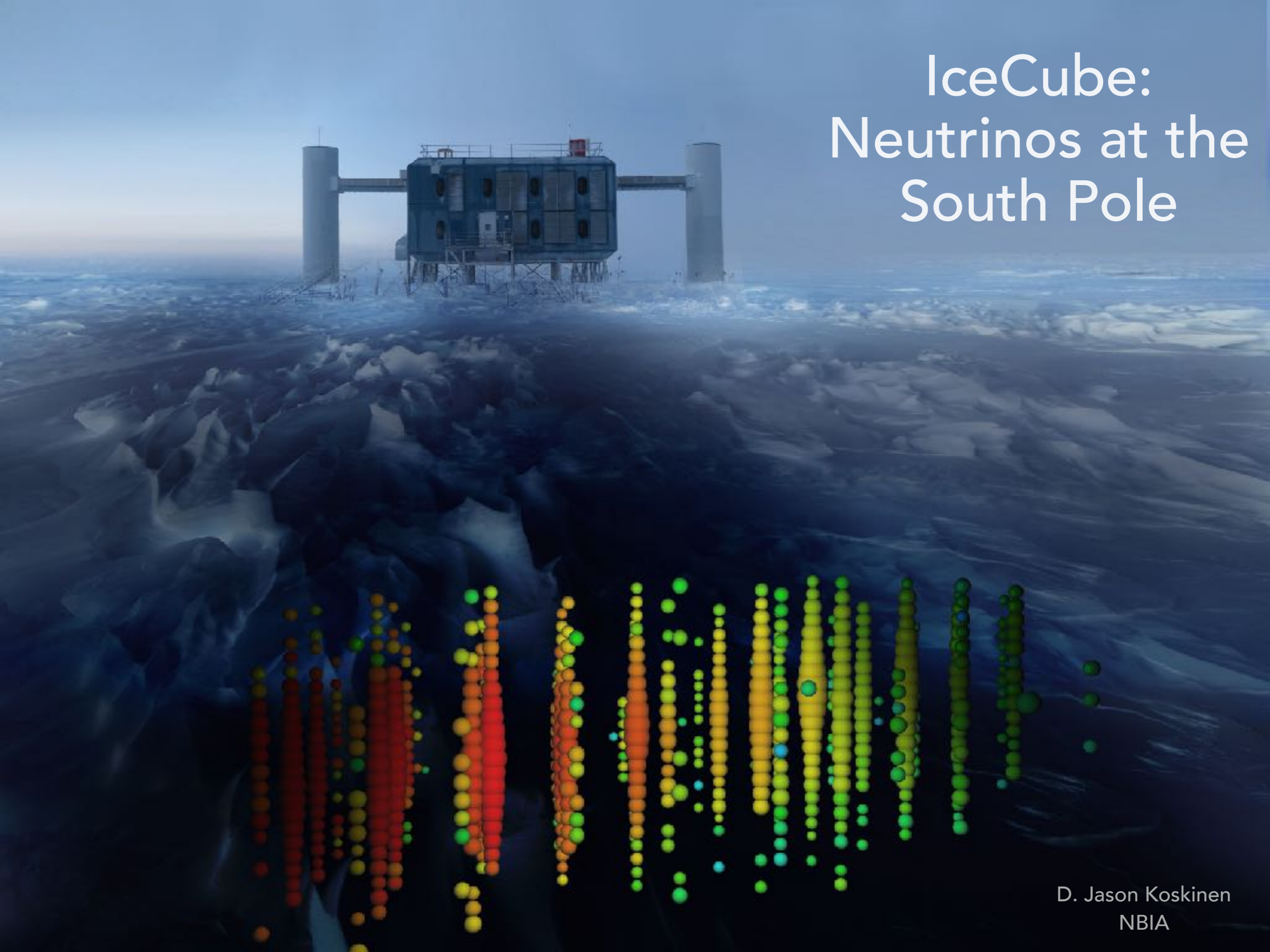


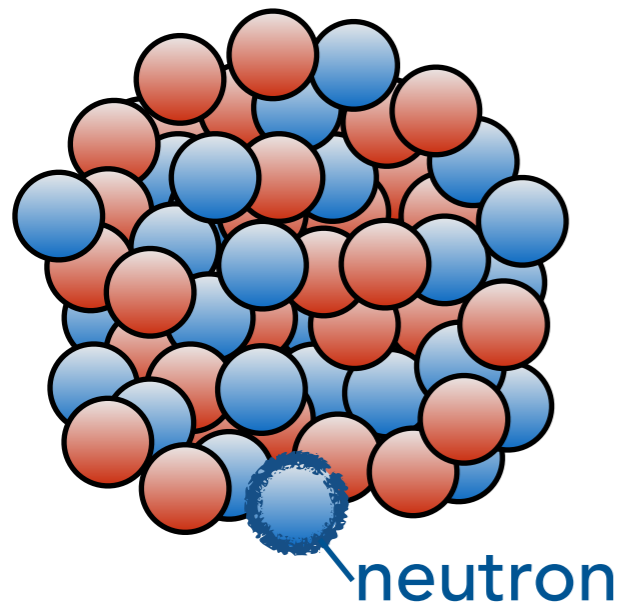
IceCube: Neutrinos at the South Pole



The Beginning... Sort of

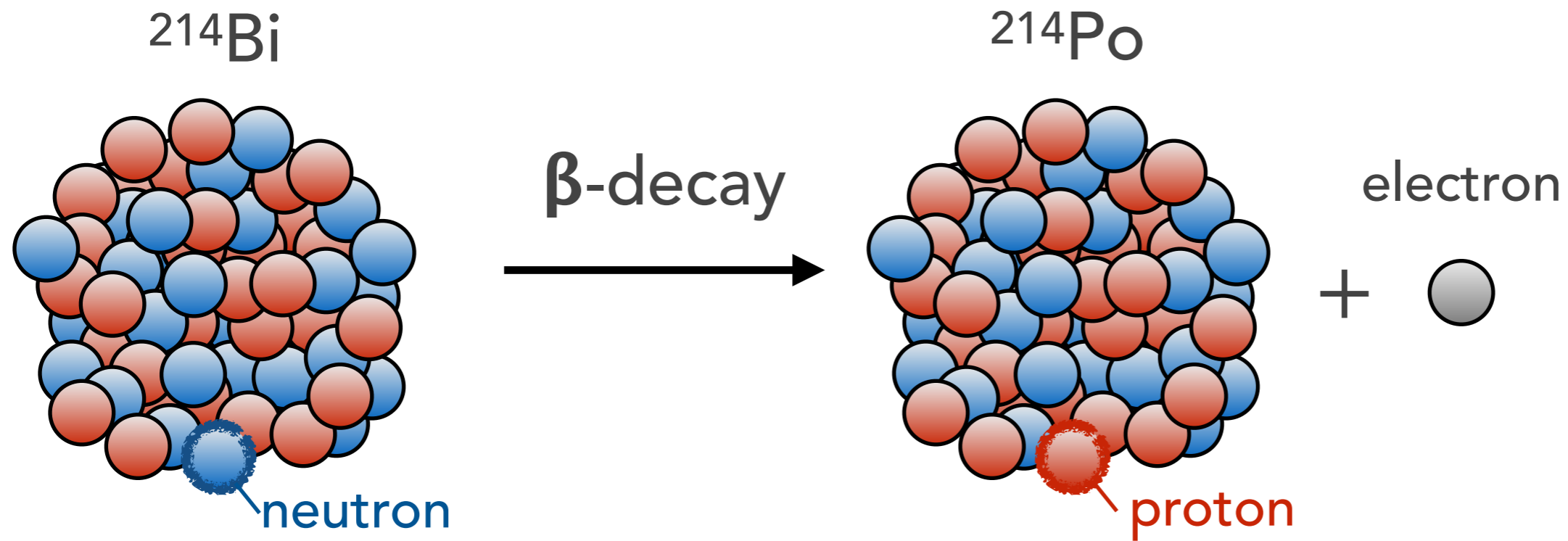
- 1910s, no neutrino
- Rutherford-Bohr model
- Radioactive decay, specifically β -decay

^{214}Bi

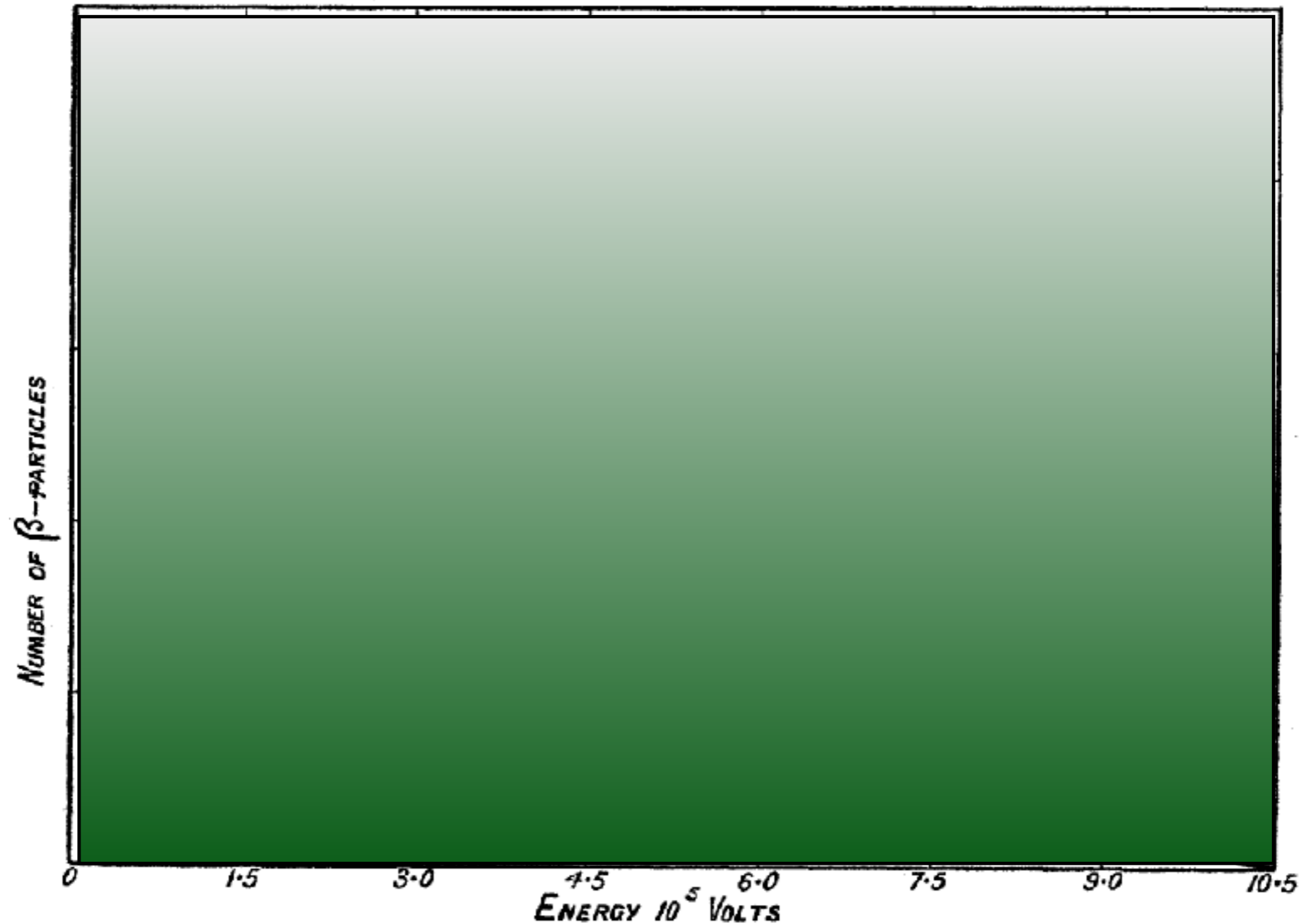


The Beginning... Sort of

- 1910s, no neutrino
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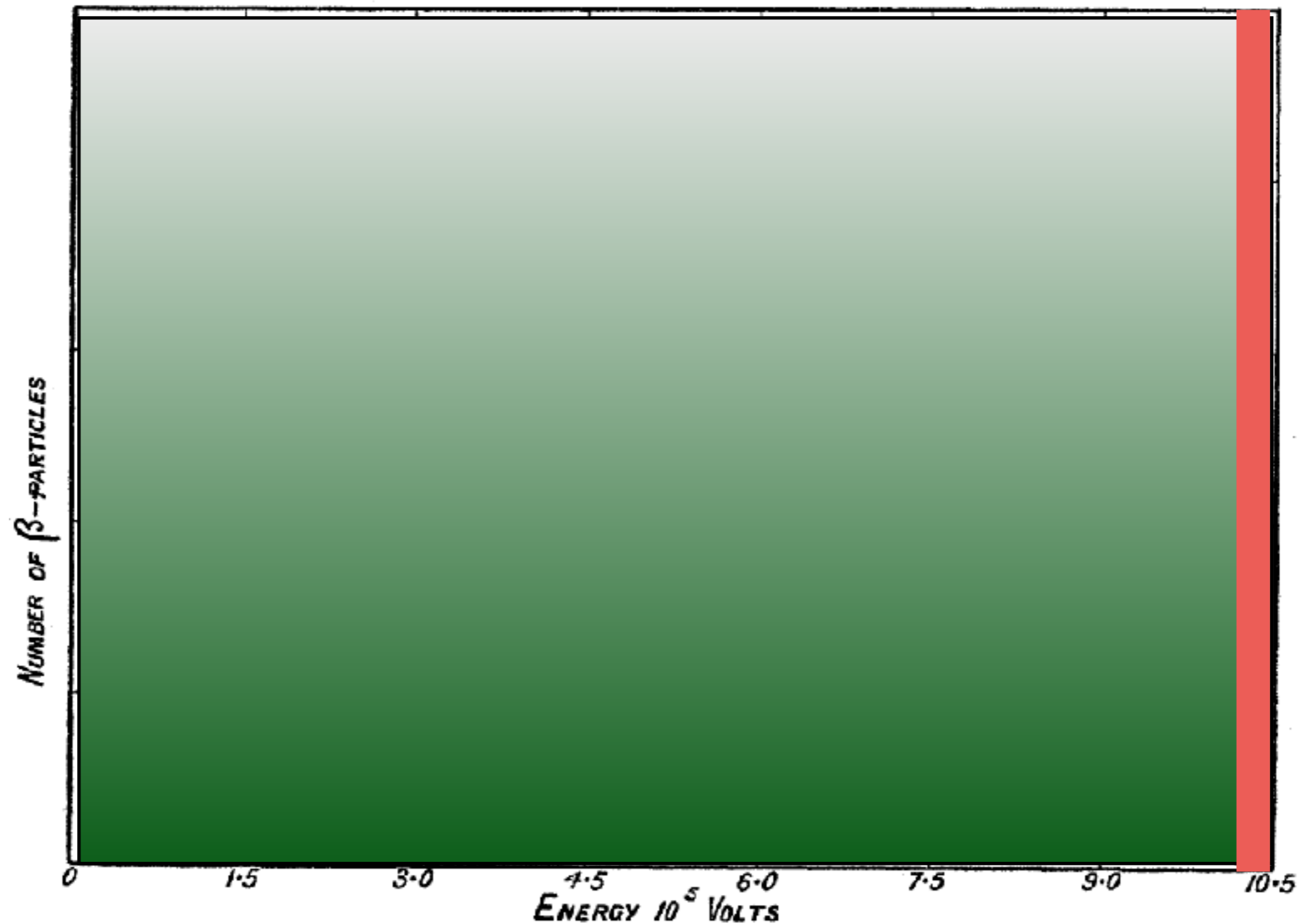


Beta-Decay Energy



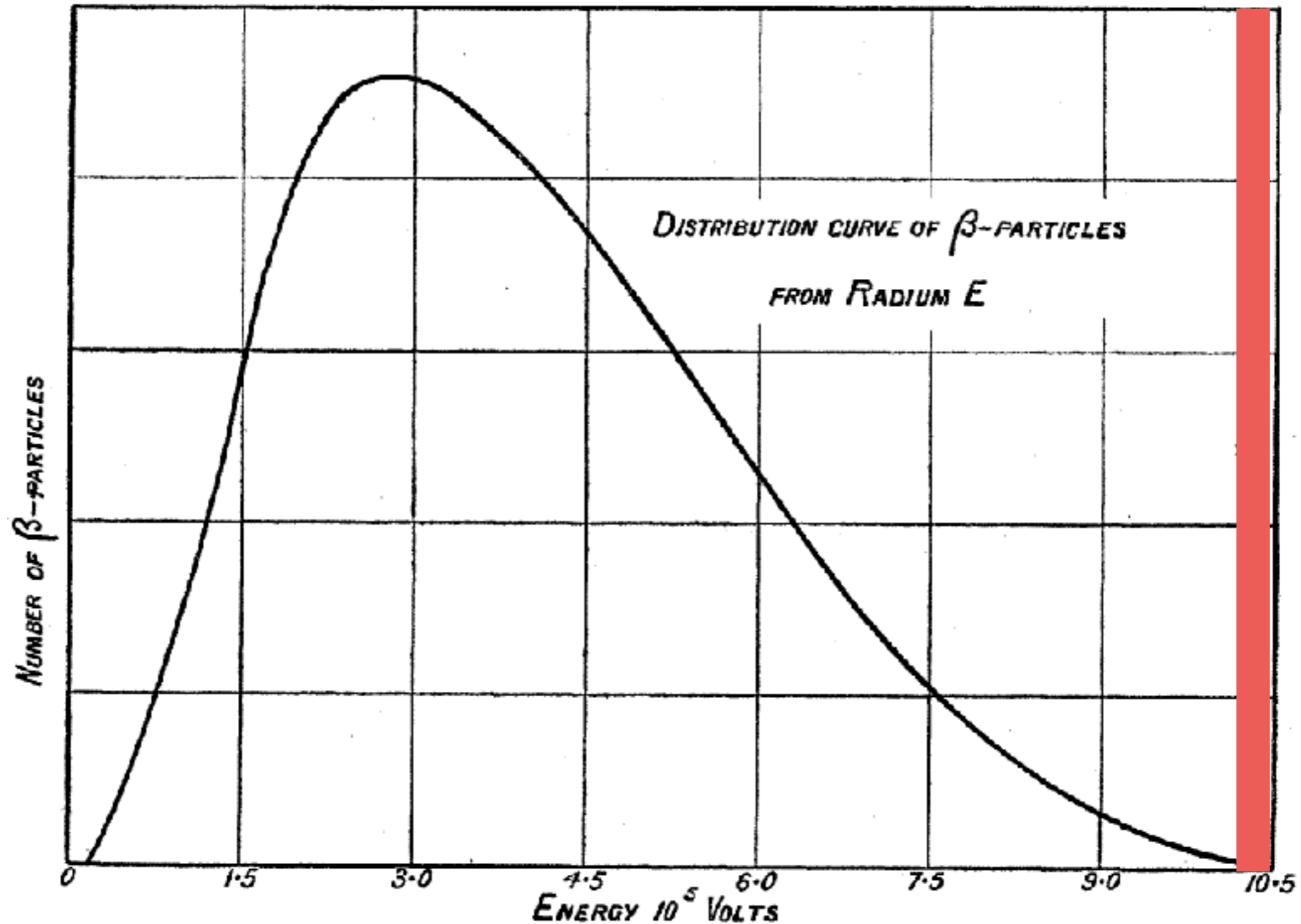
Beta-Decay Energy

Expected 'quantized'
spectrum

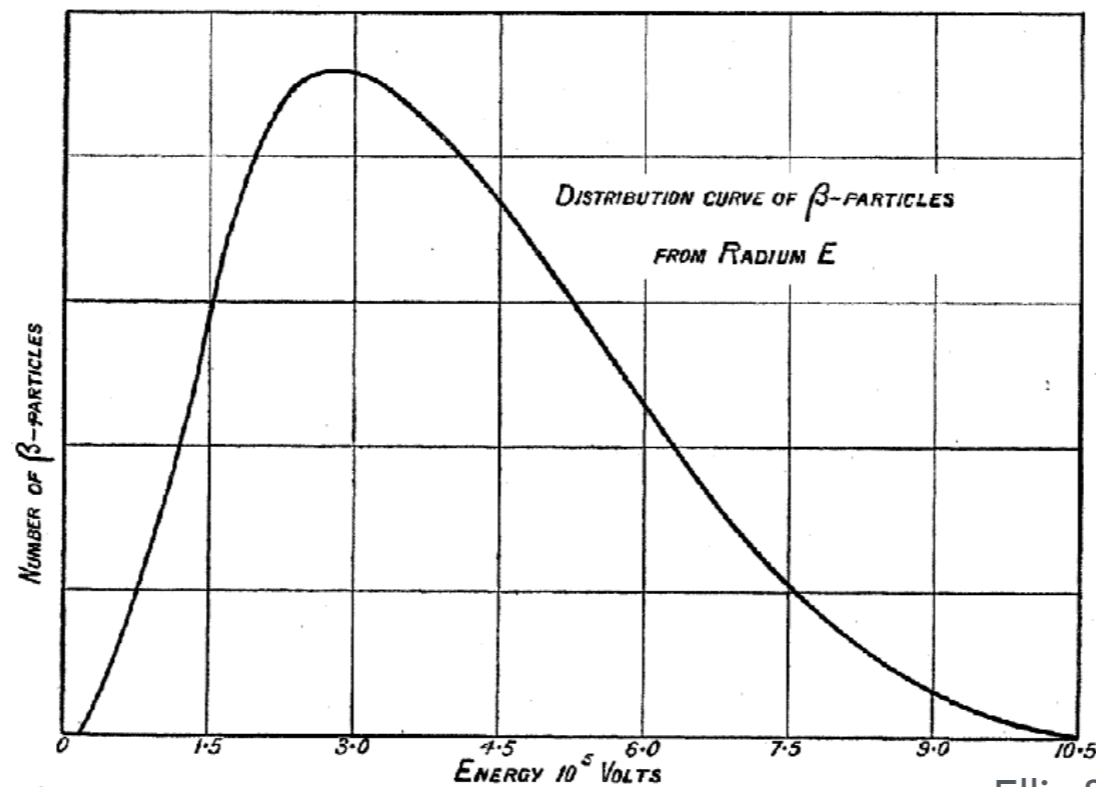
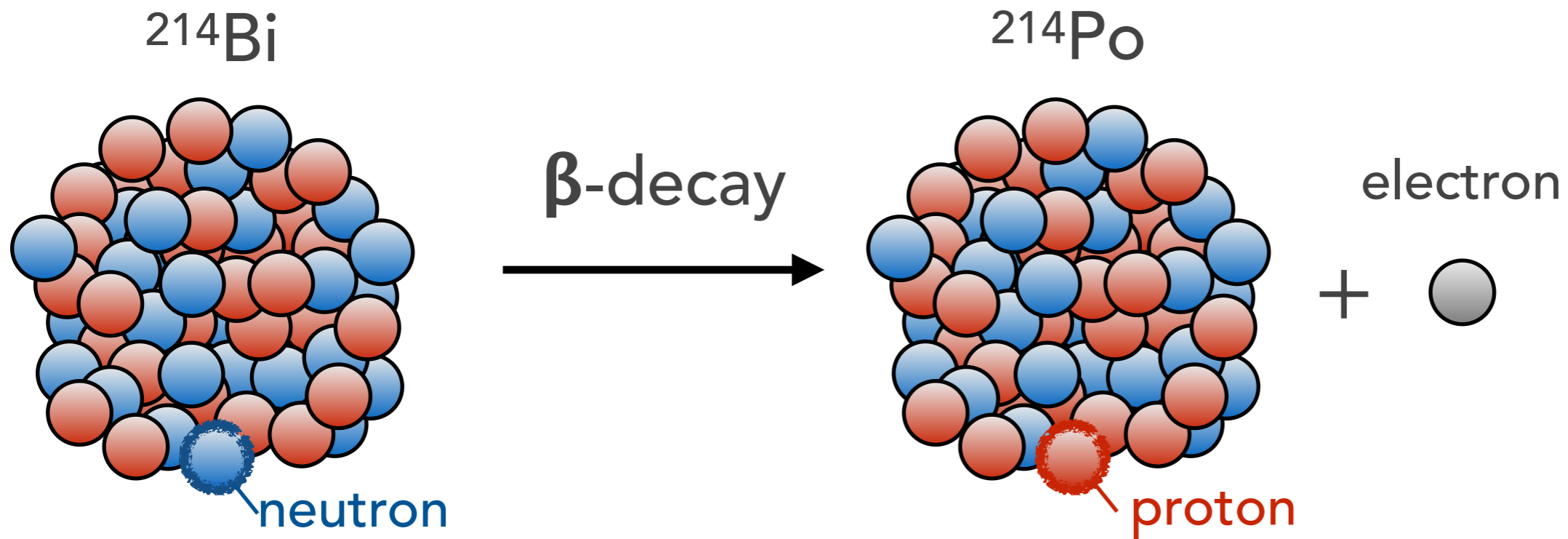


Beta-Decay Energy

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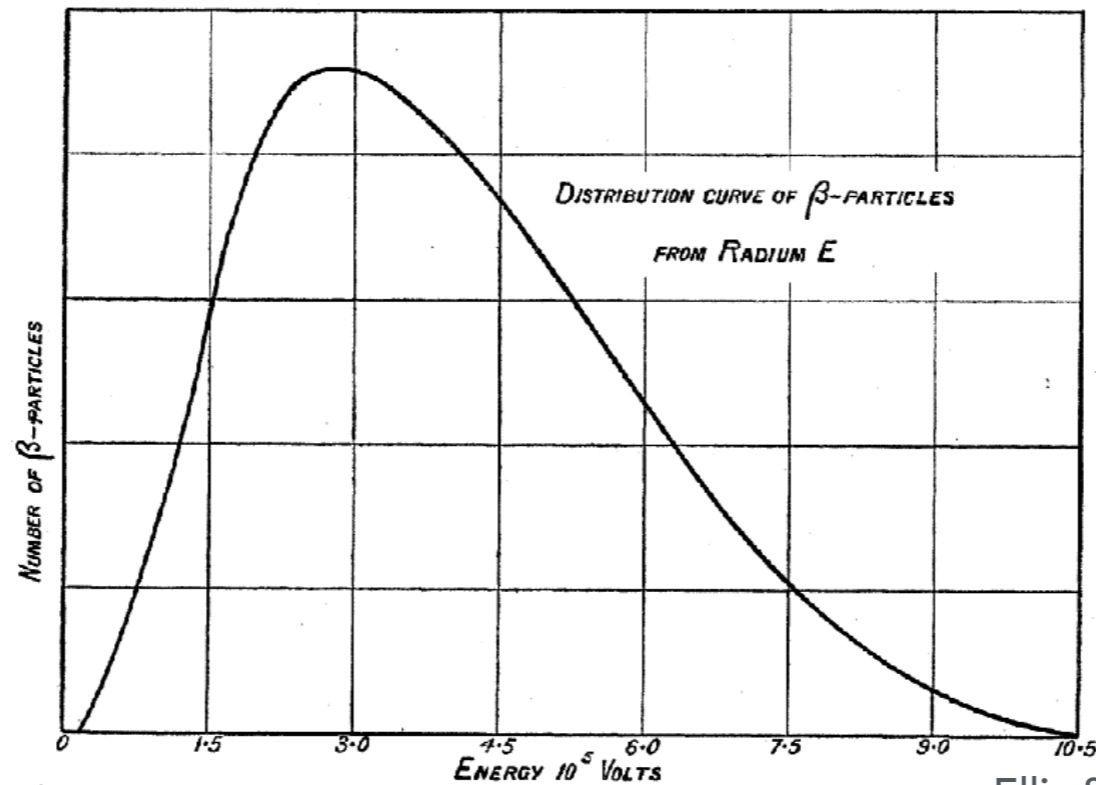
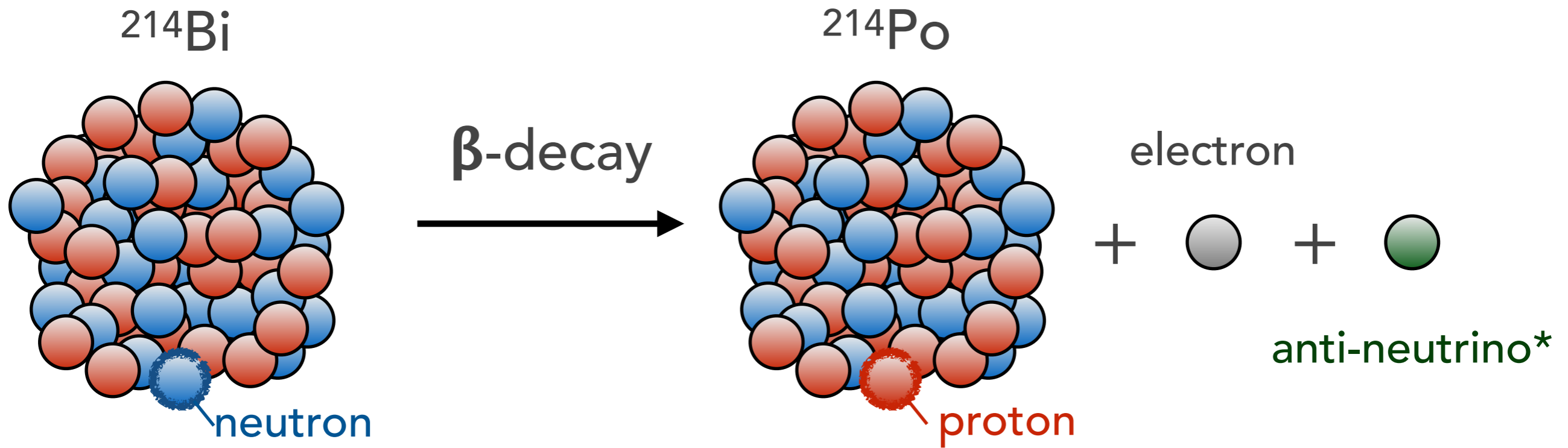


Deus ex Machina



Ellis & Wooster Proc. Roy. Soc. A117 (1927) 109

Deus ex Machina



*Pauli, 1930
Ellis & Wooster Proc. Roy. Soc. A117 (1927) 109

Experimental Neutrino

- Collision probability is very, very small
 - Collision probability increases as neutrino kinetic energy increases
- Neutral particle, has no electric charge
- Byproduct of nuclear radioactivity and particle collisions

Experimental Neutrino

- Collision probability is very, very small
 - Collision probability increases as neutrino kinetic energy increases
- Neutral particle, has no electric charge
- Byproduct of nuclear radioactivity and particle collisions

Today I have done a terrible thing, something which no theoretical physicist should ever do. I have suggested something that can never be verified experimentally.

-W. Pauli

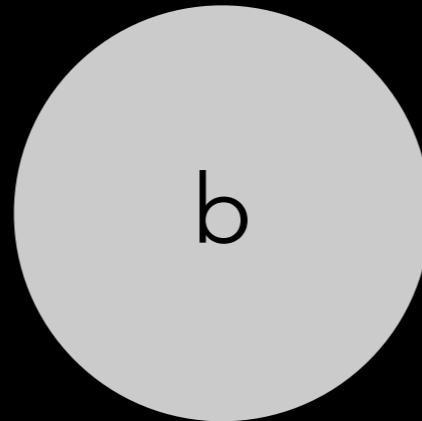
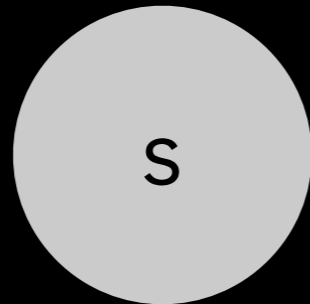
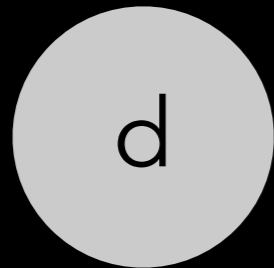
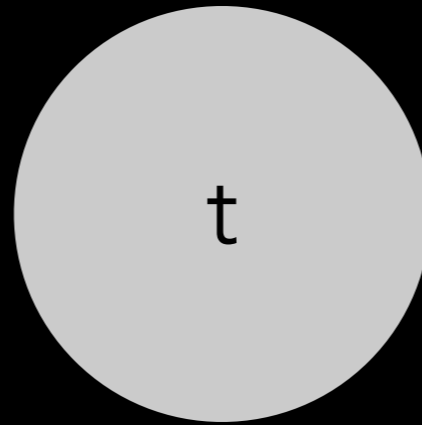
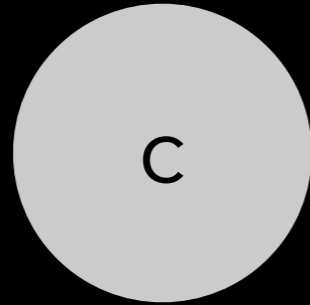
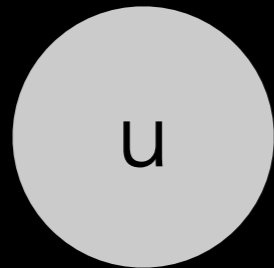


*F. Hoyle, Proc. Roy. Soc. London A 301, 171 (1967)

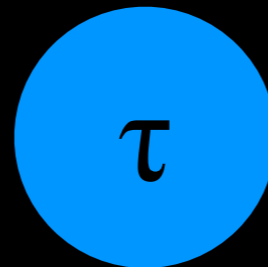
Why?

Standard Model & Neutrinos

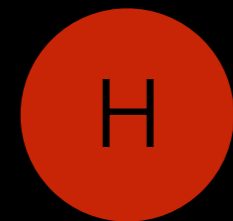
Quarks



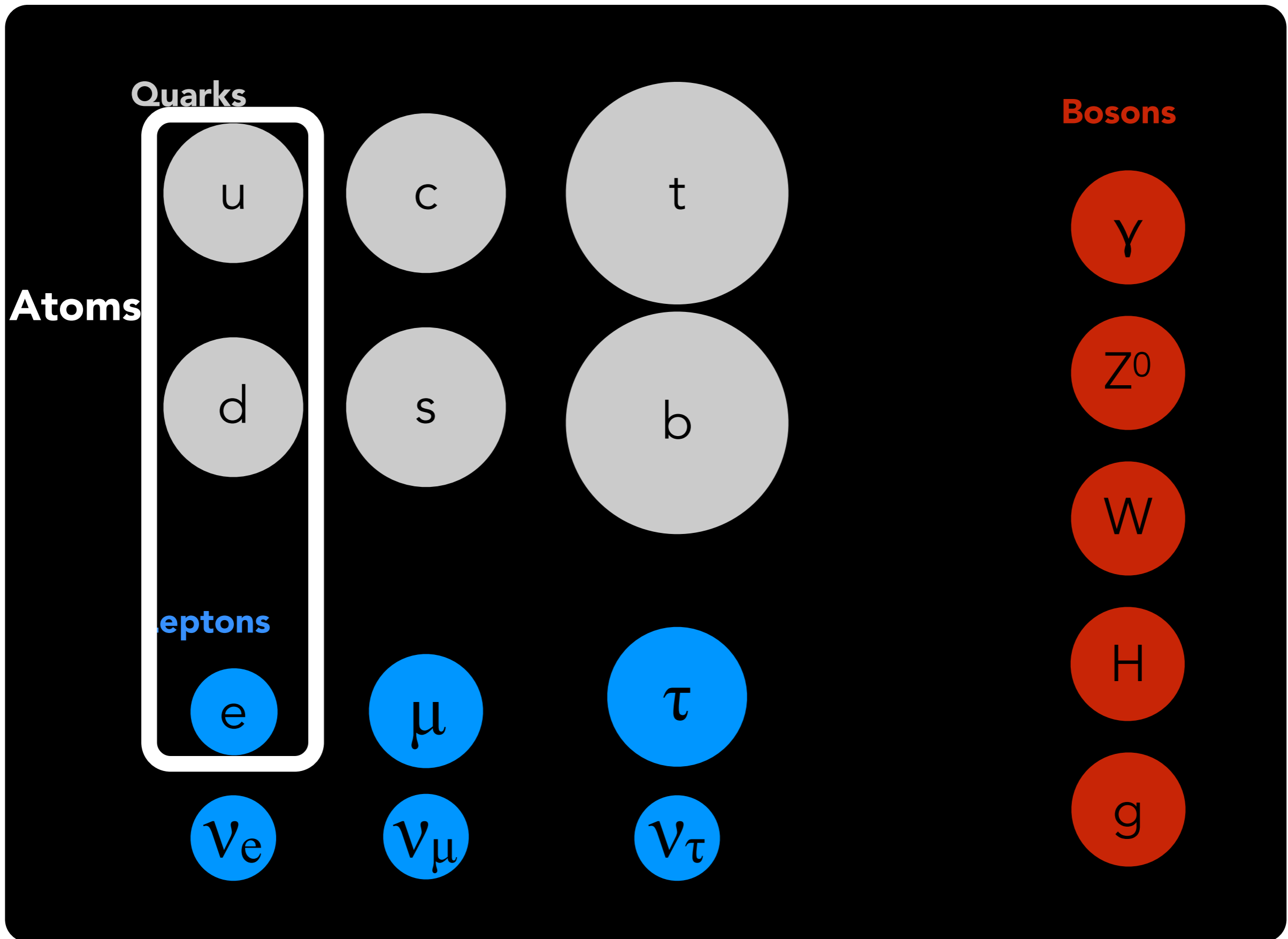
Leptons



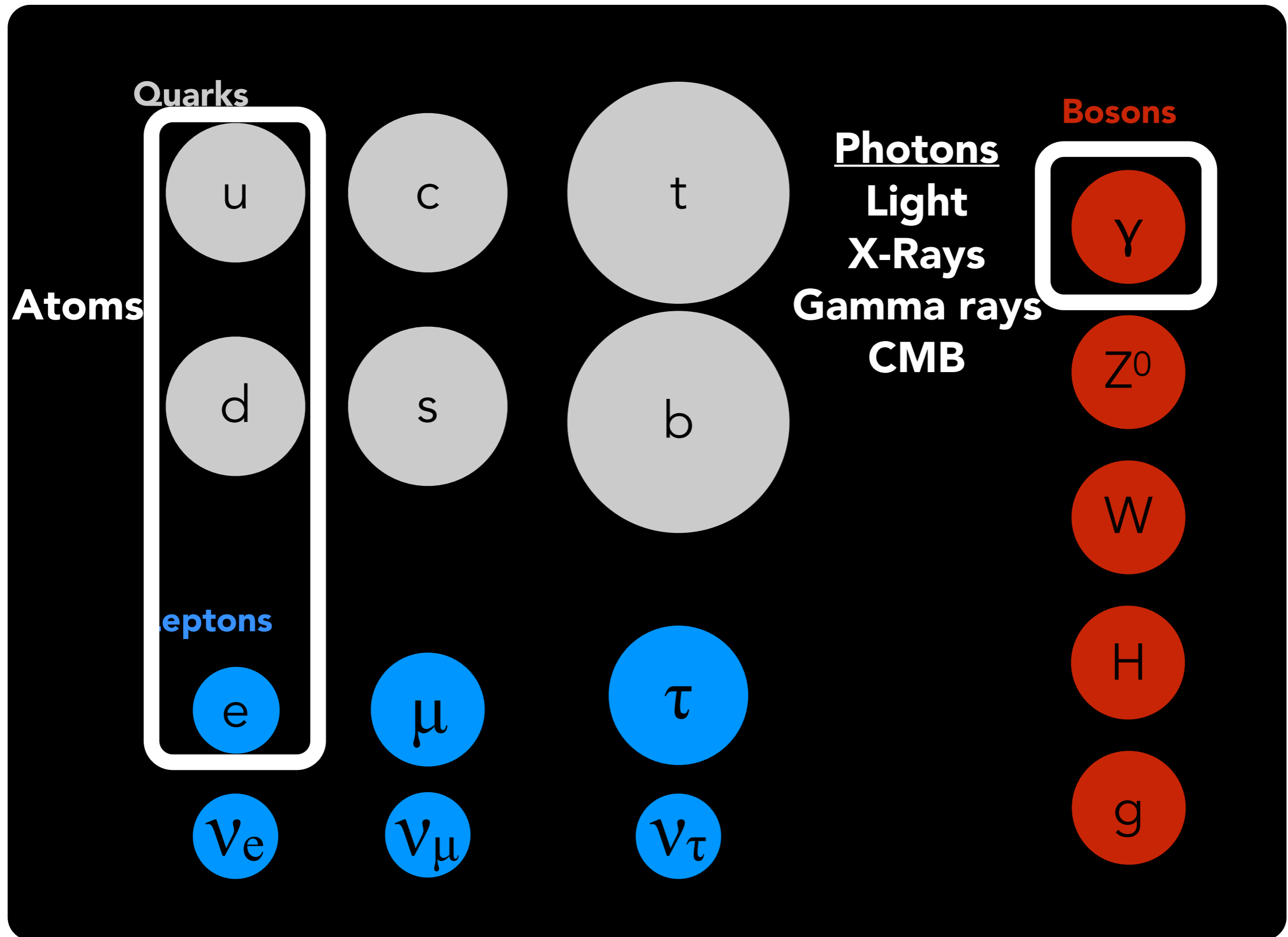
Bosons



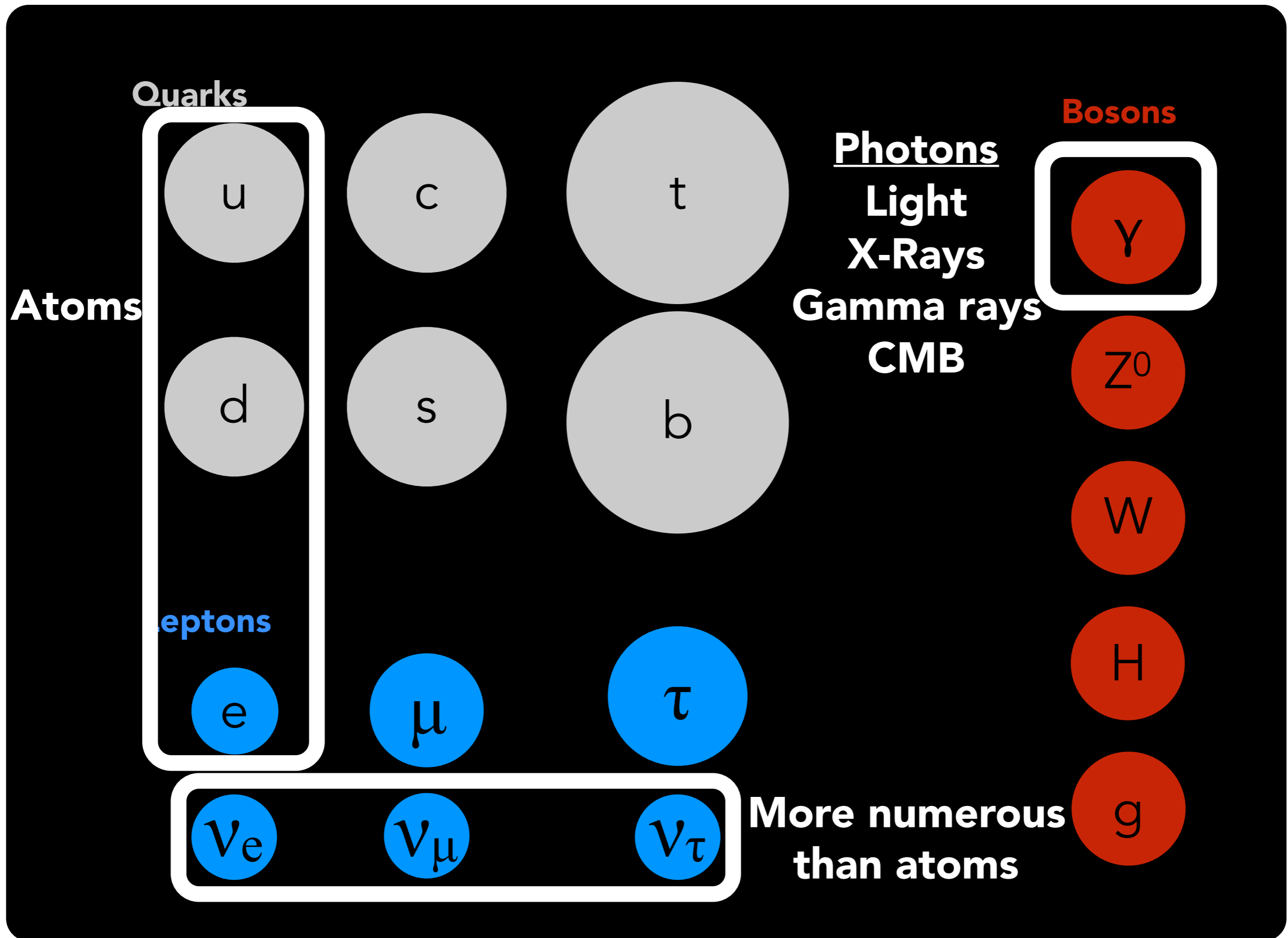
Standard Model & Neutrinos



Standard Model & Neutrinos

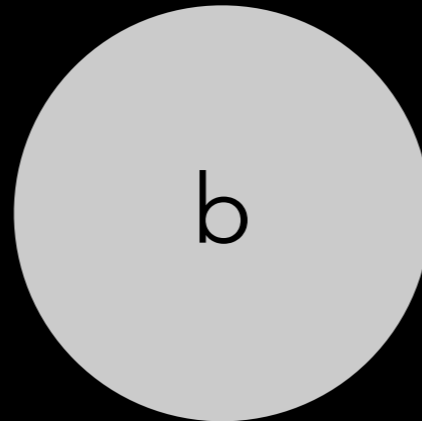
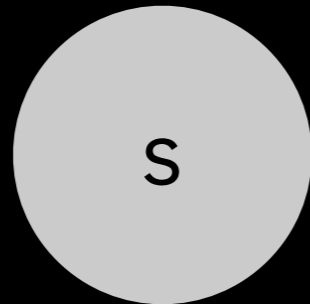
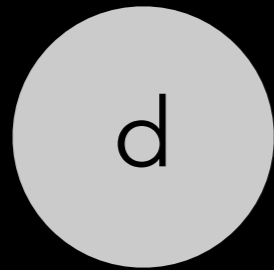
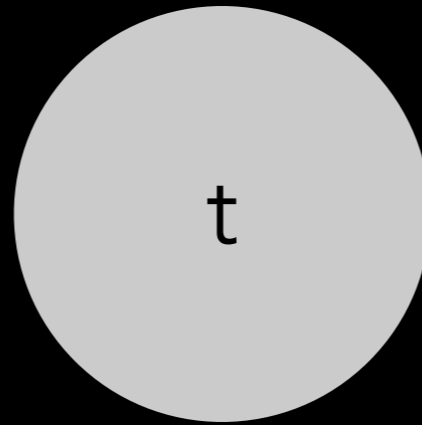
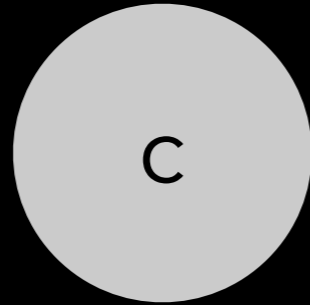
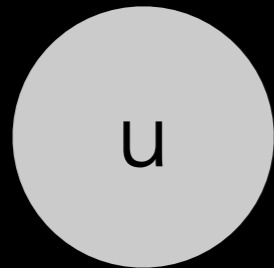


Standard Model & Neutrinos

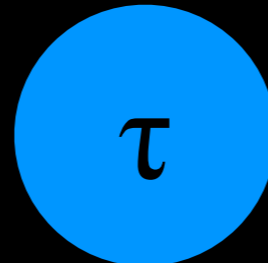


Standard Model & Neutrinos

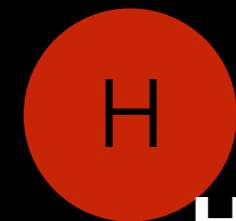
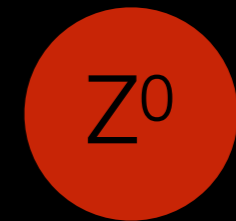
Quarks



Leptons

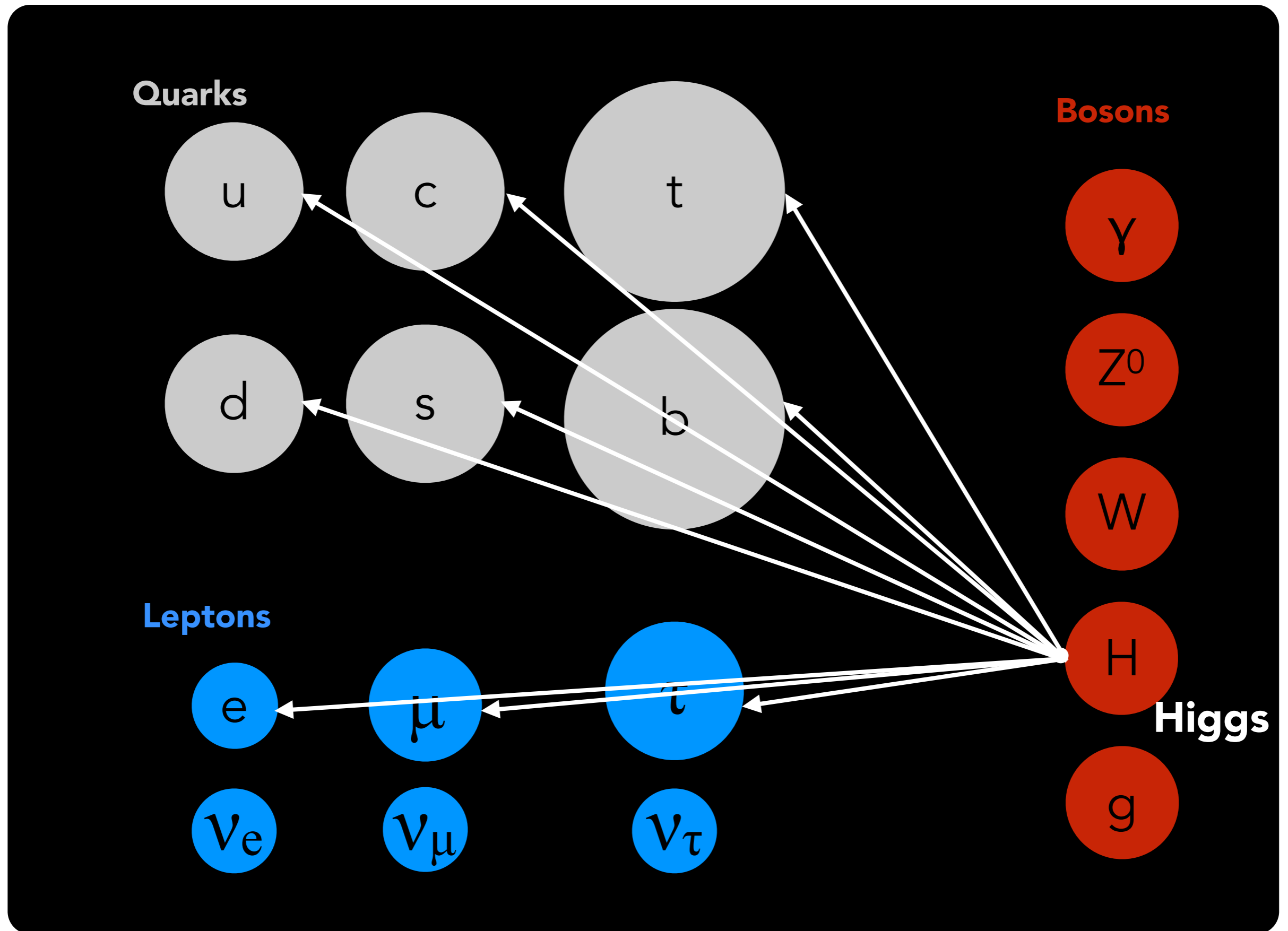


Bosons

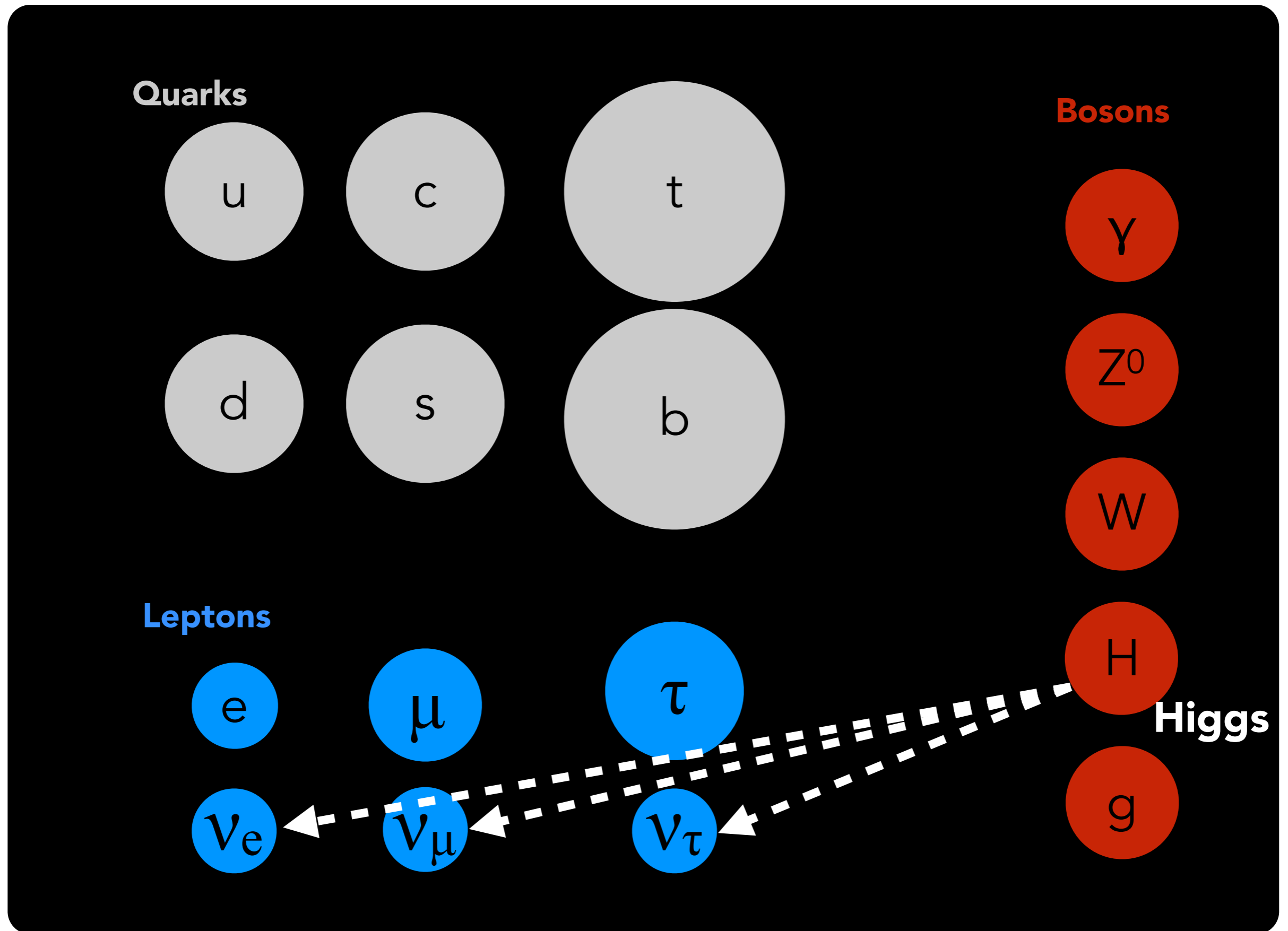


Higgs

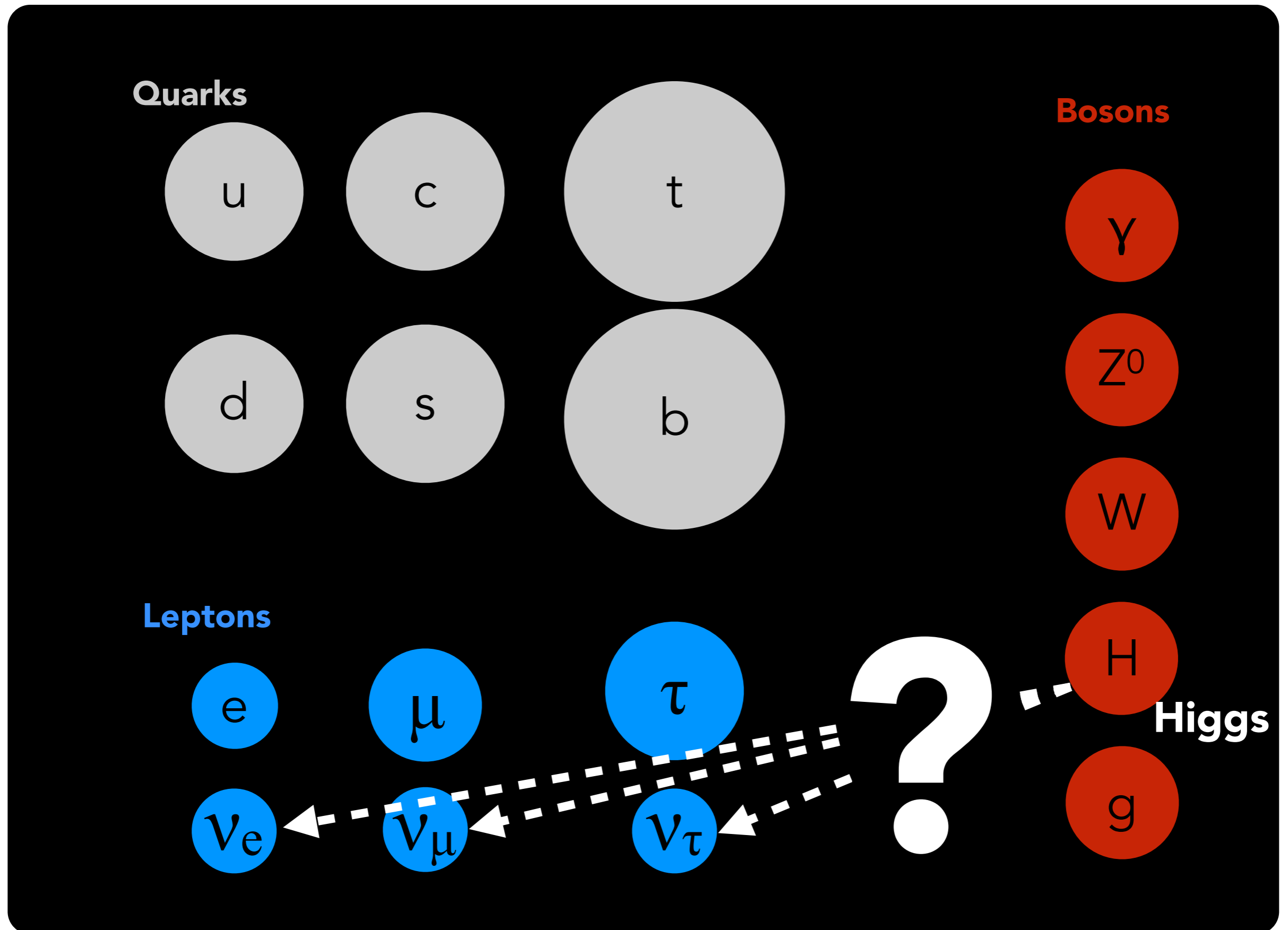
Standard Model & Neutrinos



Standard Model & Neutrinos



Standard Model & Neutrinos

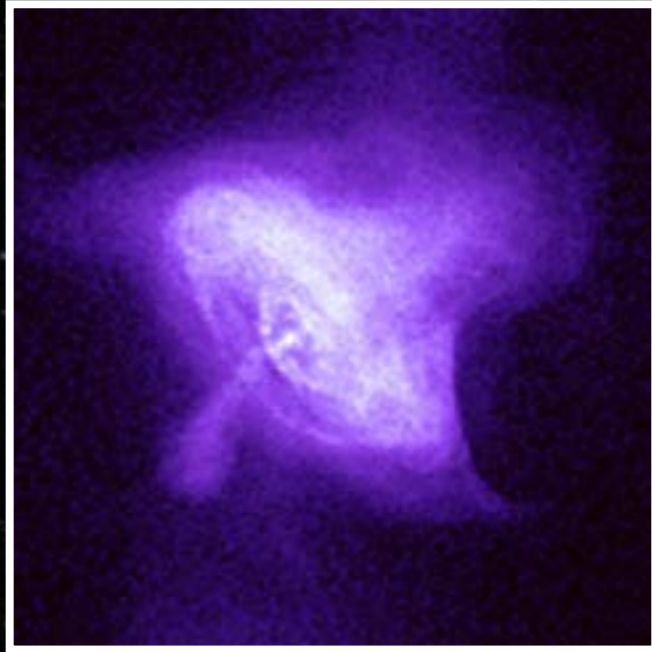


Why?

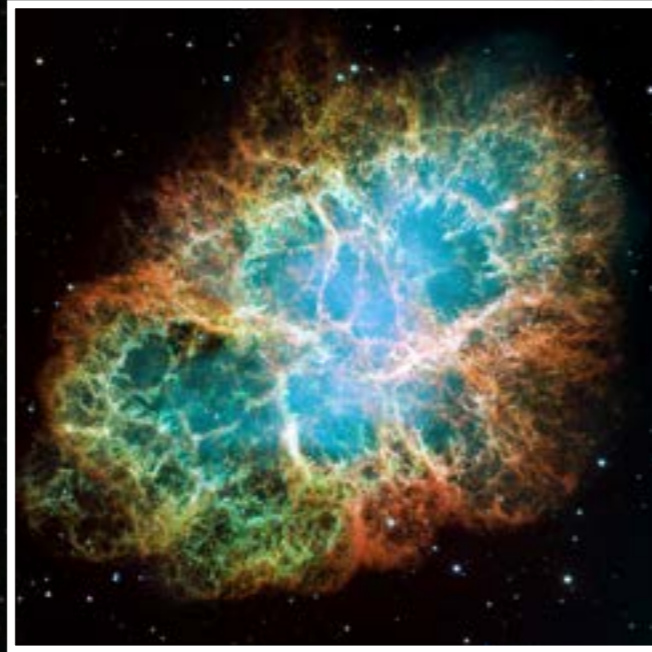
- Fundamental Physics

Cosmic Messengers

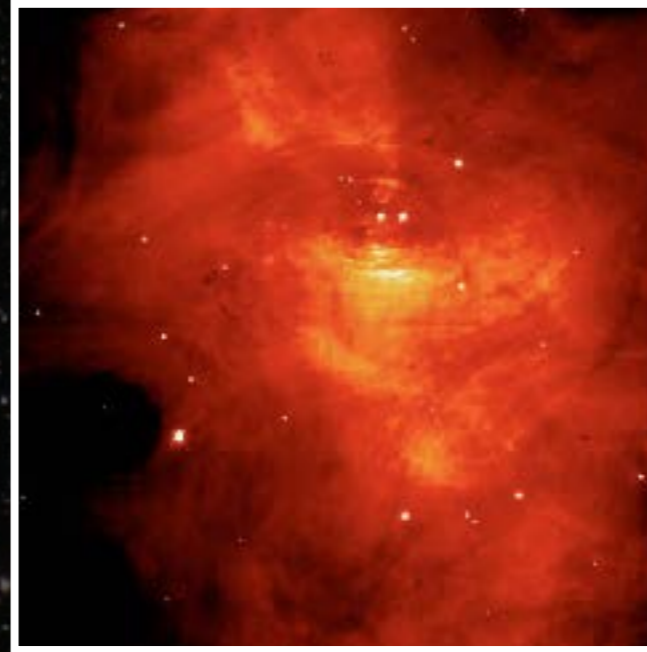
x-ray



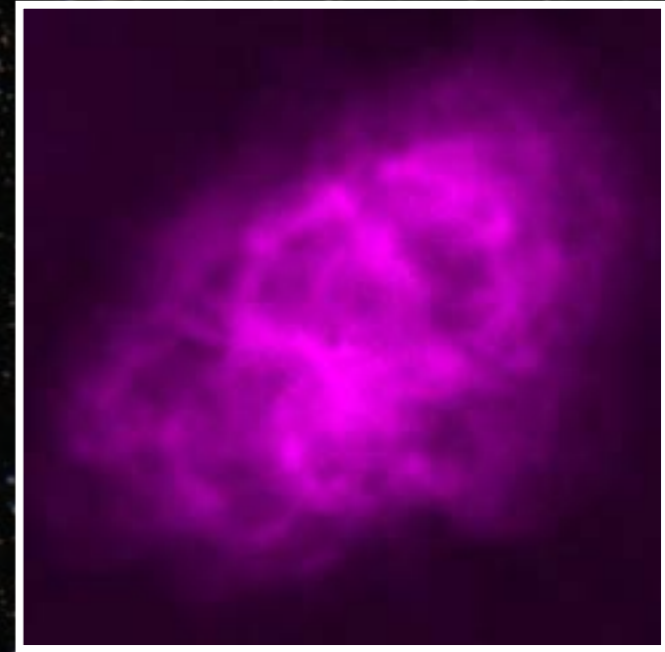
optical



infrared



radio



- 1054 AD a star went supernova which could be observed on earth by eye
- The left-over neutron star is now a pulsar
- The explosion created an expanding cloud of elements (H, He, C, O, etc.)

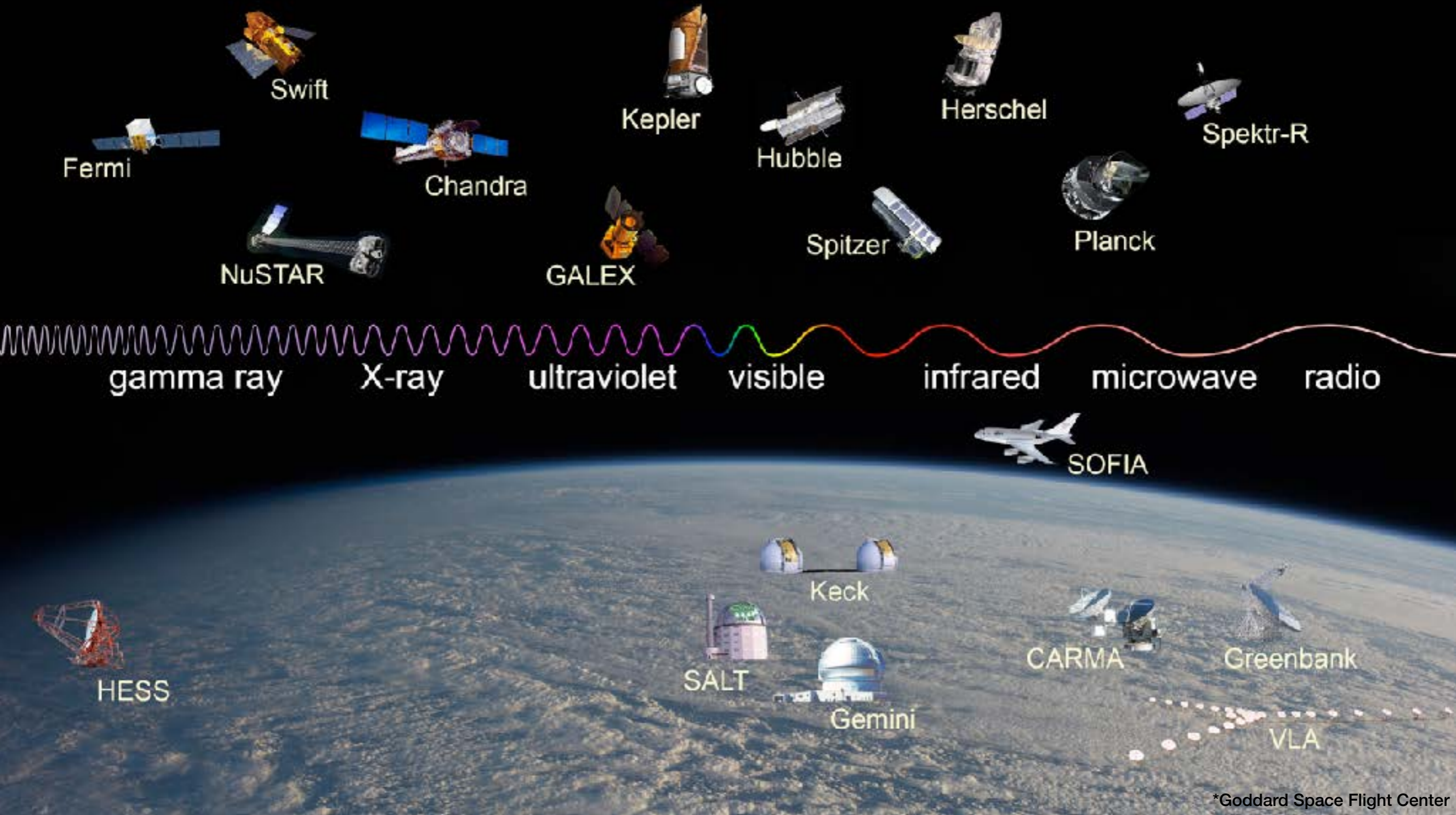
* NASA/CXC/SAO (X-ray), NASA/ESA/J. Hester and A. Loll (Arizona State University) (optical), AURA/STScI/NASA/JPL (infrared), NRAO/AUI/NSF (radio)

Supernova Observed Everywhere

歷代名臣奏議卷之三百一
灾祥
宋仁宗至和二年侍御史趙抃上言曰臣伏見自去年五月已來妖星遂見僅及周稔至今光耀未退此谷永所謂馳騁驟處芒炎長繩所懸奸犯其為譎變甚可畏也又去冬連今春京東西路及陝右川蜀諸郡旱暵不雨麥苗焦死民既艱食寇攘必興此京房所謂欲德不用茲謂張厥災荒其為災沴復可懼也邇來岷峽山谷驚裂有聲他郡數處地亦震動此伯陽所謂陽伏而不能出陰迫而不能升蓋土失其性其為災異益可駭也夫變調陰陽者三公之職天戒若曰陛下左右輔弼當得忠賢剛正之人為之乃可以召至和之氣消未萌之眚不然何以妖星譎變也旱暵災沴也地震祥異也三者皆應察明如是之著耶臣愚伏望陛下謹天之戒應天以實取天下公議與天下瞻望之所謂賢人君子者降之使居廟堂之上責以三公四輔之事業委注而仰成之若然則陰陽以和災異以消朝廷清明美狄畏服太平之風可翹足引領而待之也臣朝夕思慮載惟擇賢命相繫國家休戚治亂之本伏願陛下慎重之然後發聖斷力行而不疑則宗廟社稷之福天下生靈之幸
起居舍人知諫院范鎮上奏曰臣伏見去冬多南風今春多西北風乍寒乍暑欲雨不雨又有黑氣蔽日此皆人事之所感動也黑氣陰也小人也日陽也君象也黑氣蔽日者陰侵陽小人惑君也欲雨不雨者政事不決也陳執中為相不病而家居者百日矣陛下以御史之言決一婢死而欲退宰相為是即乞速退執中以解天意以御史之言為非亦乞勅執中起視事無使天意久不決也寒暑者賞罰也乍寒乍暑者不當賞而賞當罰而不罰也鄧保吉有過於法不當為

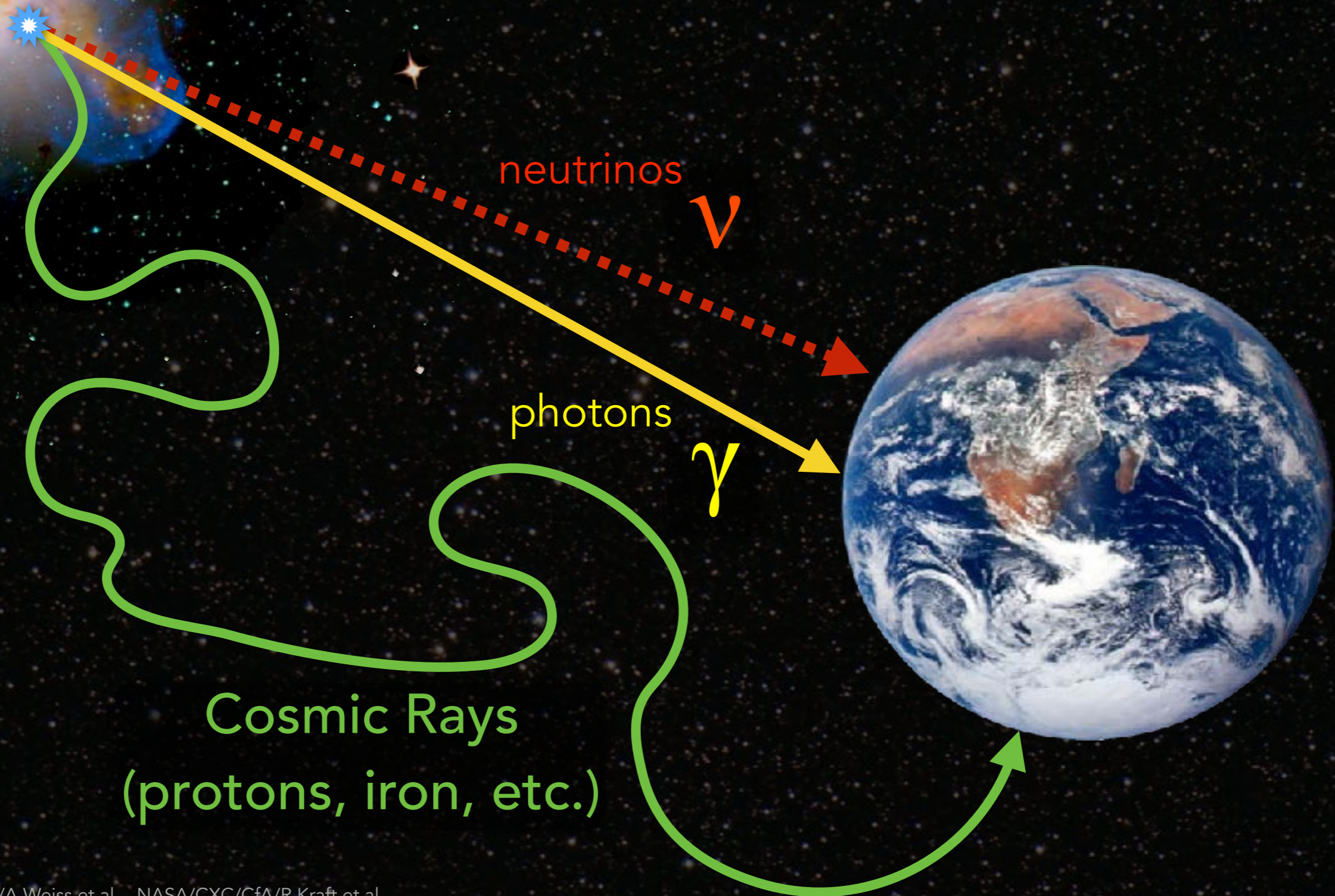
* Lidai mingchen zouyi (歷代名臣奏議)

Photon Astronomy



*Goddard Space Flight Center

Multimessenger Astronomy



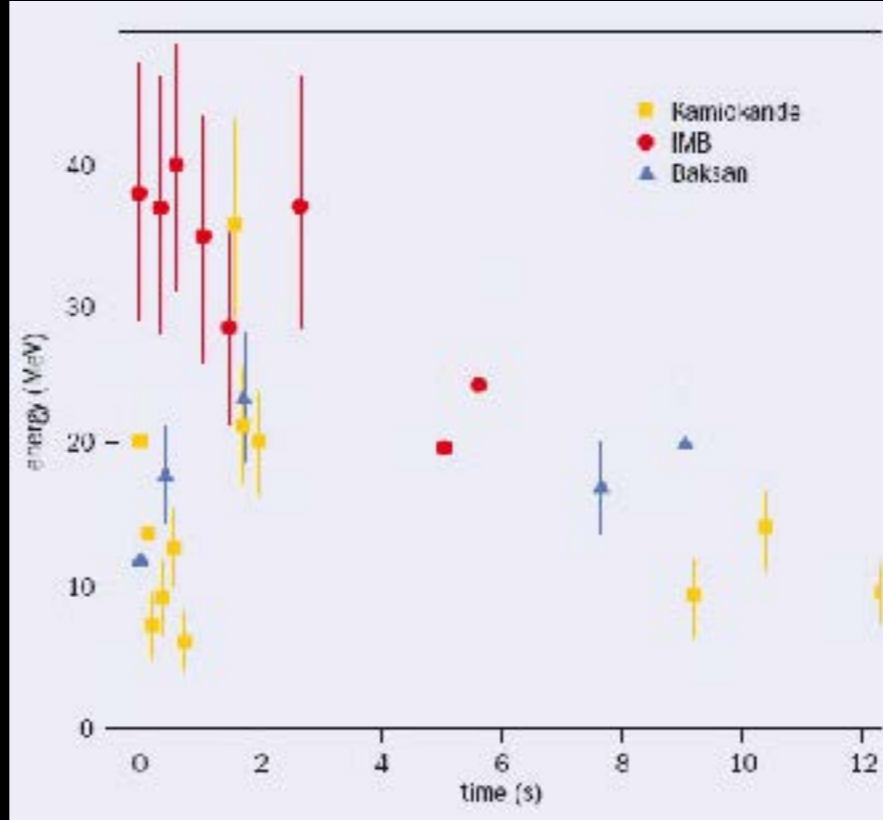
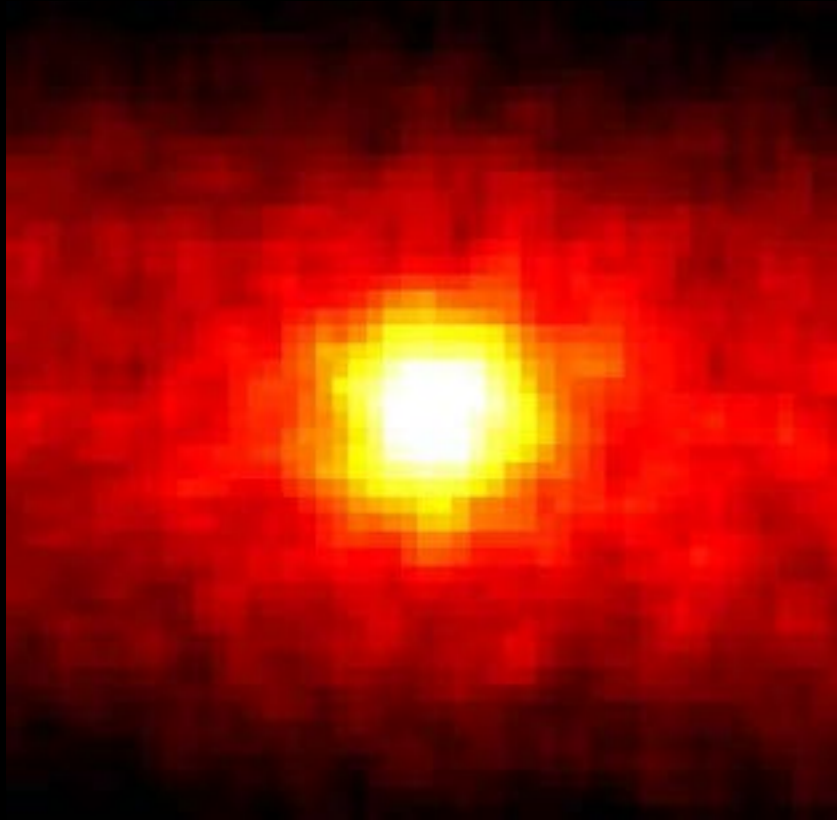
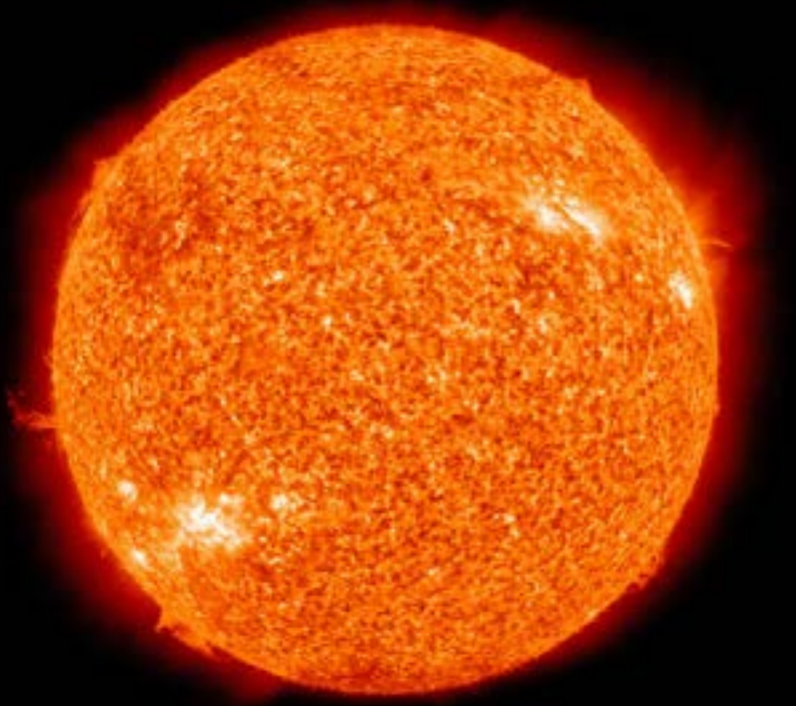
Cosmic Rays
(protons, iron, etc.)

*ESO/WFI - MPIfR/ESO/APEX/A.Weiss et al. - NASA/CXC/CfA/R.Kraft et al.

*C. Beckett, S. Meneguolo, Royal Astronomical Society of Canada

D. Jason Koskinen - IceCube & Neutrinos - Nov. 2018

Astrophysical Neutrino



- NASA/SDO
- R. Svoboda & K. Gordan (LSU)

- ESO/L. Calçada
- CERN Courier, Jan 2007

Photosynthesis

Carbon Dioxide + Water + Energy \longrightarrow Glucose + Oxygen

6CO_2 + $6\text{H}_2\text{O}$ + Energy \longrightarrow $\text{C}_6\text{H}_{12}\text{O}_6$ + 6O_2

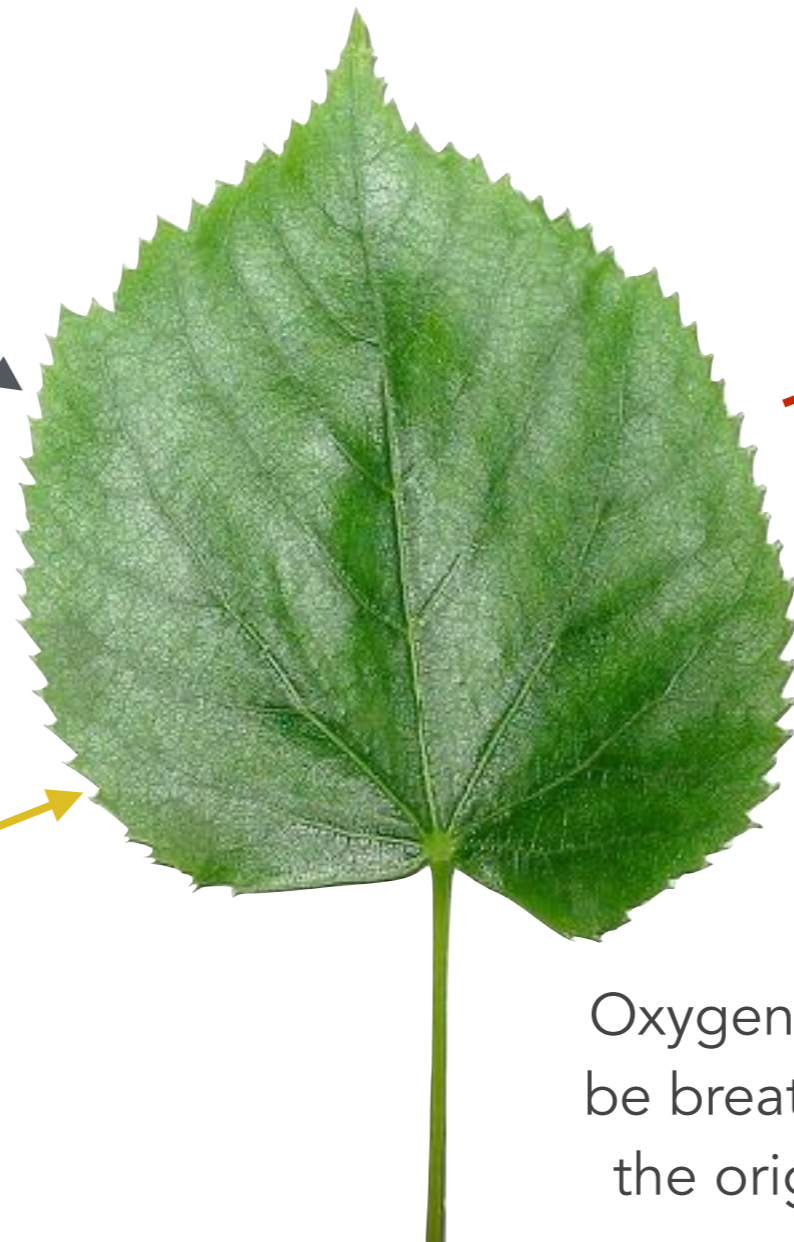
Carbon Dioxide

Water

Sunlight (energy)

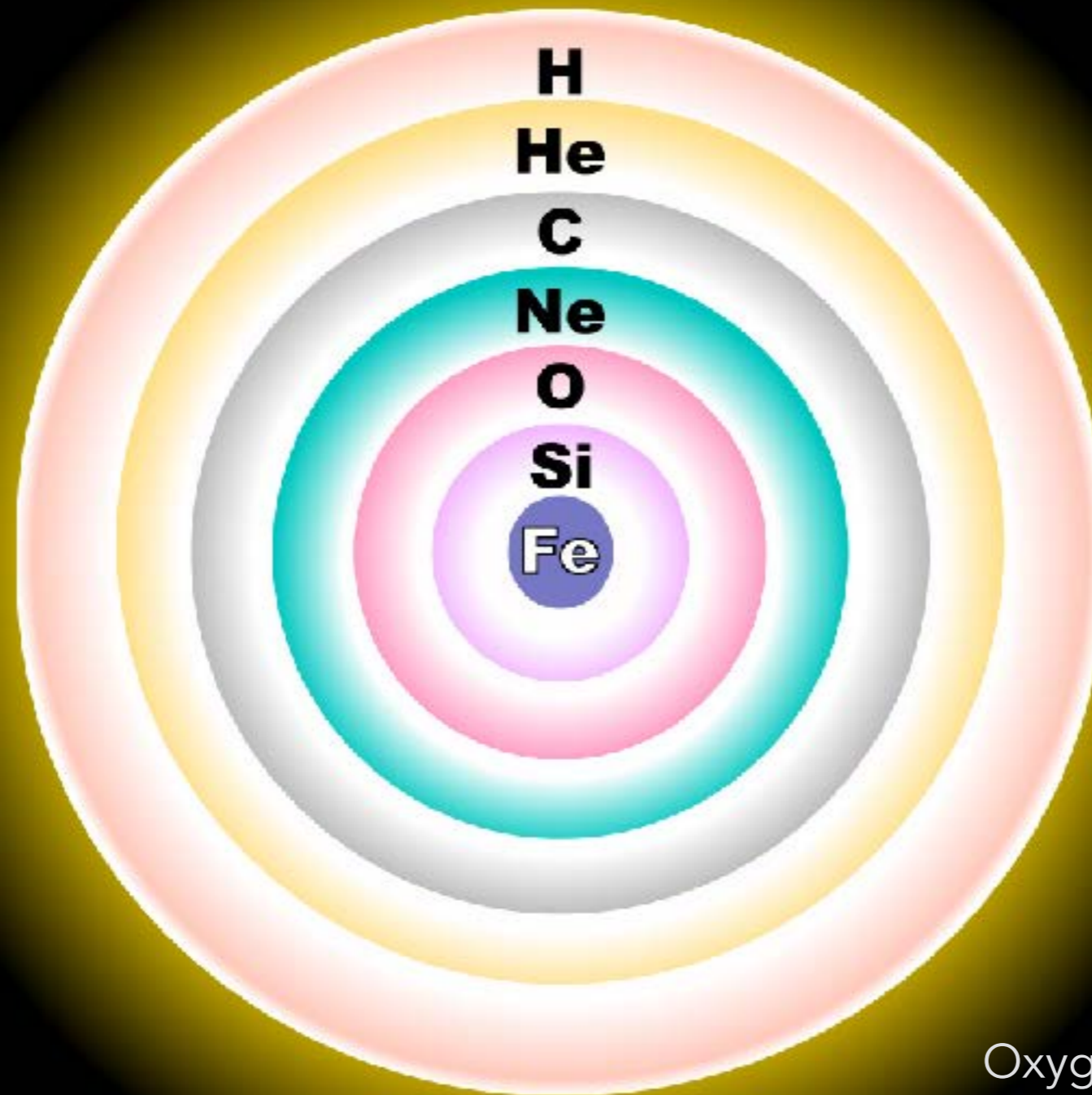
Oxygen

Glucose



Oxygen is recycled by photosynthesis to be breathable by humans. But, where do the original oxygen atoms come from?

Stellar Nucleosynthesis



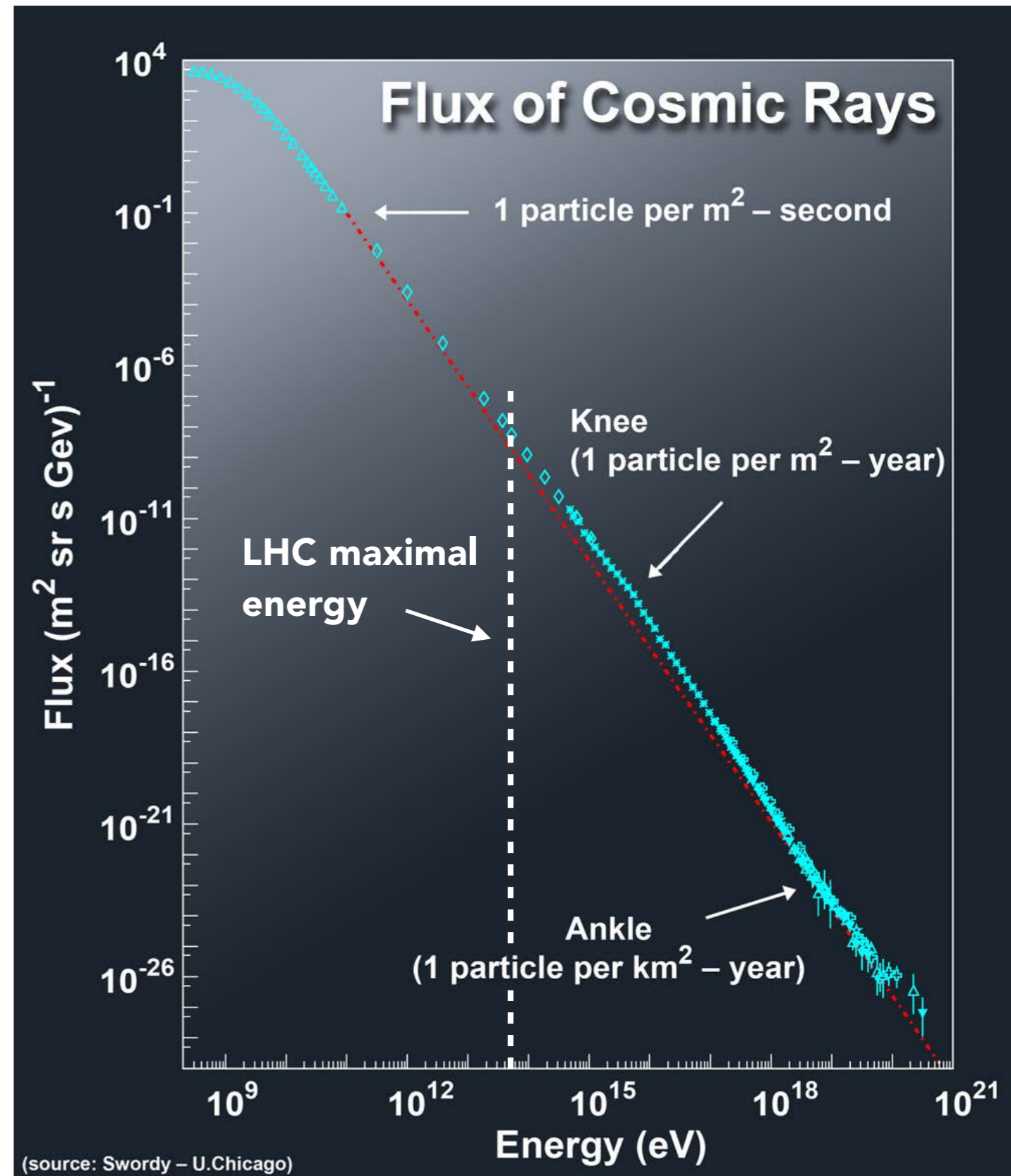
Oxygen comes from the insides of stars, and needs neutrinos in order to blowup (go supernova)

Why?

- Fundamental Physics
- Cosmic Messengers

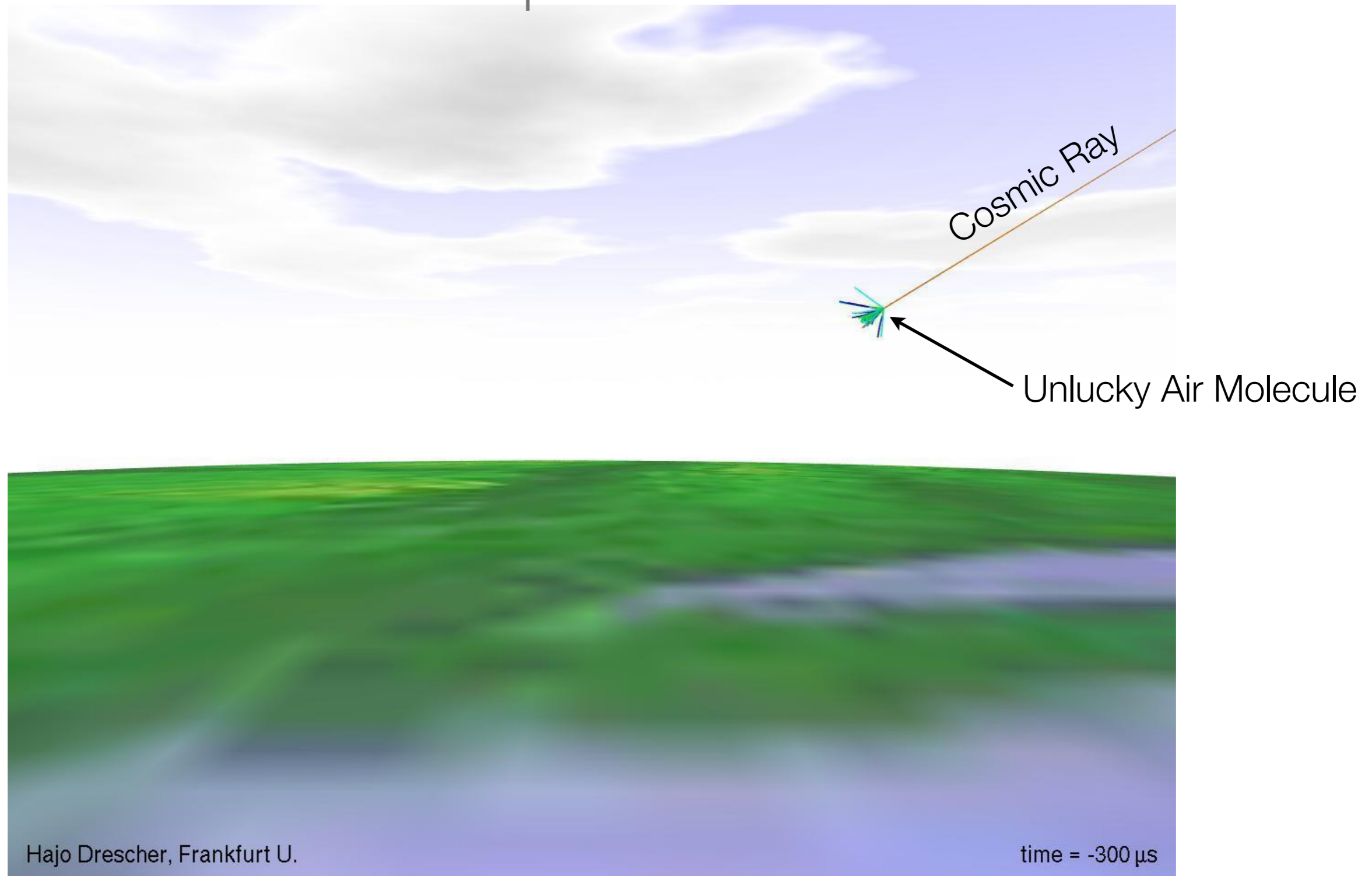
Cosmic Laboratory

- Higher energy atoms (p, H, Fe, etc.) than can ever be produced on earth
- Evidence for extremely energetic accelerators... somewhere



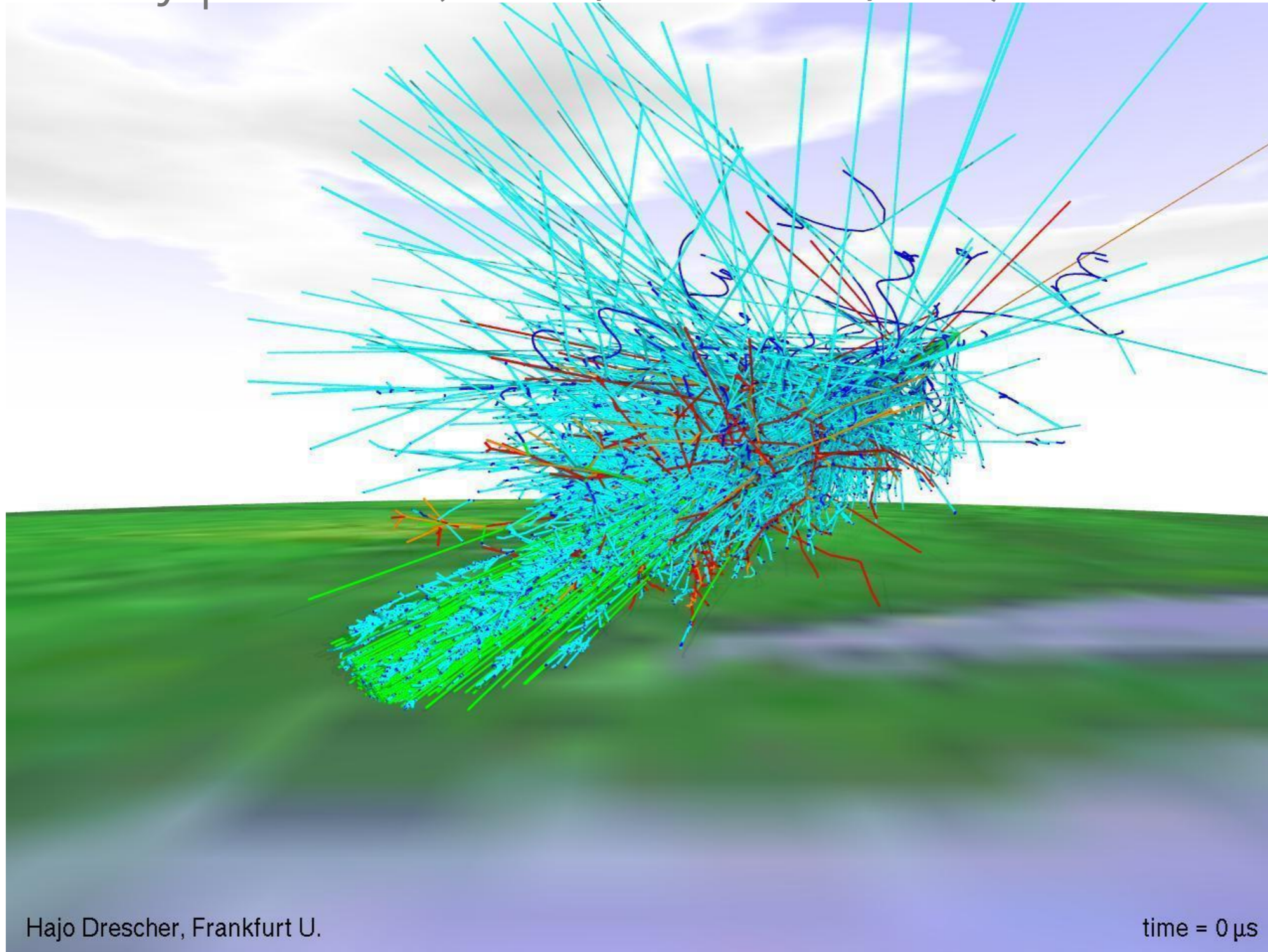
Natural Collisions

- Probes collisions at higher energies than what will ever be possible with man-made particle accelerators



Natural Collider

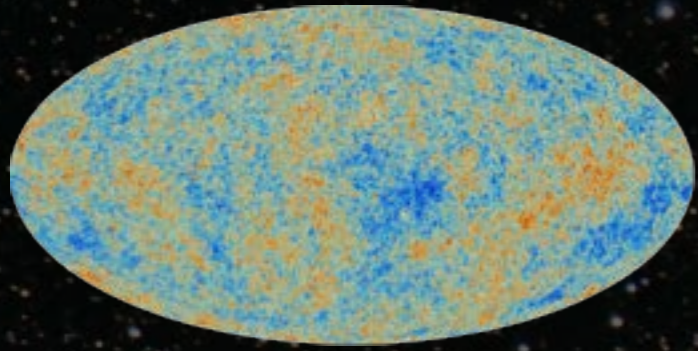
- Particle collider in the sky with a large number of secondary particles (muon, neutrinos, etc.)



Constant rain of Earth penetrating muons (μ)
and neutrinos (ν) from Cosmic Ray collisions
with the atmosphere

 ν μ

Neutrino Sources



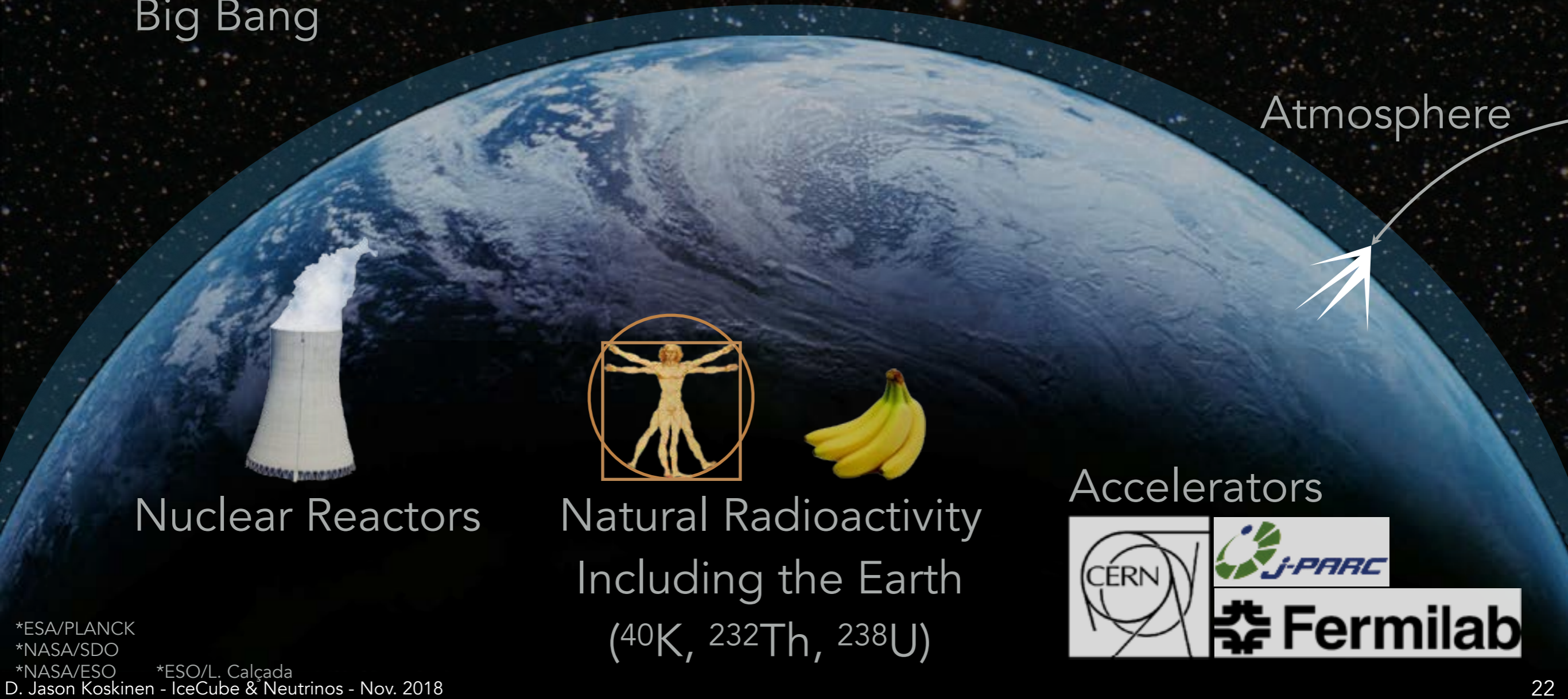
Big Bang



Sun



SuperNovae



Atmosphere



Nuclear Reactors



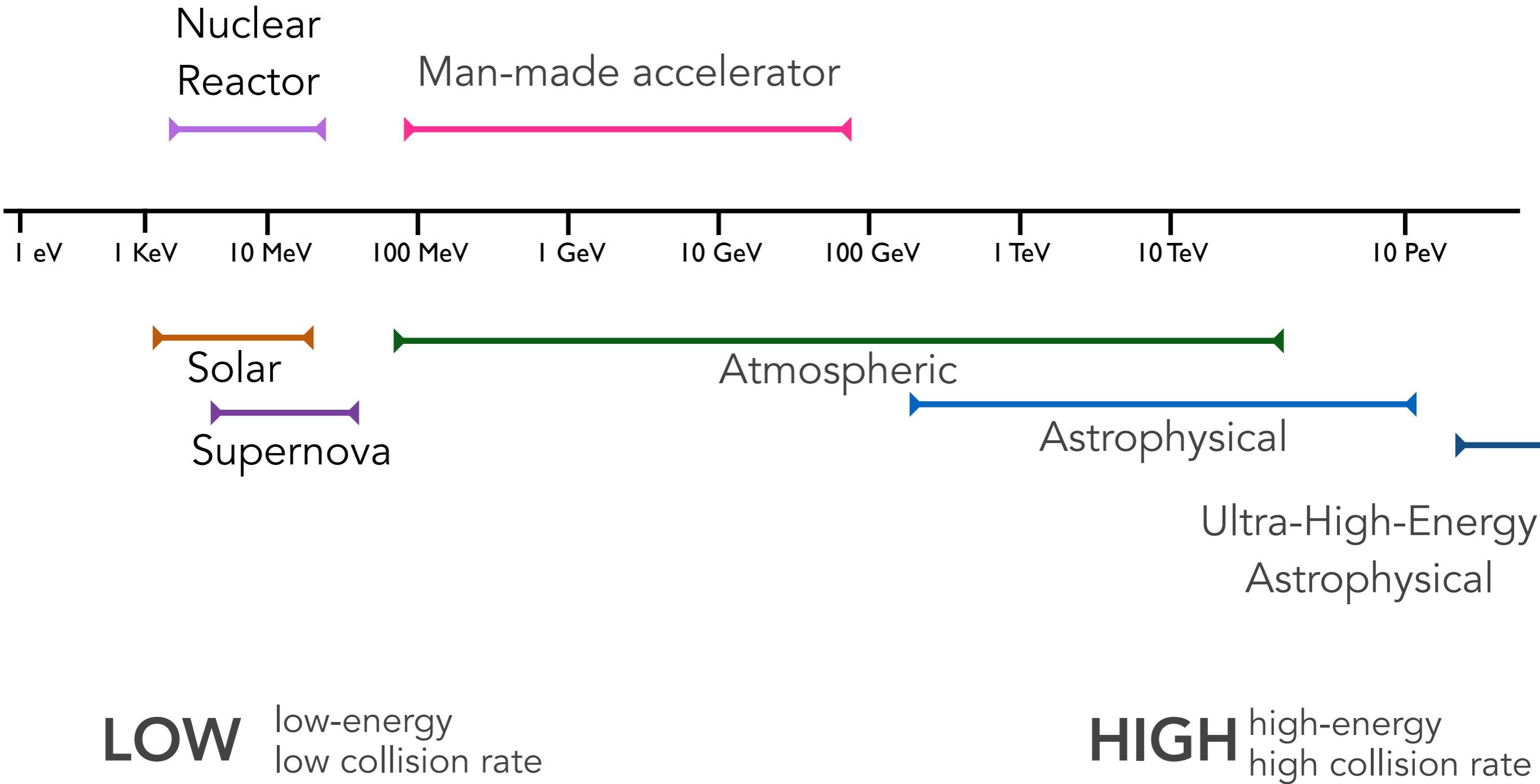
Natural Radioactivity
Including the Earth
(^{40}K , ^{232}Th , ^{238}U)

Accelerators



*ESA/PLANCK
*NASA/SDO
*NASA/ESO *ESO/L. Calçada
D. Jason Koskinen - IceCube & Neutrinos - Nov. 2018

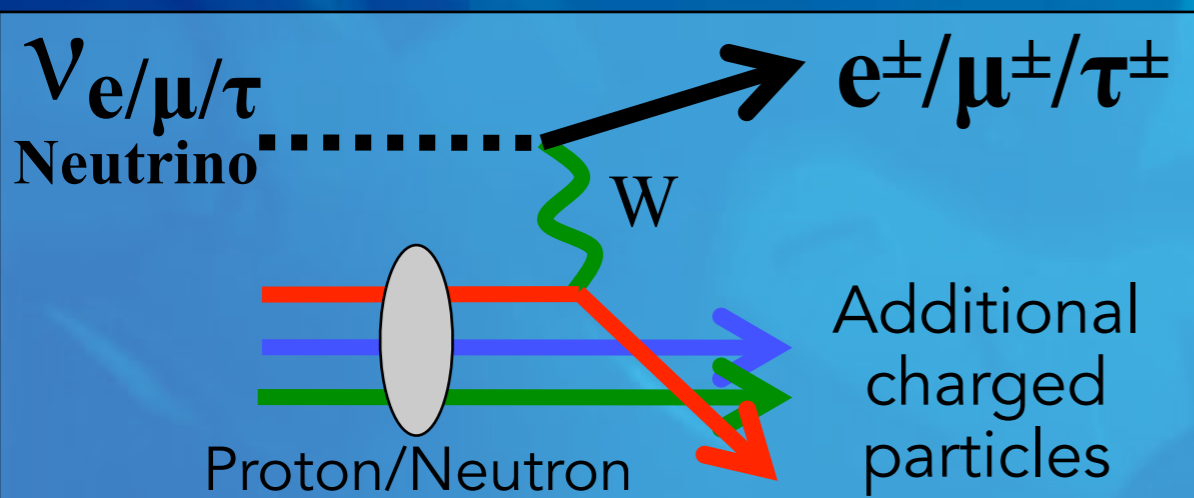
Neutrino Energies



Overview

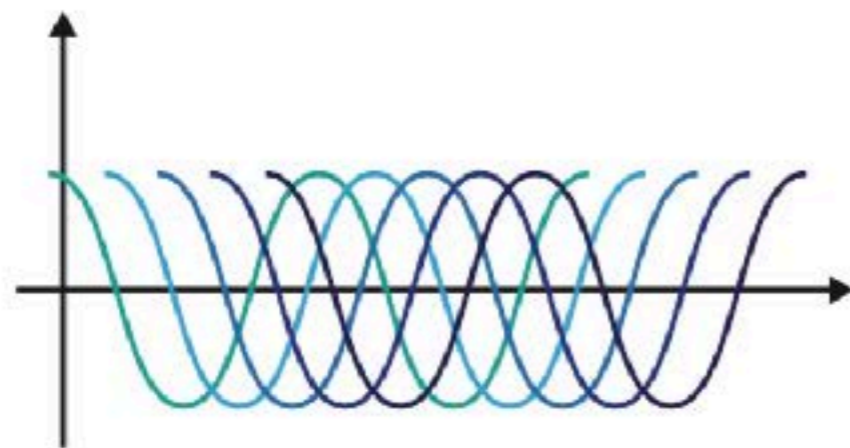
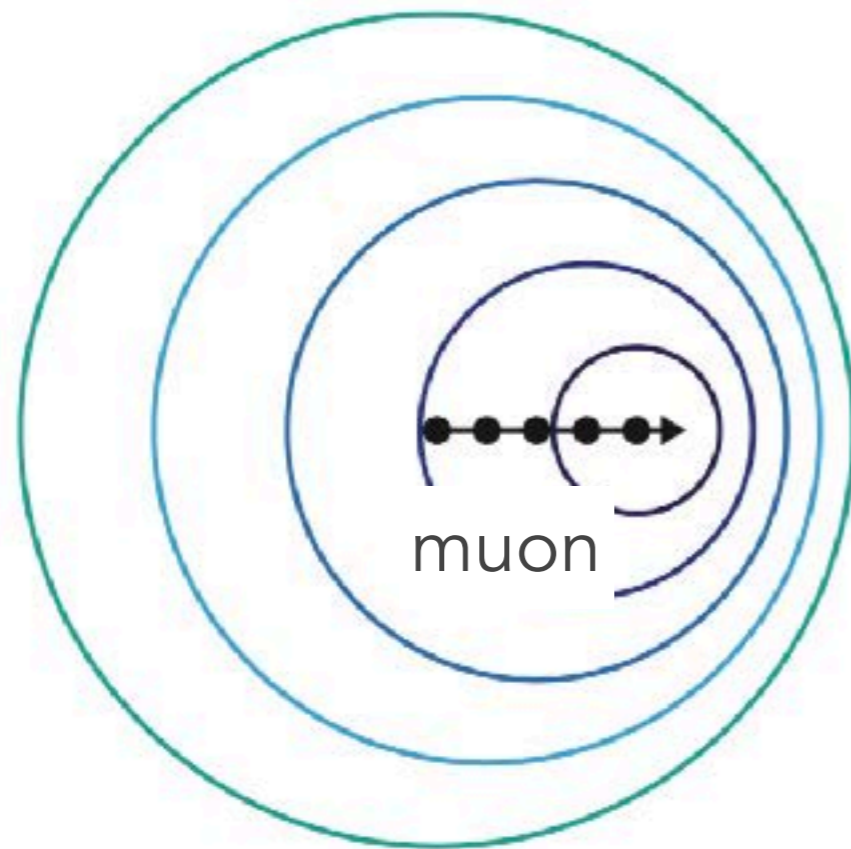
- Neutrinos are incredible
 - Fundamental particles which remain mysterious
 - Cosmic messengers
 - Probe the exotic cosmic laboratory
 - Produced over large energy range
- Neutrinos are `terrible`
 - Neutral particles
 - Low chance to interact

Charged particles traveling through water/ice produce blue (Cherenkov) light

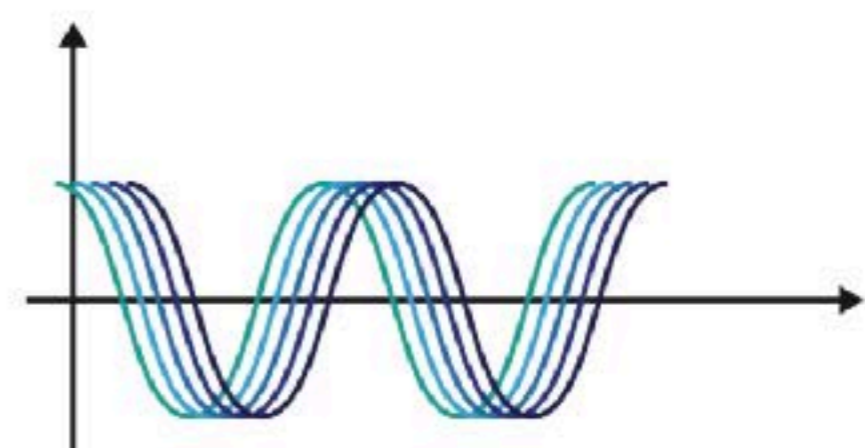
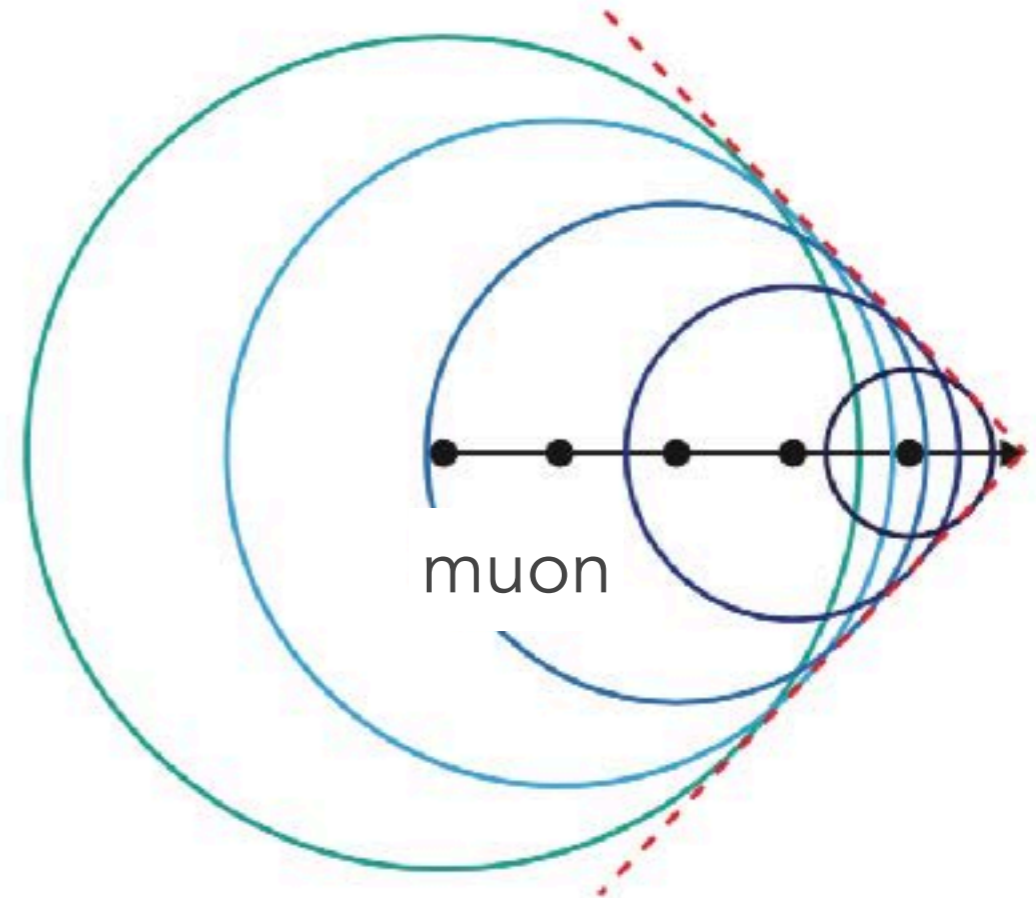


Cherenkov Light Illustration

*M. Medici, PhD thesis

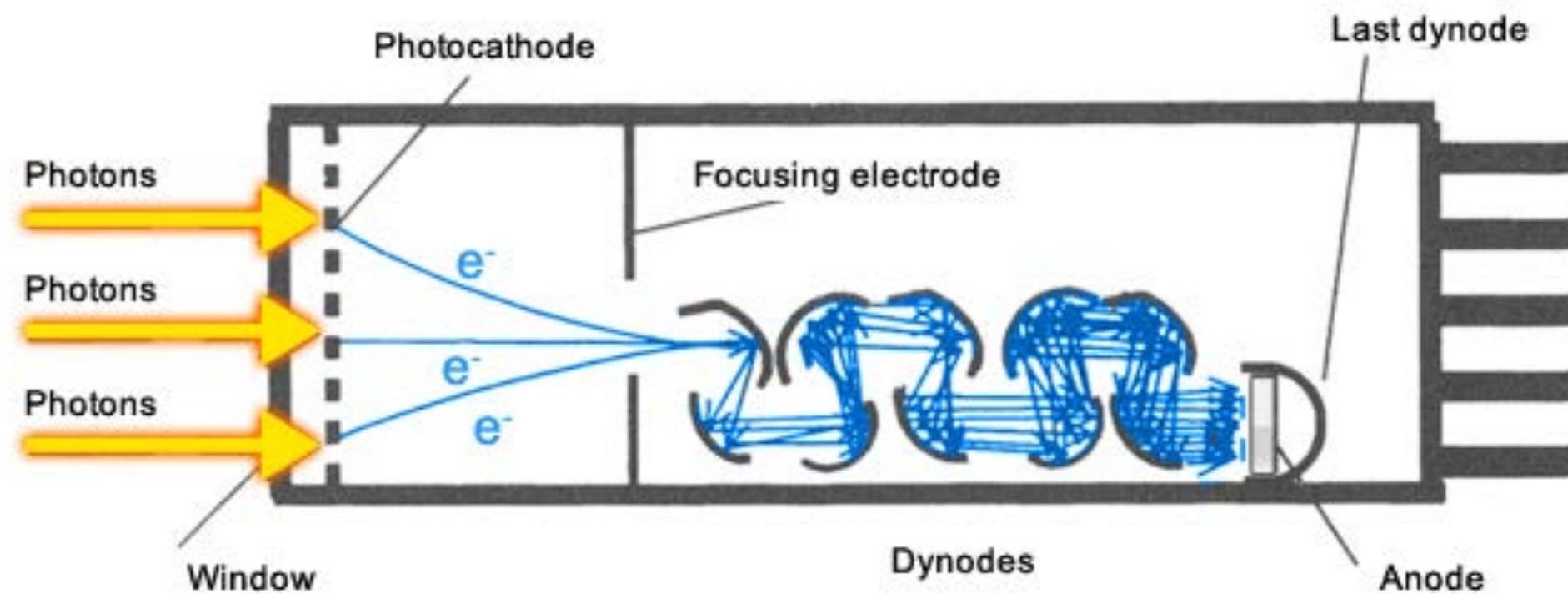


Light `waves' cancel
No Cherenkov emission



Light `waves' align
Cherenkov emission

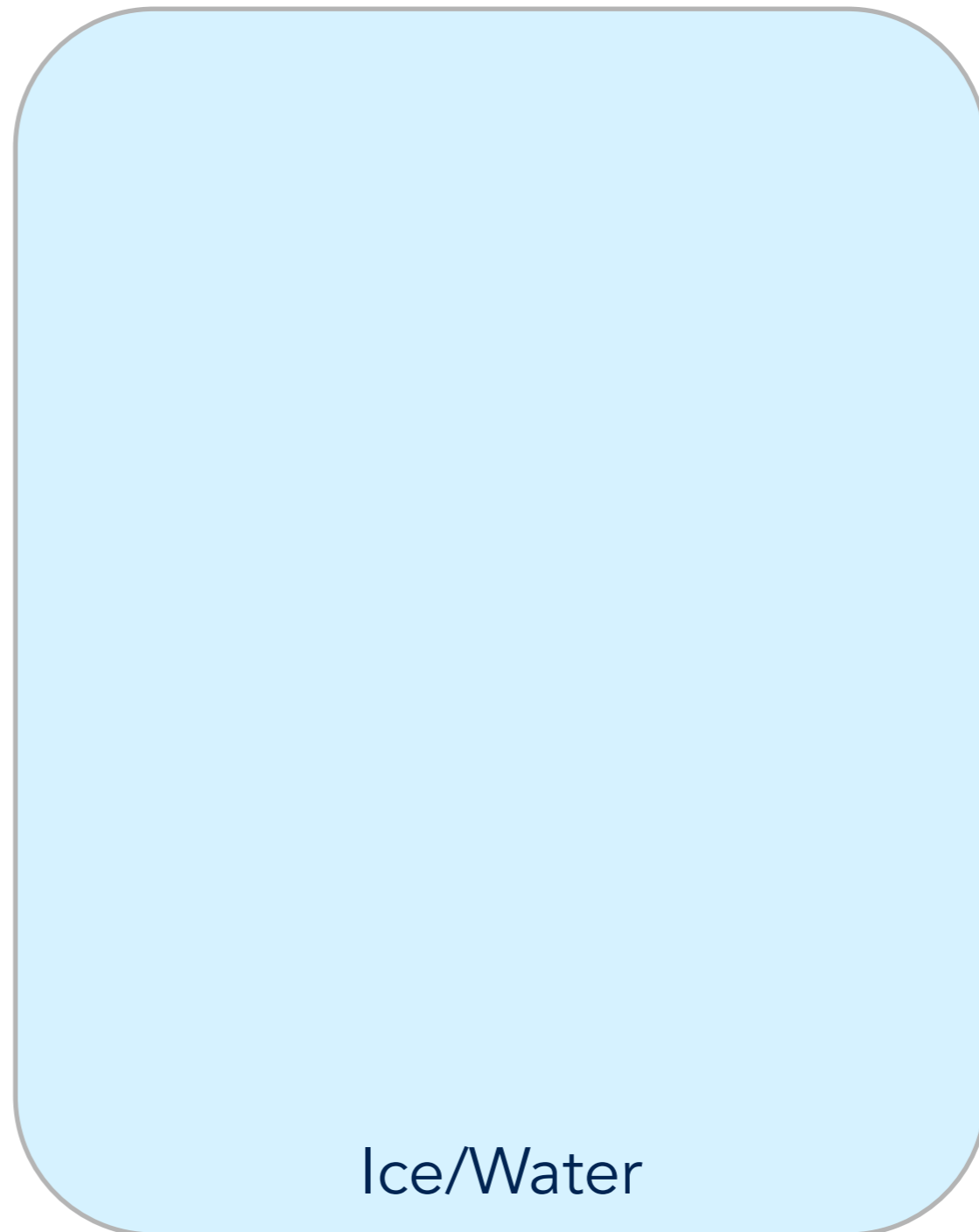
Light Receivers



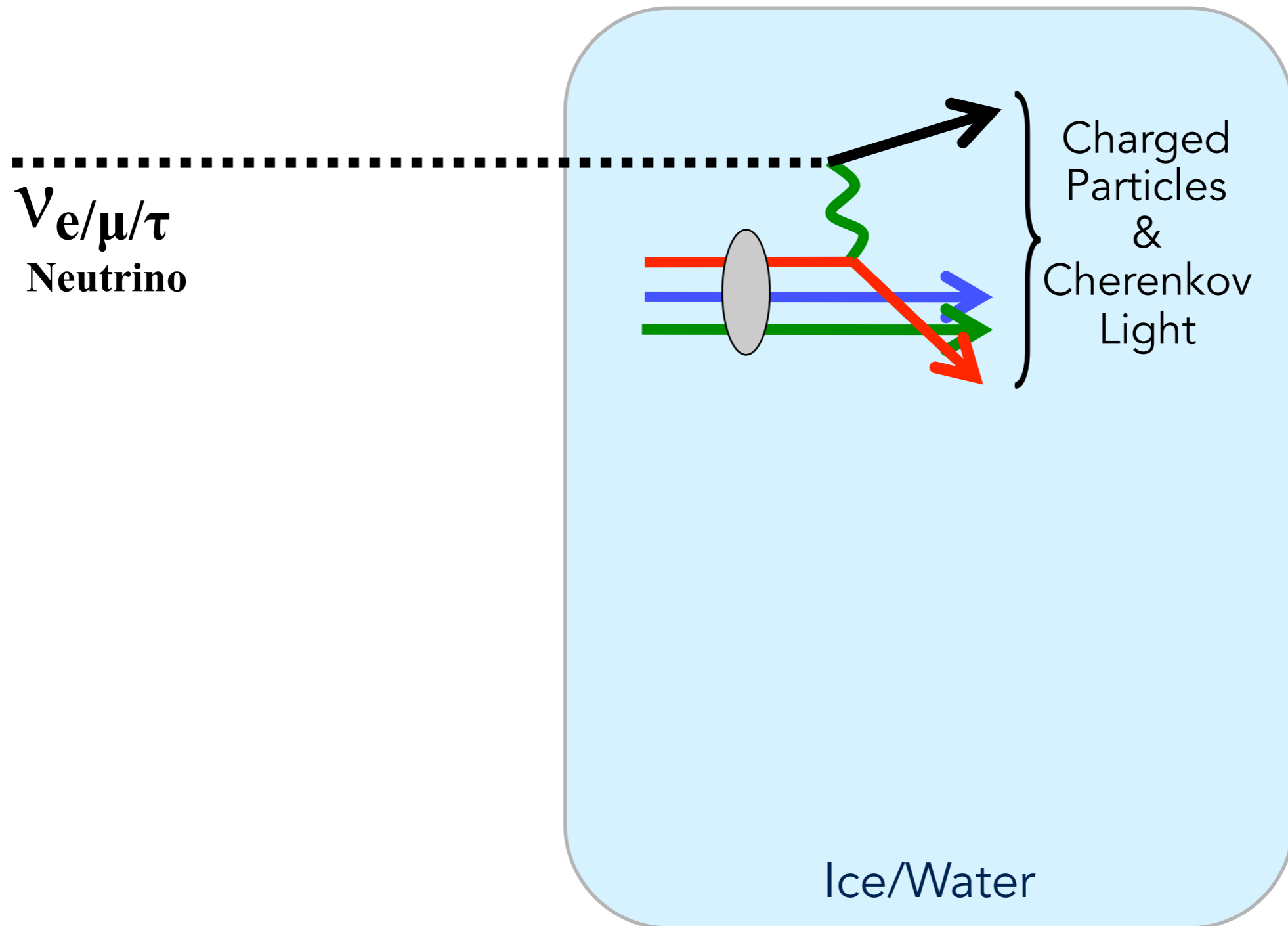
Photomultiplier tubes (PMTs)

*Australian Microscopy & Microanalysis Research Facility

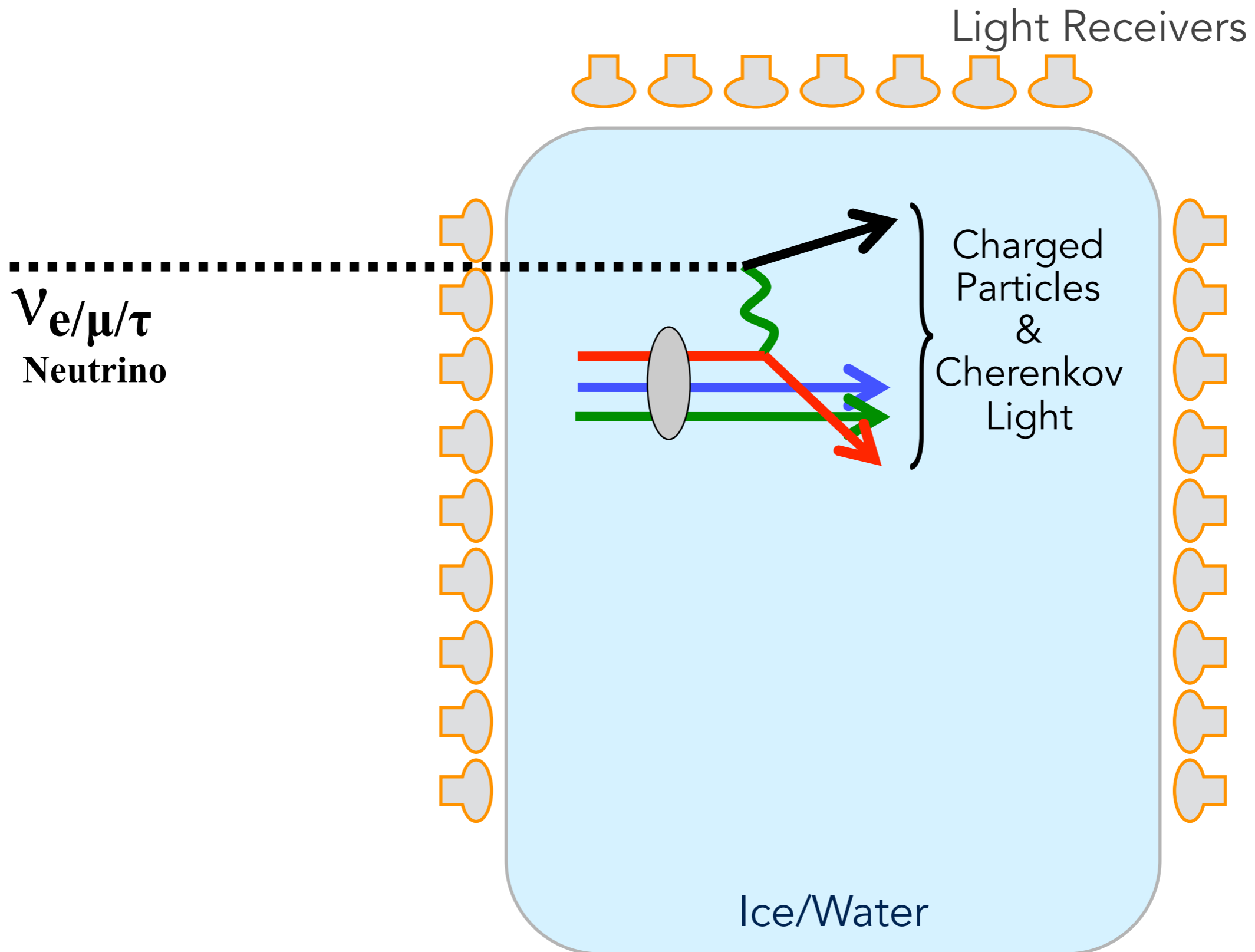
Detection



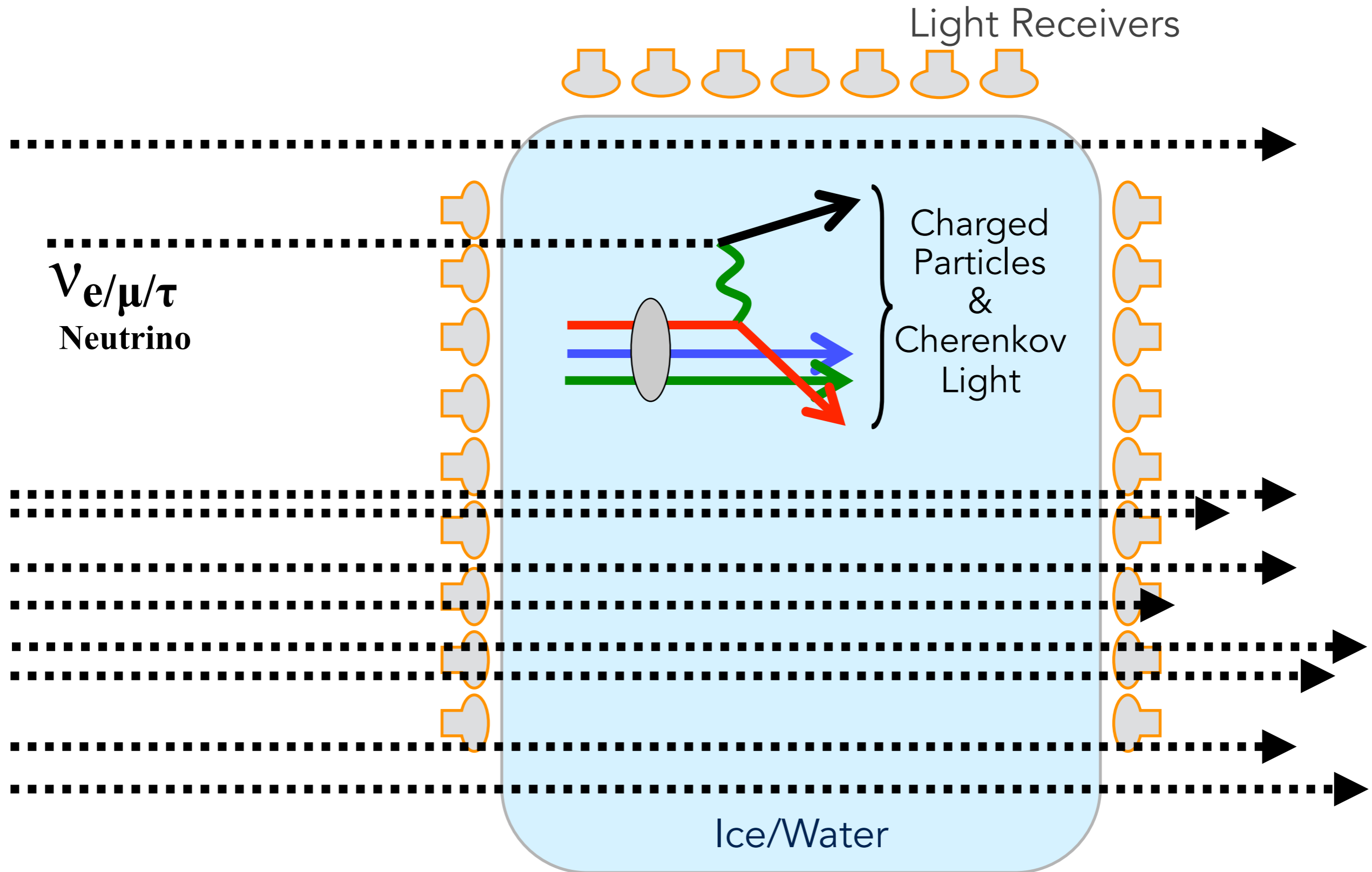
Detection



Detection



Detection



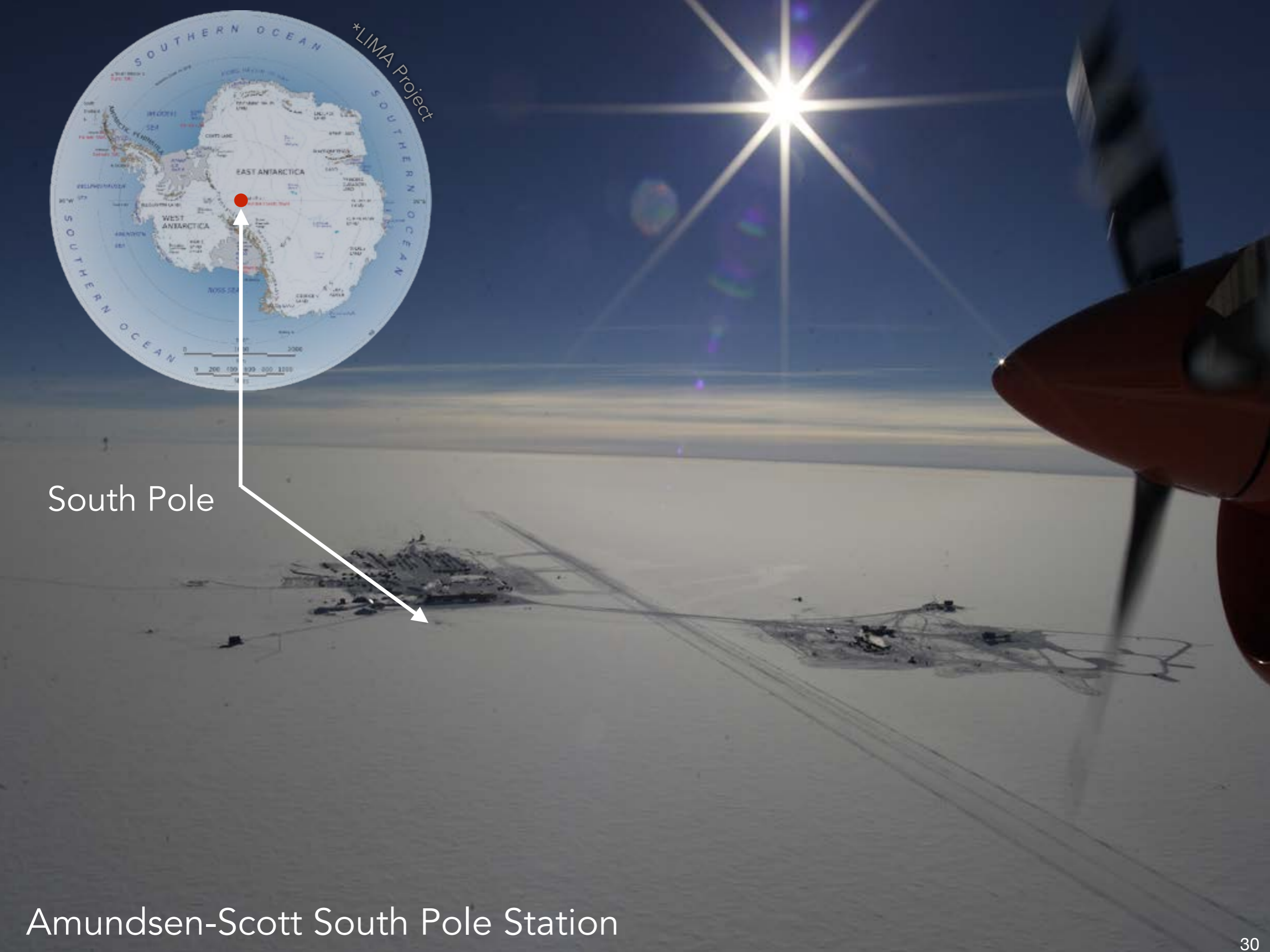
Super-Kamiokande





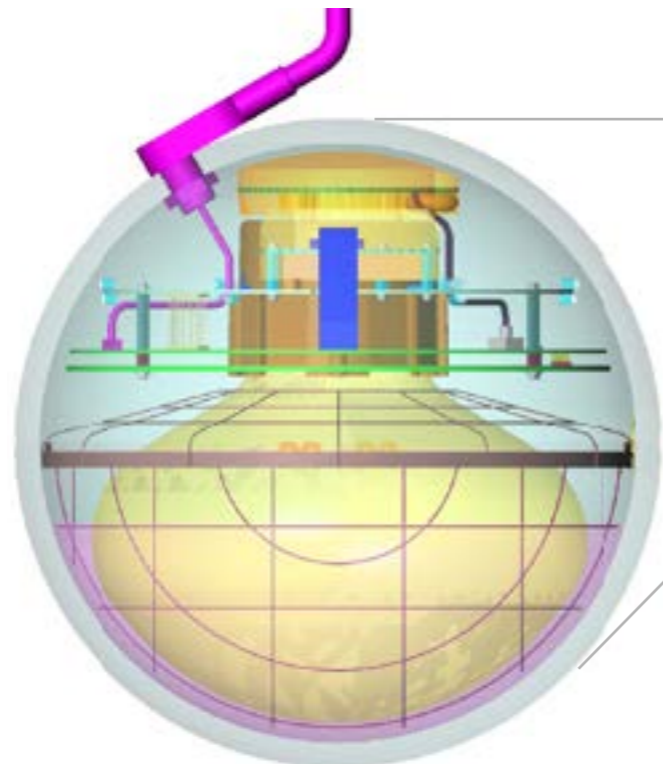
South Pole

Amundsen-Scott South Pole Station

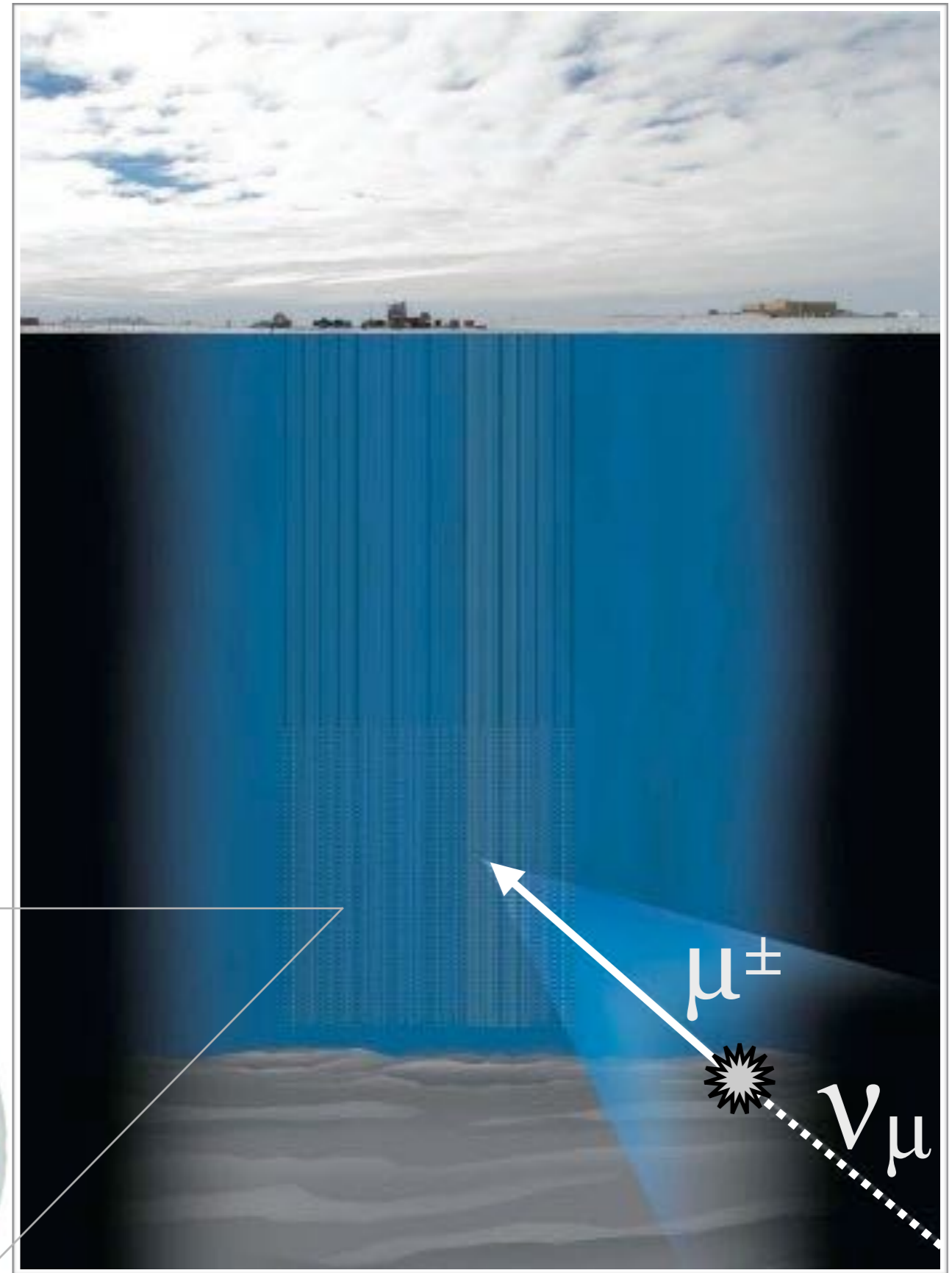


IceCube Detector

- $\sim 1\text{km}^3$ of instrumented ice
- Uses $\sim 5\text{k}$ optical sensors across 86 vertical strings to detect Cherenkov light
- Deployed 1.5 - 2.5km below the surface

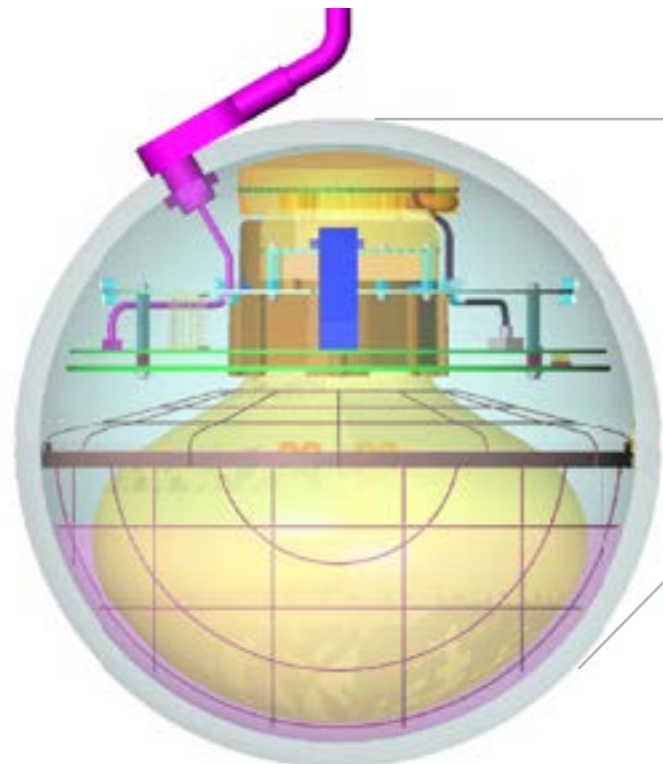


IceCube Optical Sensor

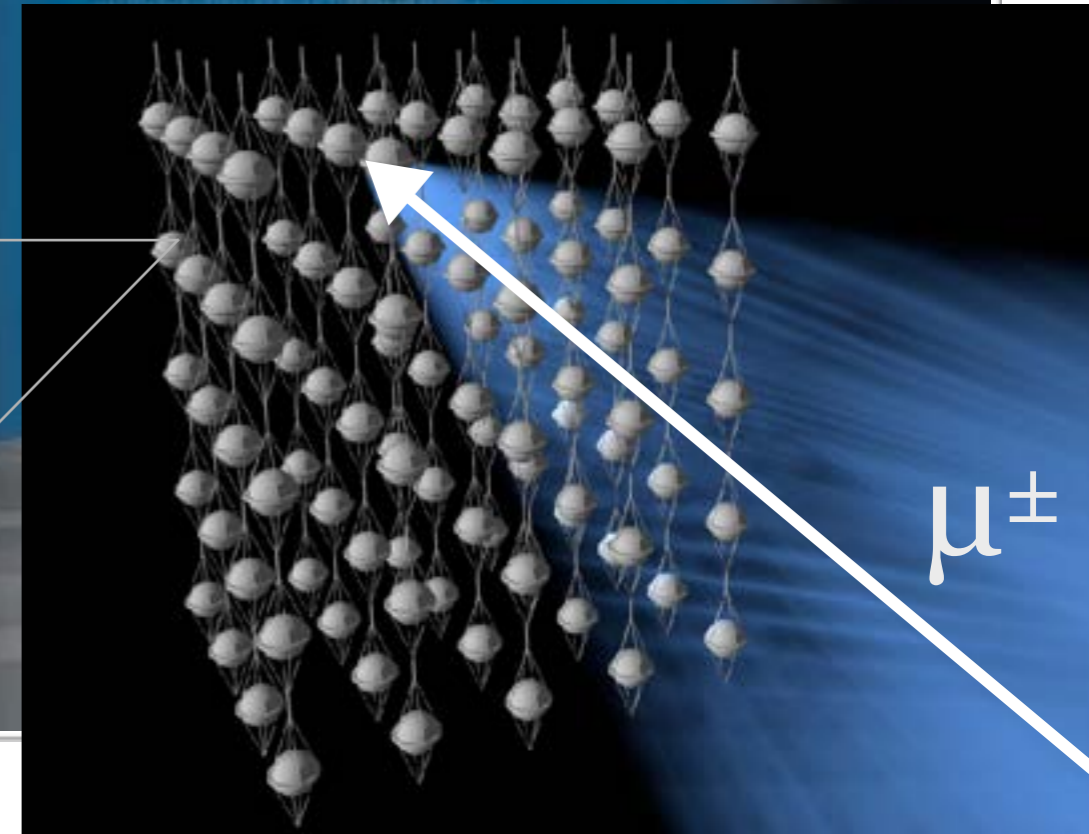
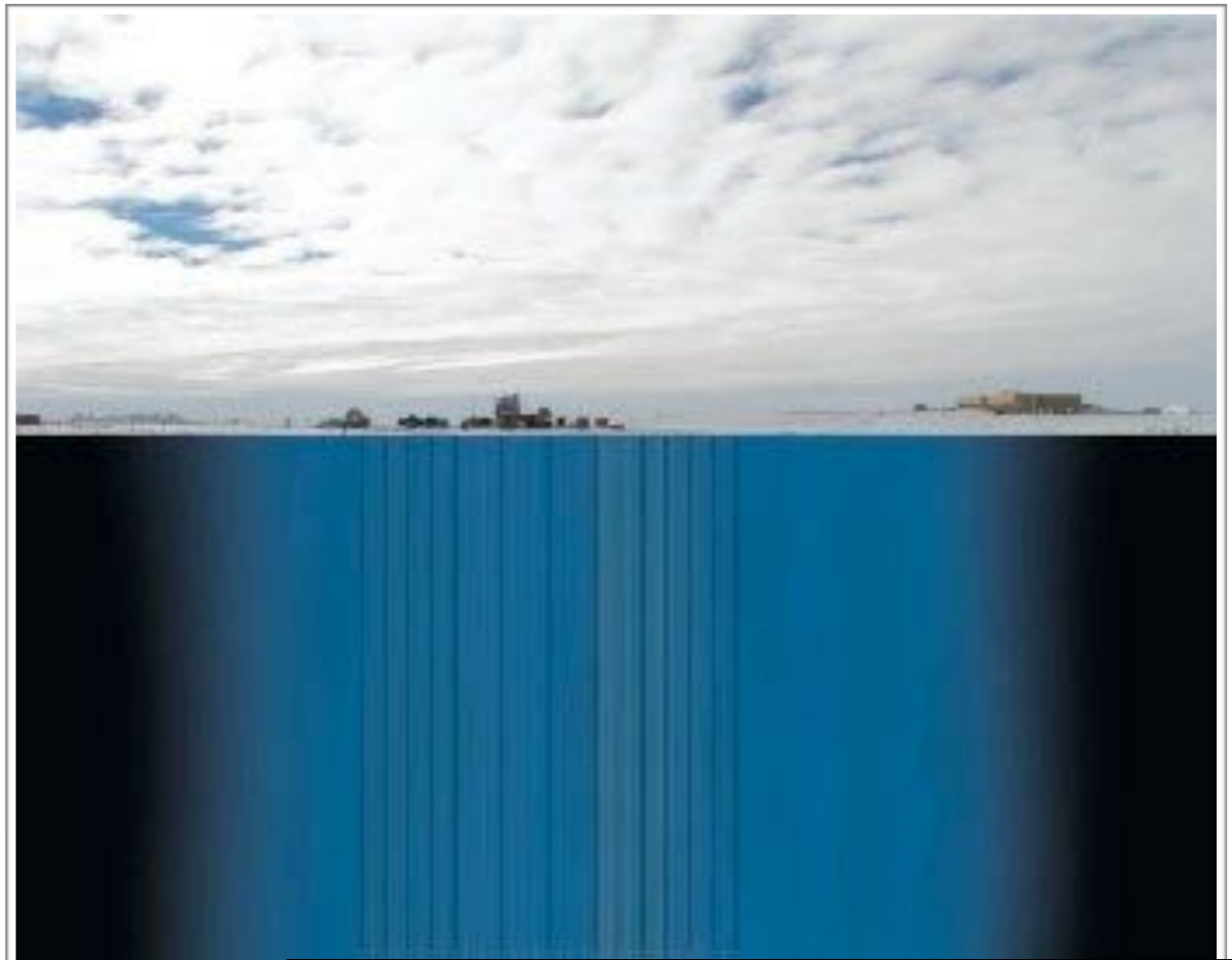


IceCube Detector

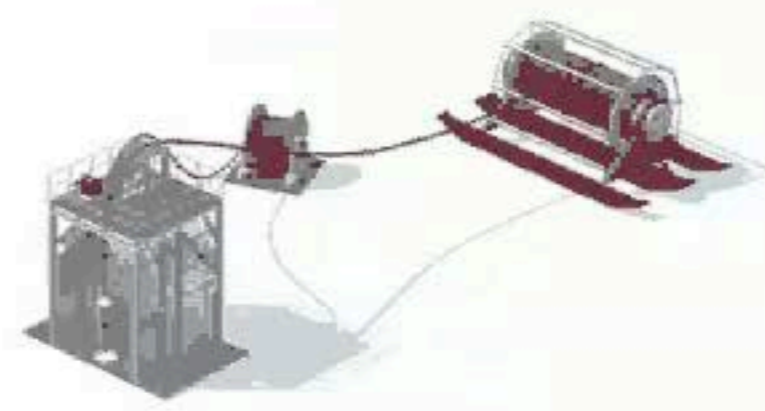
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- Uses $\sim 5\text{k}$ optical sensors across 86 vertical strings to detect Cherenkov light
- Deployed 1.5 - 2.5km below the surface



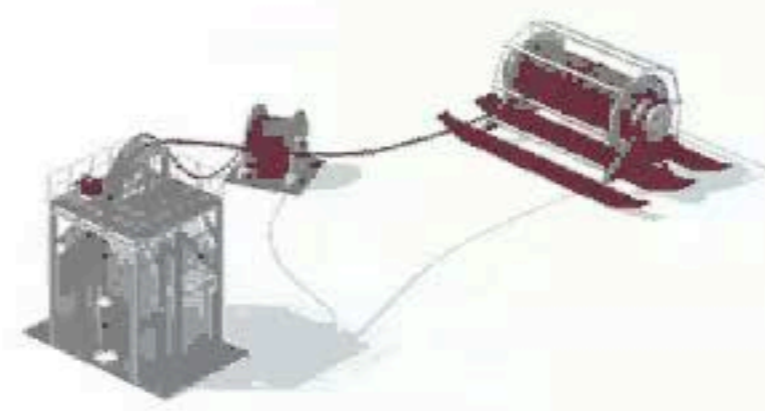
IceCube Optical Sensor



IceCube Hot Water Drill Animation

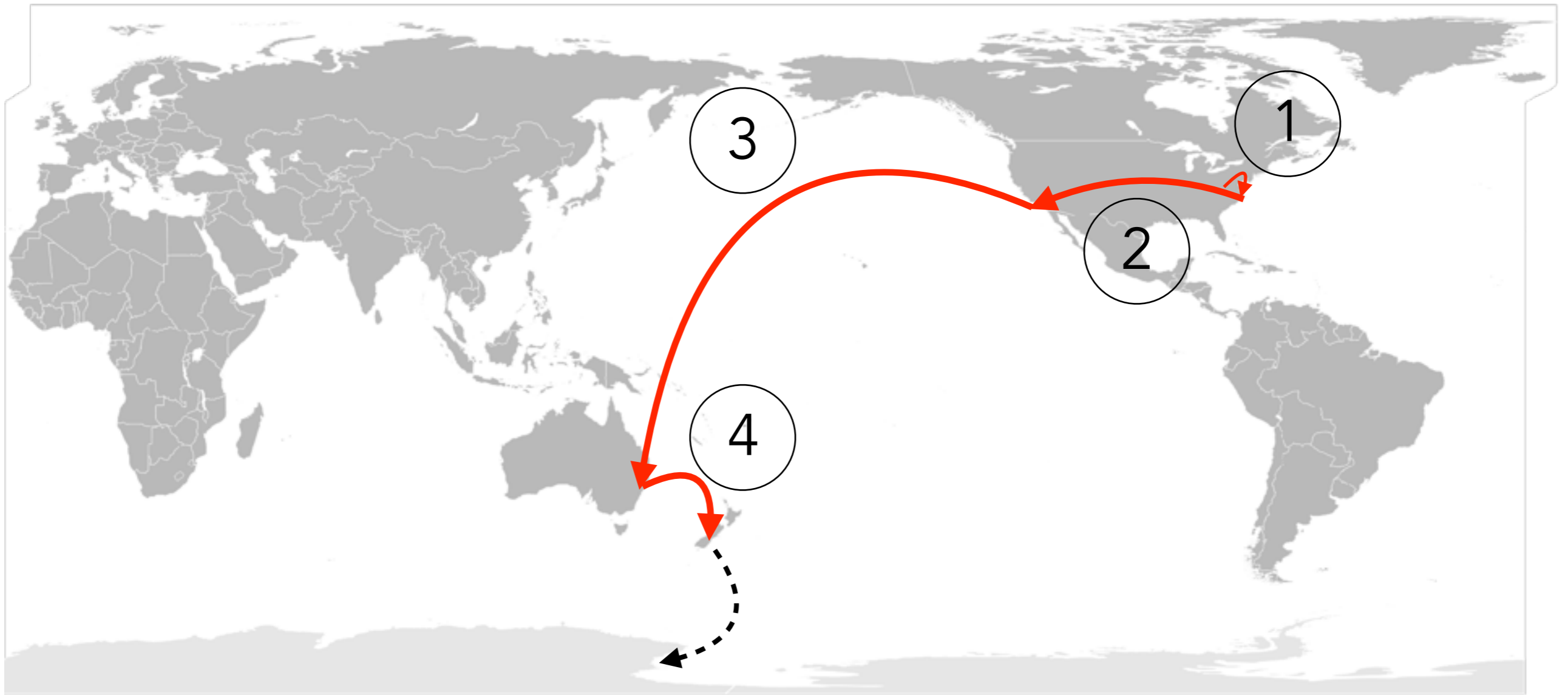


IceCube Hot Water Drill Animation



Getting to S. Pole

- People go by planes
- Cargo goes by boats and then planes or caravan





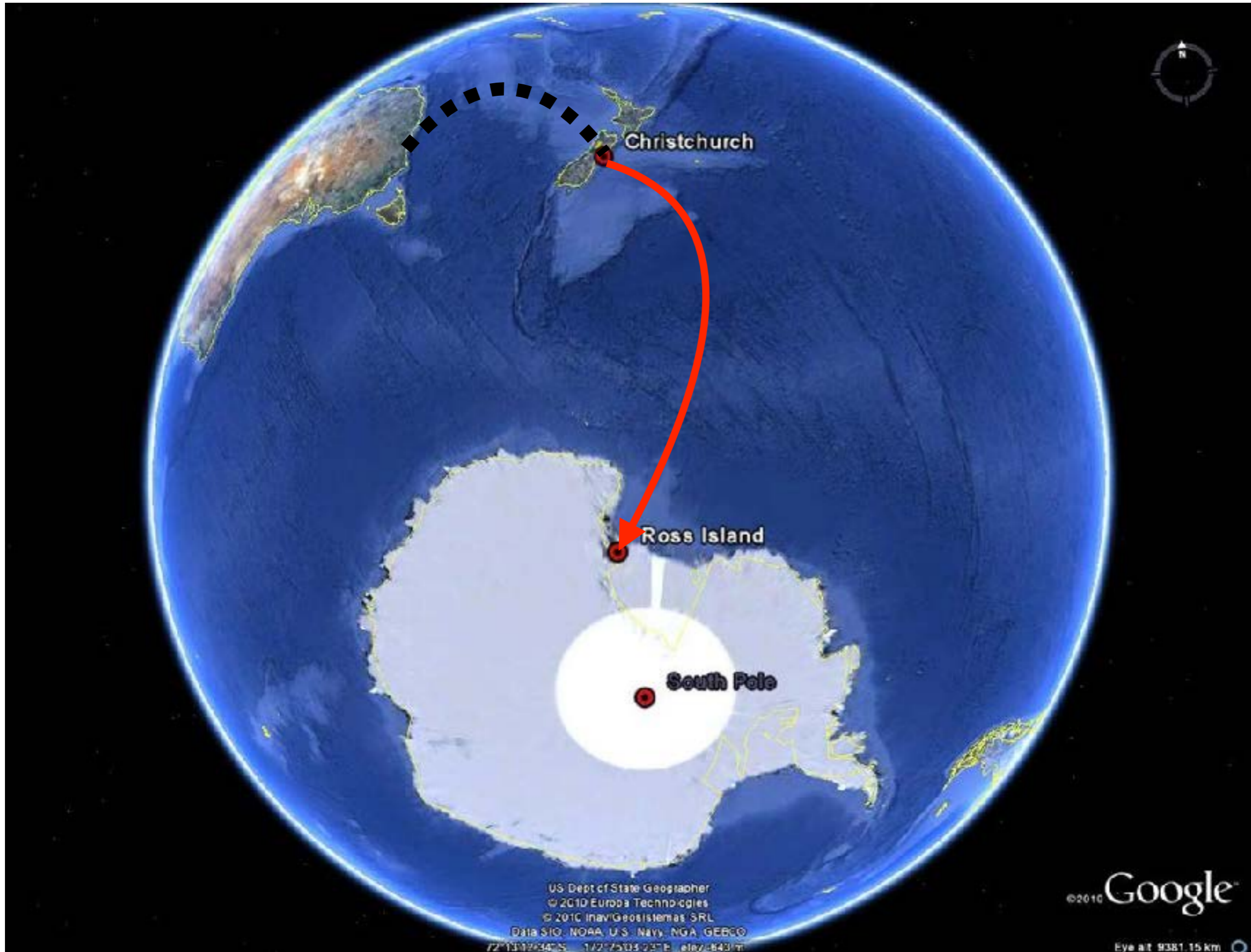
Summer in the S. Hemisphere,
but still cold at the S. Pole (-30 C
to -45 C



C-17 Globemaster



To Antarctica



First Class Luxury



Safety First



Ice Runway



To the S. Pole



More Planes







GEOGRAPHIC
SOUTH POLE



ROALD AMUNDSEN ROBERT F. SCOTT

DECEMBER 14, 1911 JANUARY 17, 1912

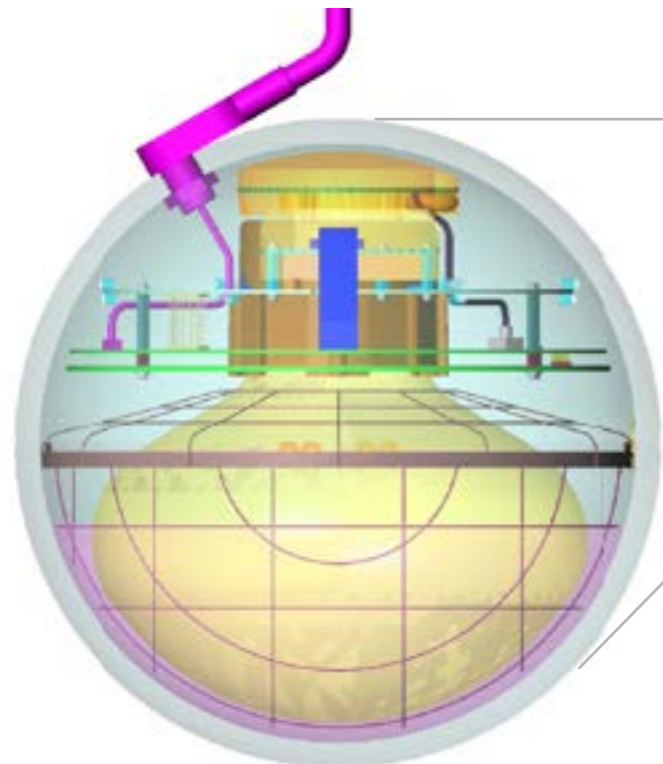
"So we arrived and were able to plant our flag at the geographical South Pole."

"The Pole. Yes, but under very different circumstances from those expected."

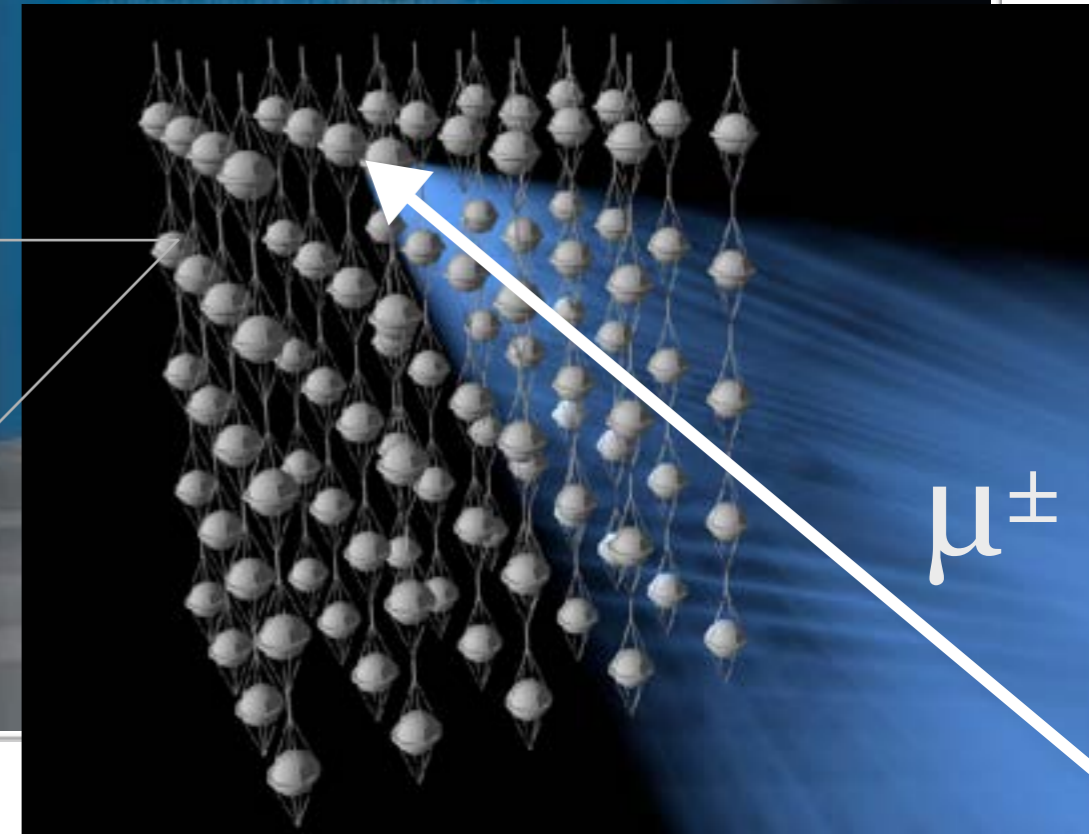
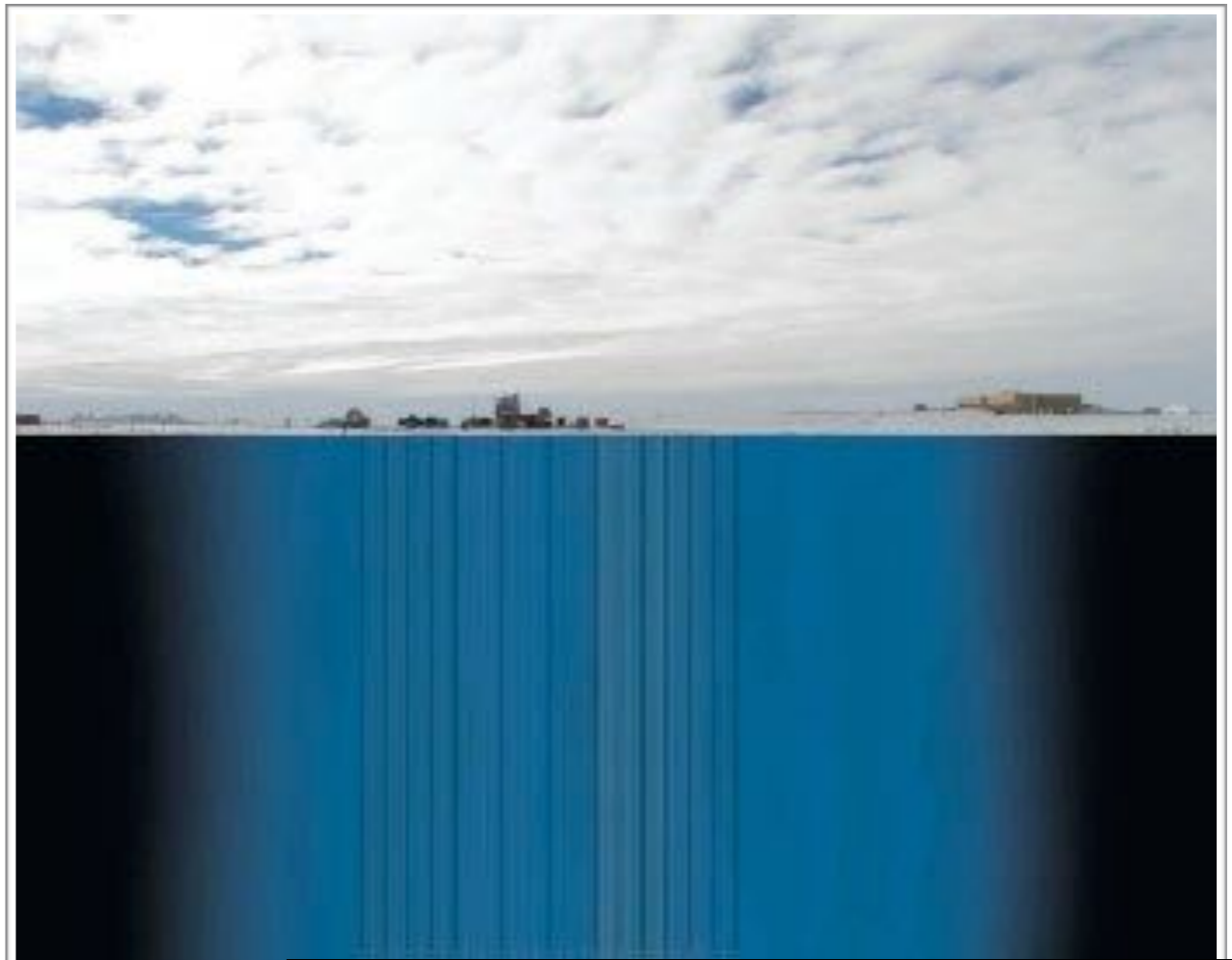
REPRODUCTION BY THE U.S. GOVERNMENT PRINTING OFFICE

IceCube Detector

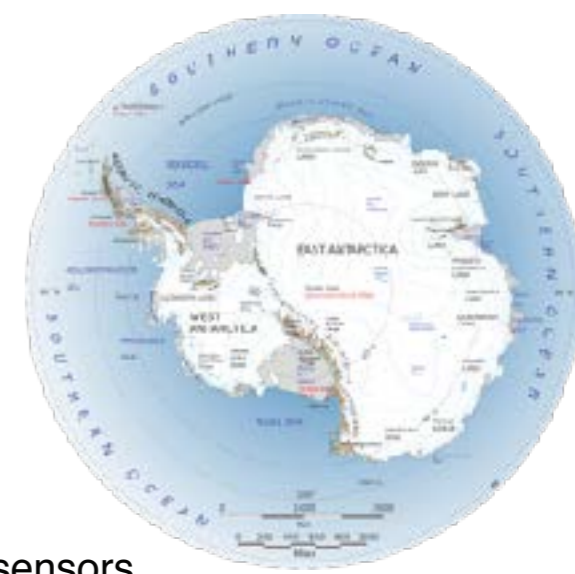
- $\sim 1\text{km}^3$ of instrumented ice
- Uses $\sim 5\text{k}$ optical sensors across 86 vertical strings to detect Cherenkov light
- Deployed 1.5 - 2.5km below the surface



IceCube Optical Sensor



IceCube



IceCube Lab

IceTop

81 Stations
324 optical sensors

50 m

IceCube Array

86 strings including
8 DeepCore strings
5160 optical sensors

1450 m

DeepCore

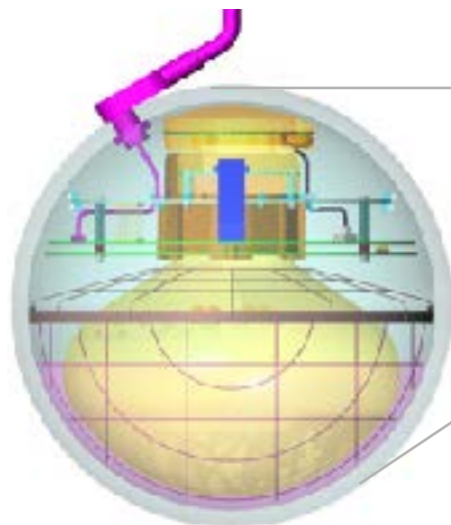
8 strings-spacing optimized
for lower energies
480 optical sensors

2450 m

Eiffel Tower
324 m

2820 m

Bedrock



IceCube Optical Sensor



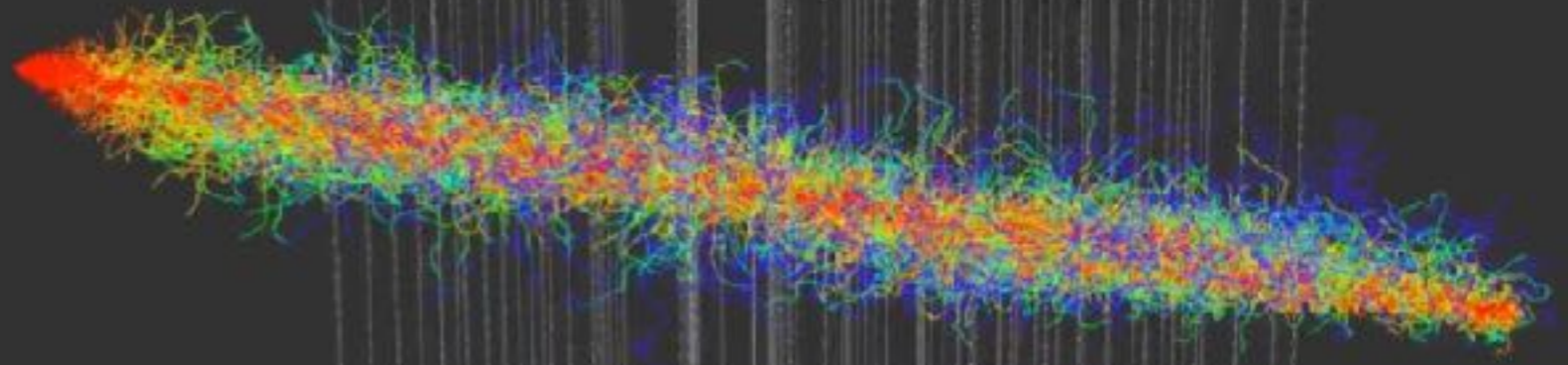


Track topology

(e.g. induced by muon neutrino)

Good pointing

IceCube: lower bound on energy for through-going events

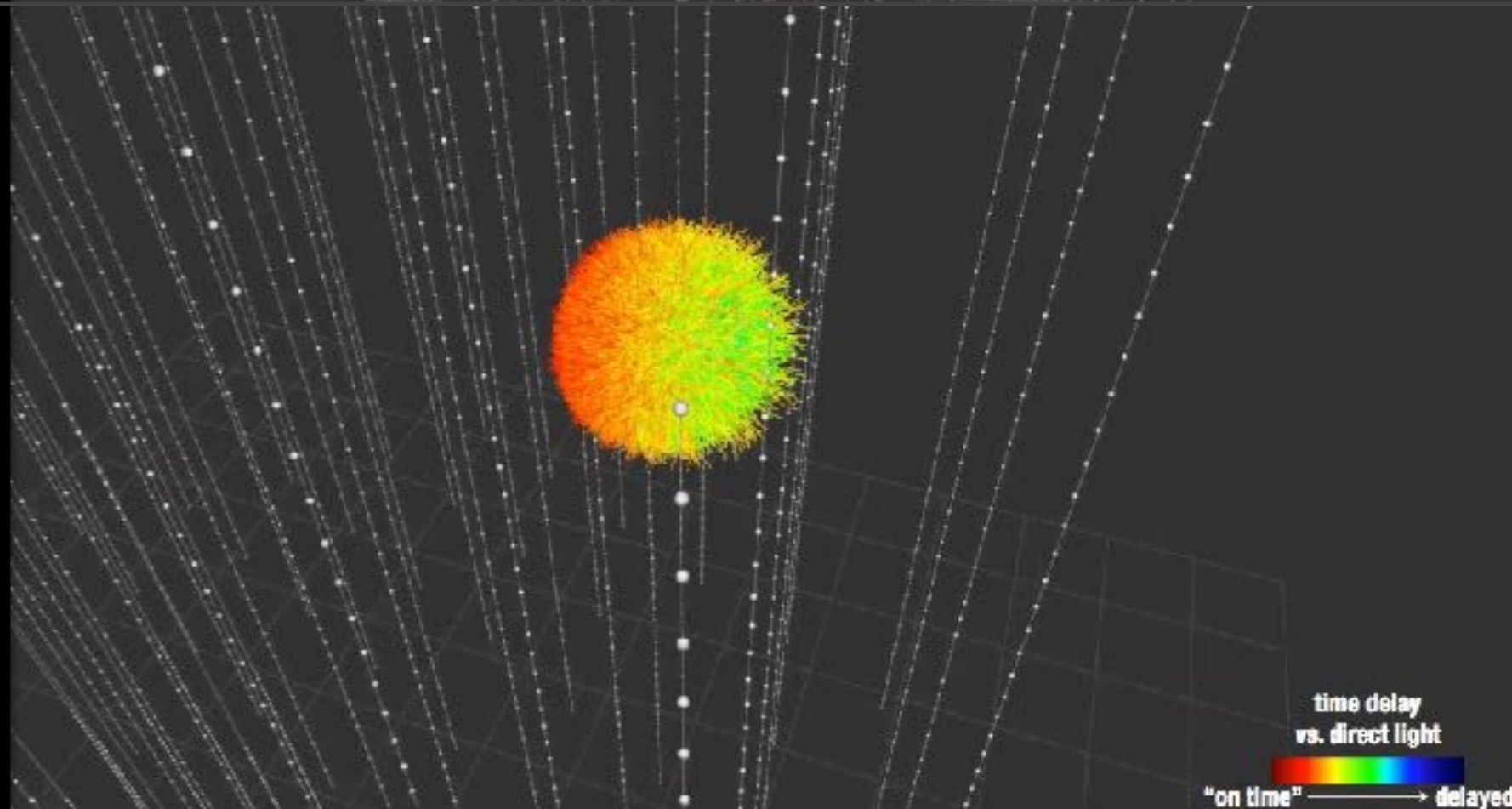


Cascade topology

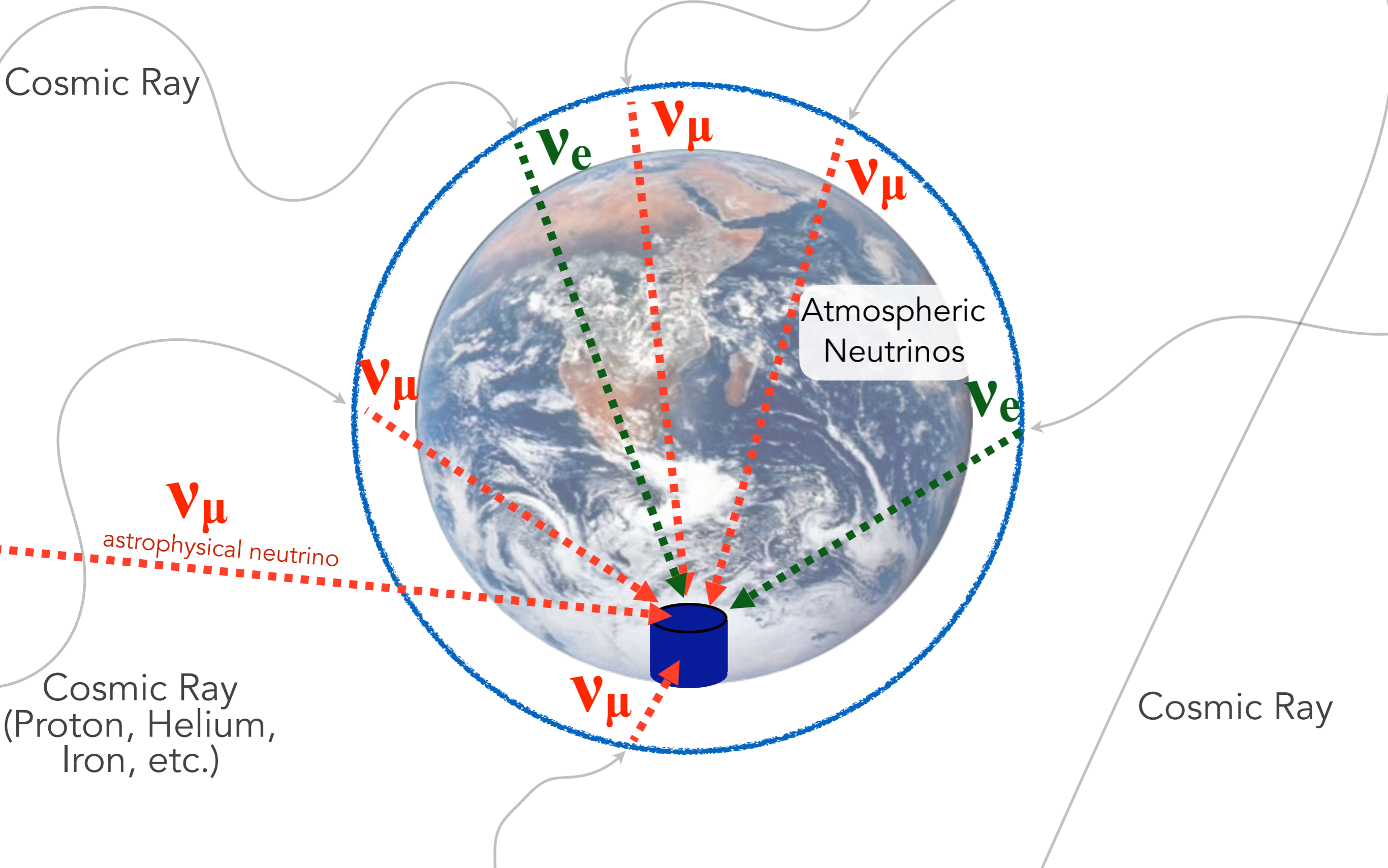
(e.g. induced by electron neutrino)

Good energy resolution

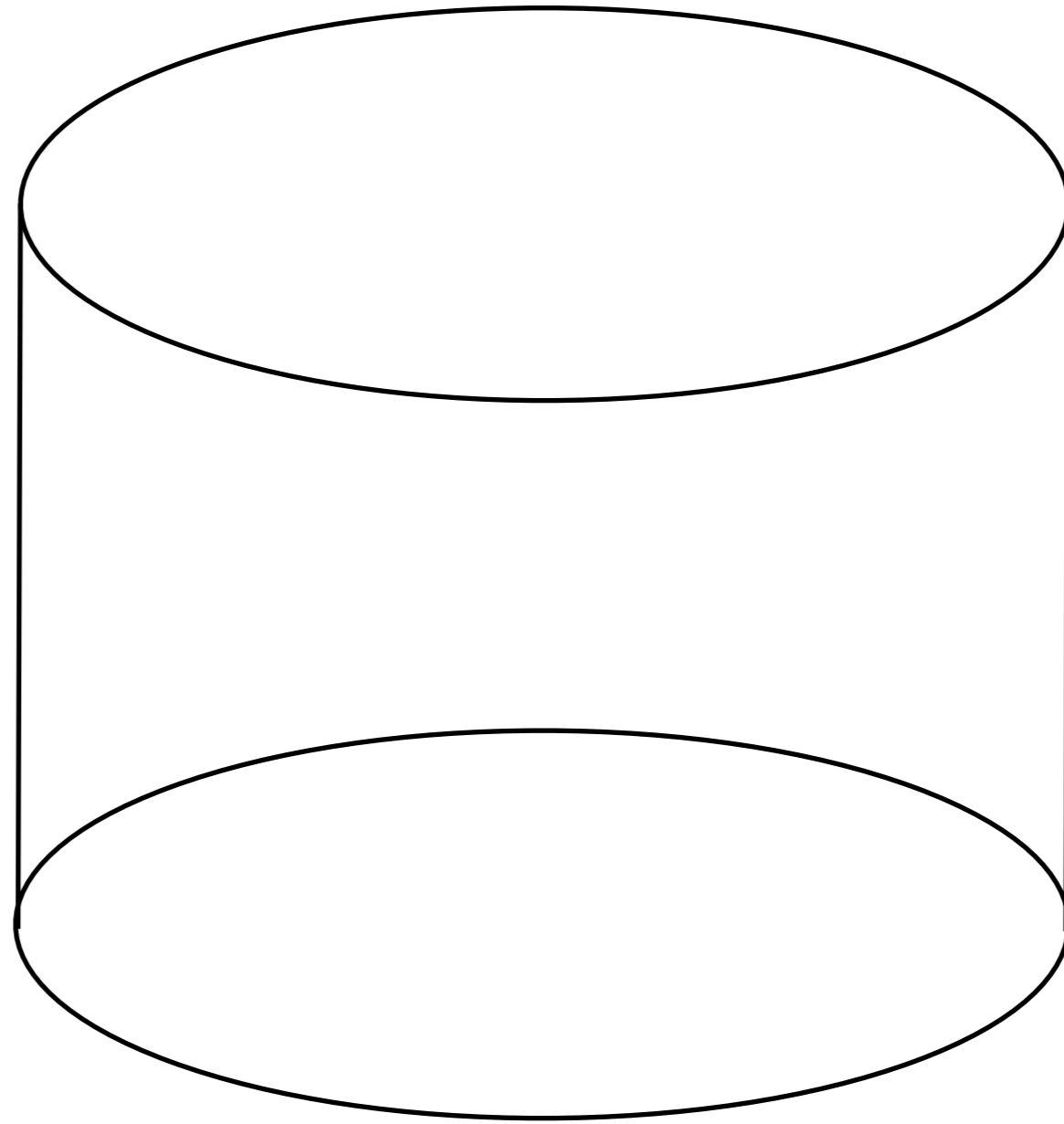
IceCube: some pointing



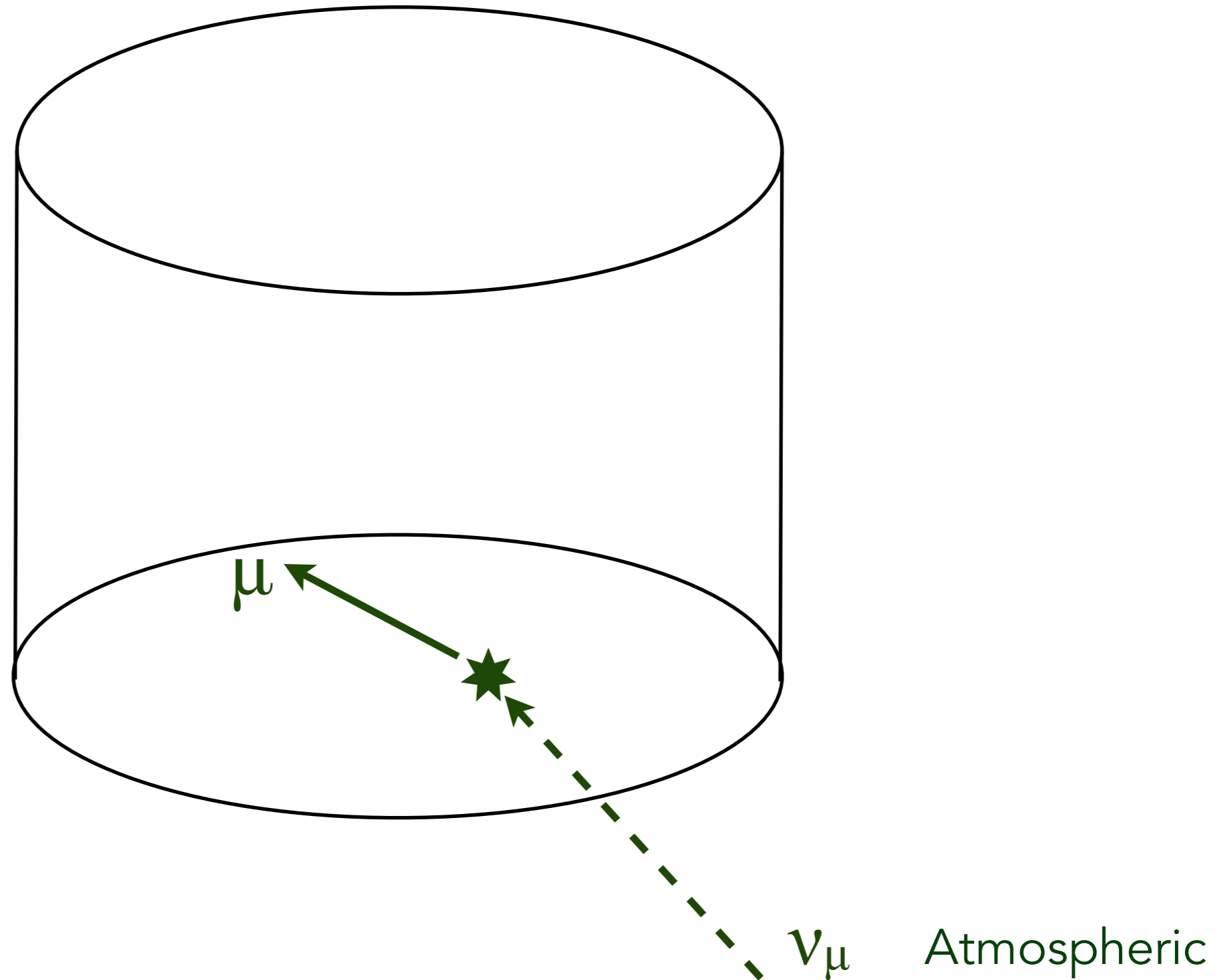
Atmospheric & Astrophysical Neutrinos



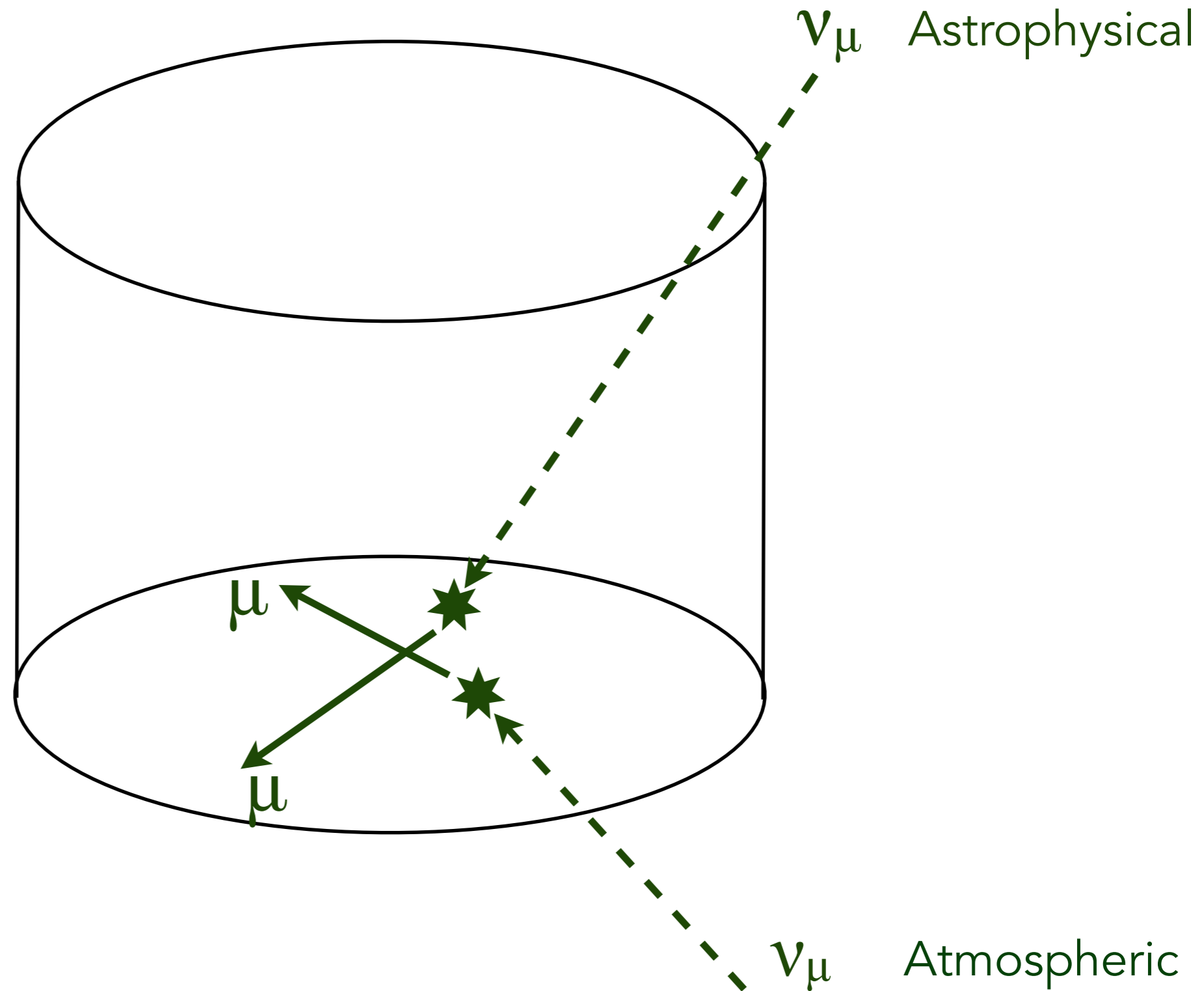
Background



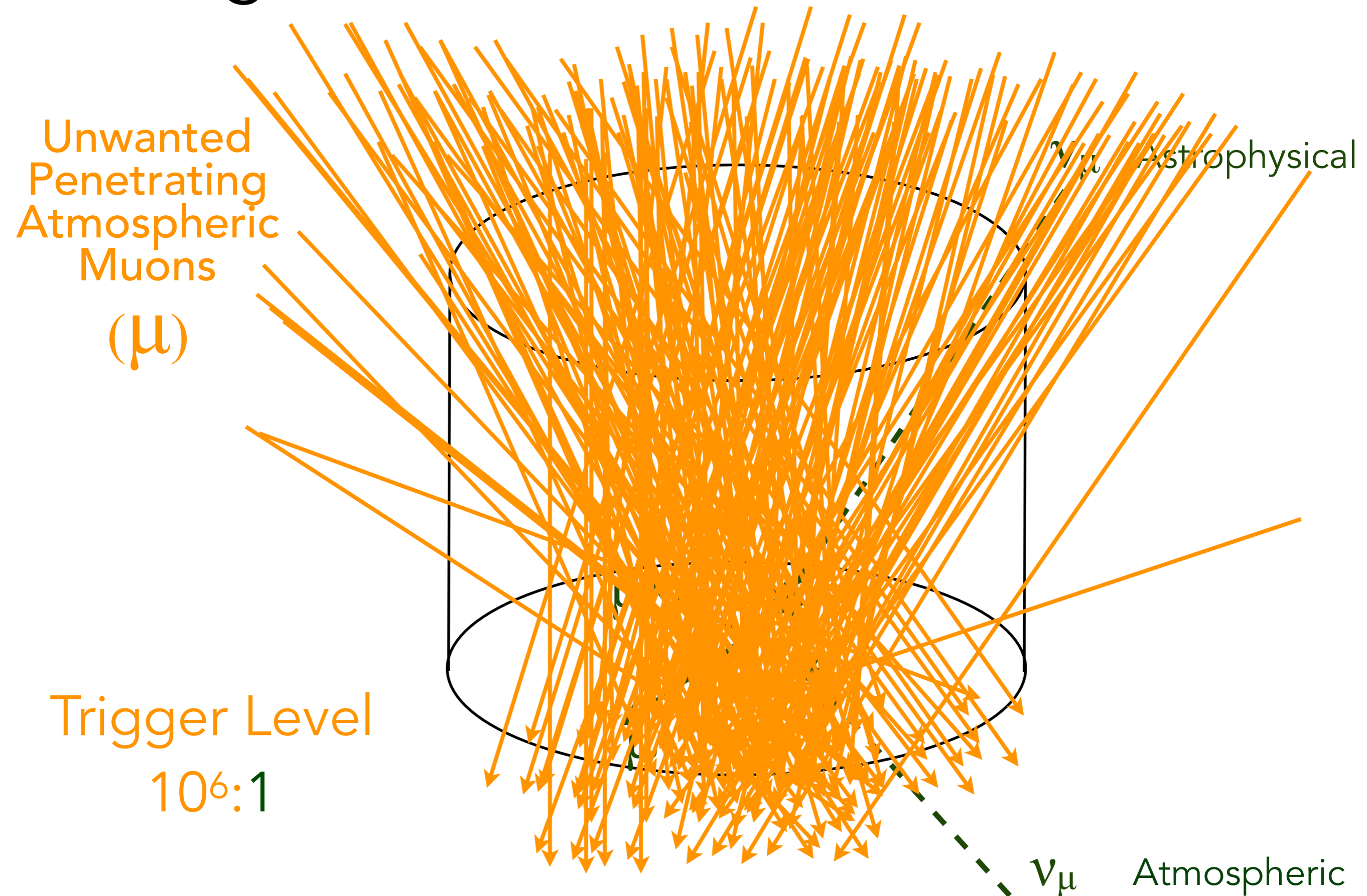
Background



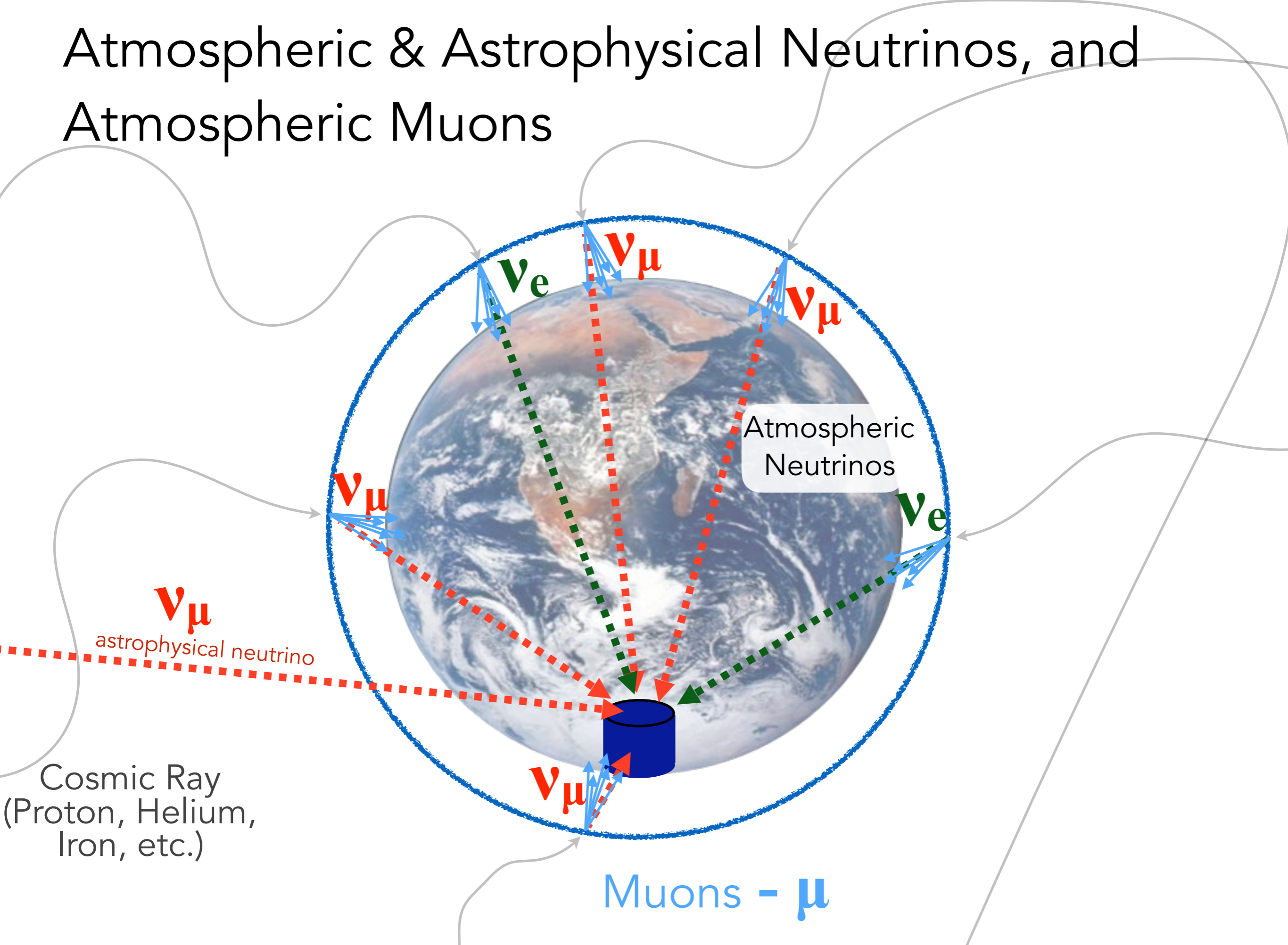
Background



Background



Atmospheric & Astrophysical Neutrinos, and Atmospheric Muons



Particle Physics with Neutrinos

-

Neutrino Oscillation

Neutrino Admixture

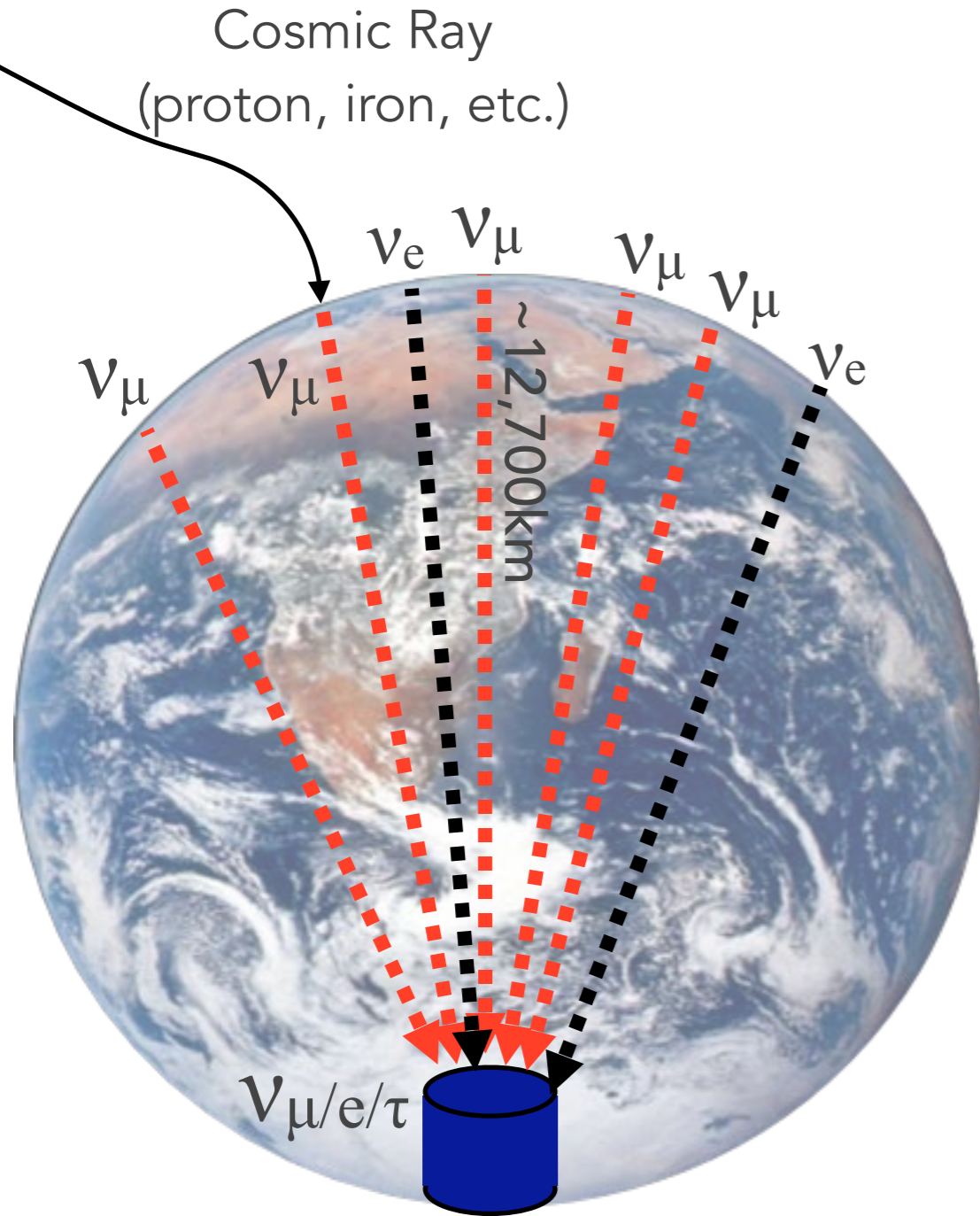
Flavor
Eigenstate

Mass
Eigenstate

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \mathcal{U}_{\text{PMNS}} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix} \\ = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

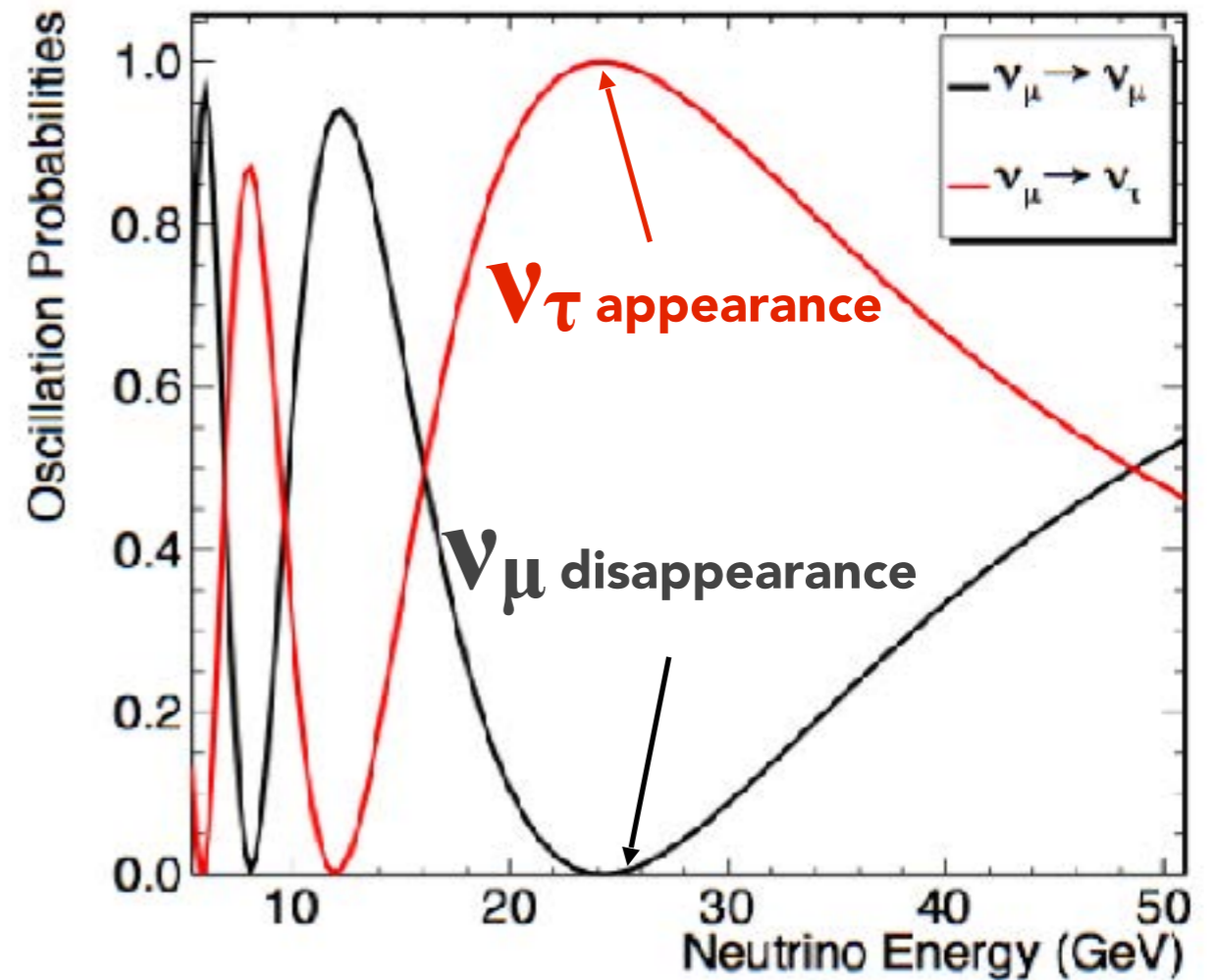
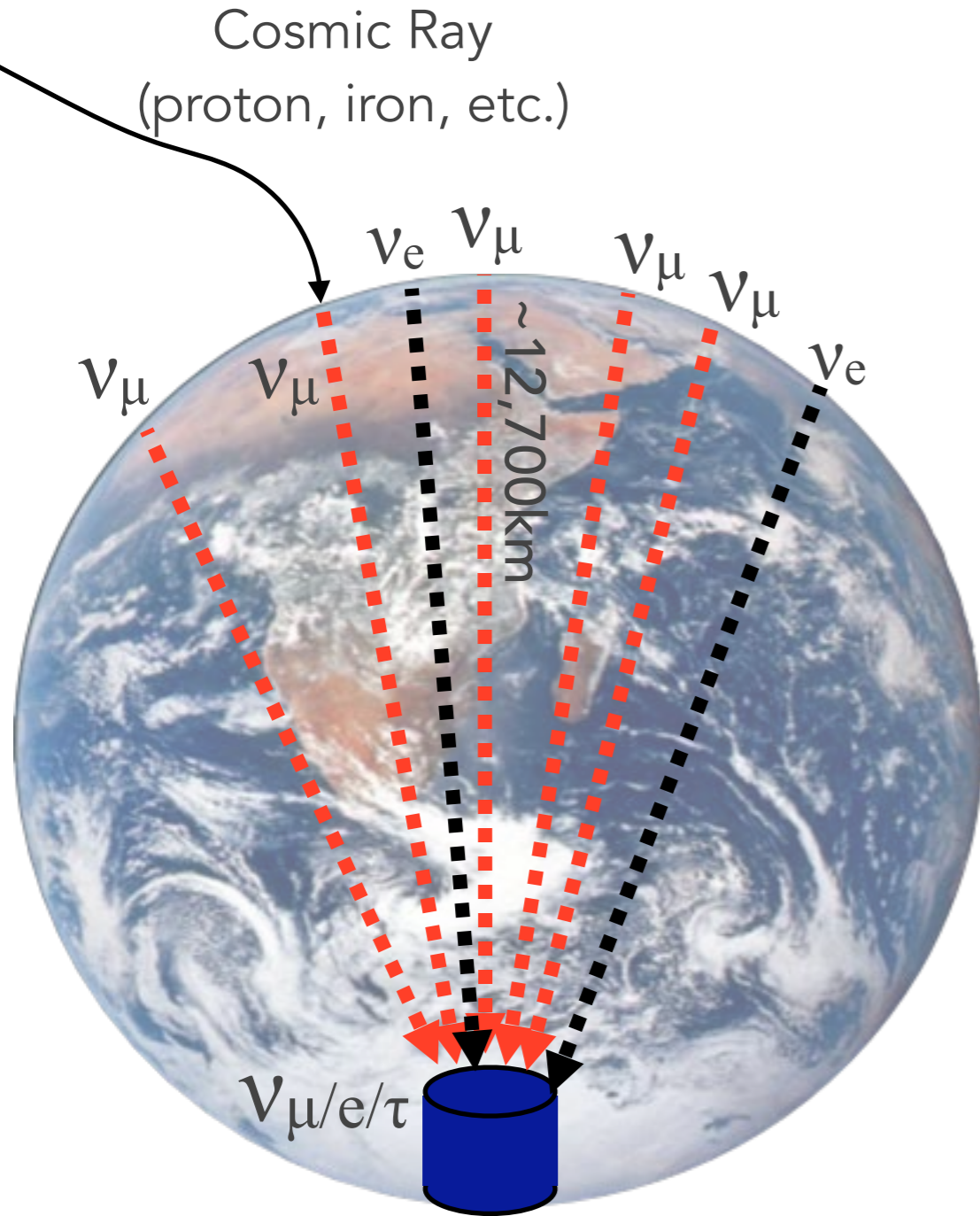
- Neutrinos are produced/detected in 'flavor' states but move through space as a composition of 'mass' states

Atmospheric Neutrino Oscillation



- Neutrinos interact in flavor states (ν_μ , ν_e , ν_τ), but they quantum mechanically oscillate between flavors as fundamental mass states (ν_1 , ν_2 , ν_3)

Atmospheric Neutrino Oscillation

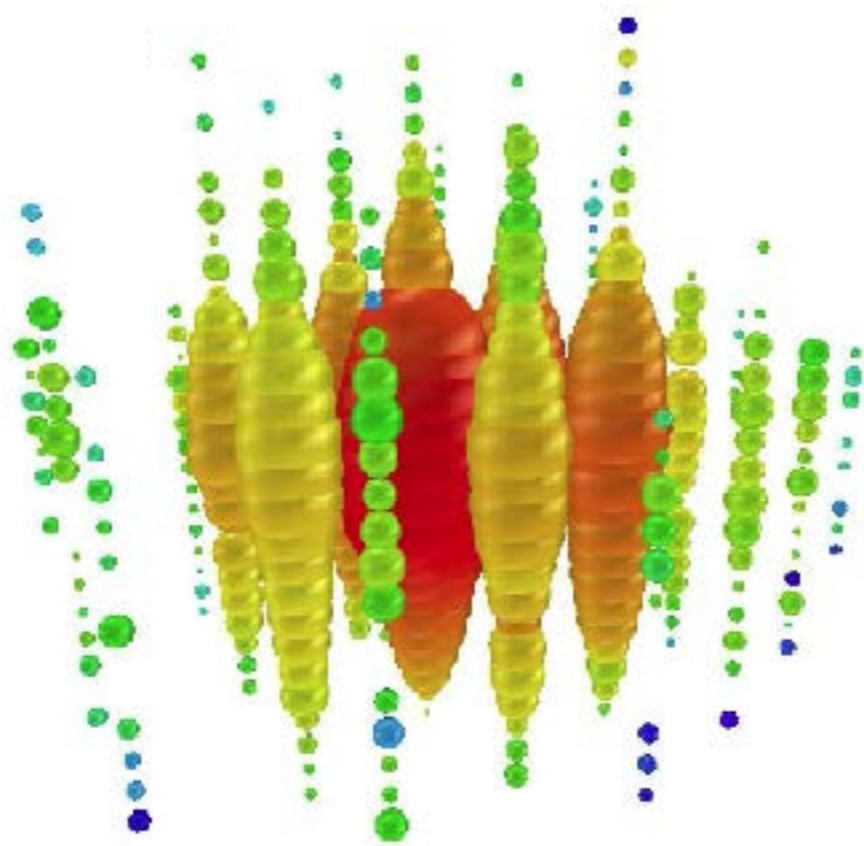


- Neutrinos interact in flavor states (ν_μ , ν_e , ν_τ), but they quantum mechanically oscillate between flavors as fundamental mass states (ν_1 , ν_2 , ν_3)

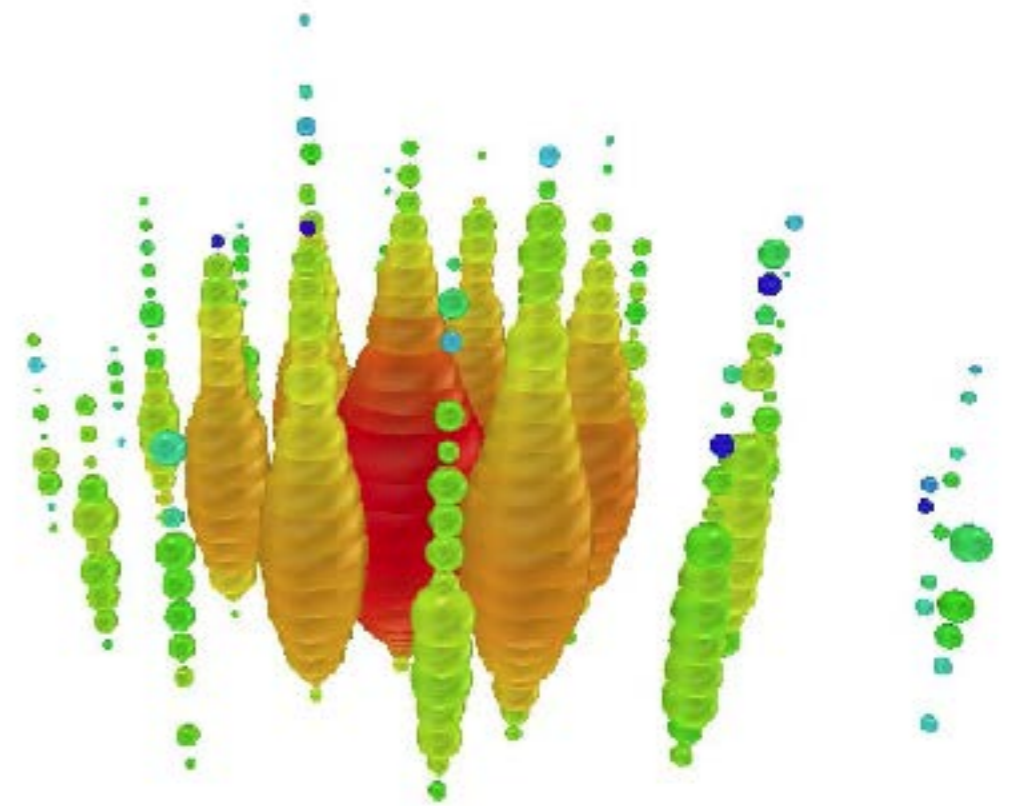
Astrophysical Neutrinos & IceCube

High Energy Neutrinos

- Ultra-high energy IceCube astrophysical search found 2 bizarre background events in the initial 2 years of data

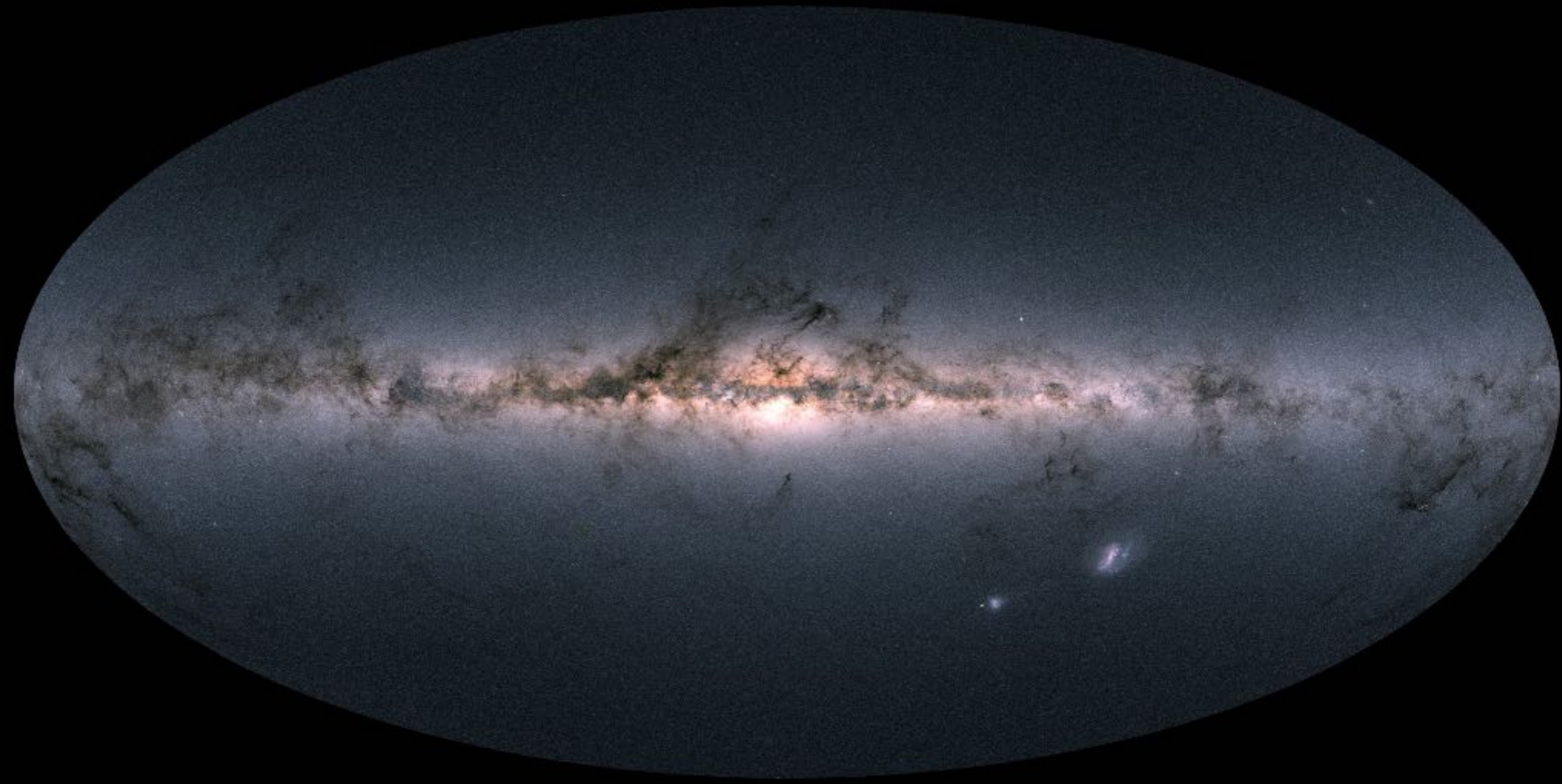


1.04 ± 0.16 PeV



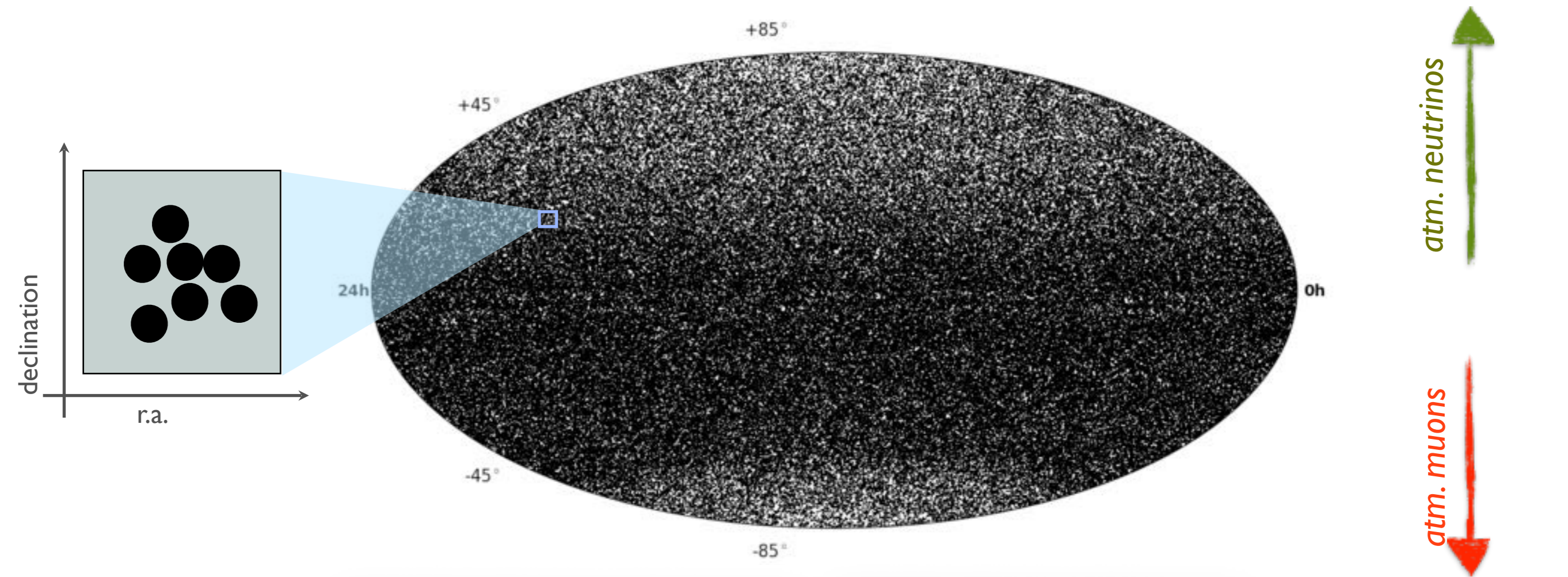
1.14 ± 0.17 PeV

Skymap

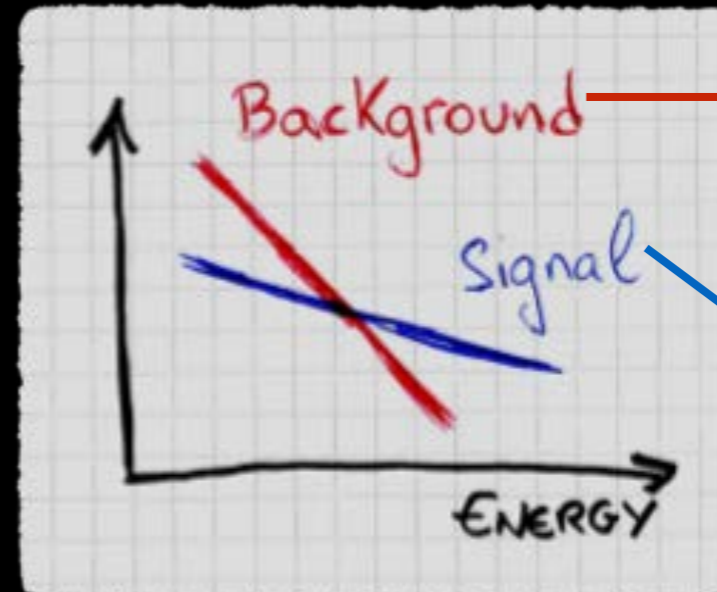
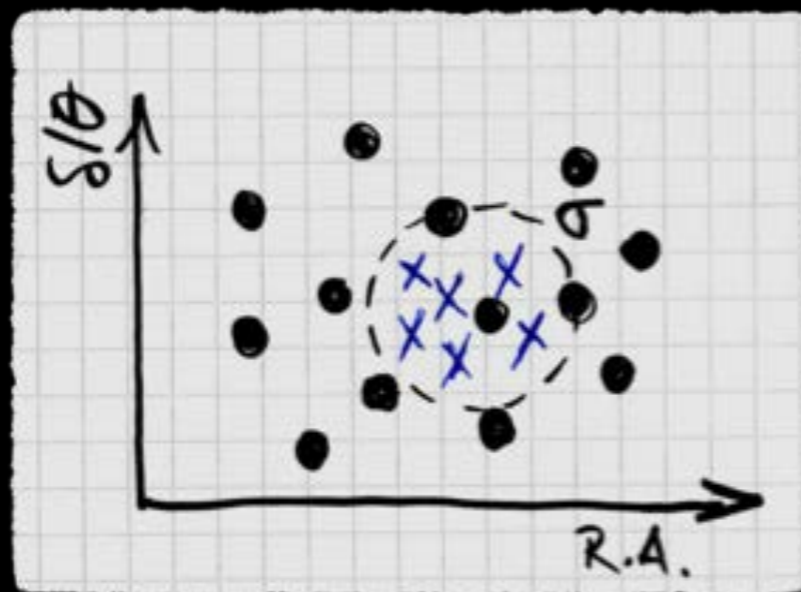


*ESA/Gaia/DPAC

IceCube Point Source Search



Ingredients:



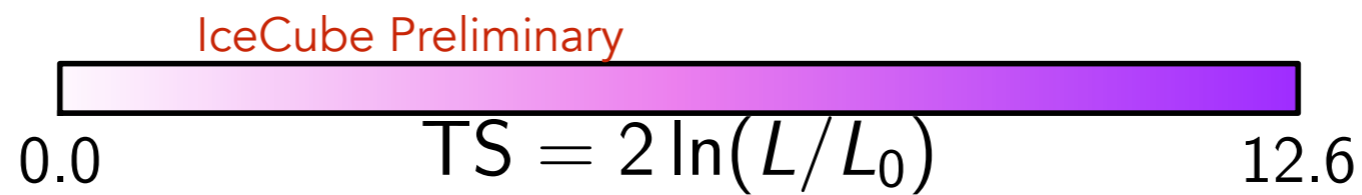
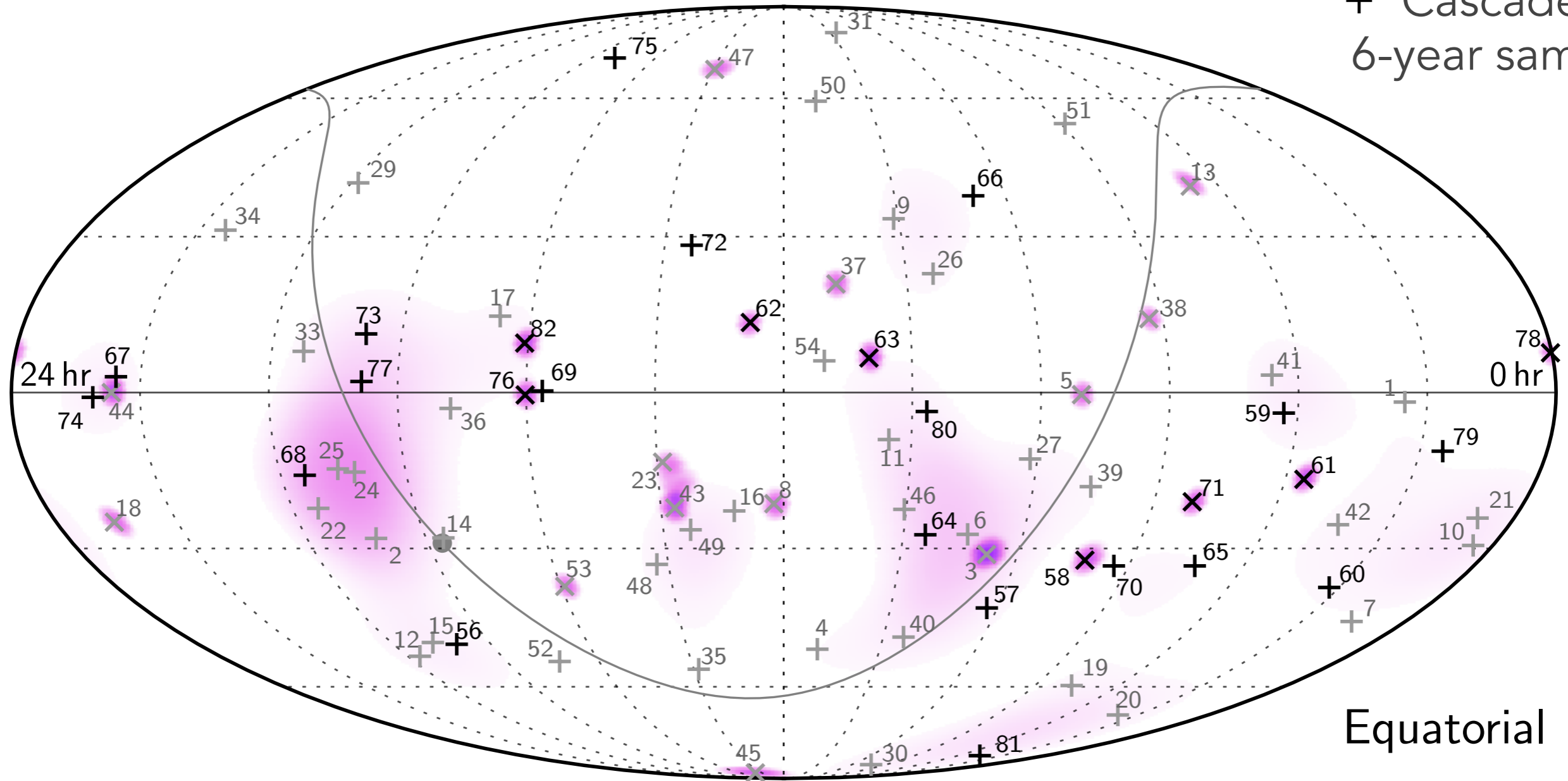
Atm. Muons & Atm. Neutrinos

Astro. Neutrinos

*M. Rameez

Neutrino Astronomy?

x Tracks
+ Cascades
6-year sample



Neutrino Astronomy?

x Tracks
+ Cascades
6-year sample



Messier 82

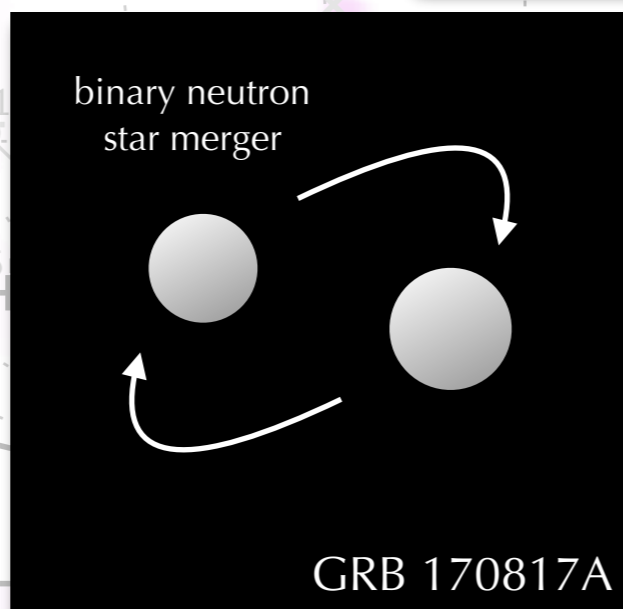
Starburst Galaxies?

extra-galactic?



Centaurus A

Supermassive Black Holes?



binary neutron star merger

GRB 170817A

Gamma Ray Bursts?

Galactic?



Crab Nebula

Pulsar Wind Nebulae?



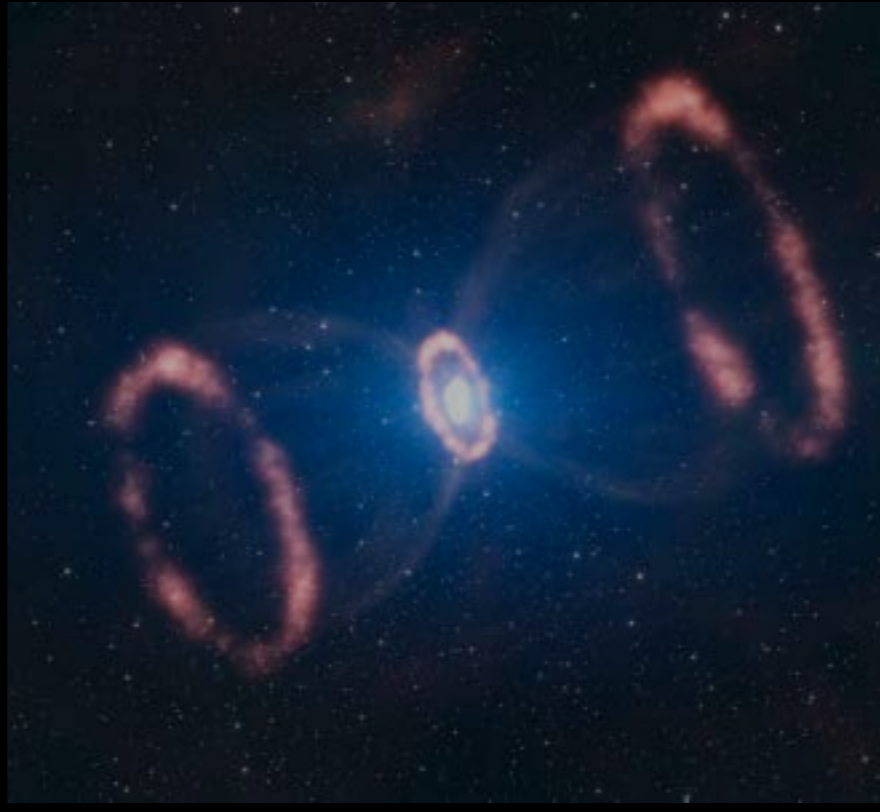
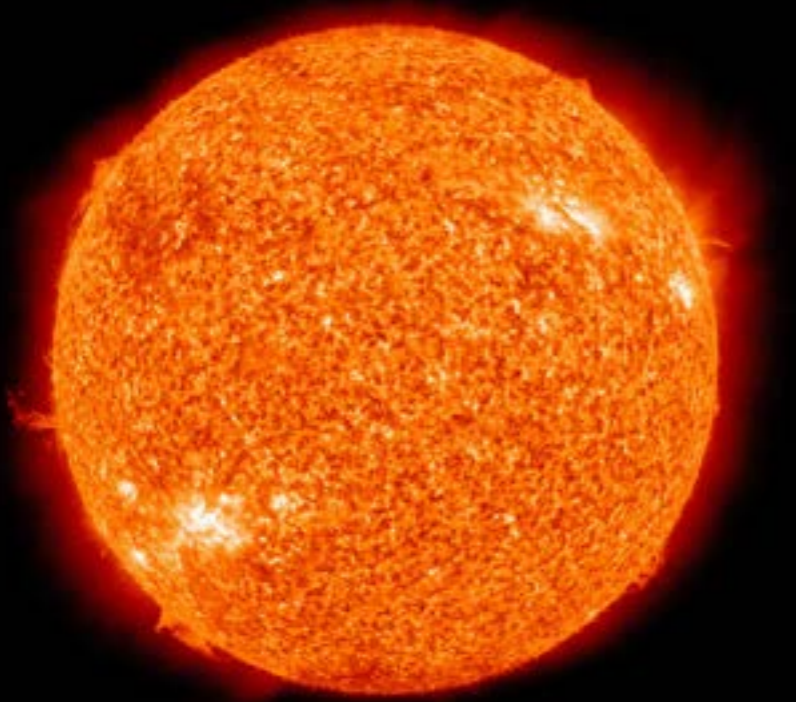
Many candidate sources!

0.0

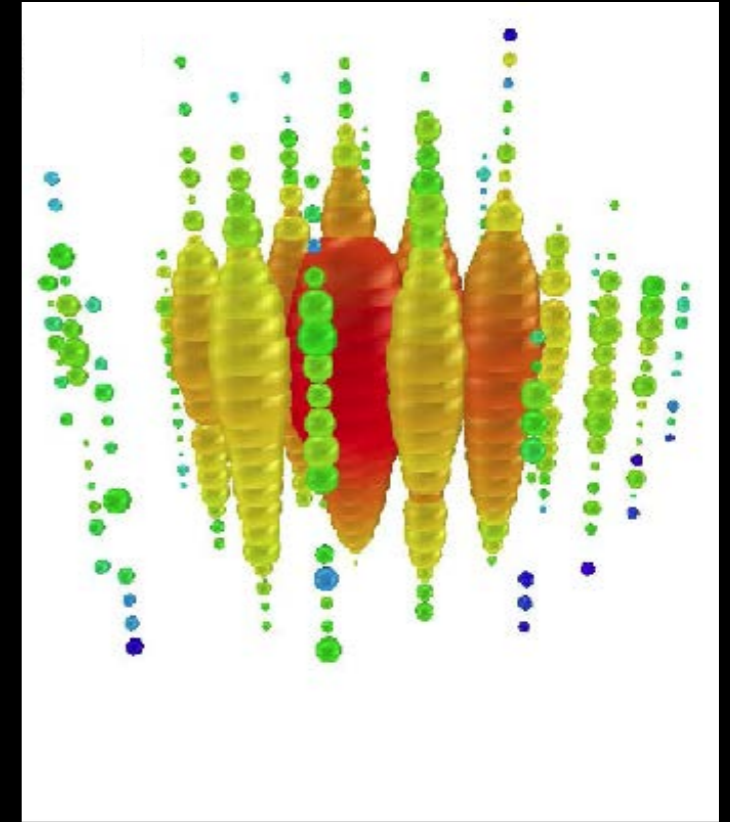
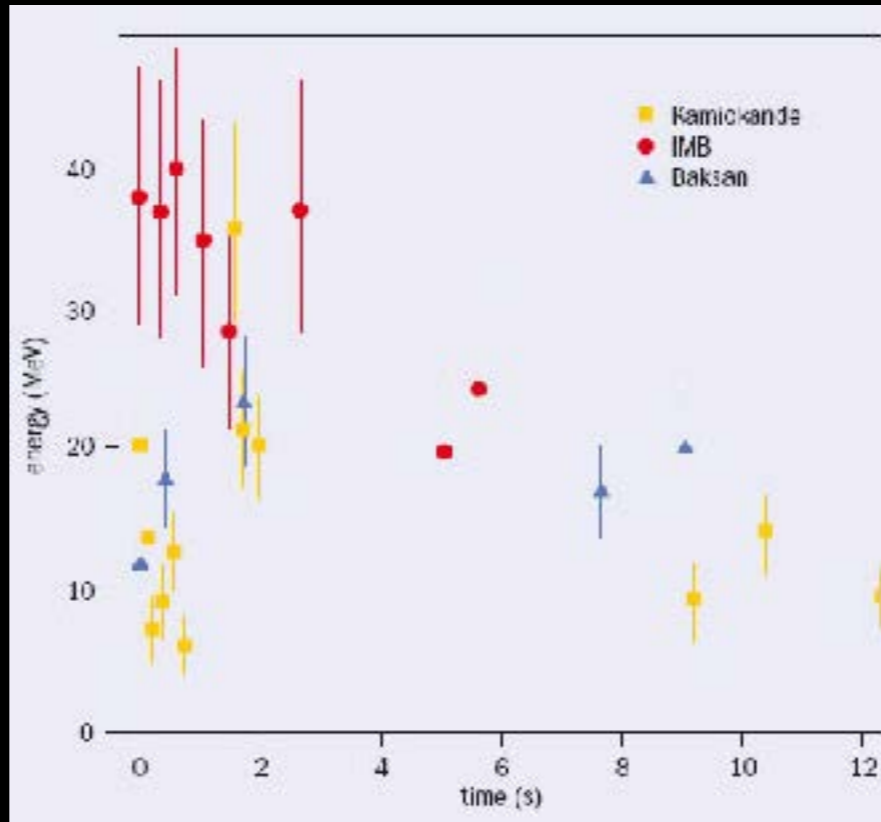
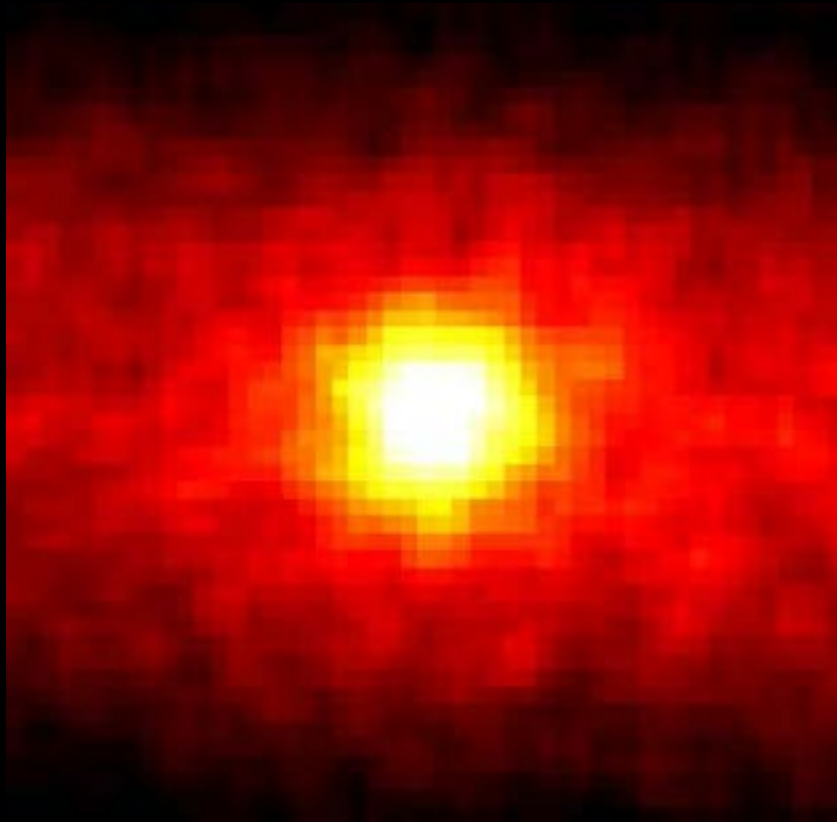
(L_0)

12.6

Astrophysical Neutrino



In 2013, IceCube established existence of high energy astrophysical neutrinos

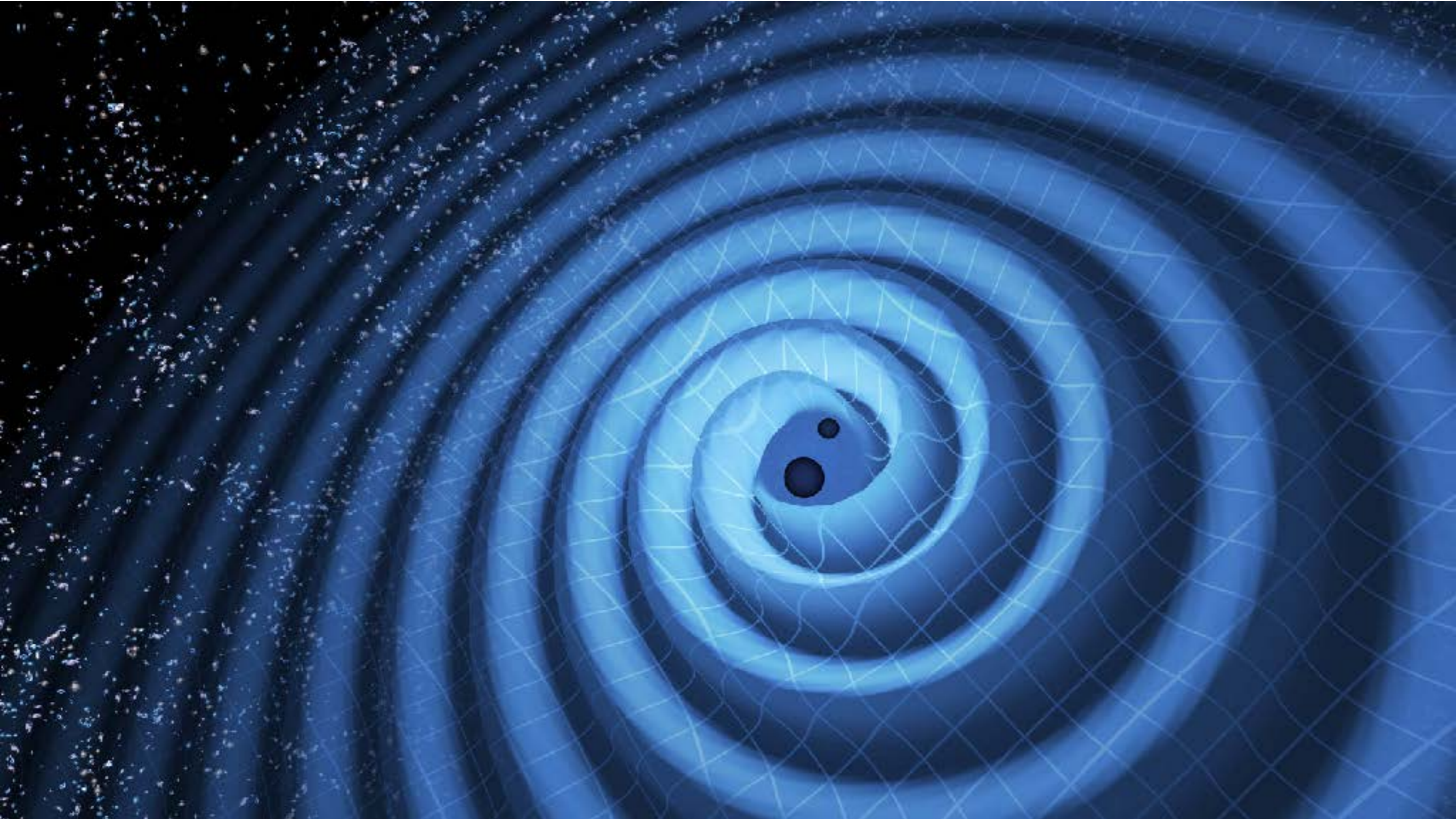


- NASA/SDO
- R. Svoboda & K. Gordan (LSU)

- ESO/L. Calçada
- CERN Courier, Jan 2007

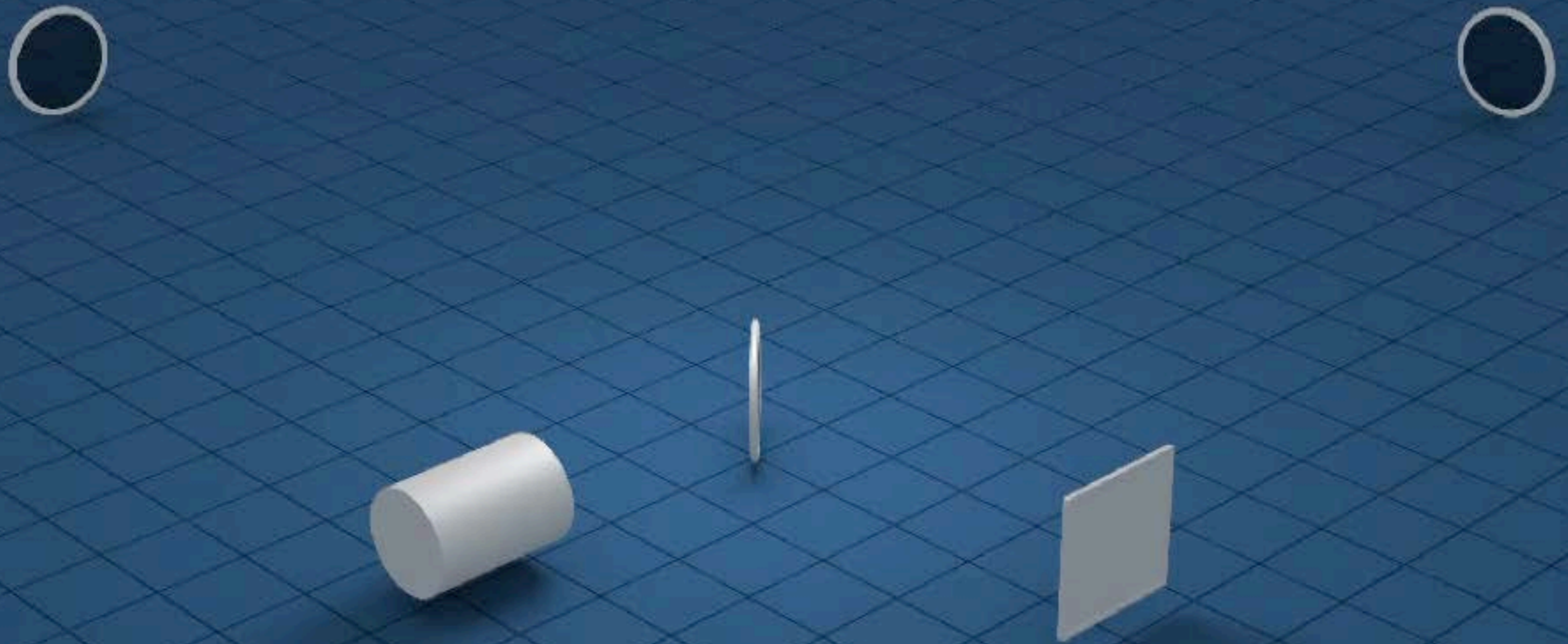
New Era in Astronomy

140915 & 110216

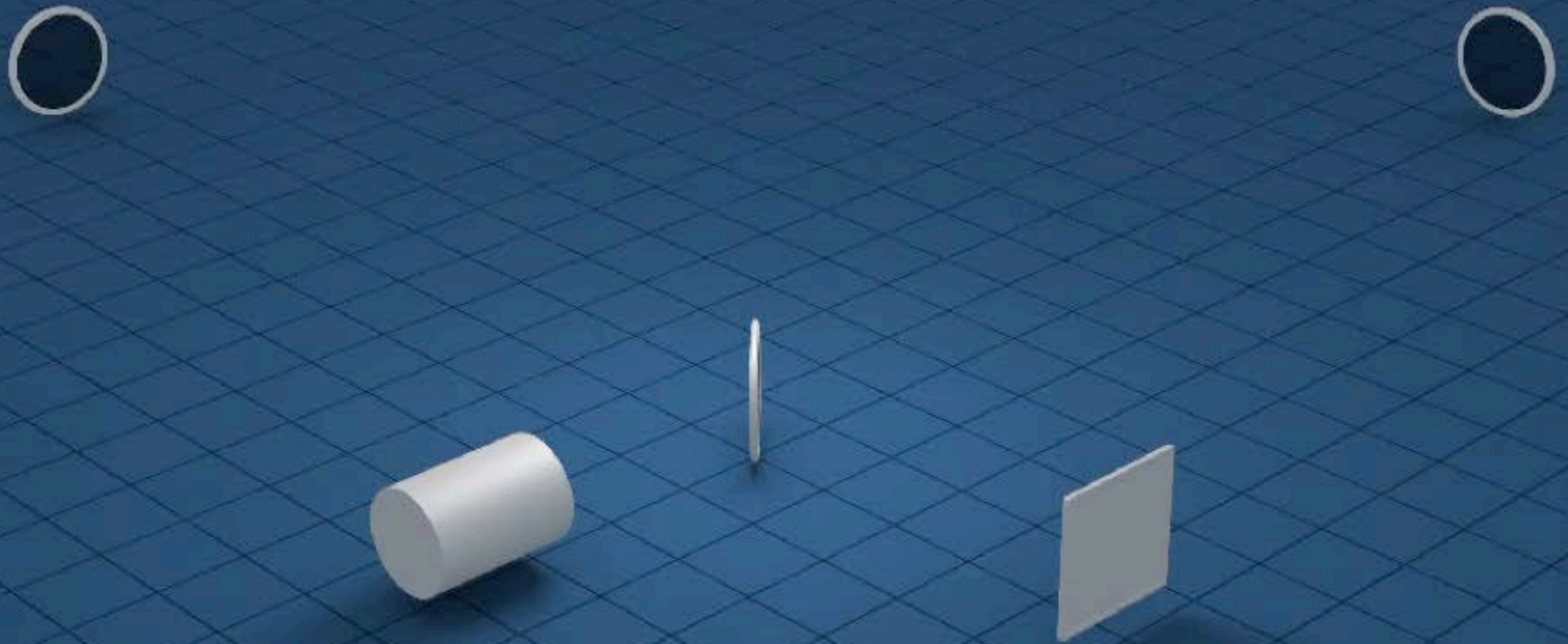


*T. Pyle, LIGO

Laser Interferometry (Movie)



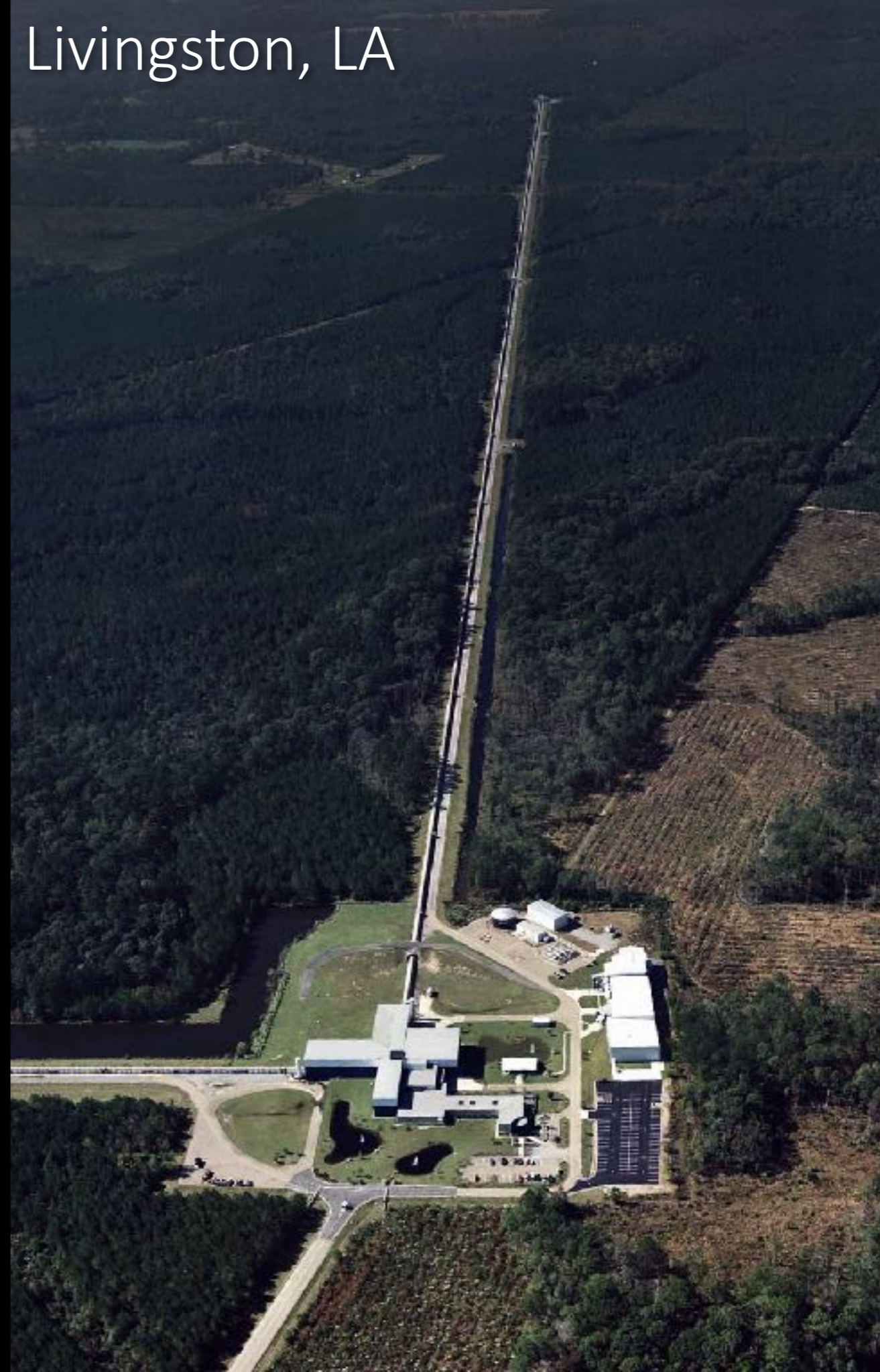
Laser Interferometry (Movie)



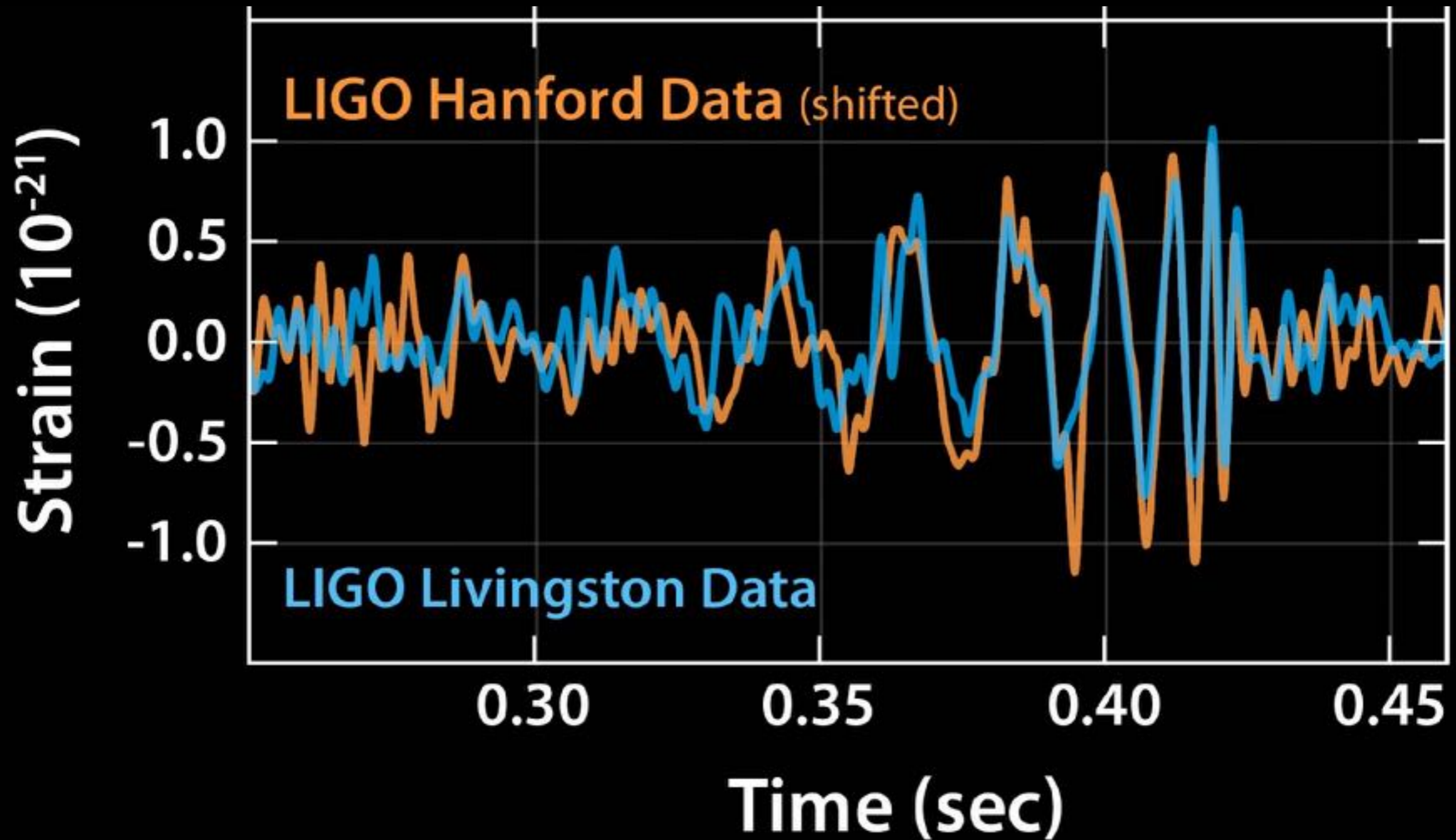
Hanford, WA



Livingston, LA



LIGO Gravitation Wave Signal



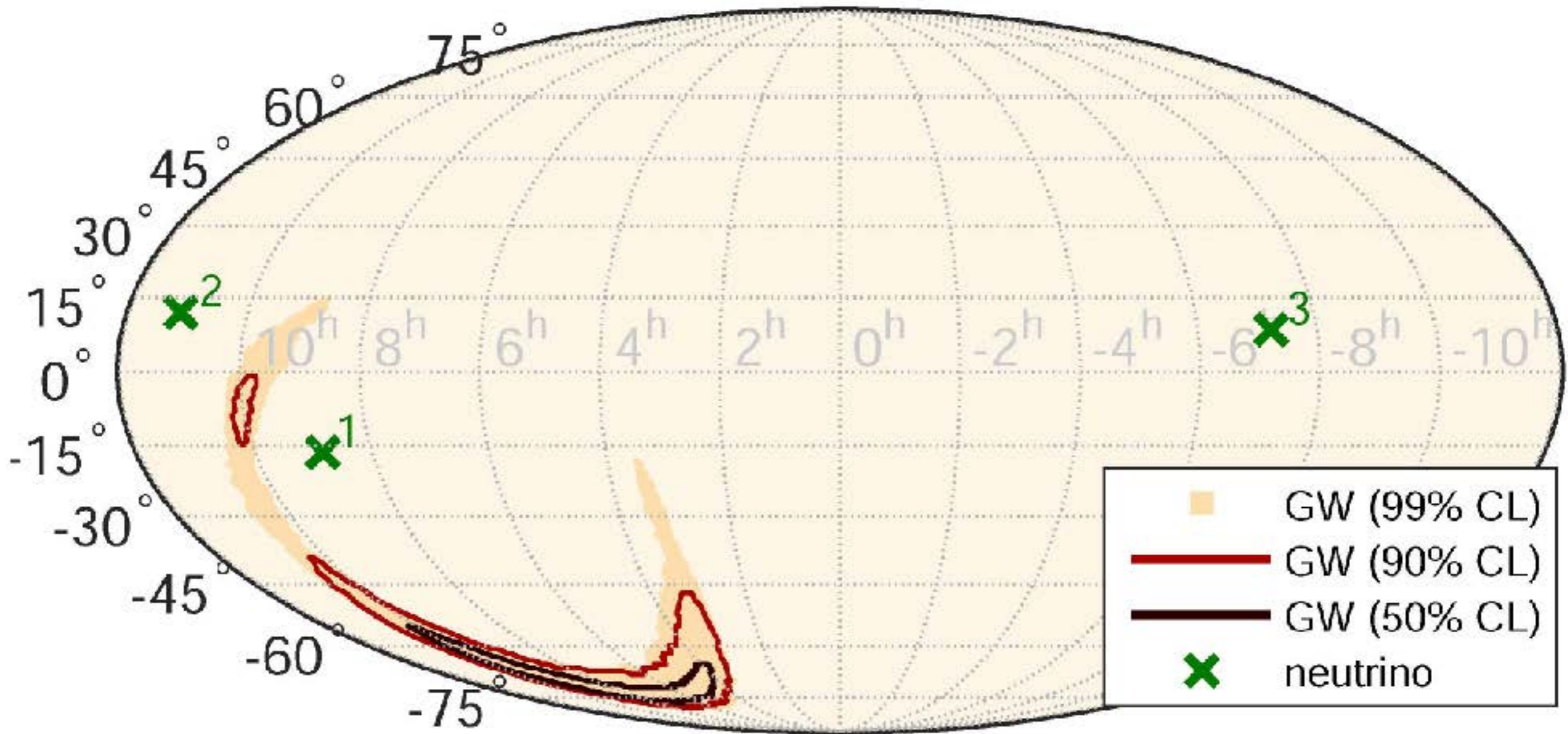
Abbott+ PRL 116, 061102 (2016)

*I. Bartos, Neutrino 2016

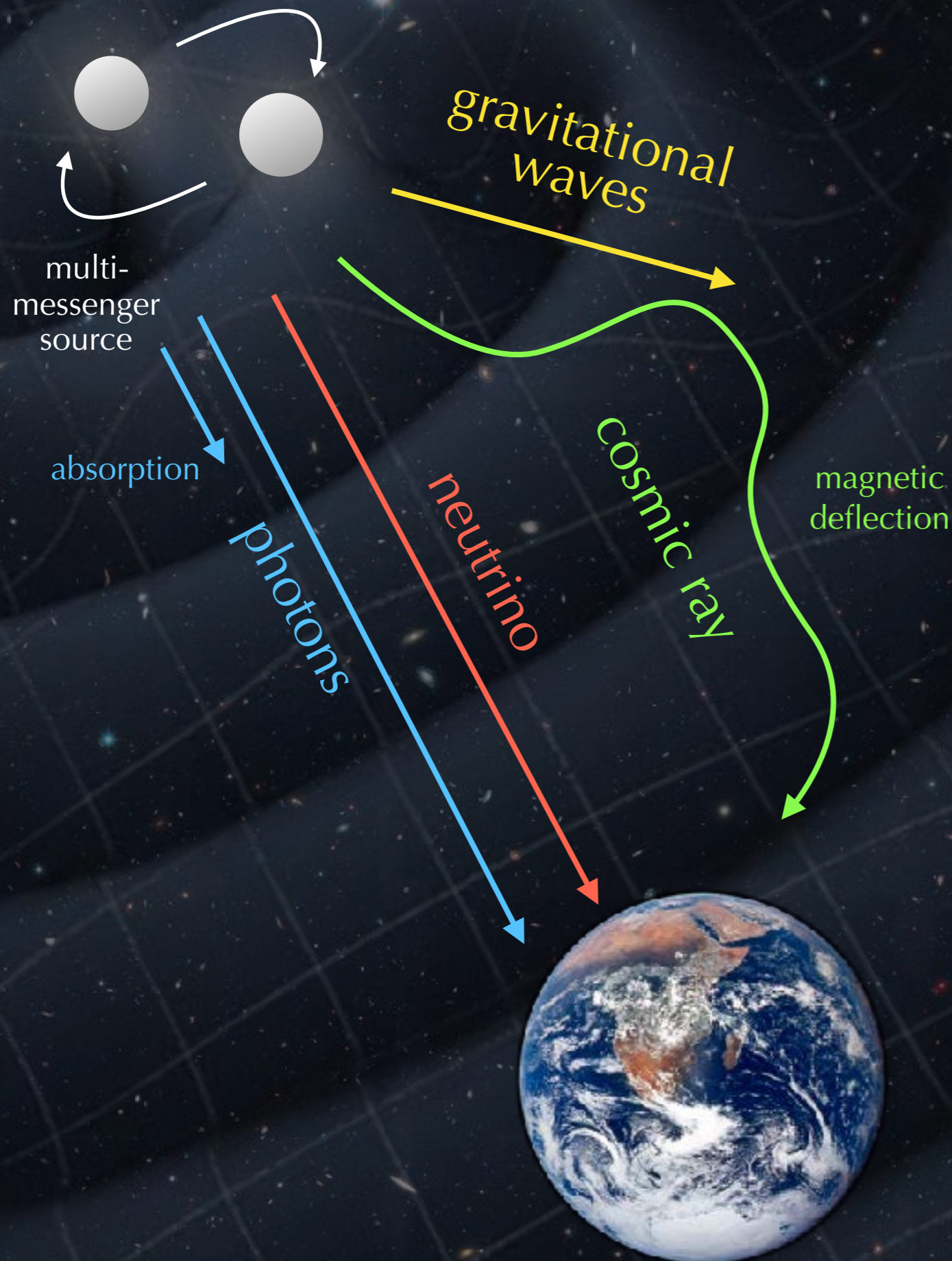


gw150914

Beyond Photons



Multi-Messenger Astronomy



photons

- ▶ excellent pointing
- ▶ easily absorbed *en-route*

cosmic rays

- ▶ energetic charged nuclei
- ▶ distorted by magnetic fields

neutrinos

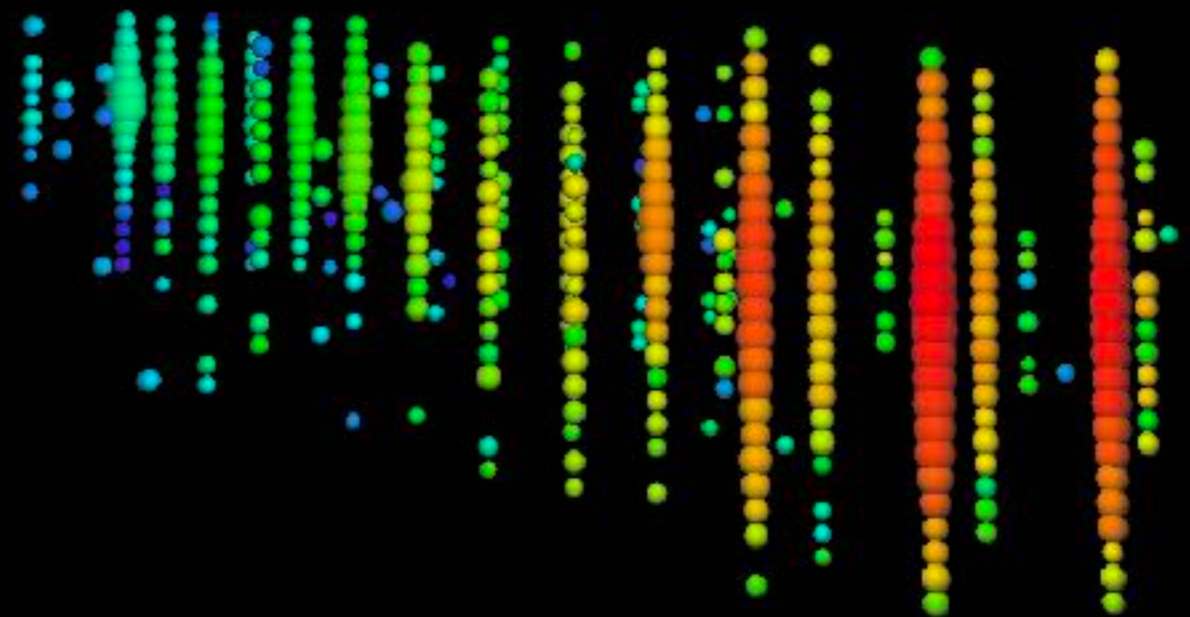
- ▶ elementary particles
- ▶ weakly interacting

gravitational waves*

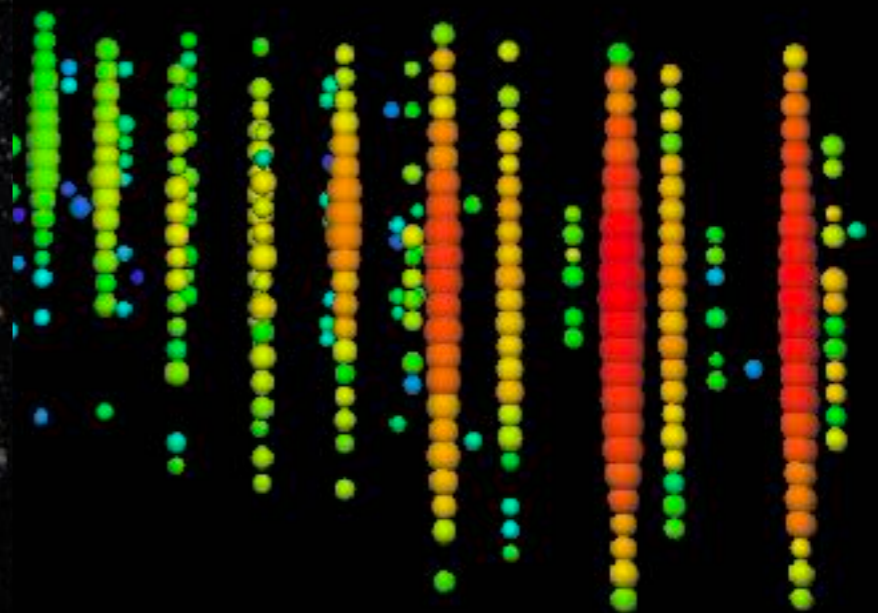
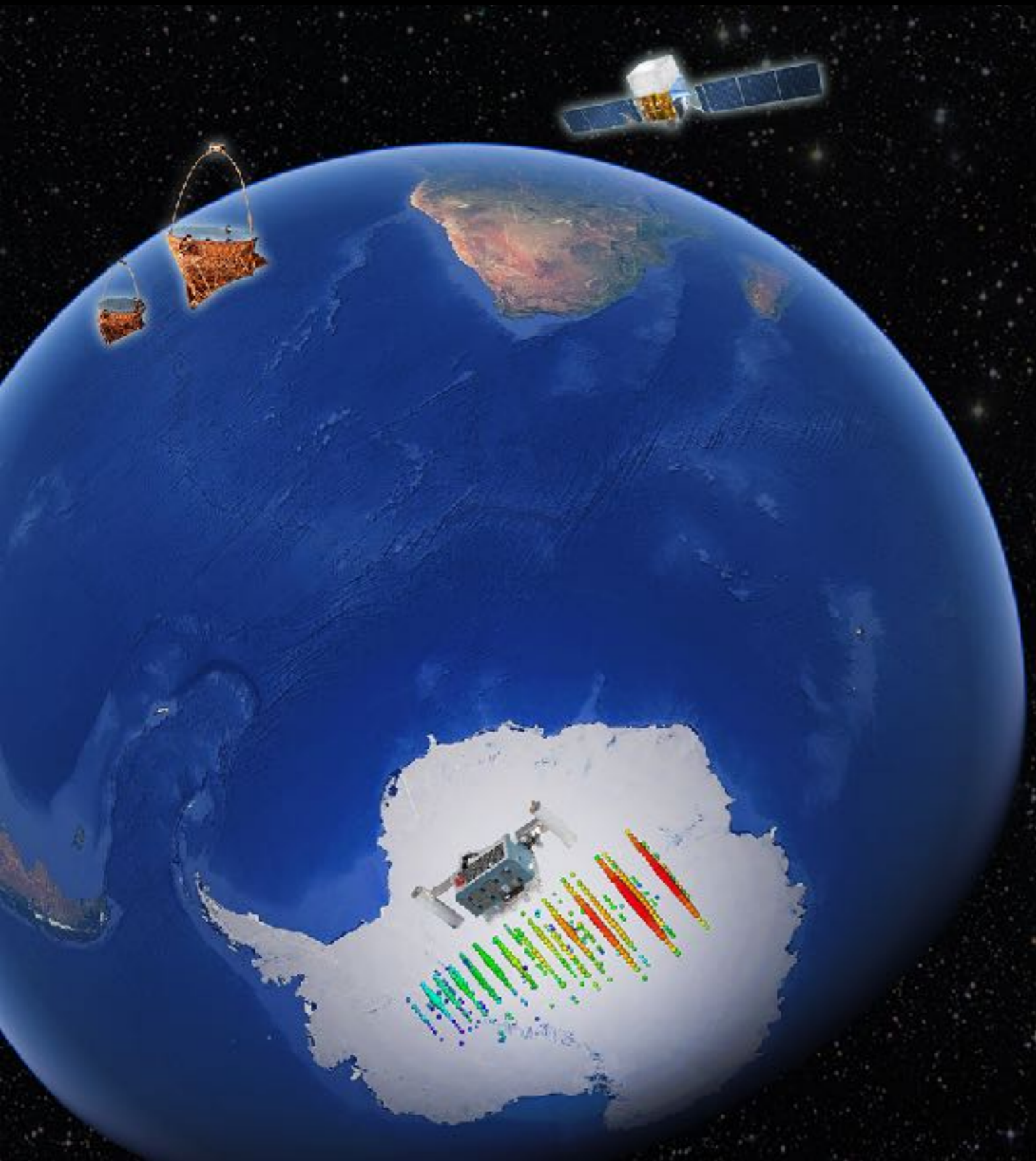
- ▶ from cataclysmic events
- ▶ very weak signature

*Nobel Prize 2017

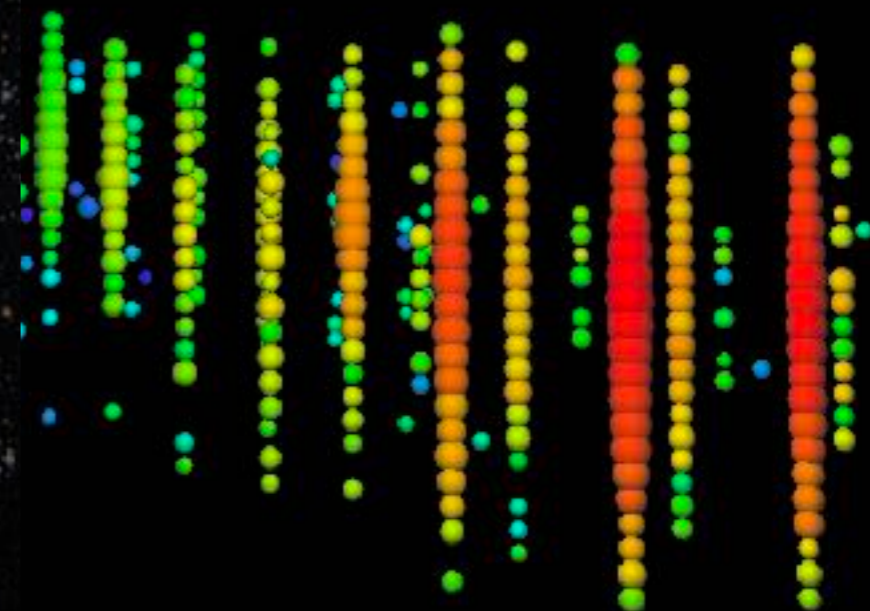
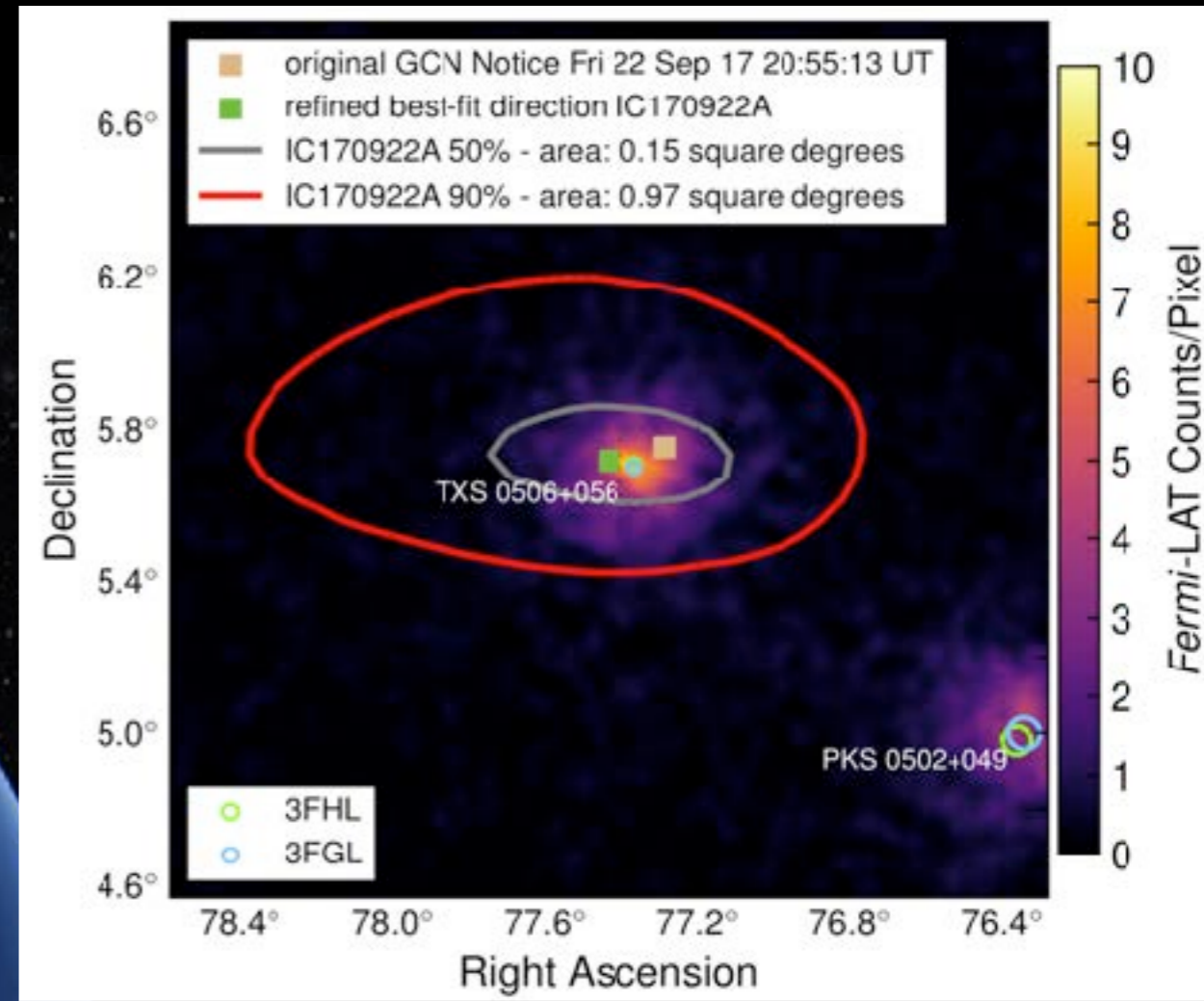
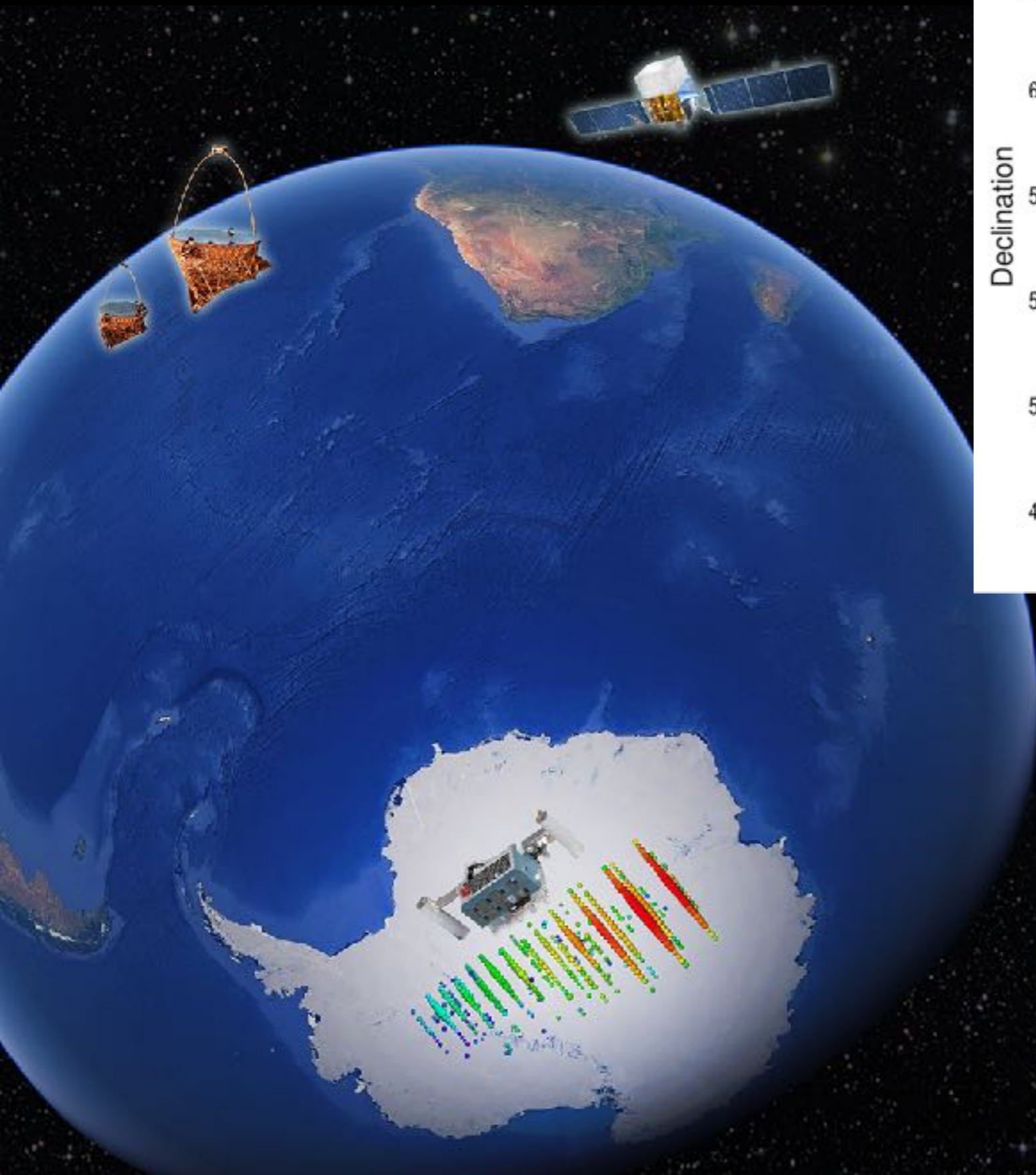
IceCube-170922A



IceCube-170922A



IceCube-170922A



Location of Neutrino

Orion

Blazar TXS 0506+056

*Axel Mellinger (C. Mich.) and NASA/DOE/Fermi LAT Collaboration



*DESY, Science Communication Lab
Artists depiction of blazar

Blazar Detection (Movie)



*NASA's Goddard Space Flight Center/CI Lab/Nicolle R. Fuller/NSF/IceCube

Blazar Detection (Movie)

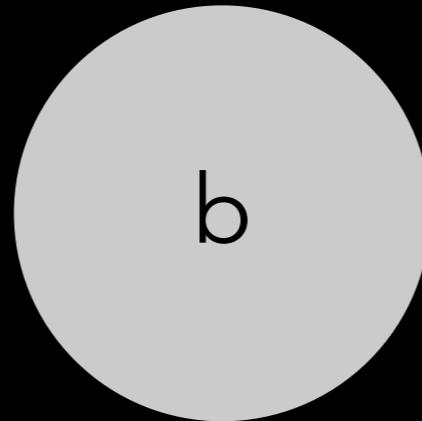
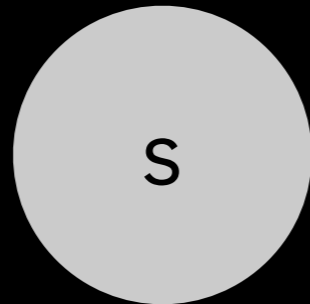
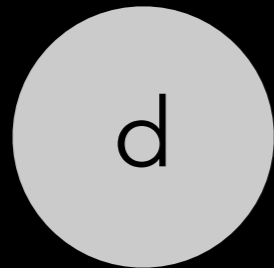
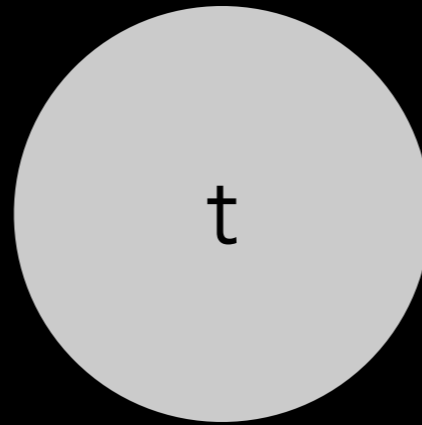
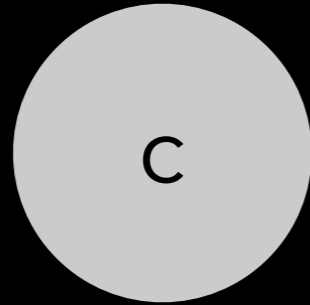
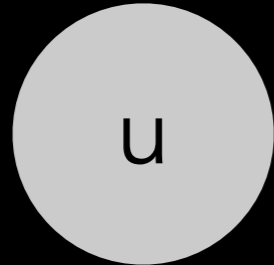


*NASA's Goddard Space Flight Center/CI Lab/Nicolle R. Fuller/NSF/IceCube

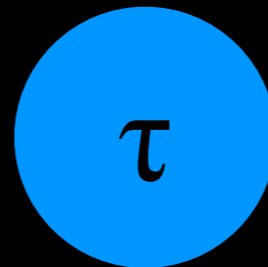
Recap

Standard Model

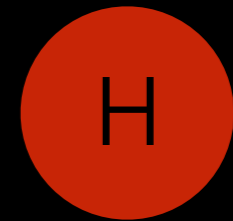
Quarks



Leptons

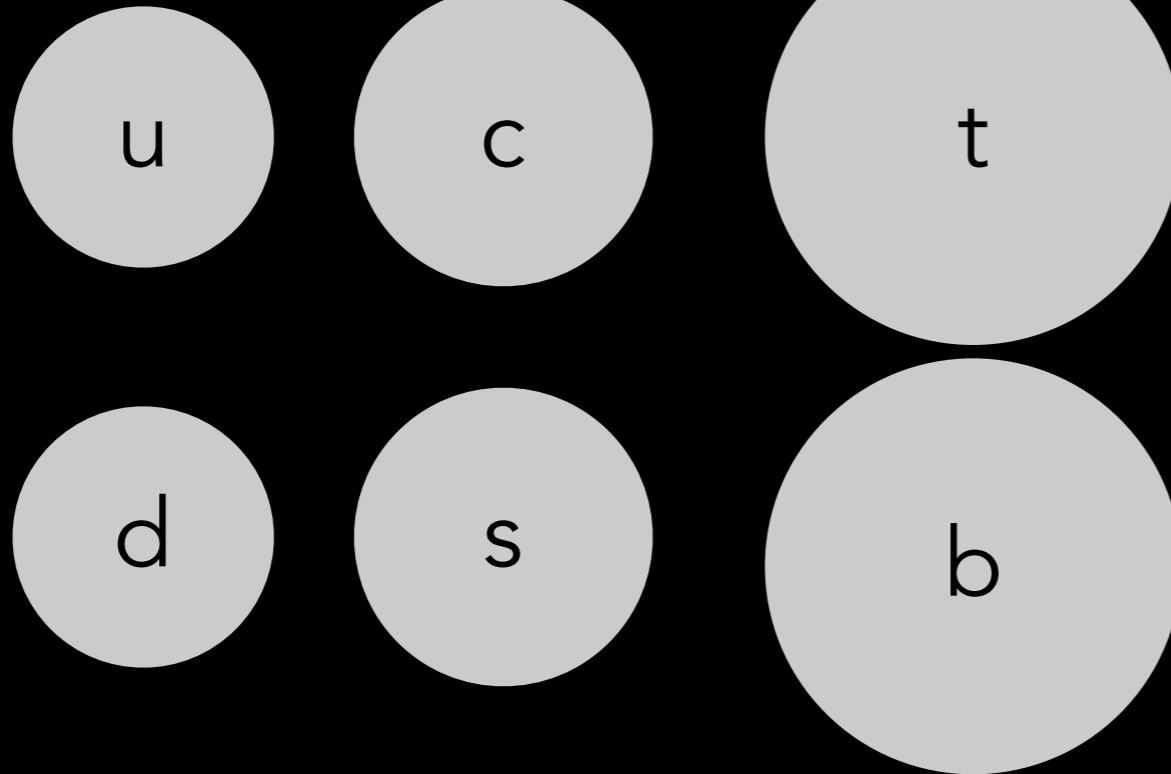


Bosons



Standard Model

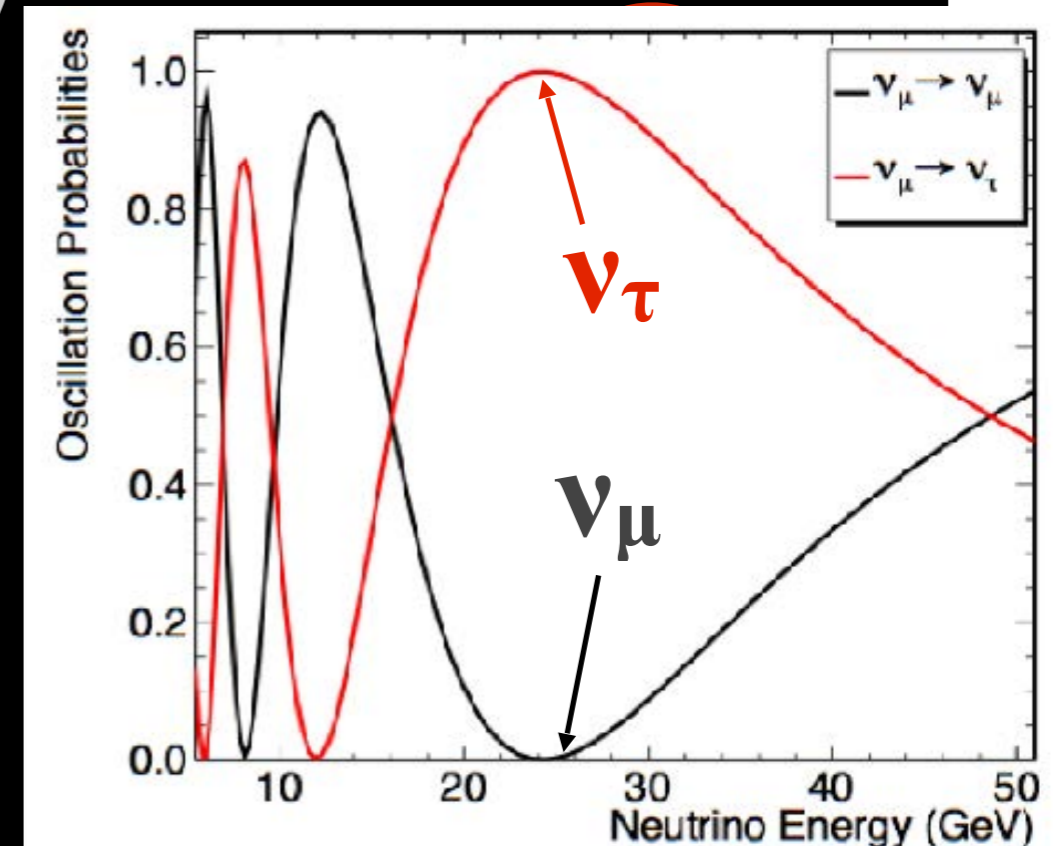
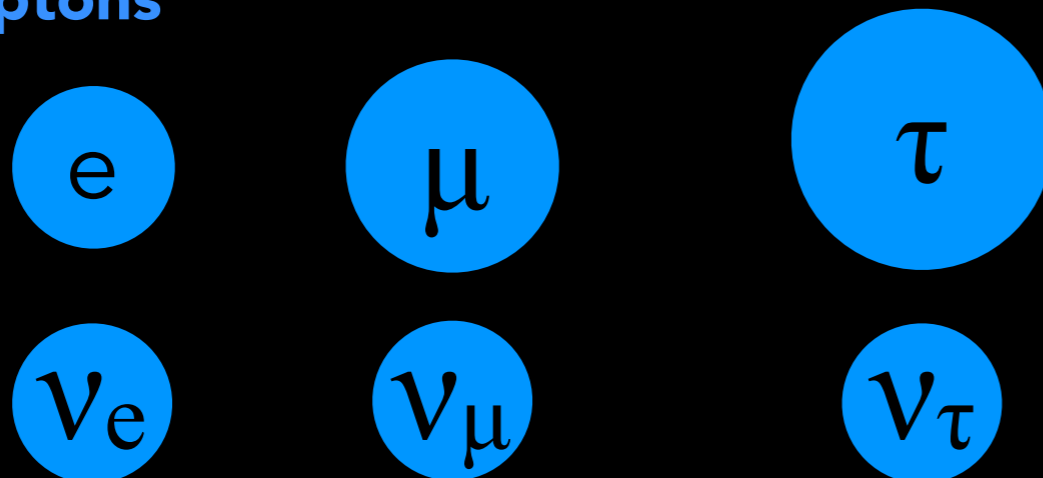
Quarks



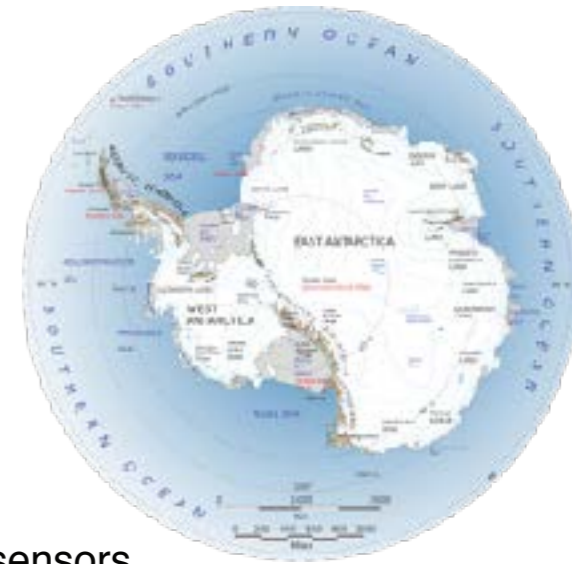
Bosons



Leptons



IceCube



IceCube Lab

IceTop
81 Stations
324 optical sensors

50 m

1450 m

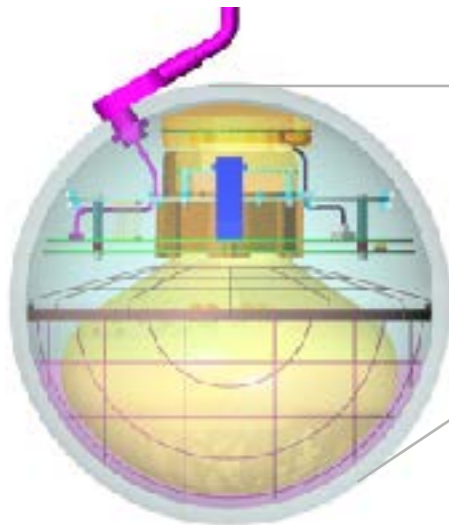
2450 m

2820 m

IceCube Array
86 strings including
8 DeepCore strings
5160 optical sensors

DeepCore
8 strings-spacing optimized
for lower energies
480 optical sensors

Eiffel Tower
324 m



IceCube Optical Sensor

Bedrock

IceCube-Gen2

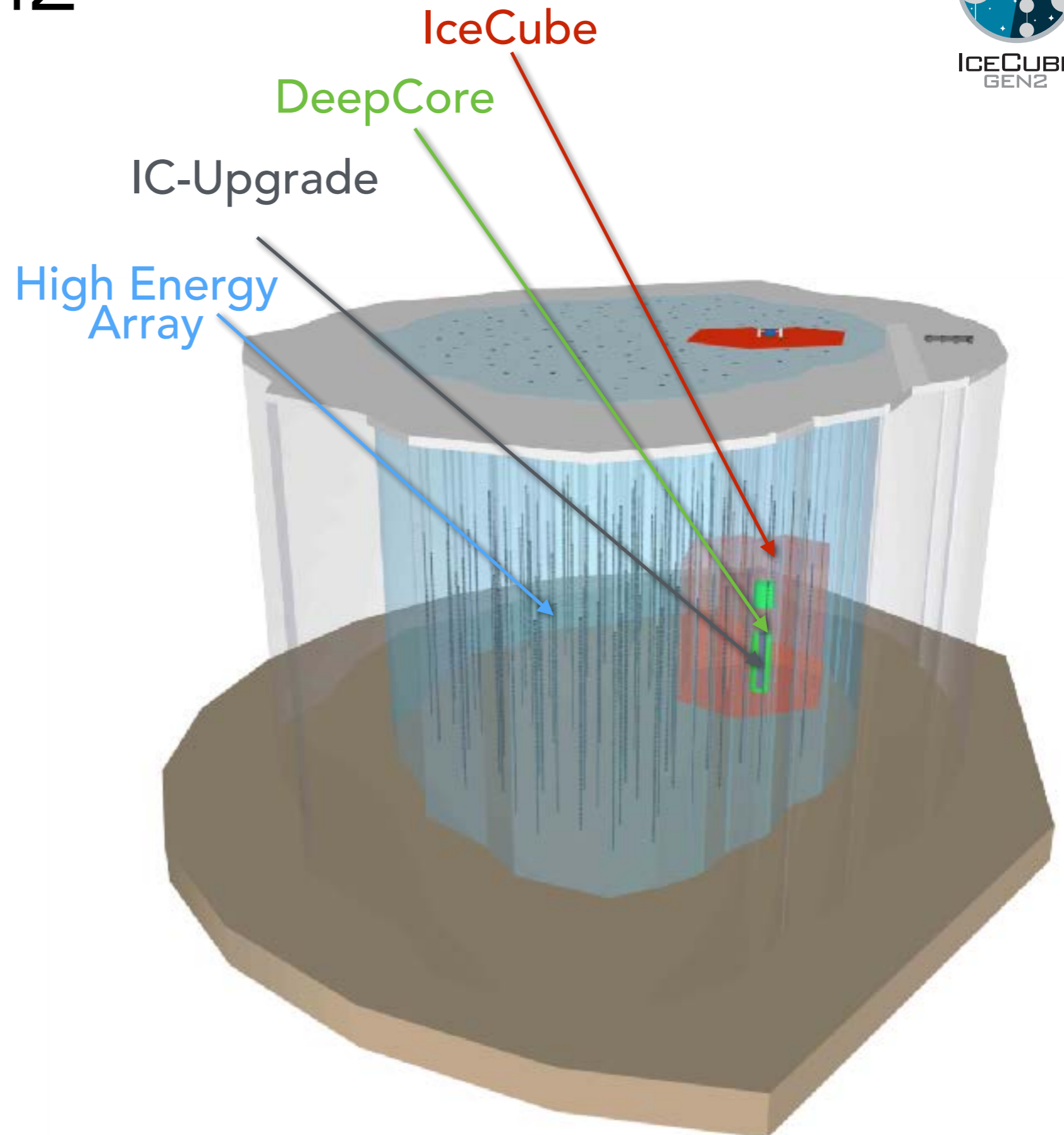


- IceCube-Upgrade

- New optical sensors
- Deploying in 2022/2023
- Optimized for particle physics

- High Energy Array

- ~8 km³ volume
- High-energy astrophysics and astronomy



Conclusion

IceCube is unlocking the fundamental particle physics secrets of the neutrino

Neutrinos and multi-messenger astronomy are an incredible new window into our Universe

