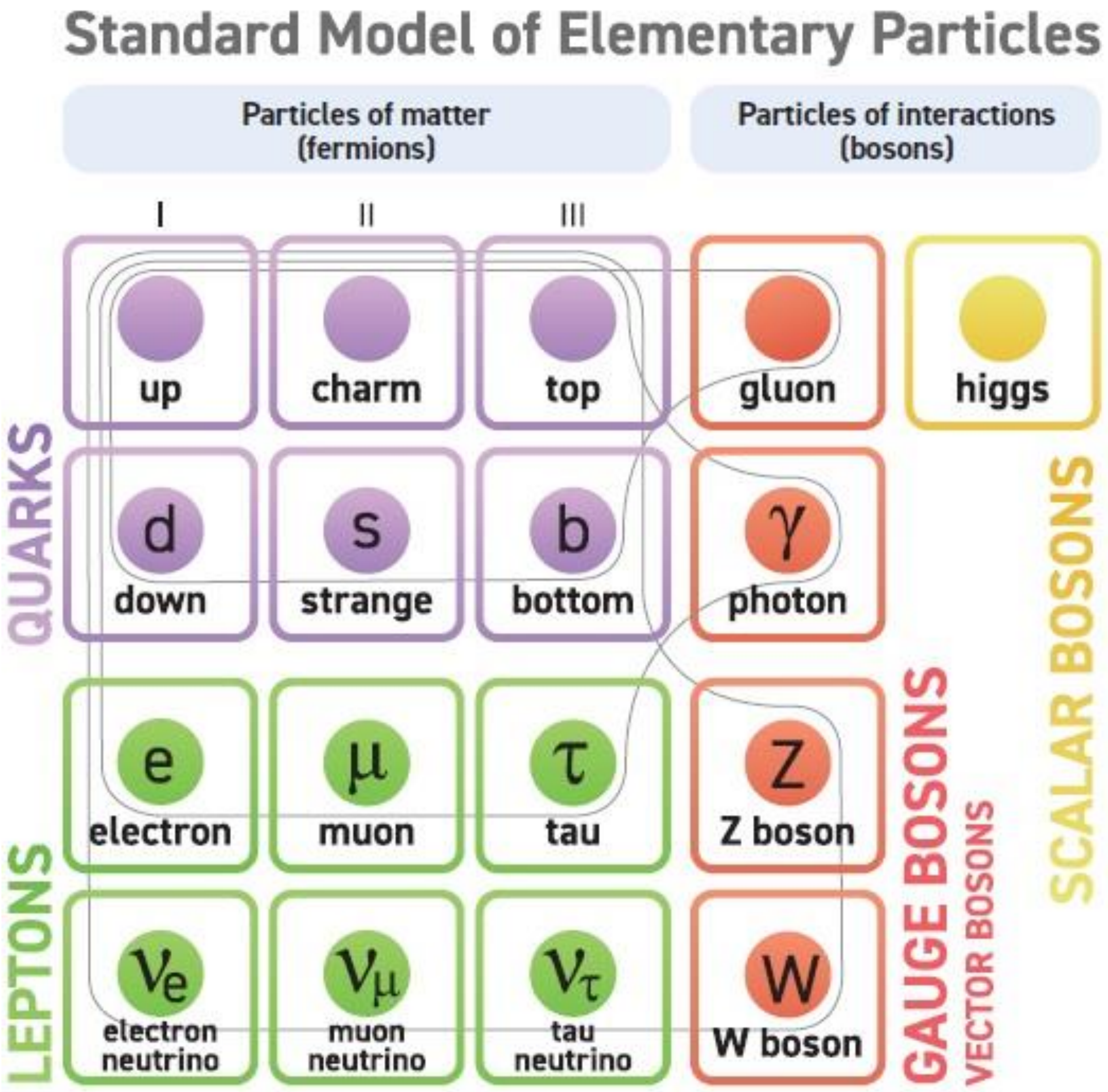
Neutrino detectors

Dan Pershey (Florida State University) – Jul 15, 2024

Second school on neutrino and dark matter detection
South American Institute for Fundamental Research

Q1: Are there neutrino interactions beyond weak force?



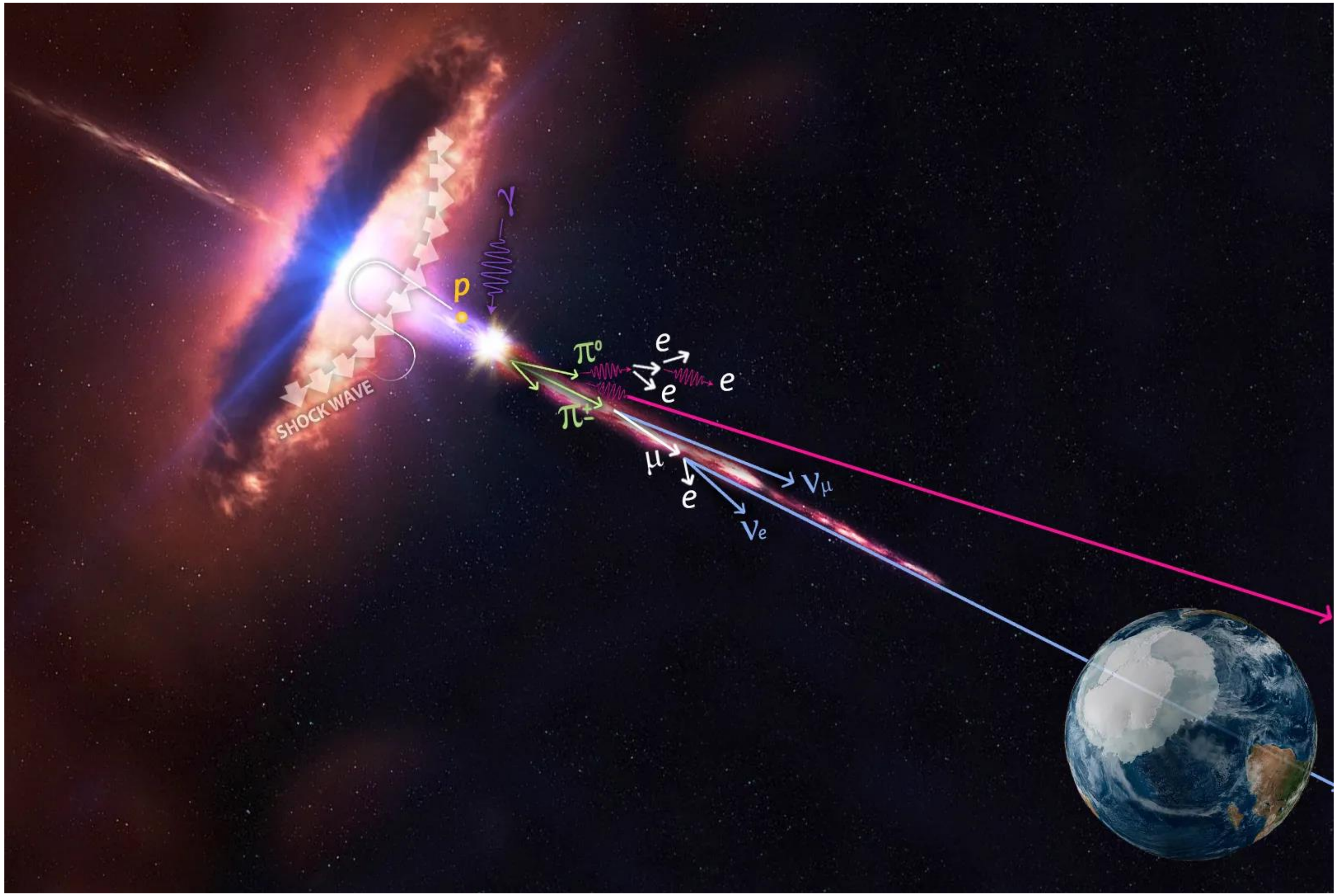
Neutrino cross sections are notoriously low. Could participate in additional forces, even stronger than the weak force.

Recent progress in low-energy neutrino scattering is illuminating cross-over between non-standard interactions and dark matter and more

Q2: How will neutrino advance astronomy?

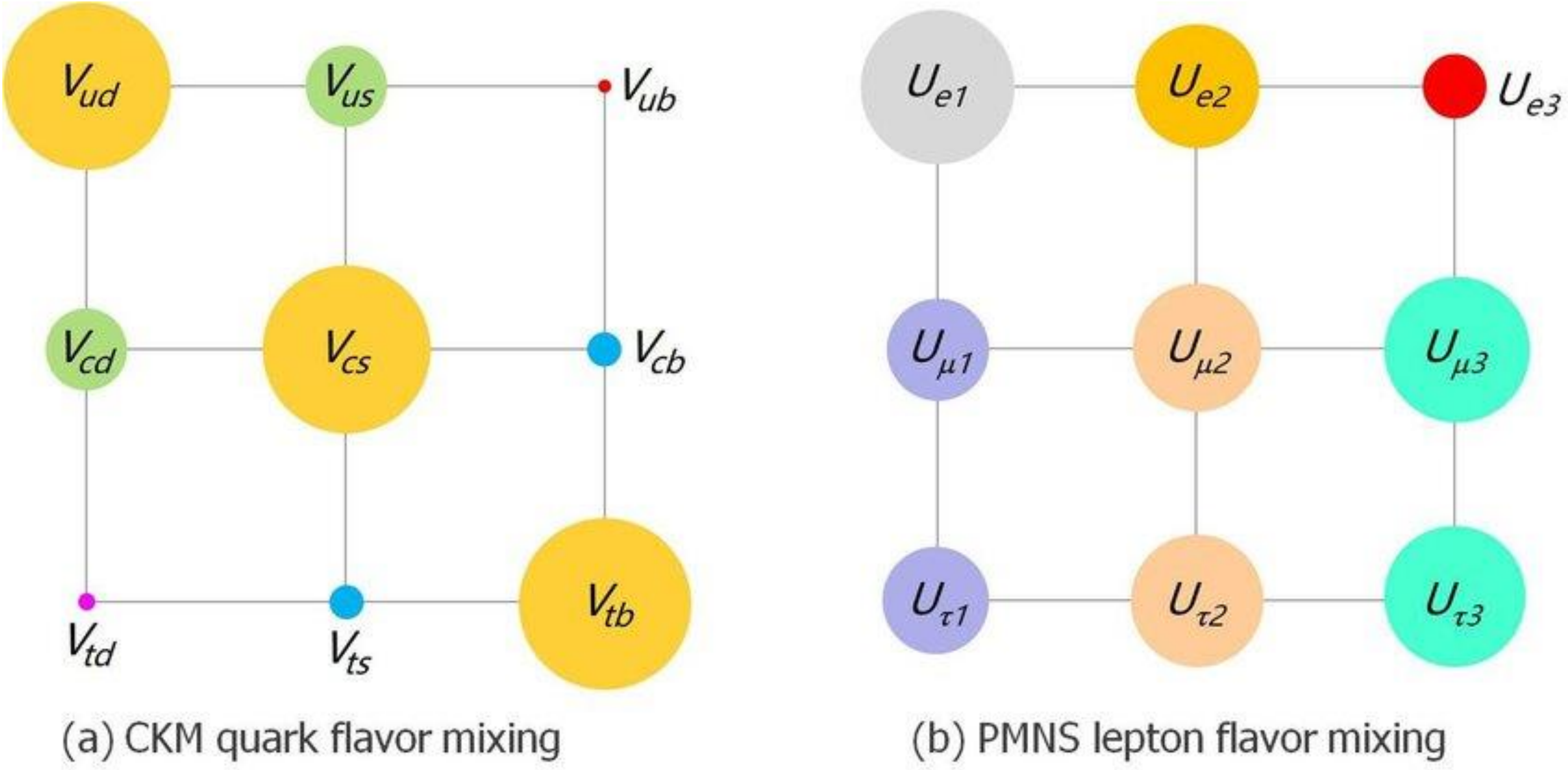
Neutrinos – most directly able to probe interiors of complex astrophysical objects – are becoming critical pillar of multi-messenger astronomy

How will discoveries from SN 1987a and IceCube shape the future in a precision era?



Q3: Why are the neutrino and quark mixings so different?

Like quarks, neutrinos mix – but without a hierarchical structure. Will future precision measurements of neutrino oscillation steer direction for neutrino mass model work



(a) CKM quark flavor mixing

(b) PMNS lepton flavor mixing

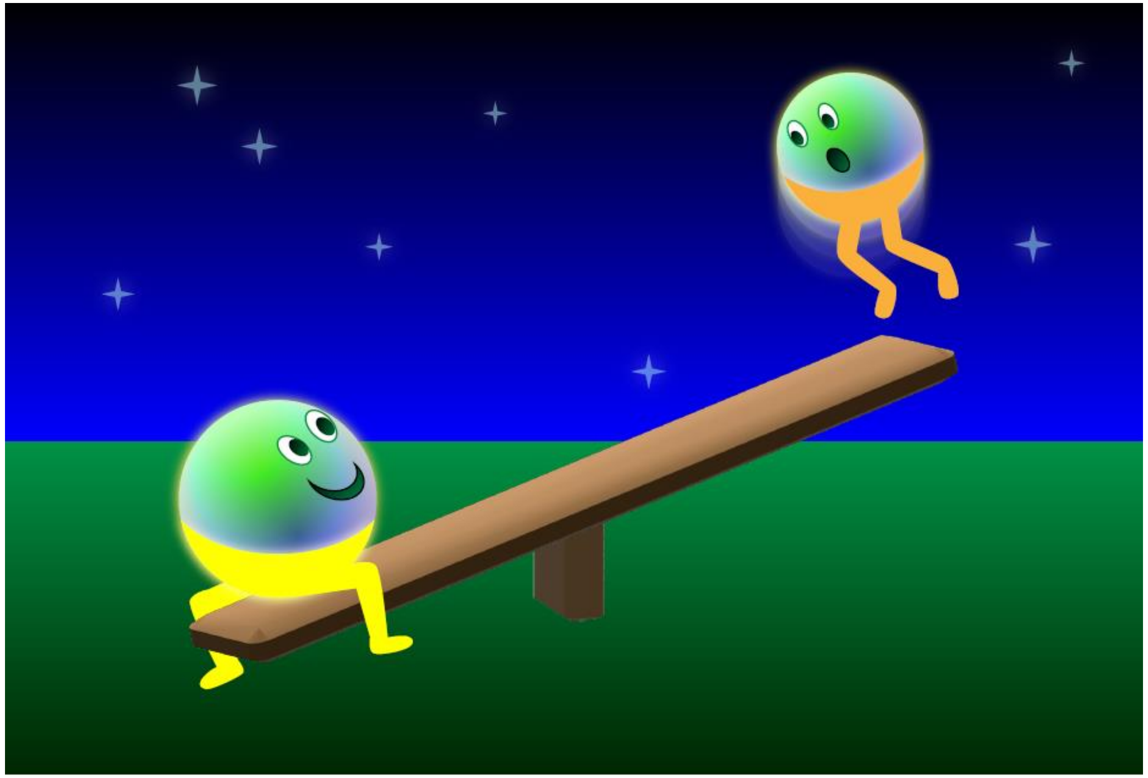
Zhi-Zhong Xing, *Rept. Prog. Phys.* **86** 076201 (2023)

Q4: Are neutrinos Dirac or Majorana?

Are ν and $\bar{\nu}$ different particles or merely different helicity states of the same particle

If Dirac, mass could be tiny Yukawa coupling to Higgs

If Majora, seesaw model could explain why neutrino masses are so small



Outline for this week

- ❑ Lecture 1: Introduction and neutrino detectors
- ❑ Lecture 2: Neutrino interactions
  - *Q1: Are there neutrino interactions beyond weak force?*
- ❑ Lecture 3: Neutrino astrophysics
  - *Q2: How will neutrino astronomy characterize the universe?*
- ❑ Lecture 4: Oscillations I
  - *Q3: Why are the neutrino and quark mixings so different?*
- ❑ Lecture 5: Oscillations II and direct mass measurements
  - *Q4: Are neutrinos Dirac or Majorana?*

How big should our detector be?

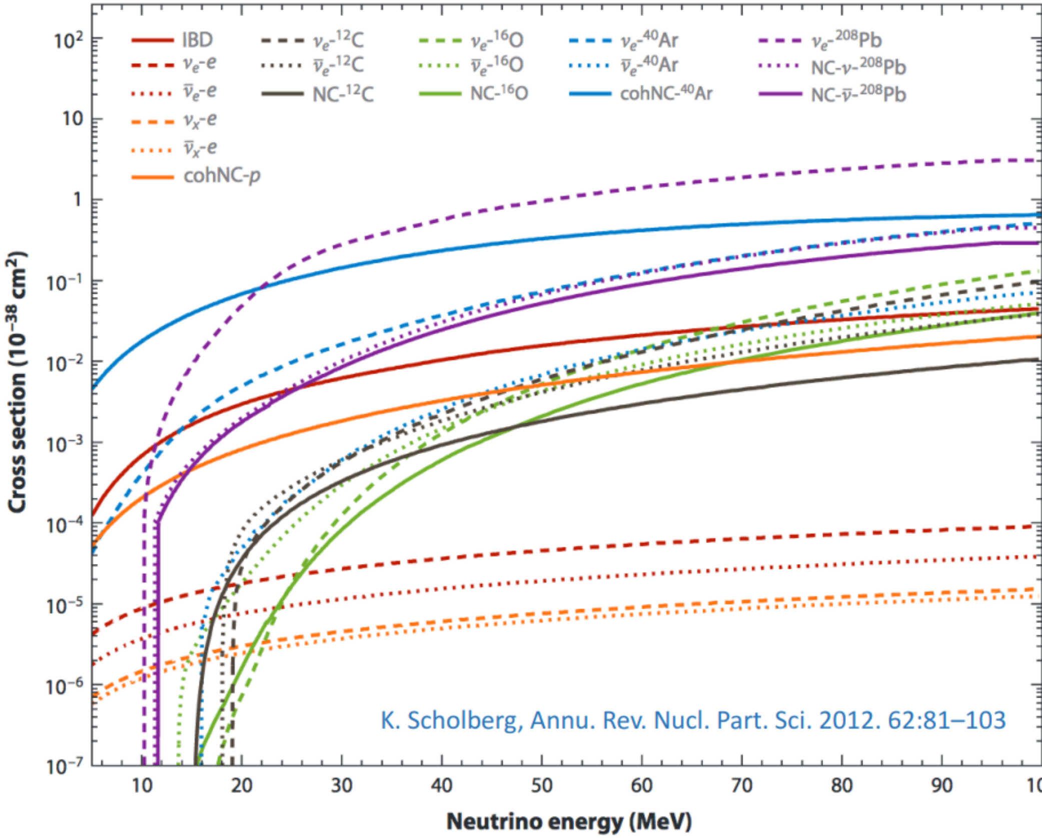
Scales of detectors set by their cross sections

@ 7 MeV, σ ~ 1e-42 cm^2 in argon

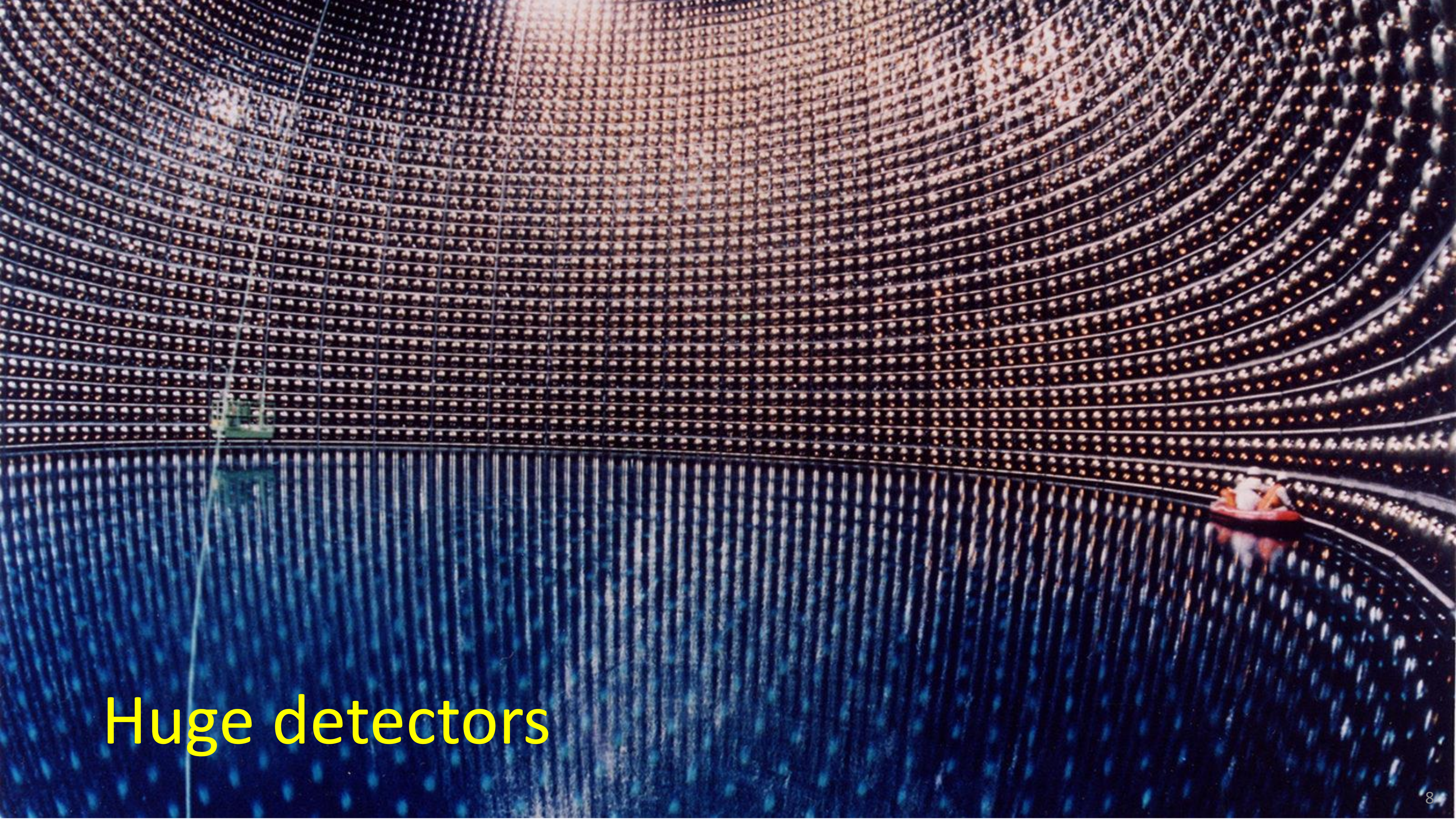
How much liquid argon do we need to shield neutrinos?
Depends on number density of Pb and cross section
L = 1/nσ = 1/((1.4 g/cm^3 x 6.02e23/40 g) x 1e-42 cm^2)
= 4e17 m = <u>400 light years</u>

How much detector do we need to record one solar ^8B neutrino per day?
Rate = n x Vol x σ x ϕ → Vol = (1/day)/(n σ ϕ)
Vol = (1/day)/(2.1e22/cm^3 x 1e-42cm^2 x 2.5e6 ν/cm^2/s)
→ <u>mass of at least 300 tons</u>

Low-energy neutrino cross sections



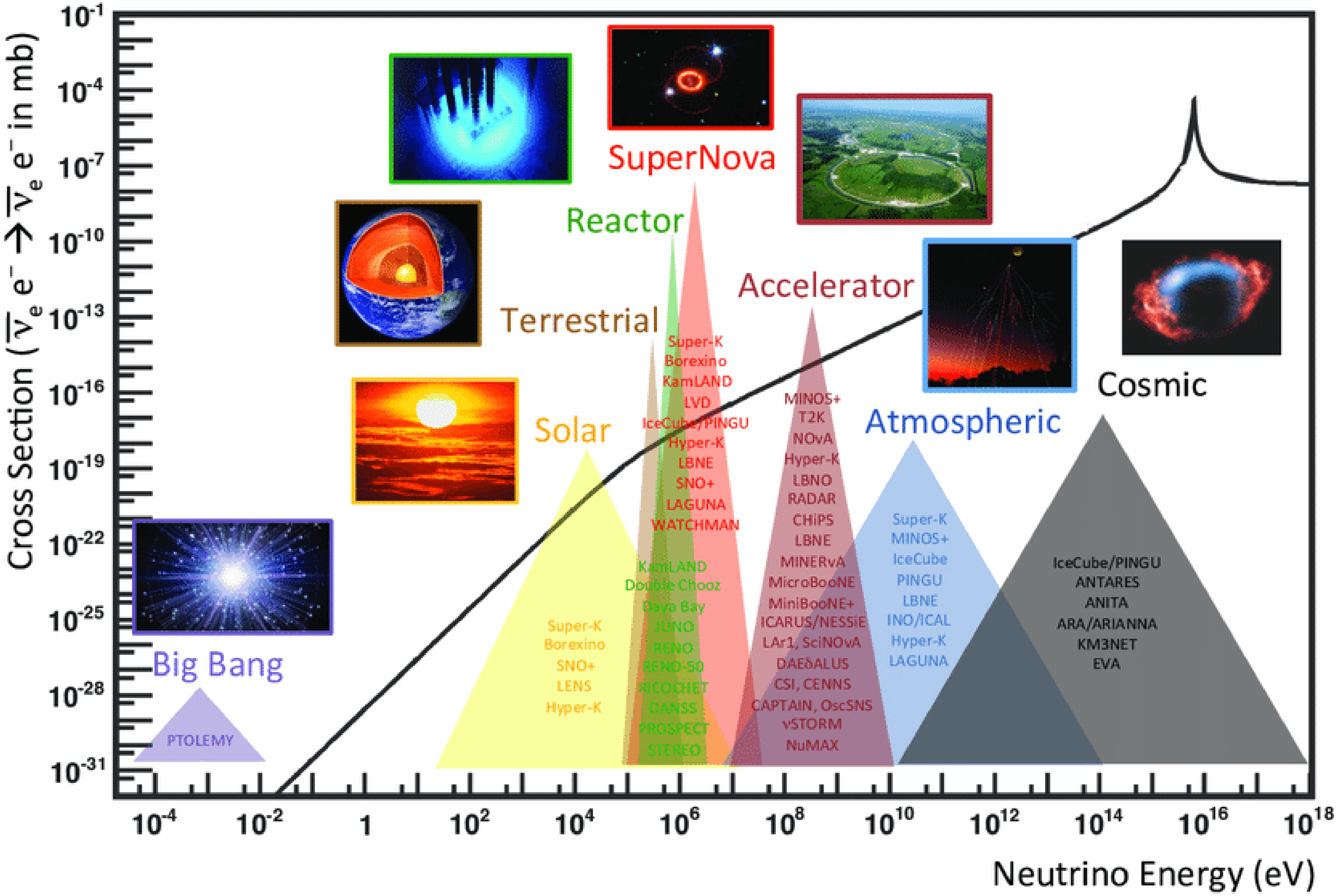
K. Scholberg, Annu. Rev. Nucl. Part. Sci. 2012. 62:81–103



Huge detectors

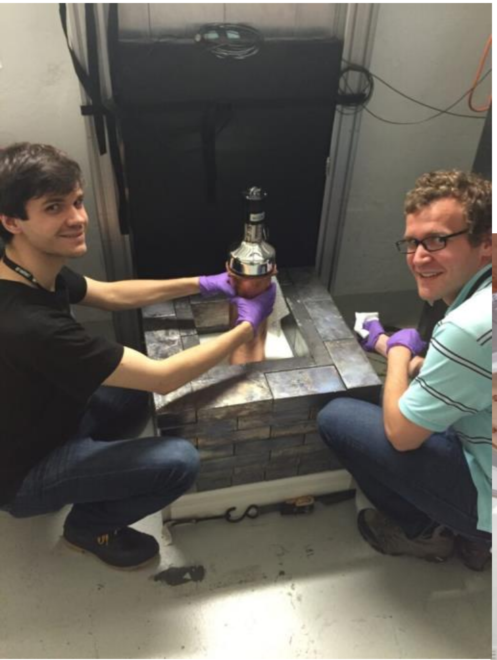
And intense sources

Neutrinos connected to big questions but hard to study. Luckily, the universe gives us plenty of sources to study! We can even make a couple ourselves



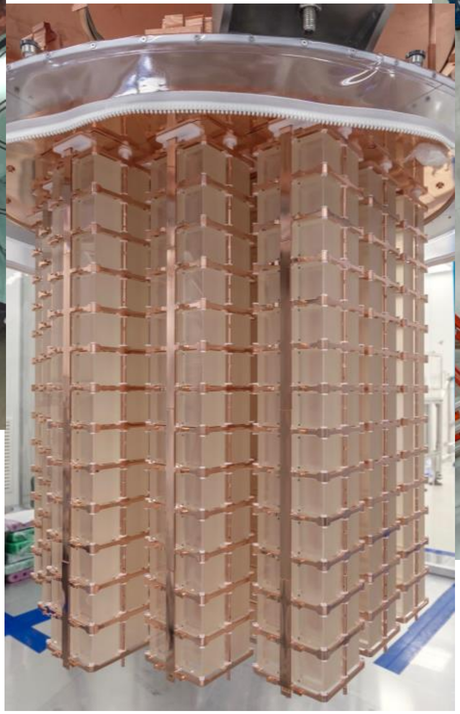
Detectors at all scales

keV MeV GeV TeV PeV



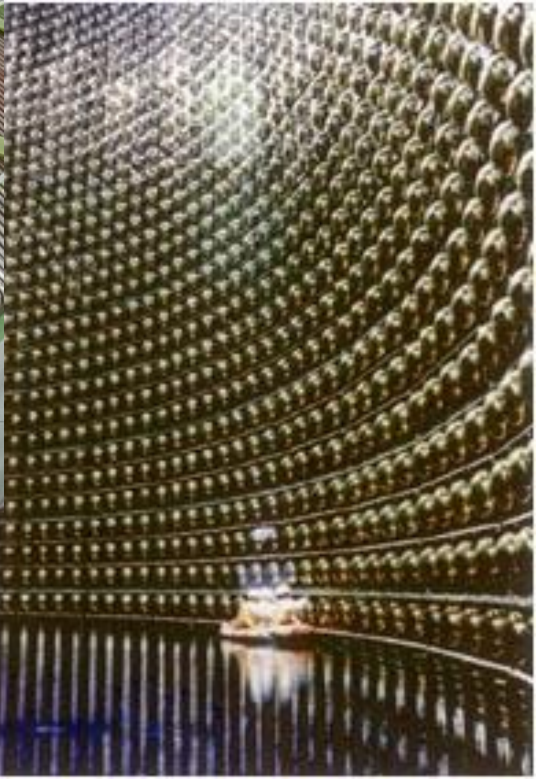
COHERENT
ν interactions
CsI (and others)

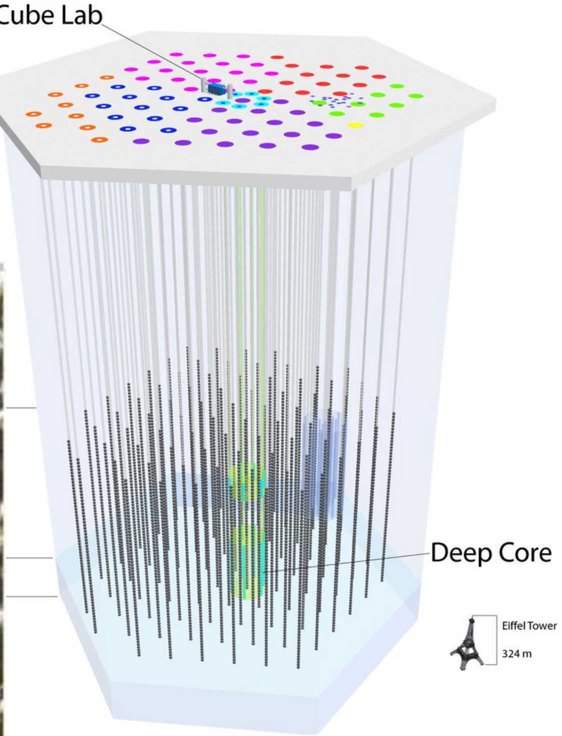
CUORE
0νββ
Neutrino mass



MicroBooNE
Osc
LArTPC

SuperK
Osc/astro
Water Cherenkov

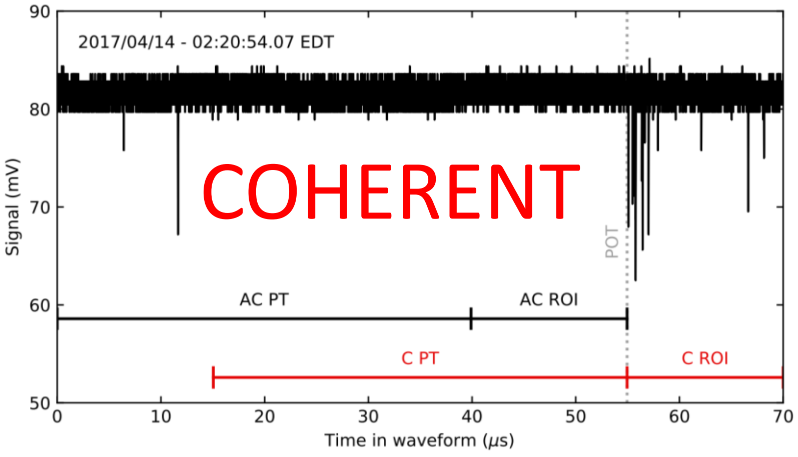




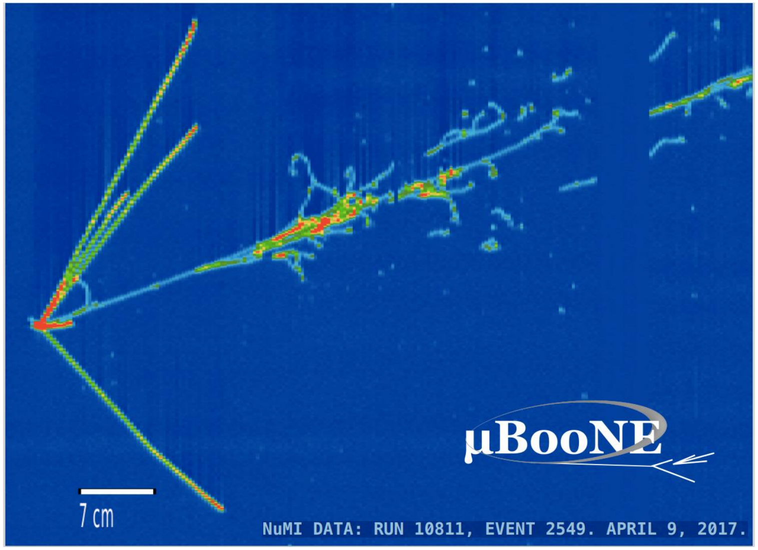
Icecube
Astro
Ice Cherenkov

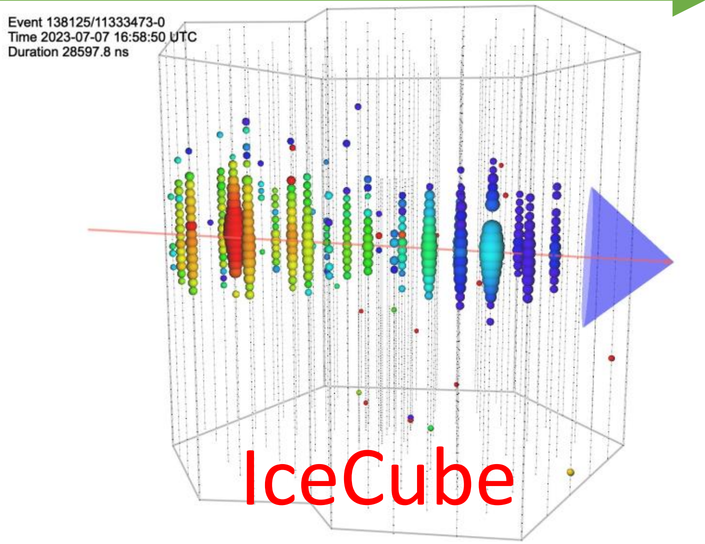
What neutrinos look like in these detectors

keV MeV GeV TeV PeV

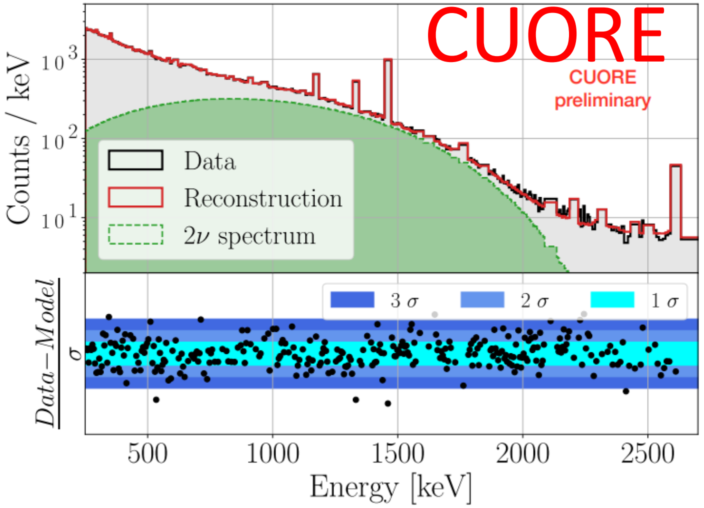


COHERENT





IceCube



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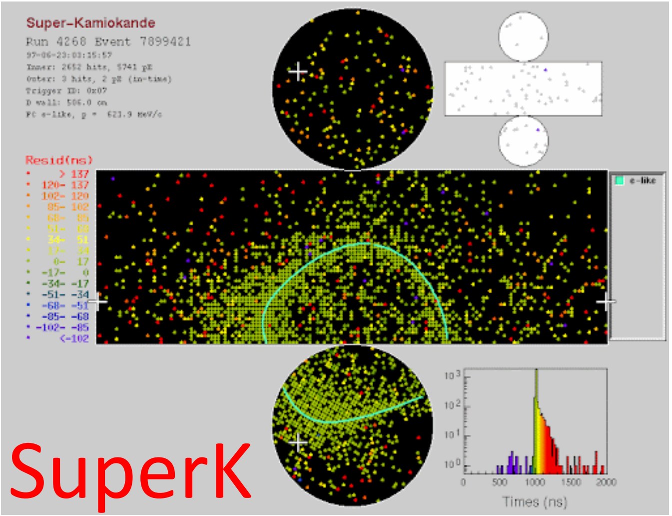


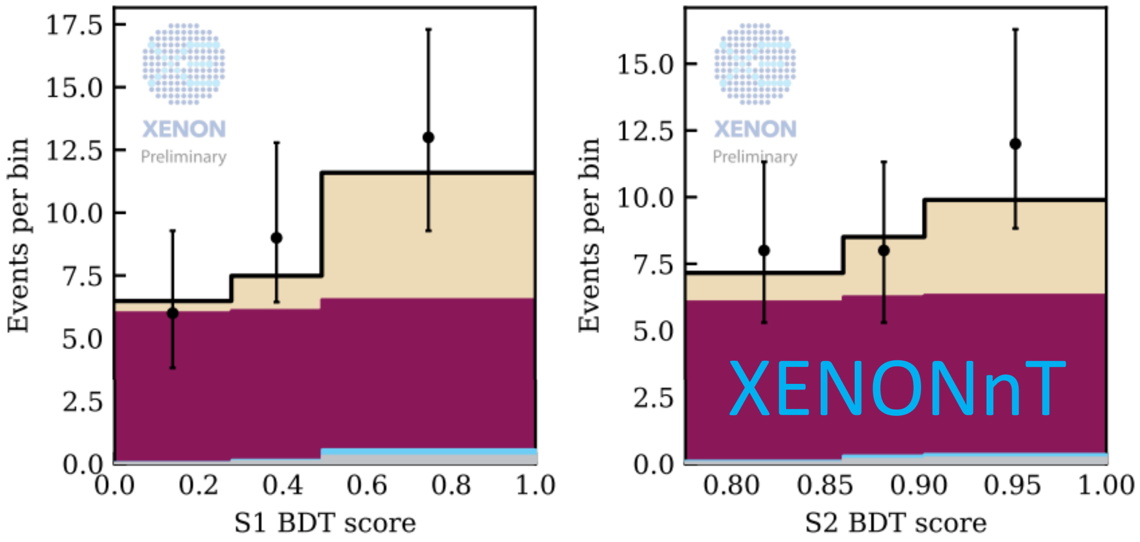
SuperK

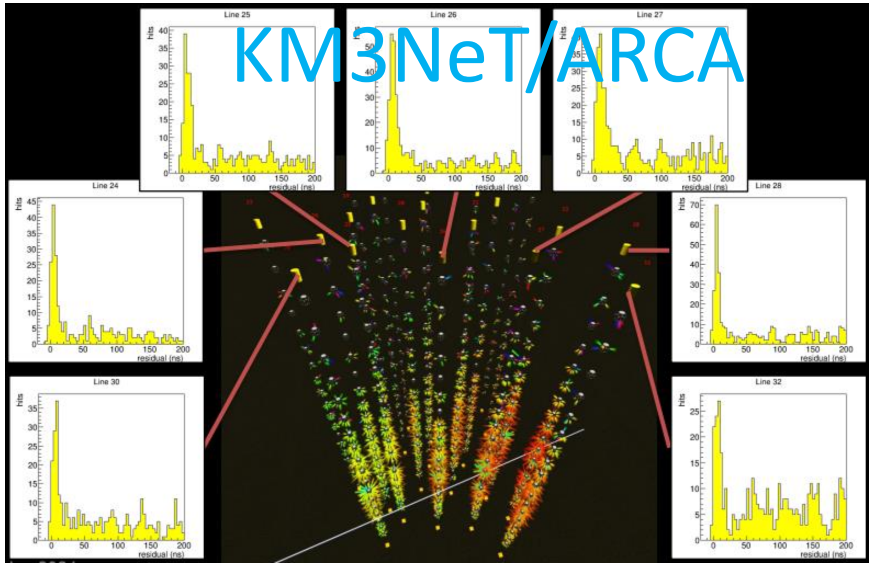
We’re constantly expanding on both frontiers!

New records in past month

< 1 keV

~ 10^{16} eV





Low-energy reactor neutrinos produce keV nuclear recoils

F. Gao, IDM 2024

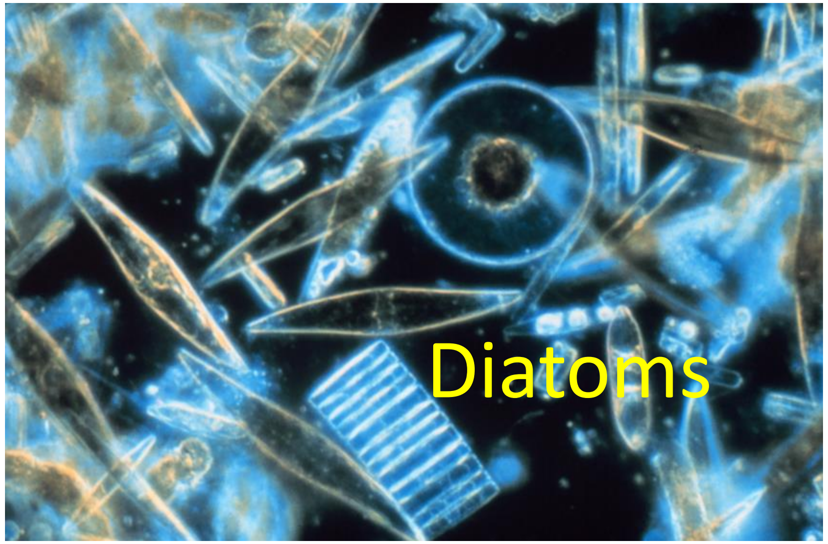
Rare cosmic neutrino (PeV’s) caught interacting in Mediterranean sea

J. Coelho, Neutrino 2024

Technology advancing to allow 10^{0} eV – 10^{21} eV detection

Huge range – comparing to biology

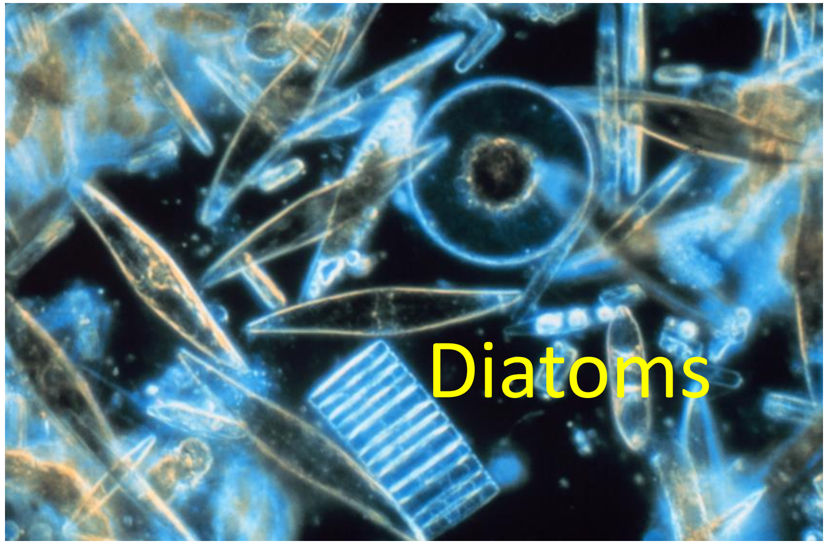
$\sim 10^{-8}$ g



$\sim 10^{6}$ g

Huge range – comparing to biology

$\sim 10^{-8}$ g



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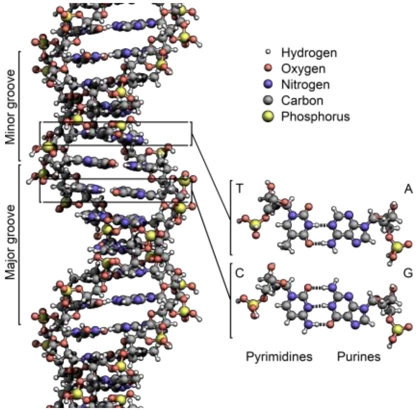
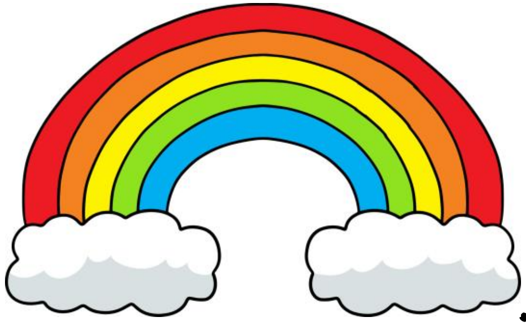


Biology uses different arrangements of four basic base pairs in DNA to produce complex types of life

Particle physics uses four basic mechanisms of energy loss for charged particles passing through matter

Future range – difference between human and covid 19 virus

The four basic mechanisms of neutrino detection



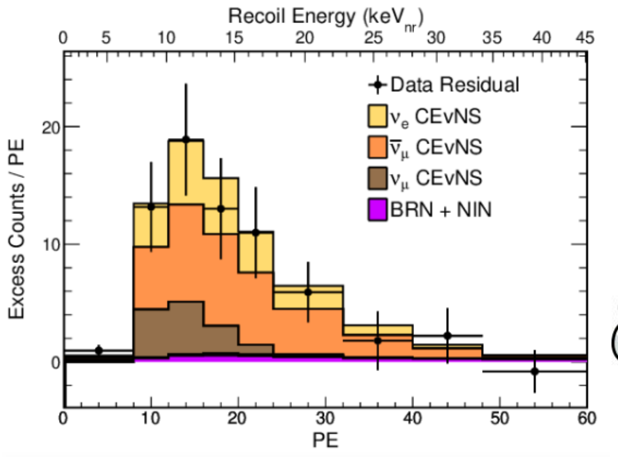
Scintillation

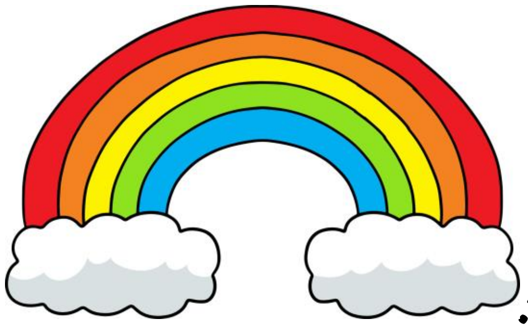
Cherenkov

Charge

Heat

The four basic mechanisms of neutrino detection





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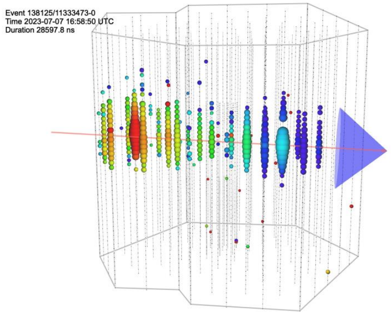
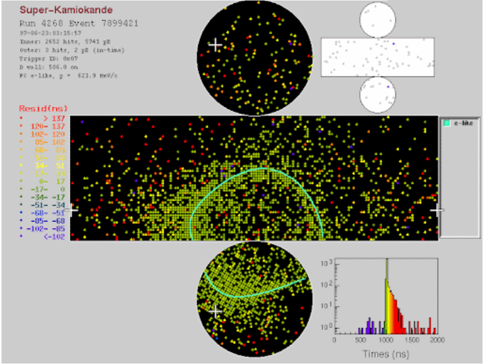
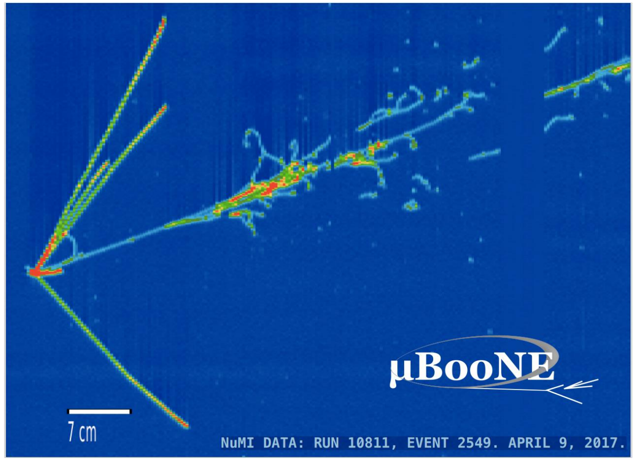
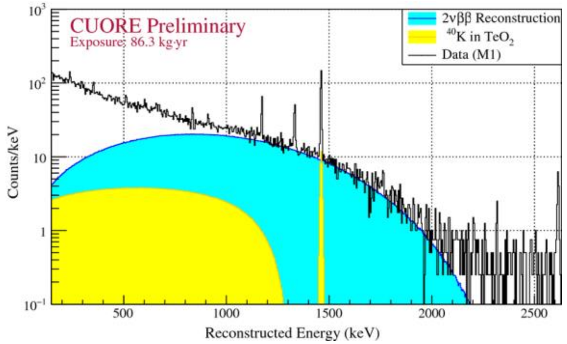






Charge

Heat



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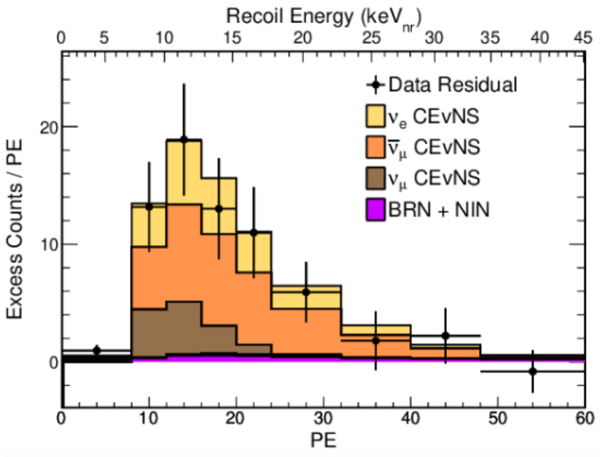

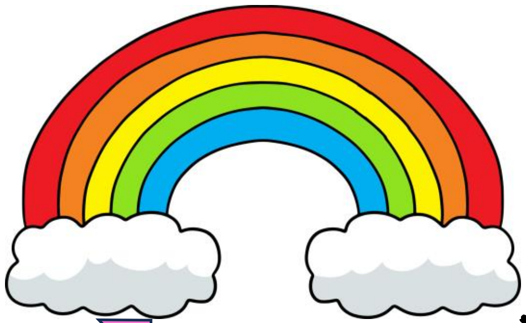

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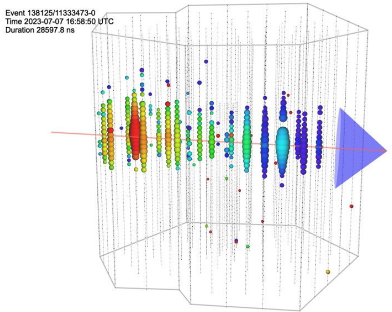

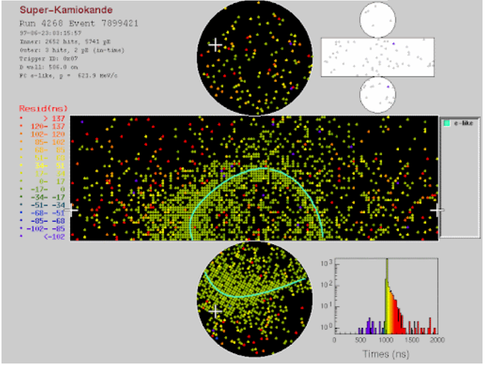

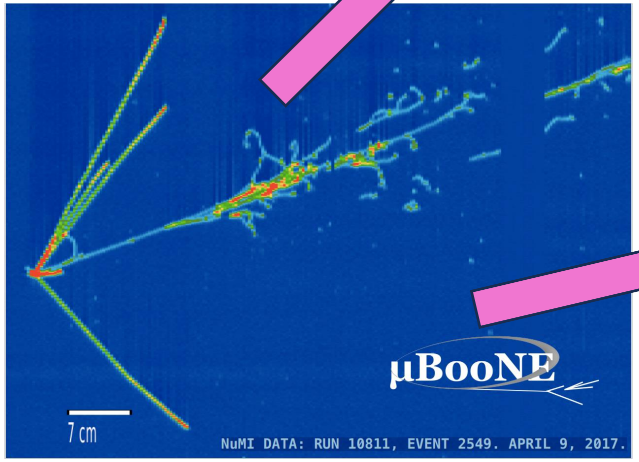

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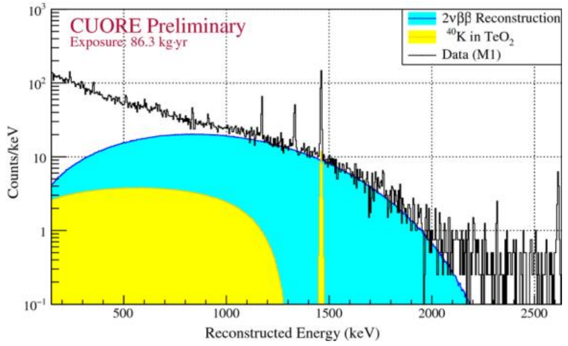
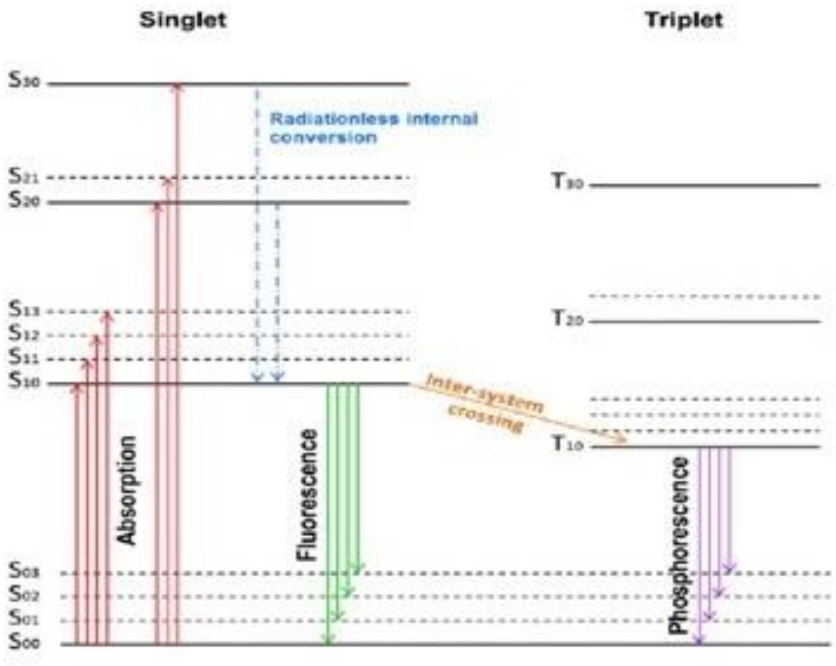


Scintillator detectors: first detection of the neutrino



Passing energetic particles excite atomic electrons to upper orbital – scintillation comes from subsequent deexcitation

Organic, inorganic, and noble element scintillators

Large variety of light yield, time-scales, physical properties to consider

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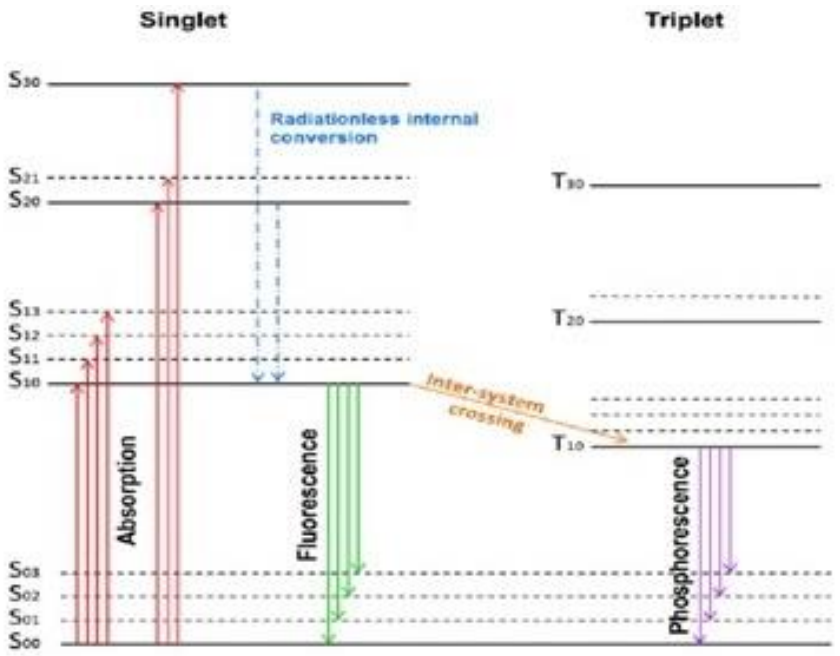

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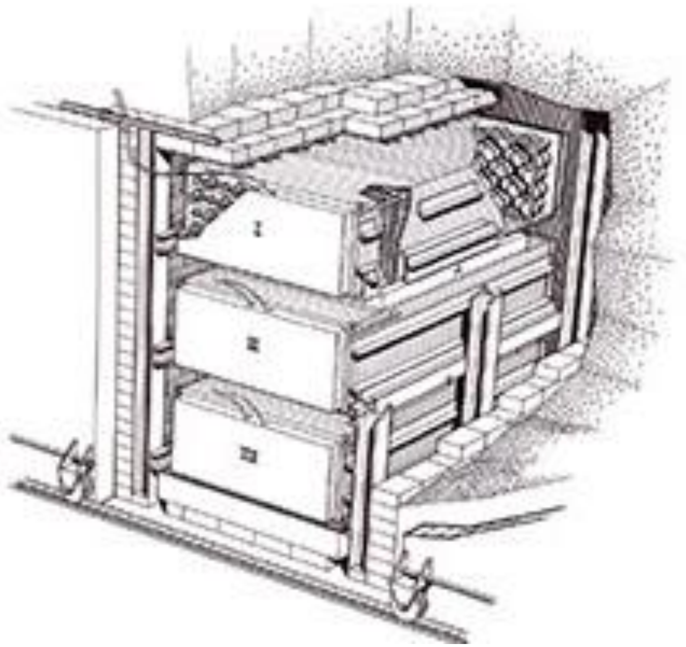
Organic, inorganic, and noble element scintillators

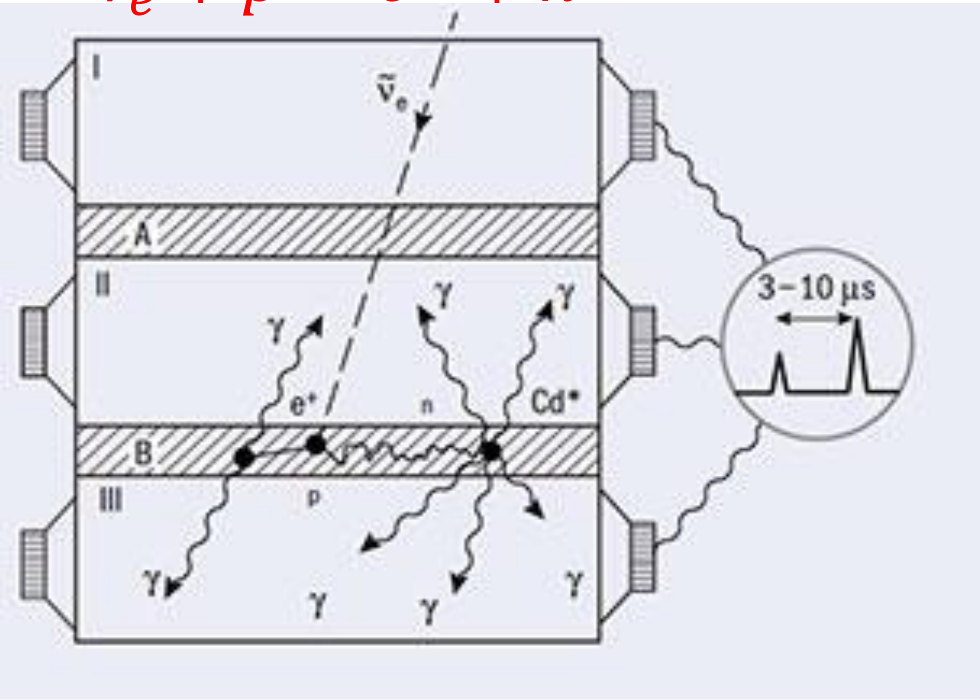
Large variety of light yield, time-scales, physical properties to consider

1956: Reines-Cowan experiment at Savannah River reactor

Background considerations: shielding and coincidence (e^+ annihilation and n capture)



$$\bar{\nu}_e + p \rightarrow e^+ + n$$

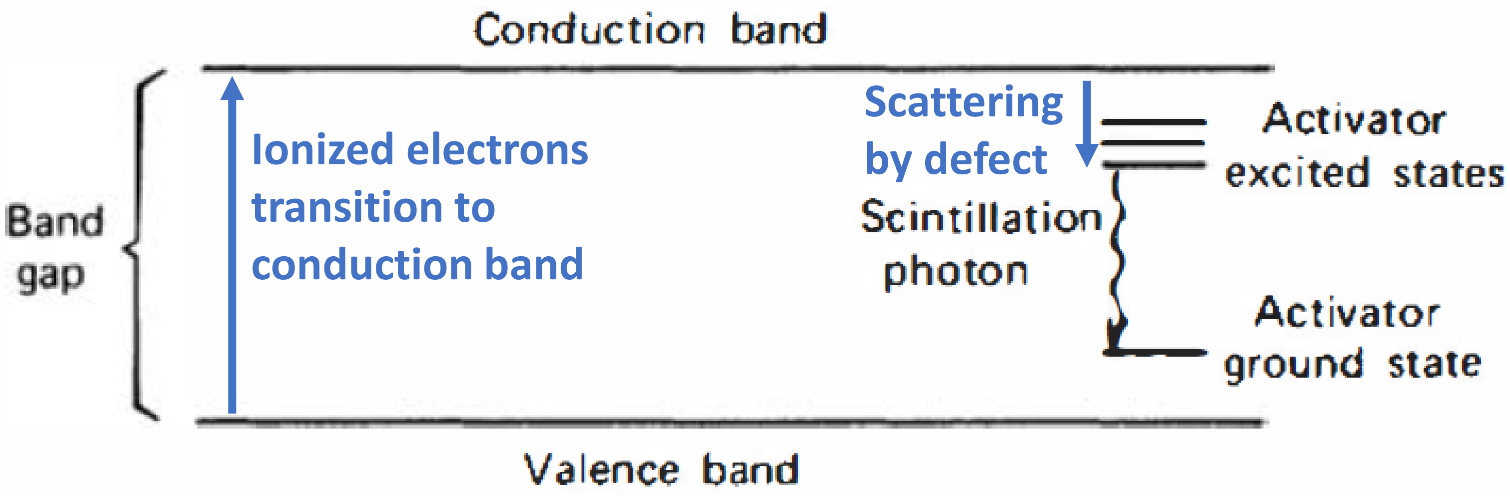


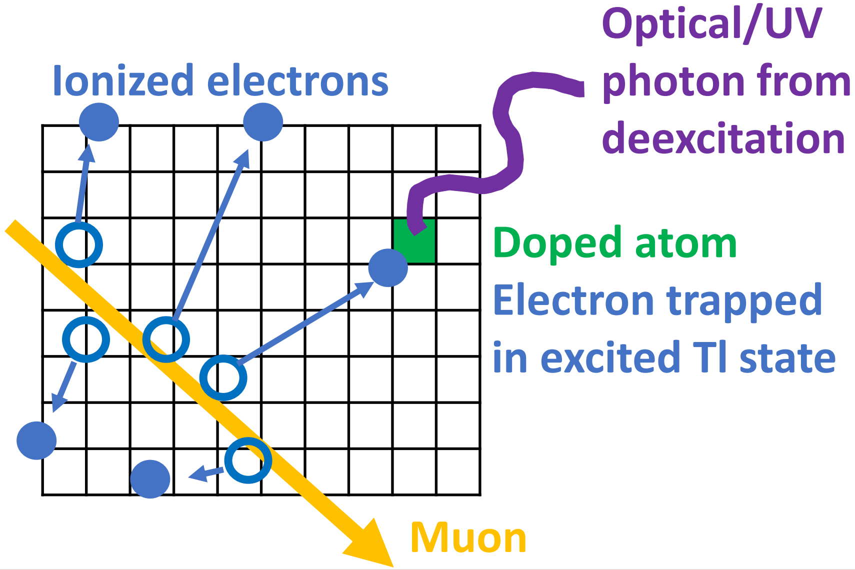
Scintillation: inorganic scintillating crystals

Inorganic crystal scintillation depends on band gap structure

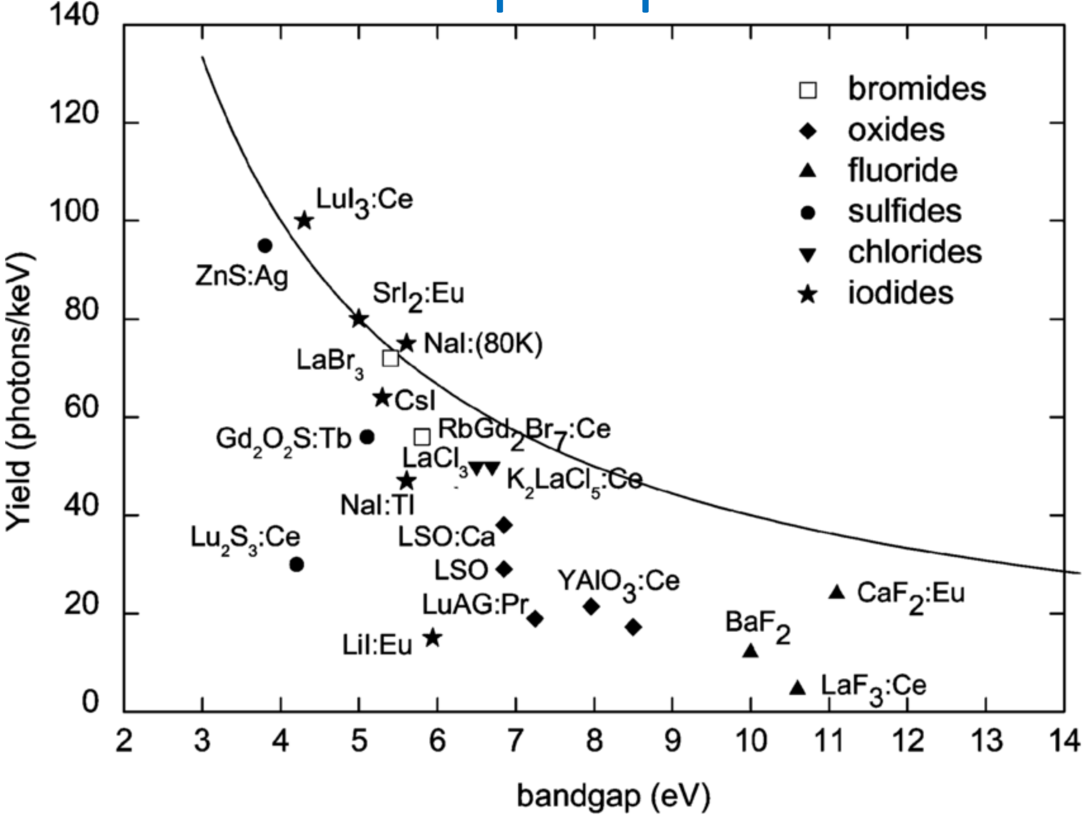
Crystals are opaque to photons at the band gap wavelength – dope the crystal!

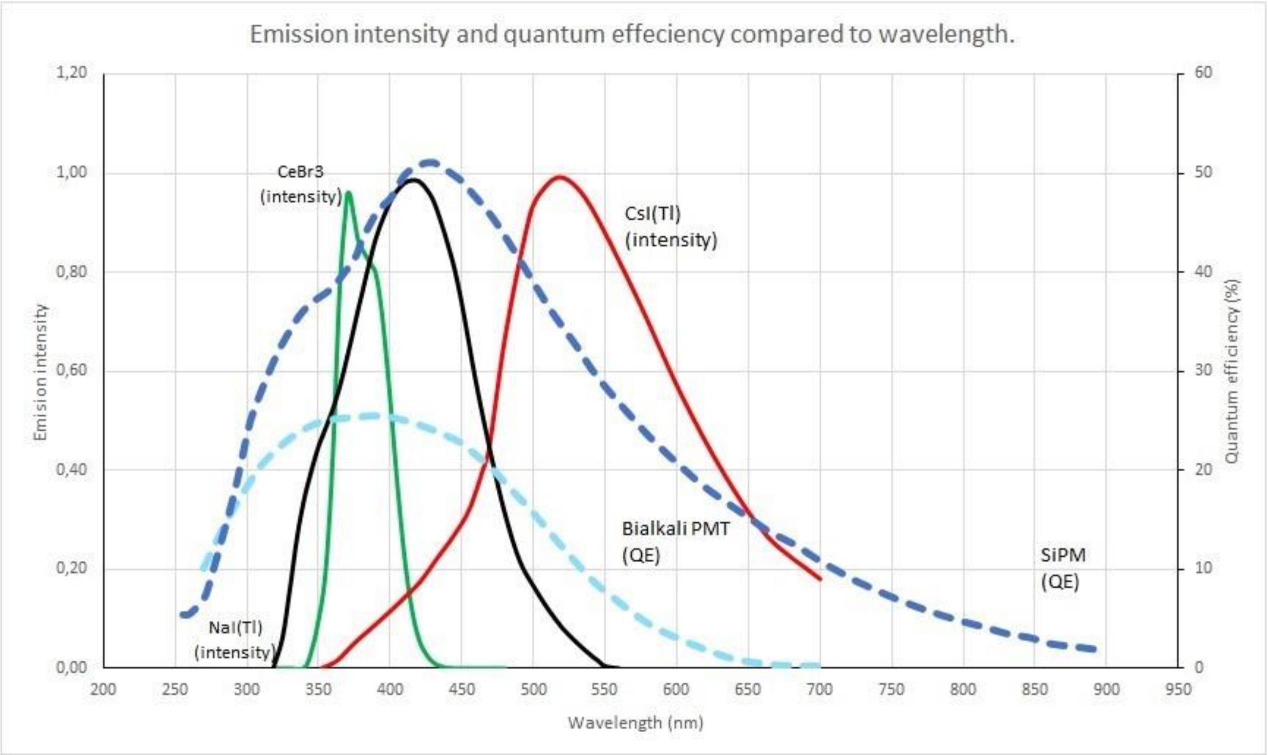
Ionized electrons enter conduction band and travel until they pass by a defect and scatter into excited state of defect
Scintillation photon released with energy lower than the band gap → crystal transparent at these energies





Scintillator properties





Diverse selection of crystals with higher light yield than organic scintillators

Produces 10s of photons / keV allowing for ~ keV energy thresholds

Emission spectra can vary wildly – check overlap between scintillator and light detectors

The COHERENT experiment's CsI detector

COHERENT experiment measures CEvNS at Oak Ridge's Spallation Neutron Source

Multiple detectors, CEvNS discovered with 14.6-kg CsI[Na] scintillator monitored by a single PMT in a composite shielding system with a cosmic veto

14.6-kg is hygroscopic: must be sealed in air-tight housing

1: CsI wrapped in reflective Teflon
2: Set in a low-activity copper cylinder
3: Sealed to PMT with optically transparent resin and epoxy

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Onion-link shielding

1: Detector lies on base poly surrounded by ancient lead
2: Next layer is HD poly to moderate neutrons
3: Enclosed in lead to contain all environmental gammas
4: Organic scintillator panels surround lead – veto cosmics
5: Water bricks surround veto for more neutron mitigation

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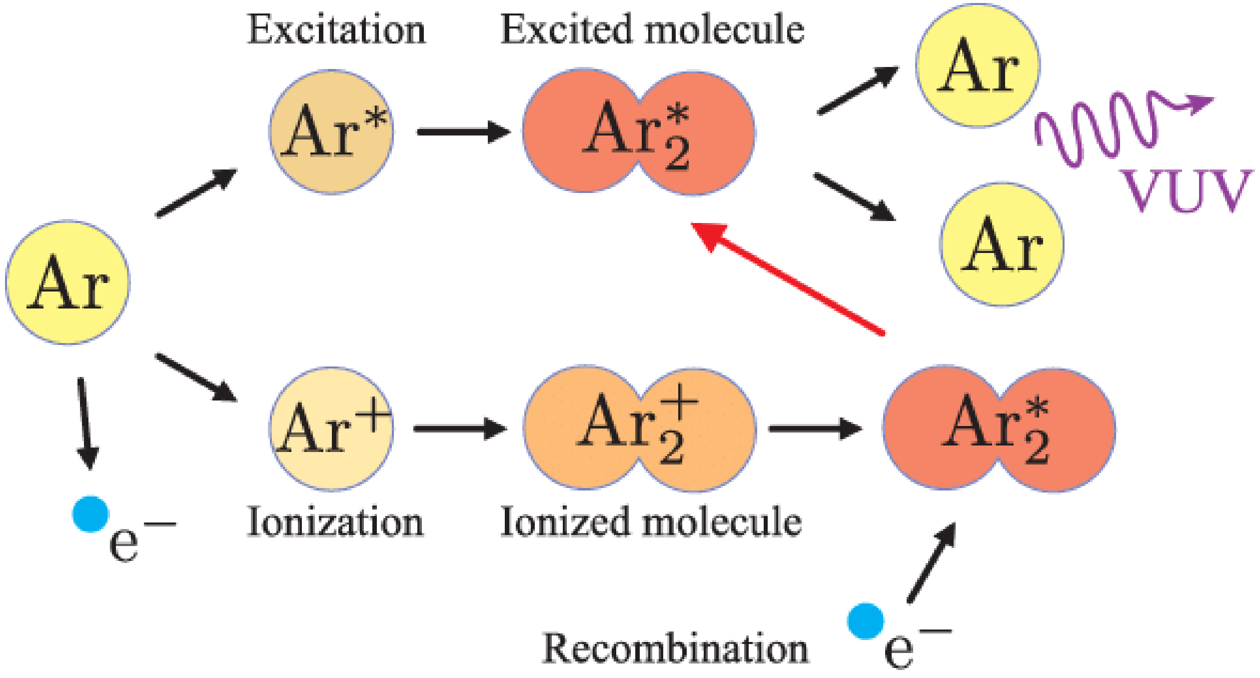
Liquid noble scintillators



ArDM, *J. Phys.: Conf. Ser.* **160** 012032 (2008)

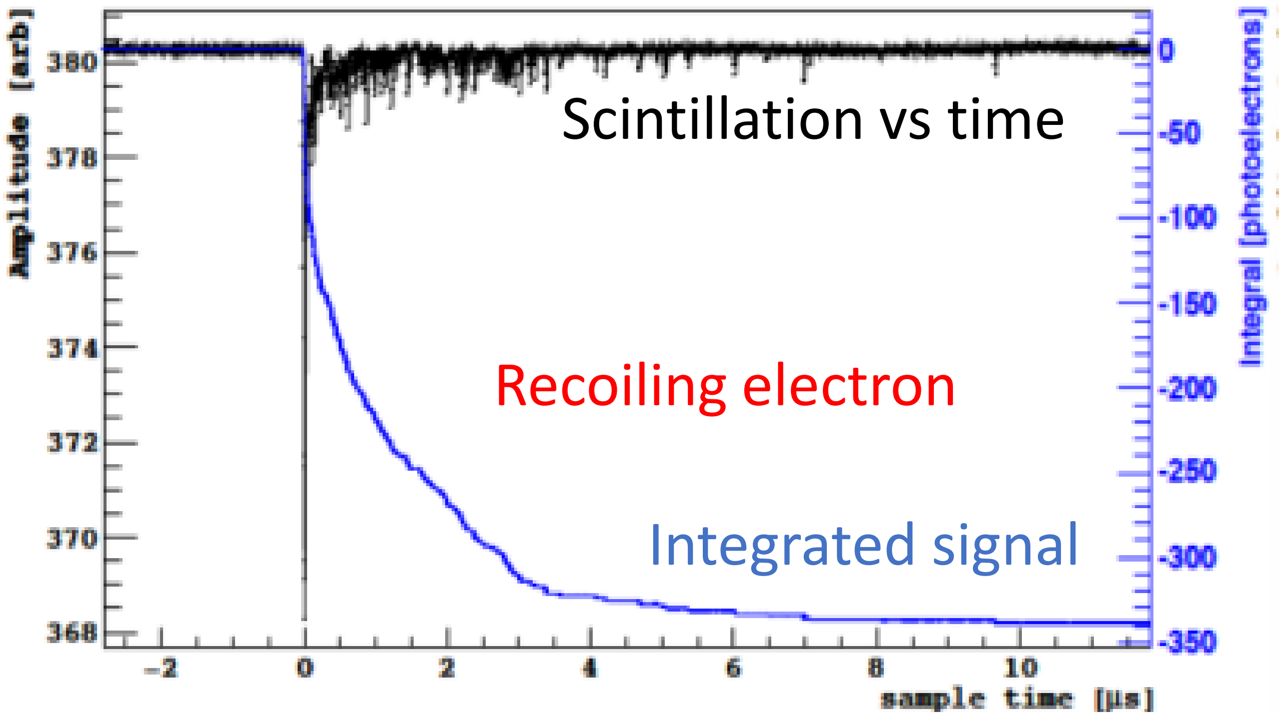
In their ground state, noble elements are inert but can form short-lived "dimer" molecules when excited with Van der Waals bond

A passing charged particle can either
1: excited an electron causing the argon atom to form a dimer
2a: ionize an electron again causing a dimer
2b: recombine with an electron forming an excited diatomic state

The excited, neutral dimer will decay by releasing a 128 nm photon

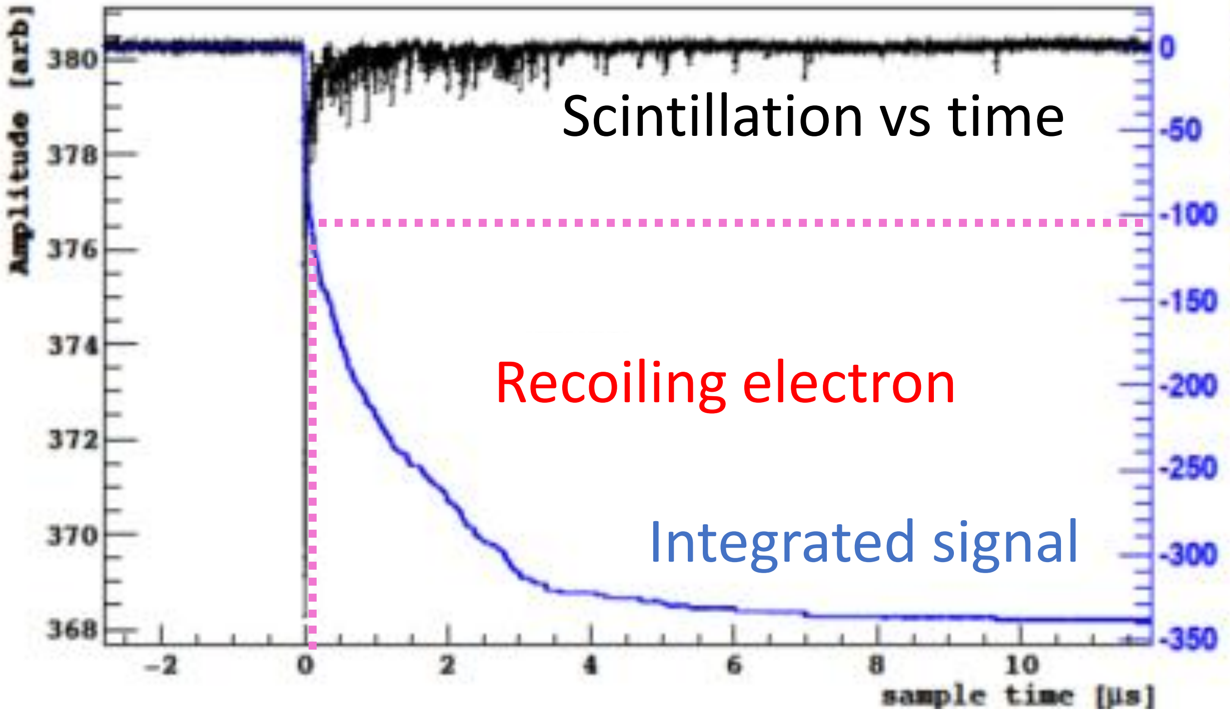
Liquid argon most important for neutrino detectors, all noble elements behave similarly

Particle identification by scintillation timing



Gabriela Araujo, MSc Thesis, TUM (2019)
ArDM, *Astr. Phys* **28**, 495 2009

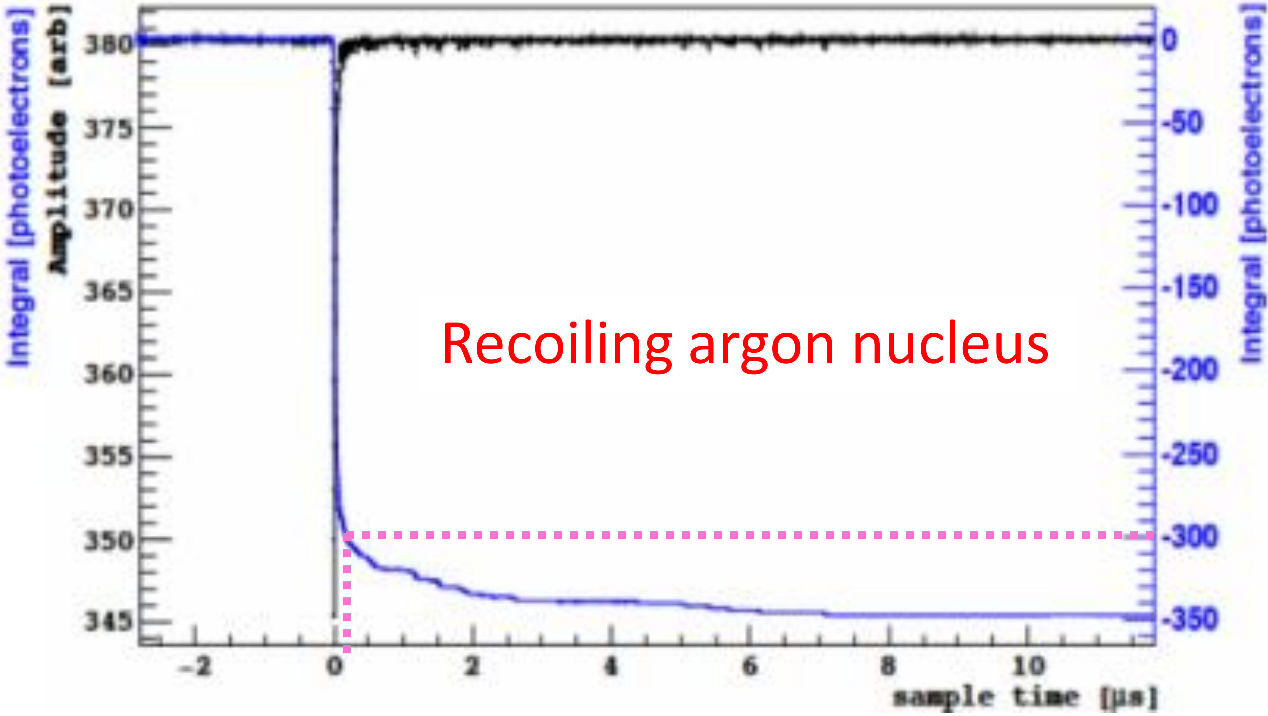
Particle identification by scintillation timing



Scintillation vs time

Recoiling electron

Integrated signal



Recoiling argon nucleus

Singlet and triplet light at different timescales

t_{sin} = 6 ns // $t_{tri} \approx$ 1500 ns

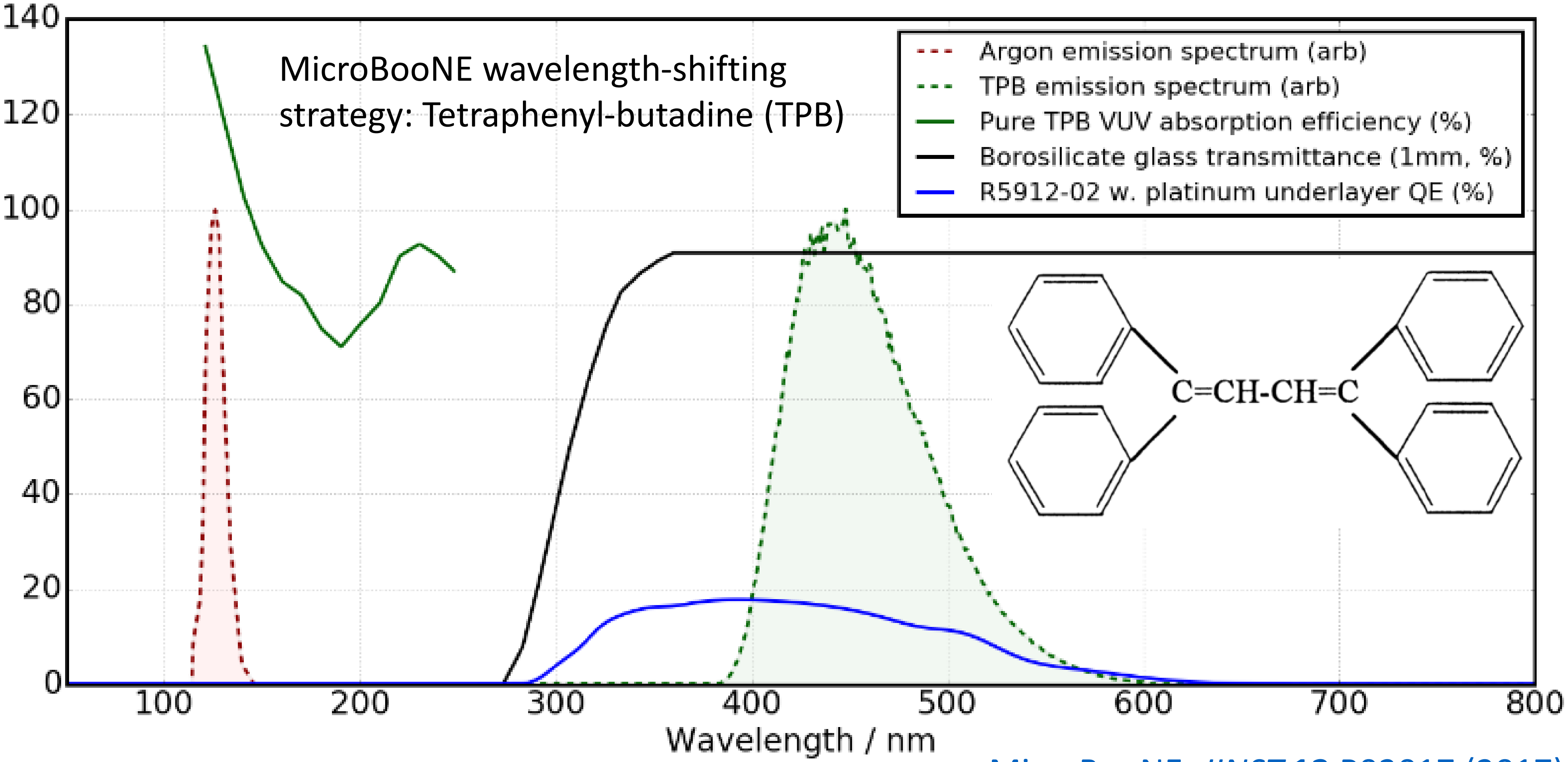
Singlet / triplet ratio:

Electron recoils	1:3
Argon recoils	3:1

Gabriela Araujo, MSc Thesis, TUM (2019)
ArDM, *Astr. Phys* **28**, 495 2009

Shifting argon scintillation to detectable wavelengths

Huge problem: argon emission far into uv – wavelengths to short for photodetectors



MicroBooNE wavelength-shifting strategy: Tetraphenyl-butadine (TPB)

[MicroBooNE, *JINST* **12** P02017 (2017)]

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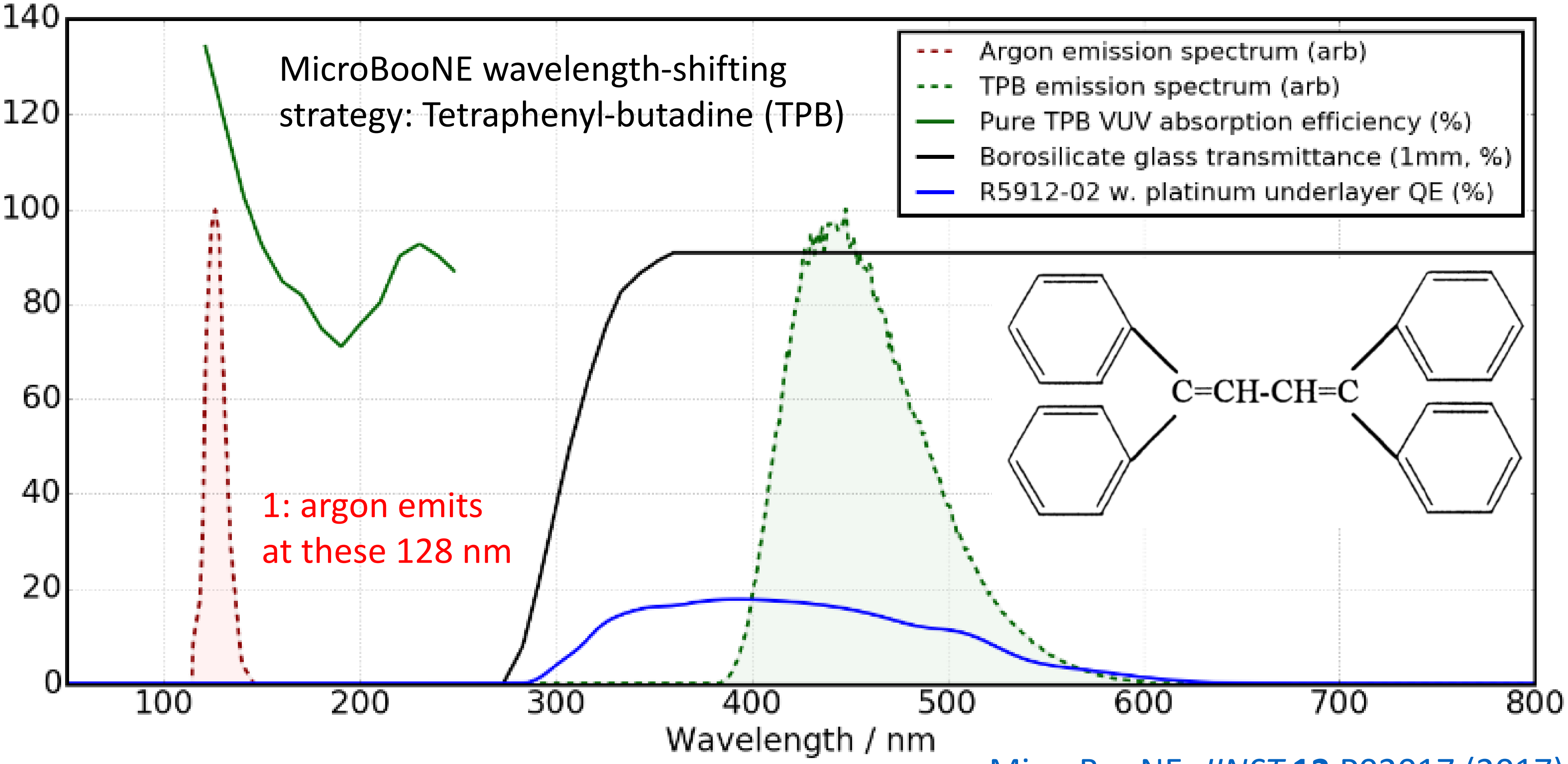

MicroBooNE wavelength-shifting strategy: Tetraphenyl-butadine (TPB)

1: argon emits at these 128 nm

MicroBooNE, *JINST* **12** P02017 (2017)

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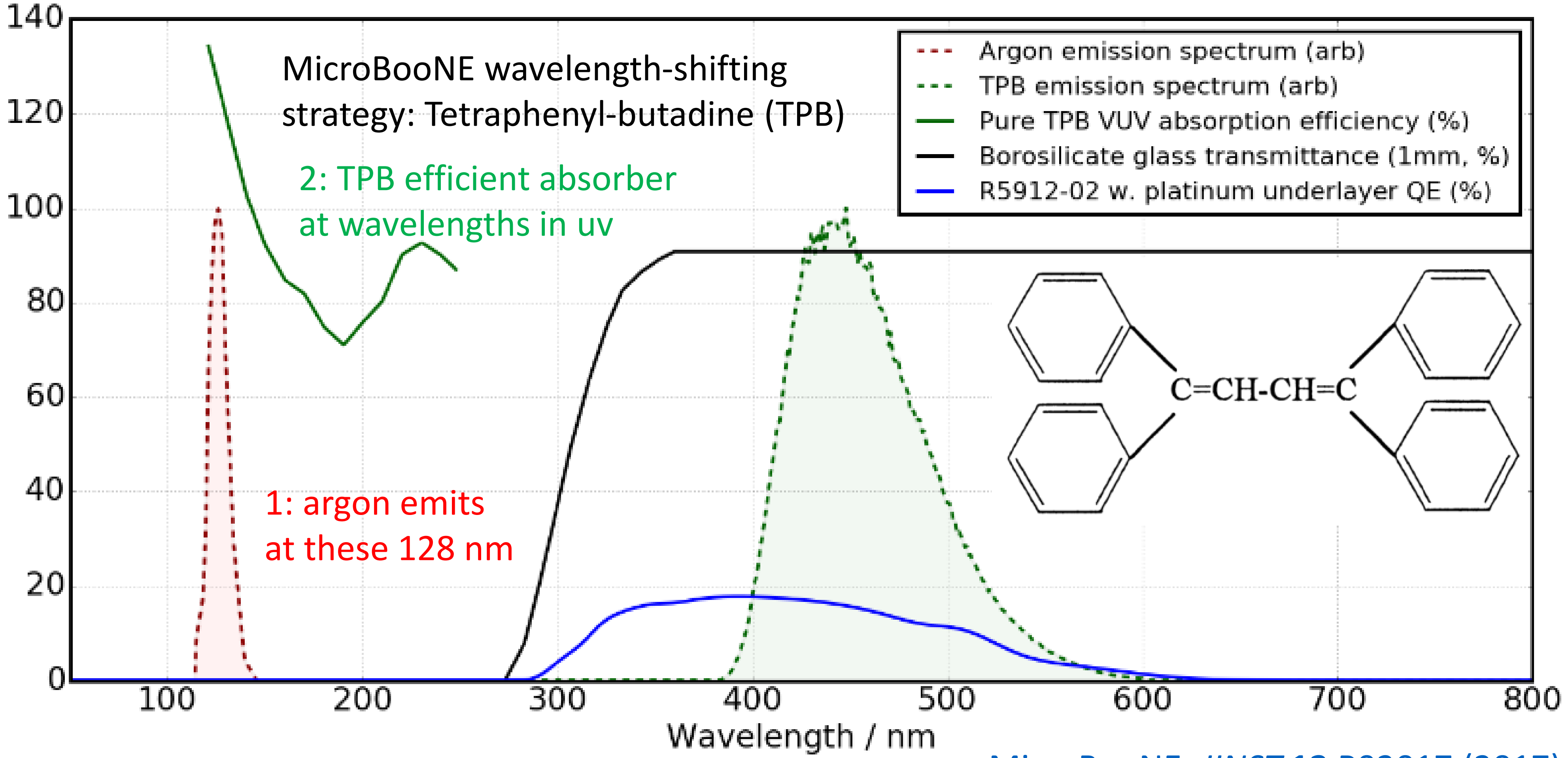


MicroBooNE wavelength-shifting strategy: Tetraphenyl-butadine (TPB)

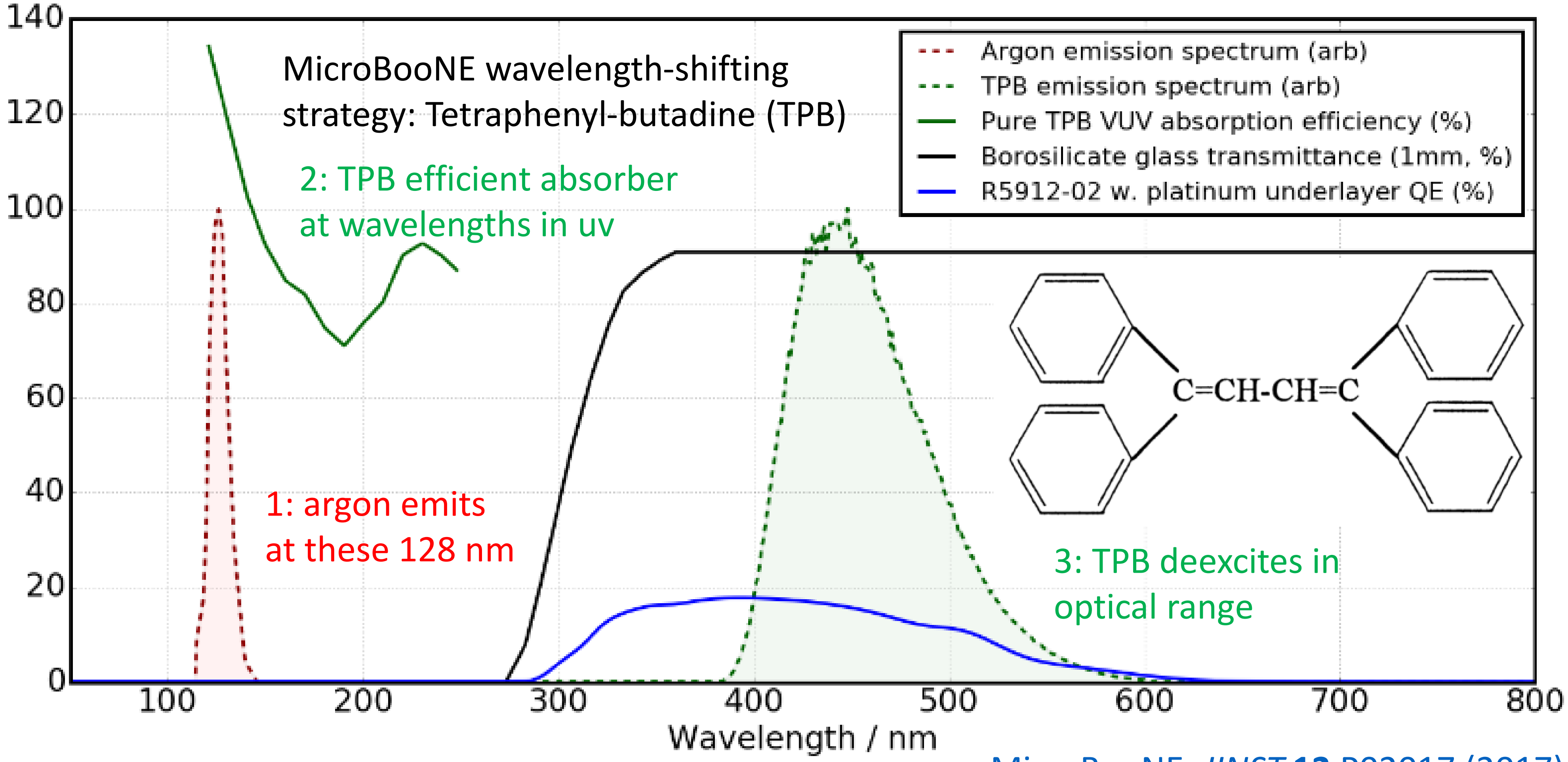
2: TPB efficient absorber at wavelengths in uv

1: argon emits at these 128 nm

[MicroBooNE, *JINST* **12** P02017 (2017)](#)

Shifting argon scintillation to detectable wavelengths

Huge problem: argon emission far into uv – wavelengths to short for photodetectors



MicroBooNE wavelength-shifting strategy: Tetraphenyl-butadine (TPB)

2: TPB efficient absorber at wavelengths in uv

1: argon emits at these 128 nm

3: TPB deexcites in optical range

MicroBooNE, *JINST* **12** P02017 (2017)

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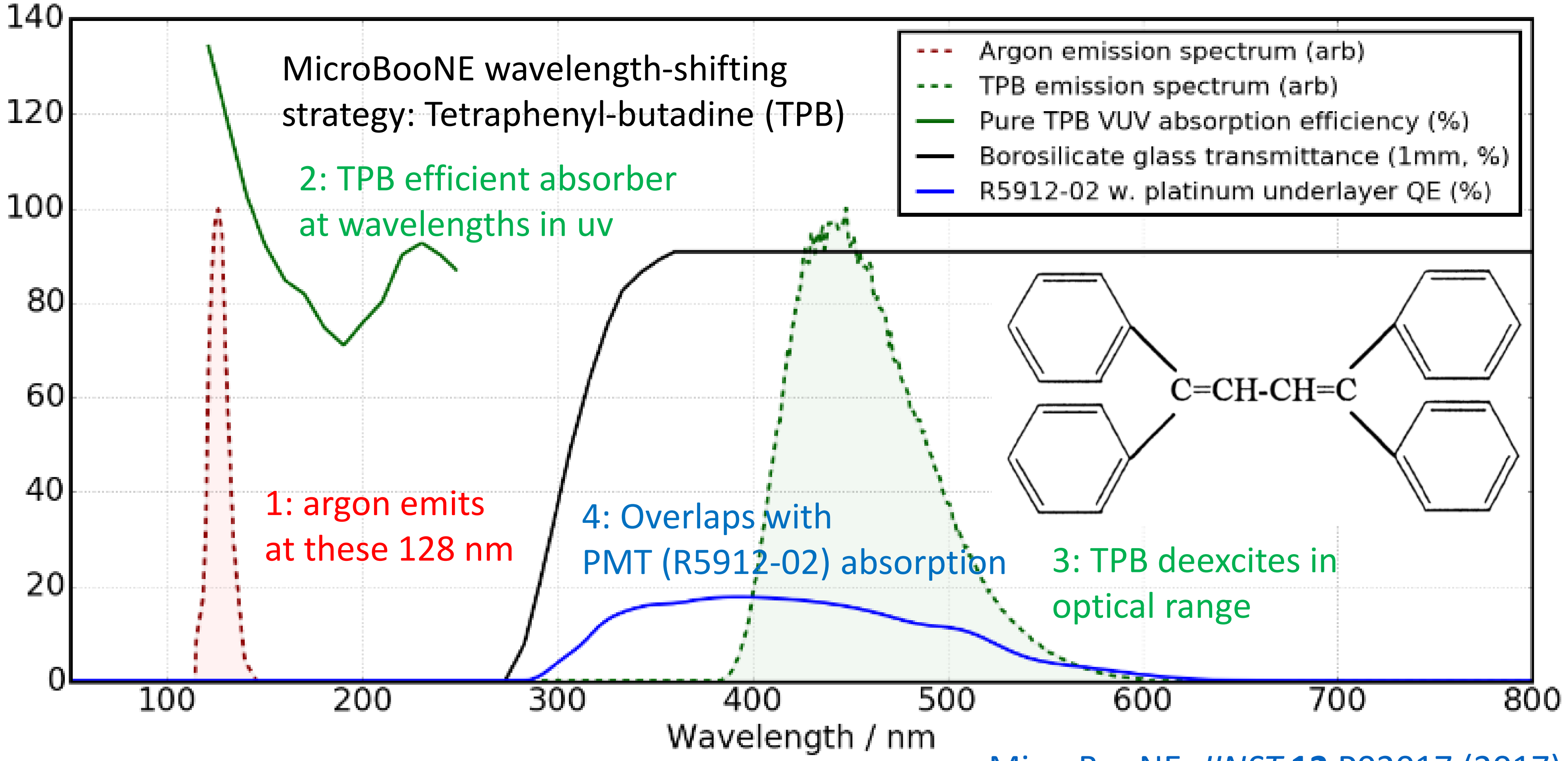


MicroBooNE wavelength-shifting strategy: Tetraphenyl-butadine (TPB)

2: TPB efficient absorber at wavelengths in uv

1: argon emits at these 128 nm

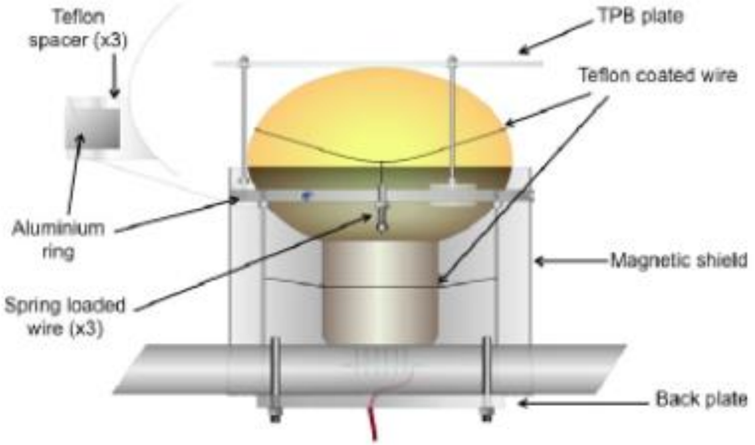
4: Overlaps with PMT (R5912-02) absorption

3: TPB deexcites in optical range

MicroBooNE, *JINST* **12** P02017 (2017)

Wavelength shifting in experiments

MicroBooNE – simple solution, adding TPB-coated disk in front of PMT units

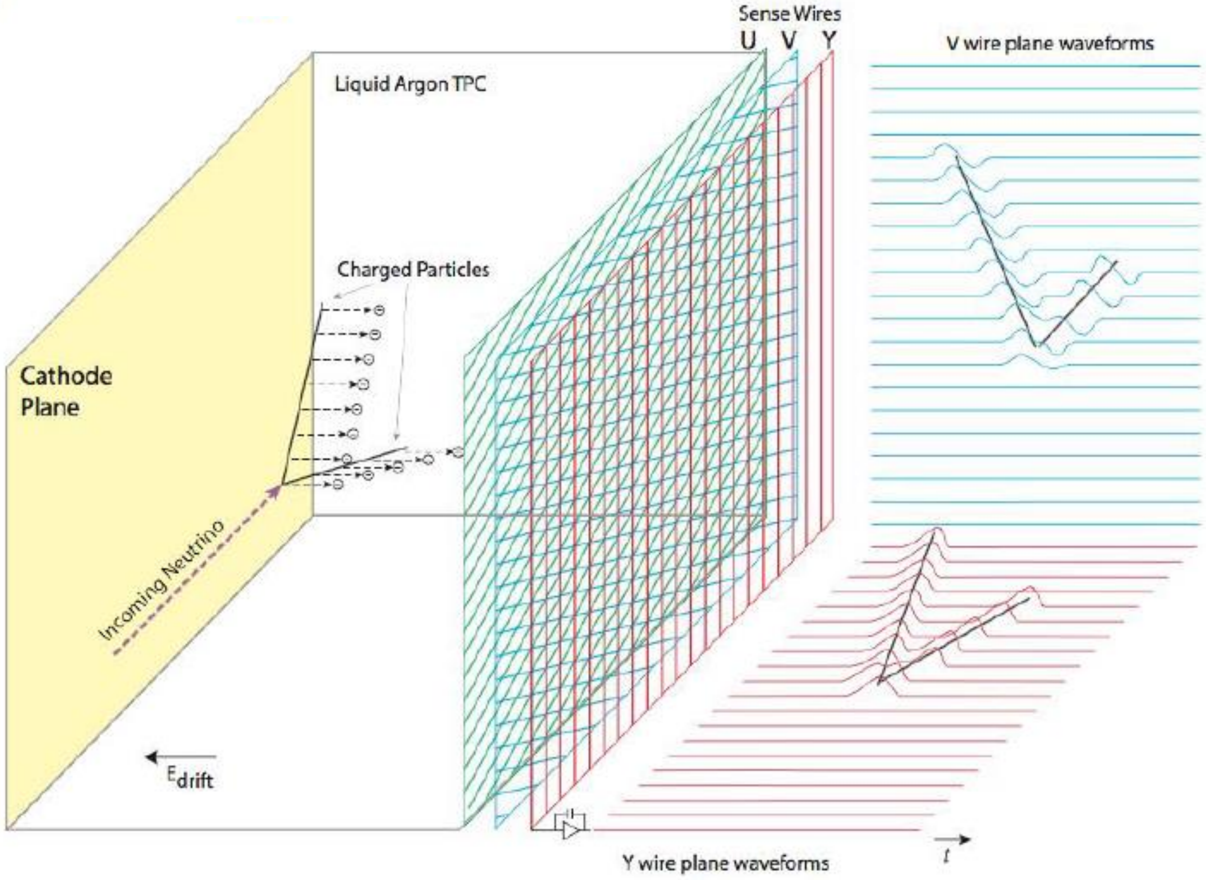


[MicroBooNE, *JINST* **12** P02017 (2017)]

[R. Tayloe, LIDINE 2017]

COHERENT: CEvNS low energy – increase light collection with coating on PMT face and reflective teflon

Liquid argon time projection chambers (LArTPC's)



Argon is wonderful because it has no chemistry – ionized charge remains stable

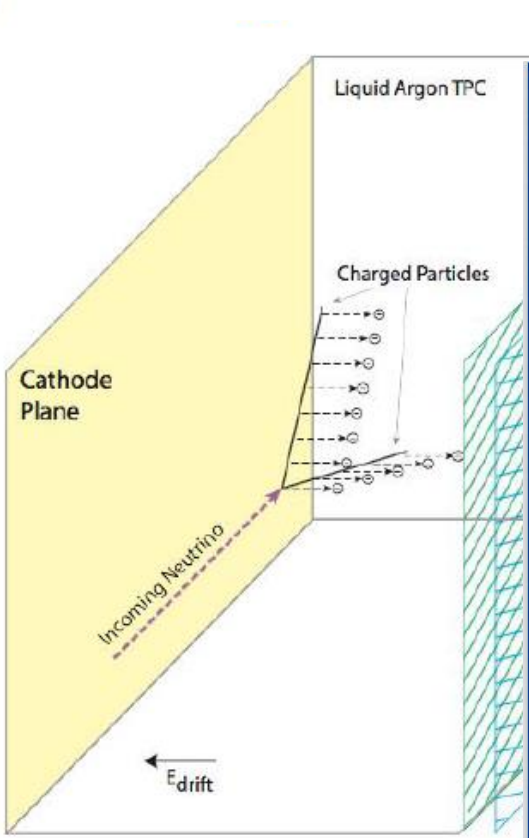
Apply electric field (≈ 500 V/cm) to drift charge to a single charge collection plane

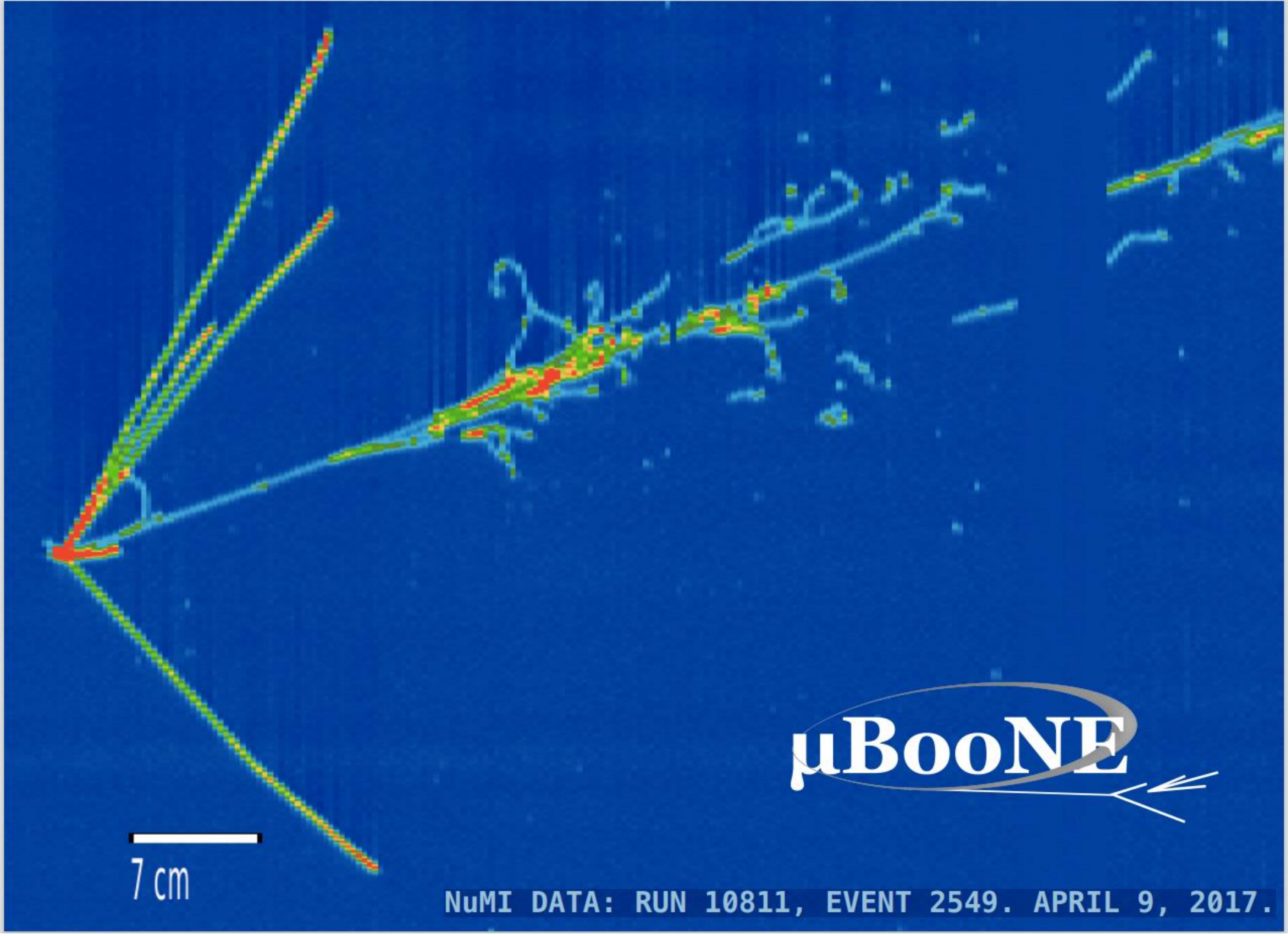
Charge collected on array of wires or pixels with sub-cm resolution

Charge drifts slowly (≈ 1 ms/m), light detectors needed to time events

Economic to scale to huge detectors! Number of readout channels $\propto \sqrt[3]{M}$

Liquid argon time projection chambers (LArTPC's)





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0 V/cm) to drift

collection plane

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ms/m), light

events

Economic to sc

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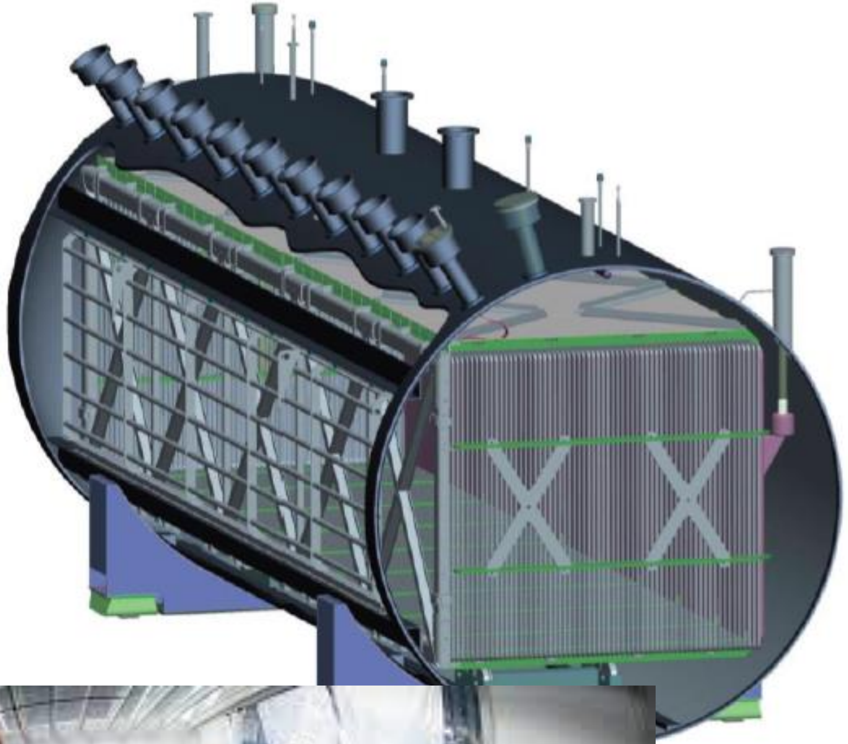
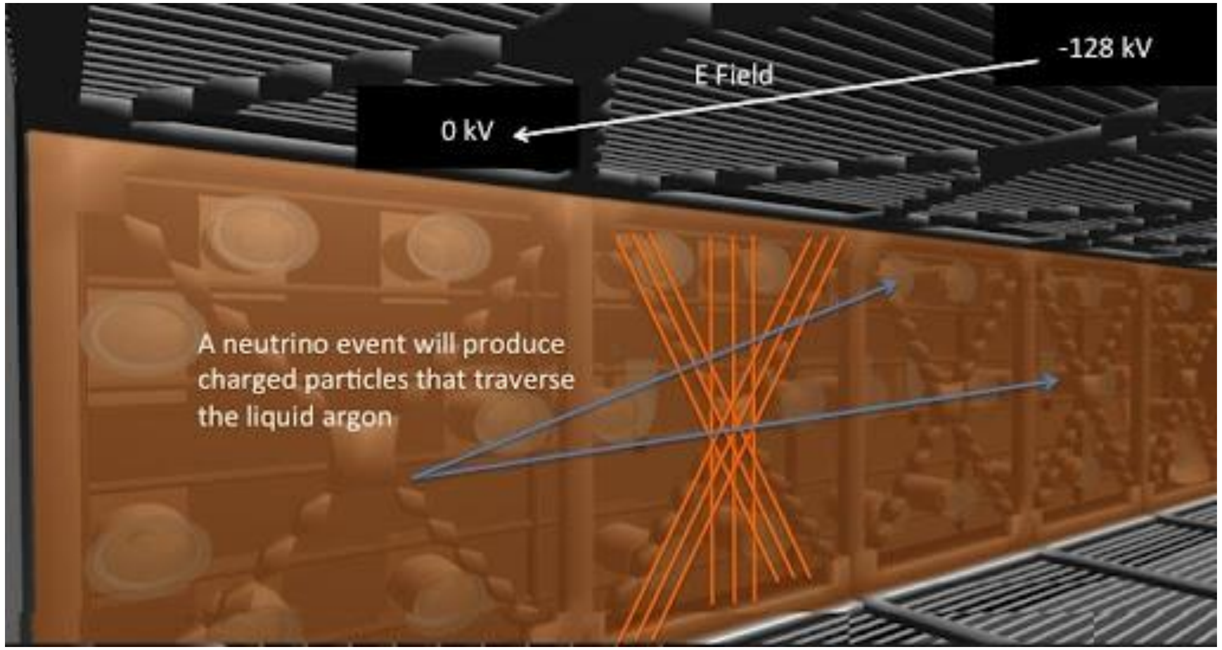
Anatomy of MicroBooNE



Cryostat maintains temperature of to within 1 K
10 m long, 2.5 m drift
Field cage maintains constant electric field 500 V/cm
PMT light collection behind charge collection wires
Utility port for TPC HV, signal, PMT signal, filtration, purity monitoring, gas escape



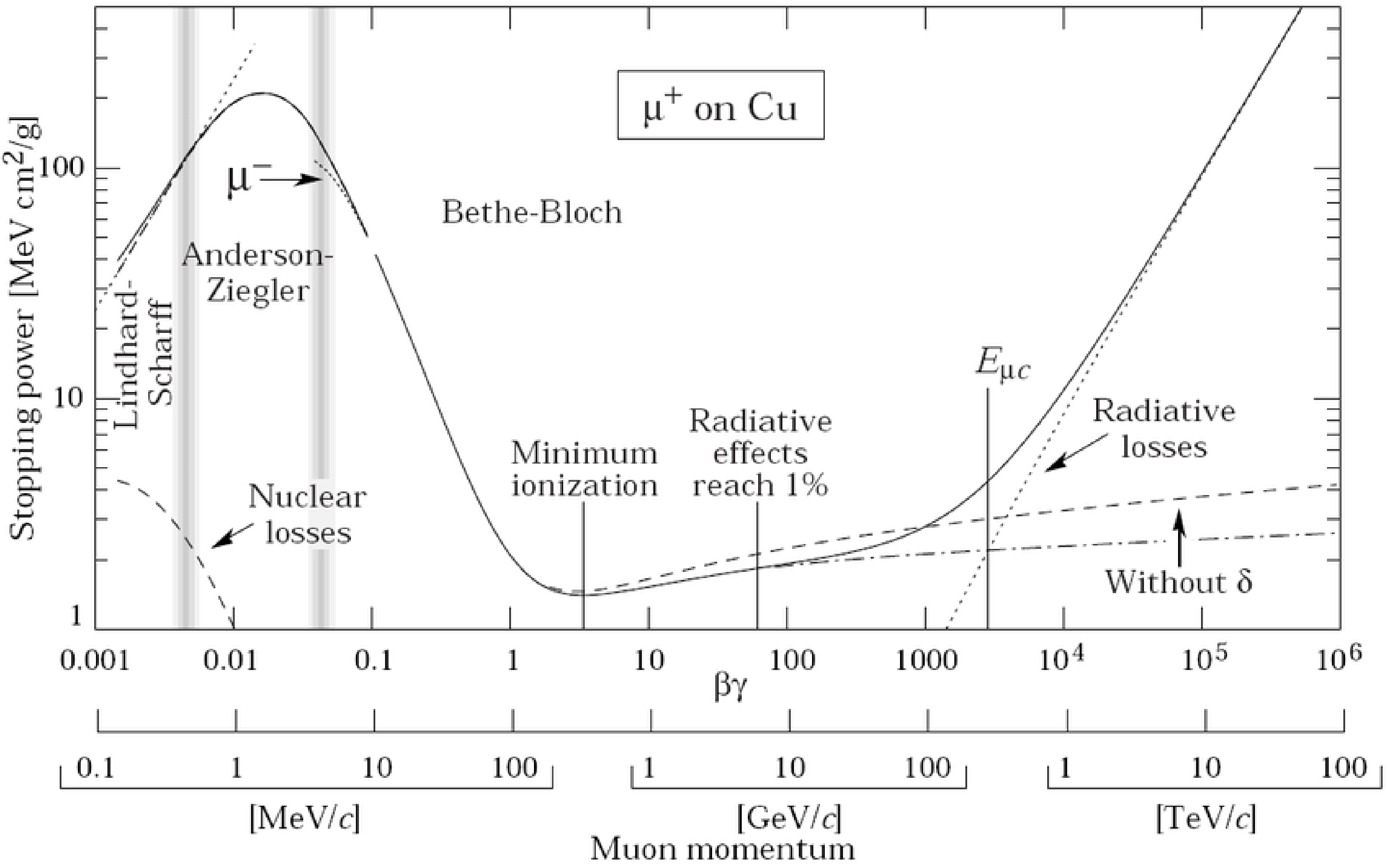
Ionization by charged particles

Classical derivation: Bohr 1915

Relativistic derivation: Bethe 1932

Calculates momentum transferred to atomic electrons from electric field of passing charged particle and compares to ionization energy

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[\ln\left(\frac{2 m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]$$



Ionization by charged particles

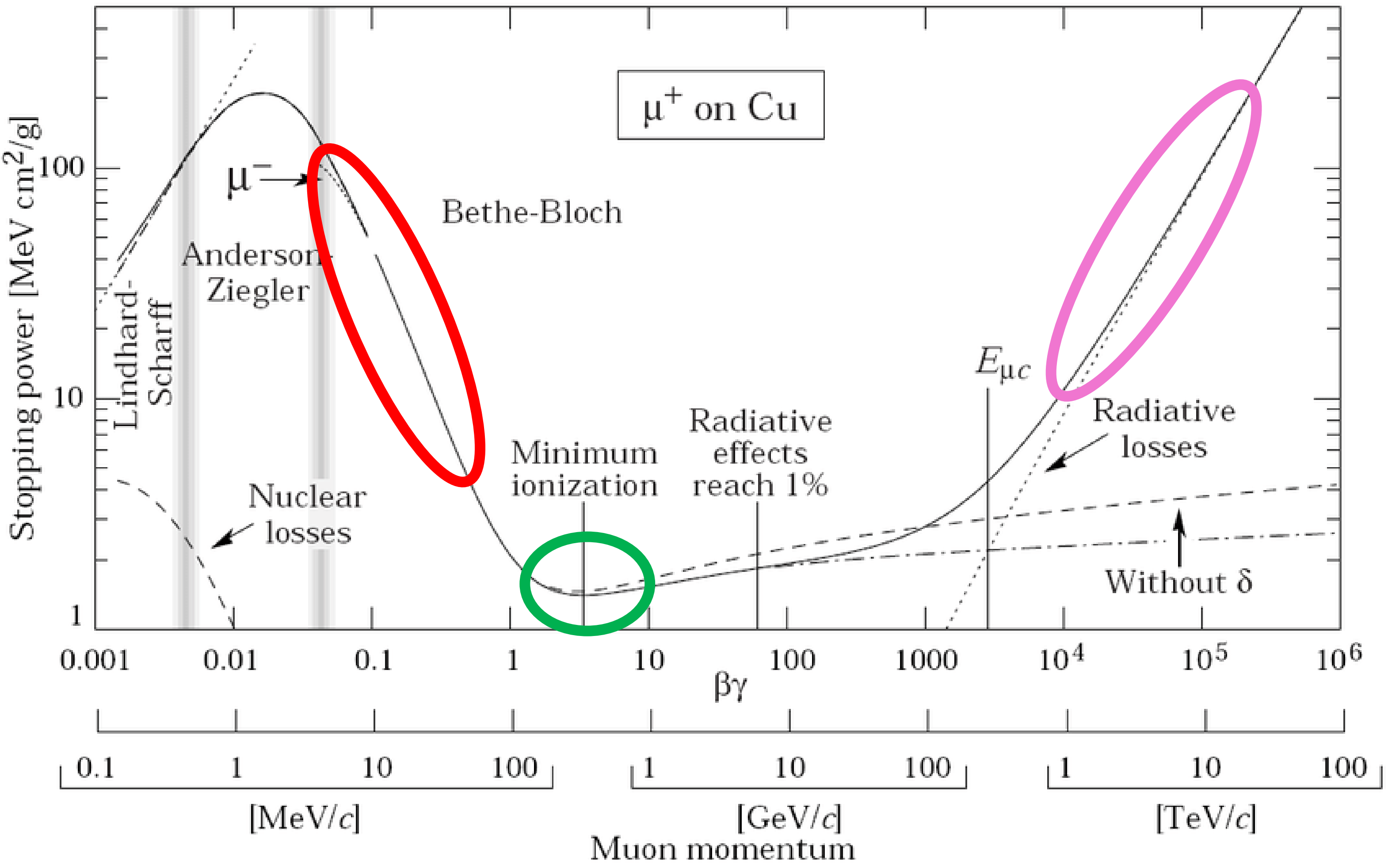
Classical derivation: Bohr 1915
Relativistic derivation: Bethe 1932
Calculates momentum transferred to atomic electrons from electric field of passing charged particle and compares to ionization energy

βγ << 1: particles travel slowly, exert more electric force -> more ionization loses

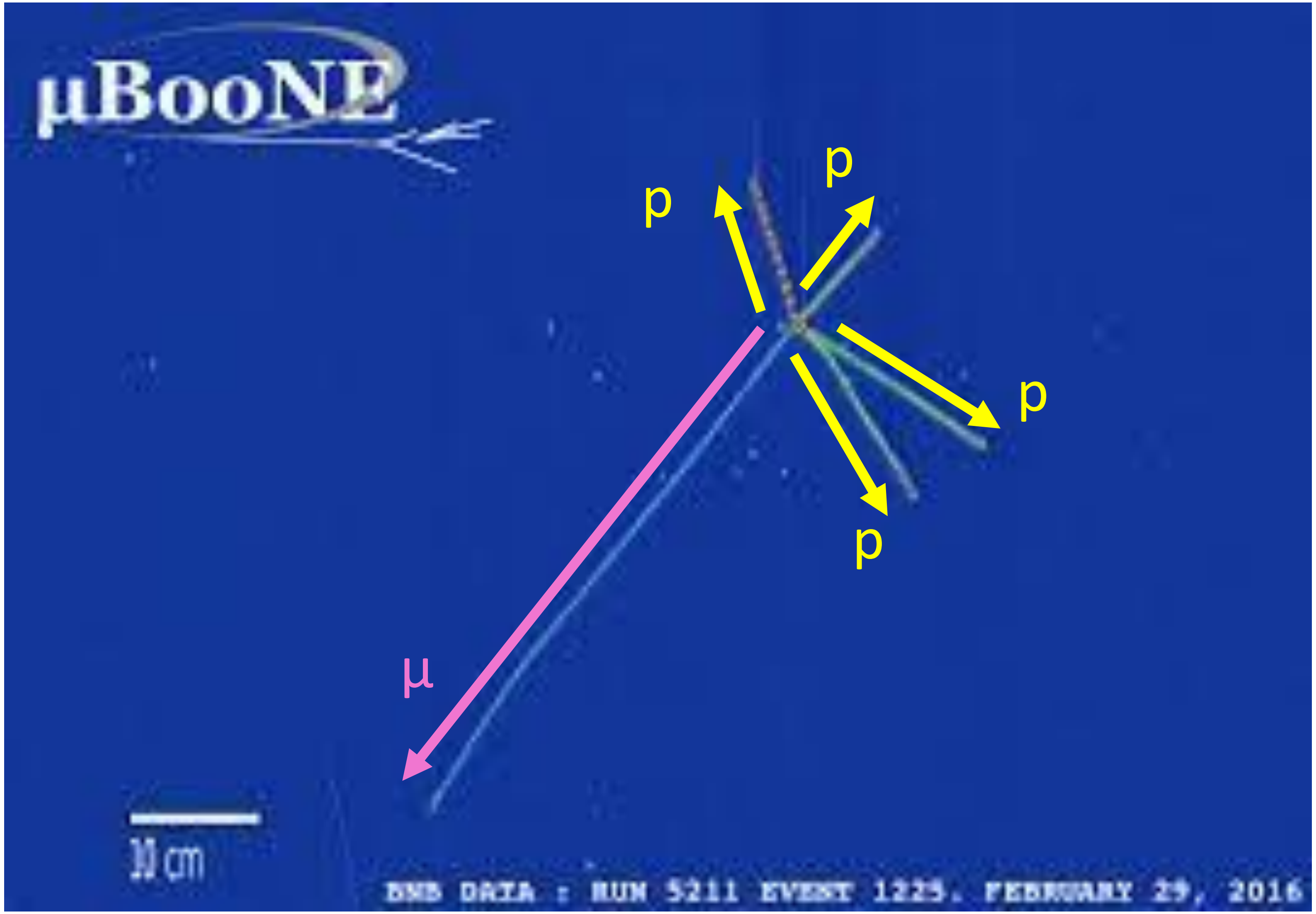
βγ ≈ 1: particles fast, but can’t lose energy radiatively -> minimal losses

βγ >> 1: high energy makes discrete energy loss possible -> more losses

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2 m_e c^2 \beta^2}{I\cdot(1-\beta^2)}\right) - \beta^2\right]$$



Particle identification by charge deposition patterns

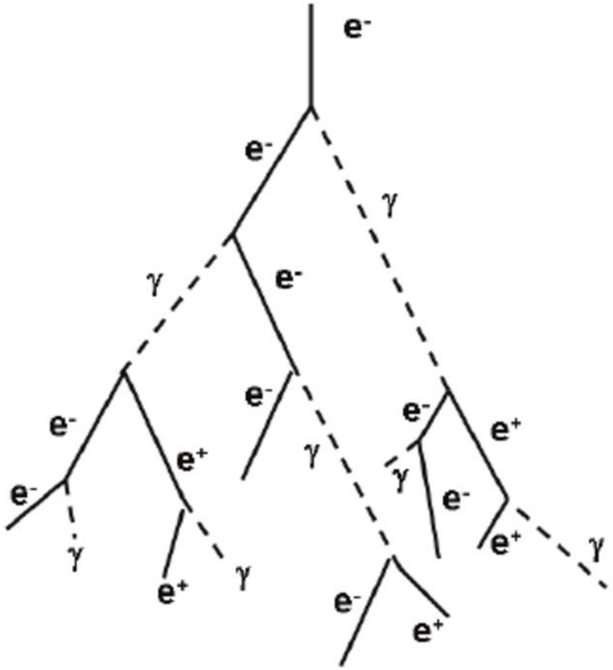


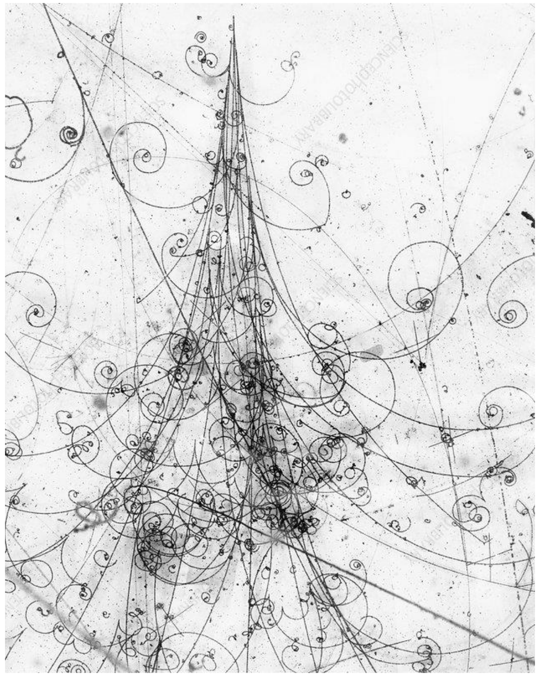
Electron energy loss

By $\beta\gamma \sim 10^4$, radiative energy loss dominates
For electrons, that's an energy $E = m\gamma \sim 5$ MeV

Electrons will develop into an electromagnetic shower above critical energy

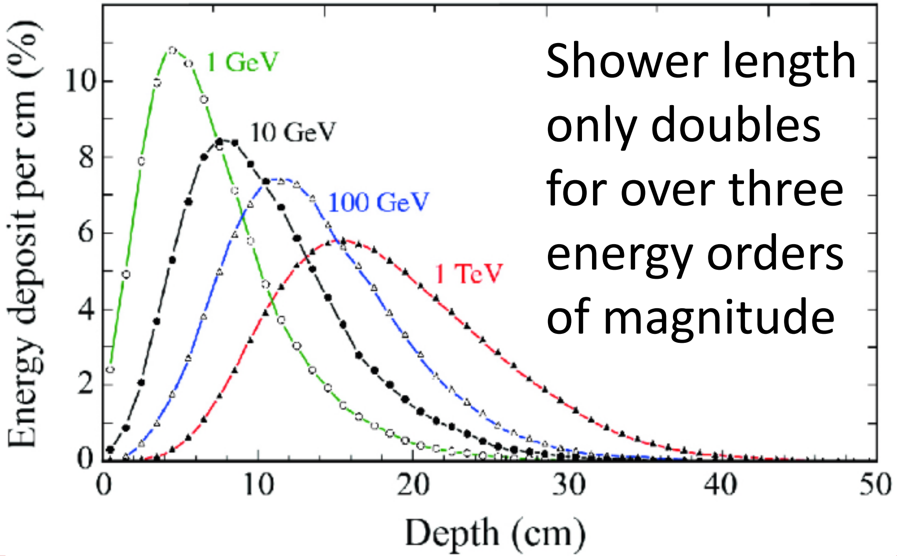
H_2O	Ar	Cu	Pb
80 MeV	37 MeV	20 MeV	7.1 MeV





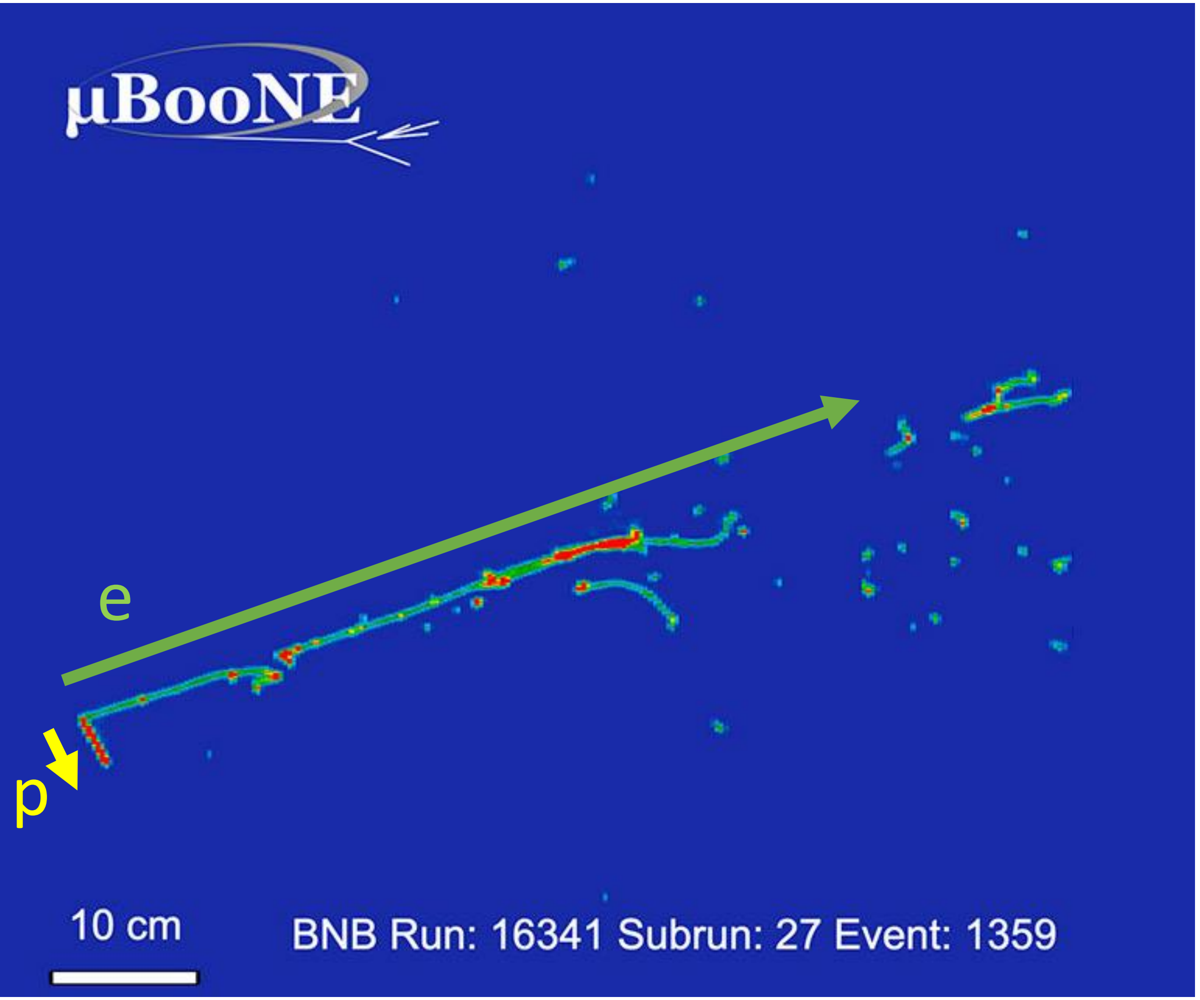
The energy deposition scales exponentially – make short, broad showers with dense energy deposition.
The shower length scales logarithmically:

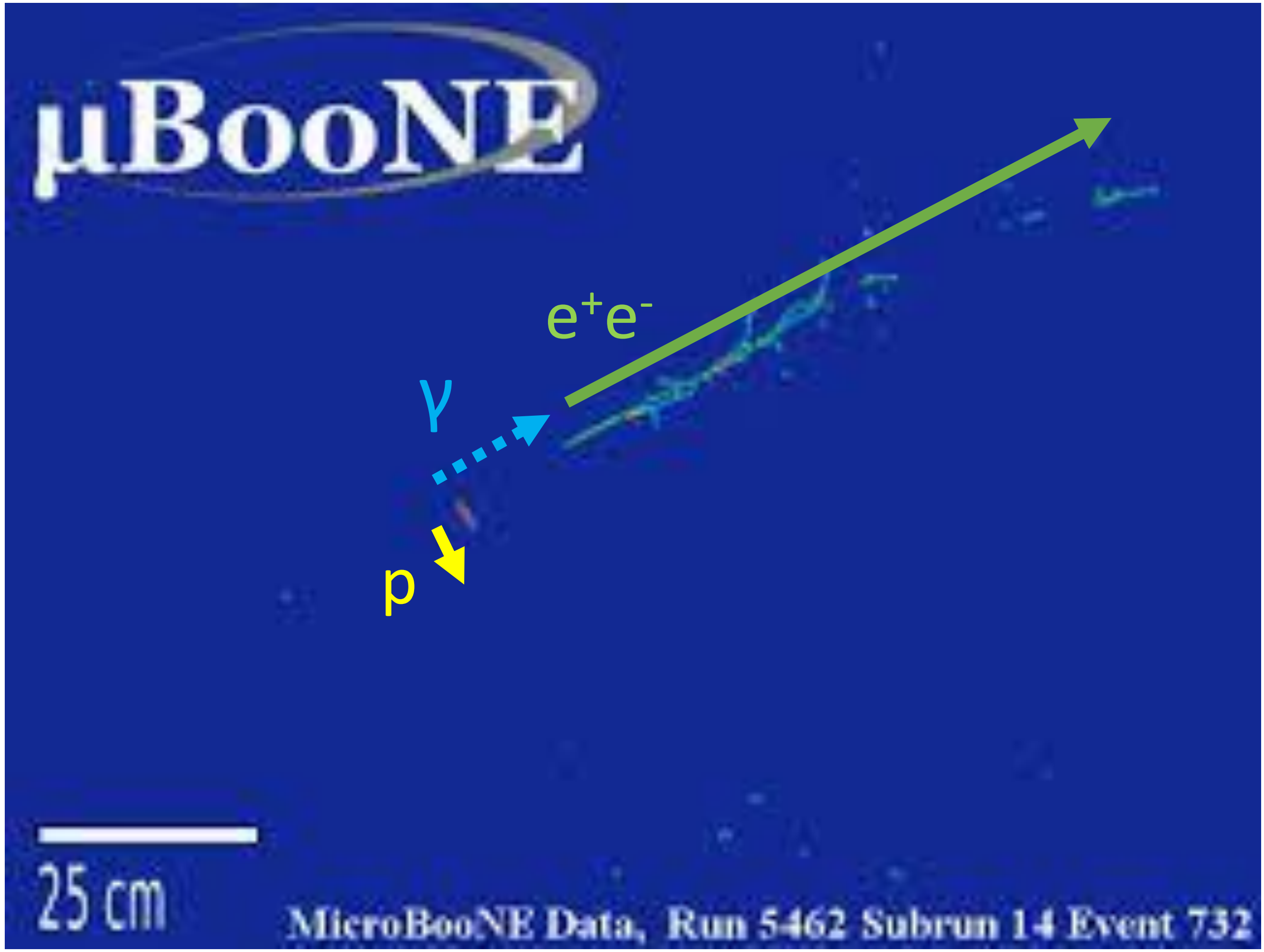
$$L \propto \log(E/E_c)$$



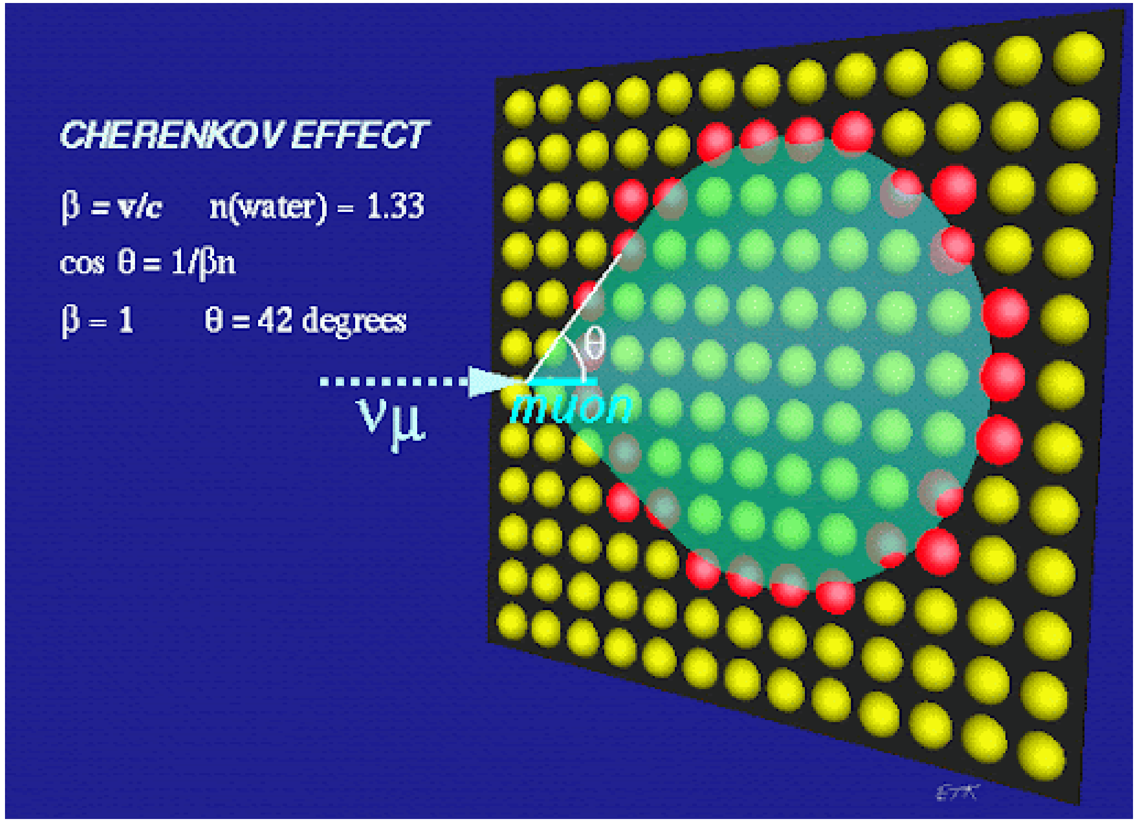
Shower length only doubles for over three energy orders of magnitude

EM showers in LArTPC's





Cherenkov light



Particles traveling faster than light produce a ring of light, analogous to a sonic boom

Particle thresholds in water

Electron	Muon	Proton
0.73 MeV	150 MeV	1350 MeV

Photon production in water

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi z^2}{\lambda^2}\alpha \underline{\sin^2\theta}$$

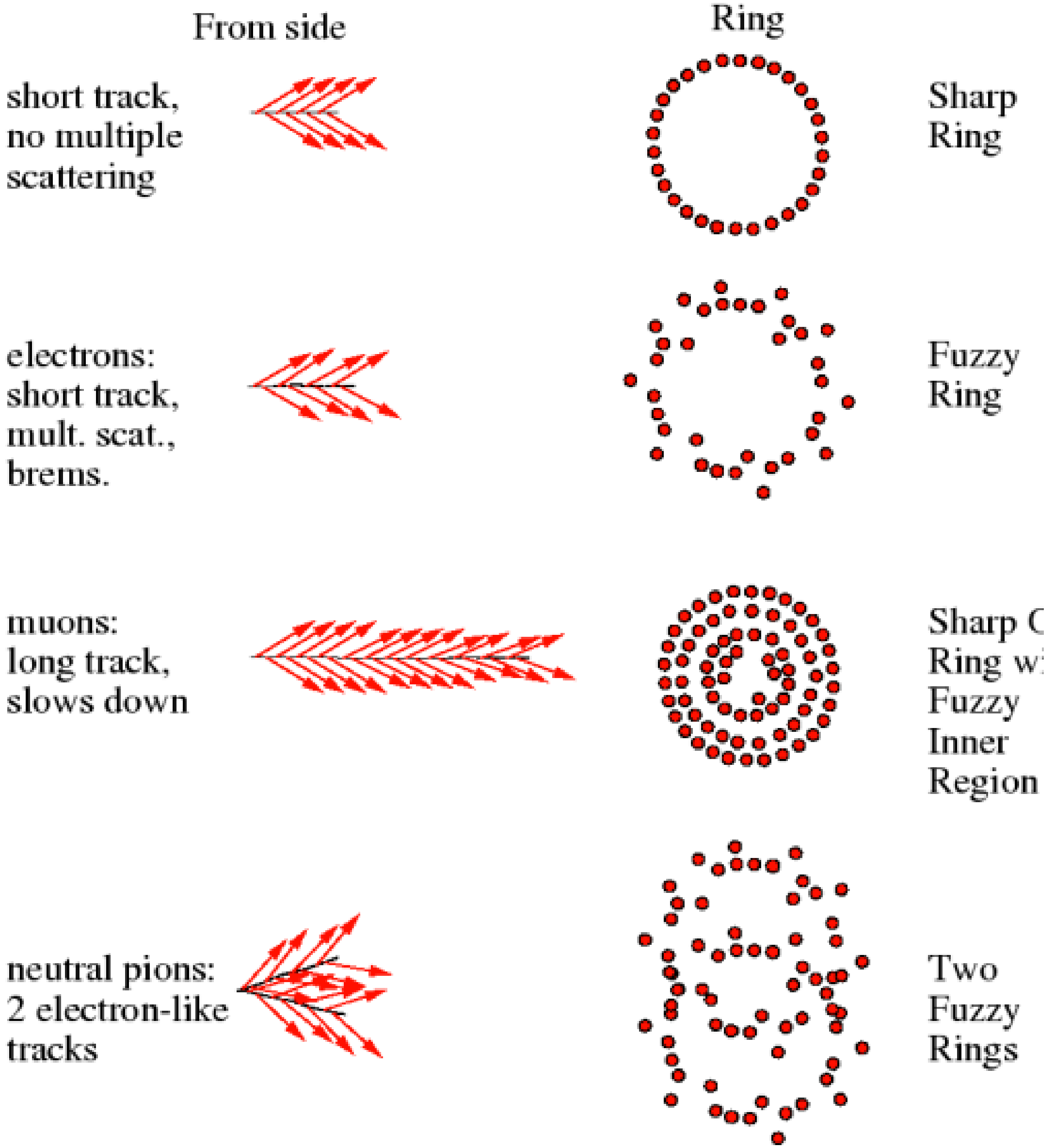
≈ 250 photons / cm over PMT response range

$$\cos\theta = 1/\beta n$$

Cons: low light yield 100s/MeV compared to 10s/keV for scintillation, physics threshold

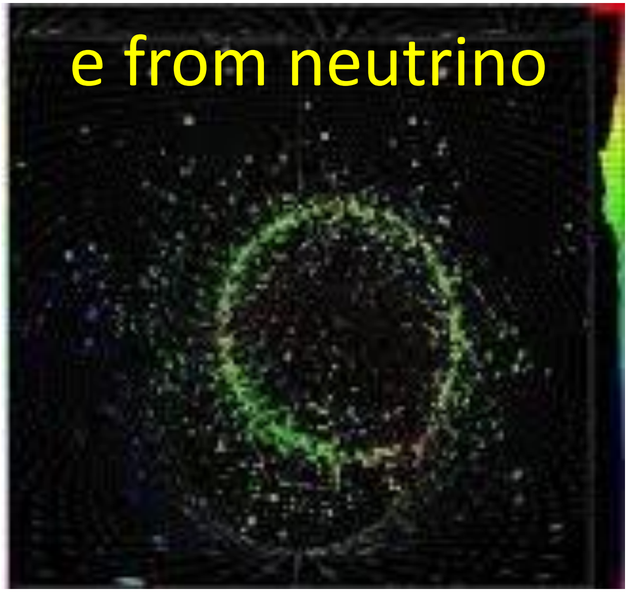
Pros: directional information, particle identification

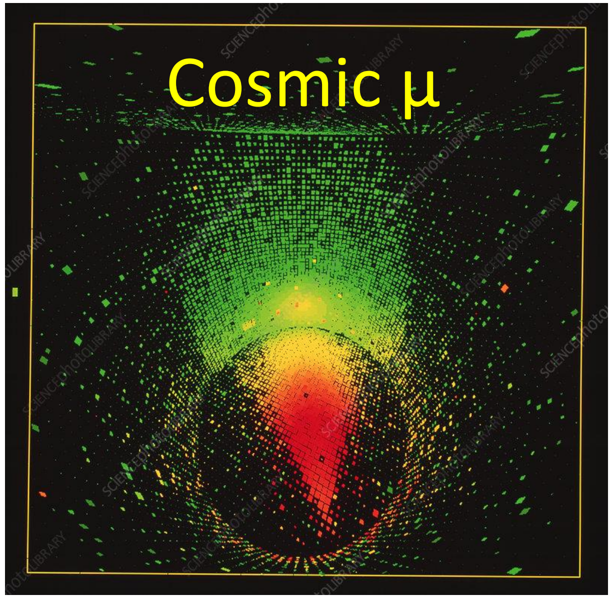
Particle identification with Cherenkov detectors

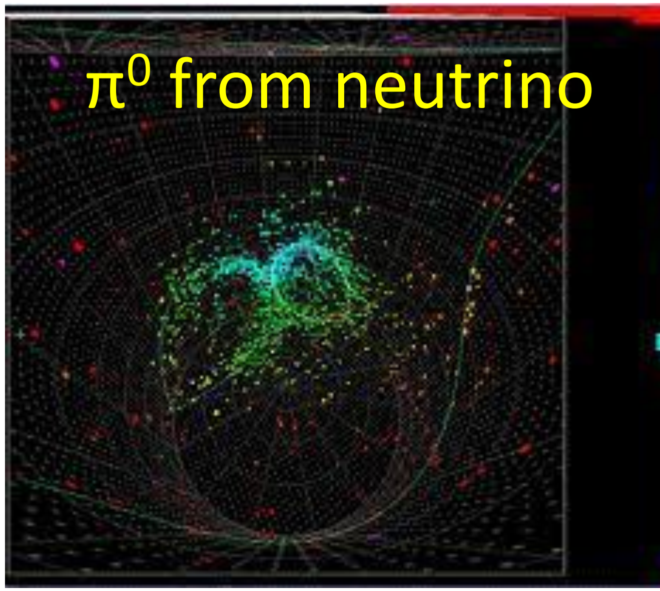



μ from neutrino

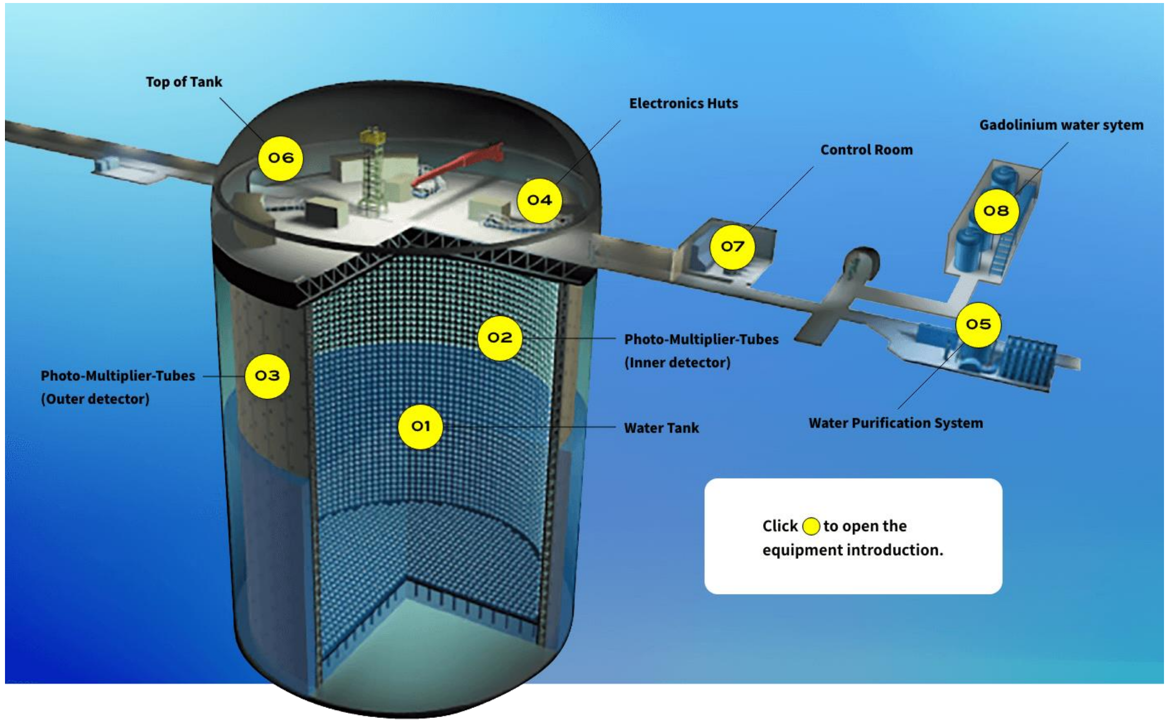
SuperKamiokande

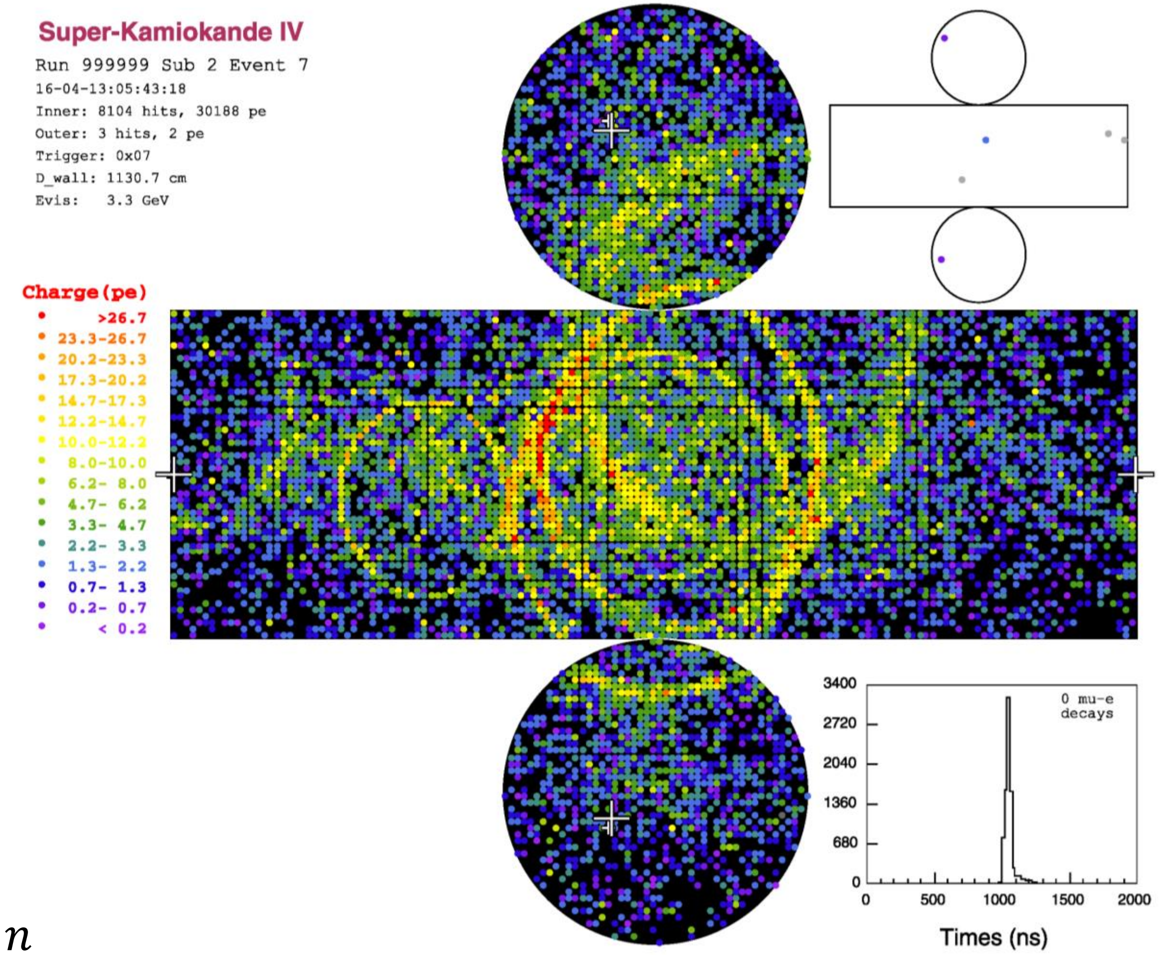

e from neutrino


Cosmic μ


π^0 from neutrino

The SuperKamiokande detector





Super-Kamiokande IV

```
Run 999999 Sub 2 Event 7
16-04-13:05:43:18
Inner: 8104 hits, 30188 pe
Outer: 3 hits, 2 pe
Trigger: 0x07
D_wall: 1130.7 cm
Evis:   3.3 GeV
```

Deep underground – below Mt. Iteno

Inner detector: 22.5 kt, 11146 20 inch PMT’s

Outer detector: cosmic veto, 27.5 kt, 1885 8 inch PMT’s

Gadolinium doped to improve low energy program: $\bar{\nu}_e + p \rightarrow e^+ + n$

Energy threshold: 6.5 MeV for electrons

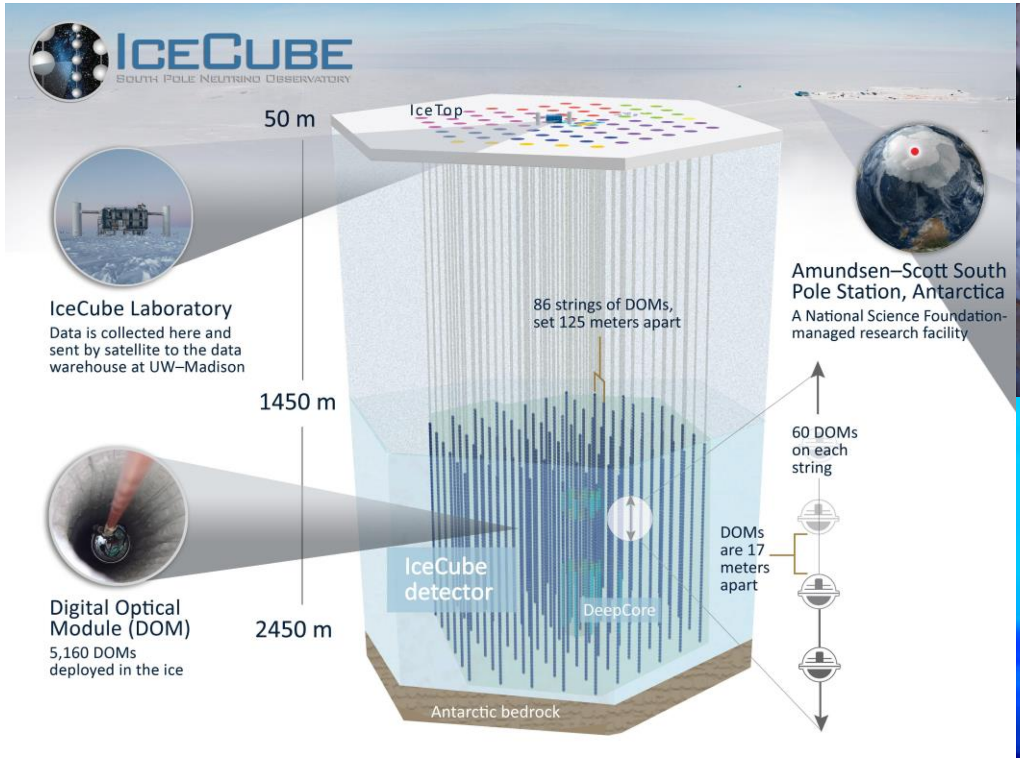
1980 1990 2000 2010 2020 SK-Gd 2030

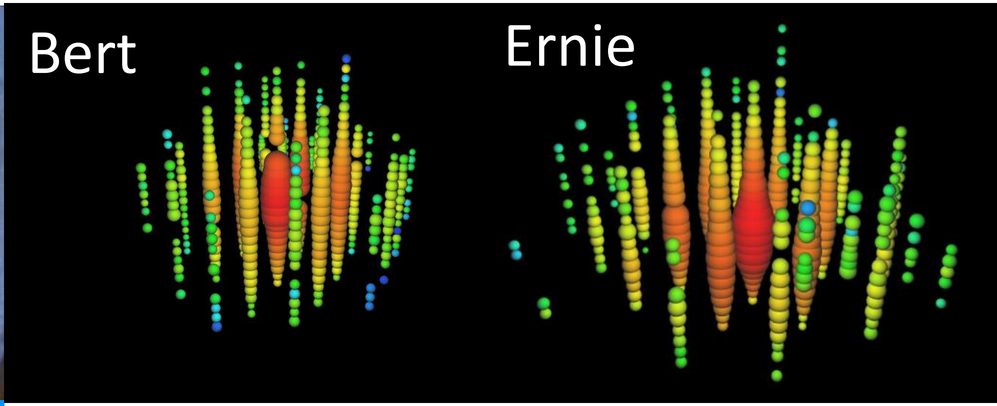
Kamiokande, 4.5 kt // PDK, SN ν

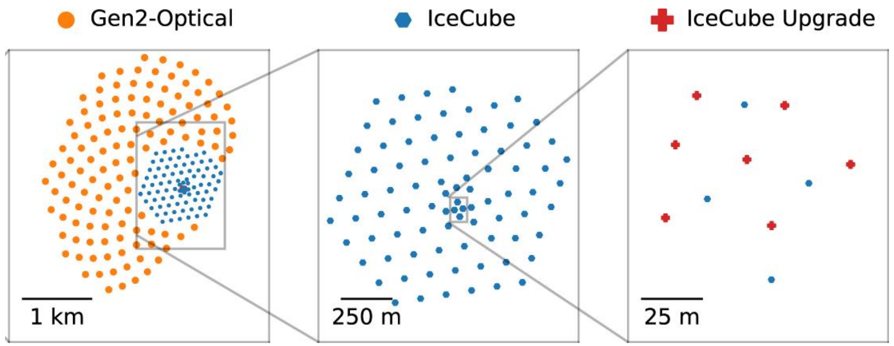
SuperKamiokande, 50 kt // oscillations, solar ν, diffuse SN ν, continued PDK

HyperKamiokande, 260 kt

The IceCUBE detector







– 1 Gt instrumented detector (50000x SK) sensitive to TeV-PeV scale neutrinos

– 86 strings of optical modules, each with 60 digital opical modules placed over 1 km length

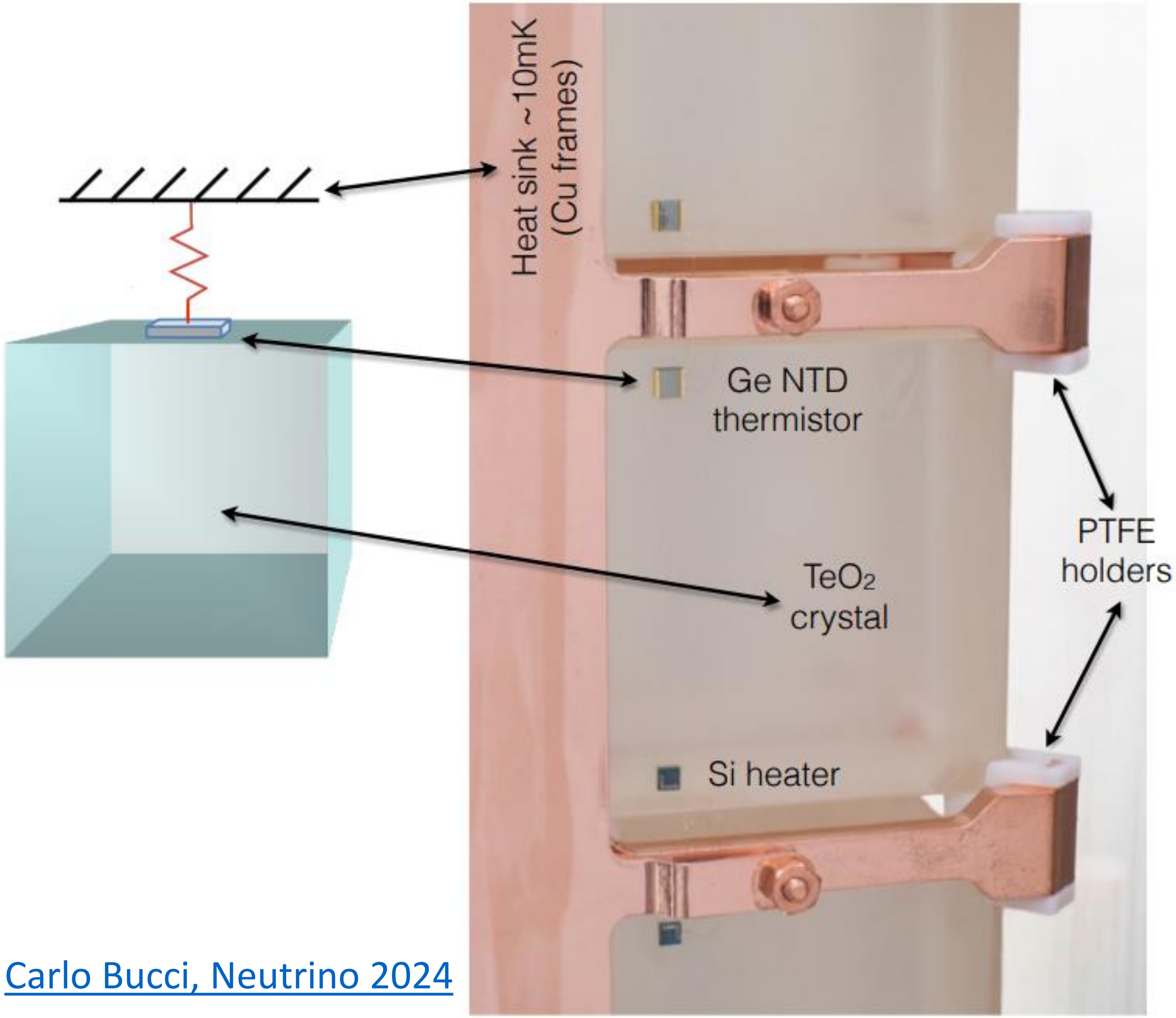
– Deep and surrounded by old glacial ice – lowest background natural laboratory in the world

– Expect expansion to IceCube gen2 with both more fiducial mass (8 Gt) for rare, EeV event detection and increased density of light detectors experiment core for GeV-scale neutrinos

Detecting heat in the CUORE experiment

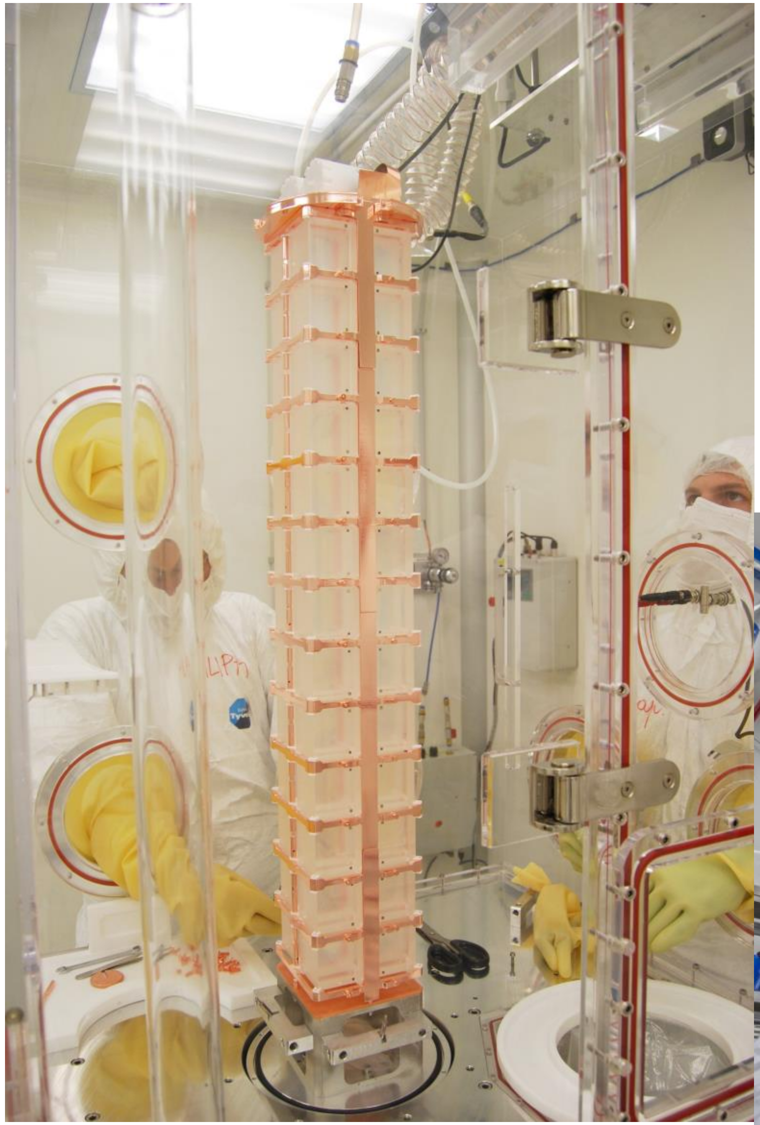
Radioactive decays deposit tiny energies into source material. The CUORE experiment uses TeO_2 crystals to search for neutrinoless double beta decay

Thermally couple germanium thermistor to TeO_2 crystals
– semiconductor, $R \propto \exp((T/T_0)^{1/4})$
– TeO_2 has low specific heat, 2.5 MeV energy deposit visible above shot noise for temperatures ≈ 10 mK
– excellent energy resolution! 0.3%



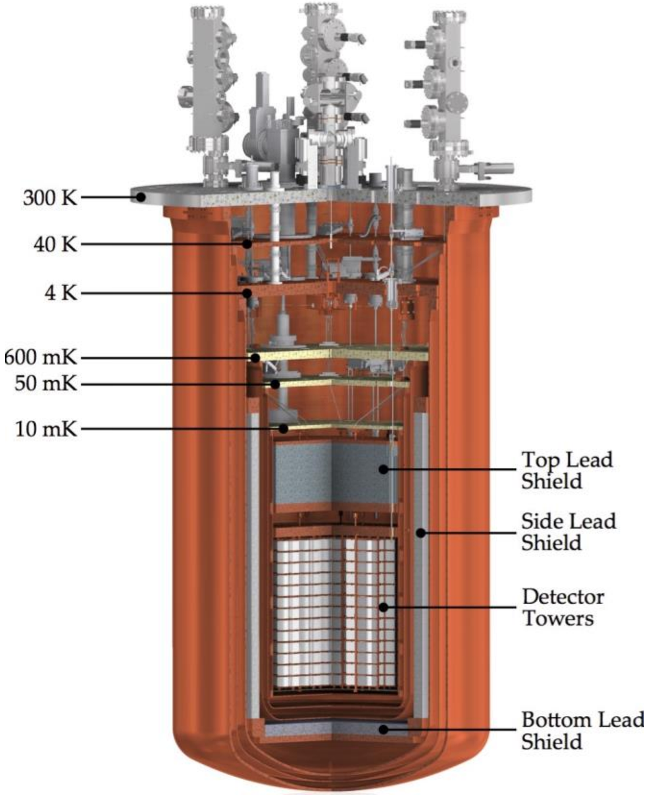
Carlo Bucci, Neutrino 2024

The CUORE detector at Gran Sasso



Assemble towers of 52 750-g TeO_2 units in glovebox

19 towers closely packed and installed into multi-stage cryostat

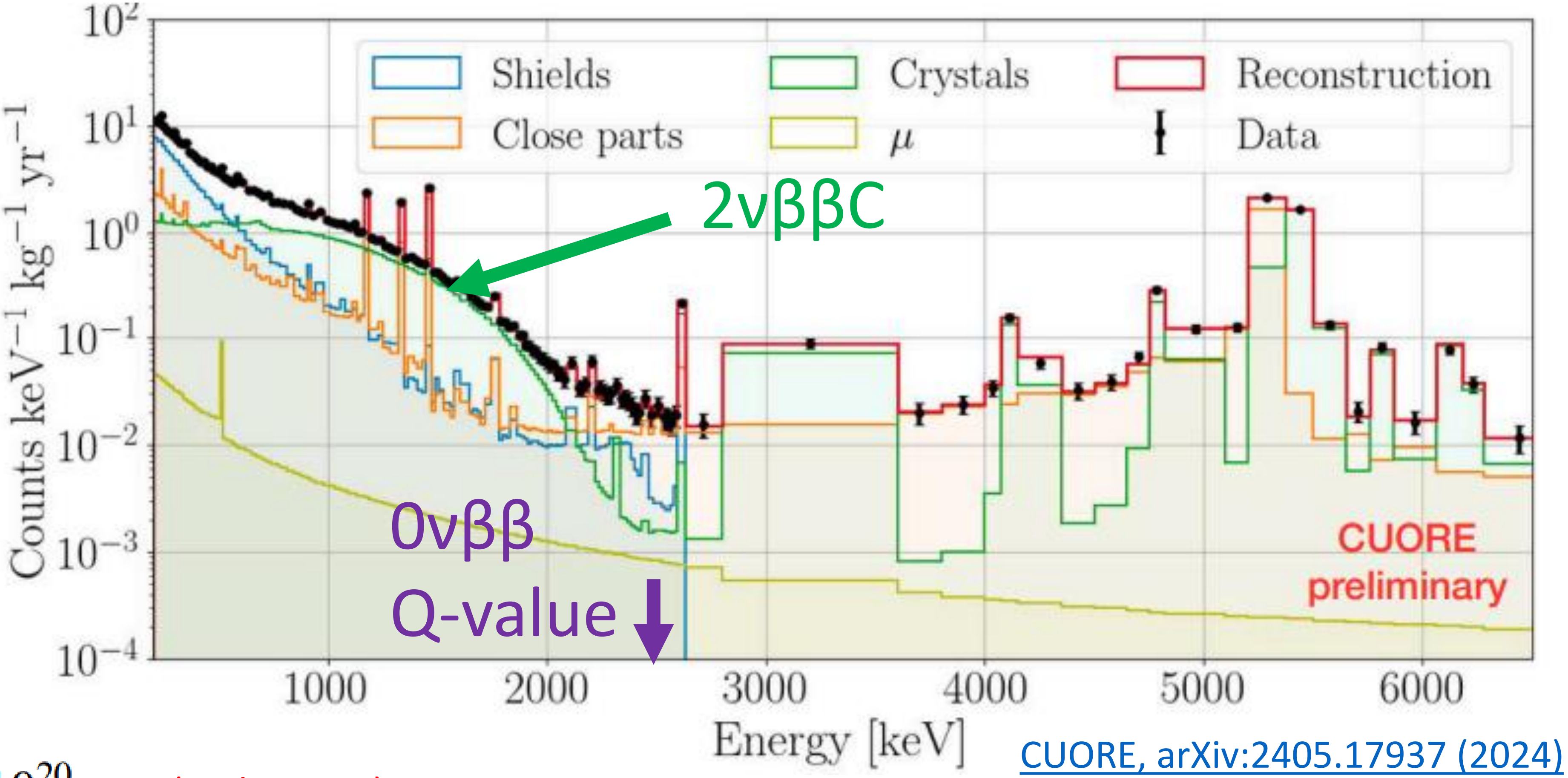


19 towers closely packed and installed into multi-stage cryostat

Measuring 2νββ

Backgrounds complex in 2νββ ROI

Assay every detector component
Careful simulation
Understand cosmic backgrounds



CUORE, arXiv:2405.17937 (2024)

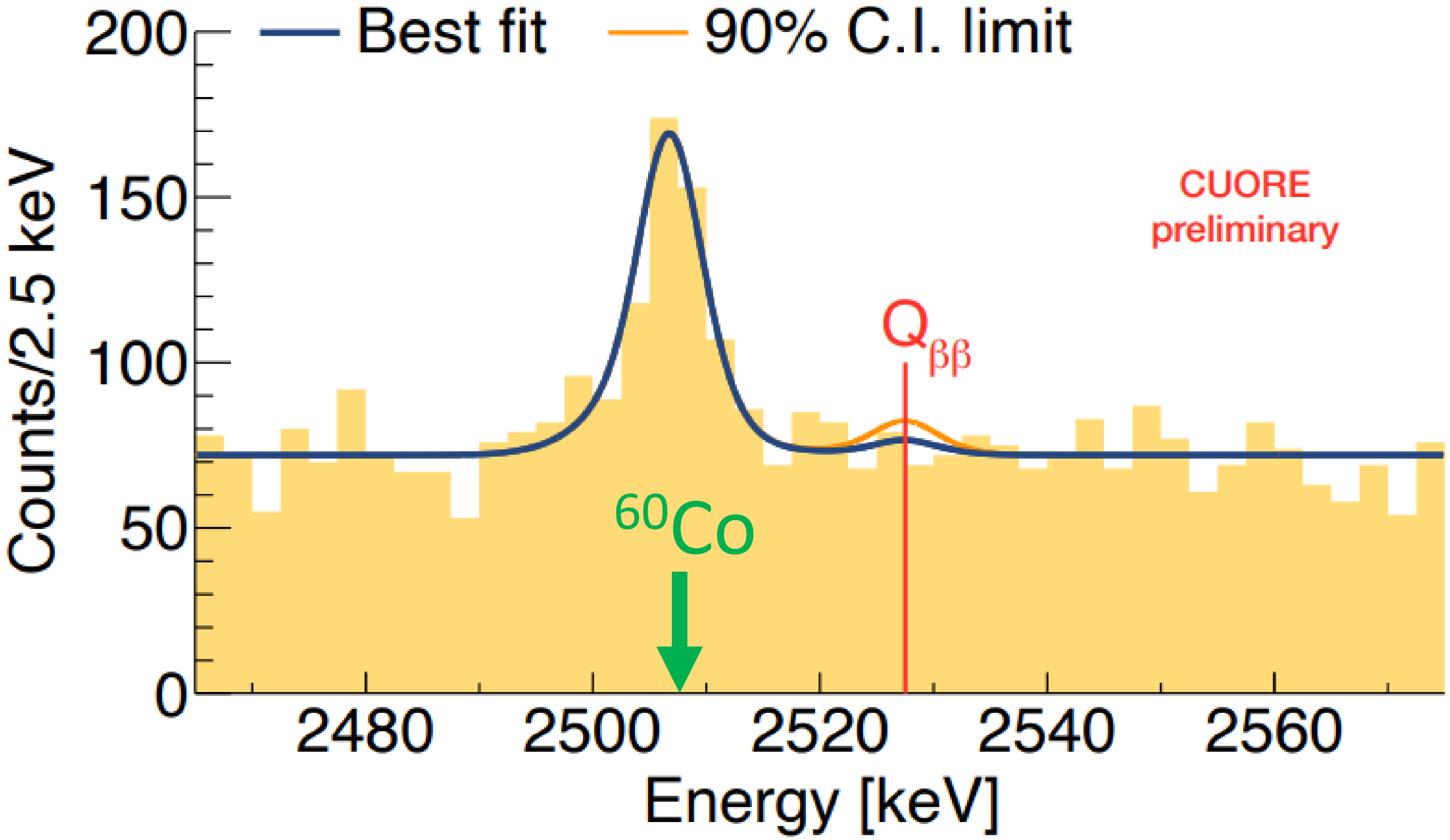
$T_{1/2}^{2\nu} = 9.323^{+0.052}_{-0.037}\ (stat.)\ \times 10^{20}\ yr$ (preliminary)

Searching for 0νββ

Background modeling often simpler for 0νββ ROI – approximately flat

Nasty background from ^{60}Co for TeO_2 – Pileup of two different gammas (1173 keV + 1332 keV)

Energy resolution + background control main experimental challenges



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Summary

– Neutrino physics connected to deep questions about the universe

– Requires understanding neutrinos across ≈ 20 orders of magnitude

– Basic detection strategies discussed laying groundwork for upcoming lectures: interactions, astrophysics, oscillations, mass measurements

– Many paths to detector development – innovative young physicists can have huge impact here