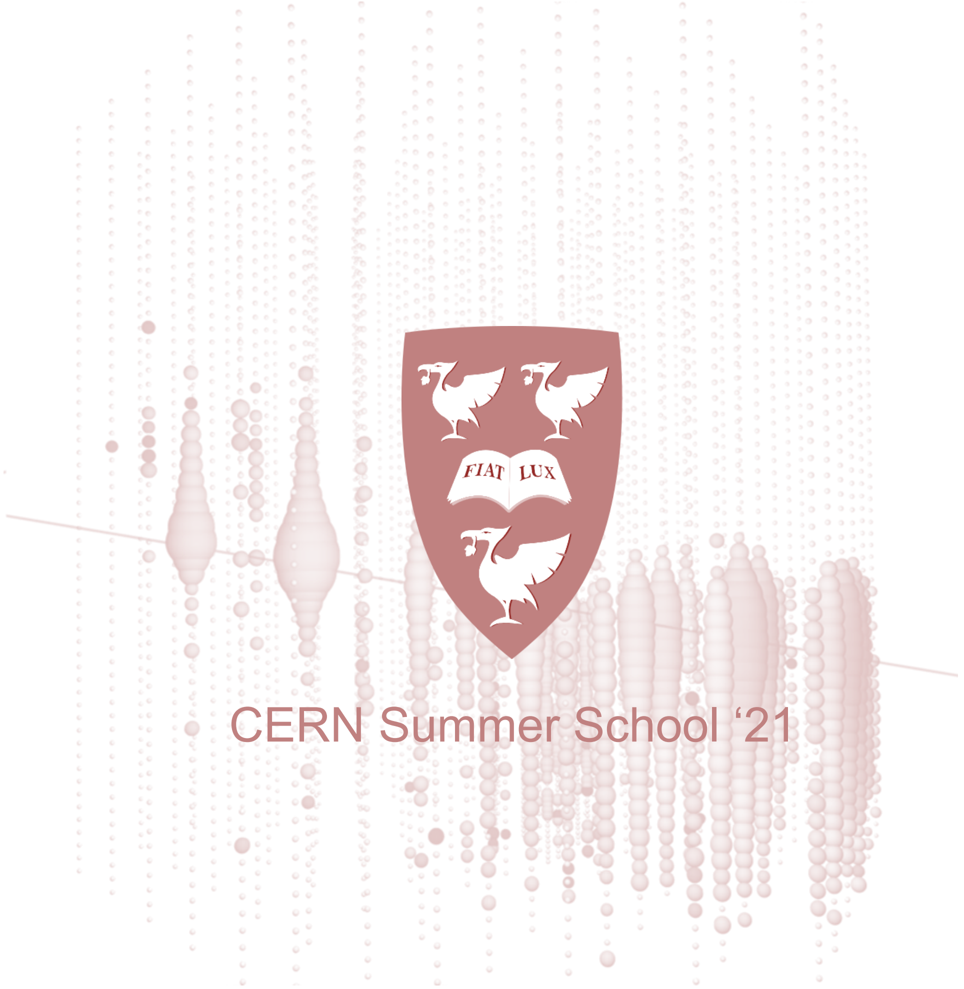
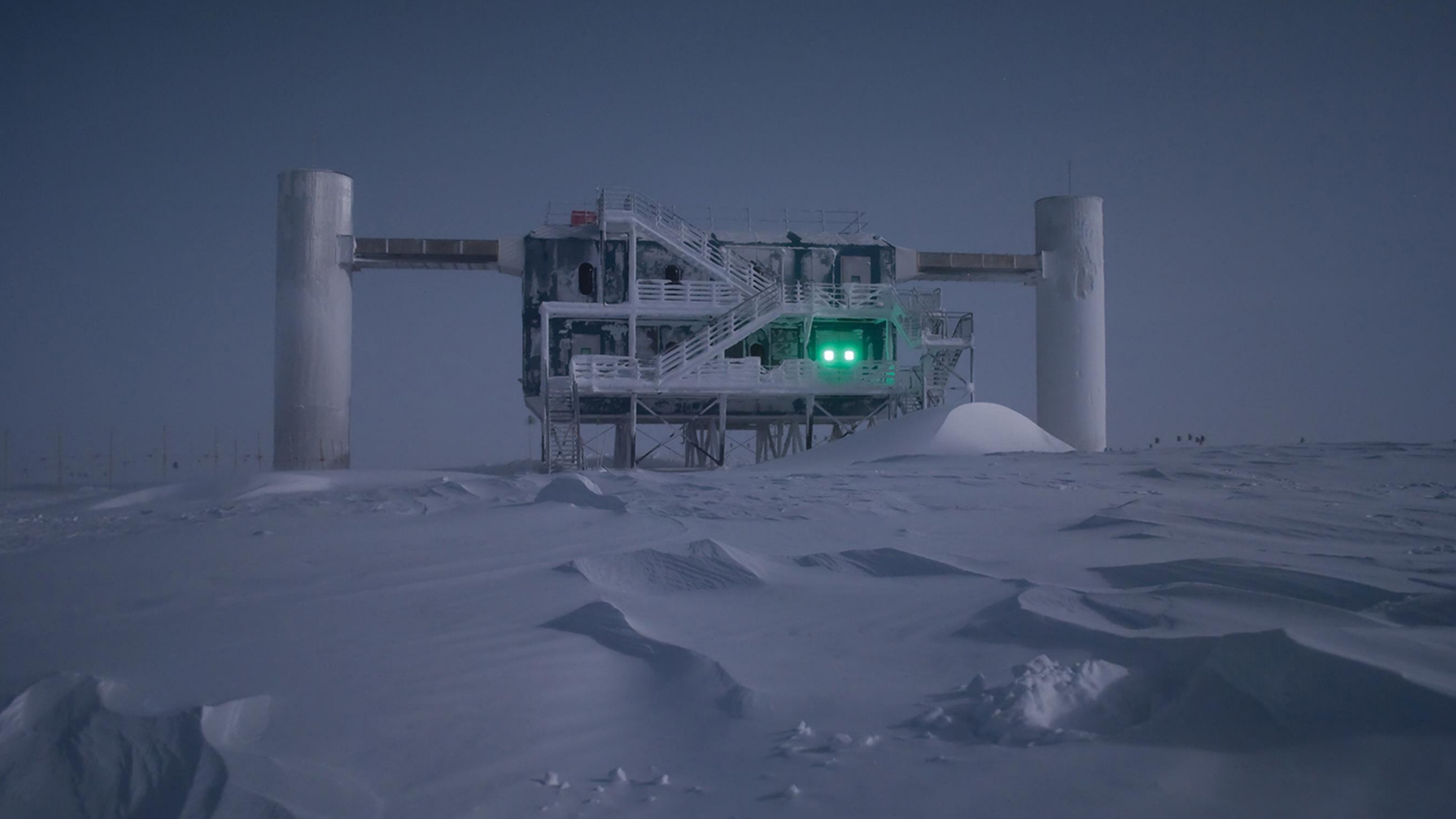
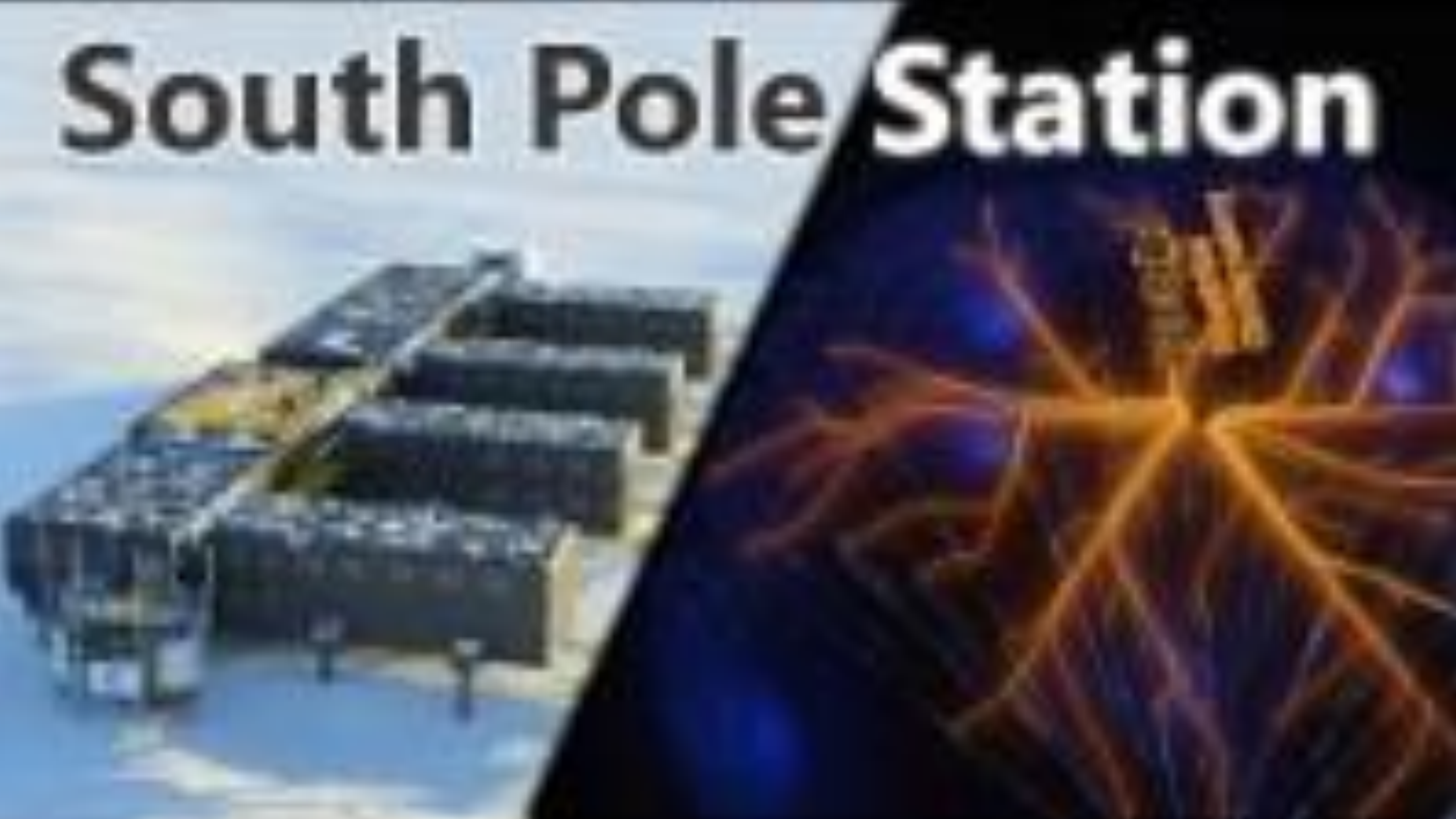
UNIVERSITY OF COPENHAGEN

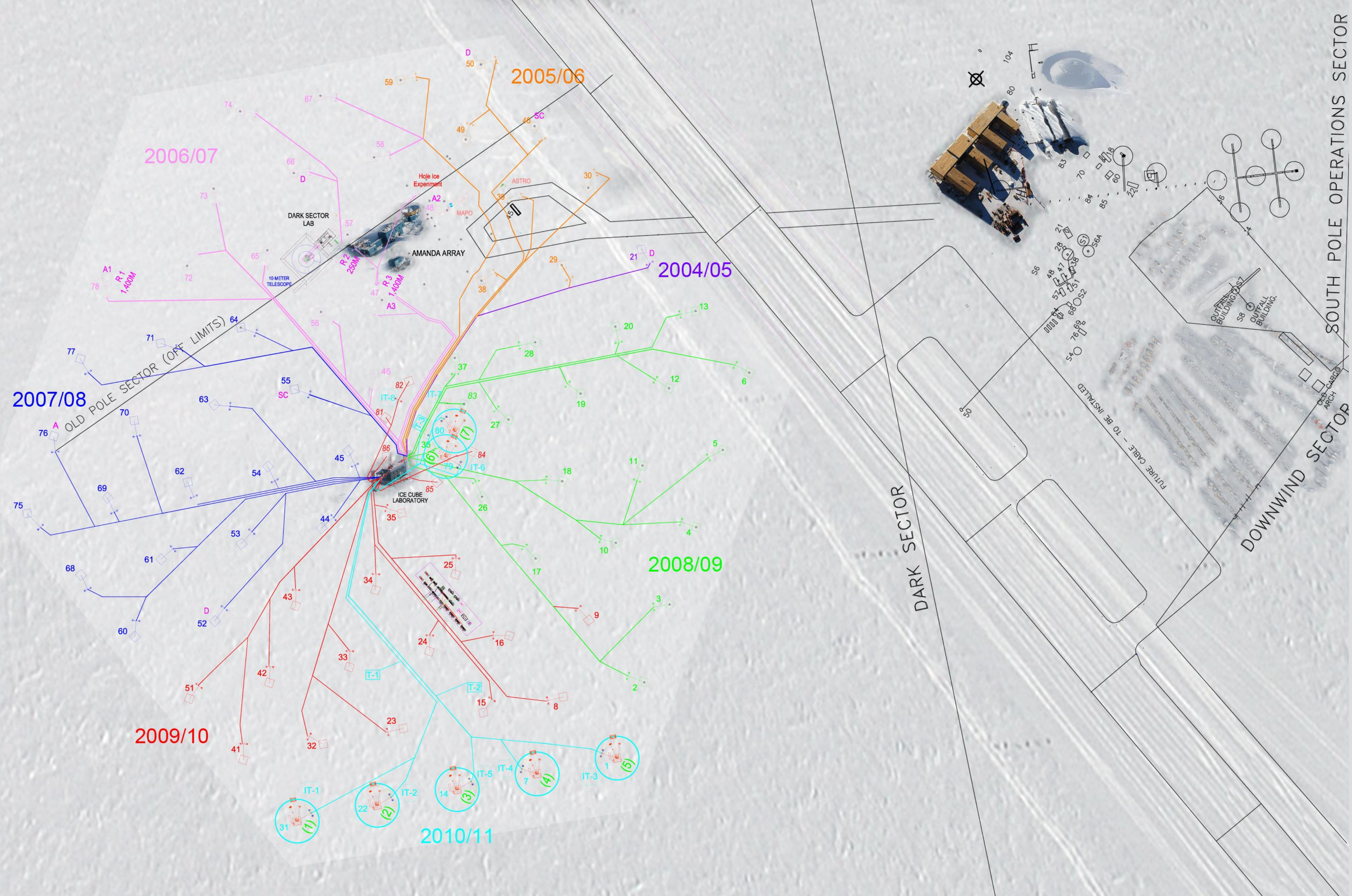
IceCube Neutrino Observatory

James Vincent Mead





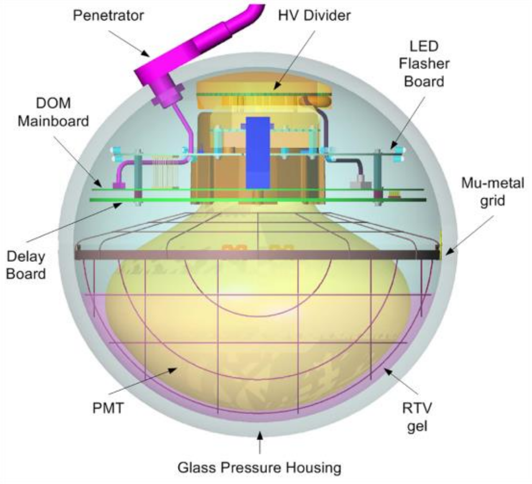

South Pole Station

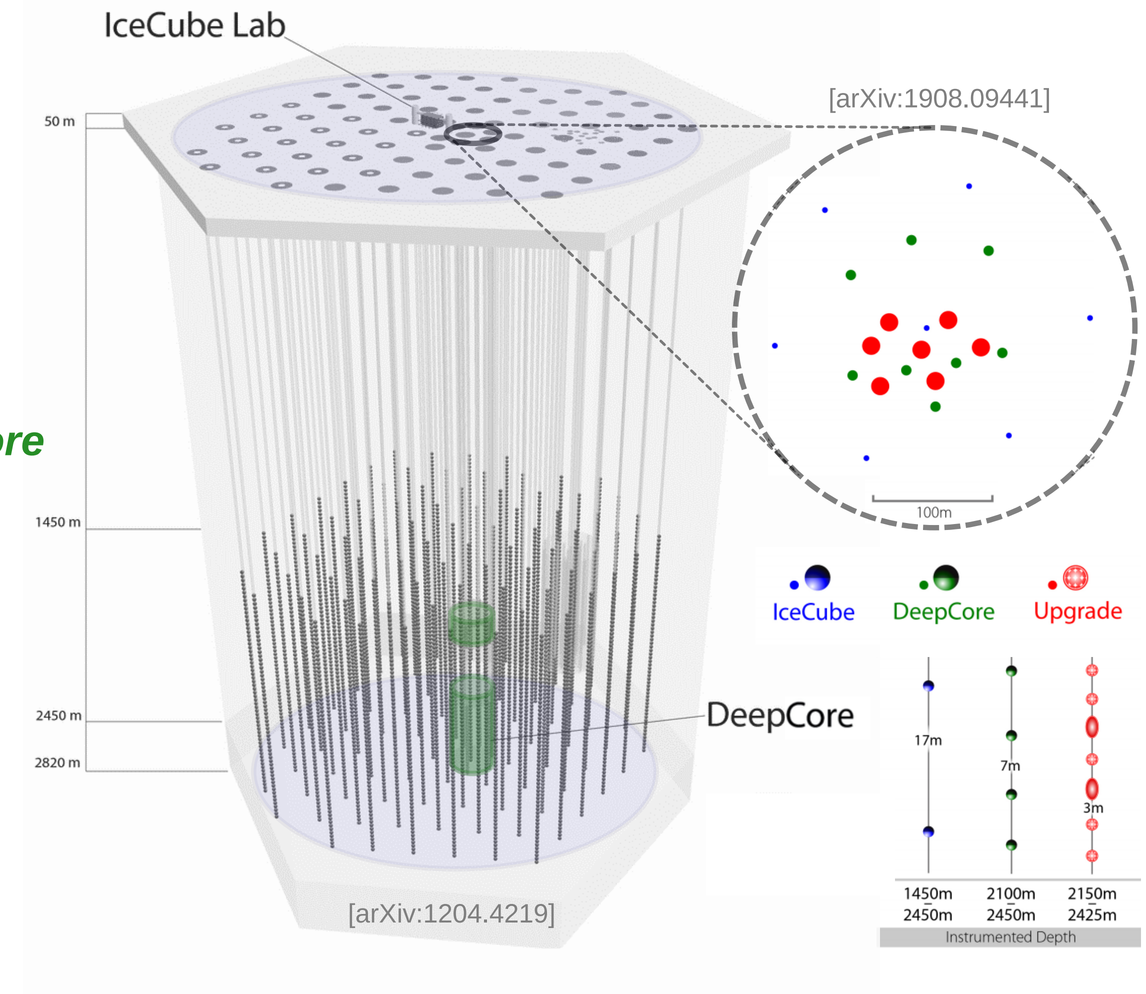


2004/05
2005/06
2006/07
2007/08
2008/09
2009/10
2010/11
DARK SECTOR LAB
AMANDA ARRAY
ICE CUBE LABORATORY
OLD POLE SECTOR (OFF LIMITS)
DARK SECTOR
SOUTH POLE OPERATIONS SECTOR
DOWNWIND SECTOR
FUTURE CABLE - TO BE INSTALLED
Hole Ice Experiment
10-METER TELESCOPE
R 1 1,400M
R 2 250M
R 3 1,400M

Digital optical module arrays

- ***IceCube* detector**
  - ν-ice interactions → relativistic charged particles
  - Superluminal products emit Cherenkov photons
- ***Instrumentation***
  - 5160 sensors embedded within 1 km^3 of glacial ice
  - Low-energy dark matter array at 5x density, ***DeepCore***





Low-energy extension

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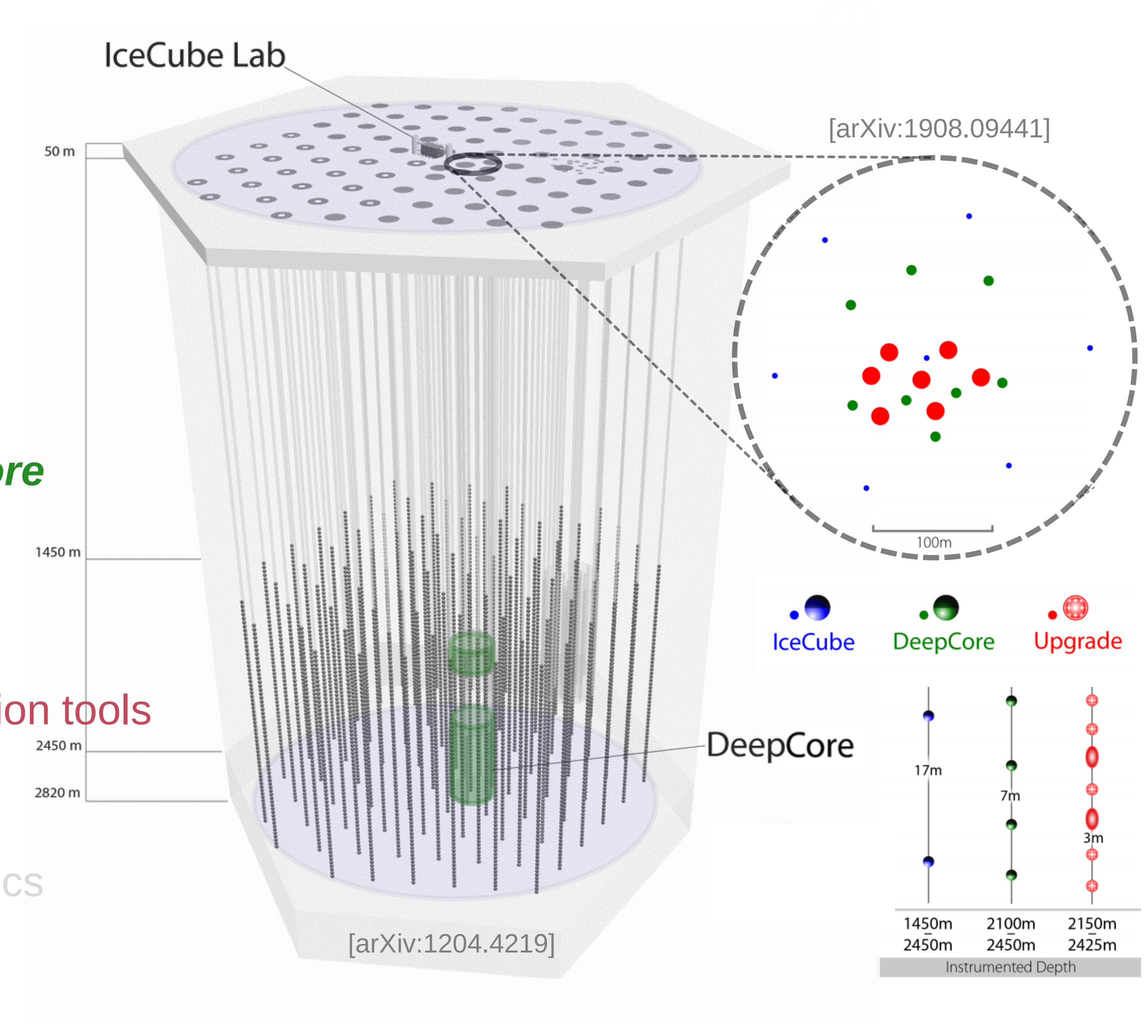
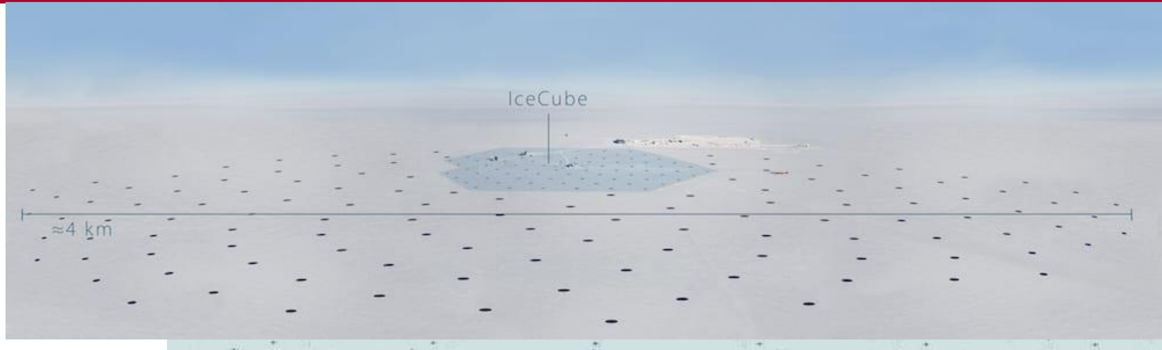
  - Low-energy dark matter array at 5x density, ***DeepCore***
- ***Upgrade*** (installation 2022-2023)
  - 7 columns of improved sensors at 10x density
  - Extending low energy range & building upon calibration tools
- ***Gen-2*** (operational 2033)
  - 10km^3 instrumented volume for huge boost in statistics
  - New surface radio array for Askaryan photons



High-energy extension



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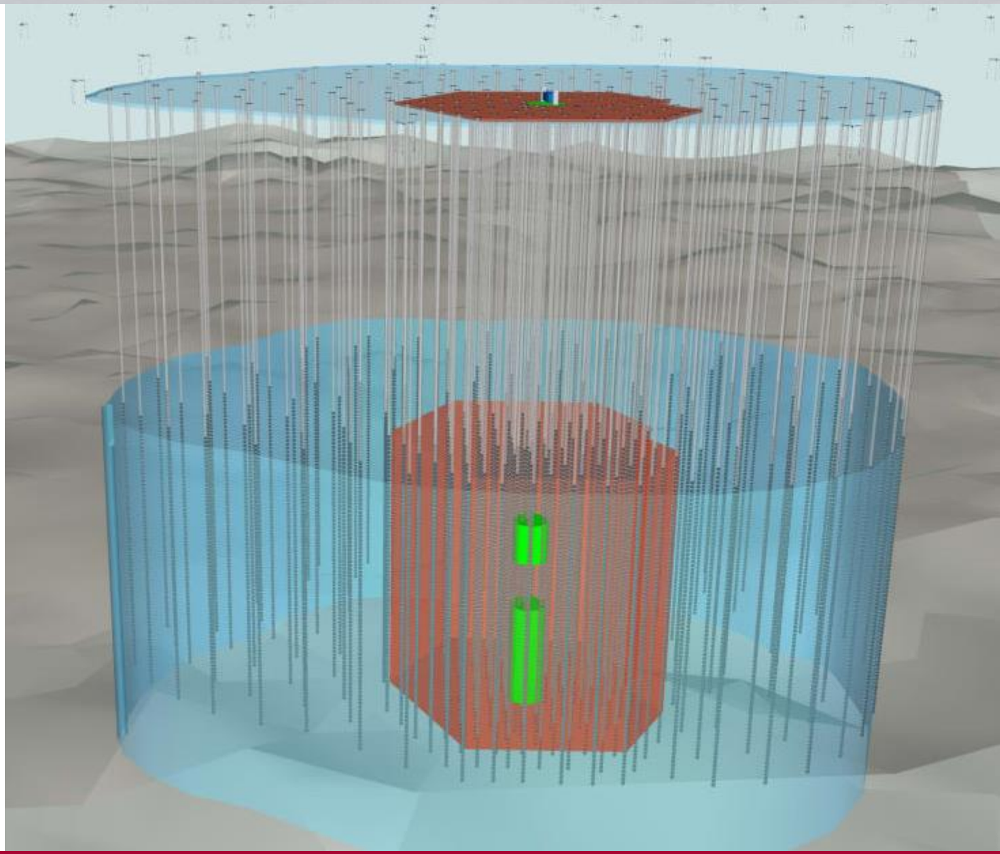

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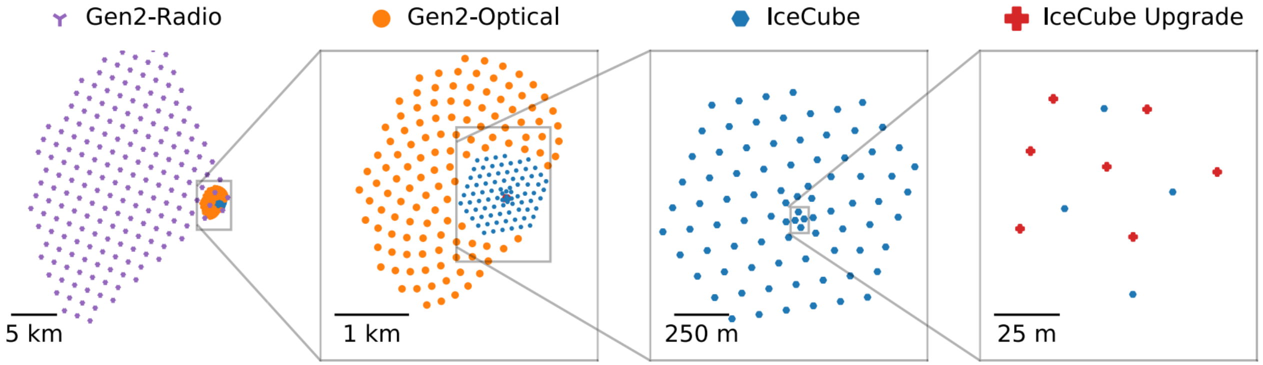
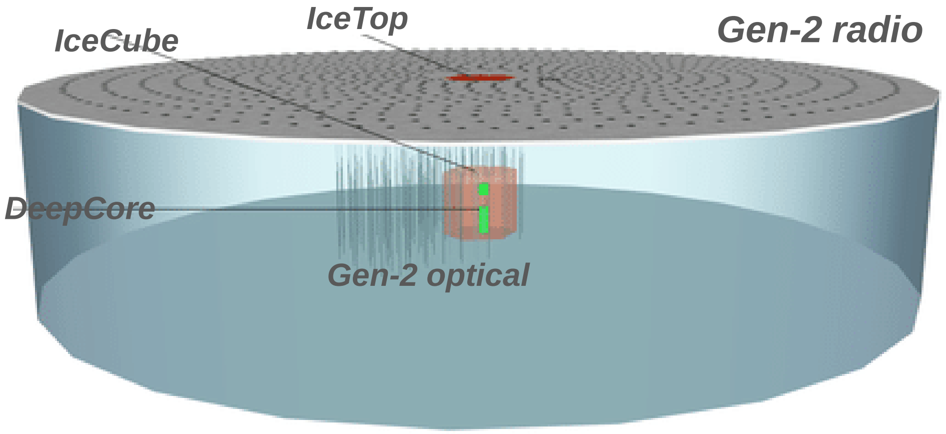
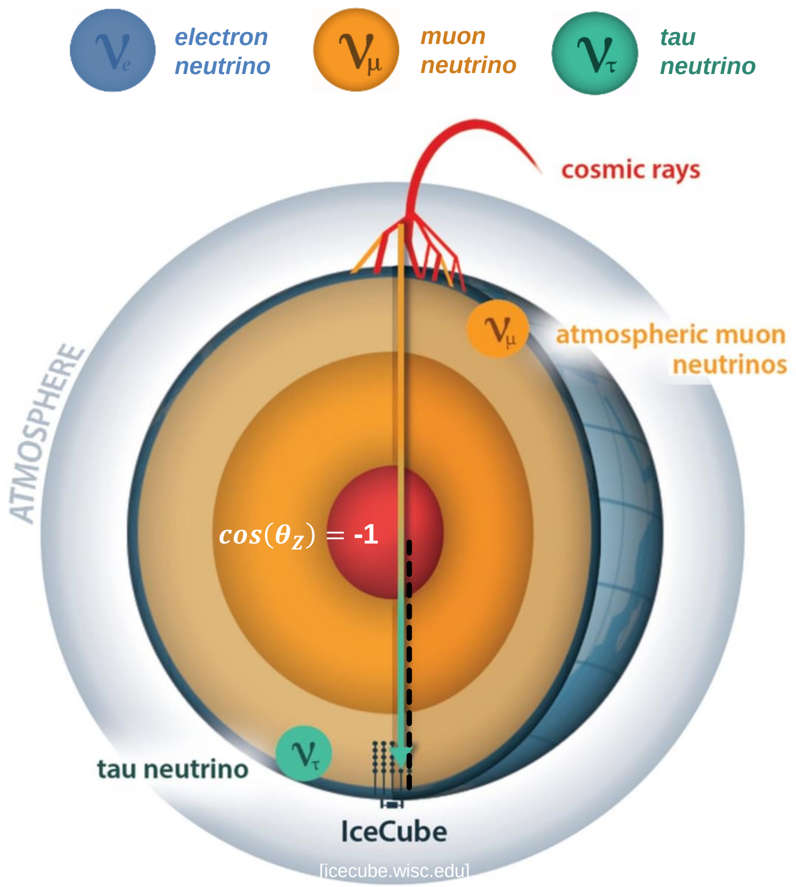


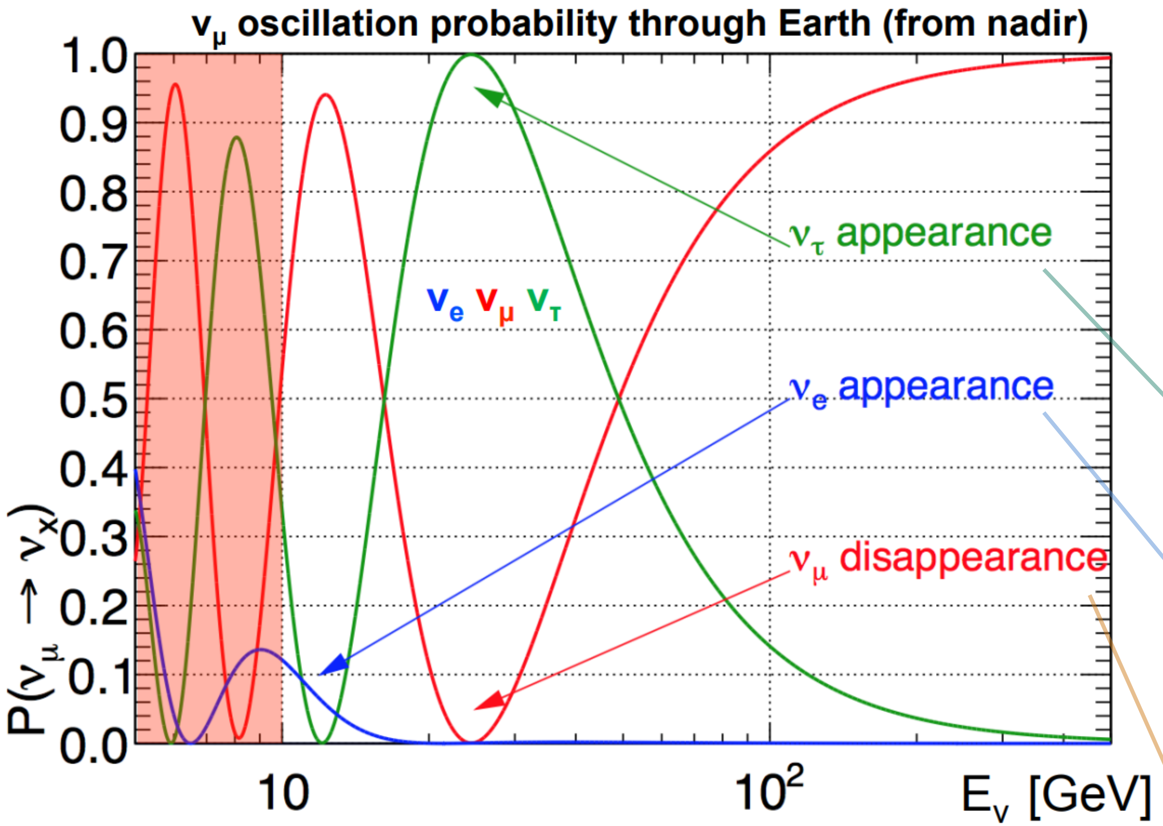


ν-oscillations at IceCube

- ***Neutrino oscillations***
  - Three flavours $\nu_{e,\mu,\tau} \nleftrightarrow$ Three mass states $\nu_{1,2,3}$
  - Propagate as flavour superpositions $\Rightarrow \Delta m_{ij} \neq 0$
  - Oscillations between flavours $\Rightarrow m(\nu)_{1,2,3} \neq 0$
  - P(Transition) $\propto f(L/E)$
- ***Upgoing atmospheric muon neutrinos***
  - Abundant & high-E source:
    - Accesses oscillations with Q^2 for transition into ν_τ
  - Maximum ~13,000km baseline, L, as $f(\theta_Z)$:
    - Near maximal ($\nu_\mu \rightarrow \nu_\tau$) oscillations for O(10 GeV)
  - DeepCore optimised for ~25 GeV, sensitive > 5 GeV:
    - Upgrade sensitivity designed for O(1 GeV)



ν-oscillations physics



$$P(\nu_\mu \to \nu_\mu) \propto \sin^2(\theta_{23}) \sin^2\left(\frac{\Delta m^2_{32} L}{E}\right)$$

L = travel length
E = energy

- ***Unitarity tests***
  - 4th generation / heavy neutral leptons
- ***Non-standard interactions***
  - New mediators / enhanced couplings
- ***ν_τ-appearance***
  - $\boldsymbol{\nu_\tau}$-normalization, $N_{\nu_\tau} \neq 1 \Rightarrow$ non-unitarity
- ***Neutrino mass ordering***
  - CP violation
  - Majorana fermions
- ***ν_μ-disappearance***
  - Mass splitting (Δm^2_{23}) & mixing angle ($\sin^2\theta_{23}$)

3x3 mixing matrix

$$U_{PMNS} =$$

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{Atmospheric term}} \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{Reactor term}} \underbrace{\begin{pmatrix} \cos\theta_{12} & \cos\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar term}}$$

Mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}$

CP violating complex phase: $\delta \equiv \delta_{CP}$

Beyond unitarity

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = U_{PMNS} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

$$= \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

If U is unitary: $U^\dagger U = UU^\dagger = I$,
then norms (magnitude of vector from origin) are preserved, crucial for probability amplitude calculations in QM

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Beyond Standard Model

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = U_{PMNS}{}^{+} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

$$= \begin{pmatrix} U_{PMNS} & \cdots & U_{en} \\ \vdots & \ddots & \vdots \\ U_{f1} & \cdots & U_{fn} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

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Beyond Standard Model

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = U_{reality} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

$$= U_{PMNS} \begin{pmatrix} ? & ? & ? \\ ? & ? & ? \\ ? & ? & ? \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

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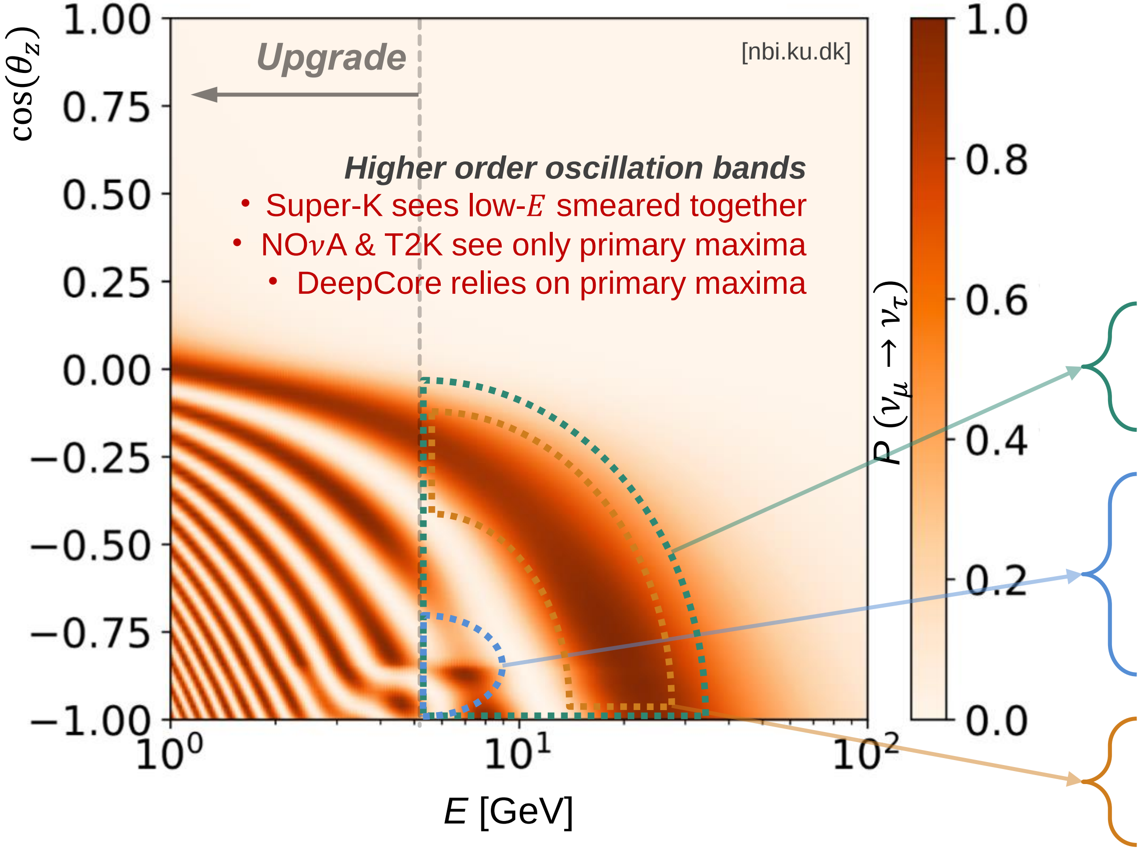
IceCube oscillogram



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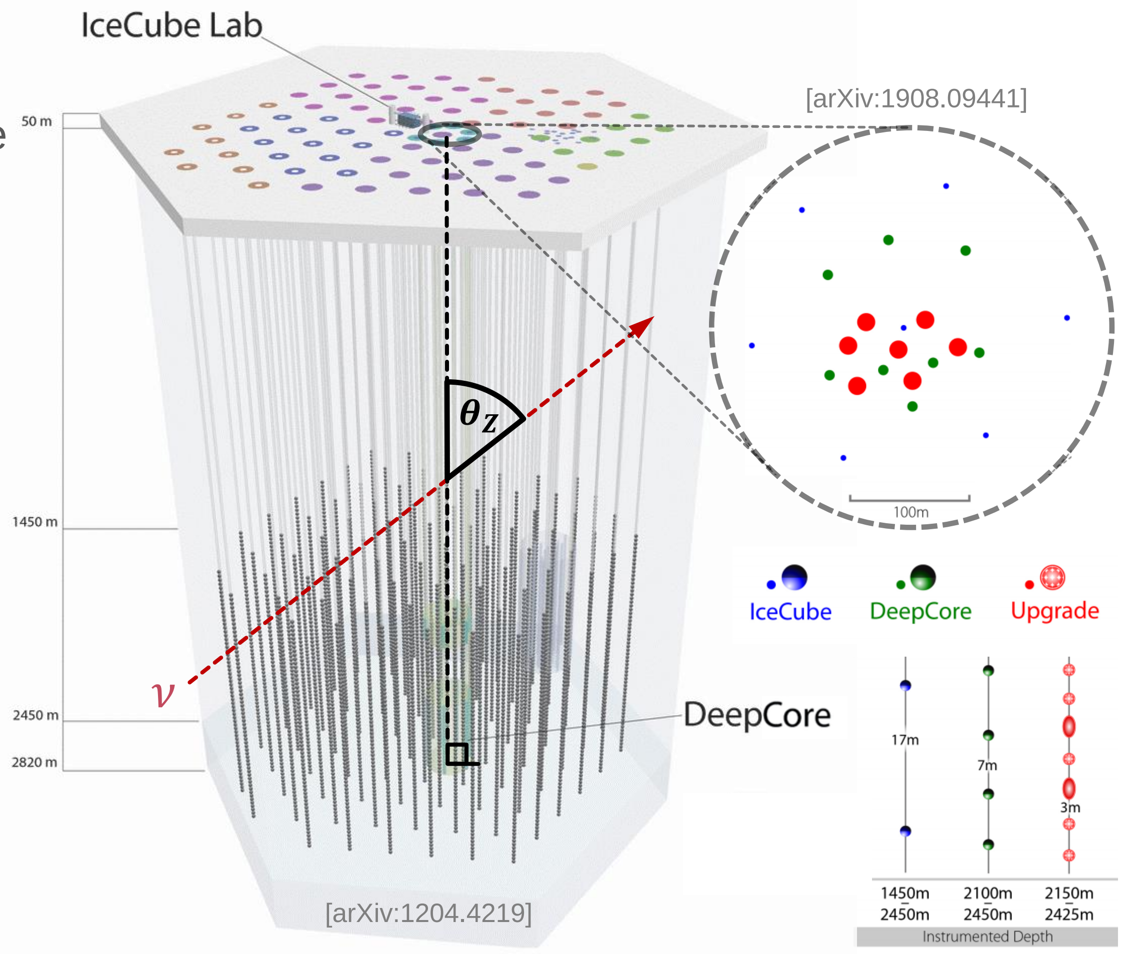
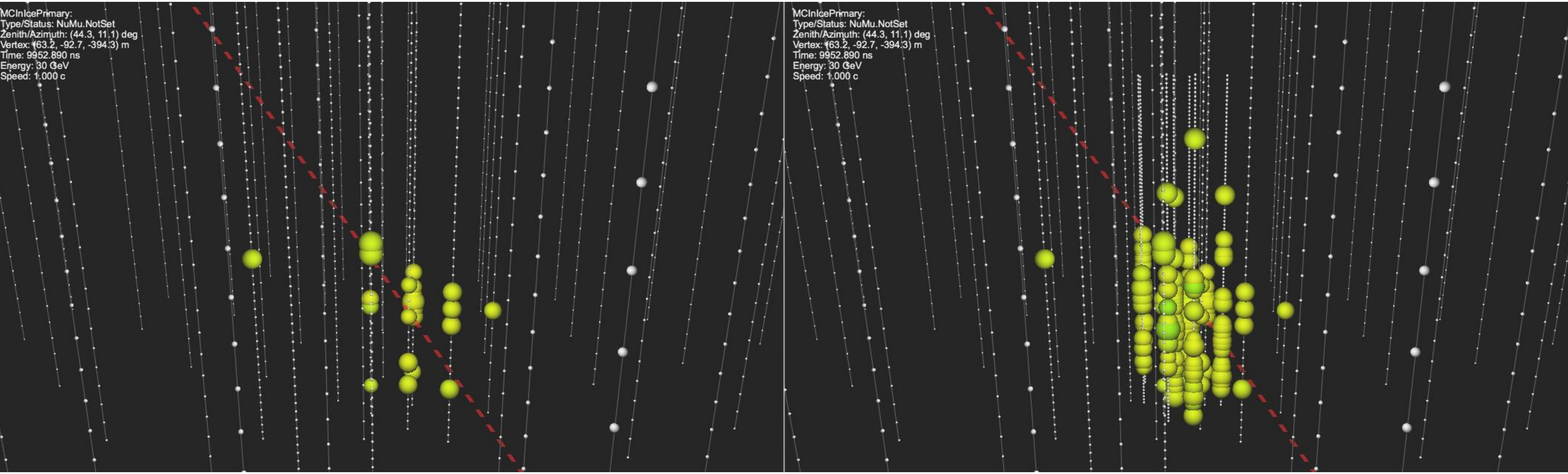
Oscillations with the Upgrade

- ***Reconstruction & particle identification***
  - 2x improvement in E resolution ⊃ 3x for τ-appearance
  - 3x improvement in θ_Z resolution
- ***Detection efficiency***
  - 2x detection efficiency ⊃ 10x efficiency below 10 GeV
  - Overall 2x $\boldsymbol{\nu_\tau}$ rate, 3x $\boldsymbol{\nu_\mu}$ rate ⇒ ν_{atm} every 15 mins
  - Systematics limited measurements
- ***Projections***
  - 1yr → world leading $\boldsymbol{\nu_\tau}$-appearance
  - 3yrs → competitive $\boldsymbol{\nu_\mu}$-disappearance



DeepCore event energy

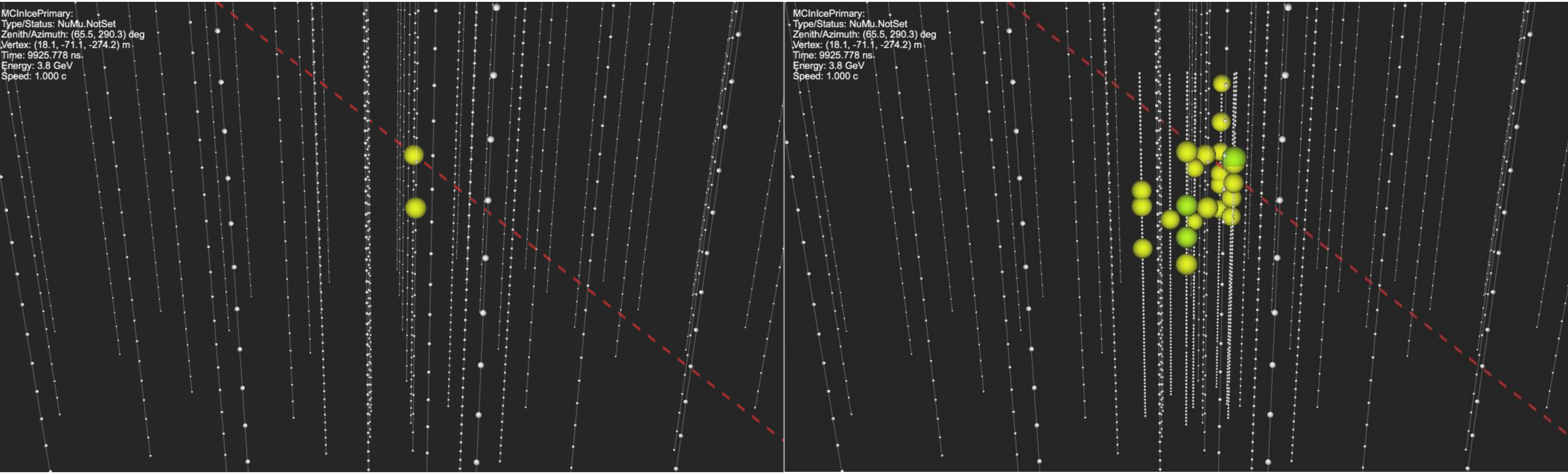
DeepCore → *Upgrade*



- The same simulated 30 GeV $\nu_\mu \rightarrow \mu$-track as viewed by each setup

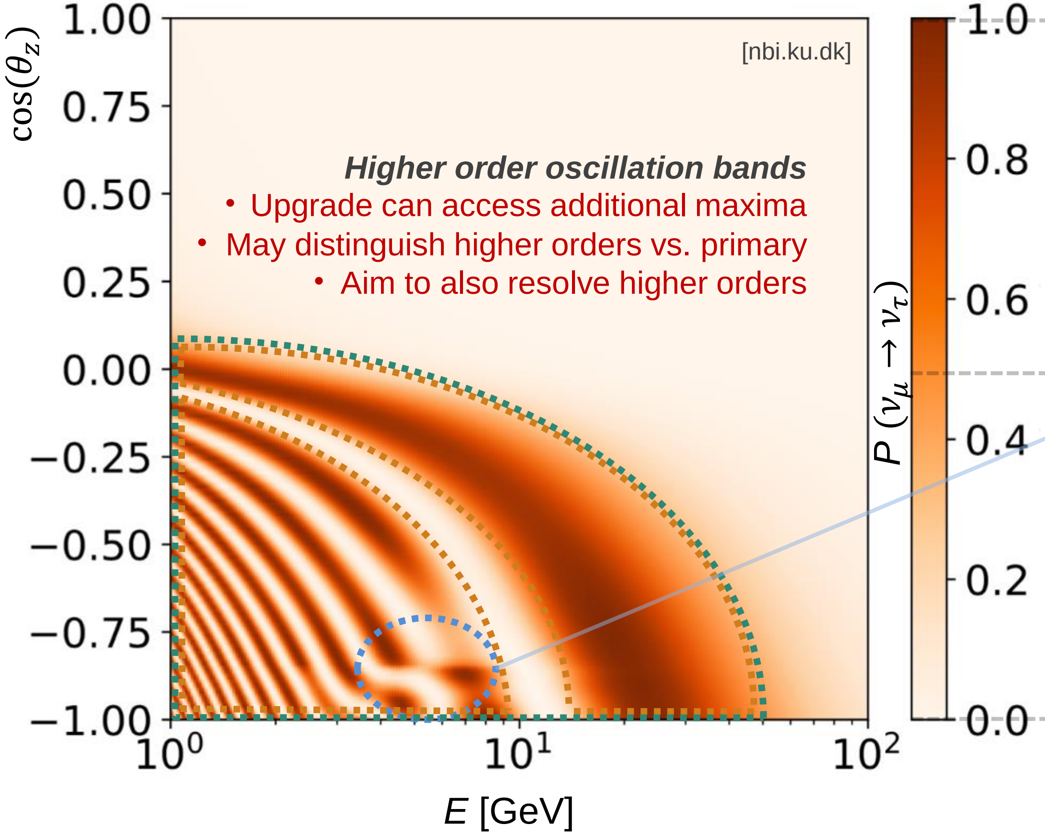
Upgrade event energy

DeepCore → *Upgrade*



- The same simulated 3.8 GeV $\nu_\mu \rightarrow \mu$-track as viewed by each setup

ν-oscillations physics



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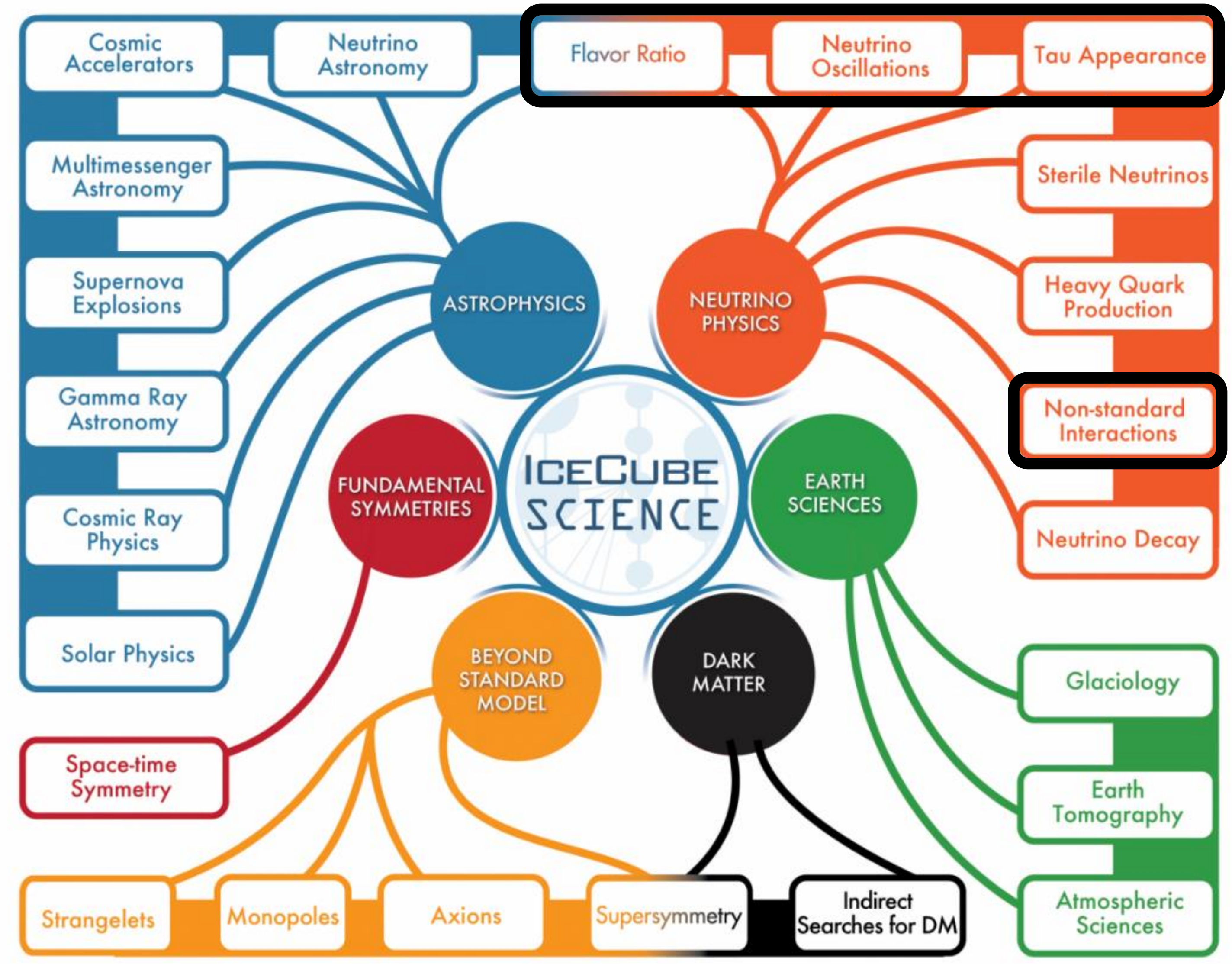


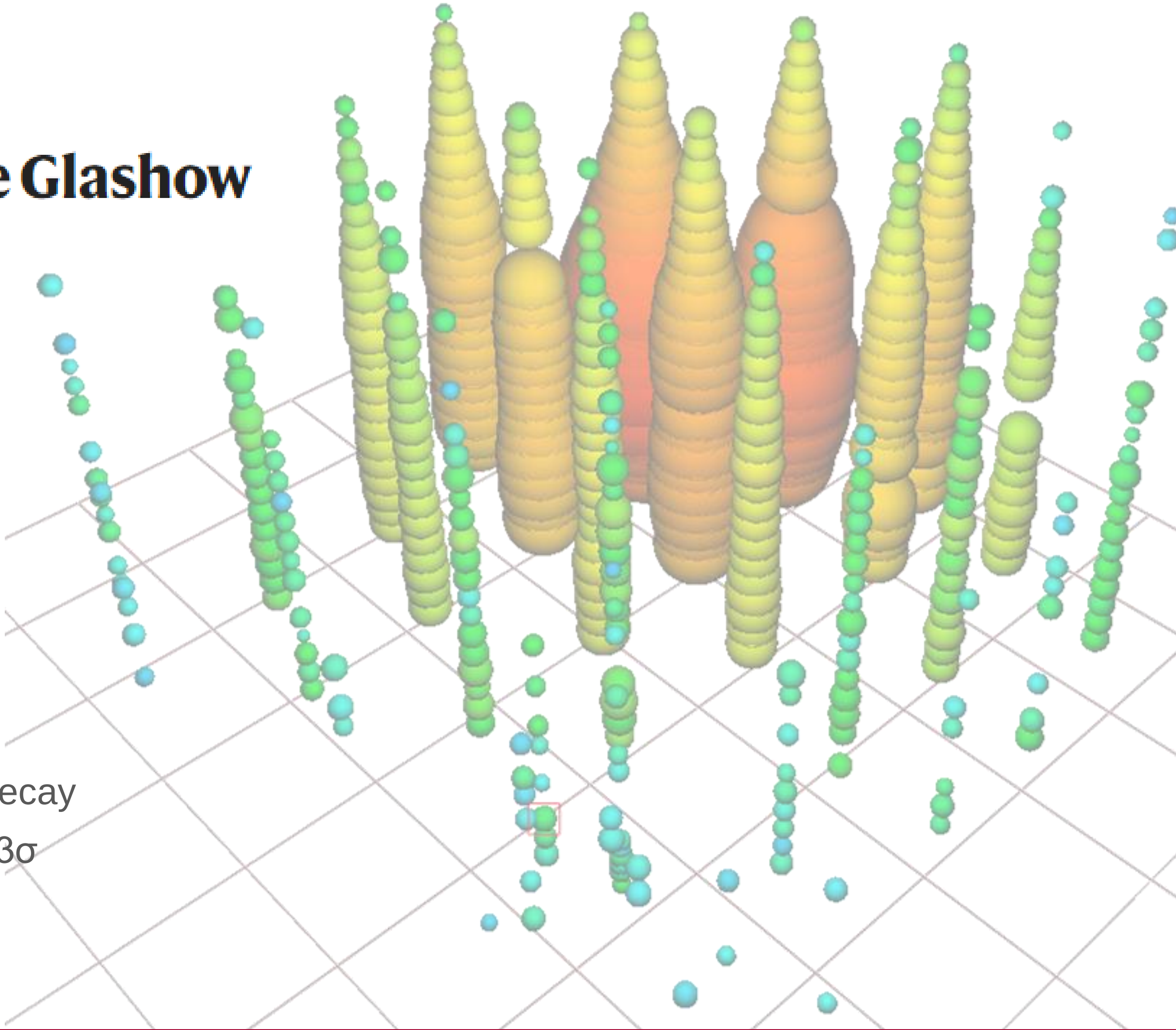
PeV resonant scattering

Article | Published: 10 March 2021

Detection of a particle shower at the Glashow resonance with IceCube

The IceCube Collaboration

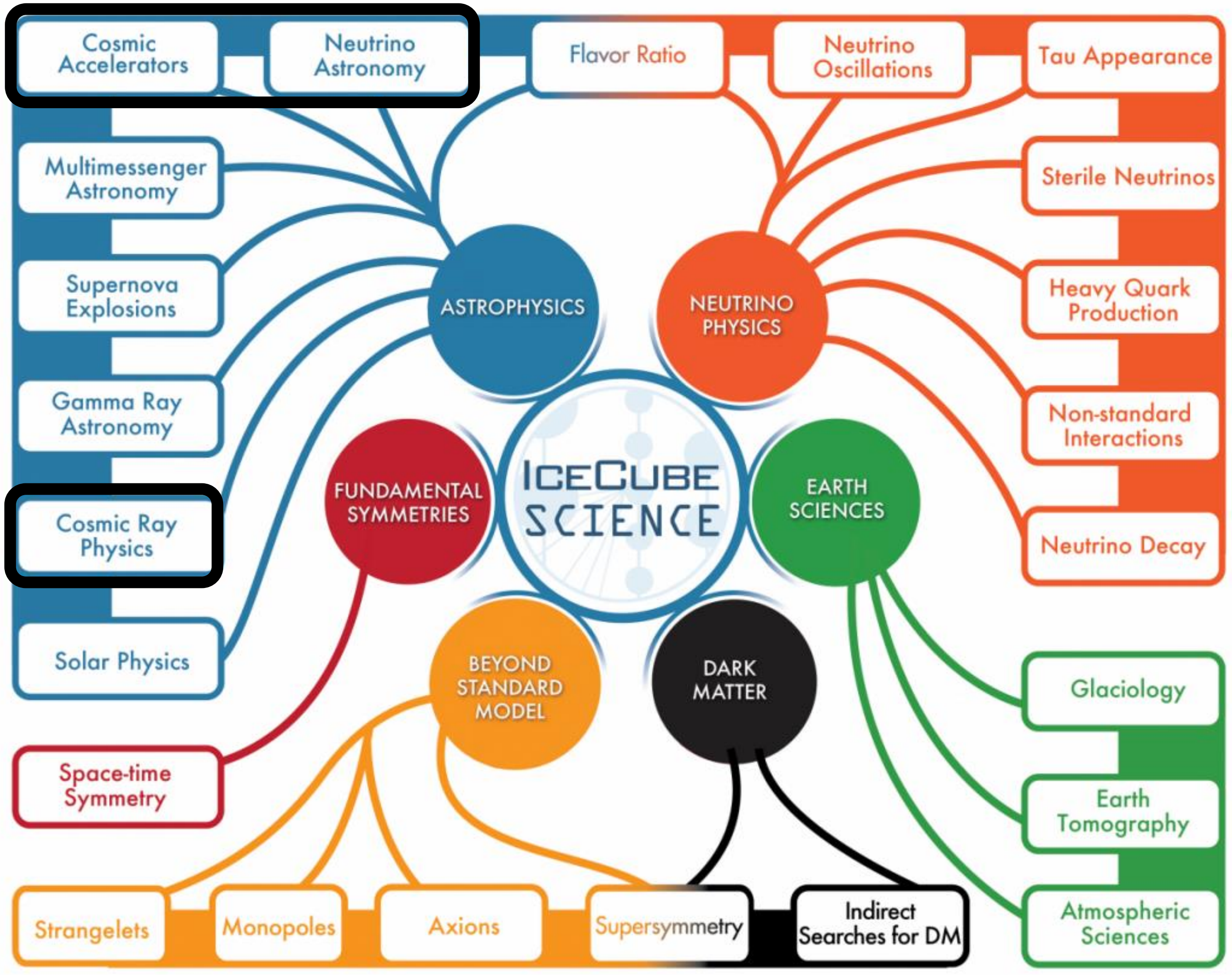
Nature **591**, 220–224 (2021) | Cite this article



Summary

- Only 3rd IceCube event with $E > 5\ PeV$
- $m_W = 80.38\ GeV \Rightarrow$ resonance at $E_{\bar{\nu}} = 6.32\ PeV$
- 5σ within expected W^- resonance width
- Early pulses ahead of cascade imply hadronic W-decay
- Likelihood ratio test prefers GR(h) over CC(e) to 2.3σ
- Suggests presence of $\bar{\nu}$ astrophysical flux

PeV resonant scattering



Astrophysical neutrino production

Letter | Published: 22 February 2021

A concordance scenario for the observed neutrino from a tidal disruption event

Walter Winter & Cecilia Lunardini

Nature Astronomy **5**, 472–477 (2021) | Cite this article

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We've spotted a neutrino blasted out by a black hole shredding a star

SPACE 22 February 2021

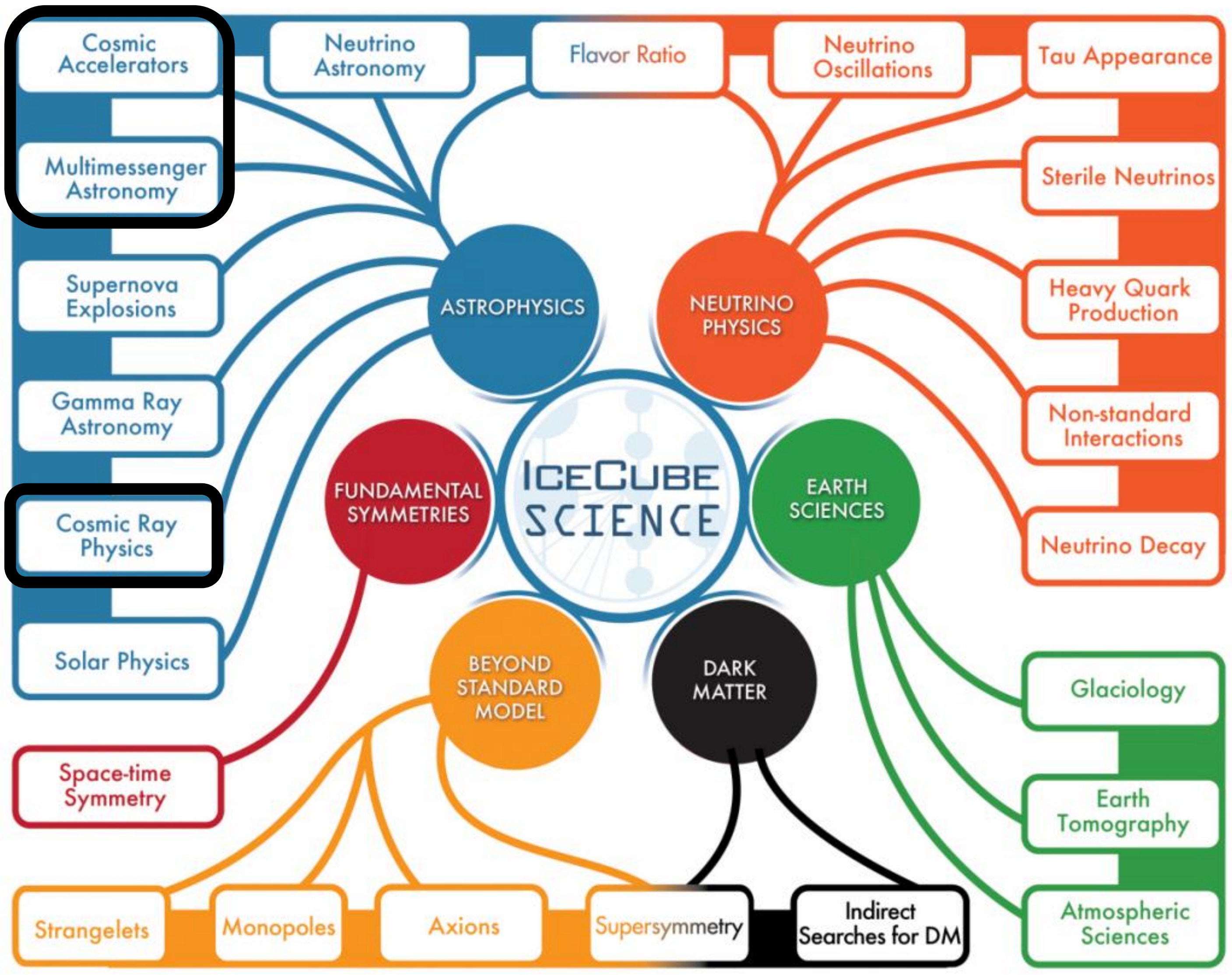
By Leah Crane

A view of the accretion disc around a supermassive black hole, with jet-like structures flowing away from the disc

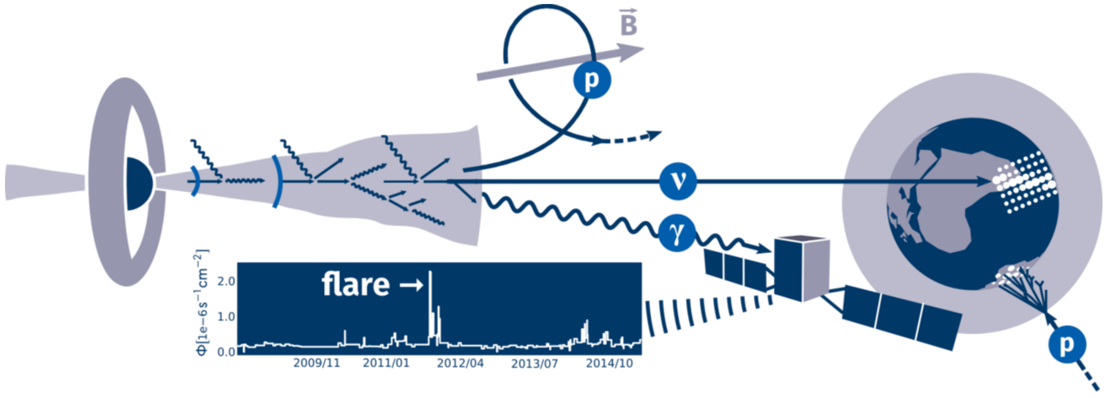
Summary

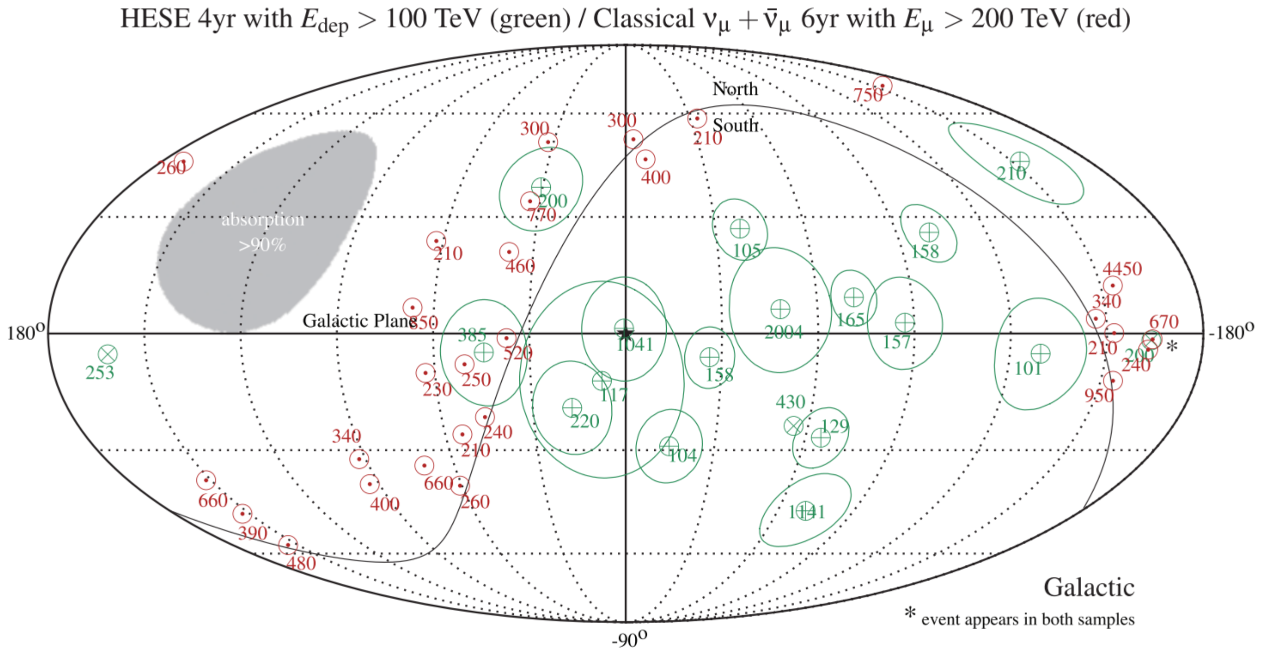
- Star torn apart by tidal forces of a supermassive black hole
- 50% of the star's mass accreted by the black hole
- Track-like astrophysical neutrino (IceCube-191001A16) associated with known tidal disruption event (AT2019dsg17)
- Indicates such events can accelerate cosmic rays to PeV energies
- Expanding cocoon progressively obscures the X-rays emitted
- Provides target for $p\gamma$-production of neutrinos

Astrophysical neutrino production

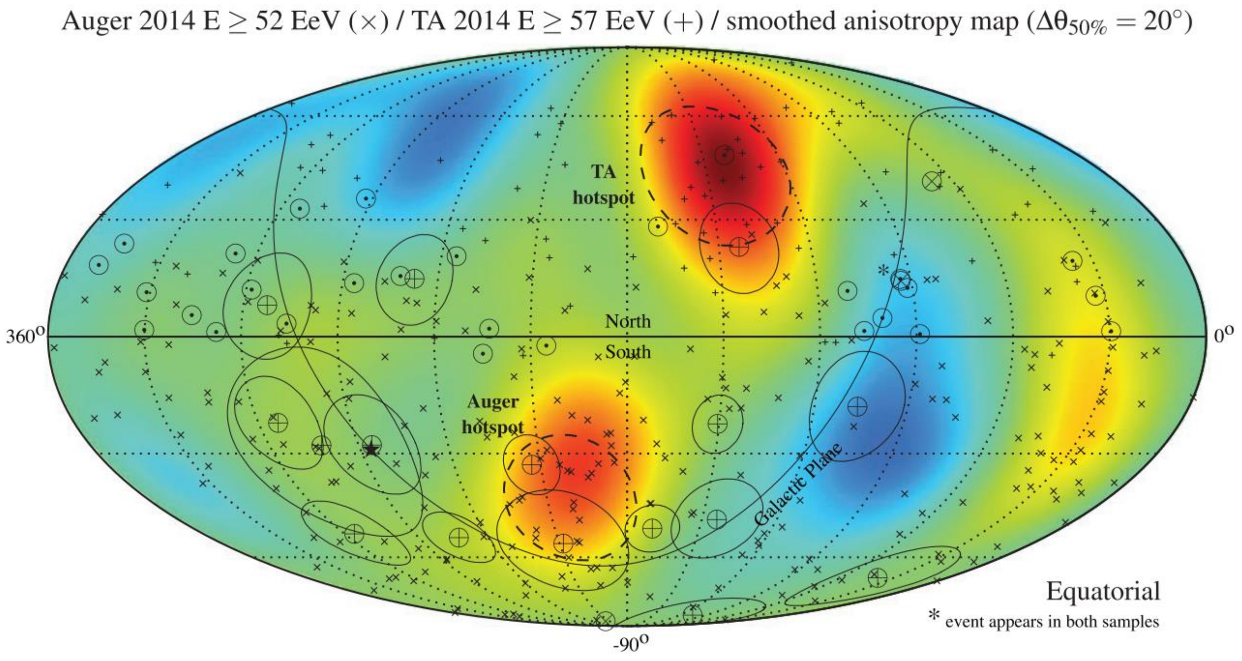


Multi-messenger astronomy





projection in Galactic coordinates of the arrival direction of neutrino events



projection of the arrival direction of neutrinos and UHE CRs

Conclusions

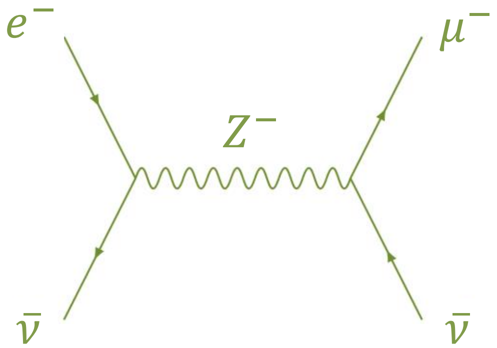
- ***Broad programme of astro- and particle physics***
  - Neutrino oscillations
  - Neutrino astrophysics
  - Multi-messenger astronomy
- ***Ongoing projects***
  - Upgrade is in finalising stages following delay due to pandemic
  - Gen-2 development well underway
  - Radio extension to be matched in Greenland (RNO-G)
- ***Opportunities for the future***
  - 3 years of Upgrade data expected to exceed 10 year DeepCore precision
  - Gen-2 on track for beginning 2025 installation and first data by 2033
  - Plenty of unanswered questions still out there, neutrino sector is still growing!

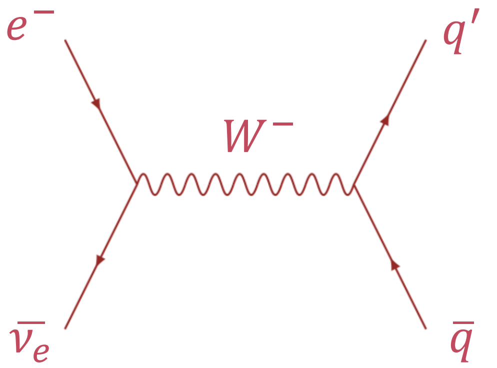
Conclusions

Conclusions

$\overline{\nu_e} + e^- \rightarrow W^-$

- ***Anti-neutrino scattering, 1959*** [10.1103/PhysRev.118.316]
  - Hypothesised 'unstable charged boson' (Z meson)
  - If $(m_Z = m_K \sim 0.5\ GeV) \Rightarrow$ resonance at $E_{\bar{\nu}} \sim M_Z^2/m_e \approx 2\ TeV$
  - e^- at rest probes incoming $\bar{\nu}$ s-channel processes





- ***In the mean-time…*** *hypothesis & discovery*
  - Neutrino flavour (ν_μ) '40 & '62
  - Quark model (u, d, s) '64 & '68
  - Unified EW bosons $(W^\pm, Z^0)$ '68 & '83

- ***Glashow resonant scattering***
  - $m_W = 80.38\ GeV \Rightarrow$ resonance at $E_{\bar{\nu}} = 6.32\ PeV$
  - IceCube sensitive to $\bar{\nu}$ sources in $l\nu_l$, $q\bar{q}$