BERGISCHE UNIVERSITÄT WUPPERTAL

bmb+f - Förderschwerpunkt
Astroteilchenphysik
Großgeräte der physikalischen Grundlagenforschung

ICECUBE

Radio-luminescence of water and ice

as a new detection channel for neutrino telescopes

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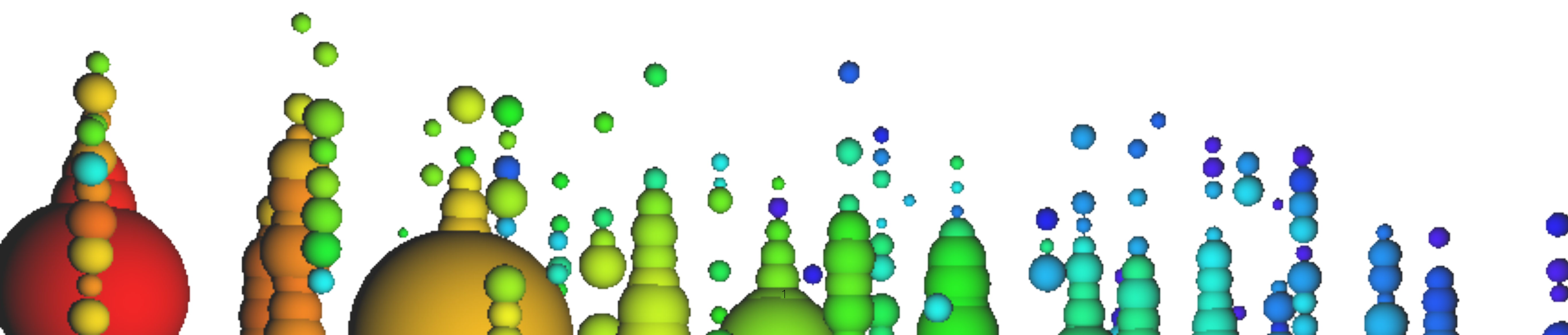
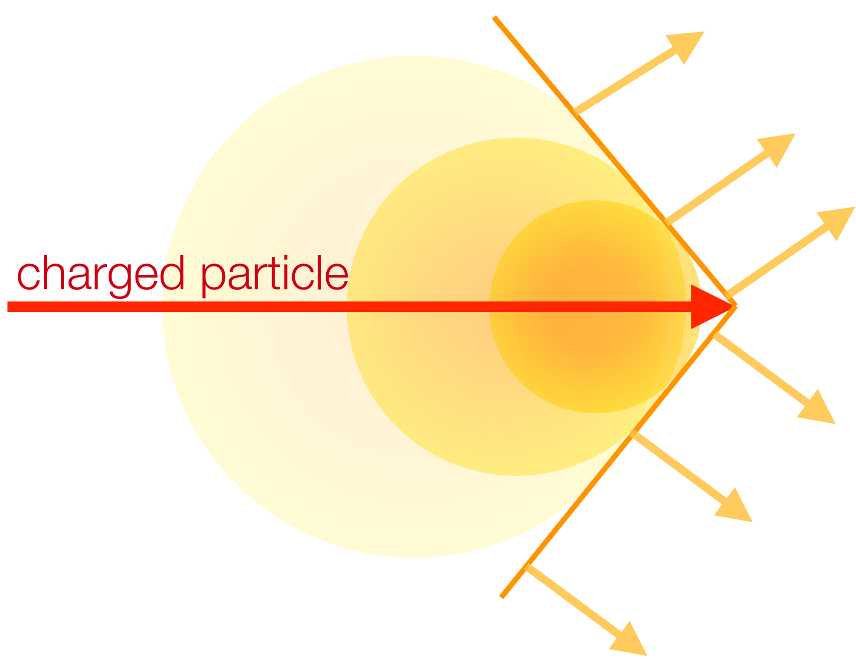


Light production by (exotic) particles in water and ice

Relativistic speeds

- continuous light emission
  - Cherenkov light
  - Cherenkov light from secondaries
- stochastic losses
  - bremsstrahlung
  - pair production
  - photonuclear interactions

Cherenkov light emission pattern



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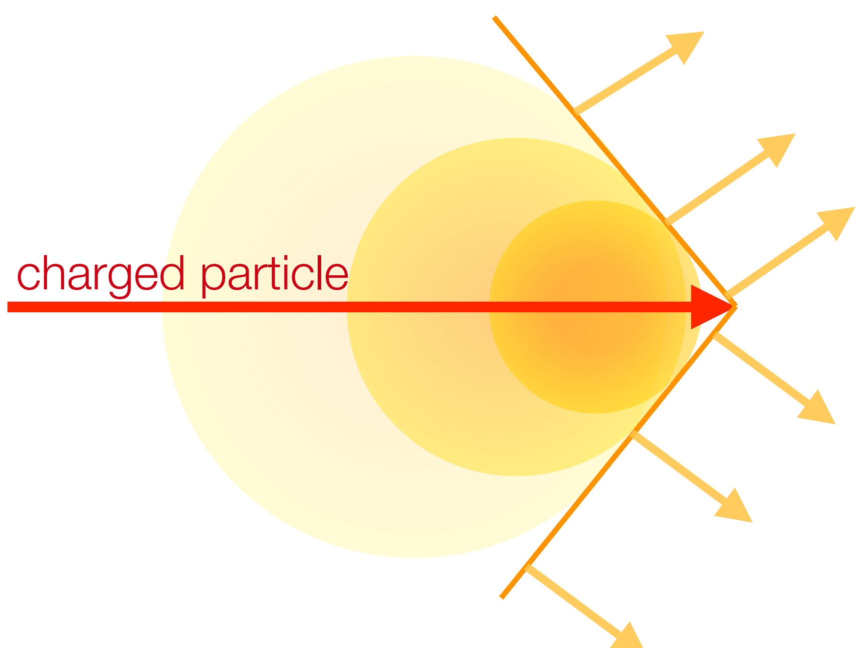
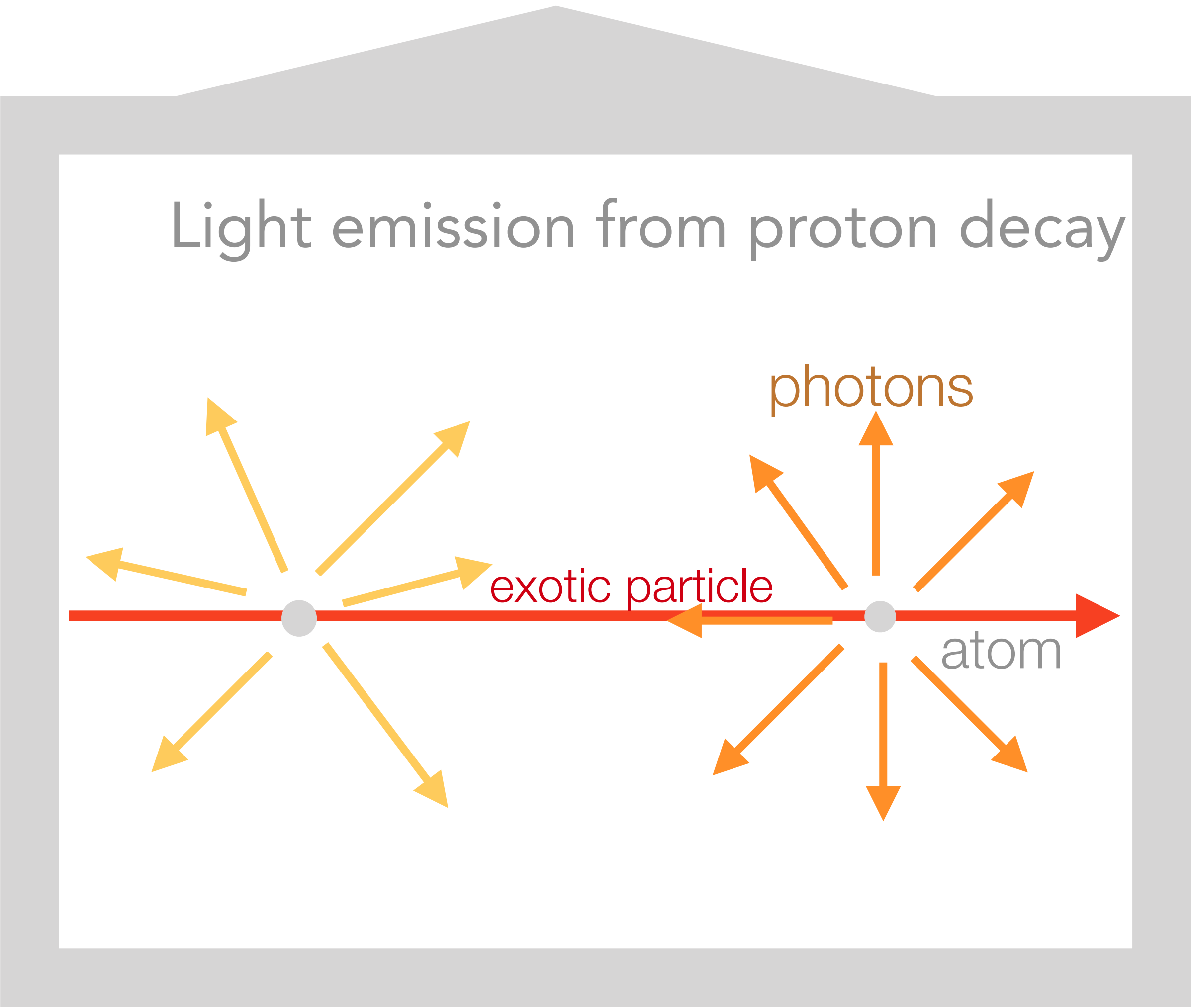
Slow particle speed (< 0.1 c)

- catalysis of proton decay via Rubakov-Callan or KKST (predicted theoretically in some models)
- thermal shock waves (not used yet)

Cherenkov light emission pattern





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

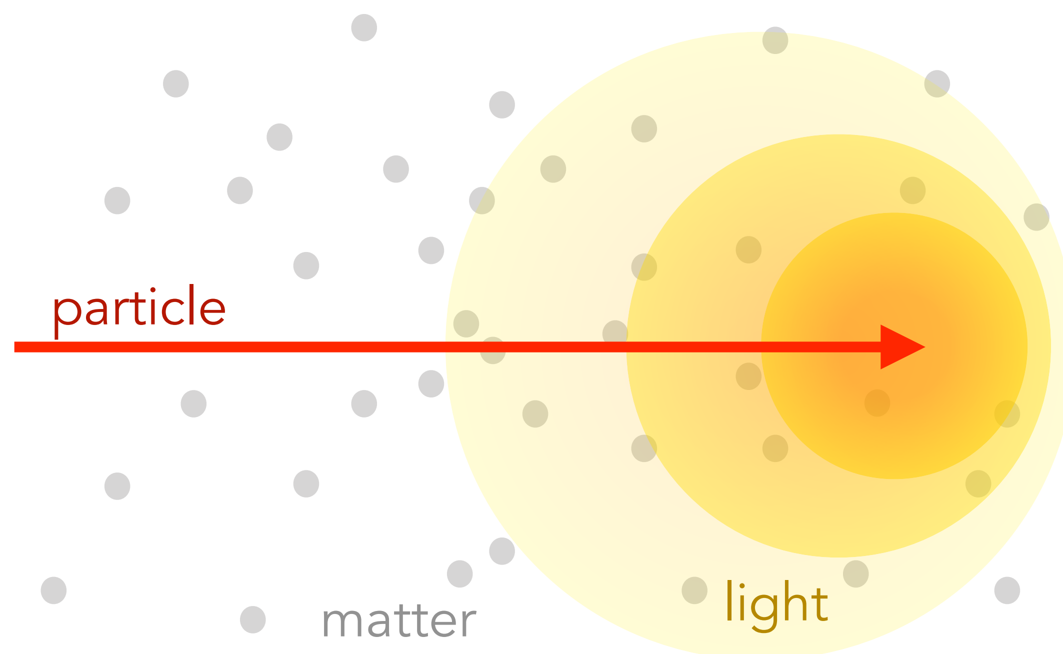
Idea: Luminescence light

- 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

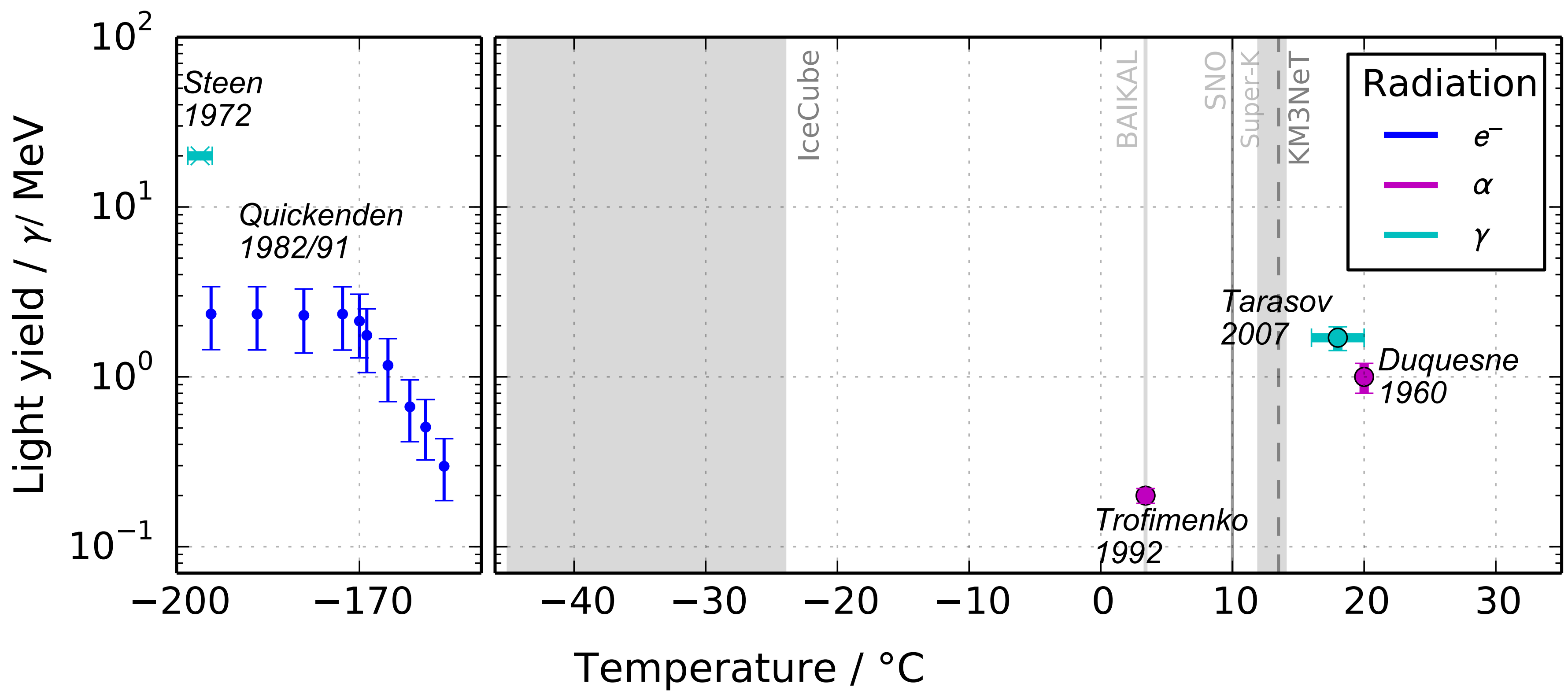
- light yield
- decay kinetics
- emission spectrum
- quenching

Dependencies

- temperature
- impurities / solubles
- radiation type
- pressure

Few existing measurements

with very different setups and results

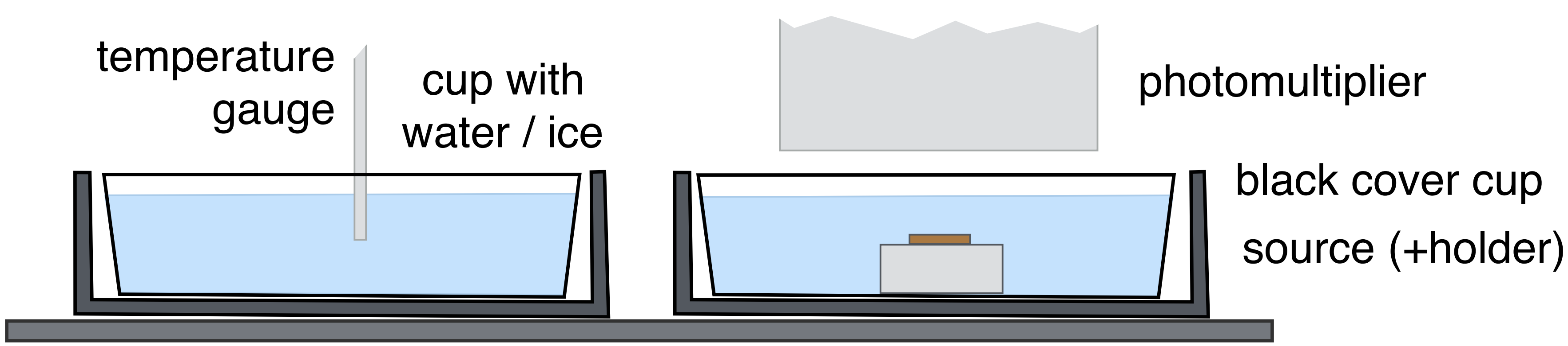


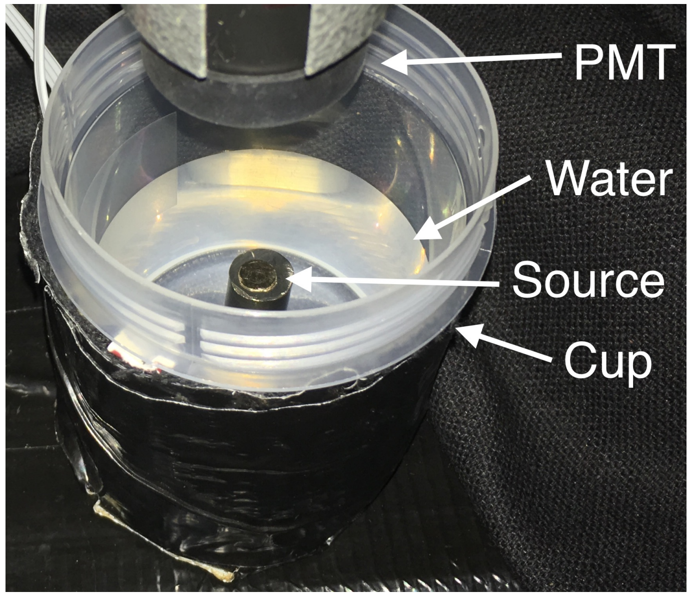
Note:

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

Light yield measurement in water

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





arxiv:1710.01197

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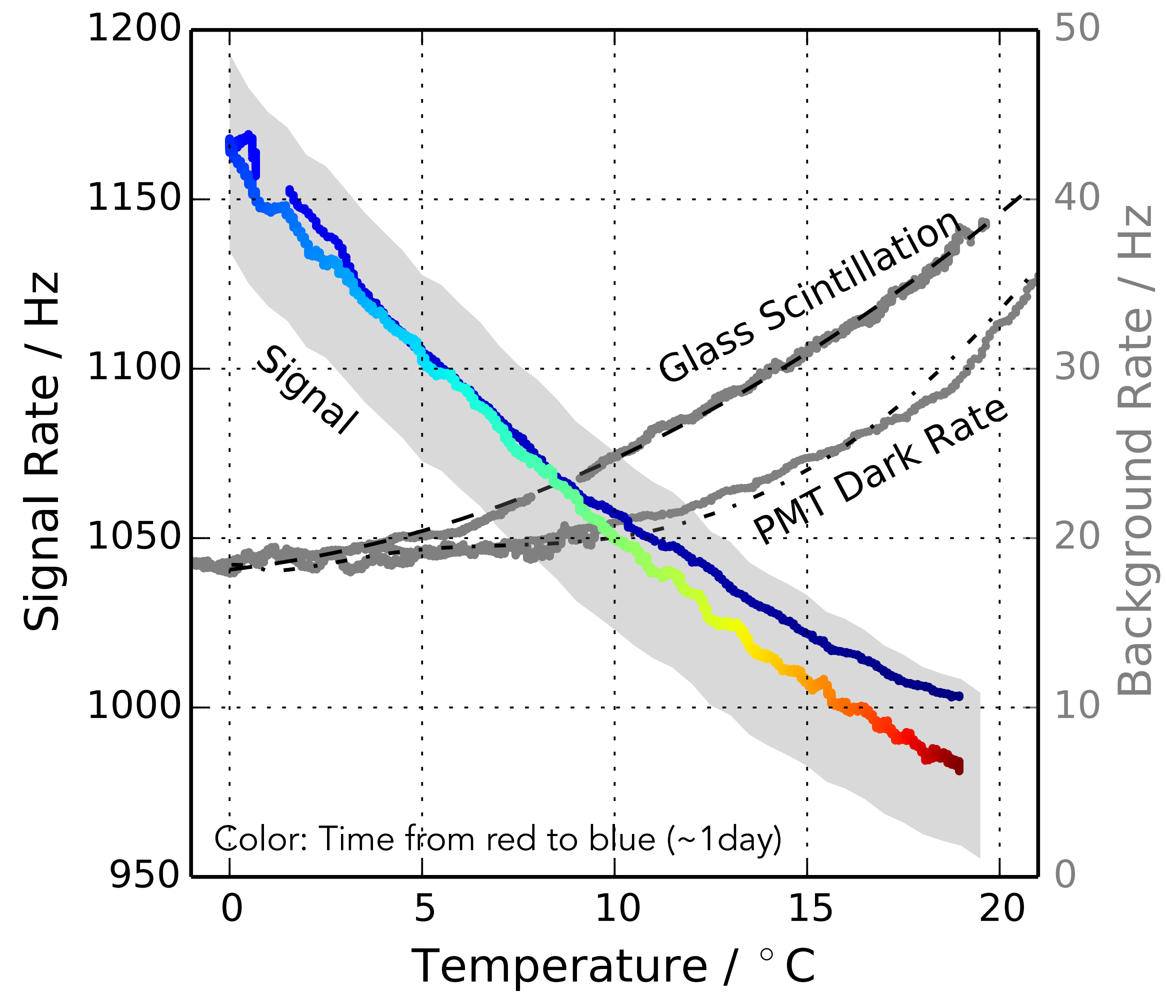

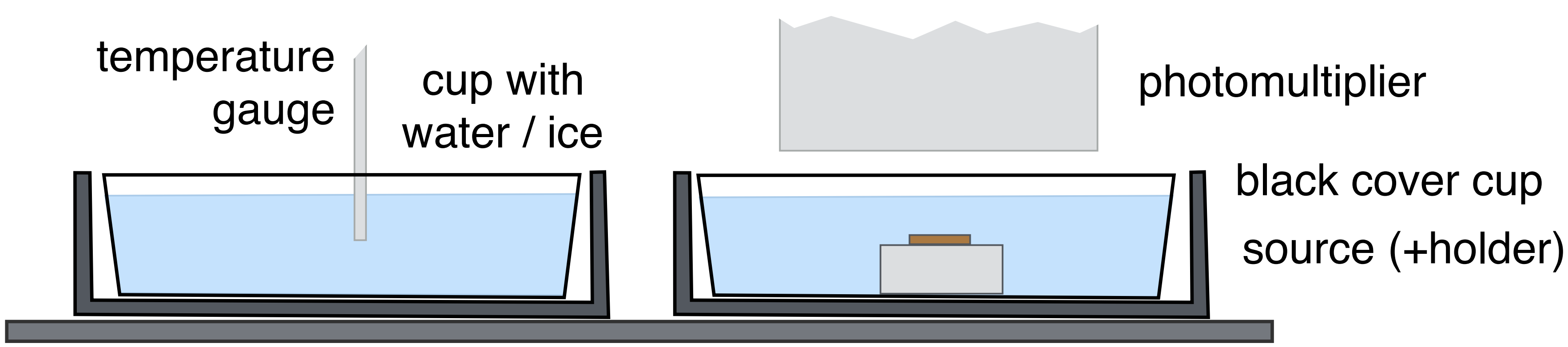

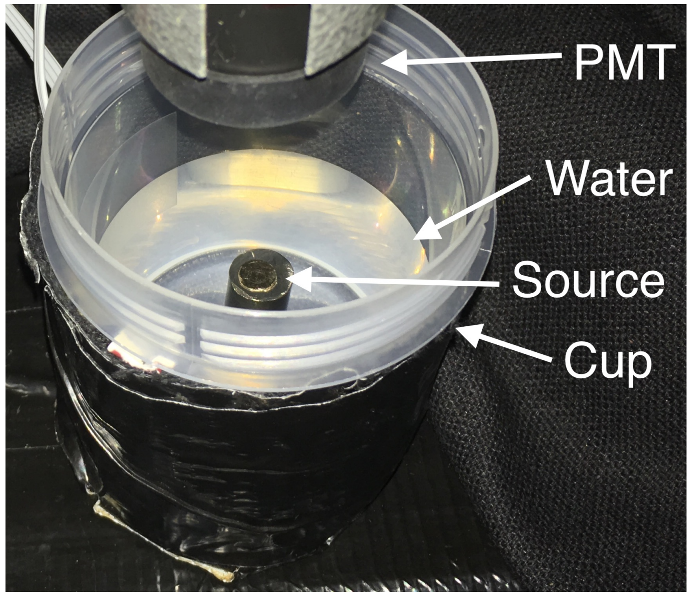

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Laboratory measurements

- ultra-purified water degassed in vacuum (frozen to bubble free ice)
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- measured single photons with photomultiplier
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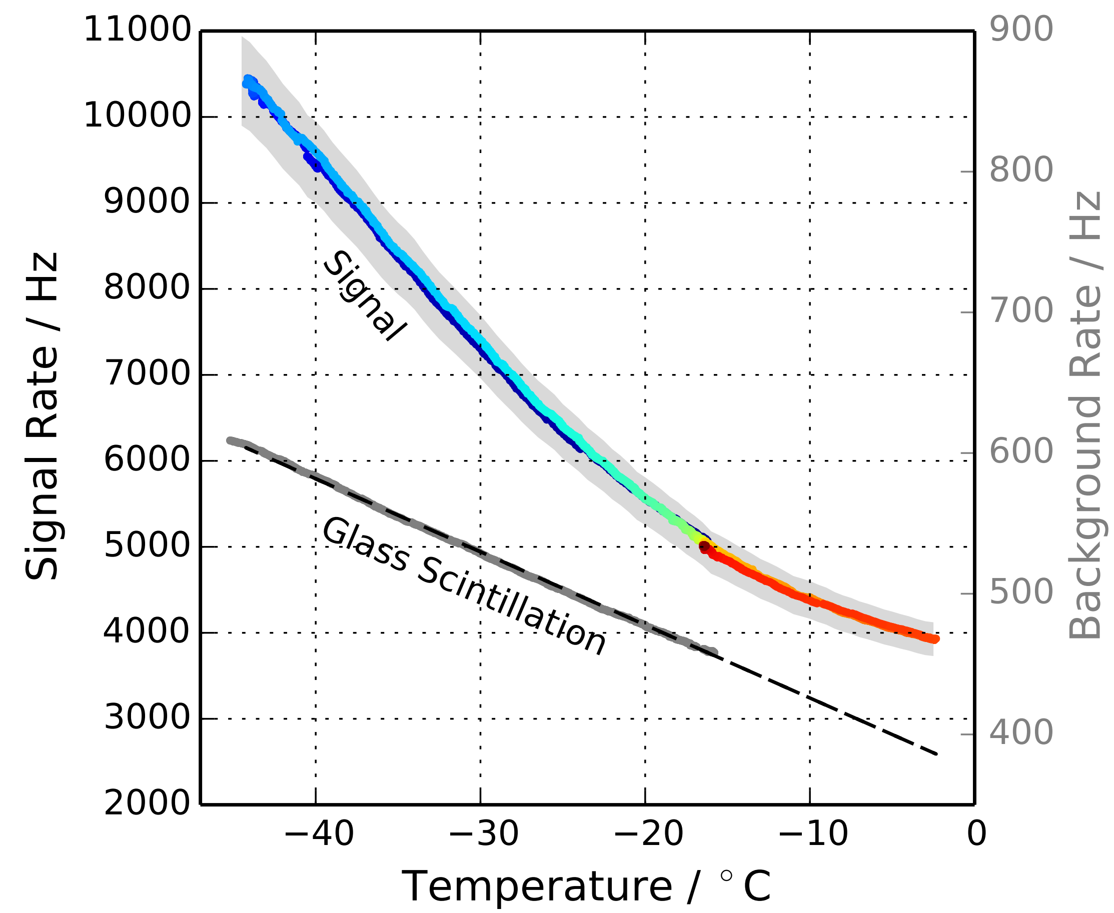

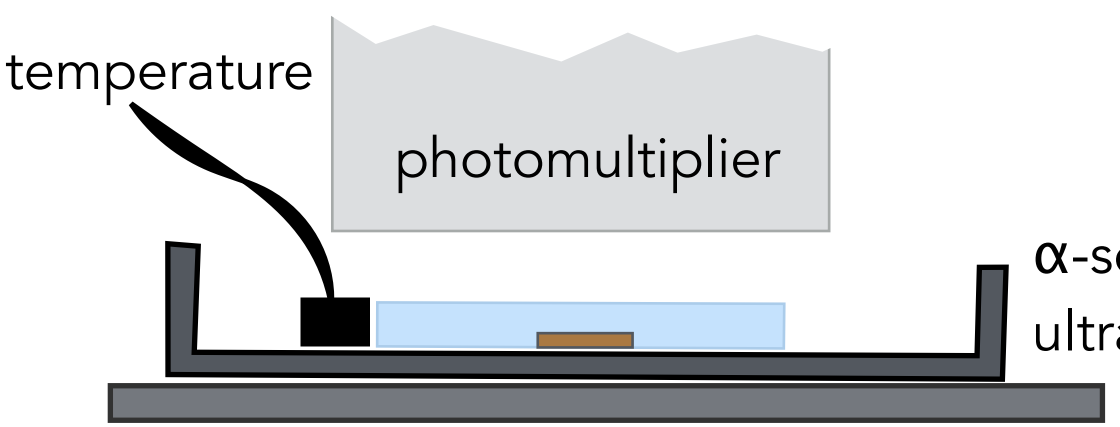

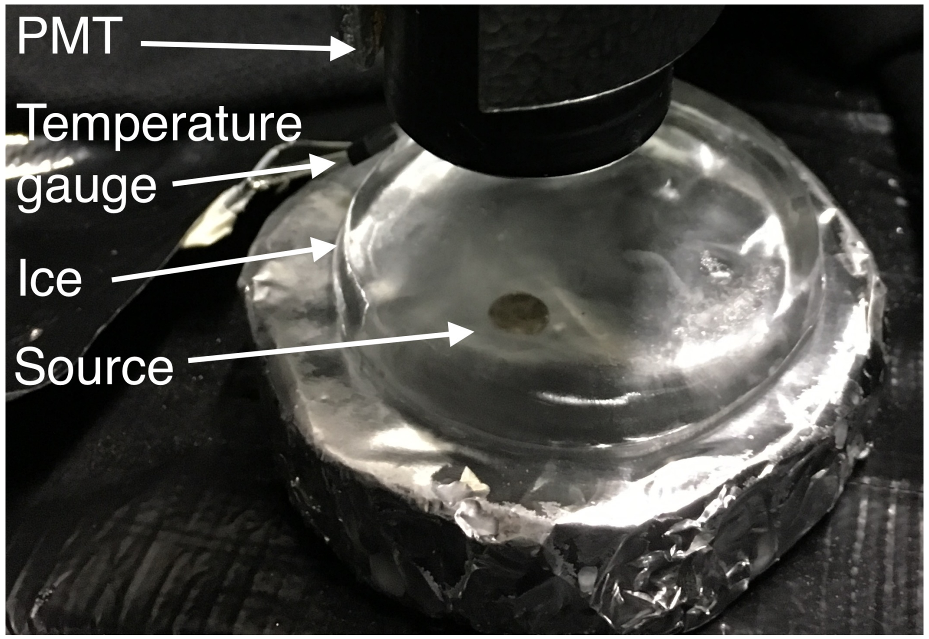

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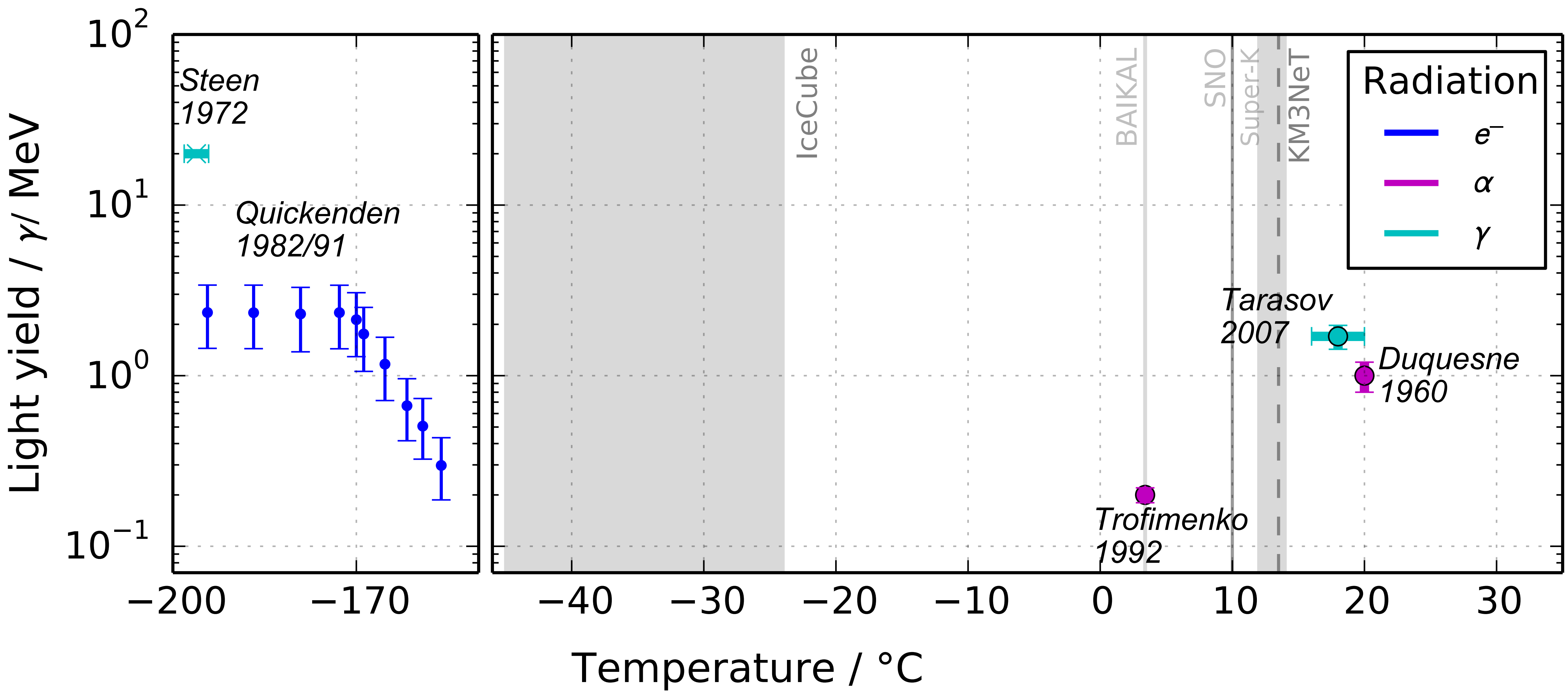
Previous light yield measurements



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Comment:

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

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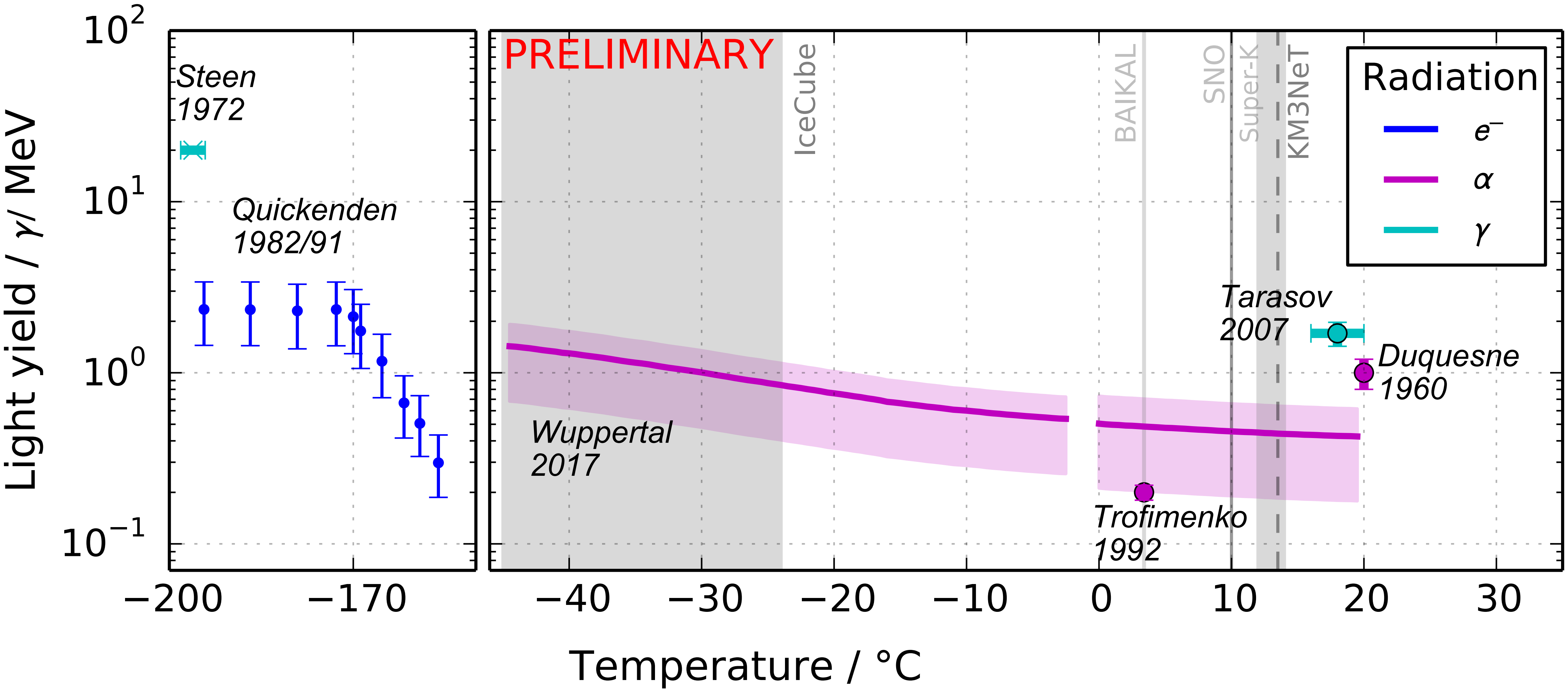
Previous light yield measurements

First laboratory measurement at temperatures of neutrino telescopes



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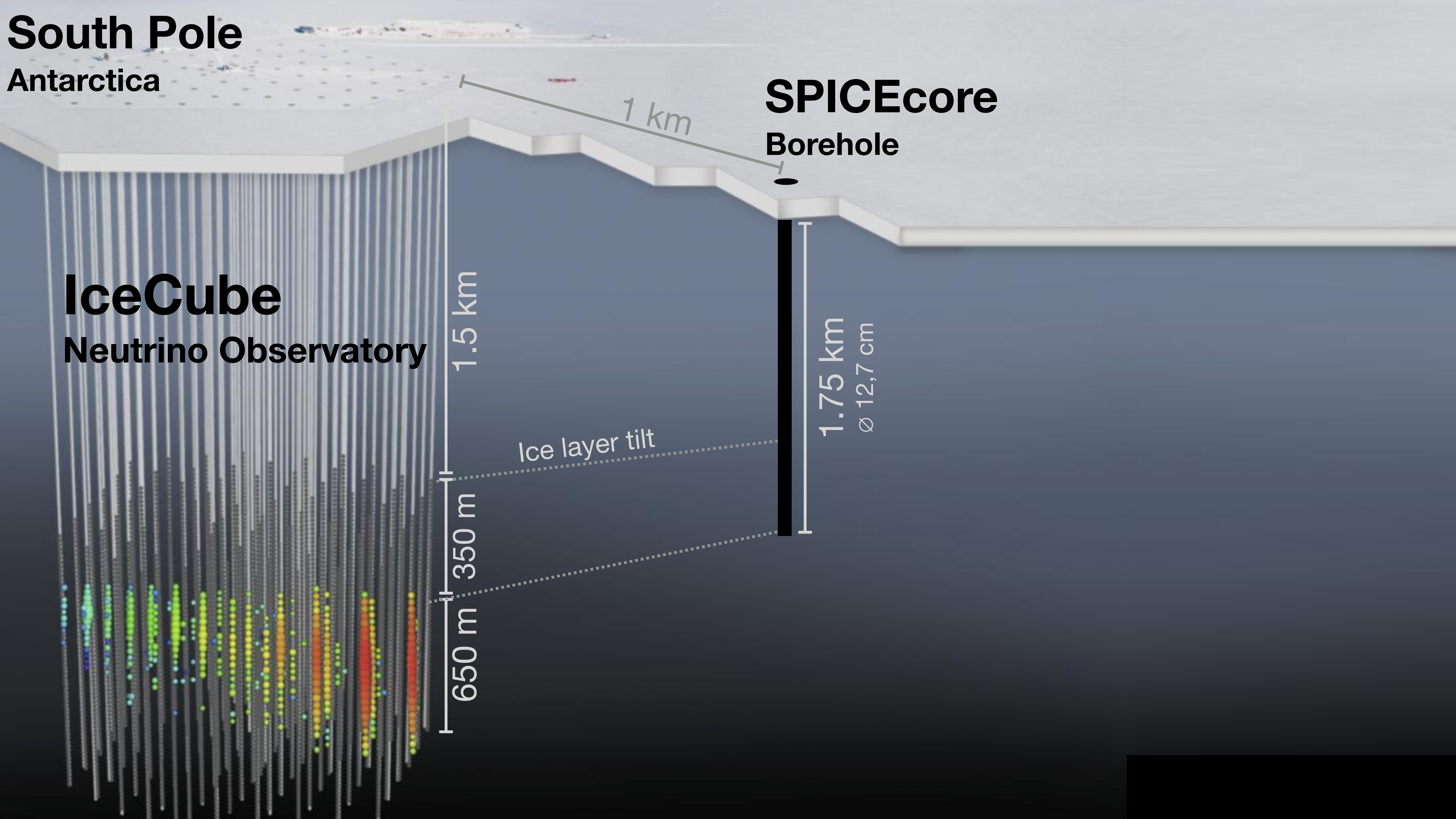
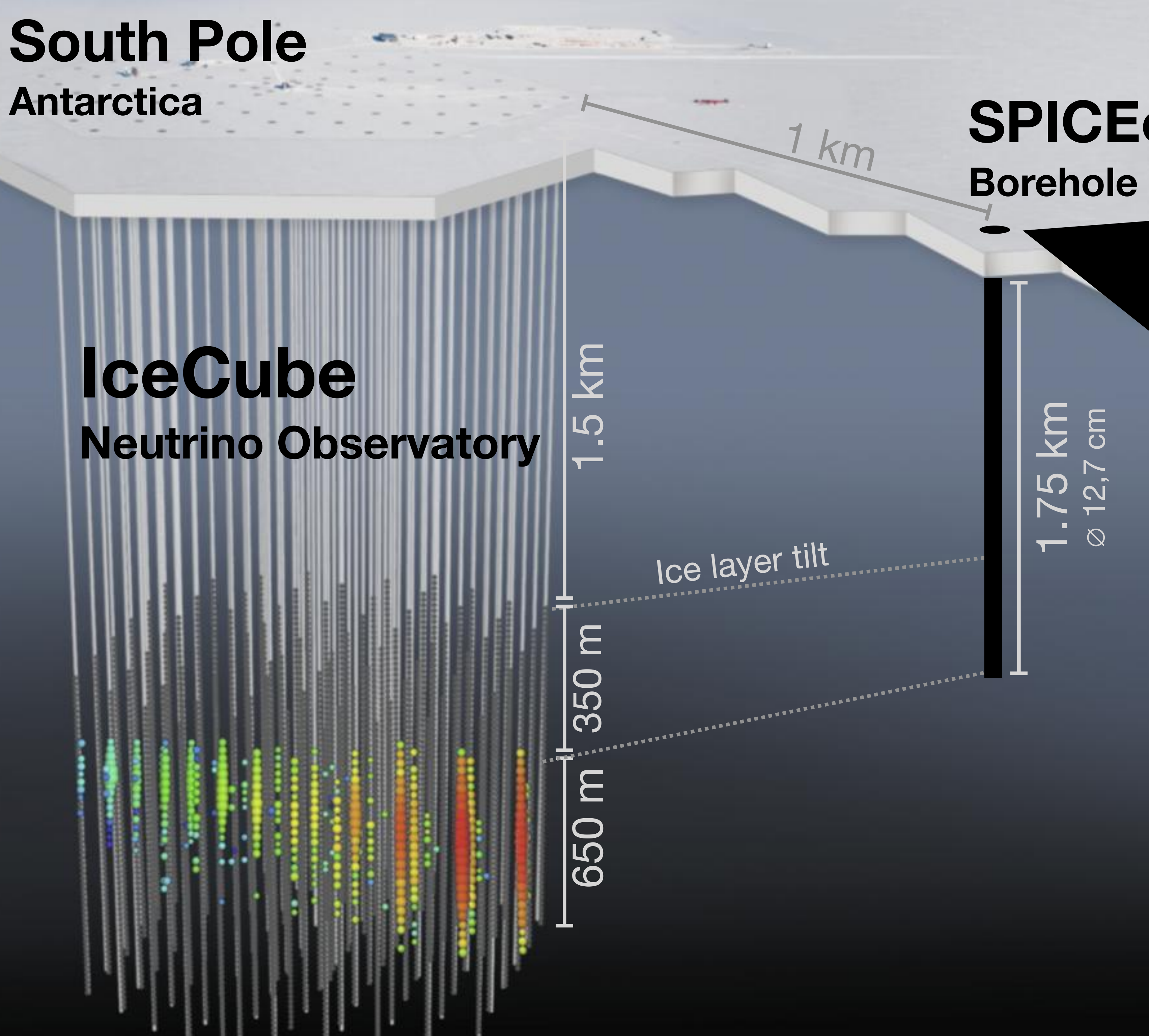
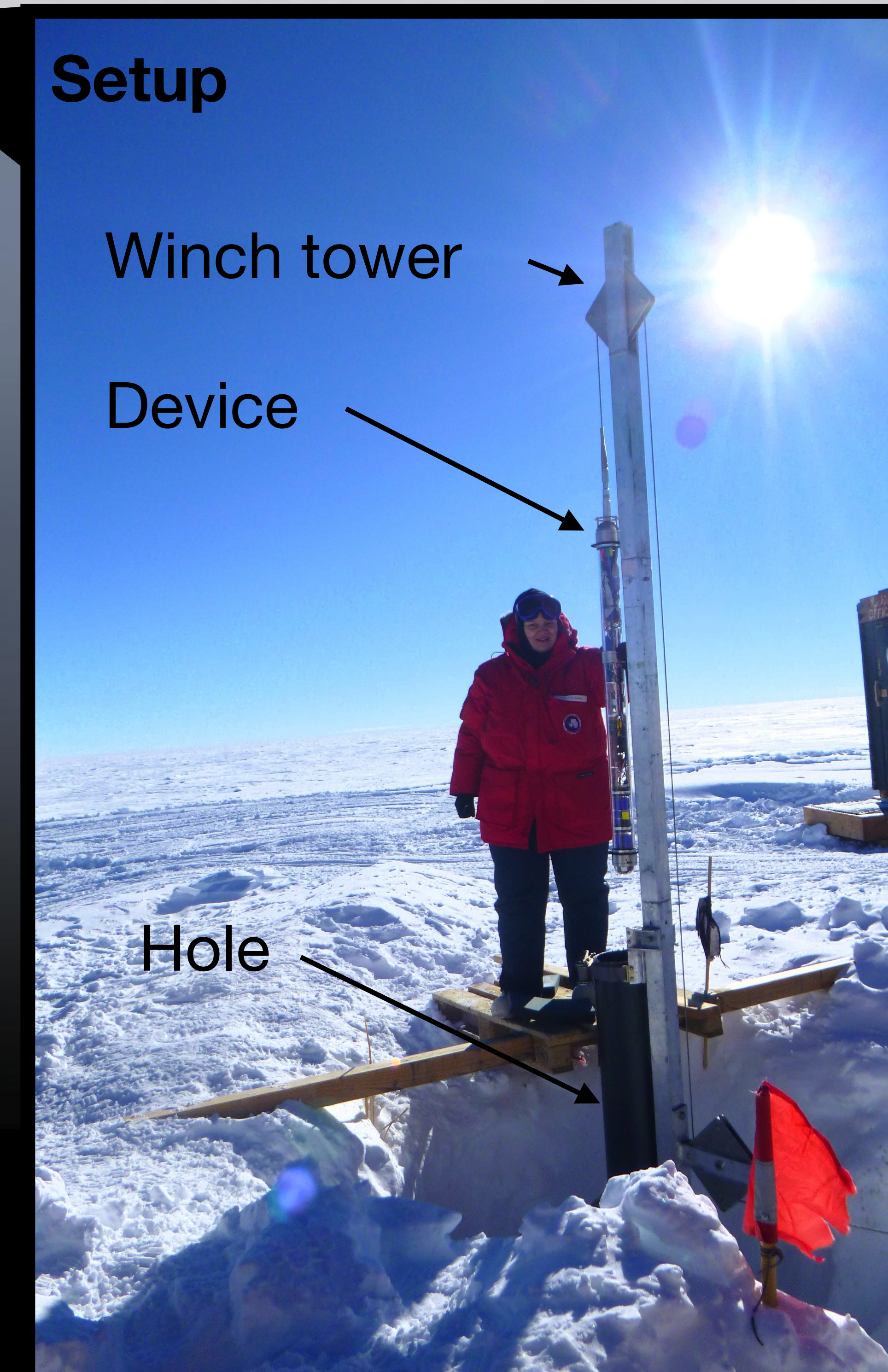


SPICEcore borehole

- filled with anti-freeze / drilling grease (Estisol)
- measurements in 2018:
    - UV transparency - DESY
    - scattering / absorption - SKKU / Berkeley
    - this work





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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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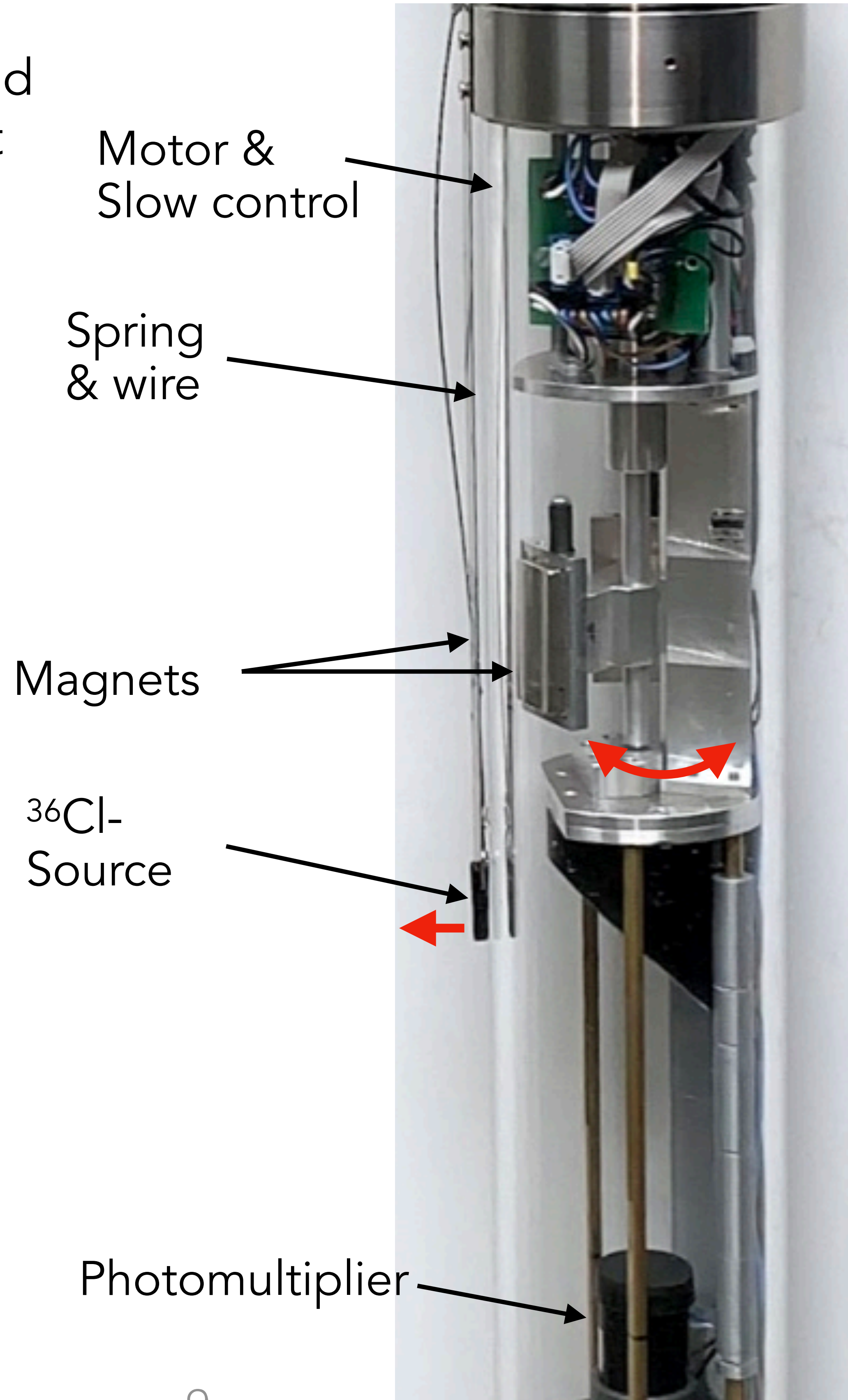

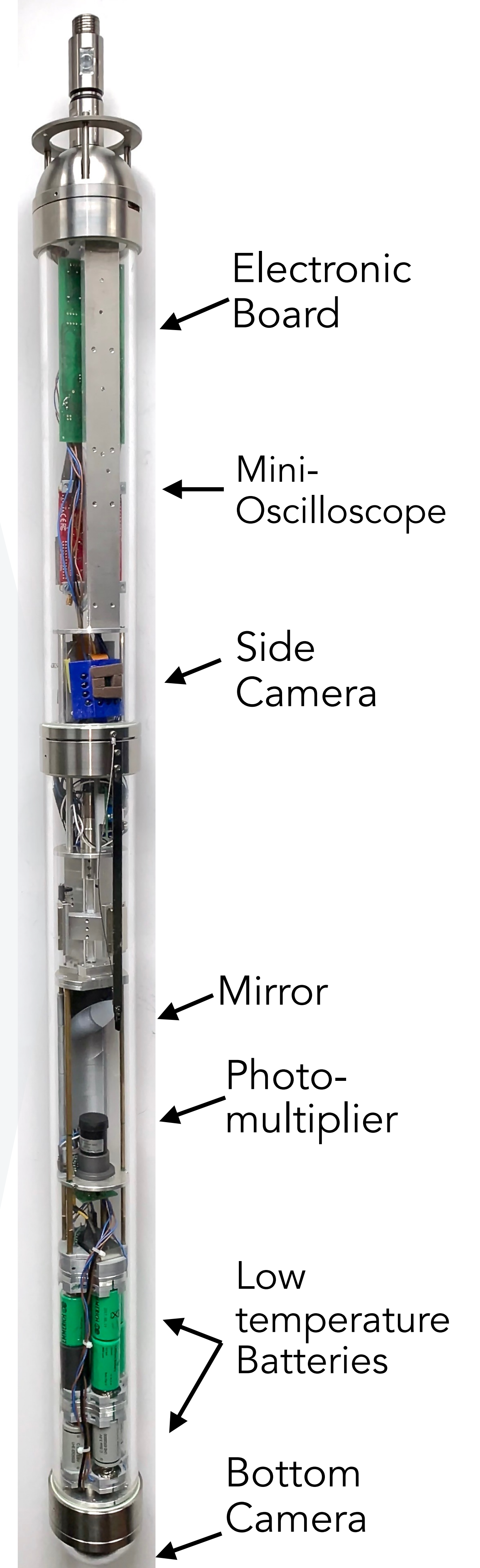

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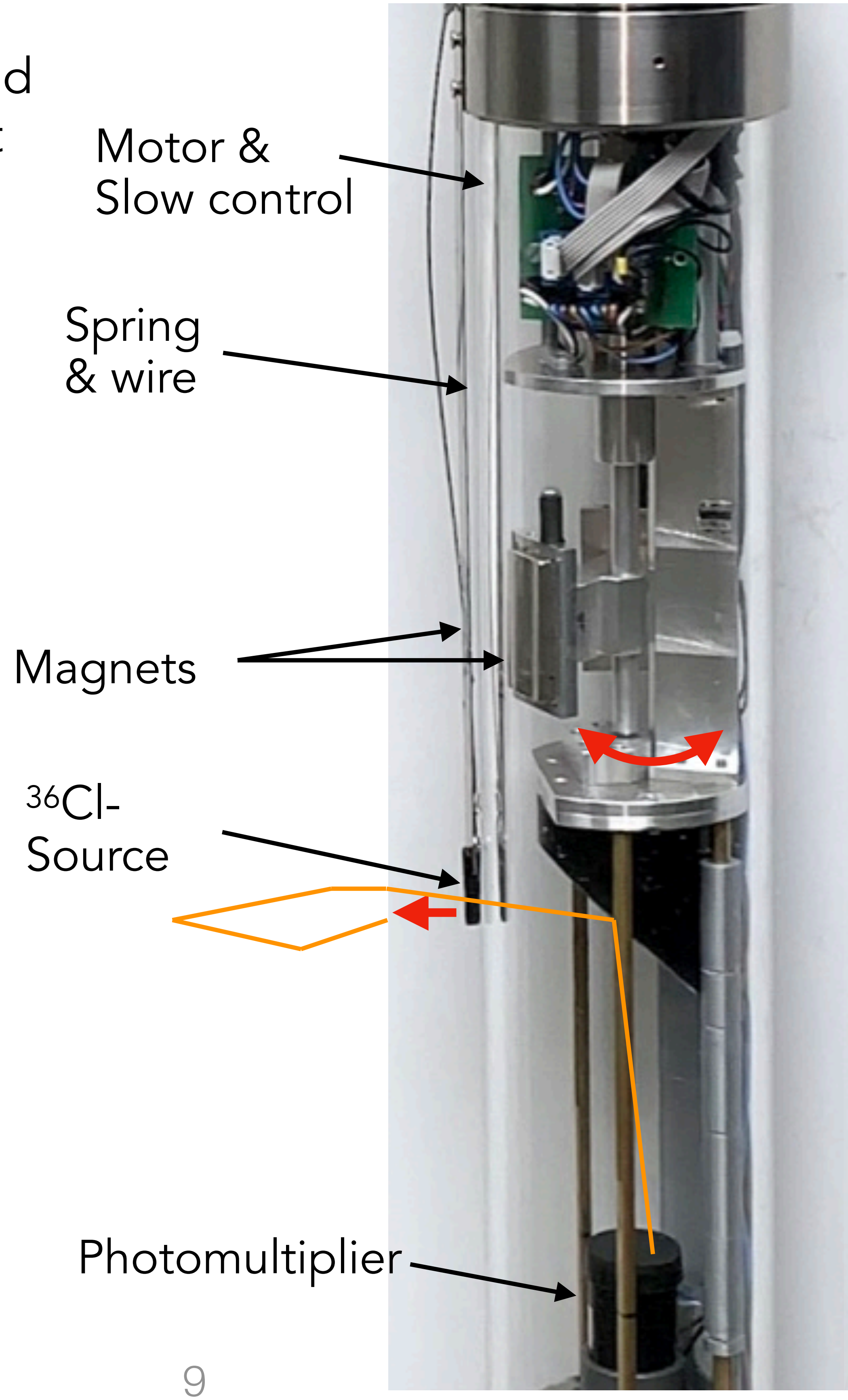

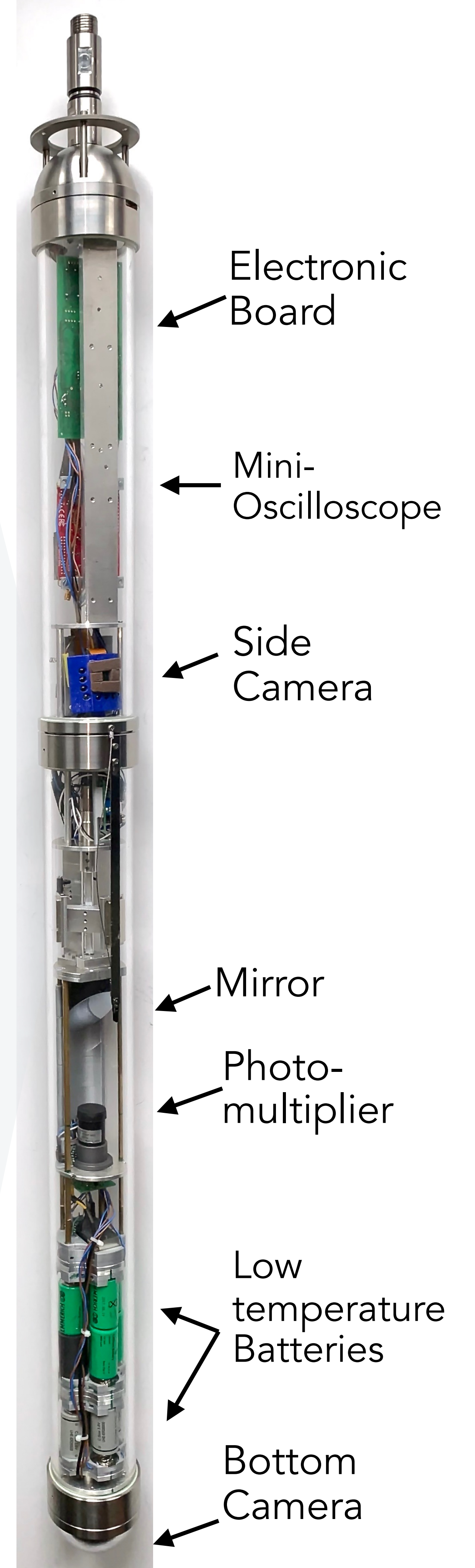

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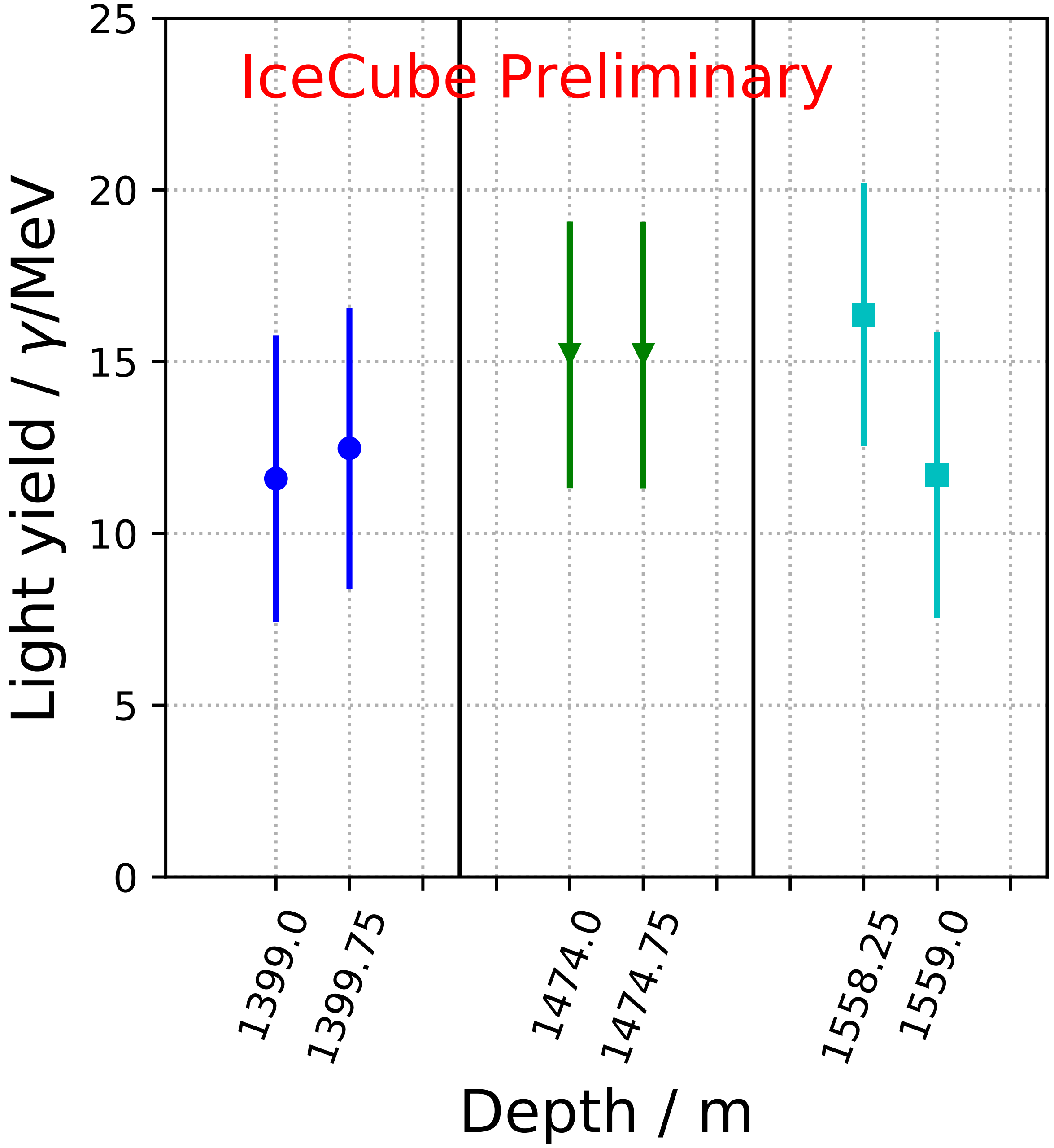
Light yield analysis

- fit resulting photon detection efficiency and compared with measured rates to obtain light yield bounds
  - Estisol luminescence
  - unknown average distance of source to ice

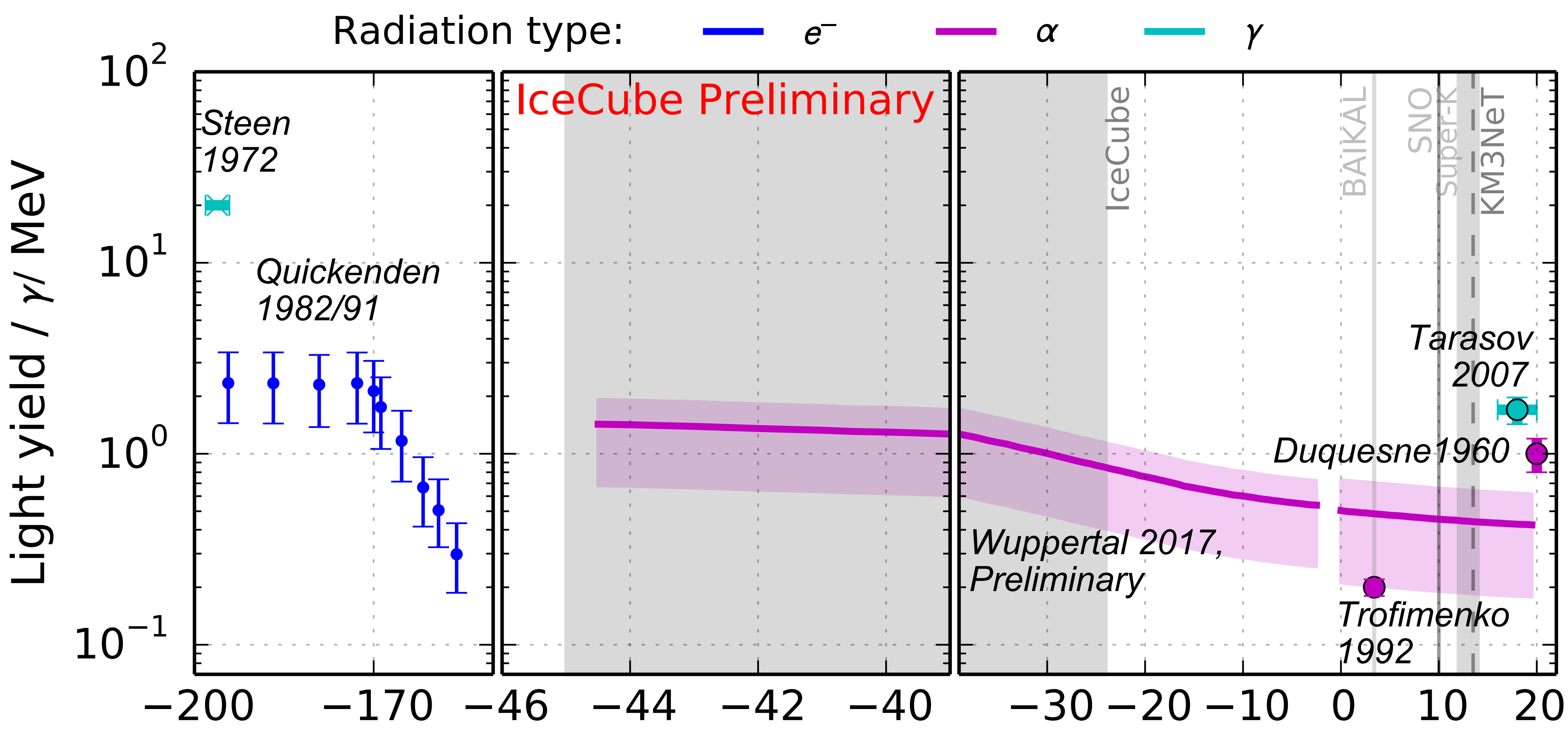
- uncertainties included (a.o.)
  - scattering (impact: +/- 13%)
  - absorption (impact: +/- 13%)
  - source activity (impact: -19% +11%)
  - anti-freeze (Estisol) luminescence yield (impact: +/- 15%)



arXiv:1908.07231

Luminescence light measurement

First laboratory measurement at temperatures of neutrino telescopes



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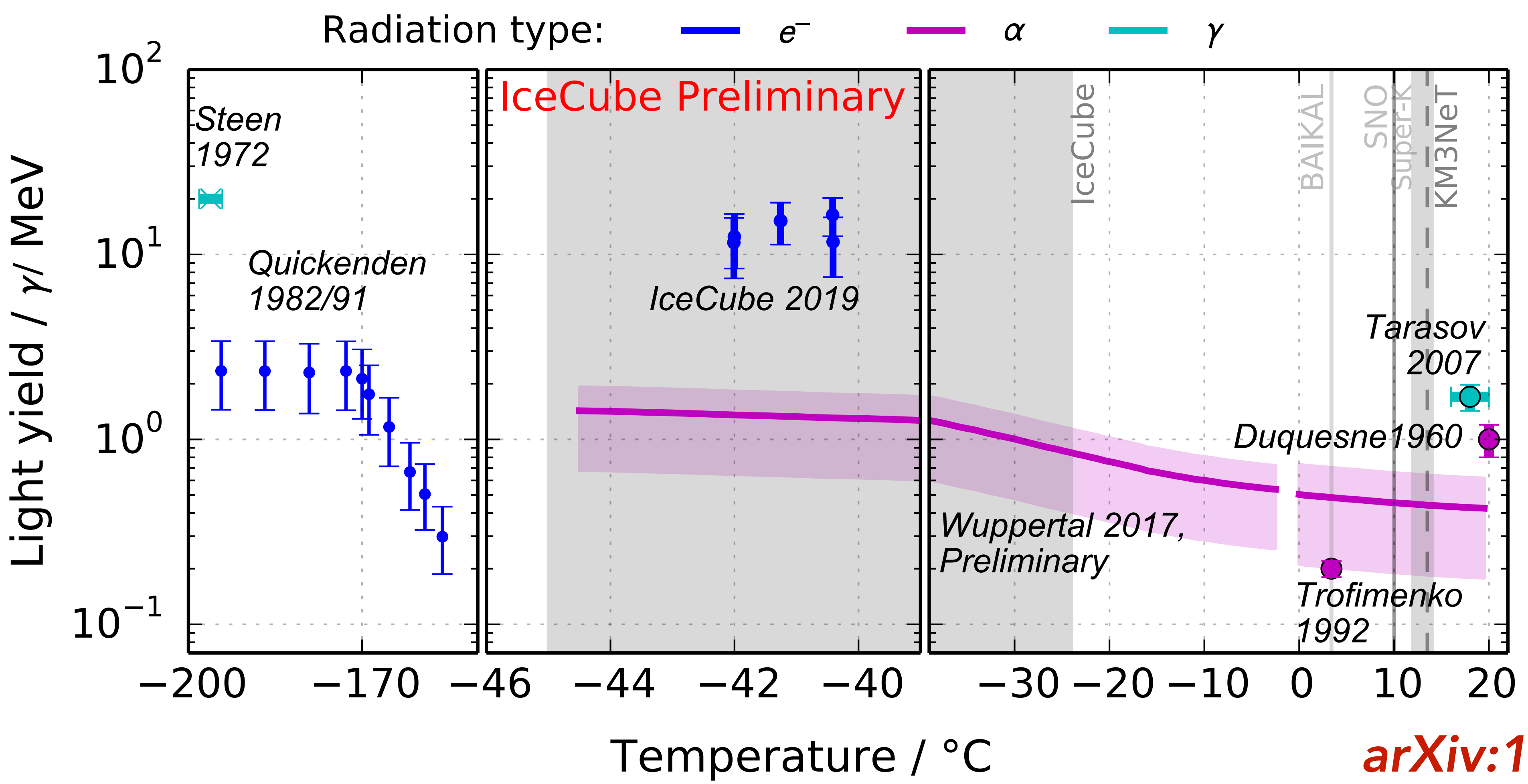
Luminescence light measurement

First laboratory measurement at temperatures of neutrino telescopes & first in-situ measurement



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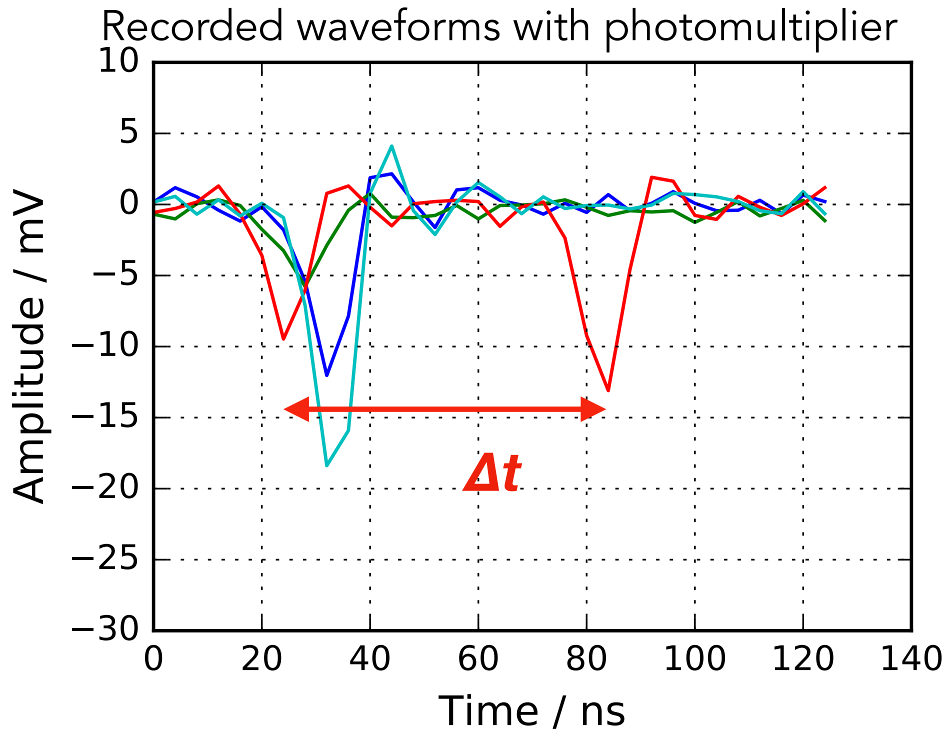
Time differences

- time differences between a pulse and all following pulses
- 40-120 ns:
  - obtained from waveform
  - corrected for PMT effects
- > 120 ns: obtained from trigger timestamps



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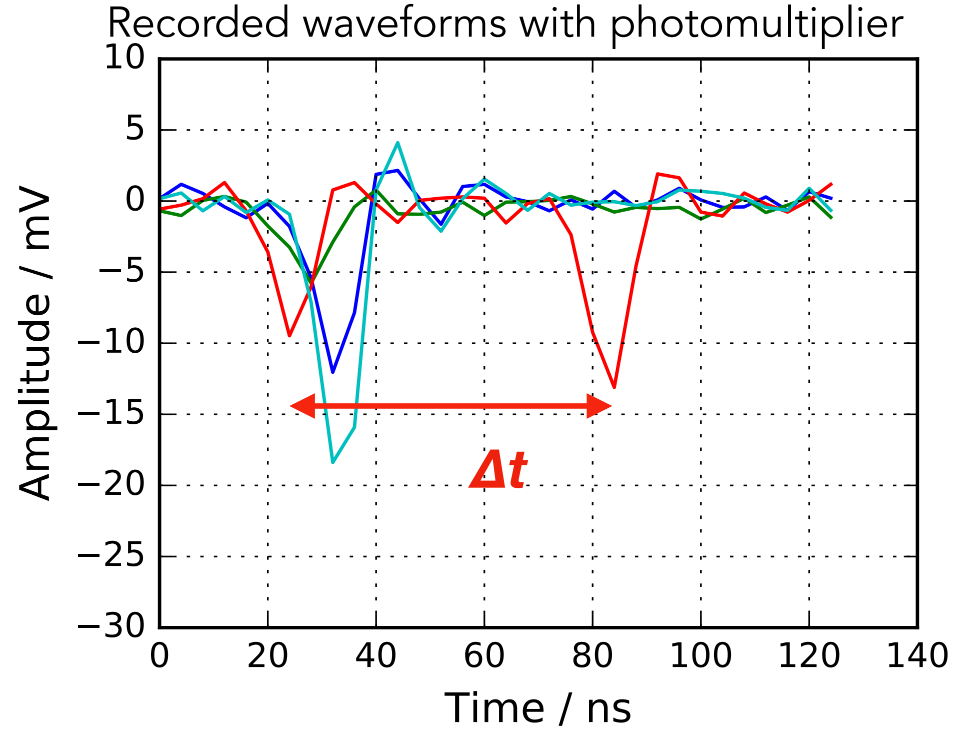
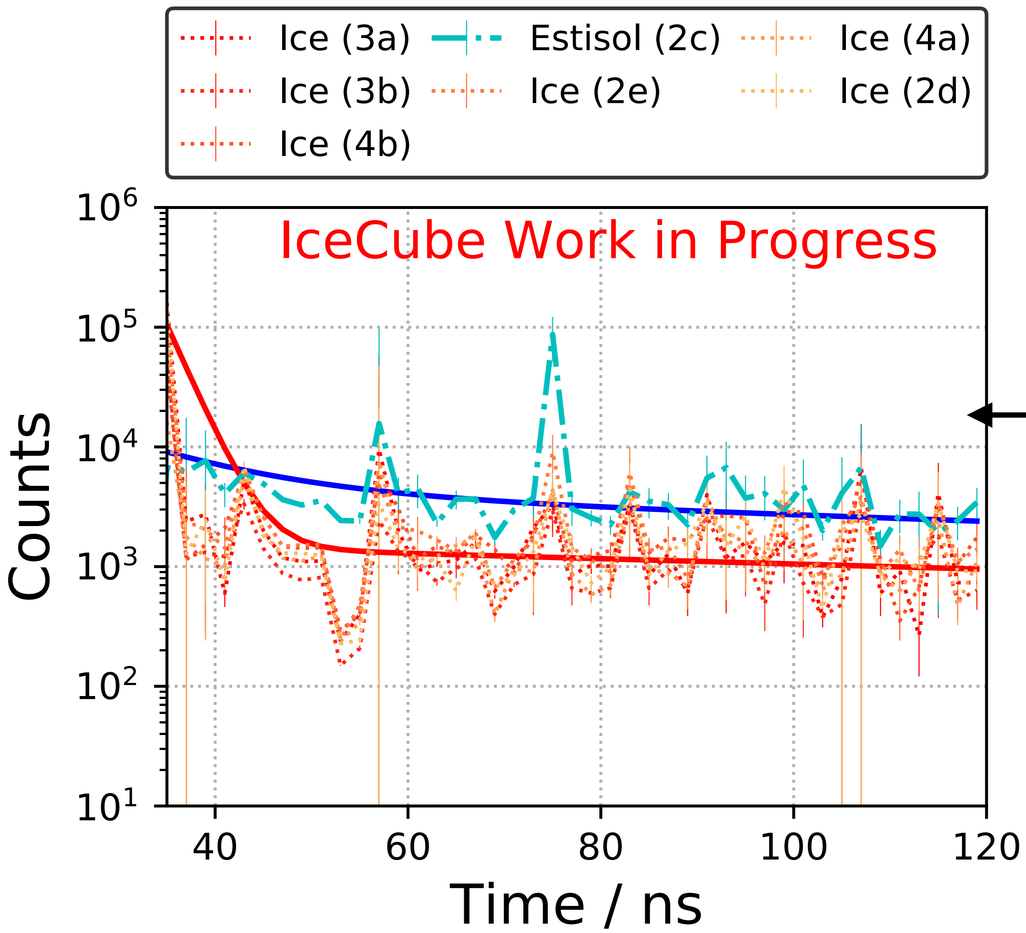
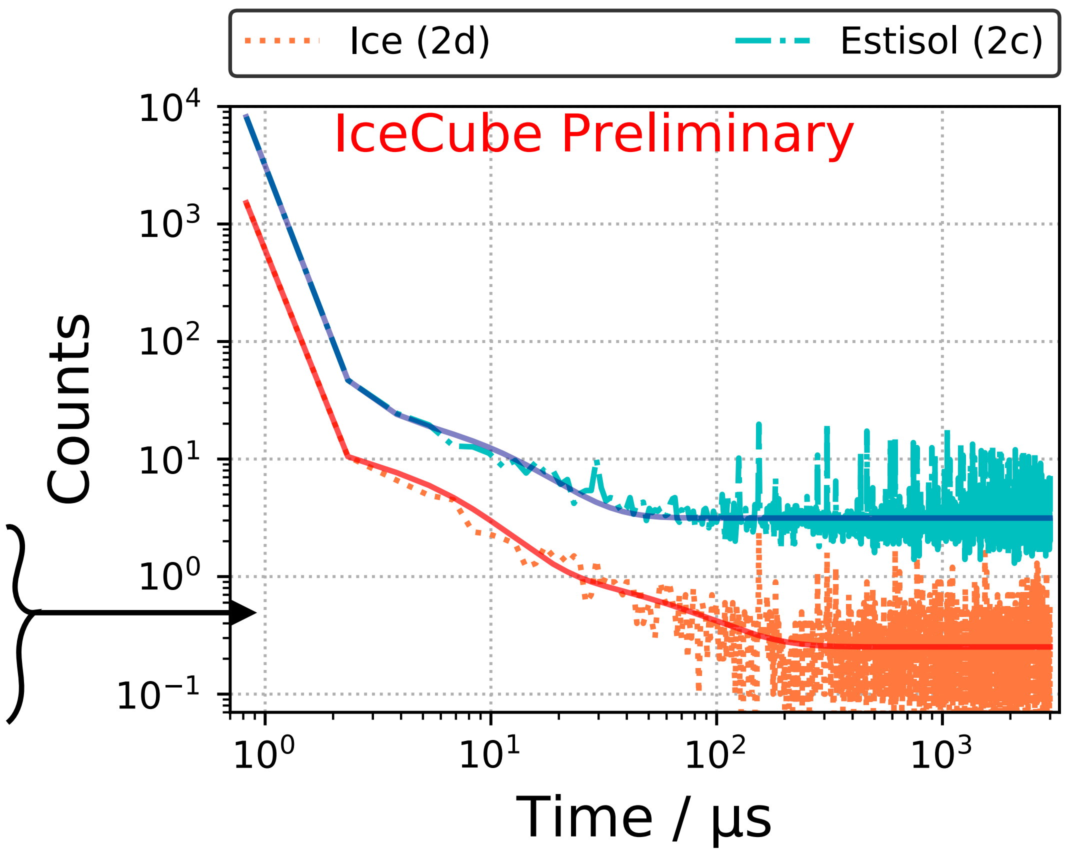




Identified decay times:

2.44 ± 2.07 ns
196.1 ± 39.1 ns

189.6 ± 29.9 ns
5.03 ± 0.06 μs
56.1 ± 6.29 μs



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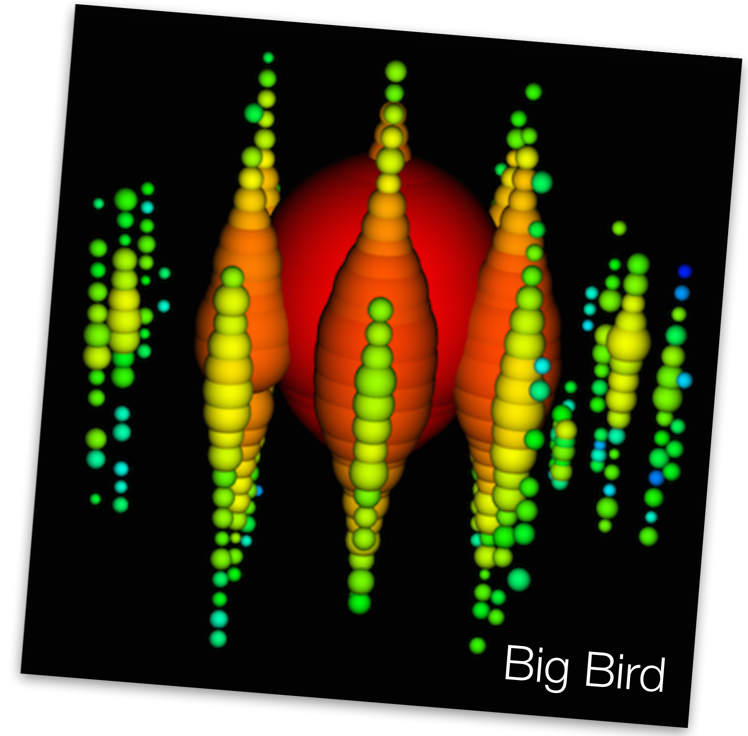
Applications of luminescence light in neutrino telescopes

Calibration

- IceCube and KM3NeT:
  - energy reconstruction of high energy neutrinos
  - correlated noise on long time scales
- Super-K: particle identification



- Cherenkov light proportional to velocity but Luminescence proportional to deposited energy
- for high energy events 1 sec around trigger is saved in IceCube
- challenge in IceCube: dead times of read-out system

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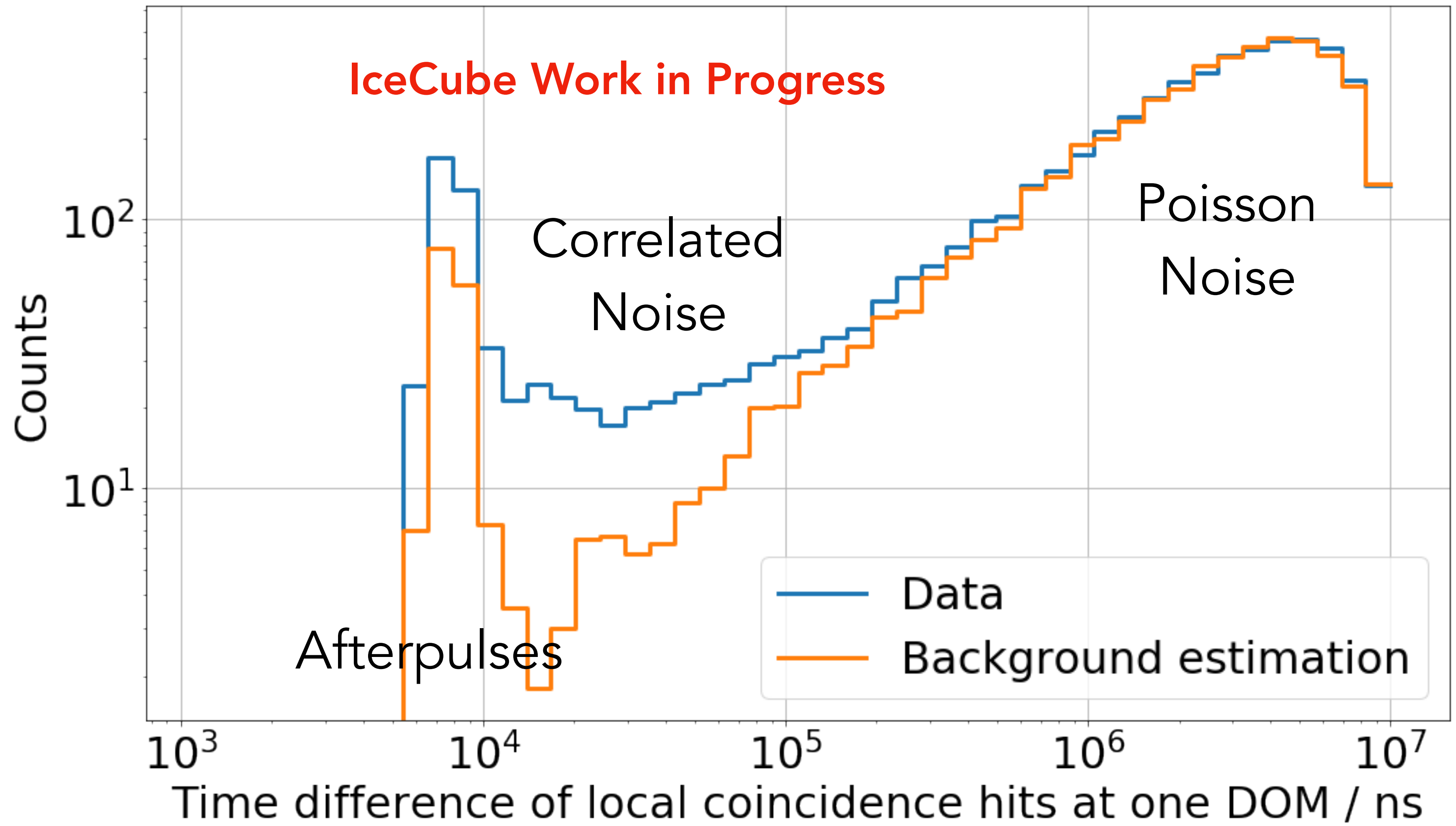

Data: taken from a random trigger

Background estimation: reshuffling data by cutting 10μs traces

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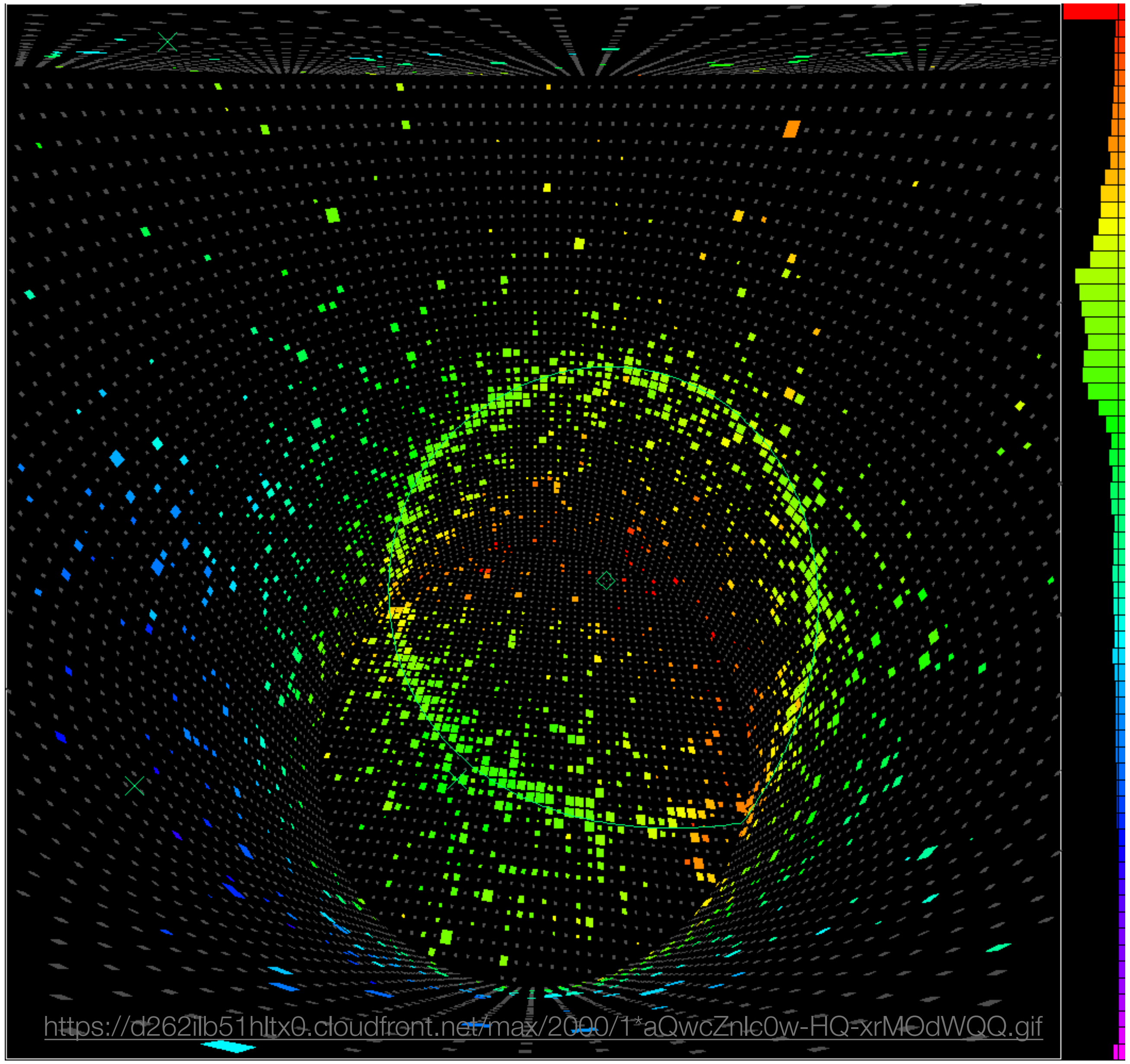

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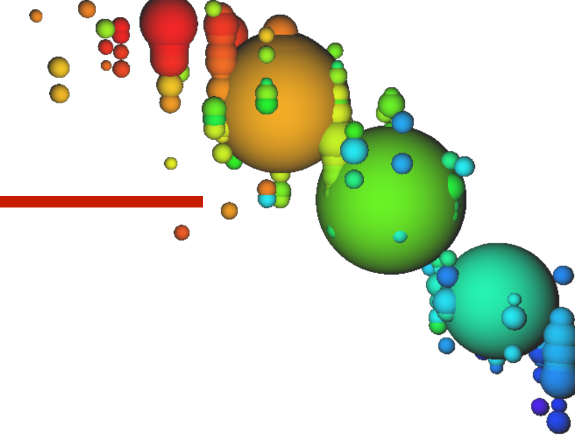

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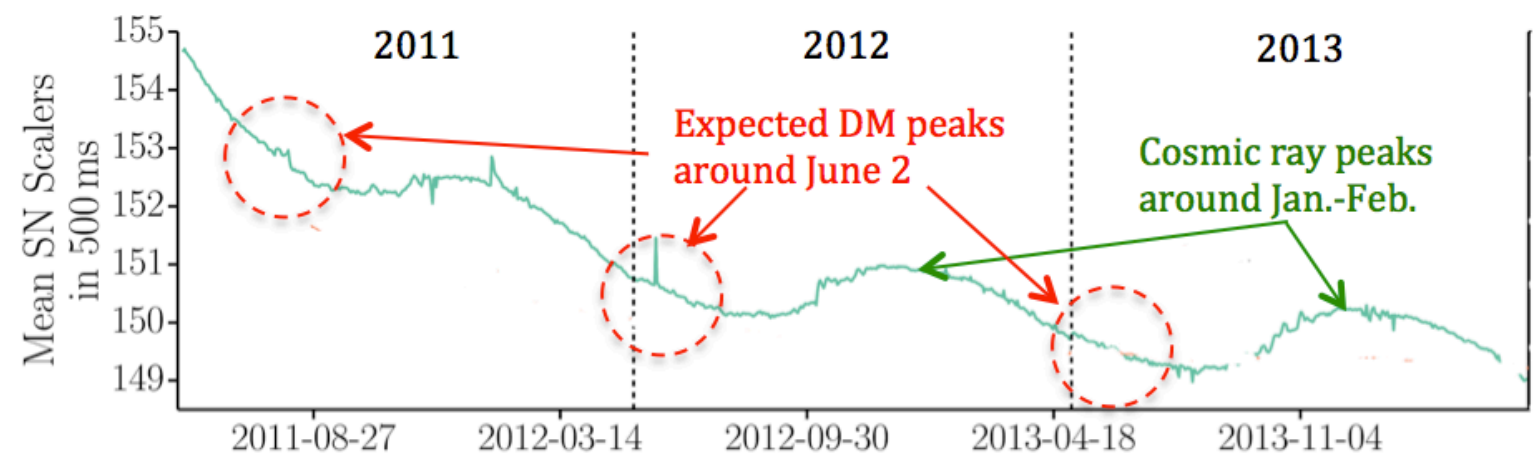
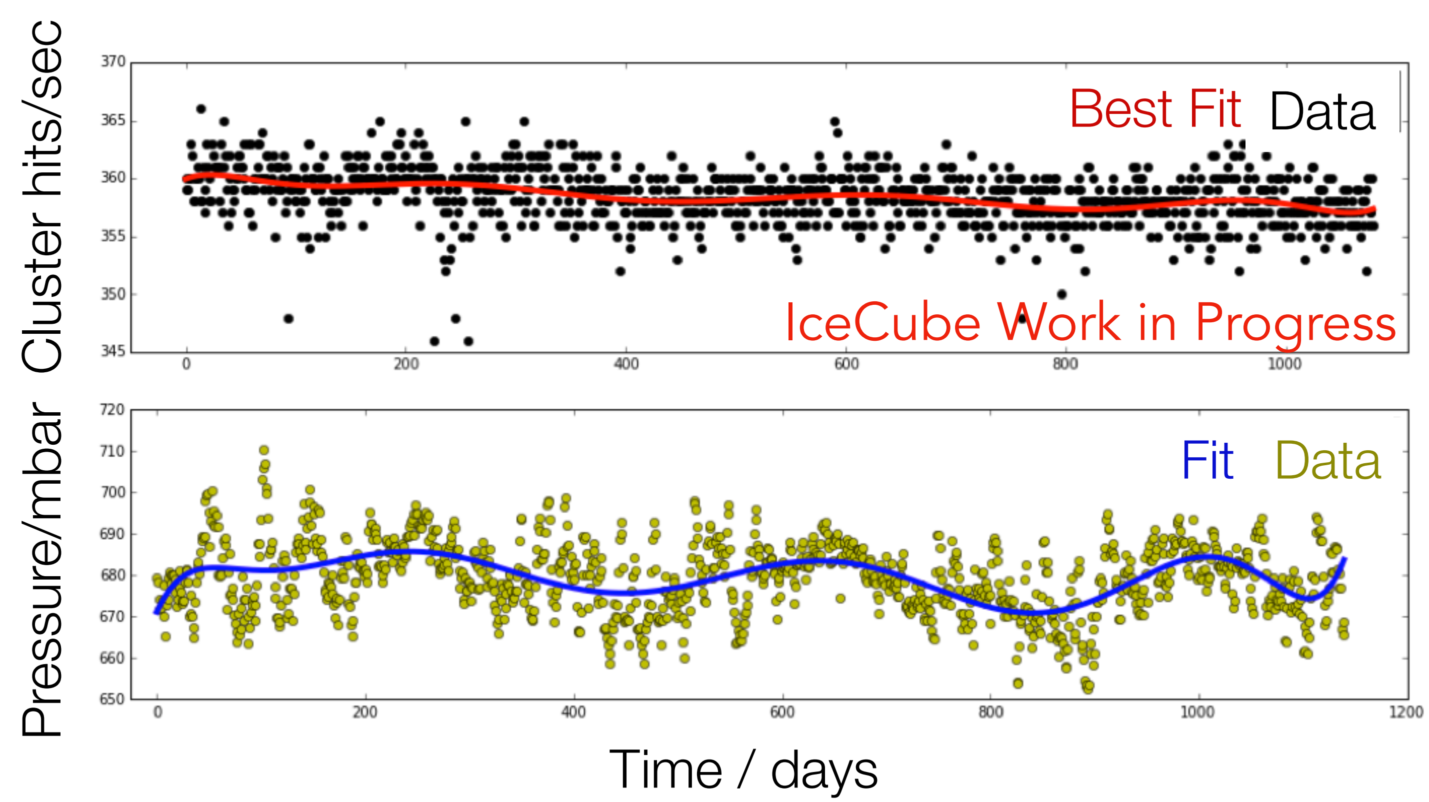
arXiv: 1402.0466v2



Neutral particle detection

- neutral exotic particles
- *dark matter annual modulation*



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Neutral particle detection

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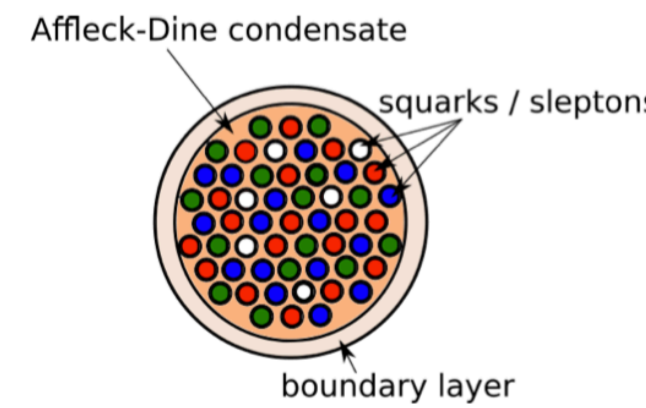
Detection of slowly moving particles

- IceCube and KM3NeT: heavy electric or magnetic charges
  e.g. *magnetic monopoles*
- Super-K: slow interaction products
  e.g. kaons

Q-Balls

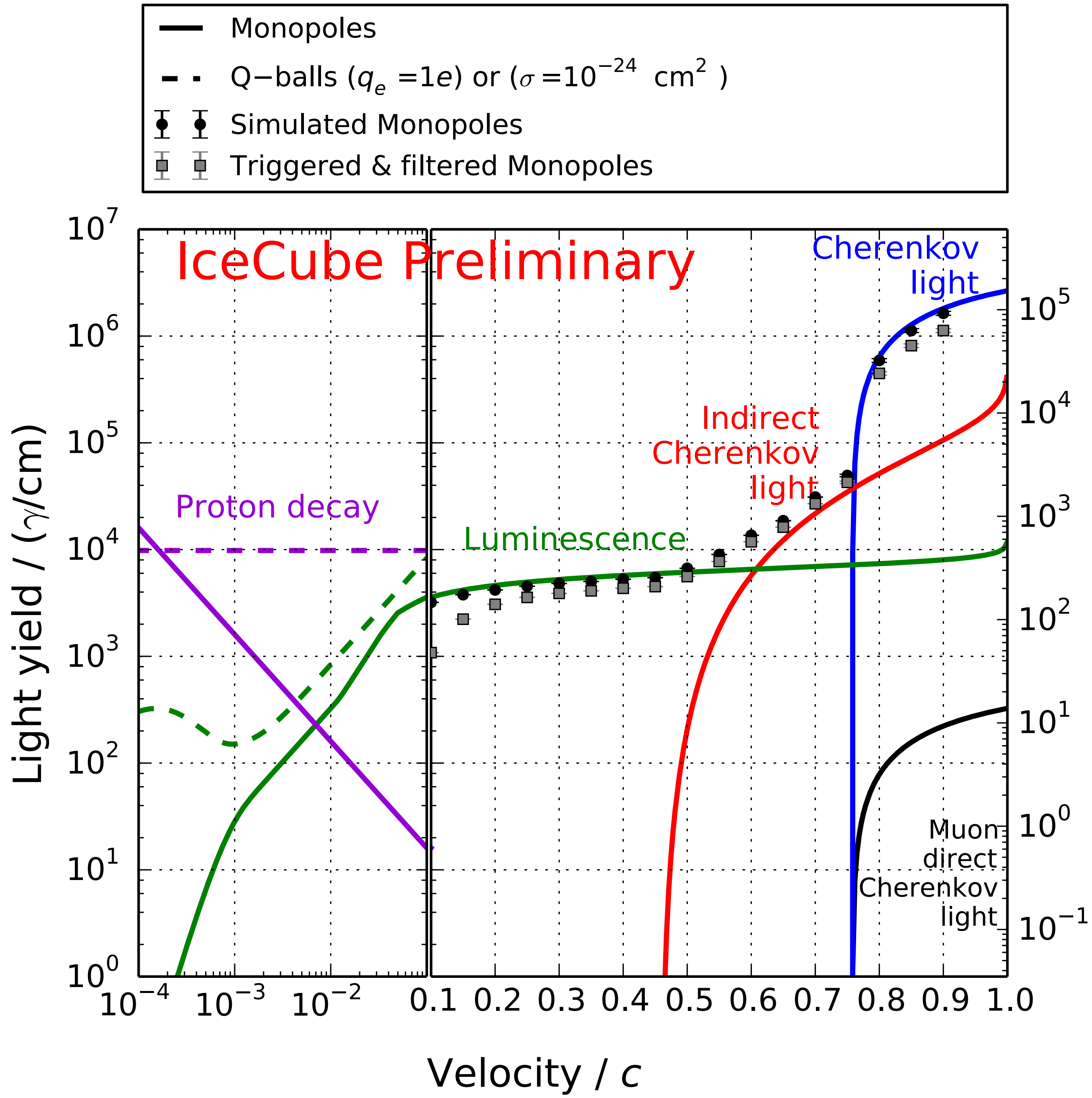


- stable condensates with high "charge" **Q** of lepton or baryon number
- candidate for dark matter
- luminescence enables search for electrically charged Q-Balls

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) or in intermediate stages of symmetry breaking (IMM)

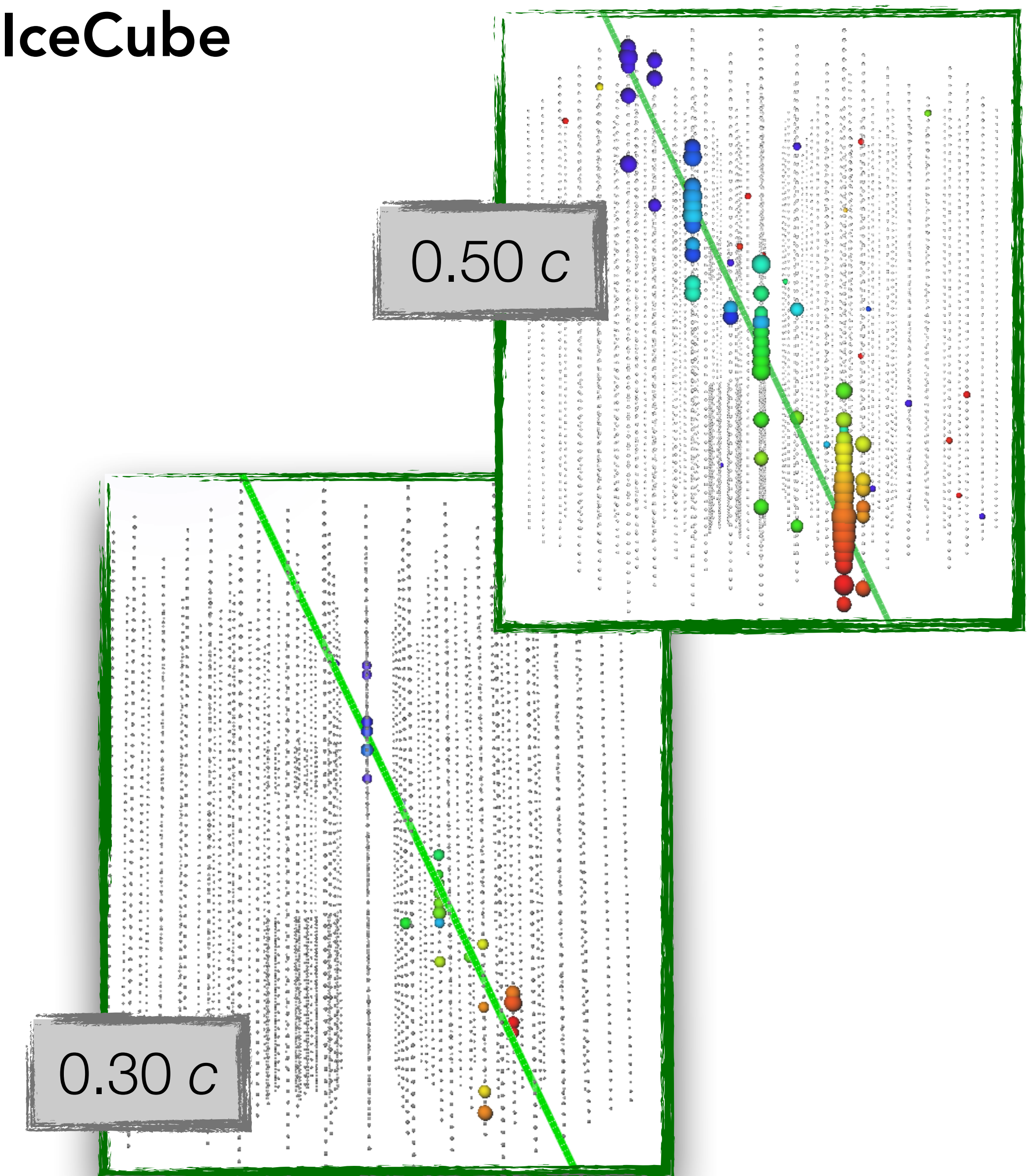
Luminescence to detect exotic particles



Calculated for ice, values vary for water.

arXiv:1908.07231

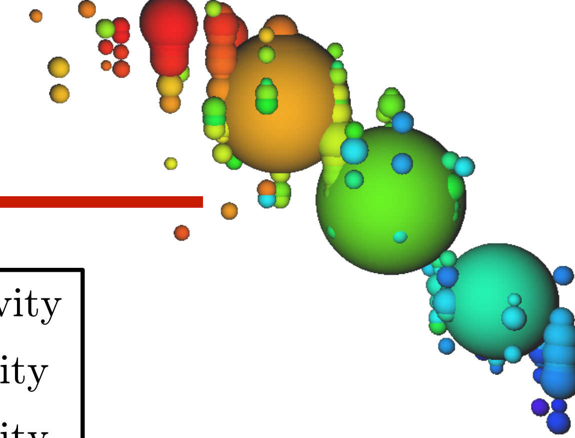
Simulation of Magnetic Monopoles in IceCube

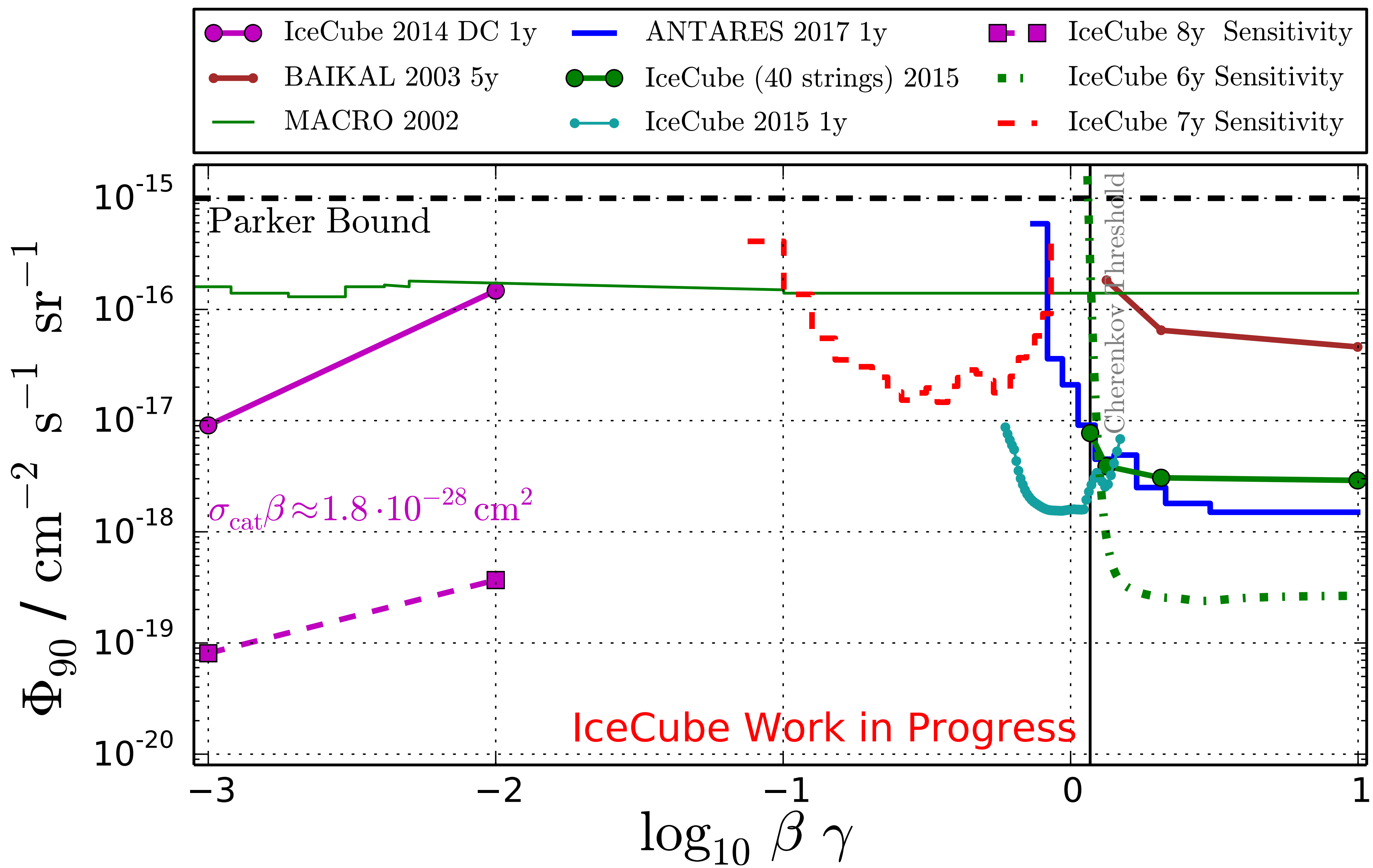


Color ≙ time (red -> blue)

Size ≙ light amount

Mapping the parameter space of magnetic monopoles





Detection channels in neutrino telescopes:

Catalysis of proton decay
Model dependent. Could be improved with luminescence, too.

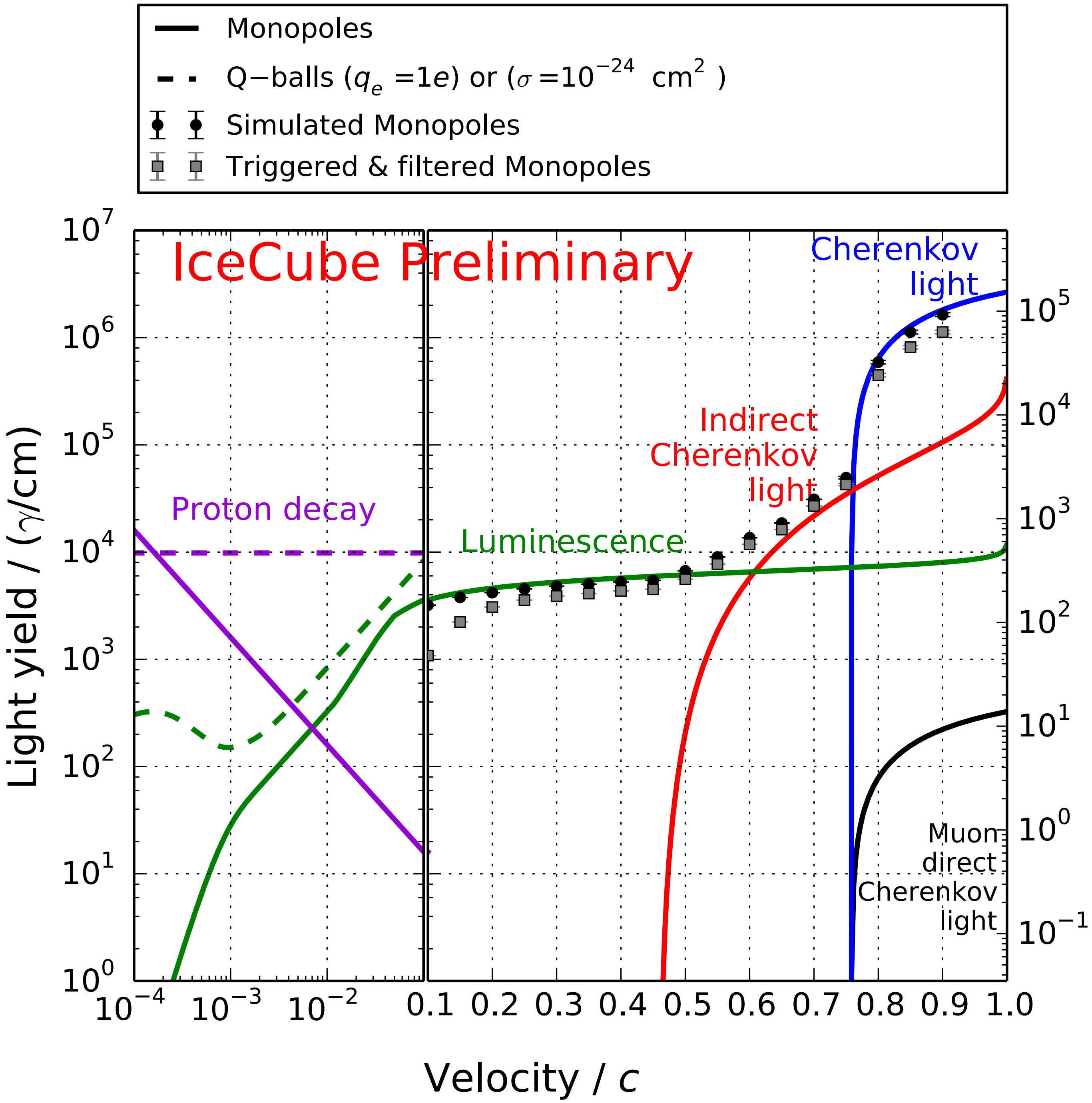
Luminescence
New sensitivity!

Indirect Cherenkov radiation

Direct Cherenkov radiation

arXiv:1908.07231

Luminescence to detect exotic particles



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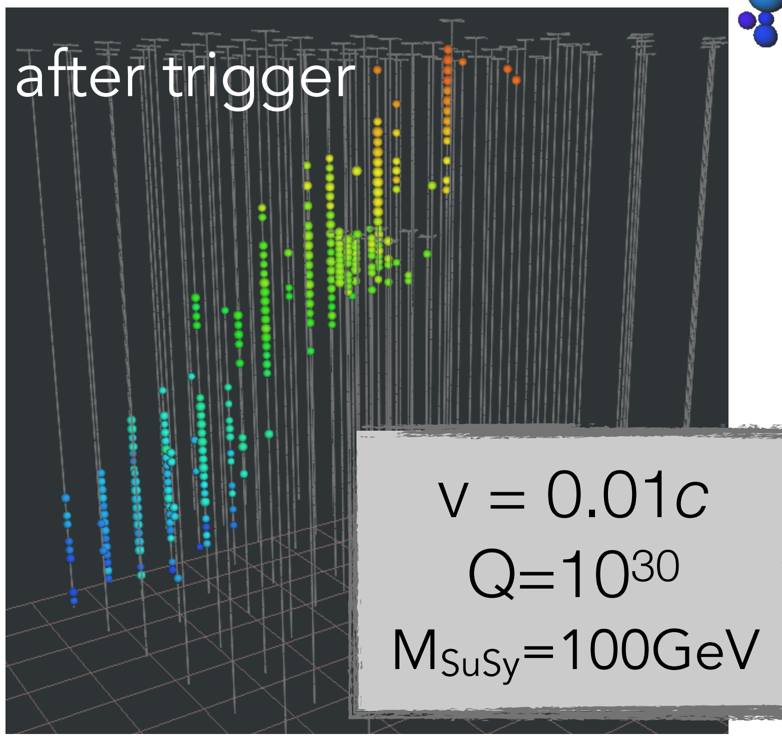
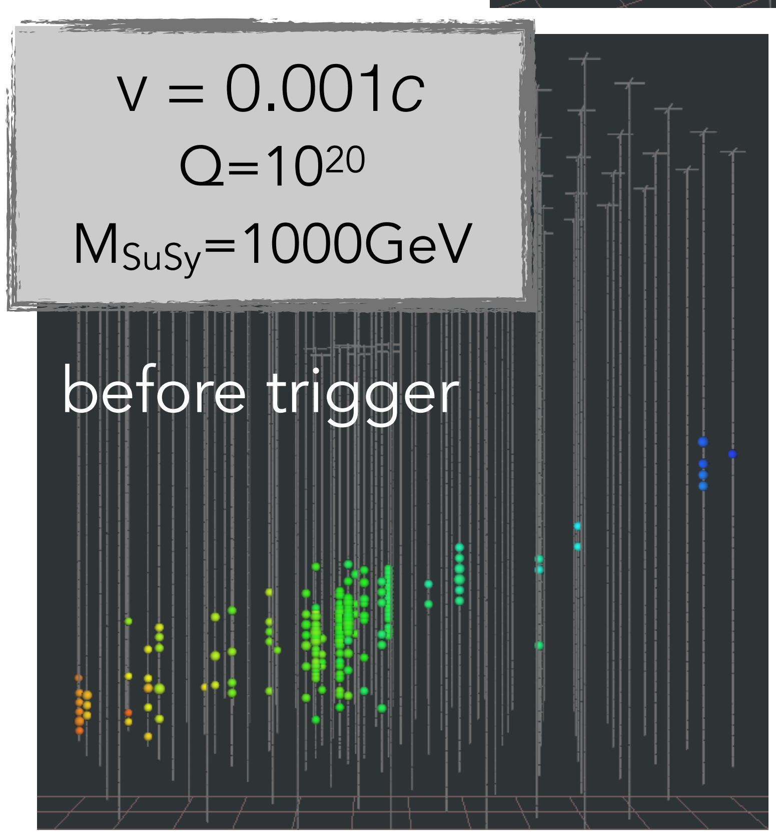
Simulation of Q-Balls in IceCube

Faster Q-Balls



Slower Q-Balls

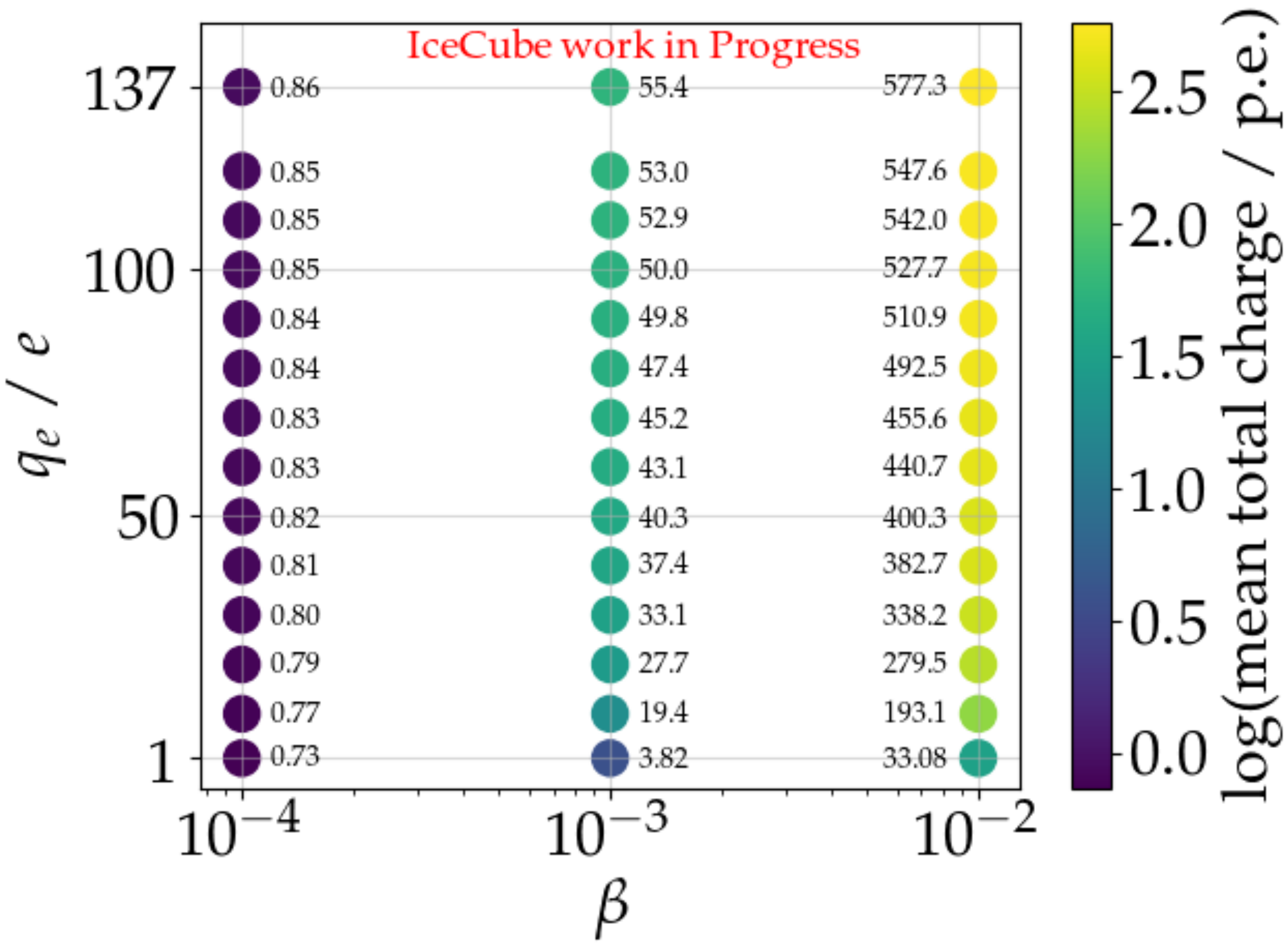


Event views omitting noise

Luminescence to detect exotic particles

Q-Balls are bright events in IceCube …

Mean total charge per event



Mean total charge detected during one event for different Q-ball configurations

Simulation of Q-Balls in IceCube

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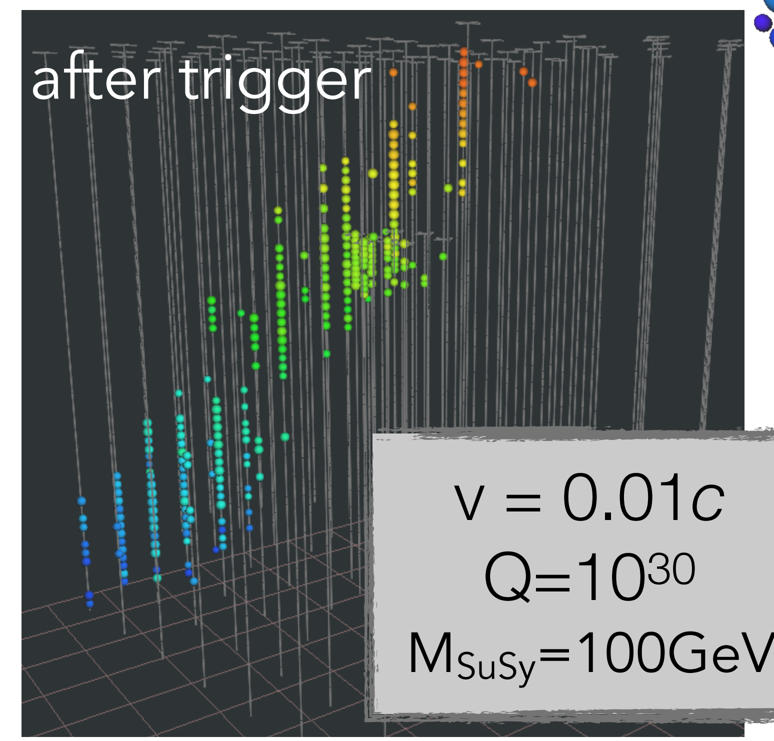

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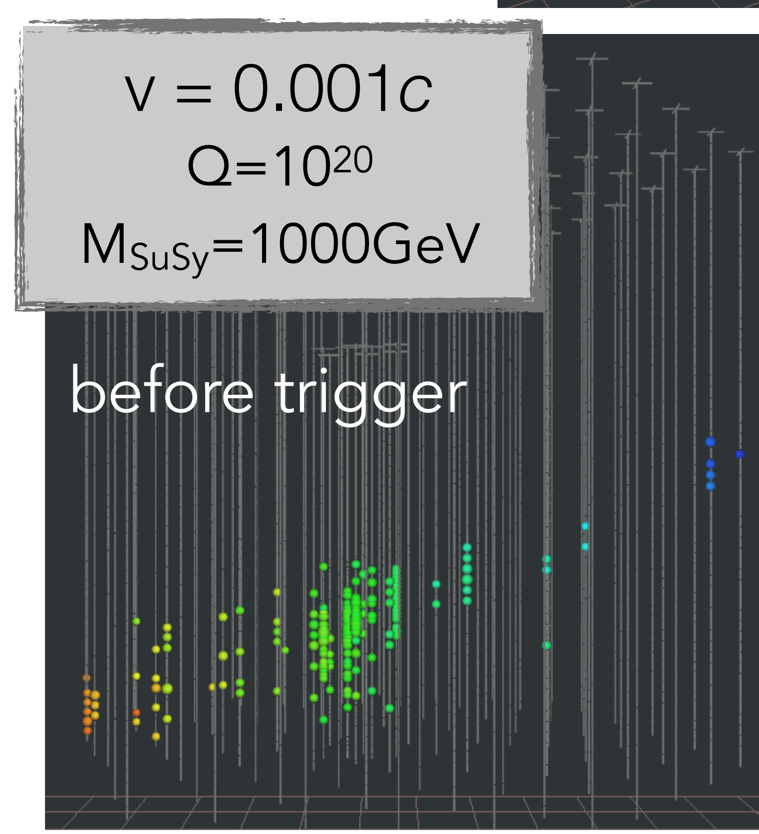
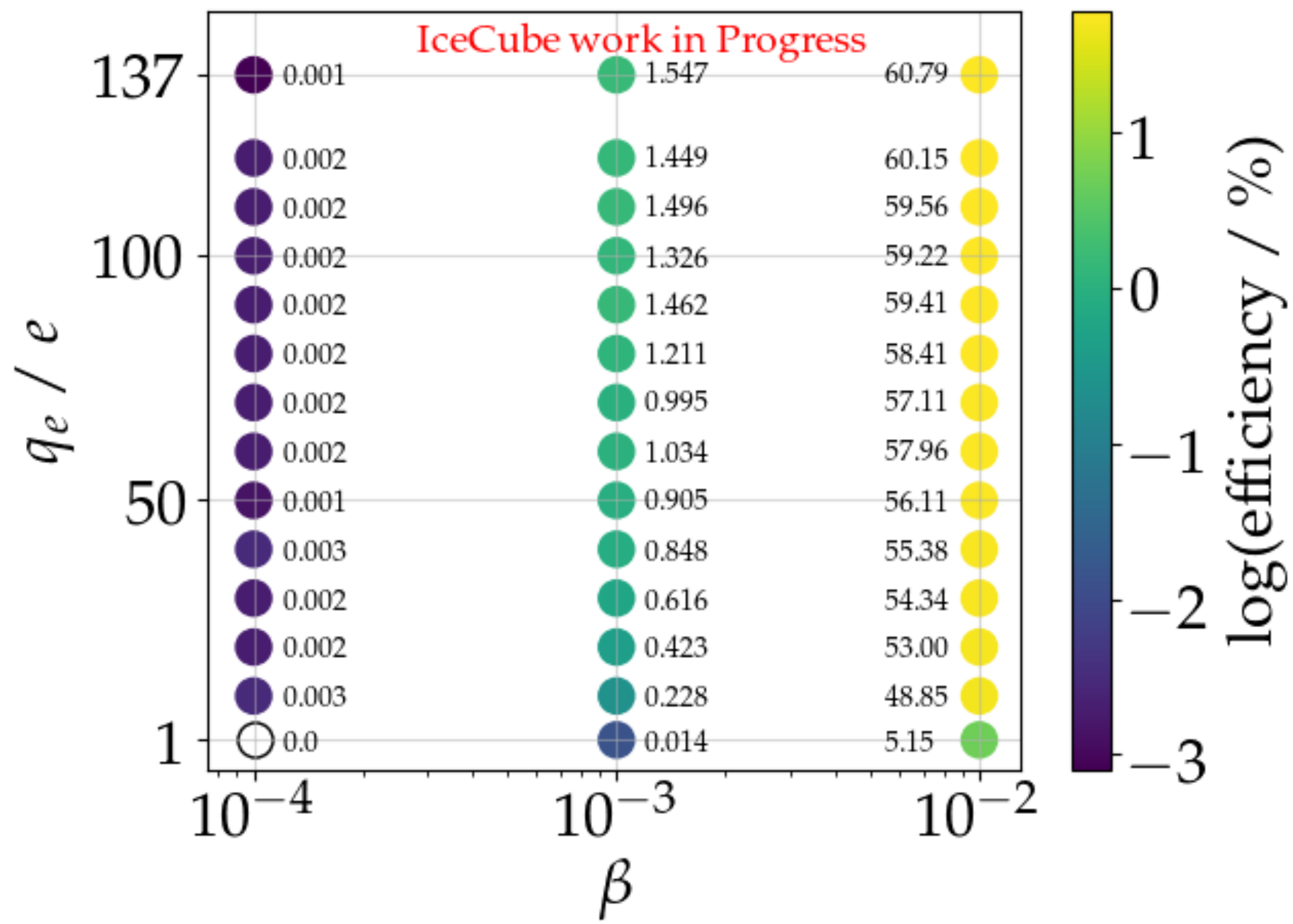


Event views omitting noise

Luminescence to detect exotic particles

… but the efficiency to trigger them is low

Efficiency to trigger an event which produces light in IceCube



trigger efficiency: triggered events divided by events wich produce light in the detector

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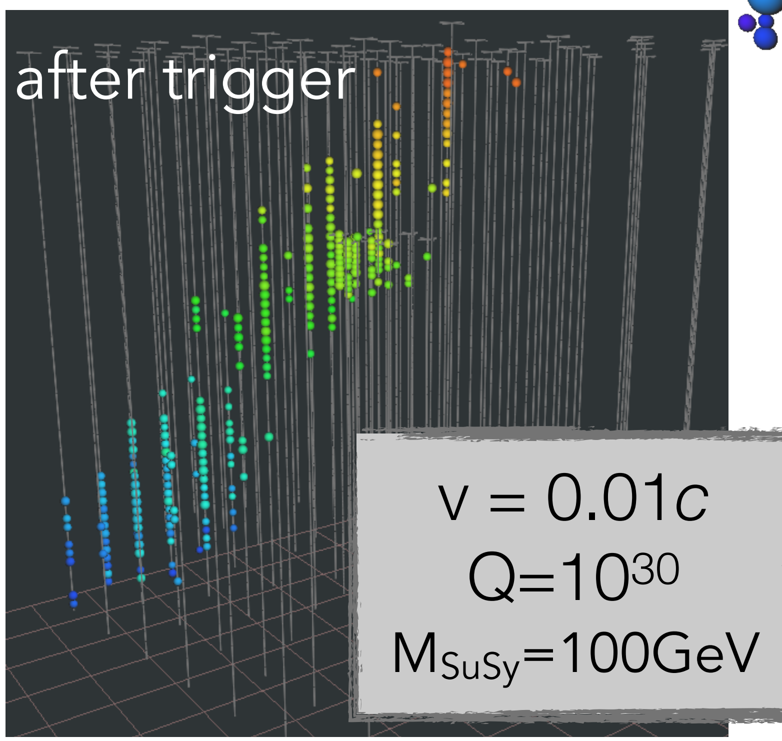

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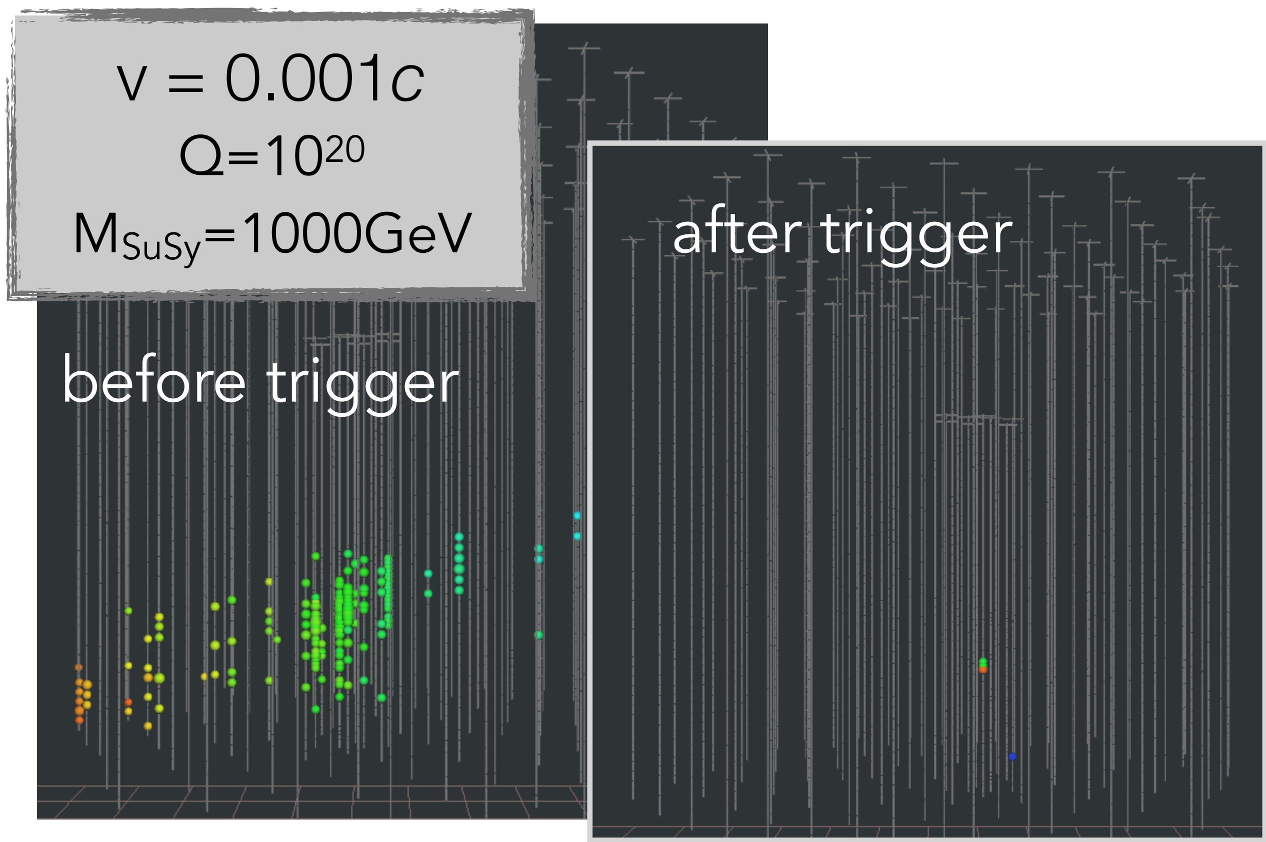
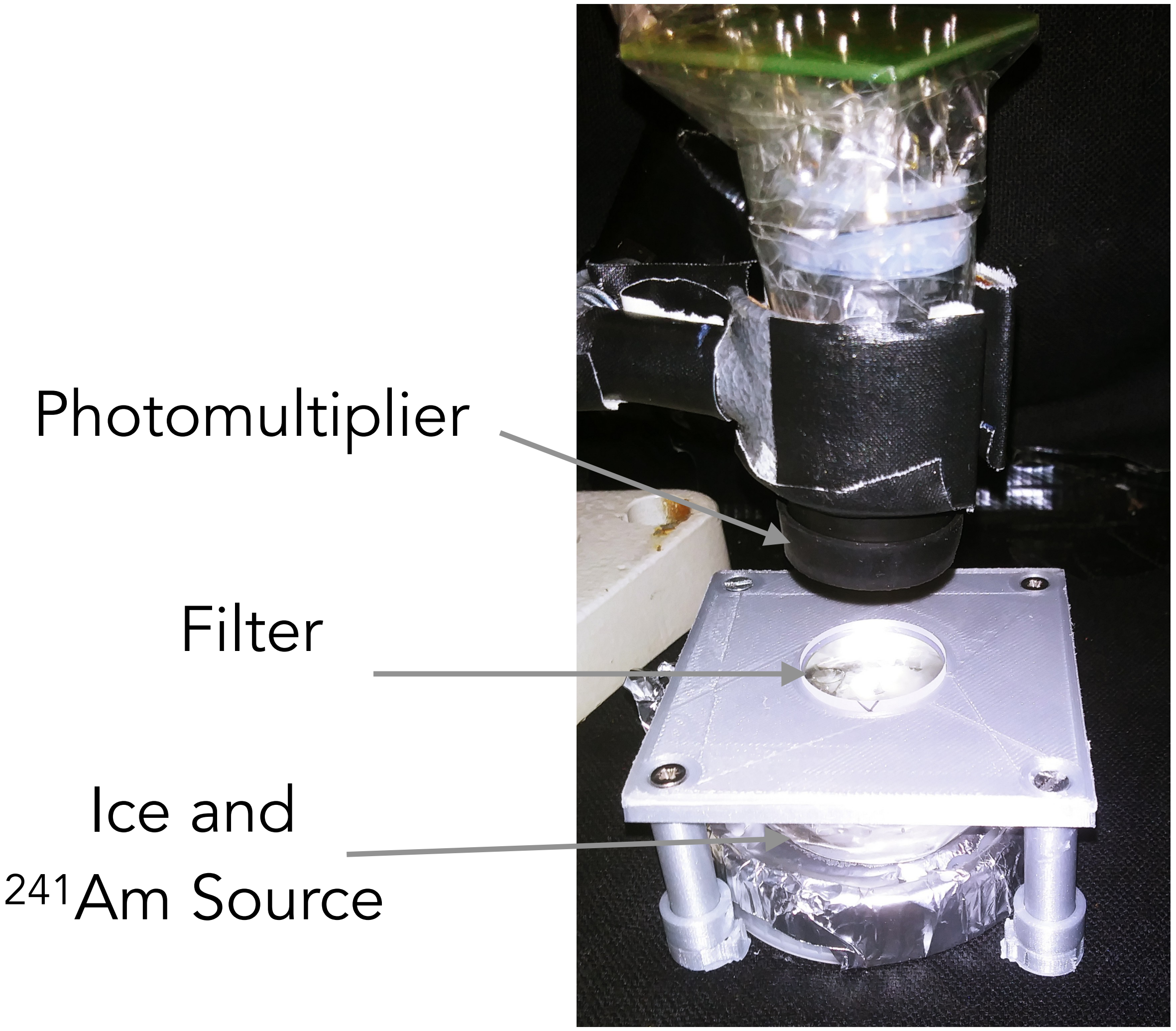
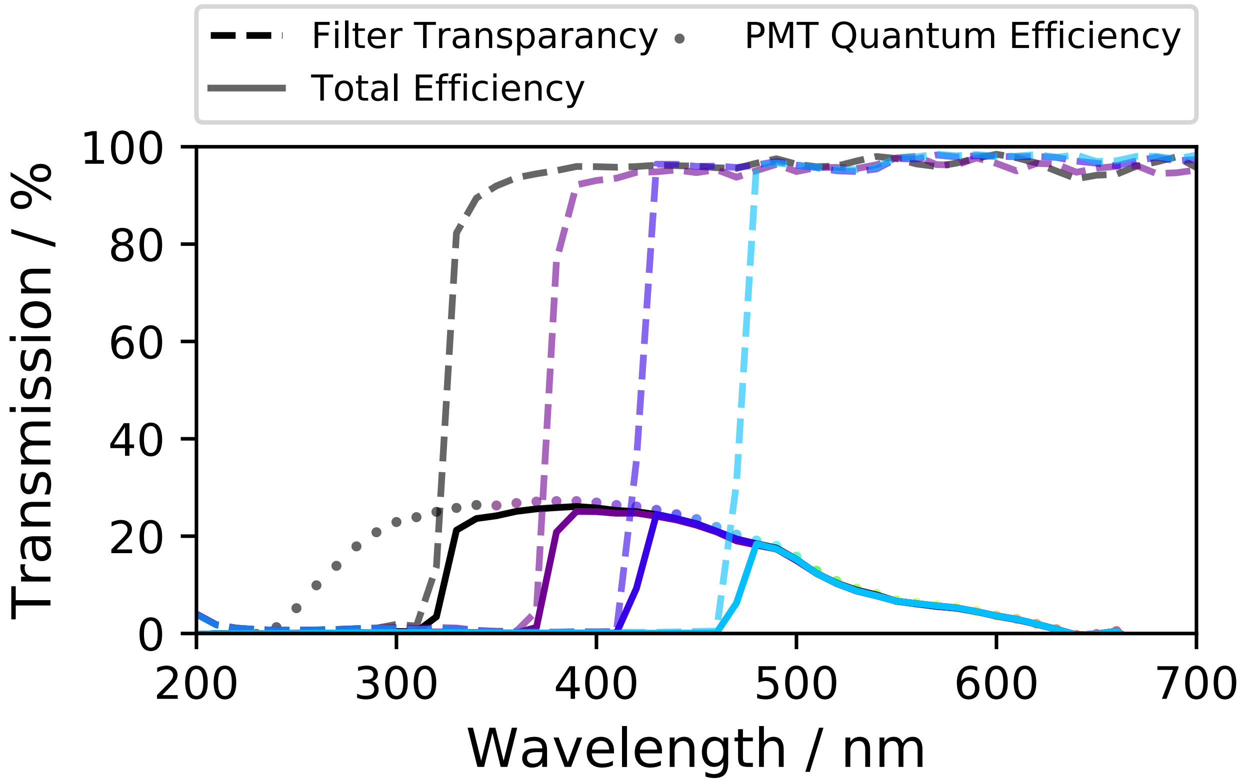


Event views omitting noise

Outlook: Spectrum measurement in laboratory and at South Pole

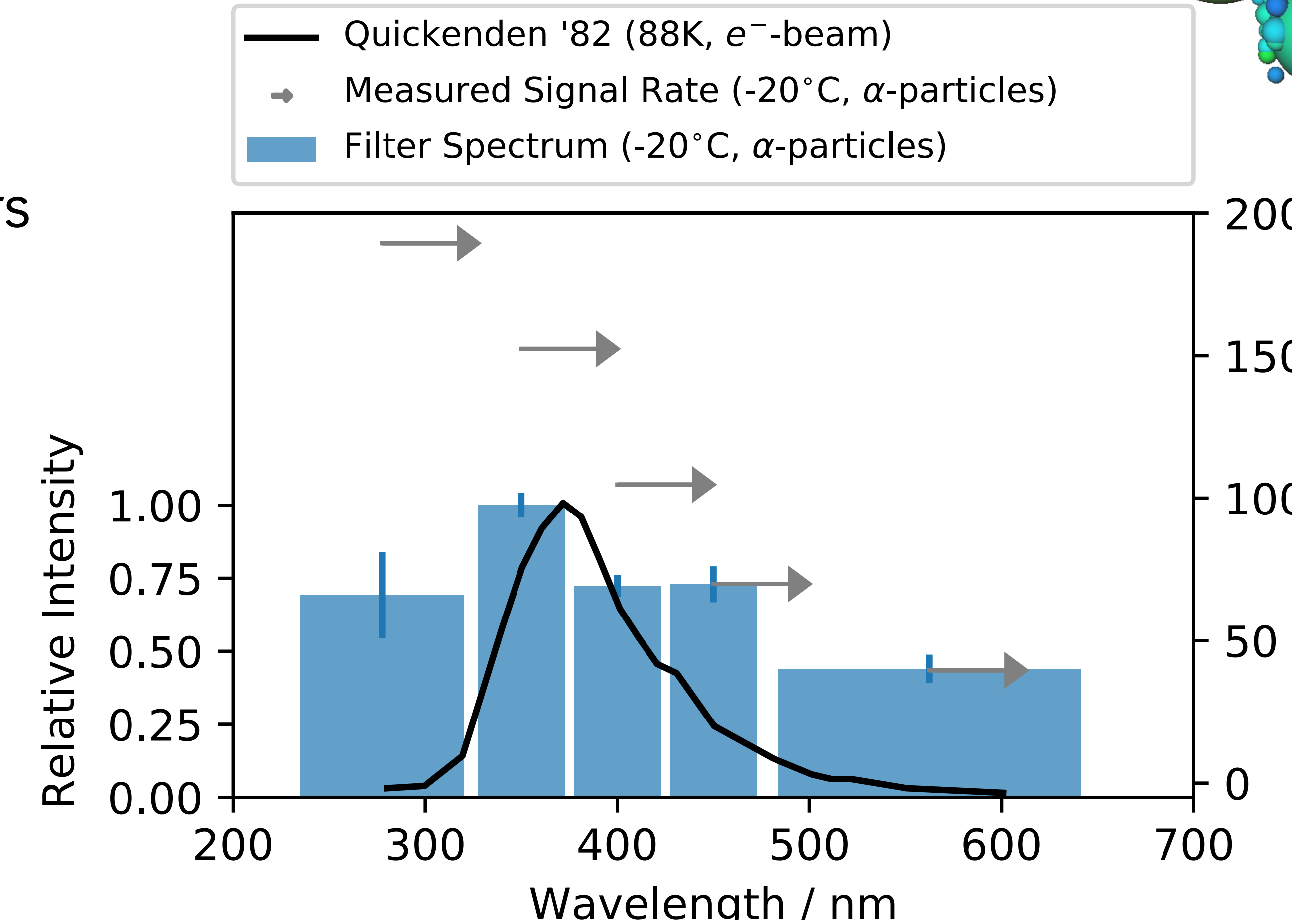
- spectrum of single photons using high efficiency filters
- first test worked, purchasing more filters
- will test with linear filter too
- filters implemented into logger
- spectrum helps identifying underlying excitation mechanism

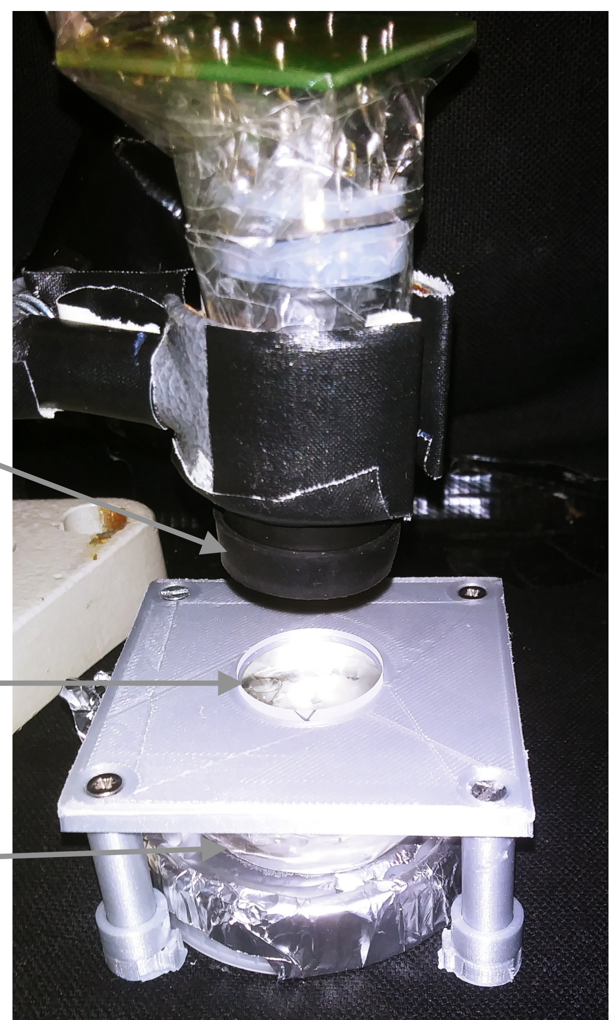


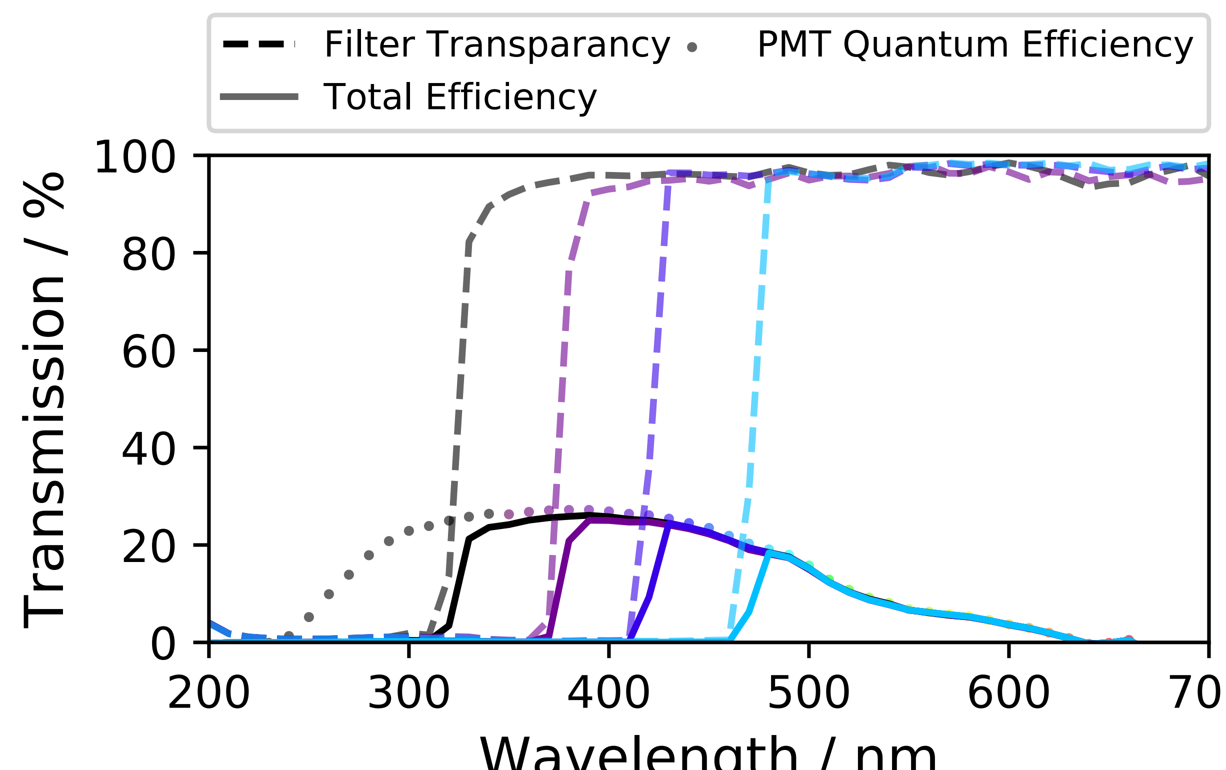


Outlook: Spectrum measurement in laboratory and at South Pole

- spectrum of single photons using high efficiency filters
- first test worked, purchasing more filters
- will test with linear filter too
- filters implemented into logger
- spectrum helps identifying underlying excitation mechanism







Summary

- first measurements of luminescence in ice in lab and in-situ
- first analyses ongoing using luminescence light as detection channel
  - low relativistic monopoles
  - (non-relativistic monopoles)
  - charged Q-Balls
- sensitivity for magnetic monopoles exceeds previous limits by far

Outlook

Measurements in season 2019:

more statistics -

more depths -

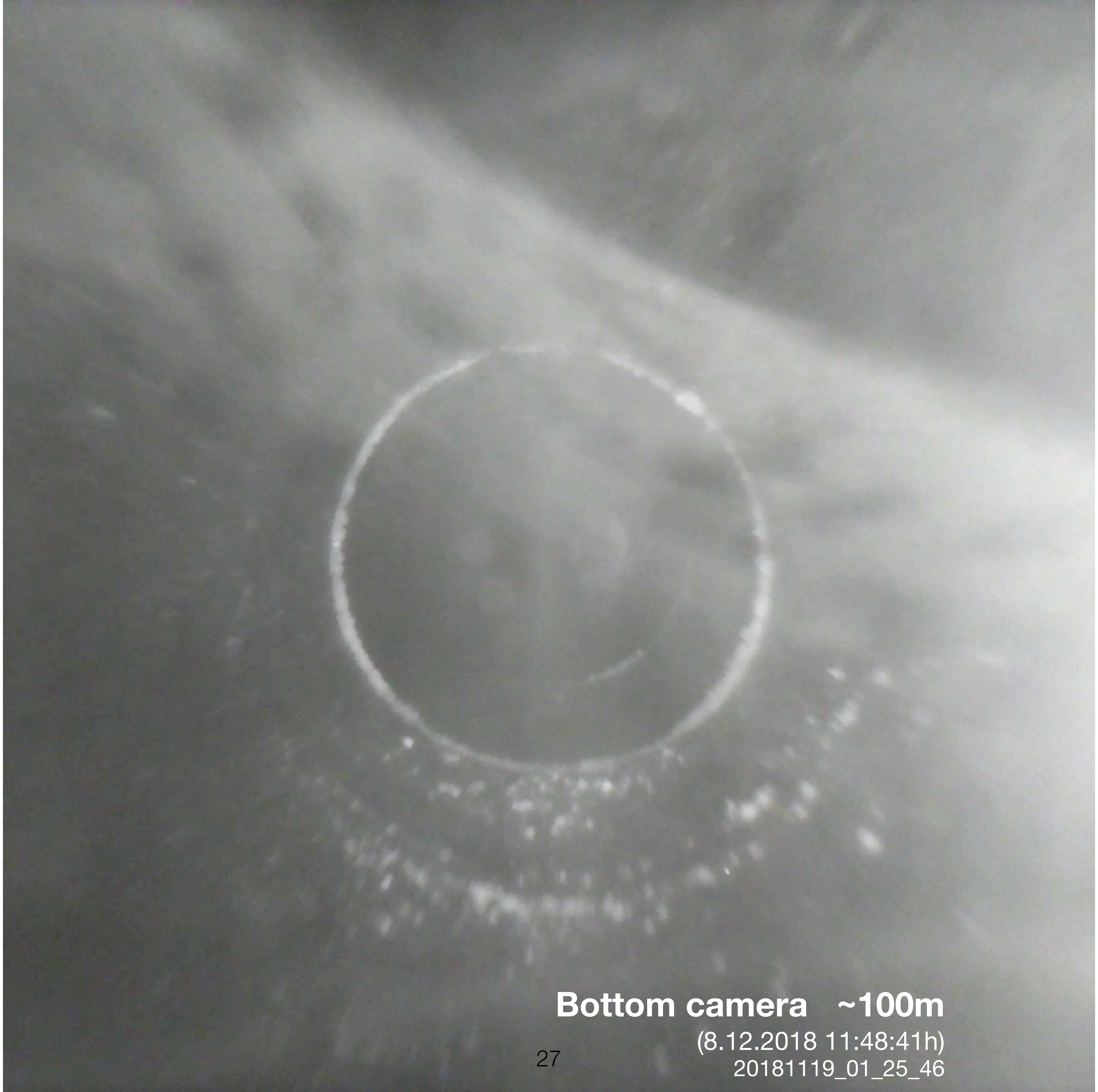
<u>new</u>: wavelengths spectrum -

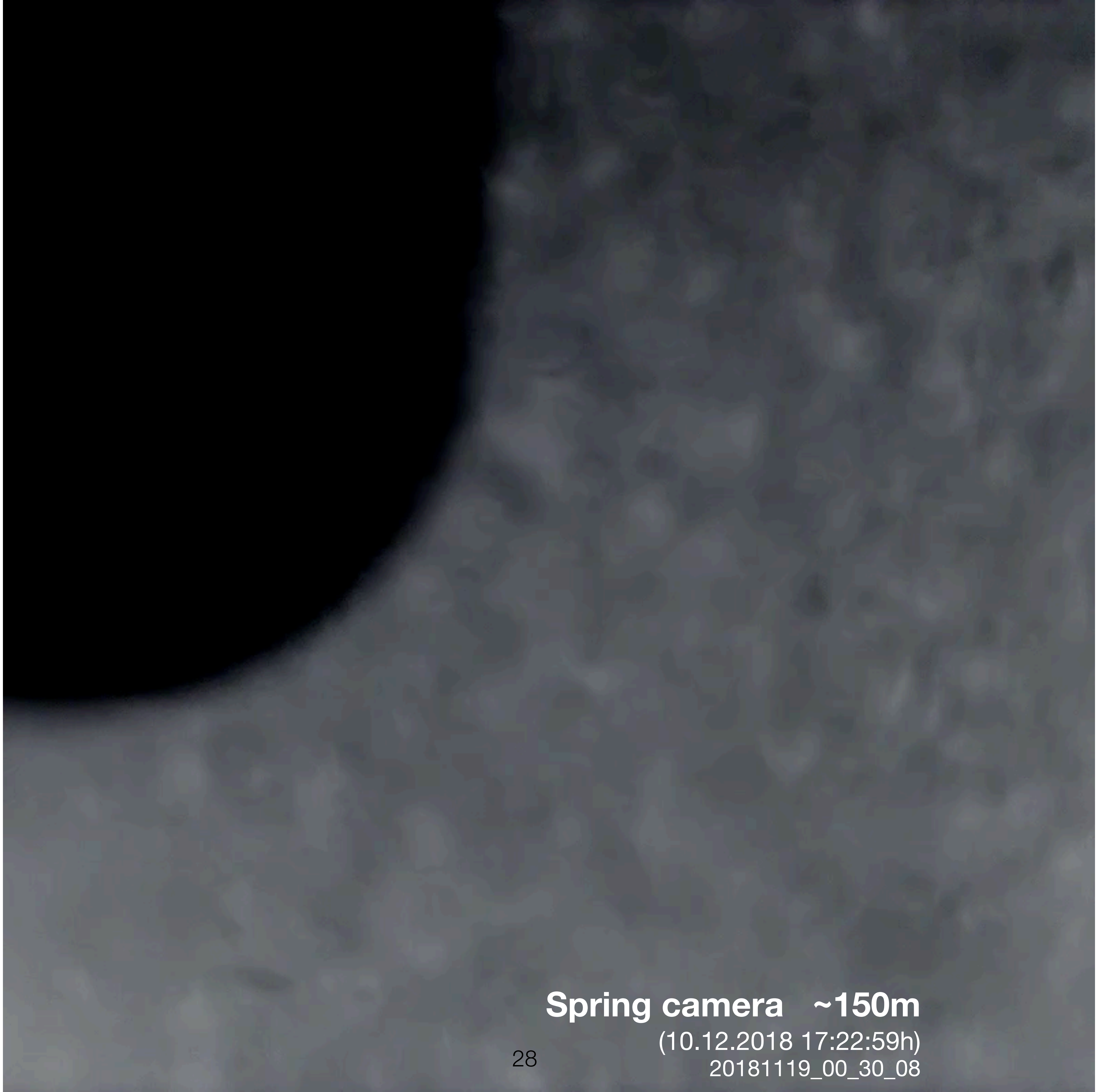
Analyses:

will be unblinded within a year -

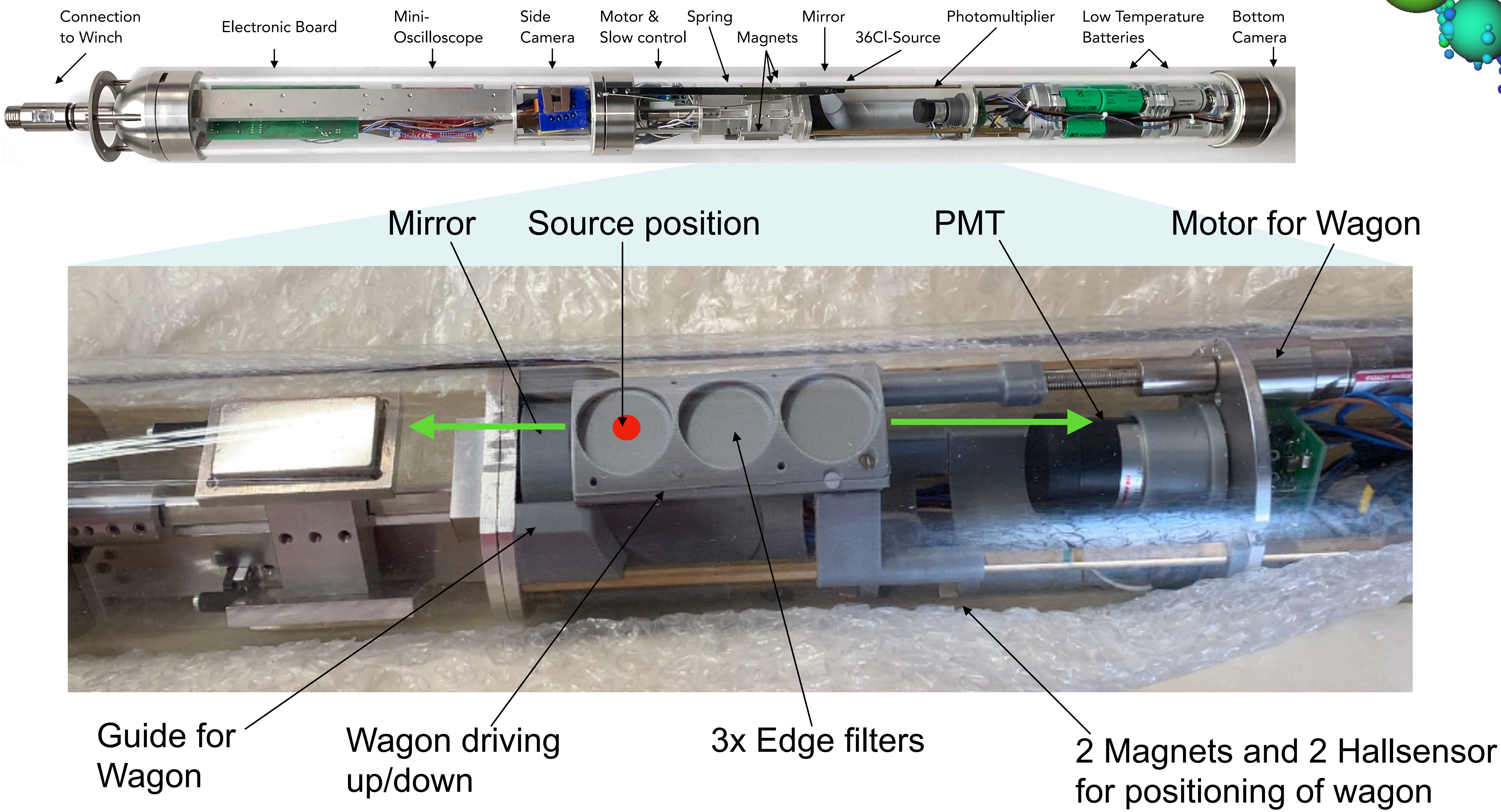
anna.pollmann@uni-wuppertal.de

Backup


Bottom camera ~100m
(8.12.2018 11:48:41h)
20181119_01_25_46


Spring camera ~150m
(10.12.2018 17:22:59h)
20181119_00_30_08

Configuration 2: Spectrum measurement

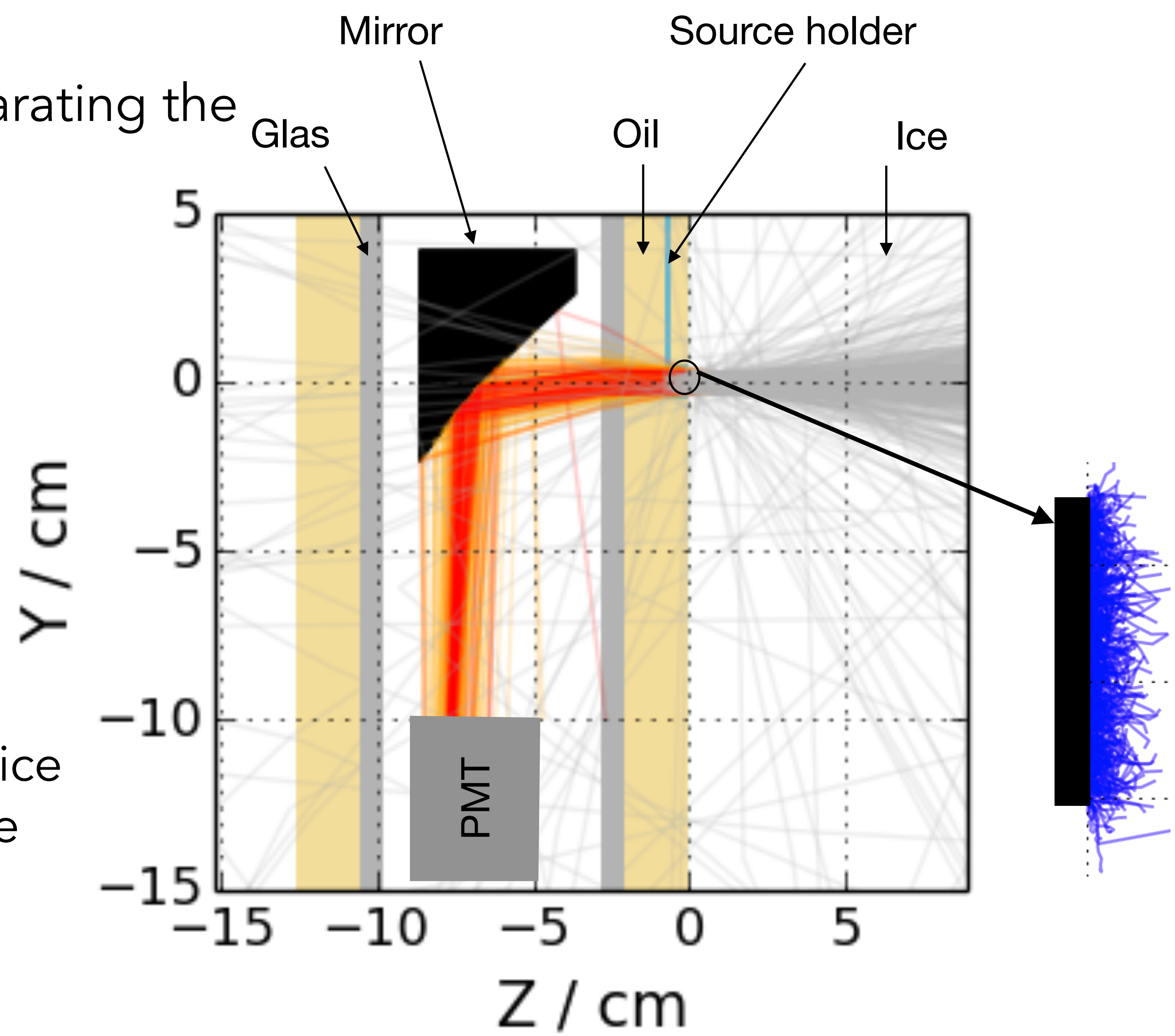


New functionality: Spectrum measurement

- second motor drives filter-wagon into optical pathway behind radioactive probe
- 3 edge filters on wagon can be exchanged to measure spectrum

Light yield analysis

- GEANT4 simulation of source and electrons in anti-freeze liquid & ice (tracks & energy losses)
- custom ray tracing of photons separating the 4 contributions of
  - Cherenkov } in anti-freeze liquid (Estisol)
  - Luminescence
  - Cherenkov } in ice
  - Luminescence
- varied the distance of source to the ice
- varied light yield of ice luminescence

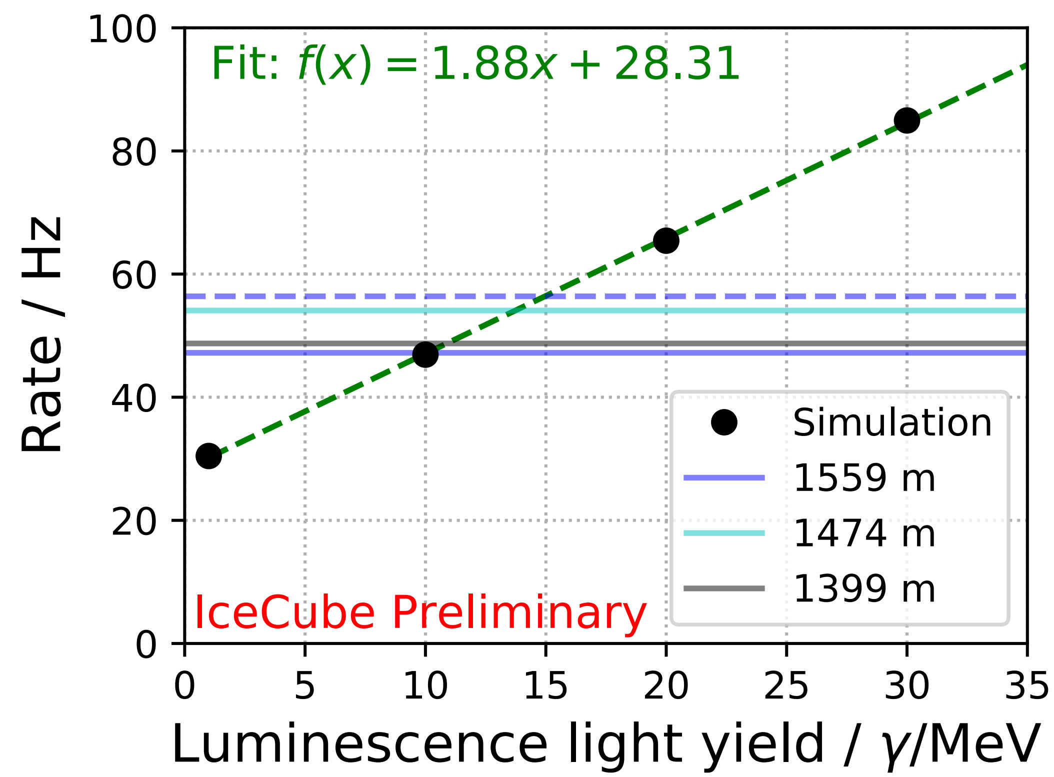


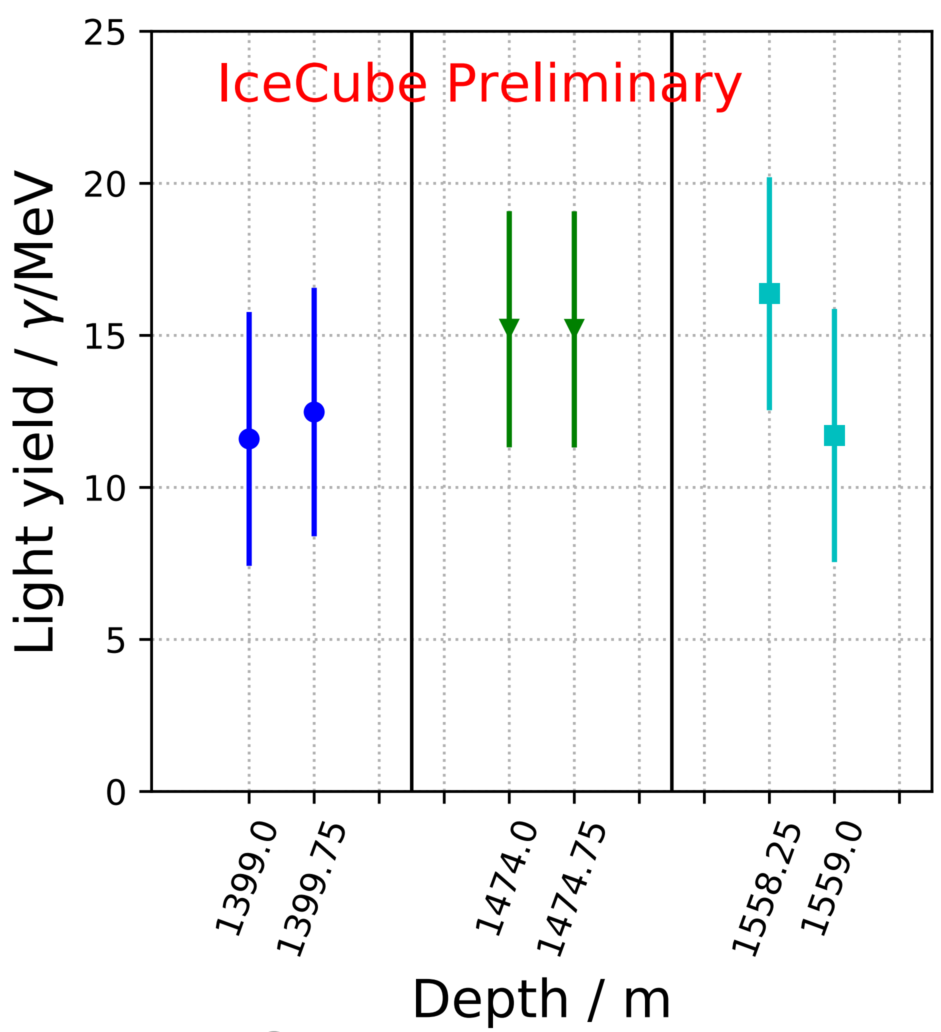
Custom ray tracing highlighting Cherenkov (orange) and Luminescence (red) photons reaching PMT plane

Electrons leaving source into Ice (GEANT)

Light yield analysis

- fit resulting photon detection efficiency and compared with measured rates to obtain light yield bounds
  - Estisol luminescence
  - unknown average distance of source to ice





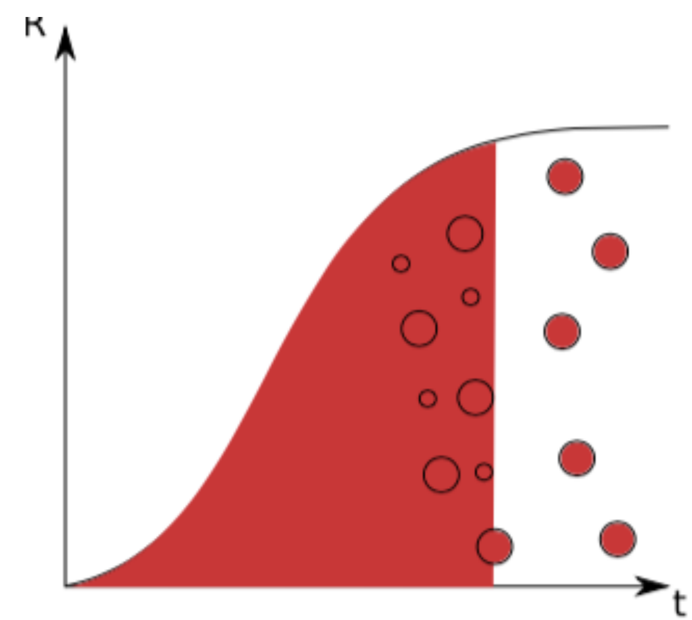
- uncertainties included (a.o.)
  - scattering (impact: +/- 13%)
  - absorption (impact: +/- 13%)
  - source activity (impact: -19% +11%)
  - estisol luminescence yield (impact: +/- 15%)

Q-ball characteristics

- Baryon number Q: 10^{20} - 10^{30}
- Mass: 10^{18} GeV - 10^{28} GeV
- Radius: 10^{-16} m - 10^{-11} m
- Velocity v ≈ 10^{-3} c
- Electric charge: $0 \leq Q_e \leq 137e$

- Before inflation the universe is filled with a scalar field
- Afterwards field starts to oscillate

→ disintegrates into Q-balls

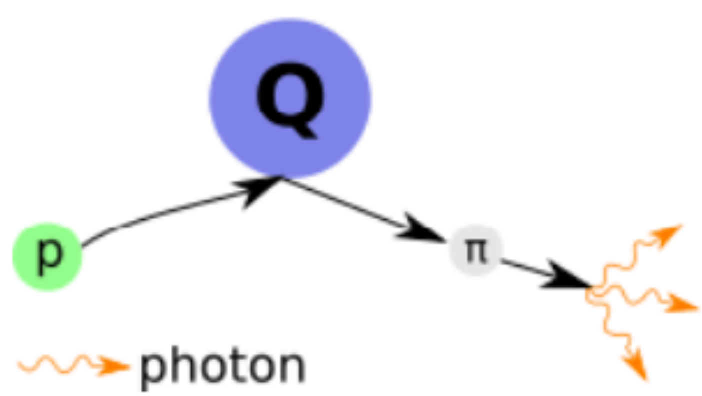


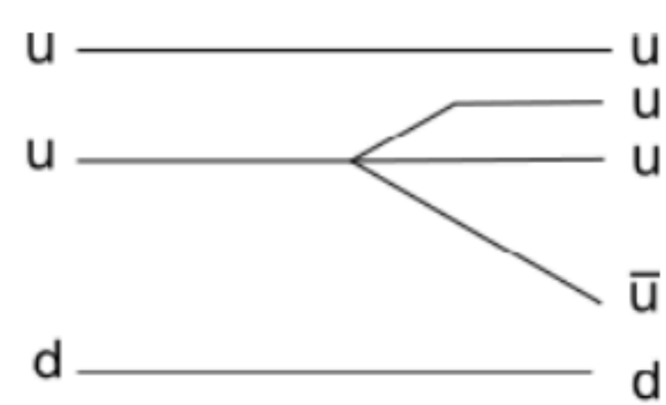
© Sarah Pieper

Interaction for electrically neutral Q-Balls:

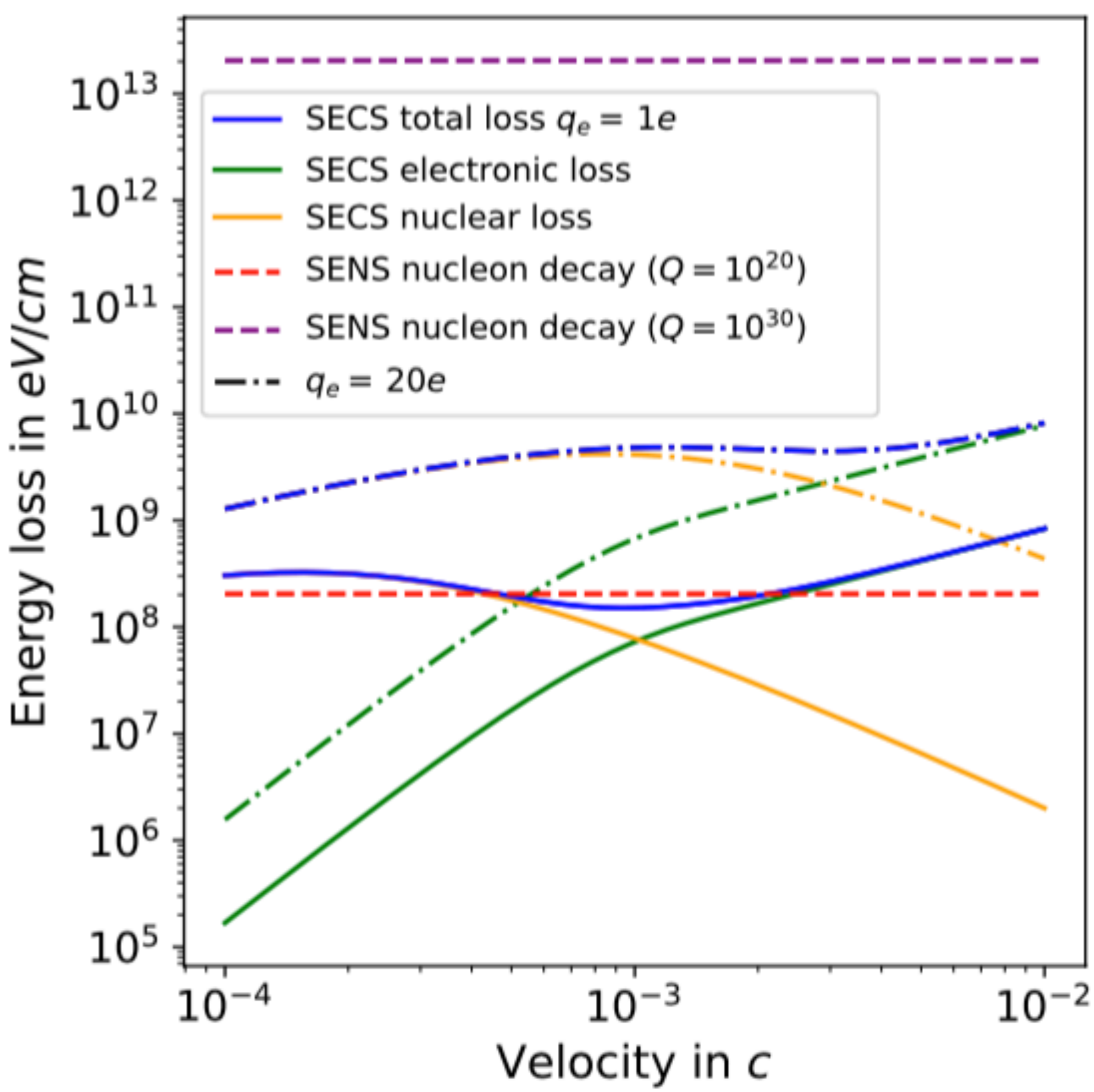
© Sarah Pieper

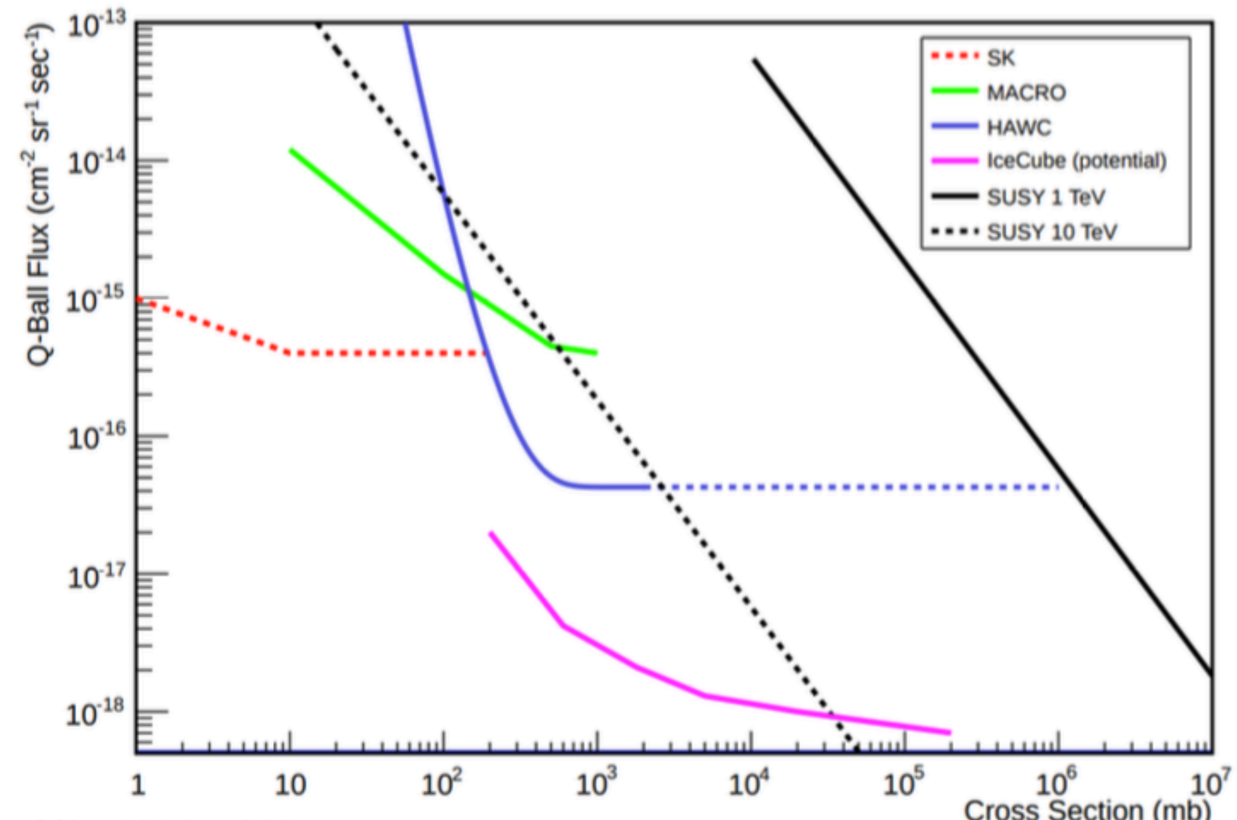
→ nucleon decay (KKST-process)





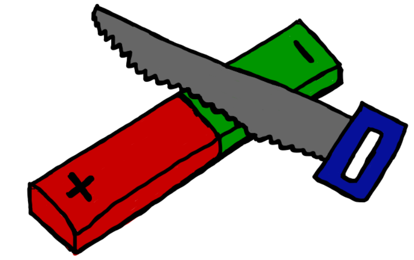
Q-ball characteristics





arXiv:1310.5662

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 ≦ M_{MM} ≦ 10^{19} GeV
  - in intermediate stages of symmetry breaking (IMM)

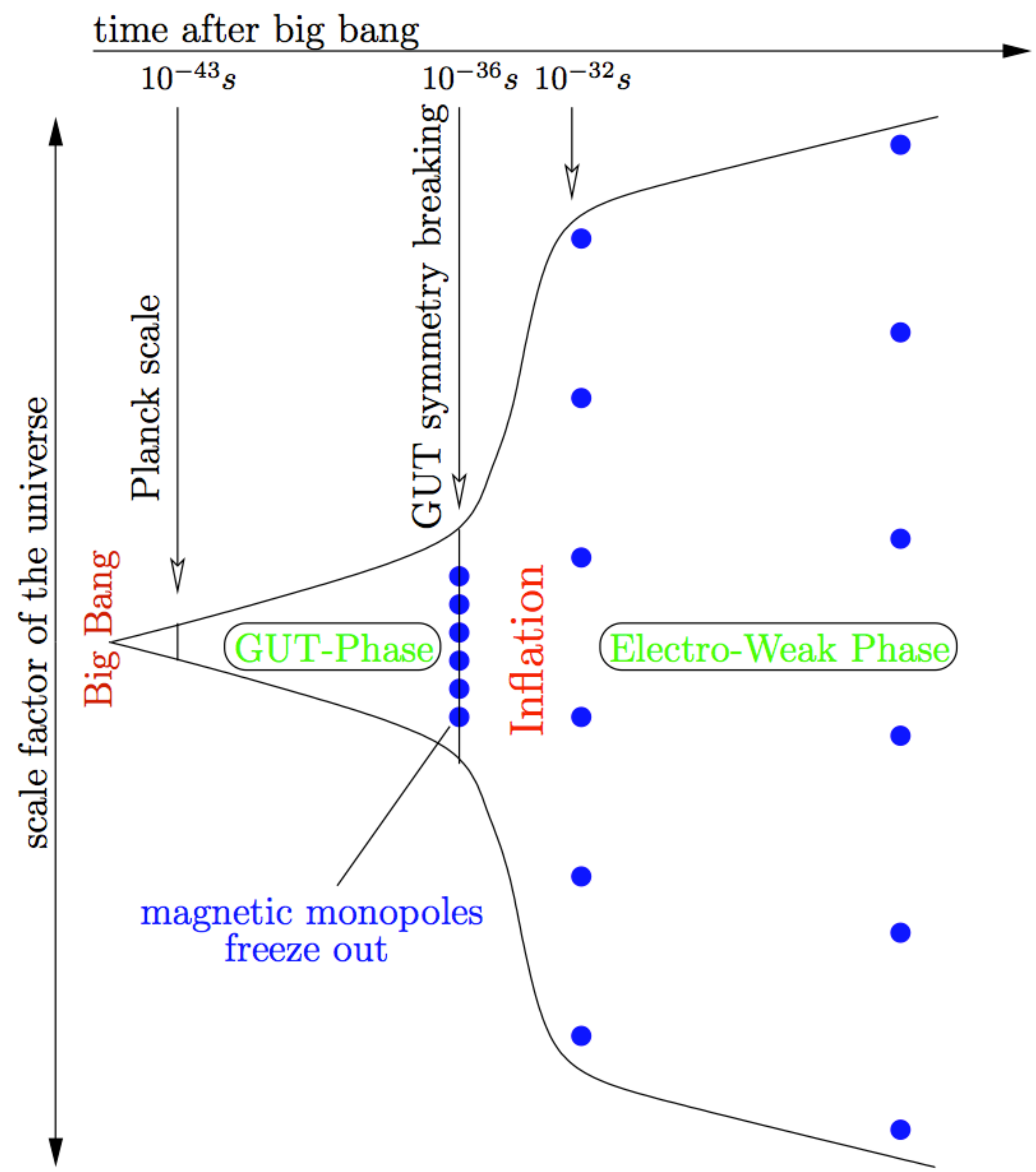
    10^{7} GeV ≦ M_{MM} ≦ 10^{13} GeV

- acceleration in magnetic fields for

  M_{MM} ≦ 10^{14} GeV to E_{kin} ≦ 10^{15} GeV

  - trapping around galaxy, sun, Earth

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

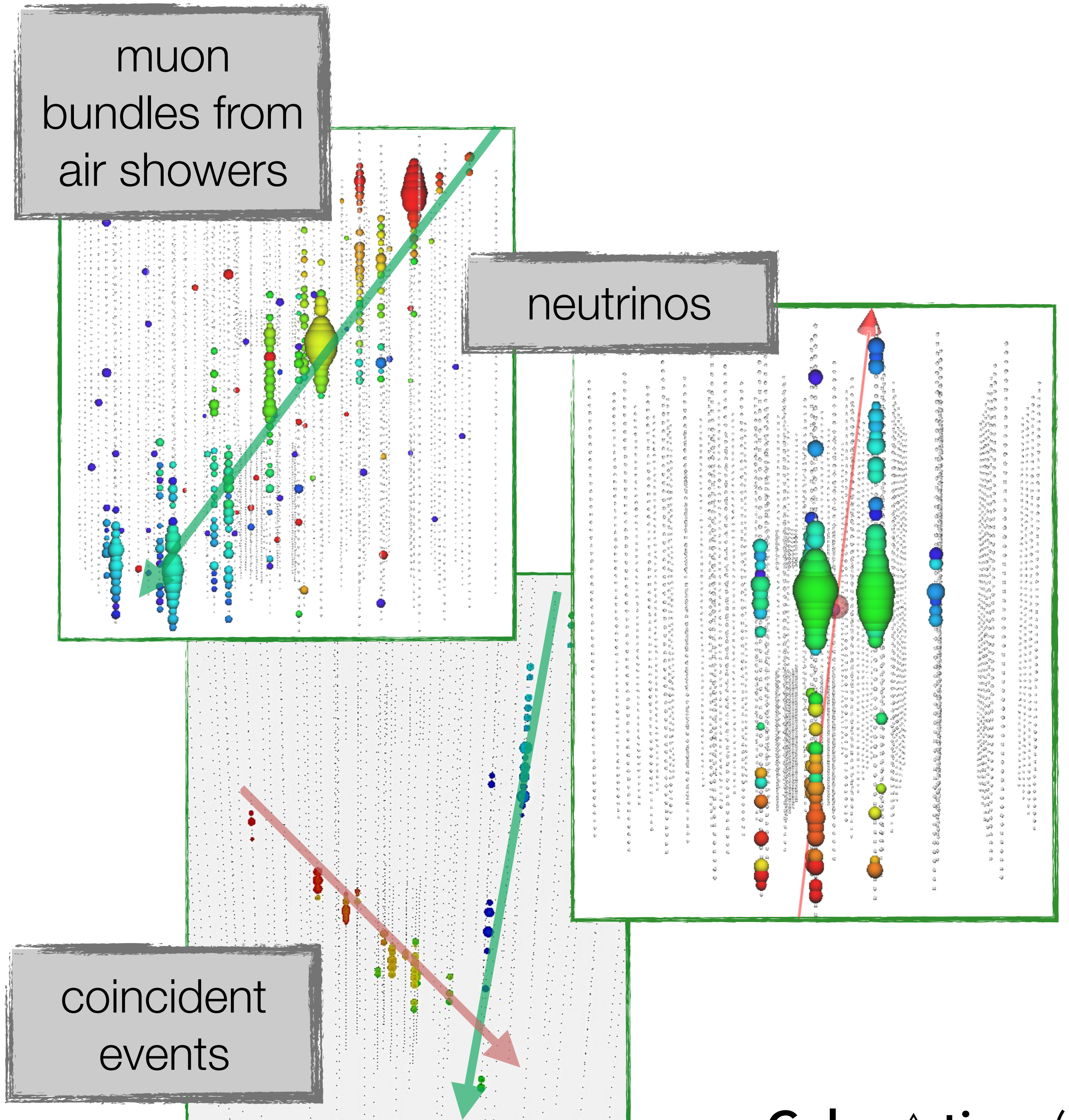


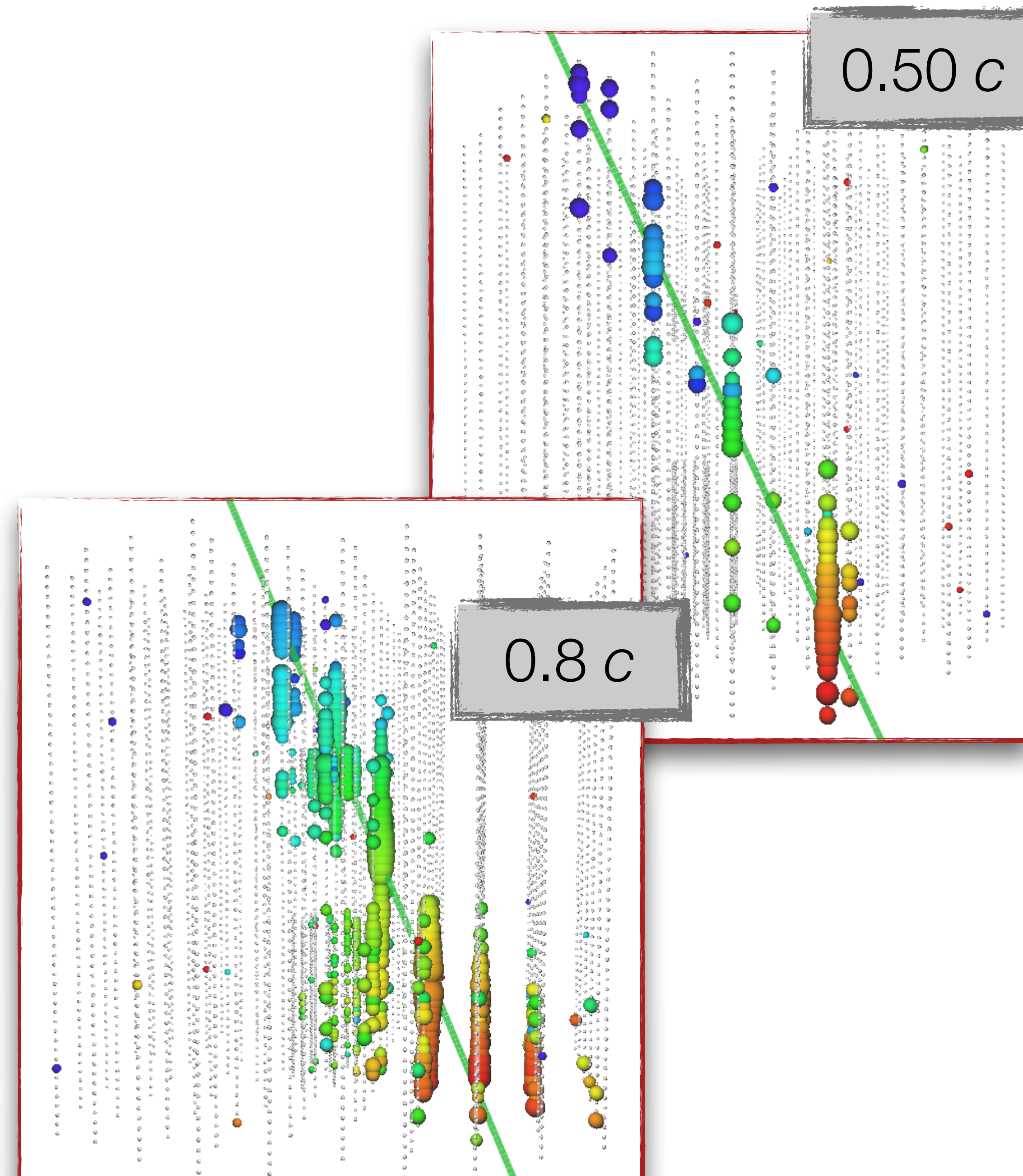
Gluesenkamp ´10

Signatures of fast Magnetic Monopoles

Background

Magnetic Monopoles





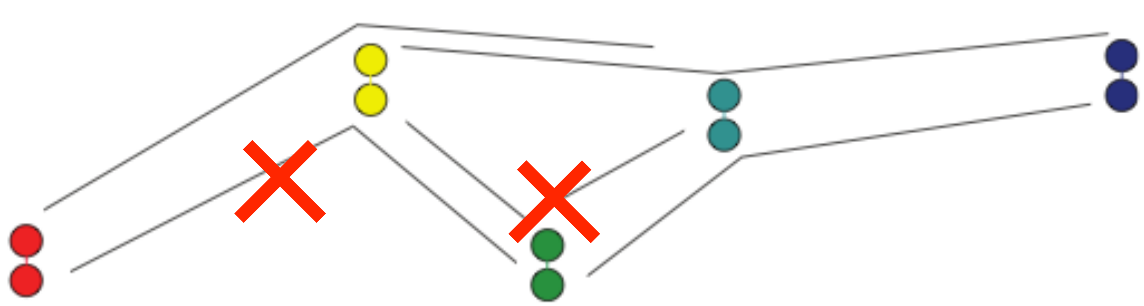
Color ≙ time (red -> blue)

Size ≙ light amount

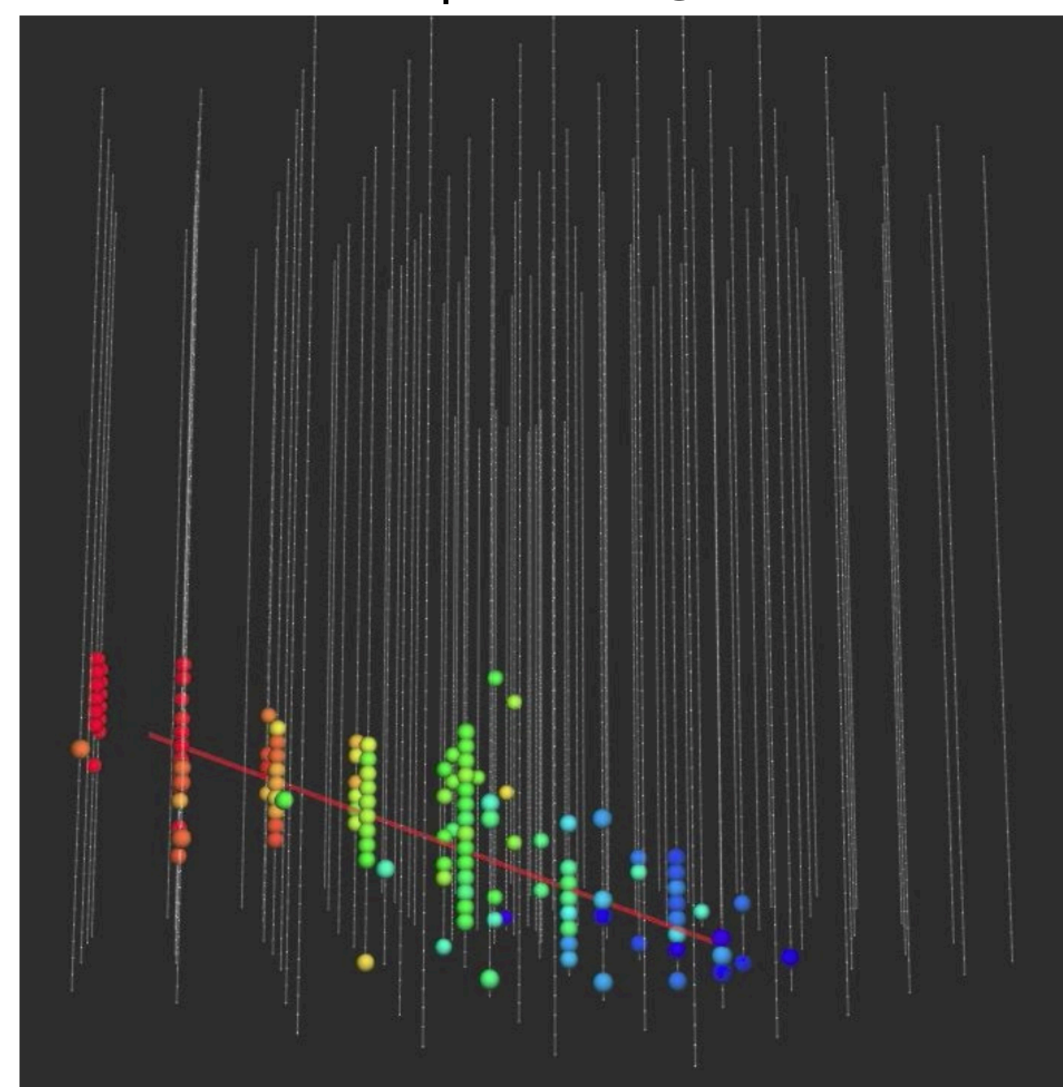
EPJ C76 (2016) 133

Non-relativistic Magnetic Monopole signature

- decay of proton -> electromagnetic cascade
- probed speeds: $10^{-3} \leqq \beta \leqq 10^{-2}$
- typical event length
  ~ milli seconds
- background: PMT noise and muons
- reconstruction
  - search for independent local coincidences
  - triplets are 3 pairs of hits fulfilling certain conditions



Monopole signal



Non-relativistic Magnetic Monopole signature

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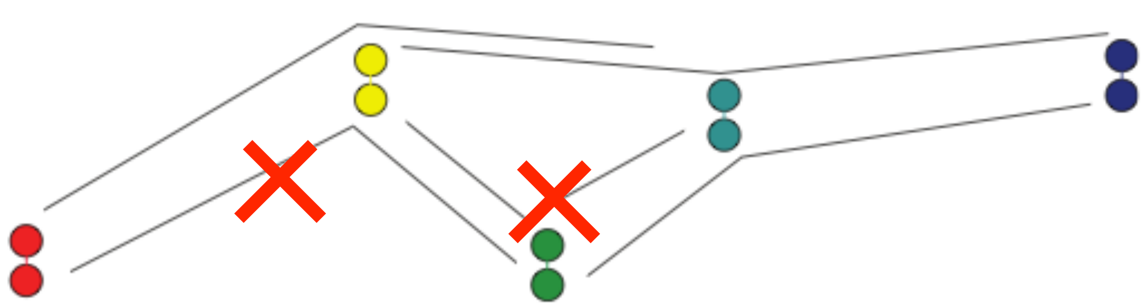
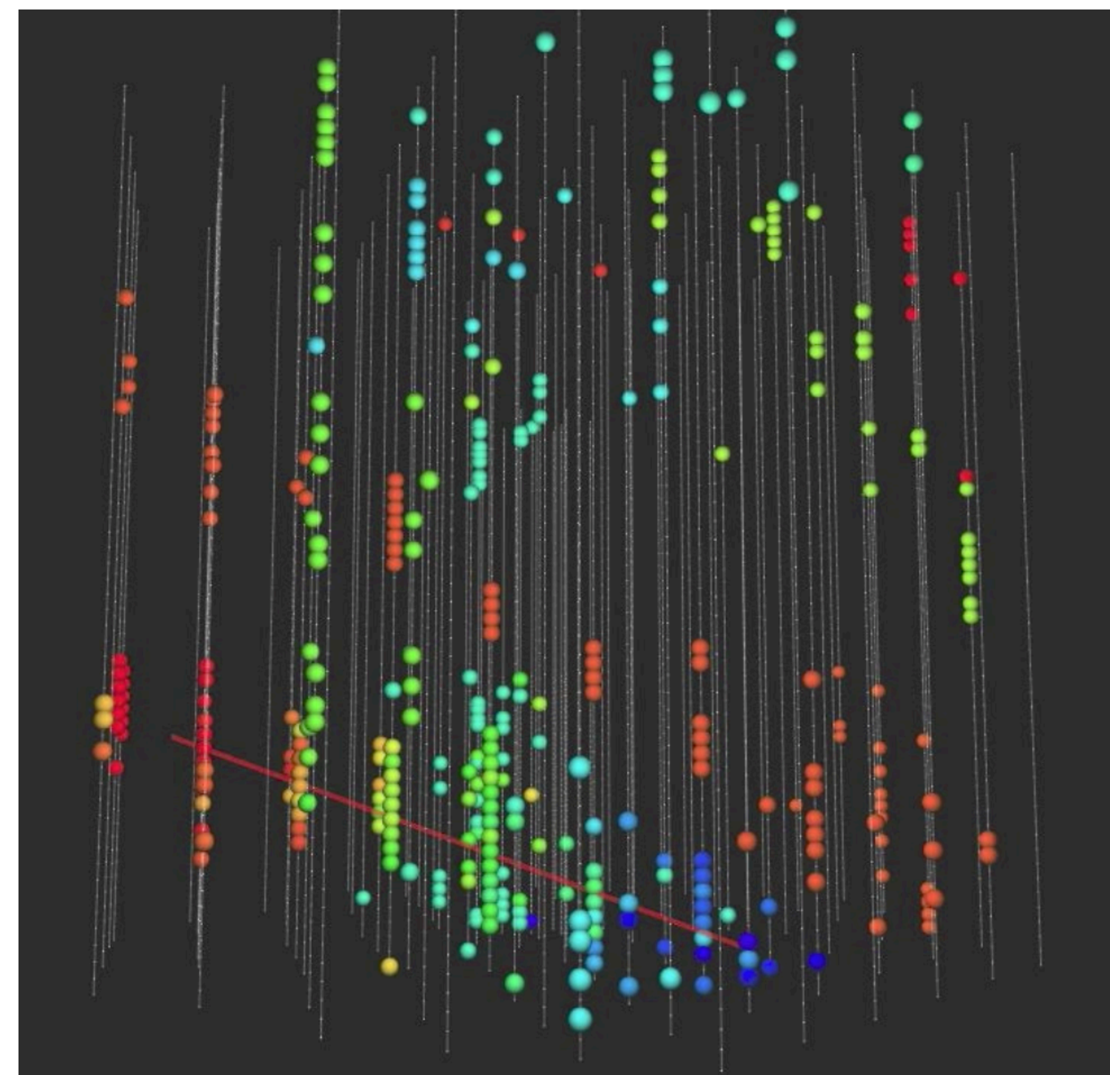
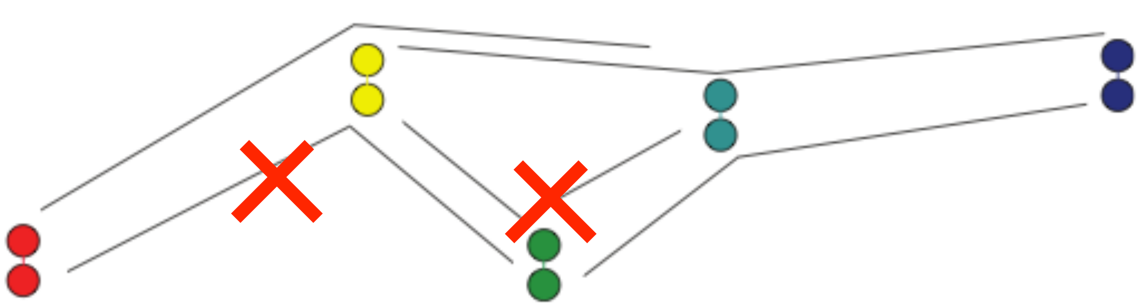


Monopole signal +
Air shower



Distinguishing non-relativistic Magnetic Monopoles

- decay of proton -> electromagnetic cascade
- probed speeds: $10^{-3} \leqq \beta \leqq 10^{-2}$
- typical event length
  ~ milli seconds
- background: PMT noise and muons
- reconstruction
  - search for independent local coincidences
  - triplets are 3 pairs of hits fulfilling certain conditions



Monopole signal +
Air shower + Noise