

The Small Things

Neutrino Mass & Double-Beta Decay

The Physics of Neutrinos: Progress and Puzzles

The 87th Compton Lecture Series

Enrico Fermi Institute, University of Chicago



Andrew T. Mastbaum

The Physics of Neutrinos: Progress and Puzzles

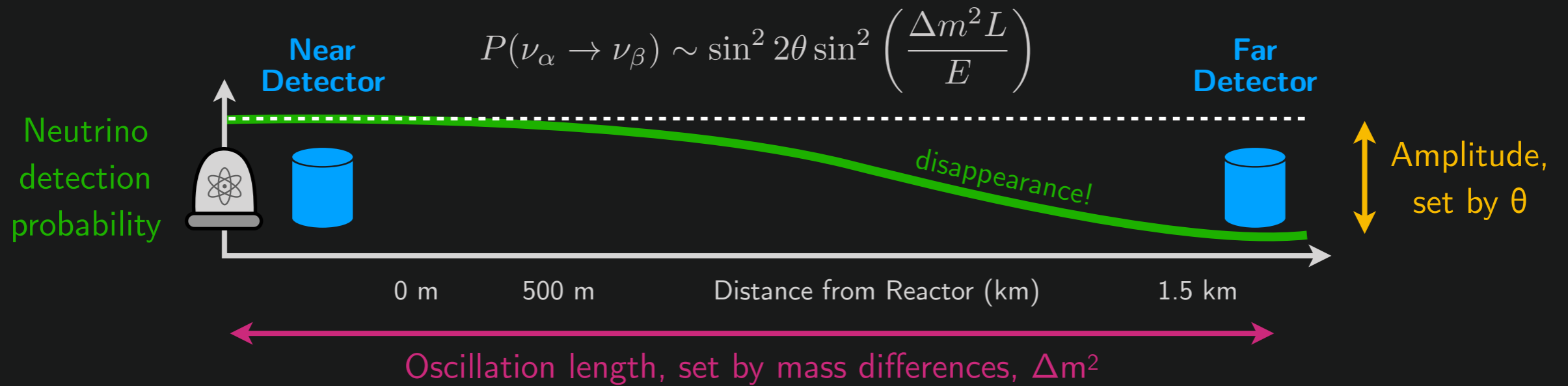
The 87th Compton Lecture Series

Agenda

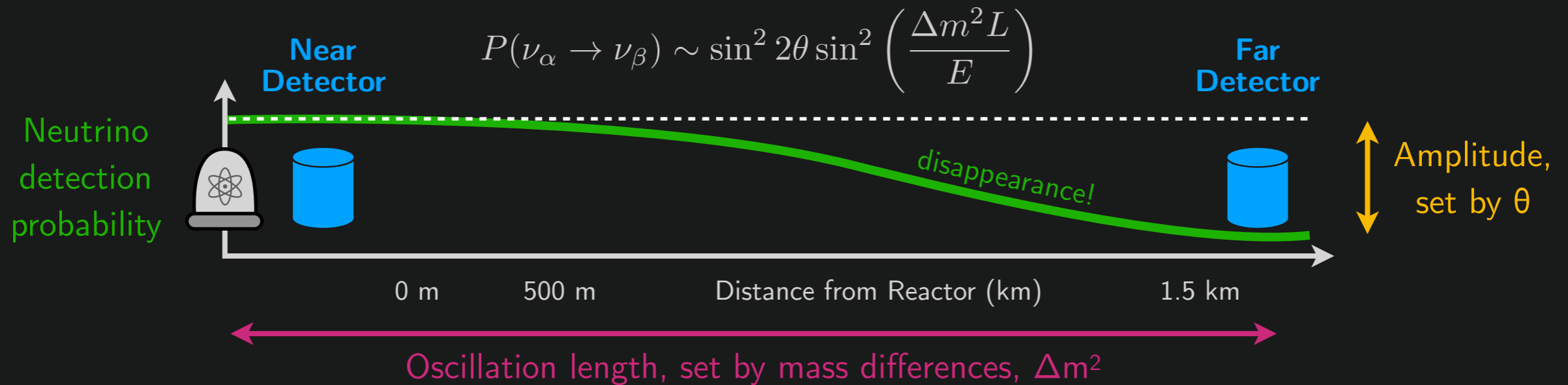
March 31	Little, Neutral, Mysterious: An Introduction to Neutrino Physics
April 7	Lost and Found: Solar Neutrinos and Oscillations
April 14	Supernova Neutrinos: Neutrinos From the Beyond the Solar System
April 21	Neutrinos in Cosmology (Dr. Marco Raveri, KICP)
April 28	Gone Fission!: Neutrinos at Nuclear Reactors
May 5	The Small Things: Neutrino Mass and Neutrinoless Double-Beta
May 12	How Many Neutrinos Are There? Sterile Neutrinos
May 19	Long-Baseline Neutrino Oscillations and CP Violation
May 26	<i>No lecture</i>
June 2	Where We Are/Where We're Going: Open Questions and Future



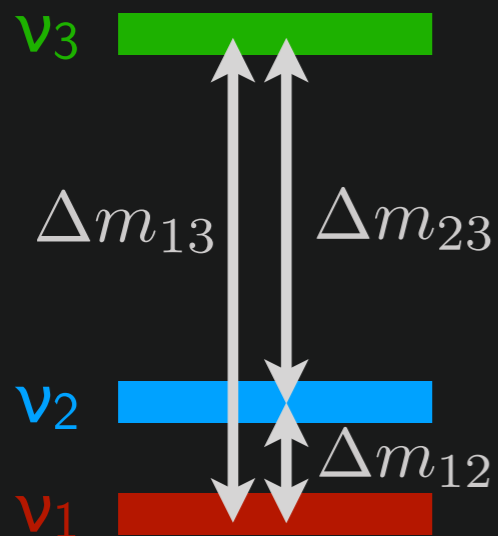
Neutrino Oscillations



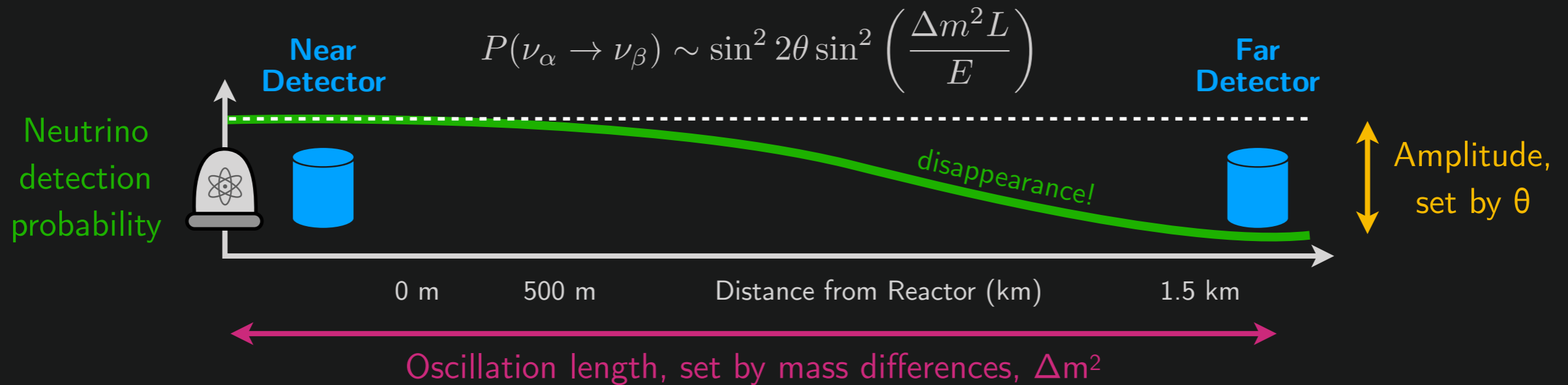
Neutrino Oscillations



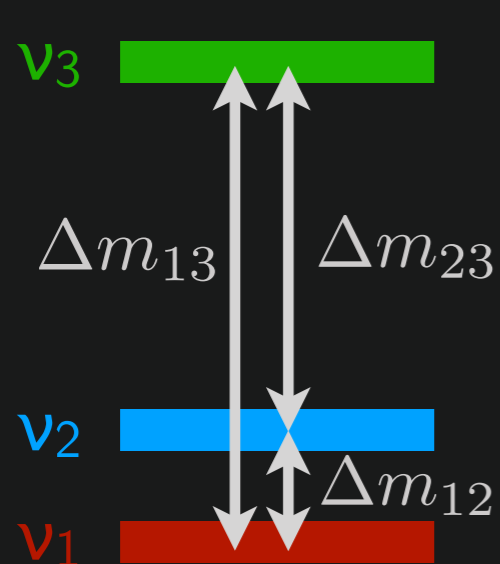
Oscillations told us
the mass **differences**



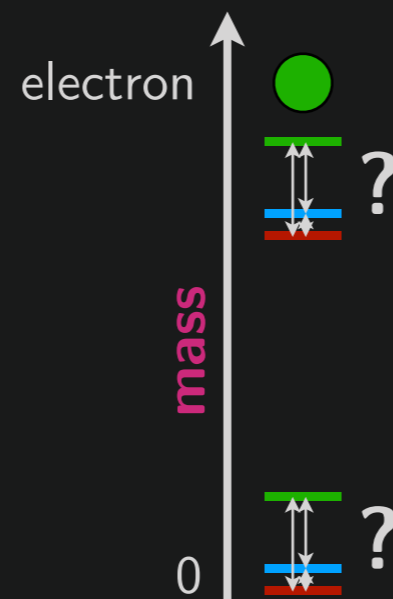
Neutrino Oscillations



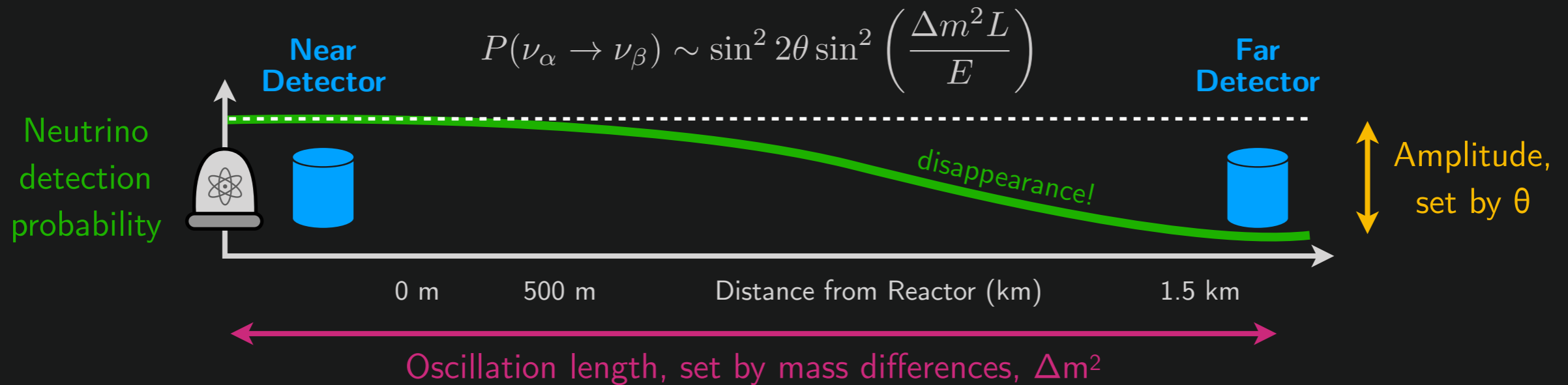
Oscillations told us
the mass **differences**



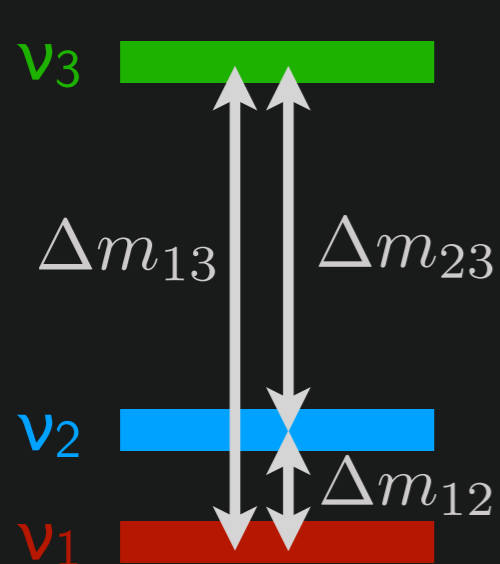
What about the
absolute mass?



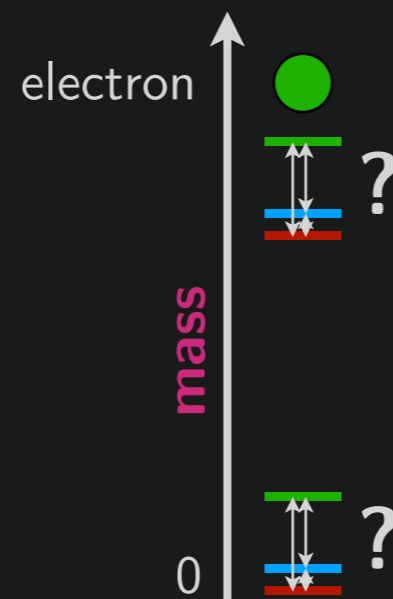
Neutrino Oscillations



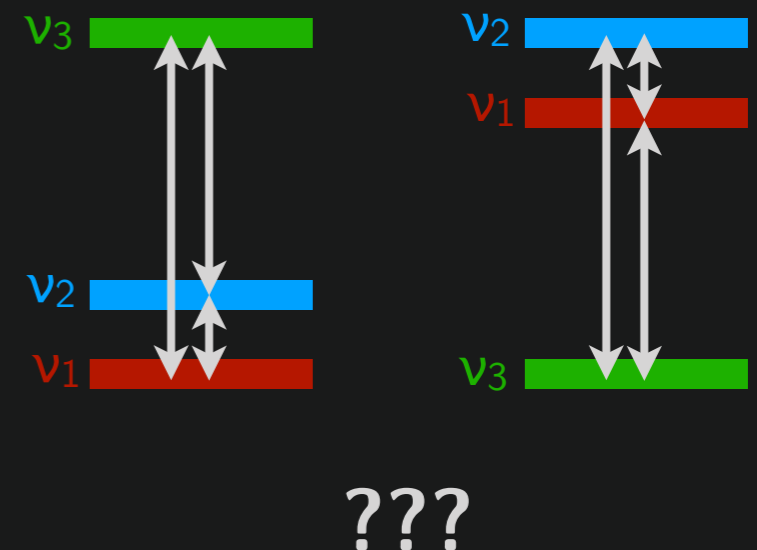
Oscillations told us
the mass **differences**



What about the
absolute mass?



What about the
mass **ordering**?



ν Neutrino Mass

ν Neutrino Mass

ν Neutrino Mass



A full accounting of mass for
Standard Model particles

ν Neutrino Mass



A full accounting of mass for
Standard Model particles



A hint of "new physics"
beyond the Standard Model

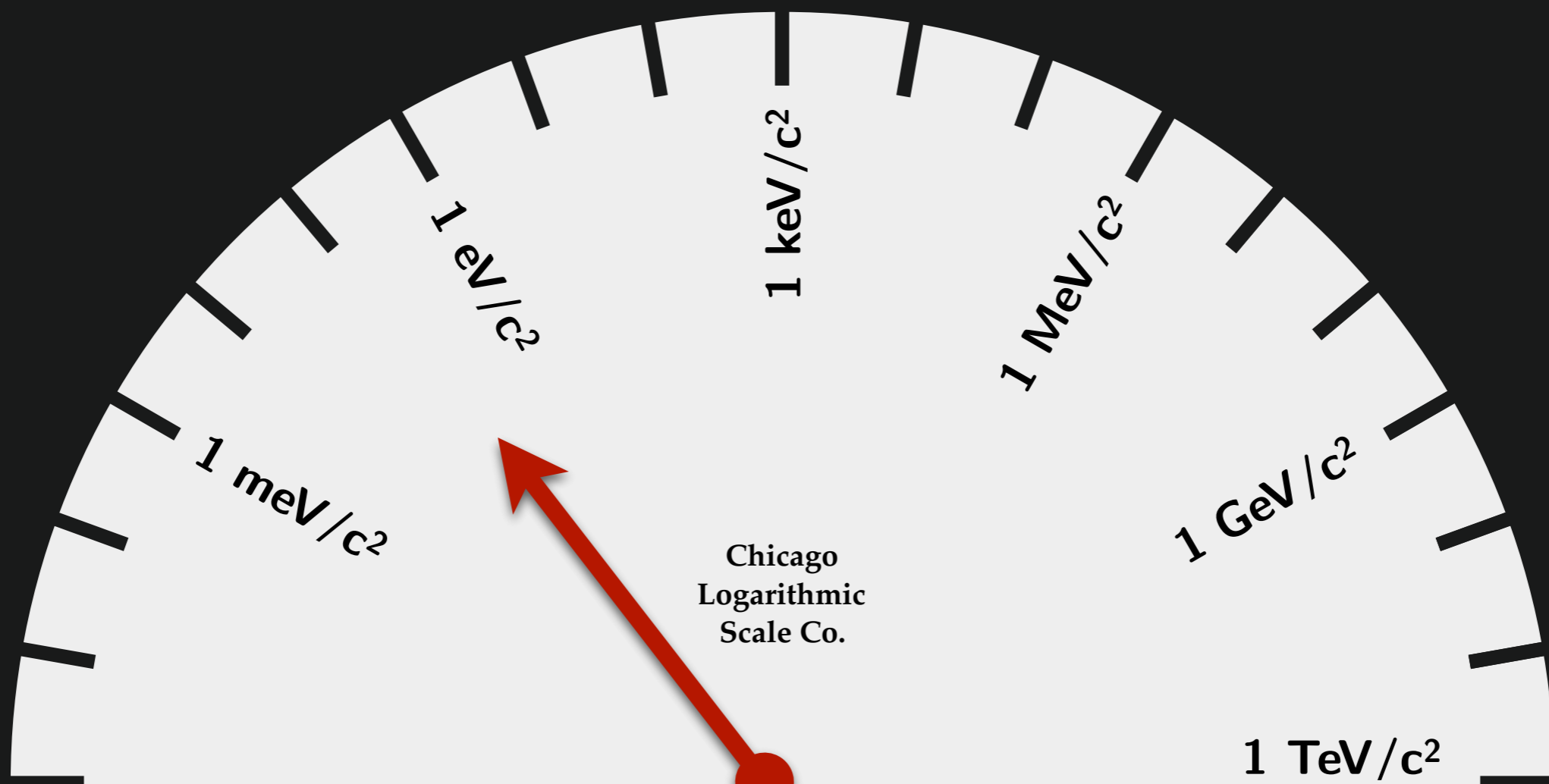
ν Neutrino Mass



A full accounting of mass for
Standard Model particles



A hint of "new physics"
beyond the Standard Model



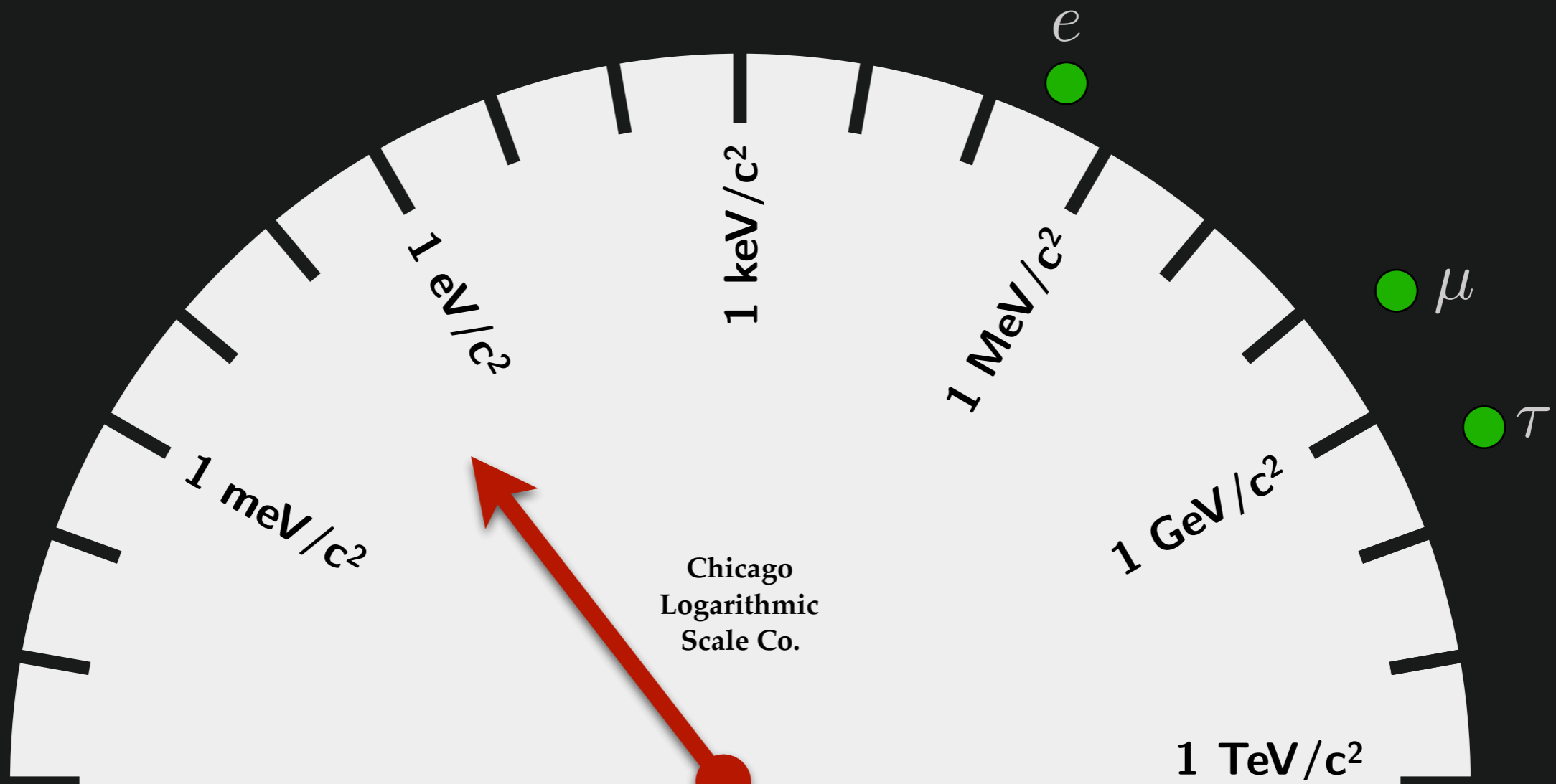
ν Neutrino Mass



A full accounting of mass for
Standard Model particles



A hint of "new physics"
beyond the Standard Model



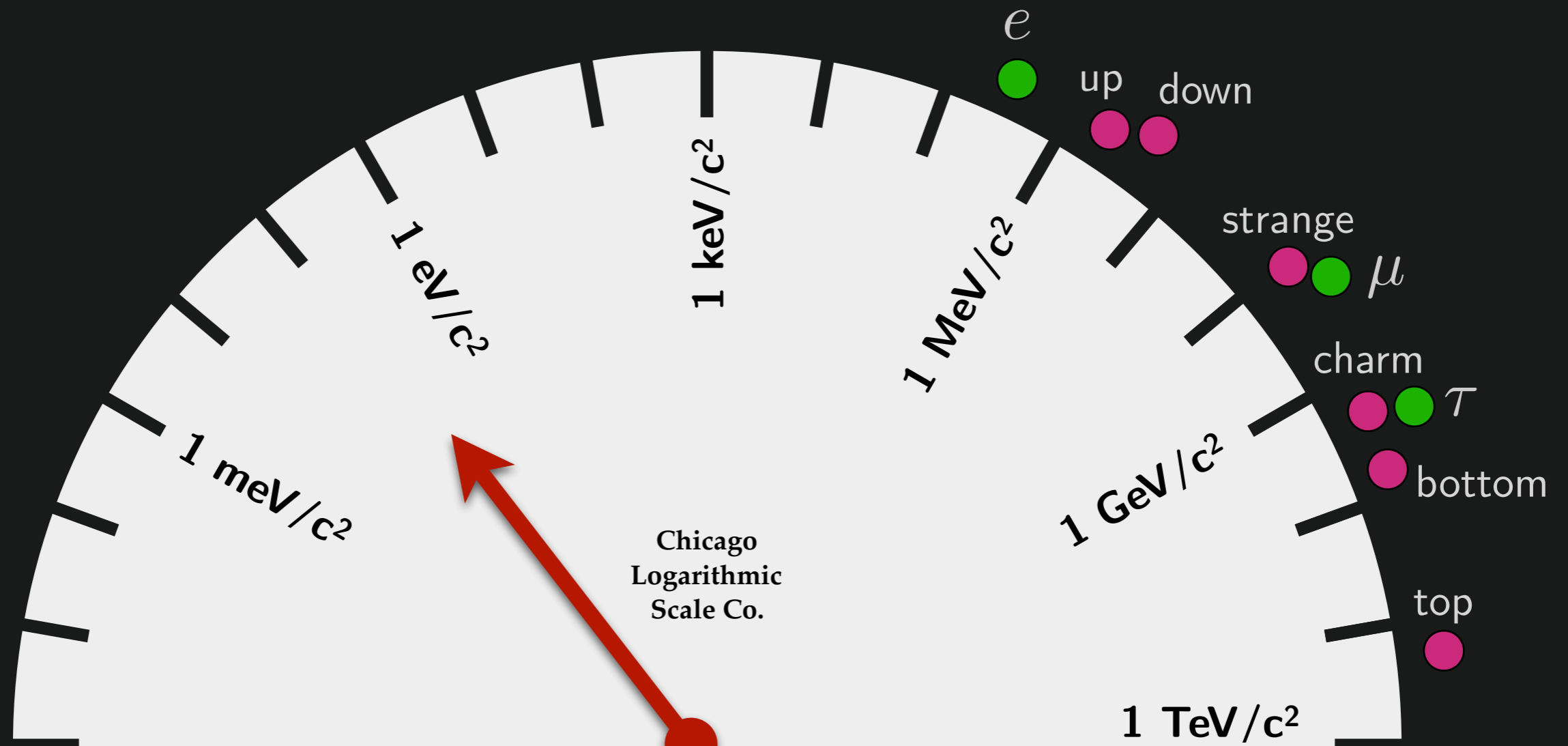
ν Neutrino Mass



A full accounting of mass for Standard Model particles



A hint of "new physics" beyond the Standard Model



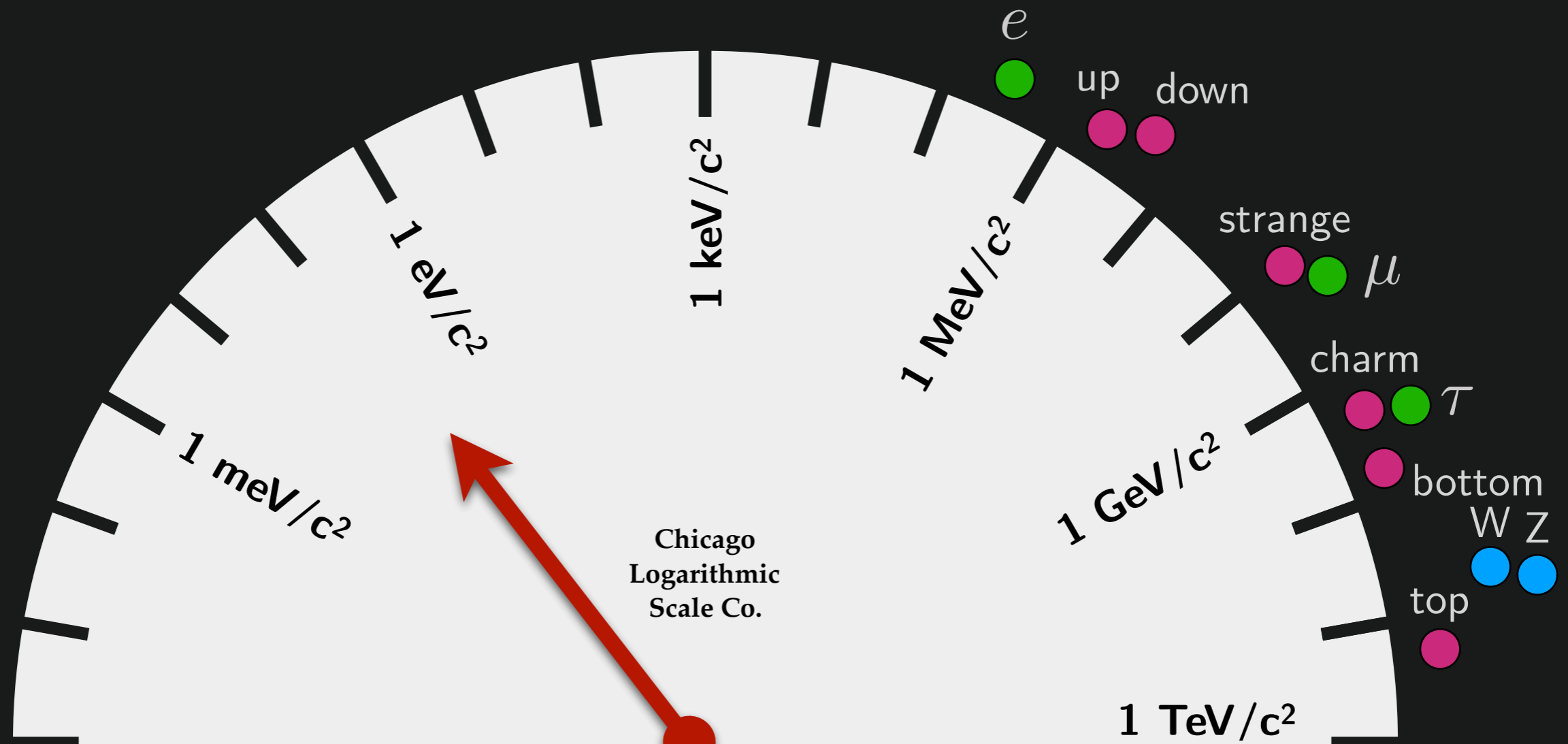
ν Neutrino Mass



A full accounting of mass for Standard Model particles



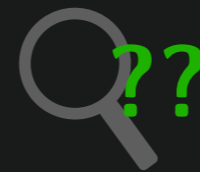
A hint of "new physics" beyond the Standard Model



ν Neutrino Mass

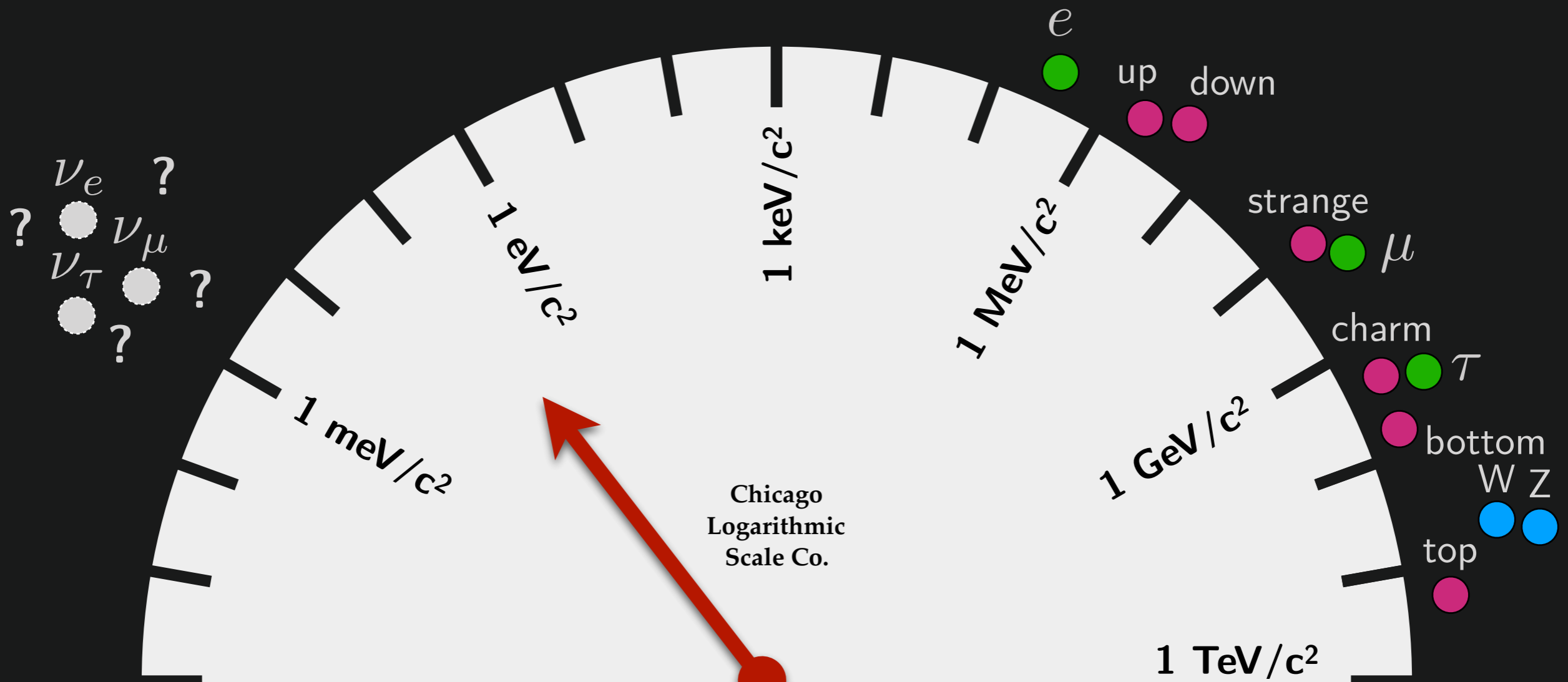


A full accounting of mass for Standard Model particles



A hint of "new physics" beyond the Standard Model

Why are the neutrino masses so weirdly tiny?



ν Neutrino Mass



A full accounting of mass for
Standard Model particles



A hint of "new physics"
beyond the Standard Model

Why are the neutrino masses so weirdly tiny?

ν Neutrino Mass



A full accounting of mass for
Standard Model particles



A hint of "new physics"
beyond the Standard Model

Why are the neutrino masses so weirdly tiny?

ν Neutrino Mass



A full accounting of mass for Standard Model particles



A hint of "new physics" beyond the Standard Model

Why are the neutrino masses so weirdly tiny?

Standard Physics?

Neutrinos work just like anything else, but the masses happen to be really small

ν Neutrino Mass



A full accounting of mass for Standard Model particles



A hint of "new physics" beyond the Standard Model

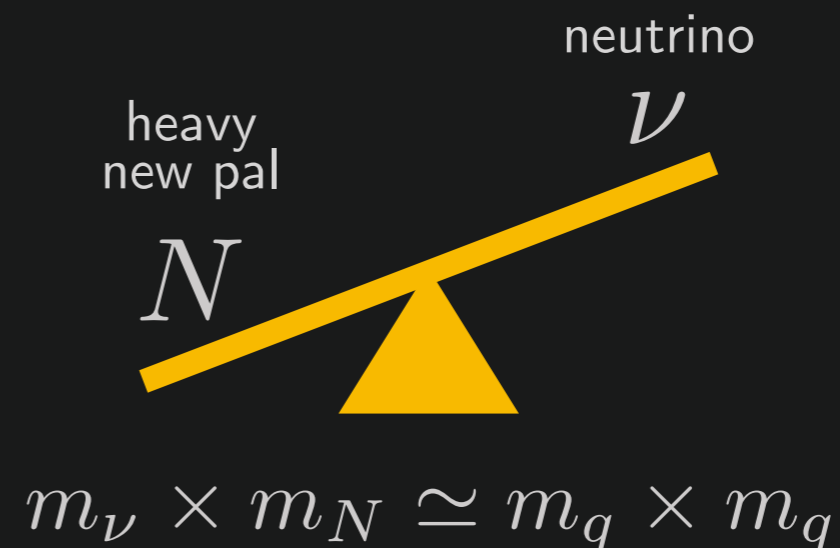
Why are the neutrino masses so weirdly tiny?

Standard Physics?

Neutrinos work just like anything else, but the masses happen to be really small

New Physics?

Ex. Seesaw Mechanism



ν Neutrino Mass



A full accounting of mass for
Standard Model particles



A hint of "new physics"
beyond the Standard Model

Why are the neutrino masses so weirdly tiny?

ν Neutrino Mass



A full accounting of mass for
Standard Model particles



A hint of "new physics"
beyond the Standard Model

How can we study it?

ν Neutrino Mass



A full accounting of mass for
Standard Model particles



A hint of "new physics"
beyond the Standard Model

How can we study it?

Cosmology



ν Neutrino Mass



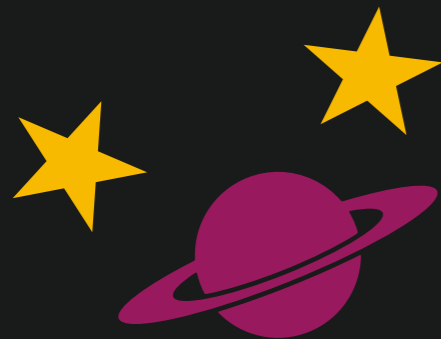
A full accounting of mass for Standard Model particles



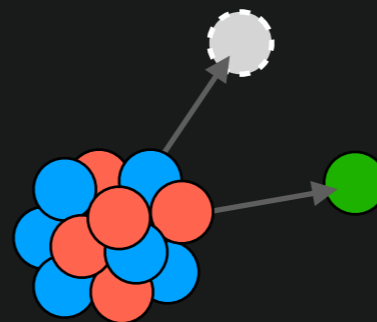
A hint of "new physics" beyond the Standard Model

How can we study it?

Cosmology



Beta Decay



ν Neutrino Mass



A full accounting of mass for Standard Model particles



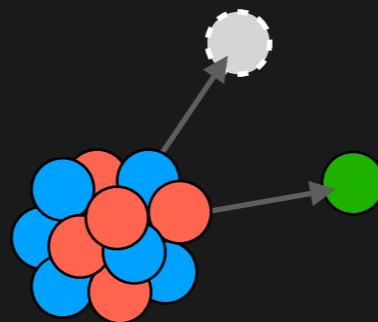
A hint of "new physics" beyond the Standard Model

How can we study it?

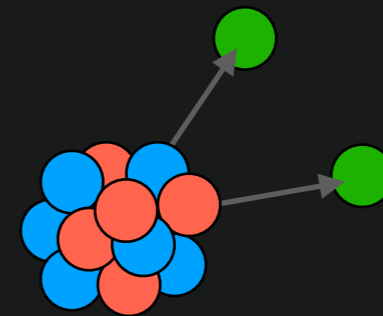
Cosmology



Beta Decay



Neutrinoless Double Beta Decay



Cosmology

"Weighing the neutrino, using the universe as a scale"

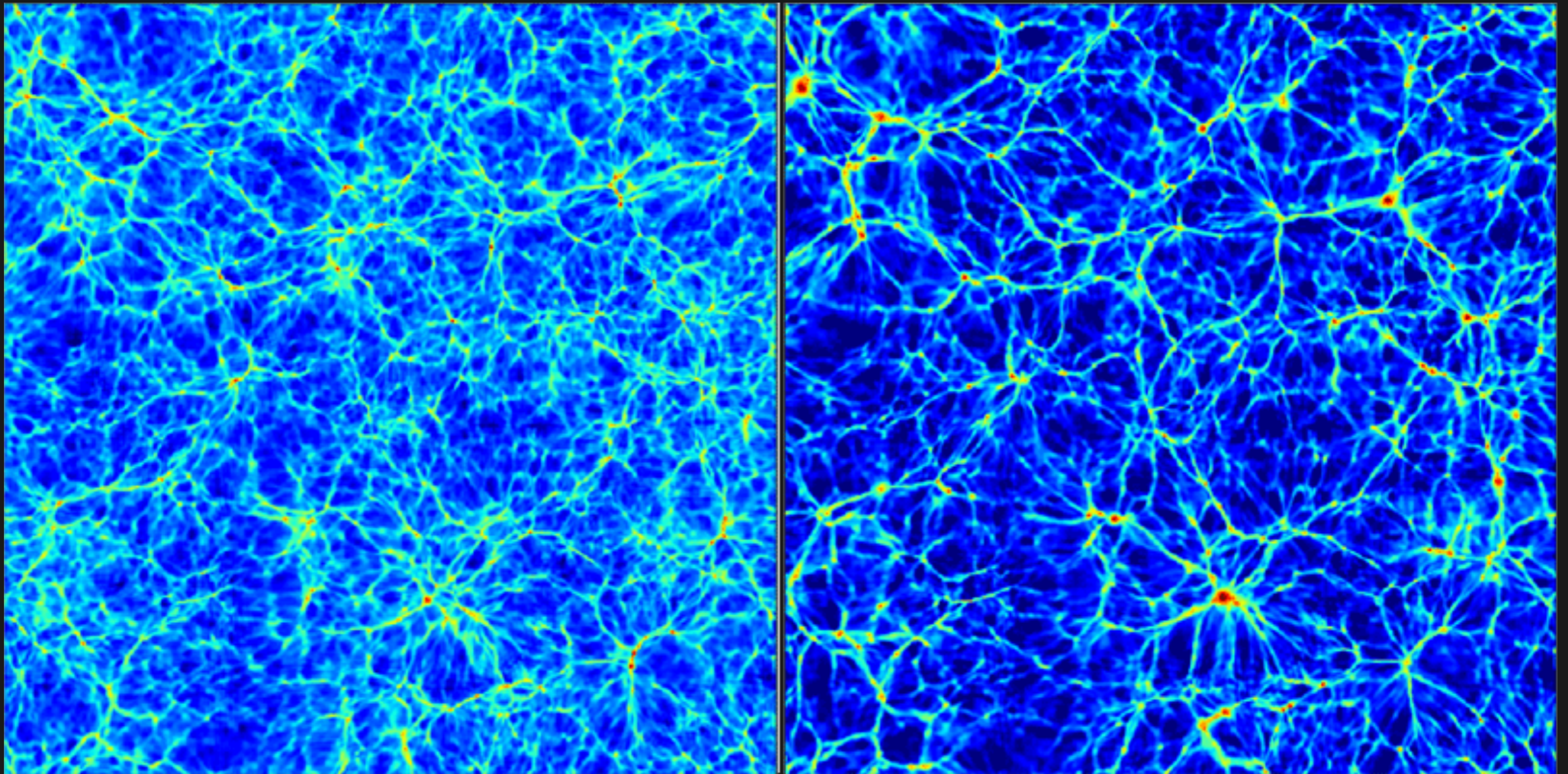


Cosmology

Neutrinos impact the formation of structures in the universe

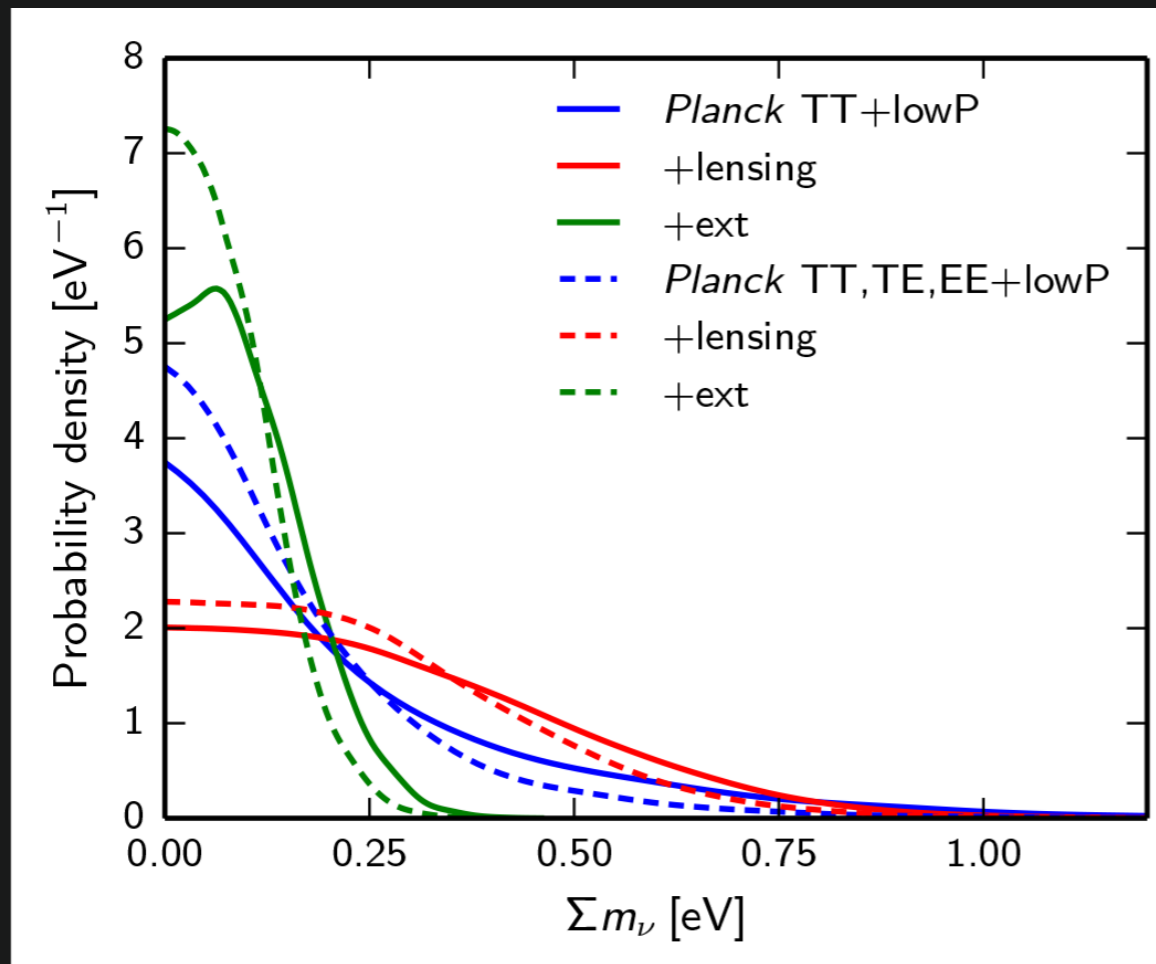
with neutrinos

without neutrinos

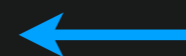


Cosmology

Constraints on the neutrino mass from cosmology

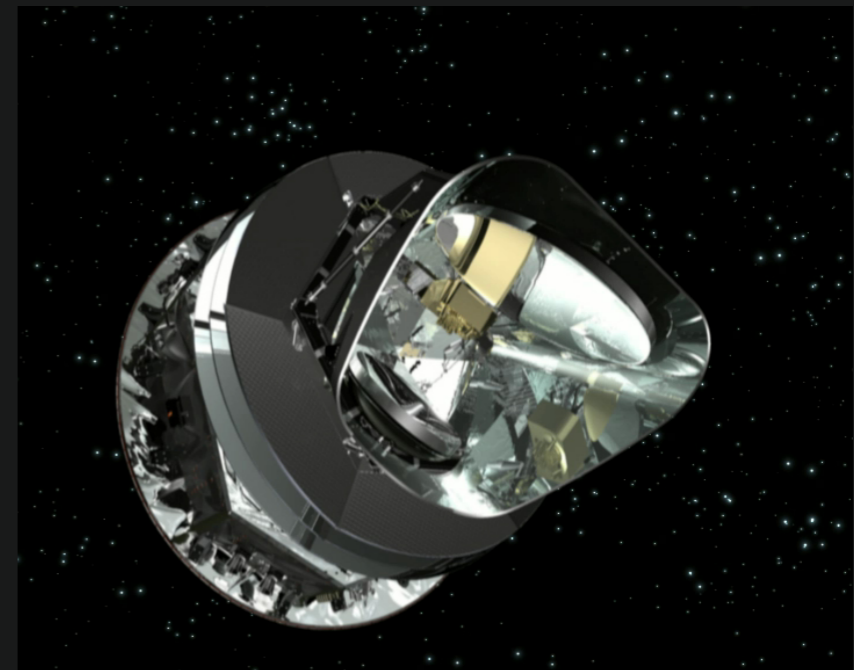


$$\Sigma_\nu m_\mu < 0.2 - 0.6 \text{ eV}$$



An upper bound on
the sum of all three
neutrino masses

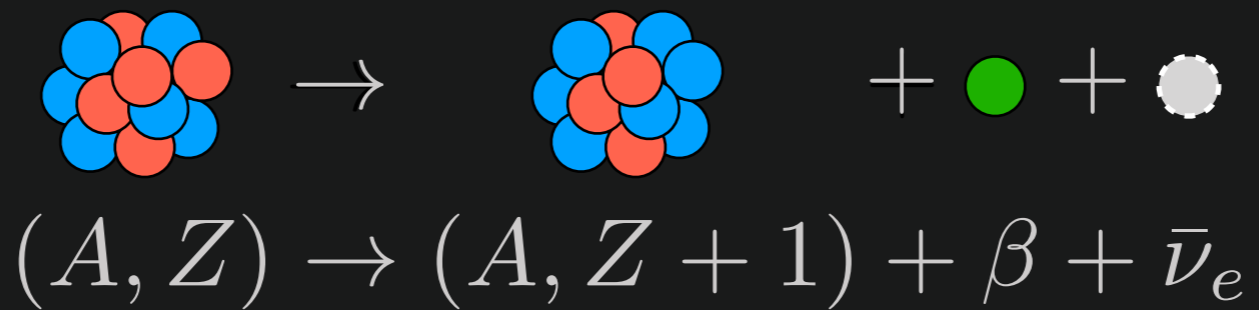
Planck Satellite



(c) ESA (Image by AOES Medialab)

Beta Decay

Beta Decay



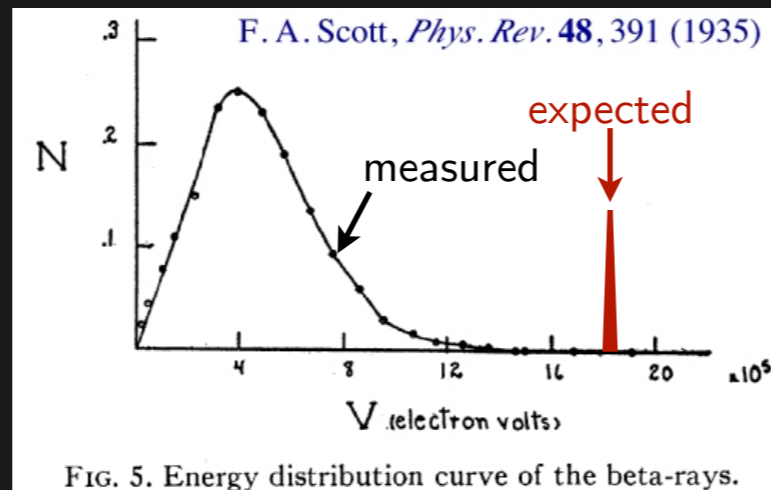
Beta Decay



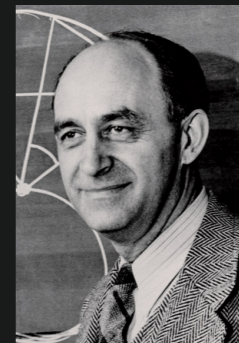
$$(A, Z) \rightarrow (A, Z + 1) + \beta + \bar{\nu}_e$$



James Chadwick

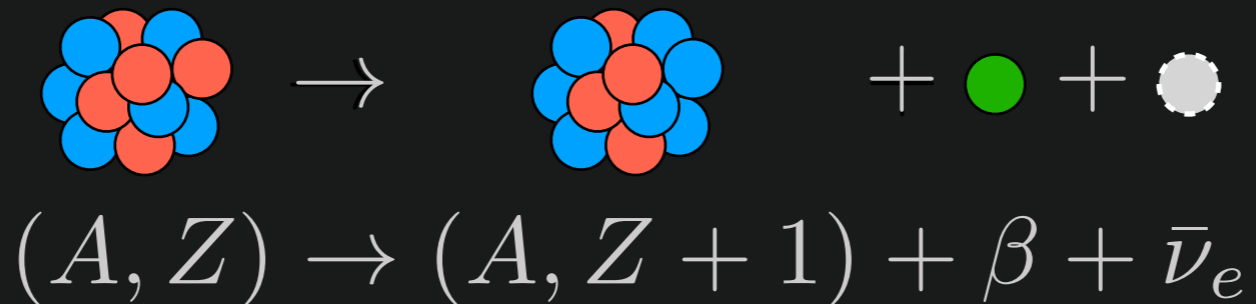


Wolfgang Pauli

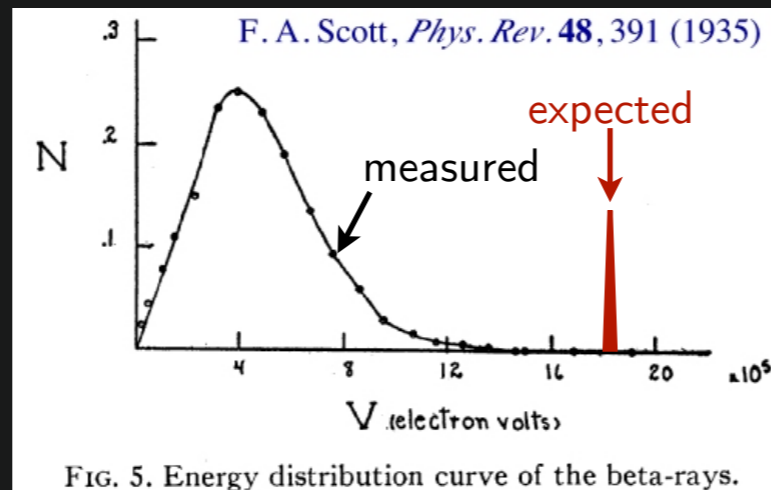


Enrico Fermi

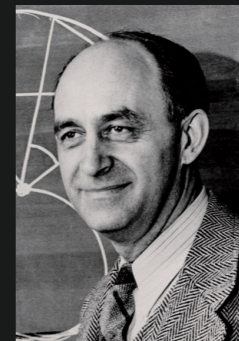
Beta Decay



James Chadwick



Wolfgang Pauli



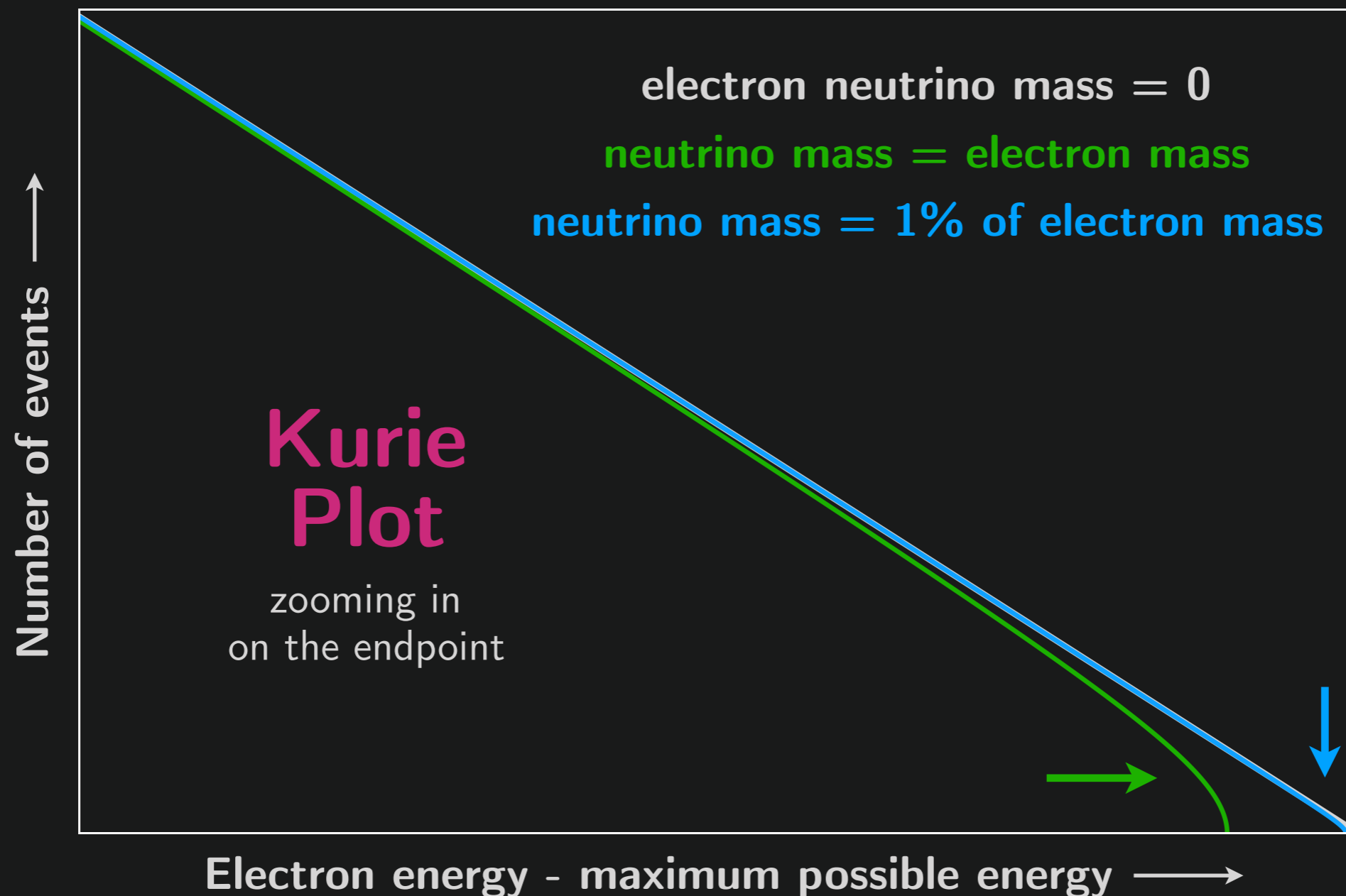
Enrico Fermi

This distribution of **electron energies** depends on the **neutrino mass**

$$(Q - E_e)^2 \Rightarrow (Q - E_e) \sqrt{(Q - E_e)^2 - m_\nu^2 c^4}$$

which apparently is really small

Beta Decay



KATRIN, Karlsruhe, Germany

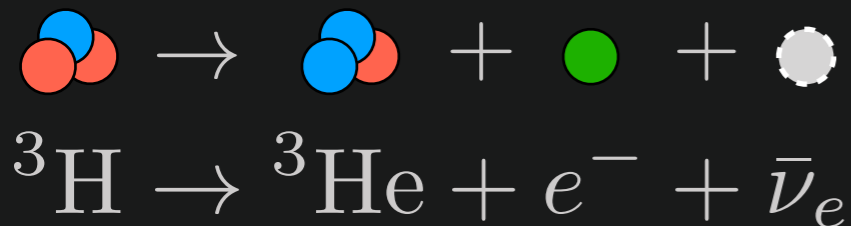
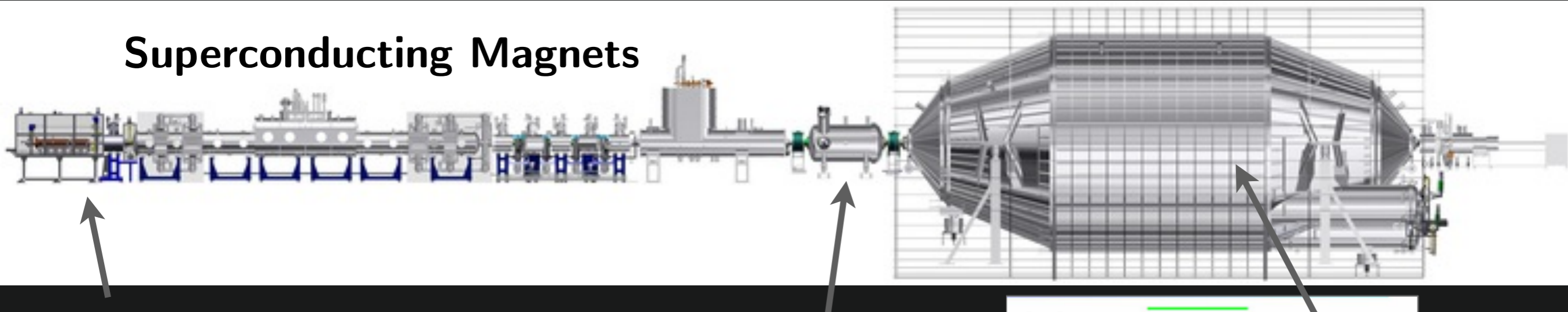




KATRIN

Karlsruhe Tritium Neutrino Experiment

Superconducting Magnets

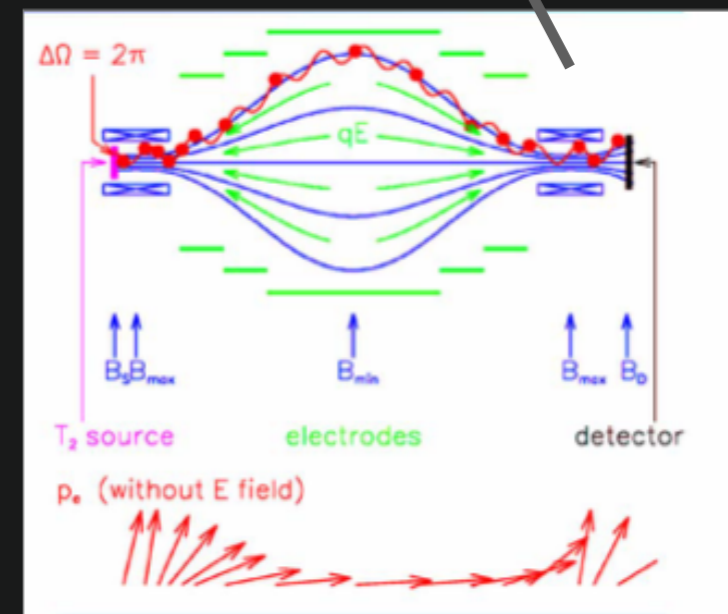


Start with a very light nucleus

Tritium, ${}^3\text{H}$

Pre-Spectrometer

Choose only electrons
near the maximum energy



Magnetic Adiabatic Collimation
combined with an Electrostatic filter

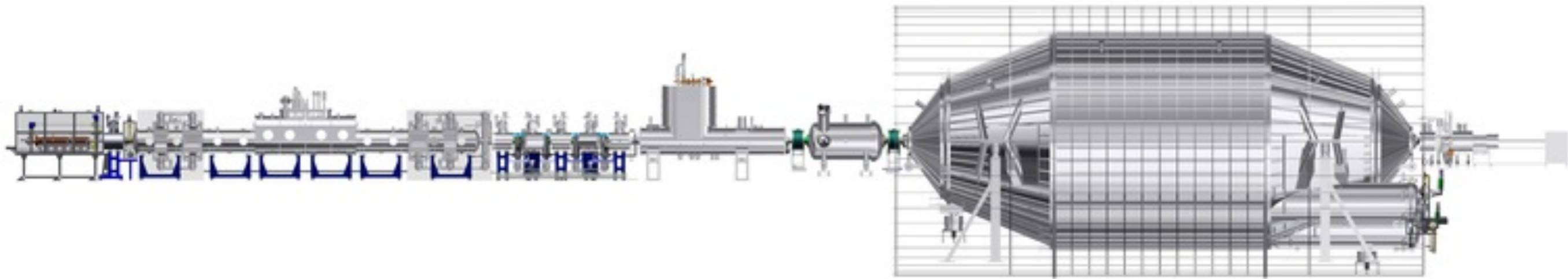
MAC-E Filter

Ultra-sensitive electron energy
measurement device



KATRIN

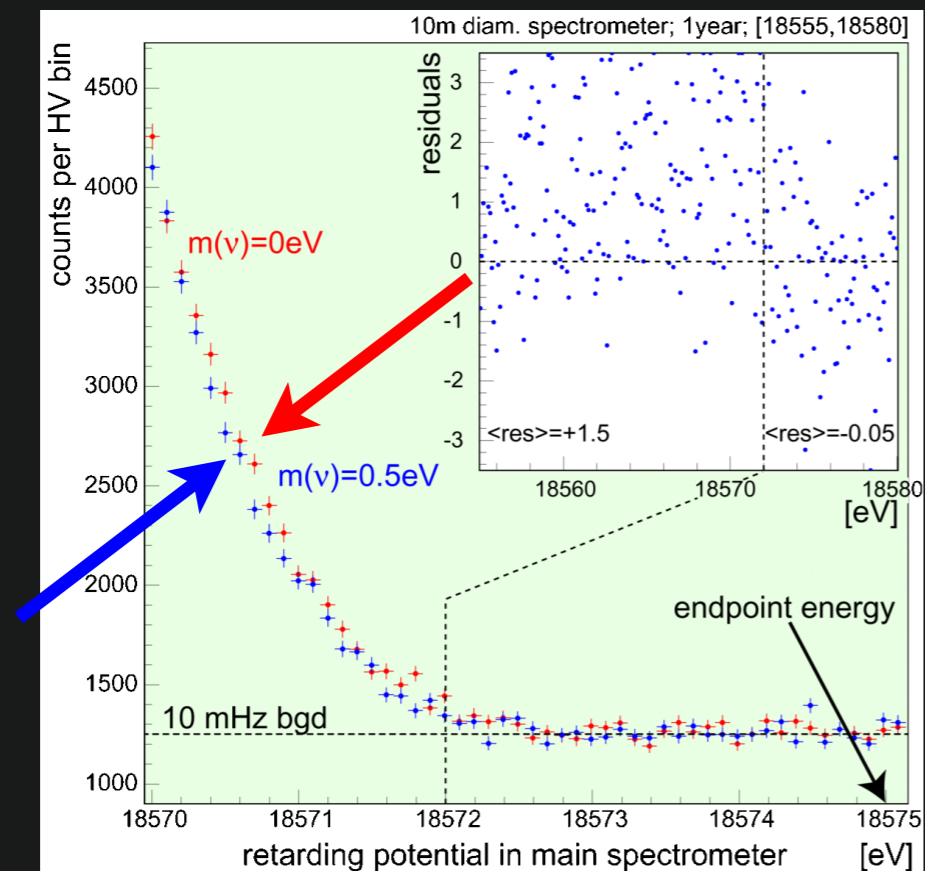
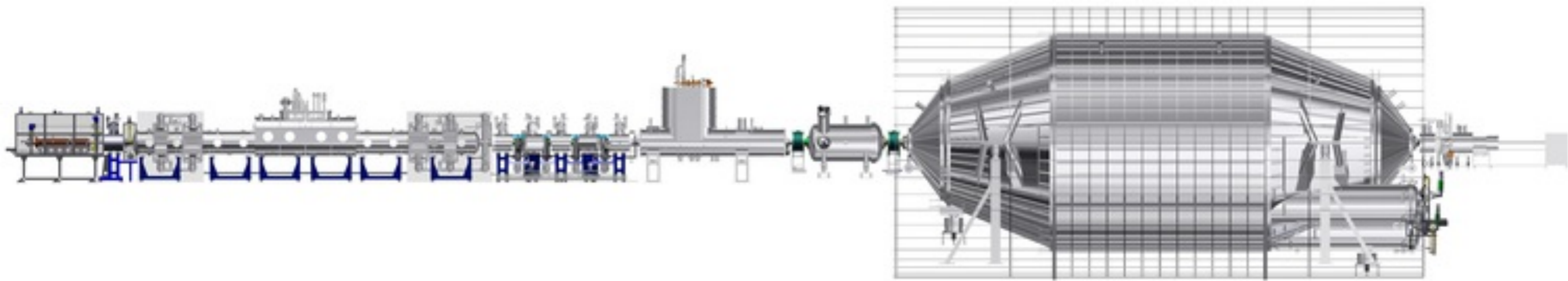
Karlsruhe Tritium Neutrino Experiment





KATRIN

Karlsruhe Tritium Neutrino Experiment



Current Measurements

$$m(\nu_e) < 2 \text{ eV}$$

0.000004% of electron mass

KATRIN Expectation

$$m(\nu_e) < 0.2 \text{ eV}$$

0.0000004% of electron mass

Commissioning now!

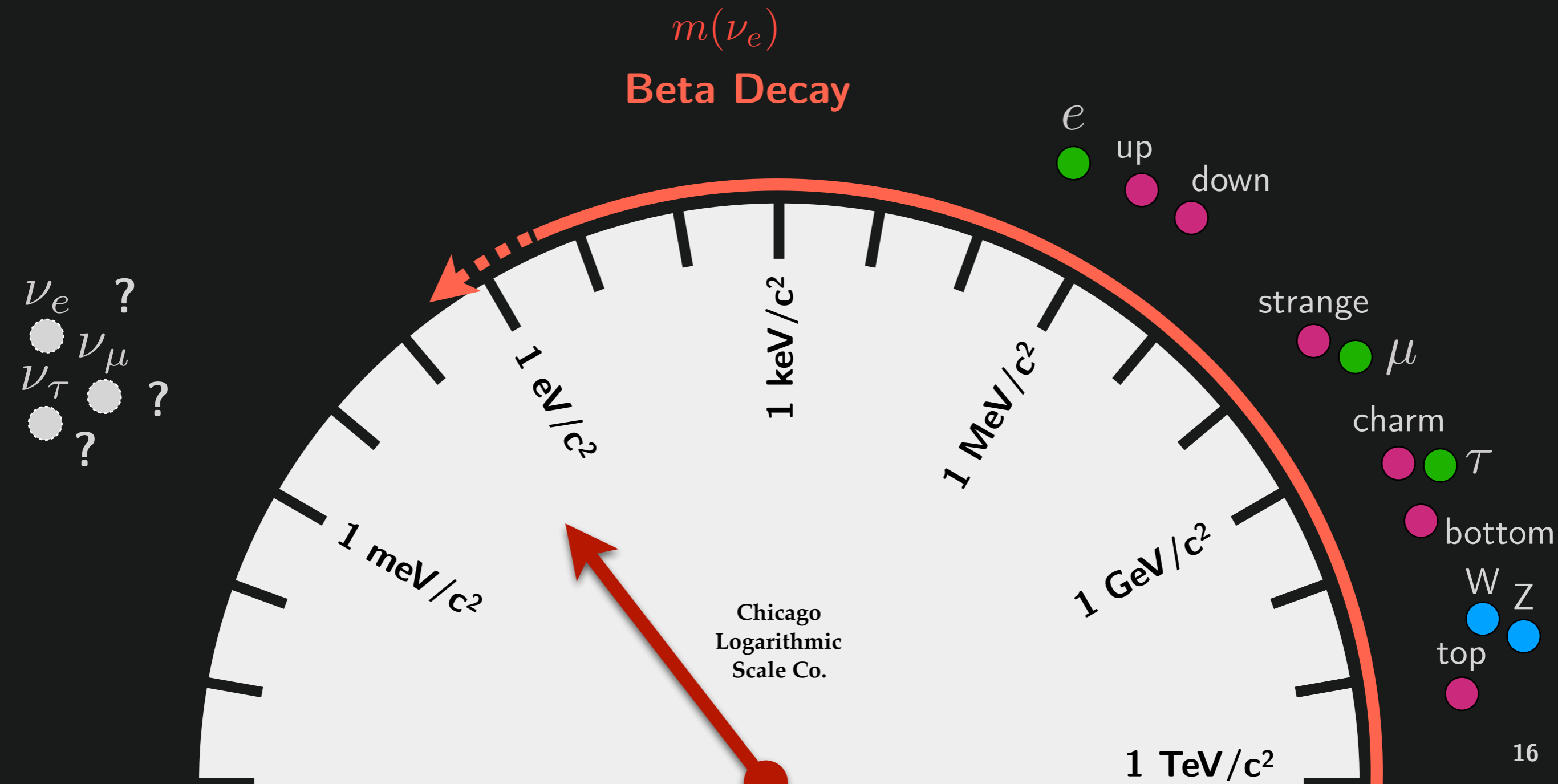
Neutrino Mass

The Experimental Scale



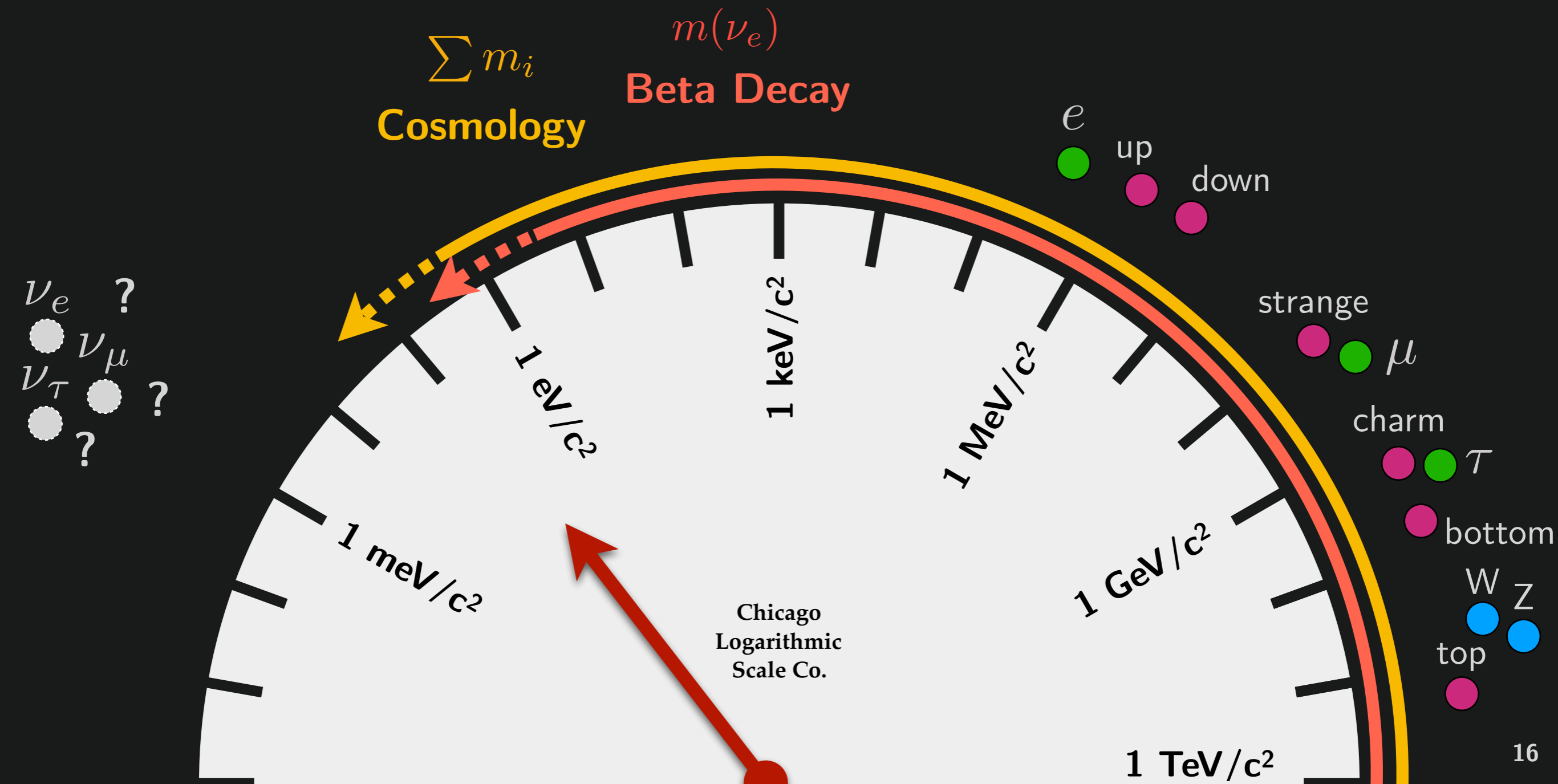
Neutrino Mass

The Experimental Scale



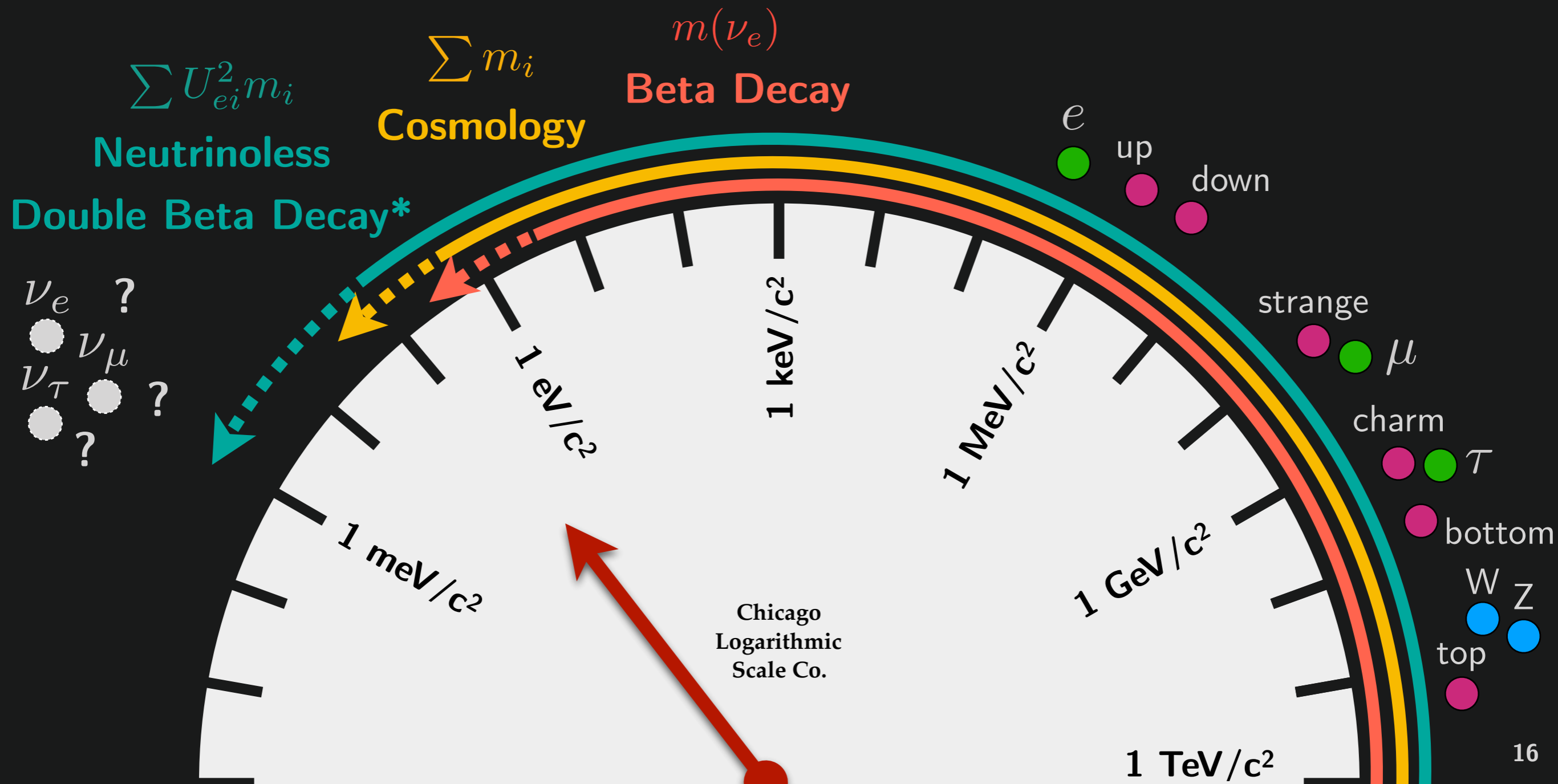
Neutrino Mass

The Experimental Scale



Neutrino Mass

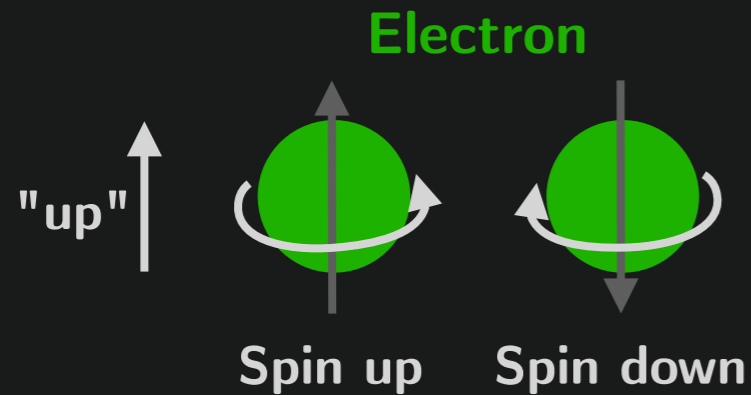
The Experimental Scale





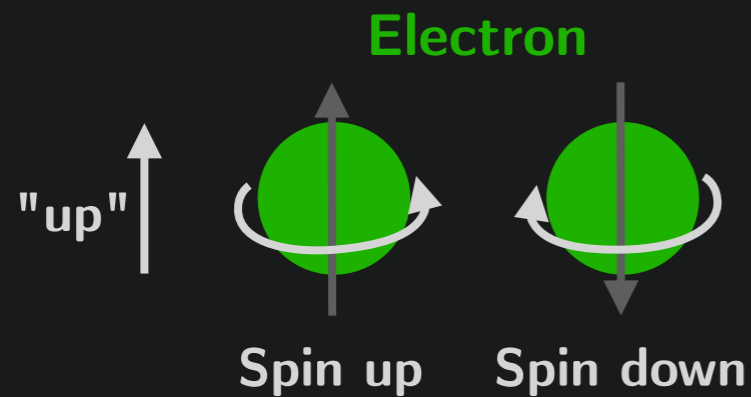
Neutrinoless Double Beta Decay

Spin & Helicity



Fundamental particles have a property called **spin**, which can be oriented "up" or "down"

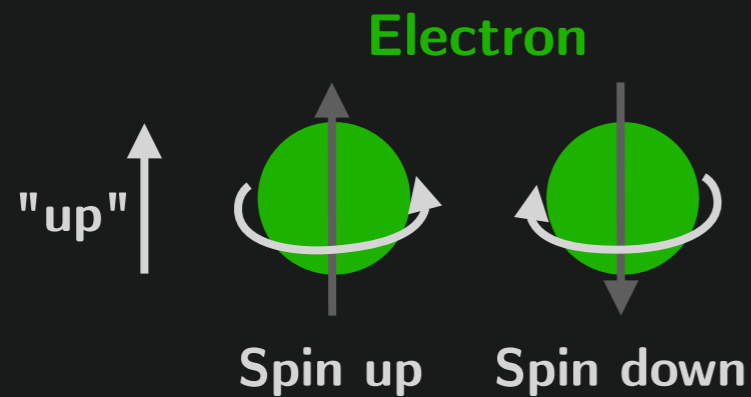
Spin & Helicity



Fundamental particles have a property called **spin**, which can be oriented "up" or "down"



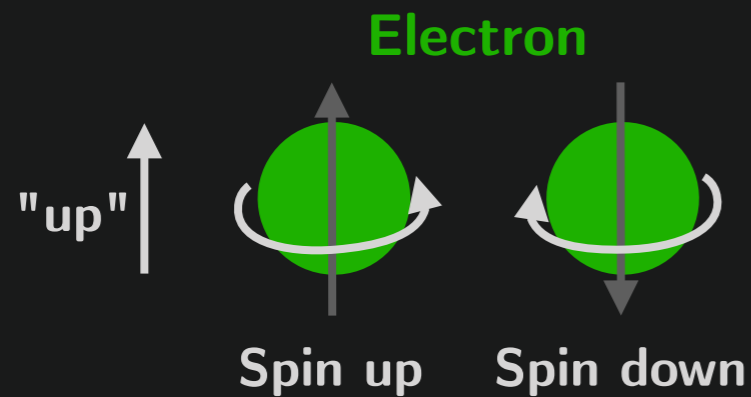
Spin & Helicity



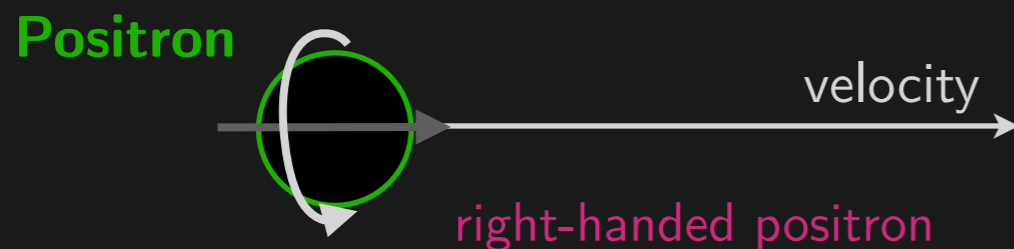
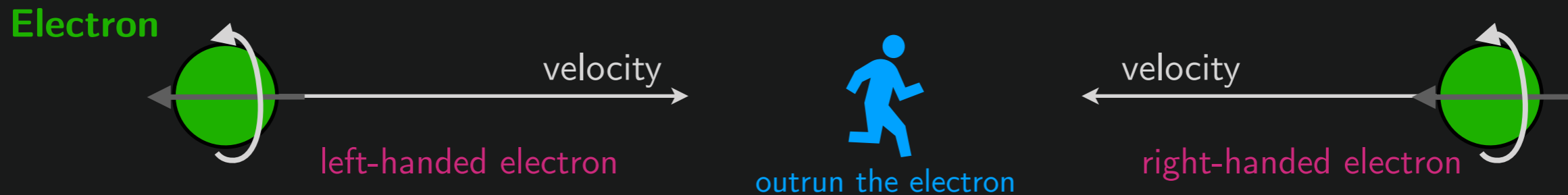
Fundamental particles have a property called **spin**, which can be oriented "up" or "down"



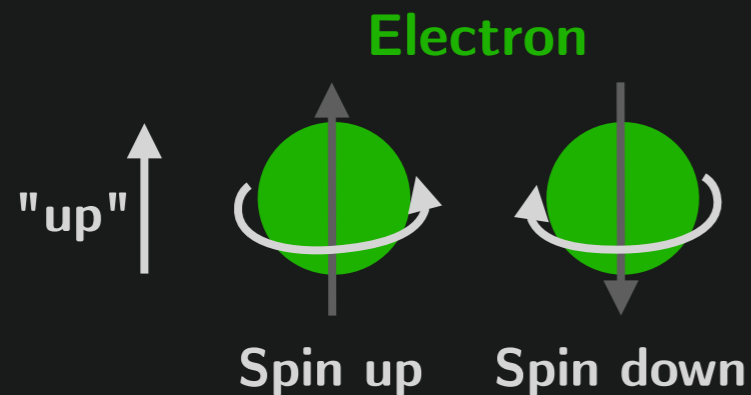
Spin & Helicity



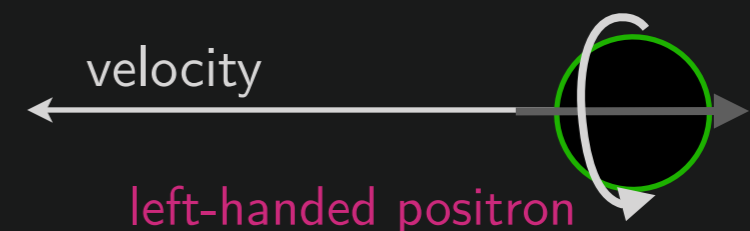
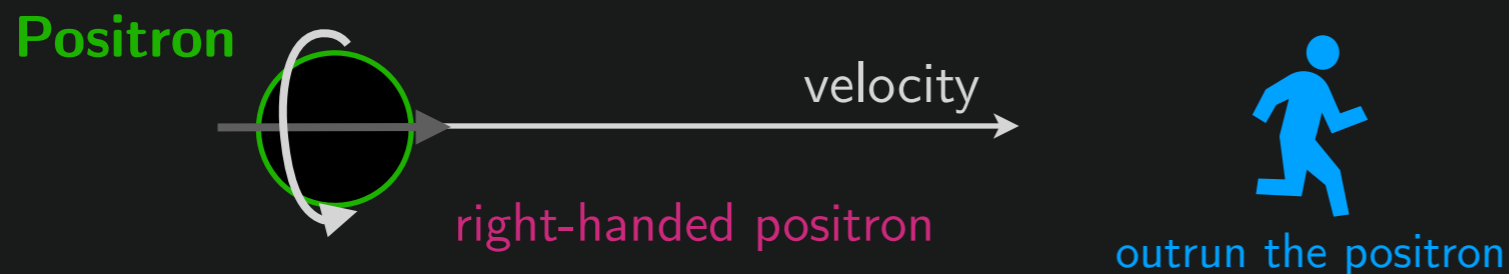
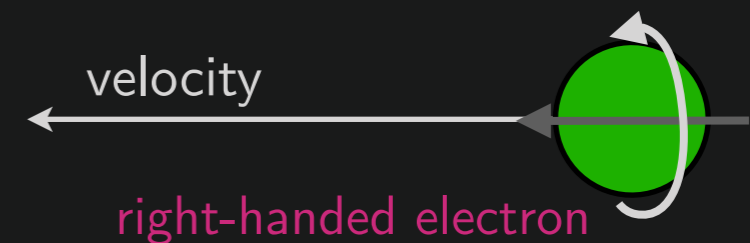
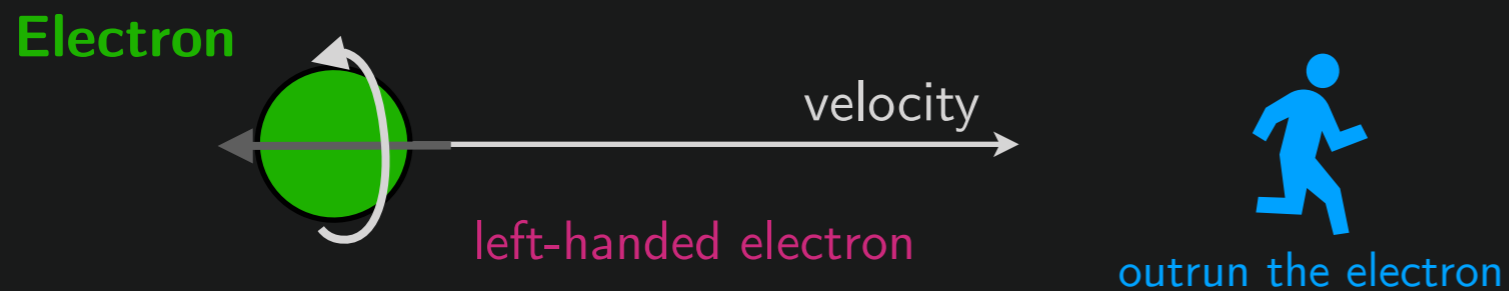
Fundamental particles have a property called **spin**, which can be oriented "up" or "down"



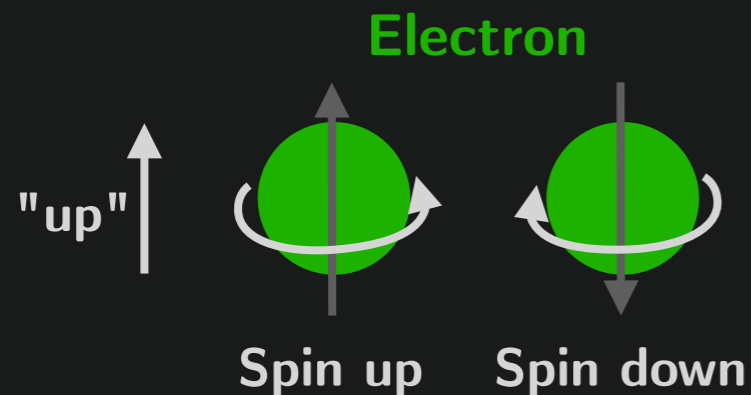
Spin & Helicity



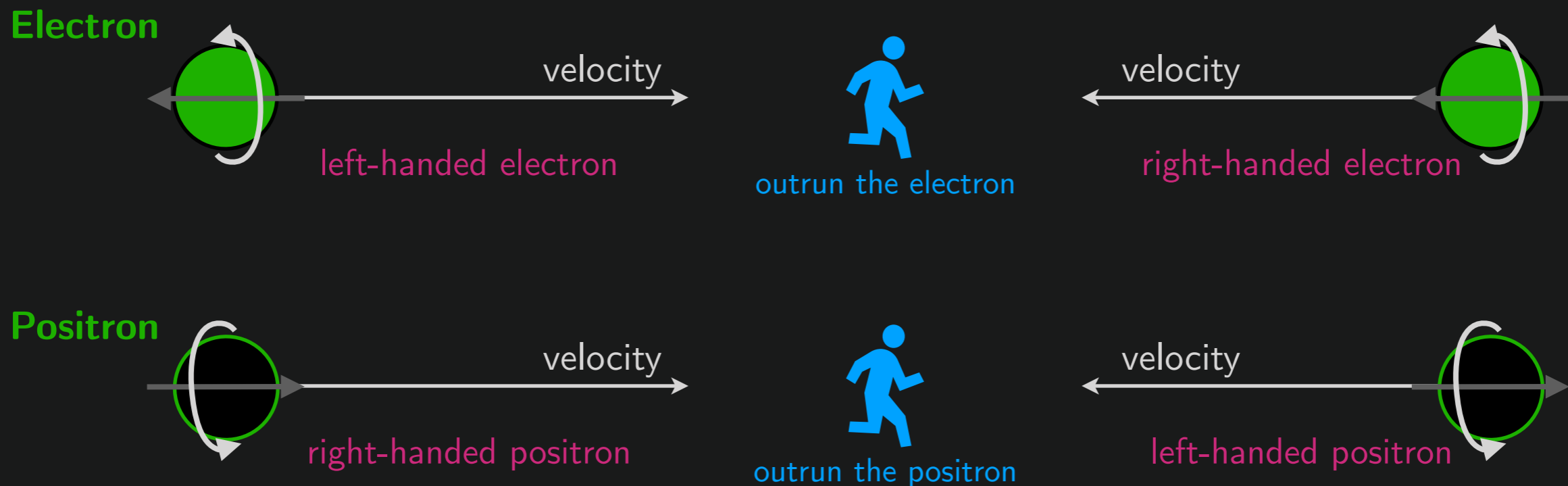
Fundamental particles have a property called **spin**, which can be oriented "up" or "down"



Spin & Helicity



Fundamental particles have a property called **spin**, which can be oriented "up" or "down"



The handedness is called **helicity**

Spin & Helicity

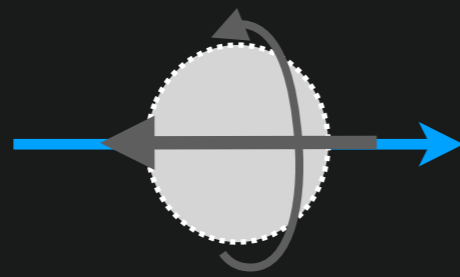
Spin & Helicity

For whatever reason, the weak interaction only talks to ν_L **left-handed** neutrinos and **right-handed** antineutrinos $\bar{\nu}_R$

Spin & Helicity

For whatever reason, the weak interaction only talks to

ν_L **left-handed** neutrinos and **right-handed** antineutrinos $\bar{\nu}_R$

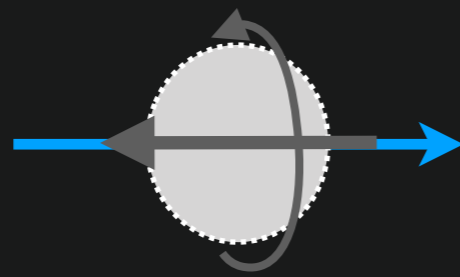


left-handed neutrino

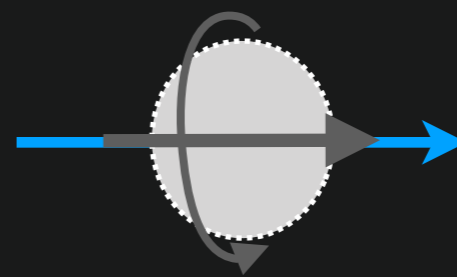
Spin & Helicity

For whatever reason, the weak interaction only talks to

ν_L **left-handed** neutrinos and **right-handed** antineutrinos $\bar{\nu}_R$



left-handed neutrino

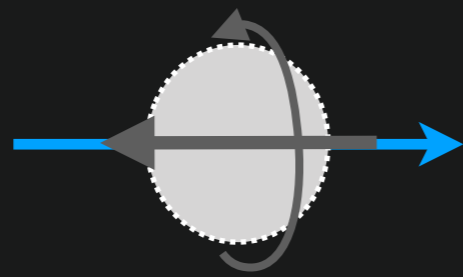


right-handed neutrino

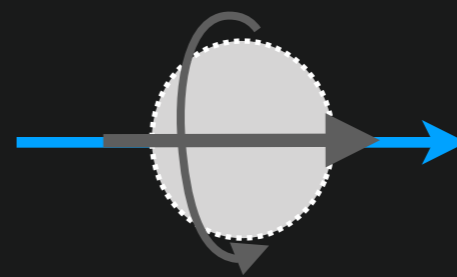
Spin & Helicity

For whatever reason, the weak interaction only talks to

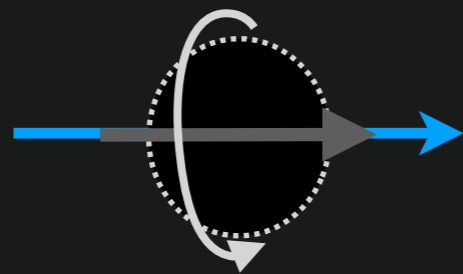
ν_L **left-handed** neutrinos and **right-handed** antineutrinos $\bar{\nu}_R$



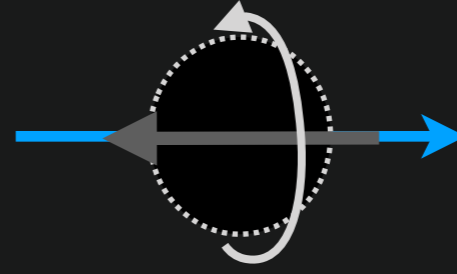
left-handed neutrino



right-handed neutrino



right-handed antineutrino

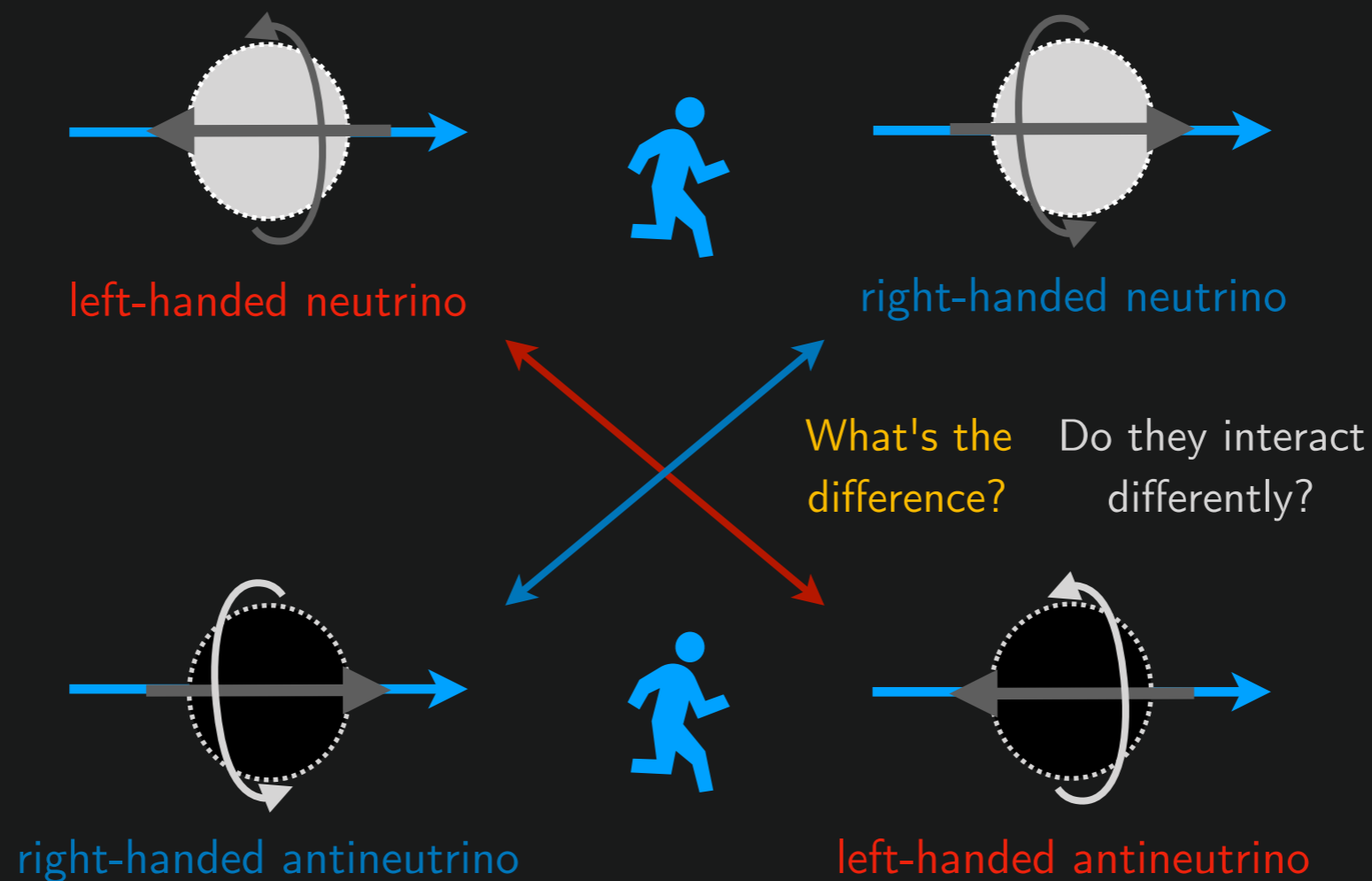


left-handed antineutrino

Spin & Helicity

For whatever reason, the weak interaction only talks to

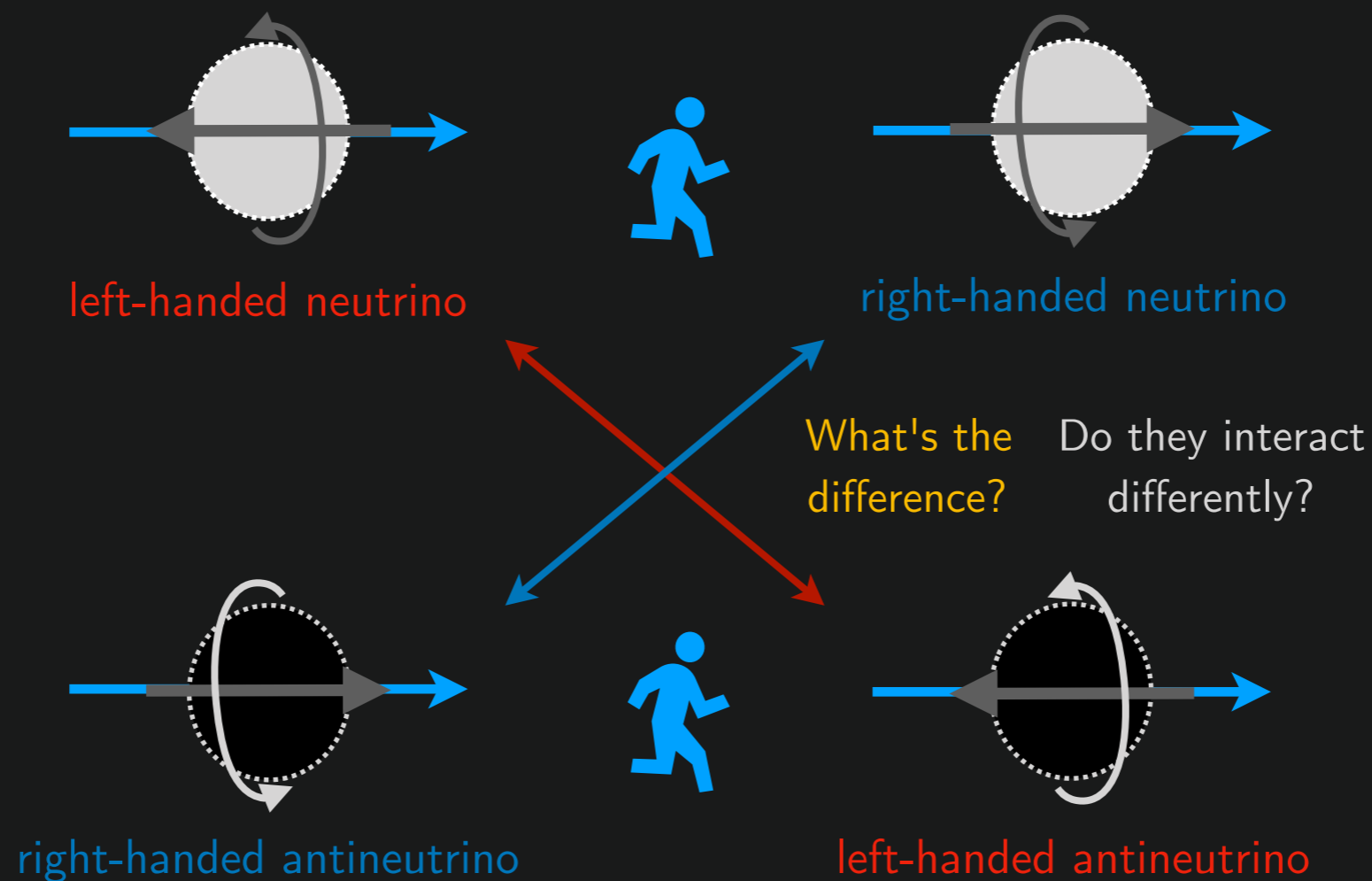
ν_L **left-handed** neutrinos and **right-handed** antineutrinos $\bar{\nu}_R$



Spin & Helicity

For whatever reason, the weak interaction only talks to

ν_L **left-handed** neutrinos and **right-handed** antineutrinos $\bar{\nu}_R$



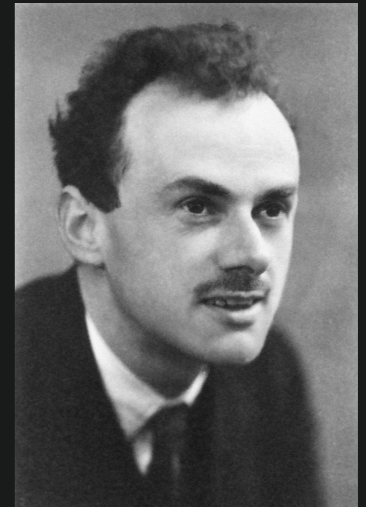
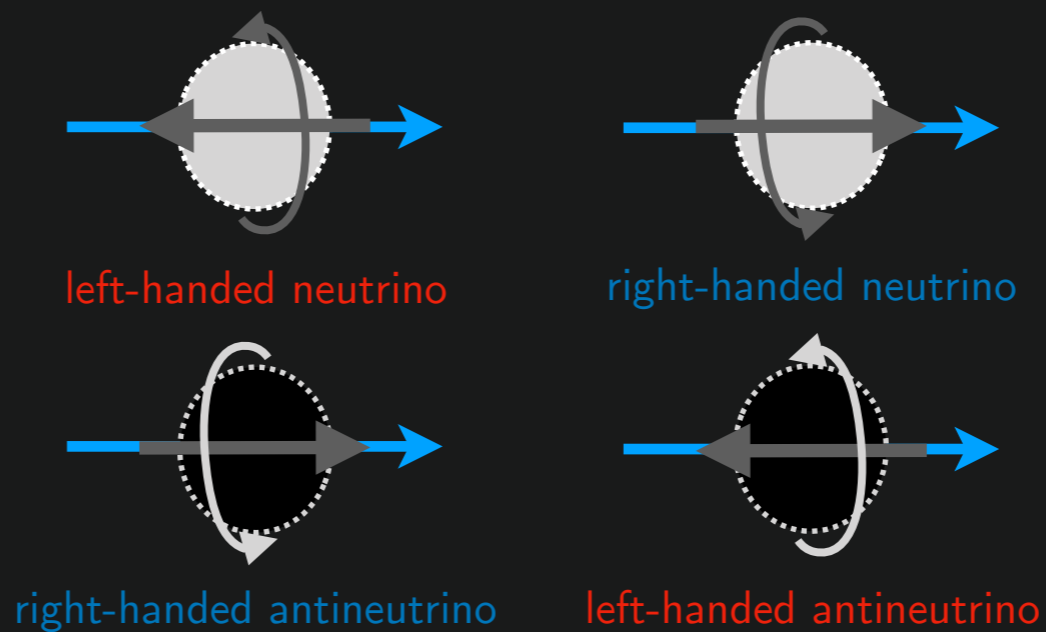
Is there really something different, **besides** the label?

Neutrino Masses

Neutrino Masses

A Dirac Fermion

Distinct particle and antiparticle, each with left and right handed states

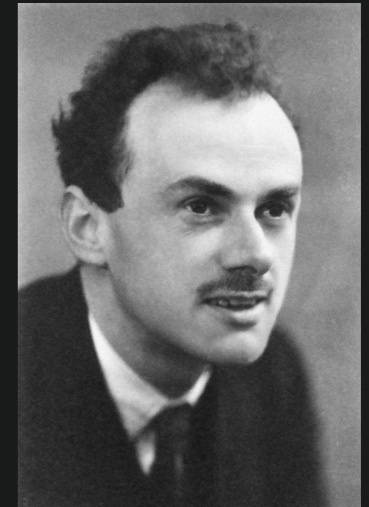
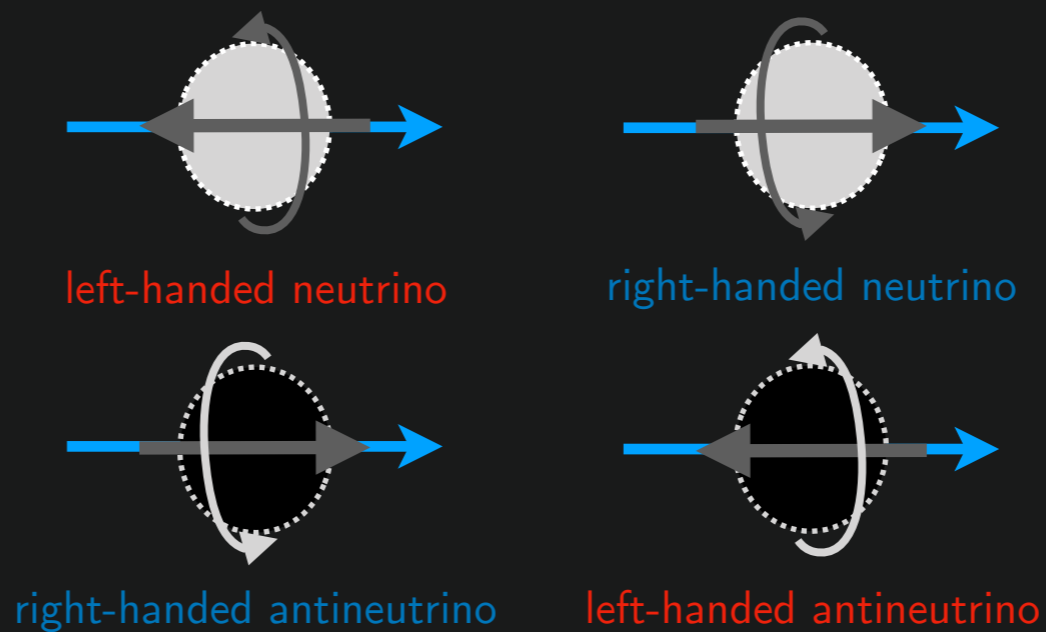


Paul Dirac

Neutrino Masses

A Dirac Fermion

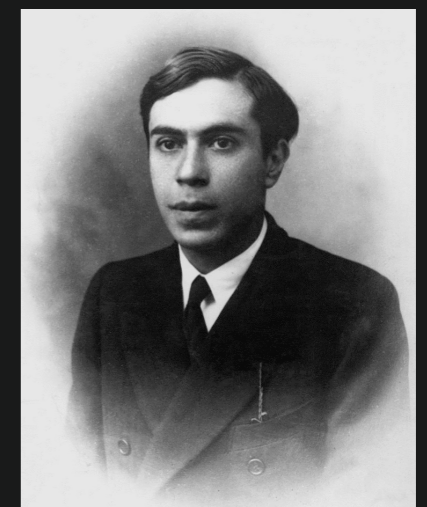
Distinct particle and antiparticle, each with left and right handed states



Paul Dirac

A Majorana Fermion

One particle with left and right handed states



Ettore Majorana

(Anti)Neutrinos?

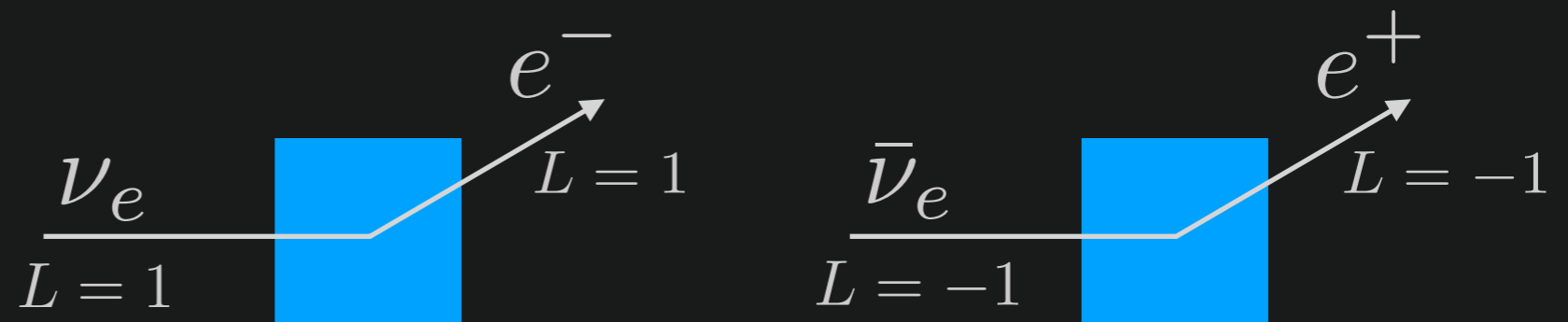
What's the difference between **neutrinos** and **antineutrinos**?

(Anti)Neutrinos?

What's the difference between **neutrinos** and **antineutrinos**?

A Dirac Fermion

Distinct particle and antiparticle, each with left and right handed states

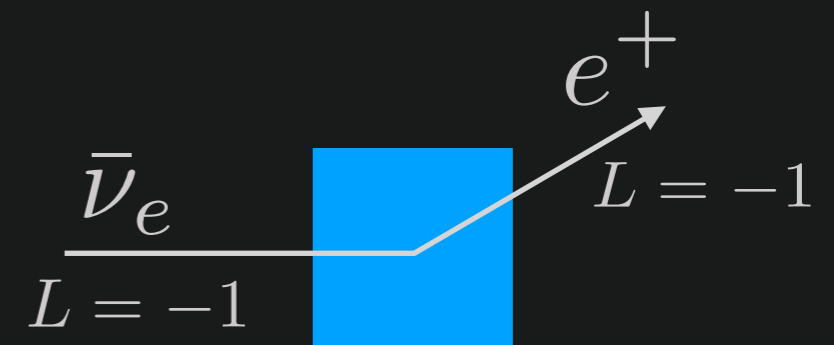
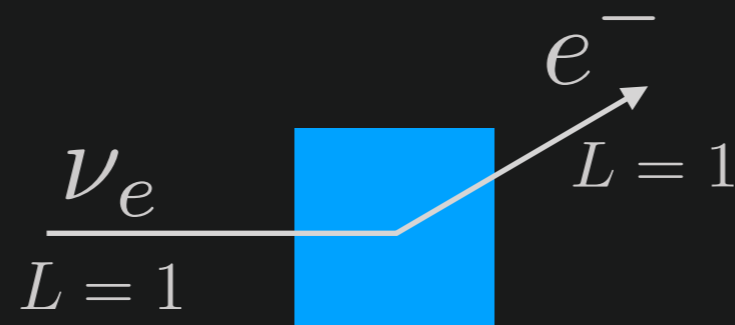


(Anti)Neutrinos?

What's the difference between **neutrinos** and **antineutrinos**?

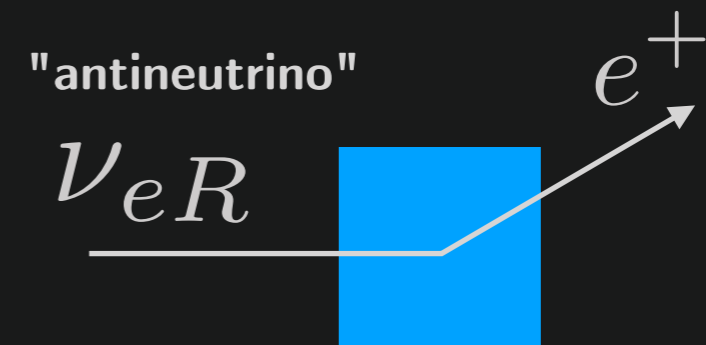
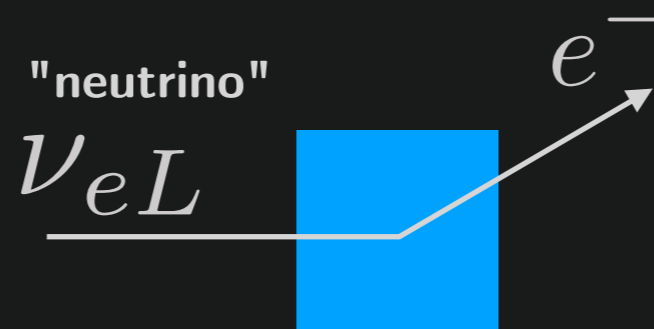
A Dirac Fermion

Distinct particle and antiparticle, each with left and right handed states



A Majorana Fermion

One particle with left and right handed states

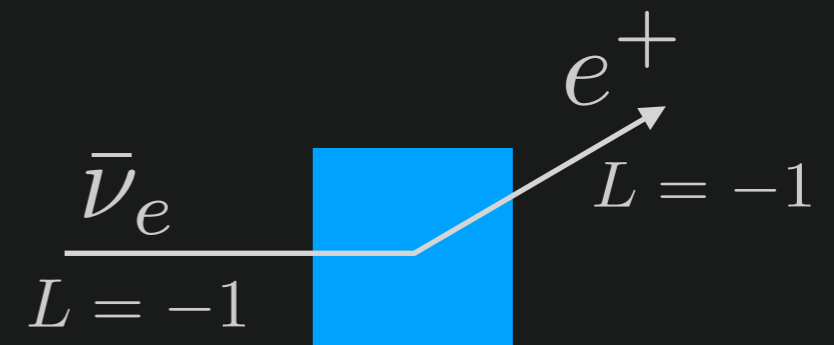
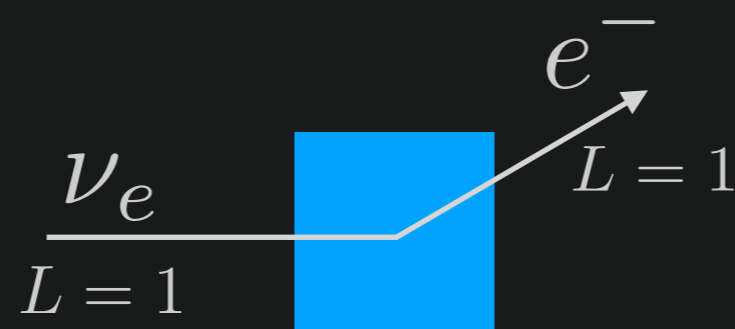


(Anti)Neutrinos?

What's the difference between **neutrinos** and **antineutrinos**?

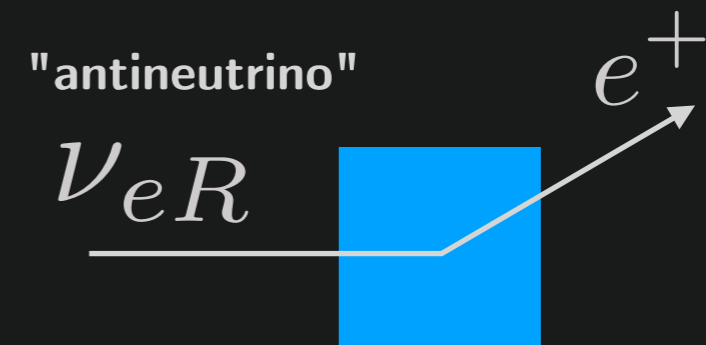
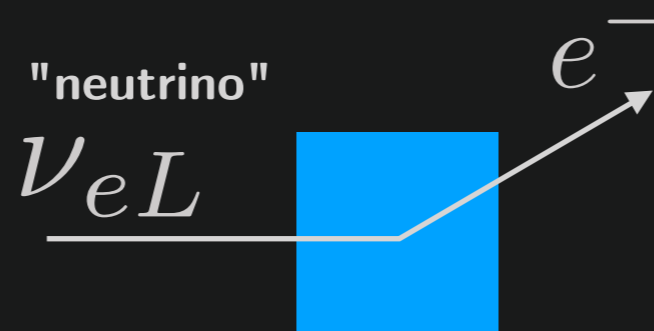
A Dirac Fermion

Distinct particle and antiparticle, each with left and right handed states



A Majorana Fermion

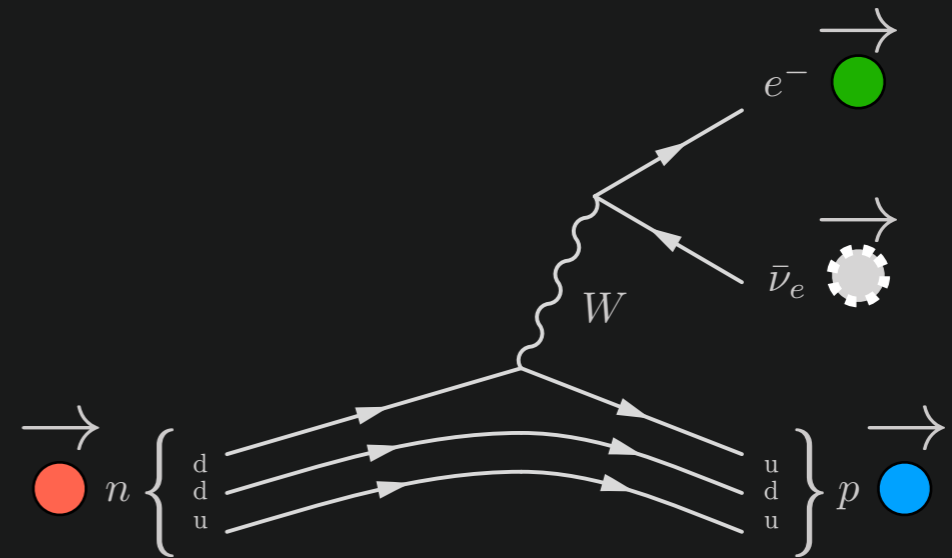
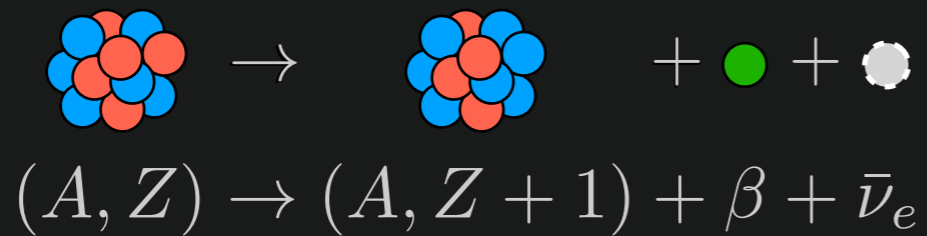
One particle with left and right handed states



Here, the neutrino is its own antiparticle, with **L** and **R** states

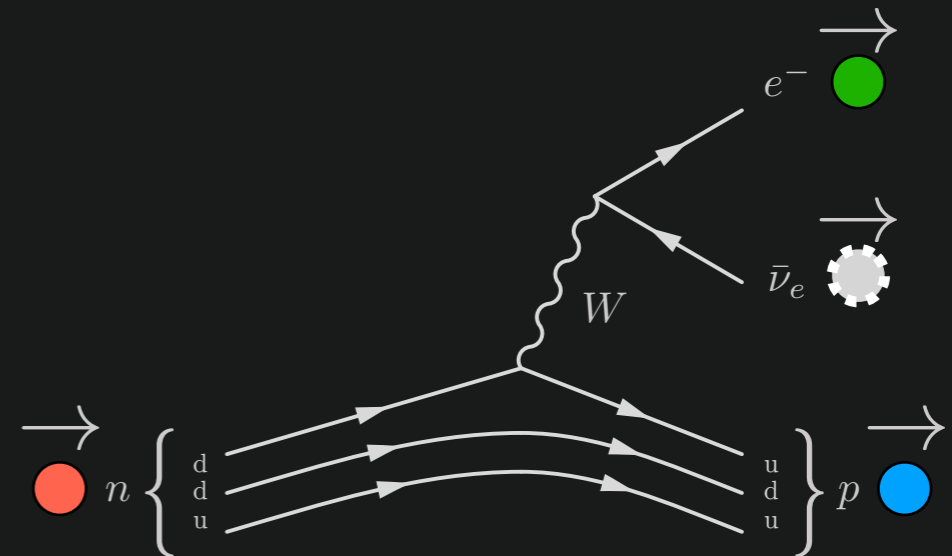
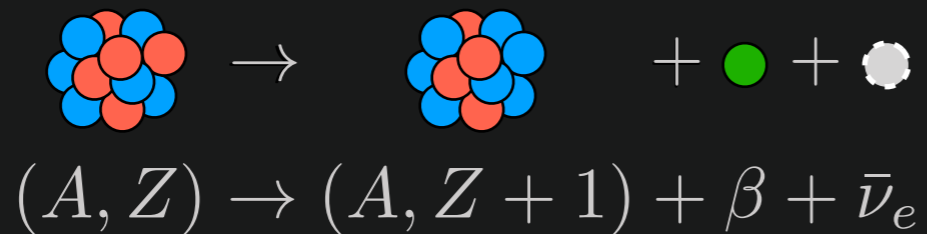
Neutrinoless Double-Beta Decay

Beta Decay



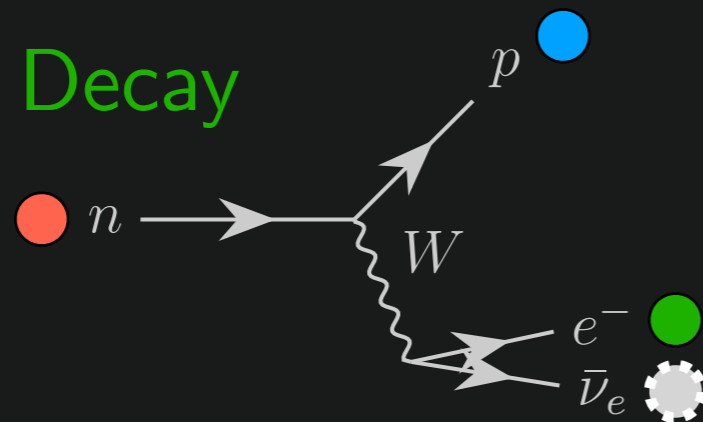
Neutrinoless Double-Beta Decay

Beta Decay

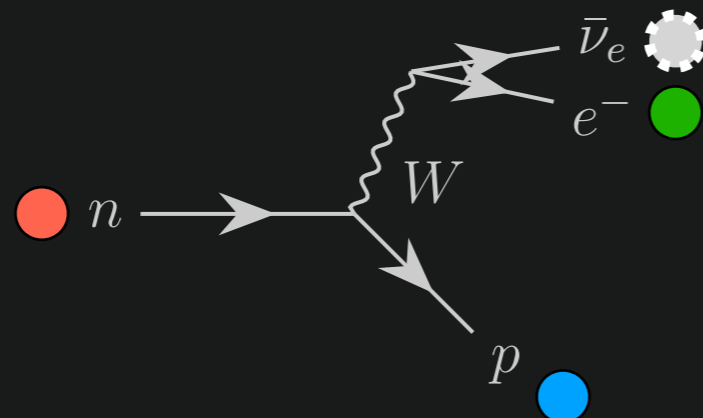


Double Beta Decay

Correlated,
simultaneous
beta decays

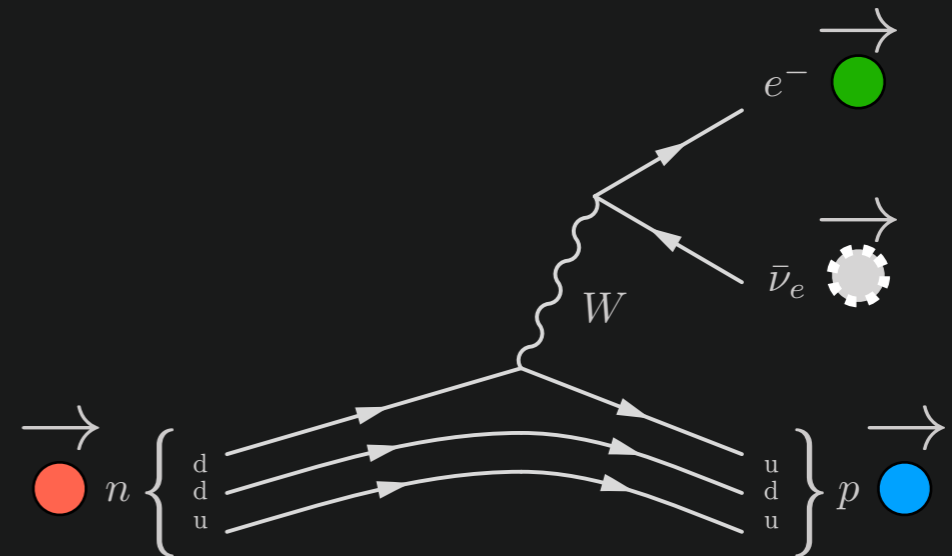
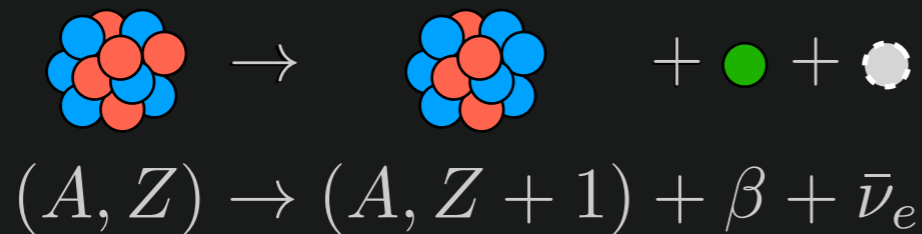


Normal Standard
Model Process



Neutrinoless Double-Beta Decay

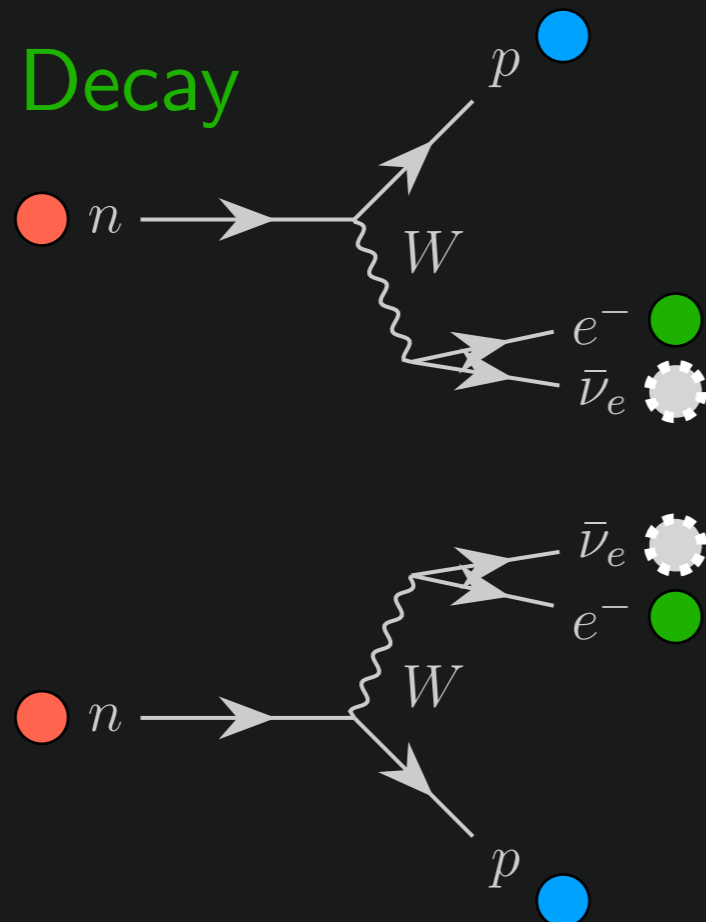
Beta Decay



Double Beta Decay

Correlated,
simultaneous
beta decays

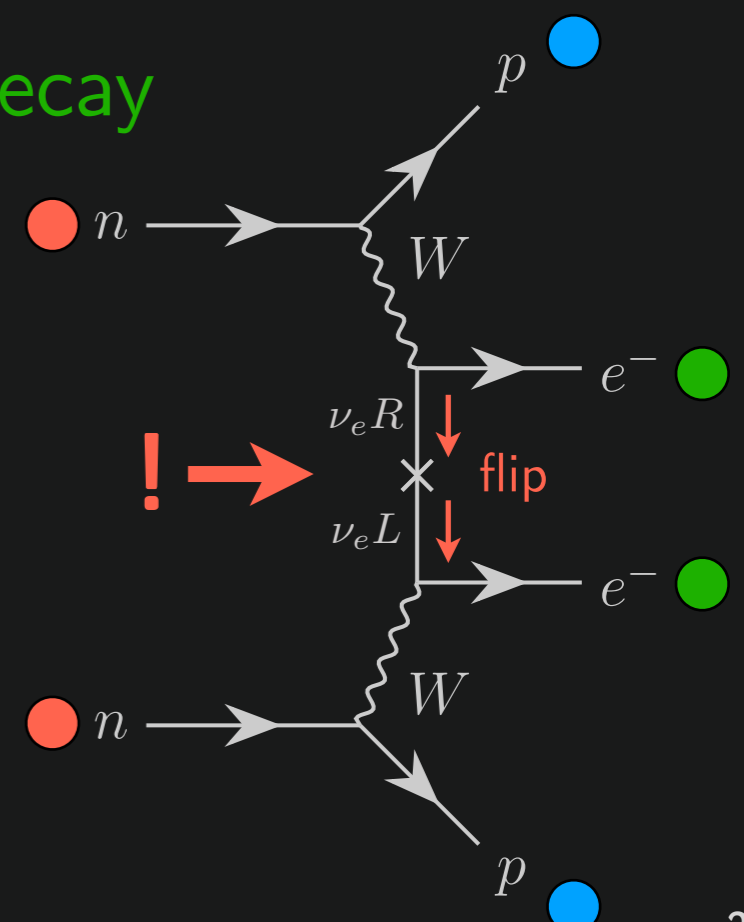
Normal Standard
Model Process



Neutrinoless Double Beta Decay

"Antineutrino"
is internally
absorbed as a
"neutrino"

Only if neutrino is
its own antiparticle



Big Implications

$$\nu = \bar{\nu}$$

Neutrinos are their own antiparticles

"Neutrinos" are the left-handed form,
"antineutrinos" are the right-handed form

$$\Delta L \neq 0$$

Conservation of Lepton Number is violated

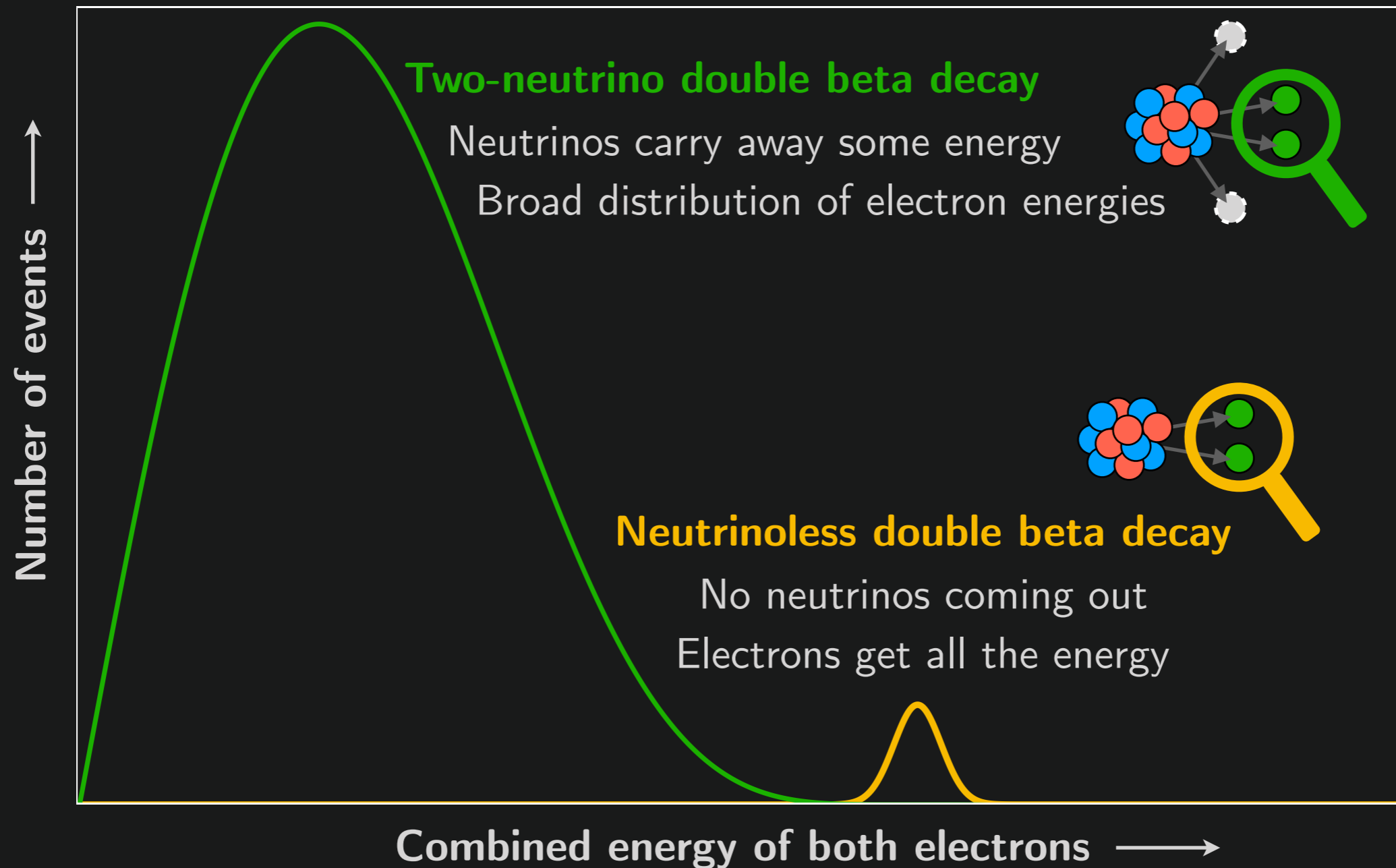
Neutrinoless double beta decay creates leptons without any antileptons, breaking the balance. Ingredient for matter/antimatter asymmetry.

$$\mathcal{L}_5$$

Physics Beyond the Standard Model

Evidence that the Standard Model is just a glimpse of a more complete theory.

Experimental Searches

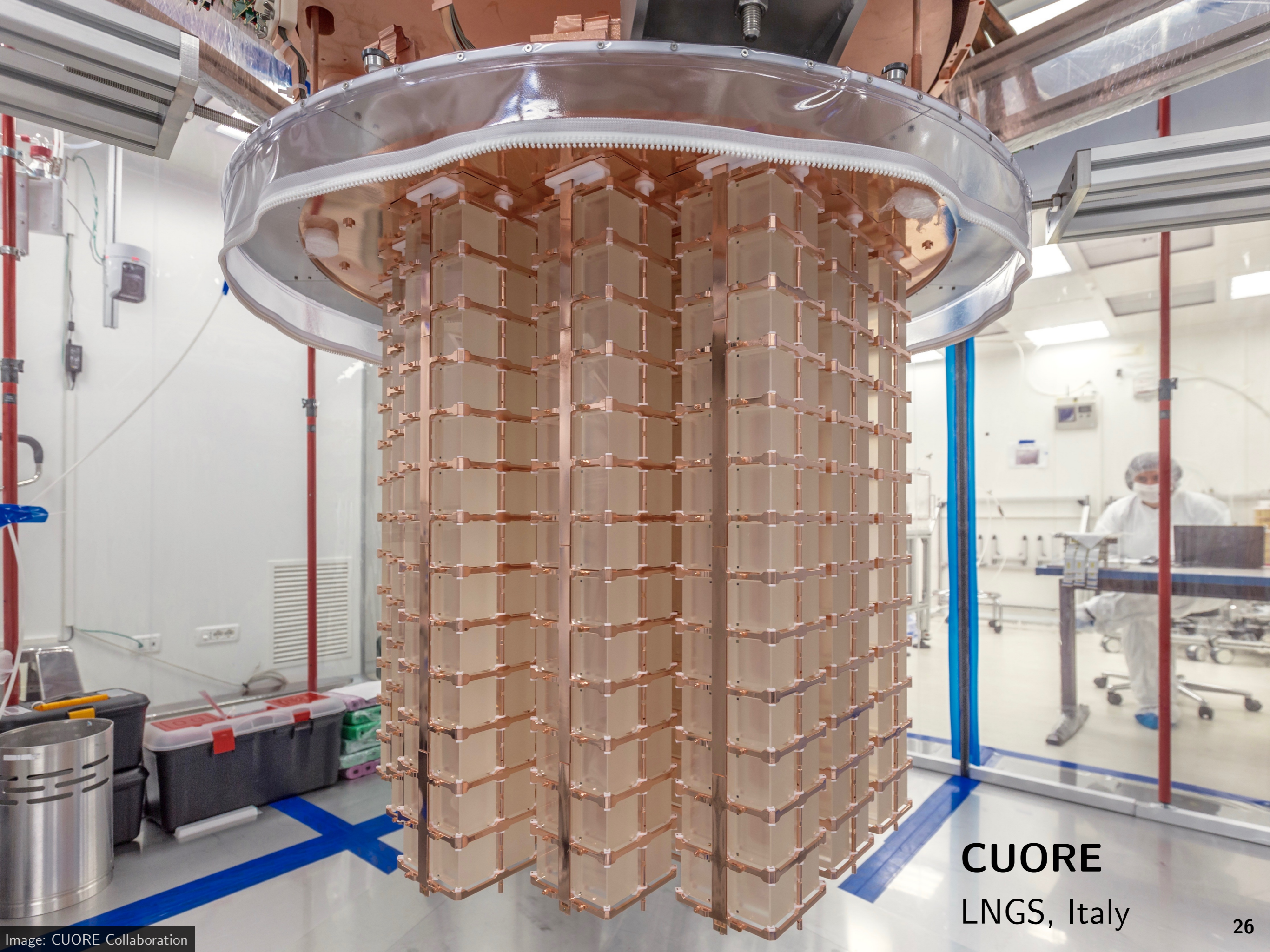


The **neutrinoless** version would be extremely rare,
so you need a whole lot of nuclei to see it



MAJORANA Demonstrator

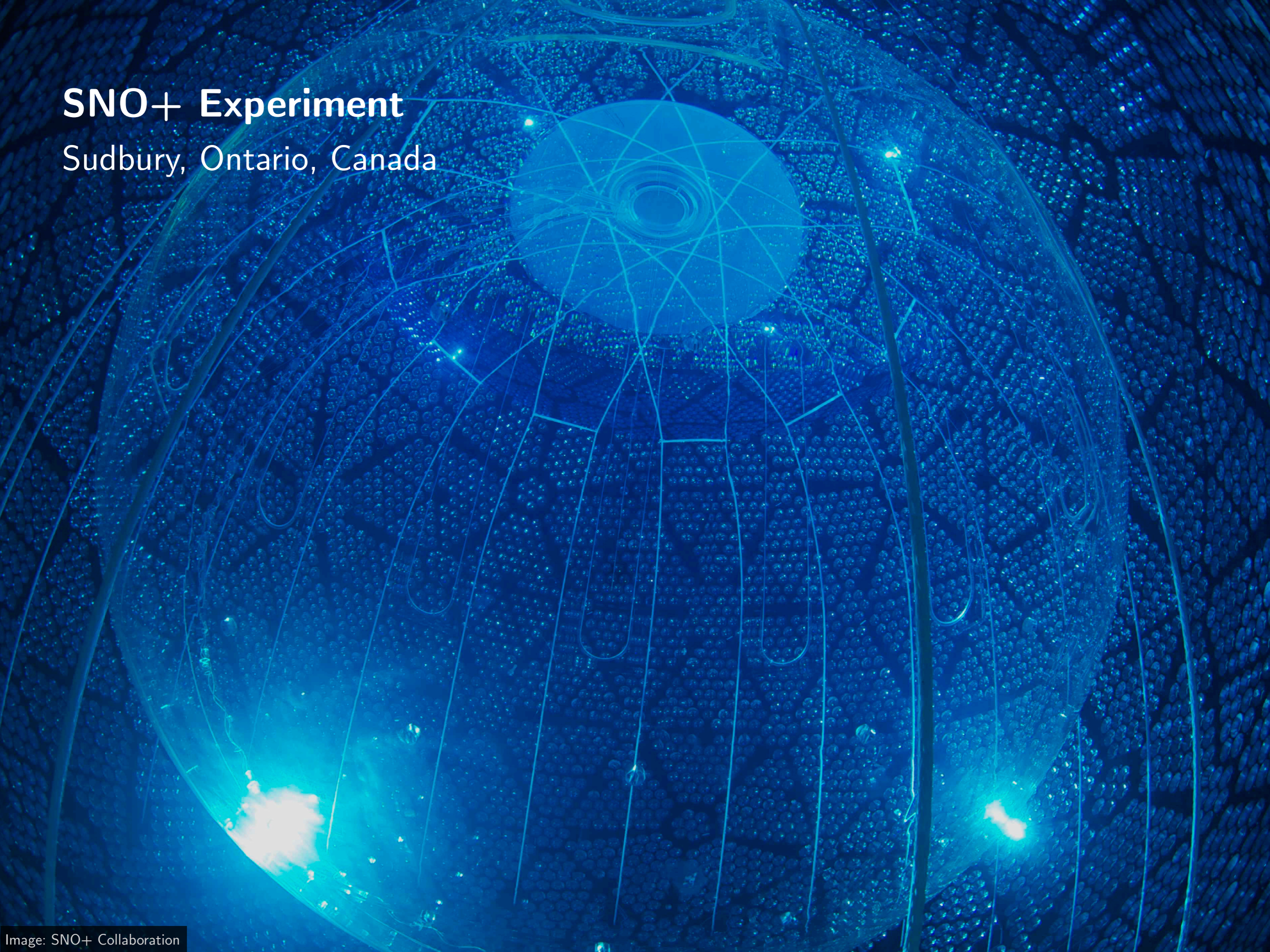
SURF, South Dakota, USA



CUORE
LNGS, Italy

SNO+ Experiment

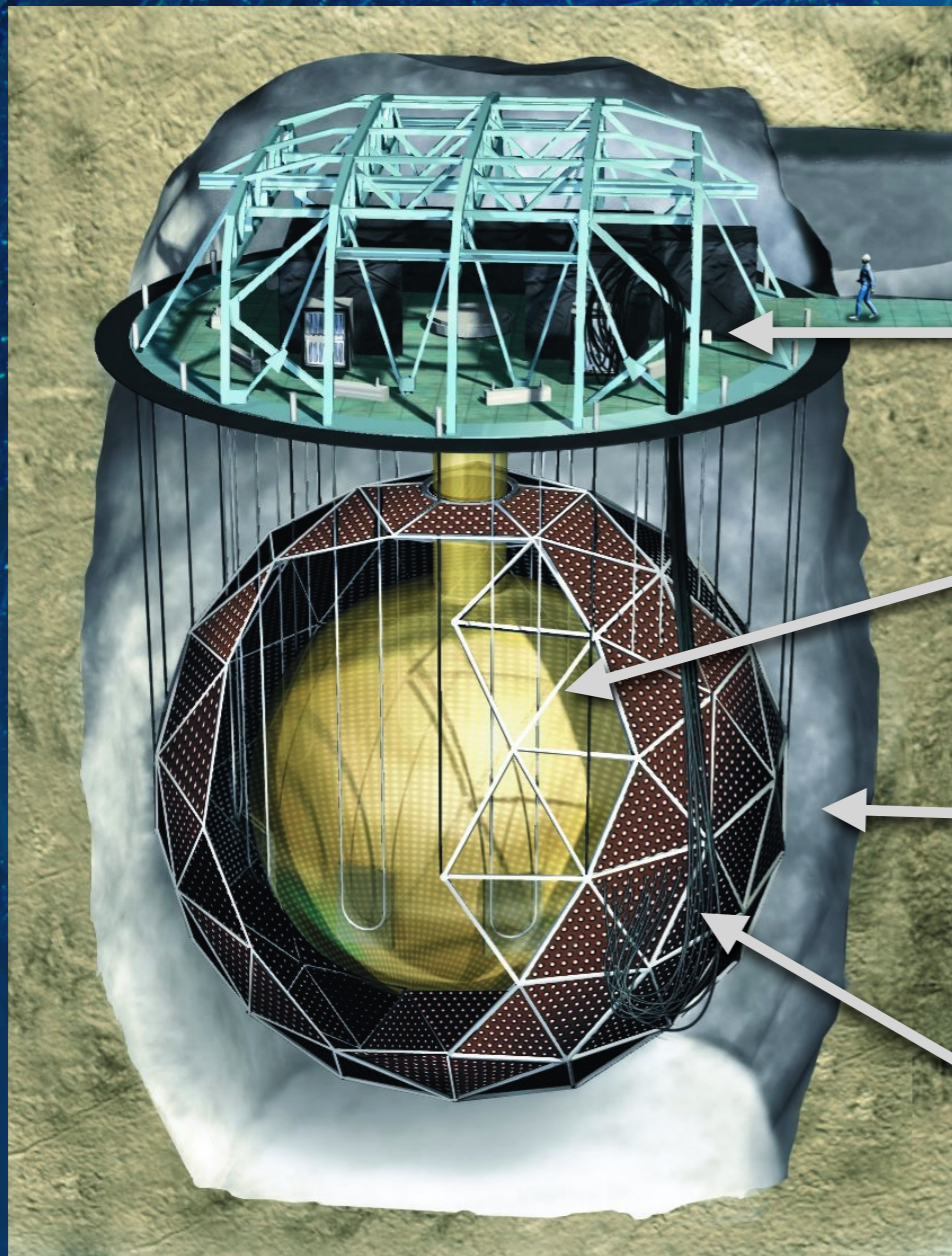
Sudbury, Ontario, Canada





The SNO+ Experiment

SNO+



↓ 6800 feet underground!

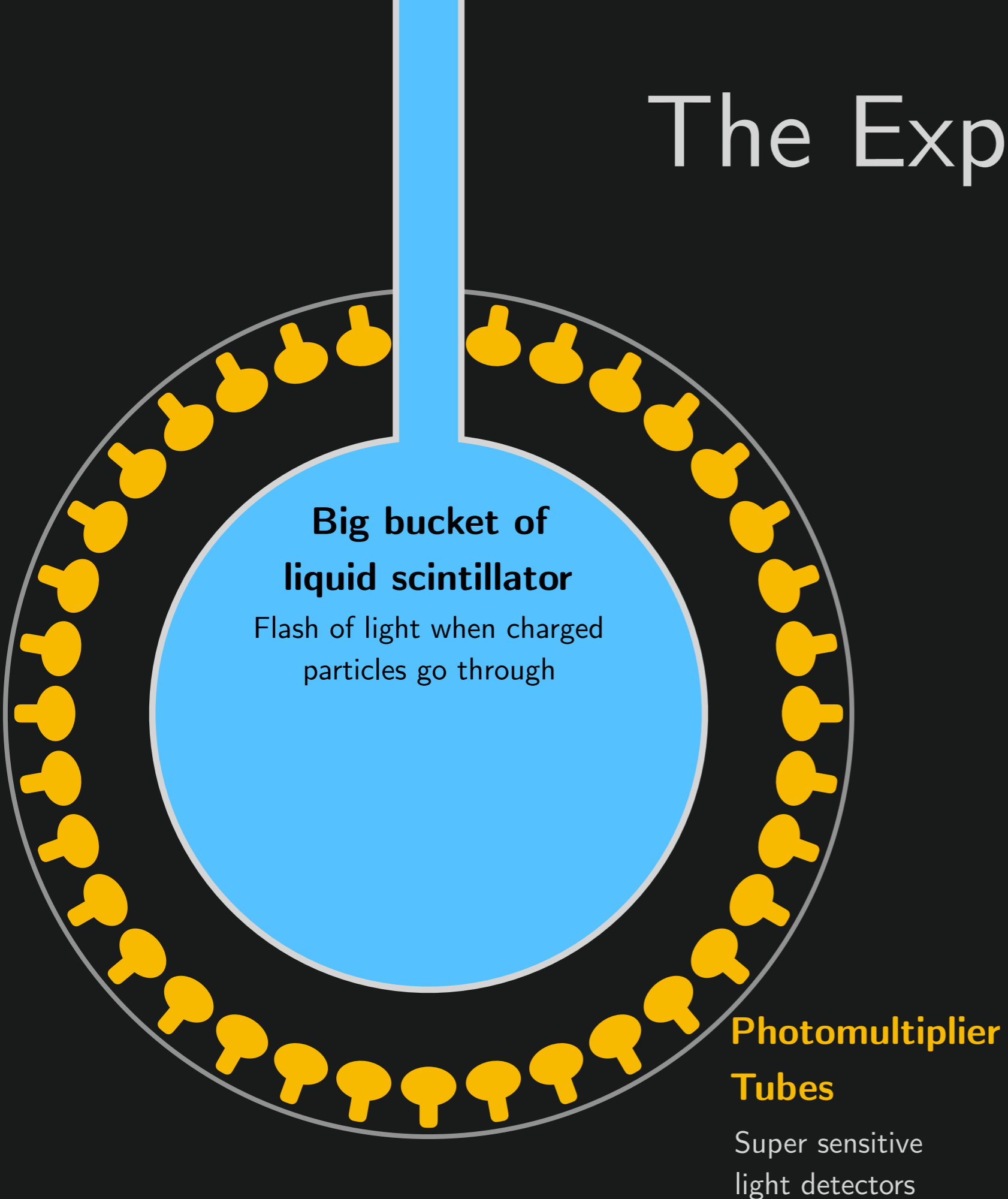
← Electronics & Instrumentation

← 780 tonnes scintillator (LAB)
inside a 12 meter diameter acrylic sphere

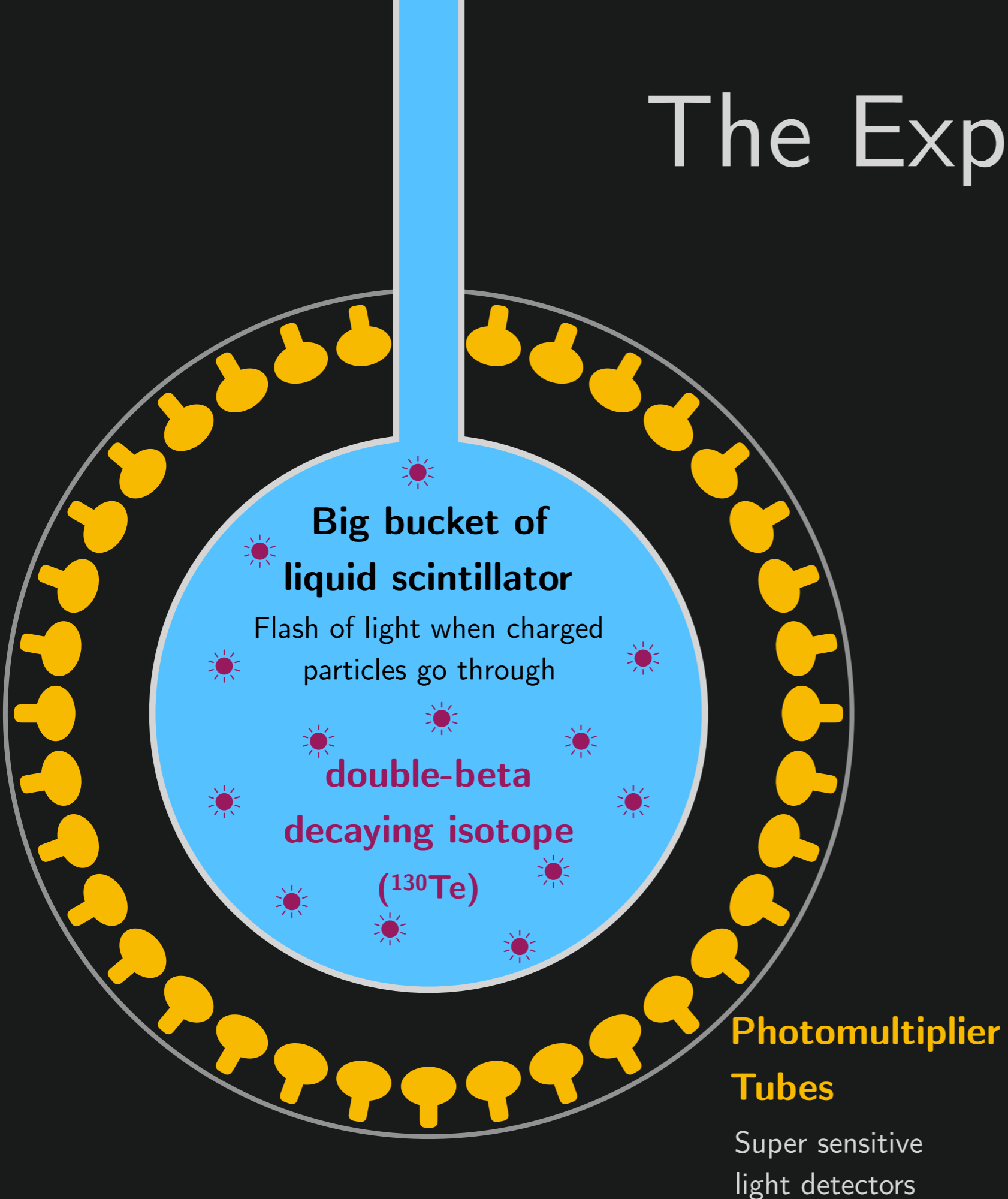
← 7,000 tonnes water (shielding)

← 10,000 Photomultiplier Tubes

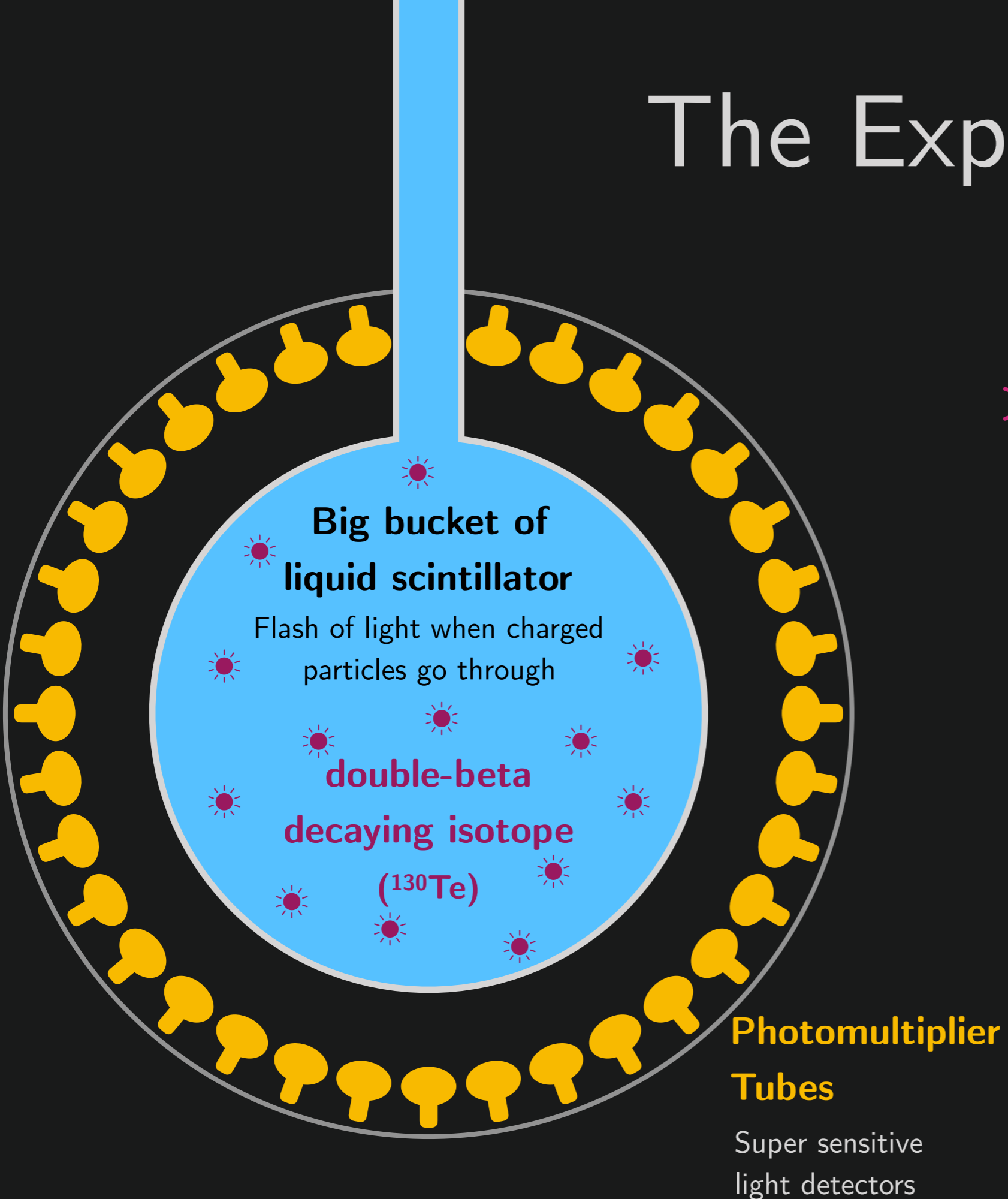
The Experiment



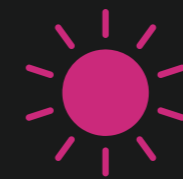
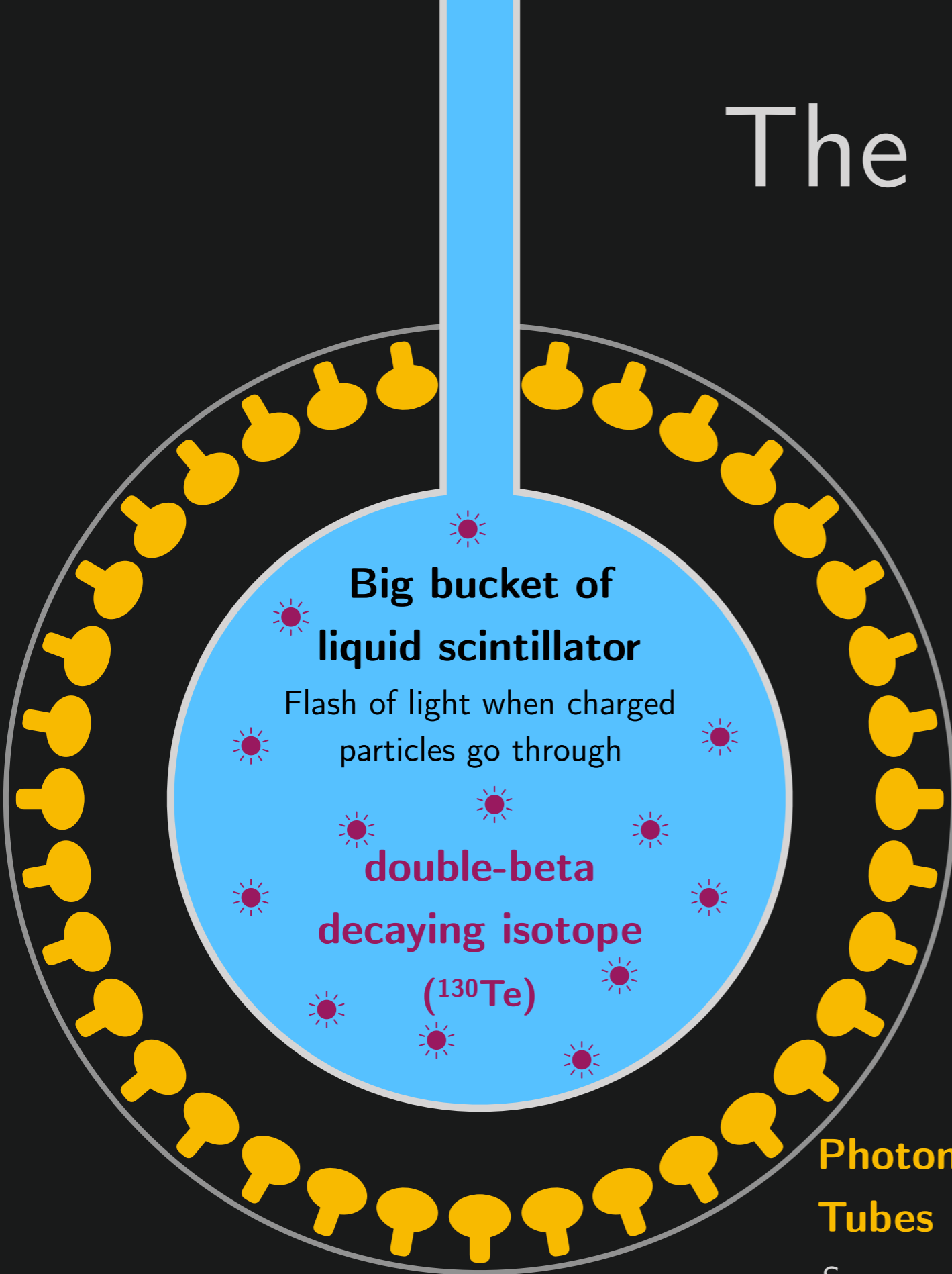
The Experiment



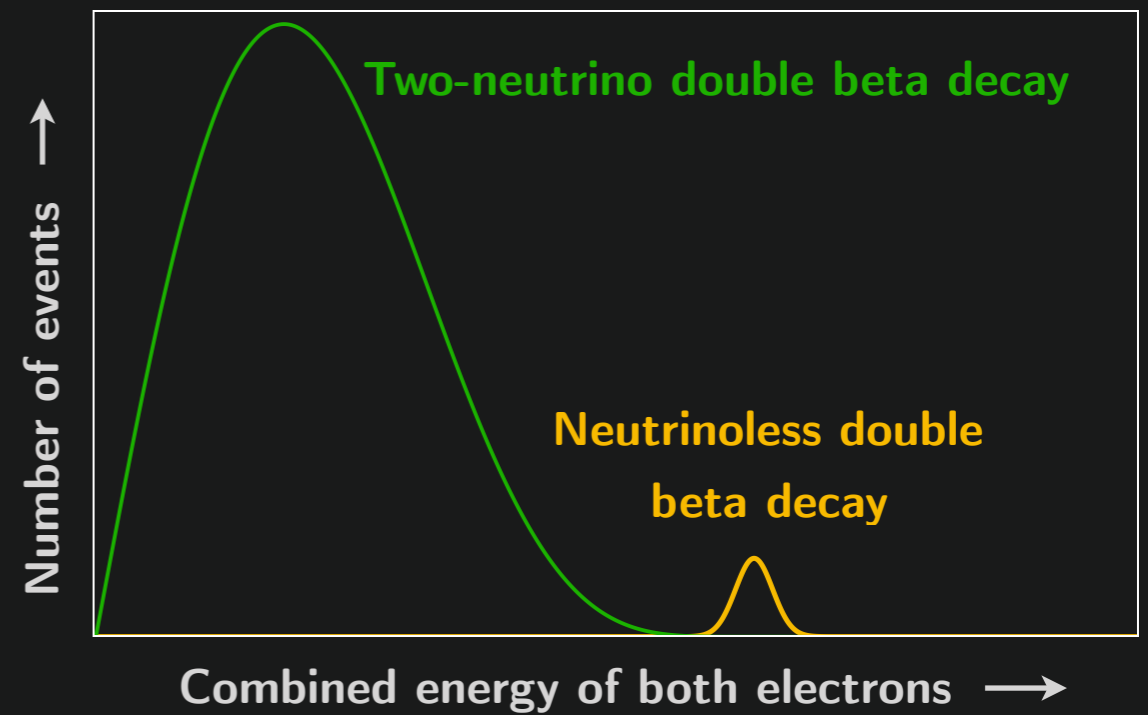
The Experiment



The Experiment



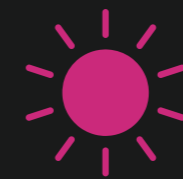
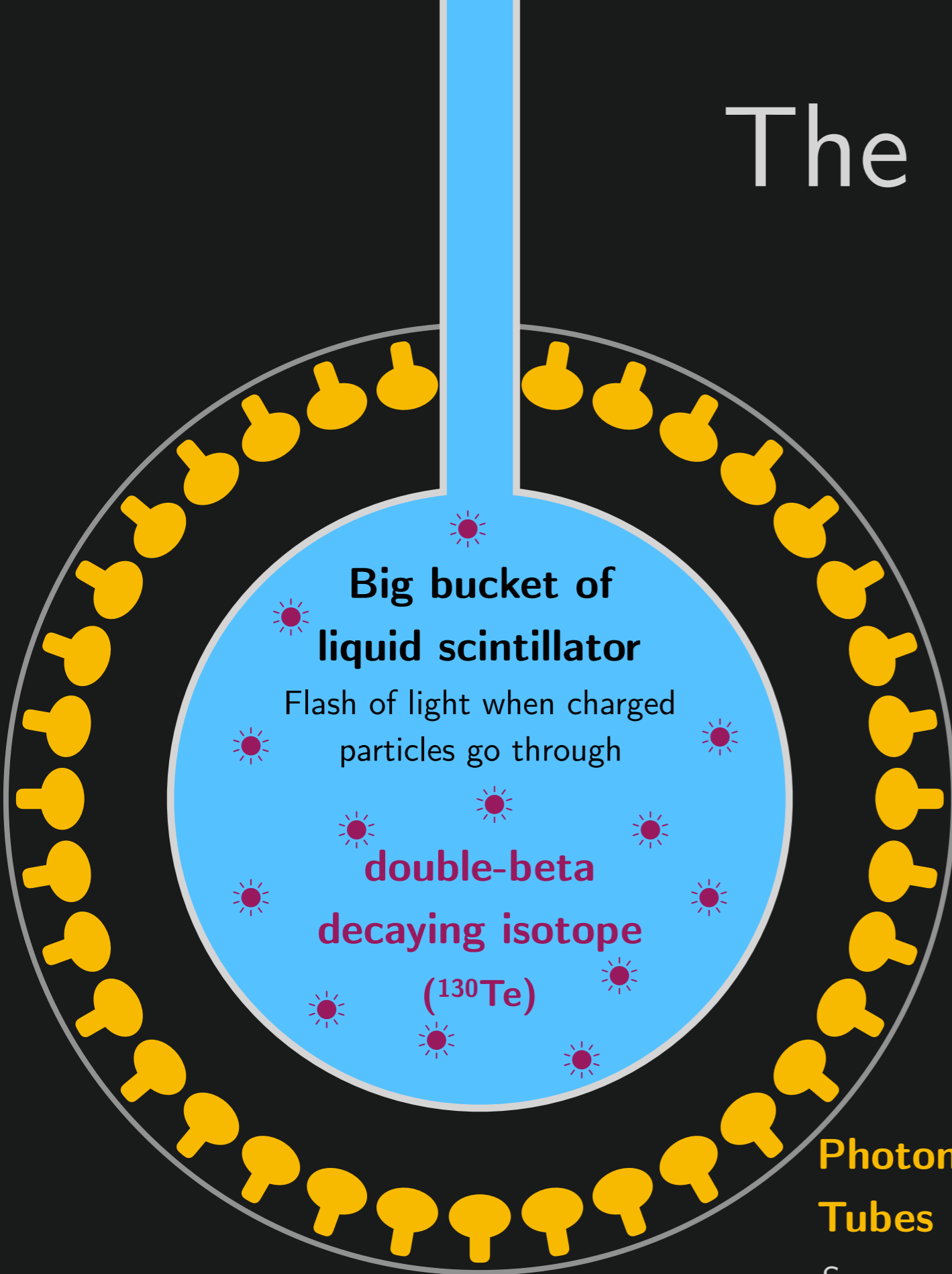
brightness = energy



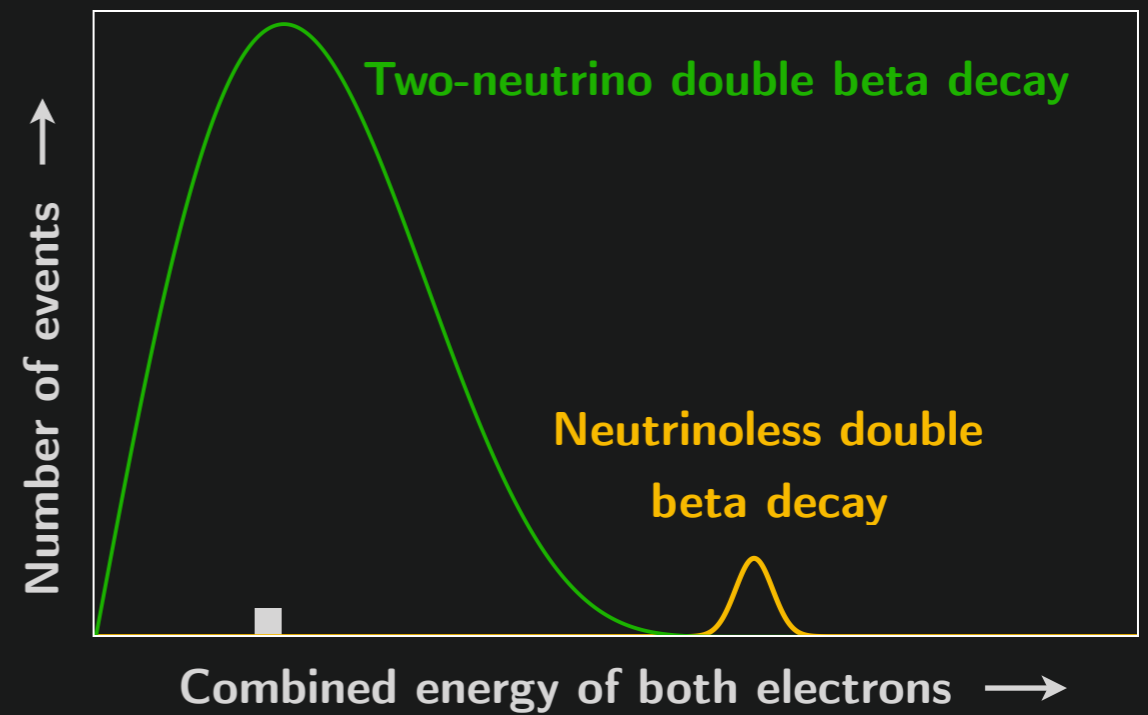
**Photomultiplier
Tubes**

Super sensitive
light detectors

The Experiment



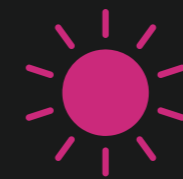
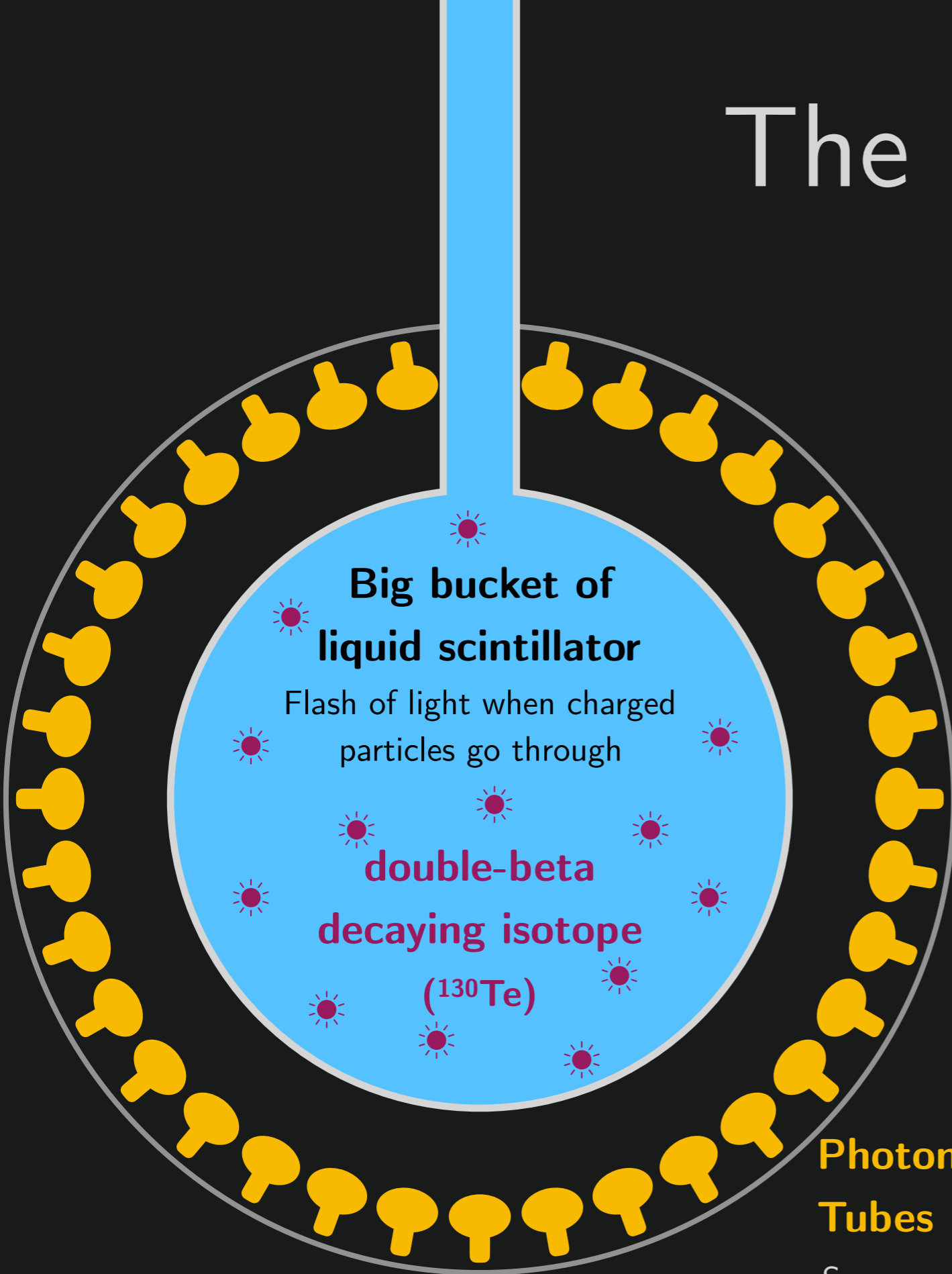
brightness = energy



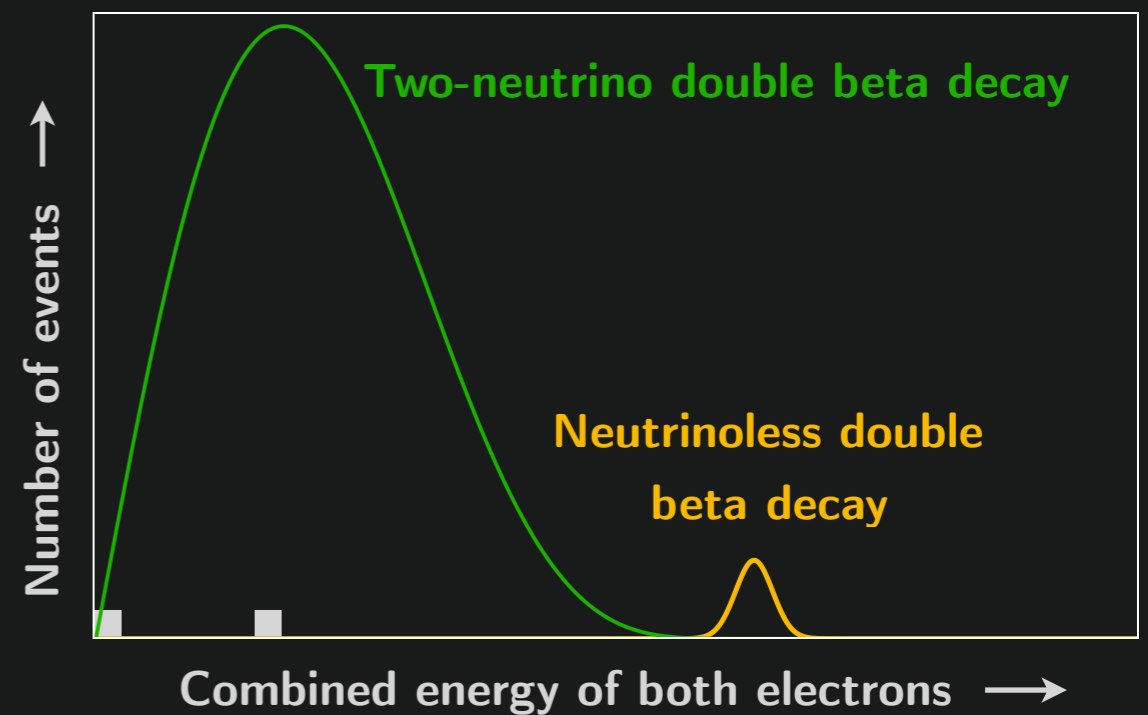
**Photomultiplier
Tubes**

Super sensitive
light detectors

The Experiment



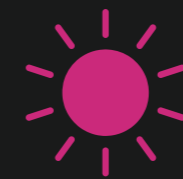
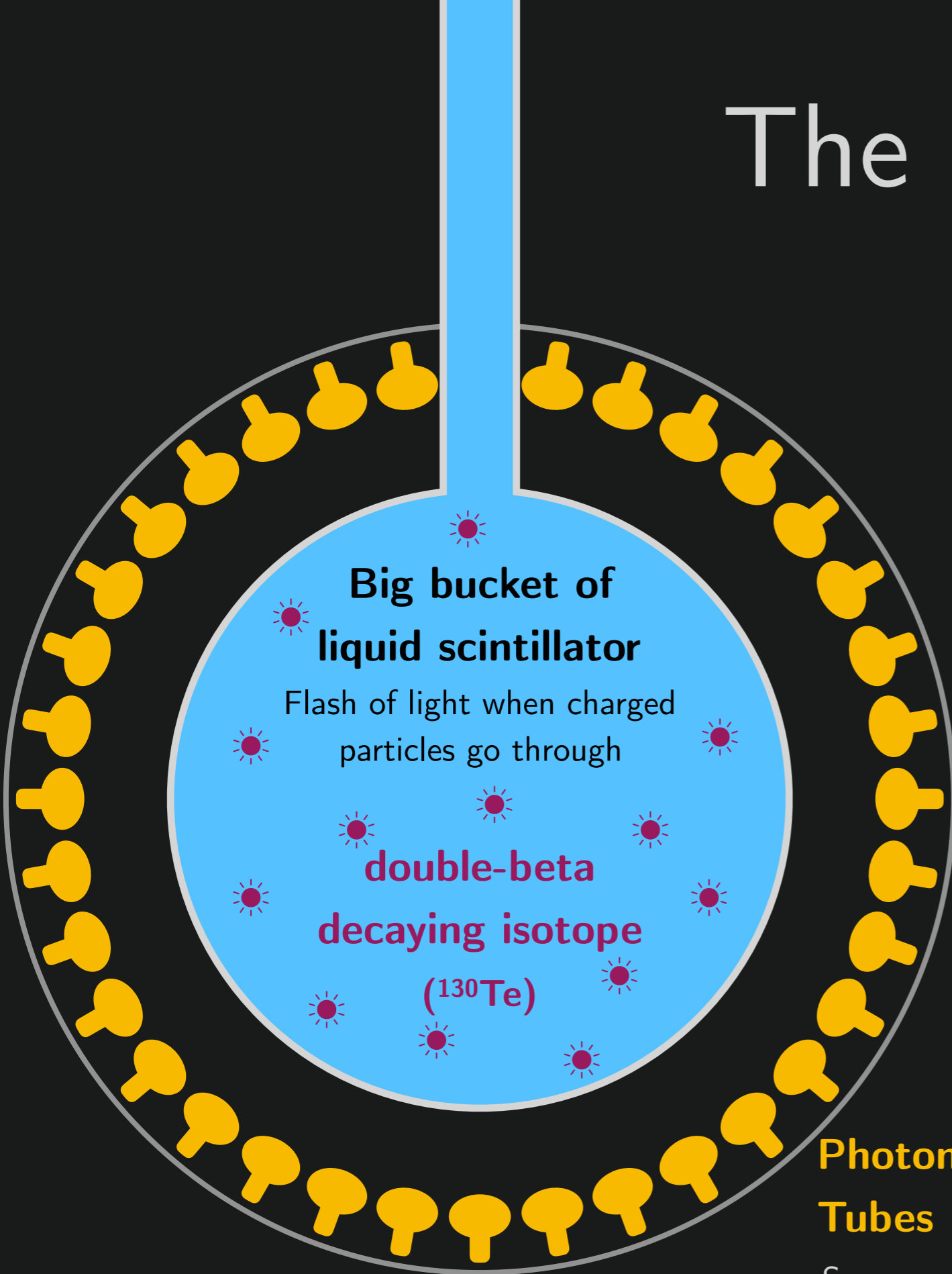
brightness = energy



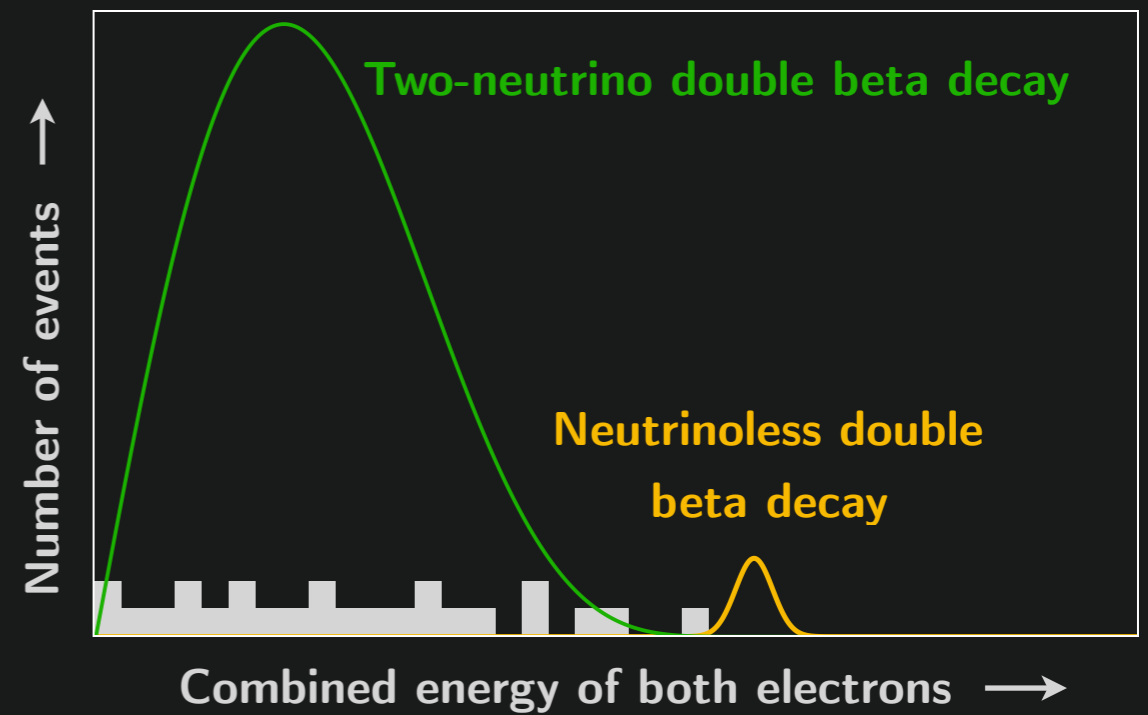
**Photomultiplier
Tubes**

Super sensitive
light detectors

The Experiment



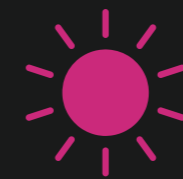
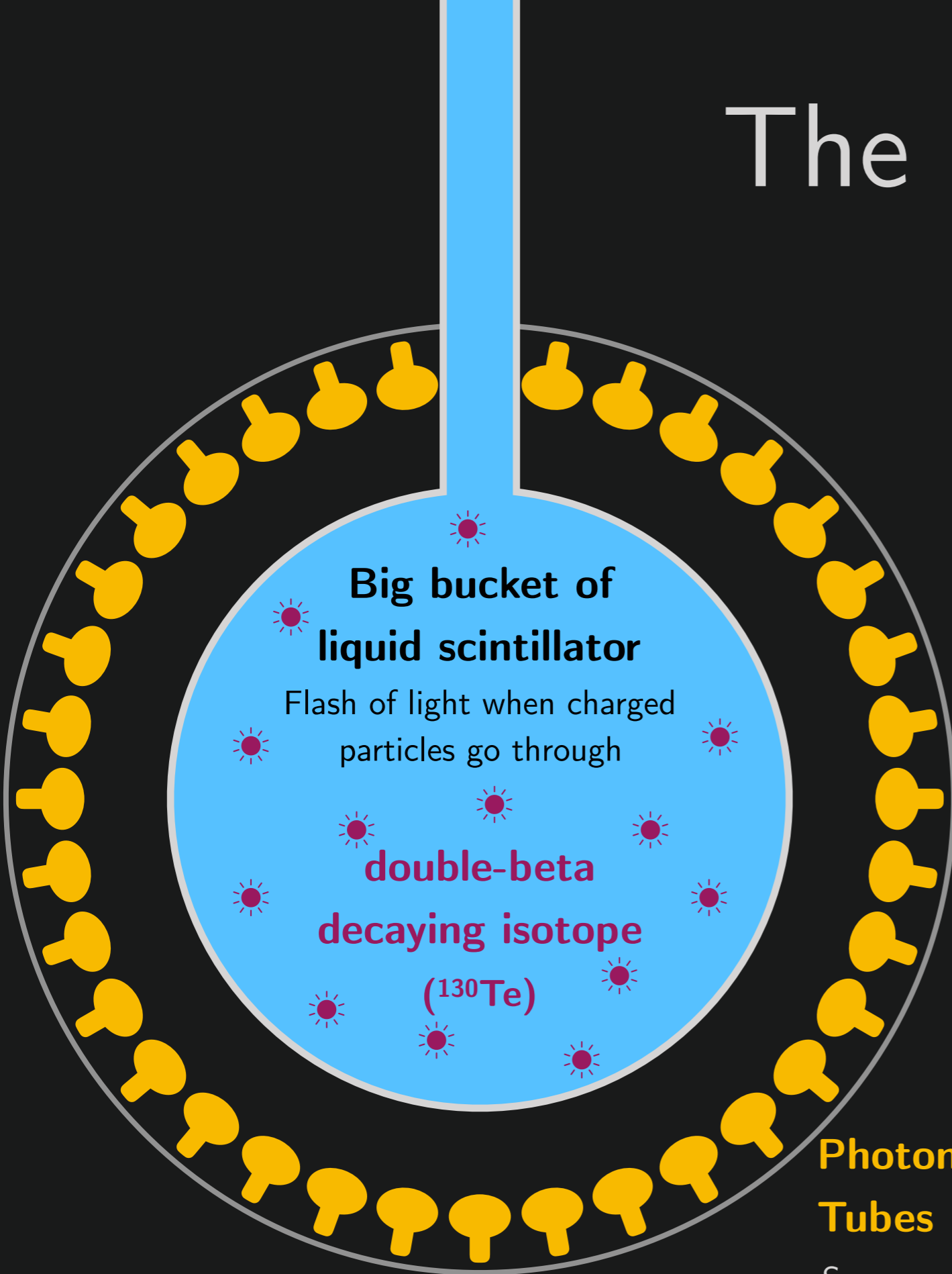
brightness = energy



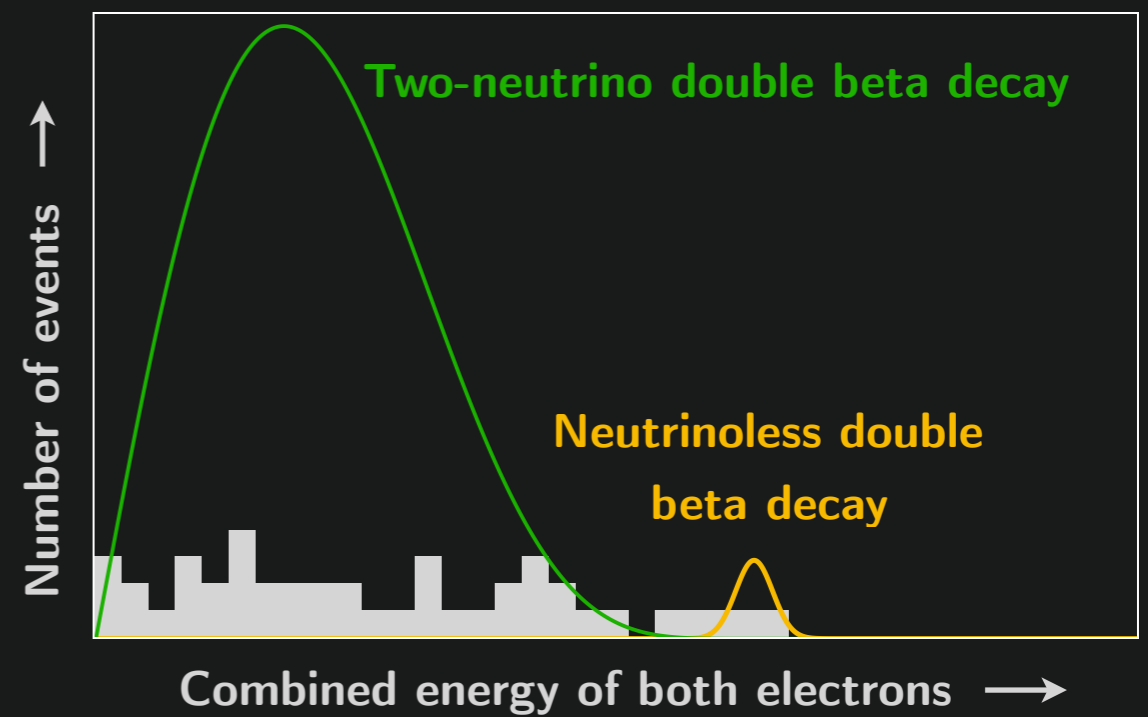
**Photomultiplier
Tubes**

Super sensitive
light detectors

The Experiment



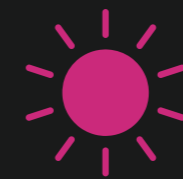
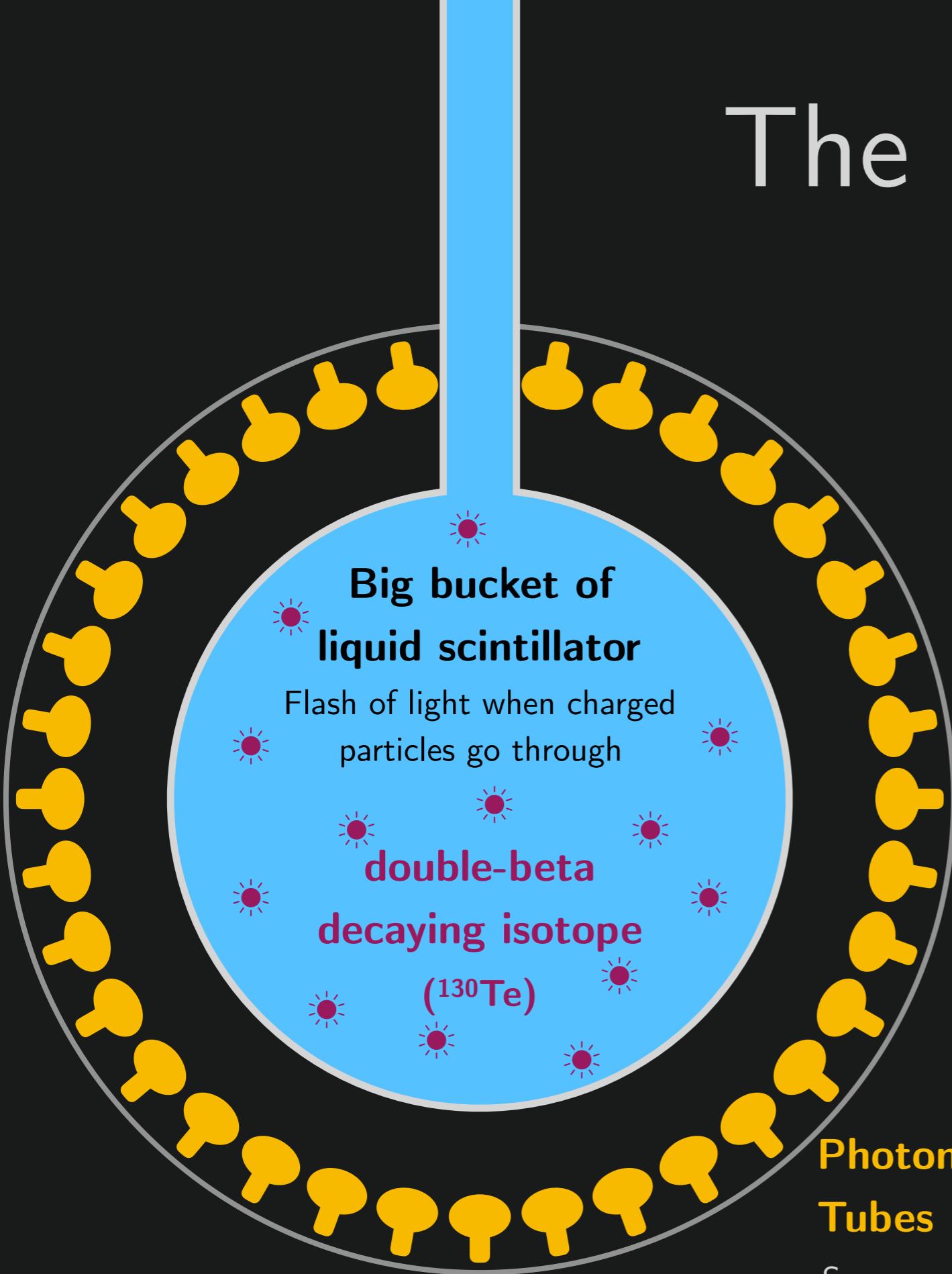
brightness = energy



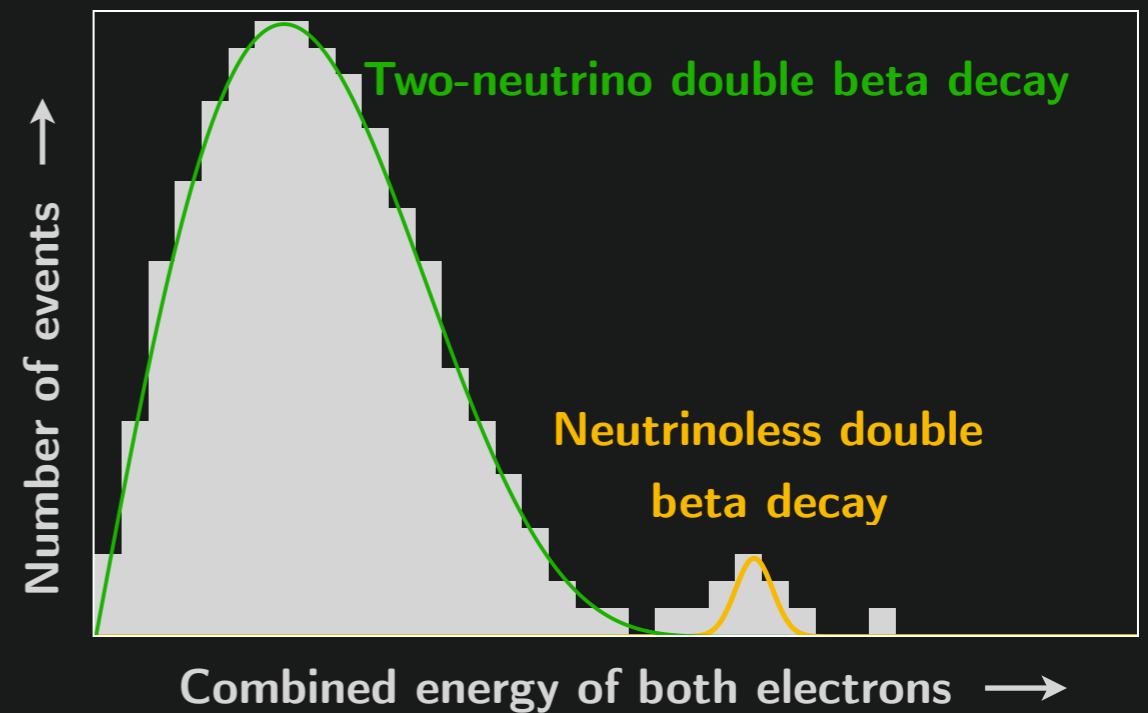
**Photomultiplier
Tubes**

Super sensitive
light detectors

The Experiment



brightness = energy

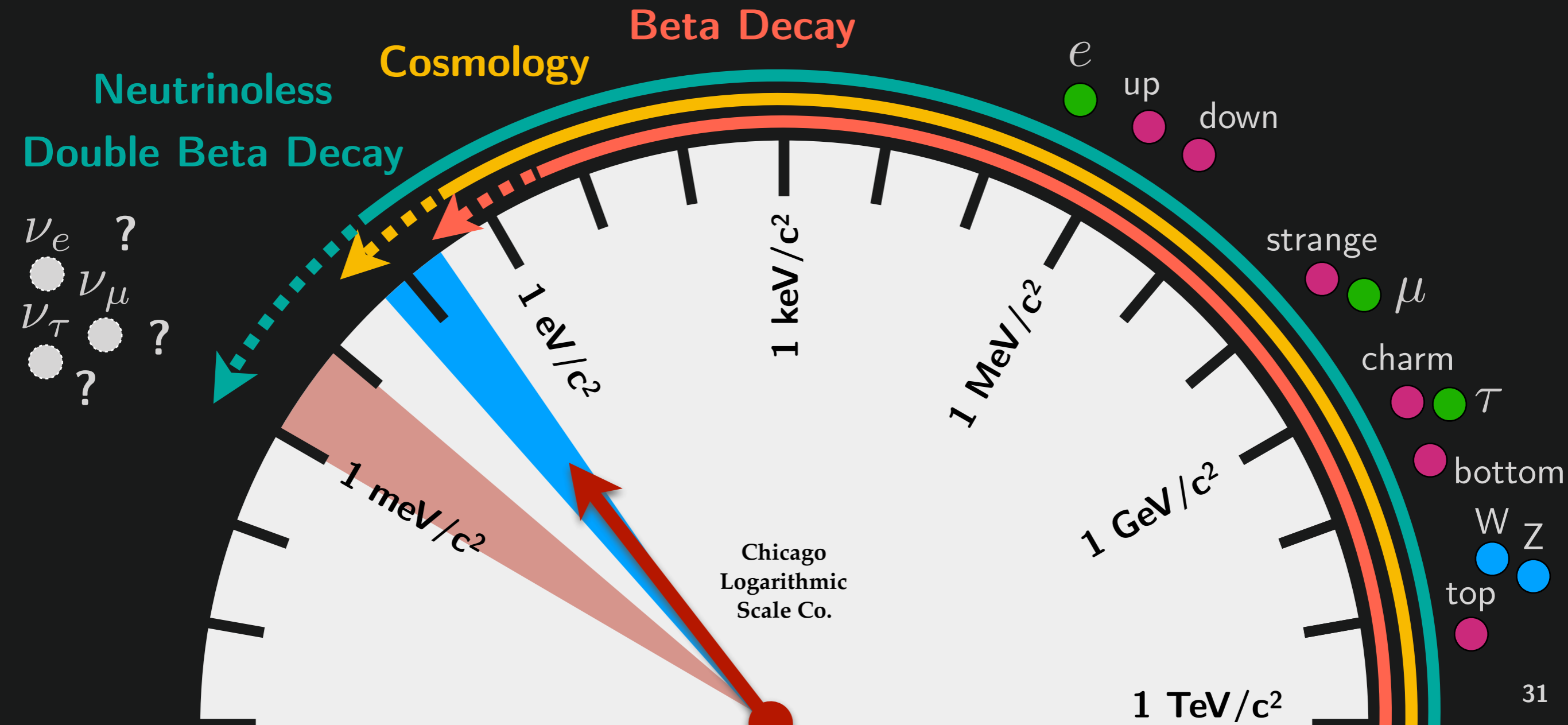


**Photomultiplier
Tubes**

Super sensitive
light detectors

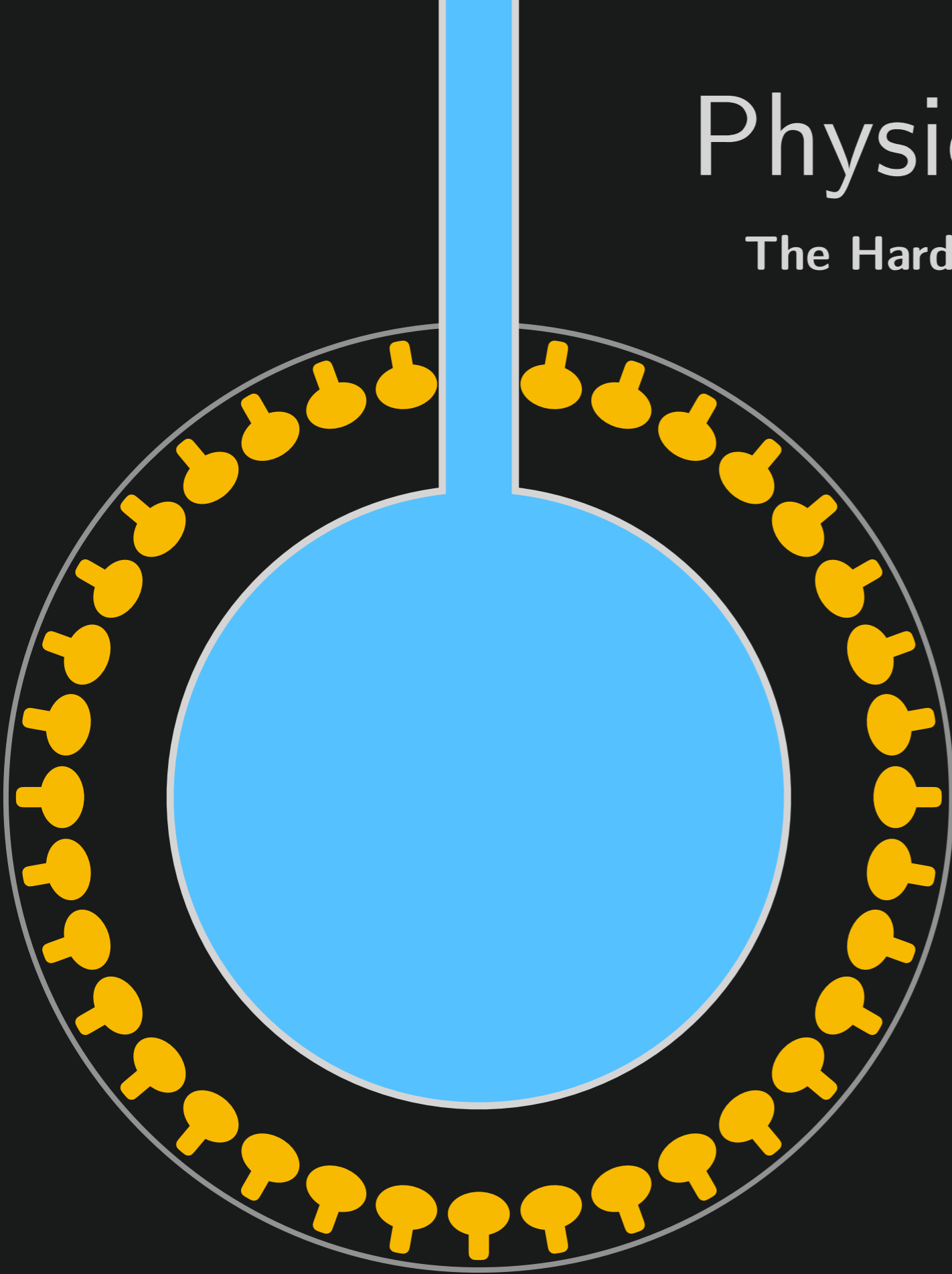
Neutrino Mass

SNO+ Reach
(Phase I)



Physics Challenges

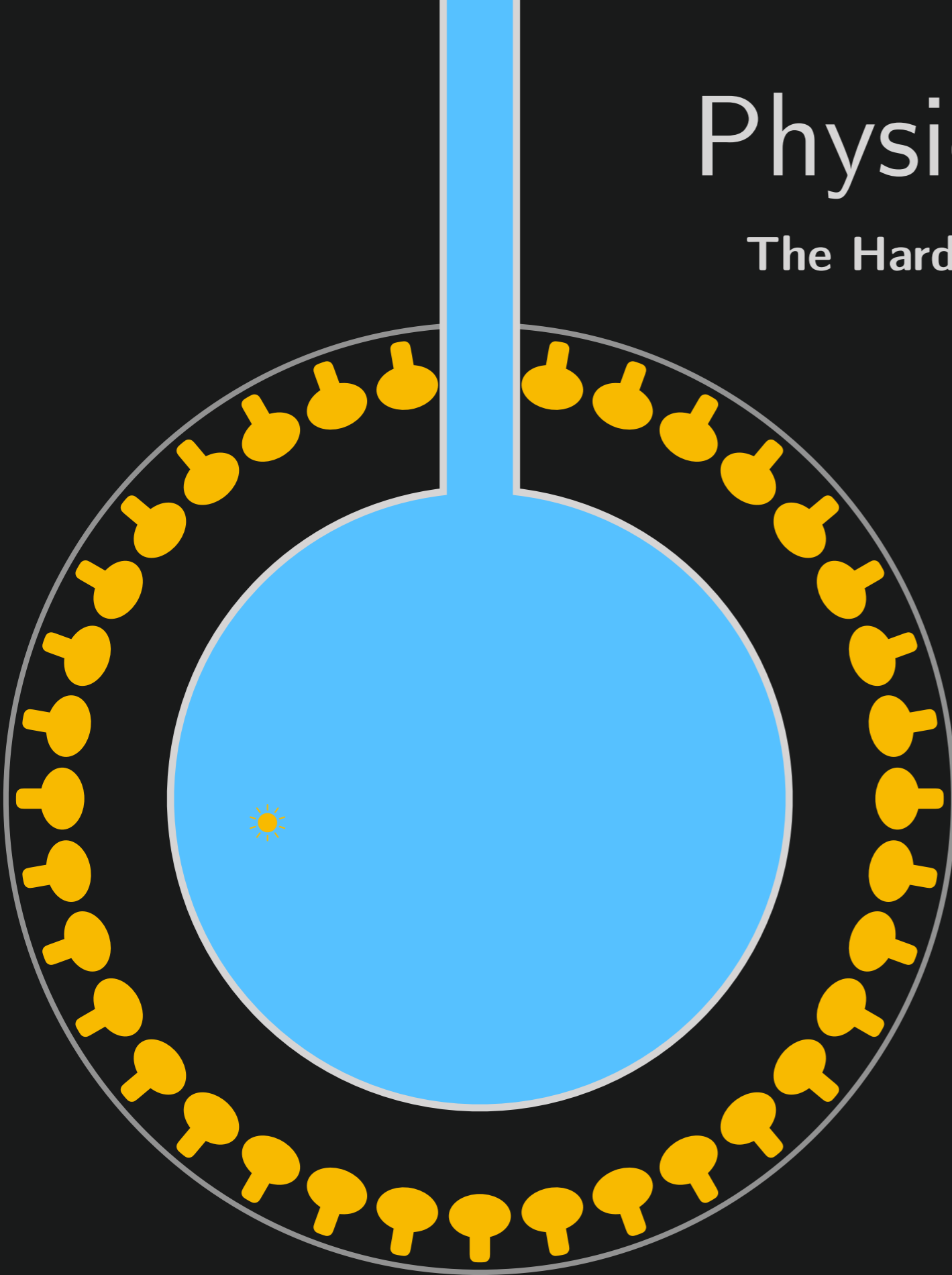
The Hard Part Is Not Being Fooled



Physics Challenges

The Hard Part Is Not Being Fooled

Neutrinoless Double Beta Decay

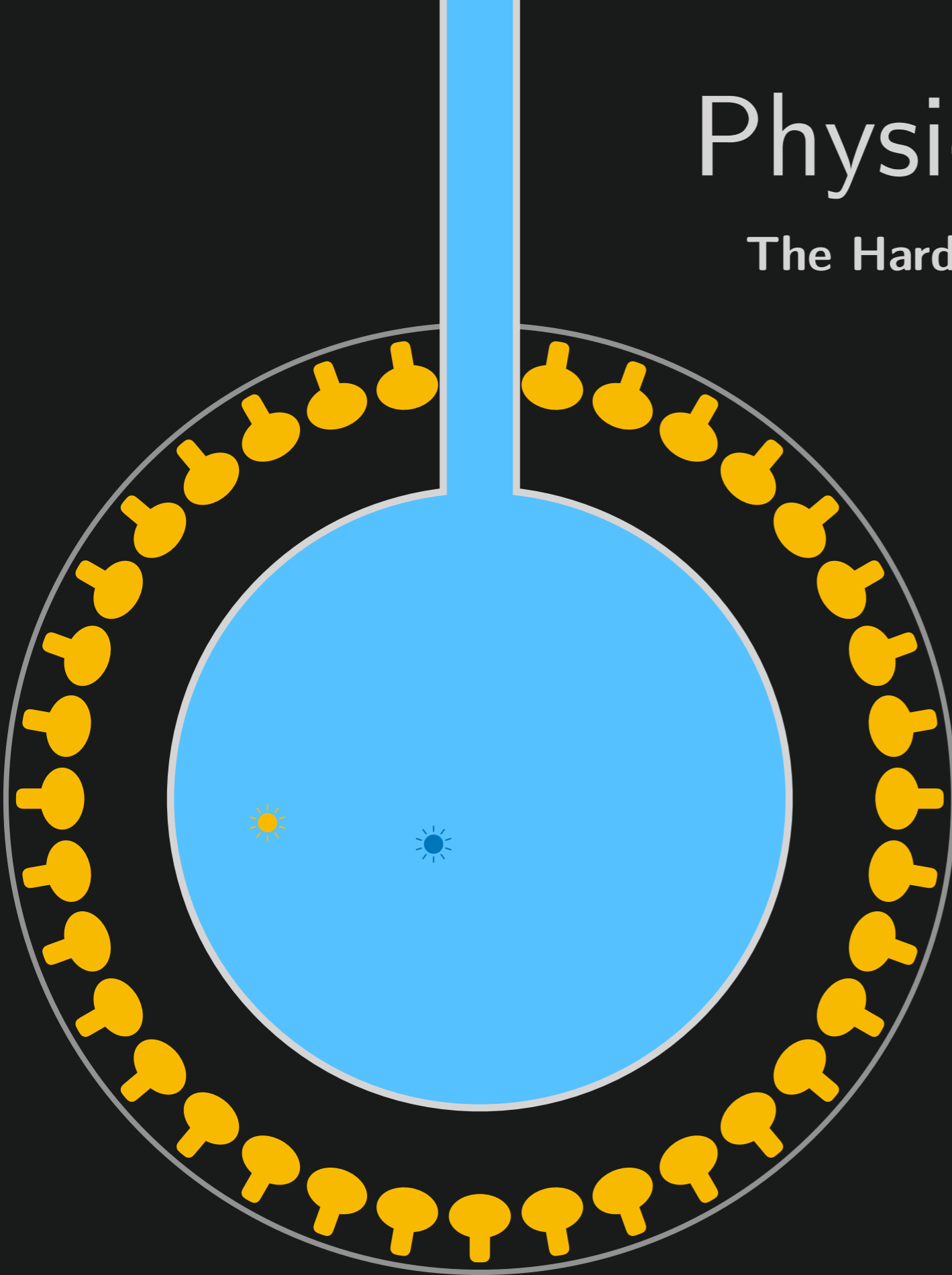


Physics Challenges

The Hard Part Is Not Being Fooled

Neutrinoless Double Beta Decay

Two-Neutrino Double Beta Decay



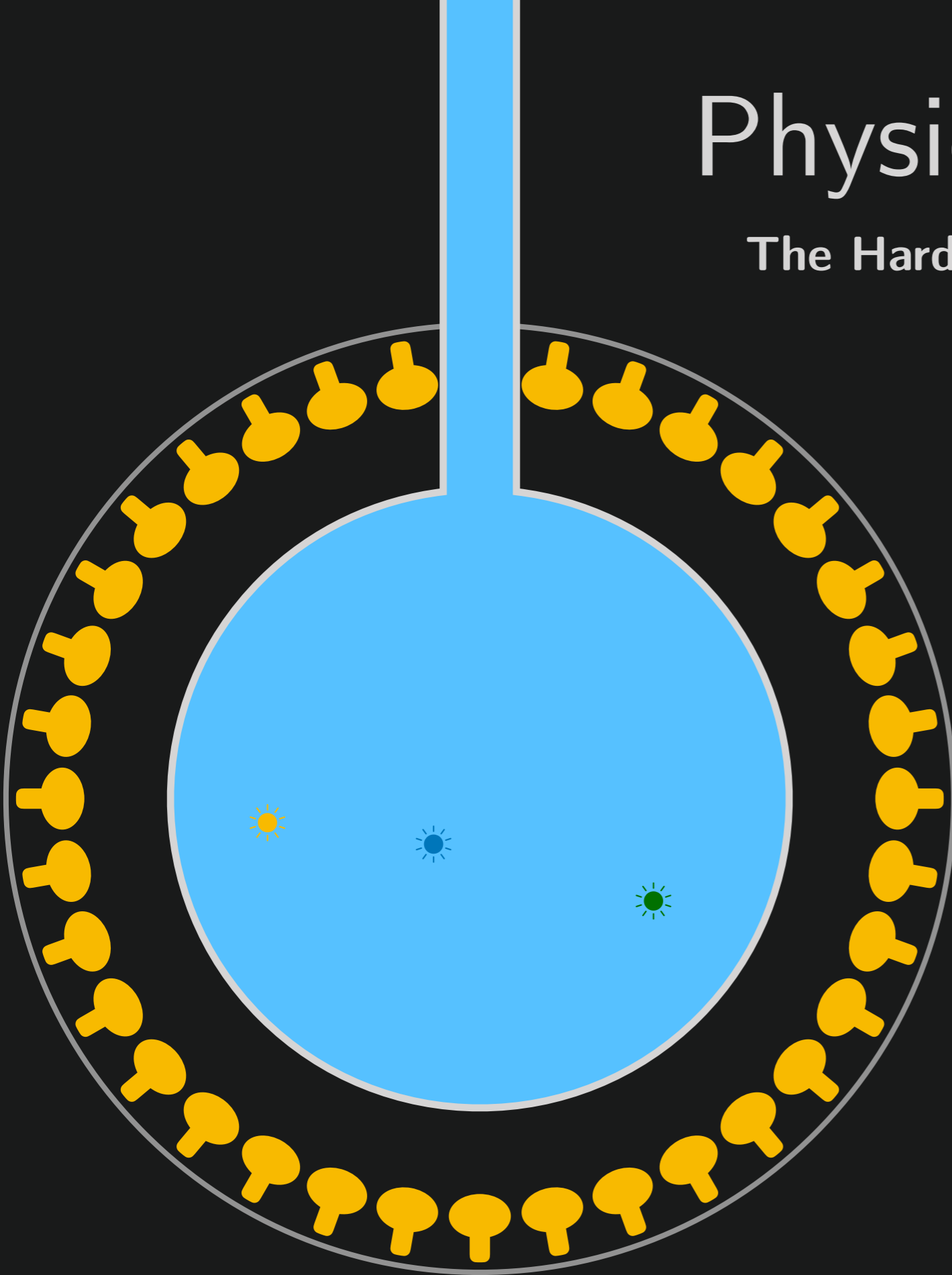
Physics Challenges

The Hard Part Is Not Being Fooled

Neutrinoless Double Beta Decay

Two-Neutrino Double Beta Decay

Radioactive Decays



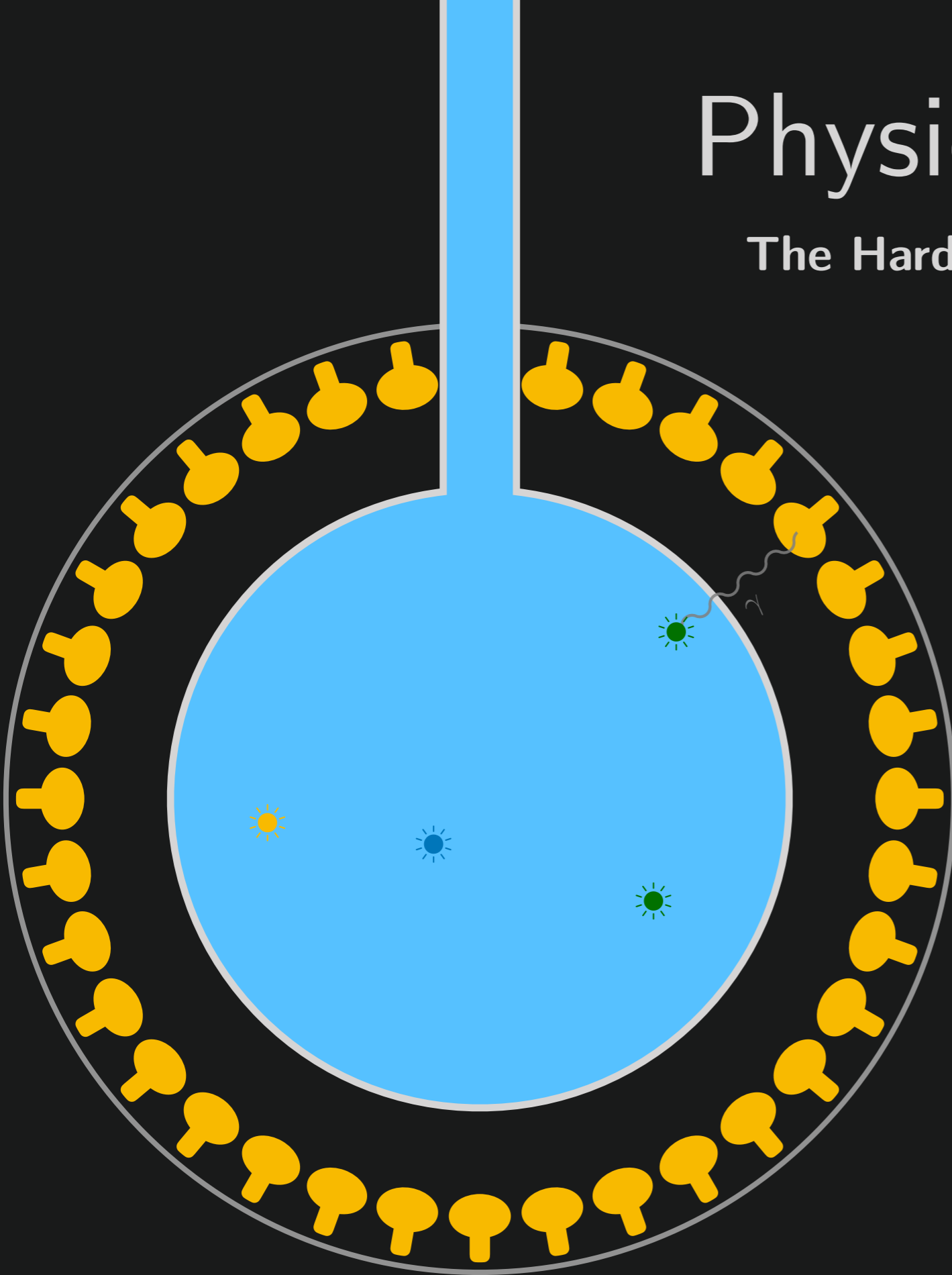
Physics Challenges

The Hard Part Is Not Being Fooled

Neutrinoless Double Beta Decay

Two-Neutrino Double Beta Decay

Radioactive Decays



Physics Challenges

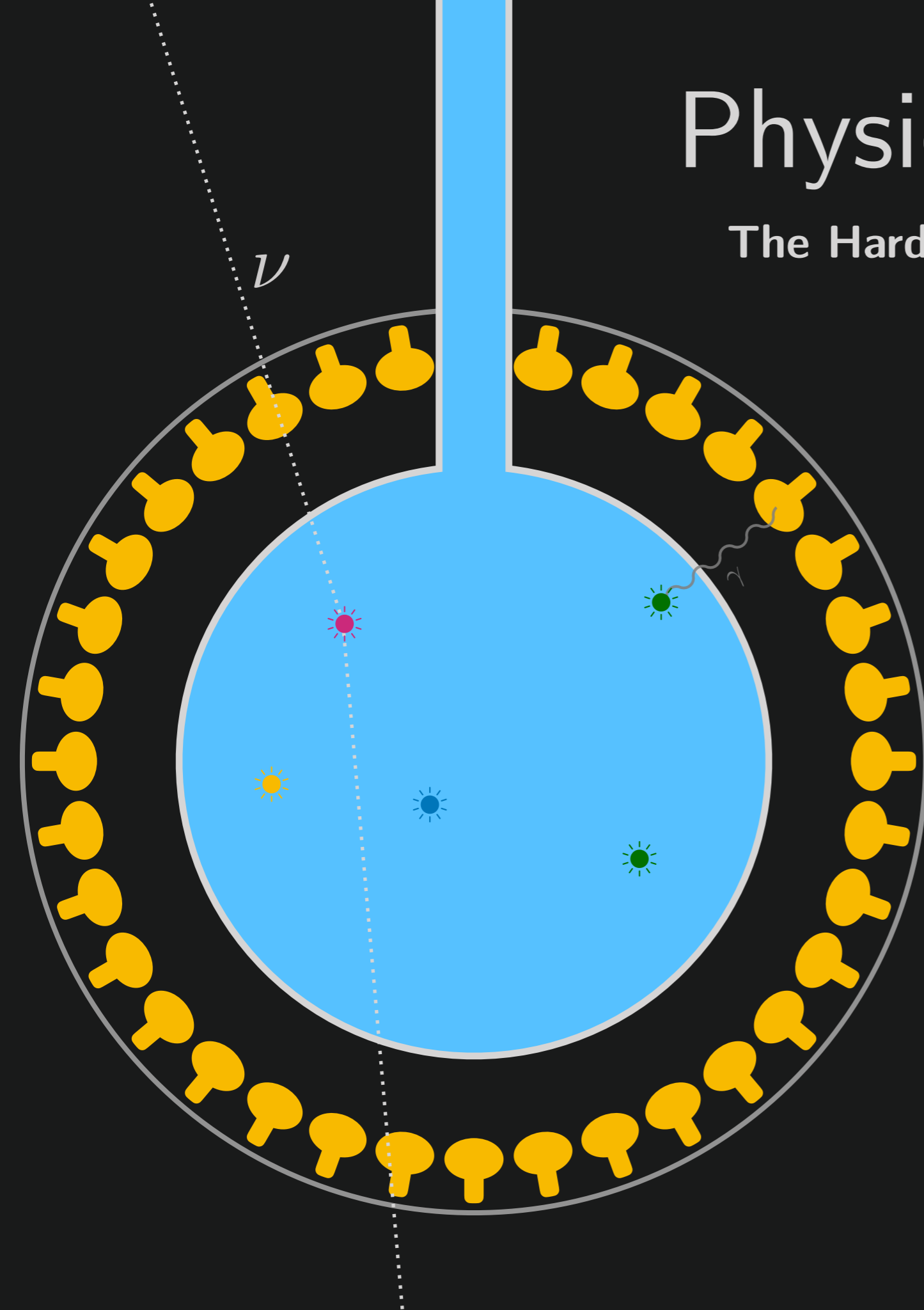
The Hard Part Is Not Being Fooled

Neutrinoless Double Beta Decay

Two-Neutrino Double Beta Decay

Radioactive Decays

Solar Neutrinos



Physics Challenges

The Hard Part Is Not Being Fooled

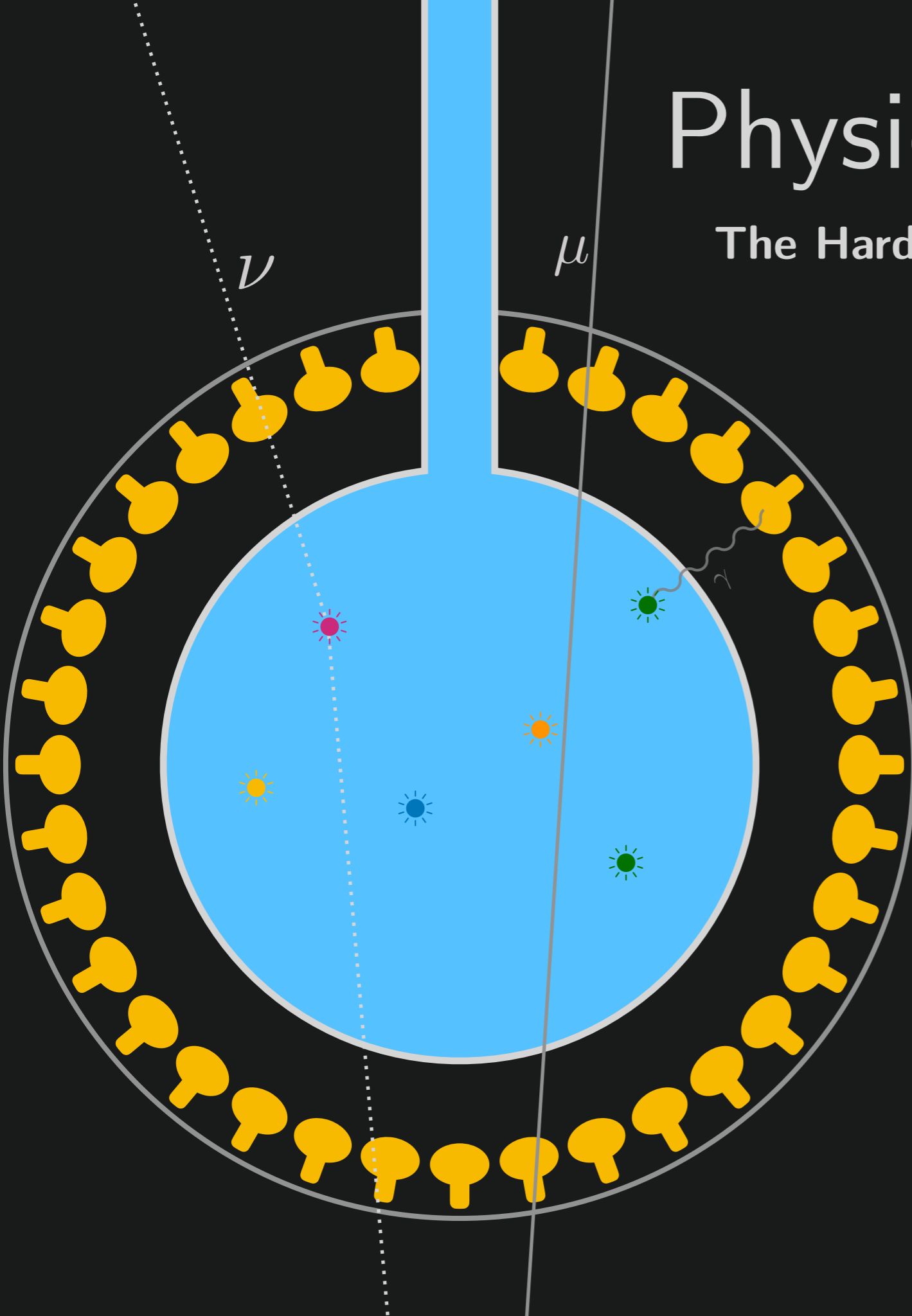
Neutrinoless Double Beta Decay

Two-Neutrino Double Beta Decay

Radioactive Decays

Solar Neutrinos

Muon Spallation



Physics Challenges

The Hard Part Is Not Being Fooled

Neutrinoless Double Beta Decay

Two-Neutrino Double Beta Decay

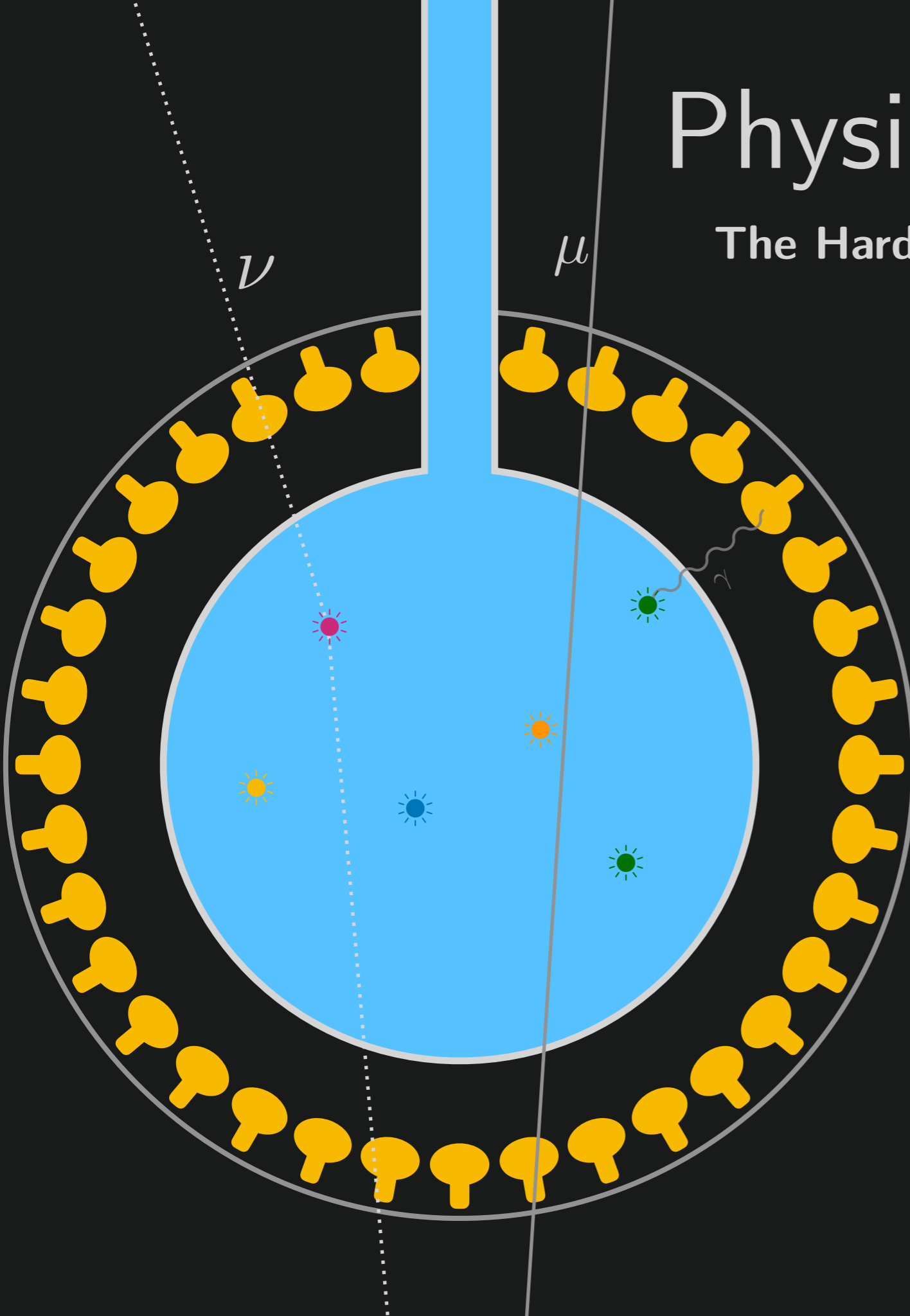
Radioactive Decays

Solar Neutrinos

Muon Spallation



flashes of light



Physics Challenges

The Hard Part Is Not Being Fooled

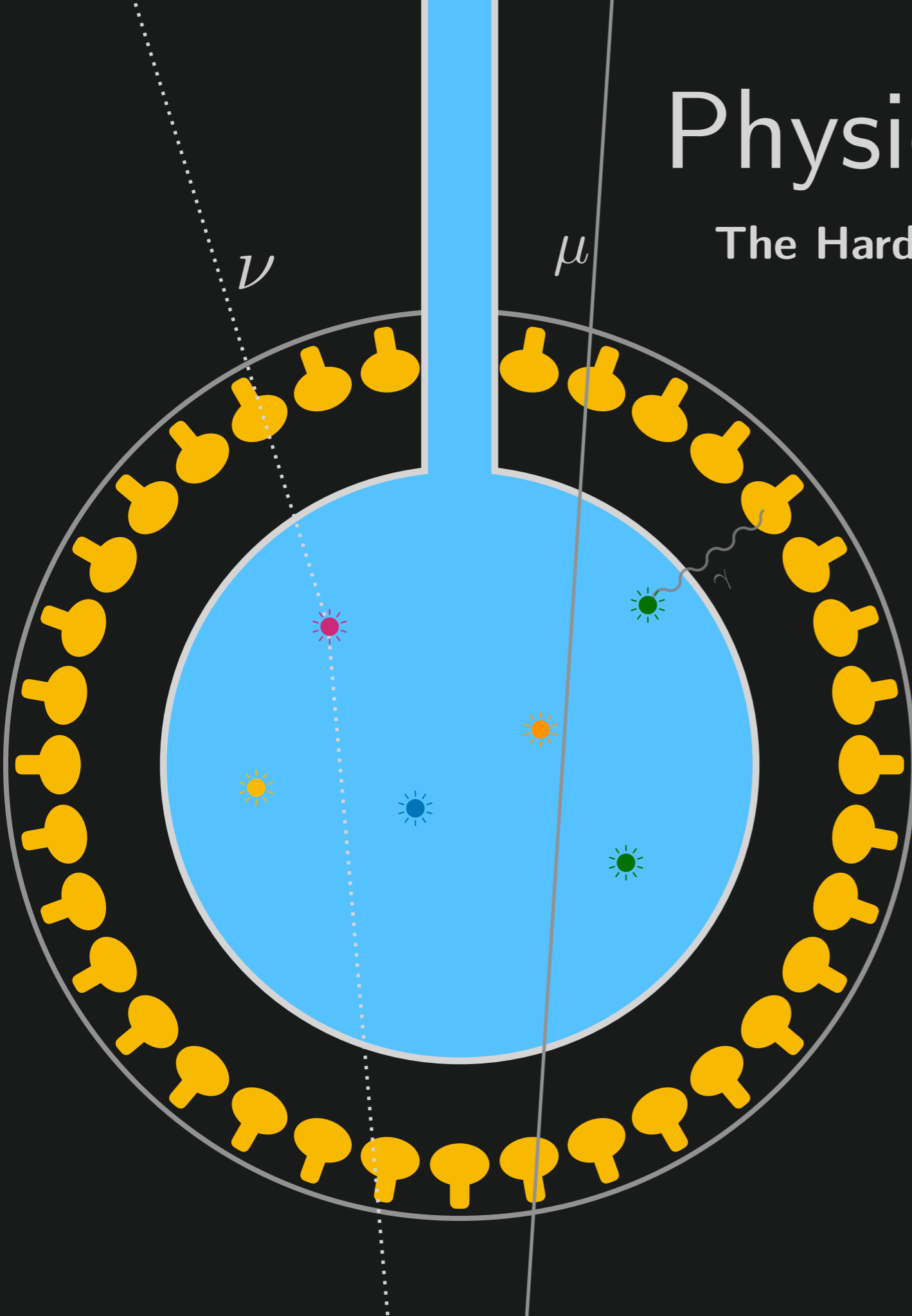
Neutrinoless Double Beta Decay

Two-Neutrino Double Beta Decay

Radioactive Decays

Solar Neutrinos

Muon Spallation



Physics Challenges

The Hard Part Is Not Being Fooled

Neutrinoless Double Beta Decay

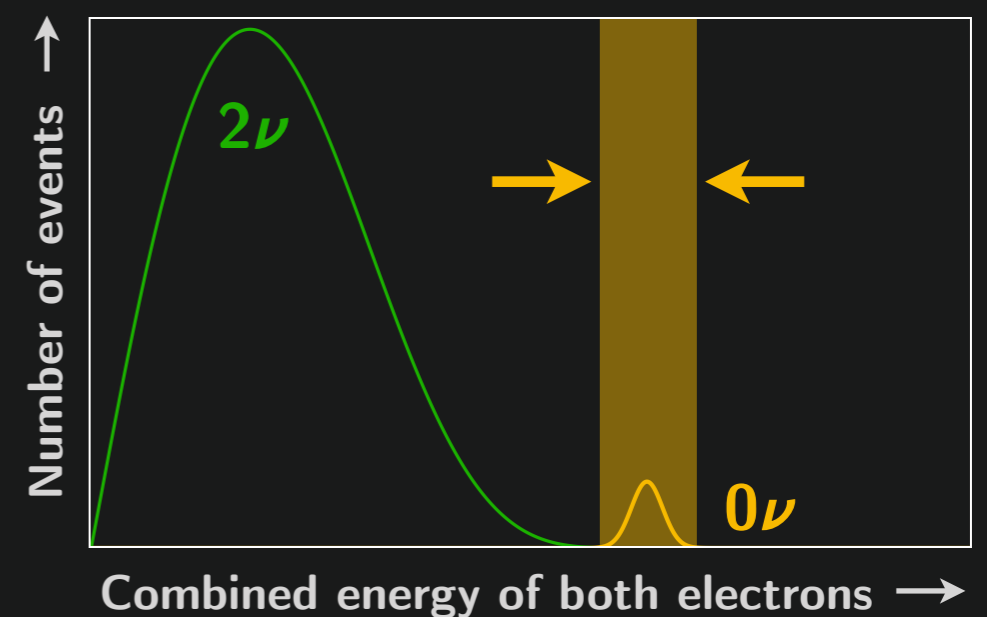
Two-Neutrino Double Beta Decay

Radioactive Decays

Solar Neutrinos

Muon Spallation

1. Look at a narrow range of energies



Physics Challenges

The Hard Part Is Not Being Fooled

Neutrinoless Double Beta Decay

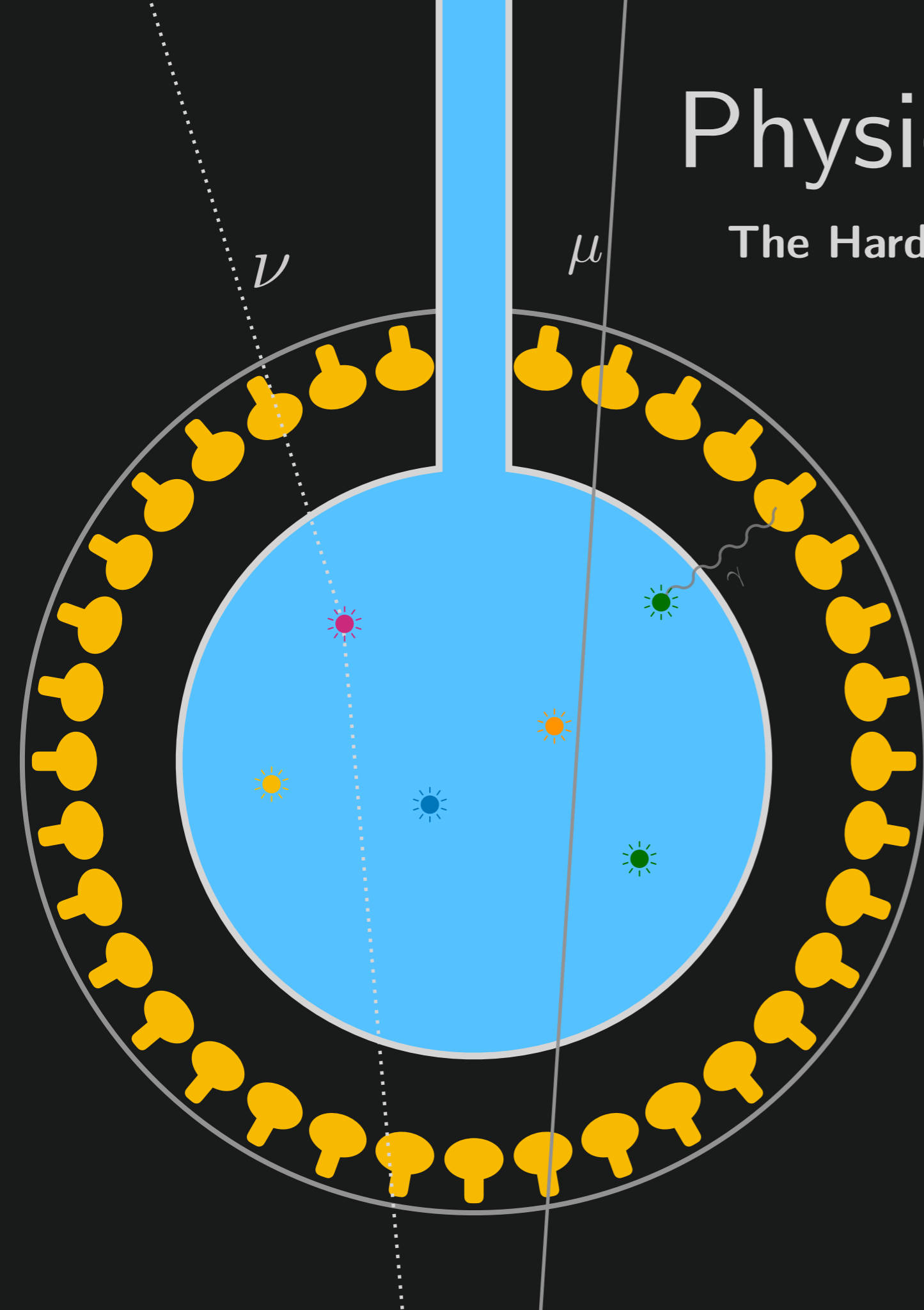
Two-Neutrino Double Beta Decay

Radioactive Decays

Solar Neutrinos

Muon Spallation

1. Look at a narrow range of energies



Physics Challenges

The Hard Part Is Not Being Fooled

Neutrinoless Double Beta Decay

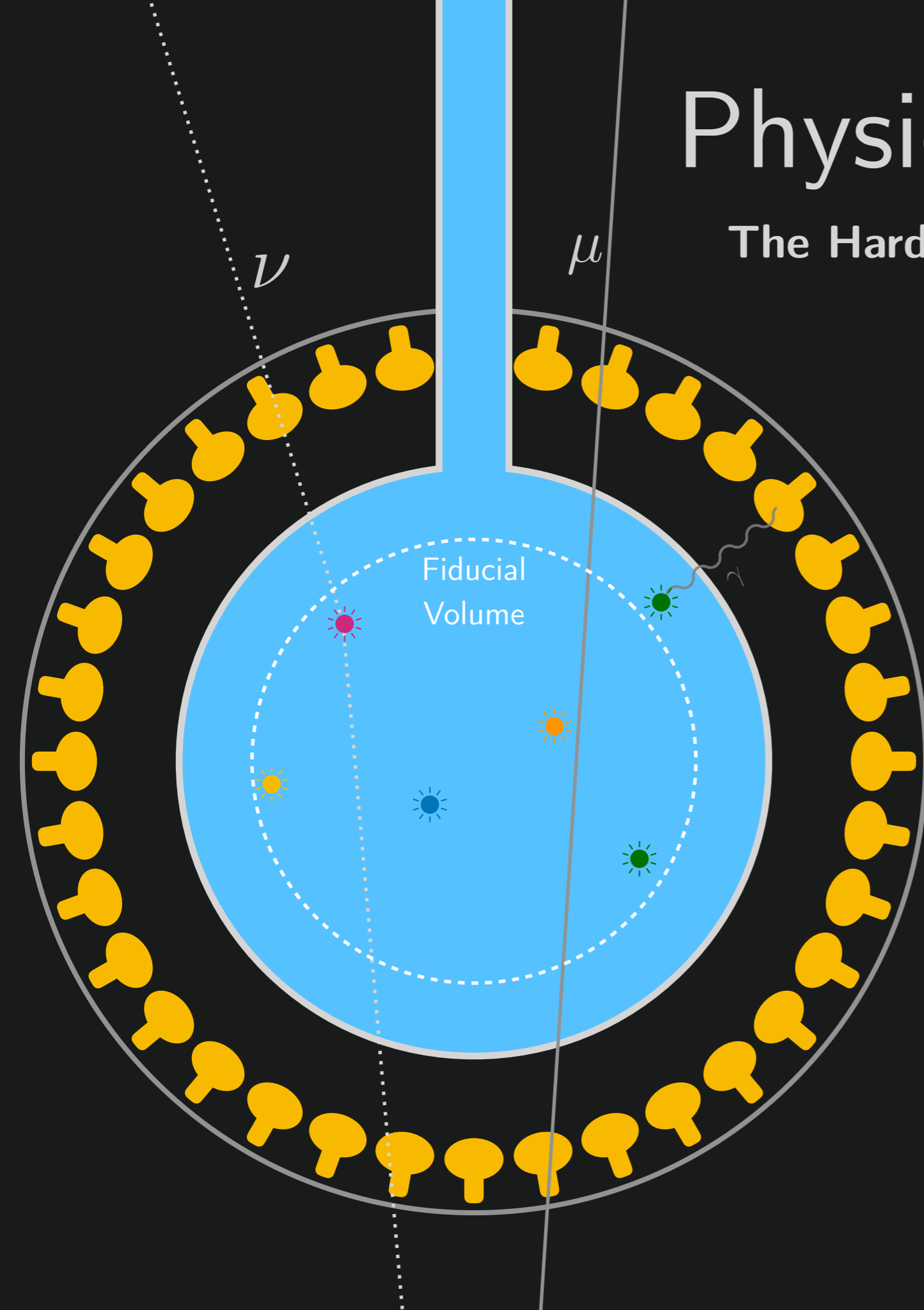
Two-Neutrino Double Beta Decay

Radioactive Decays

Solar Neutrinos

Muon Spallation

1. Look at a narrow range of energies
2. Fiducial volume: cut away the edges



Physics Challenges

The Hard Part Is Not Being Fooled

Neutrinoless Double Beta Decay

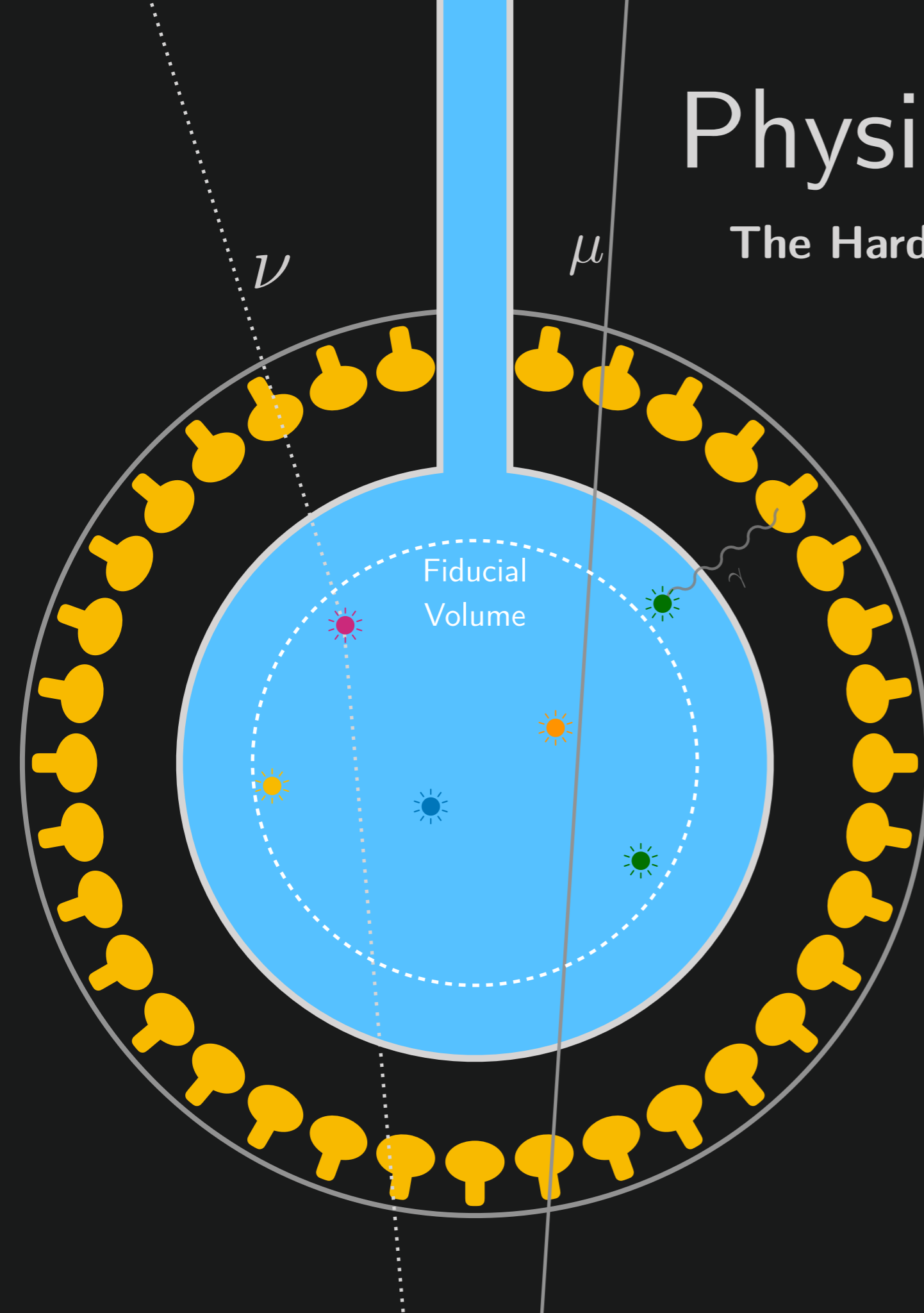
Two-Neutrino Double Beta Decay

Radioactive Decays

Solar Neutrinos

Muon Spallation

1. Look at a narrow range of energies
2. Fiducial volume: cut away the edges
3. Muons: go deep underground



Physics Challenges

The Hard Part Is Not Being Fooled

Neutrinoless Double Beta Decay


Two-Neutrino Double Beta Decay

Radioactive Decays

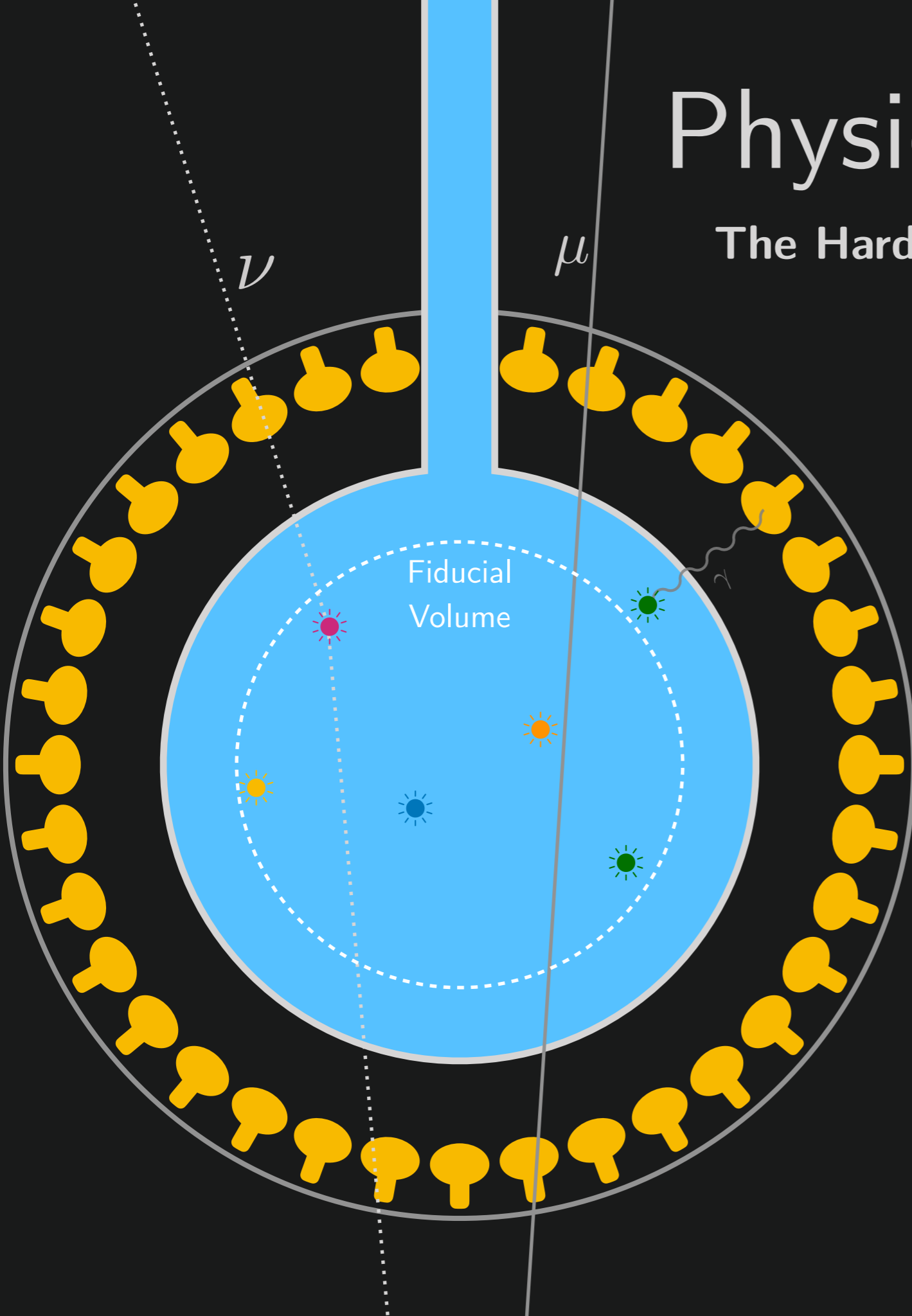
Solar Neutrinos

Muon Spallation

1. Look at a narrow range of energies
2. Fiducial volume: cut away the edges
3. Muons: go deep underground
4. Decays: use flash timing

 often two nearby
flashes superimposed

This can get very fancy.
Machine learning, AI, etc.



Physics Challenges

The Hard Part Is Not Being Fooled

Neutrinoless Double Beta Decay

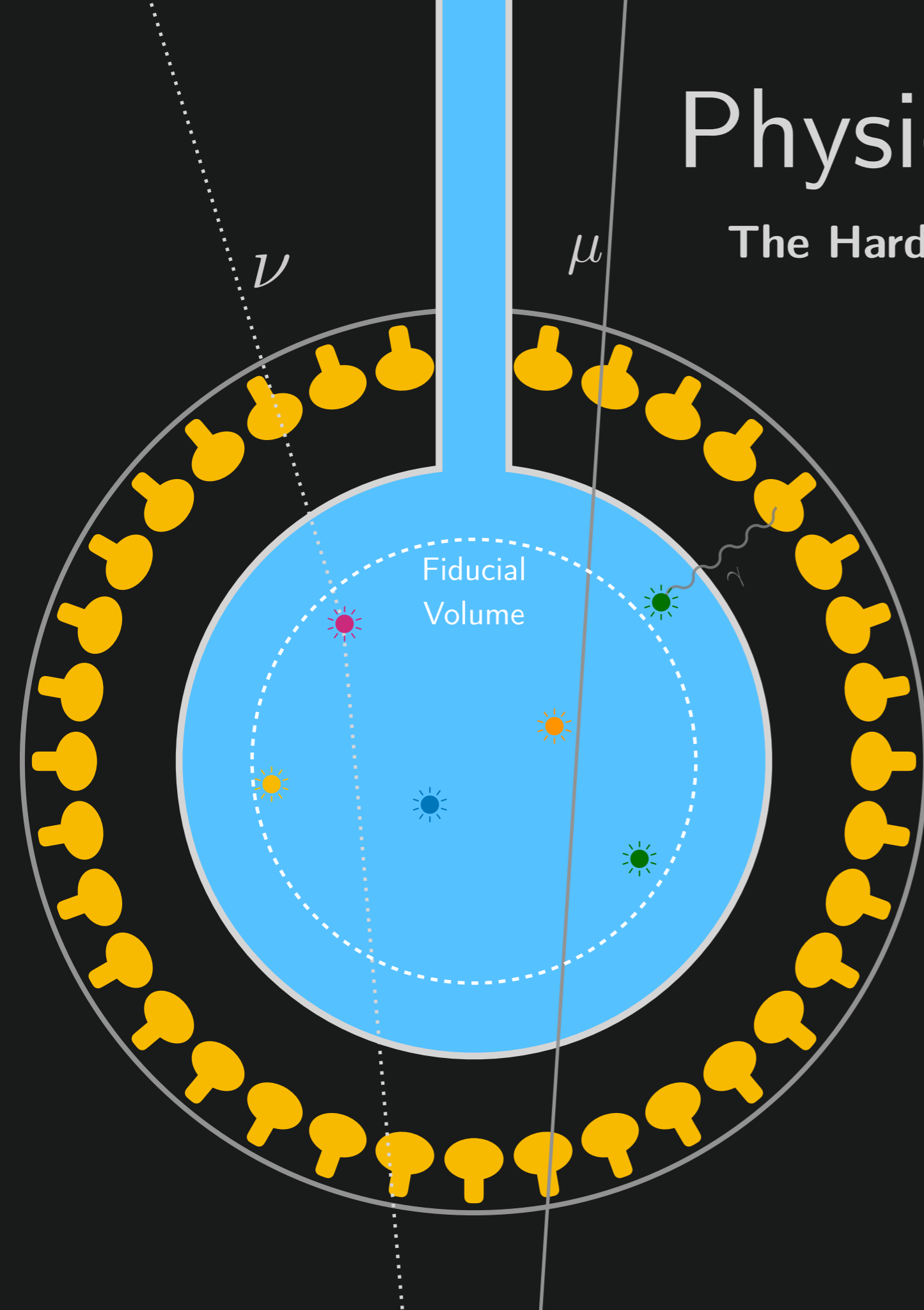
Two-Neutrino Double Beta Decay

Radioactive Decays

Solar Neutrinos

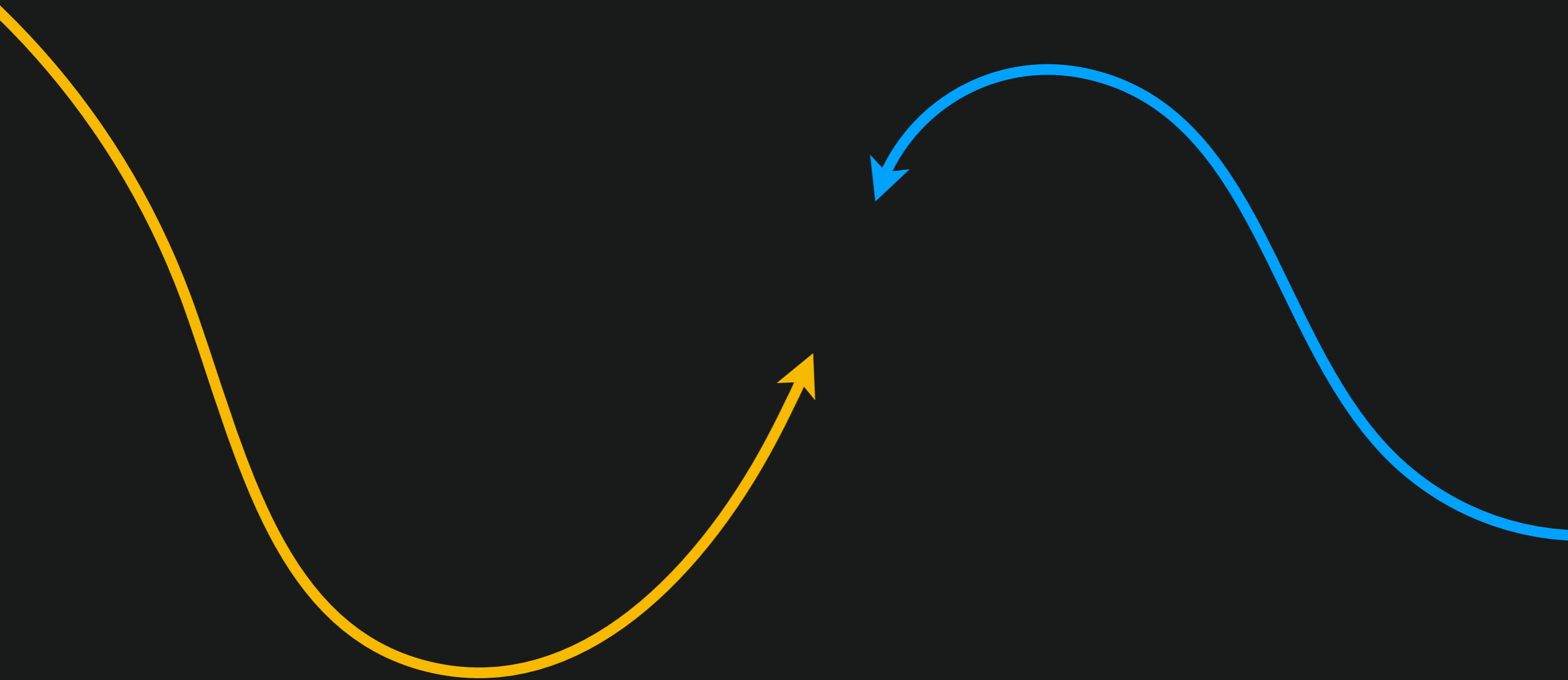
Muon Spallation

1. Look at a narrow range of energies
2. Fiducial volume: cut away the edges
3. Muons: go deep underground
4. Decays: use flash timing
5. Solar neutrinos: use energy
 - And direction to Sun??



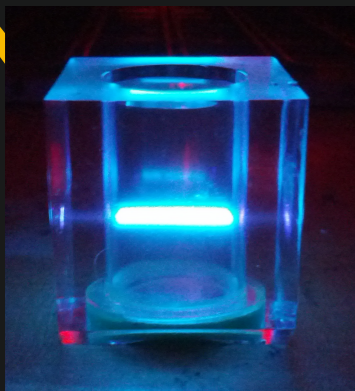
Physics Challenges

Understanding the Detector



Physics Challenges

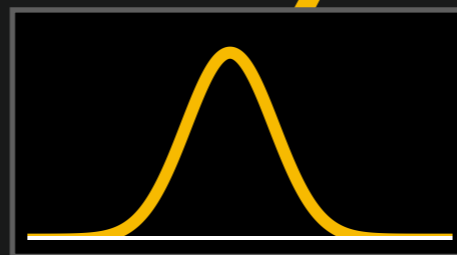
Understanding the Detector



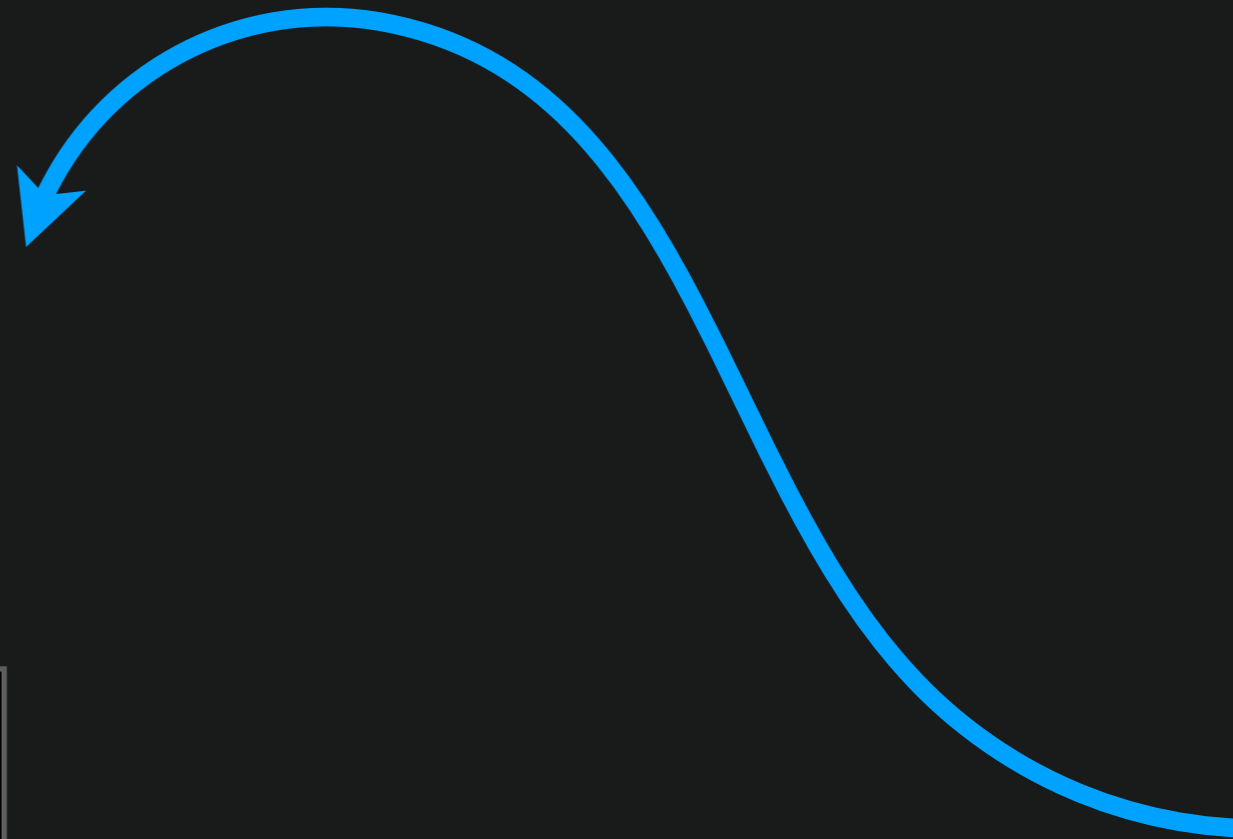
Laboratory
Experiments



Computer
Simulations

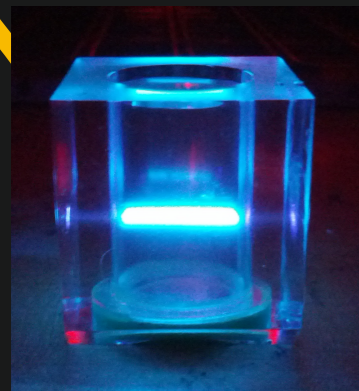


Prediction



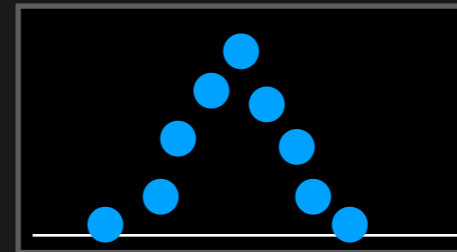
Physics Challenges

Understanding the Detector

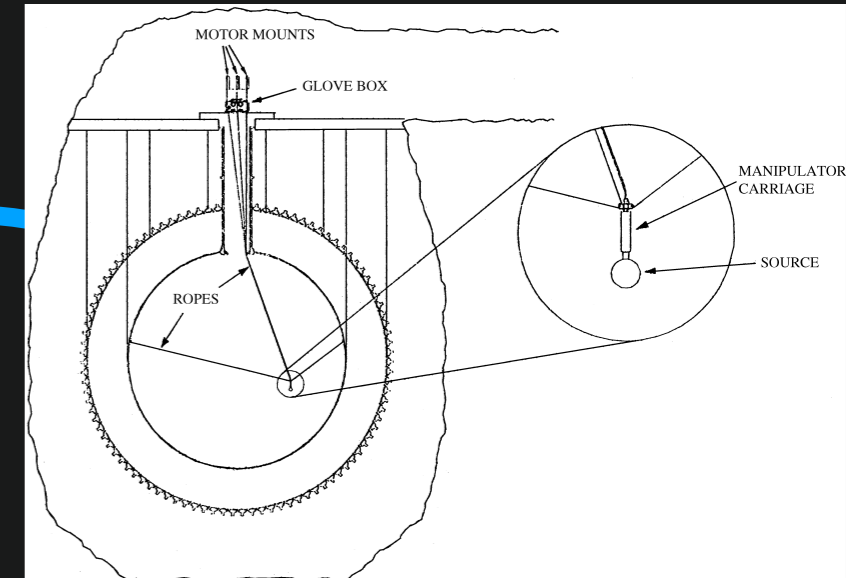


Laboratory Experiments

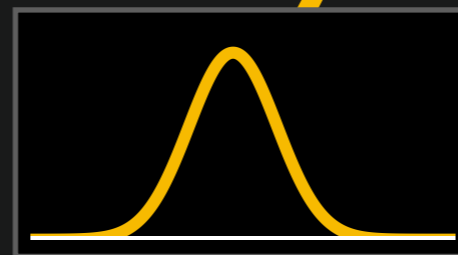
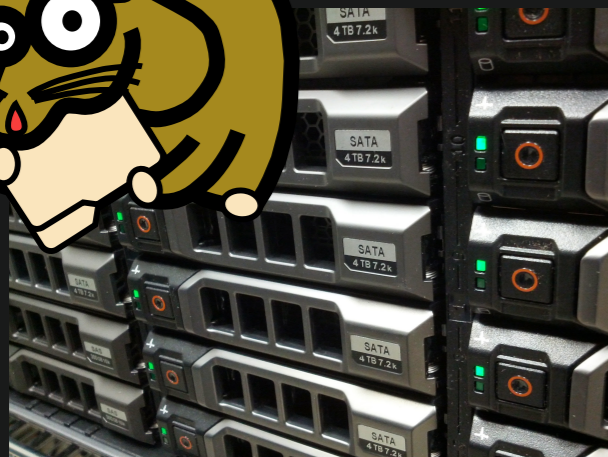
Data



Deployment in Detector



Computer Simulations



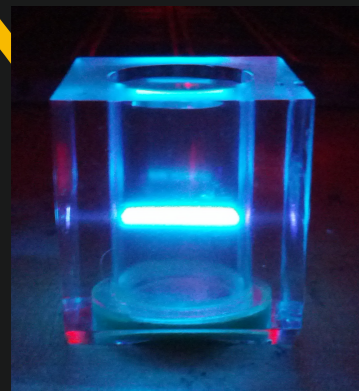
Prediction



Calibration Sources

Physics Challenges

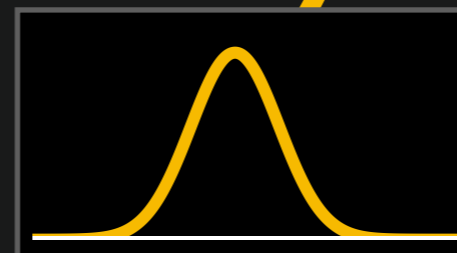
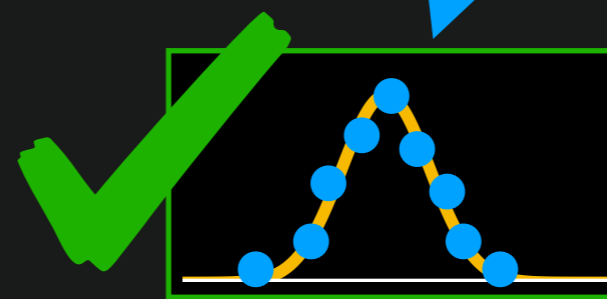
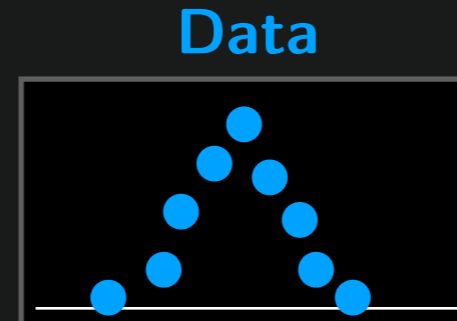
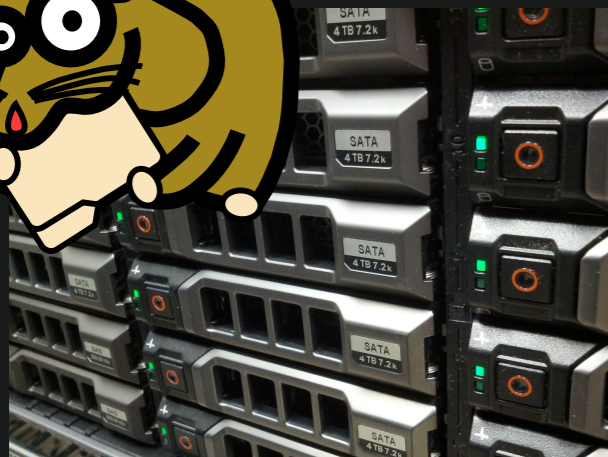
Understanding the Detector



Laboratory Experiments

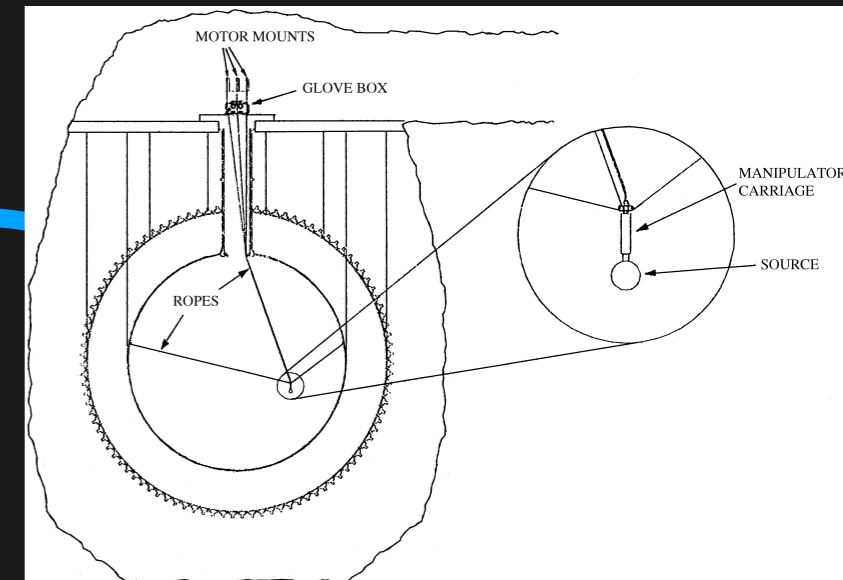


Computer Simulations

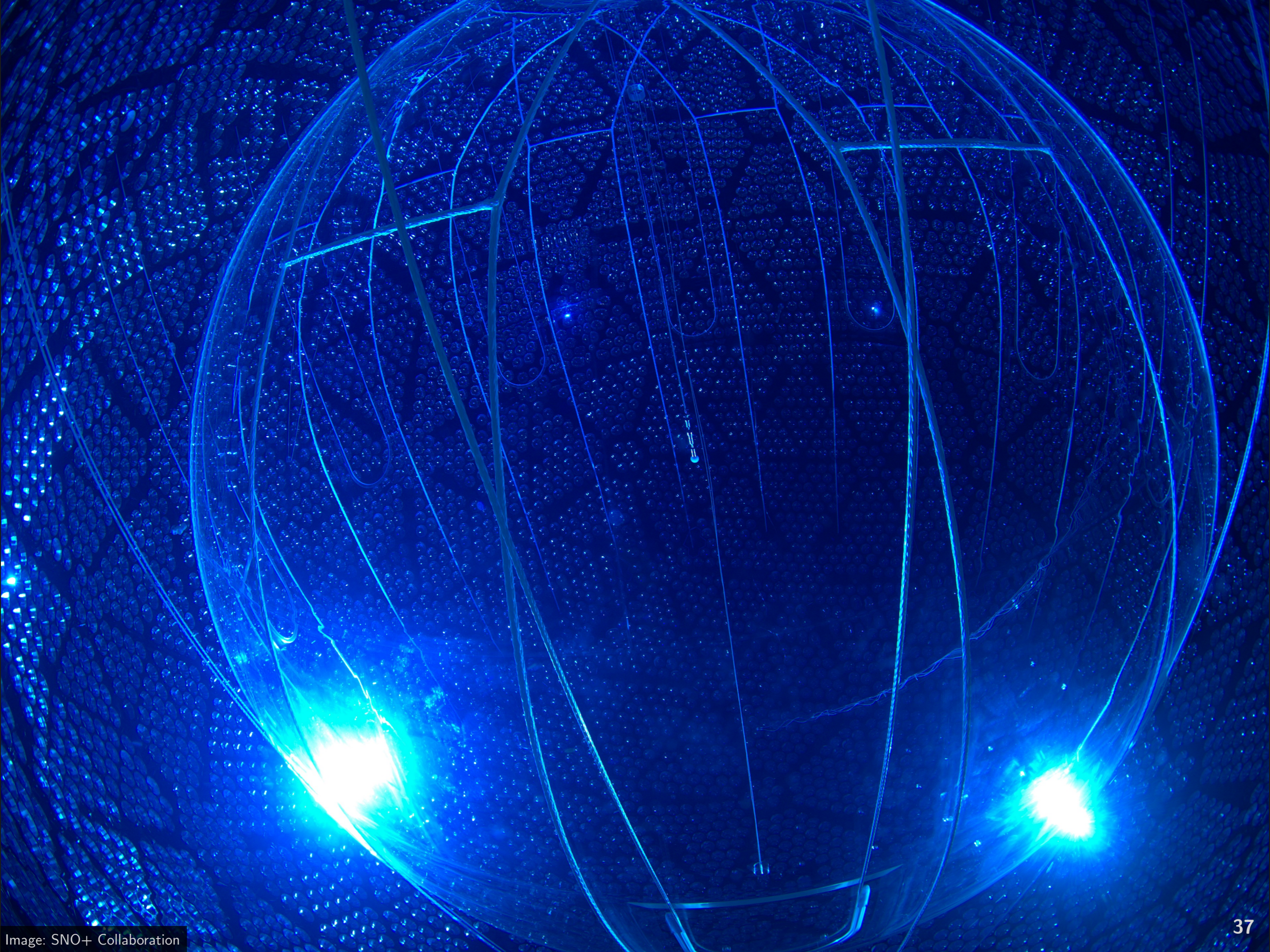


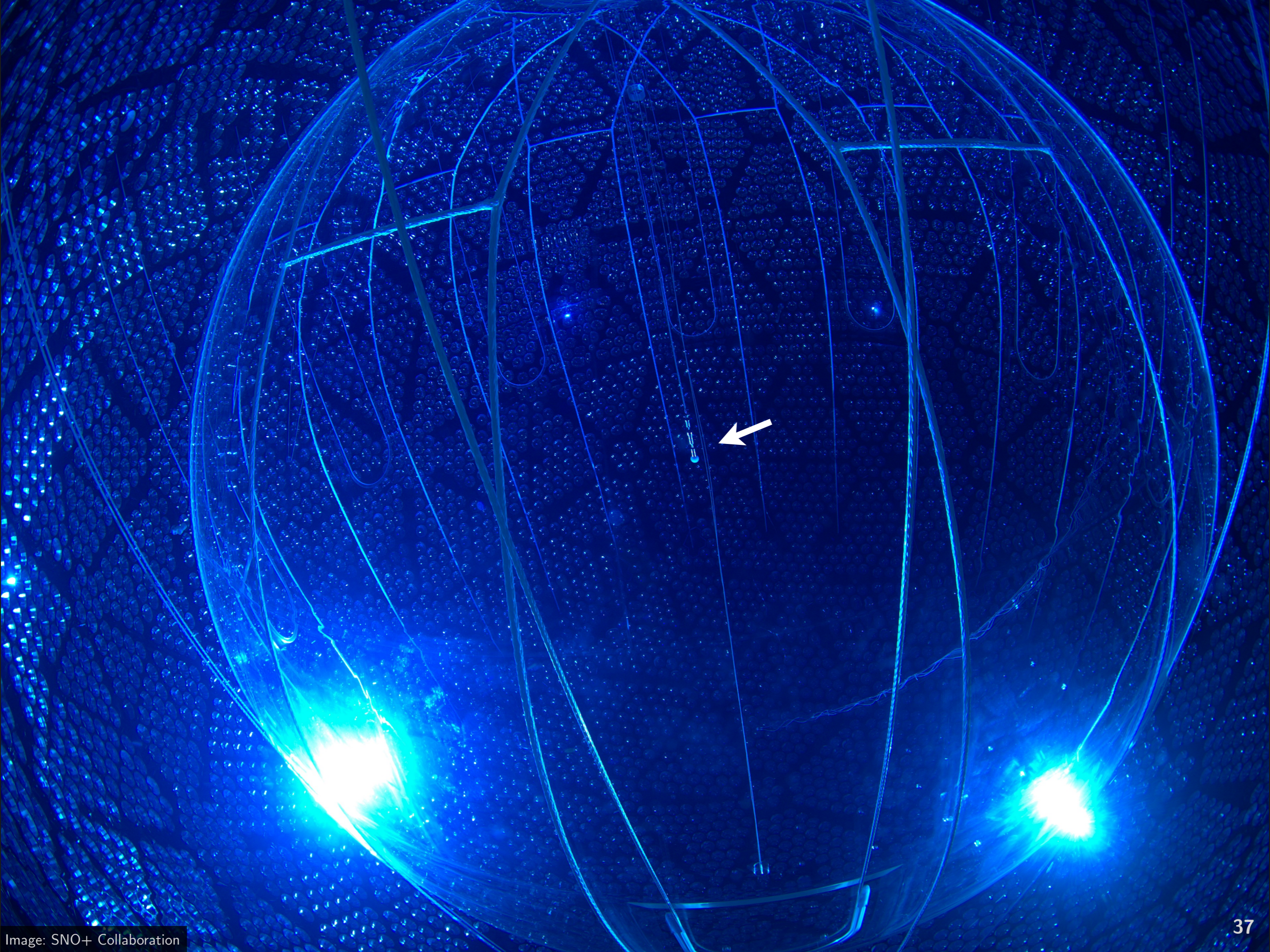
Prediction

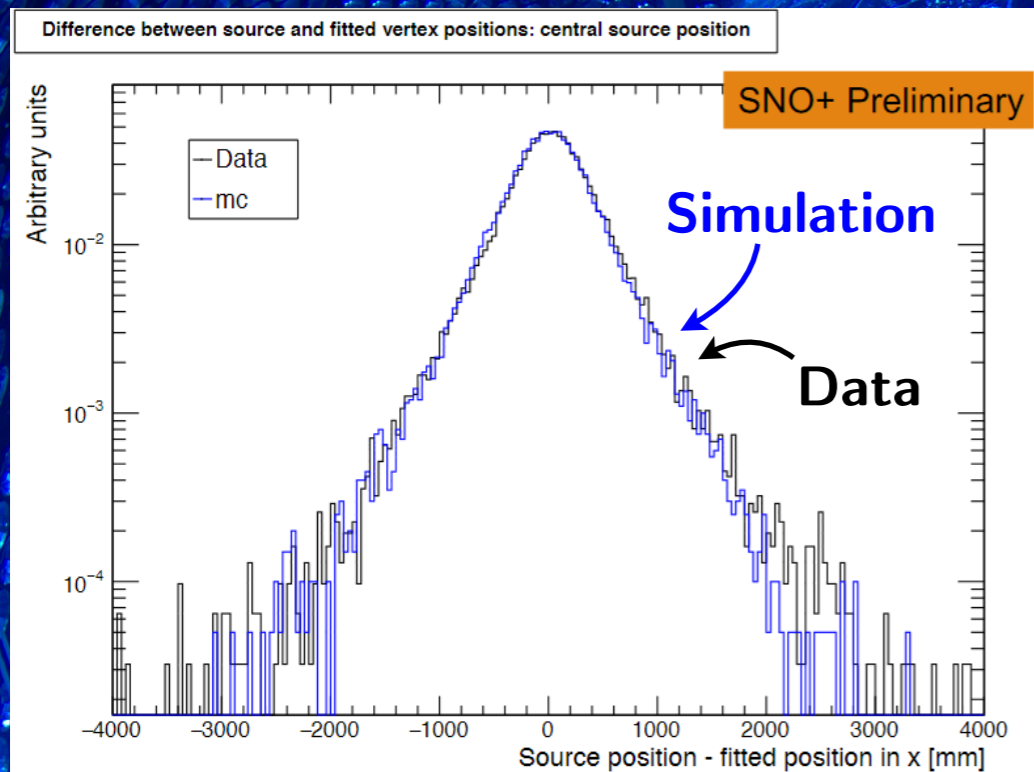
Deployment in Detector



Calibration Sources





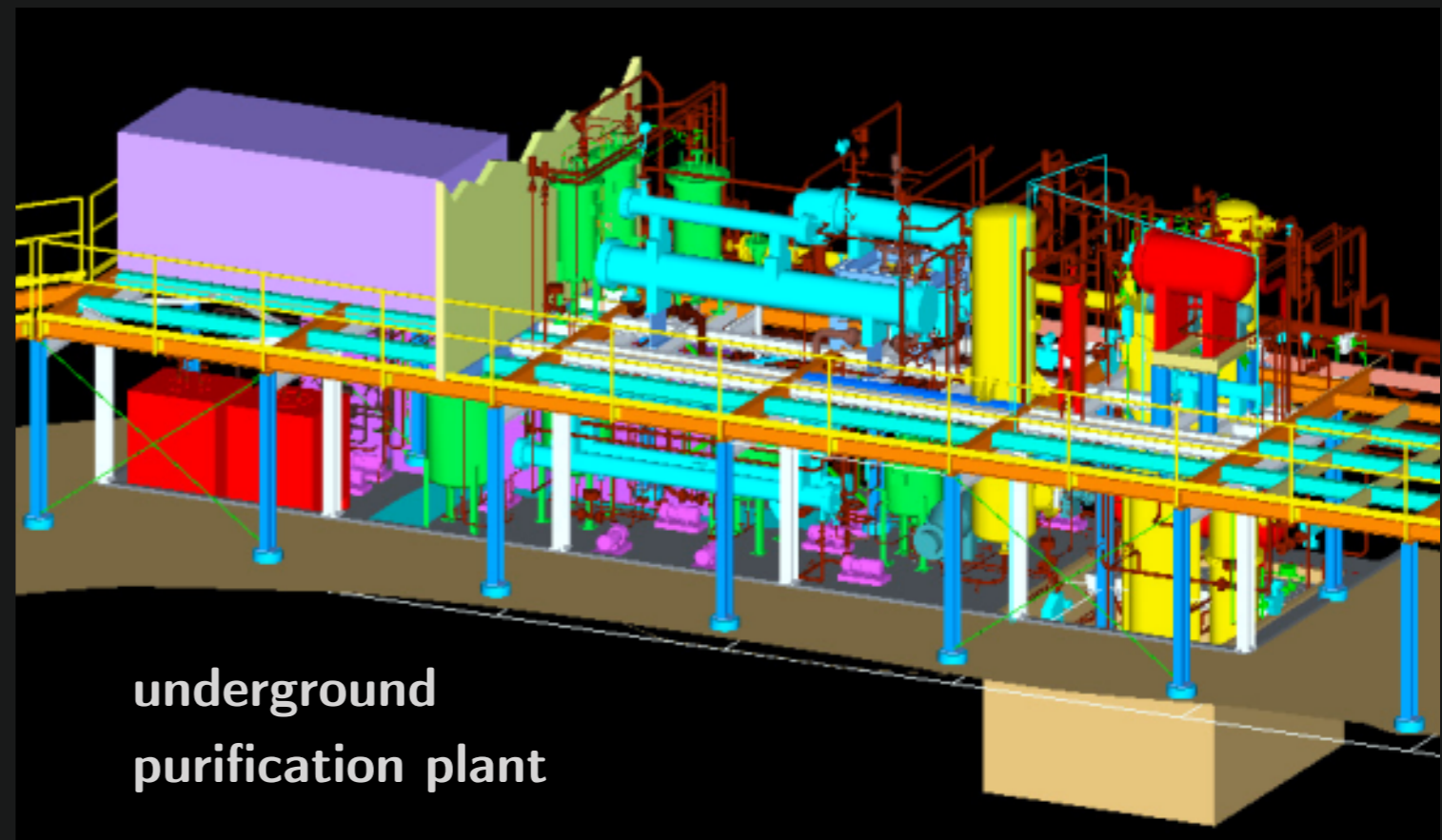


Technical Challenges

1000 tonnes of ultra high
purity liquid scintillator
... a mile underground

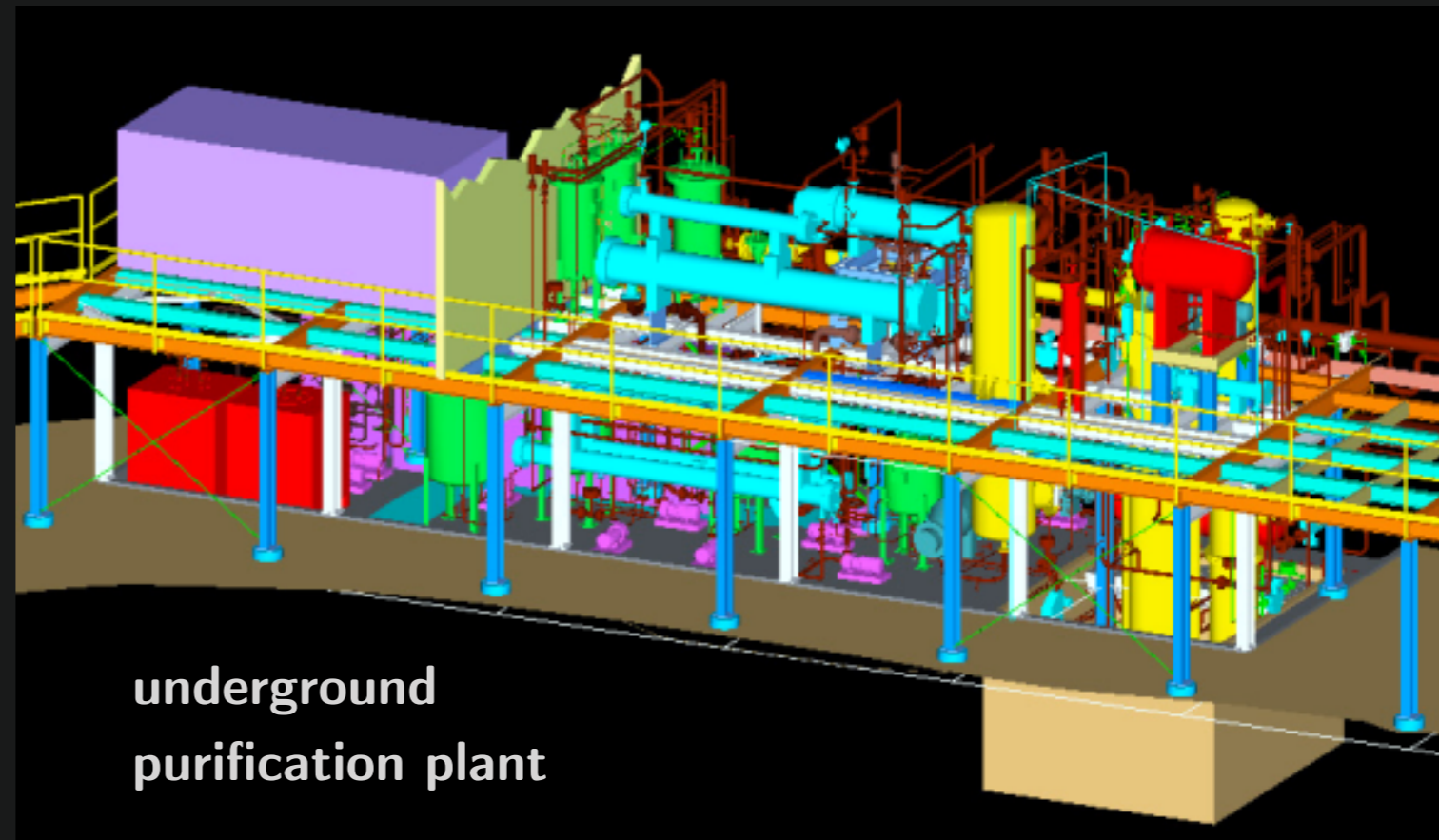
Technical Challenges

1000 tonnes of ultra high
purity liquid scintillator
... a mile underground



Technical Challenges

1000 tonnes of ultra high
purity liquid scintillator
... a mile underground



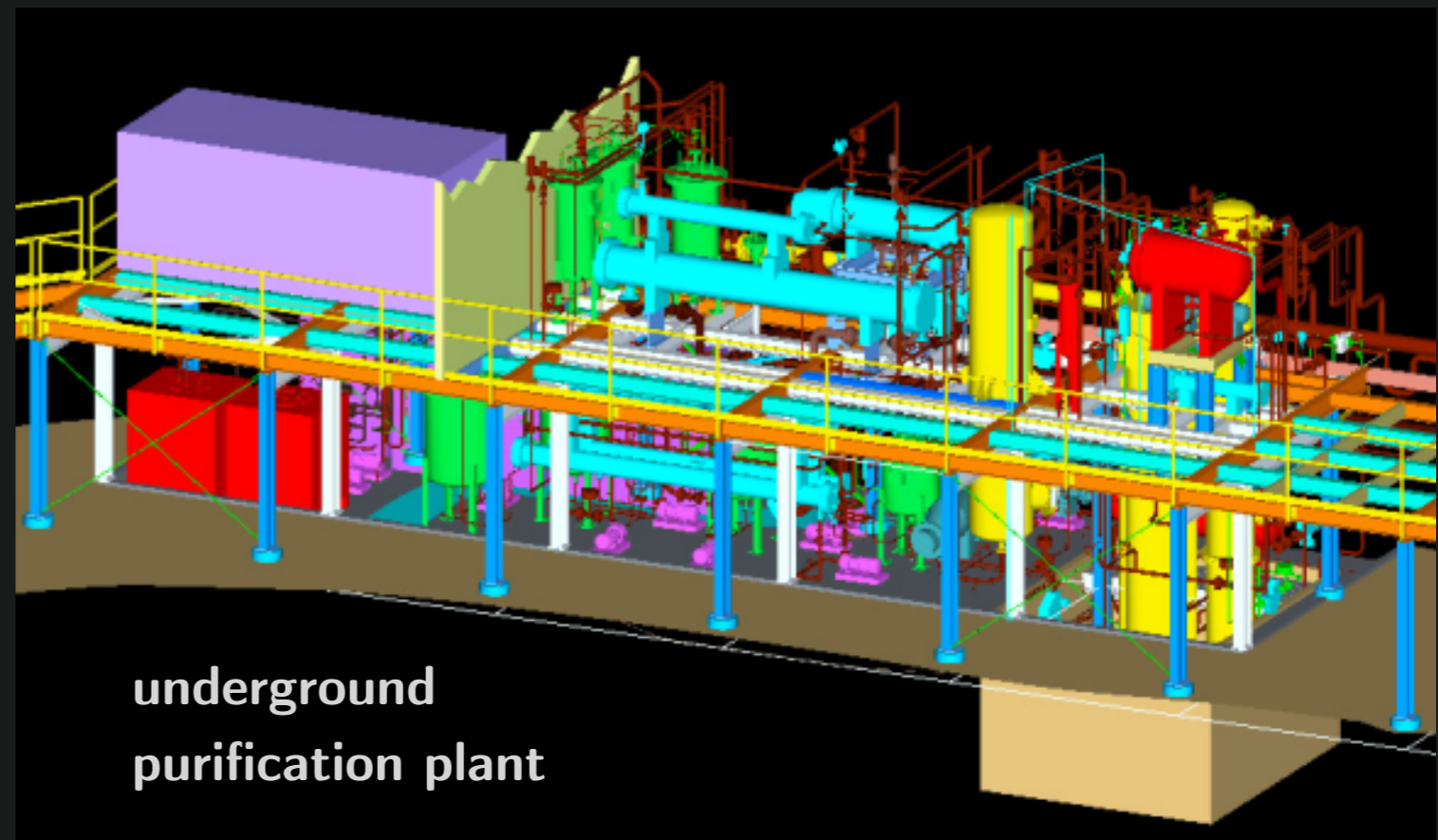
underground
purification plant



over 5,200 feet of pipes, and 4,000 welds

Technical Challenges

1000 tonnes of ultra high
purity liquid scintillator
... a mile underground



underground
purification plant



over 5,200 feet of pipes, and 4,000 welds

scintillator brought in on rail cars

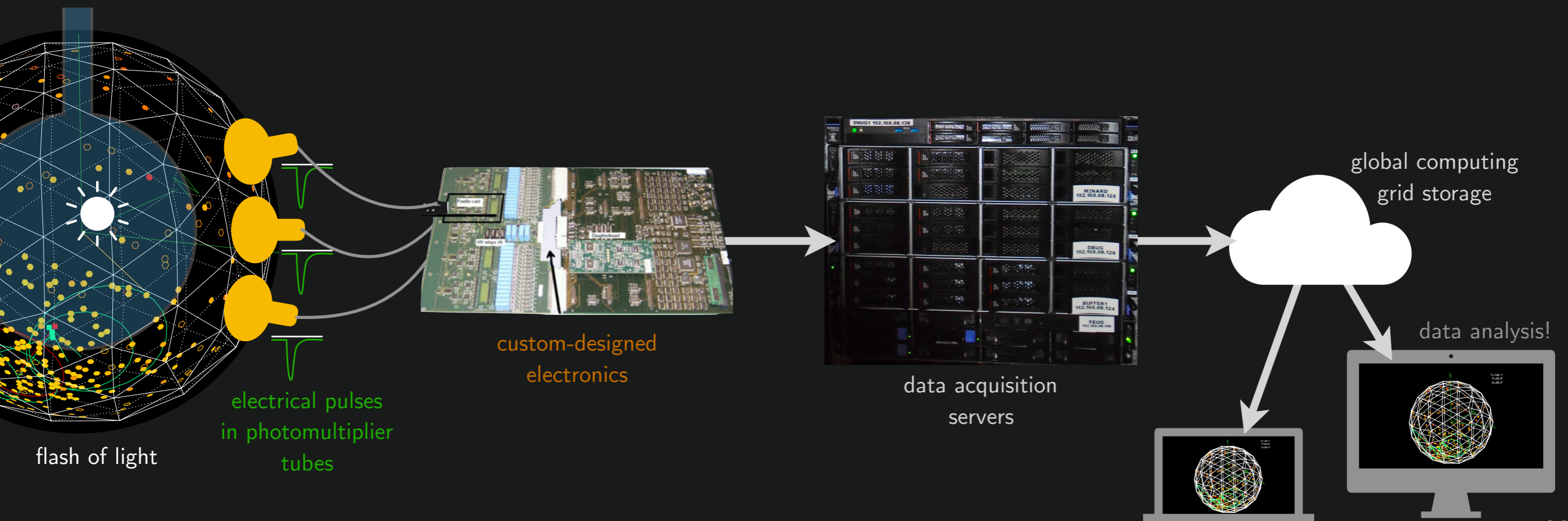


Technical Challenges

Need to record the signals
from **10,000** light detectors

Technical Challenges

Need to record the signals from **10,000** light detectors



Technical Challenges

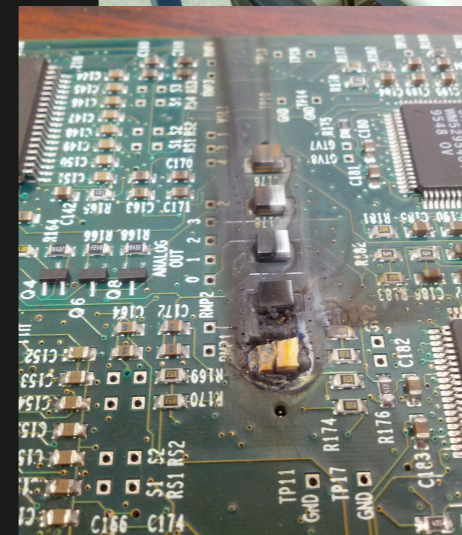
Need to record the signals from **10,000** light detectors



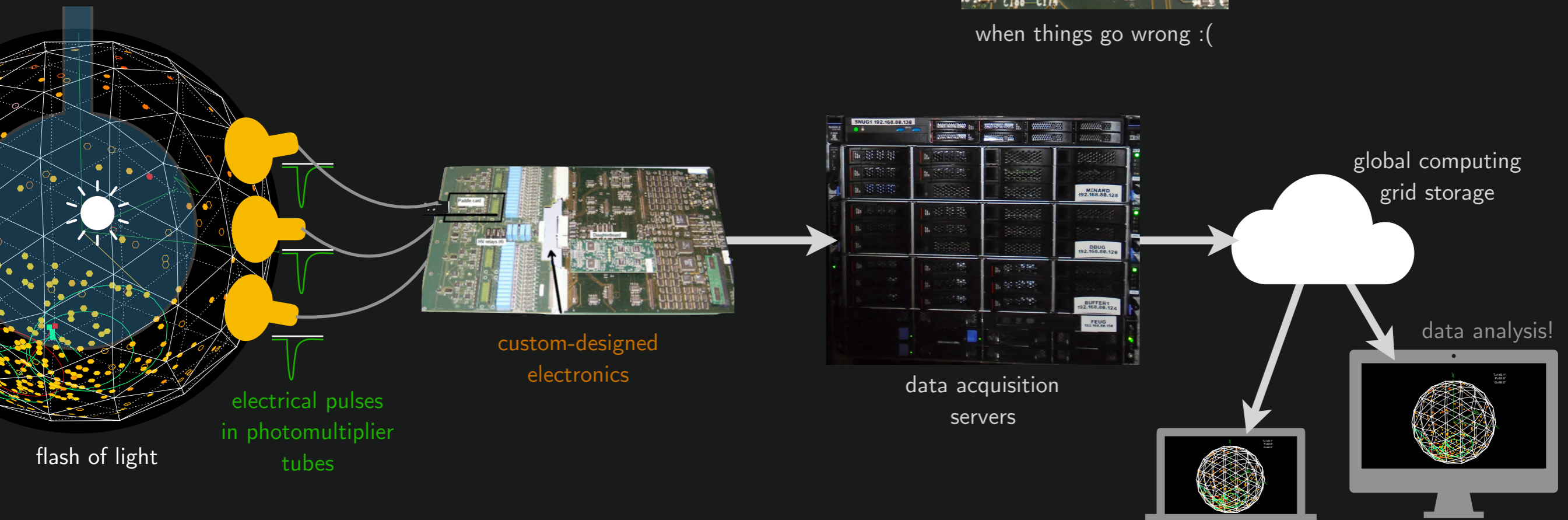
electronics
"maintenance"



a lot of TLC



when things go wrong :(



Status

May 2017

Start of Water Phase

Detector filled with ultra-pure water

- Similar configuration to SNO
- Understanding detector & backgrounds
- Search for proton decay (beyond the SM)

Fall 2018

Start of Scintillator Phase

Detector filled with ultra-pure scintillator

- Solar neutrinos, reactor & geoneutrinos
- Understanding the scintillator

Early 2019

Start of Double-Beta Phase

Isotope ^{130}Te added to the scintillator

- Search for neutrinoless double-beta decay

Collaboration



Queen's University
University of Alberta
Laurentian University
SNOLAB
TRIUMF



BNL, AASU
Penn, UNC, BHSU
U. Washington
UC Berkeley/LBNL
Chicago, UC Davis



Oxford
Sussex
QMUL
Liverpool
Lancaster



LIP Lisboa
LIP Coimbra



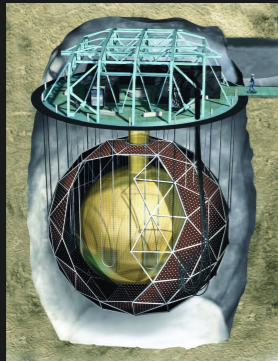
TU Dresden



UNAM

The Future is **BIG**

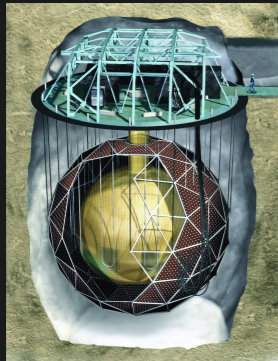
SNO⁺



780 tonnes
liquid scintillator

The Future is **BIG**

SNO⁺

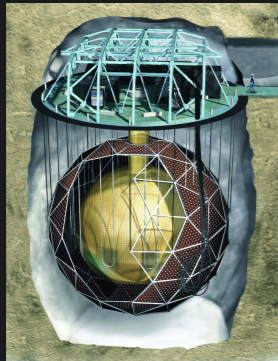


780 tonnes
liquid scintillator



The Future is **BIG**

SNO+

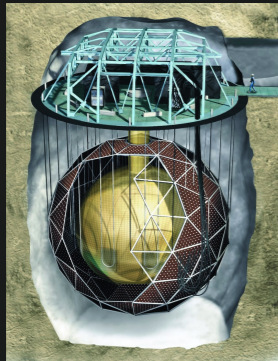


780 tonnes
liquid scintillator



The Future is **BIG**

SNO+



780 tonnes
liquid scintillator



Many other promising
technologies under
development around
the world!

CUORE
MAJORANA
GERDA

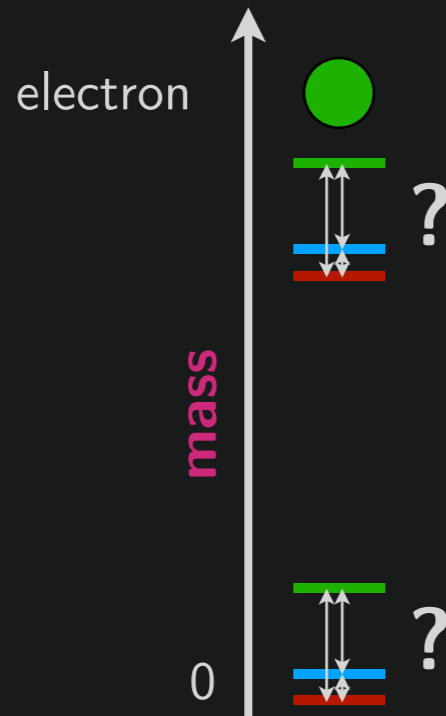
EXO/nEXO
NEXT
KamLAND-Zen

PandaX-III
SuperNEMO

A very exciting,
highly competitive
field



Neutrino Mass



Neutrino oscillations teach us about mass **differences**, but not the absolute scale

Measuring the mass can address questions of fundamental significance:

- Anything beyond the Standard Model?
- Neutrinos' role in the universe's matter/antimatter imbalance?

Beta Decay

Neutrino mass affects electron energy



KATRIN

Cosmology

Weighing the neutrino using structures in the universe

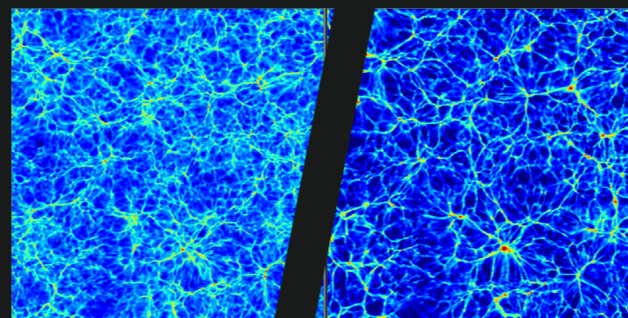


Image: Agarwal and Feldman

Neutrinoless Double Beta Decay

Beyond the Standard Model
 $\text{neutrino} = \text{antineutrino}$



Planisphaerium

Neutrinorum

Terra Cognita I
($\vartheta_{12}, \Delta m^2_{12}$)

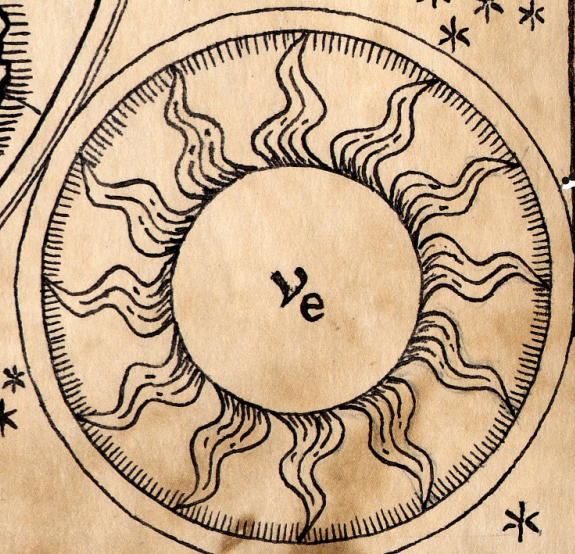
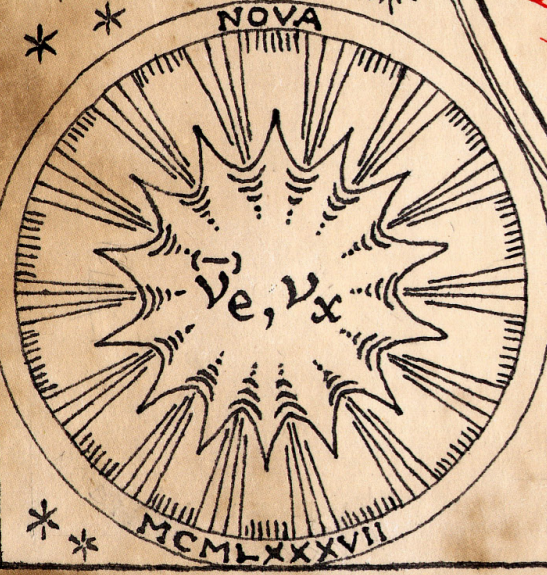
Terra Incognita I
($\vartheta_{13}, \delta_{13}, \nu_s, \dots$)

Atlas

Coelestis

Terra Incognita II
(m_s, ν_s, \dots)

Terra Cognita II
($\vartheta_{23}, \Delta m^2_{23}$)



NOW

MMIV

ELIGIO LISI



Thank You!

