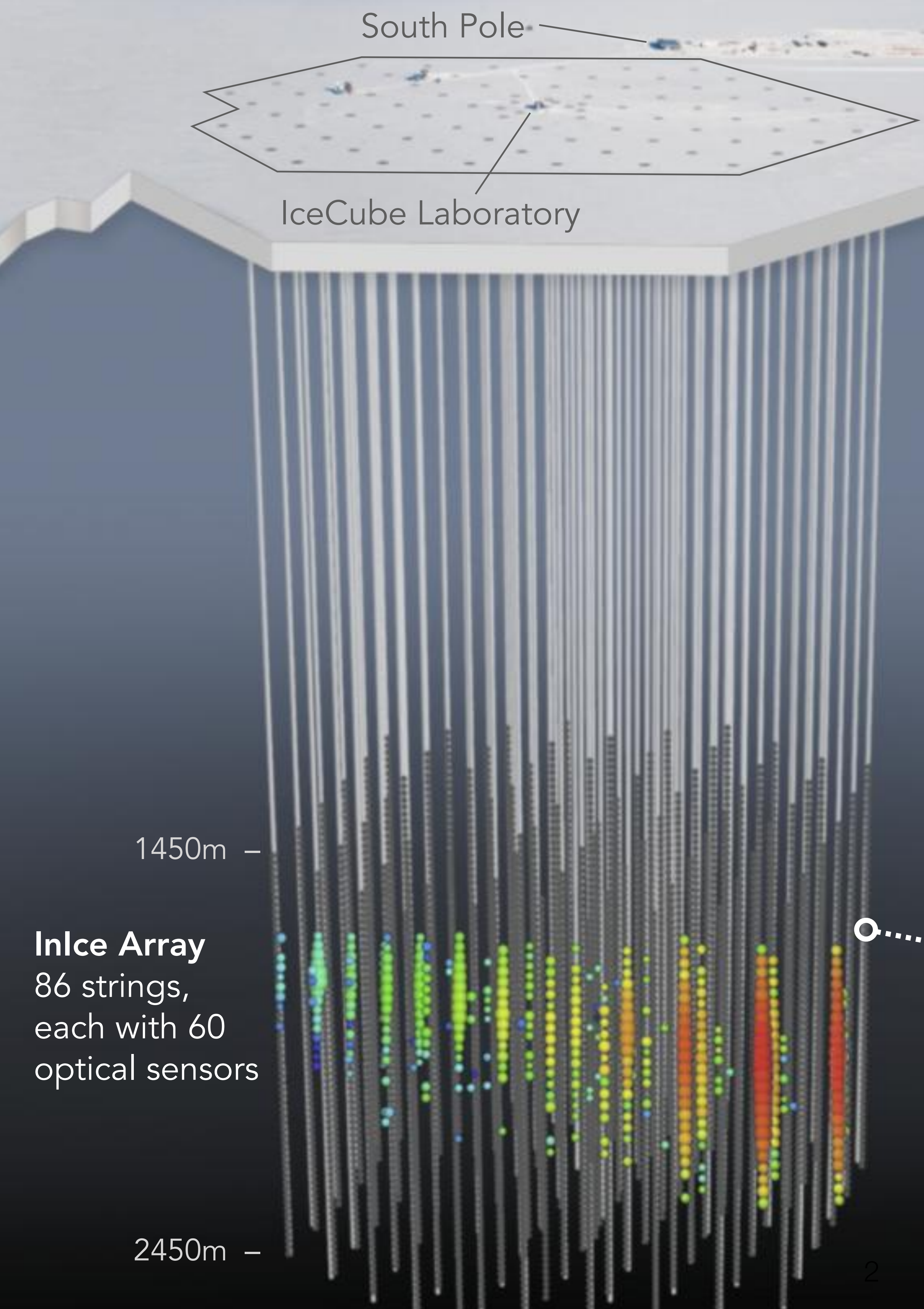
IceCube



Working principle

- Particles interact with the deep clear ice
- Emitted light is detected by sensors

IceCube



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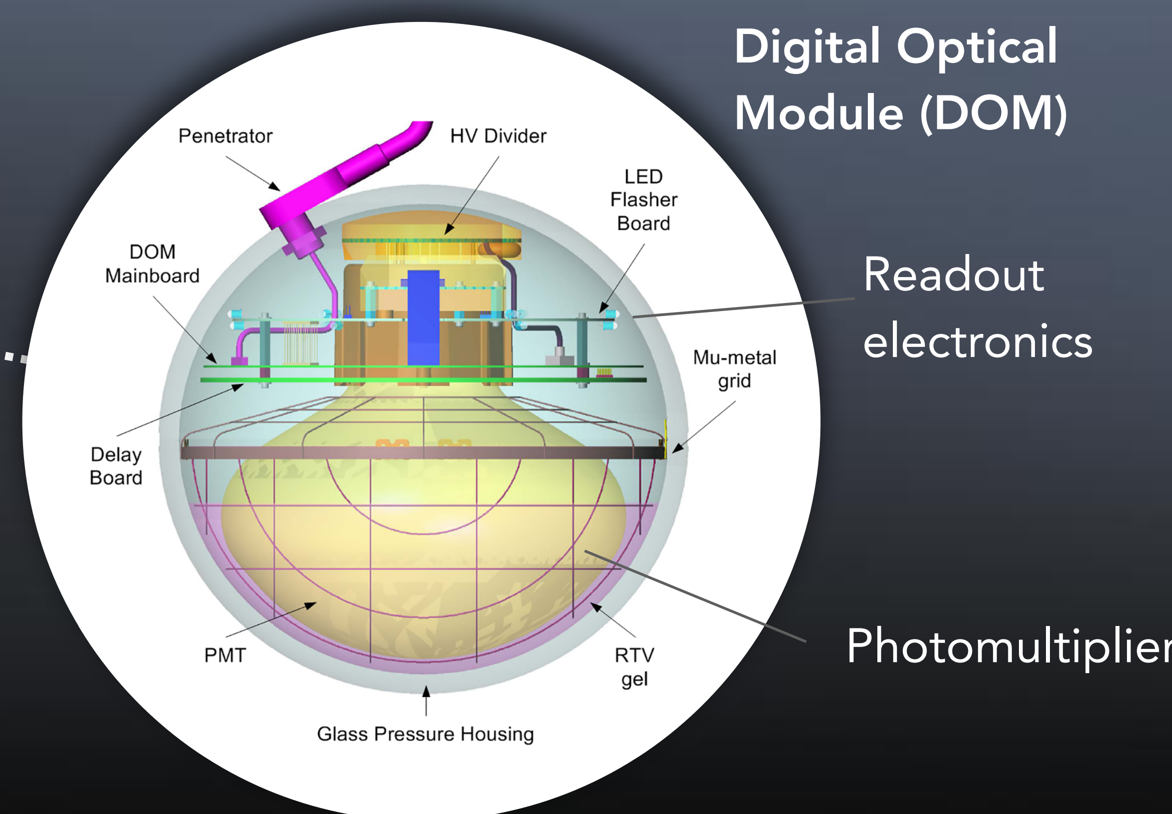
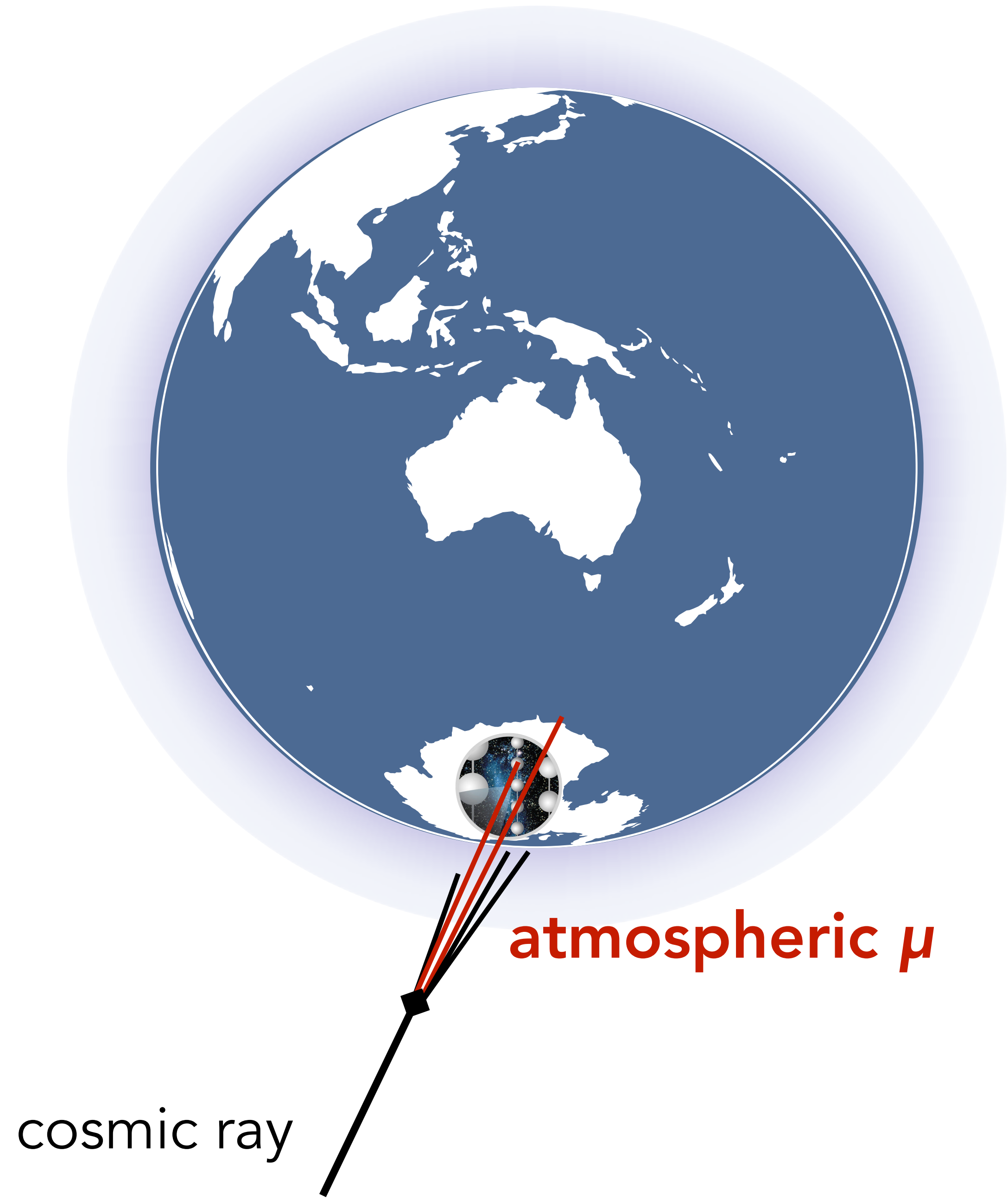


Particle types in IceCube

Atmospheric Muons (~10^8 per day)

- cosmic HE particles interact with atmosphere **(cosmic ray)**
- a particle shower develops through the atmosphere **(air shower)**
- **muons** reach IceCube



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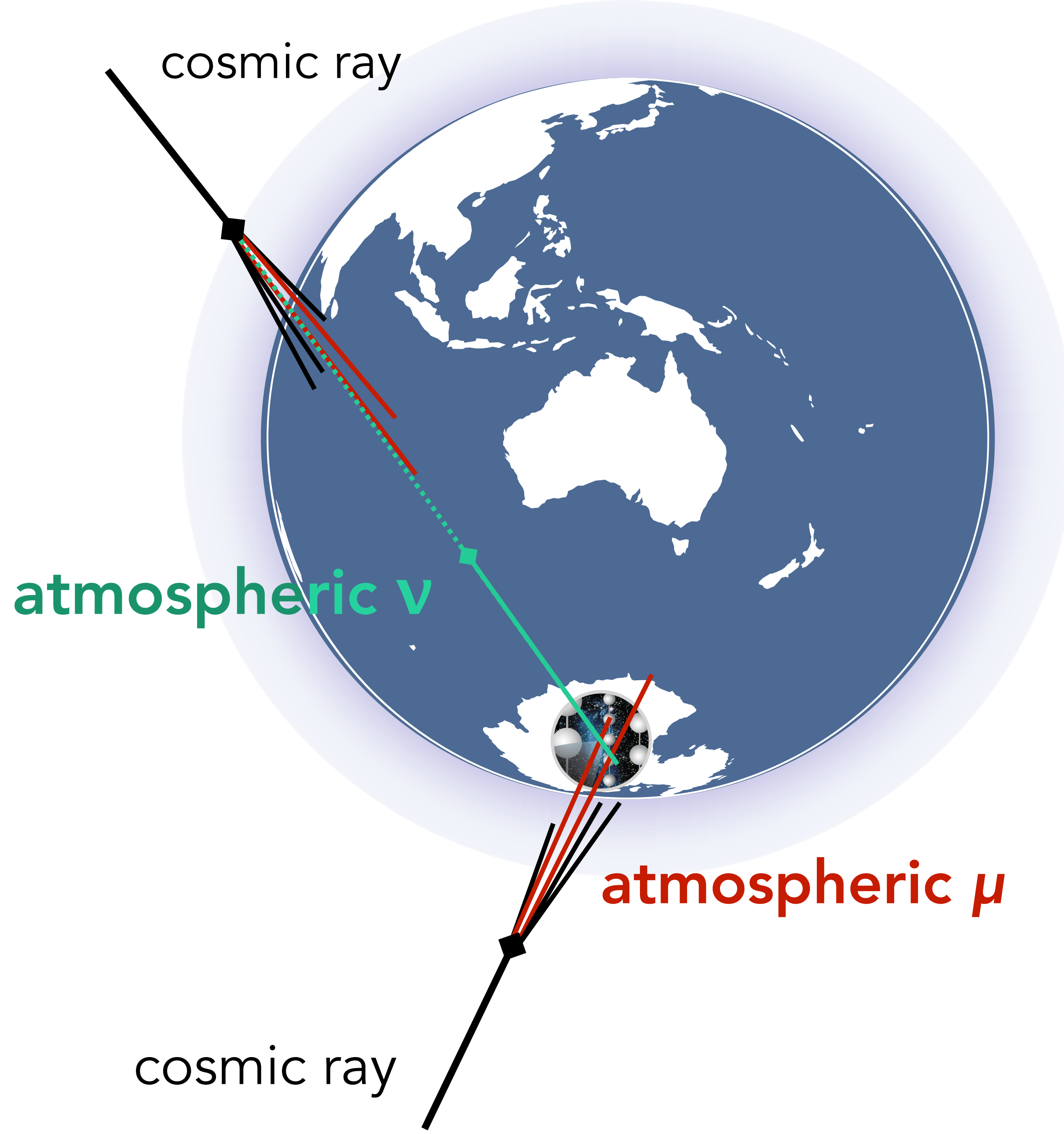
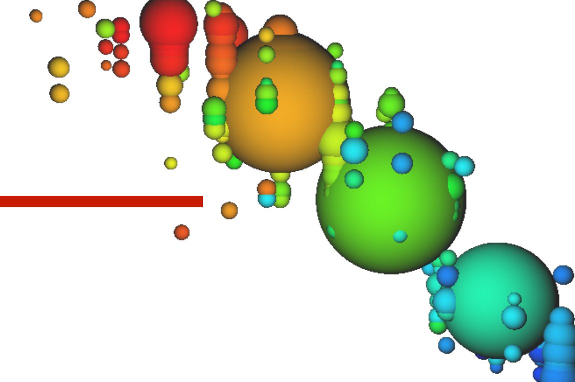
Atmospheric Neutrinos (~200 per day)

- cosmic ray induces air shower
- neutrino is created in shower
- neutrino interacts in Earth or ice
- visible muon or shower in IceCube
- energy threshold ~10 GeV



Particle types in IceCube



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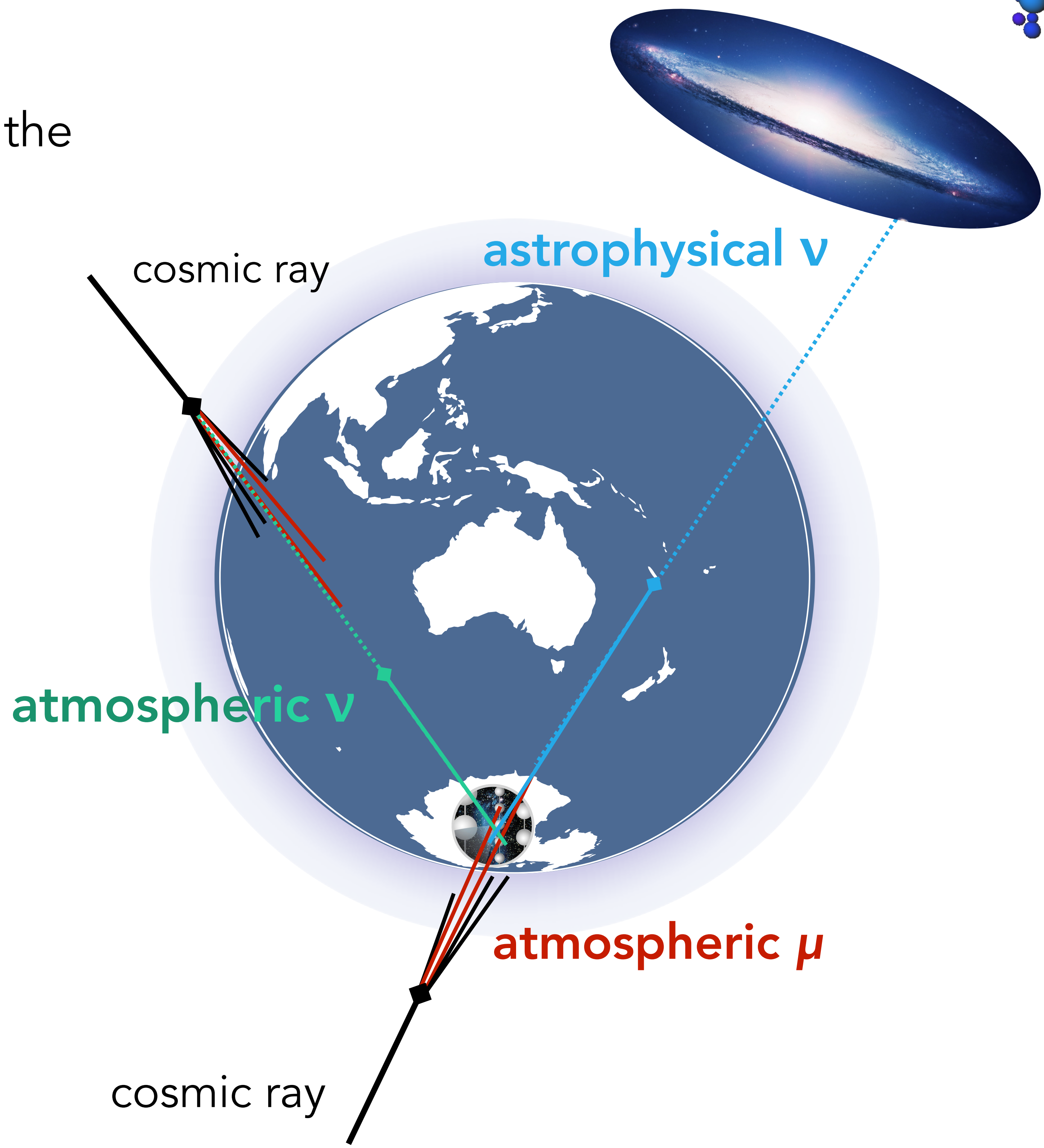
- visible muon or shower in IceCube
- energy threshold ~10 GeV

Astrophysical Neutrinos (~10 per year)

- neutrino from outer space passes through Earth
- neutrino interacts in Earth or ice
- visible muon or shower in IceCube



Outline

- Introduction of IceCube
- Beyond Standard Model physics with IceCube
  - Direct detection of exotic particles
    - Standard detection channels
    - Development of new detection channels
  - Development of new detector modules

Beyond Standard Model physics with IceCube

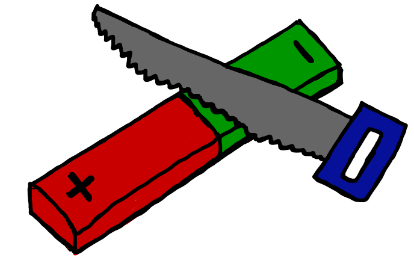
Indirect detection

- exotic source of particles contributes to particle flux
- exotic interactions/particles contribute to propagation of particle fluxes
- unexpected particle properties at unprecedentedly high energies
- different fundamental laws of physics appear at long scales

Direct detection

- exotic particle (or interaction secondary) passes through the detector
- often distinct event signature expected

Relic Magnetic Monopoles



- elemental magnetic charge (Dirac)

  $g_D = e / 2\,\alpha \approx 68.5\ e$

- with huge mass created
  - shortly after the Big Bang (GUT)

    10^{13} GeV $\leqq M_{MM} \leqq 10^{19}$ GeV

  - in intermediate stages of symmetry breaking (IMM)

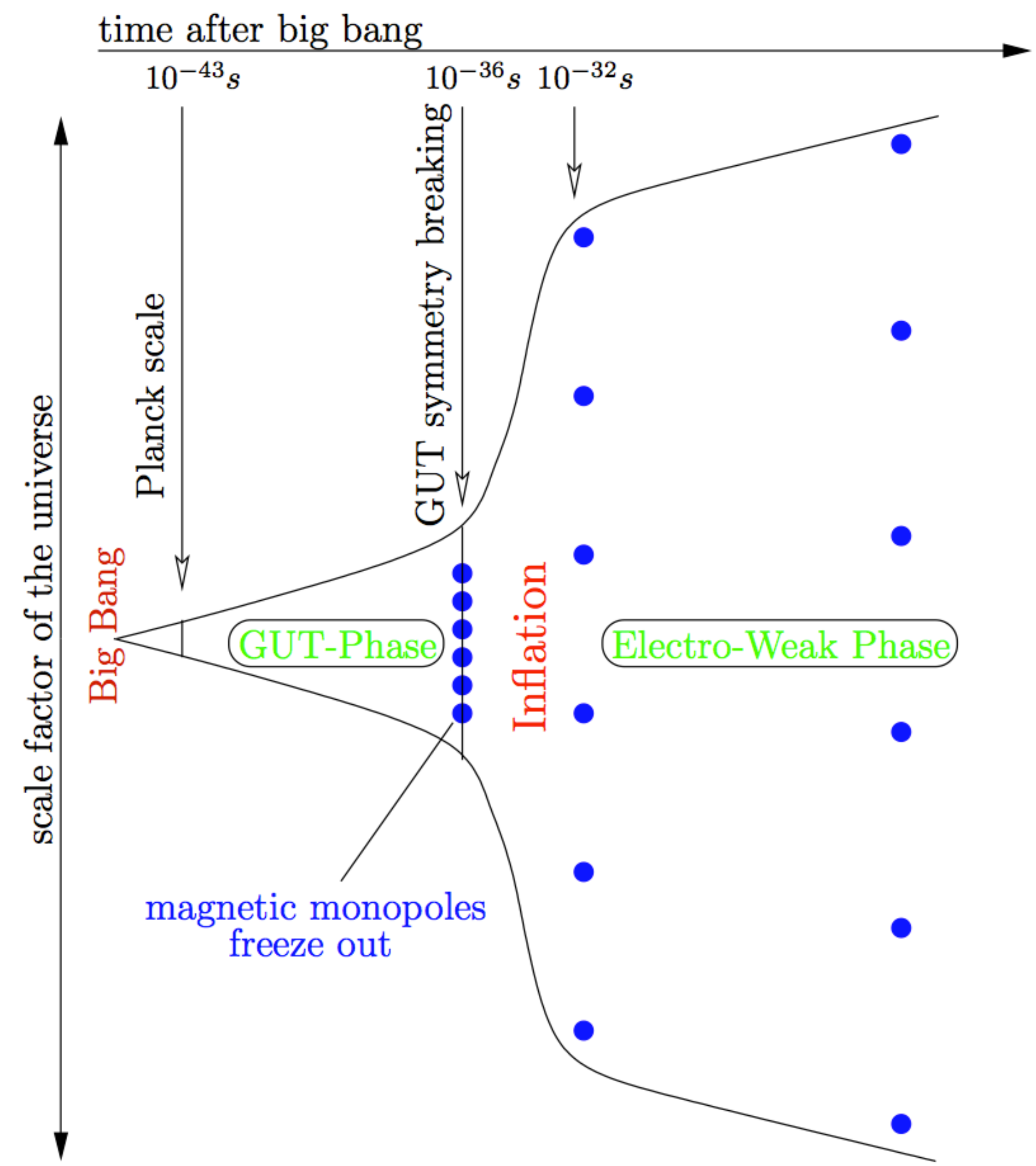
    10^{7} GeV $\leqq M_{MM} \leqq 10^{13}$ GeV

- acceleration in magnetic fields for

  $M_{MM} \leqq 10^{14}$ GeV to $E_{kin} \leqq 10^{15}$ GeV

  - trapping around galaxy, sun, Earth

    $v \sim 10^{-3}$ / 10^{-4} / 10^{-5} c



Gluesenkamp ´10

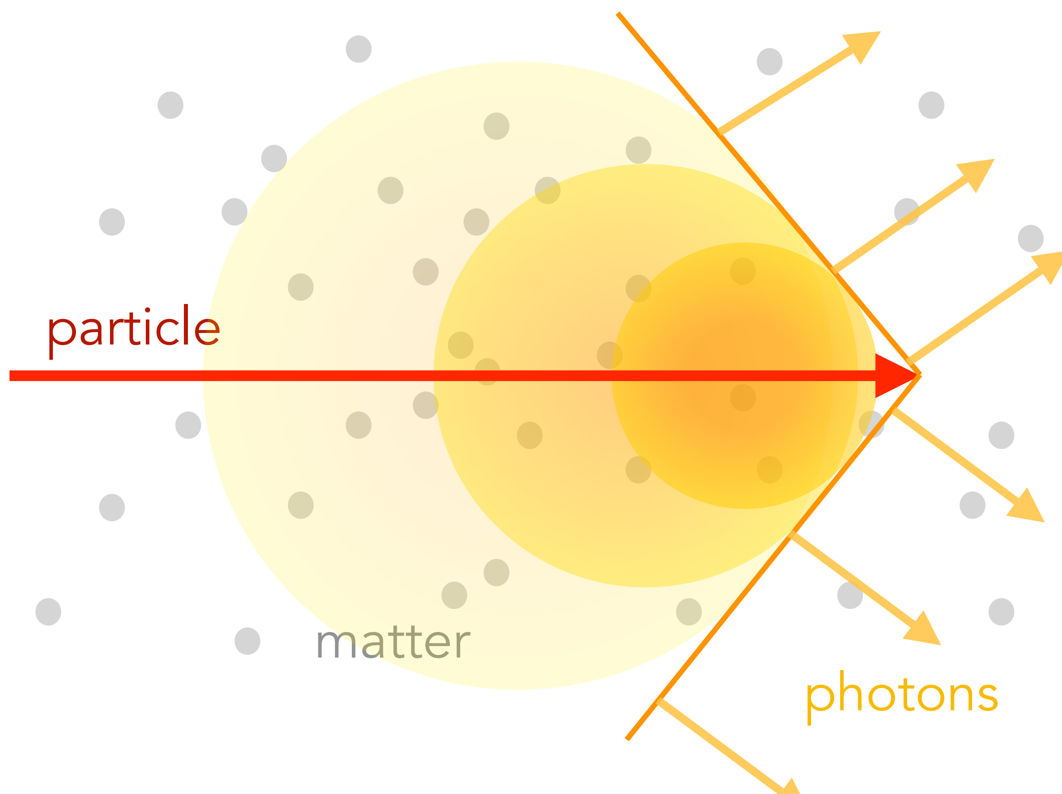
Light production in water-Cherenkov telescopes

Relativistic speeds

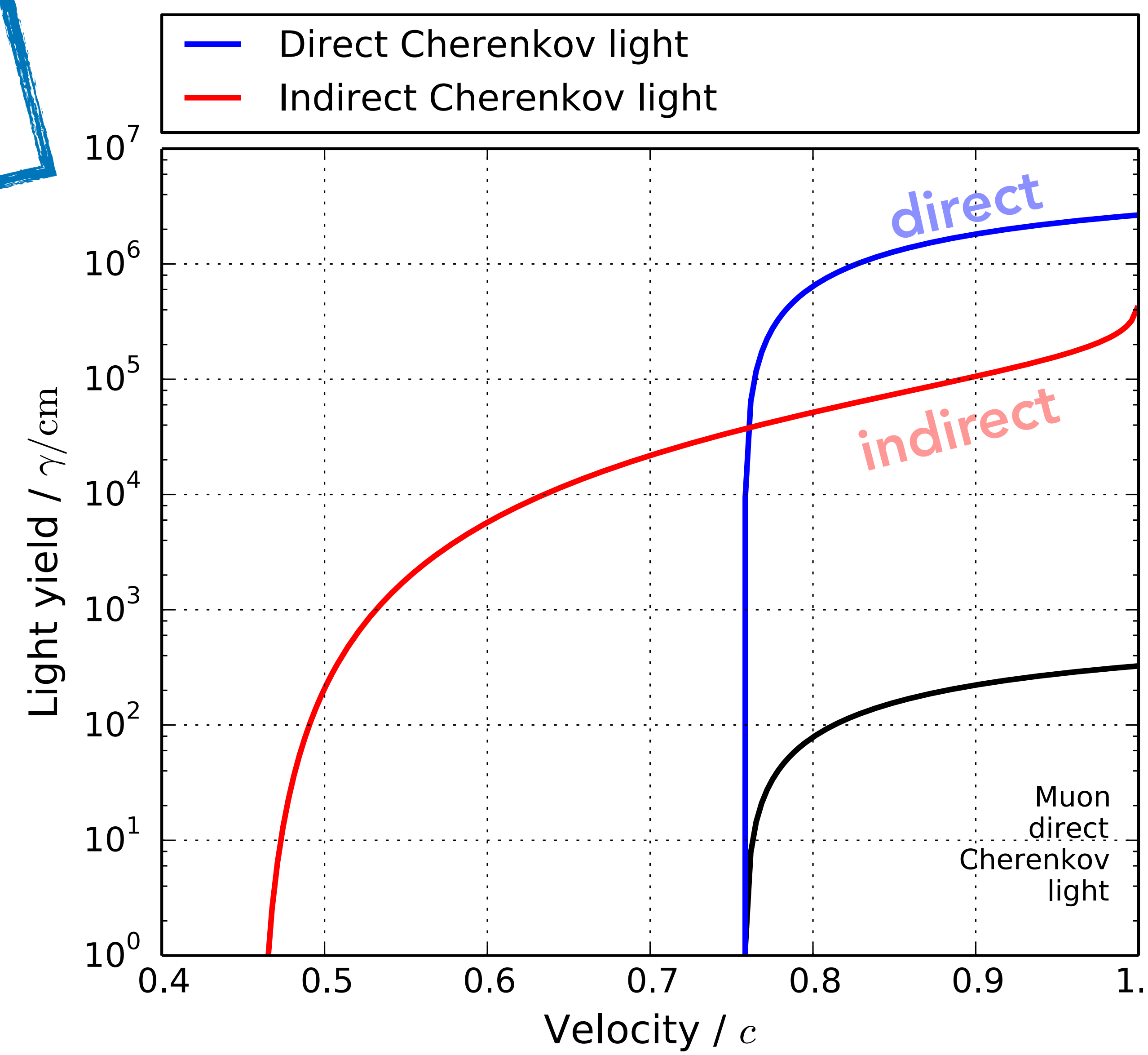
- Continuous light emission
  - Cherenkov Light
  - Cherenkov light from secondaries
- Stochastic losses
  - Bremsstrahlung
  - Pair production
  - Photonuclear interactions

also valid for Standard Model particles

Cherenkov light emission pattern



Monopole light yield



Light production in water-Cherenkov telescopes

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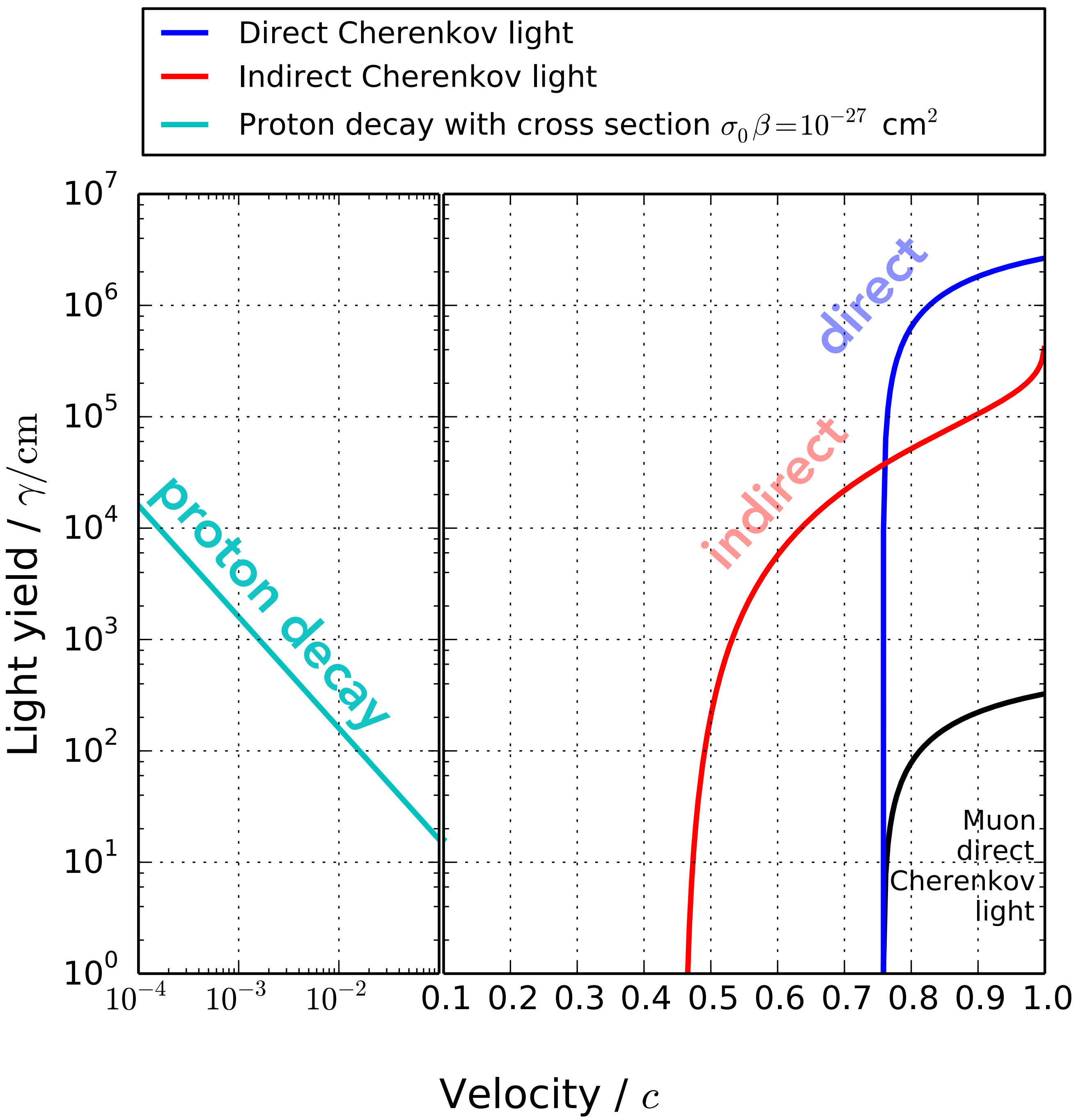


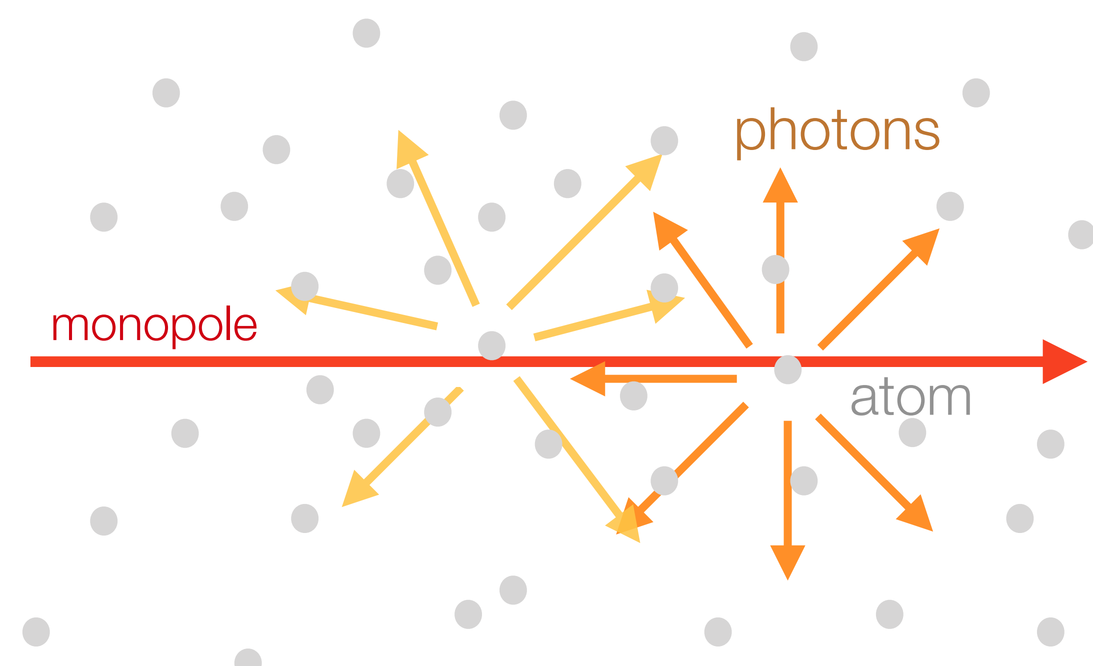
Slow speeds

exotic scenarios

- catalysis of proton decay
- thermal shock waves (not used yet)

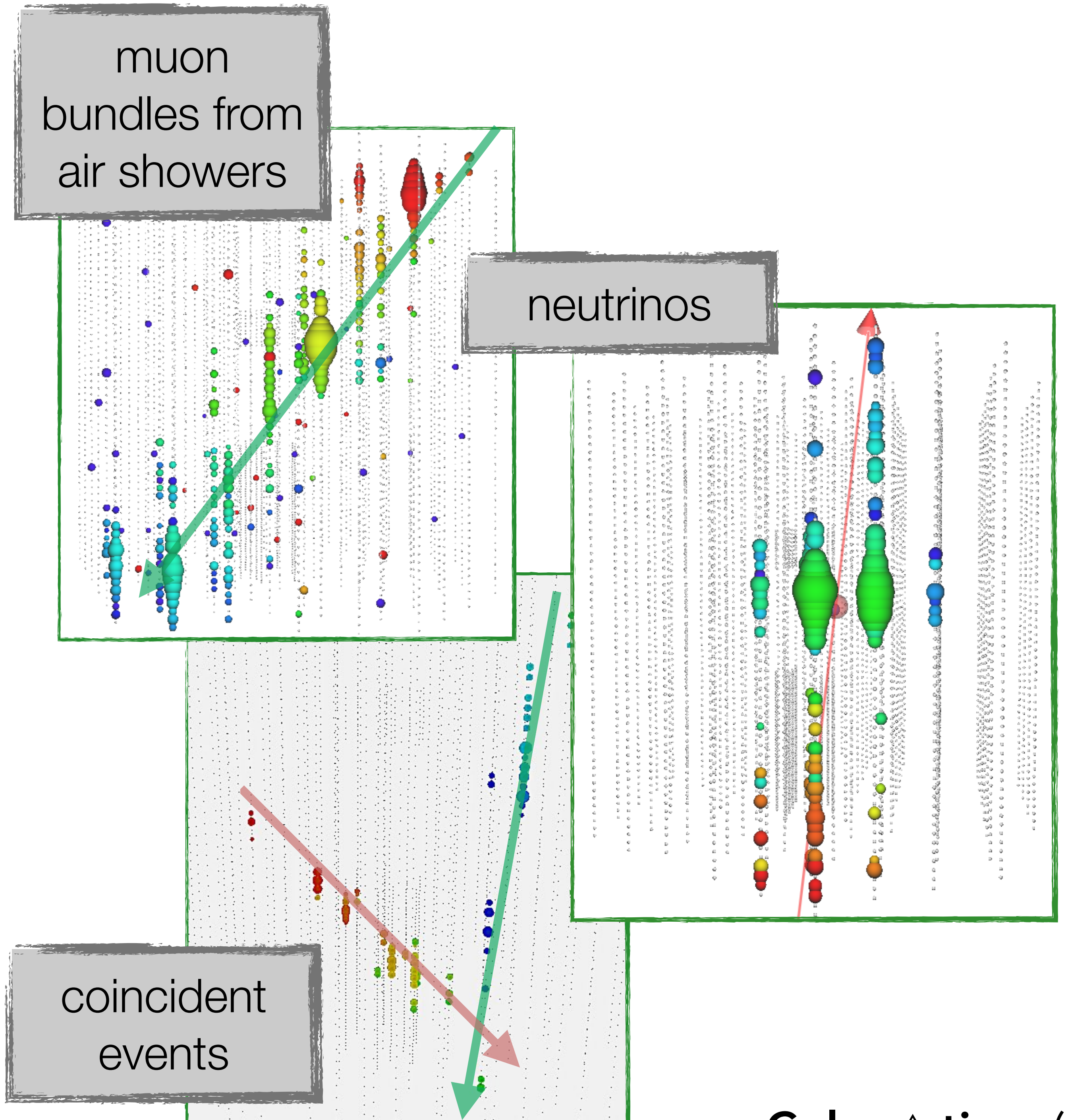
➡ model dependent

Light emission from proton decay

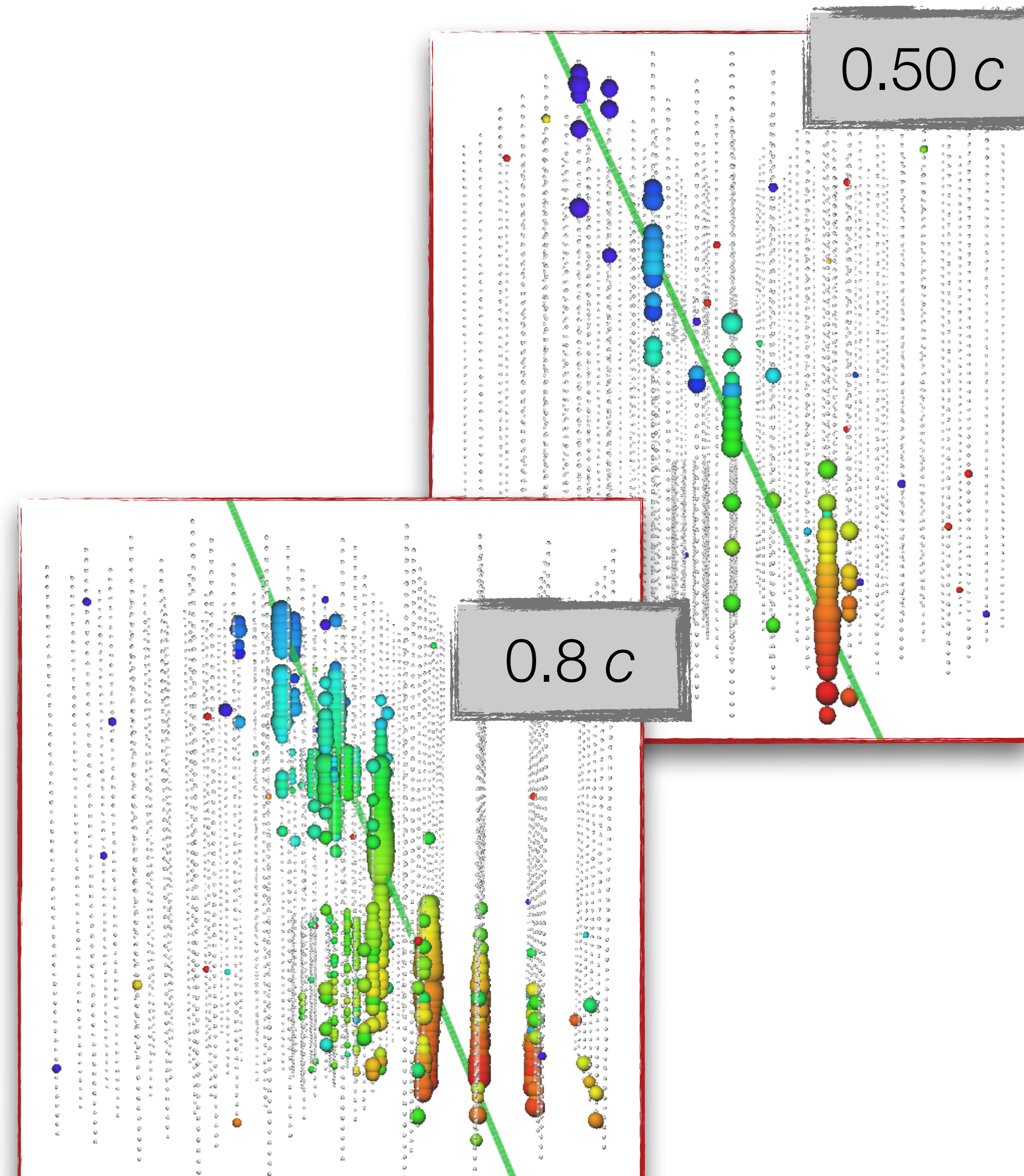


Signatures of fast Magnetic Monopoles

Background



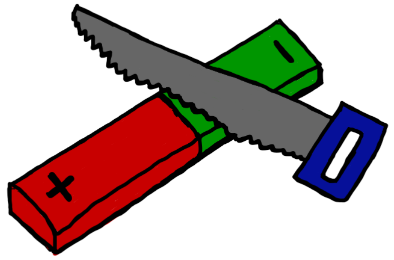
Magnetic Monopoles

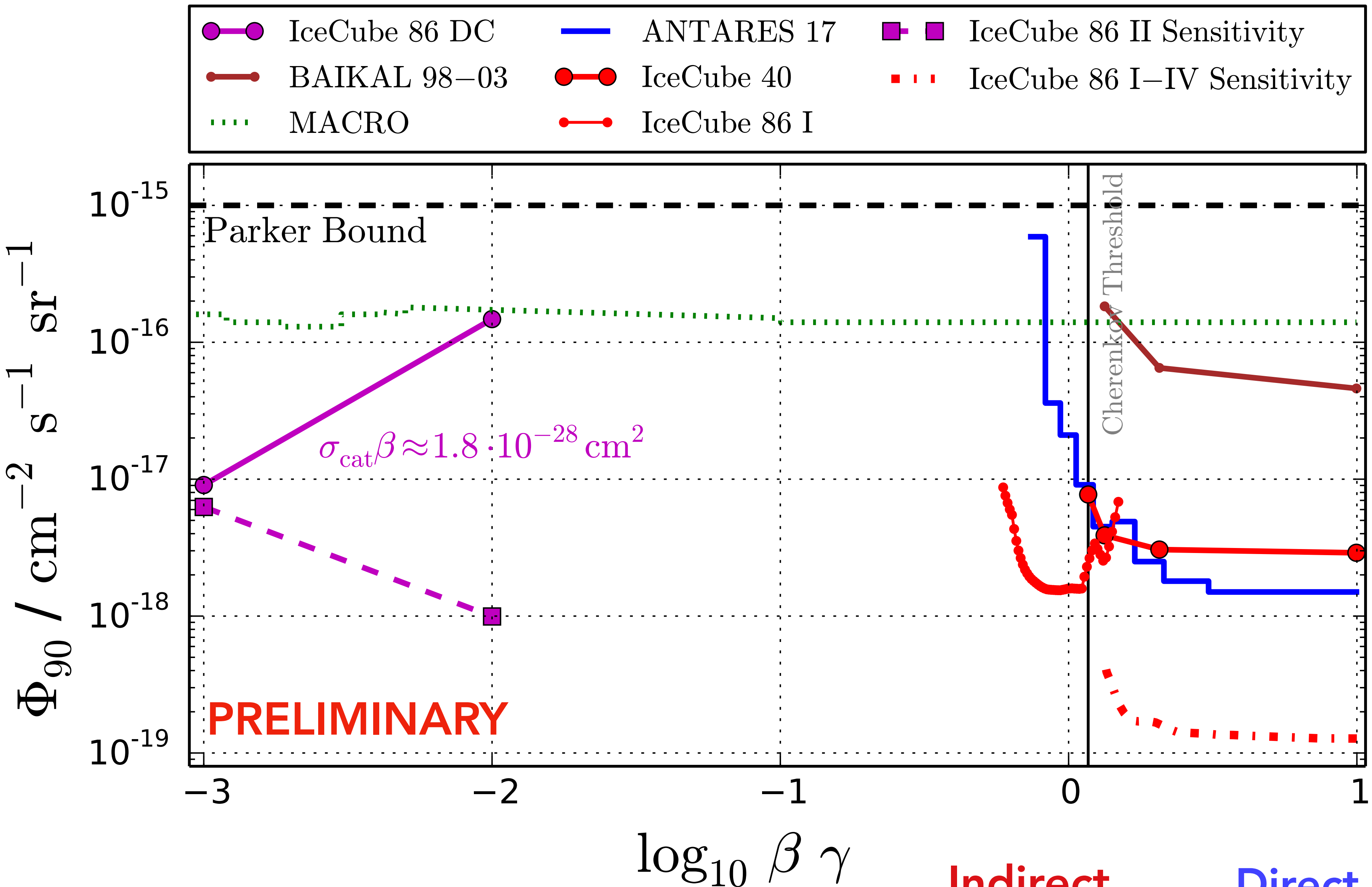


Color ≙ **time** (red -> blue)
Size ≙ **light amount**

EPJ C76 (2016) 133

Mapping the parameter space of Magnetic Monopoles





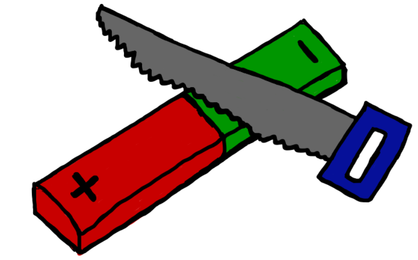
Catalysis of proton decay

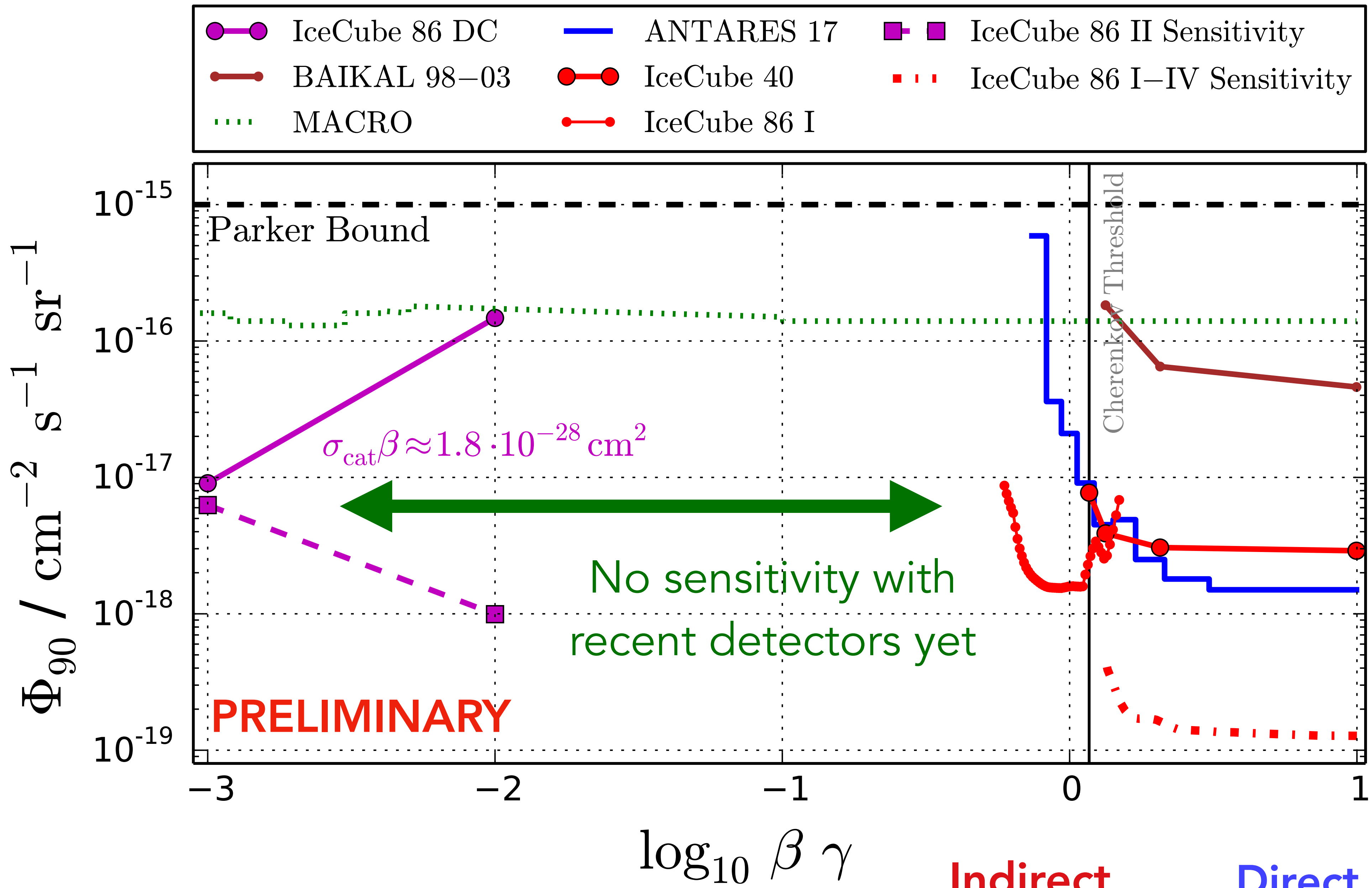
Indirect Cherenkov radiation

Direct Cherenkov radiation

EPJ C76 (2016) 133 &
EPJ C74 (2014) 2938

Mapping the parameter space of Magnetic Monopoles





Catalysis of proton decay

Luminescence

Indirect Cherenkov radiation

Direct Cherenkov radiation

EPJ C76 (2016) 133 &
EPJ C74 (2014) 2938

Light production by (exotic) particles in water and ice

Relativistic speeds
- continuous light emission
- stochastic losses

Intermediate speed

➡ **not covered yet**

Slow particle speed (< 0.1 c)
- catalysis of proton decay
- thermal shock waves

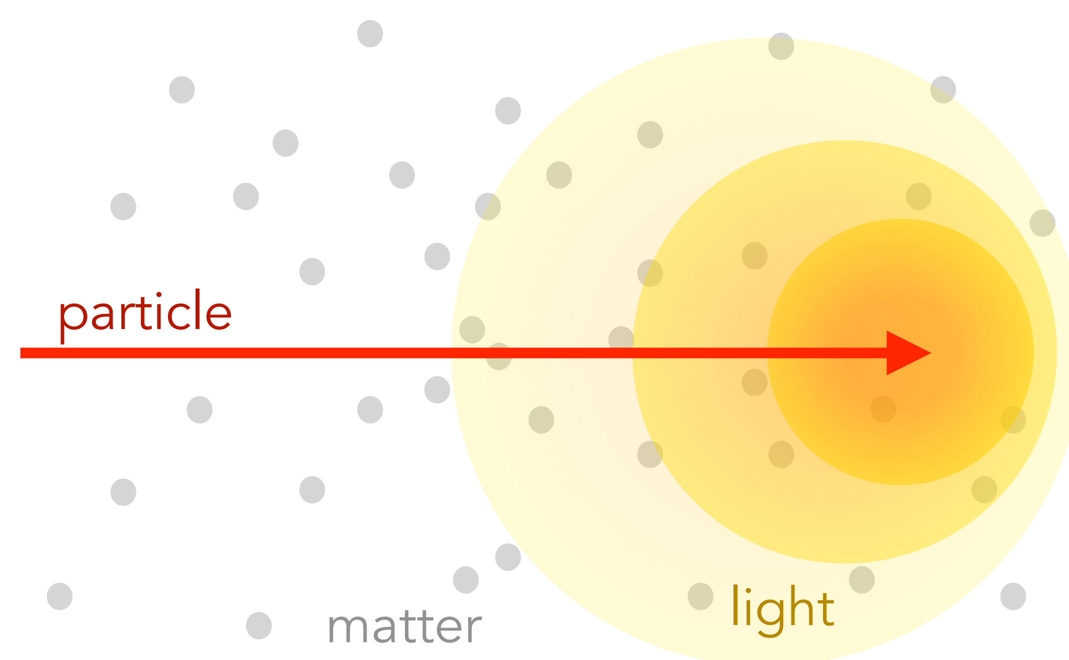
Idea: Luminescence light
- ionising radiation passes through matter
- it excites atoms/molecules
- relaxation with light emission

‣ works for all speeds

‣ works for all ionising particles

Light yield defines detectability!

Luminescence light emission pattern



Luminescence light measurement

Characterisation via

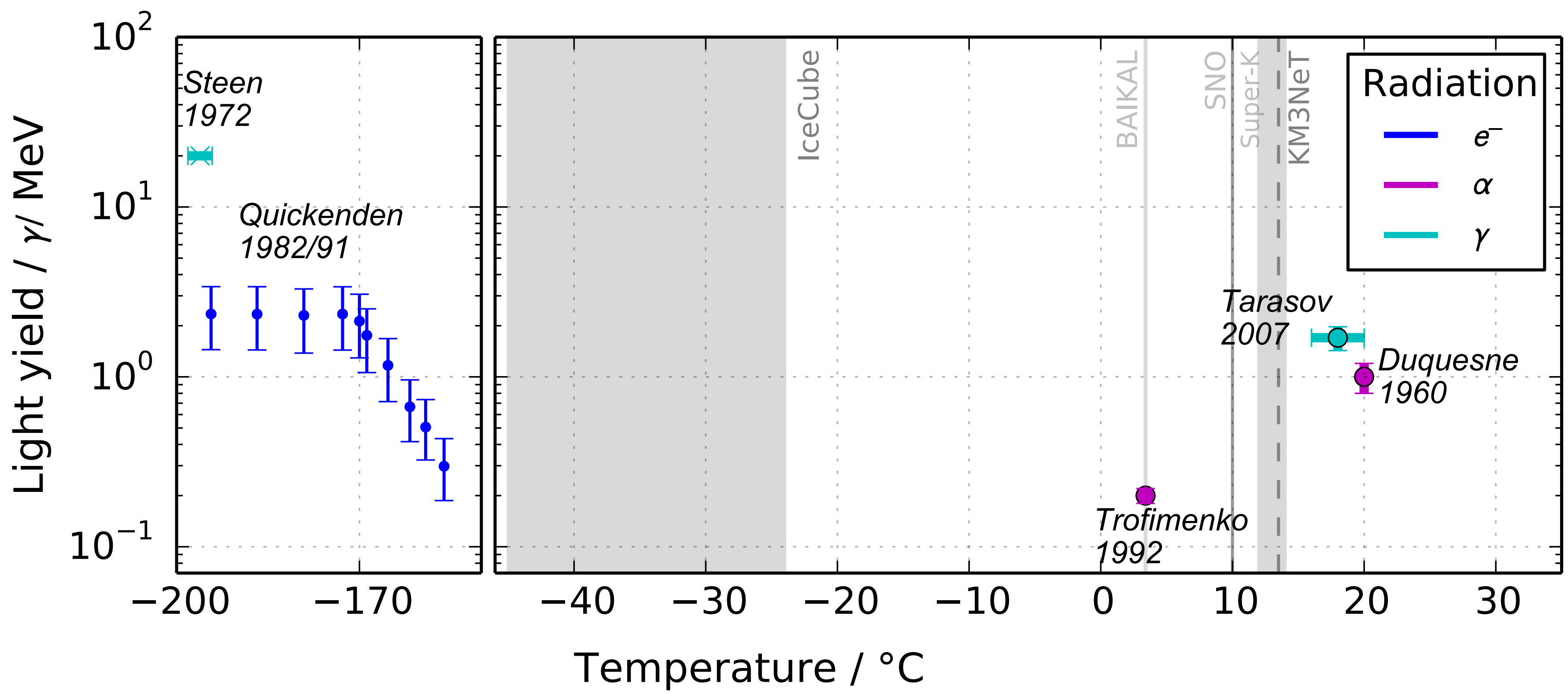
- light yield
- decay kinetics
- emission spectrum
- quenching

Dependencies

- temperature
- impurities / solubles
- radiation type
- pressure

Few existing measurements

with very different setups and results



Note:

- sample quality varies significantly between measurements
- different radiation causes different amount of quenching

Luminescence light measurement

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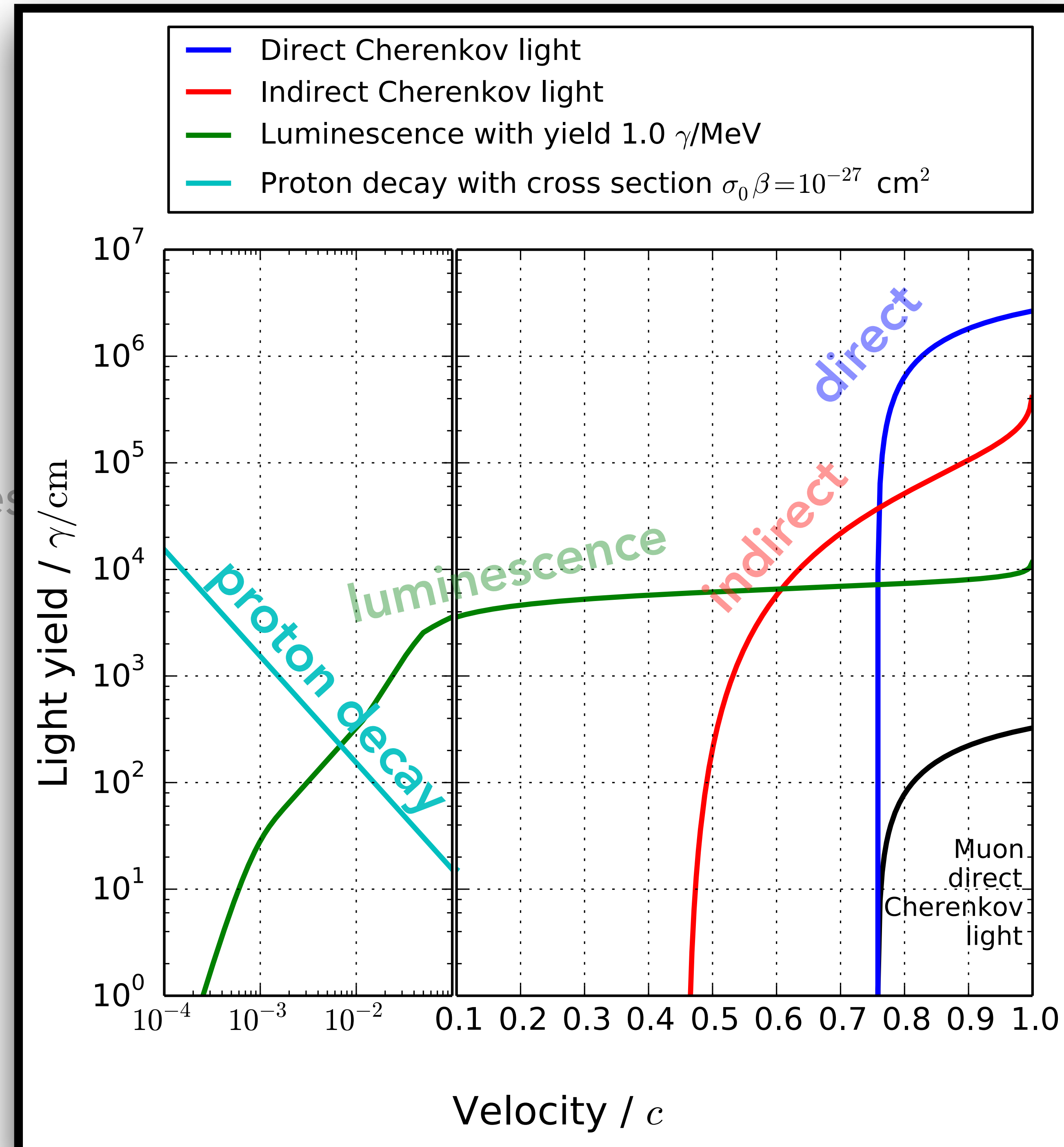
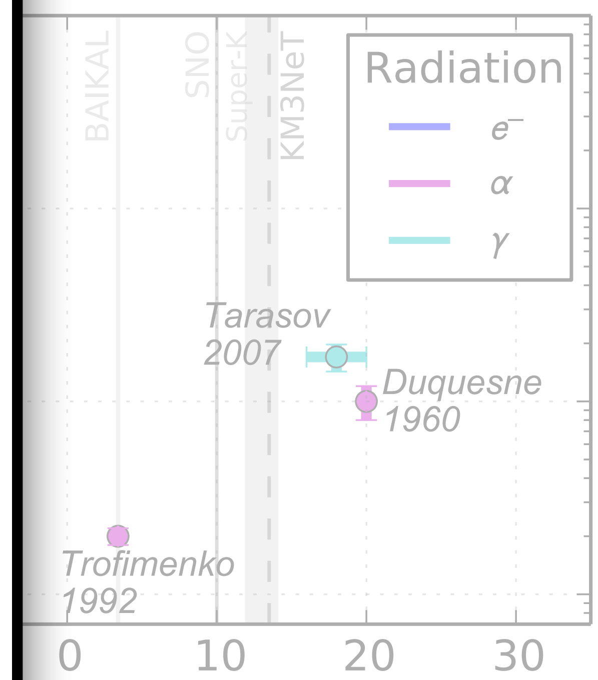


lts



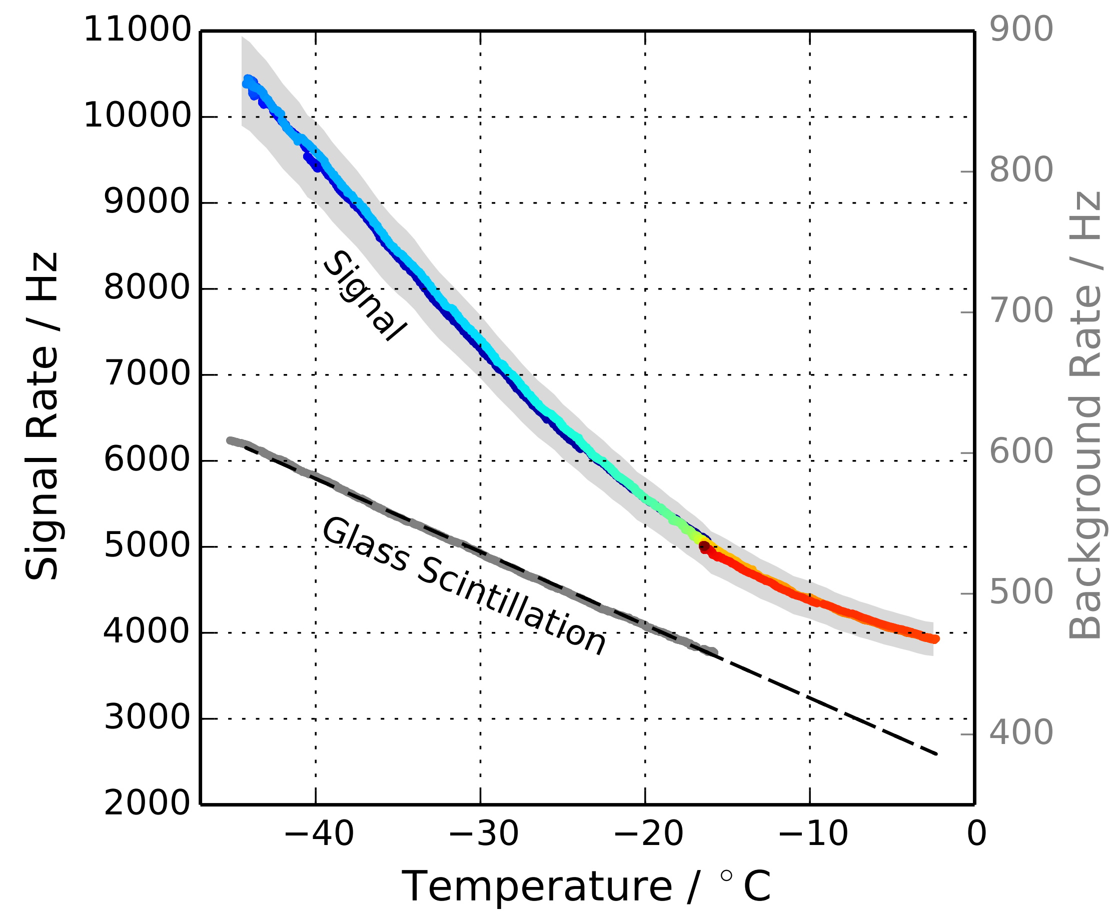
gnificantly

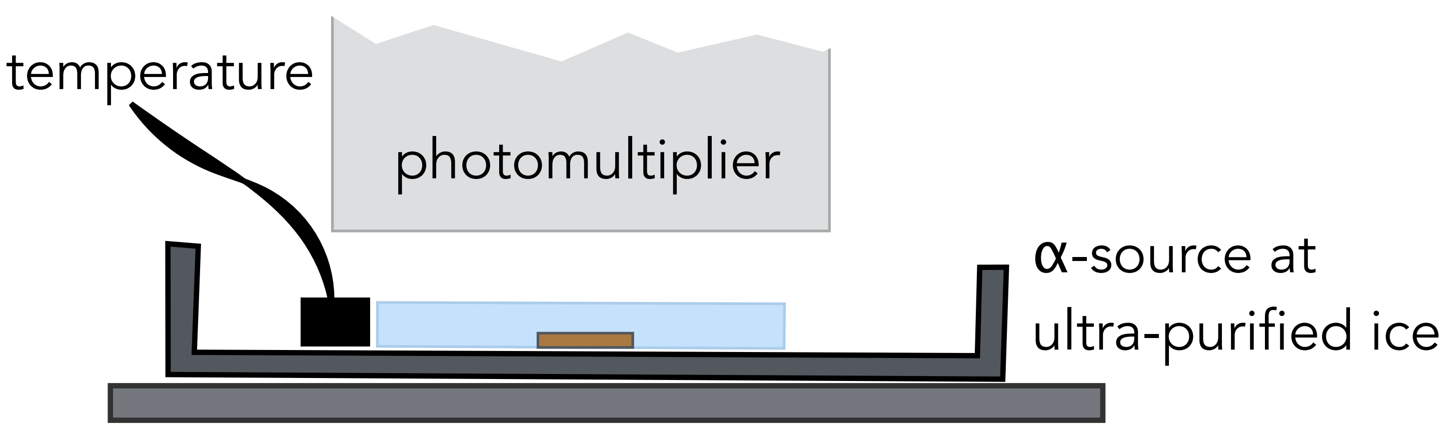
es different

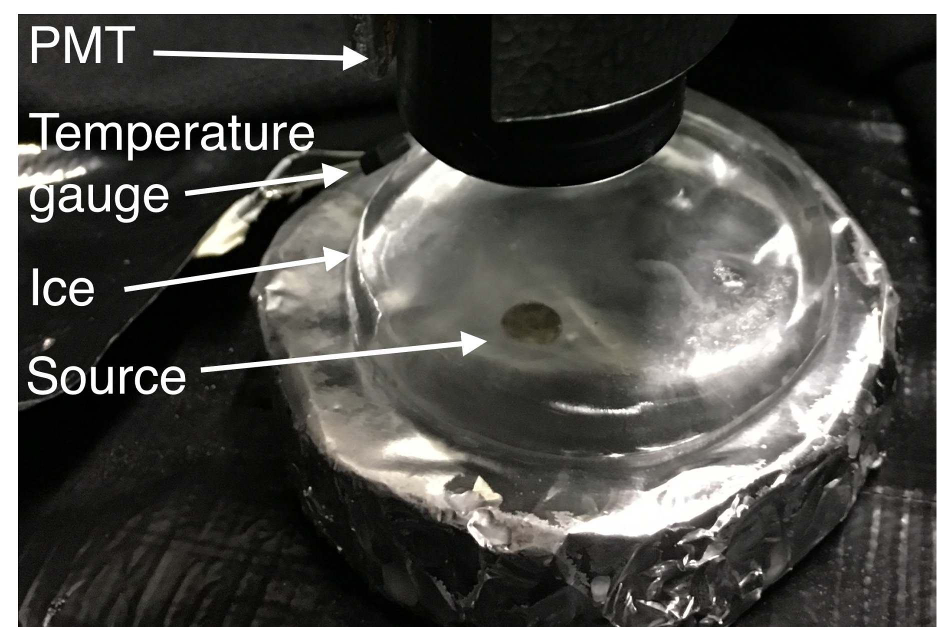
amount of quenching

Laboratory measurements

- ultra-purified water degassed in vacuum (frozen to bubble free ice)
- induced luminescence light with α-particles from ^{241}Am
- measured single photons with photomultiplier
- probed background (temperature dependent)
- calibrated & calculated optics

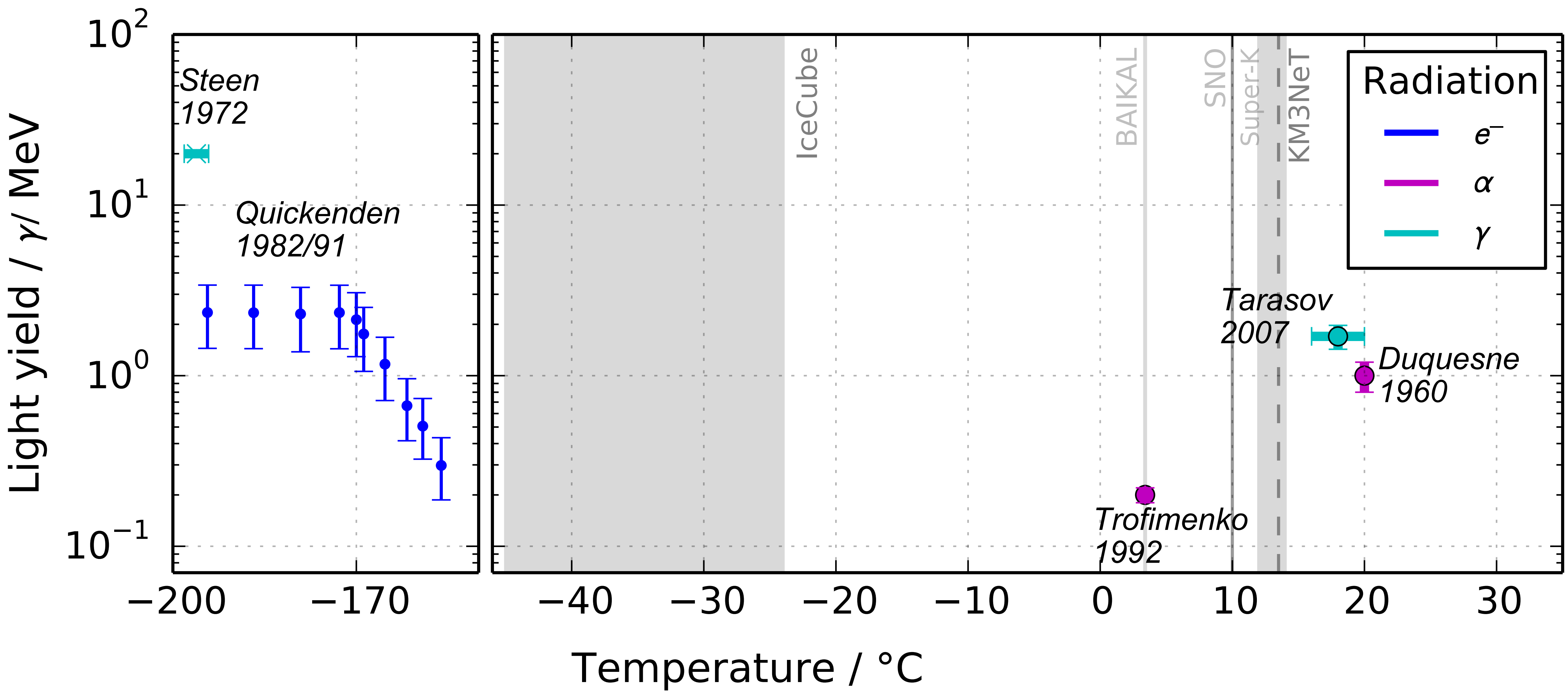






arxiv:1710.01197

Previous light yield measurements



Note:

- sample quality varies significantly between measurements
- different radiation causes different amount of quenching

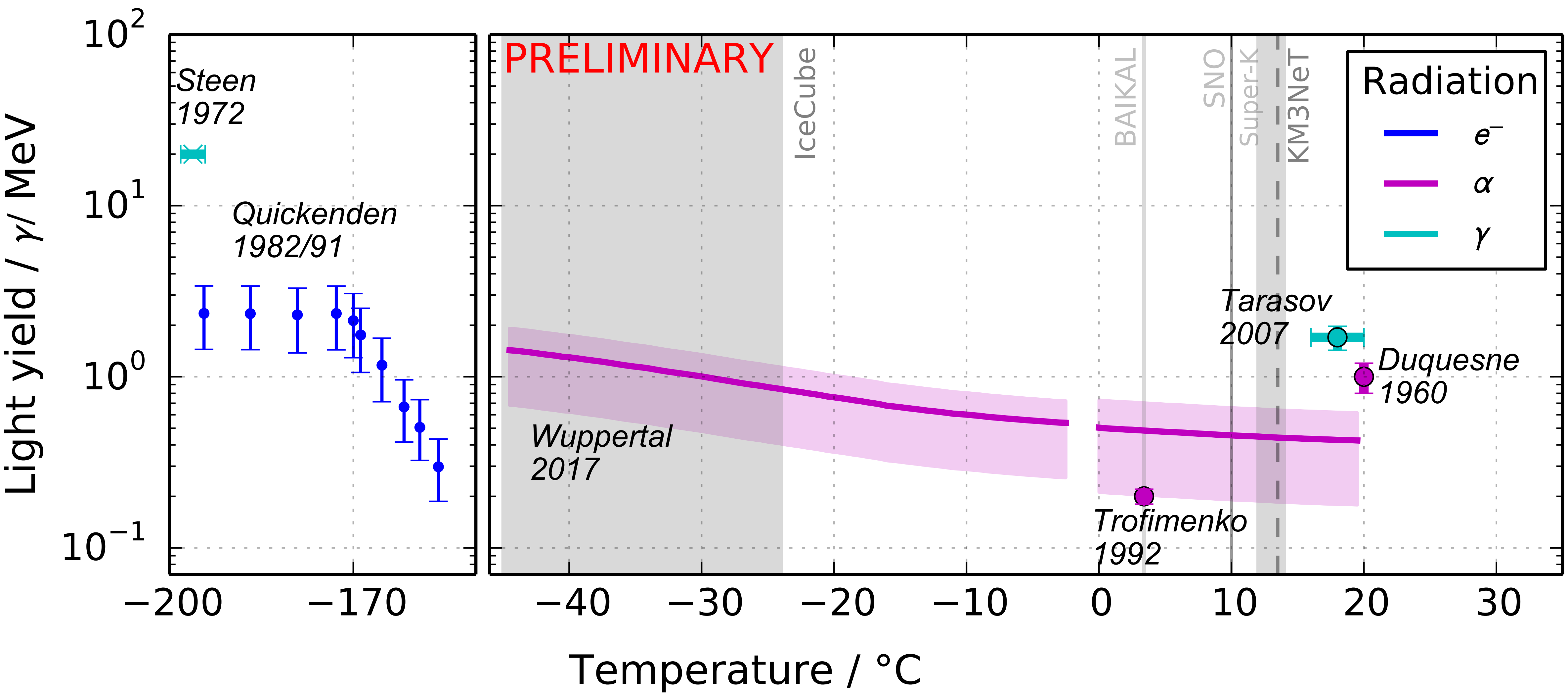
Comment:

- uncertainties of new laboratory measurement originates from water quality
- "Trofimenko" is the only <u>in-situ</u> measurement, all others use cleaned water

arxiv:1710.01197

Previous light yield measurements

First laboratory measurement at temperatures of neutrino telescopes



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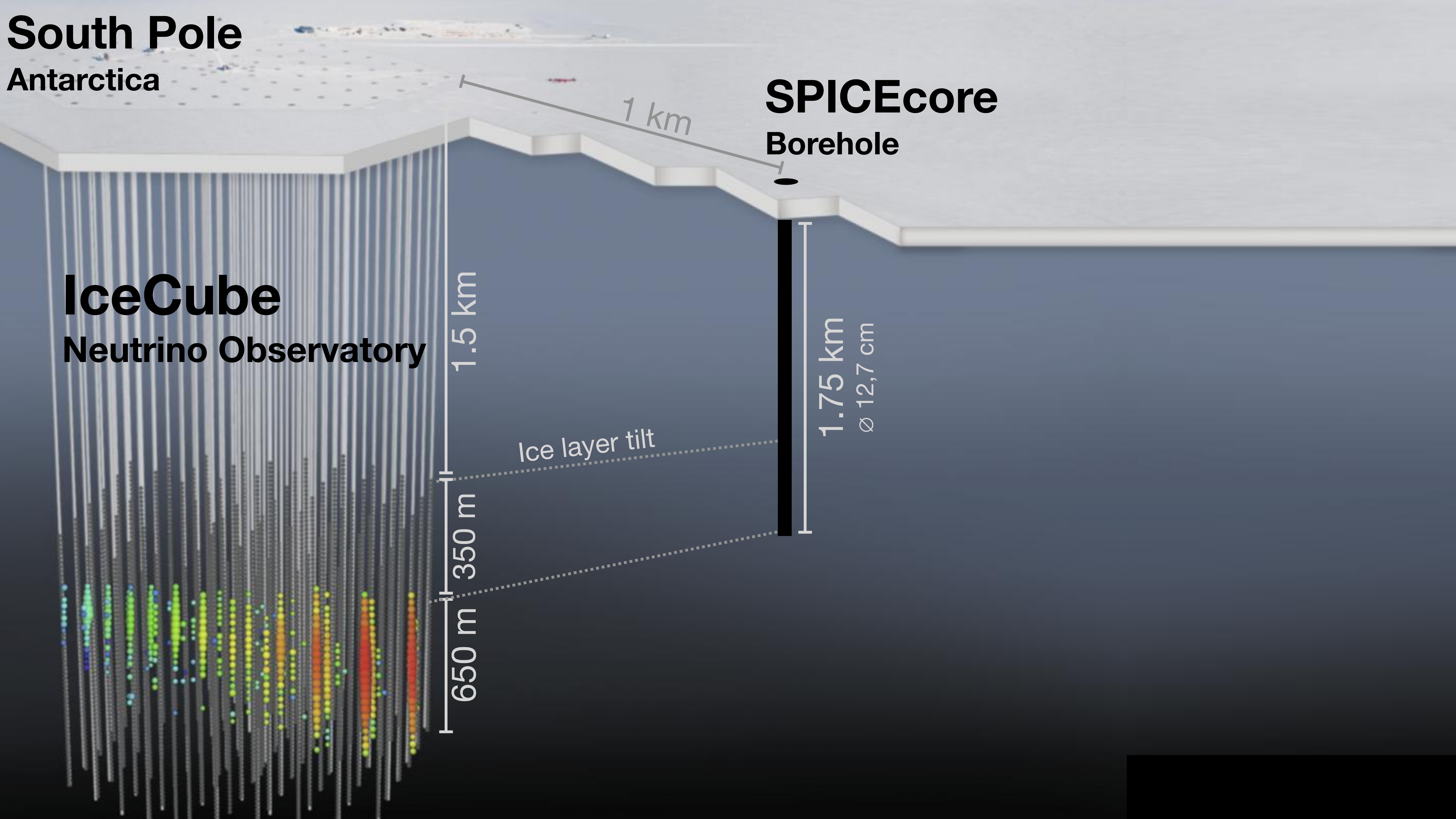
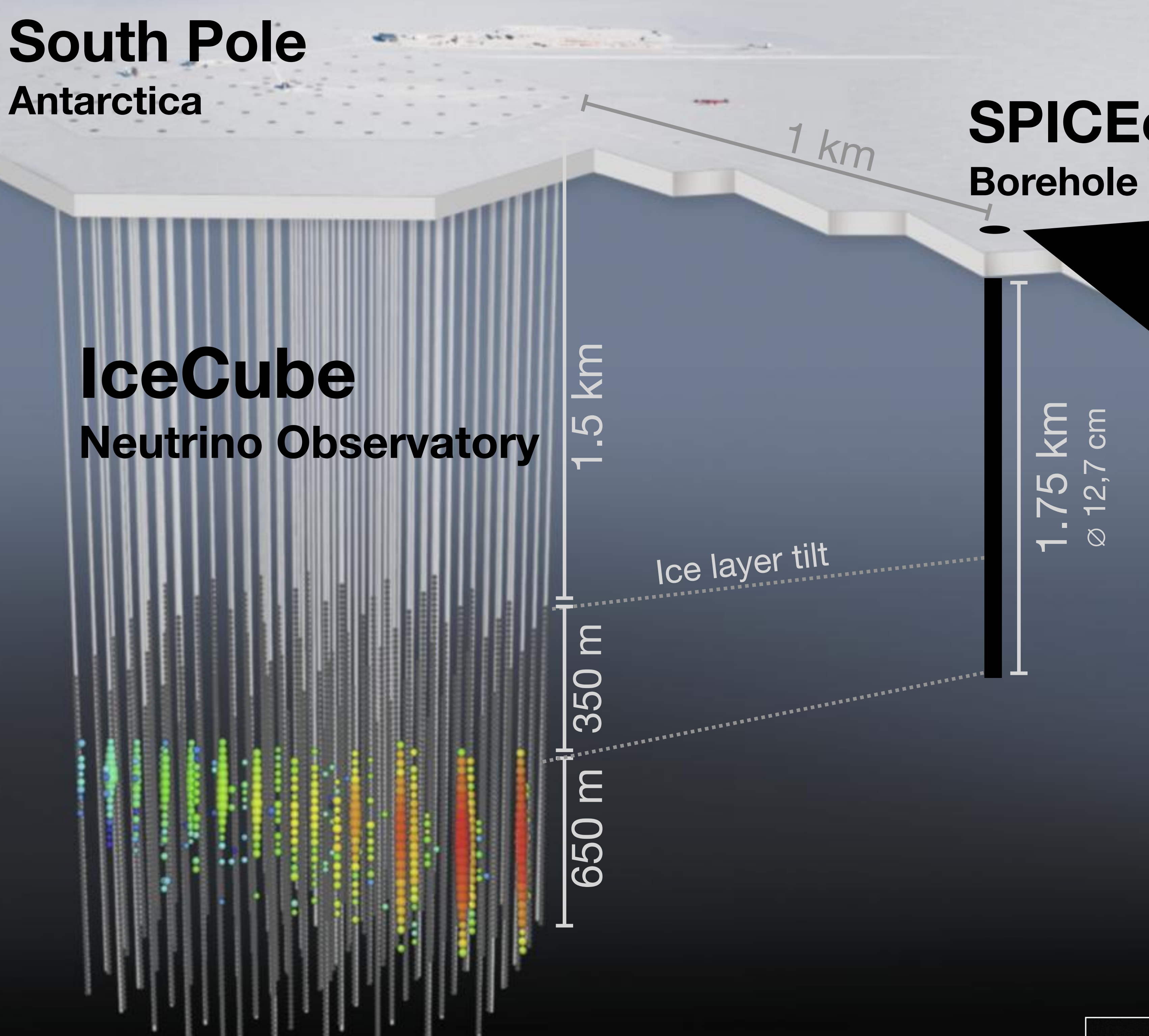
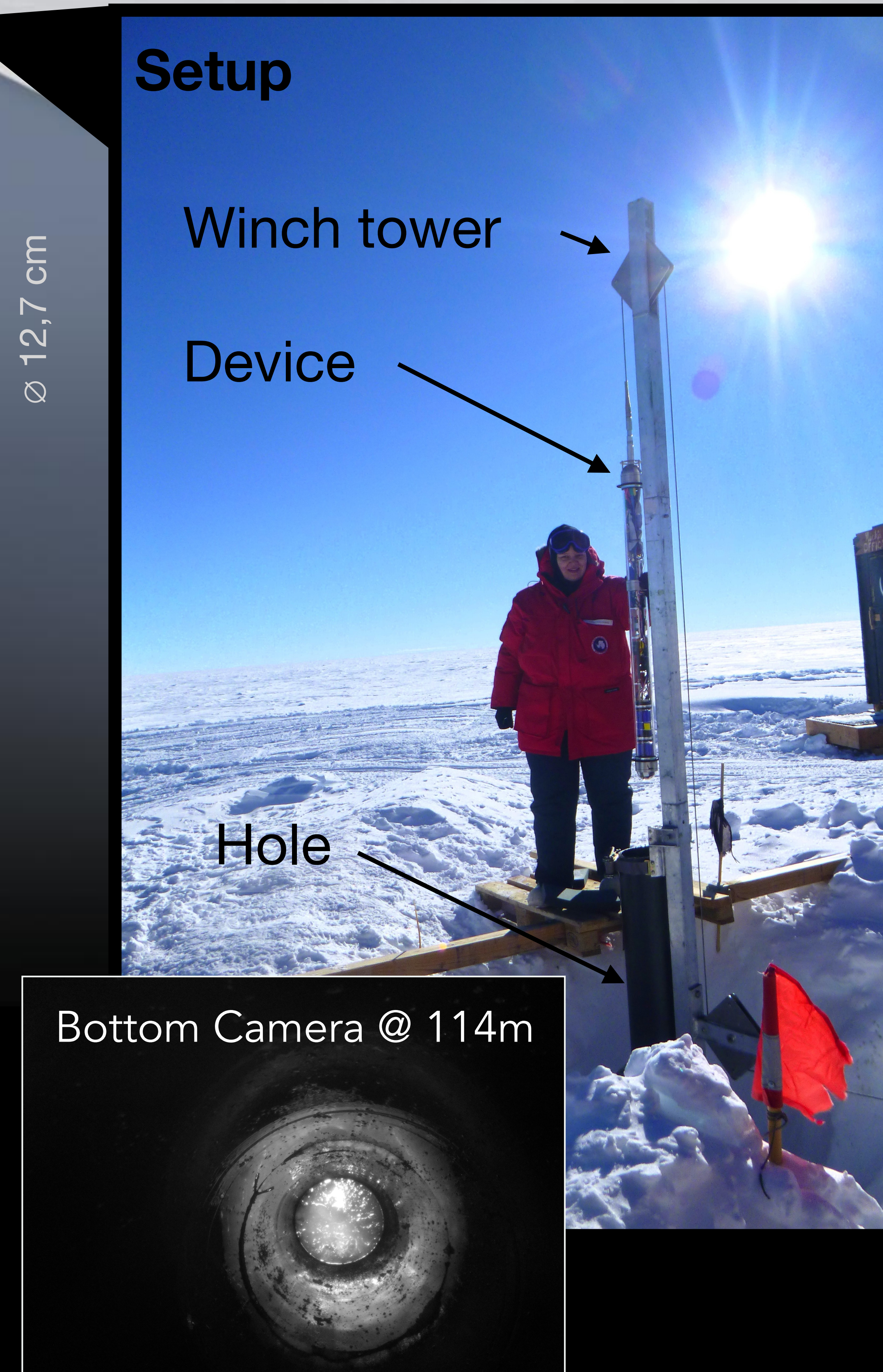


SPICEcore borehole

- filled with anti-freeze / drilling grease (Estisol)
- measurements in 2018 / 2019





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Luminescence Logger

Goal

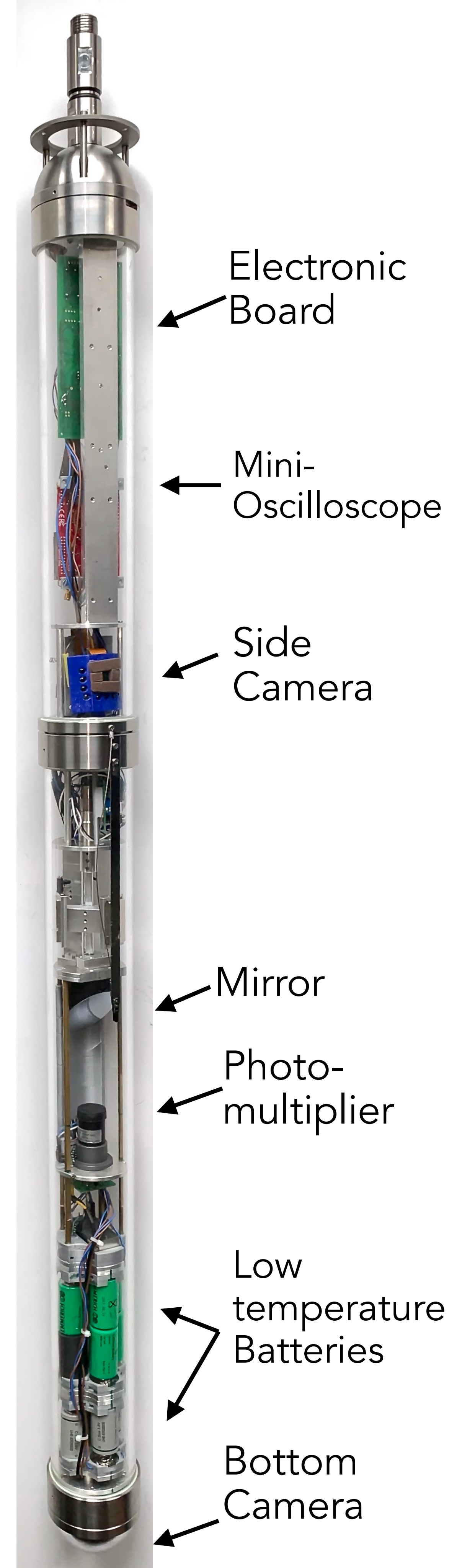
- irradiate ice with β-source and measure back-scattered light

Method

- press source against ice
- guide scattered light onto photomultiplier

Details

- diameter: max 92 mm
- length: 1.30 m
- commercial mini USB-oscilloscope for readout
- light detection with photomultiplier tube
- several sensors: i.e. temperature, gyro, IR camera



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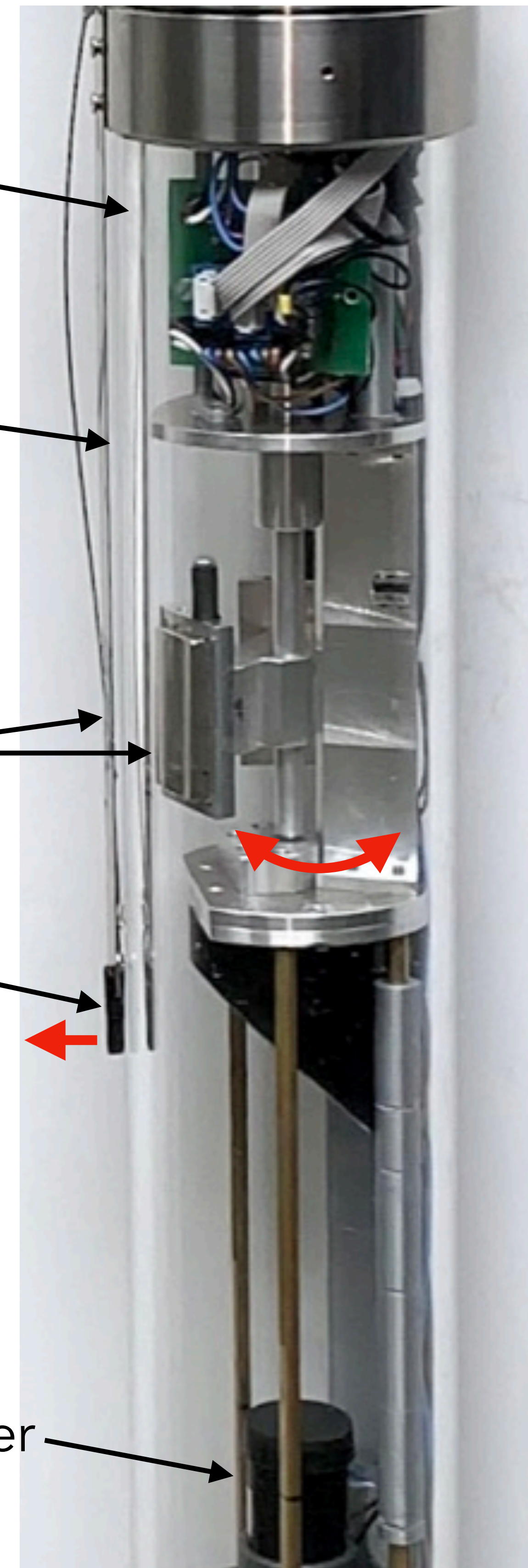

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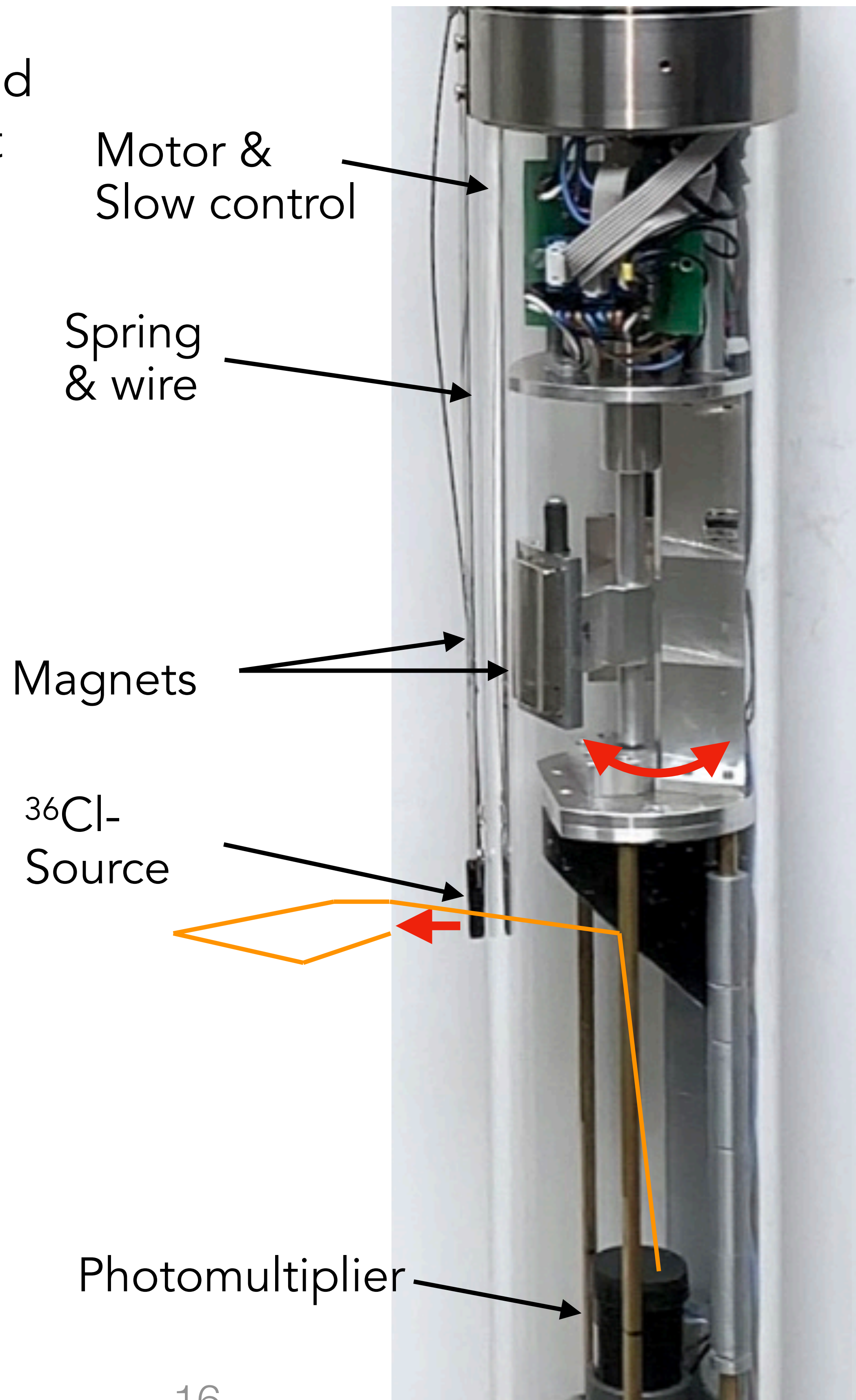
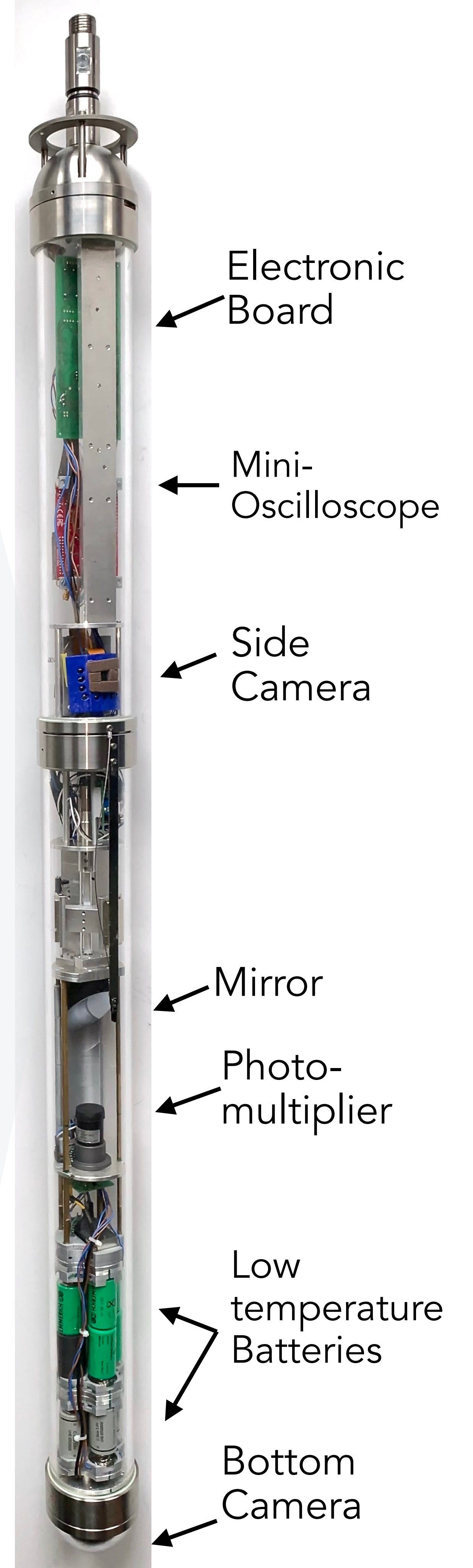
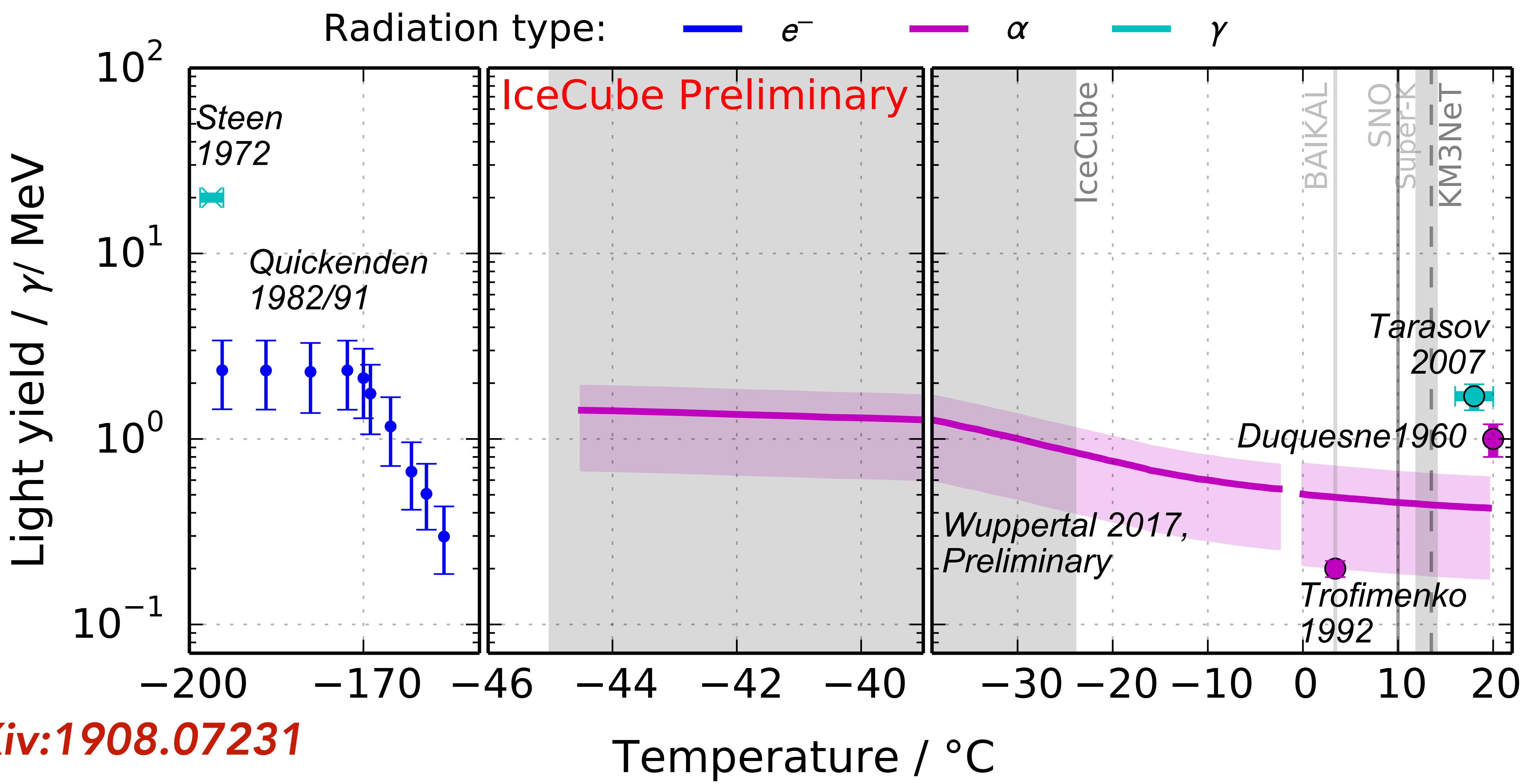




Results: Luminescence light measurement



arXiv:1908.07231

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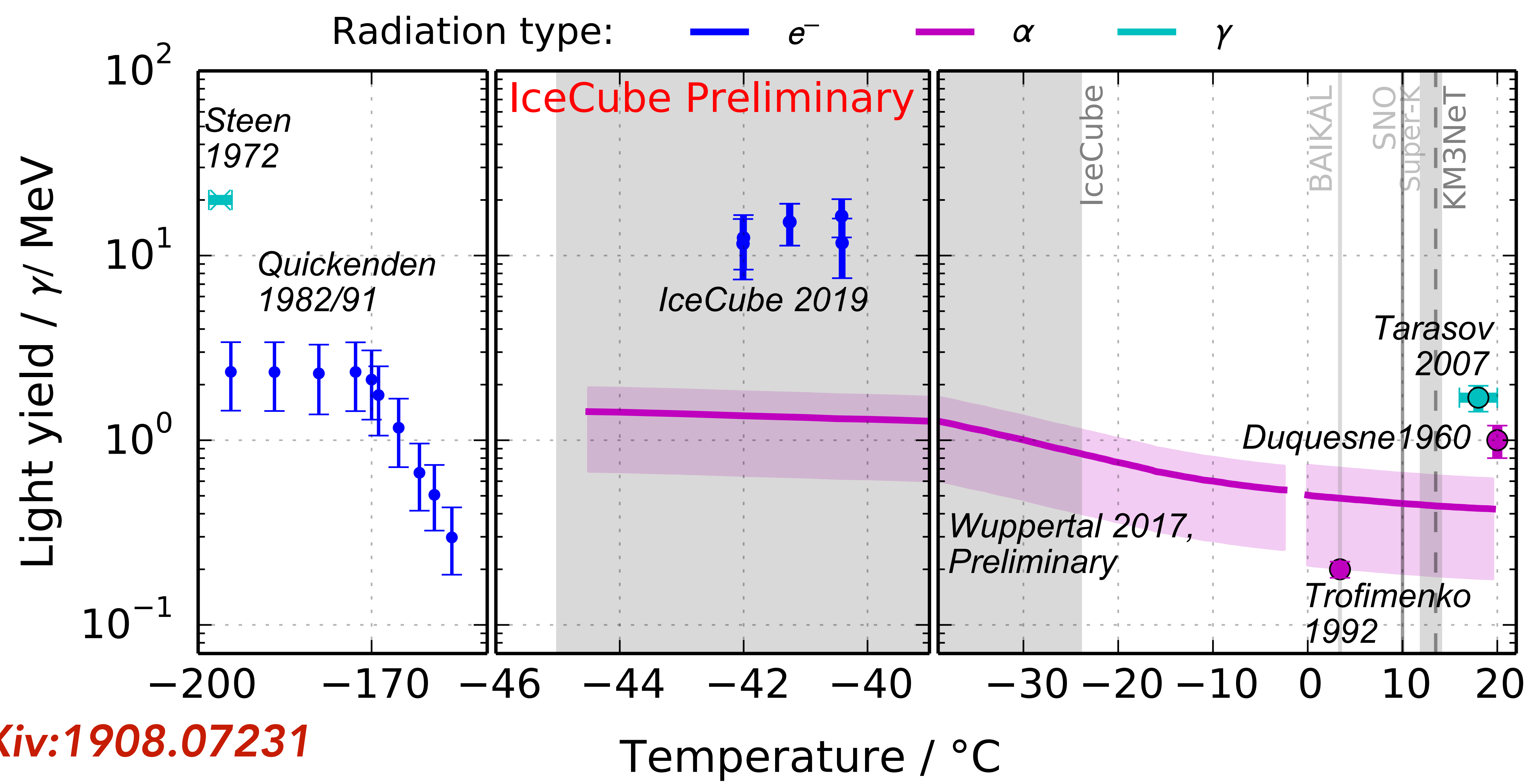

arXiv:1908.07231

Decay times

2.44 ± 2.07 ns

196.1 ± 39.1 ns

5.03 ± 0.06 μs

56.1 ± 6.29 μs

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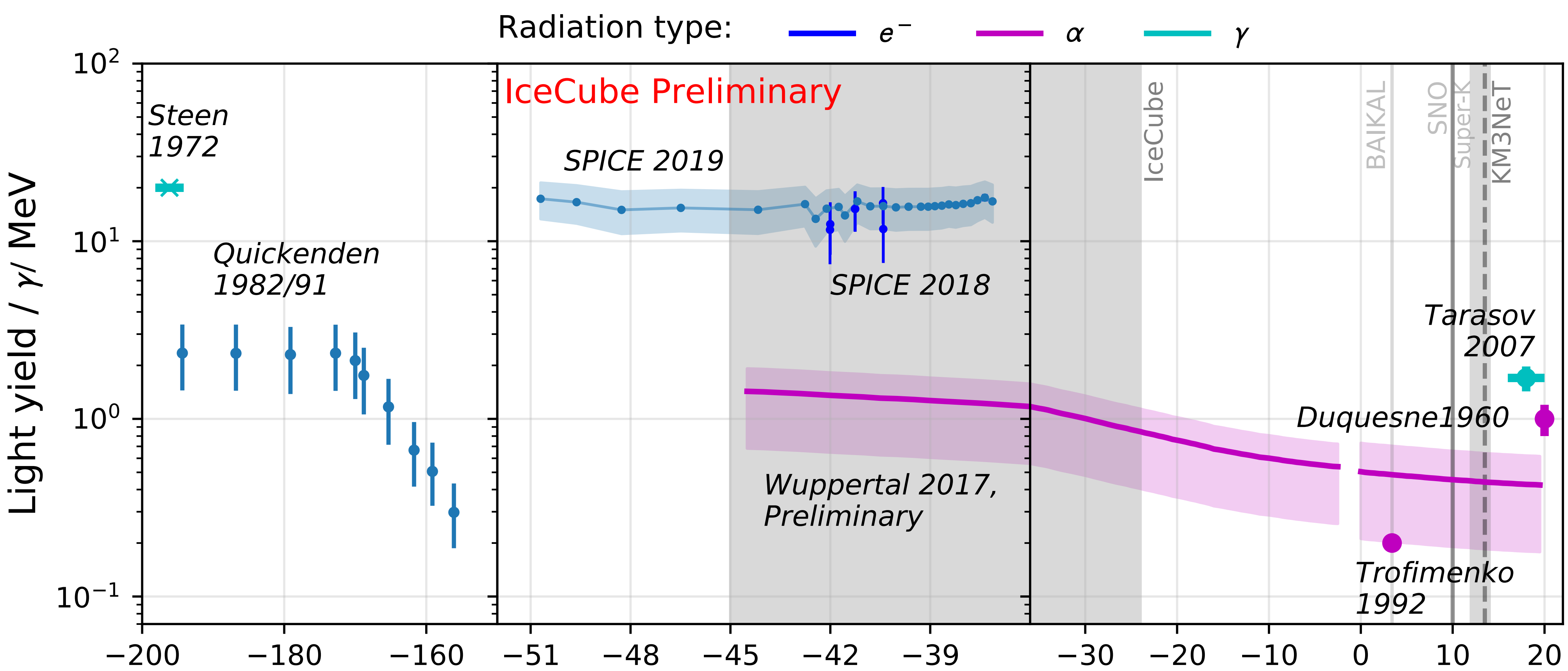

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Publication under preparation

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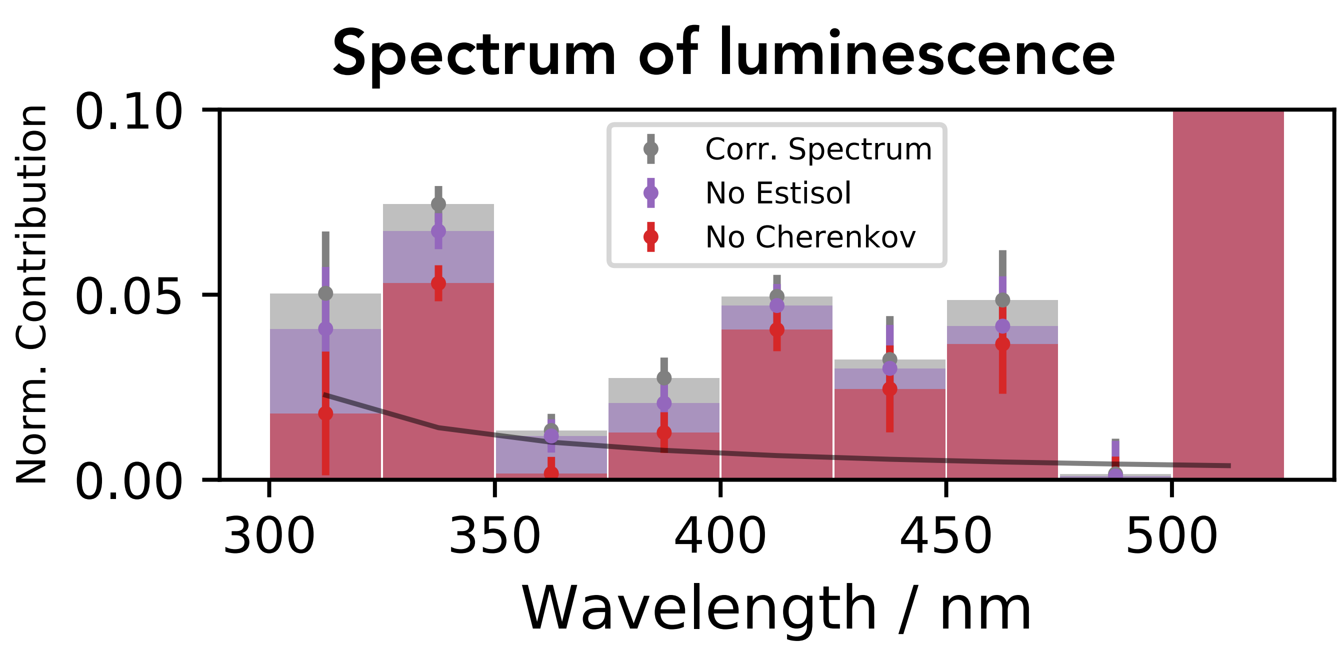
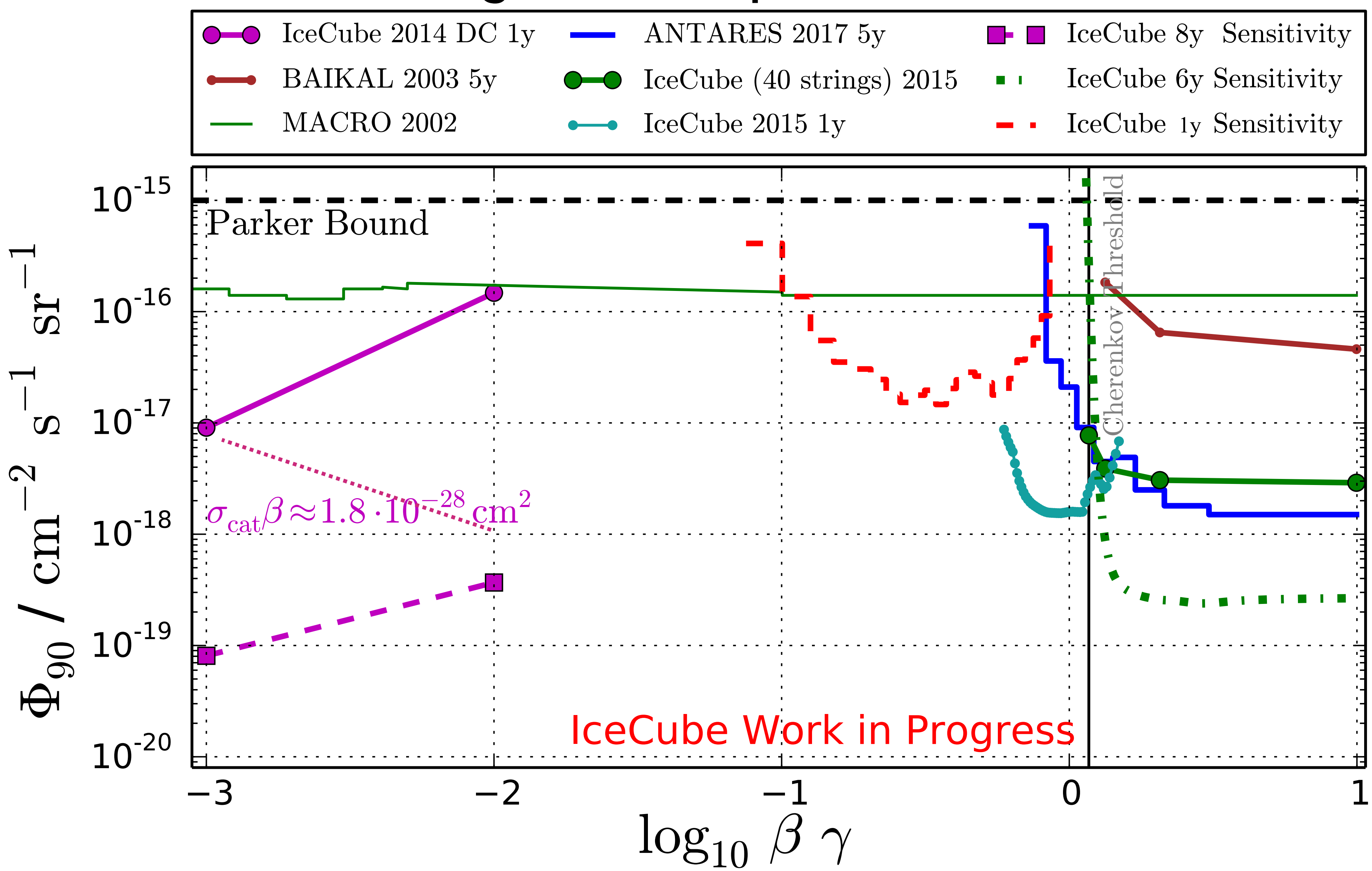
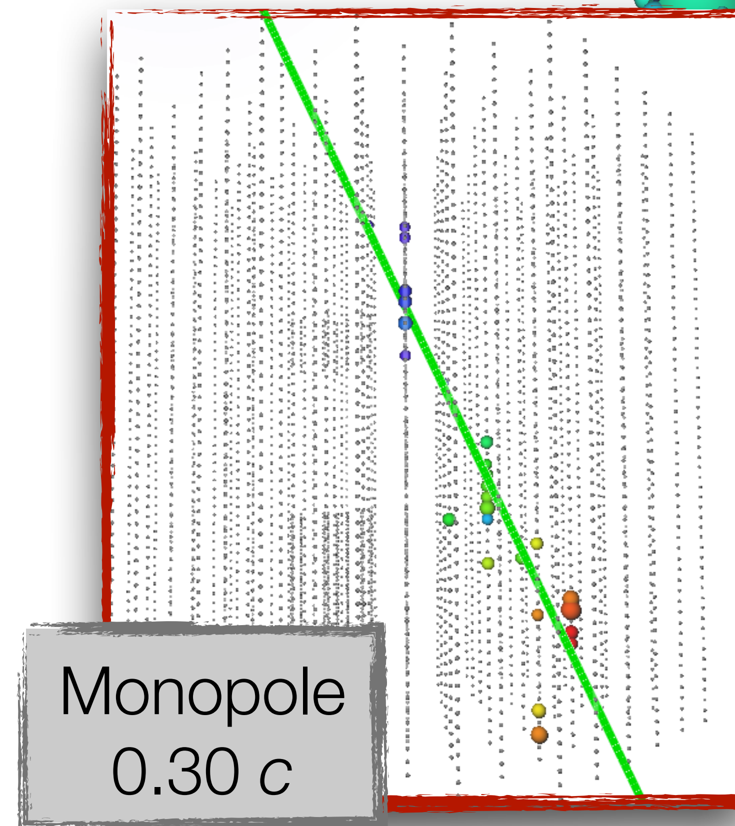


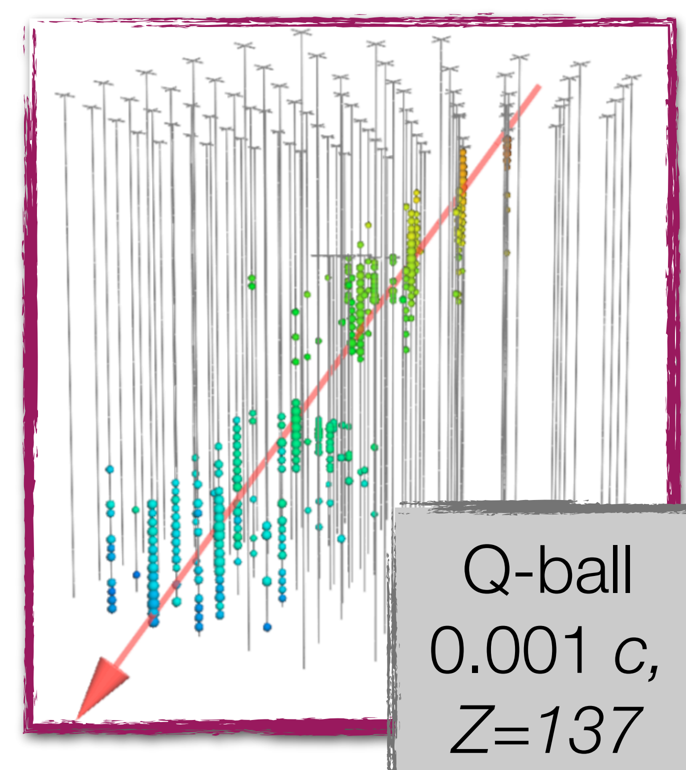
Applications of ice luminescence

- searches for exotic particles incl. neutral particles
- calibration of ultra high energy neutrinos
- particle identification
- ice classification on icy moons in the solar system

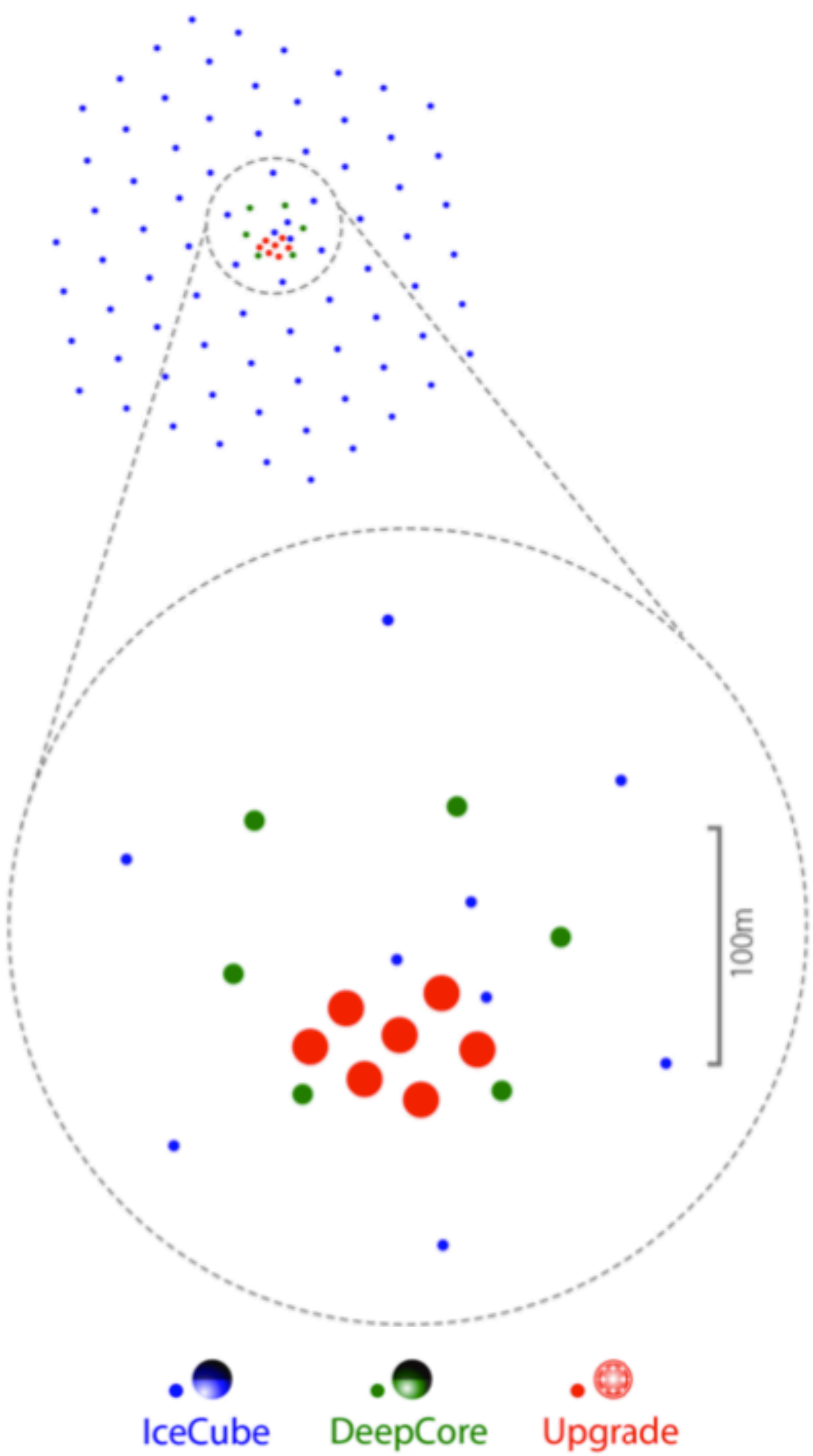
Magnetic monopole exclusion limits



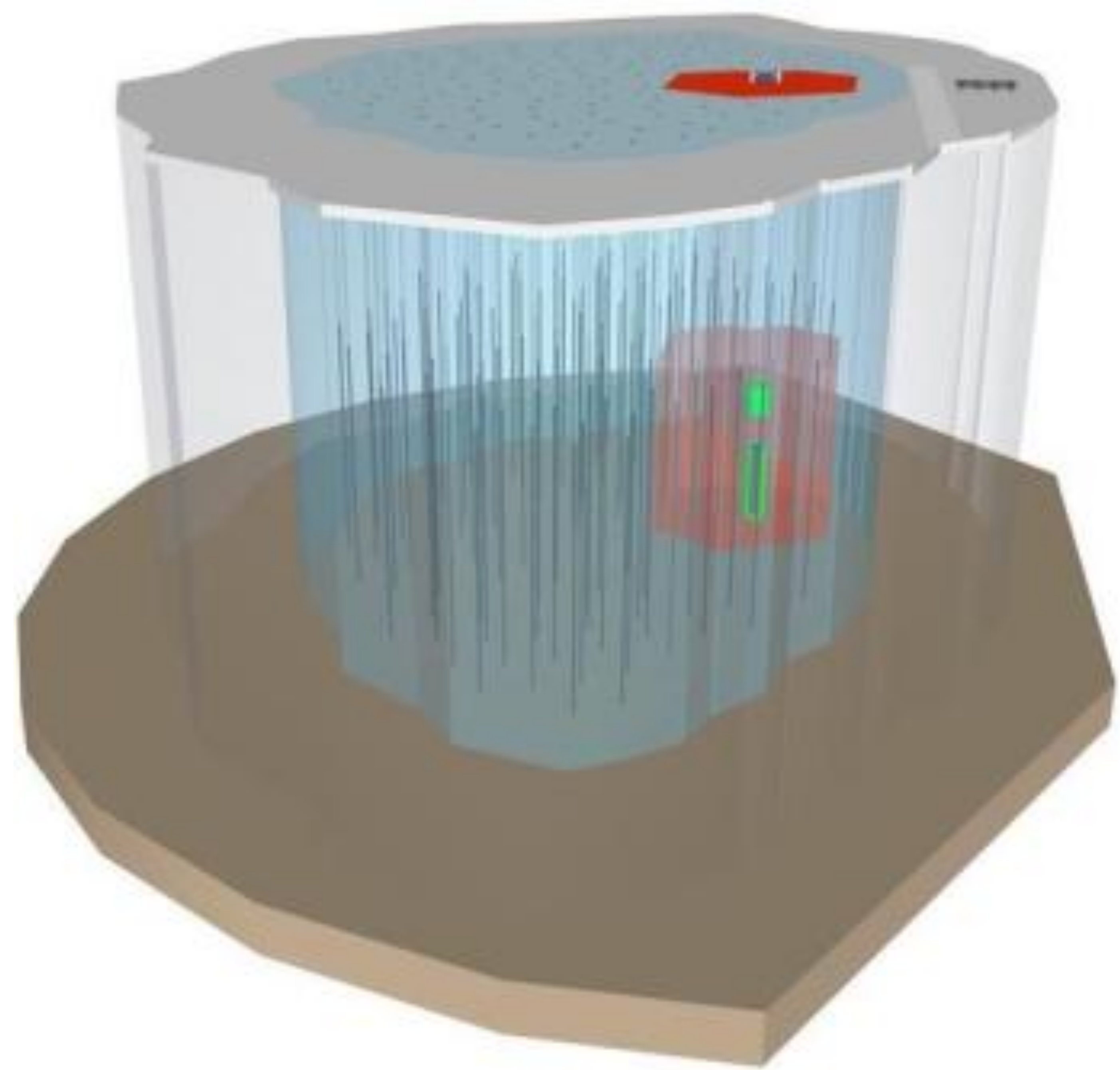




IceCube Upgrade
(construction end 2022)



IceCube Gen2
(starting ~2025)



Towards more sensitive & larger particle detectors

mDOM: new detector module for the Upgrade (2022)

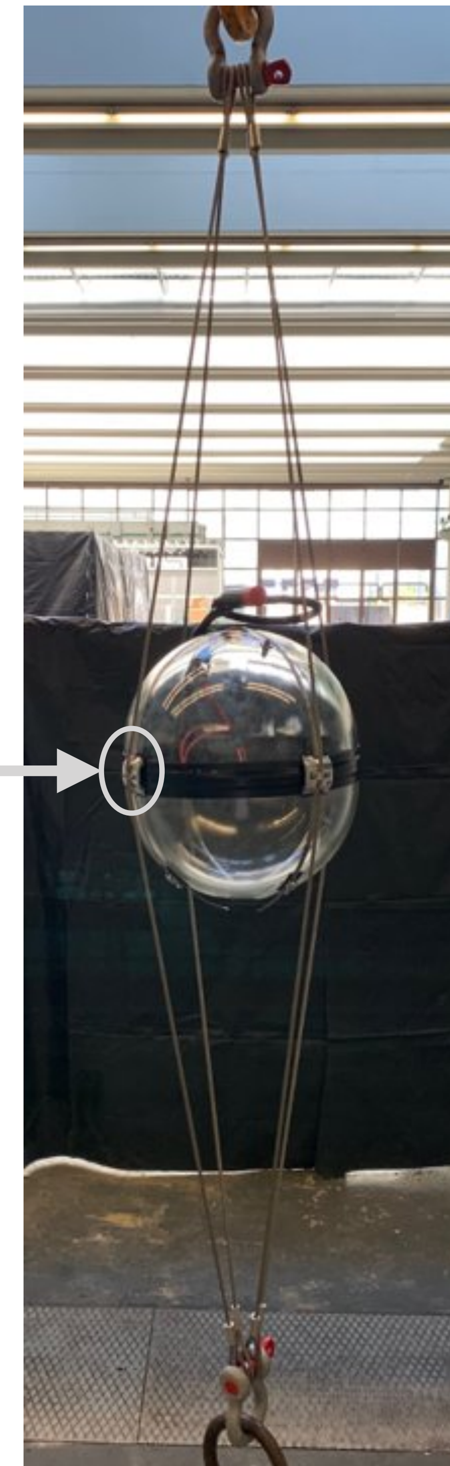
- 24 instead of 1 PMT
- better signal/noise ratio
- directional sensitivity
- 450 modules to be build in Berlin and Michigan

Mechanical integration

- low coverage of sensors
- safety at extreme environment

Current status:

- prototype reviewed
- test production of 10 modules



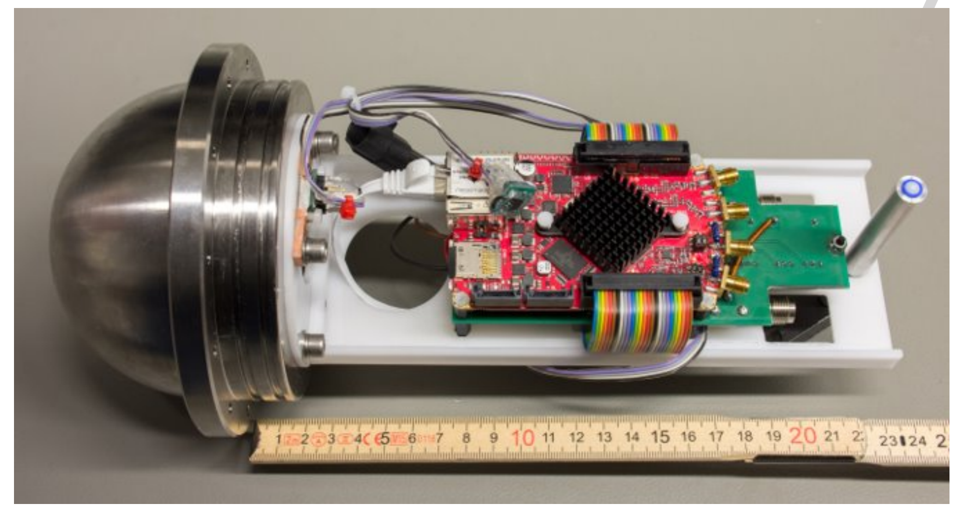
Towards more sensitive & larger particle detectors

WOM: new detector module for the Generation 2 (>2025)

- 1 prototype on its way to the ocean network canada (ONC)
- 15 modules for the Upgrade 2022
- O(1000) modules for Generation 2 >2025

Prototype for ONC

Electronics based on logger



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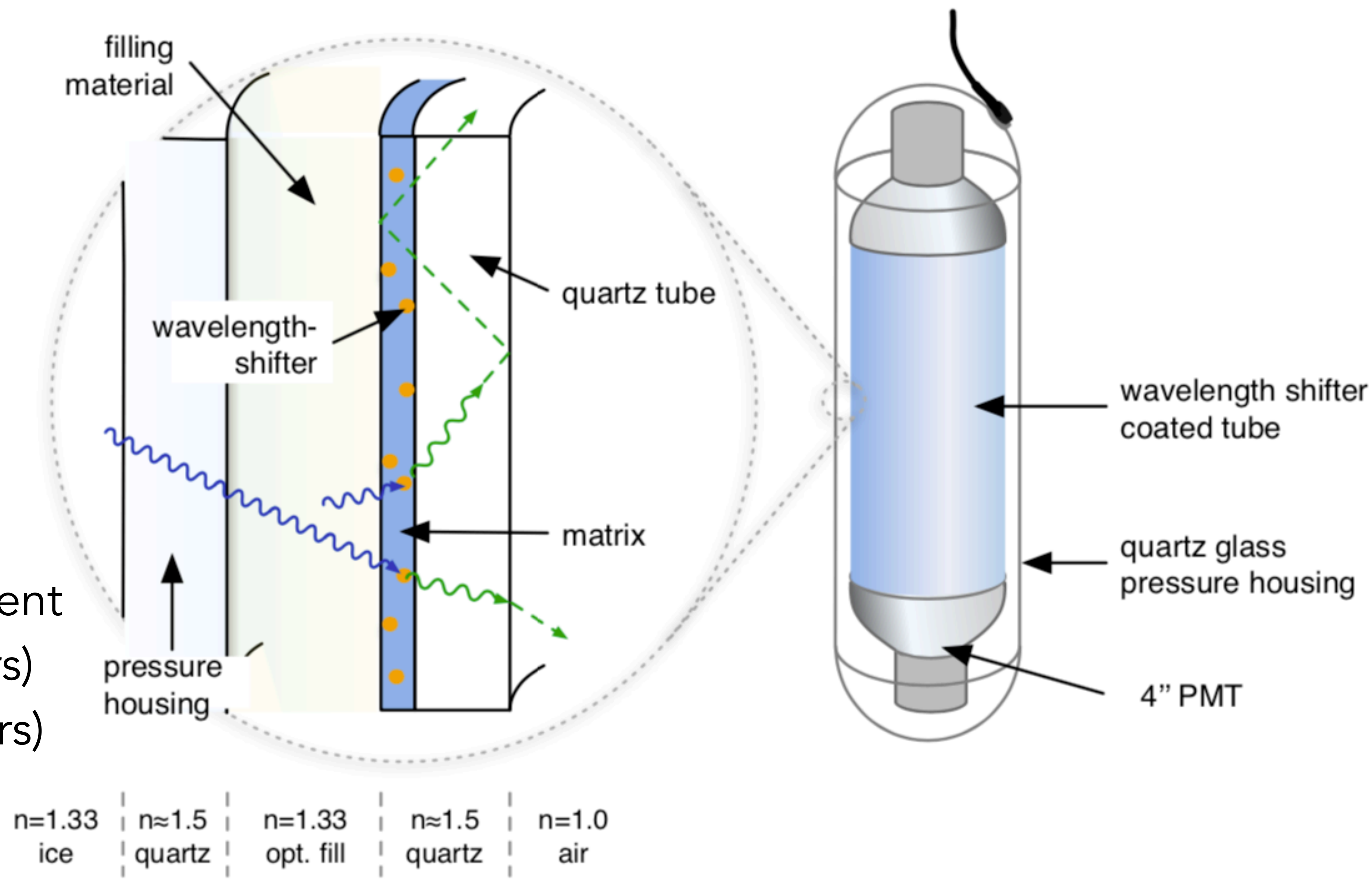
- 1 prototype on its way to the ocean network canada (ONC)
- 15 modules for the Upgrade 2022
- O(1000) modules for Generation 2 >2025

Tasks (Sept. 2021)

- overall mechanical integration
- pressure vessel
- electronics development
- calibration (with others)
- production (with others)

Physics to improve sensor



Back to beyond standard model physics

- fractionally charged particles
- Q-balls (via standard methods and using luminescence)
- nuclearites (via thermal shocks, maybe experiments needed)
- … and many more

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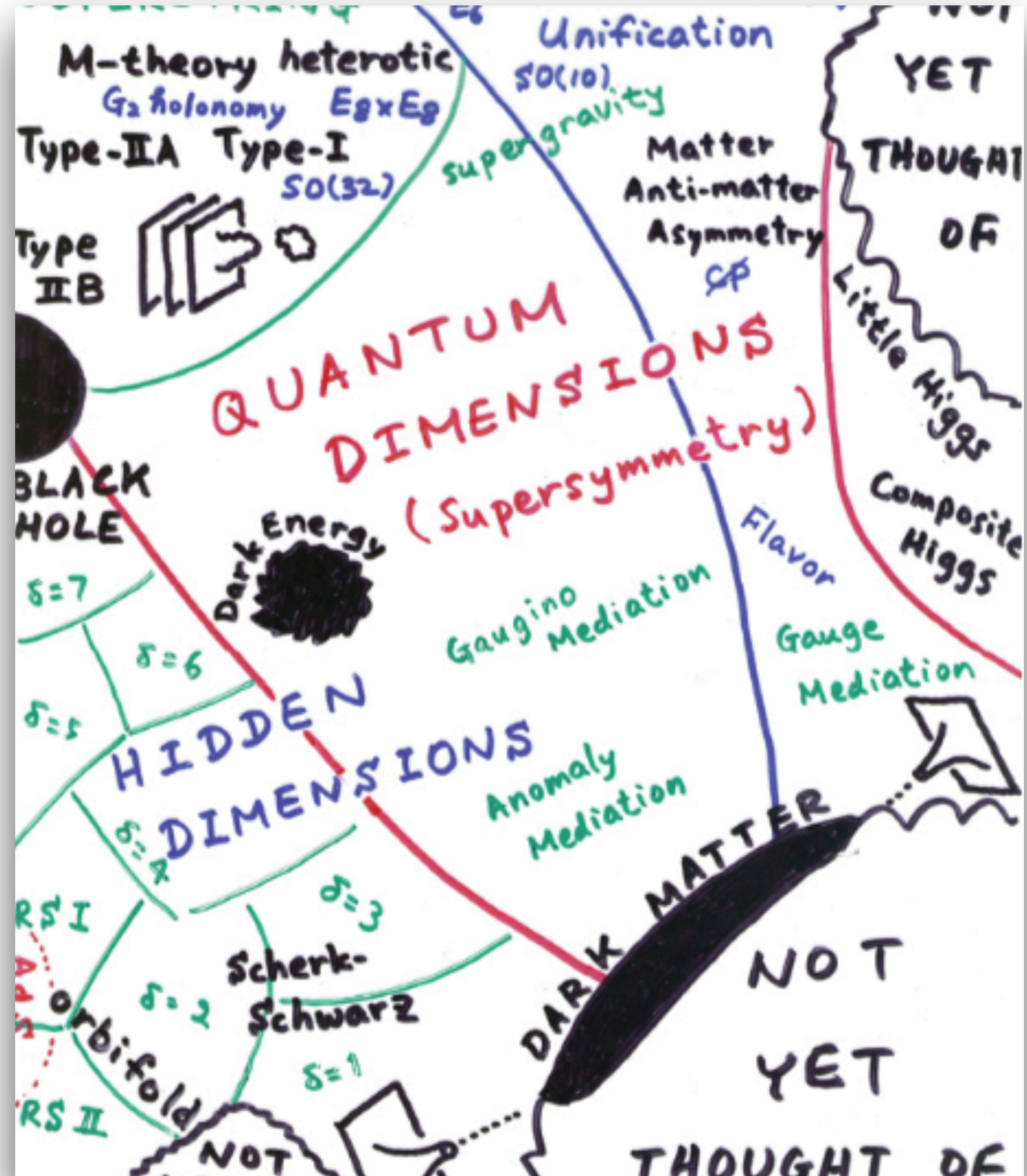


Summary

- large neutrino detectors are sensitive to any ionising particles
- large detection volume facilitates unprecedented sensitivities to new physics
- many channels to probe new physics

➡ Lots to discover!

Backup

Dark Matter annihilation and decay

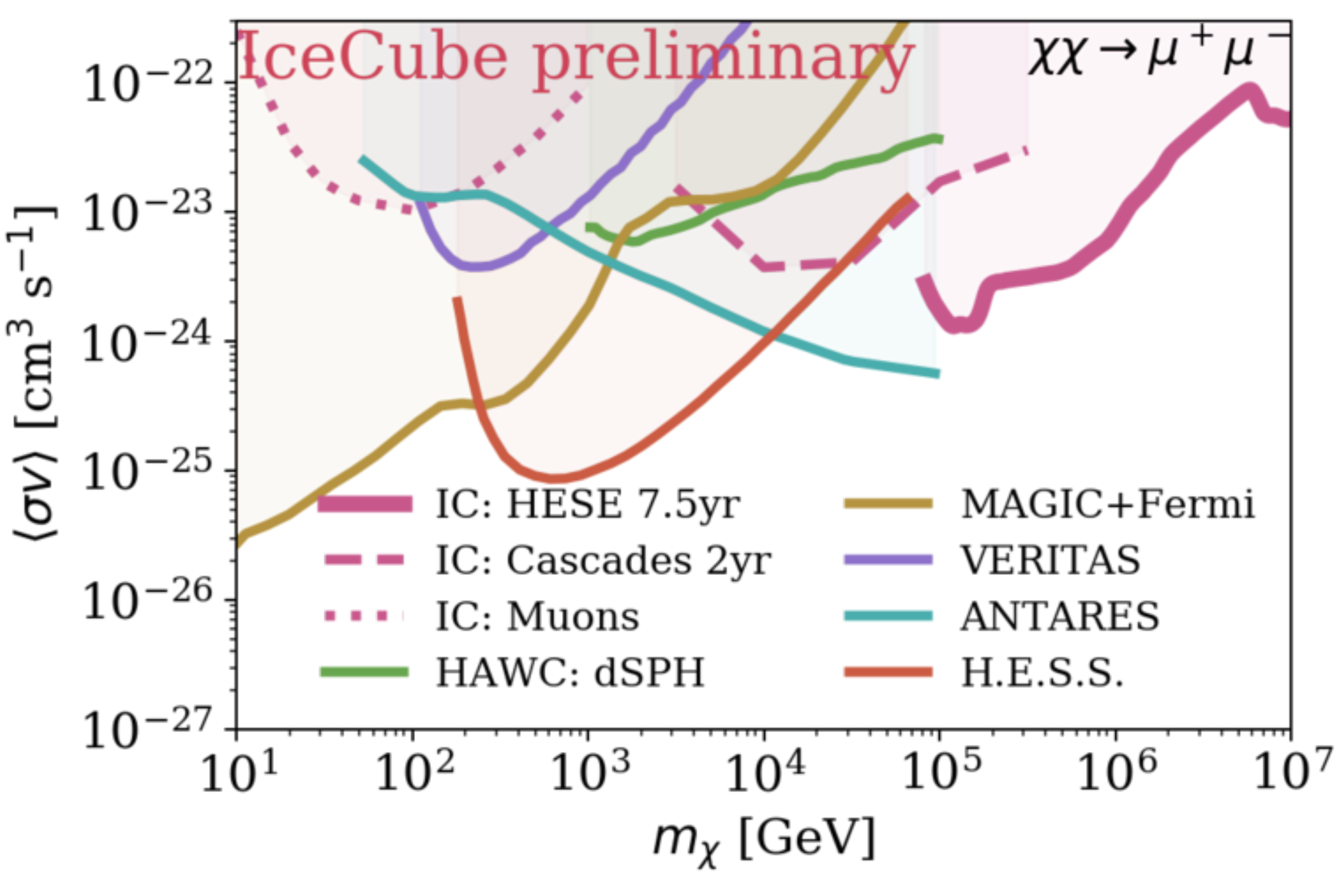
TeV WIMP increasingly disfavoured due to non observation at LHC/elsewhere

Search for annihilation / decay of DM in

- galactic DM (anisotropic)
- extra-galactic DM (isotropic, red shifted)

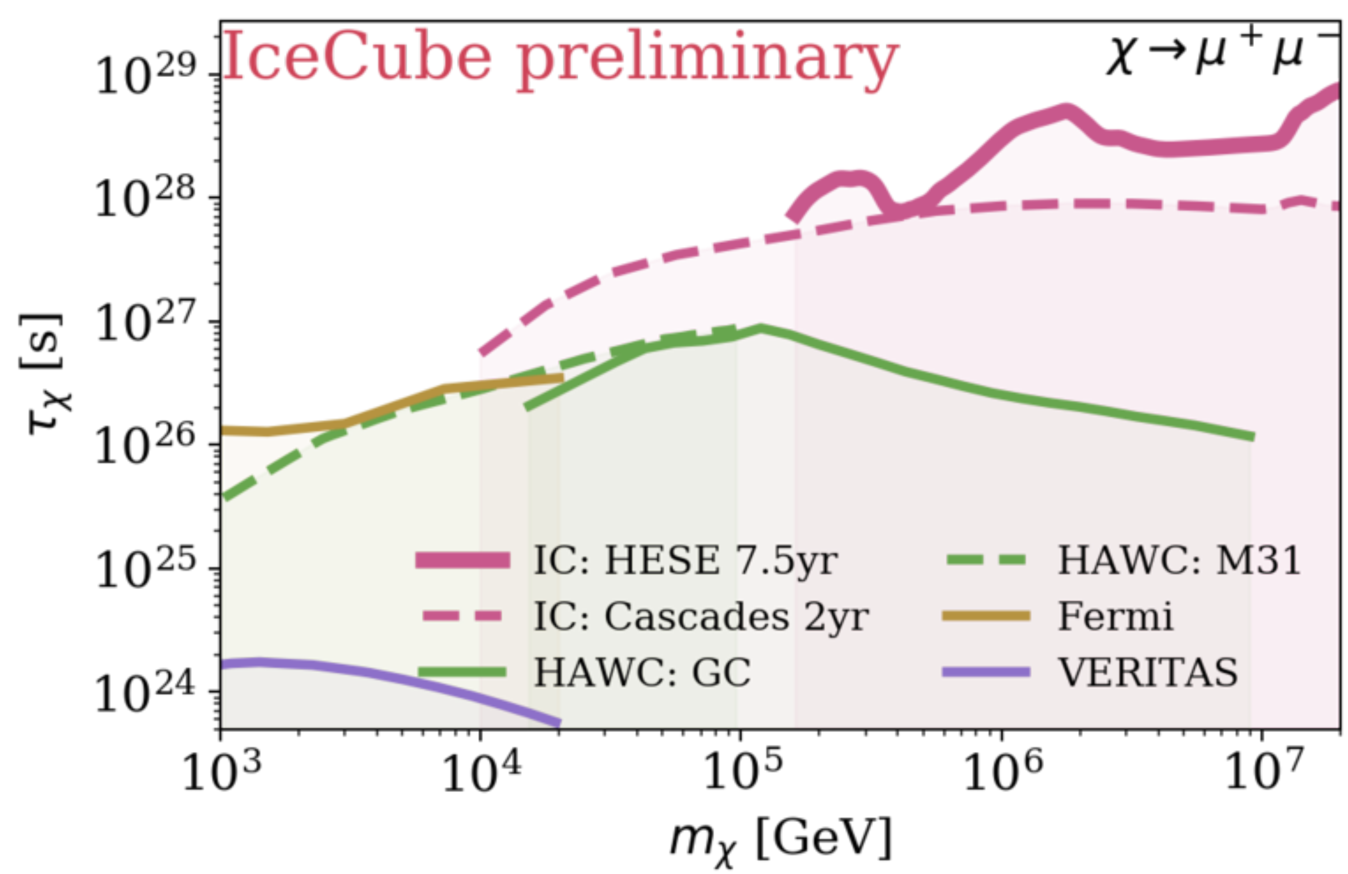
Annihilation

heavy Spin-0 particle annihilates into SM particles such as mono-energetic neutrinos



Decay

heavy DM decays into SM particles (directly or indirectly) with neutrinos in final state



Neutrino 2018 & arxiv:1804.03848 & 1705.08103

Beyond Standard Model physics with IceCube

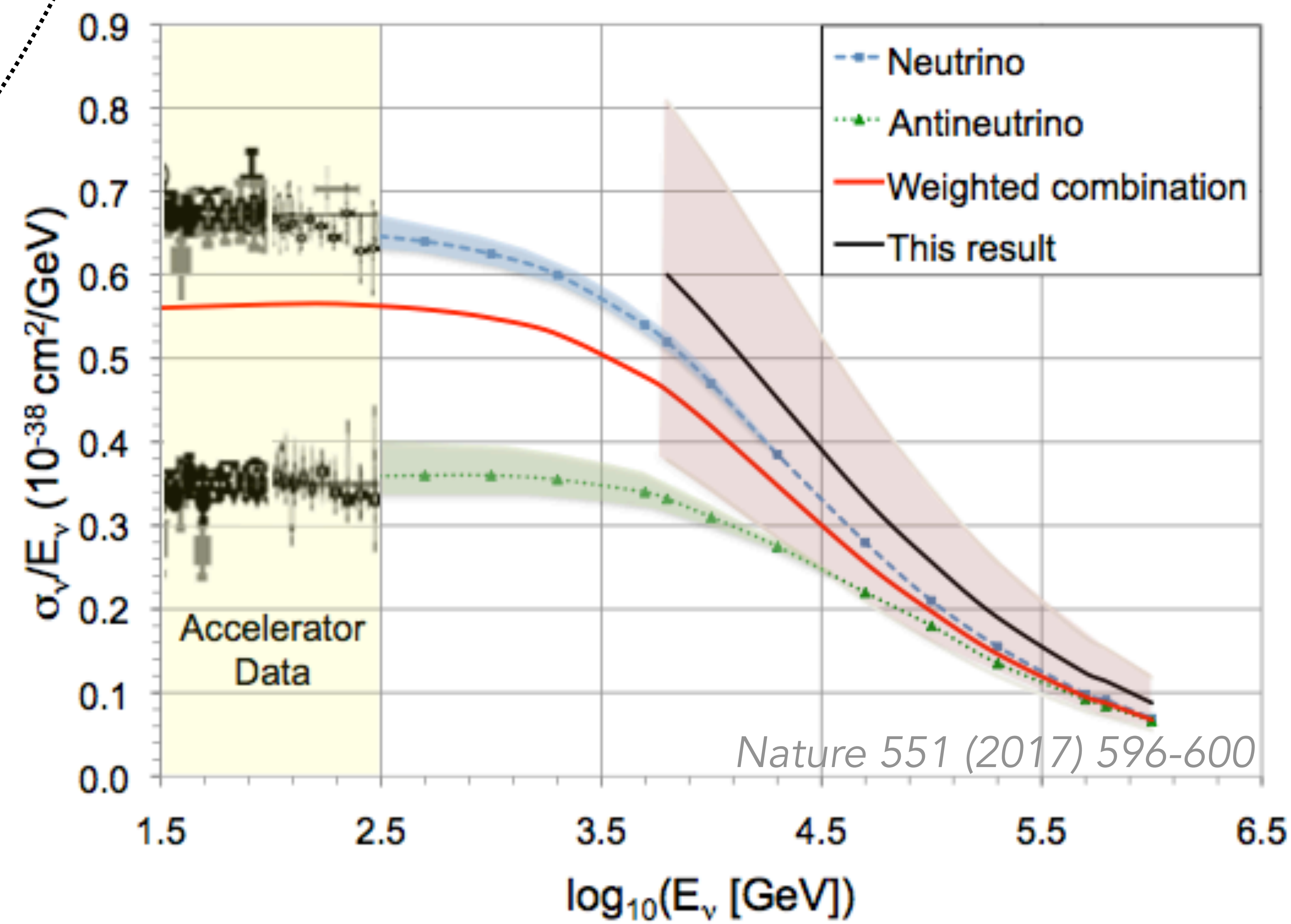
Indirect detection

- exotic source of particles contributes to particle flux
- exotic interactions/partices contribute to propagation of particle fluxes
- unexpected particle properties at unprecedentedly high energies
- different fundamental laws of physics appear at long scales

Example

Neutrino crosssection

- atmospheric neutrinos pass different lengths of Earth ~ different amount of matter



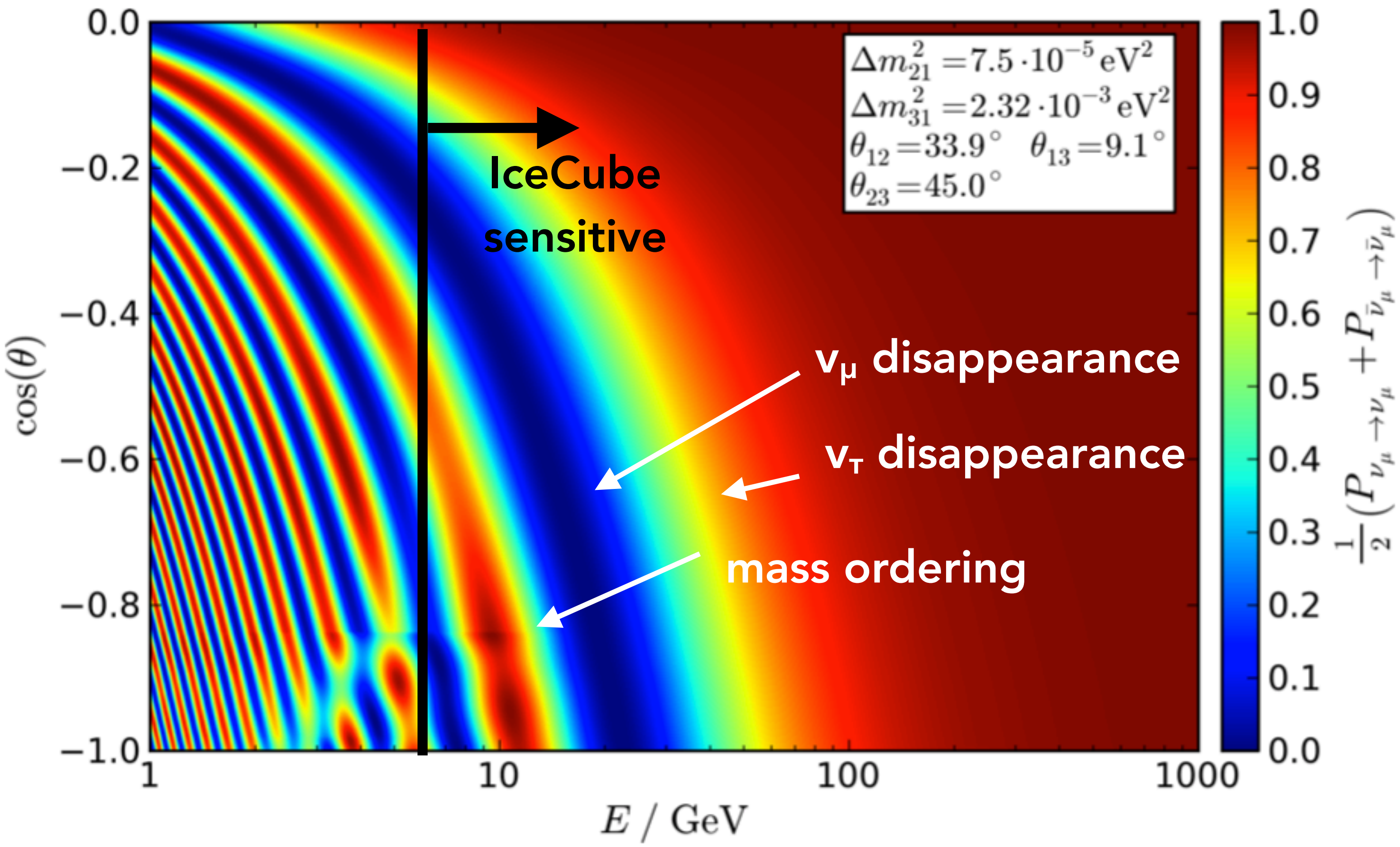
Nature 551 (2017) 596-600

Neutrino oscillation

Strategy

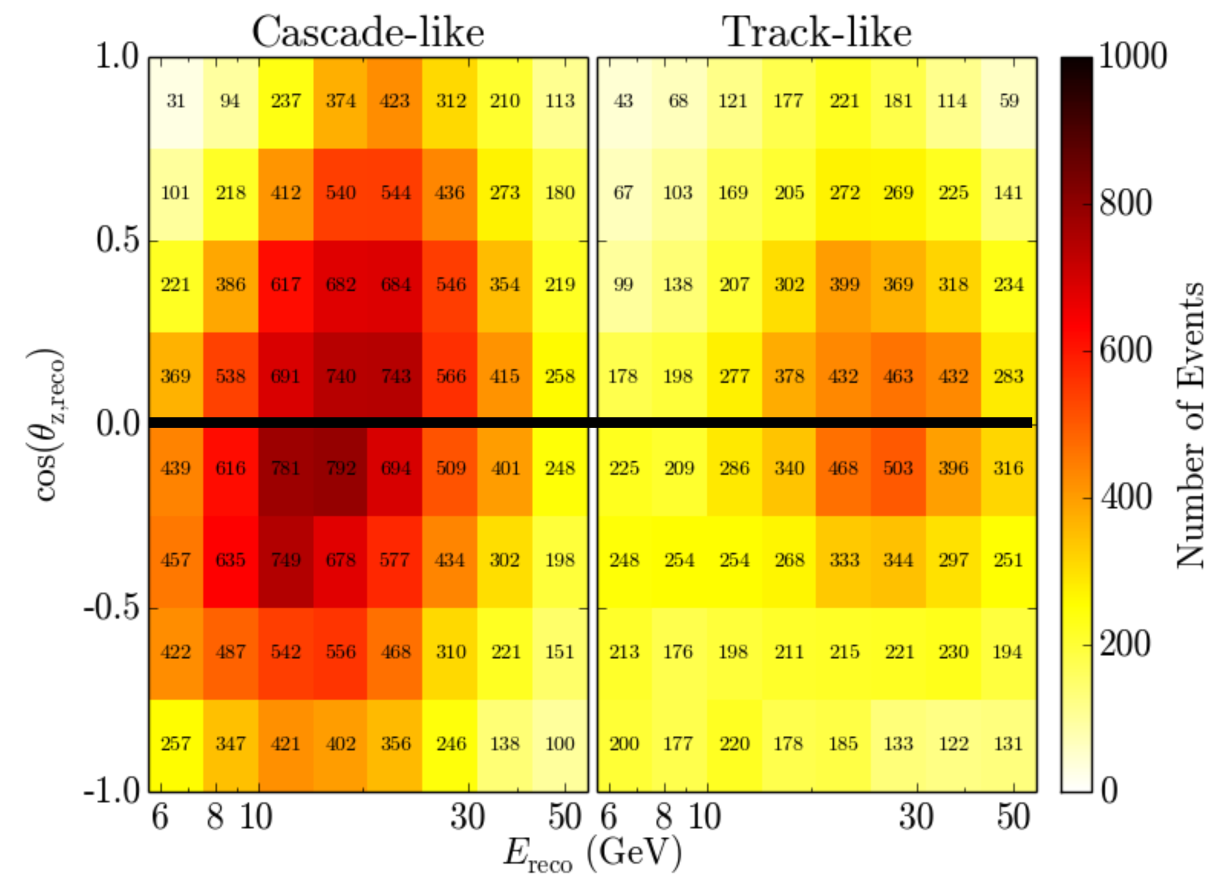
- atmospheric neutrinos from a wide range of baselines (~angles)
- energies: few GeV to 100 TeV

Model expectation



matter resonances — vacuum dominated

Event histogram



ν_μ disappearance (less up-going track-like events)

Phys. Rev. Lett. 120, 071801 (2018)

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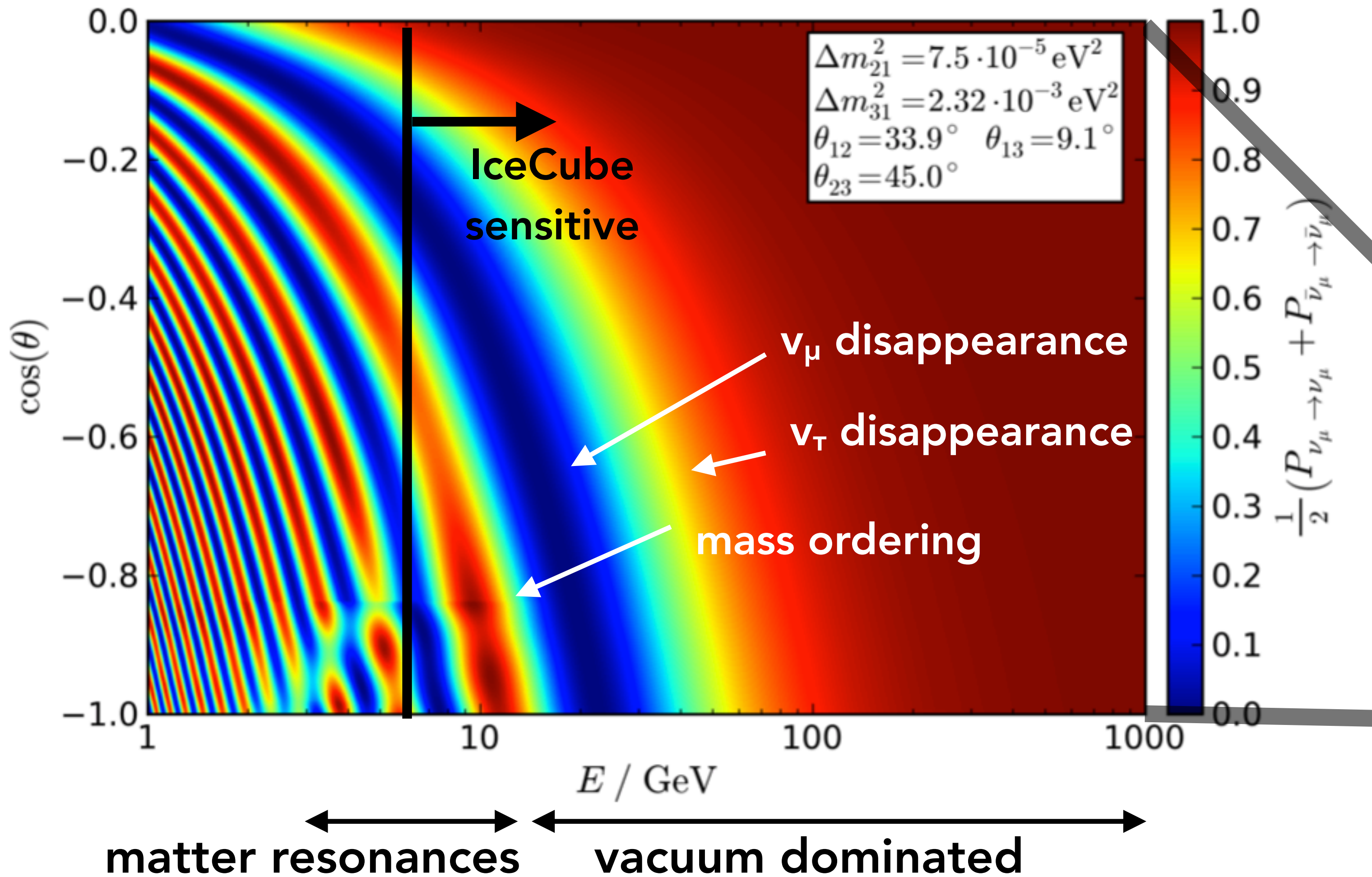
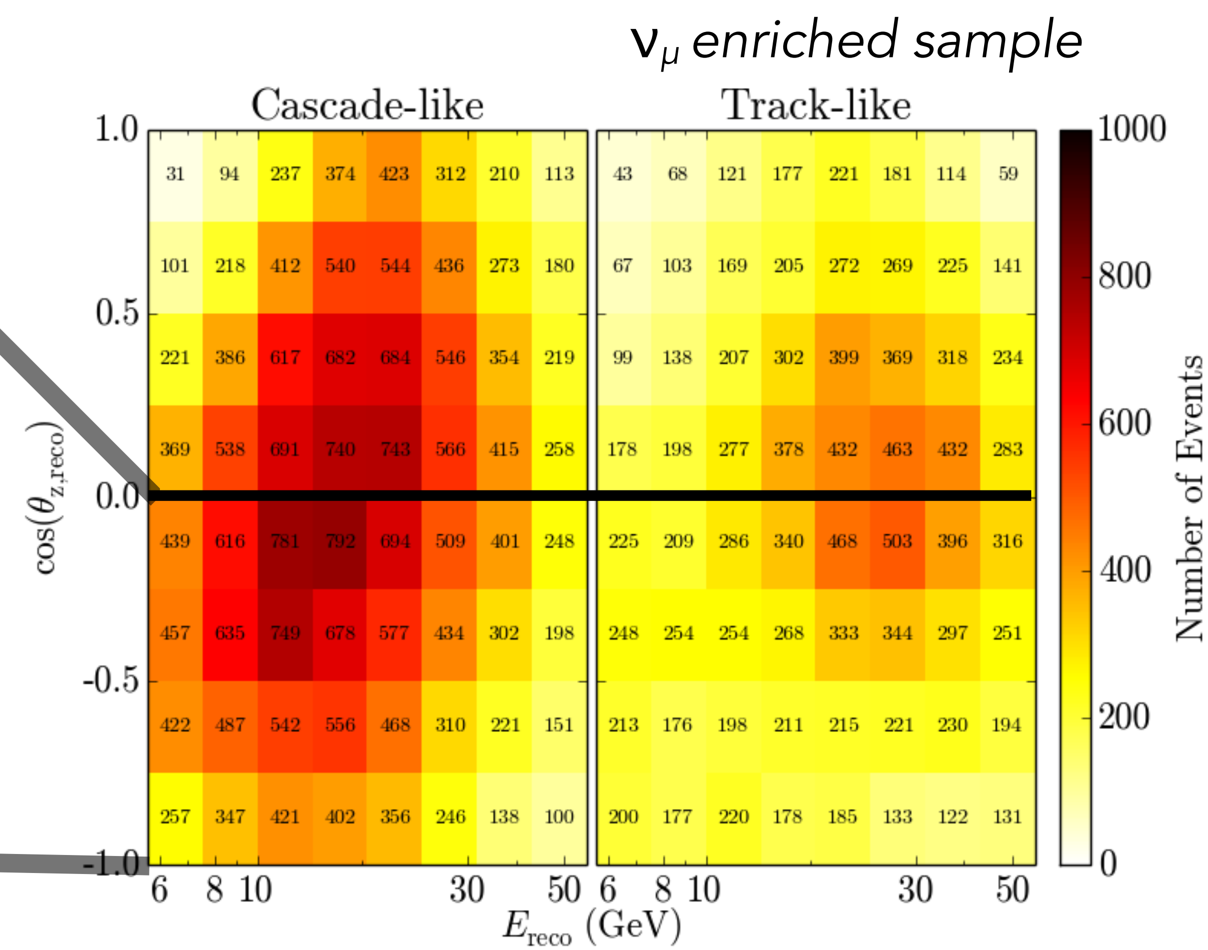


Event histogram



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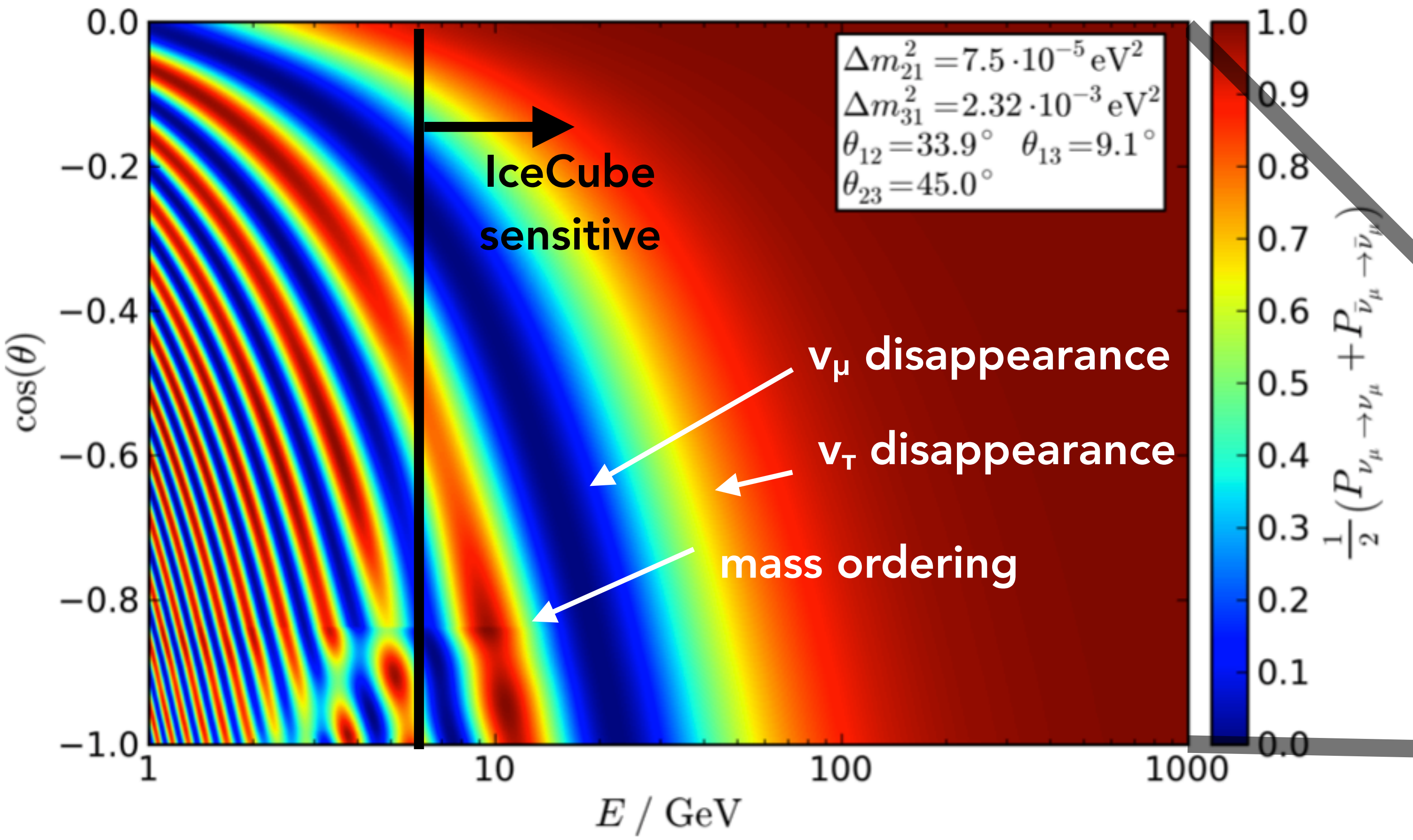
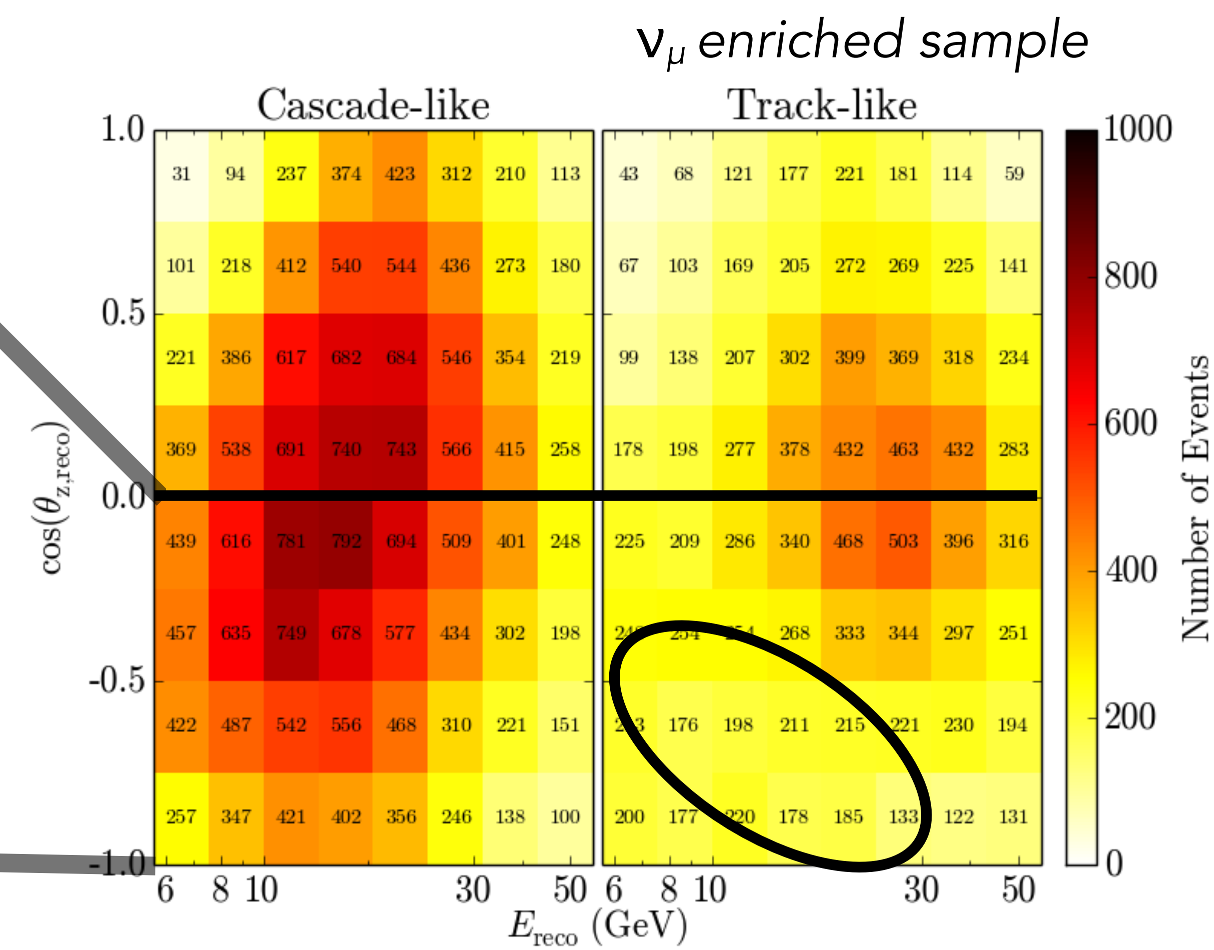


Event histogram



ν_μ disappearance
(less up-going
track-like events)

Phys. Rev. Lett. 120, 071801 (2018)

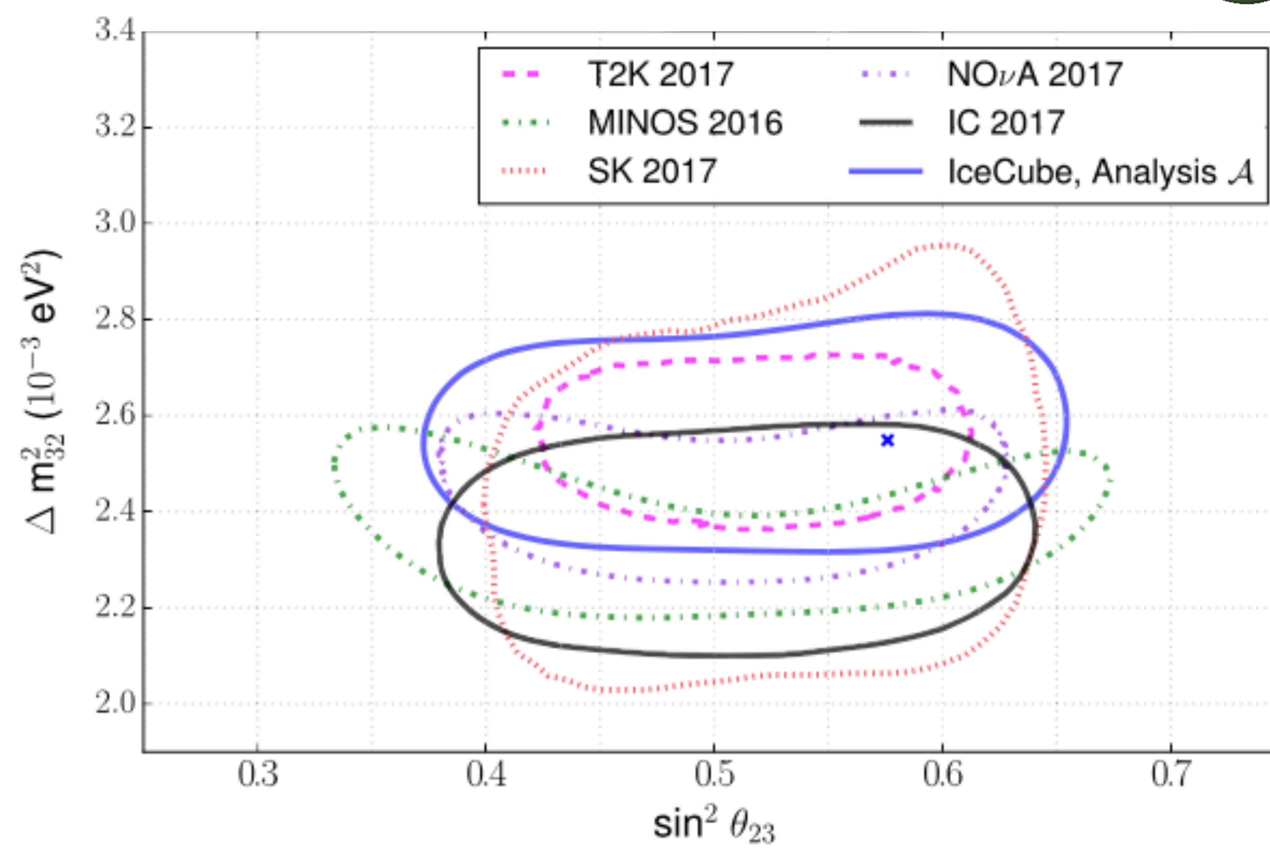
Neutrino oscillation

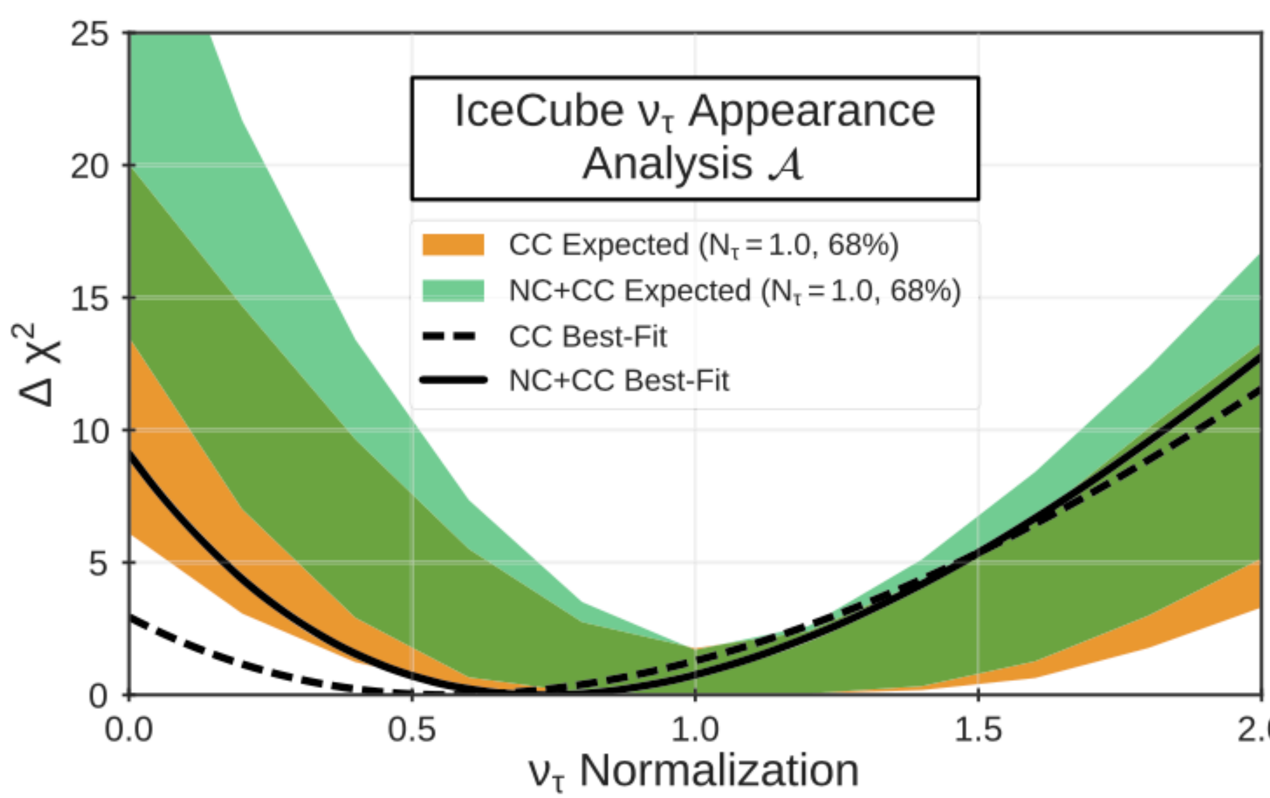
Strategy

- atmospheric neutrinos from a wide range of baselines (~angles)
- energies: few GeV to 100 TeV
- distinctive pattern in energy / angle / particle ID histograms

Recent result

- improved handling of systematics
- MC driven background handling
- consistent with previous IceCube / long baseline experiments within statistical uncertainties (shift due to statistical fluctuations)
- maximal mixing preferred



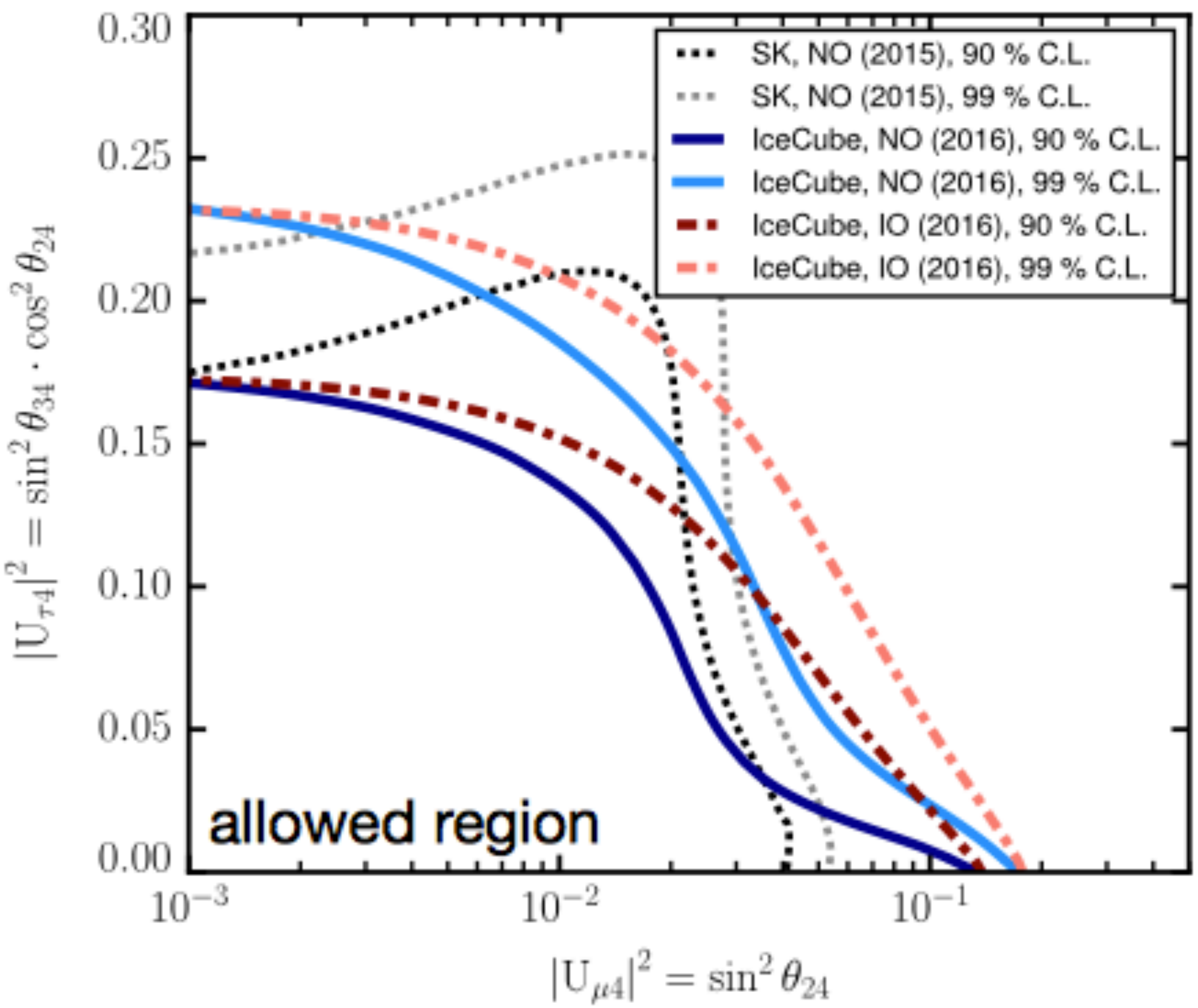


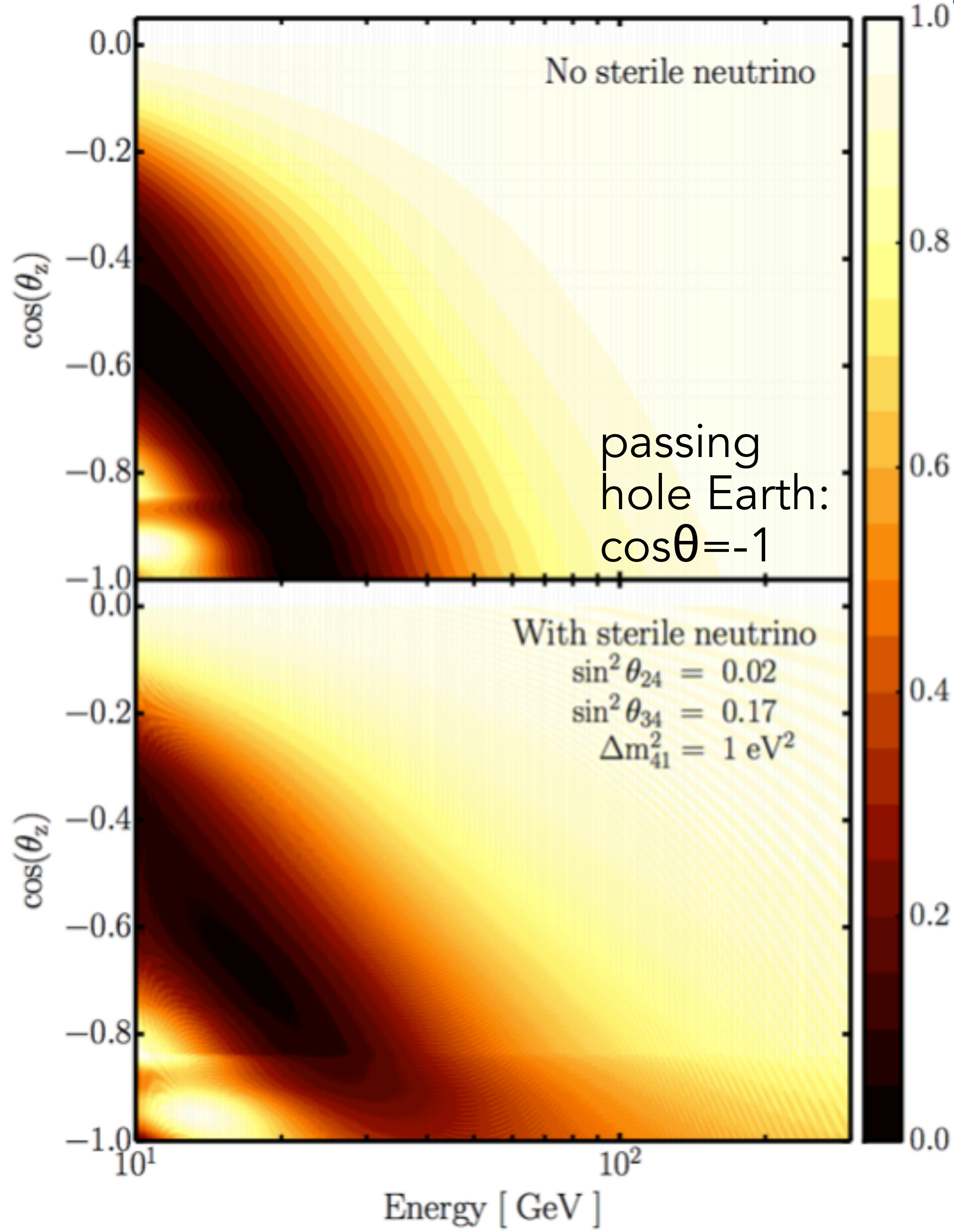
Phys. Rev. D 99, 032007 (2019)

Sterile neutrinos

Strategy

- for Δm^2_{41} ~ 1 eV^2 sterile neutrino states produce a change in the matter potential



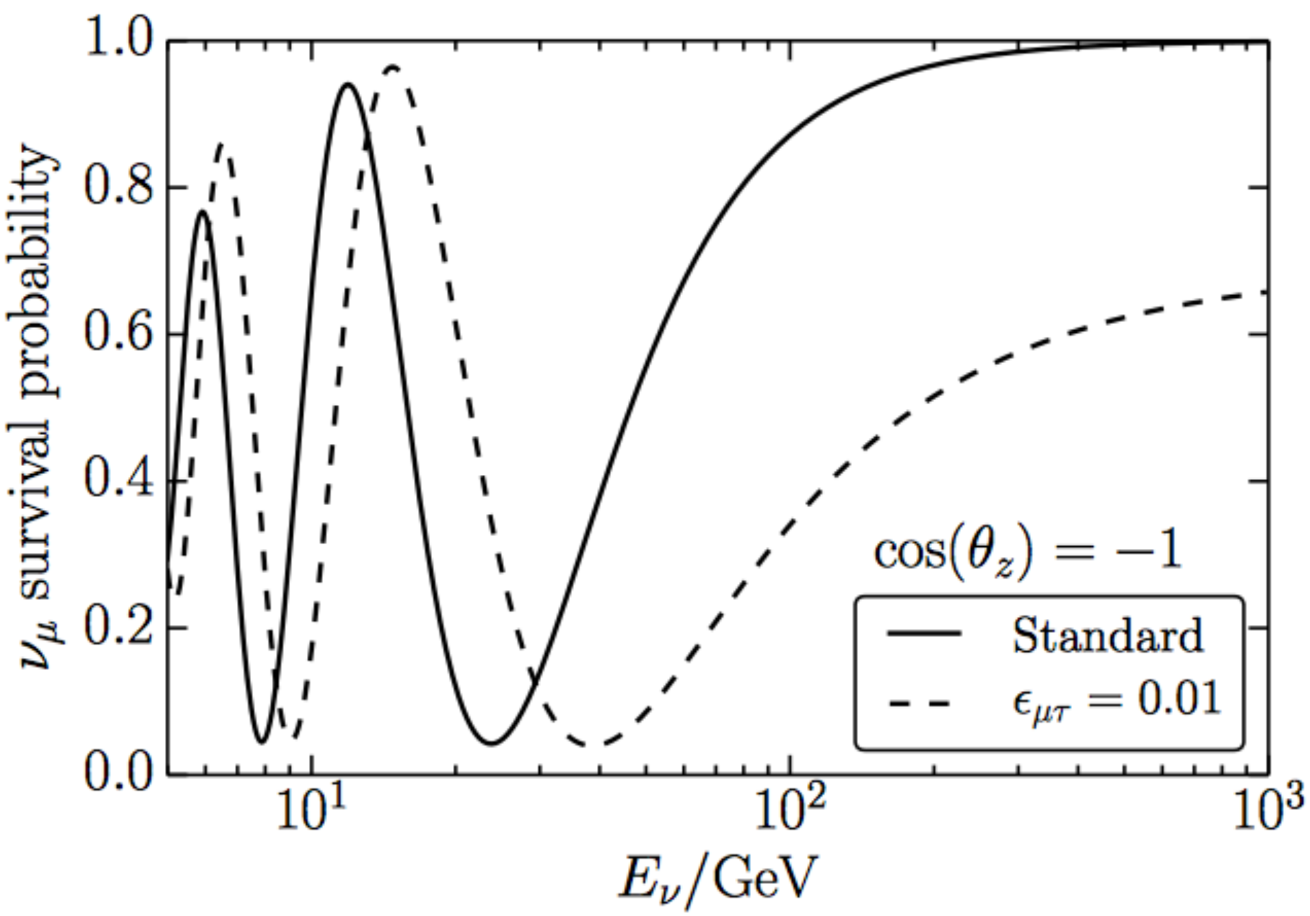


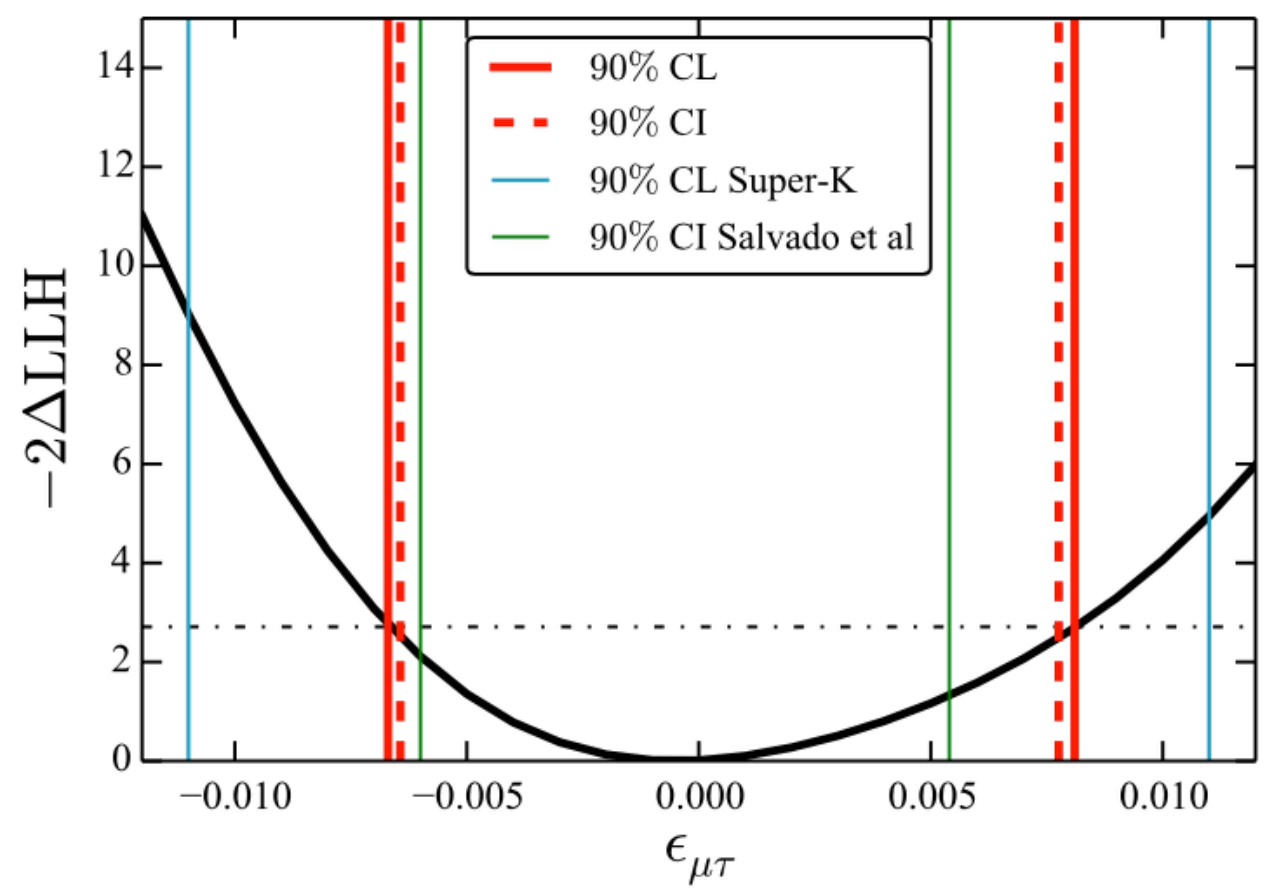
Phys. Rev. D95, 112002 (2017)

Non-standard neutrino interactions

Strategy

- additional potential by non-standard neutrino interactions changes oscillation pattern



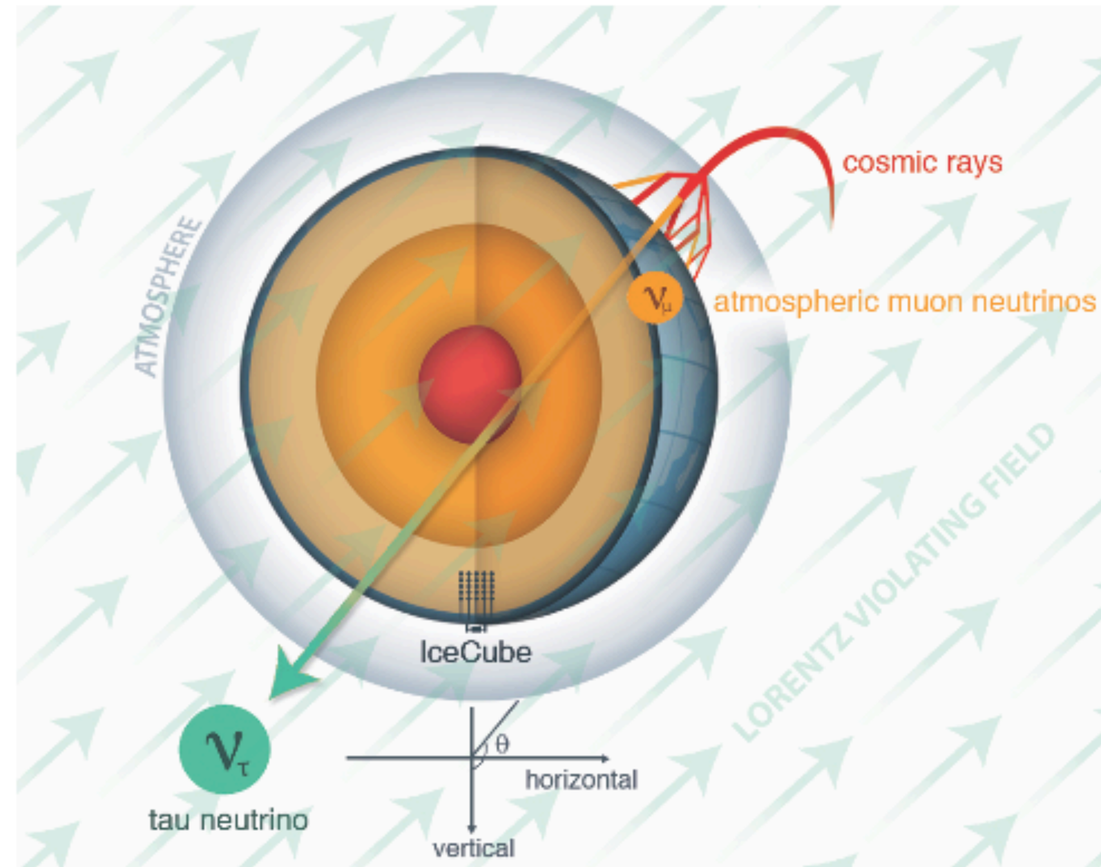


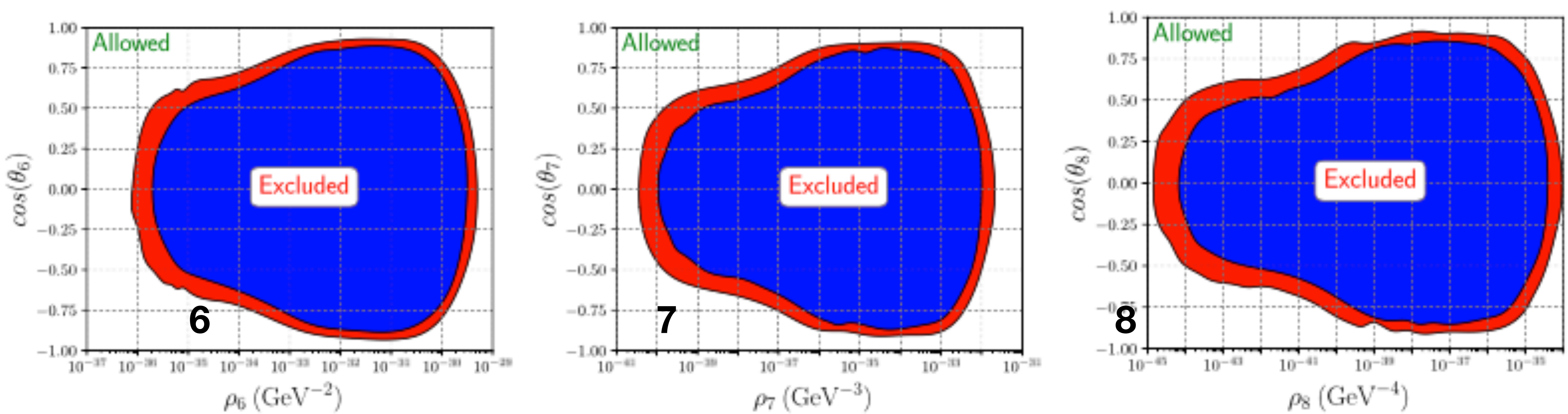
Phys. Rev. D 97, 072009 (2018)

Lorentz Invariance Violation

Strategy

- atmospheric neutrino sample
- Standard Model extension describes different LIV effects as operators of different dimension
- these change the neutrino oscillation probability
- signal: anomalous muon neutrino disappearance
- using 30k > TeV scale muon neutrinos
- result: best limits on LIV for higher dimensions

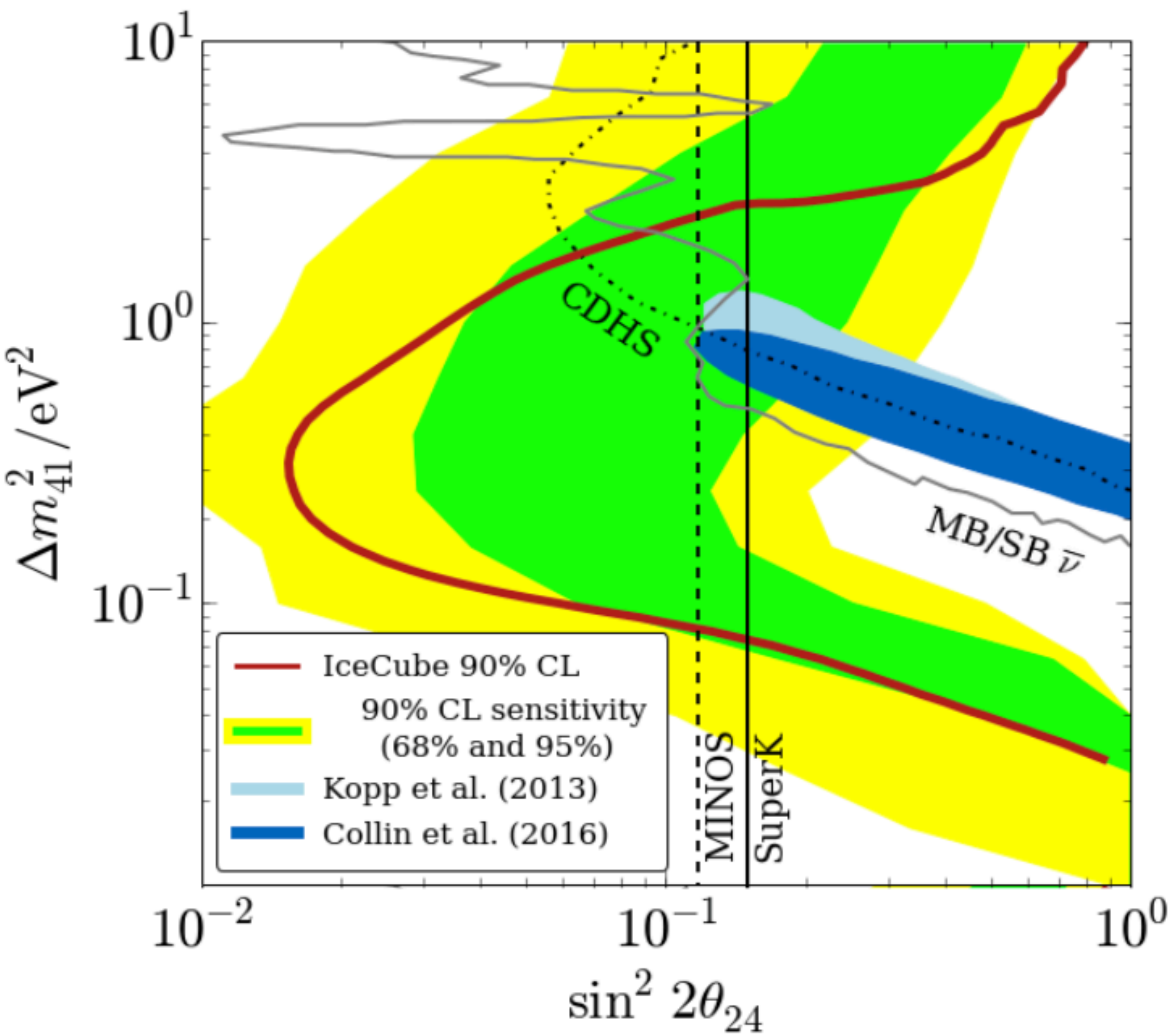


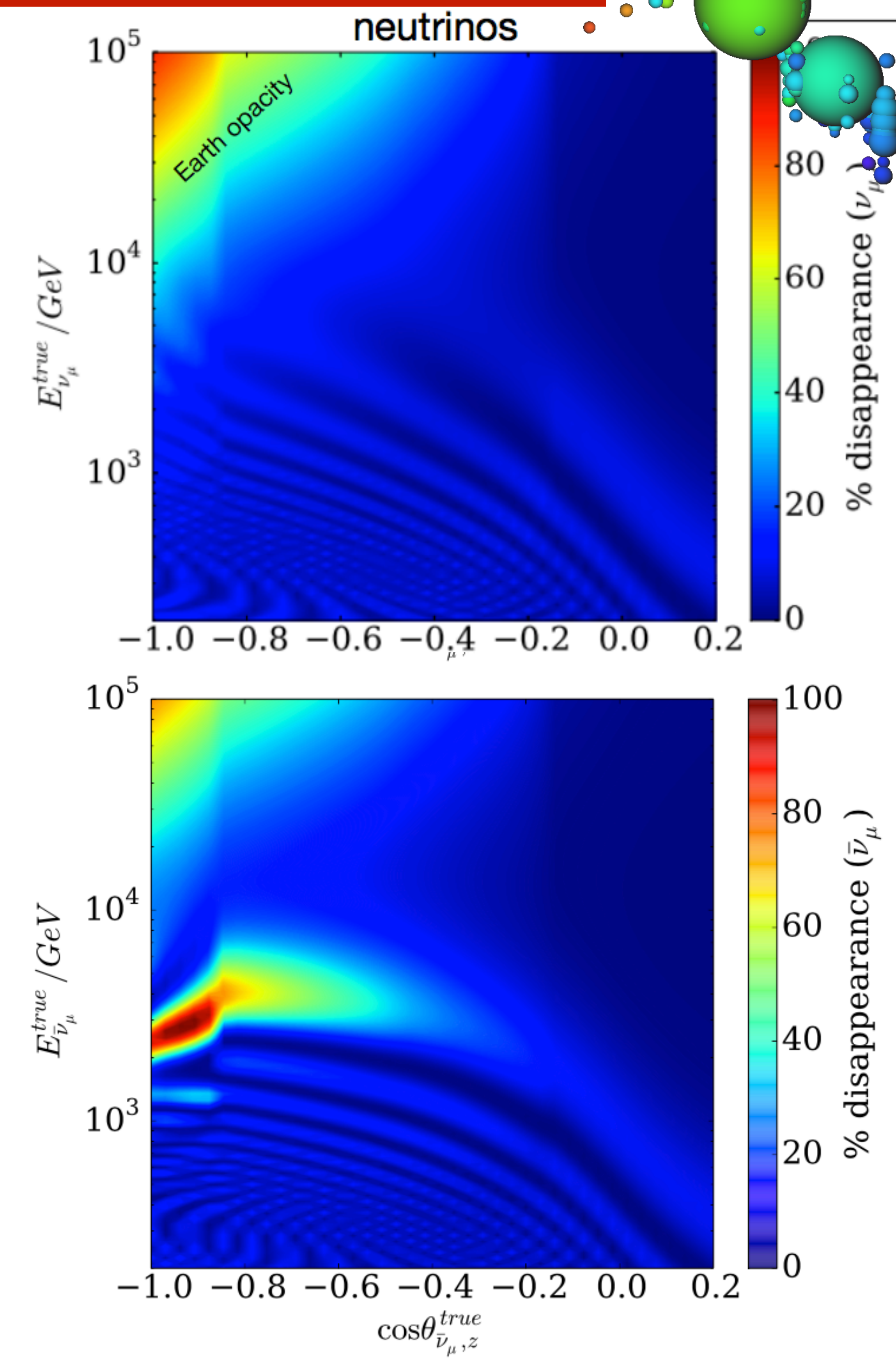


Sterile neutrinos at high energies

Strategy

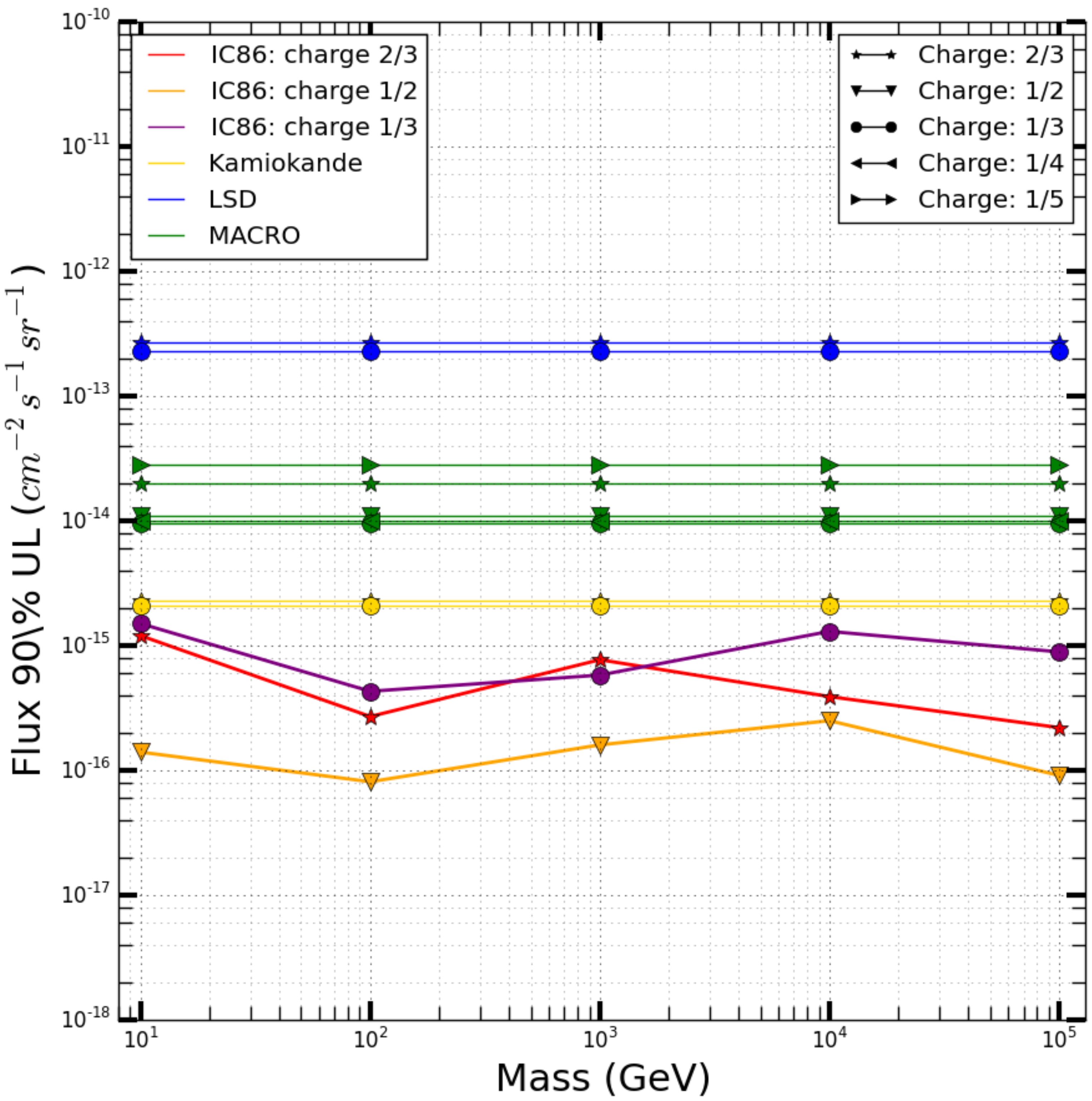
- for $\Delta m^2_{41} \sim 1$ eV^2 sterile neutrino states try to identify the resonant oscillation from ν_μ into ν_s





Phys. Rev. Lett. 117, 071801 (2016)

Sensitivity for Fractional Charges



anna.pollmann@uni-wuppertal.de