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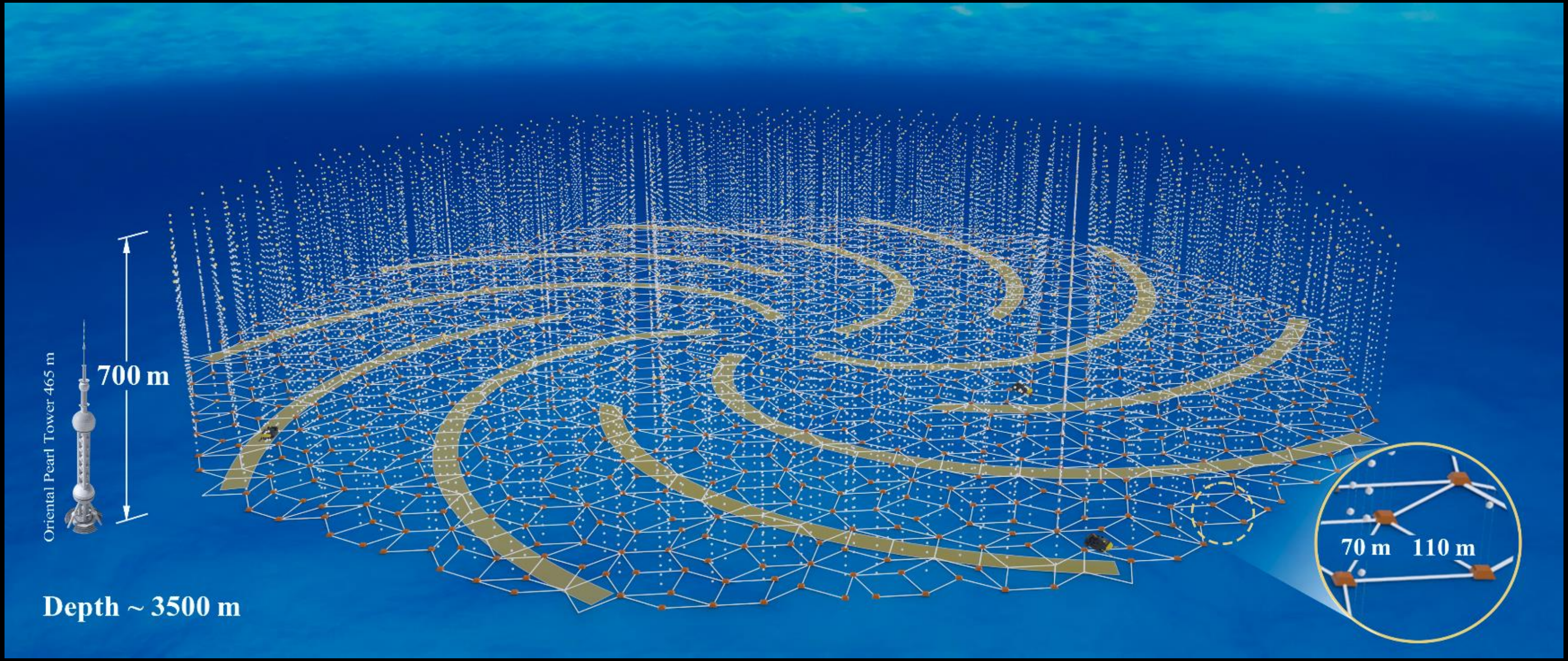
TRIDENT Paper:
https://arxiv.org/abs/2207.04519

Next-Gen Neutrino Telescope in the South China Sea



Iwan Morton-Blake
Tsung-Dao Lee Institute / Shanghai Jiao Tong University

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Next-Gen Neutrino Telescope in the South China Sea

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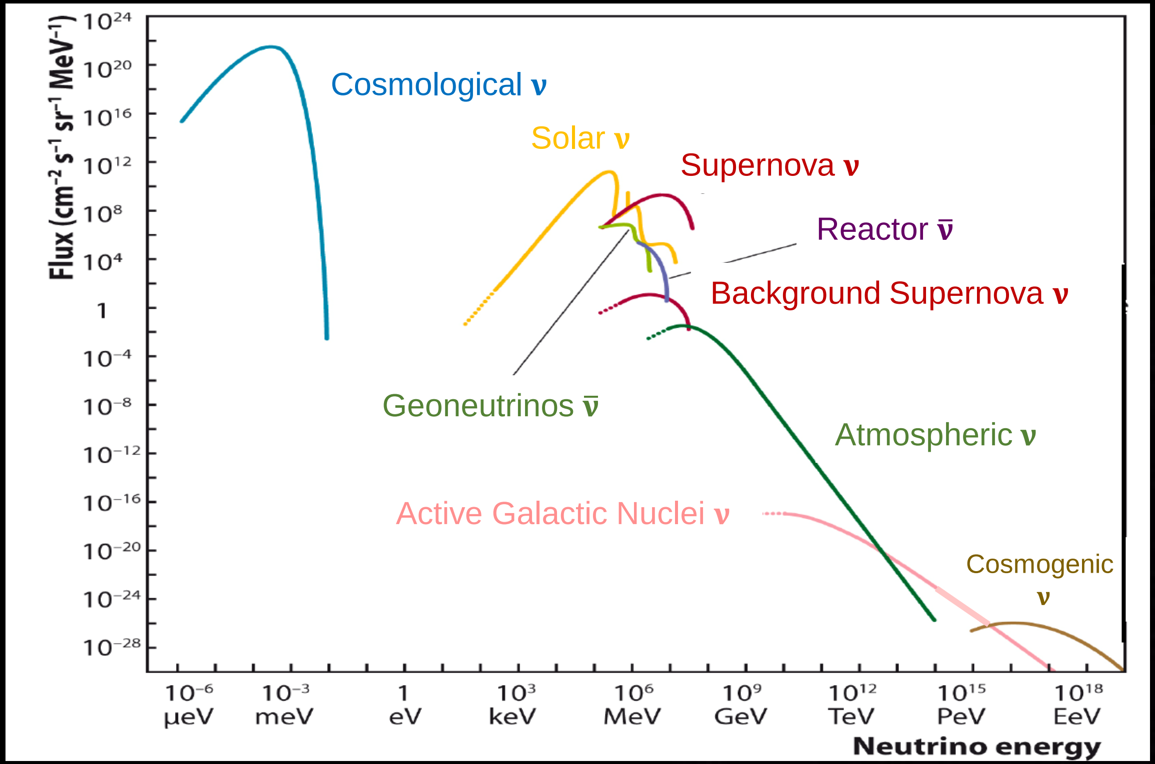
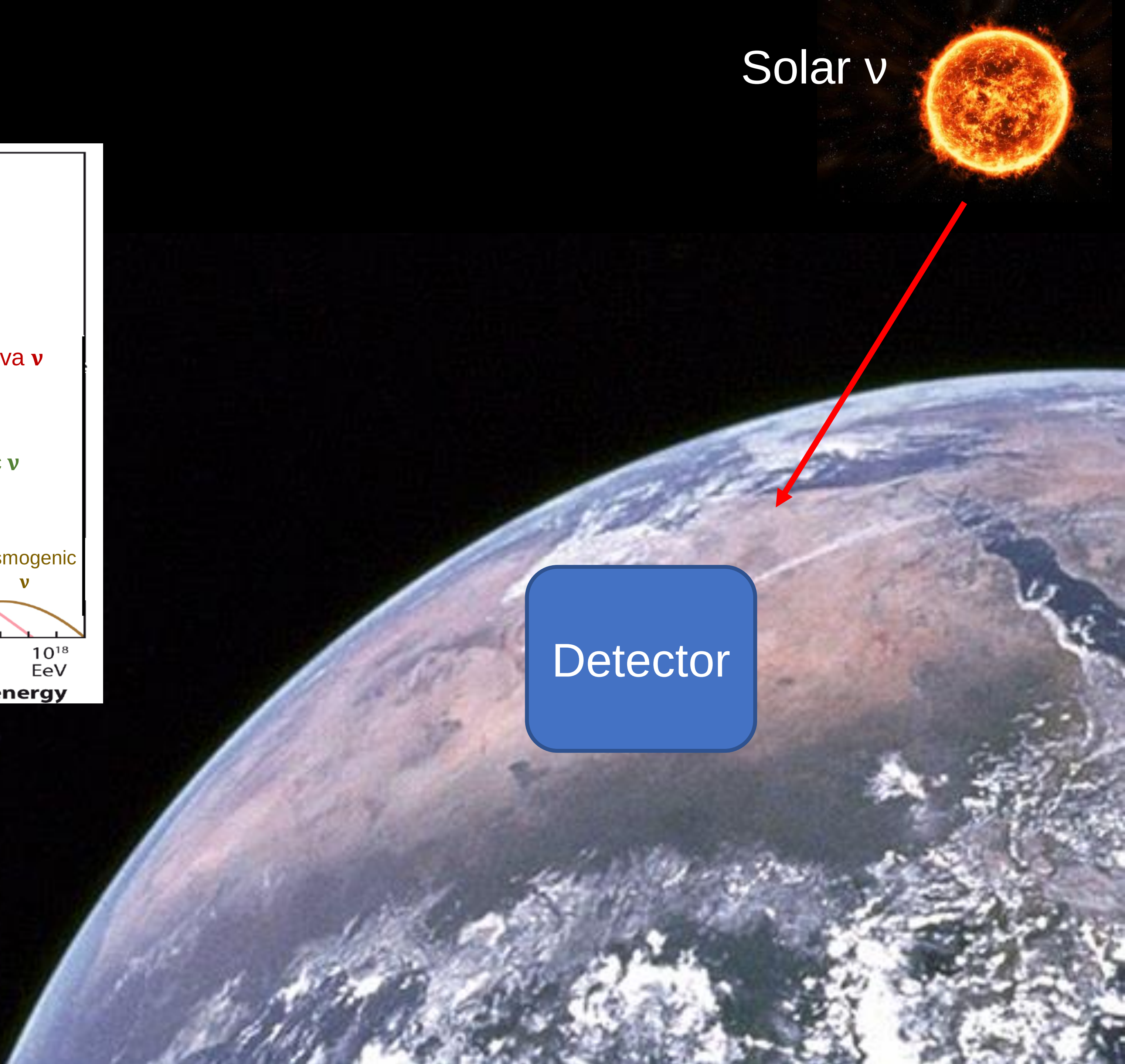
Neutrino Sources





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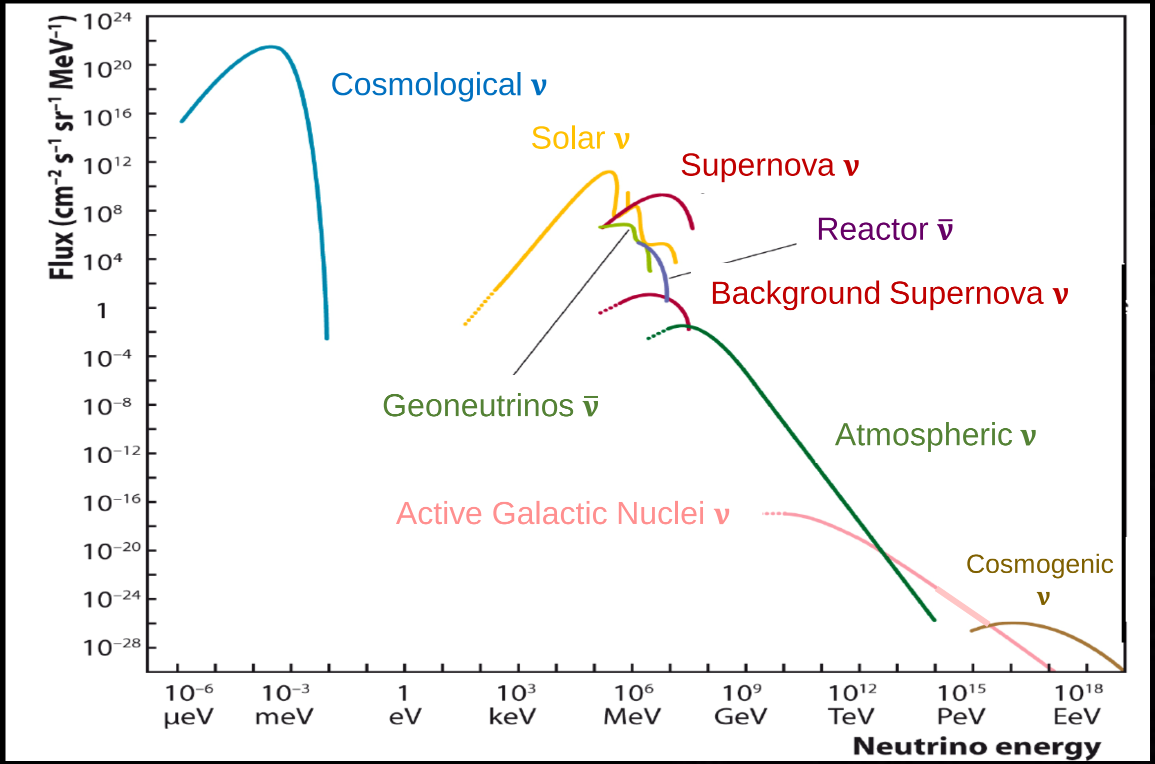

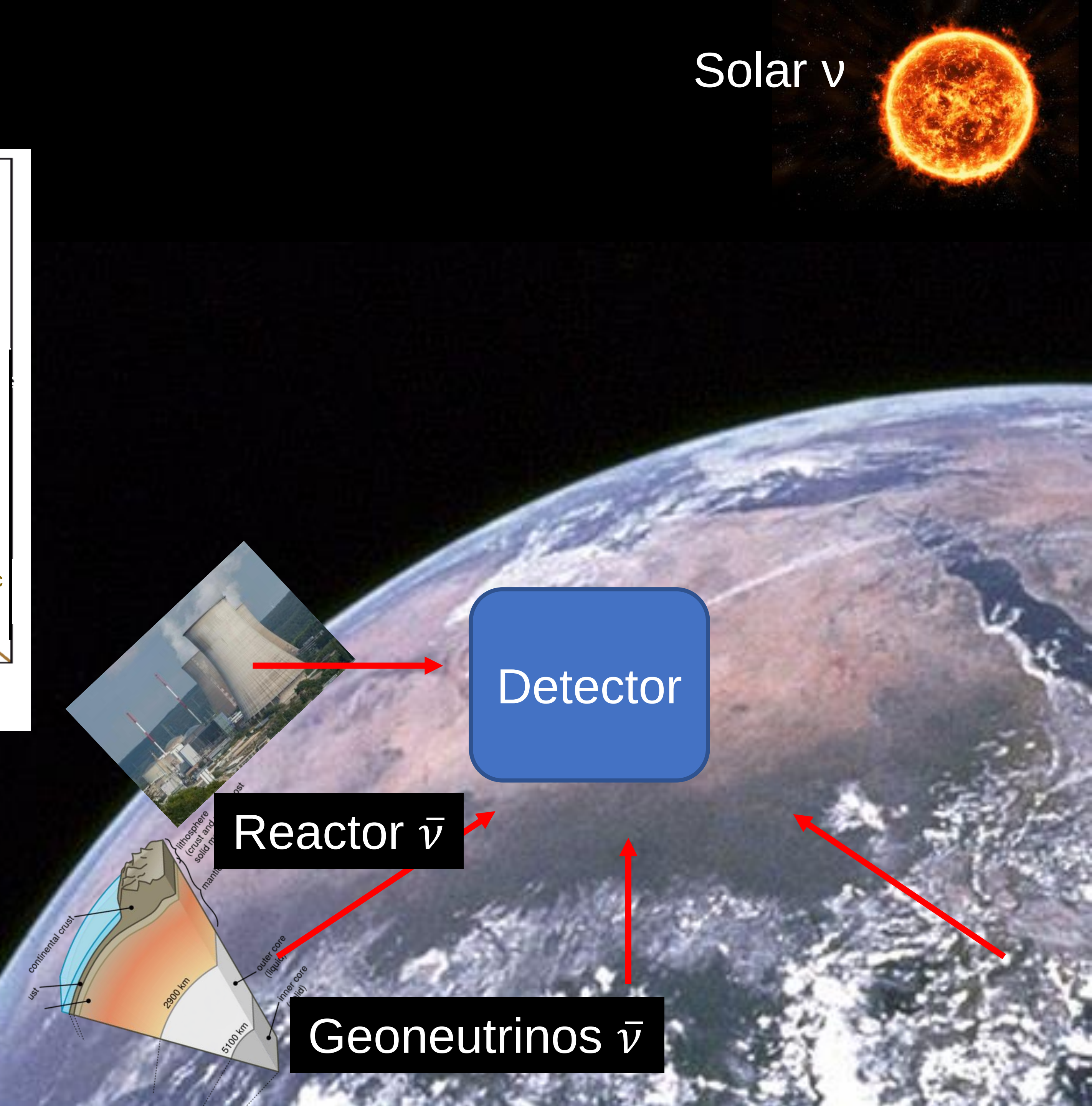

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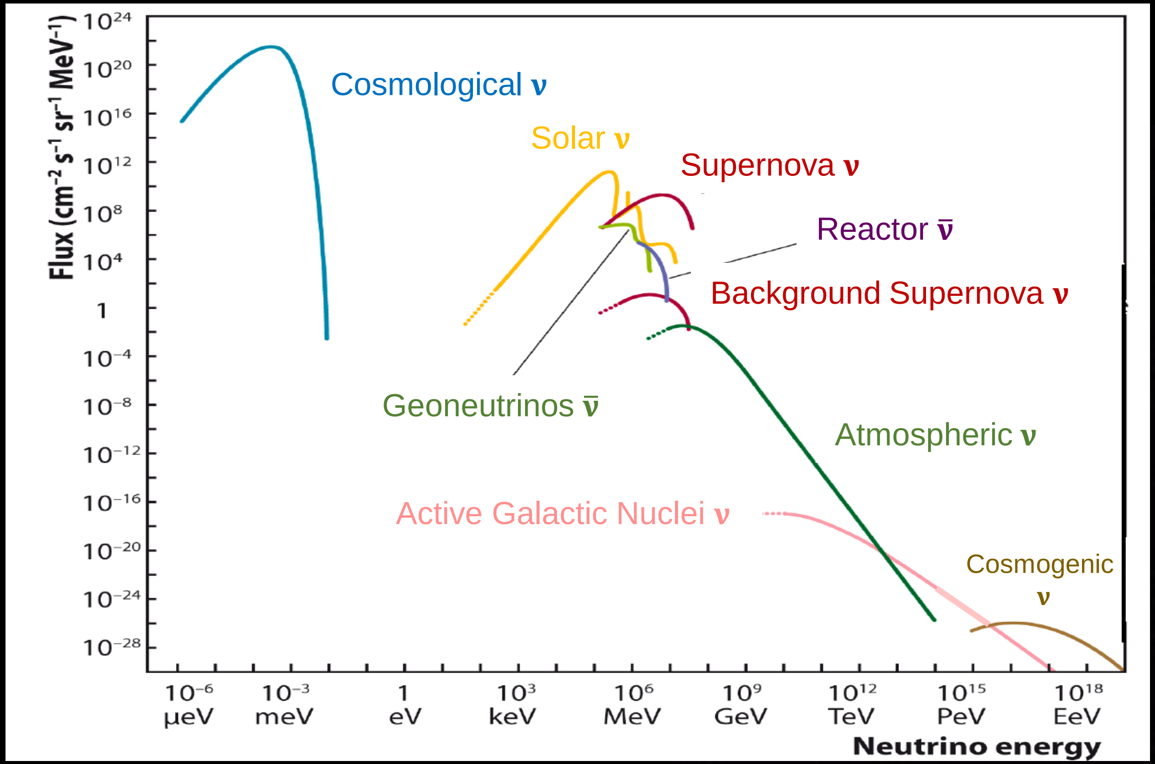

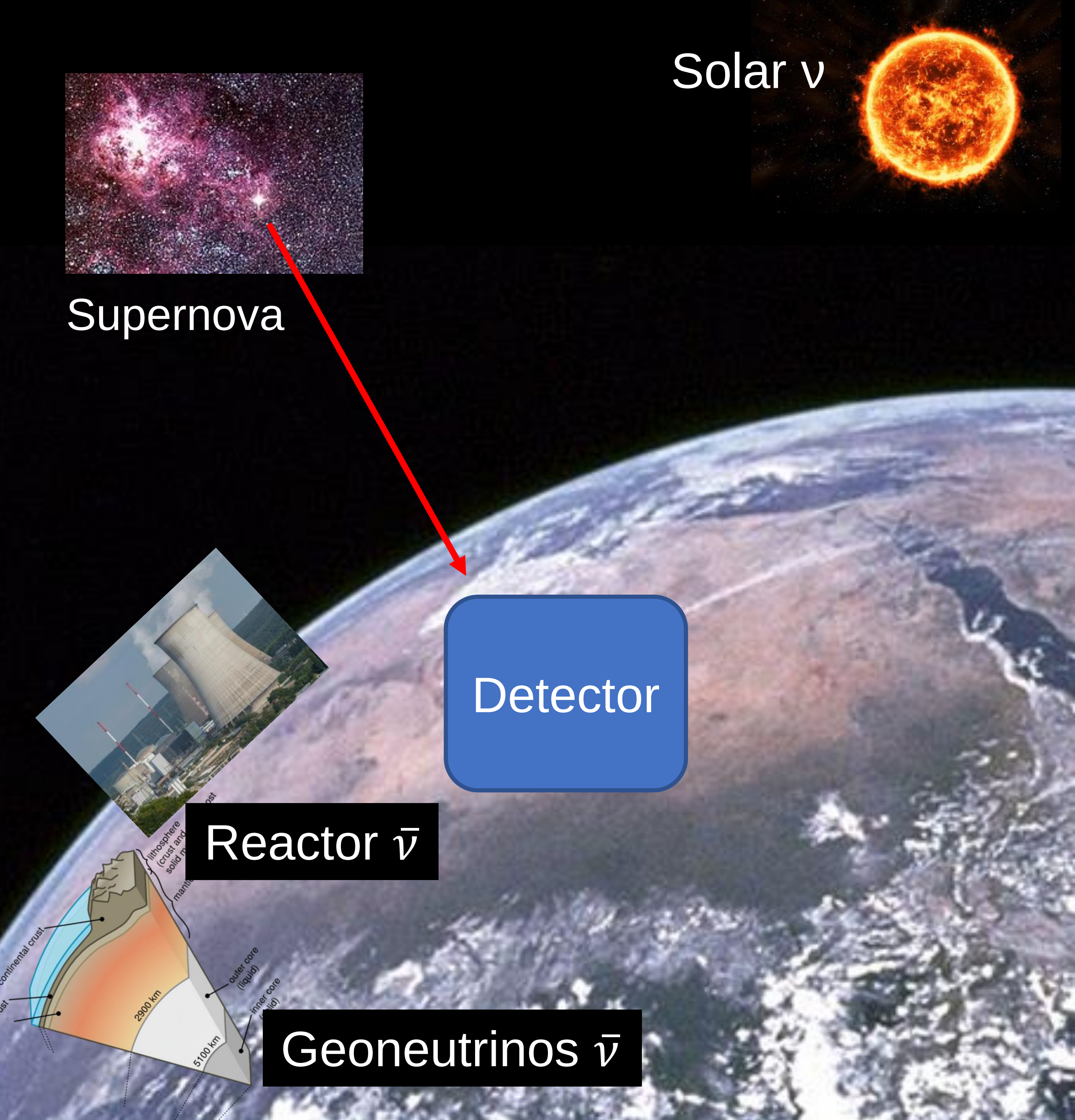

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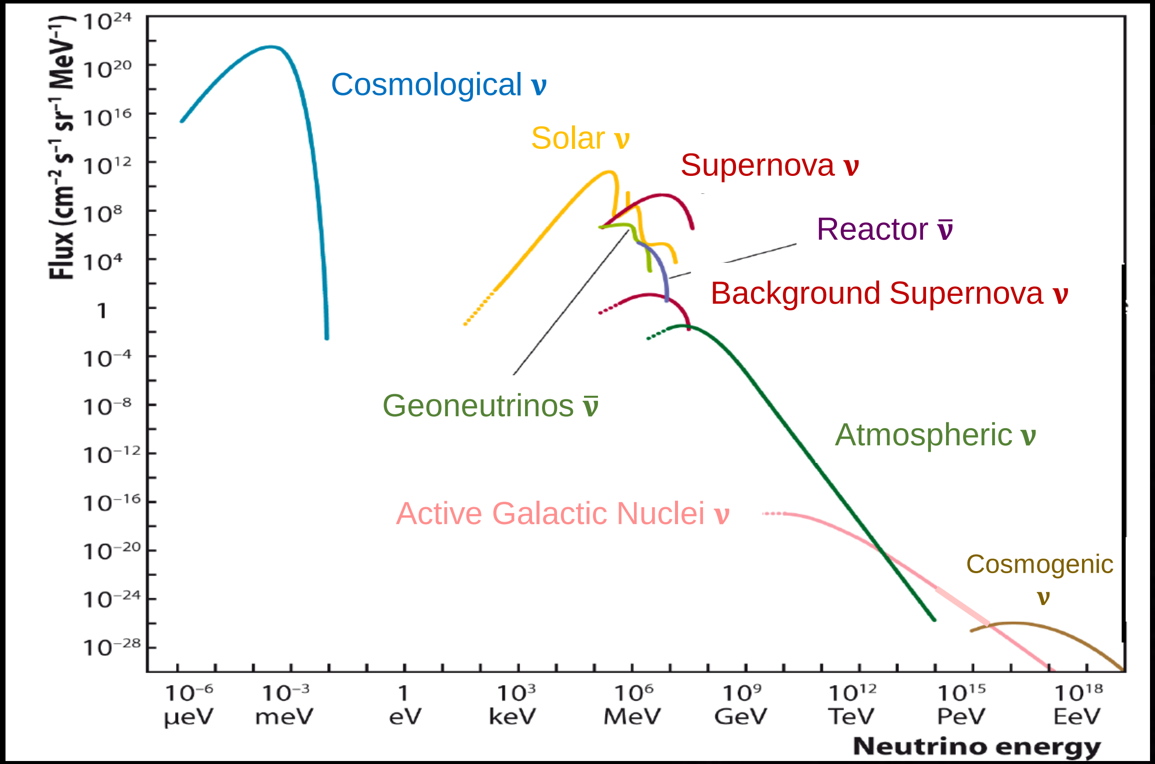
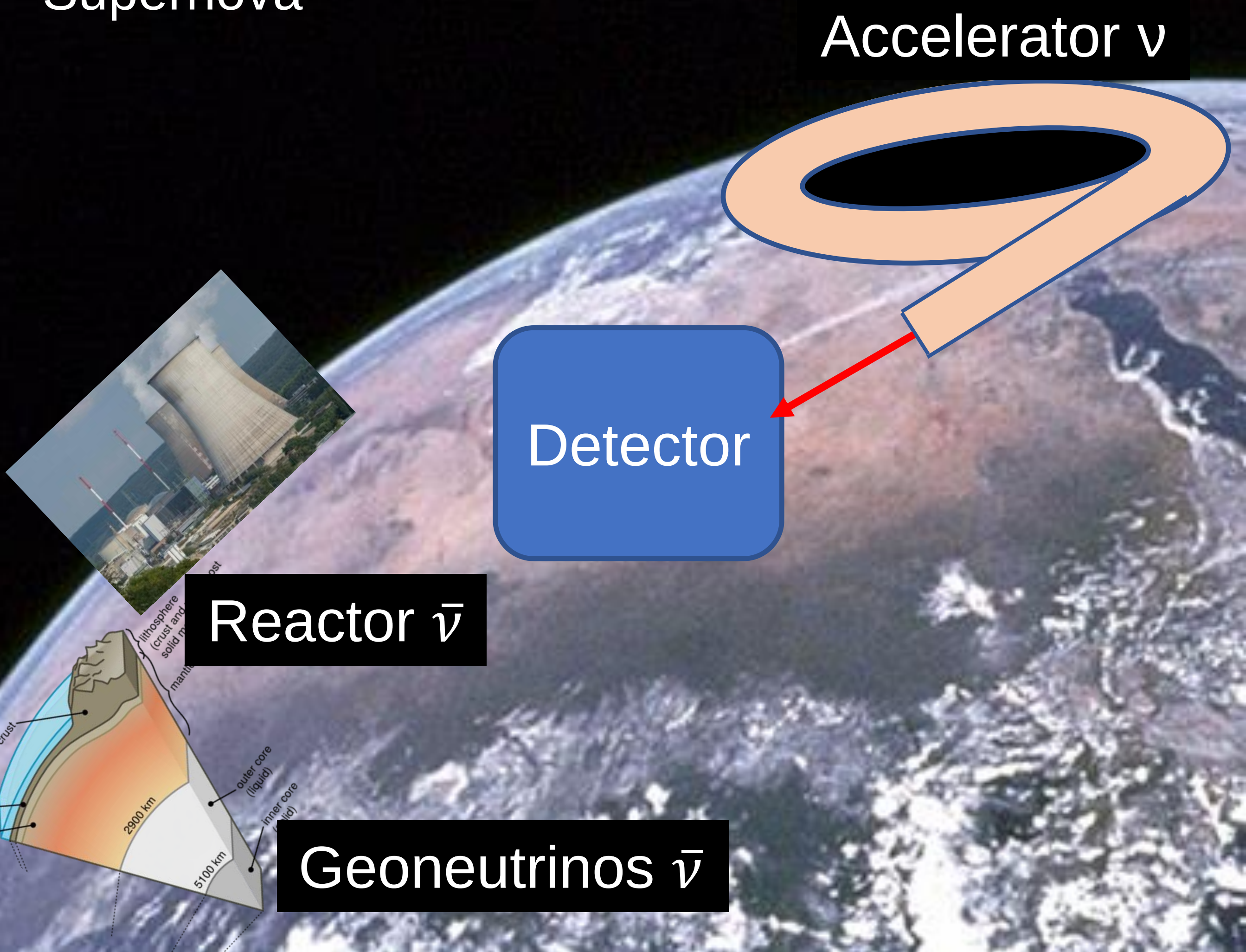


Supernova

Solar ν



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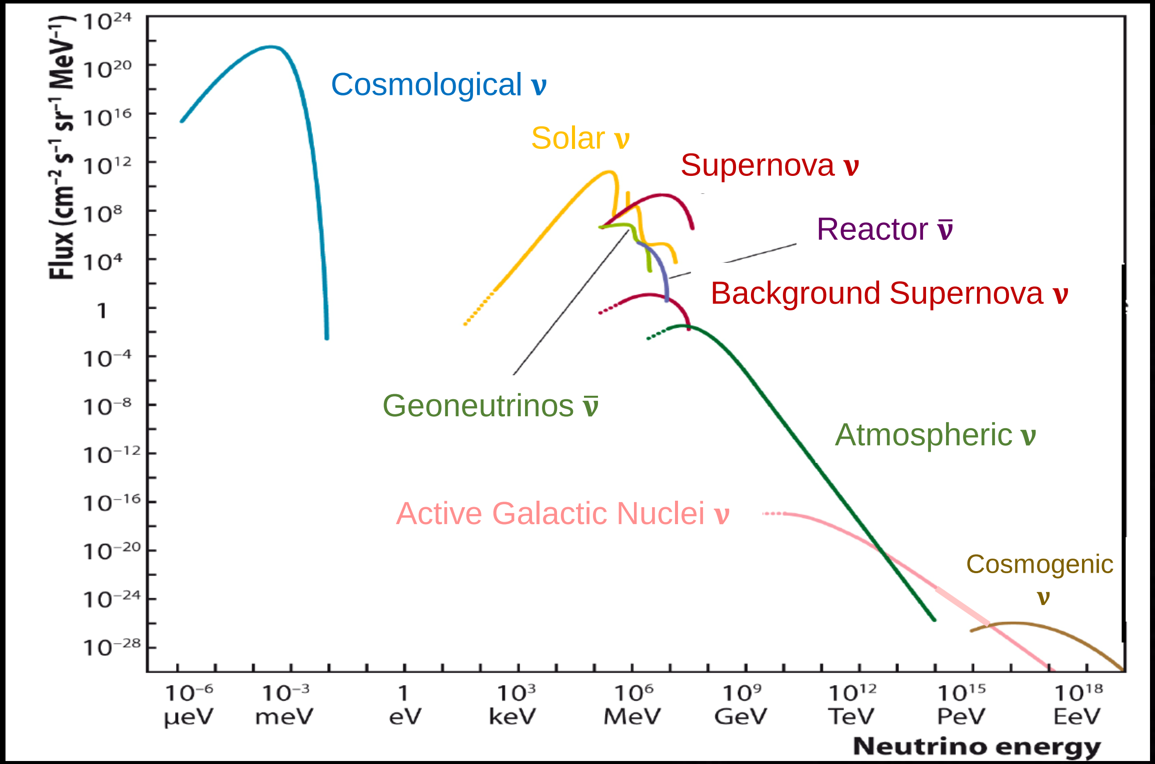

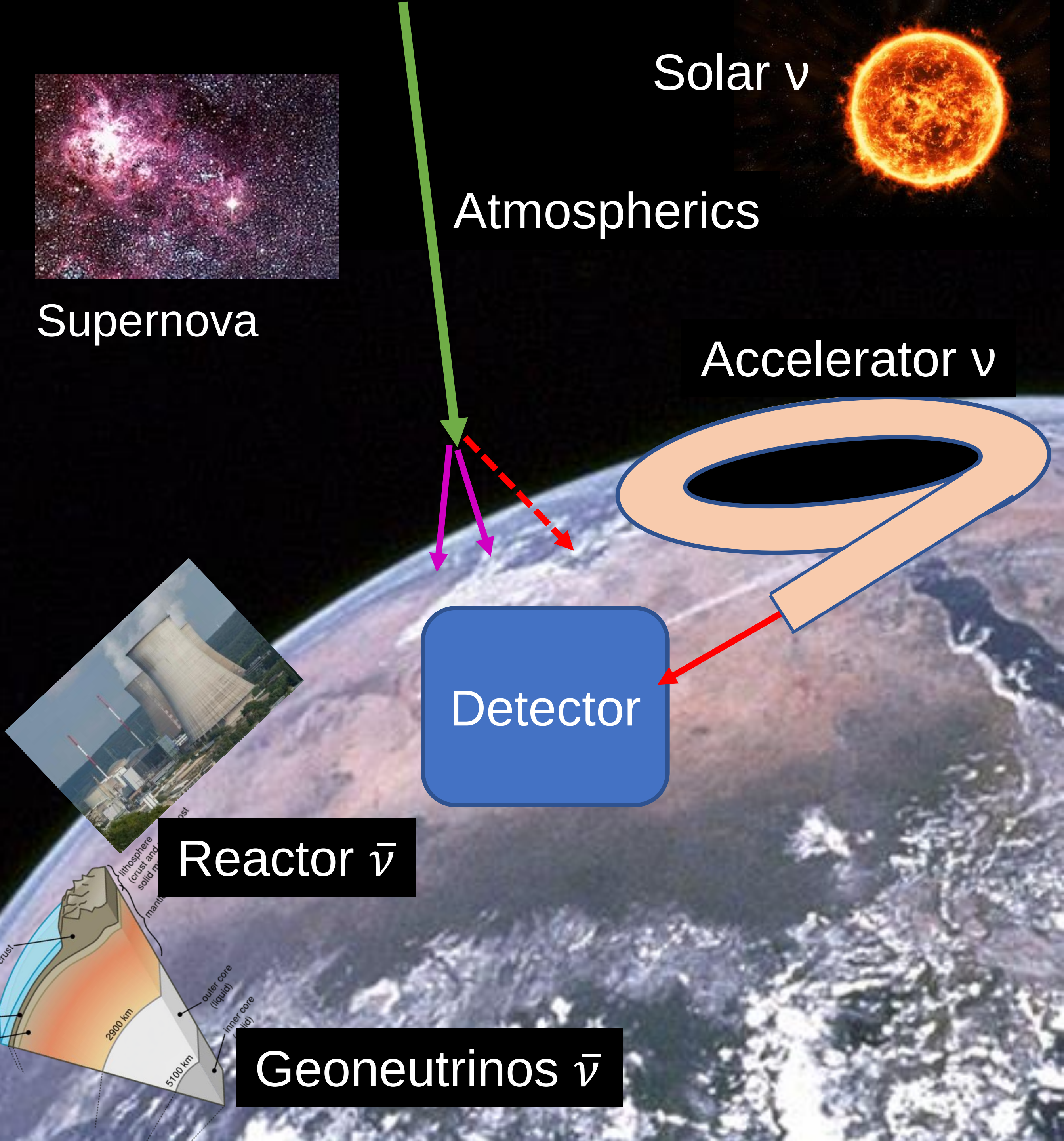

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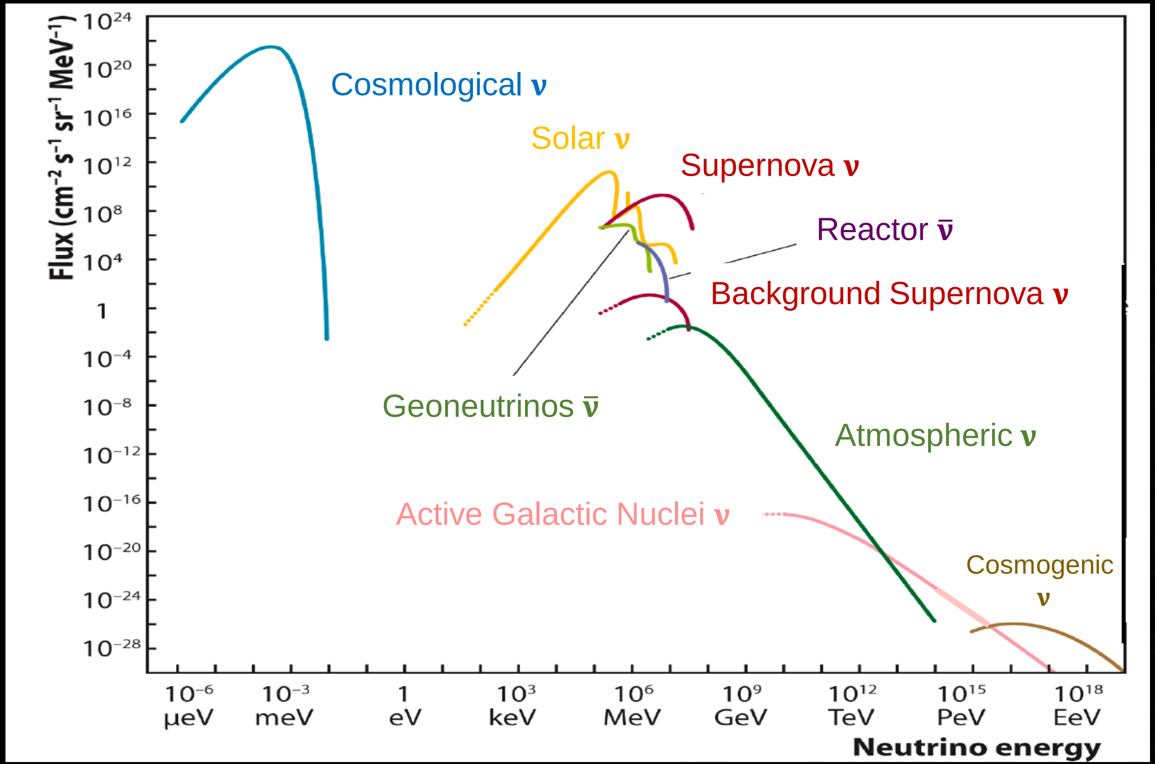

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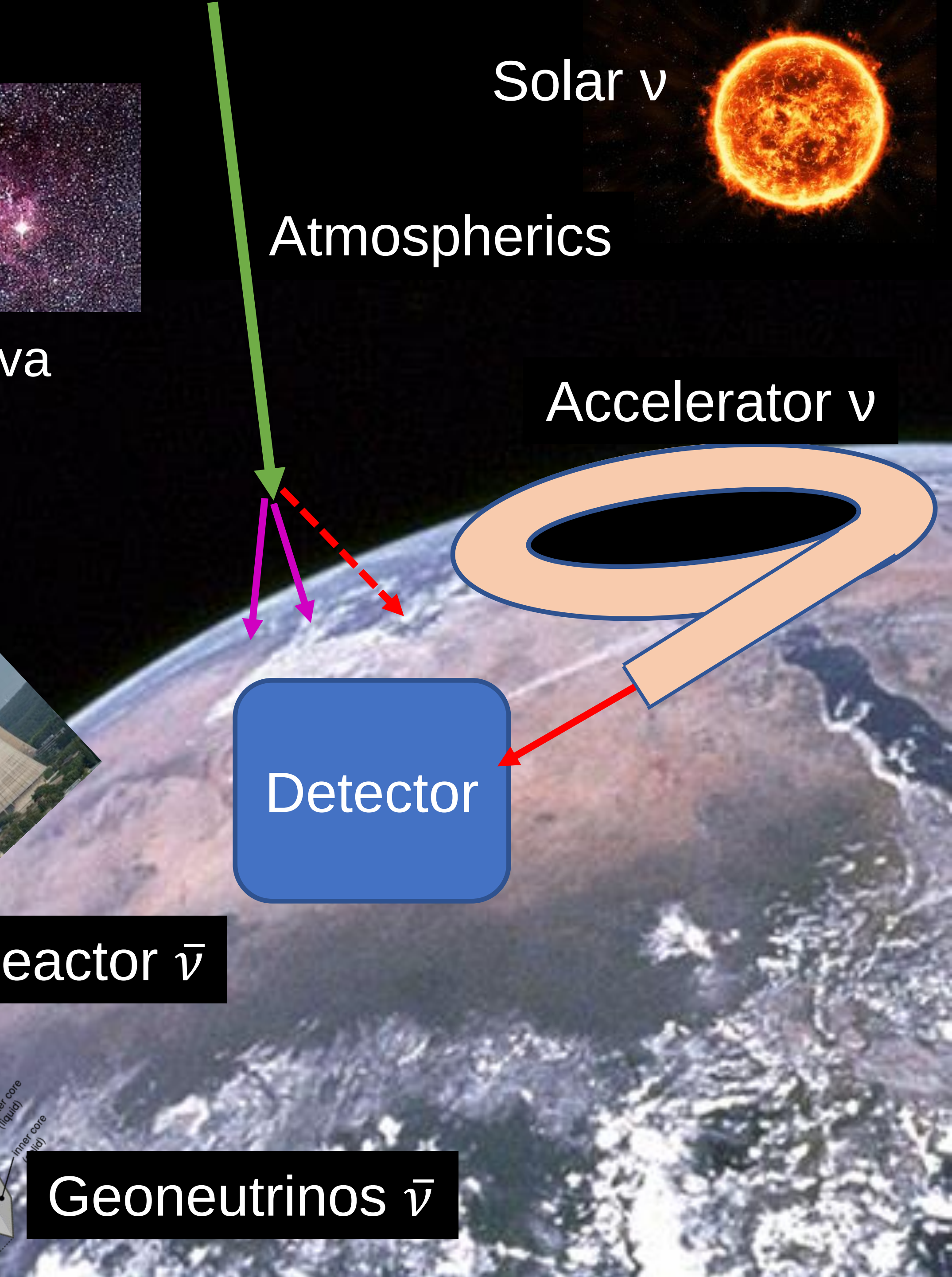
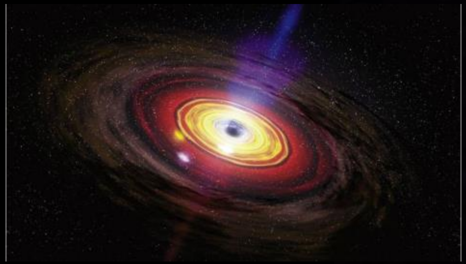
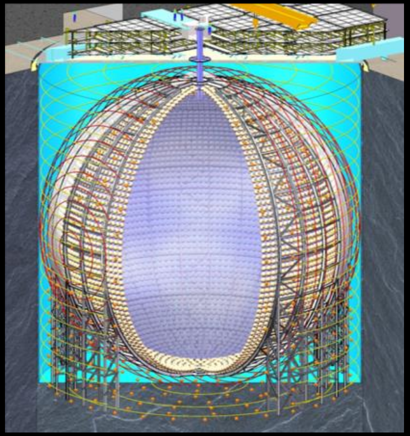


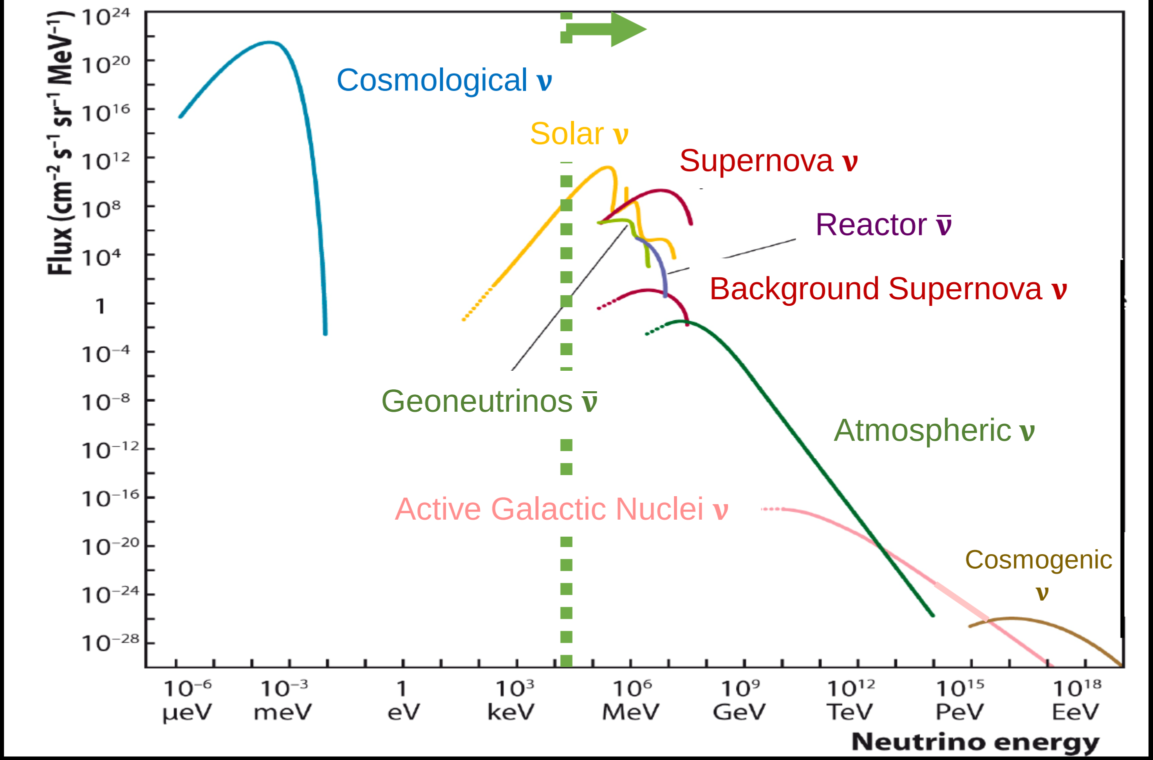


Active Galactic Nucleus

Next-Gen Neutrino Experiments

JUNO ~20kT





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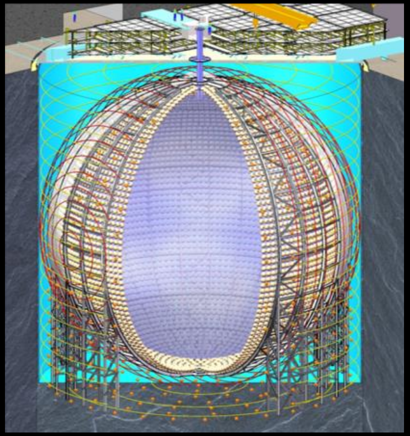
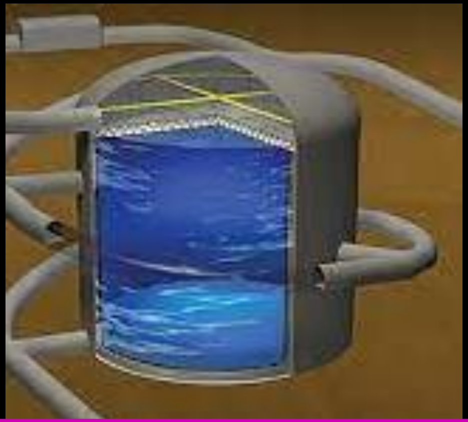
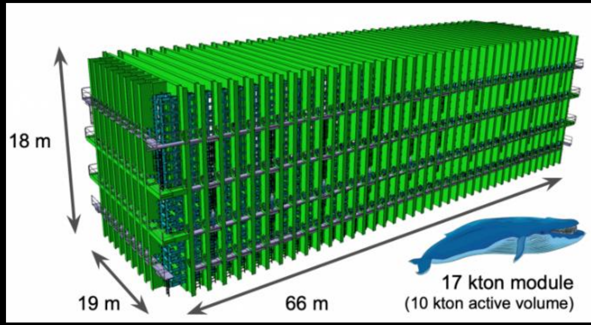
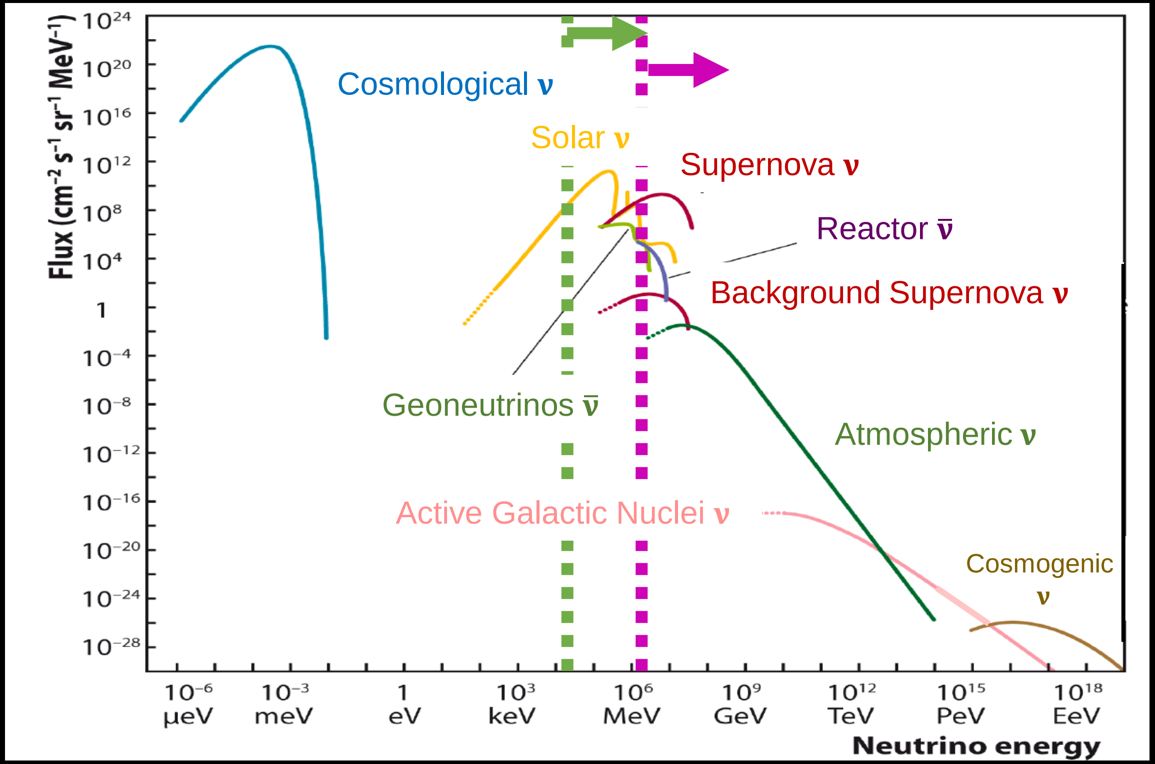


Hyper-K ~200kT



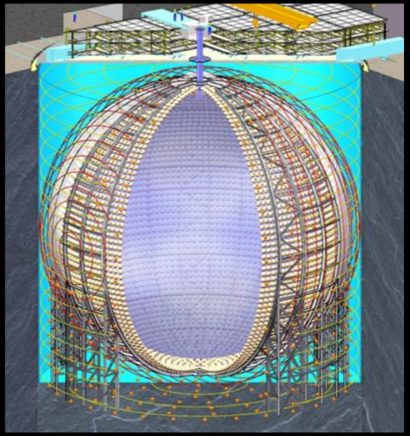
DUNE ~70kT





Next-Gen Neutrino Experiments

JUNO ~20kT



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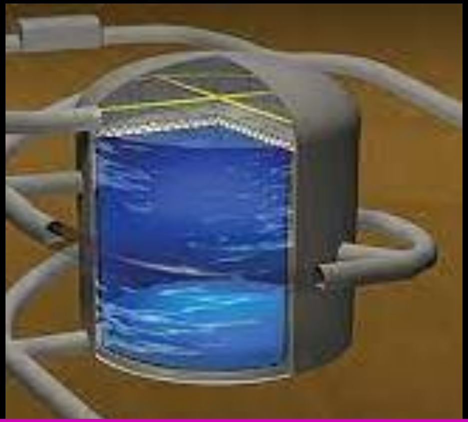

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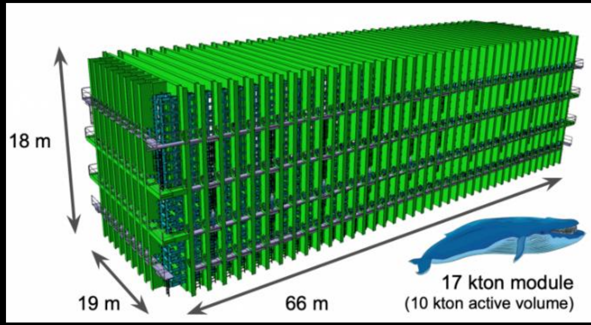
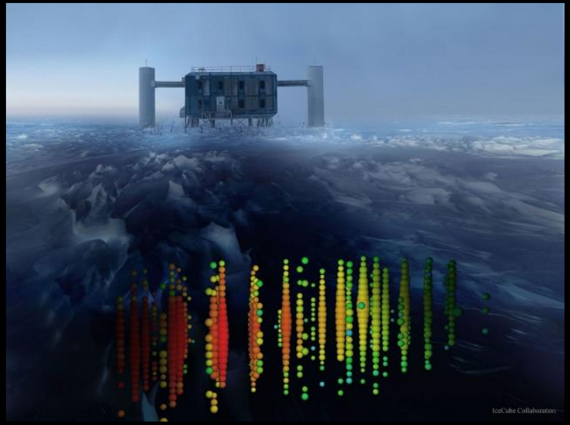
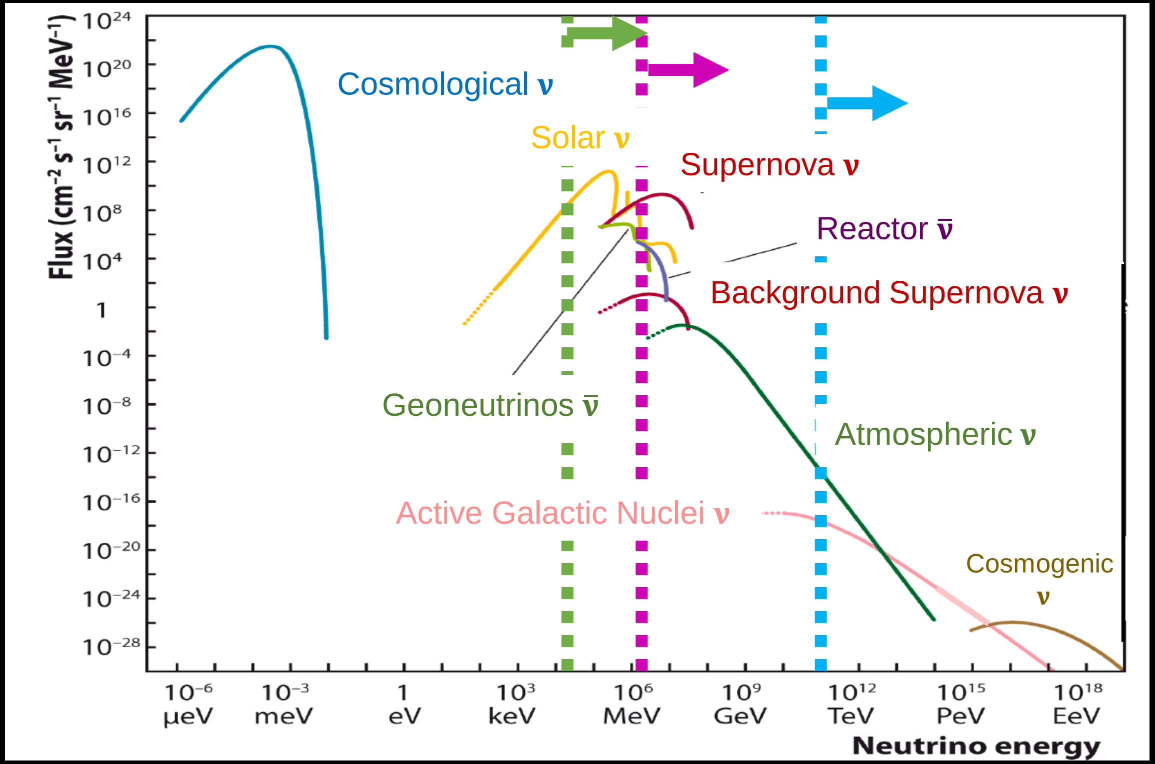
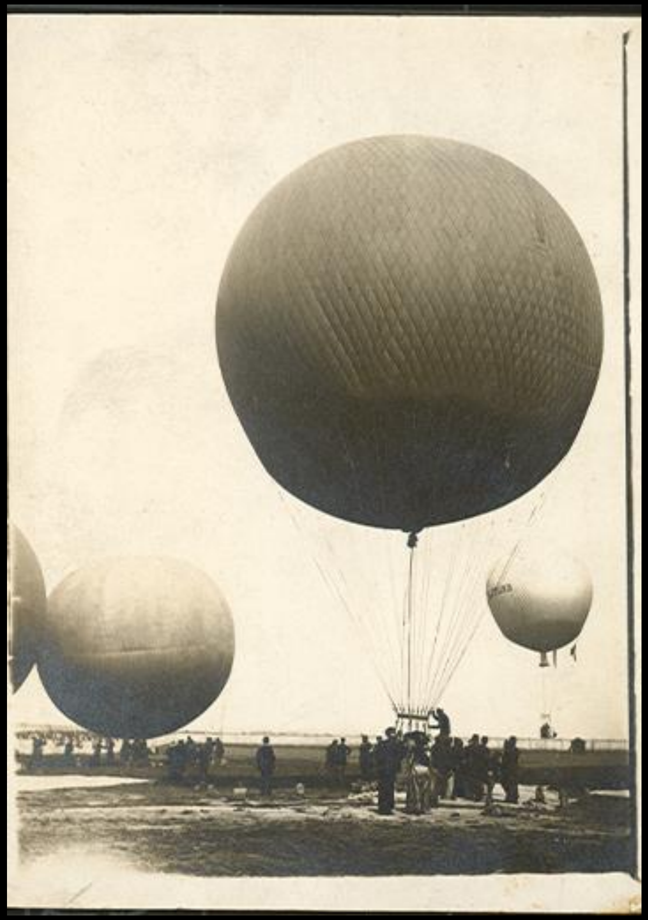


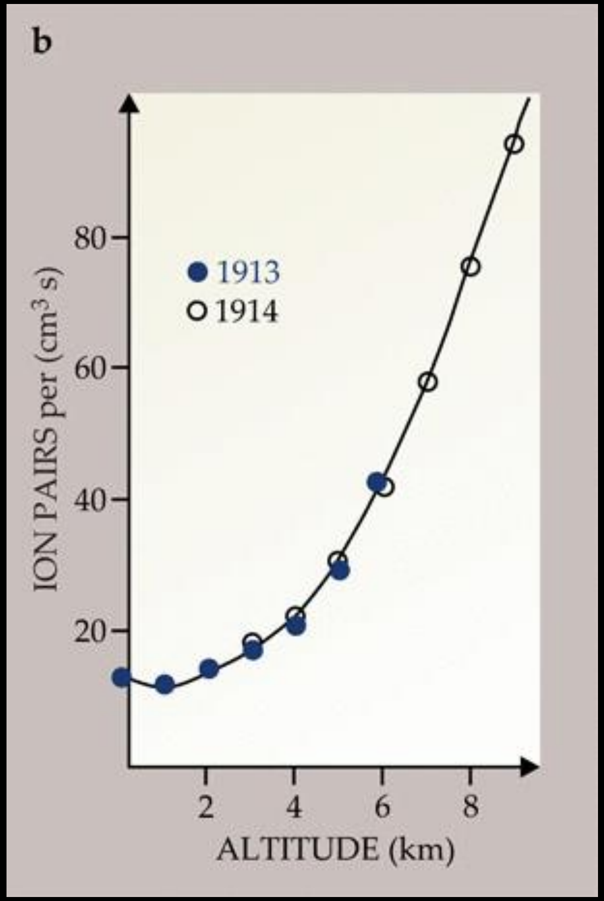
IceCube 1km^3





Neutrinos as a messenger

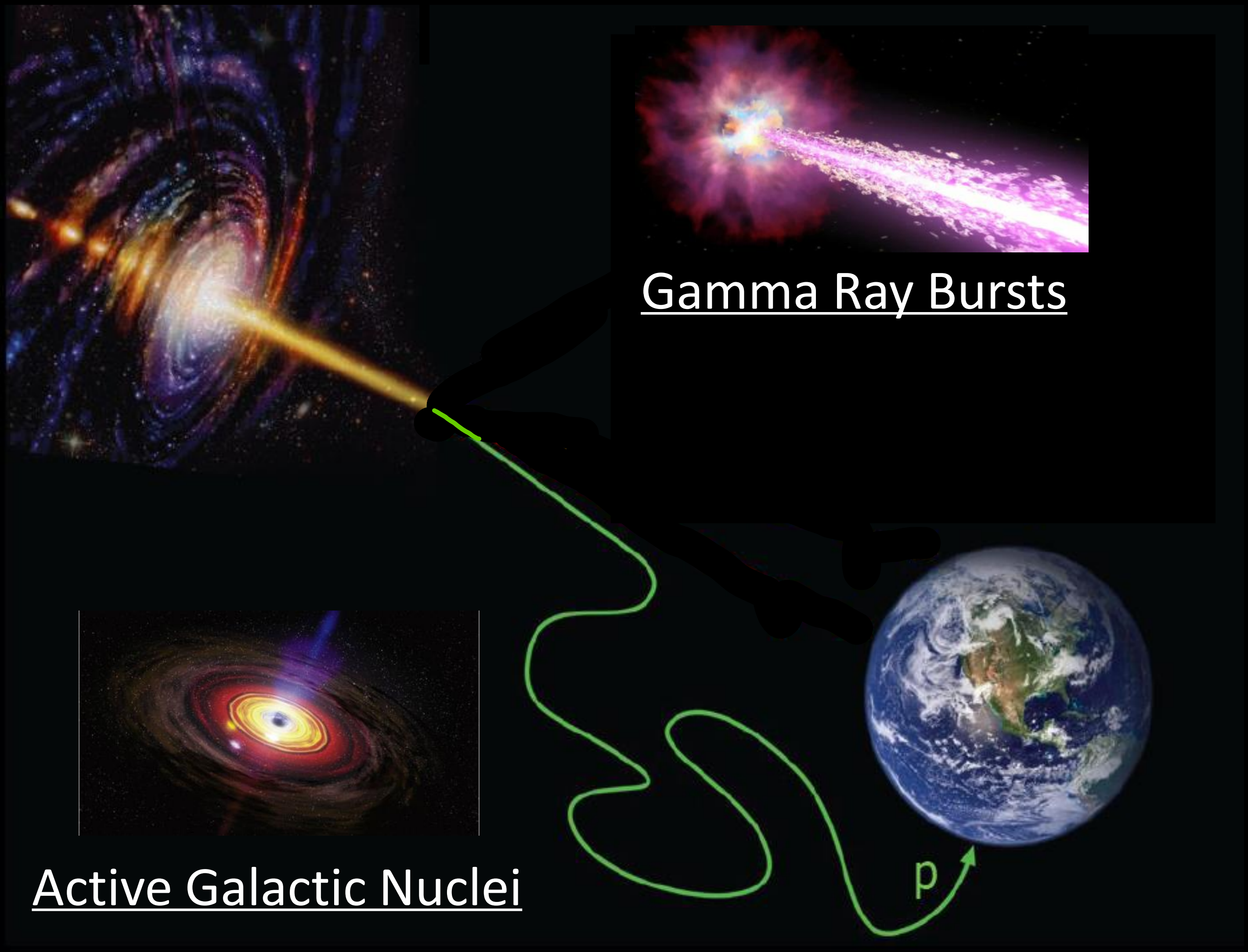




Hess Balloon experiments

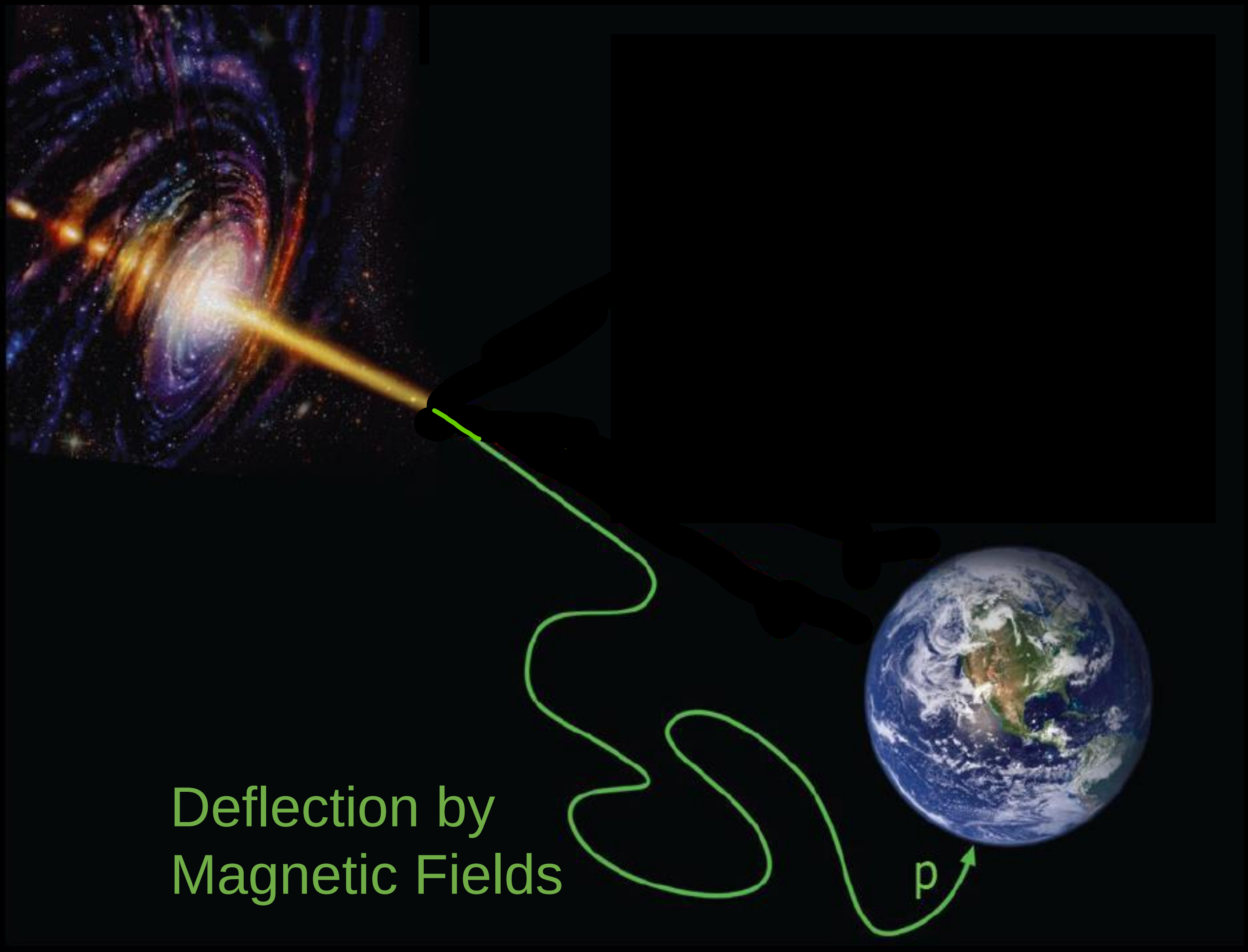
- Cosmic rays (energetic protons/nuclei) known for over a century now

Neutrinos as a messenger



- Cosmic rays (energetic protons/nuclei) known for over a century now
- Source of the **highest energy** cosmic rays remains unknown

Neutrinos as a messenger



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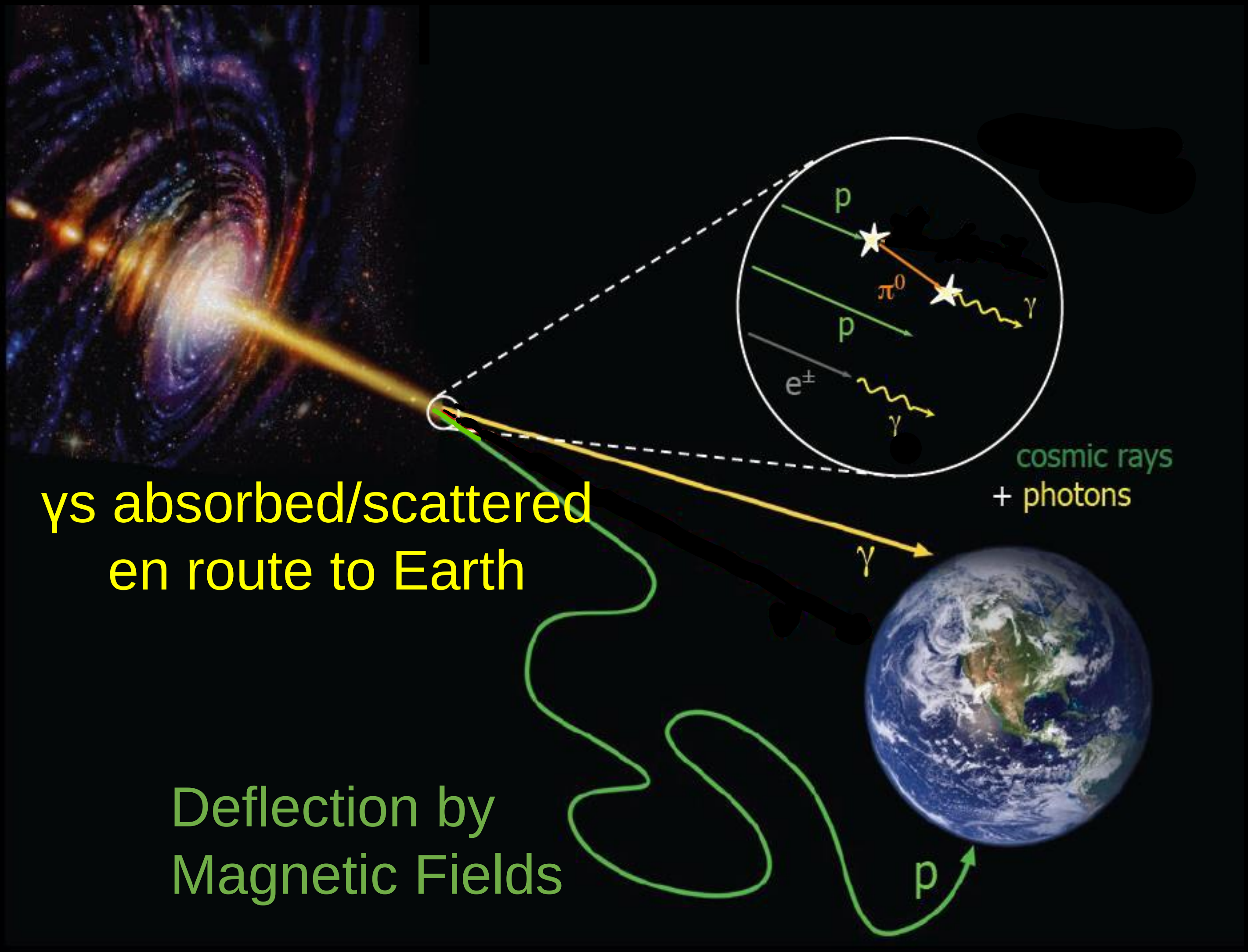

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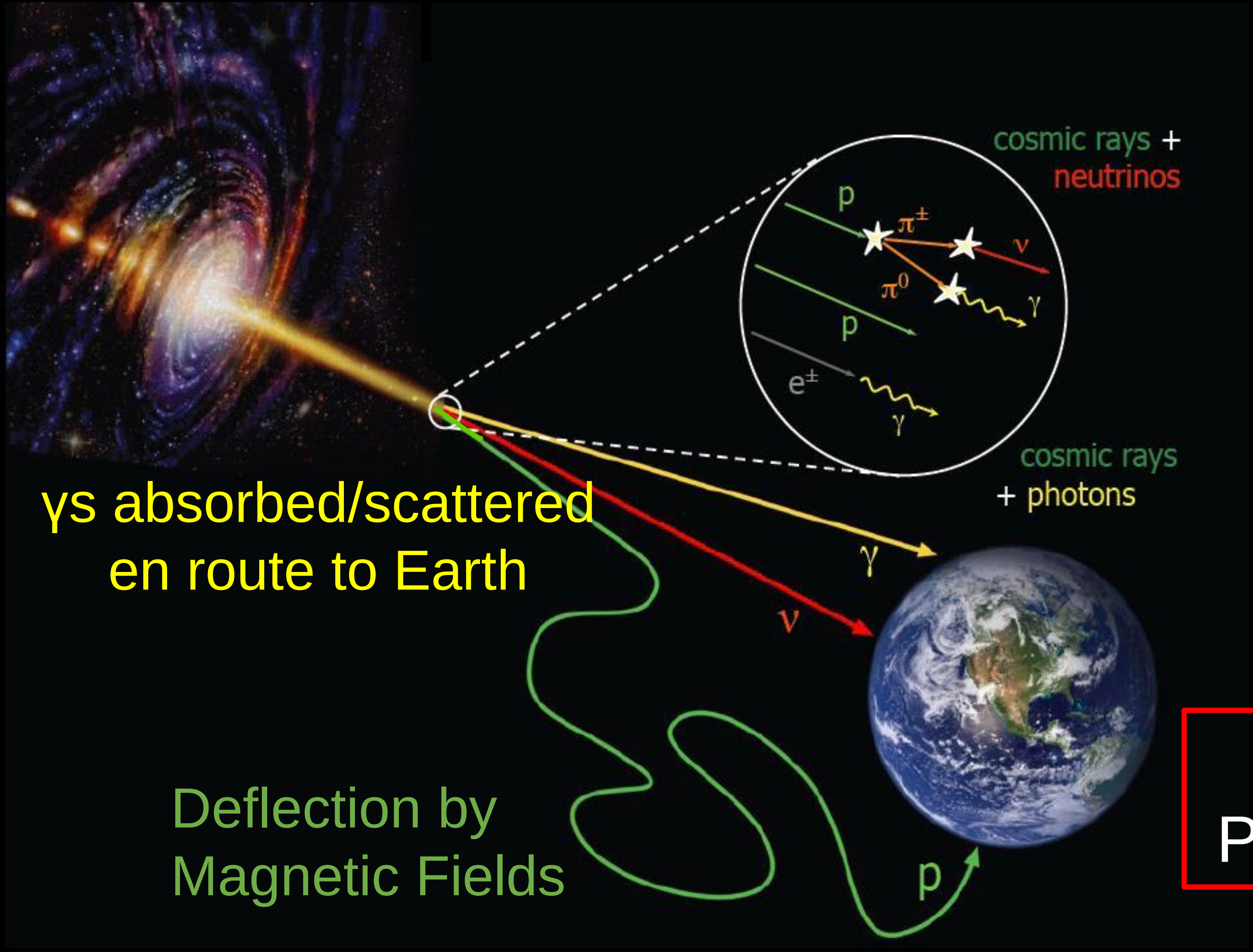

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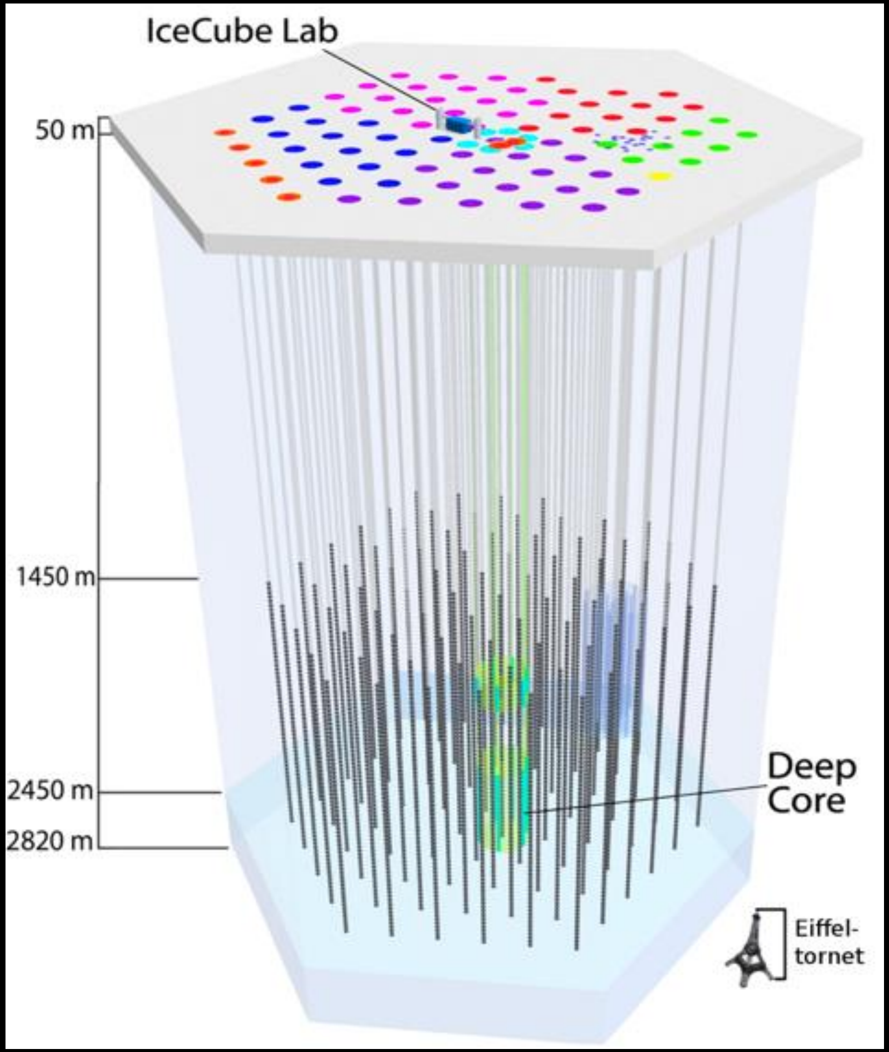
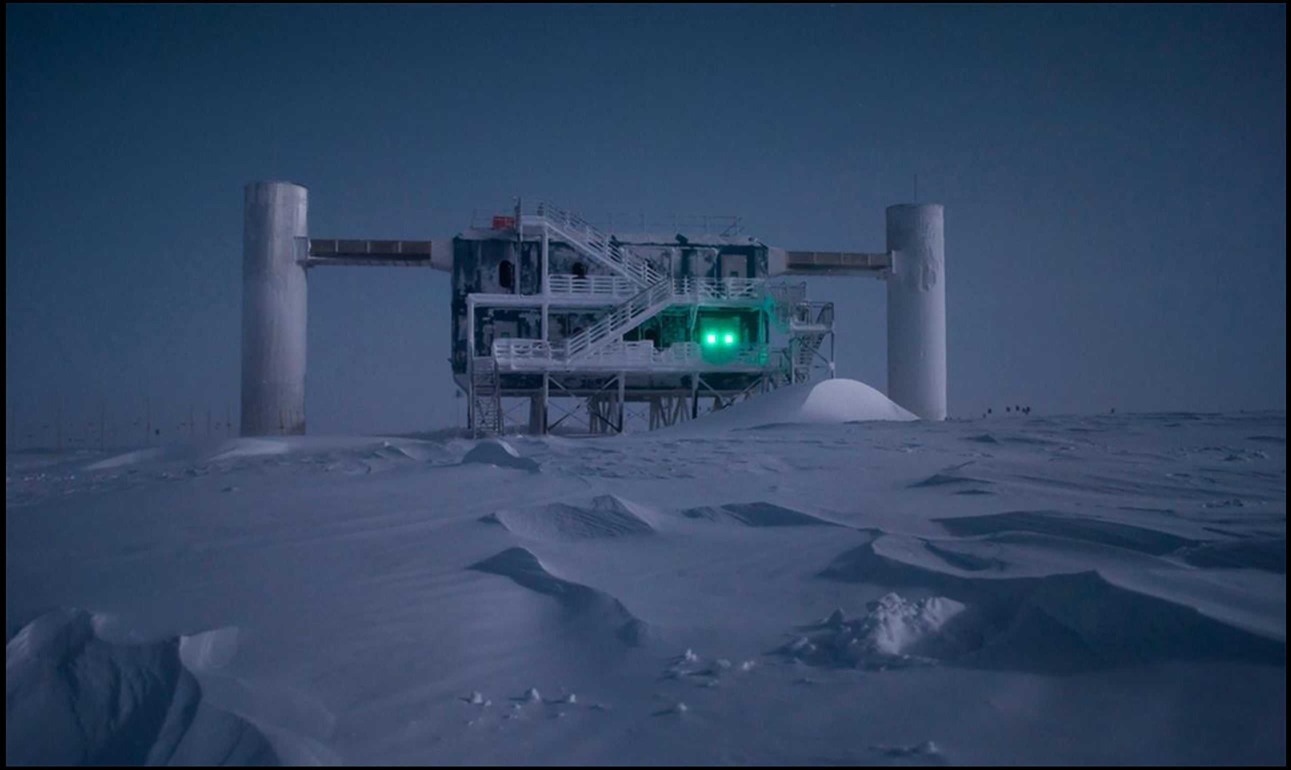
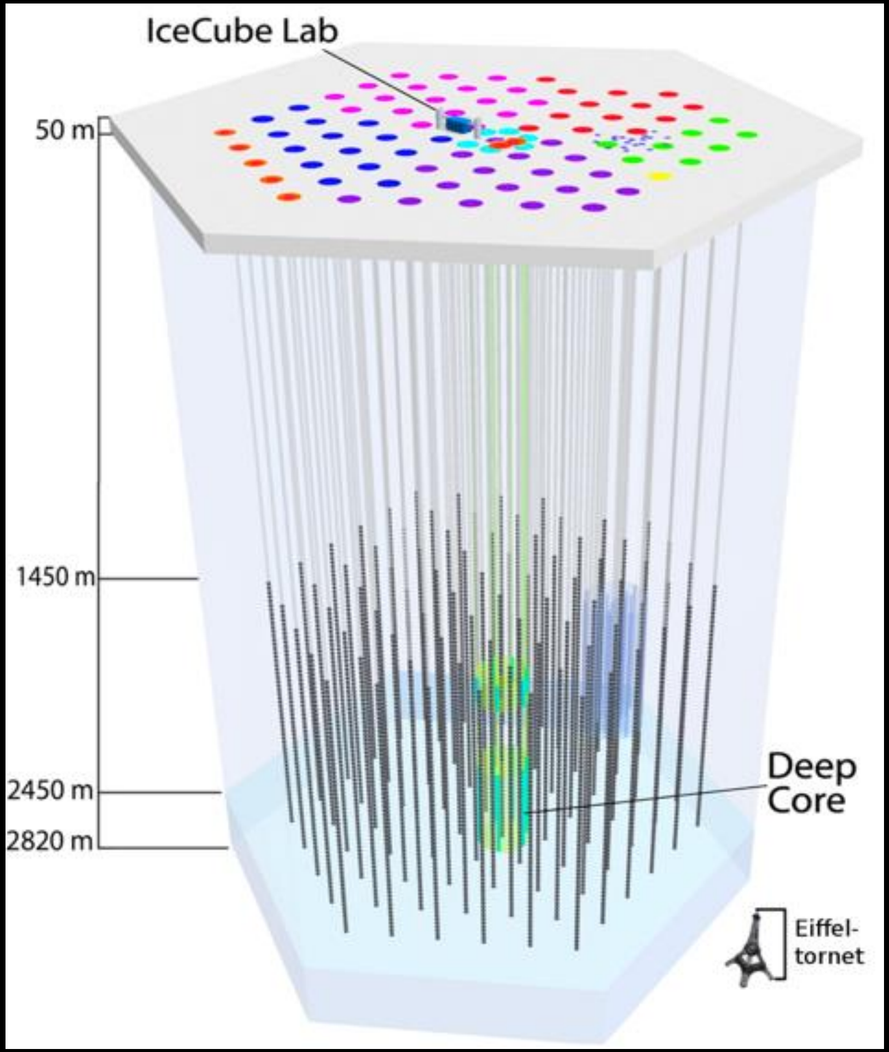
Neutrinos rarely interact:
Point directly back to their source

IceCube



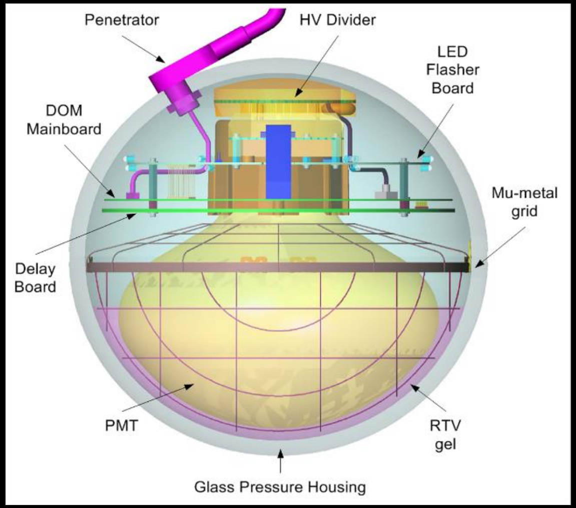


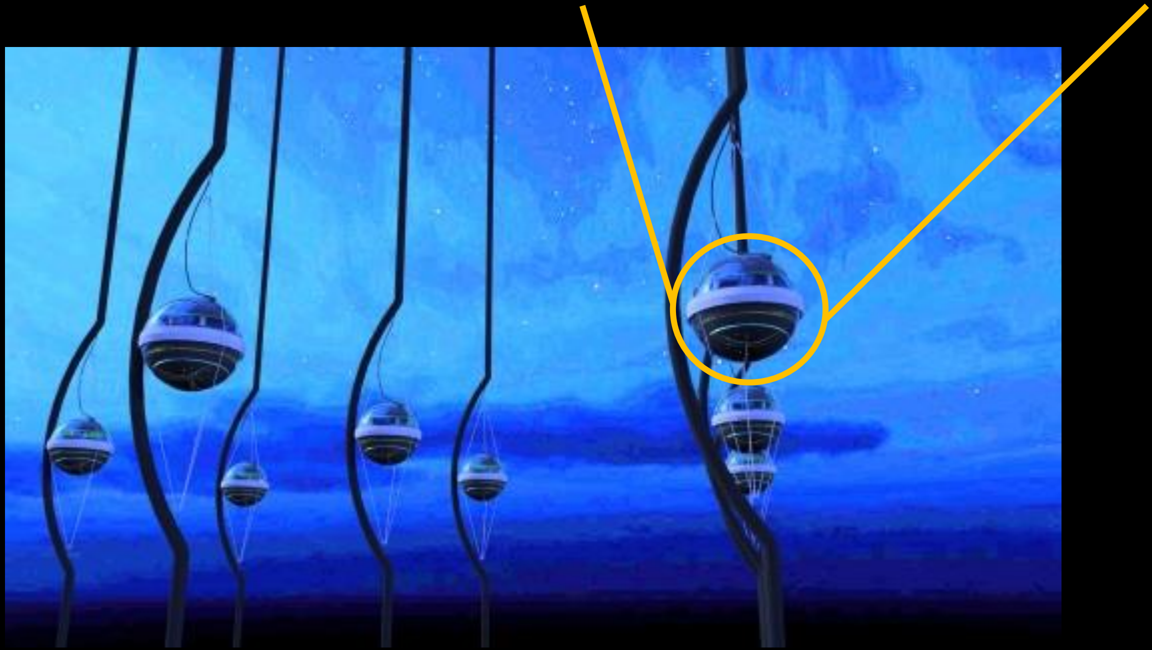
IceCube



Hot Water Drilling

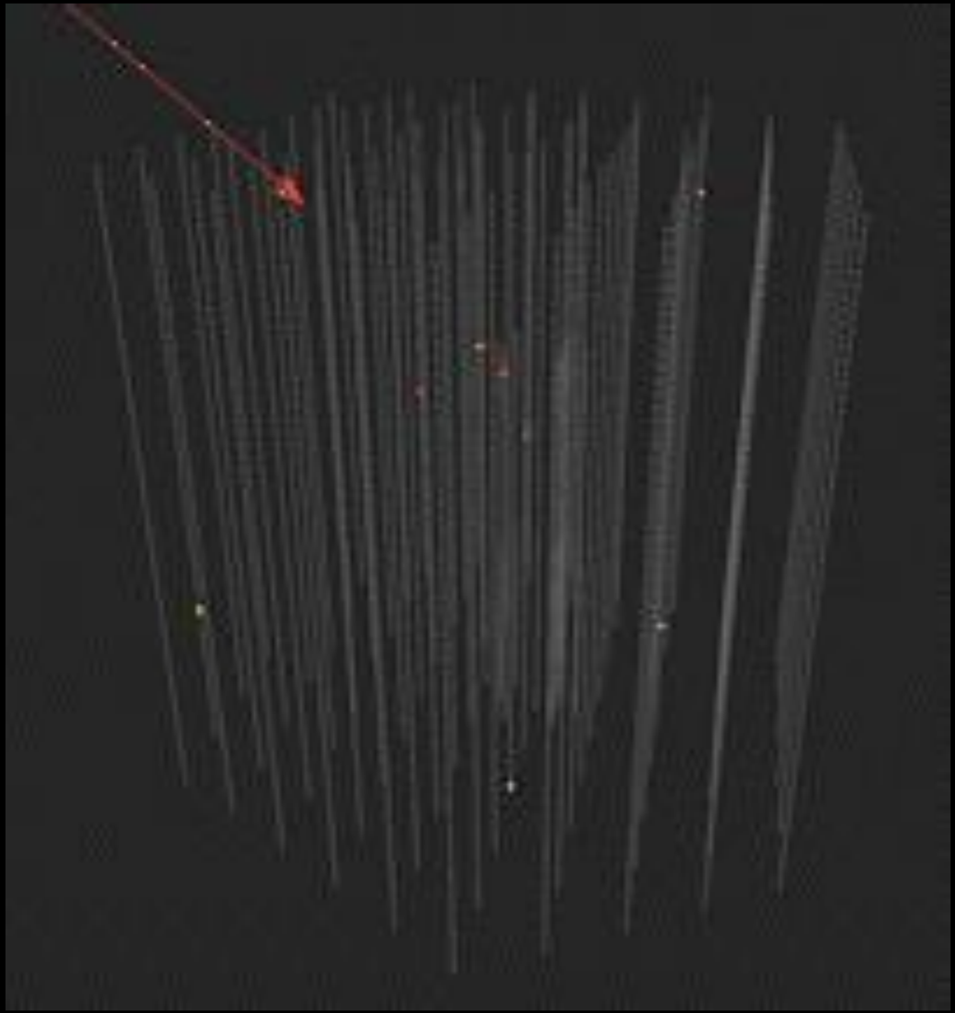
Single Downward 10” PMT





IceCube

Muon from a ν_μ-interaction



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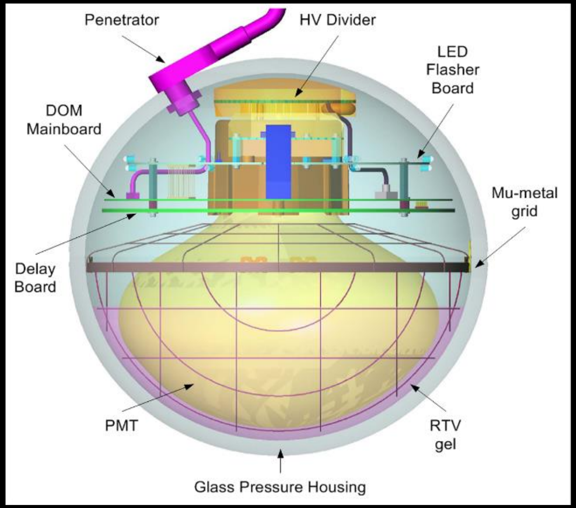

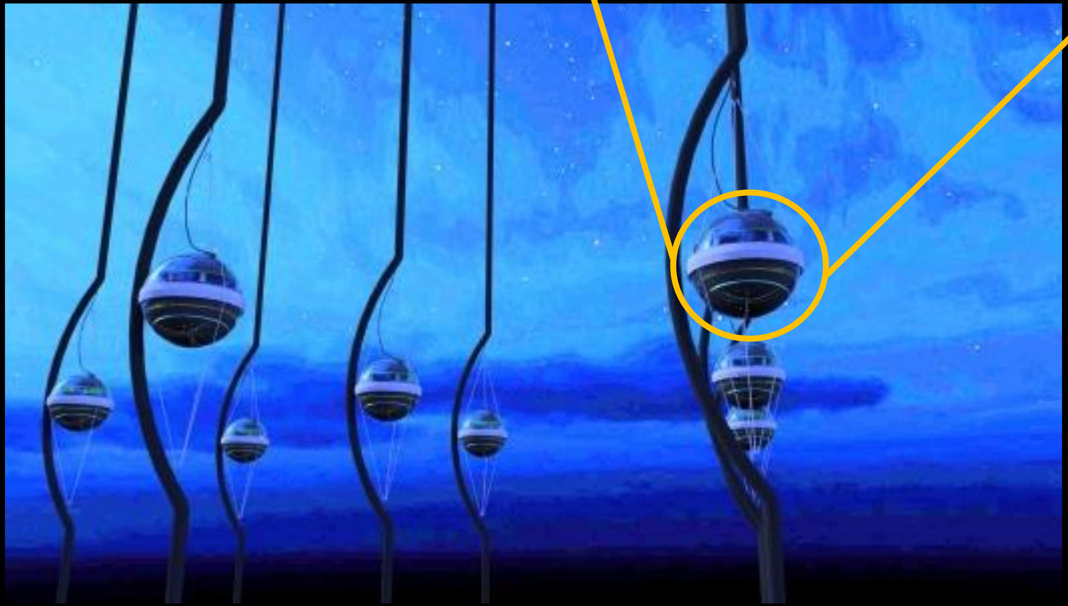

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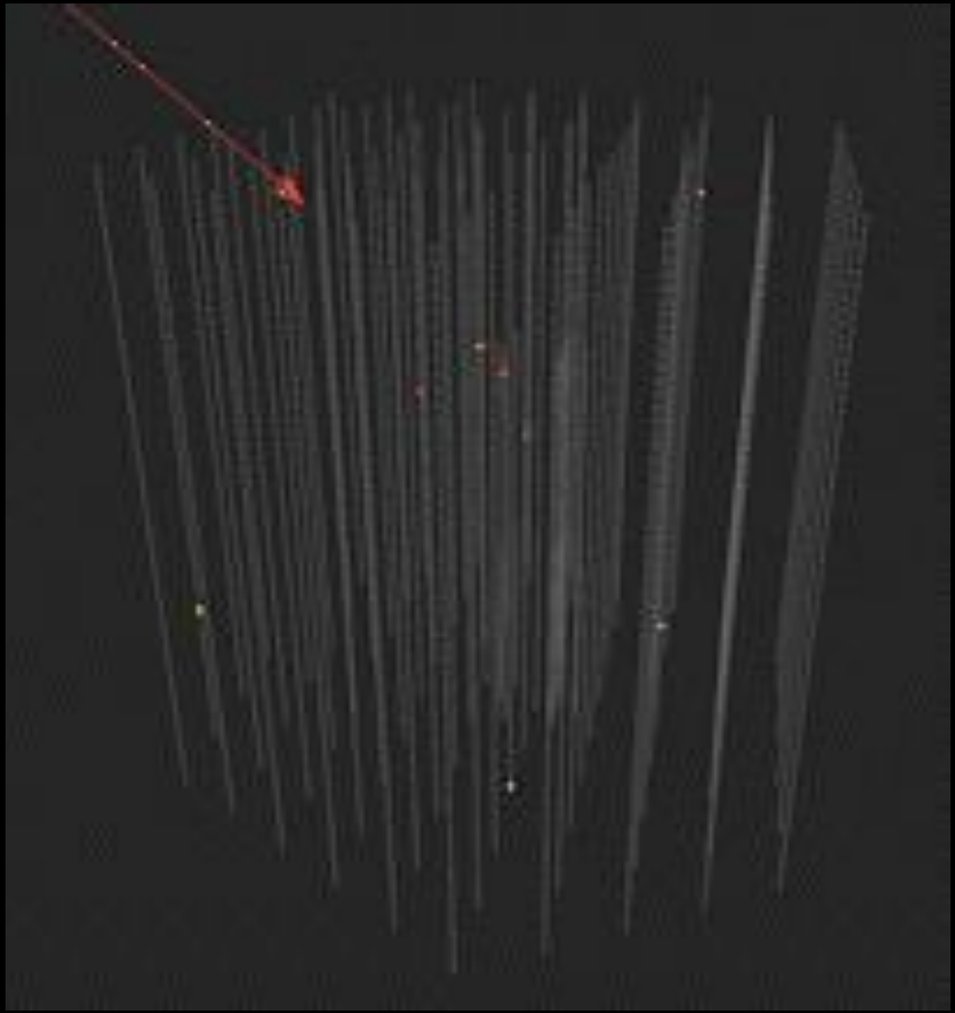
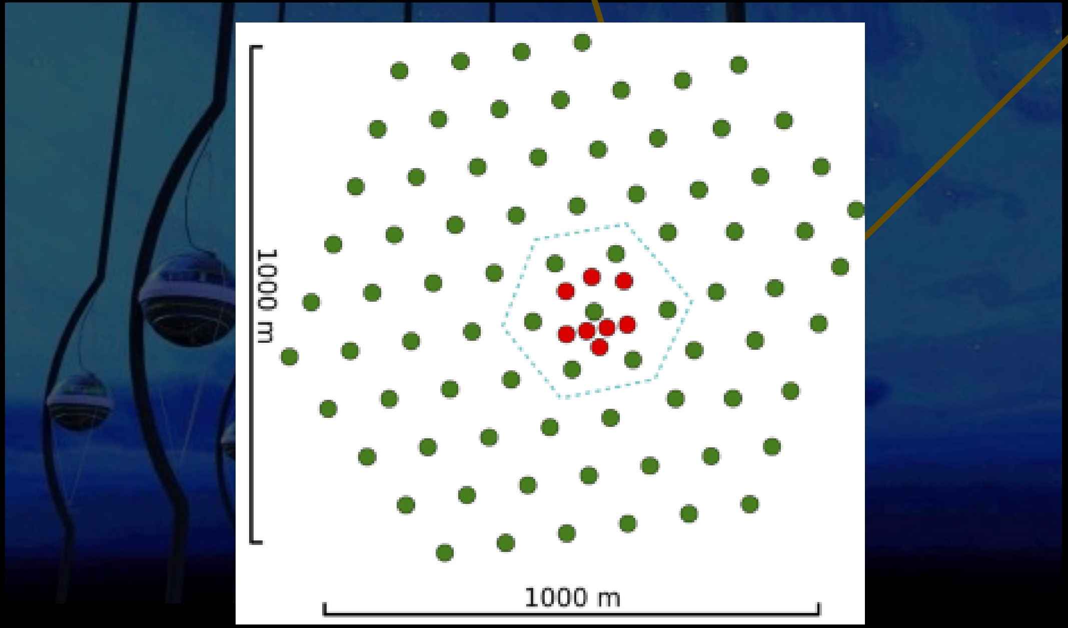


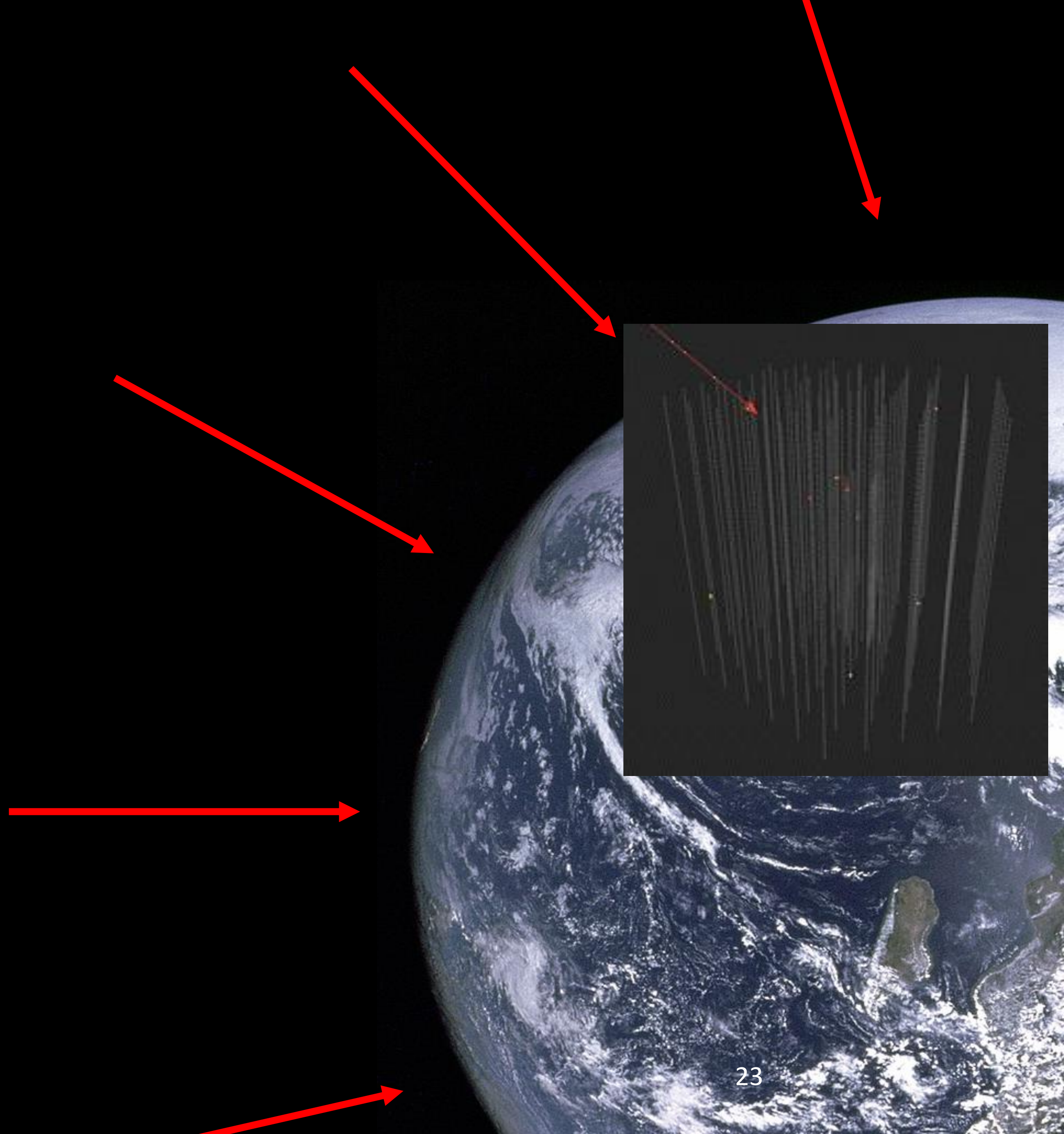
Construction from 2004 to 2010

- 5160 digital optical modules (DOMs)
- 1km^3 footprint
- 86 Strings - 125m apart



Search for Astrophysical Neutrino Sources

2013: First detection of High-energy Extraterrestrial Neutrinos



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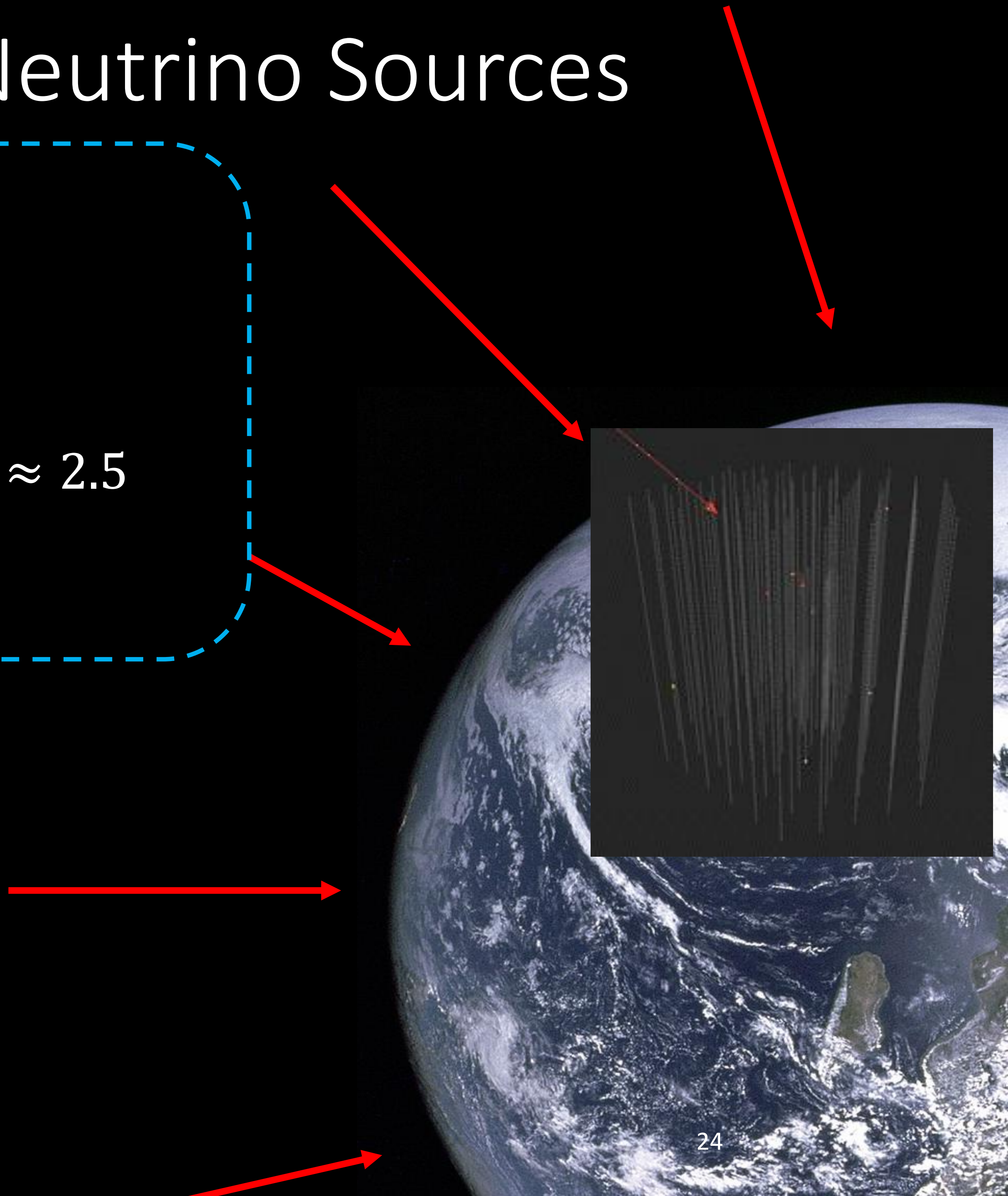
2013: First detection of High-energy Extraterrestrial Neutrinos

- Equally distributed in flavor
- ~ TeV – PeV in energy: $\frac{d\phi}{dE} = \phi * E^{-\gamma}, \quad \gamma \approx 2.5$
- Largely isotropic, origin unresolved



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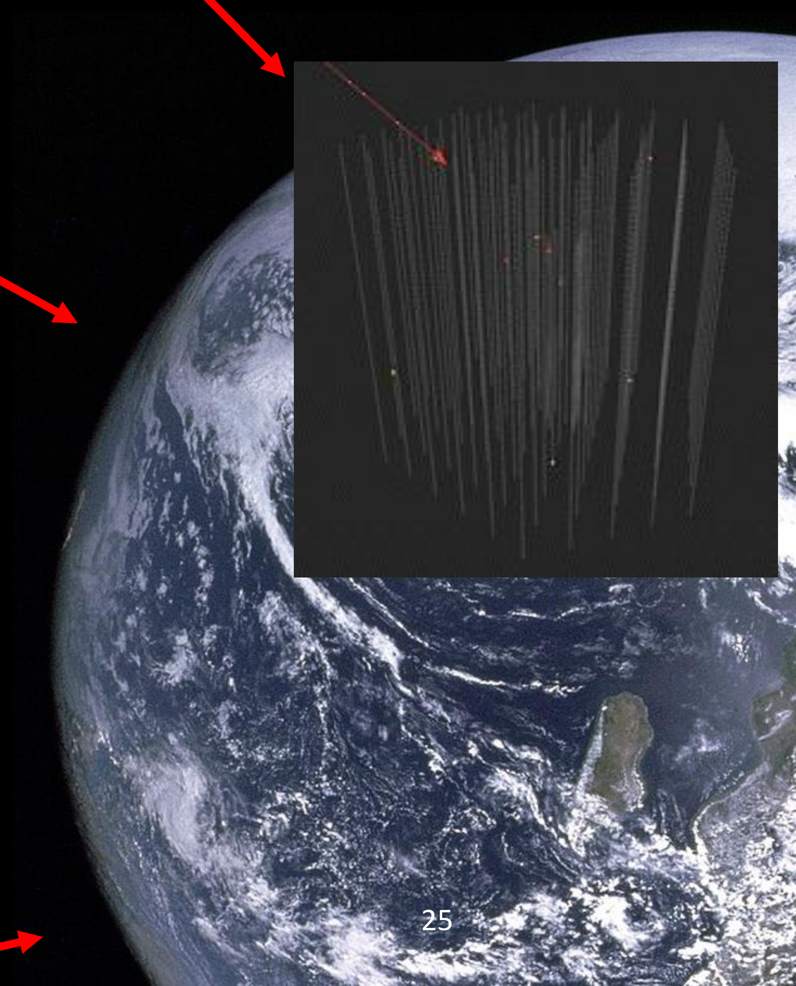

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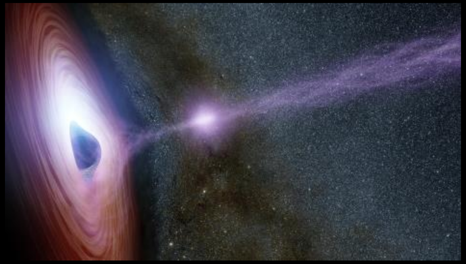
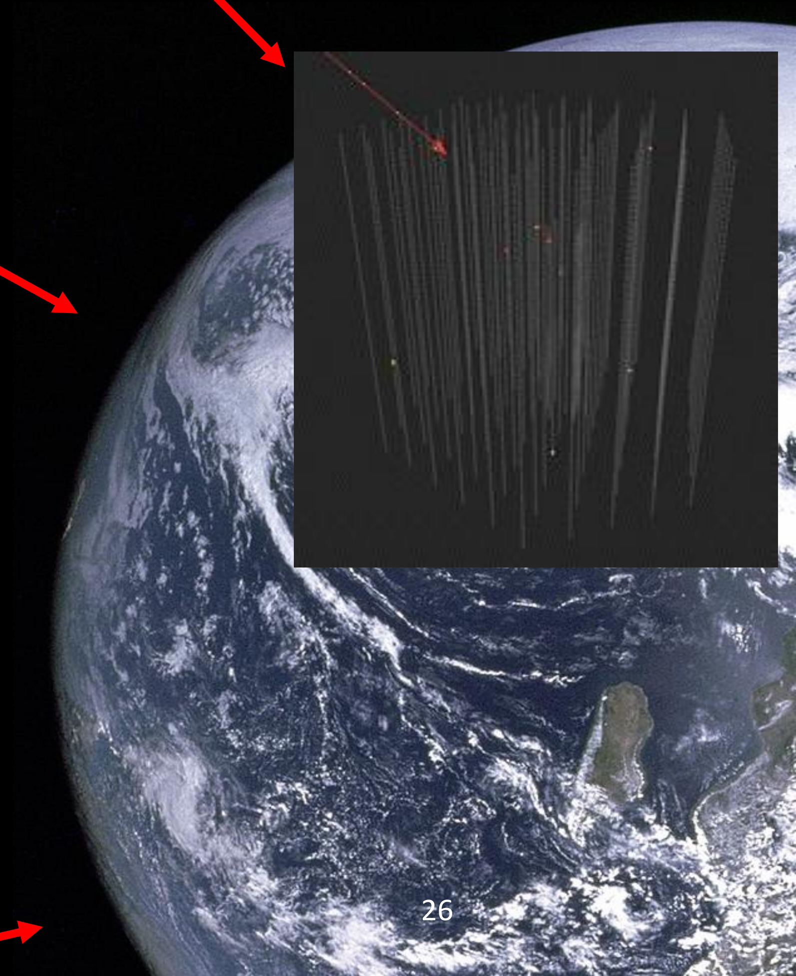
<u>2017</u>: First compelling evidence for neutrino emission in the direction of a flaring γ-ray blazar



TXS0506+056



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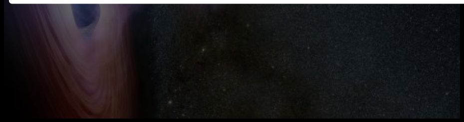
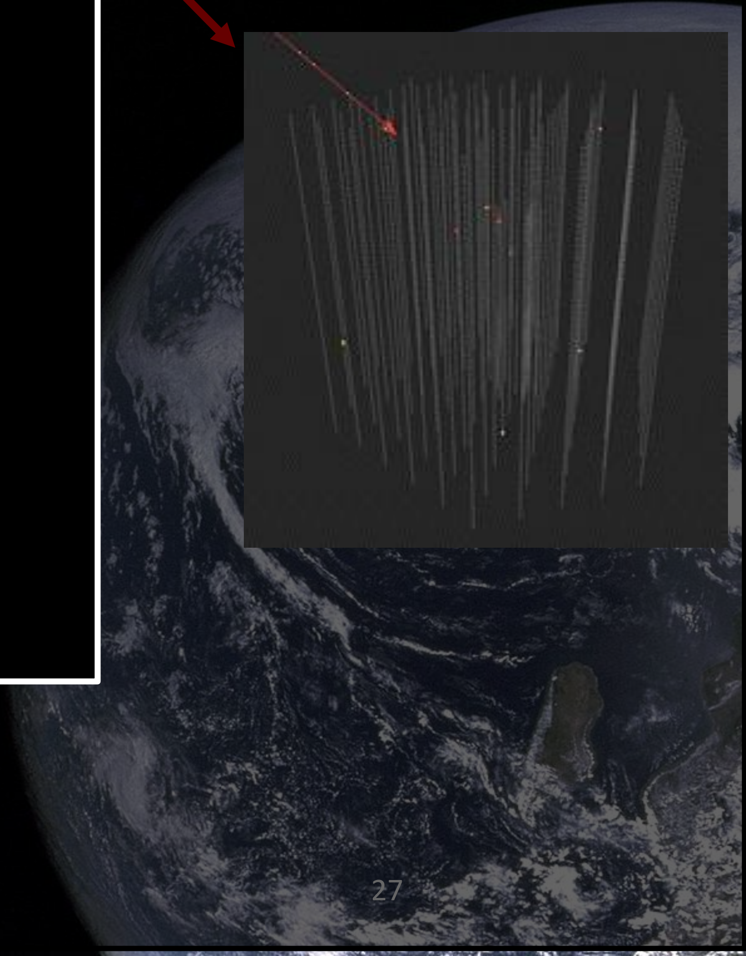


TXS0506+056

A lot learned in the last 12 years, Where to Next?

Statistics:
More/Larger Detectors

Pointing Resolution:
Improving IceCube’s ~1° (TeV)



The Next-Generation

Muon Tracks: **Kilometres**

Best channel for direction detection

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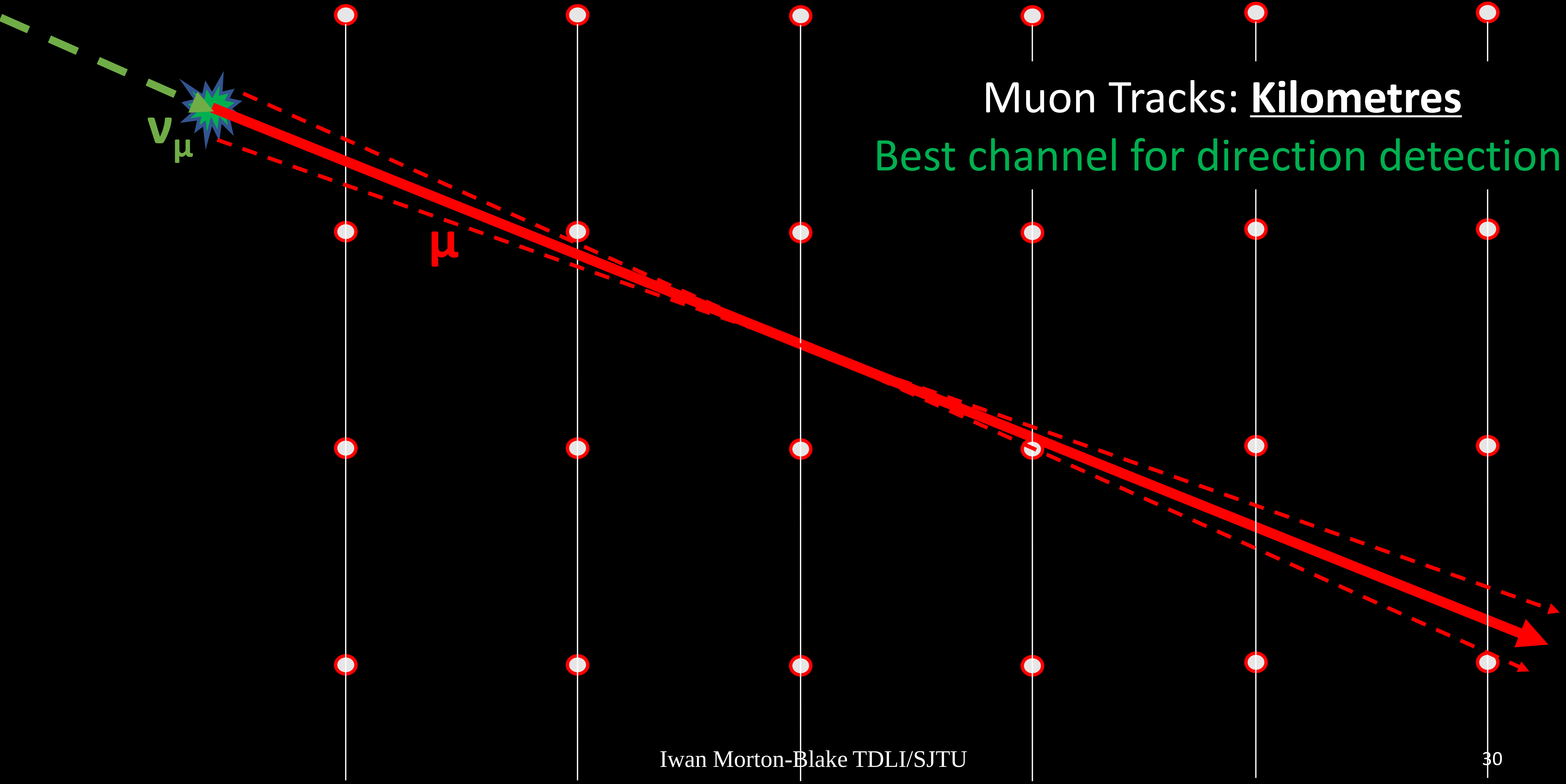
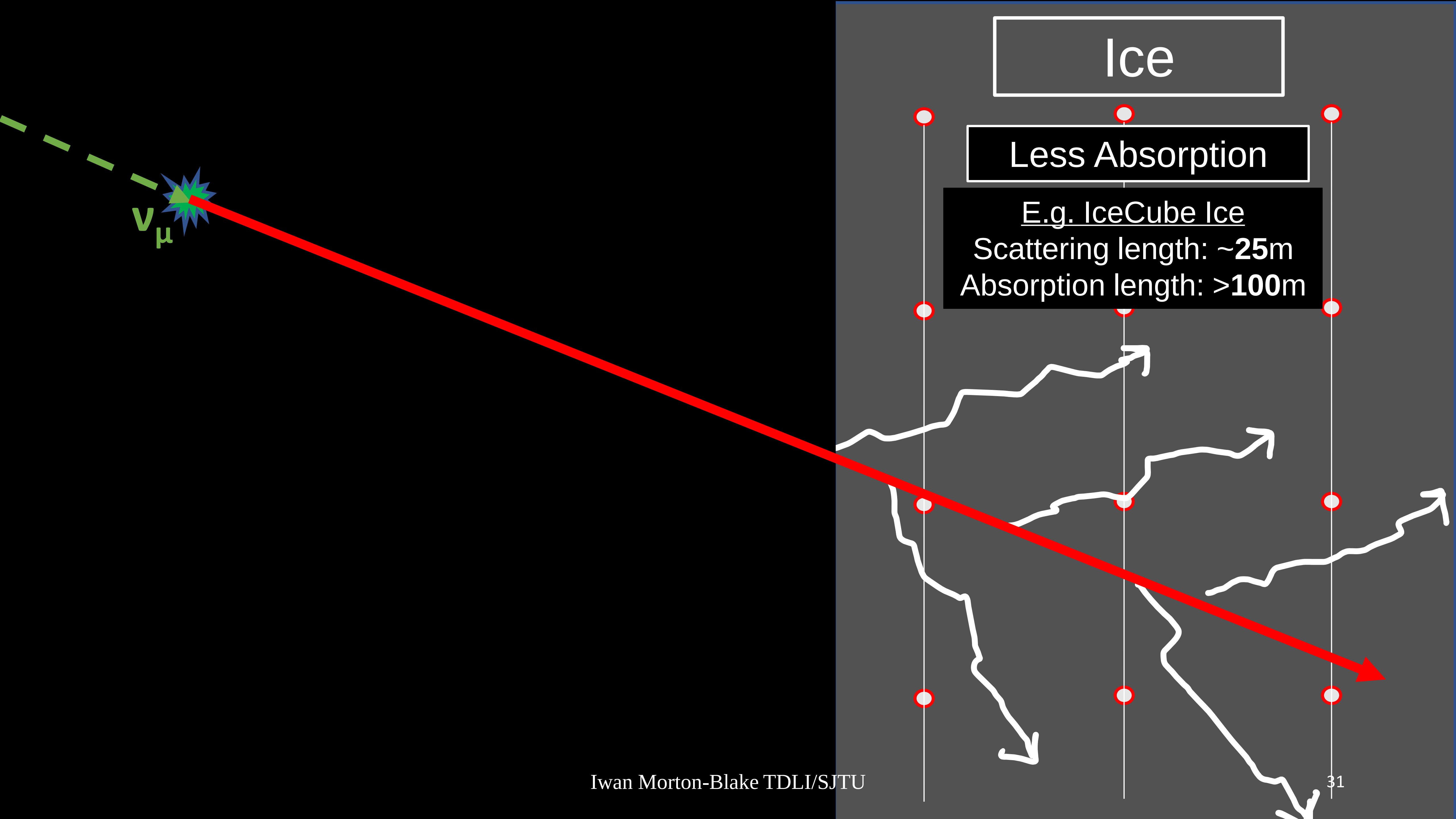
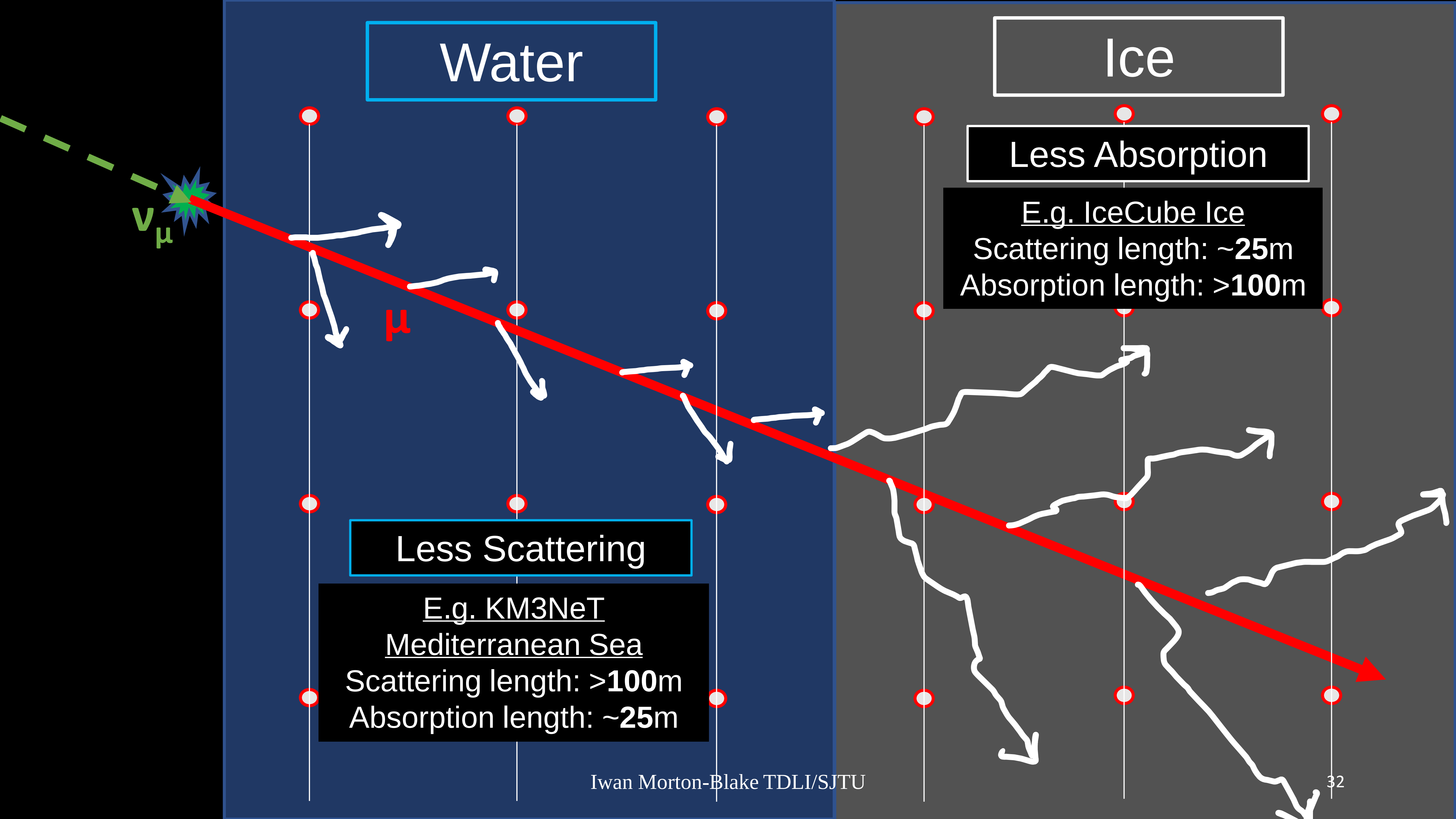
Best channel for direction detection

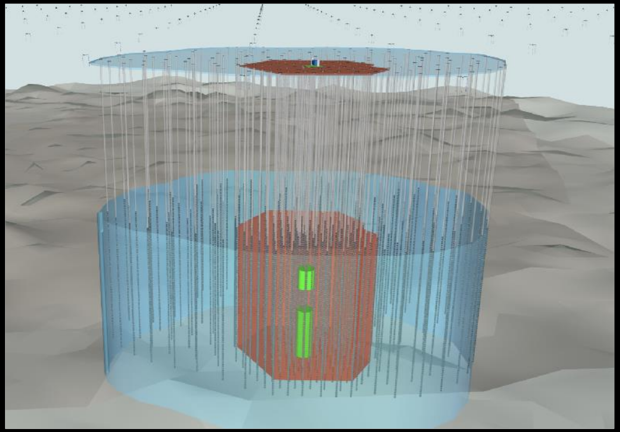




ν_μ
Ice
Less Absorption
E.g. IceCube Ice
Scattering length: ~**25**m
Absorption length: >**100**m


Water
Ice
ν_μ
μ
Less Absorption
E.g. IceCube Ice
Scattering length: ~**25**m
Absorption length: >**100**m
Less Scattering
E.g. KM3NeT
Mediterranean Sea
Scattering length: >**100**m
Absorption length: ~**25**m

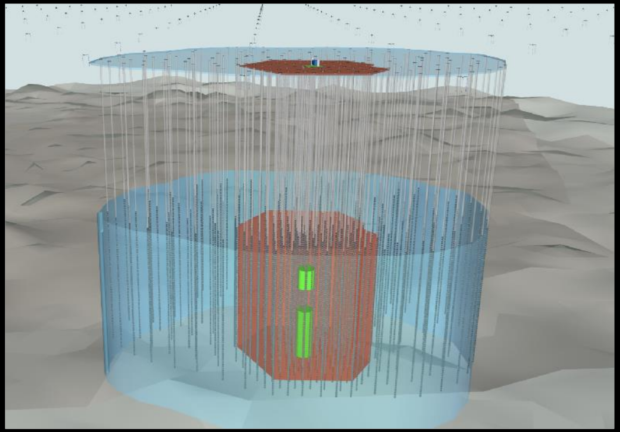
Planned Future Neutrino Telescopes

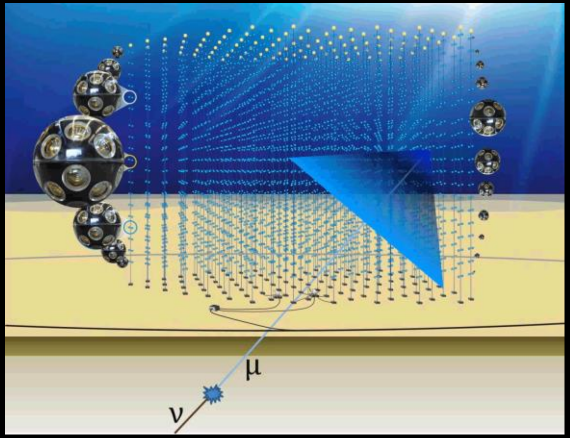


IceCube-Gen2

Depth: 2.5km
Volume: ~8 km^3
 # strings: ~210

Planned Future Neutrino Telescopes





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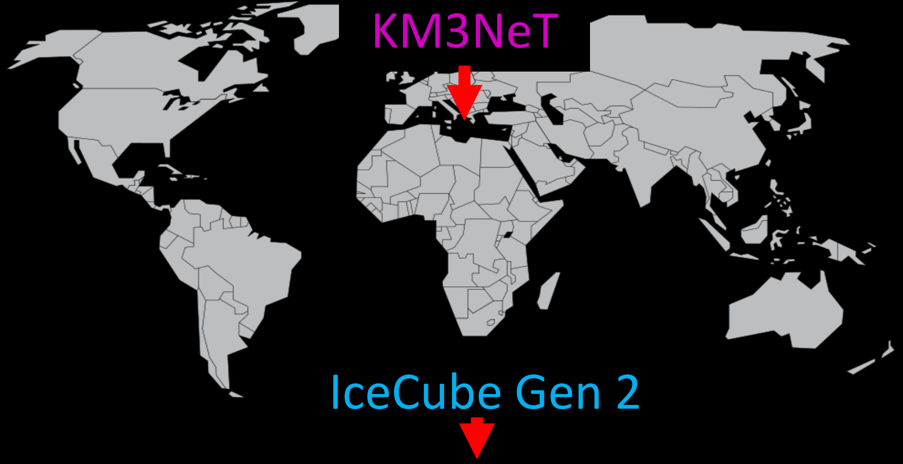
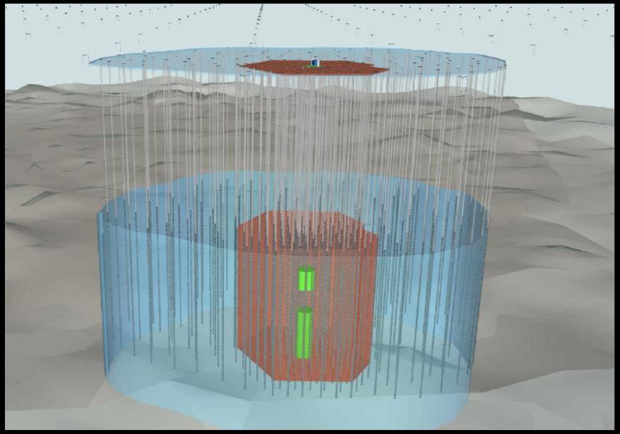
KM3NeT (ARCA)

3.5km deep
~1 km^3
2*115 strings



Planned Future Neutrino Telescopes



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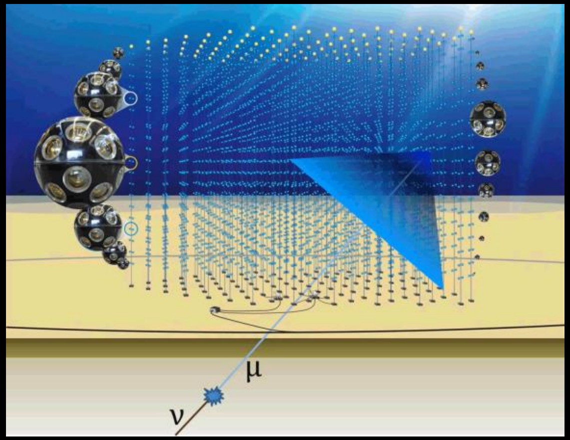

KM3NeT (ARCA)

<u>3.5km deep</u>
<u>~1 km^3</u>
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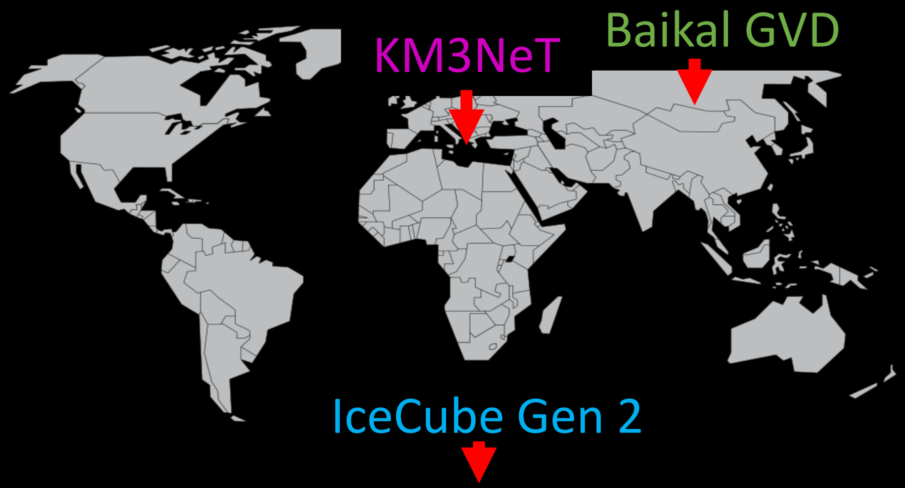
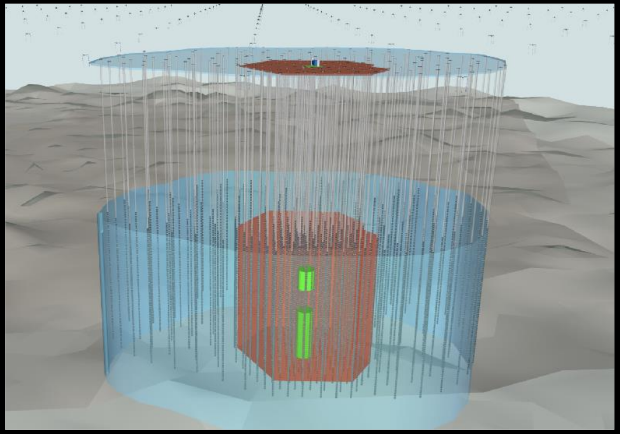
Baikal-GVD

<u>1.4km deep</u>
<u>~1 km^3</u>
<u>~140 strings</u>



Planned Future Neutrino Telescopes



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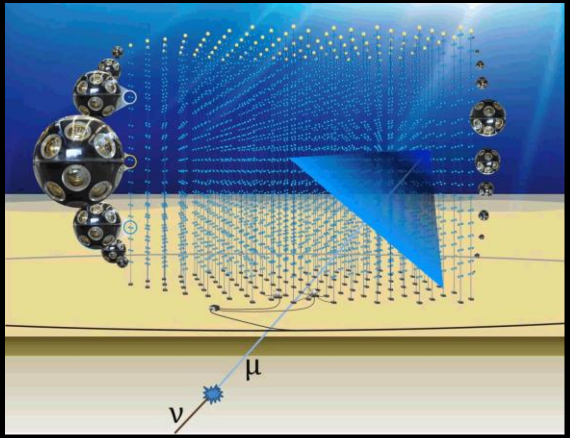

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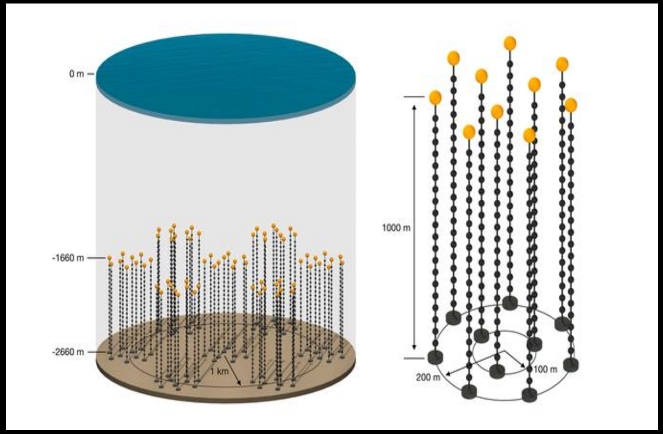
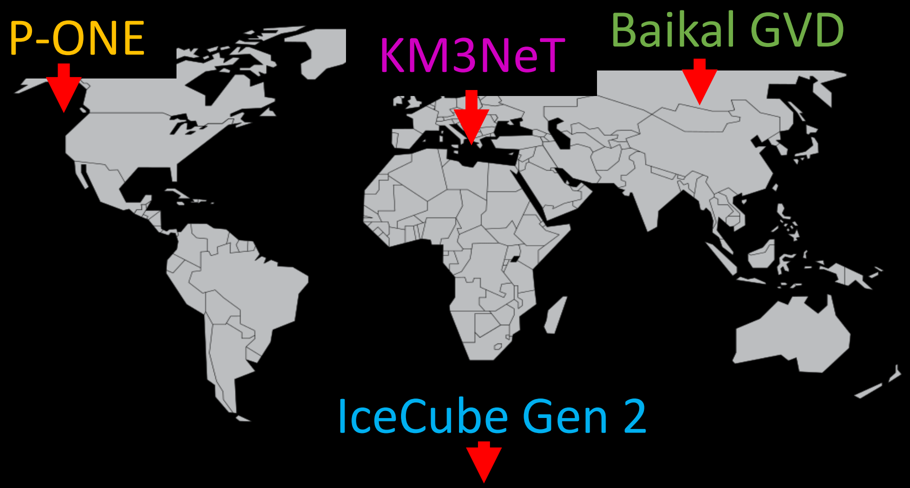
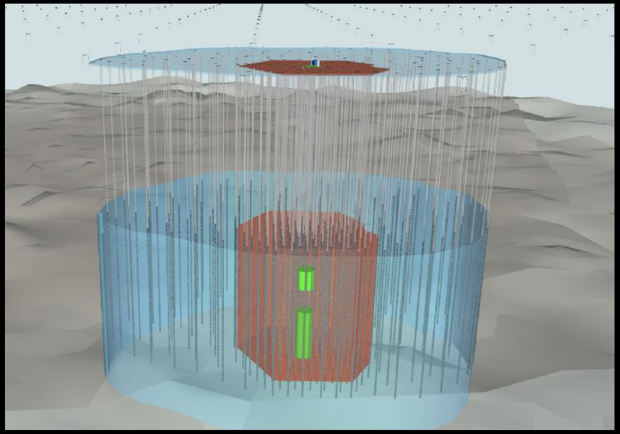


P-One

2.6km deep
~1 km^3
70 strings

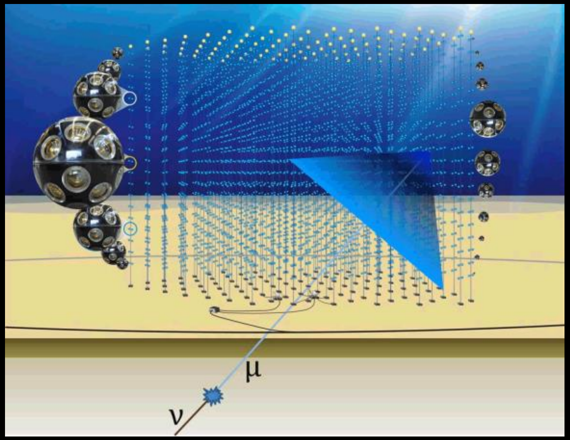


Planned Future Neutrino Telescopes



IceCube-Gen2

Depth: 2.5km
Volume: ~8 km^3
 # strings: ~210

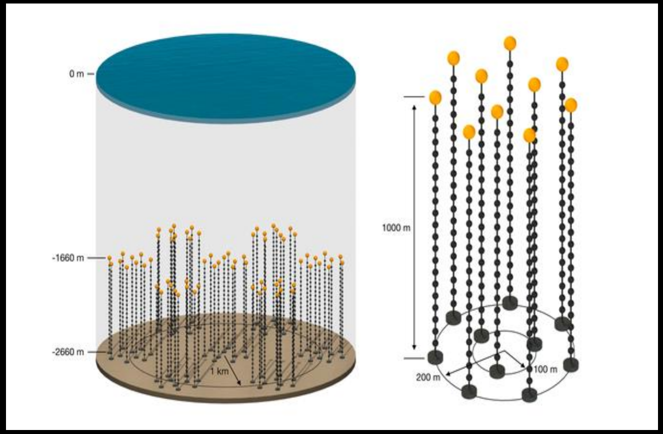


KM3NeT (ARCA)

3.5km deep
~1 km^3
2*115 strings

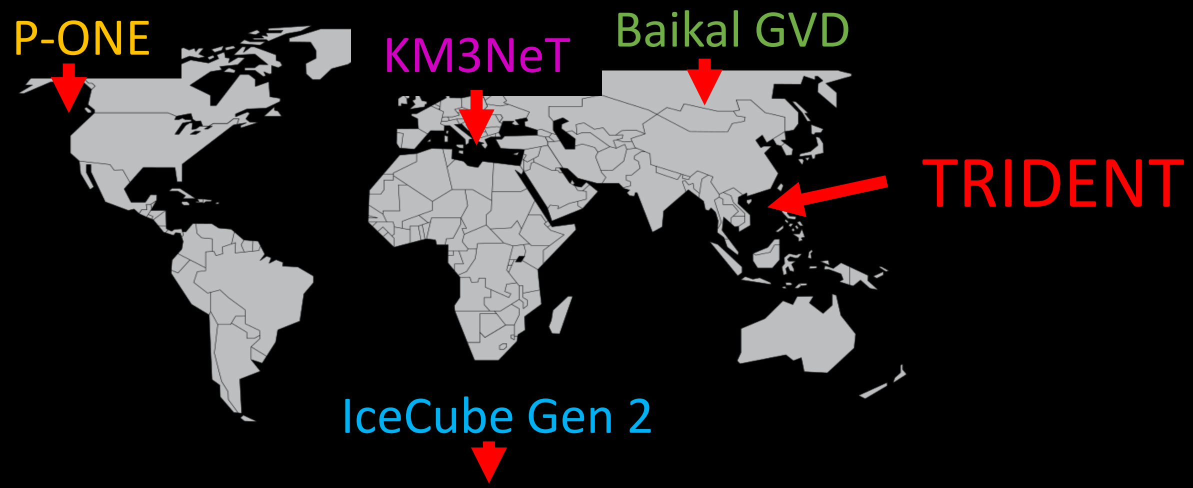
Baikal-GVD

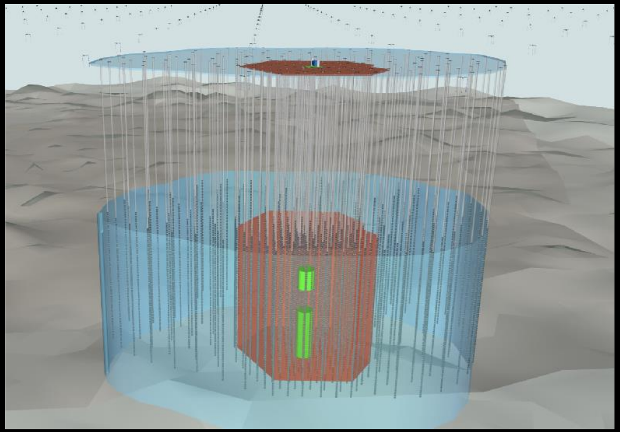
1.4km deep
~1 km^3
~140 strings

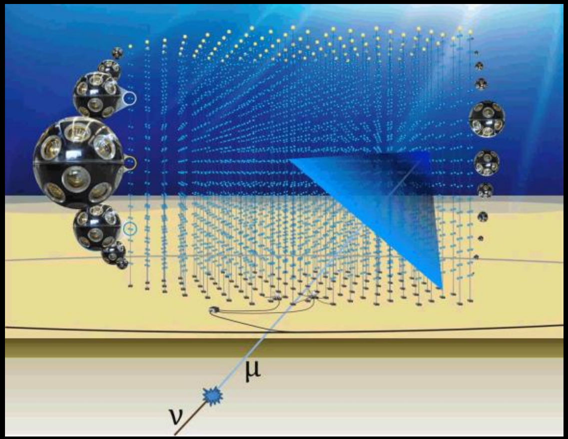


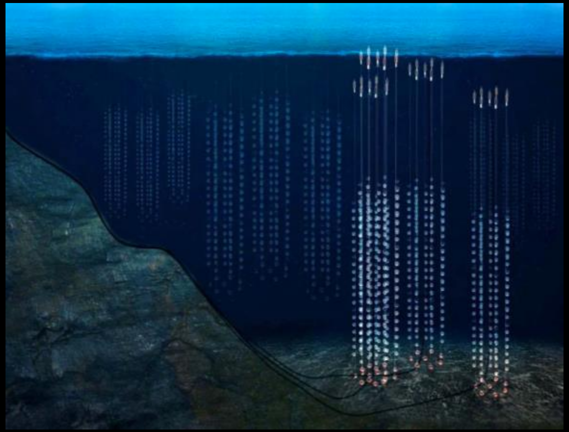
P-One

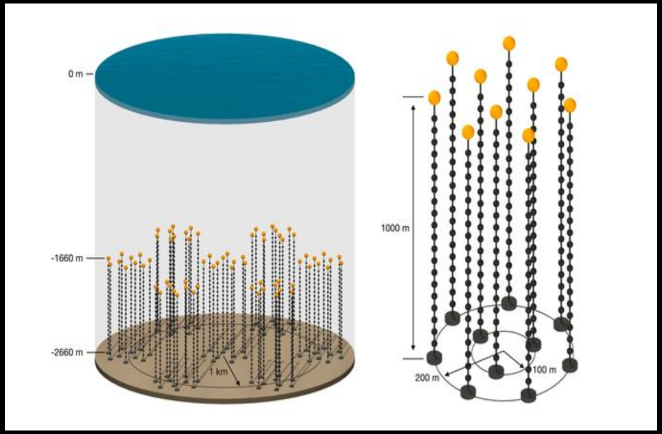
2.6km deep
~1 km^3
70 strings











IceCube-Gen2

Depth: 2.5km
Volume: ~8 km^3
 # strings: ~210

KM3NeT (ARCA)

3.5km deep
~1 km^3
2*115 strings

Baikal-GVD

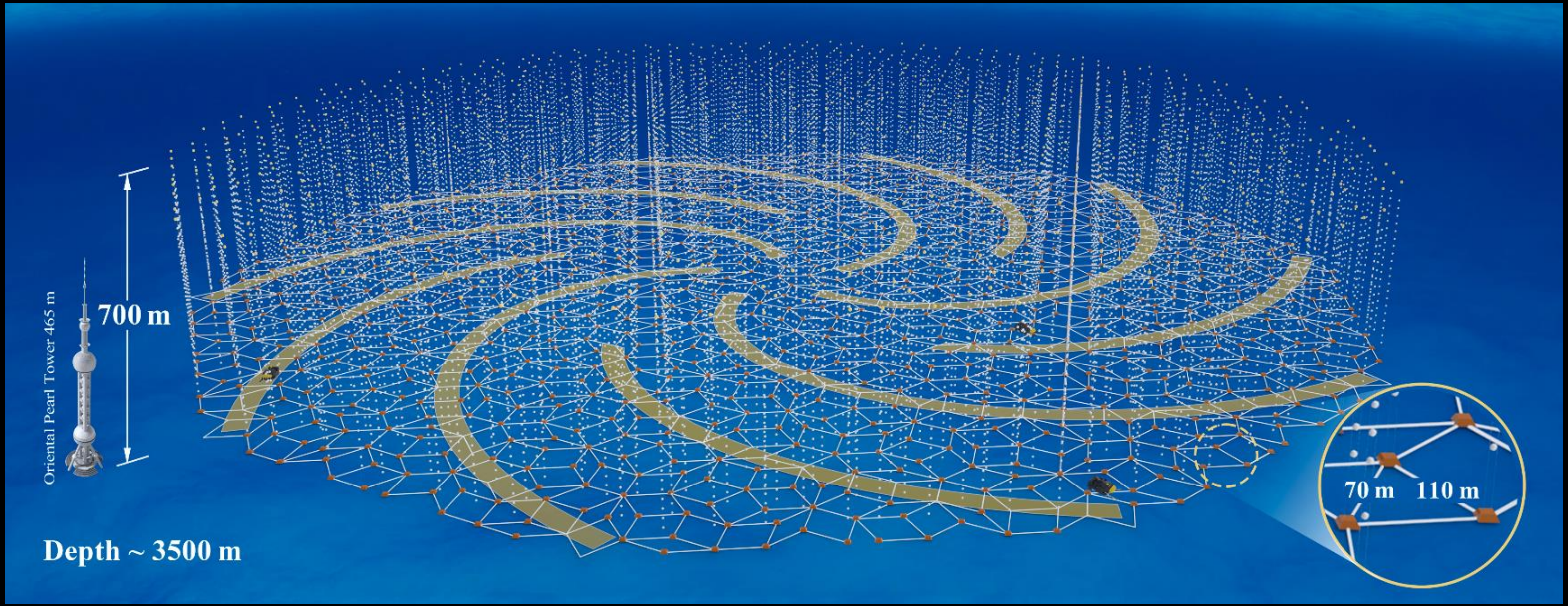
1.4km deep
~1 km^3
~140 strings

P-One

2.6km deep
~1 km^3
70 strings

TRIDENT

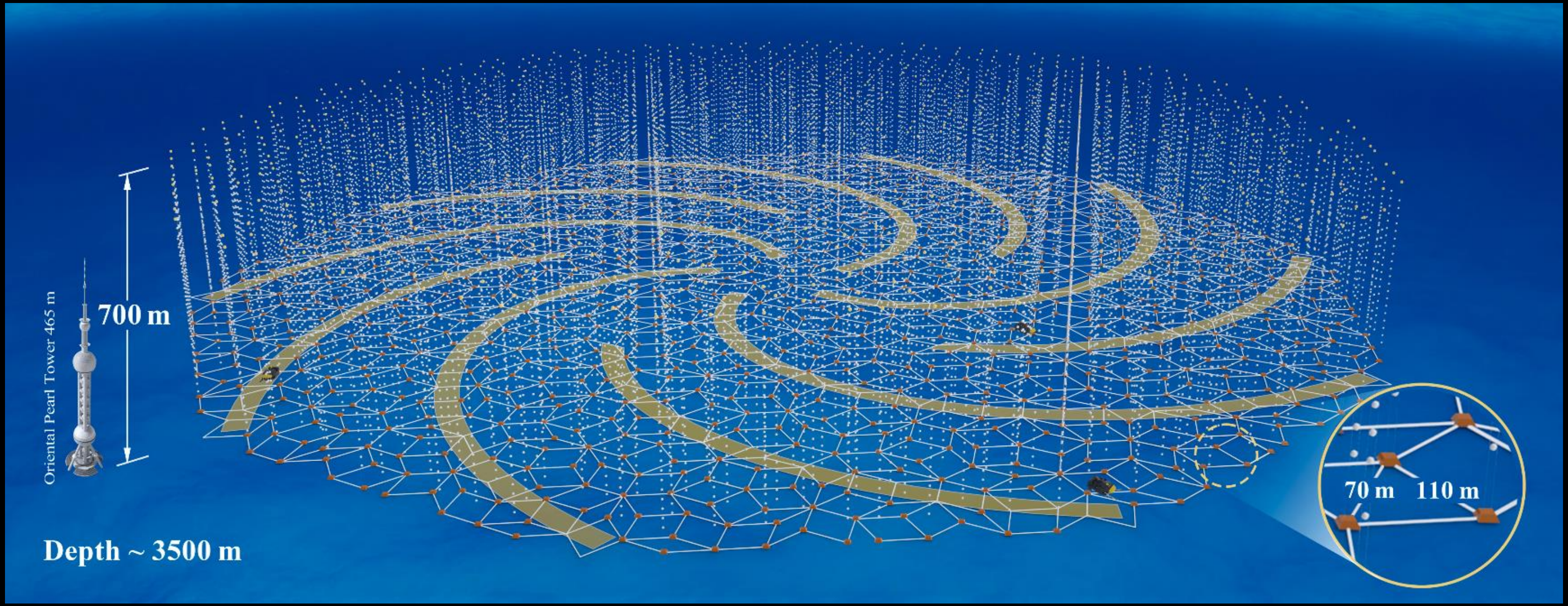
Depth: 3.5km
Volume: ~8 km^3
strings: 1200



Why TRIDENT?

- Location
- Size
- Detector Design

TRIDENT	
Depth:	3.5km
Volume:	~8 km^3
# strings:	1200



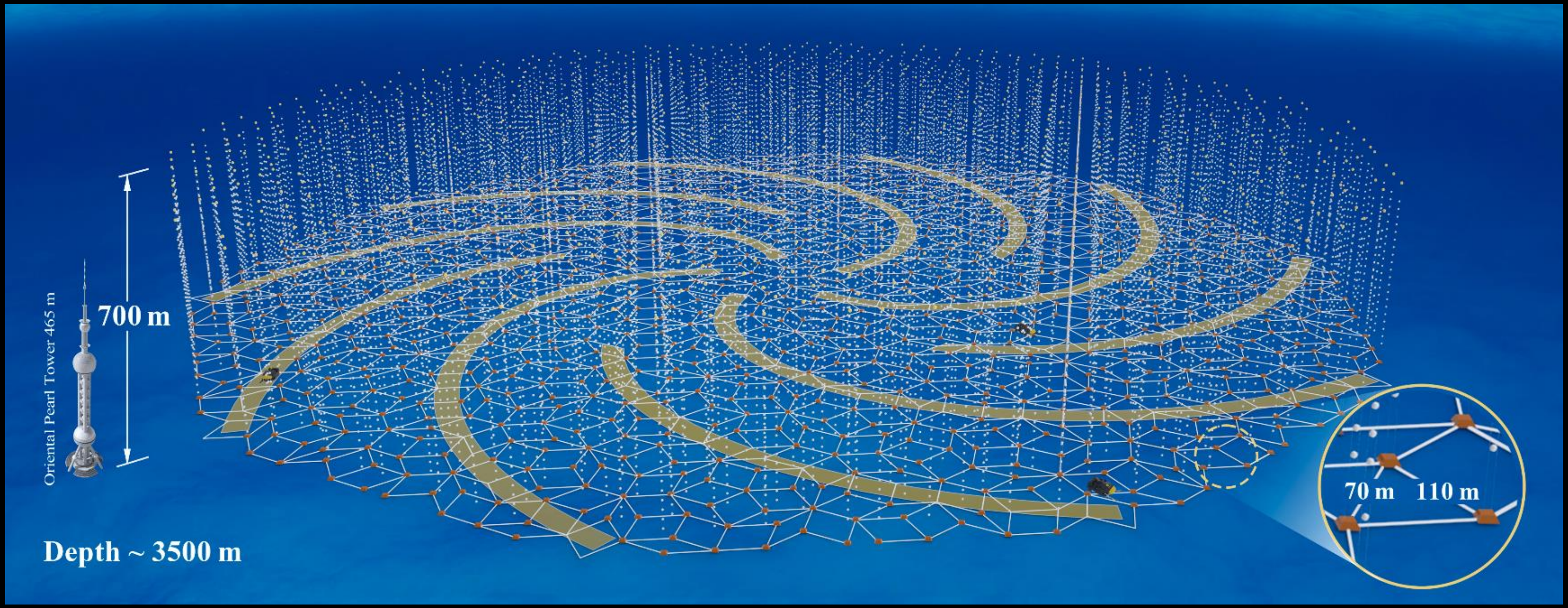
Why TRIDENT?

- Location
- Size
- Detector Design

Primary Goal: Rapidly discover point sources

TRIDENT

Depth:	3.5km
Volume:	~8 km^3
# strings:	1200



Why TRIDENT?

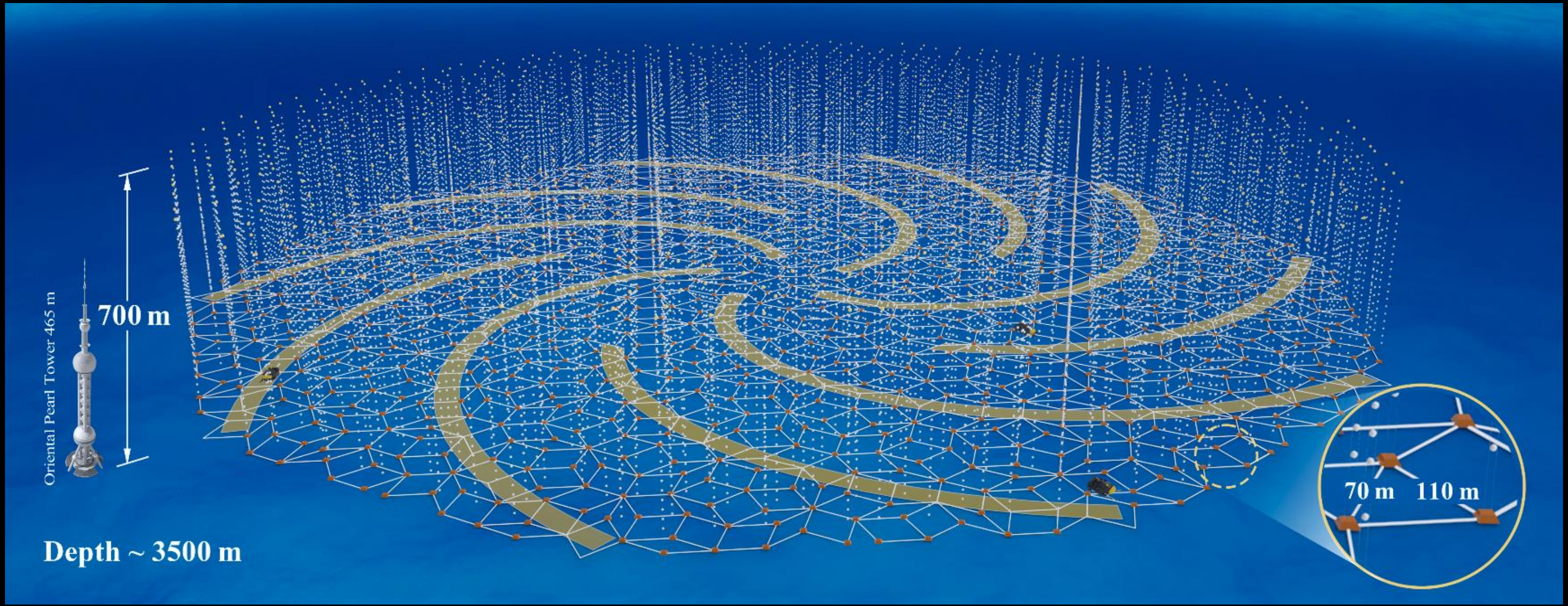
Rapidly discover point sources

- Signal Flux
- Backgrounds

- Location
- Size
- Detector Design

TRIDENT

Depth:	3.5km
Volume:	~8 km^3
# strings:	1200



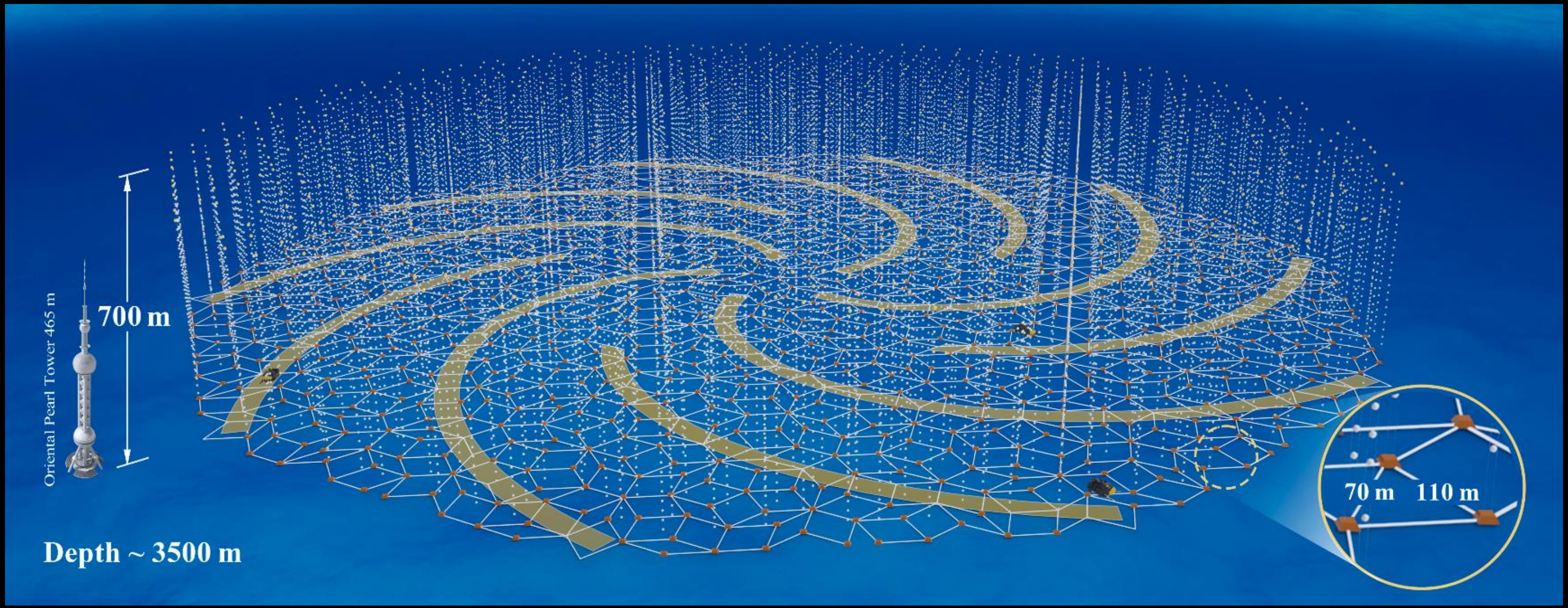
Why TRIDENT?

- Location
- Size
- Detector Design

Rapidly discover point sources

- Signal Flux
- Backgrounds
- Neutrino Pointing Resolution
- Energy Resolution and Range

TRIDENT	
Depth:	3.5km
Volume:	~8 km^3
# strings:	1200



Why TRIDENT?

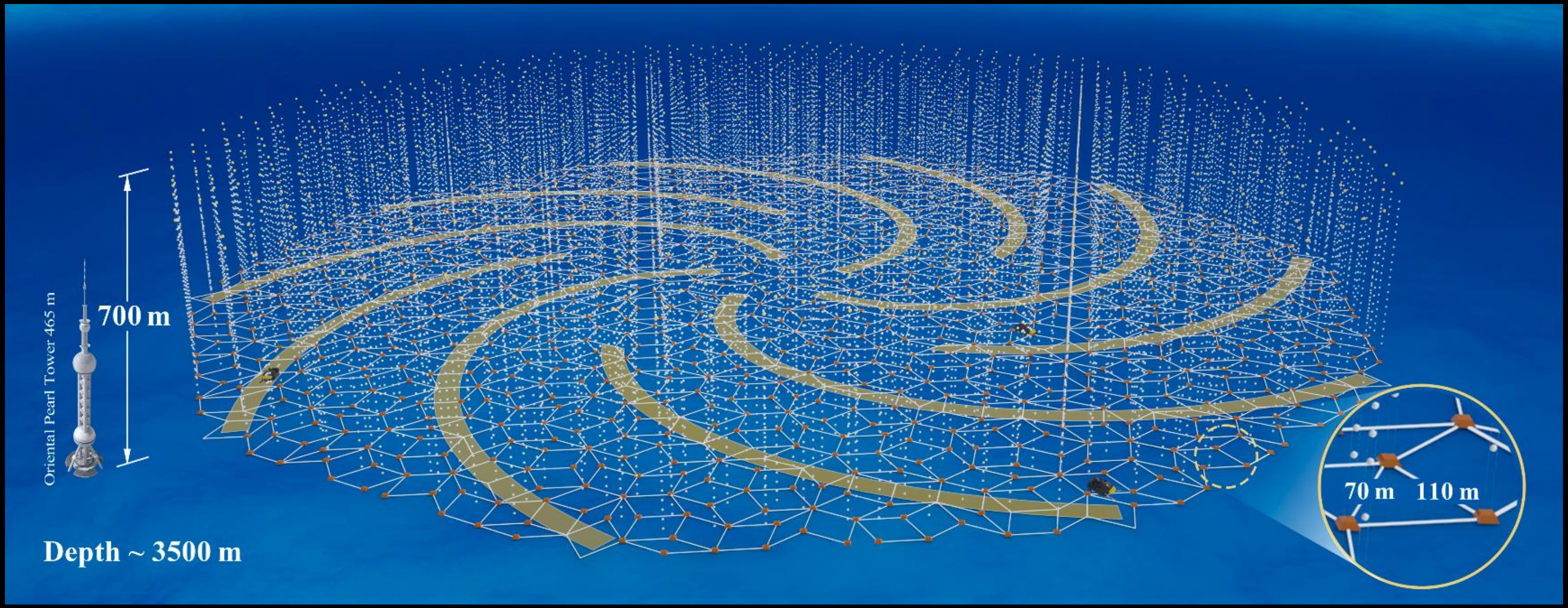
- Location
- Size
- Detector Design

Rapidly discover point sources

- Signal Flux
- Backgrounds
- Neutrino Pointing Resolution
- Energy Resolution and Range
- Neutrino Flavour Sensitivity

TRIDENT

Depth:	3.5km
Volume:	~8 km^3
# strings:	1200



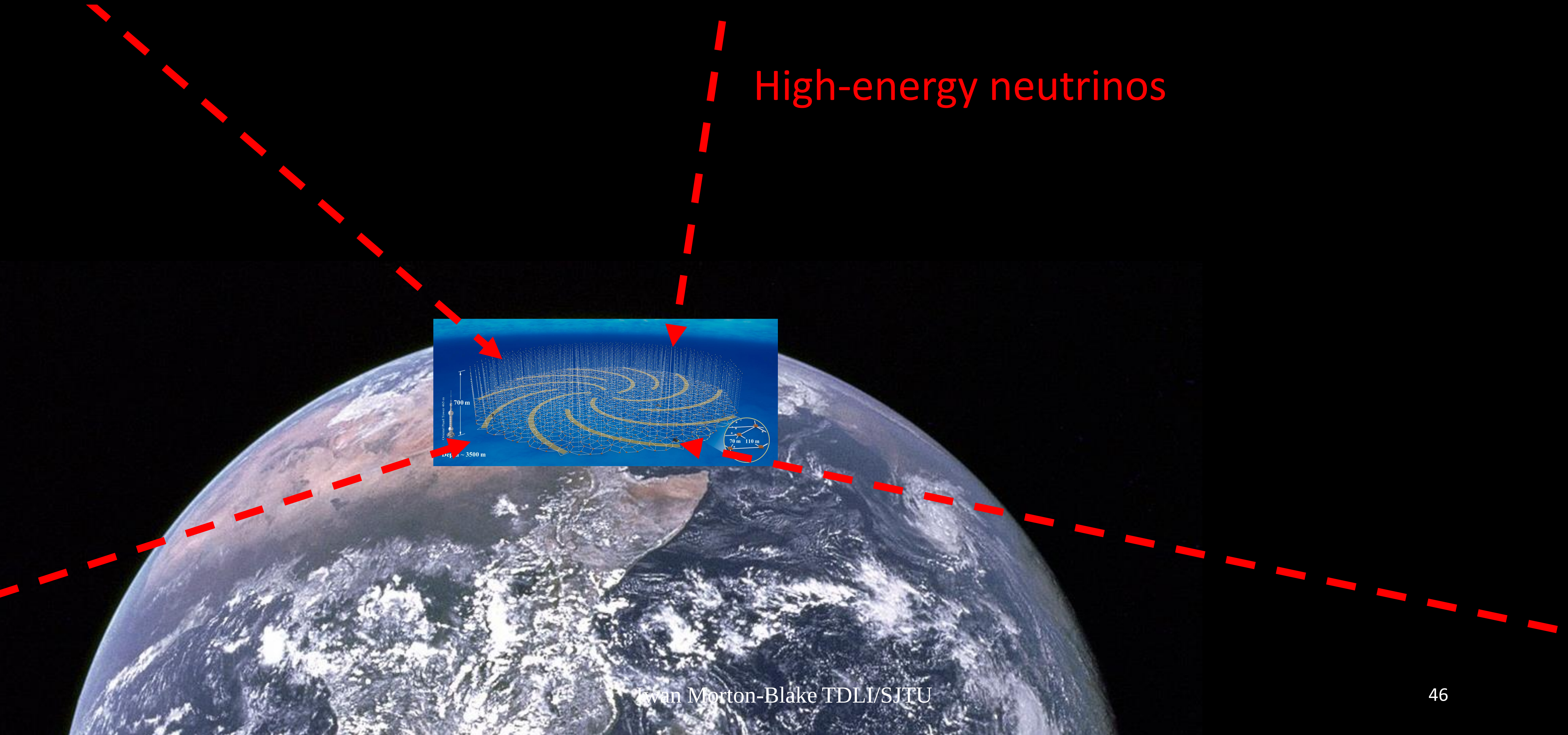
1. Location

2. Telescope Design

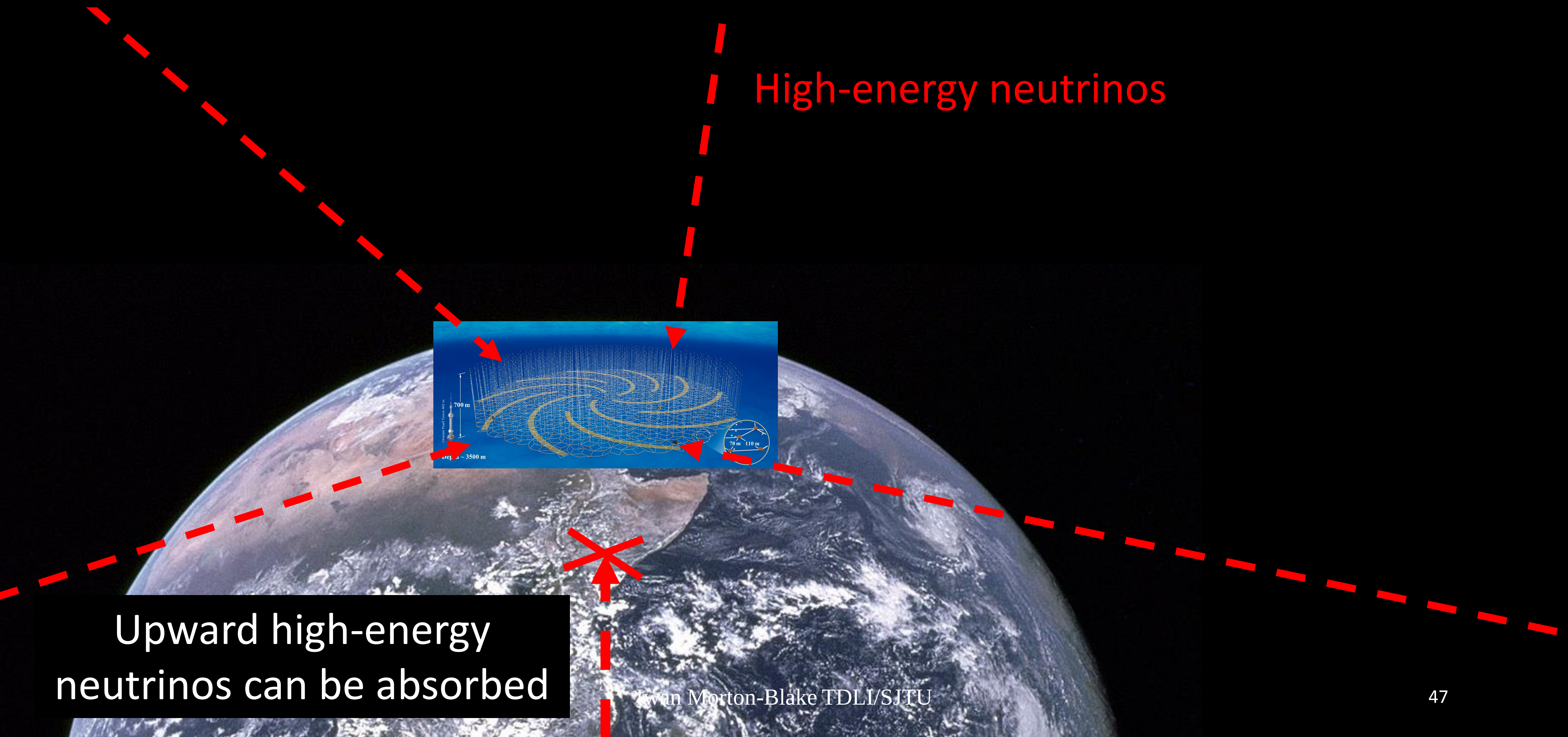
3. Telescope Ability

Location

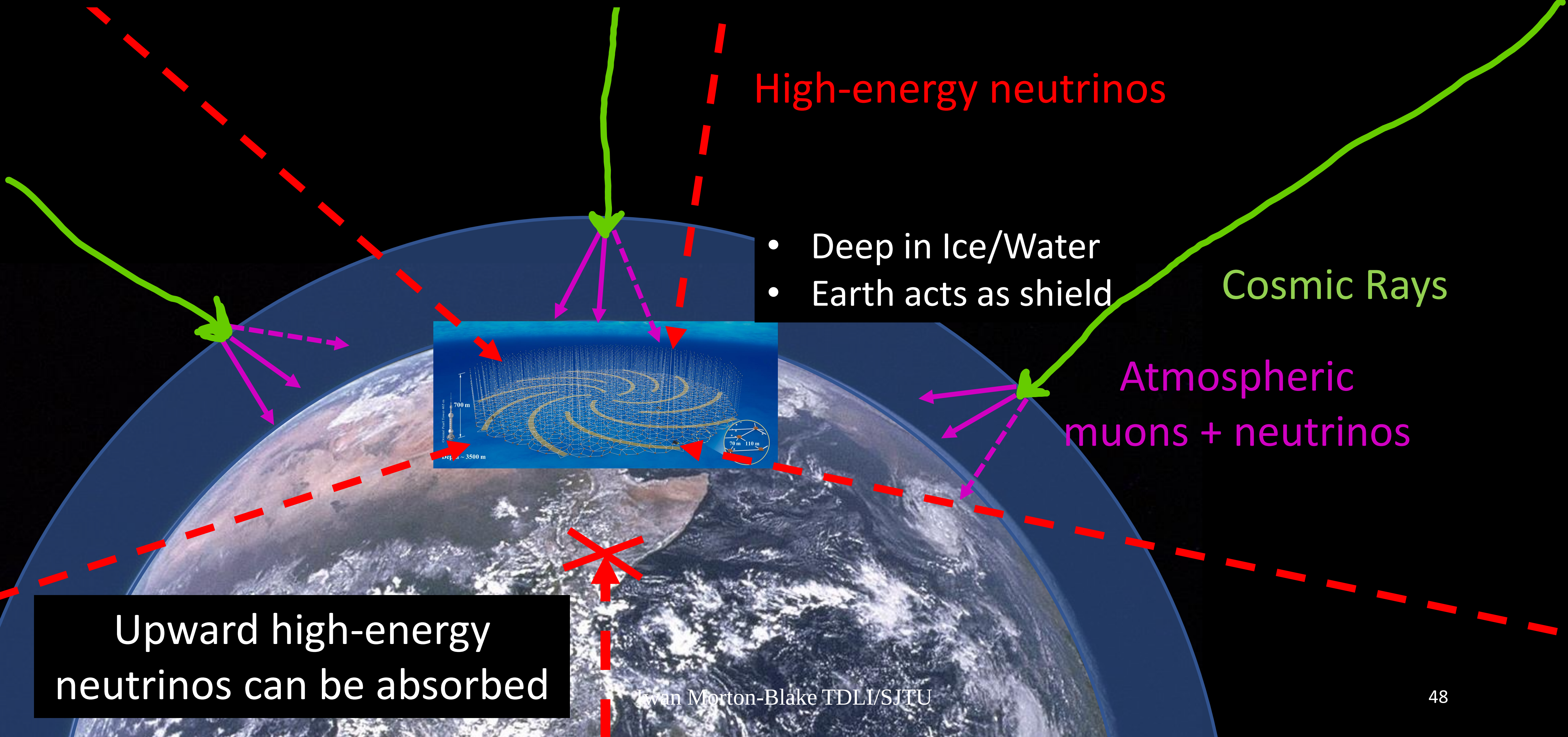
Telescope Operation Principles



Telescope Operation Principles



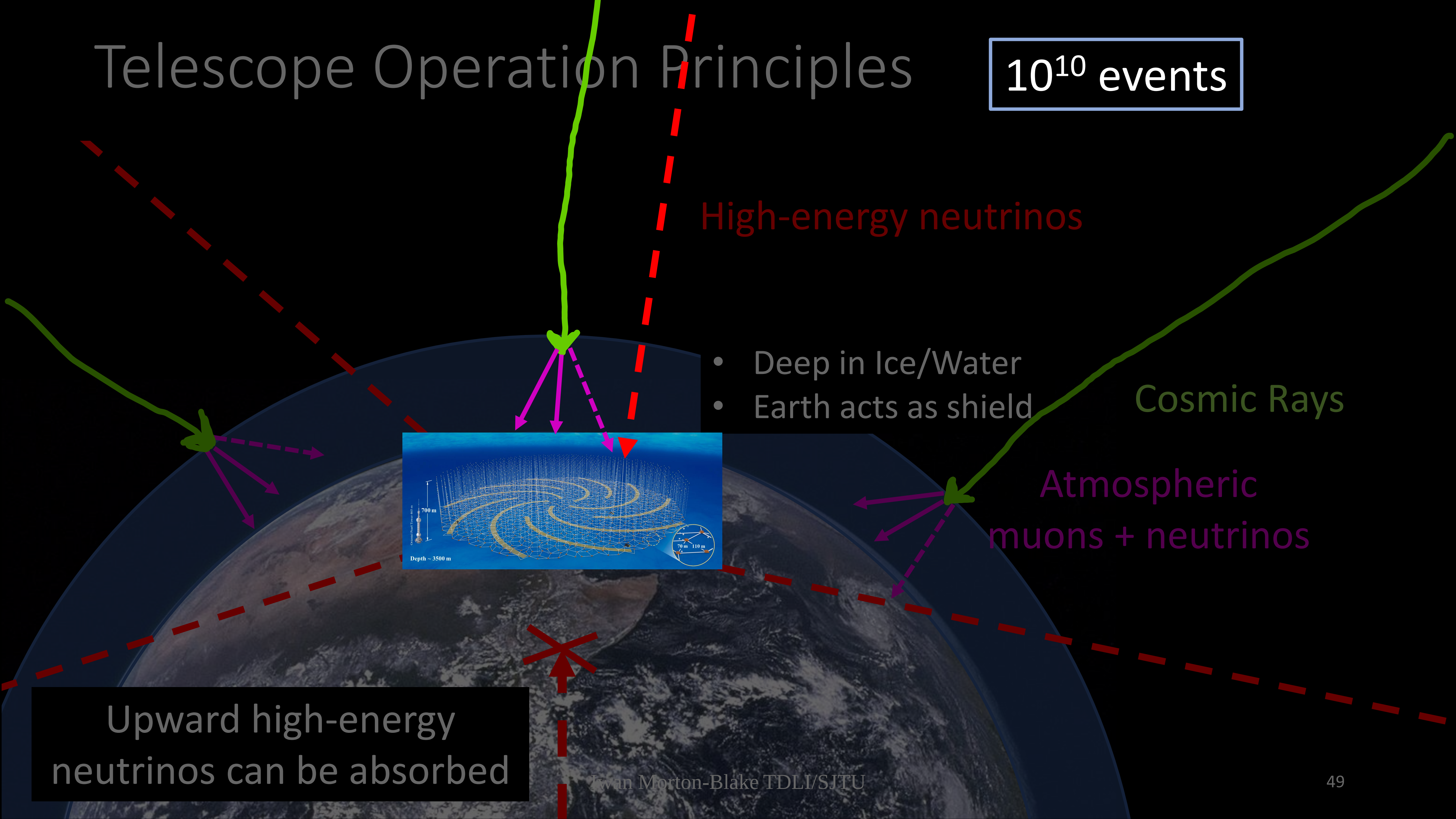
Telescope Operation Principles



Telescope Operation Principles

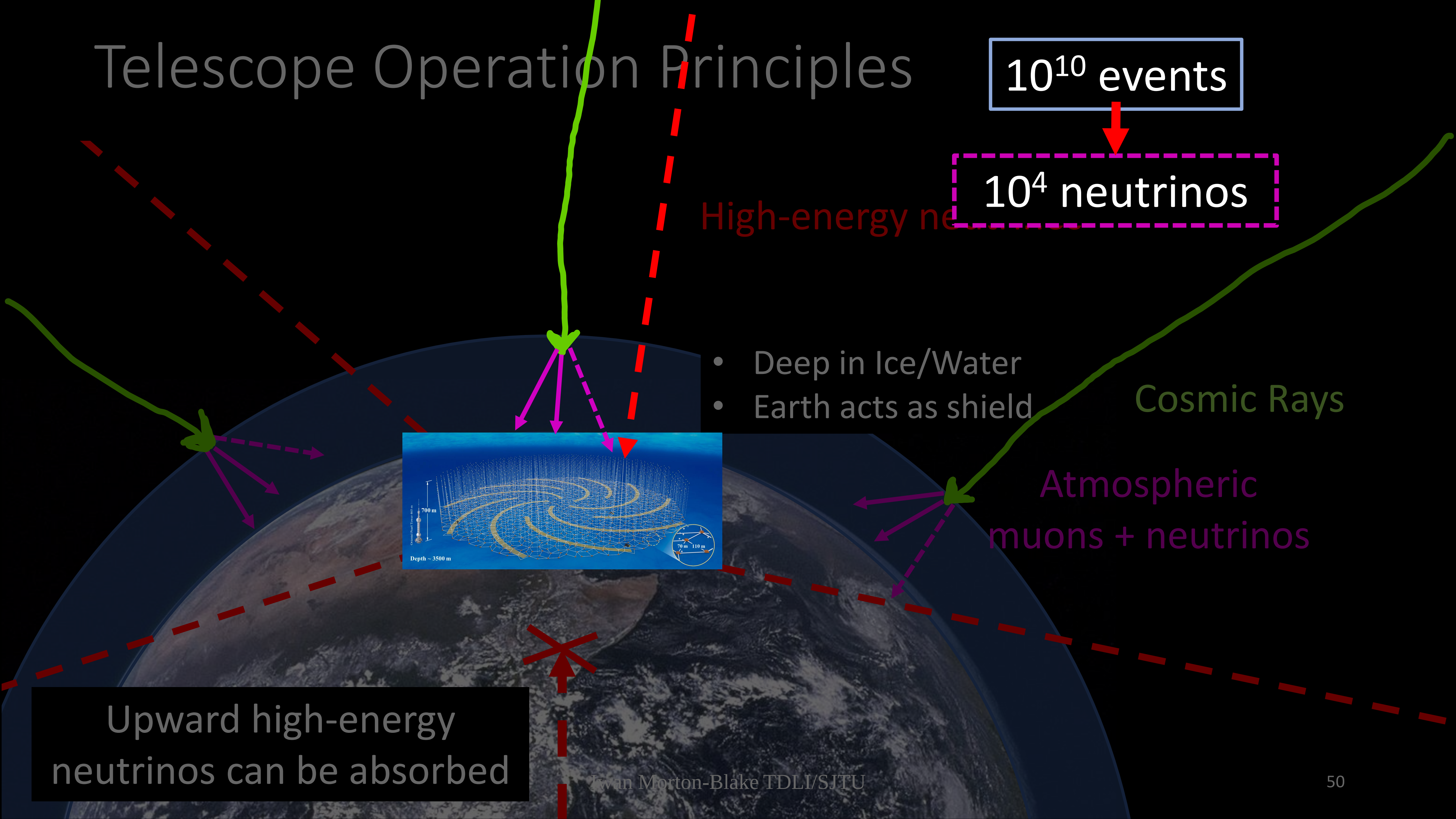
10^{10} events

- Deep in Ice/Water
- Earth acts as shield

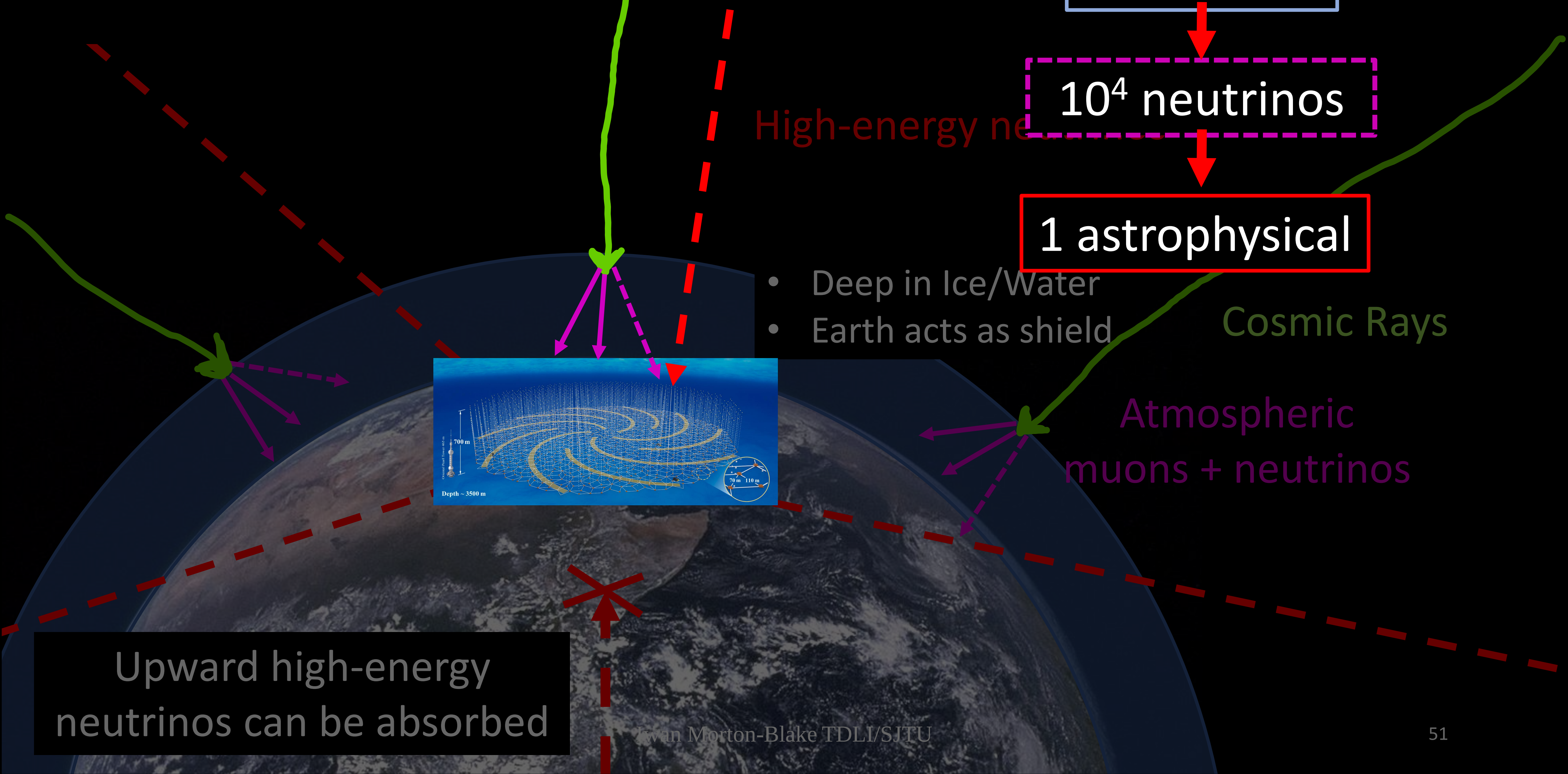


Telescope Operation Principles

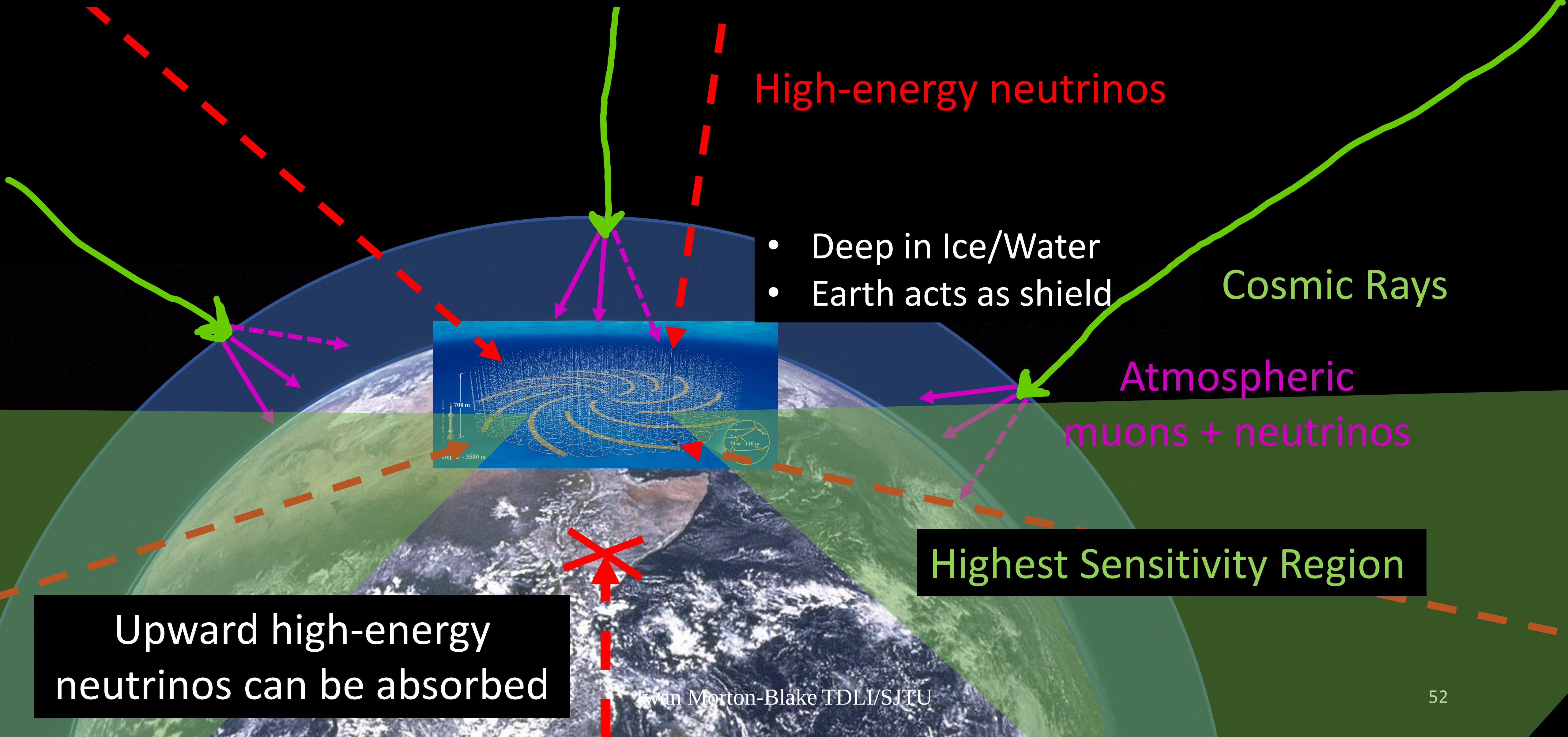
- Deep in Ice/Water
- Earth acts as shield



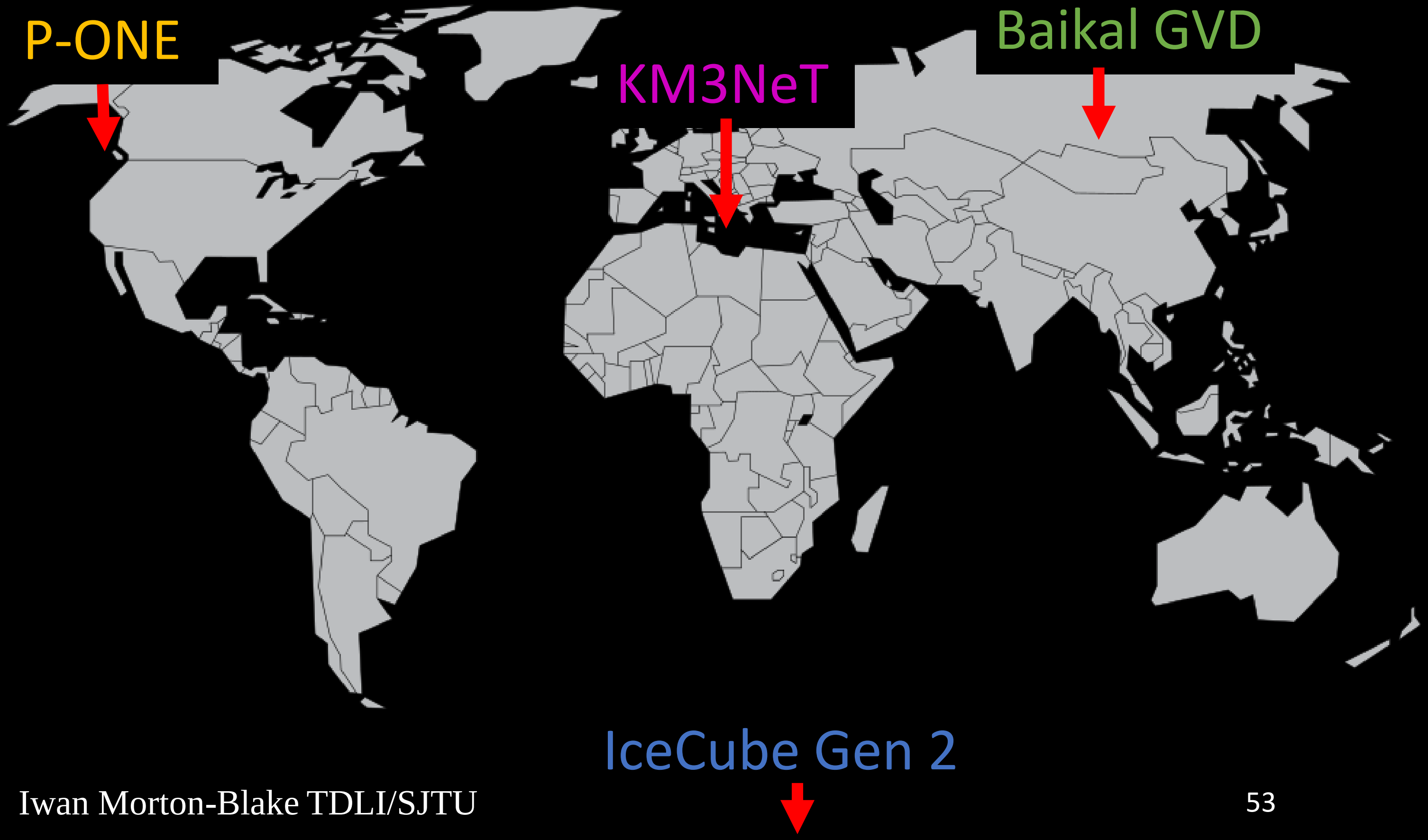
Telescope Operation Principles



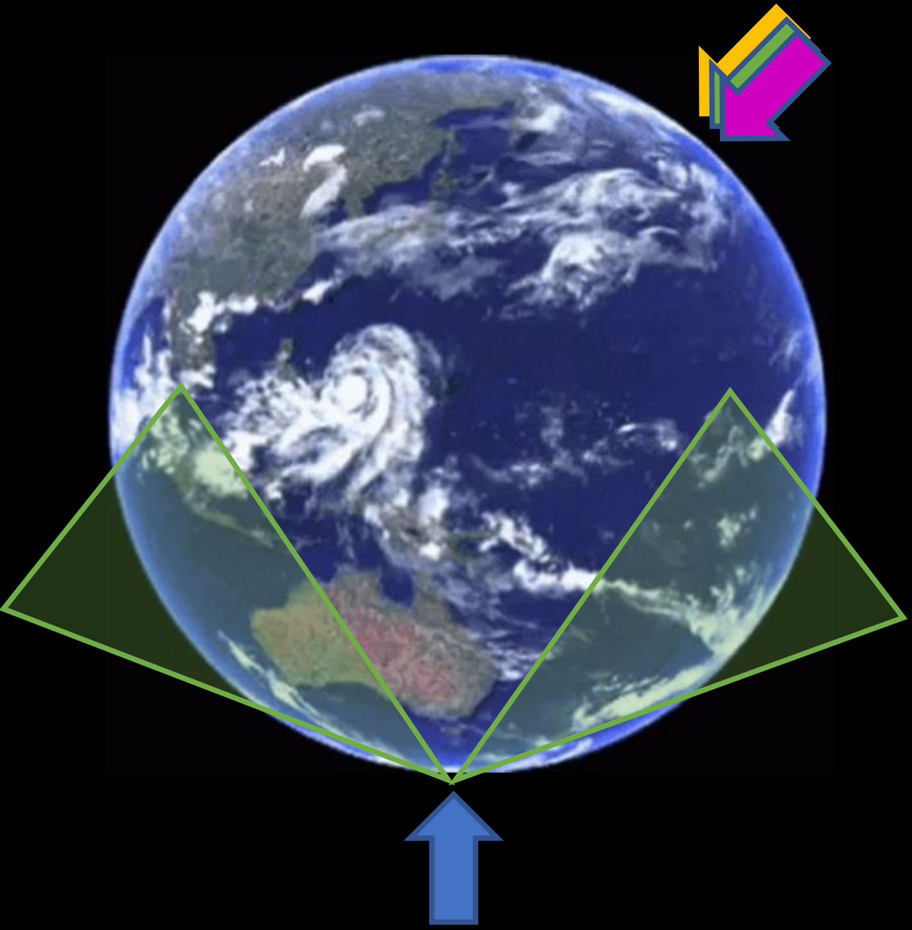
Telescope Operation Principles

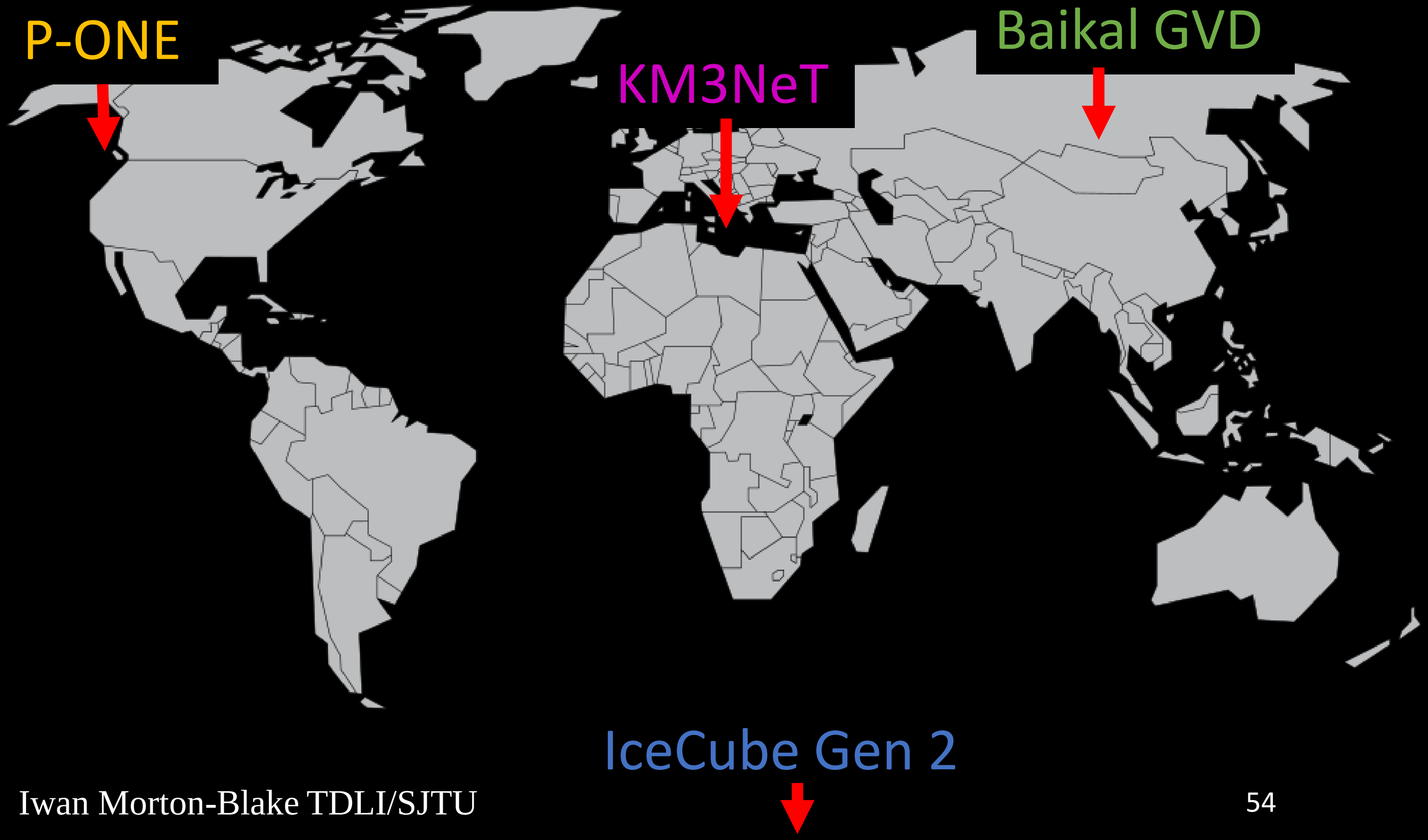


Location: Future Neutrino Telescopes

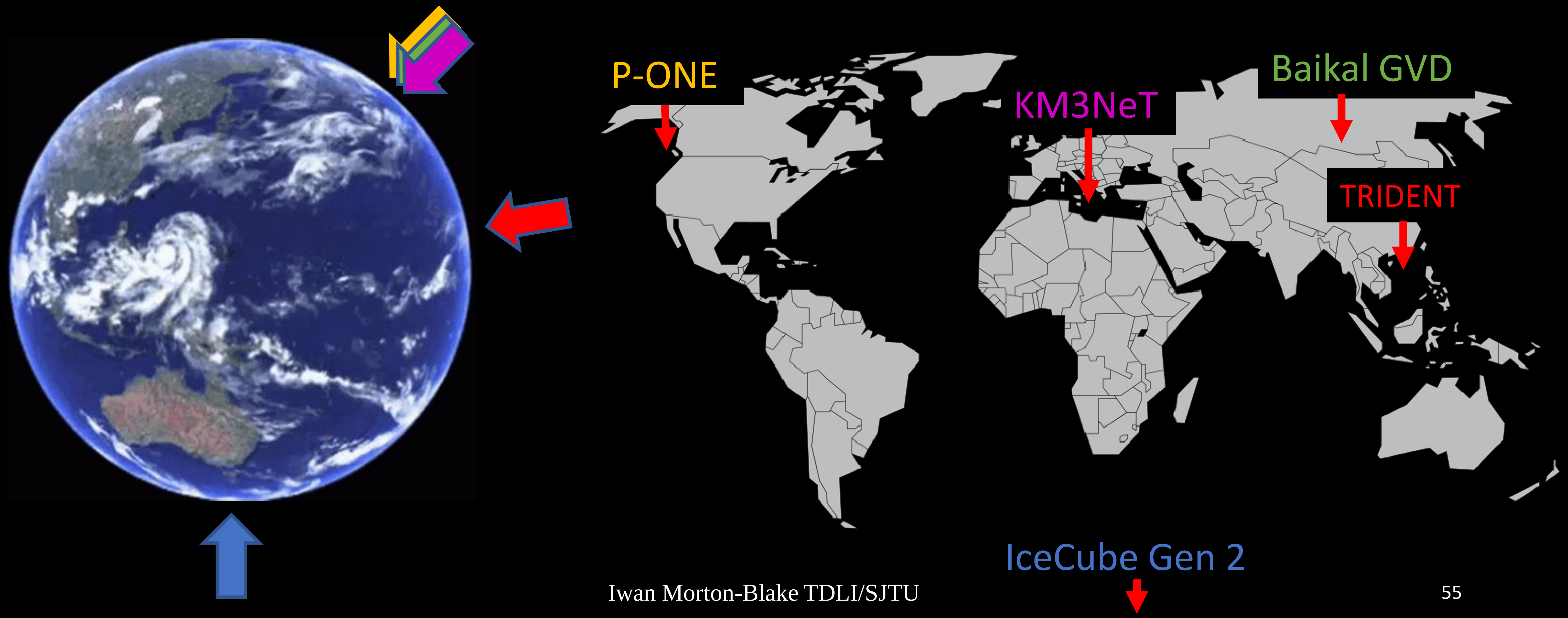


Location: Future Neutrino Telescopes

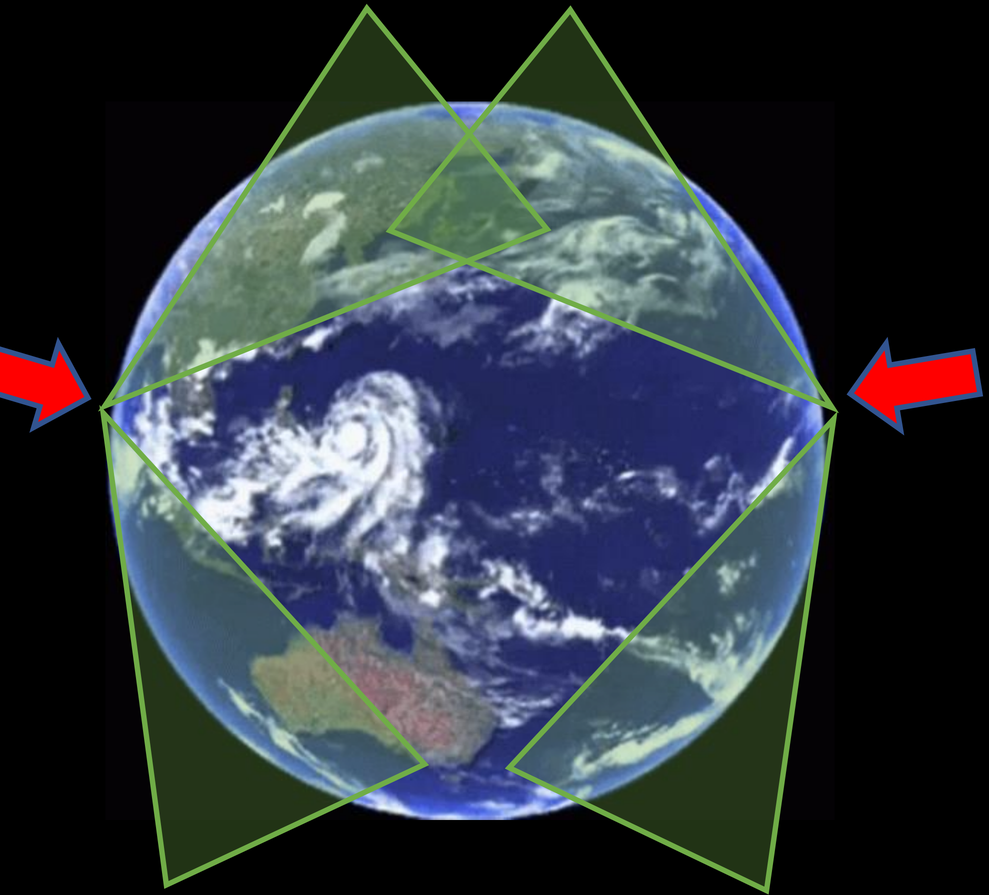


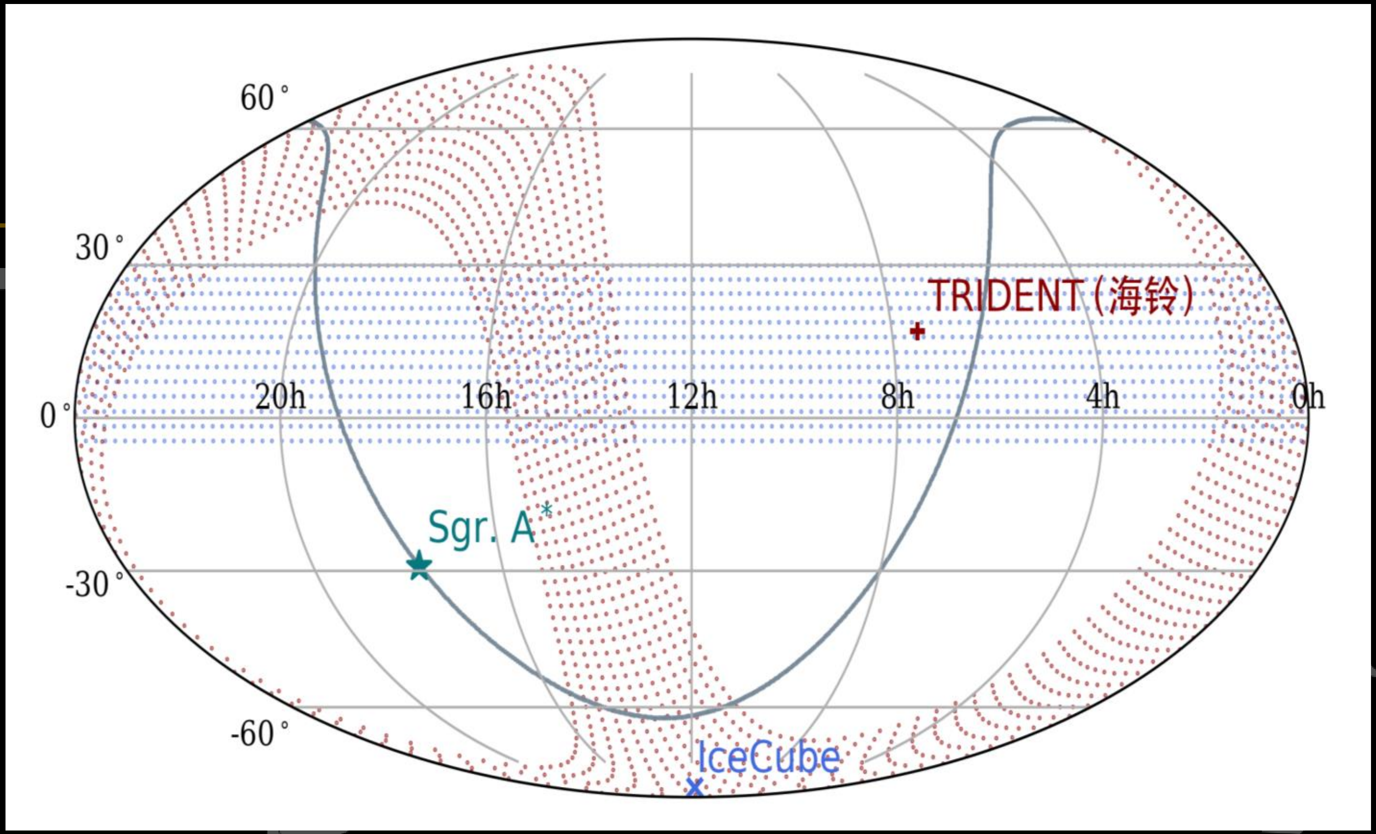


Location: Future Neutrino Telescopes



Location: Future Neutrino Telescopes





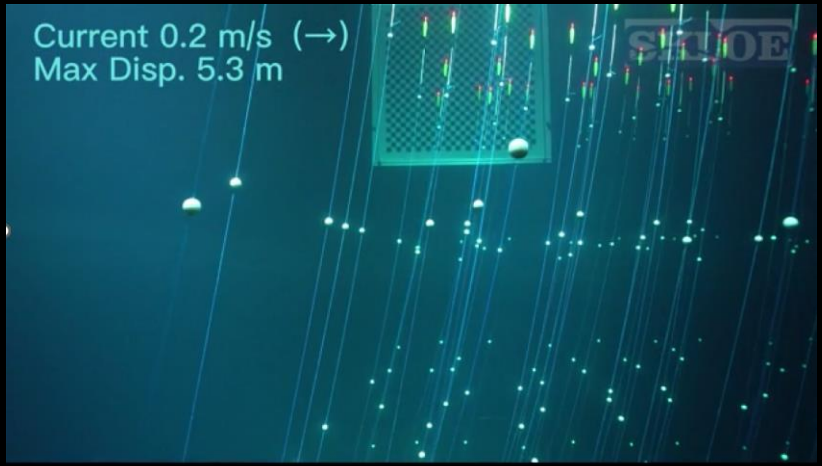
IceCube Gen 2

Location:

Measurements at Site

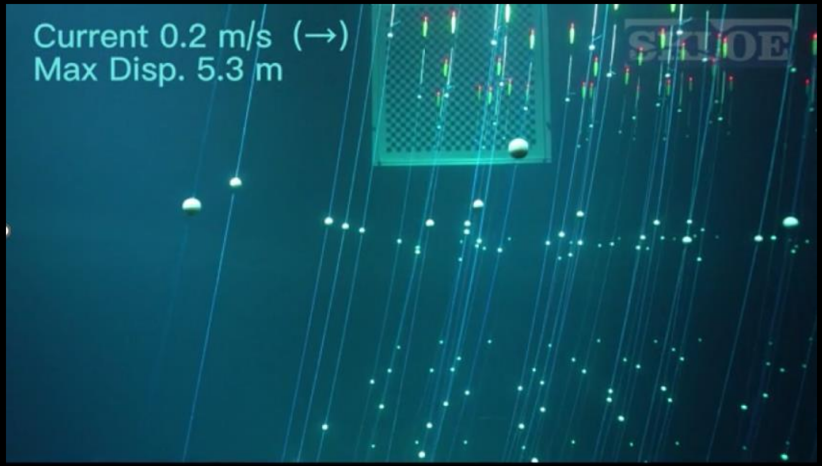
Testing at Location

- **Sea current speeds**



Testing at Location

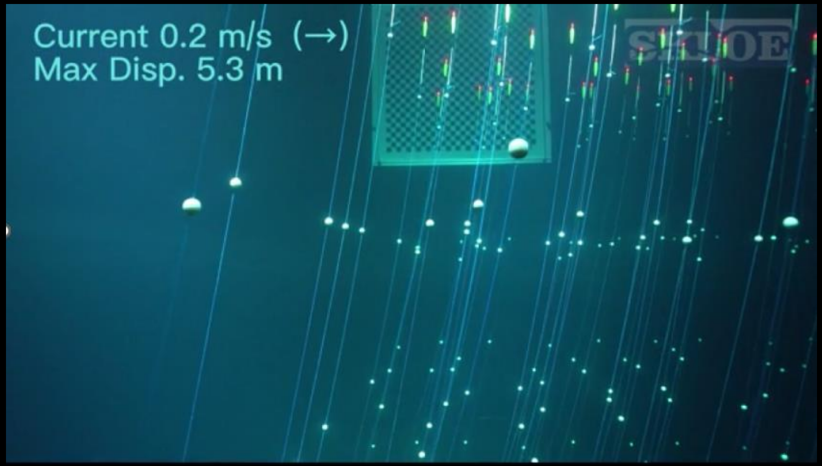
- Sea current speeds



- Light Absorption

  Scattering

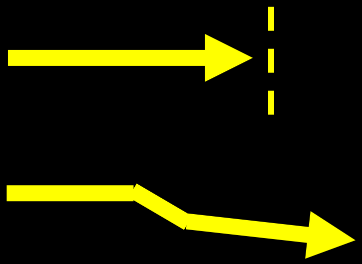
Testing at Location



- **Sea current speeds**

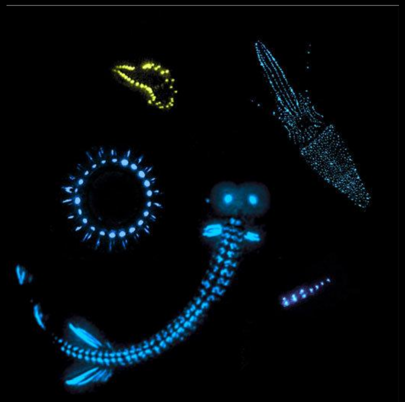
- **Light Absorption**

  Scattering

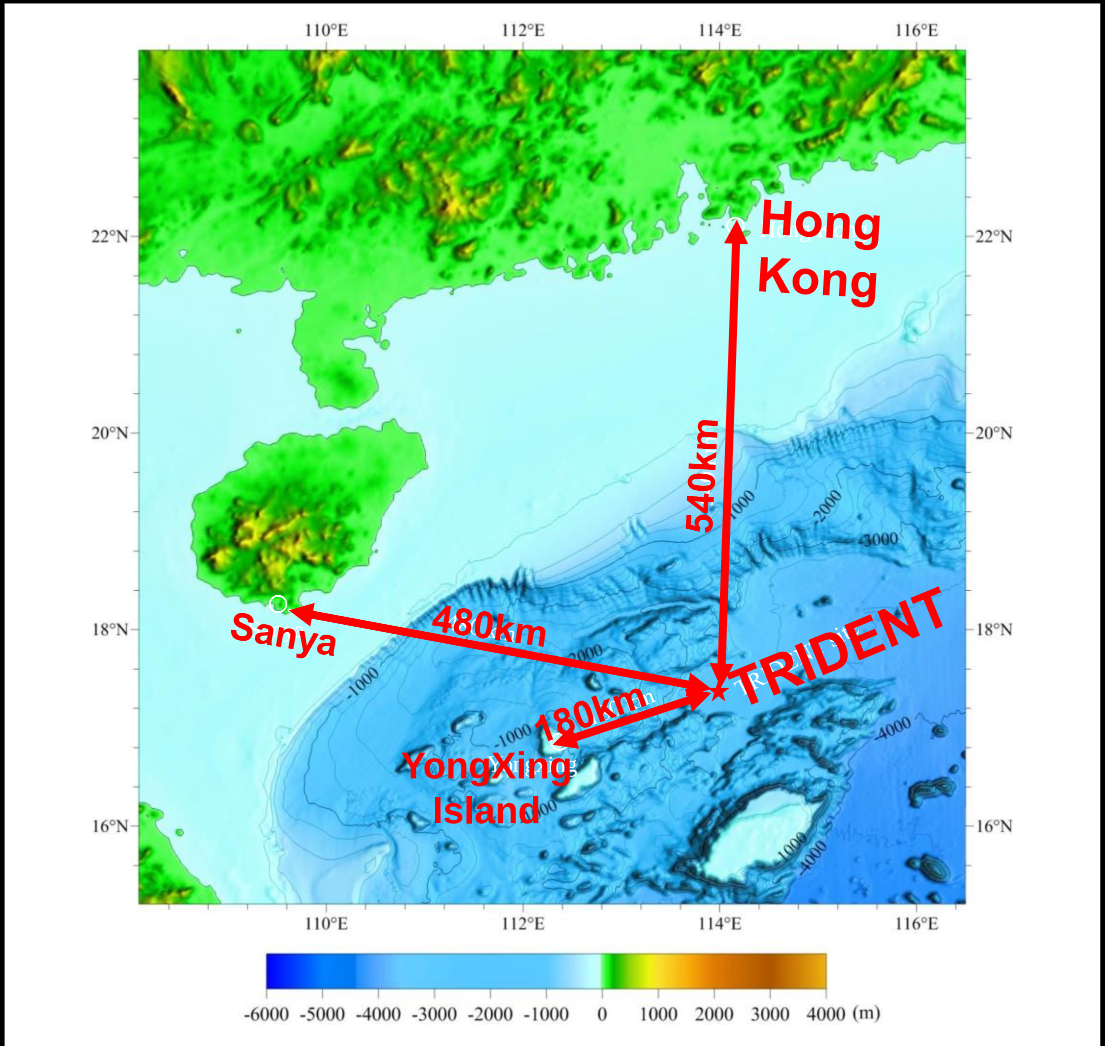


- **Radioactivity, Bioactivity,**

  Pressure, Temperature, Salinity



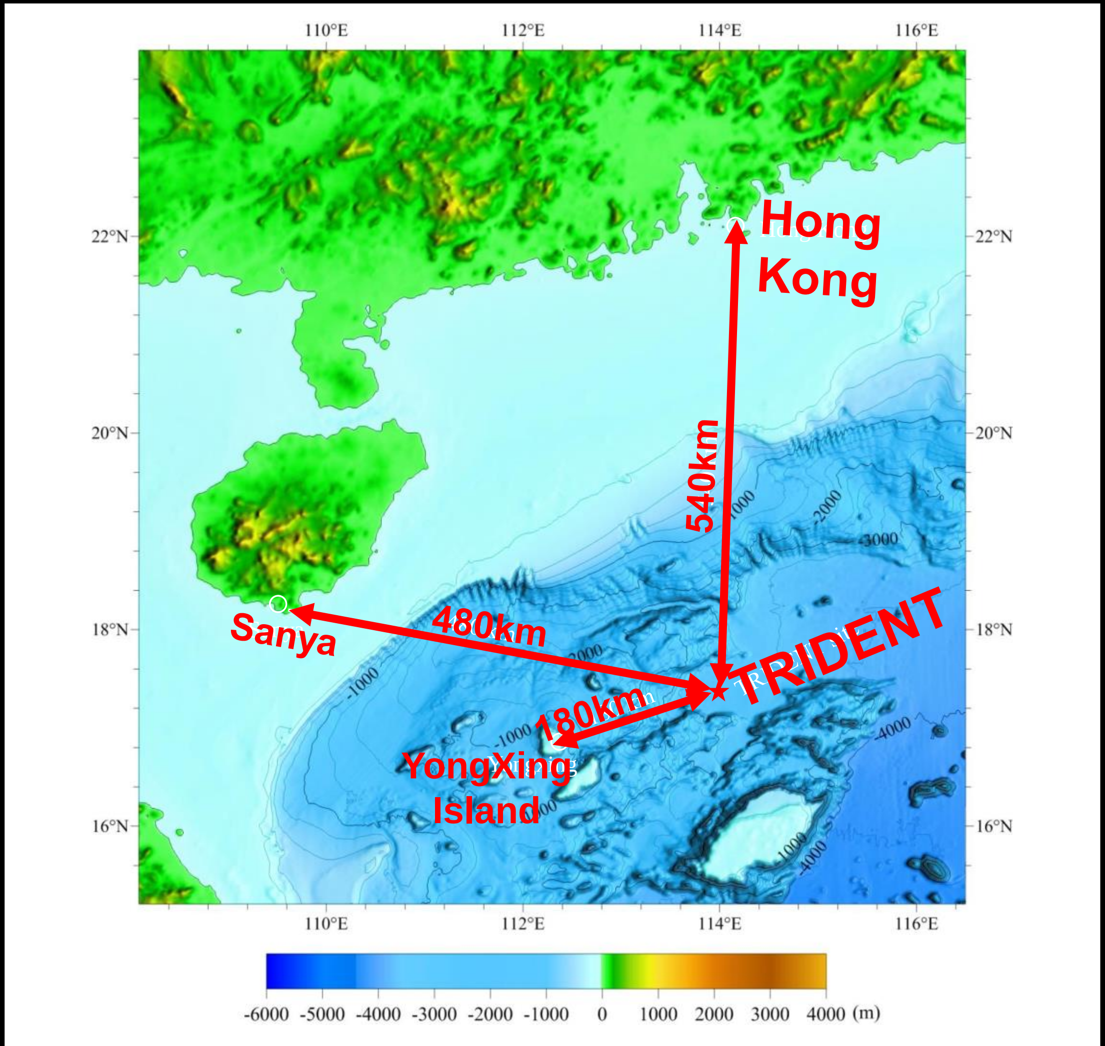
TRIDENT Explorer : T-REX



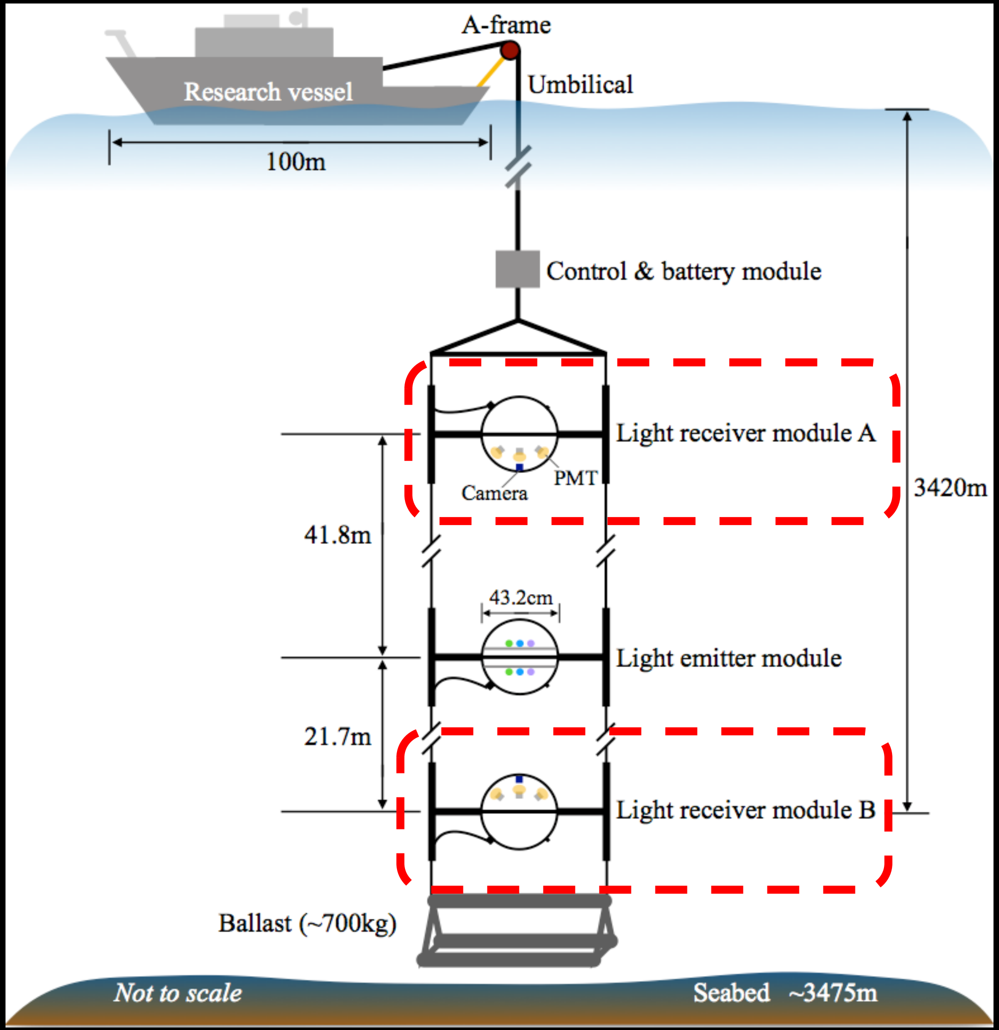
Oceanographic data:

- Deep
  - -> avoid bioactivity
  - -> shield from muons
- Huge flat plain found
- Small, steady sea currents
- Near an Island (power/data)

TRIDENT Explorer : T-REX



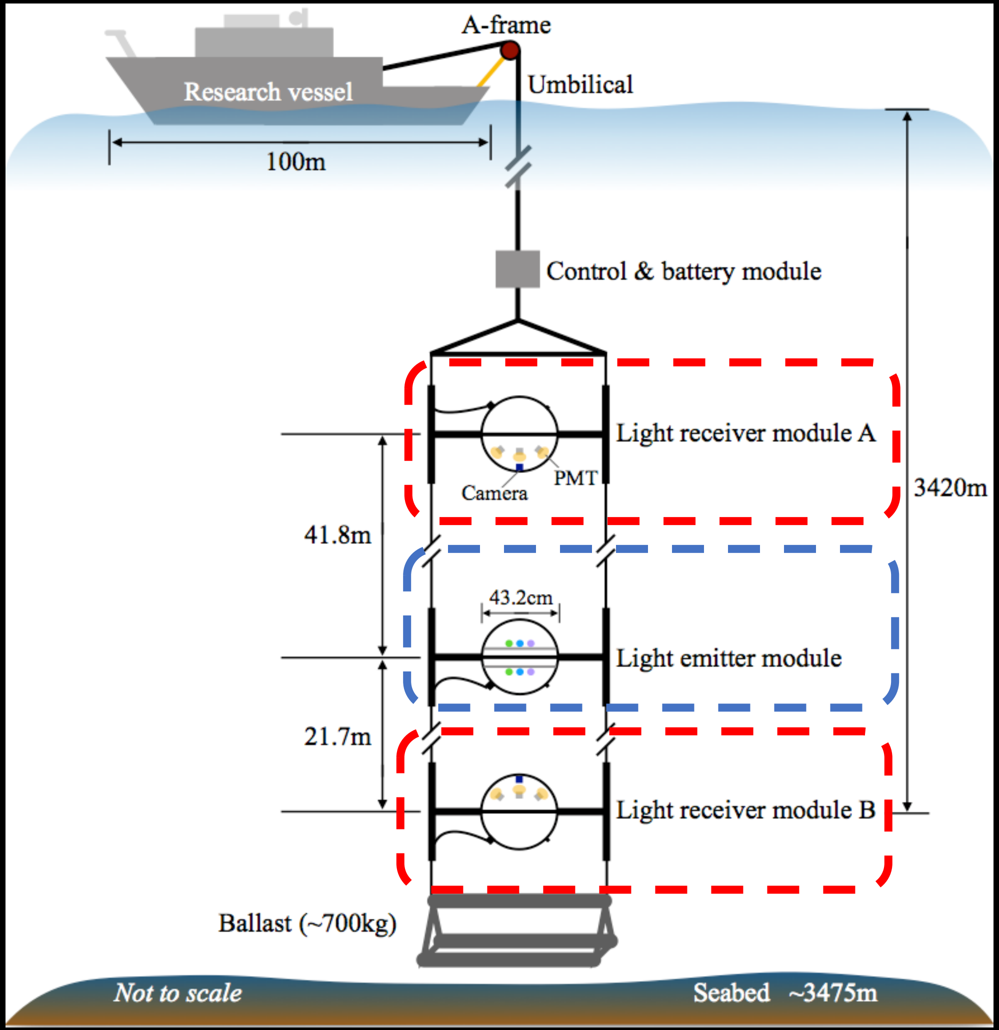
TRIDENT Explorer : T-REX



2 Light Receivers

- 3x 3” PMTs
- Camera system

TRIDENT Explorer : T-REX

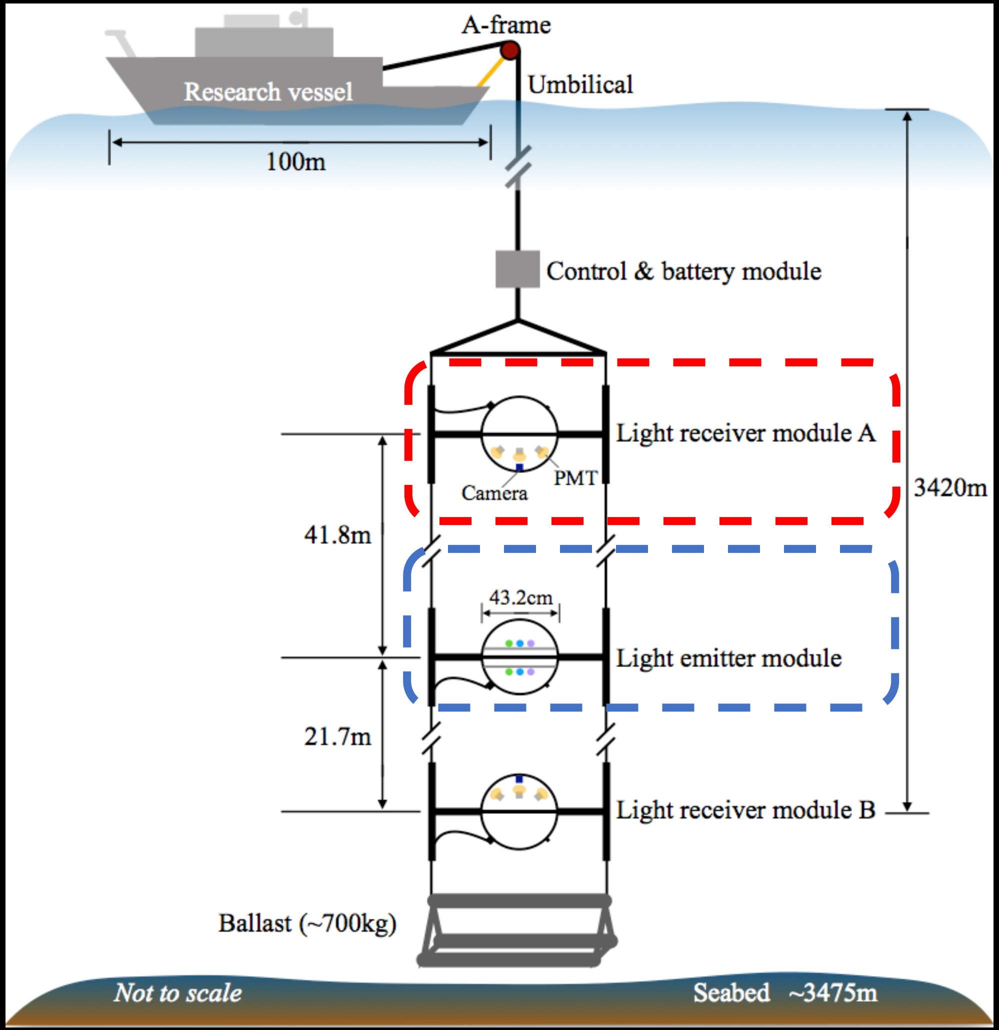


2 Light Receivers

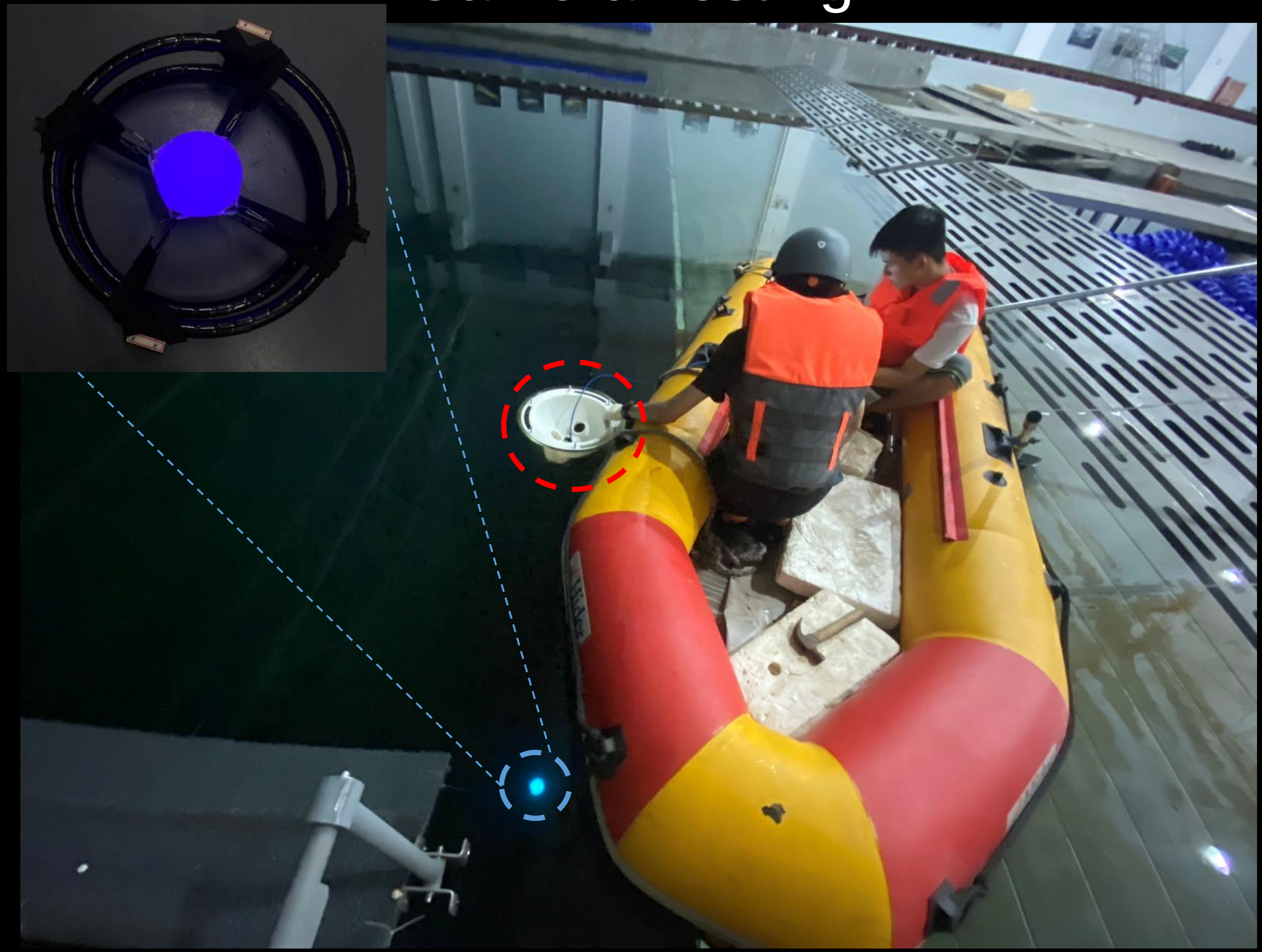
- 3x 3” PMTs
- Camera system

LEDs at various wavelengths
- Pulsed mode for PMTs
- Continuous mode for cameras

TRIDENT Explorer : T-REX

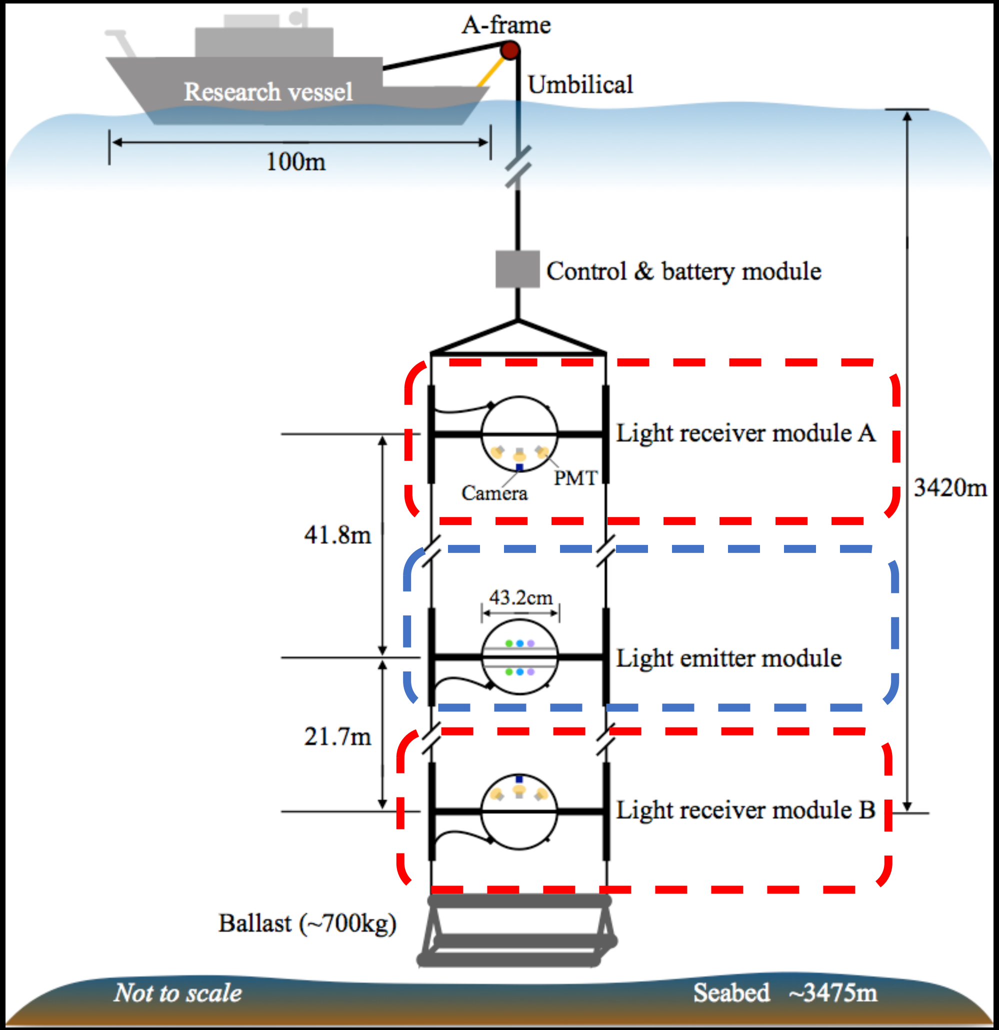


Camera Testing

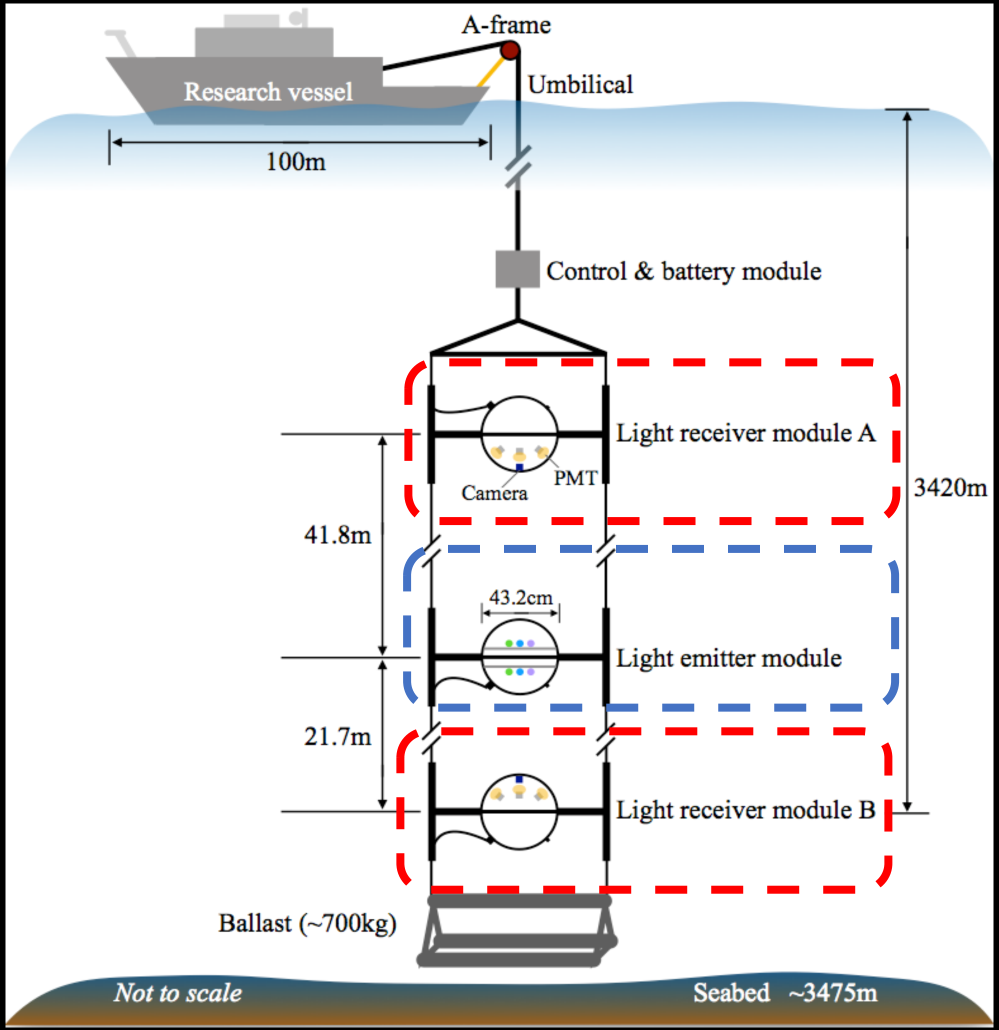


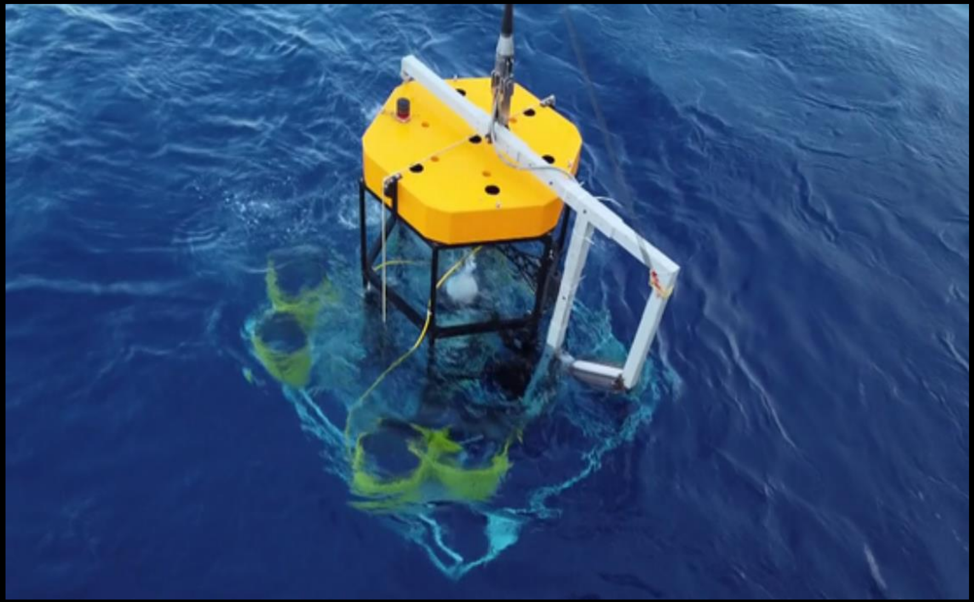
Ship towing tank in Shanghai Jiao Tong University

TRIDENT Explorer : T-REX

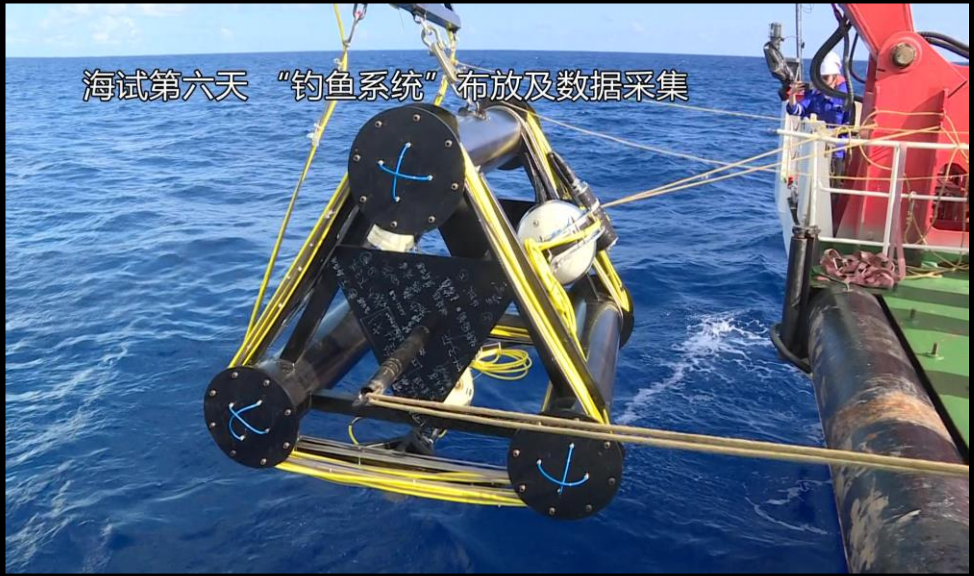


TRIDENT Explorer : T-REX

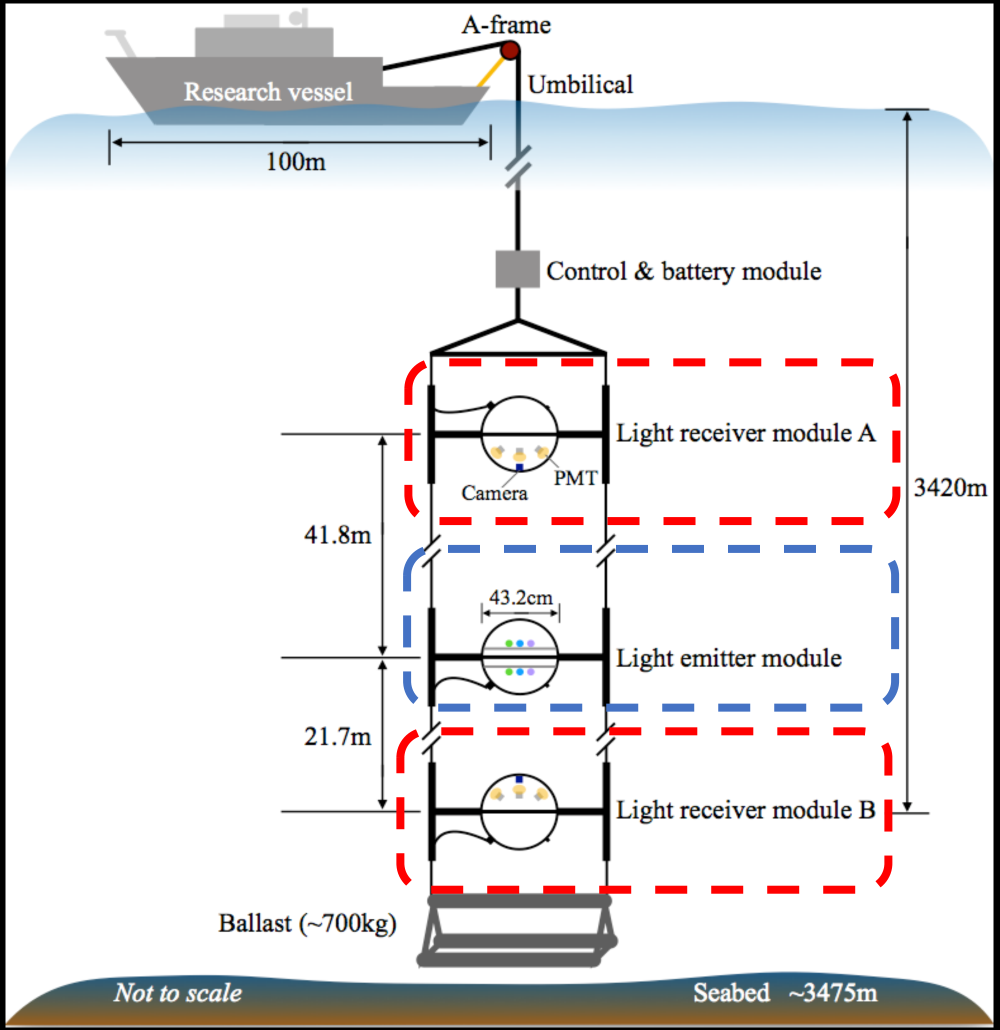




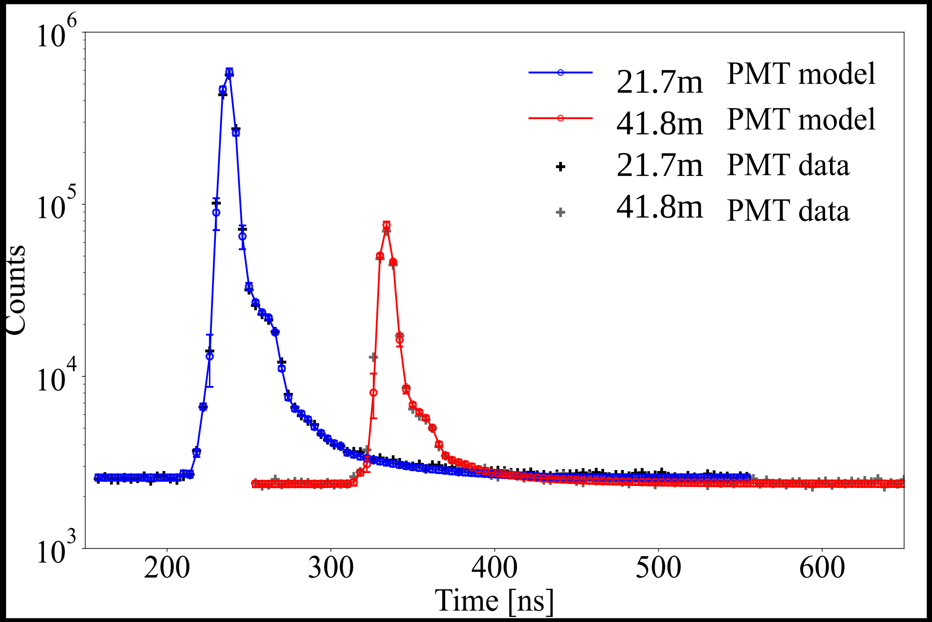
T-REX Deployment



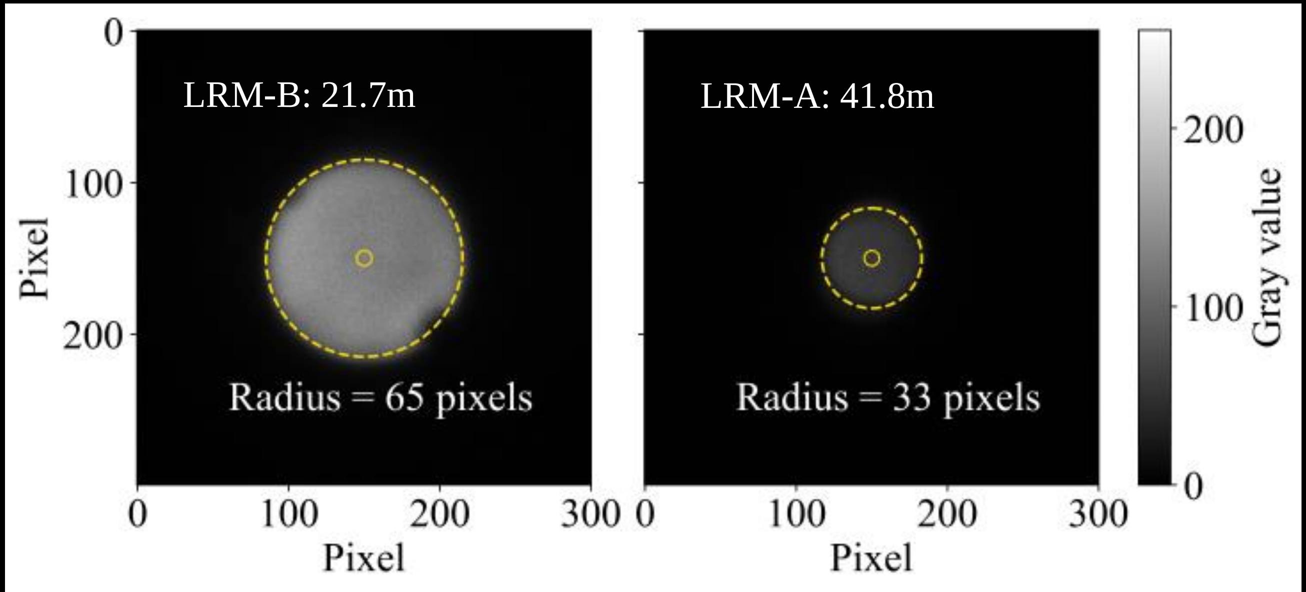
TRIDENT Explorer : T-REX



PMTs

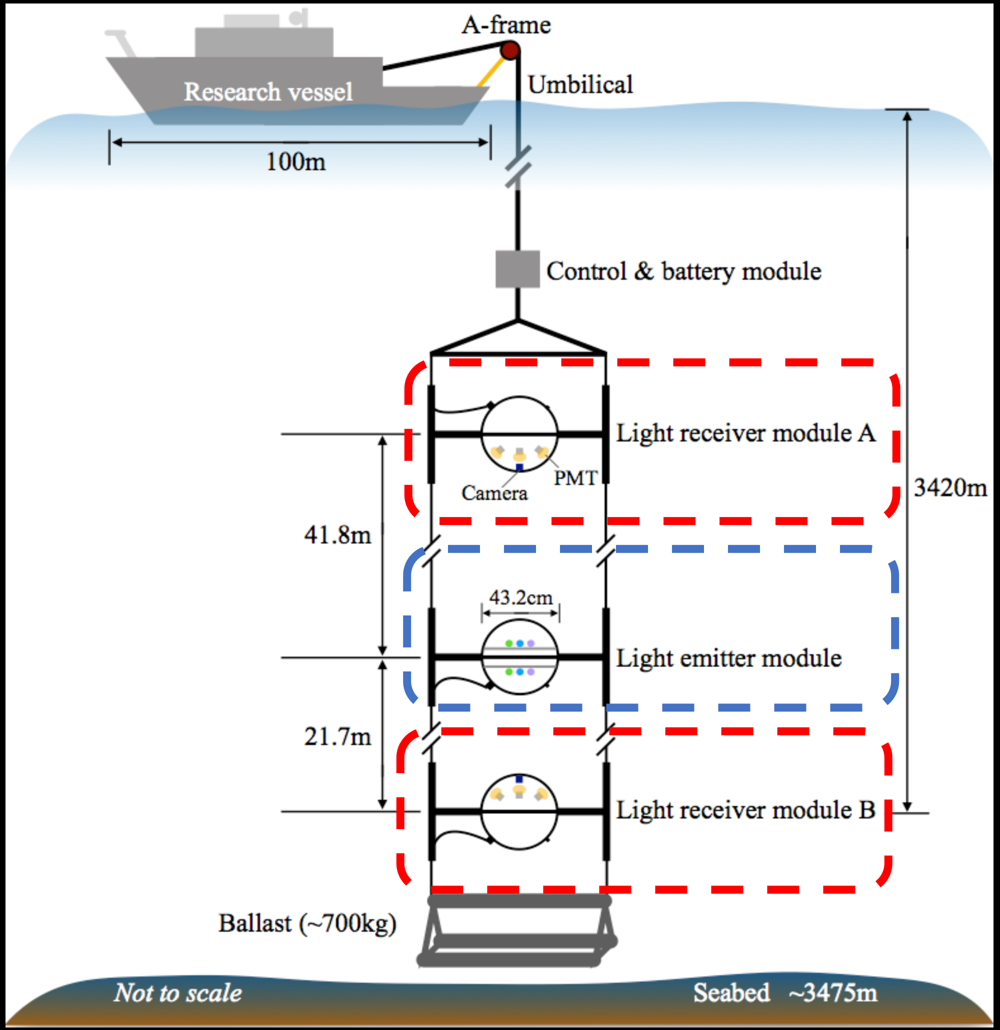


Cameras

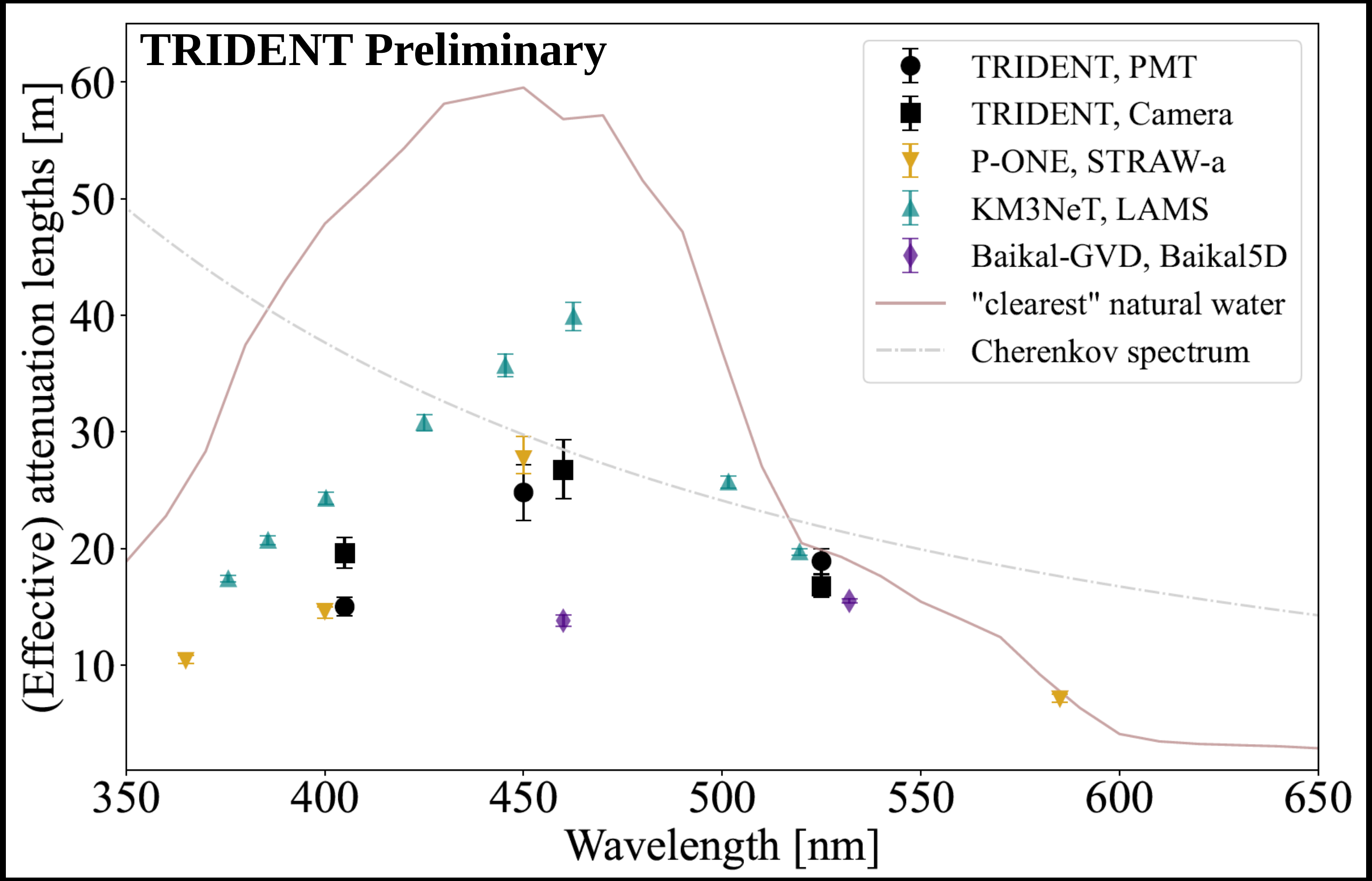


TRIDENT Explorer : T-REX

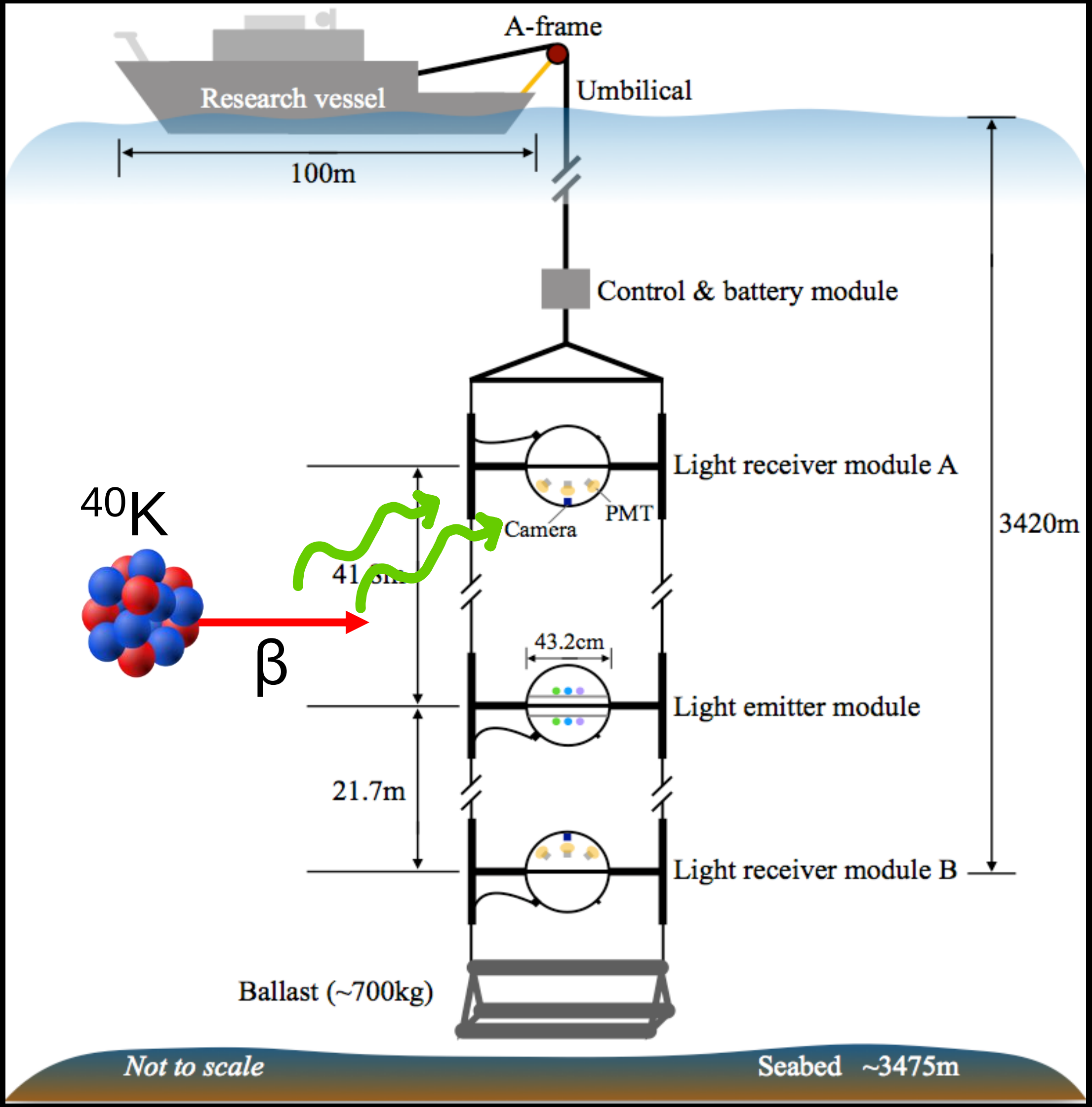
$\lambda_{abs} \simeq 27$ m , $\lambda_{scat} \simeq 63$ m



Effective Attenuation Length



TRIDENT Explorer : T-REX



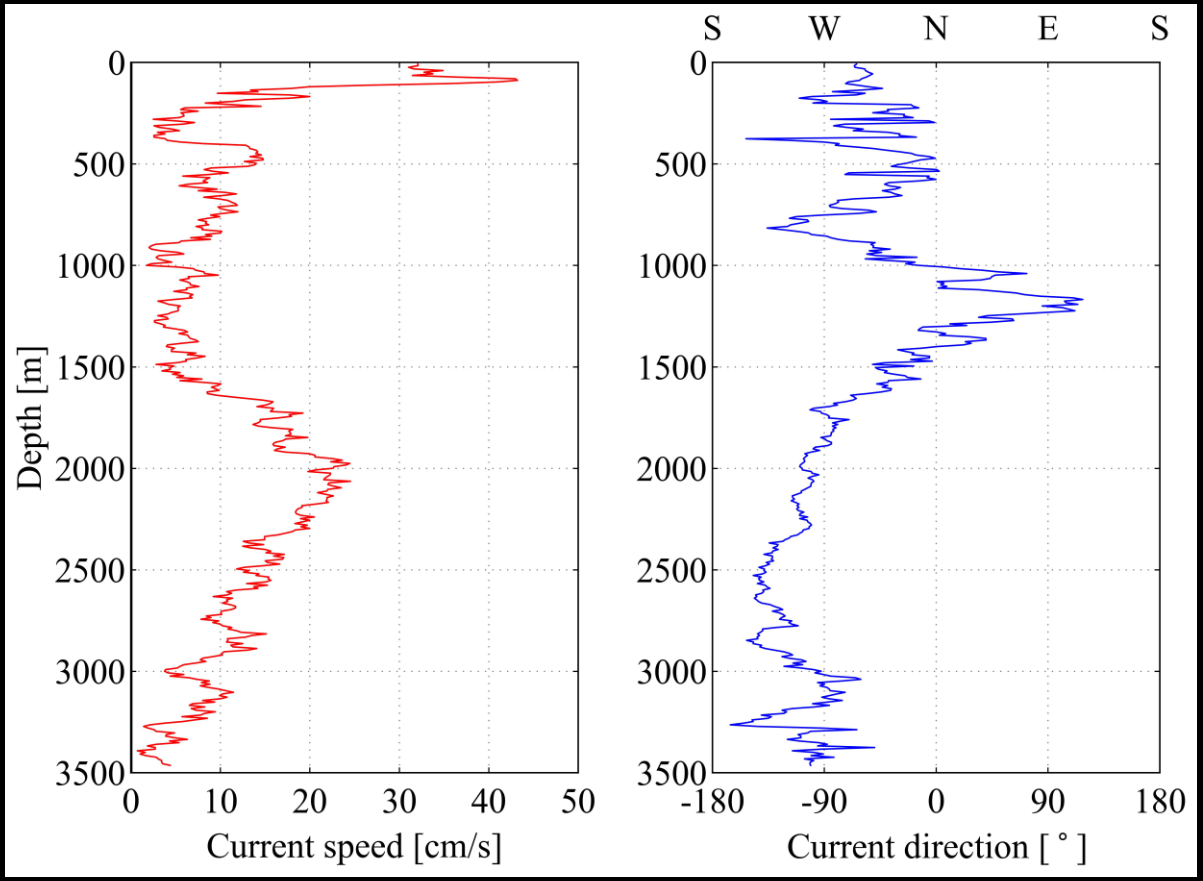
Radioactivity

^{40}K Rate [$s^{-1}m^{-3}$]

TRIDENT (Western Pacific)	ANTARES (Mediterranean)	P-ONE (Eastern Pacific)
11100 ± 119	13700 ± 200	12526 ± 752

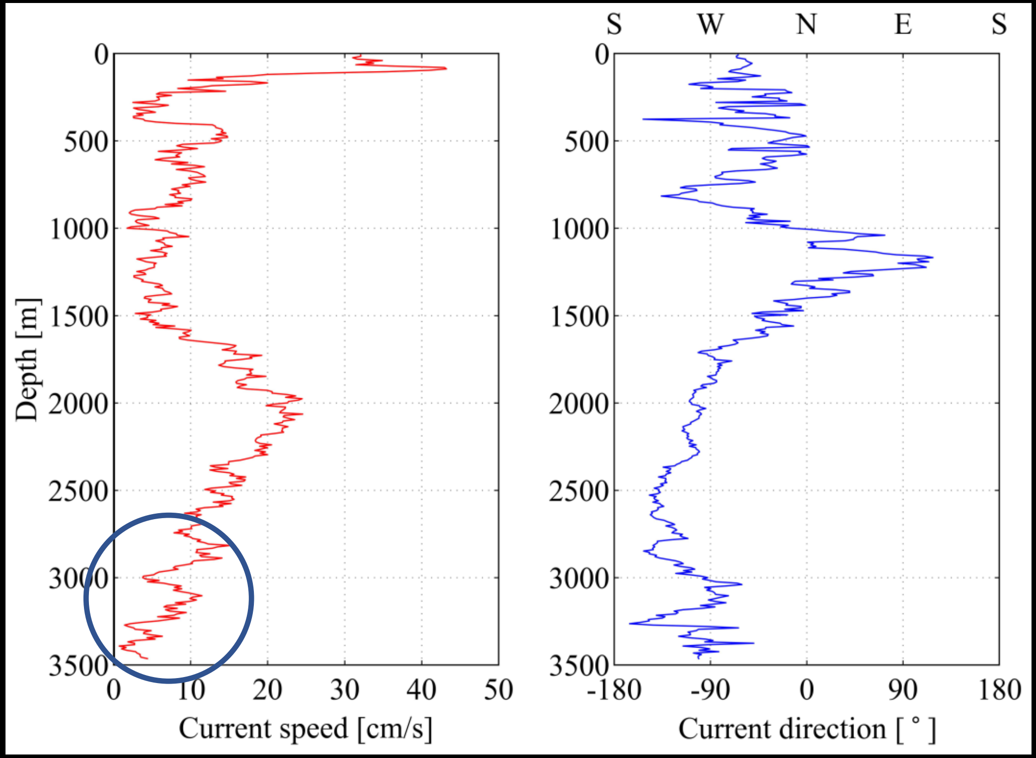
TRIDENT Explorer : T-REX

Sea Current Velocity



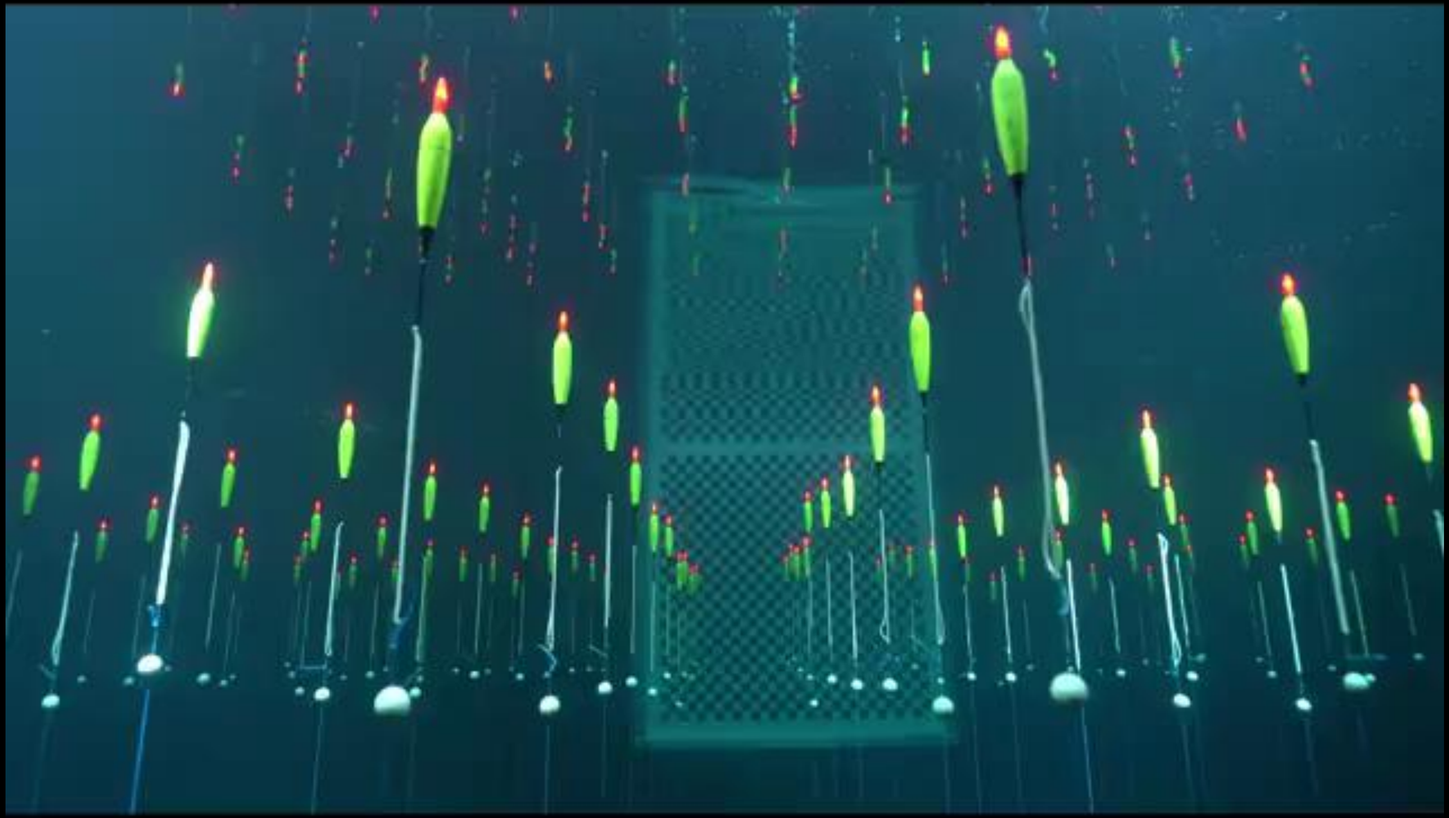
Impact of Sea Currents

Low sea current velocity at ~3km

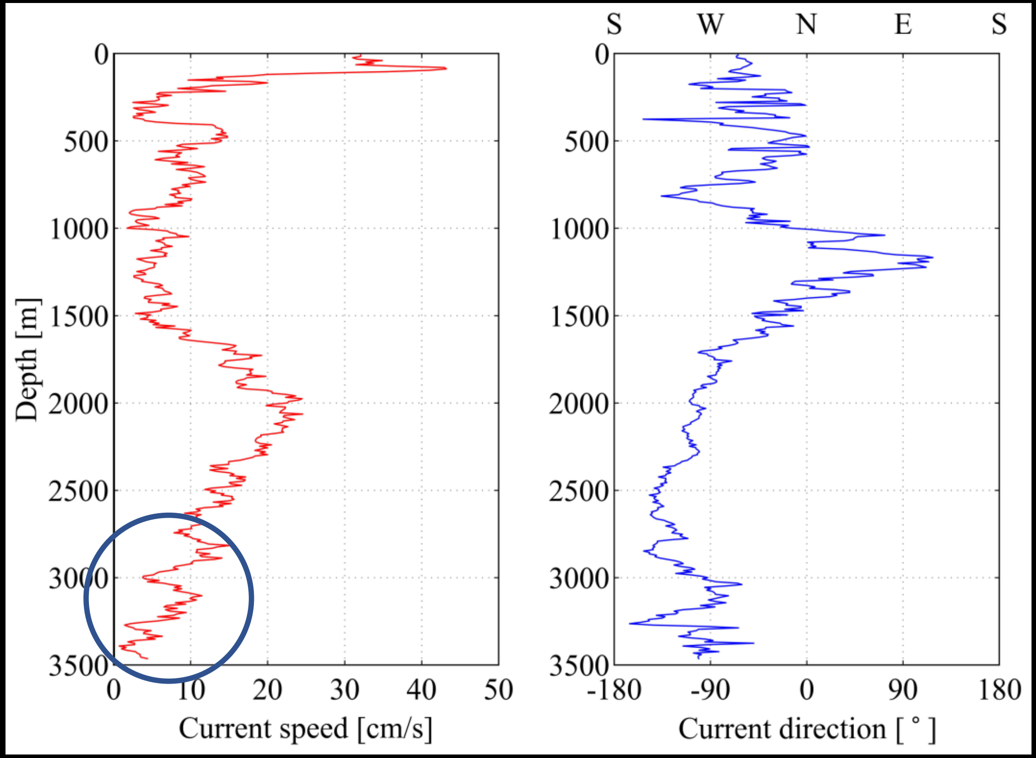


Impact of Sea Currents

1:25 scale string models
in SJTU Ship-towing tank



Low sea current velocity at ~3km



Need very frequent DOM position calibration!

Location

↓

Telescope Design

- Location → View of the sky

Backgrounds:

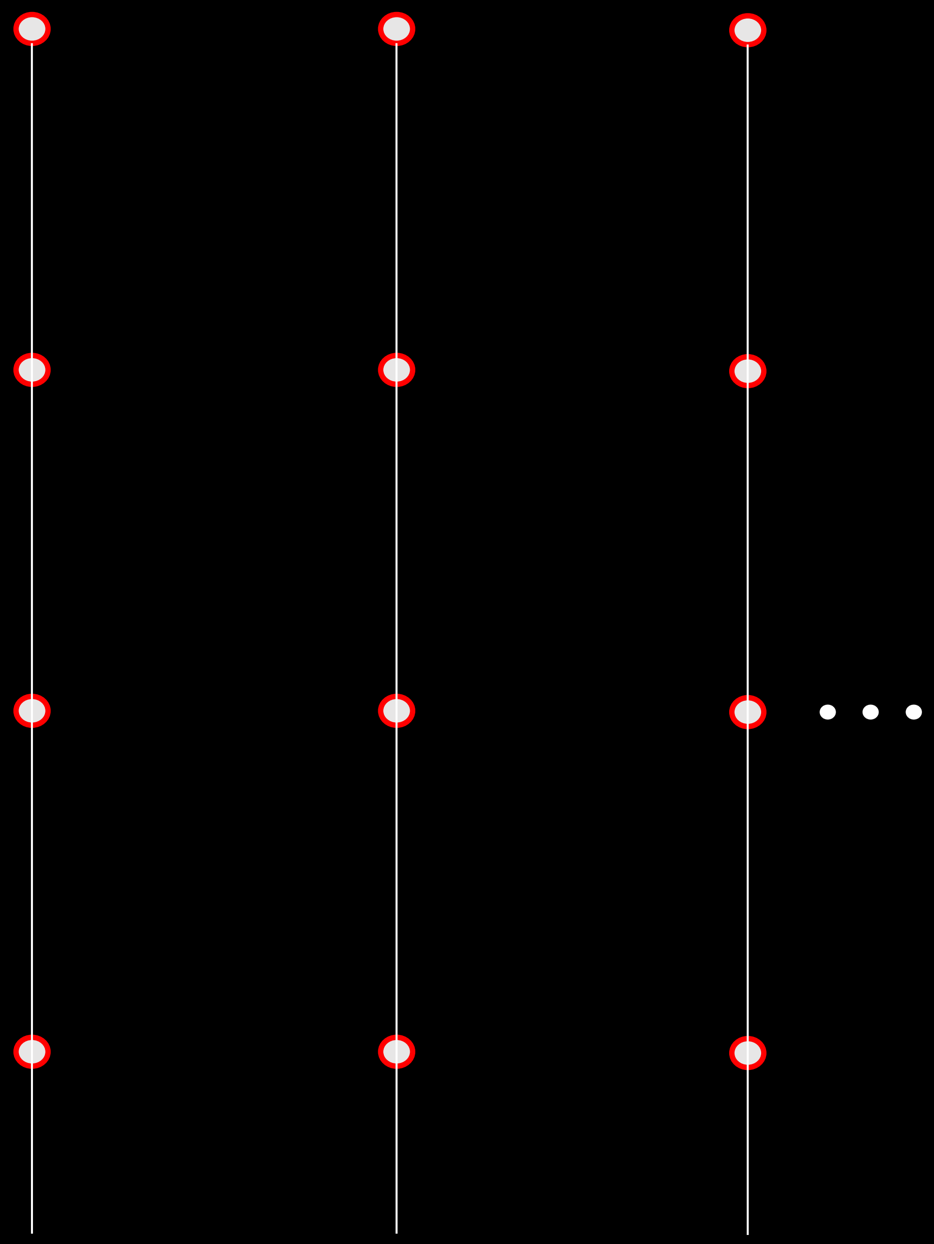
Atmospherics   Bioactivity   Radioactivity

- Location → View of the sky

Backgrounds:

<u>Atmospherics</u> <u>Bioactivity</u> <u>Radioactivity</u>

- **<u>Size</u>** → Statistics

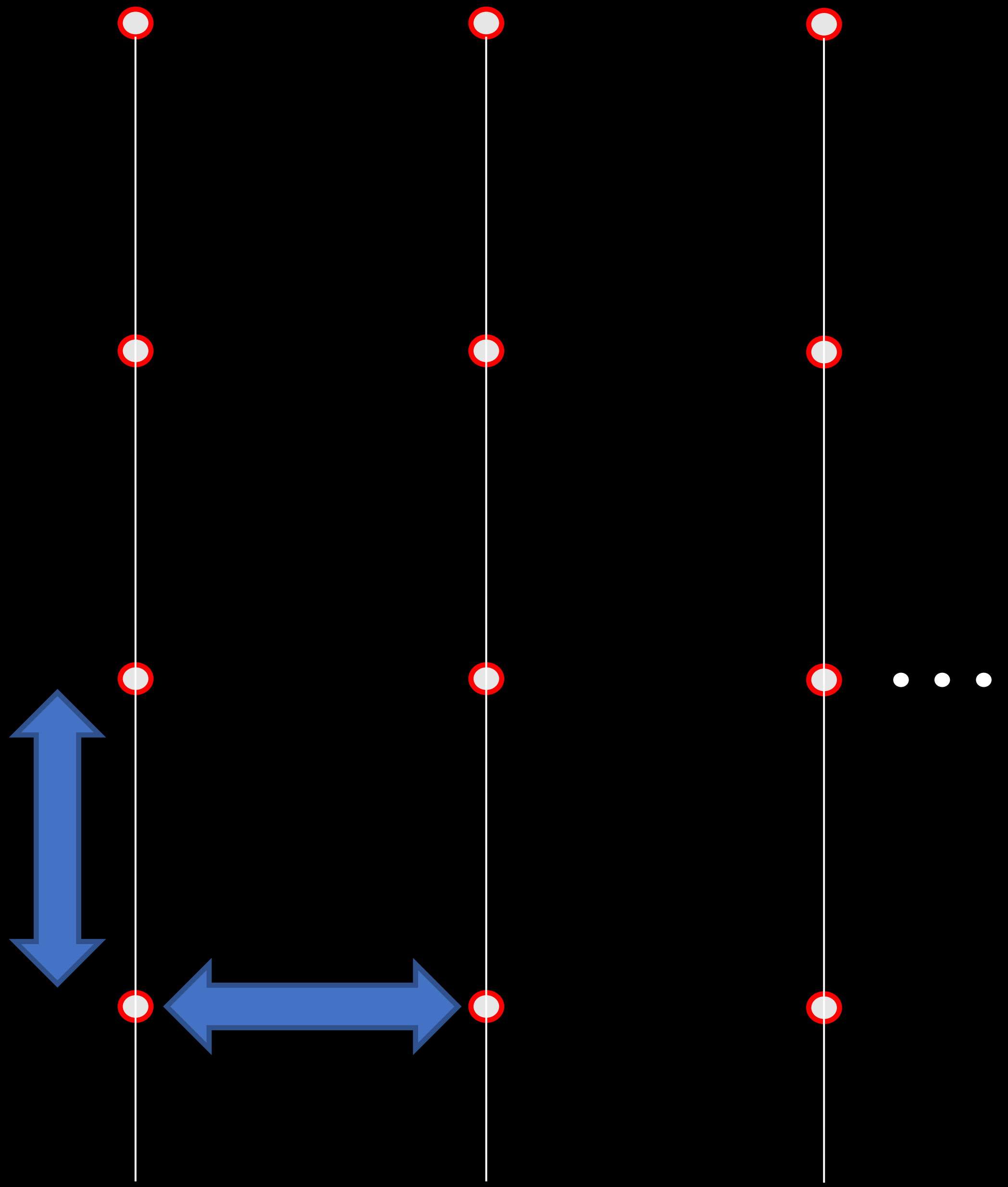


- Location → View of the sky

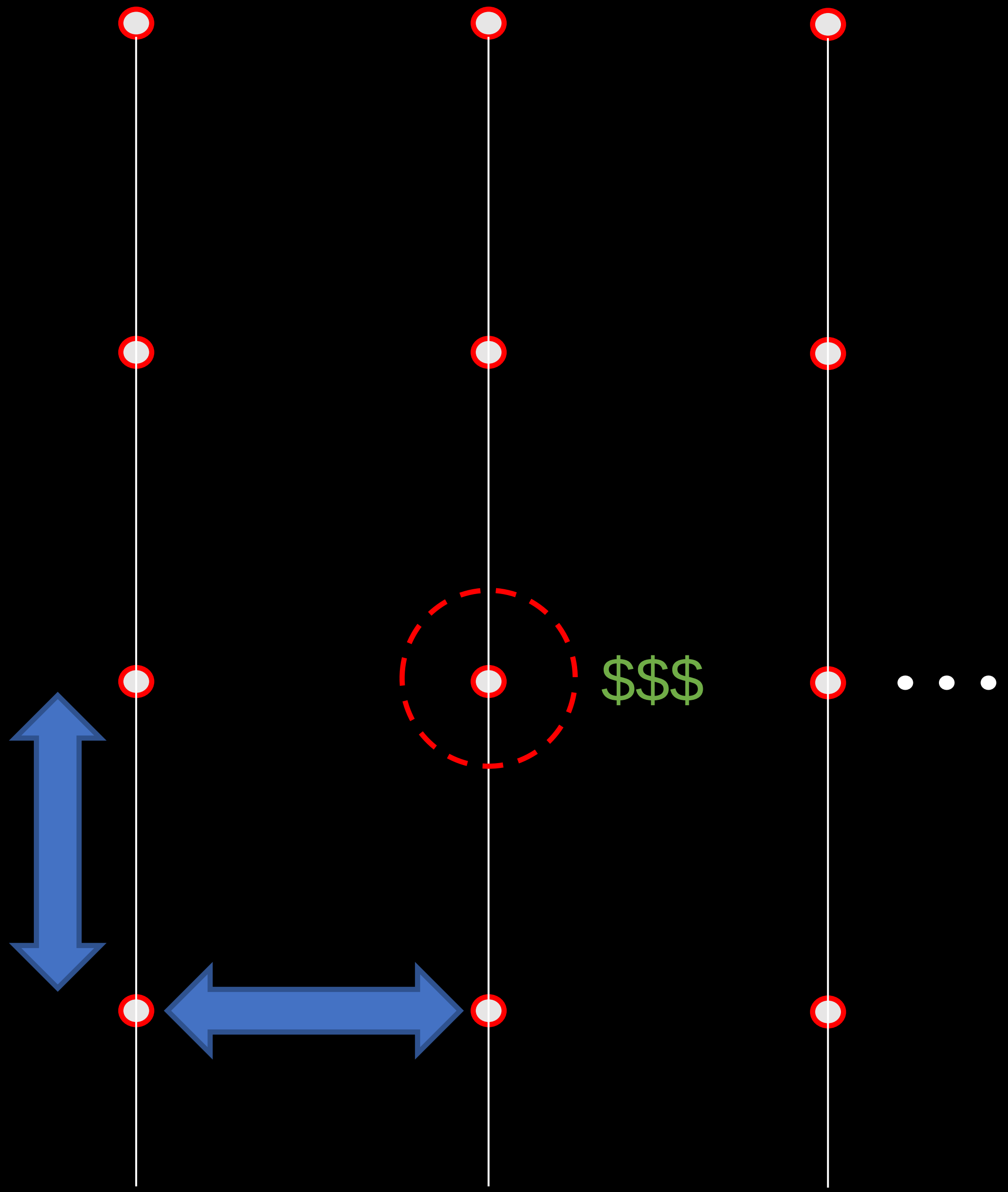
Backgrounds:
Atmospherics Bioactivity Radioactivity

- **Size** → Statistics

- **String + DOM separation**

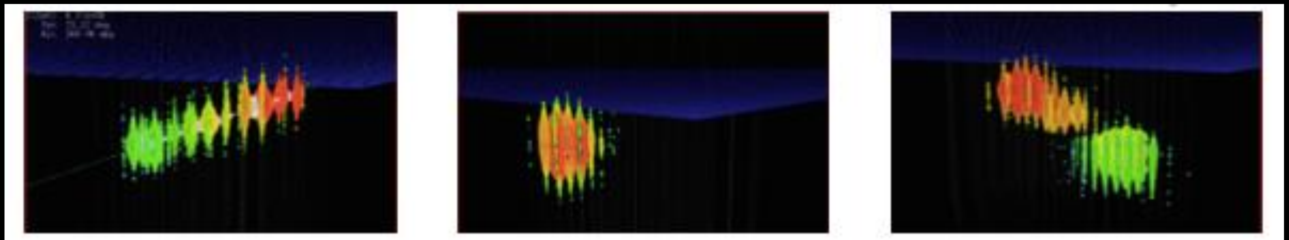


- Location → View of the sky
  - ↘ Backgrounds: Atmospherics, Bioactivity, Radioactivity
- **Size** → Statistics
- **String + DOM separation**
- **Optical Module quality**

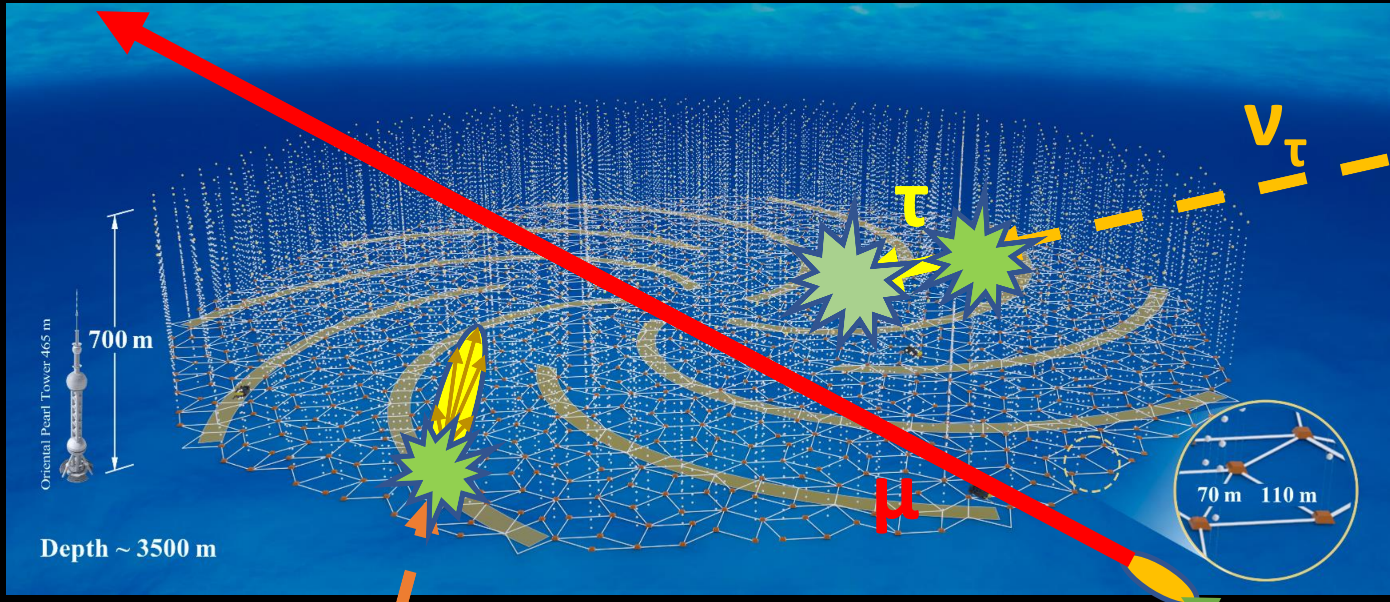


IceCube demonstrated the importance in measuring all neutrino flavours

ν_μ ν_e ν_τ



Track Cascade Double Cascade



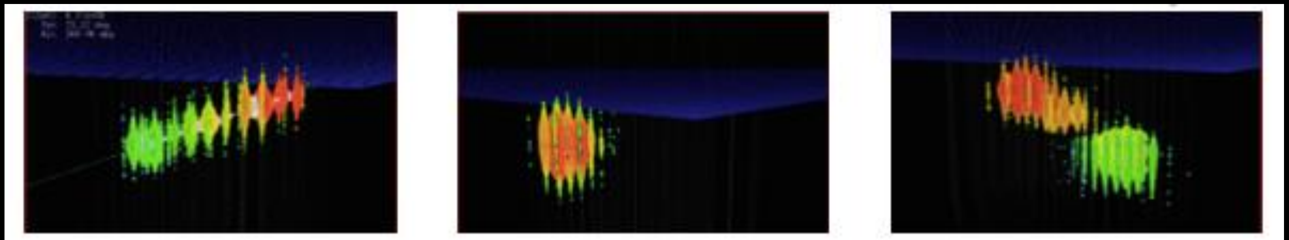
IceCube demonstrated the importance in measuring <u>all</u> neutrino flavours

Improved Signal Extraction

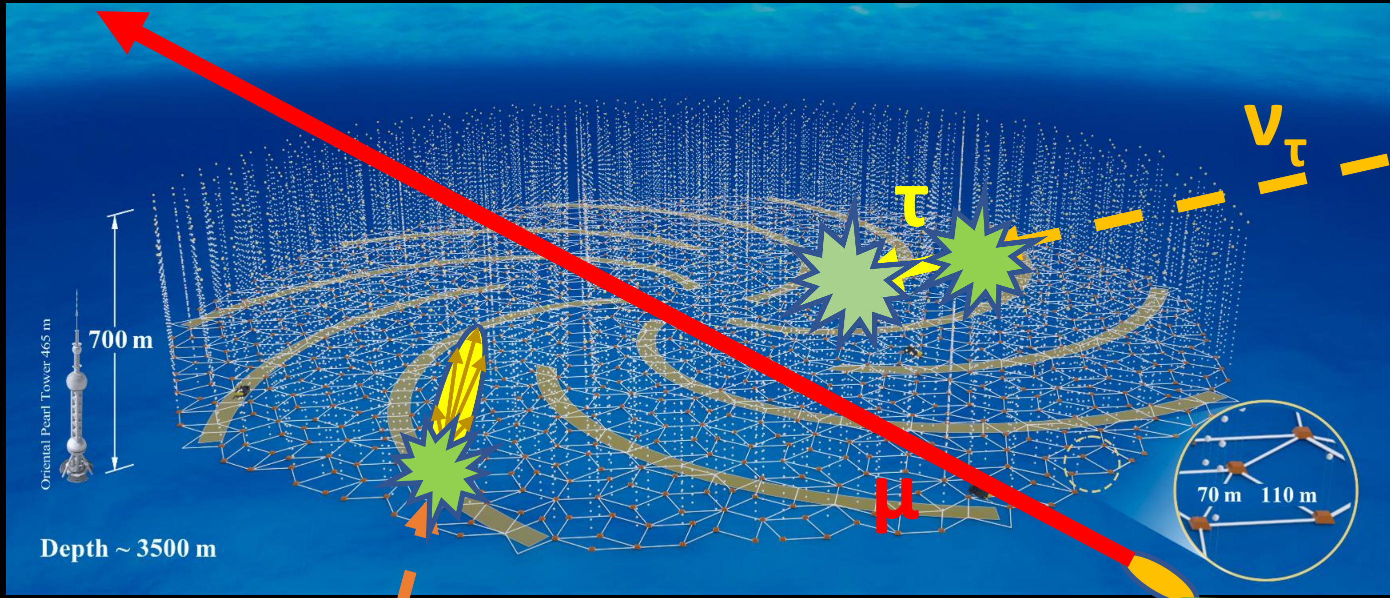
- Probe for neutrino acceleration mechanisms

Neutrino Flavour Ratios:
- Tests Beyond Standard Model

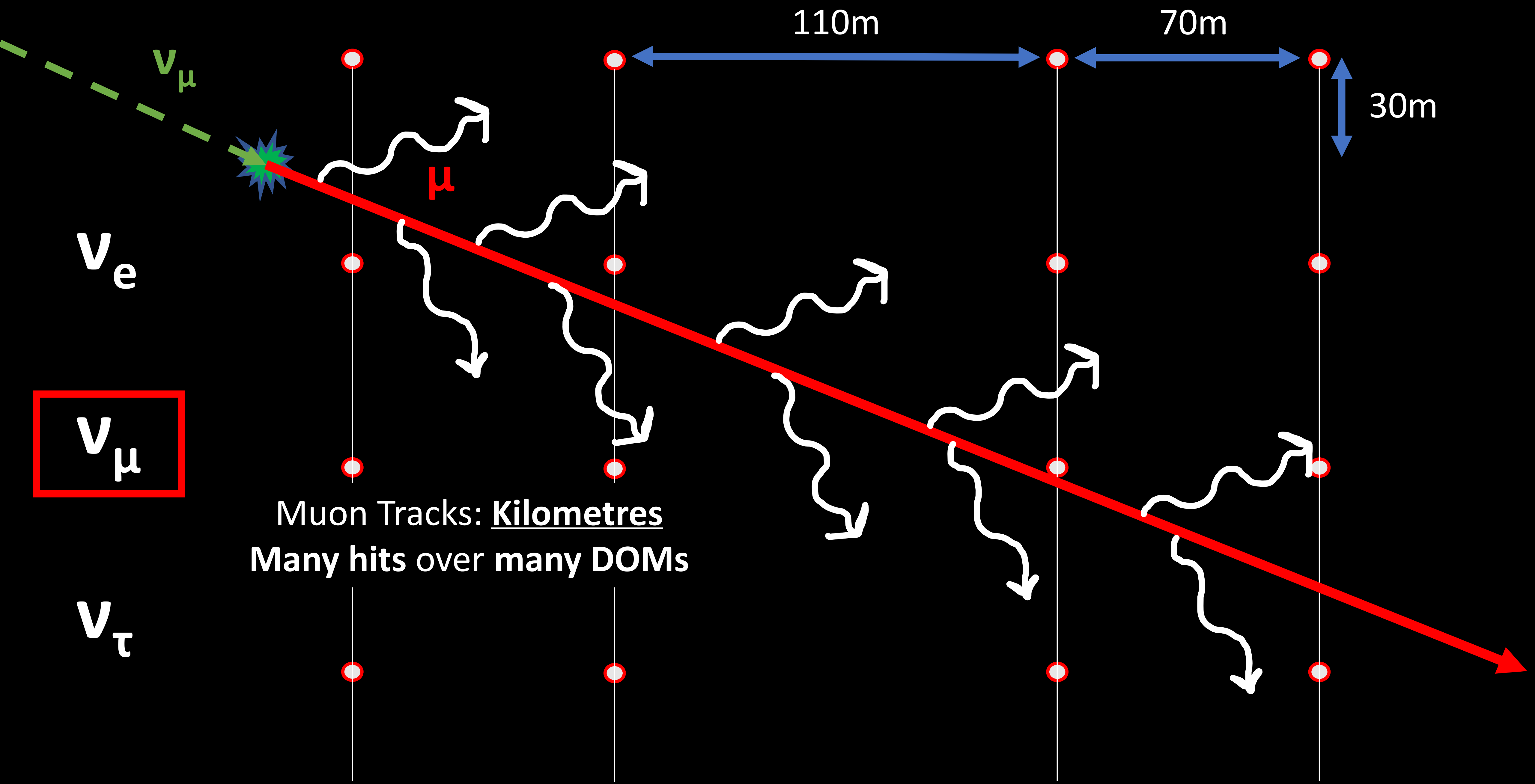
ν_μ ν_e ν_τ



Track | Cascade | Double Cascade



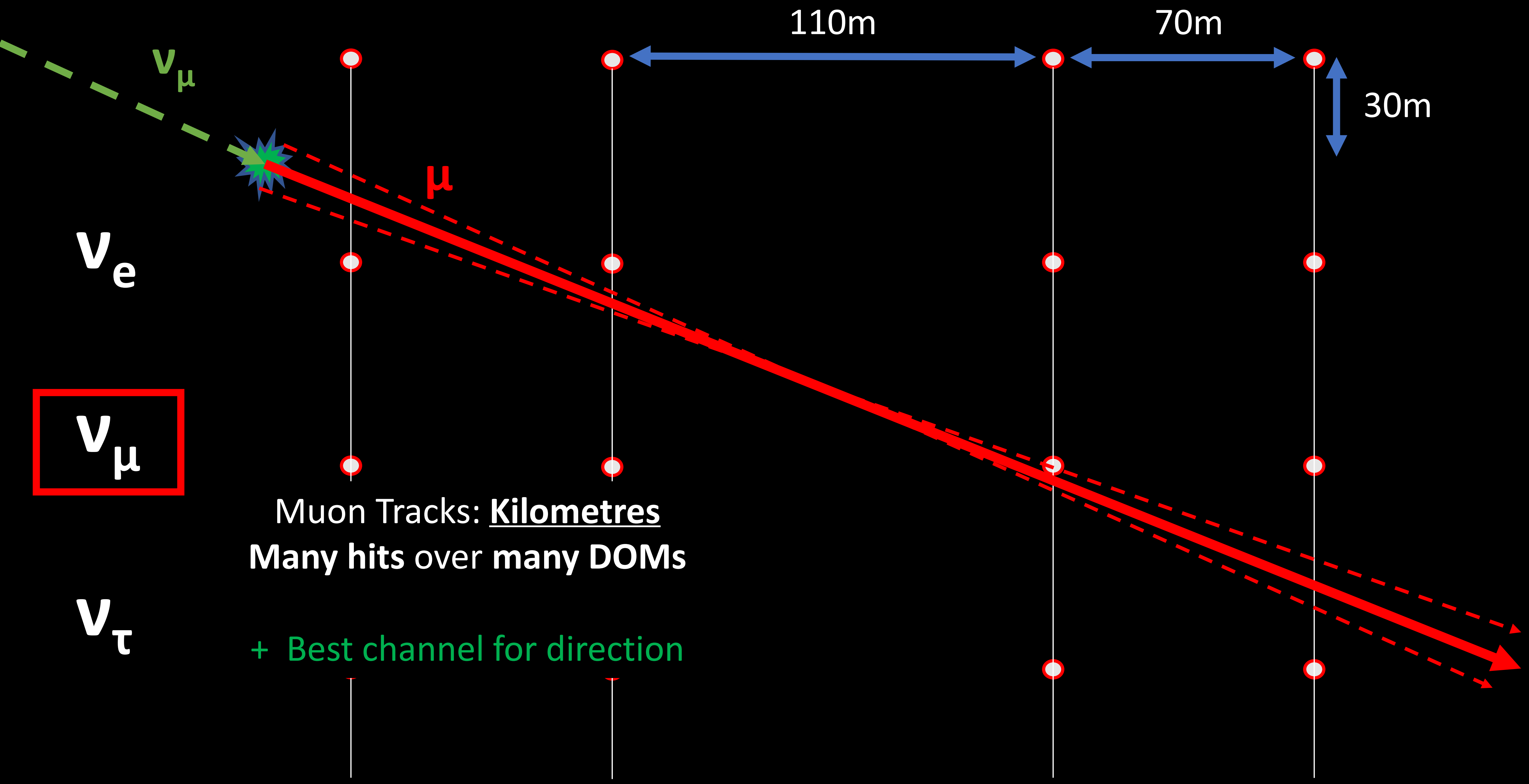
ν_e ν_μ


110m
70m
30m
νμ
μ
νe
νμ
ντ
Muon Tracks: **Kilometres**
Many hits over **many DOMs**

ν_e

ν_μ

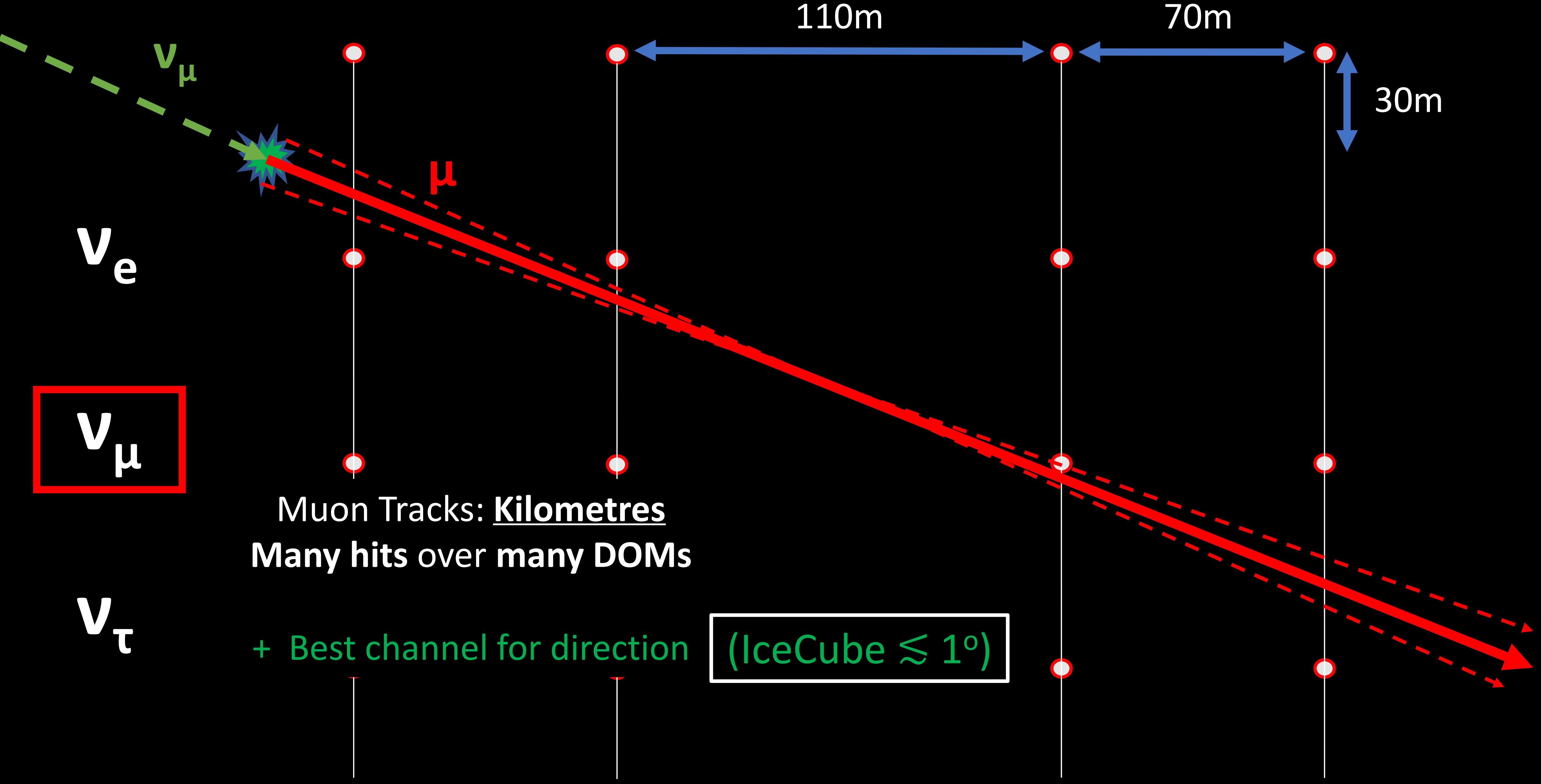
ν_τ



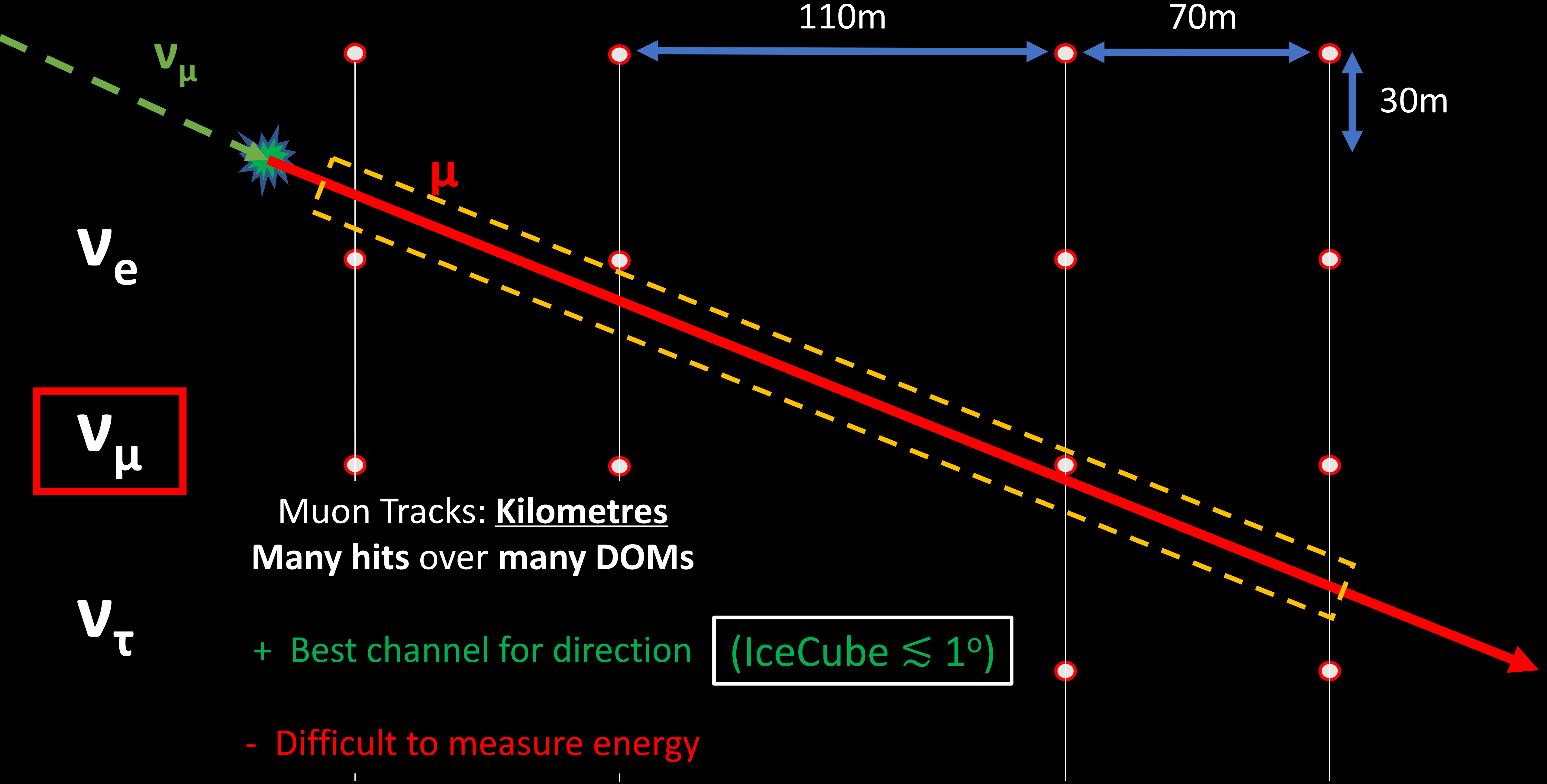
Muon Tracks: **Kilometres**

Many hits over **many DOMs**

\+ Best channel for direction



110m
70m
30m
ν_μ
μ
ν_e
ν_μ
ν_τ
Muon Tracks: **Kilometres**
Many hits over **many DOMs**
+ Best channel for direction
(IceCube ≲ 1°)



ν_e

ν_μ

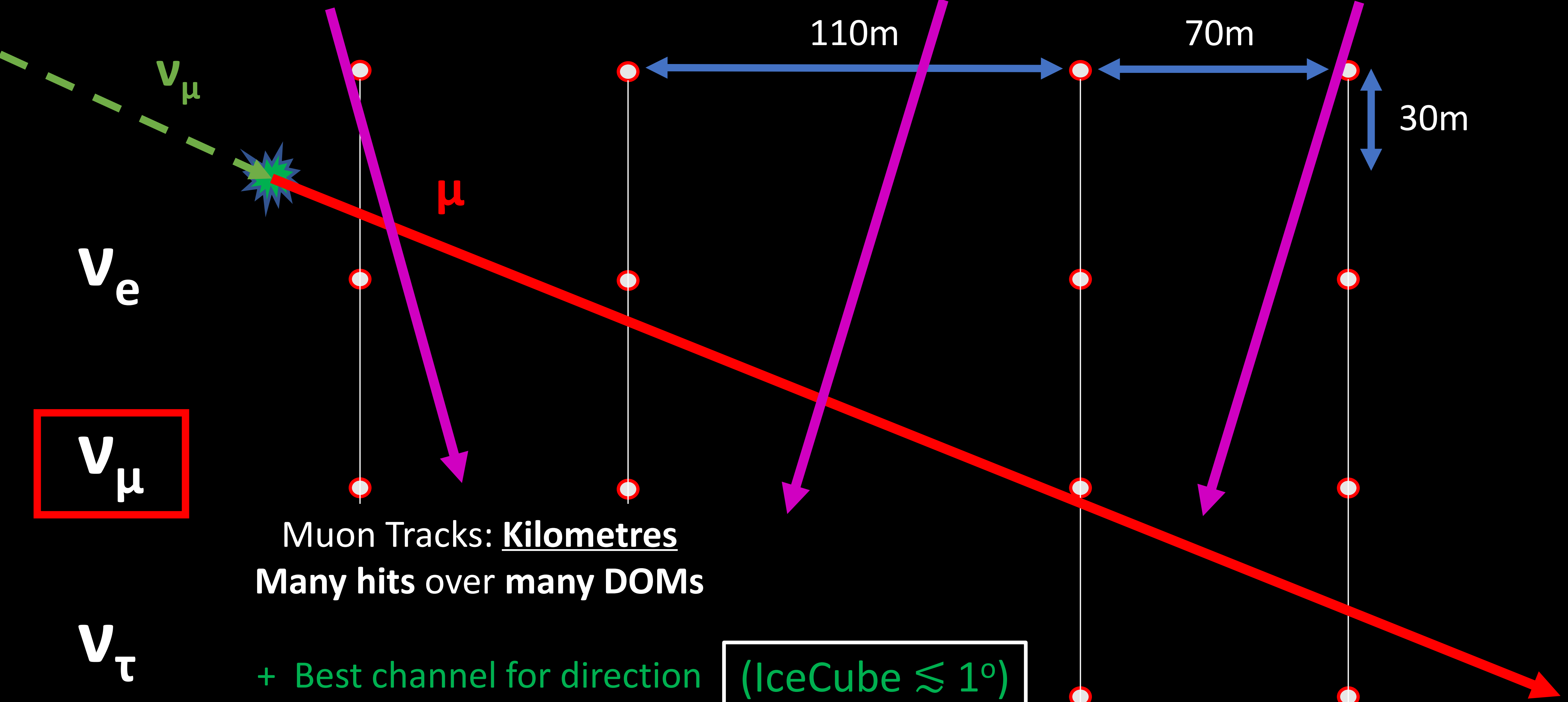
ν_τ

Muon Tracks: **Kilometres**

Many hits over **many DOMs**

\+ Best channel for direction (IceCube $\lesssim 1^o$)

\- Difficult to measure energy



ν_e

ν_μ

Muon Tracks: **Kilometres**

Many hits over **many DOMs**

ν_τ

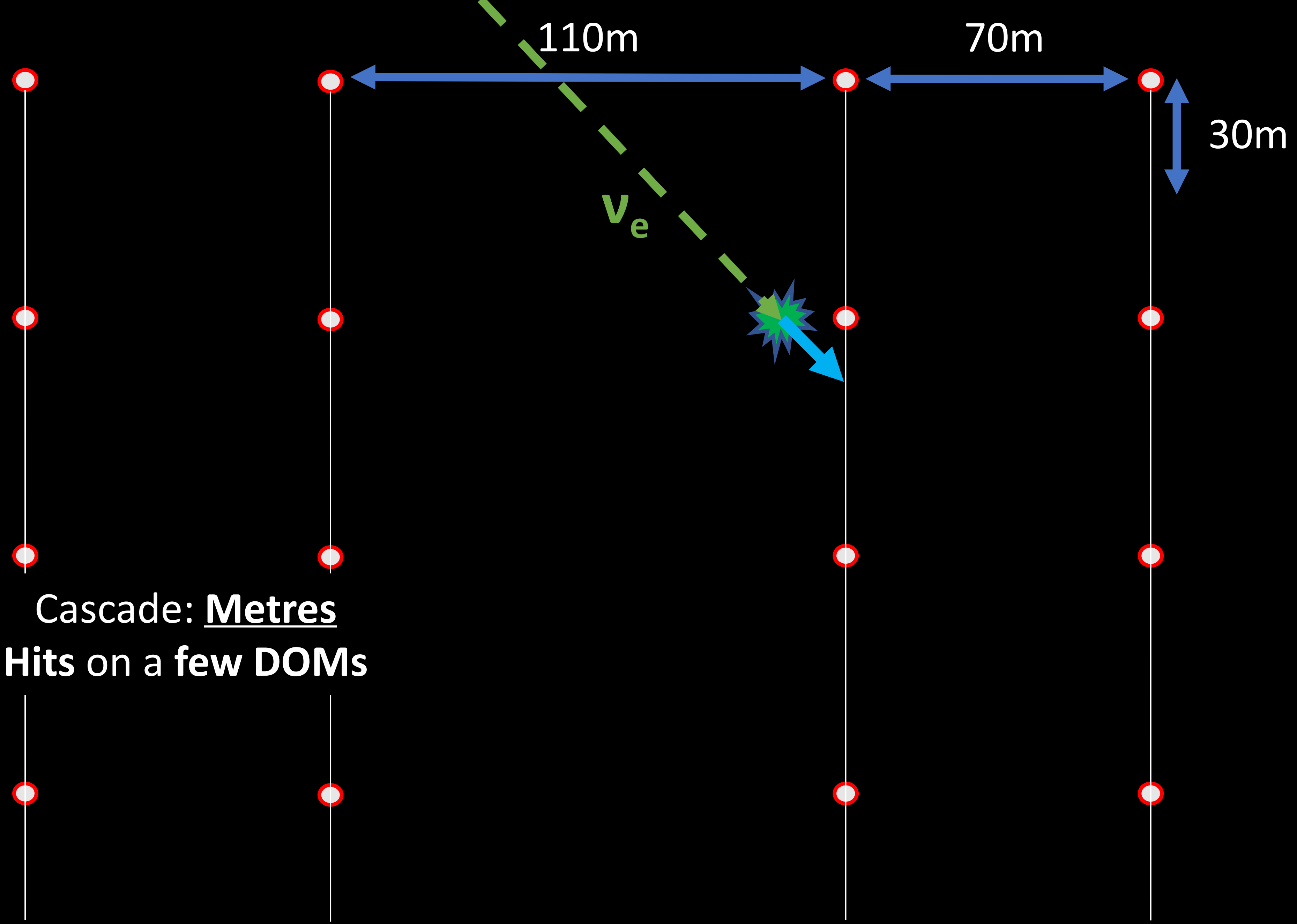
+ Best channel for direction (IceCube $\lesssim 1^o$)

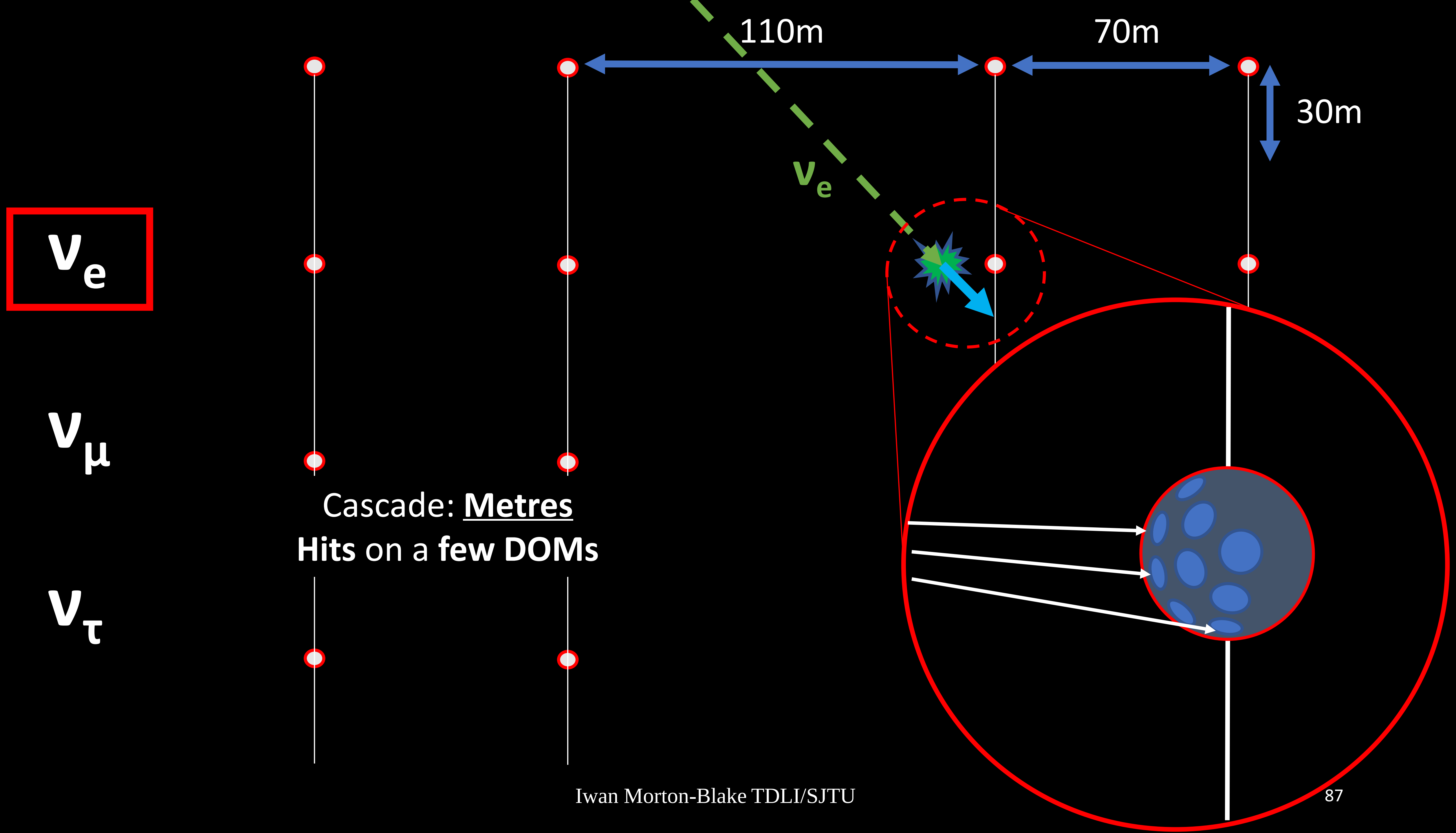
- Difficult to measure energy
- Atmospheric backgrounds

ν_e

ν_μ

ν_τ





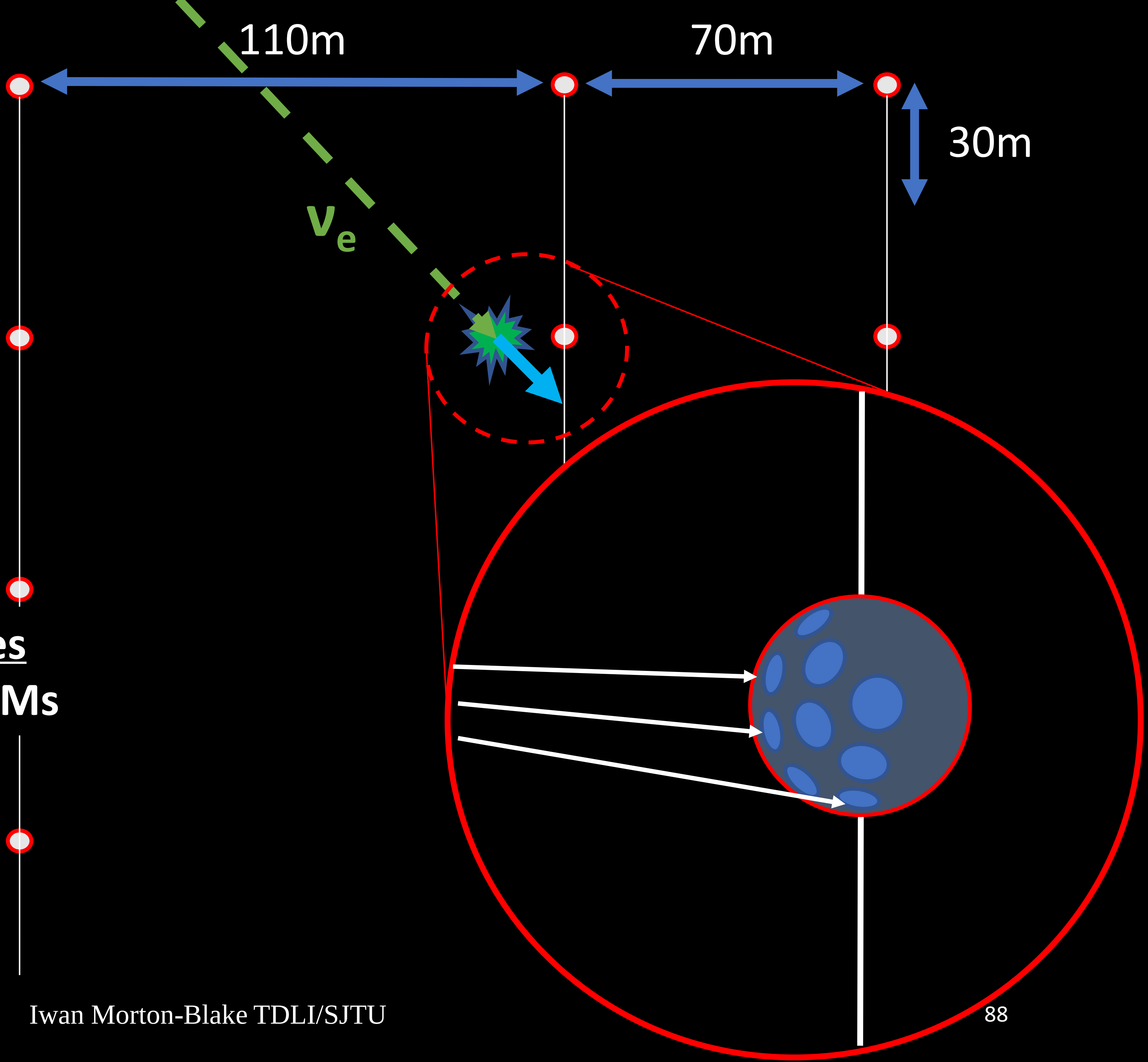
ν_e
ν_μ
ν_τ
110m
70m
30m
ν_e
Cascade: **Metres**
Hits on a **few DOMs**

ν_e

ν_μ

ν_τ

e.g. Super-K
13,000 PMTs



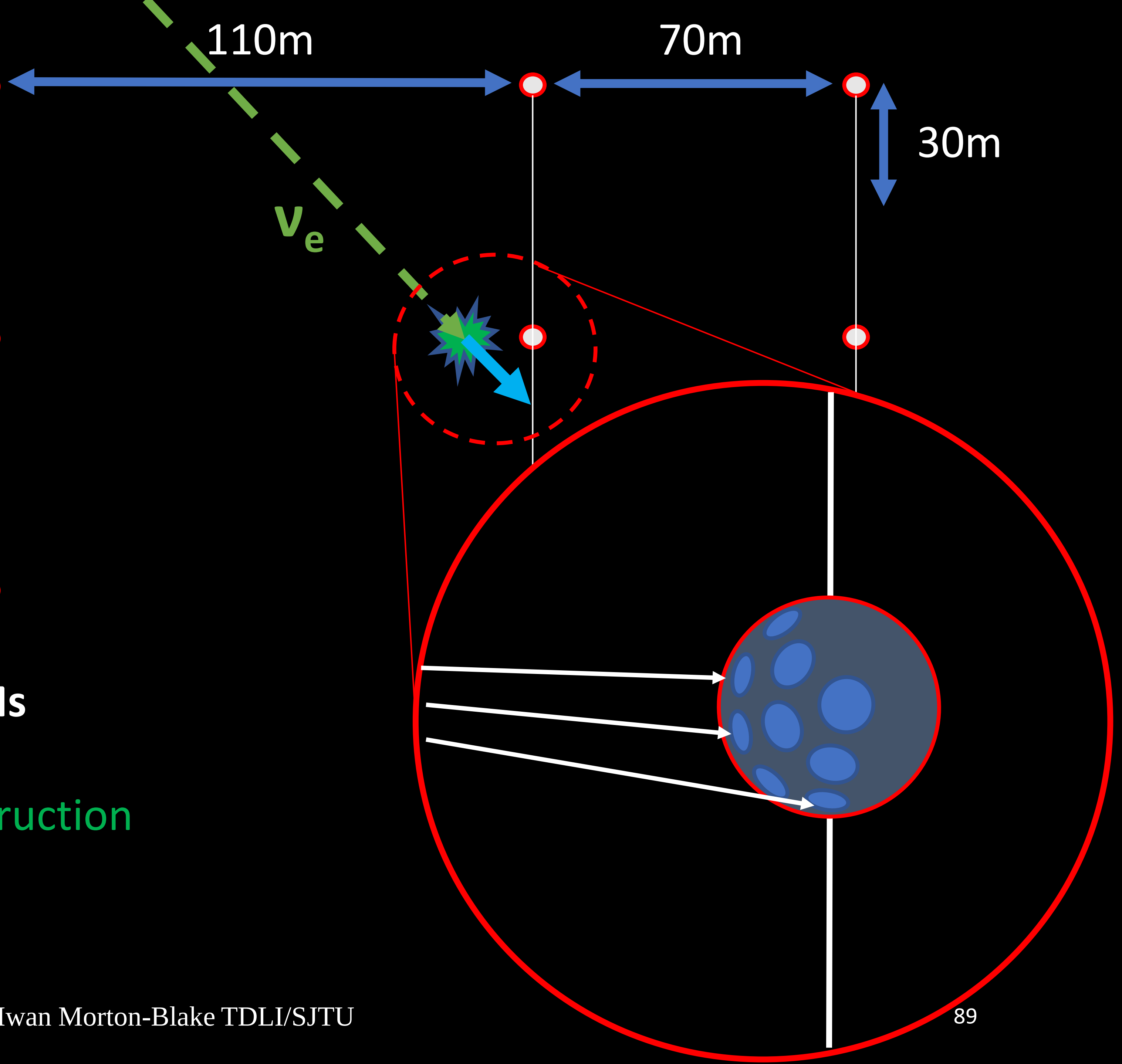
Cascade: **Metres**

Hits on a **few DOMs**

ν_e

ν_μ

ν_τ



Cascade: **Metres**

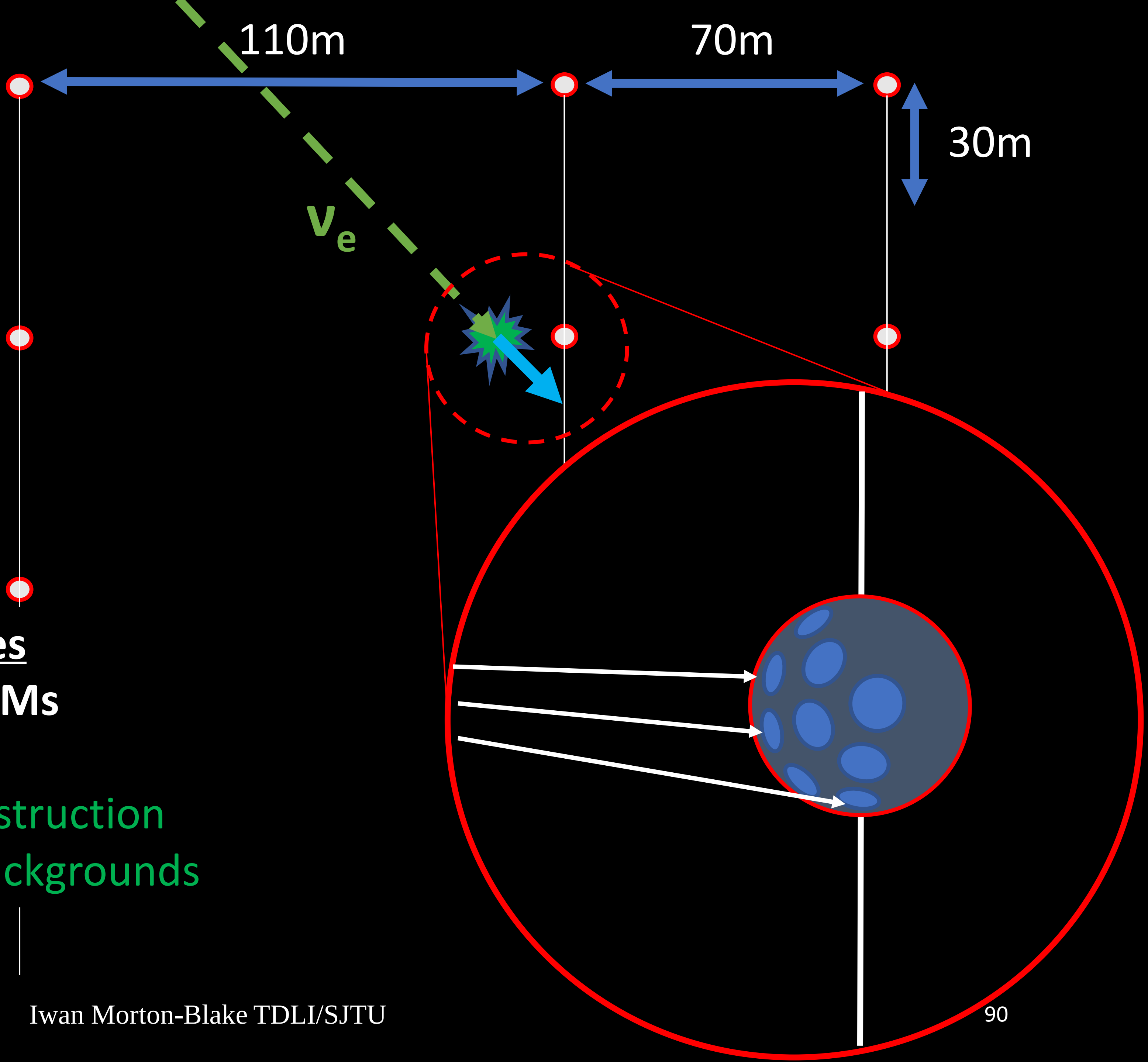
Hits on a **few DOMs**

\+ Better energy reconstruction

ν_e

ν_μ

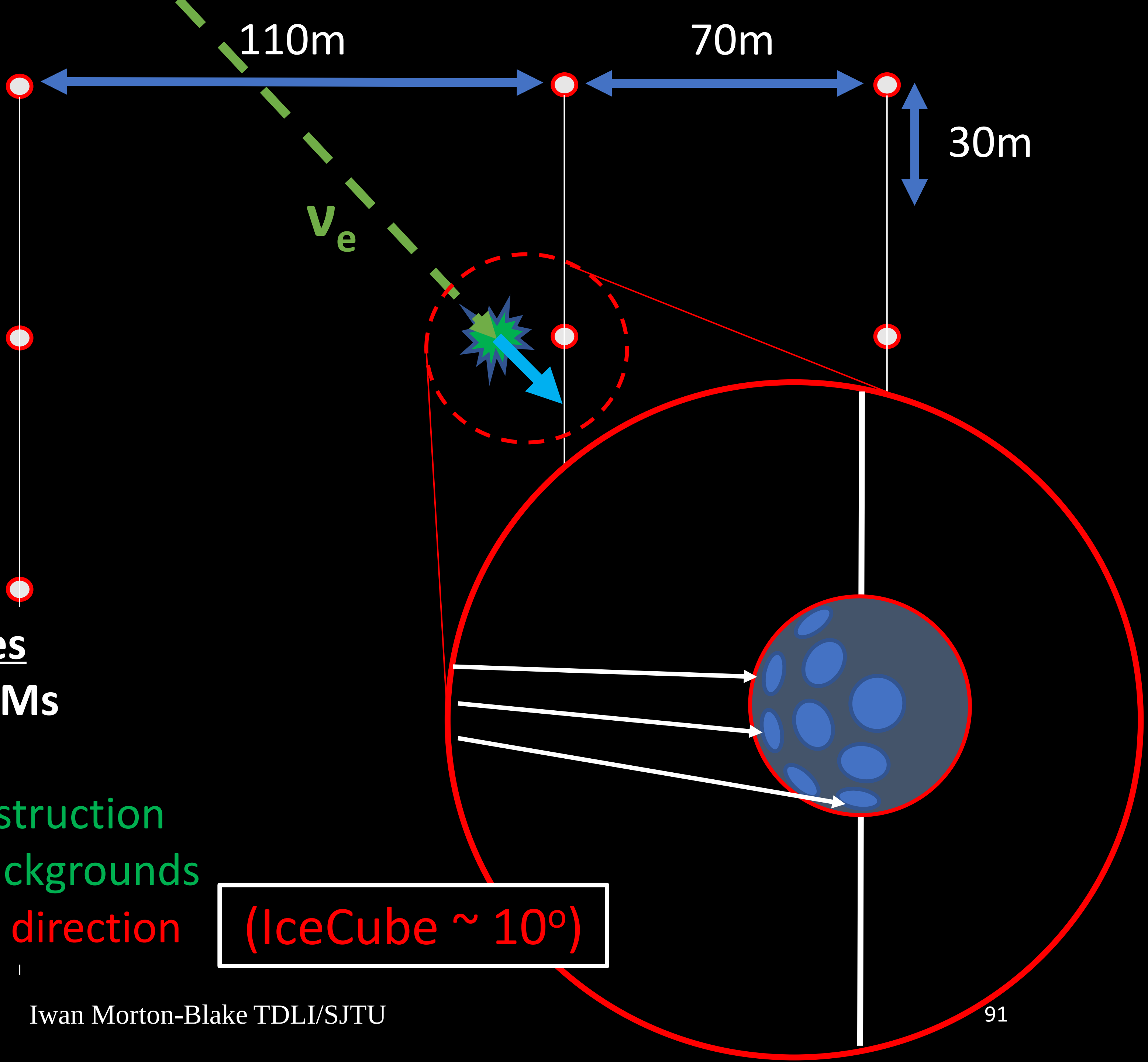
ν_τ



Cascade: **Metres**

Hits on a **few DOMs**

+ Better energy reconstruction
+ Lower atmospheric backgrounds



ν_e

ν_μ

ν_τ

Cascade: **Metres**

Hits on a **few DOMs**

\+ Better energy reconstruction

\+ Lower atmospheric backgrounds

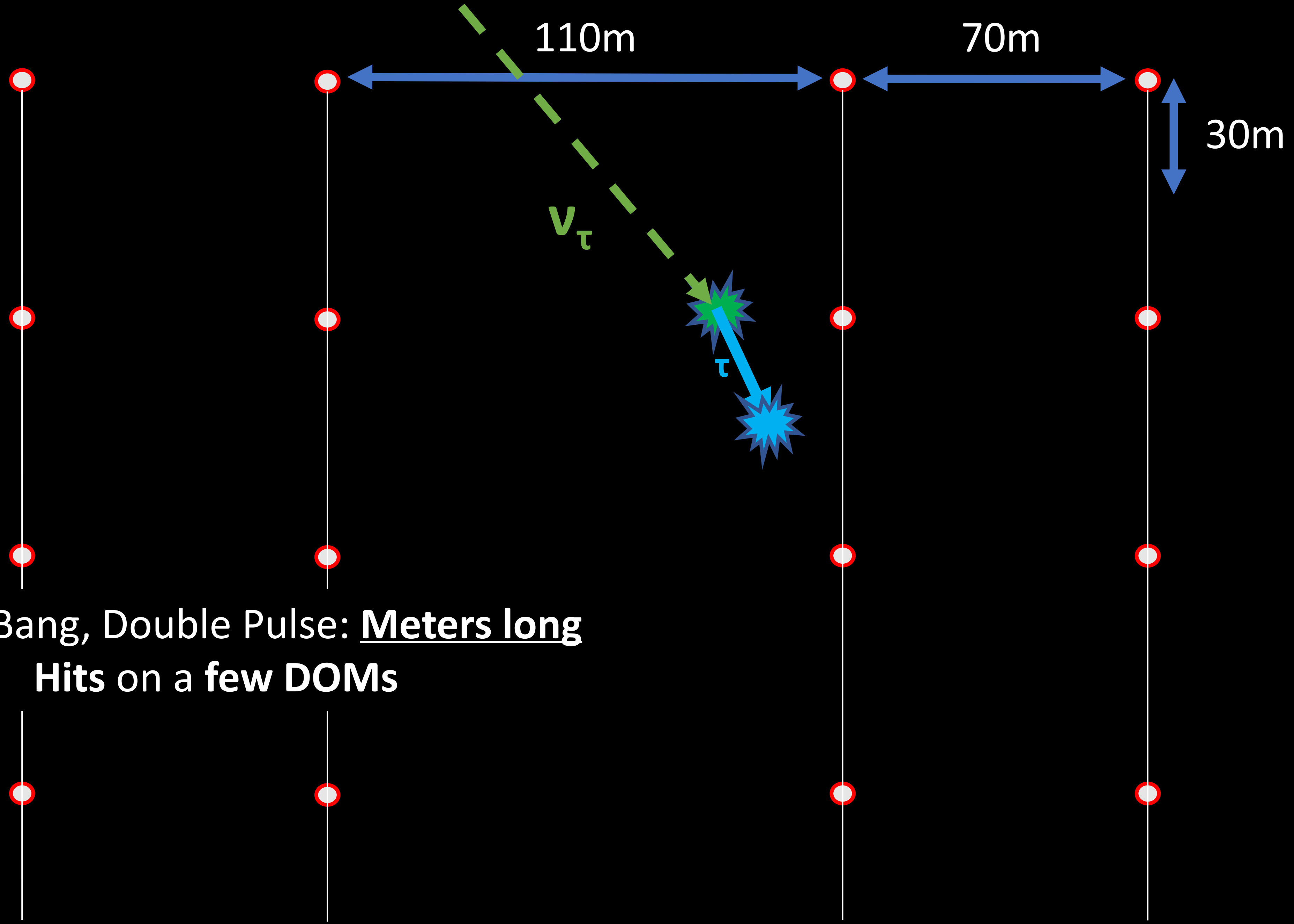
\- Harder to reconstruct direction

(IceCube ~ 10°)

ν_e

ν_μ

ν_τ



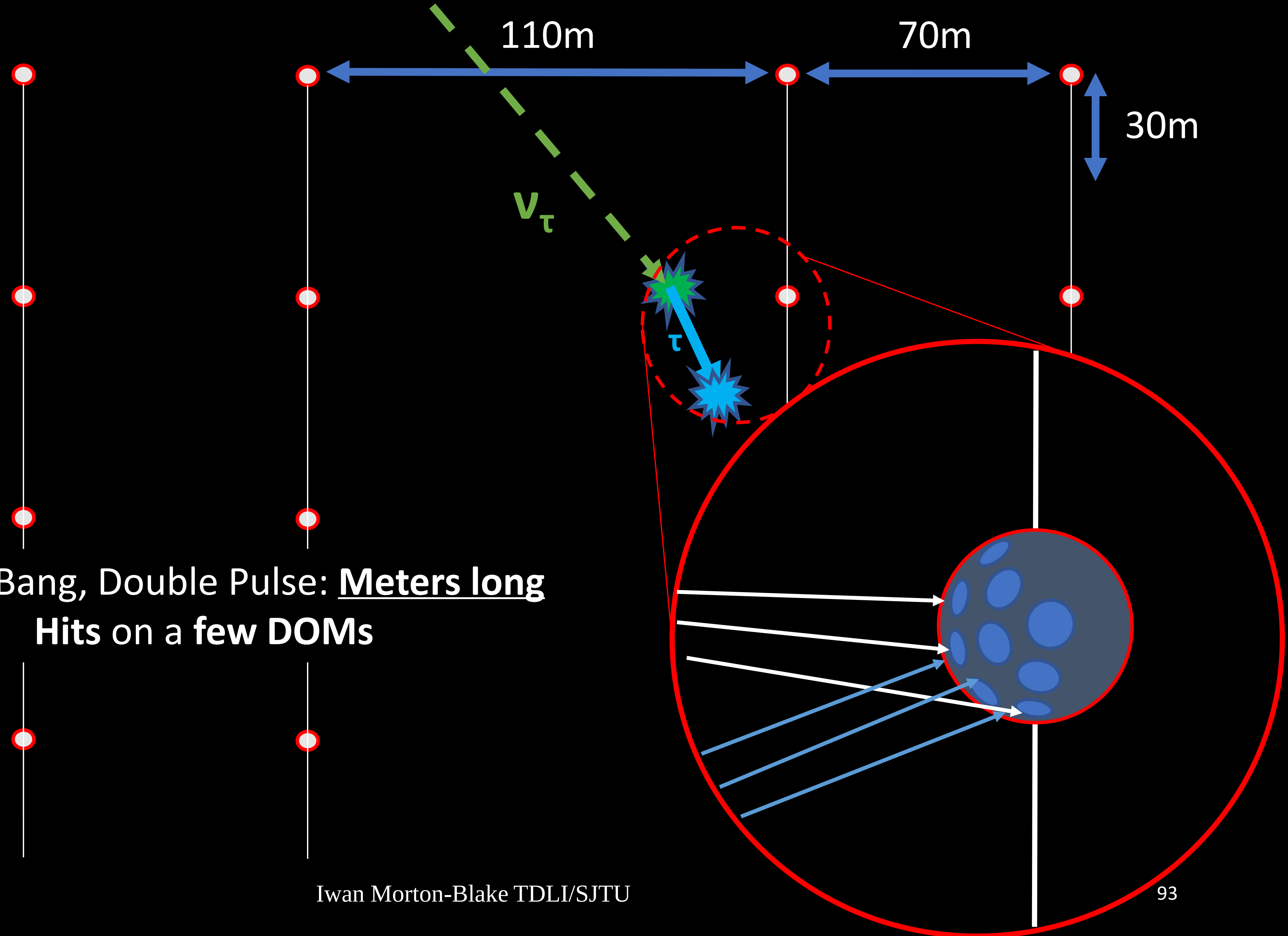
Double Bang, Double Pulse: **<u>Meters long</u>**

Hits on a **few DOMs**

ν_e

ν_μ

ν_τ



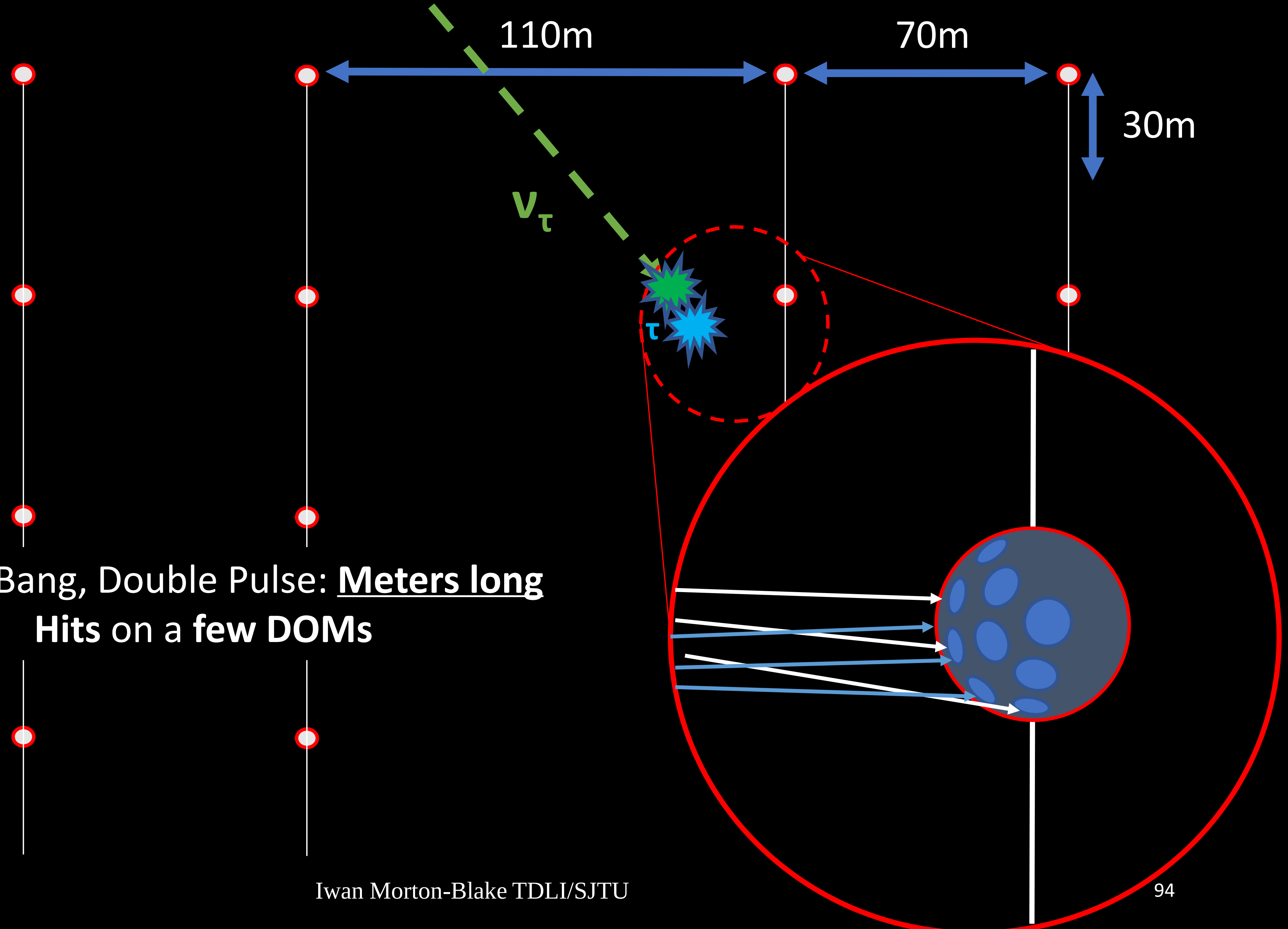
Double Bang, Double Pulse: **Meters long**

Hits on a **few DOMs**

ν_e

ν_μ

ν_τ



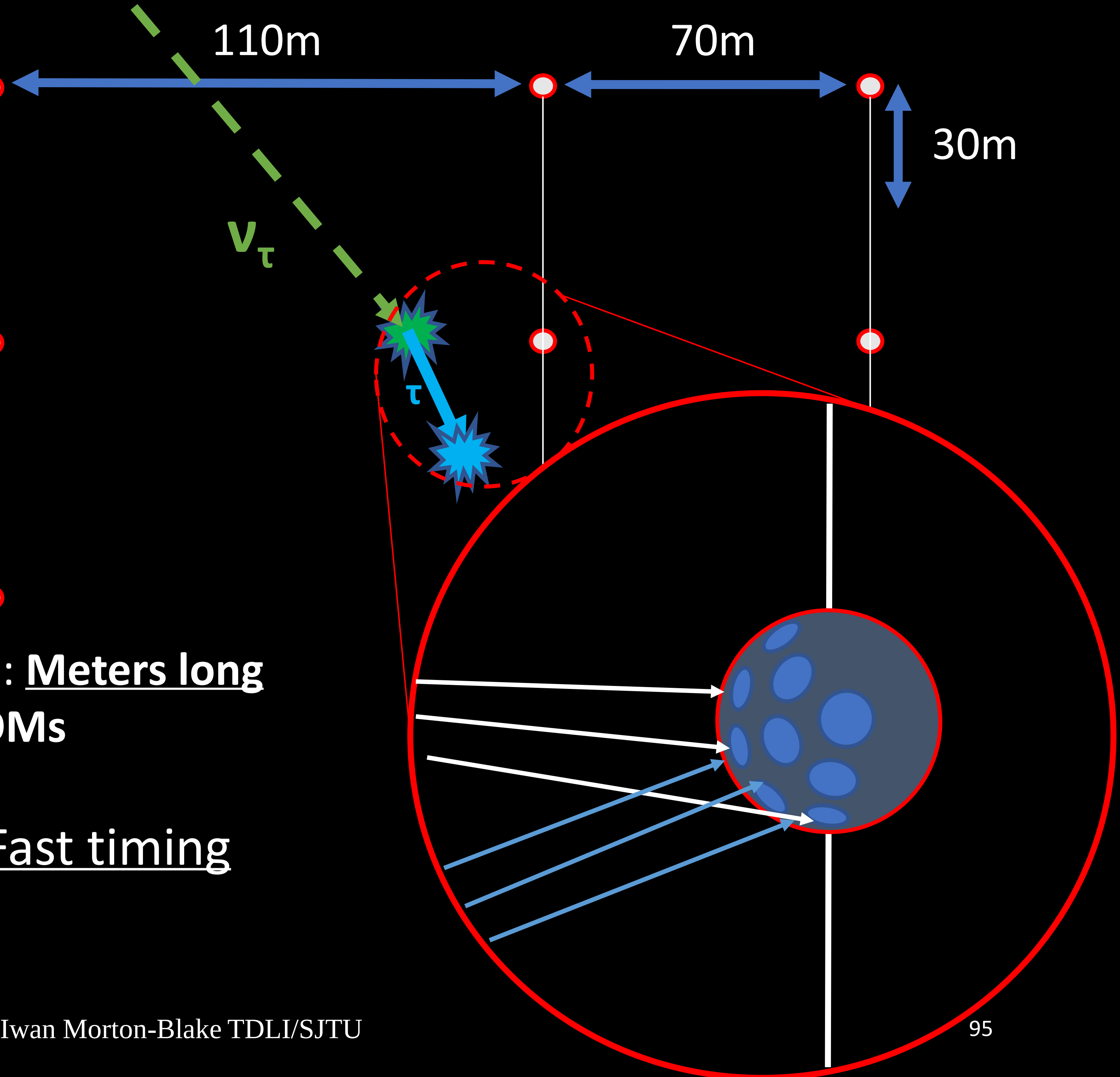
Double Bang, Double Pulse: **Meters long**

Hits on a **few DOMs**

ν_e

ν_μ

ν_τ



Double Bang, Double Pulse: **Meters long**
Hits on a **few DOMs**

Separate tau decay - Fast timing

ν_e

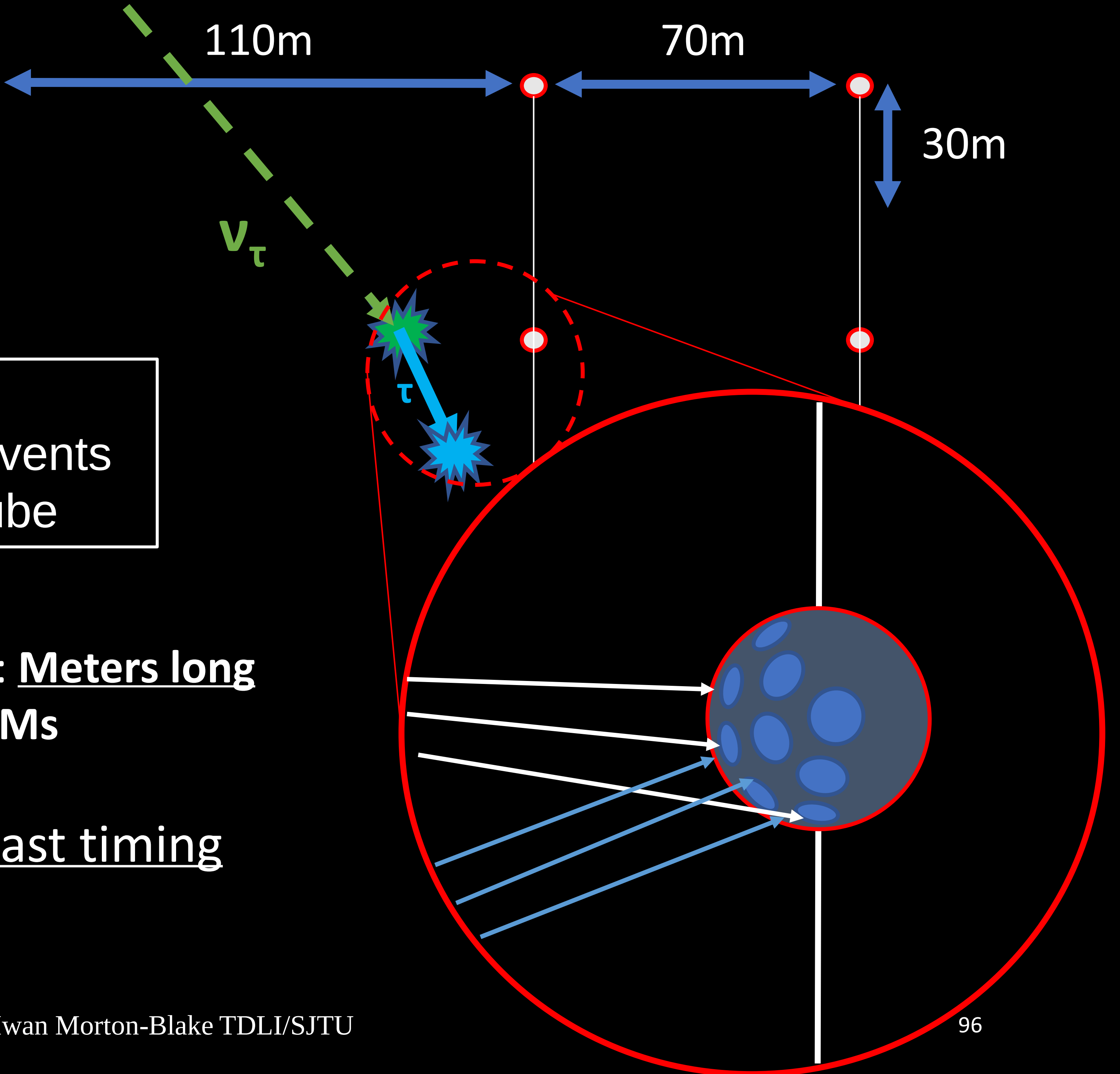
ν_μ

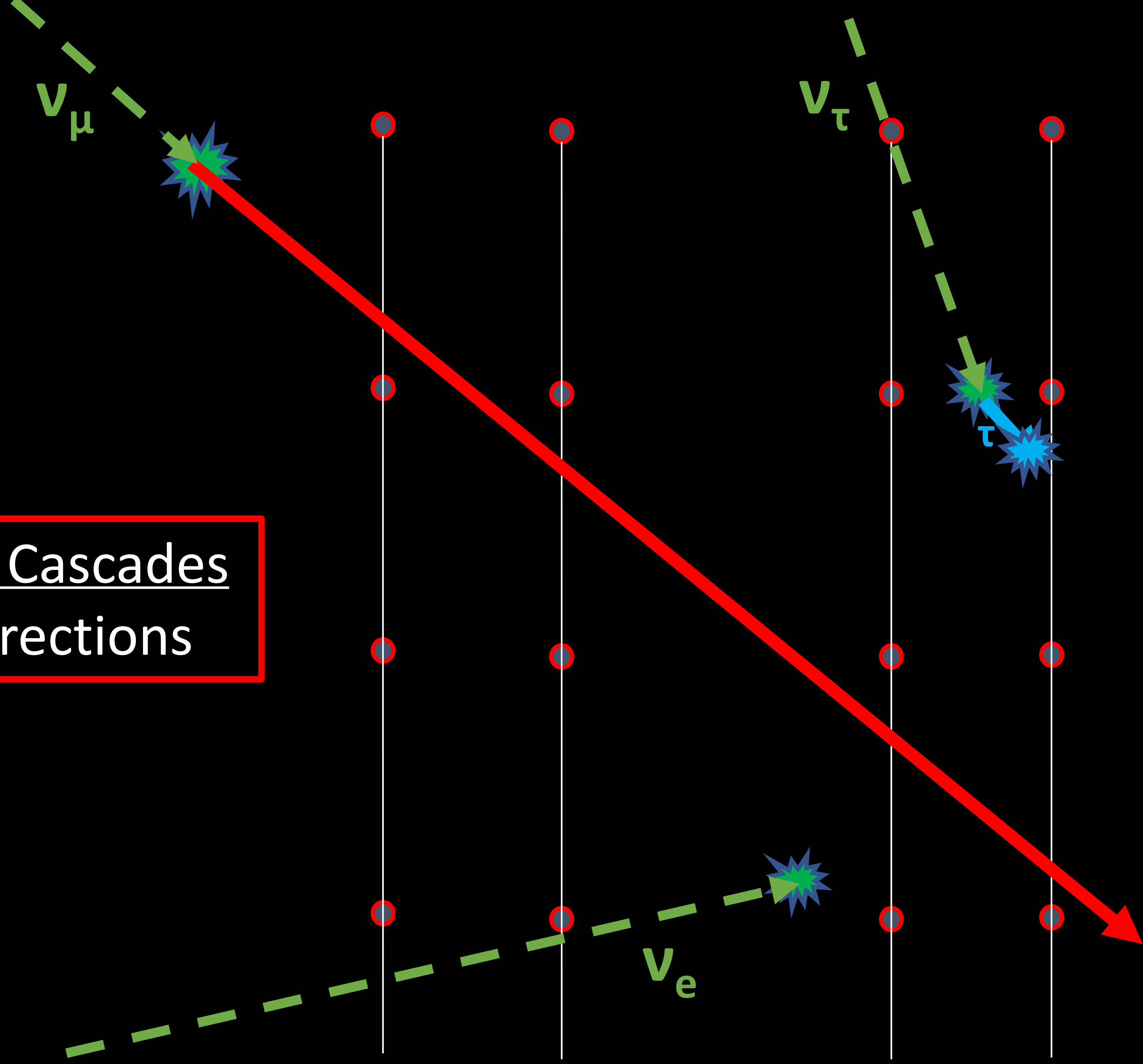
ν_τ

Difficult!
e.g. 3 tau candidate events
in ~8years of IceCube

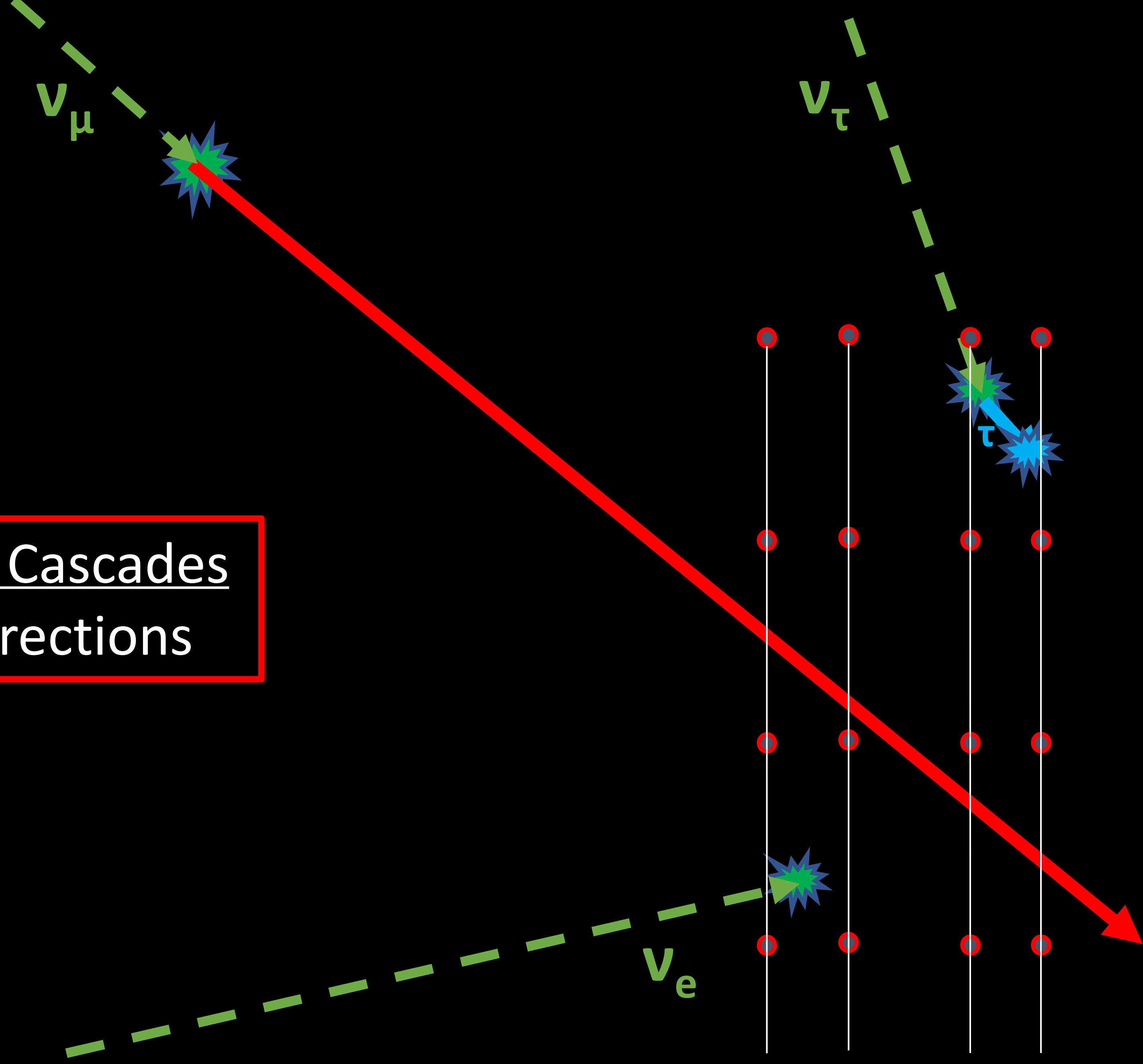
Double Bang, Double Pulse: **Meters long**
Hits on a **few DOMs**

Separate tau decay - Fast timing





Optimising Design for Tracks **and** Cascades
Pushes geometry in opposite directions



Optimising Design for Tracks **and** Cascades
Pushes geometry in opposite directions

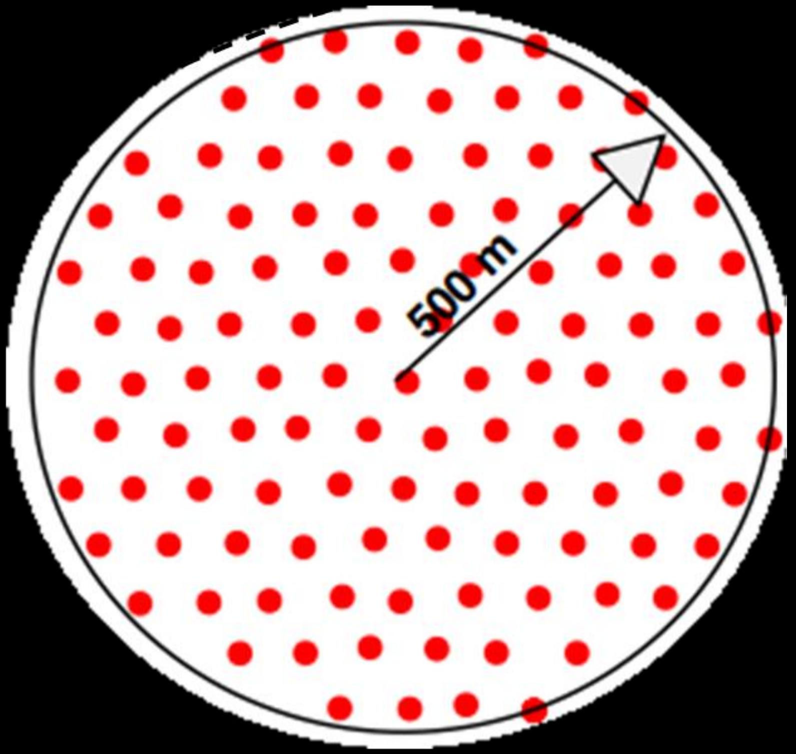
String + DOM Spacing

KM3NeT

Neutrino Oscillation

ORCA: ~GeV

Point Source Search



ARCA: 10s of GeV to PeV

DOM Design

IceCube
Downward-facing
10-inch PMT

KM3NeT
31x 3-inch PMTs

TRIDENT
Hybrid DOM:
3-inch PMTs + Silicon PMs

DOM Design

- High Detection Efficiency
- Fast Timing Resolution

  -> Track pointing resolution

  -> Tau identification

KM3NeT

P-ONE

Baikal GVD

IceCube Gen-2

TRIDENT

DOM Design

- High Detection Efficiency
- Fast Timing Resolution

  -> Track pointing resolution

  -> Tau identification
- High signal/noise ratio
- Incoming photon direction
- PMT hit pattern triggers on single DOMs

KM3NeT

P-ONE

Baikal GVD

IceCube Gen-2

TRIDENT

TRIDENT hybrid DOM – hDOM

Transit time spread

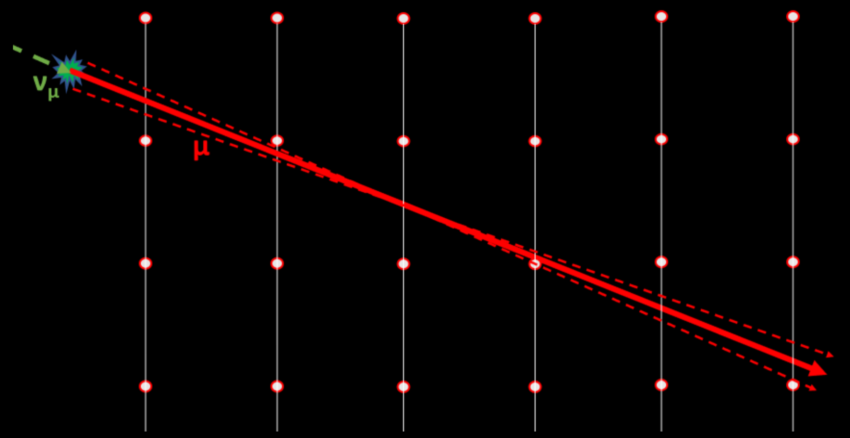
3-inch PMTs : nanoseconds

SiPMs: Picoseconds

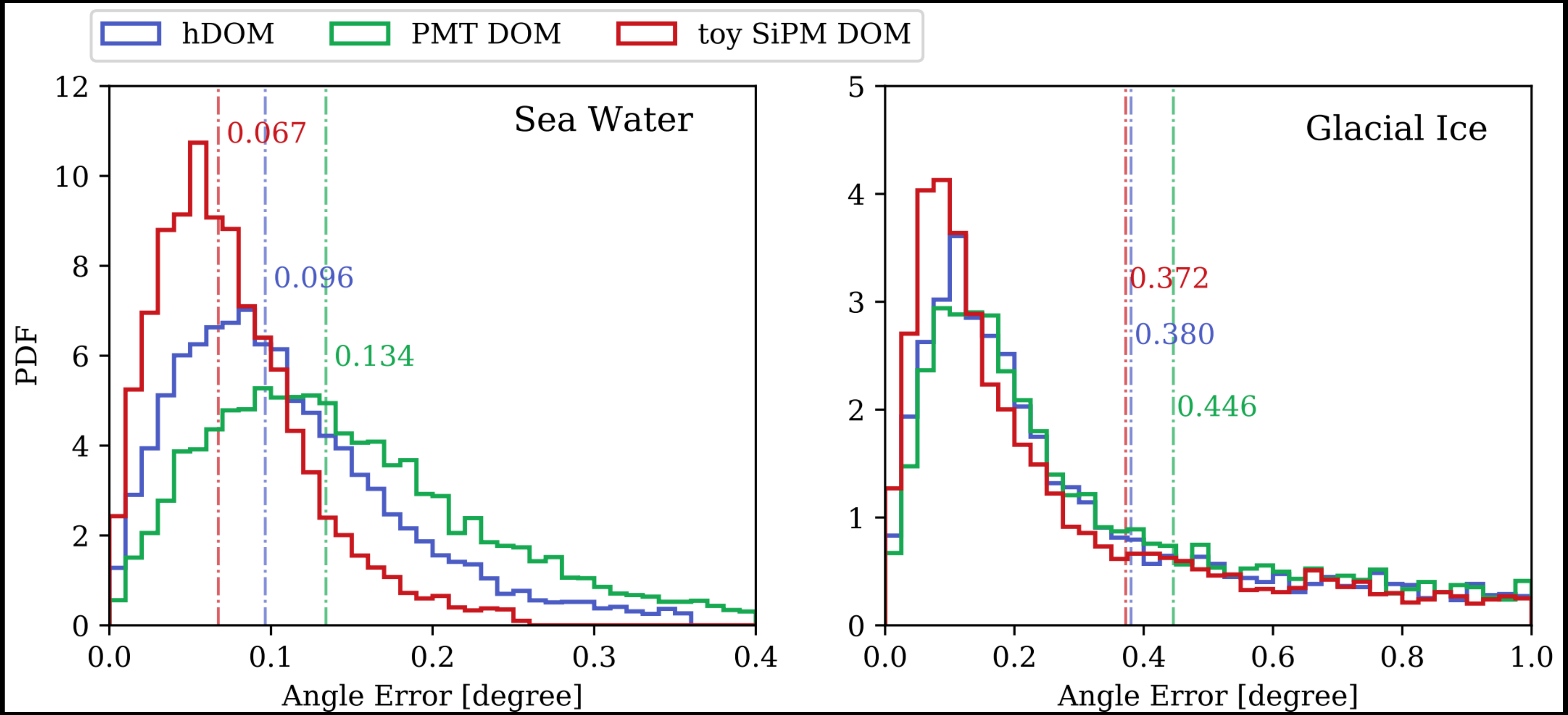
- Higher noise
- Expensive

Hybrid DOM:
3-inch PMTs + Silicon PMs

TRIDENT hybrid DOM – hDOM

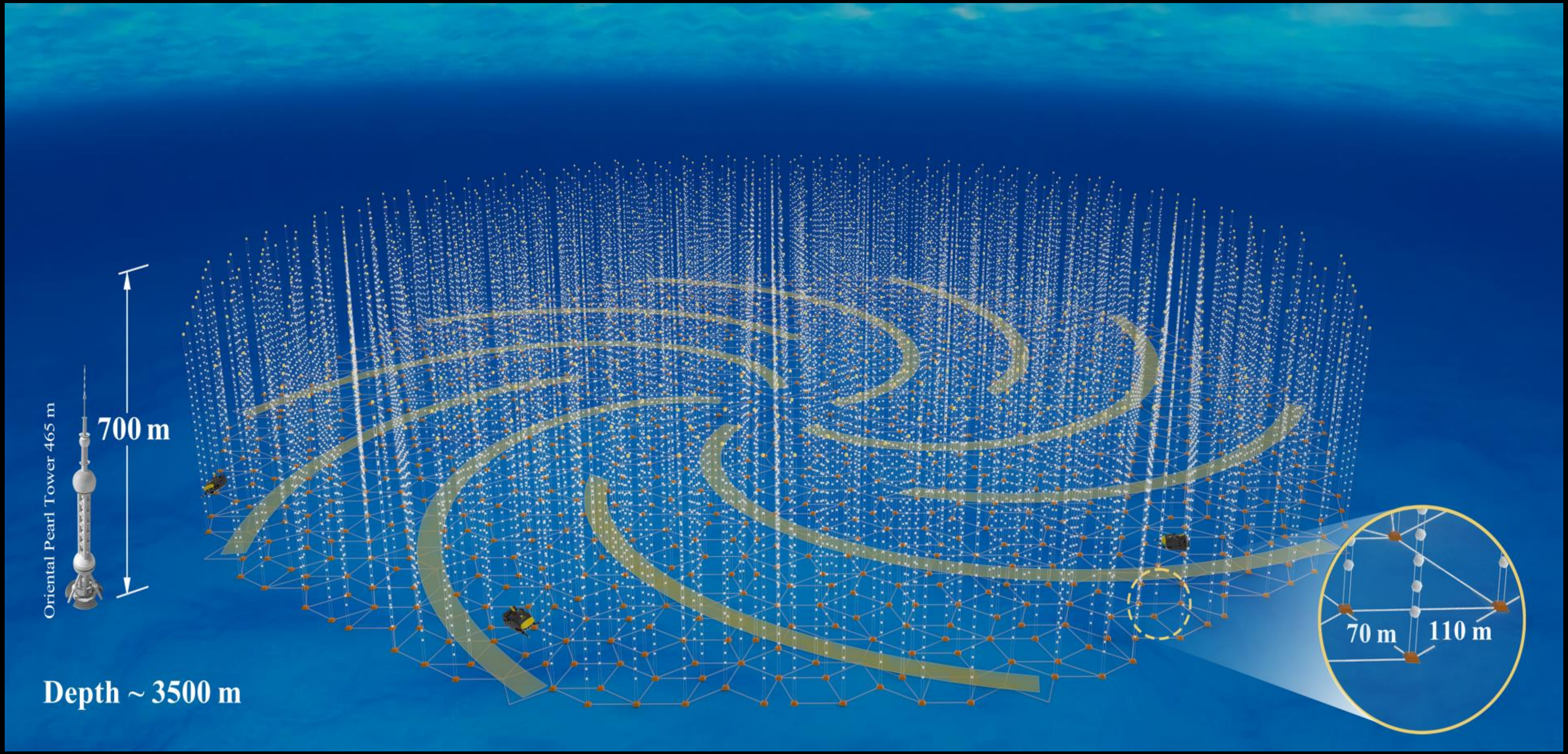


PMT + SiPM hDOM:
Muon track singular resolution ~40% improvement
Better than 0.1° (E > 100TeV)



TRIDENT Design

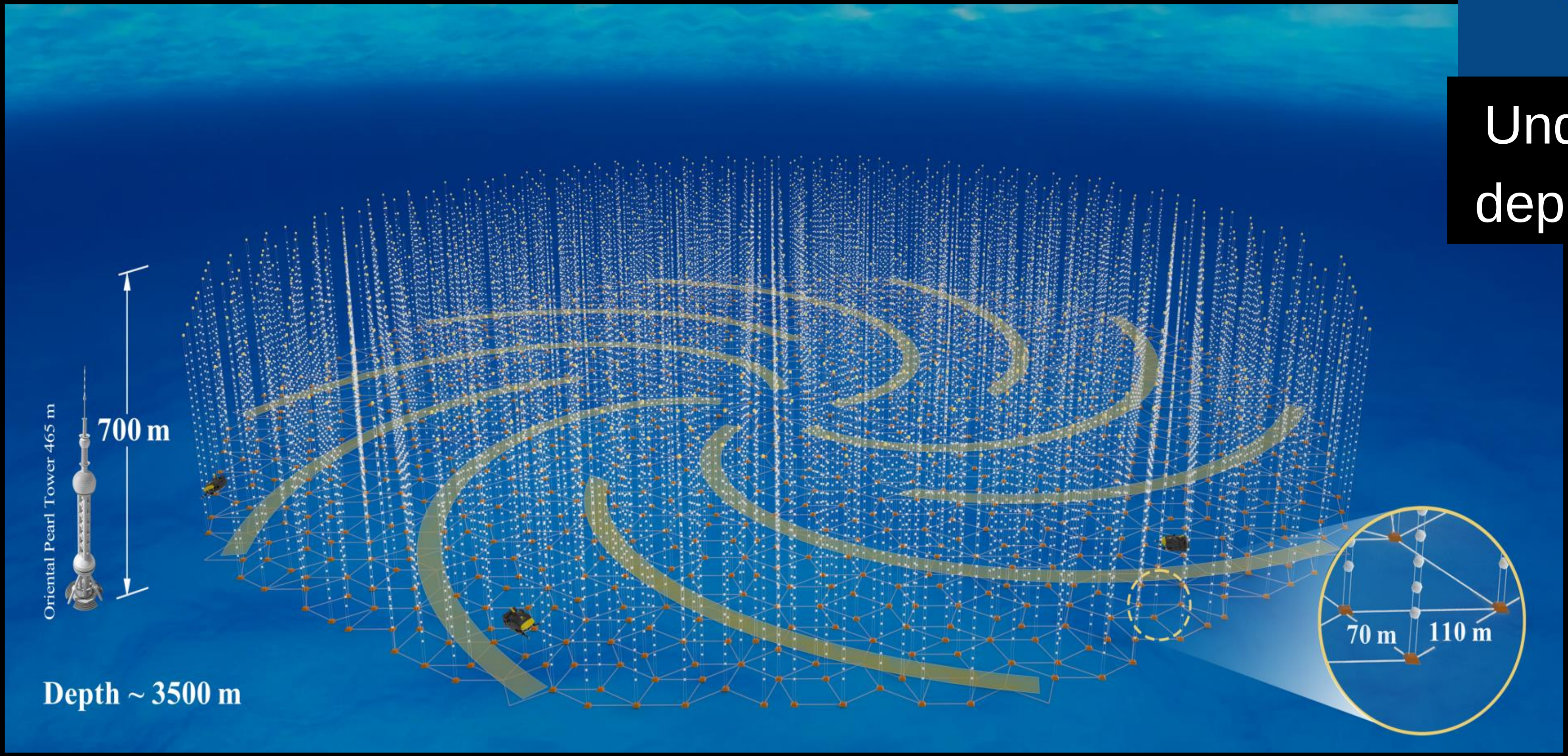
Rapidly resolve point sources, sensitivity to all flavours



- 1200 strings
- 700m long strings
- 20 hDOMs / string
- Volume ~8km^3

TRIDENT Design

Rapidly resolve point sources, sensitivity to all flav

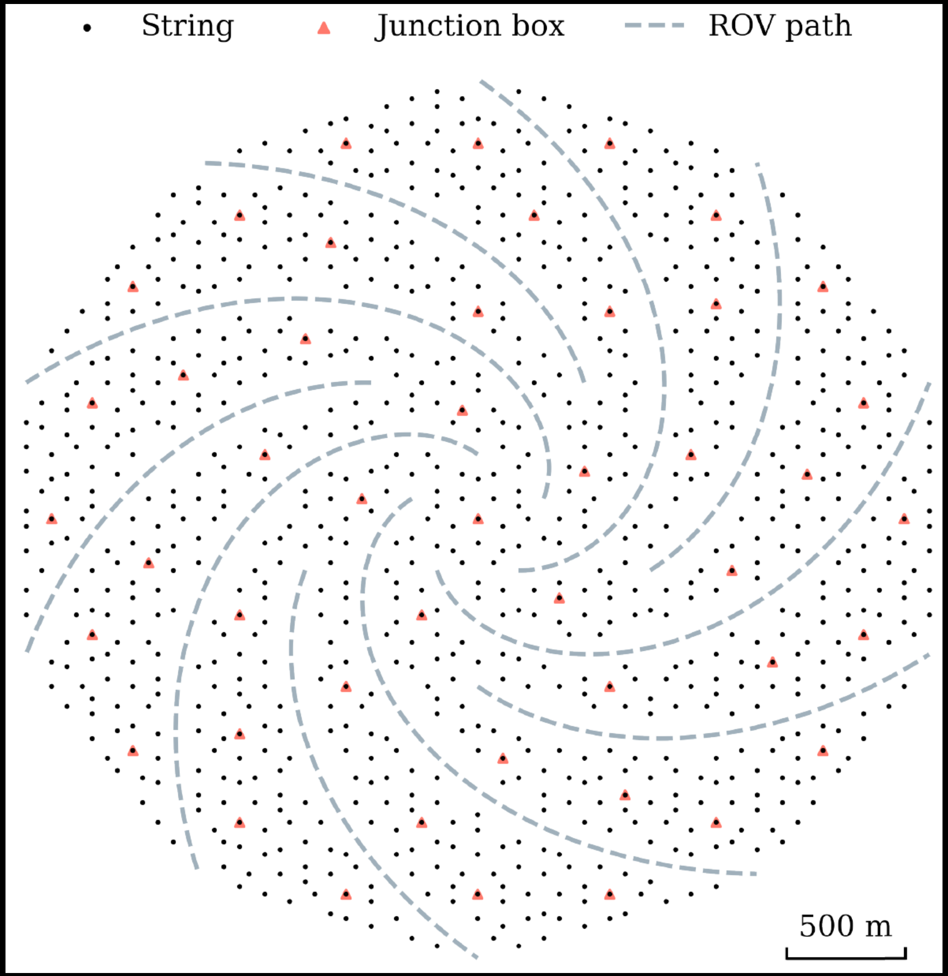


Underwater ROV for string deployment & maintenance

- 700m long strings
- 20 hDOMs / string
- Volume ~8km^3

TRIDENT Design

Rapidly resolve point sources, sensitivity to all flavours



Uneven String Layout

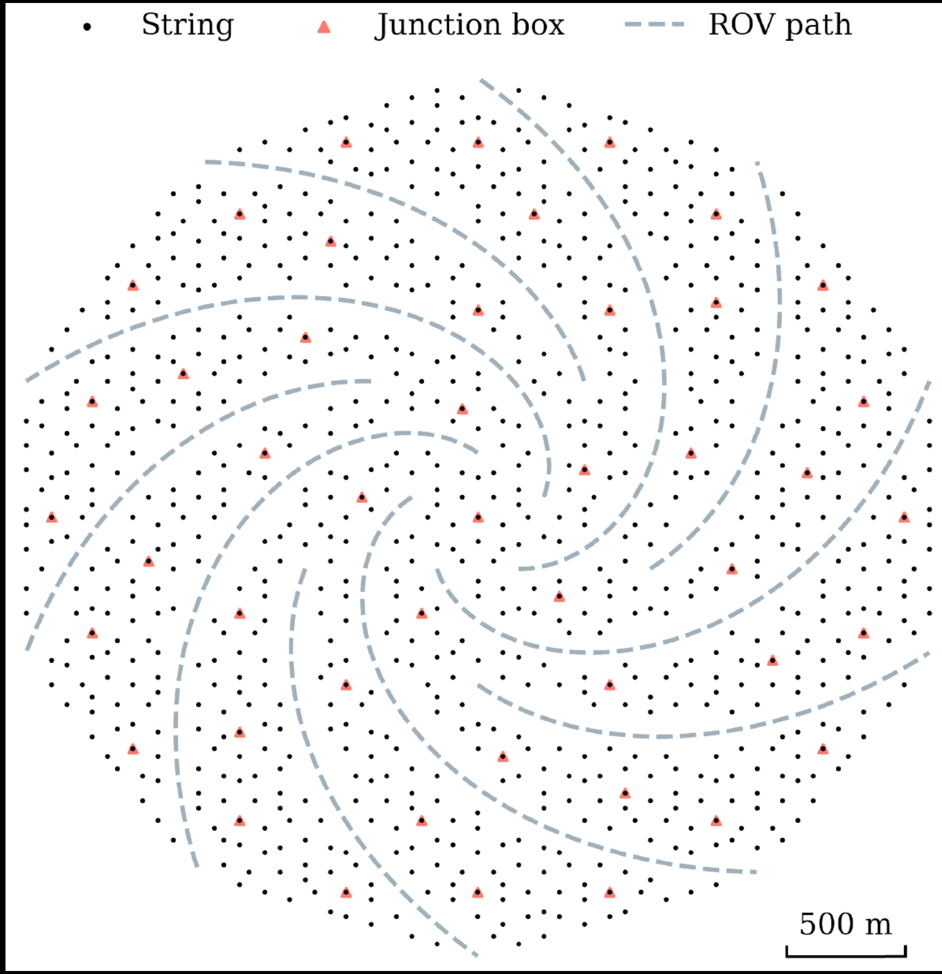
70 and 110m spacings

- Large Volume

- 1200 strings
- 700m long strings
- 20 hDOMs / string
- Volume ~8km^3

TRIDENT Design

Rapidly resolve point sources, sensitivity to all flavours



Uneven String Layout

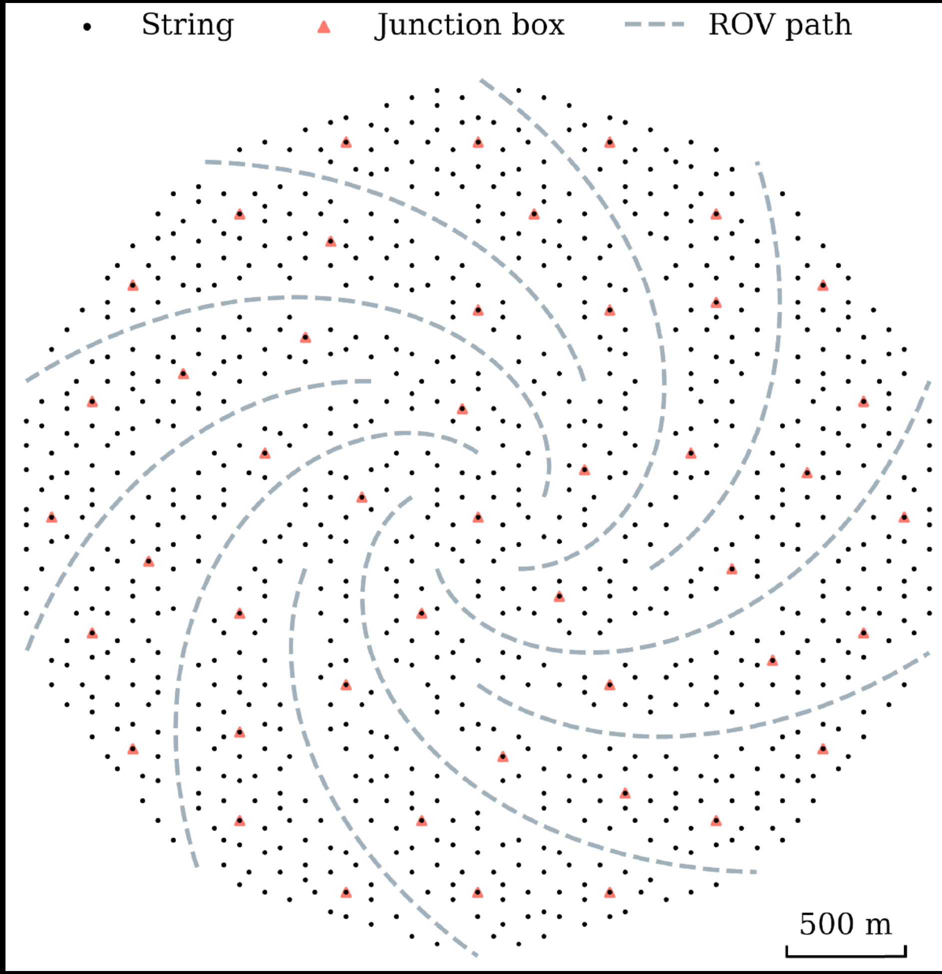
70 and 110m spacings

- Large Volume
- Wide energy range:
  Sub TeV – EeV

- 1200 strings
- 700m long strings
- 20 hDOMs / string
- Volume ~8km^3

TRIDENT Design

Rapidly resolve point sources, sensitivity to all flavours



Uneven String Layout

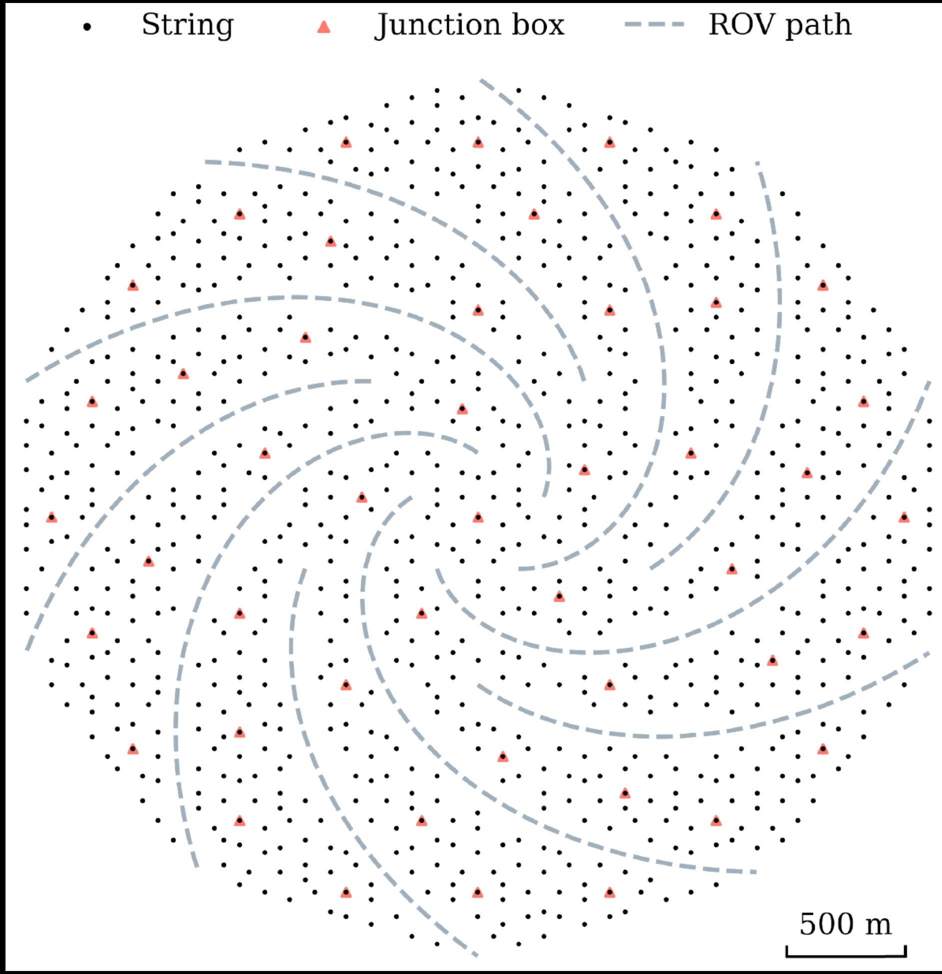
70 and 110m spacings

- Large Volume
- Wide energy range:
  Sub TeV – EeV
- Photon propagation length

- 1200 strings
- 700m long strings
- 20 hDOMs / string
- Volume ~8km^3

TRIDENT Design

Rapidly resolve point sources, sensitivity to all flavours



Uneven String Layout

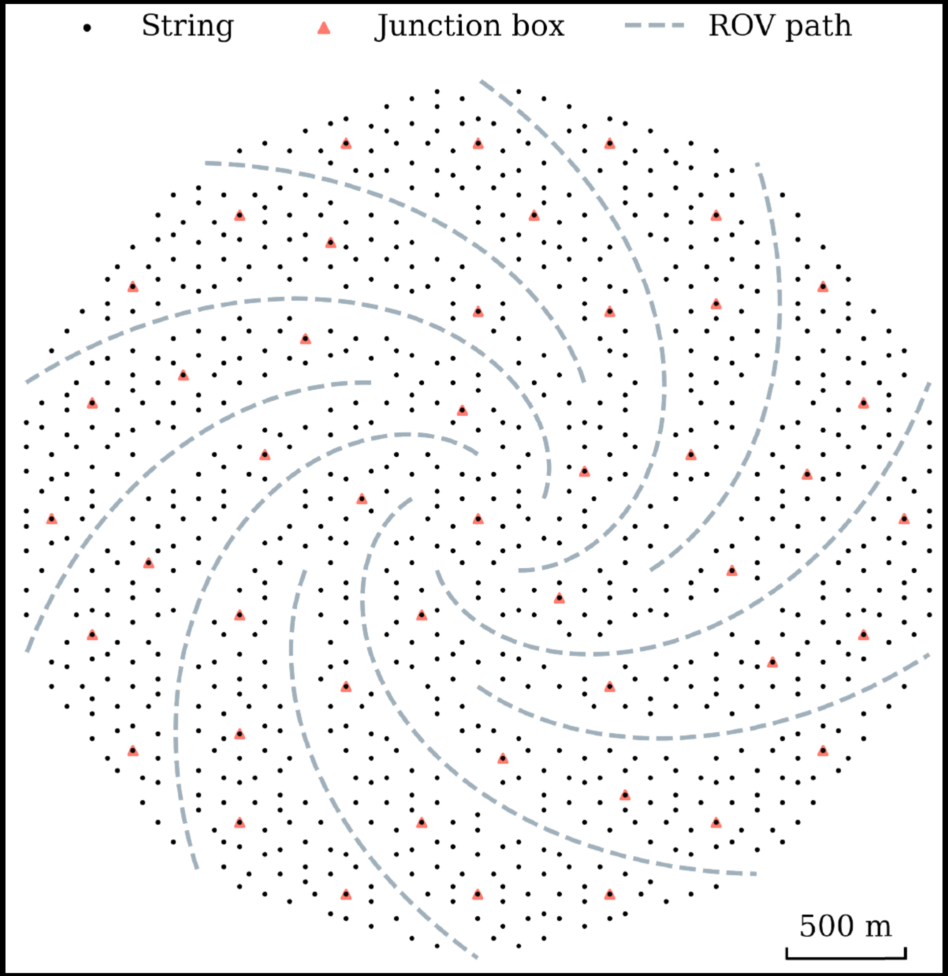
70 and 110m spacings

- Large Volume
- Wide energy range:
  Sub TeV – EeV
- Photon propagation length
- Construction + Maintenance

- 1200 strings
- 700m long strings
- 20 hDOMs / string
- Volume ~8km^3

TRIDENT Design

Rapidly resolve point sources, sensitivity to all flavours



Uneven String Layout

70 and 110m spacings

- Large Volume
- Wide energy range:
  Sub TeV – EeV
- Photon propagation length
- Construction + Maintenance
- Avoid Straight Corridors

- 1200 strings
- 700m long strings
- 20 hDOMs / string
- Volume ~8km^3

Location

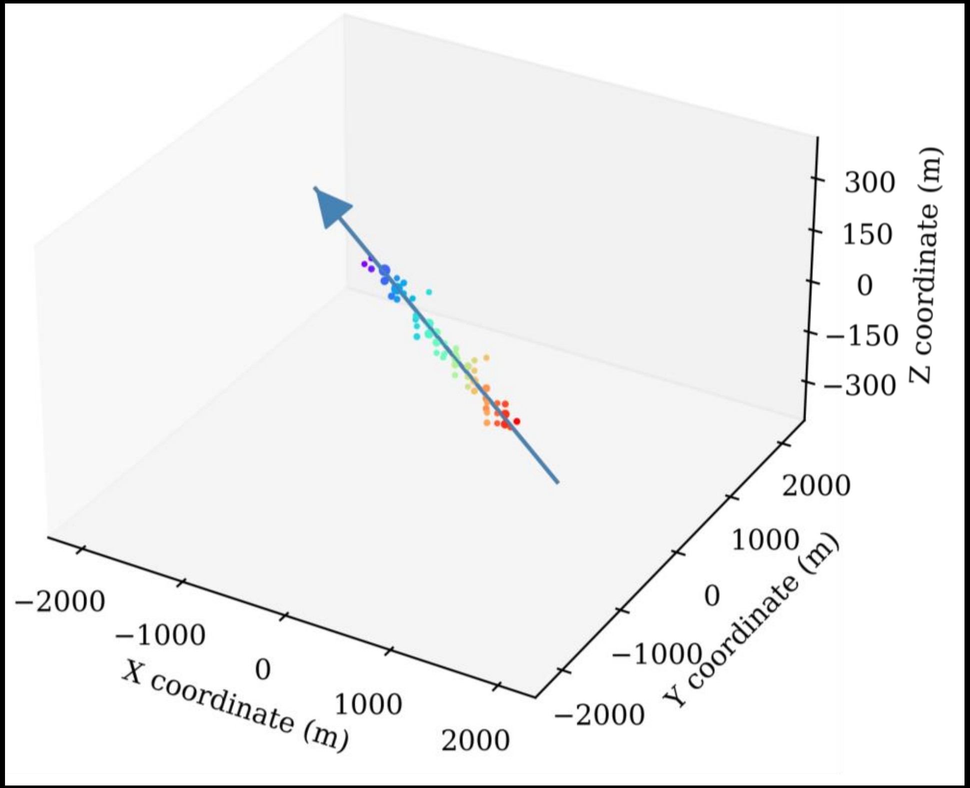
↓

Telescope Design

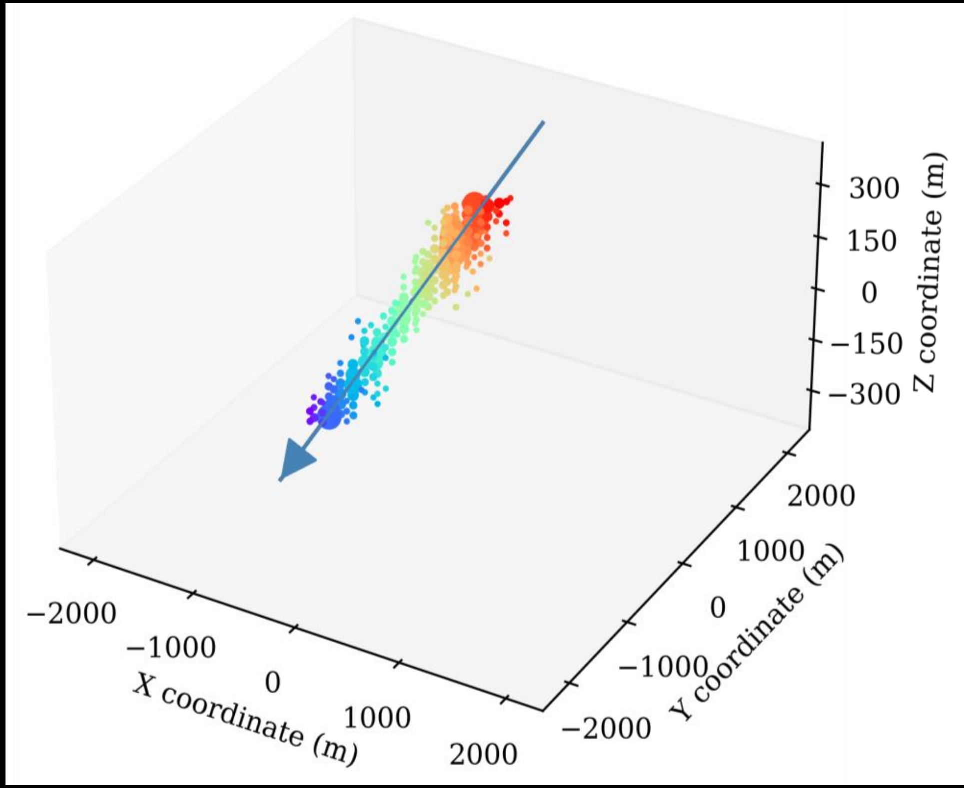
↓

Telescope Ability

TRIDENT Sensitivity + Discovery Potential

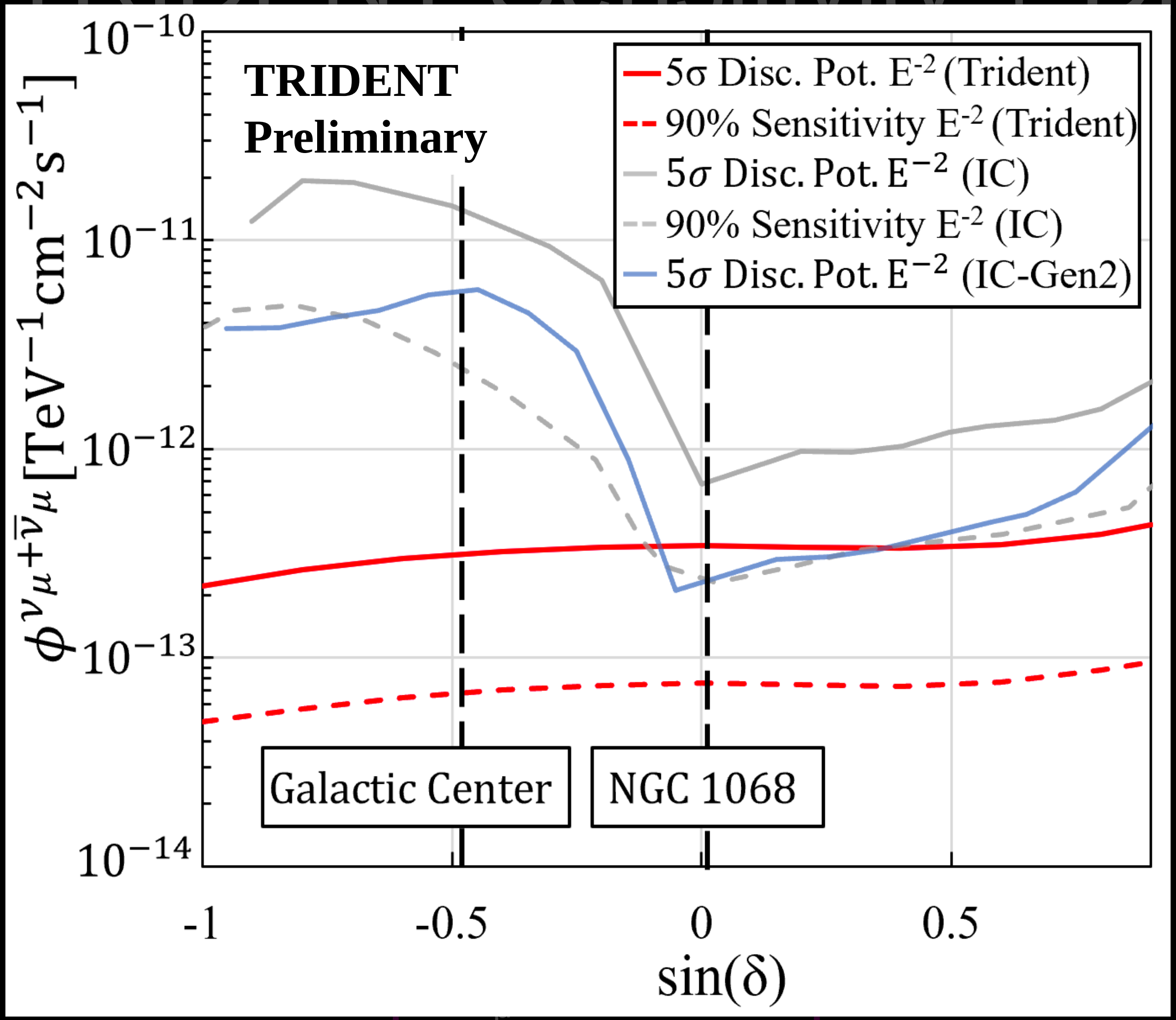


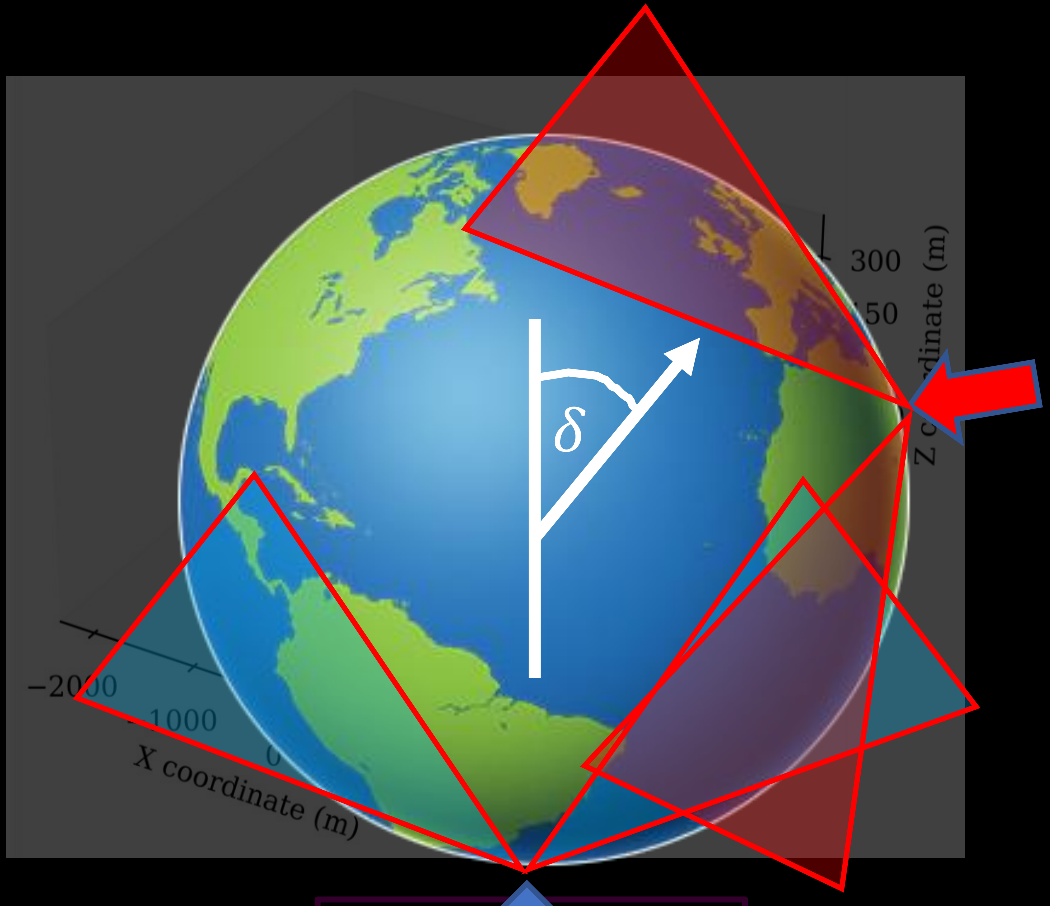
ν_μ CC event
7 TeV muon



ν_μ CC event
1.2 PeV muon

TRIDENT Sensitivity + Discovery Potential

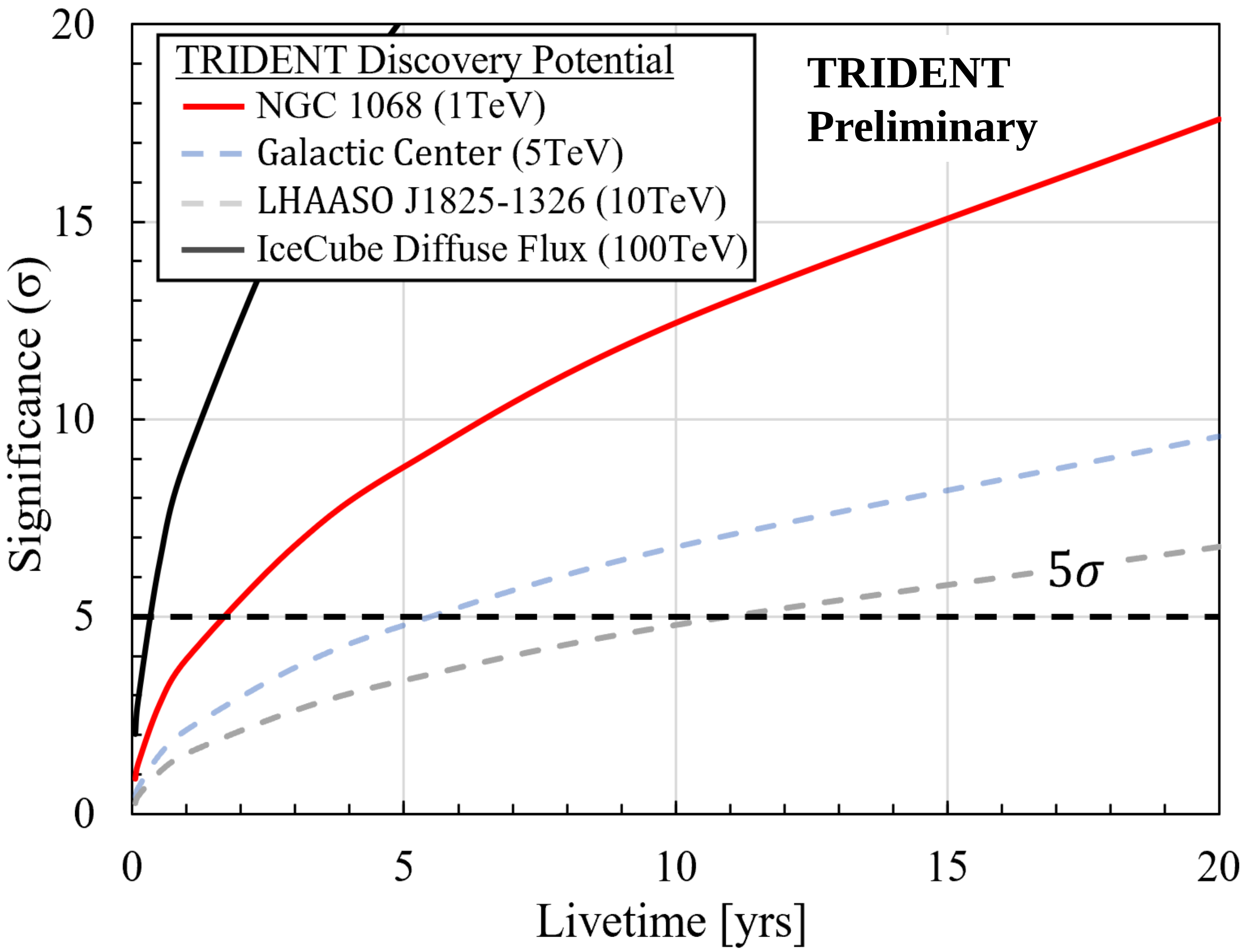




1.2 PeV muon

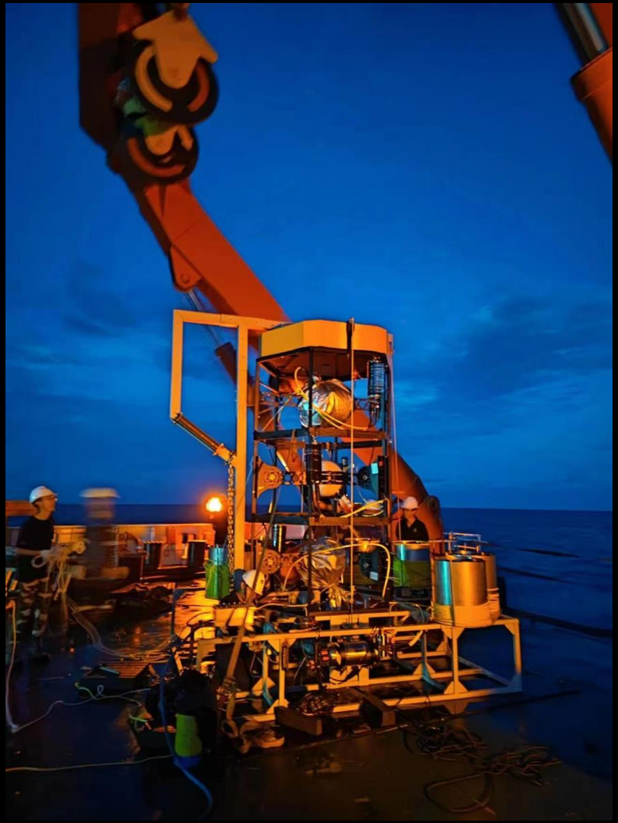
TRIDENT - Large & Good Pointing
Smooth sensitivity to the whole sky

IceCube Candidate Sources vs Time



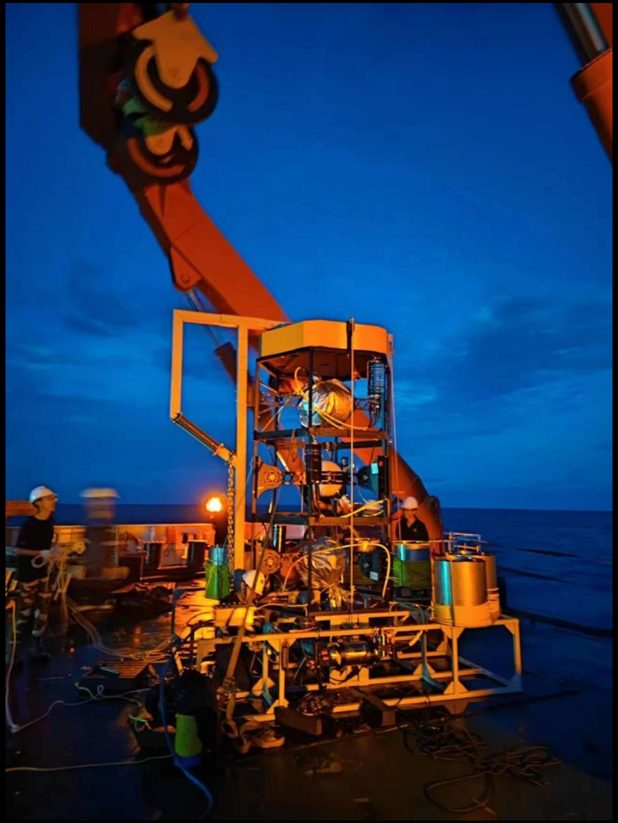
Can discover NGC 1068 in less than 2 years

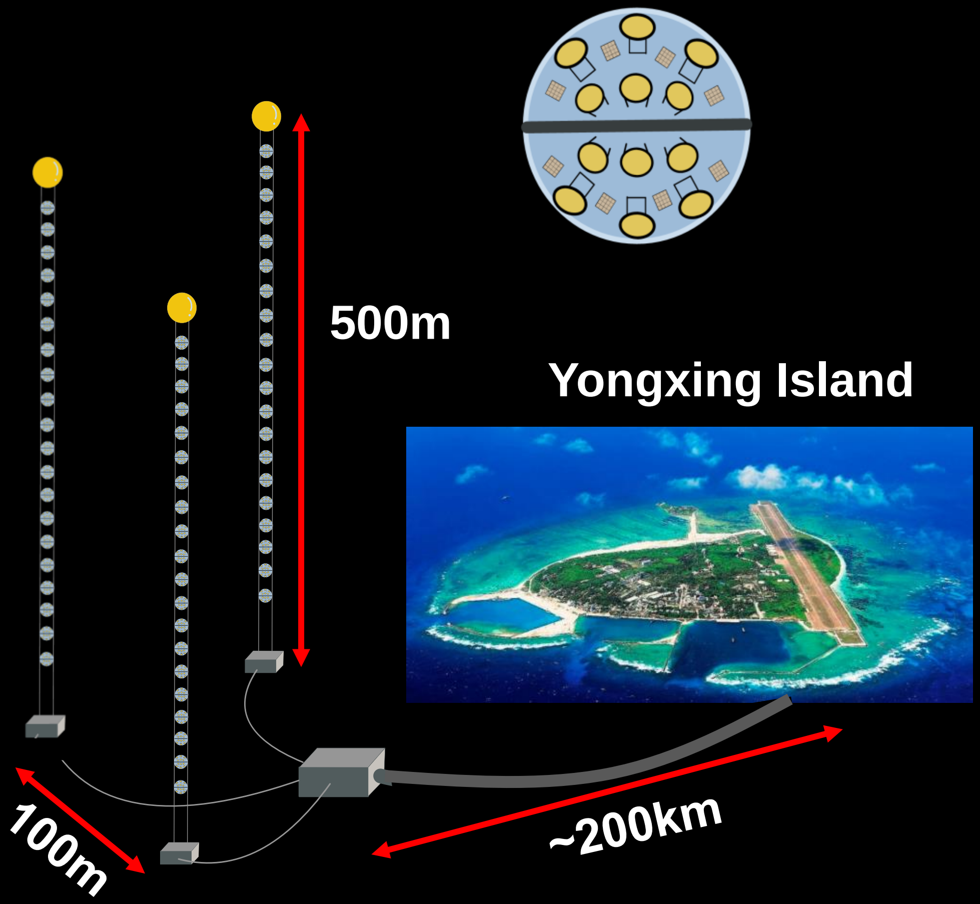
Timeline



Pathfinder: 2019-2021

Timeline

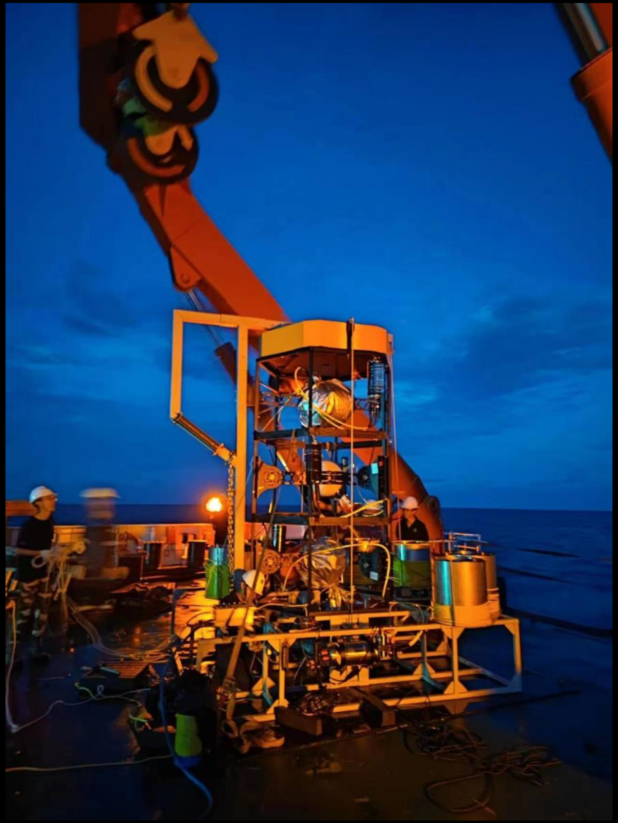


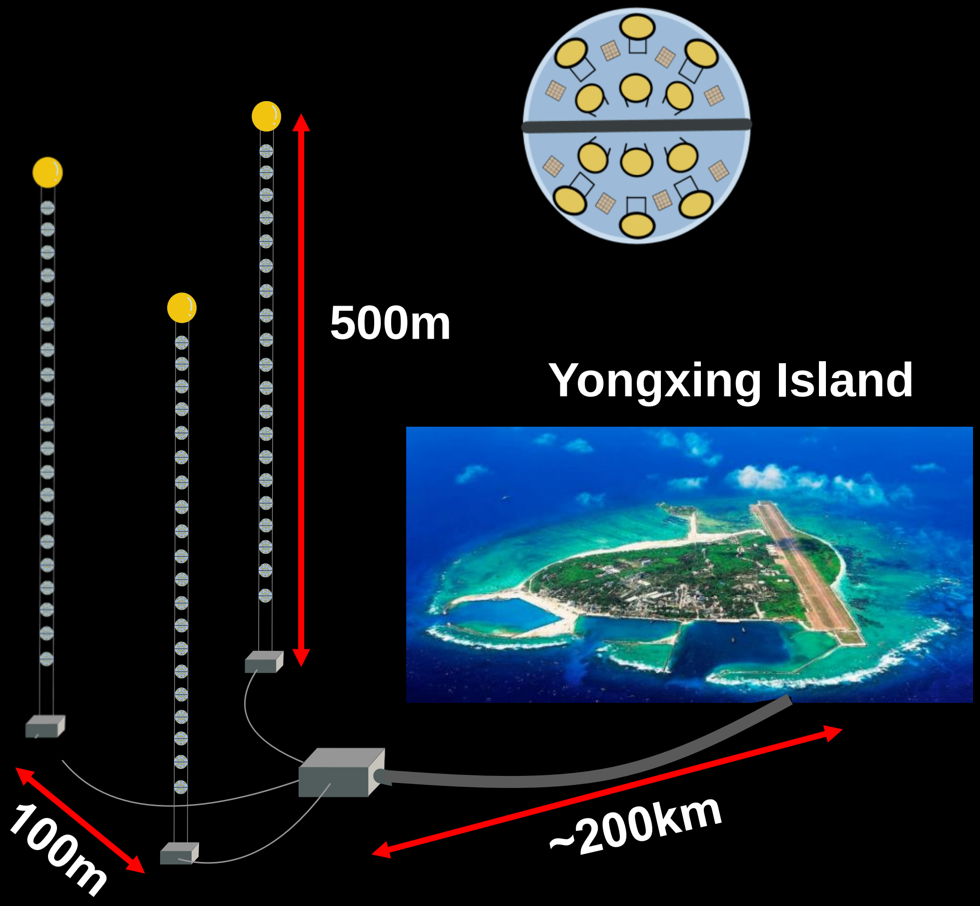


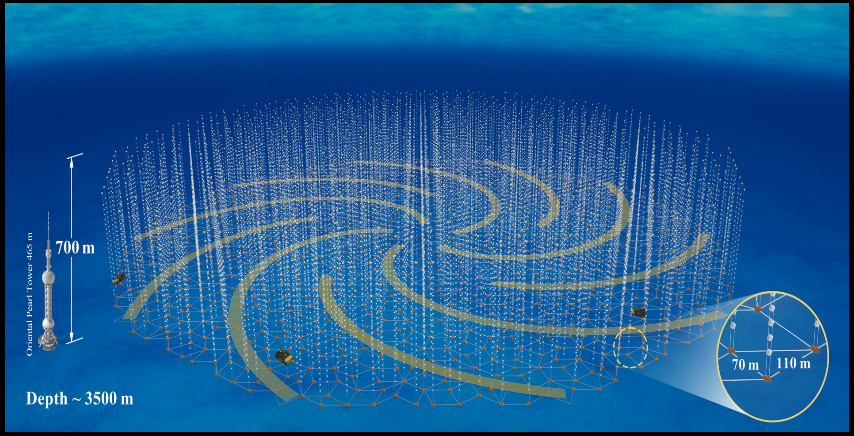
Build 11 strings + power/data communication with island

Pathfinder: 2019-2021 → **Pilot project: 2022-2025**

Timeline

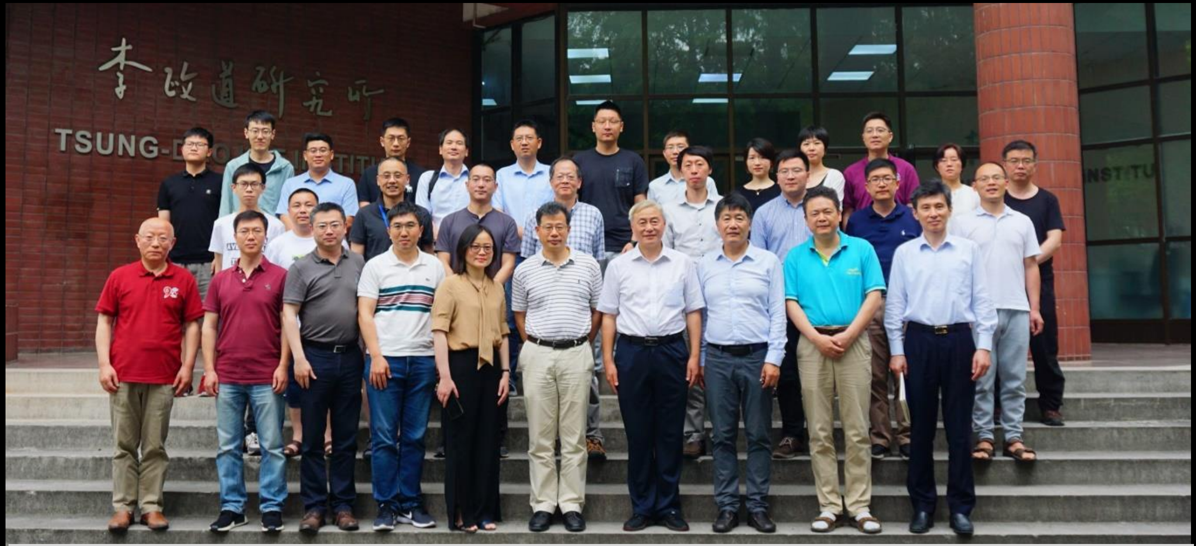




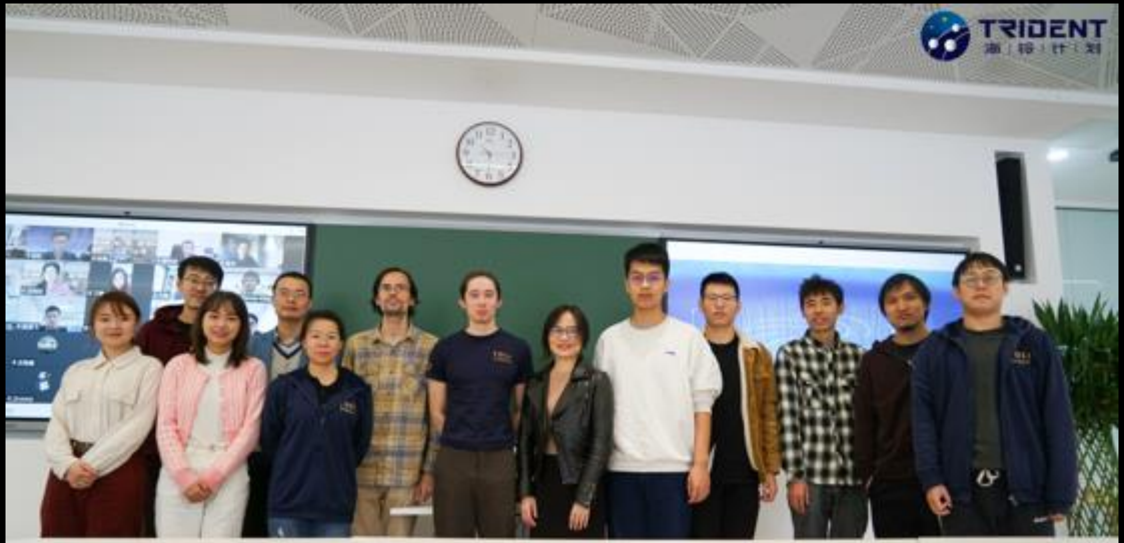


Build 11 strings + power/data communication with island

Pathfinder: 2019-2021 → **Pilot project: 2022-2025** → **Big array construction: 2026-**

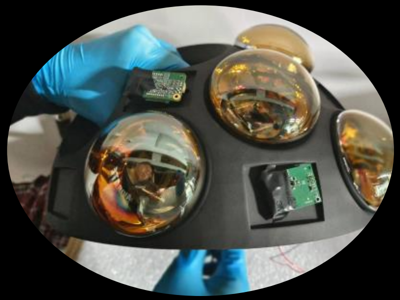


Establishment of the TRIDENT collaboration, June 8, 2021, TDLI, Shanghai



First TRIDENT collaboration meeting, Nov.18, 2022, Tsung-Dao Lee Institute, Shanghai

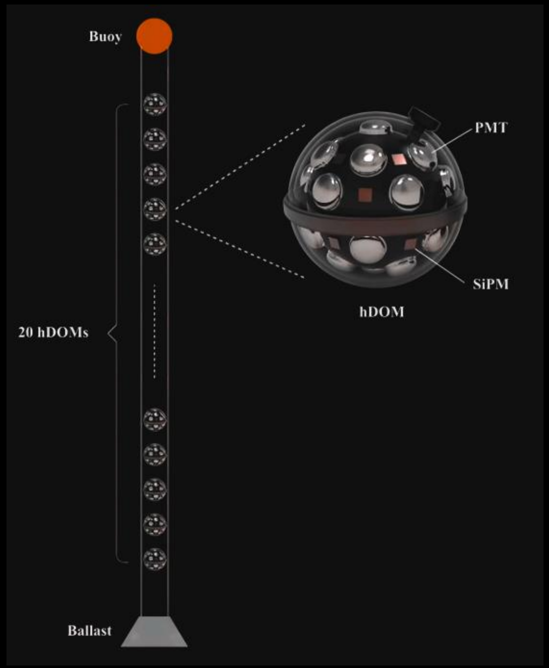
First TRIDENT interdisciplinary forum
Nov. 16, 2022











TRIDENT website:
https://trident.sjtu.edu.cn/en
TRIDENT Paper:
https://arxiv.org/abs/2207.04519

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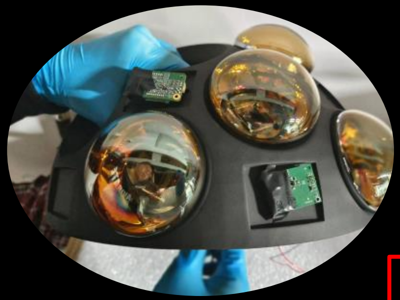
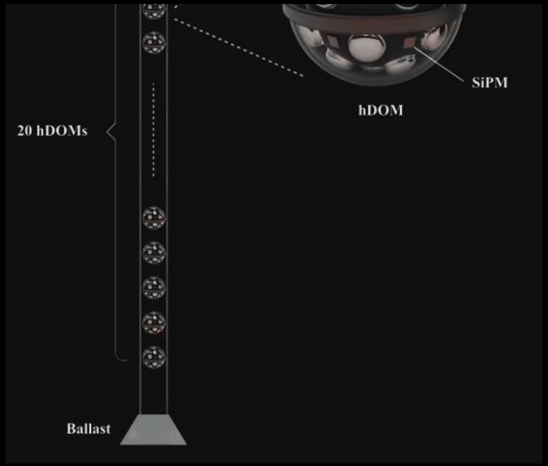
TSUNG-DAO LEE INSTITUTE



Collaborators Welcome!

TRIDENT
海 | 铃 | 计 | 划



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