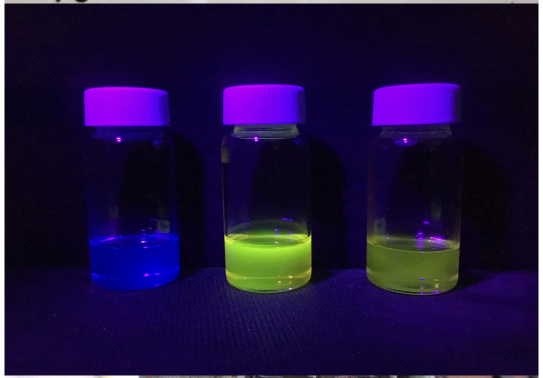
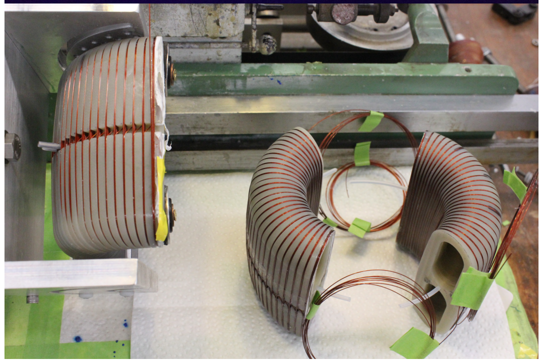




Axion Dark Matter and Neutrinoless Double-Beta Decay:

New Techniques for New Physics

Lindley Winslow
Massachusetts Institute of Technology

Things my group searches for:

Axions

Neutrinoless Double-Beta Decay

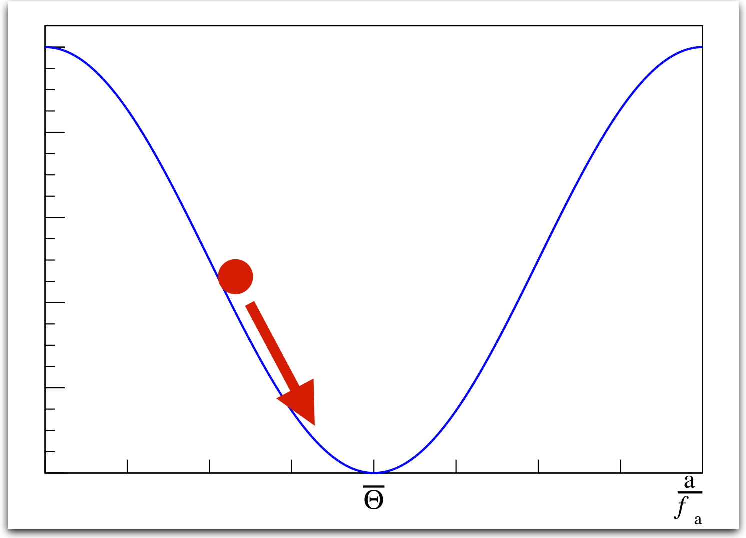
Remaining Standard Model Issues:

Strong CP Problem

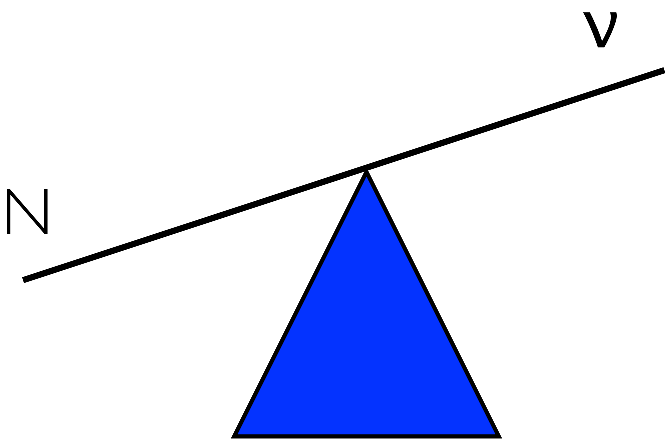
Majorana vs. Dirac Neutrinos

What unites these two topics?

Peccei-Quinn Mechanism



See-Saw Mechanism



$$m_a \sim \frac{m_\pi f_\pi}{f_a} 10^{-9}\,\mathrm{eV}\left(\frac{10^{16}\,\mathrm{GeV}}{f_a}\right)$$

nano-eV mass

GUT scale axion

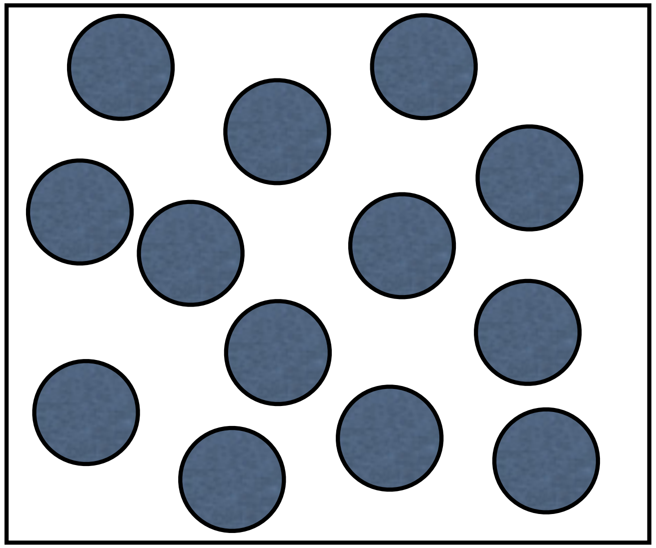
$$L_m = -\frac{1}{2}\frac{m_D^2}{m_R}\bar{\nu}\nu - \frac{1}{2}m_R\bar{N}N$$

Our
Standard
Light ν

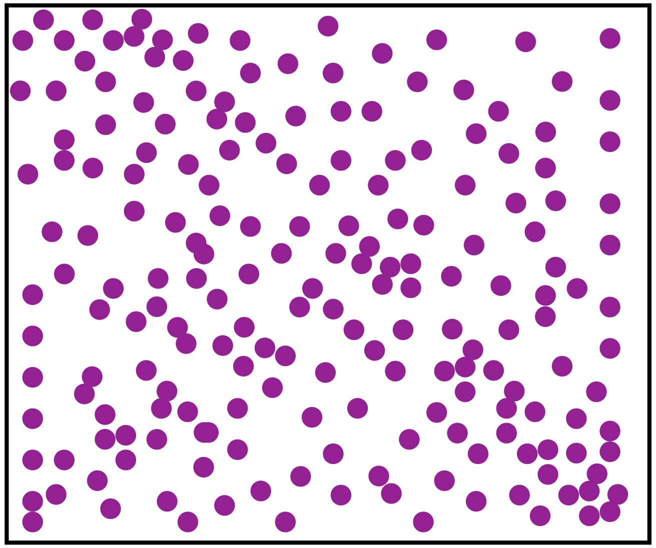
GUT scale ν

Let’s start with Axions

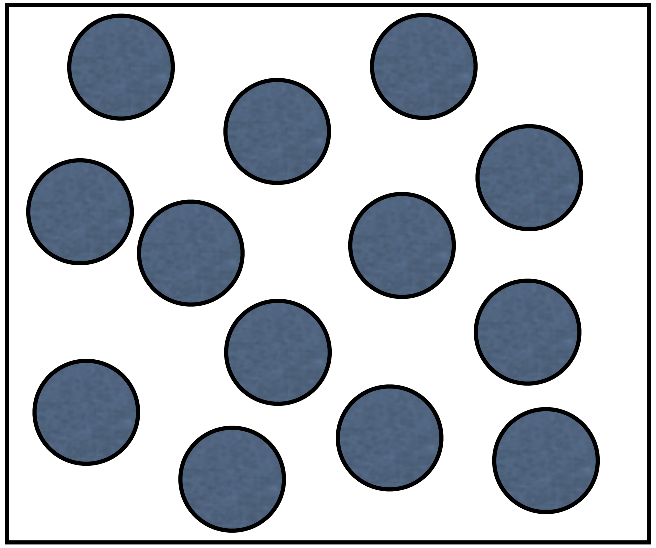
Heavy Dark Matter



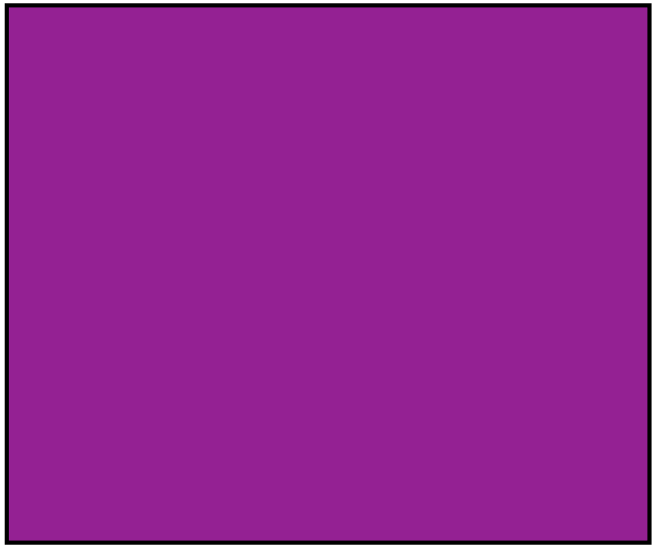
Axion Dark Matter



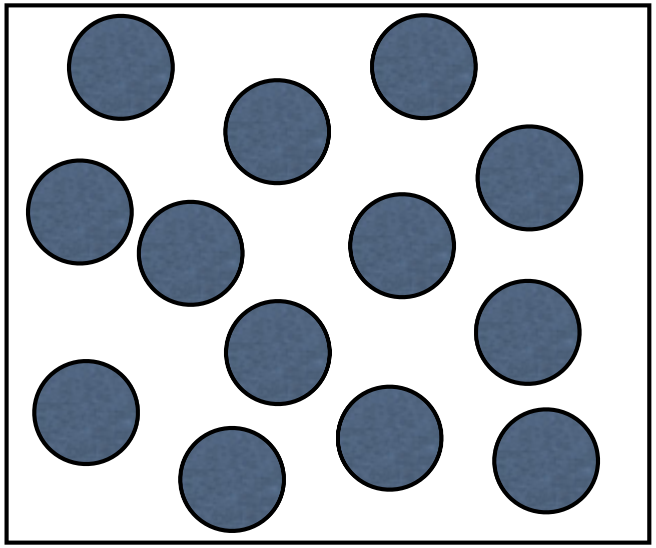
Heavy Dark Matter



Axion Dark Matter

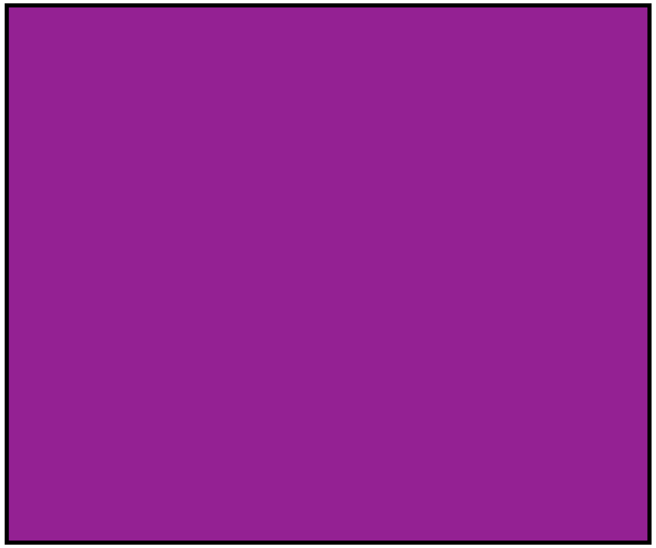


Heavy Dark Matter



These are billiard balls.

Axion Dark Matter



This is a field.

Some Details:

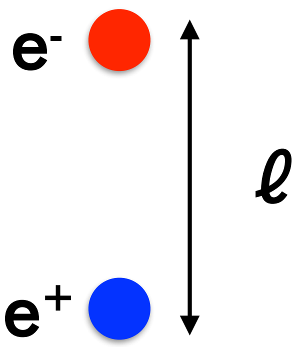
- The Strong CP Problem
- Axion Cosmology
- How do we detect them?
- ABRACADABRA

A quick side-trip to Neutron EDM

What is it?
Why is there a problem?

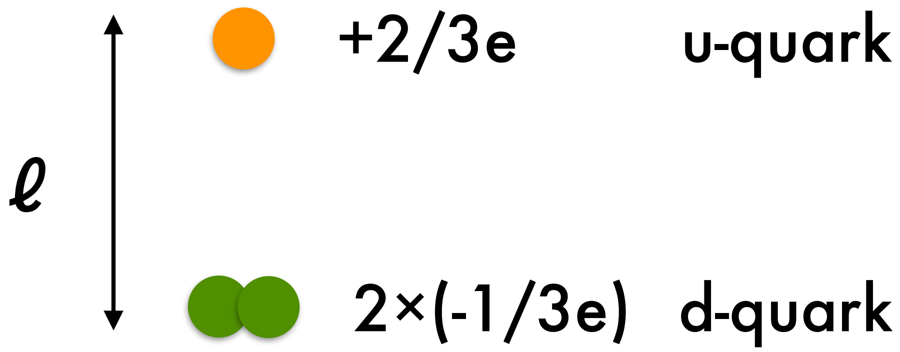
A quick side-trip to Neutron EDM

Classical Electric Dipole



$d = e\ell$

Neutron Electric Dipole



If $\ell \sim 0.1 r_n$

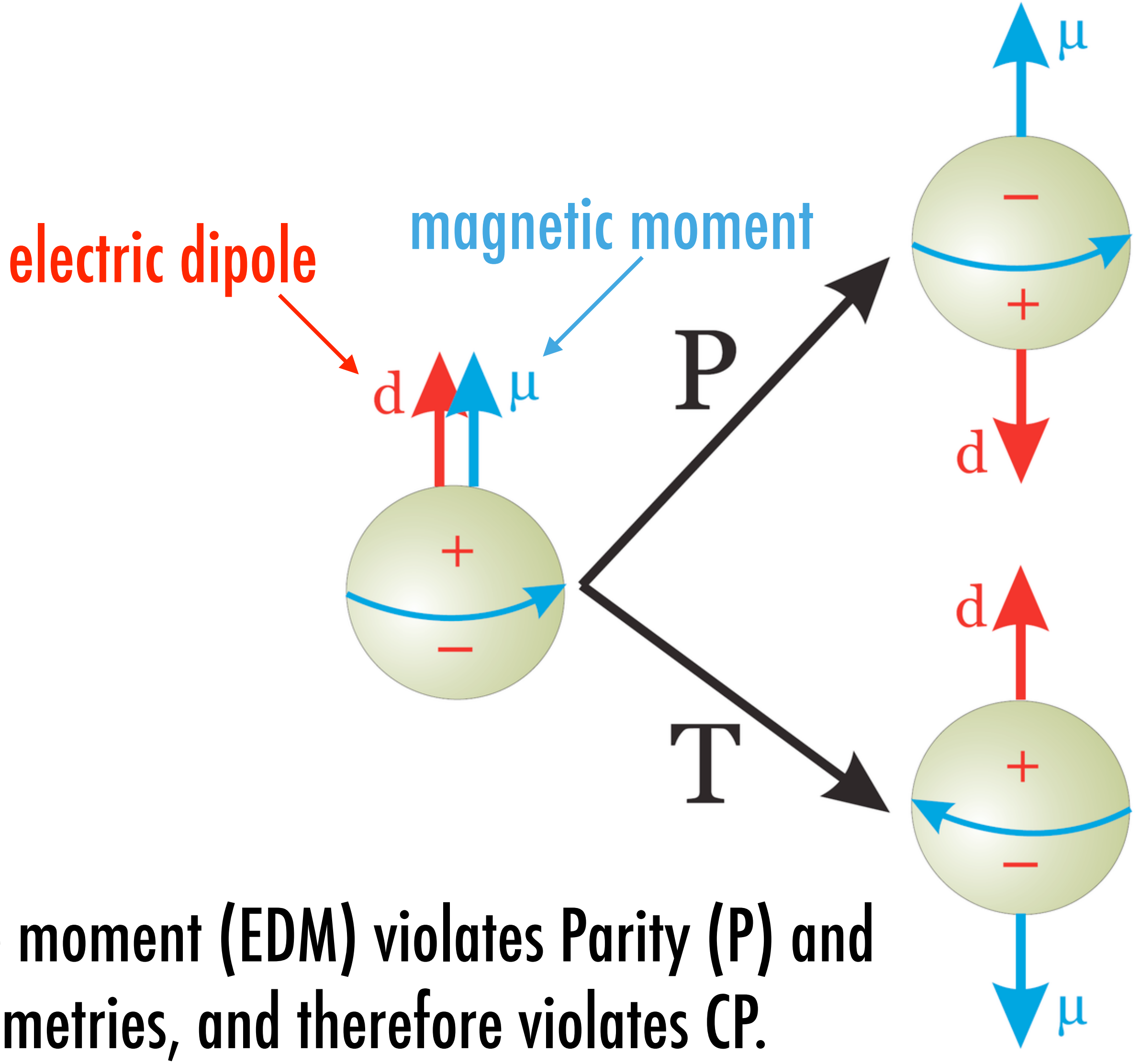
$d_n \sim 4\times10^{-14}$ e-cm

Experiment

$d_n < 3\times10^{-26}$ e-cm

Inspired by B. Filippone's nEDM Lecture

What is more important is symmetry.

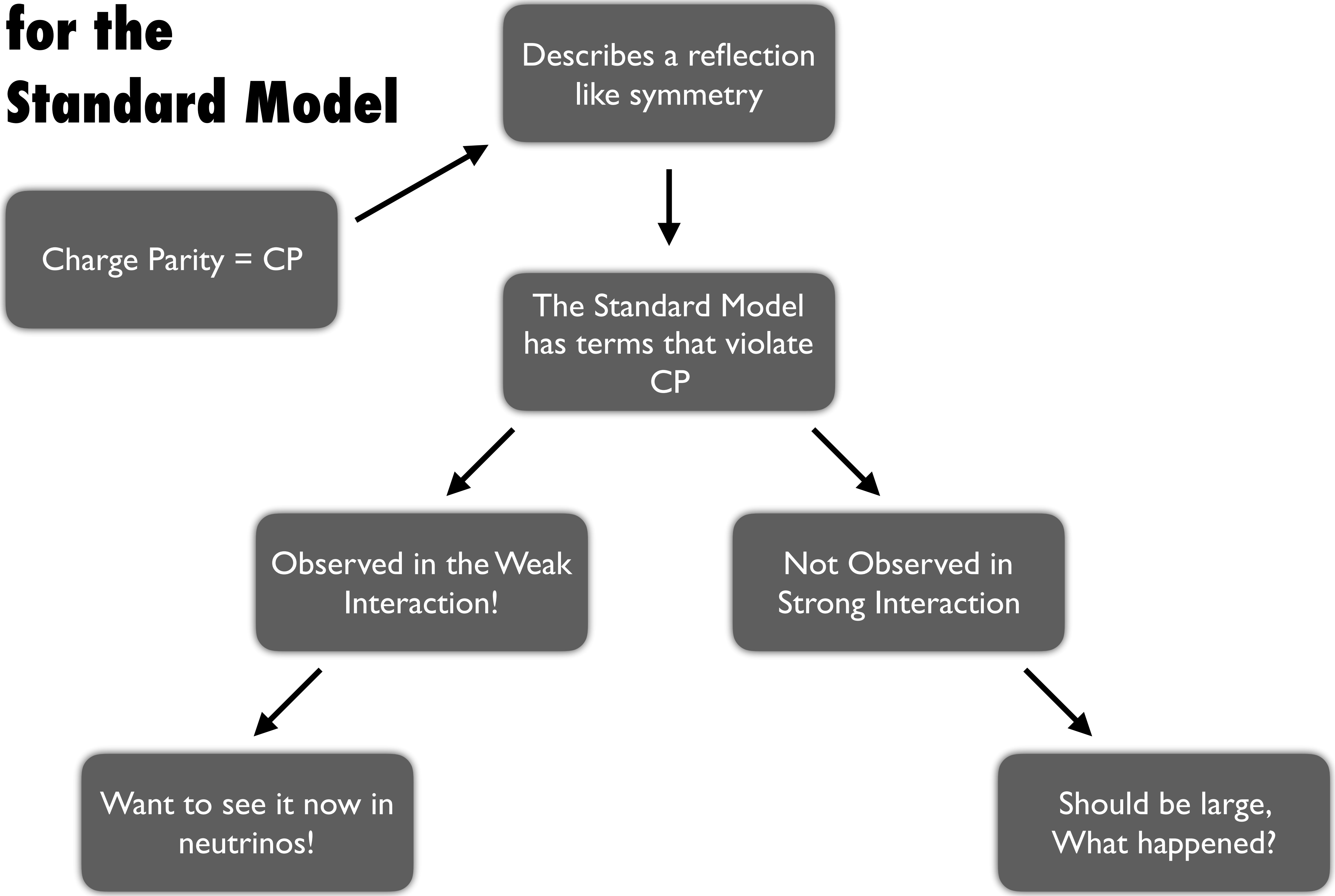


The electric dipole moment (EDM) violates Parity (P) and Time (T) symmetries, and therefore violates CP.

https://en.wikipedia.org/wiki/Neutron_electric_dipole_moment

Charge Parity (CP) Violation is a key ingredient in generating the matter-antimatter asymmetry in the universe.

CP Flow Chart for the Standard Model



Charge Parity = CP

Describes a reflection like symmetry

The Standard Model has terms that violate CP

Observed in the Weak Interaction!

Not Observed in Strong Interaction

Want to see it now in neutrinos!

Should be large, What happened?

Some Details:

This is the CP violating term of the QCD Lagrangian.

$$\mathcal{L}_\Theta = -\bar{\Theta}\,(\alpha_s/8\pi)\,G^{\mu\nu a}\tilde{G}^a_{\mu\nu}$$

↑

Gluon field strength tensor

This term gives rise to an electric dipole moment.

$$d_n \approx 3.6 \times 10^{-16}\theta_{\rm QCD}\,e\ {\rm cm}$$

The current limit:

$$|d_n| < 2.9 \times 10^{-26}\,e\,{\rm cm}\ (90\%\ {\rm C.L.})$$

This implies....

$$\theta_{\rm QCD} \lesssim 10^{-10}$$

Well thats not very natural.

The Solution: Peccei-Quinn Symmetry

SU(3)xSU(2)xU(1)

SU(3): Strong Force
SU(2): Weak Force
U(1): Electromagnetic

Add

$U(1)_{PQ}$

$U(1)_{PQ}$: Peccei Quinn

The Breaking of PQ Symmetry restores CP Symmetry!

Axion Field

$$\mathcal{L} = \left(\frac{\phi_A}{f_A} - \bar{\Theta} \right) \frac{\alpha_s}{8\pi} G^{\mu\nu a} \tilde{G}^a_{\mu\nu}$$

Axion Decay Constant

$$m_A = 5.70(7) \left(\frac{10^9 \text{ GeV}}{f_A} \right) \text{meV}$$

mass of the axion

Dynamically sends Θ to zero!

Originally, we thought...

$$f_A \sim v_{\text{weak}}$$

where

$$v_{\text{weak}} = (\sqrt{2}G_{\text{F}})^{-1/2} = 247 \text{ GeV}$$

but that has been ruled out by experiment.

$$f_A \gg v_{\text{weak}}$$

these invisible axions are mostly unconstrained.

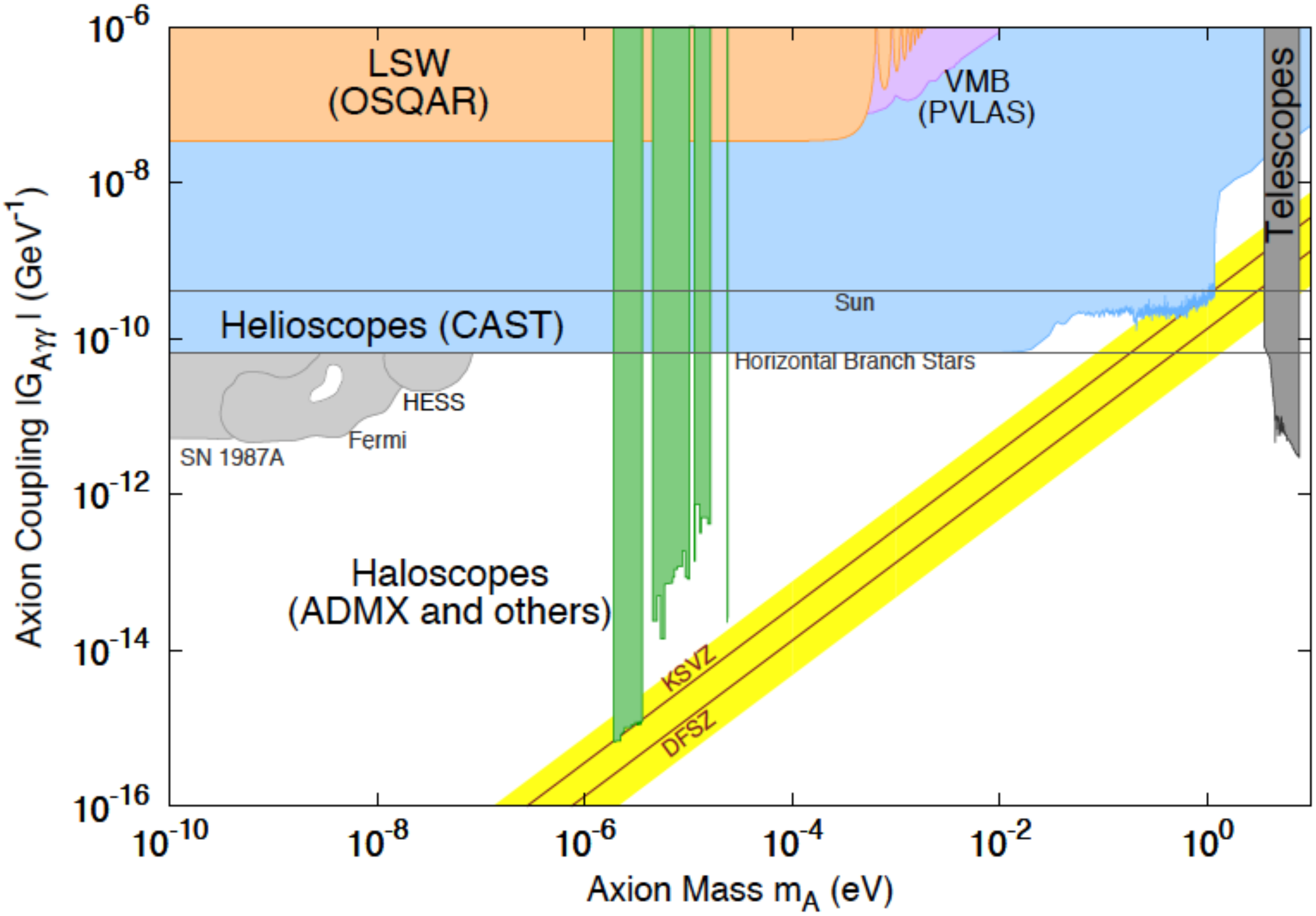
Kim-Shifman-Vainshtein-Zakharav (KSVZ) Axion

Introduces heavy quarks as well as the PQ scalar.

Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) Axion

Introduces additional Higgs field as well as the PQ scalar.

An Equivalent plot for Axions



...so thats what the yellow bands are on this plot.

Some Details:

- The Strong CP Problem
- Axion Cosmology
- How do we detect them?
- ABRACADABRA

Slightly Different Cosmology

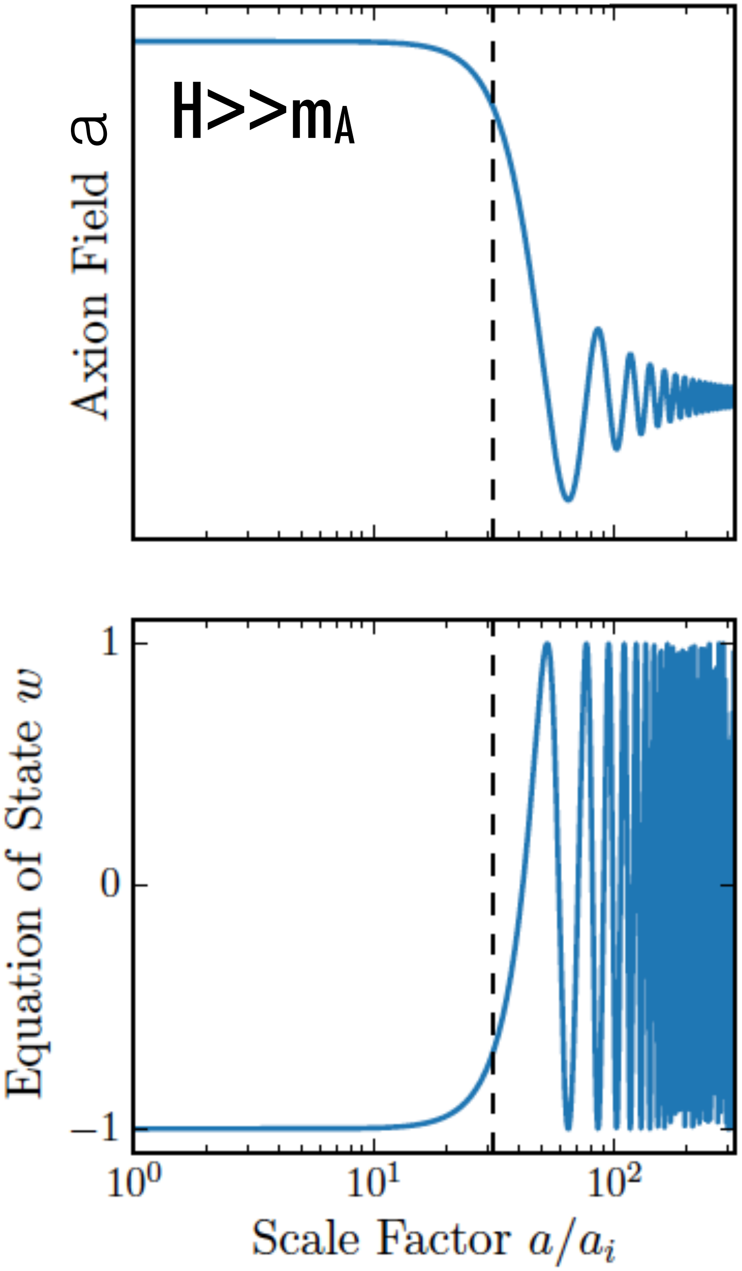
PQ Phase Transition Before Inflation

PQ Phase Transition After Inflation

Misalignment Mechanism

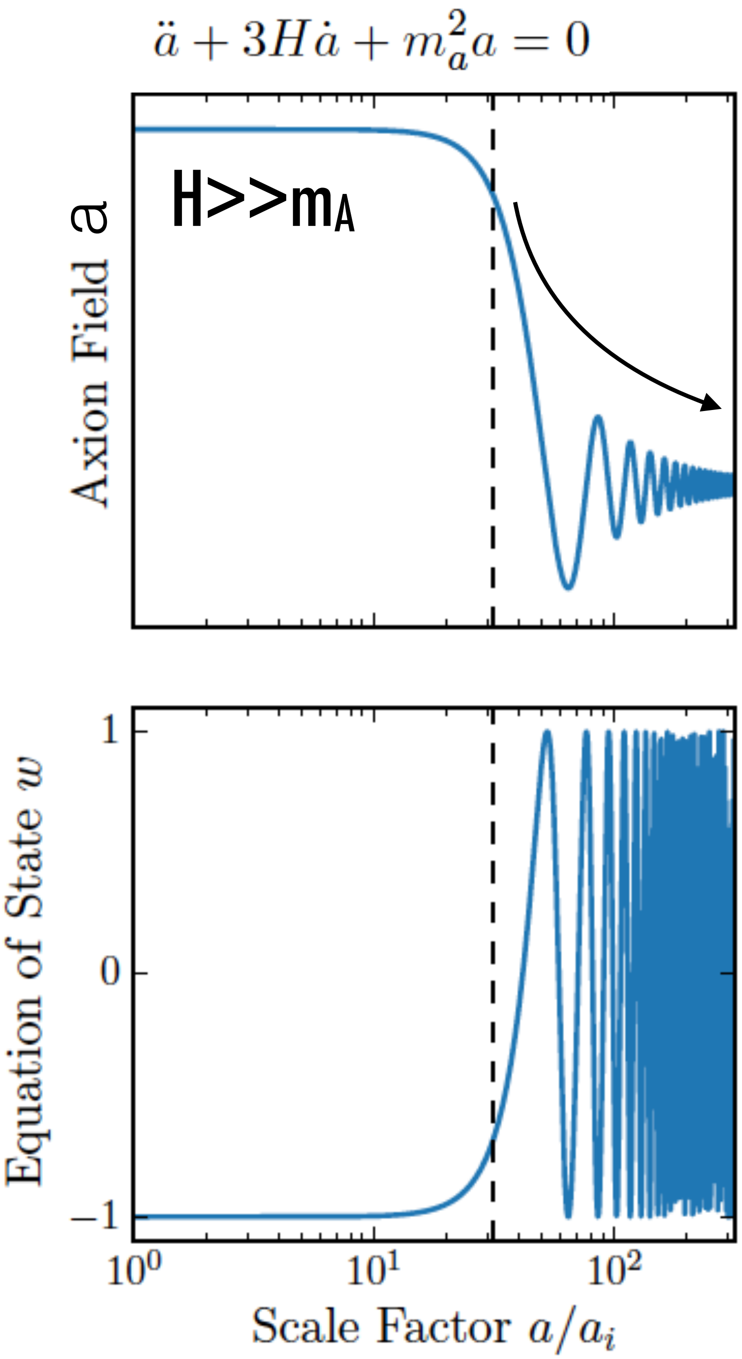
The most straight forward mechanism to generate cold axion dark matter.

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$



In this period the field is damped.
The initial value of the field is determined by the scenario for when symmetry breaking occurred relate to inflation.

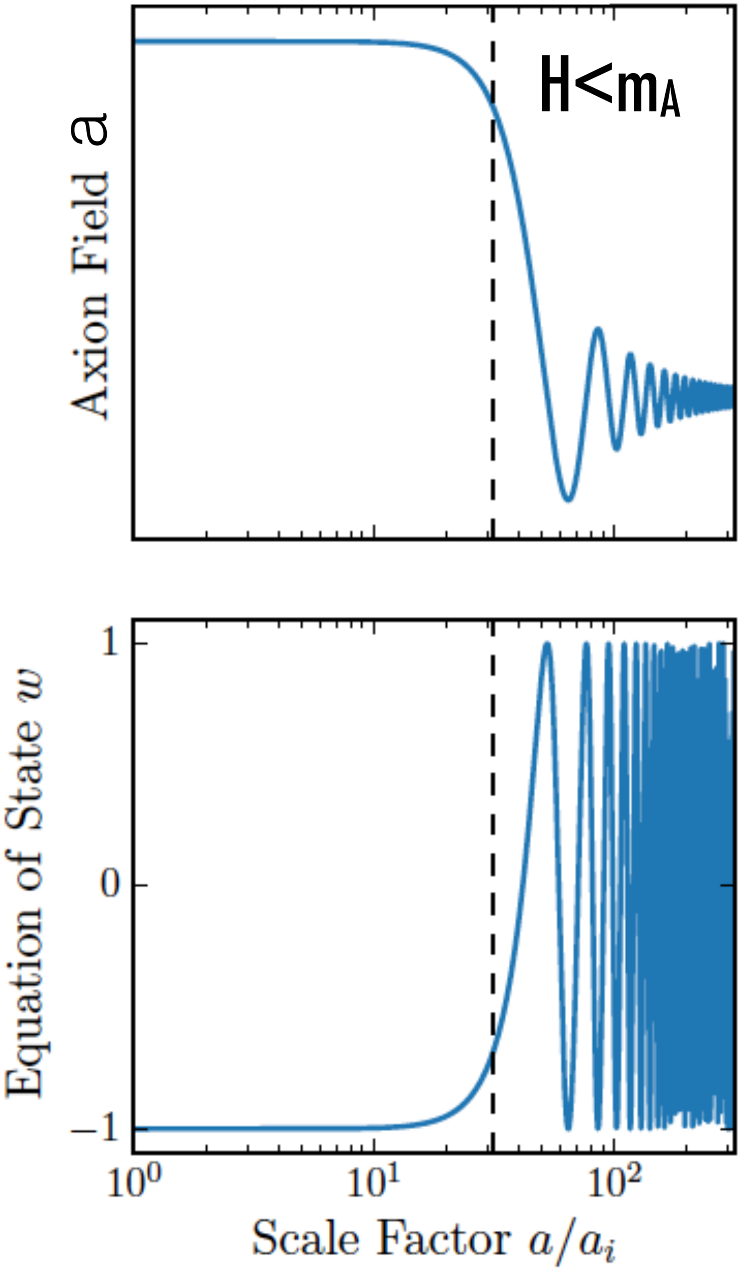
From: David Marsch, arXiv1510.07633



Misalignment refers to the scenario where there is an initial coherent displacement and it relaxes to the potential minimum.

From: David Marsch, arXiv1510.07633

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$



The field is now underdamped and oscillations begin!

Locally,

$$a(t) \approx a_0 \sin(m_a t)$$

$$\frac{1}{2} m_a^2 {a_0}^2 = \rho_{\mathrm{DM}}$$

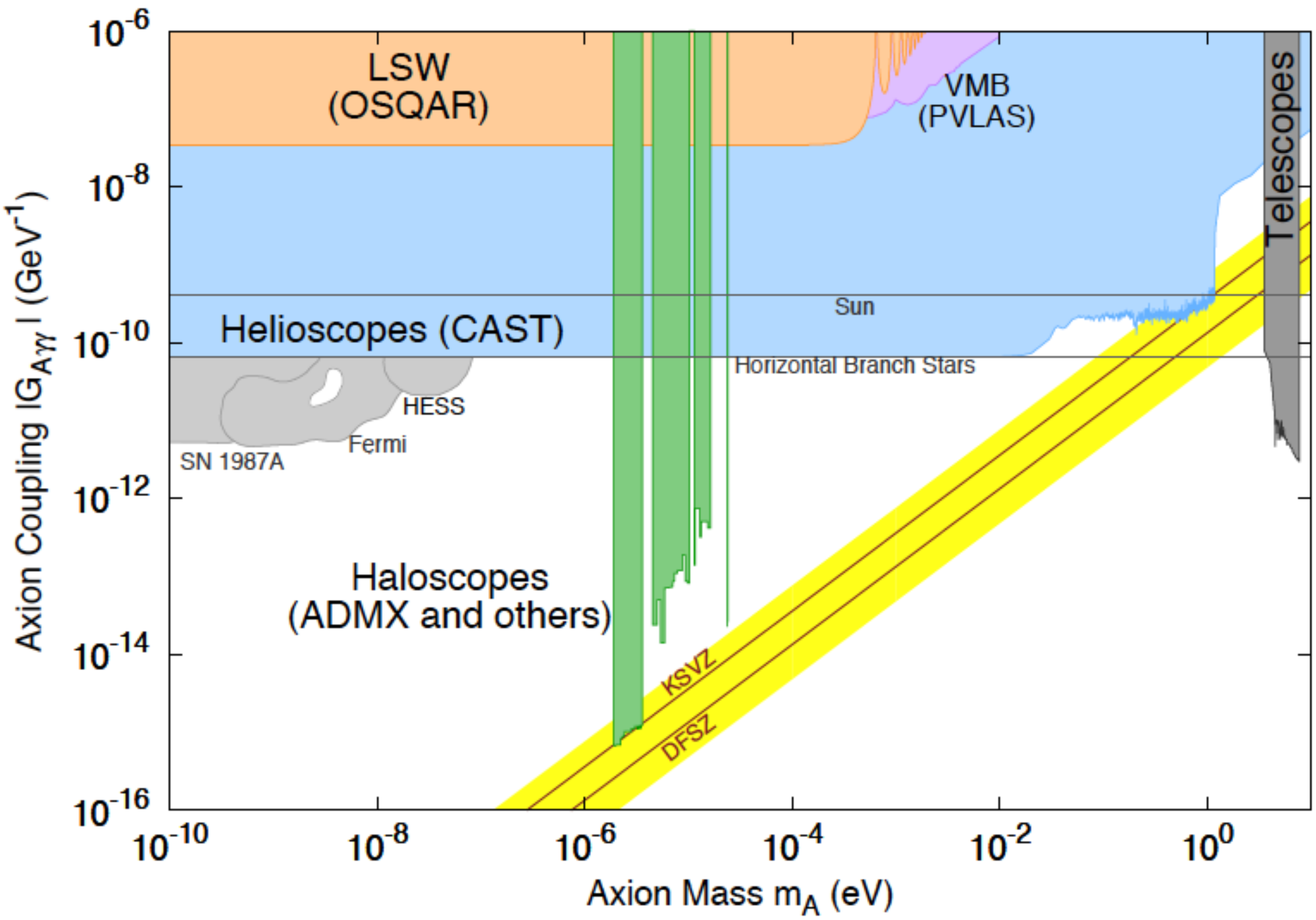
From: David Marsch, arXiv1510.07633

And the key equation for axions as dark matter:

$$\begin{aligned}\Omega_A^{\mathrm{vr}} h^2 &\approx 0.12 \left(\frac{f_A}{9\times 10^{11}\ \mathrm{GeV}}\right)^{1.165} F\,\bar{\Theta}_{\mathrm{i}}^2 \\ &\approx 0.12 \left(\frac{6\ \mu\mathrm{eV}}{m_A}\right)^{1.165} F\,\Theta_{\mathrm{i}}^2\,,\end{aligned}$$

axion dark matter mass
density

Why are the experimental limits focused at micro-eV?



PDG - Axion Review 2018

And the key equation for axions as dark matter:

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Because that is natural.

And the key equation for axions as dark matter:

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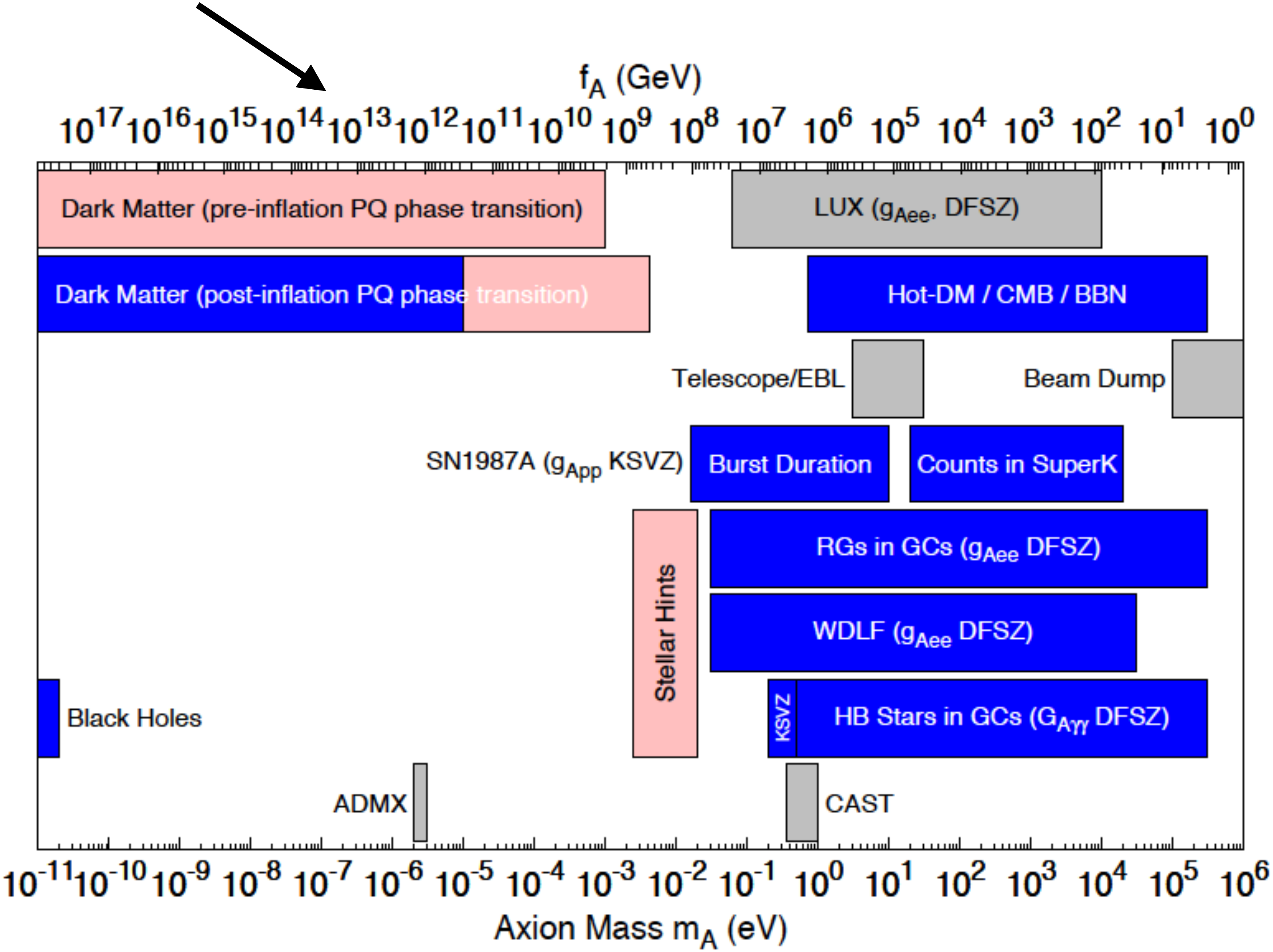
Because that is natural.

Theoretical Preferences in Pink



PDG - Axion Review 2018

There are some preferences but a lot of wiggle room!

Some Details:

- The Strong CP Problem
- Axion Cosmology
- How do we detect them?
- ABRACADABRA

From: Yoni Kahn

Axion-SM interactions

[Graham and Rajendran, Phys. Rev. D88 (2013)]

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \widetilde{F}^{\mu\nu} - \frac{i}{2} g_d a \overline{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu} + g_{aNN} (\partial_\mu a) \overline{N} \gamma^\mu \gamma_5 N + g_{aee} (\partial_\mu a) \overline{e} \gamma^\mu \gamma_5 e$$

Axion-photon conversion

Nucleon EDM

Nuclear axial moment

Electron axial moment

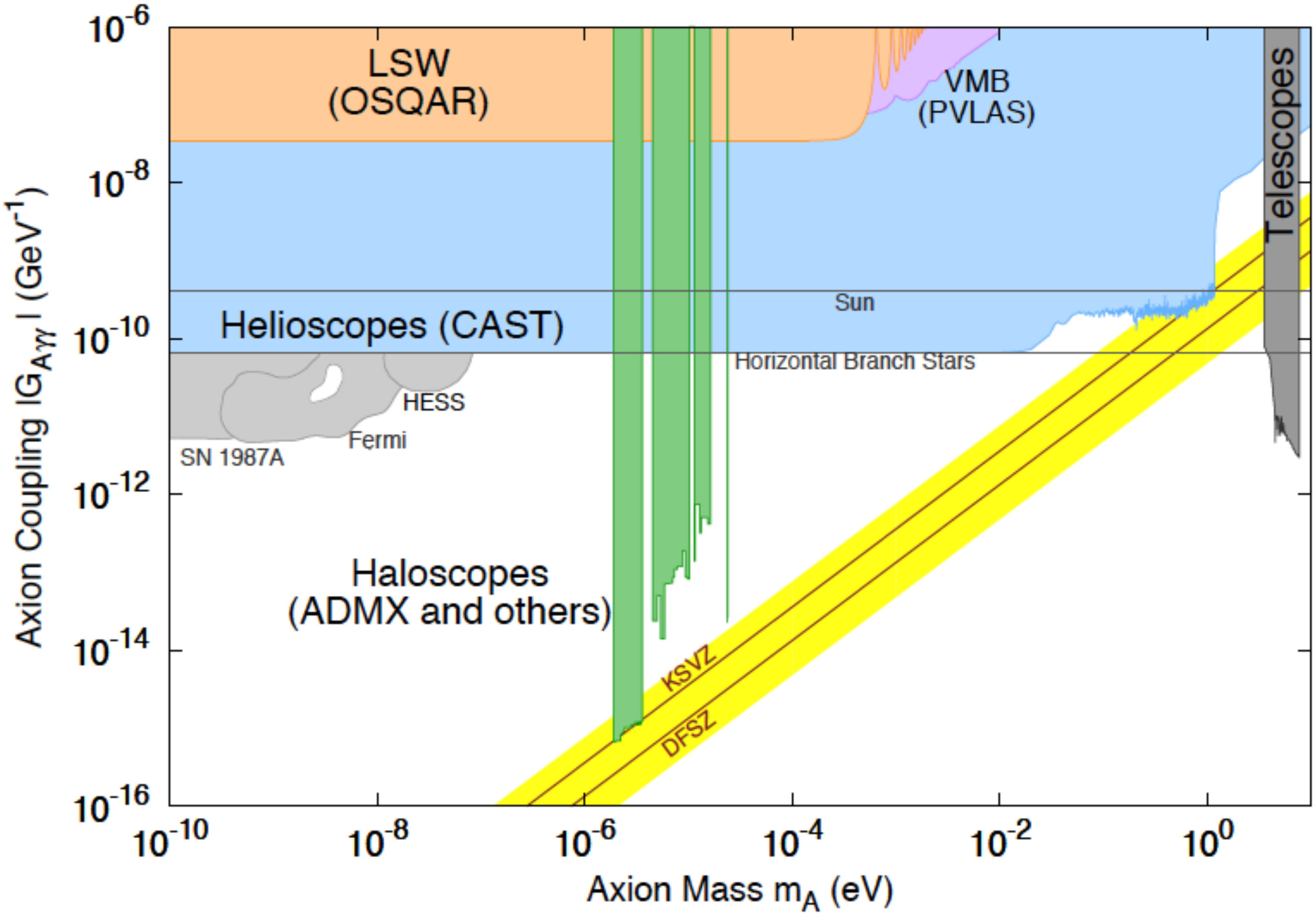
$\propto \nabla a$

Note: for QCD axion, $m_a \sim 6 \times 10^{-10}\ \mathrm{eV} \left(\frac{10^{16}\ \mathrm{GeV}}{f_a}\right)$

All couplings of order $1/f_a$

For "axion-like particles" (ALPs), couplings independent of m_a

The Summary of the Axion Parameter Space



PDG - Axion Review 2018

Axions modify Maxwell's Equations!

$$\nabla \cdot E = -g_{a\gamma\gamma} B \cdot \nabla a$$

$$\nabla \cdot B = 0$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times B = \frac{\partial E}{\partial t} - g_{a\gamma\gamma}(E \times \nabla a - \frac{\partial a}{\partial t} B)$$

Modified Source-free Maxwell's Equations

Axions modify Maxwell's Equations!

$$\nabla \cdot E = -g_{a\gamma\gamma} B \cdot \cancel{\nabla a}$$

$$\nabla \cdot B = 0$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times B = \frac{\partial E}{\partial t} - g_{a\gamma\gamma}(E \cancel{\times \nabla a} - \frac{\partial a}{\partial t} B)$$

These terms are assumed to be small.

From: Yoni Kahn

Axion-photon searches

$$\underbrace{\nabla \times \mathbf{B}_r = \frac{\partial \mathbf{E}_r}{\partial t}} + g_{a\gamma\gamma} \mathbf{B}_0 \frac{\partial a}{\partial t}$$

Cavity regime: $\lambda_{\mathrm{Comp}} \sim R_{\mathrm{exp}}$

ADMX

$$\nabla \times \mathbf{B}_r = \cancel{\frac{\partial \mathbf{E}_r}{\partial t}} + \underbrace{g_{a\gamma\gamma} \mathbf{B}_0 \frac{\partial a}{\partial t}}_{\mathbf{J}_{\mathrm{eff}}}$$

Quasistatic regime: $\lambda_{\mathrm{Comp}} \gg R_{\mathrm{exp}}$

ABRACADBRA

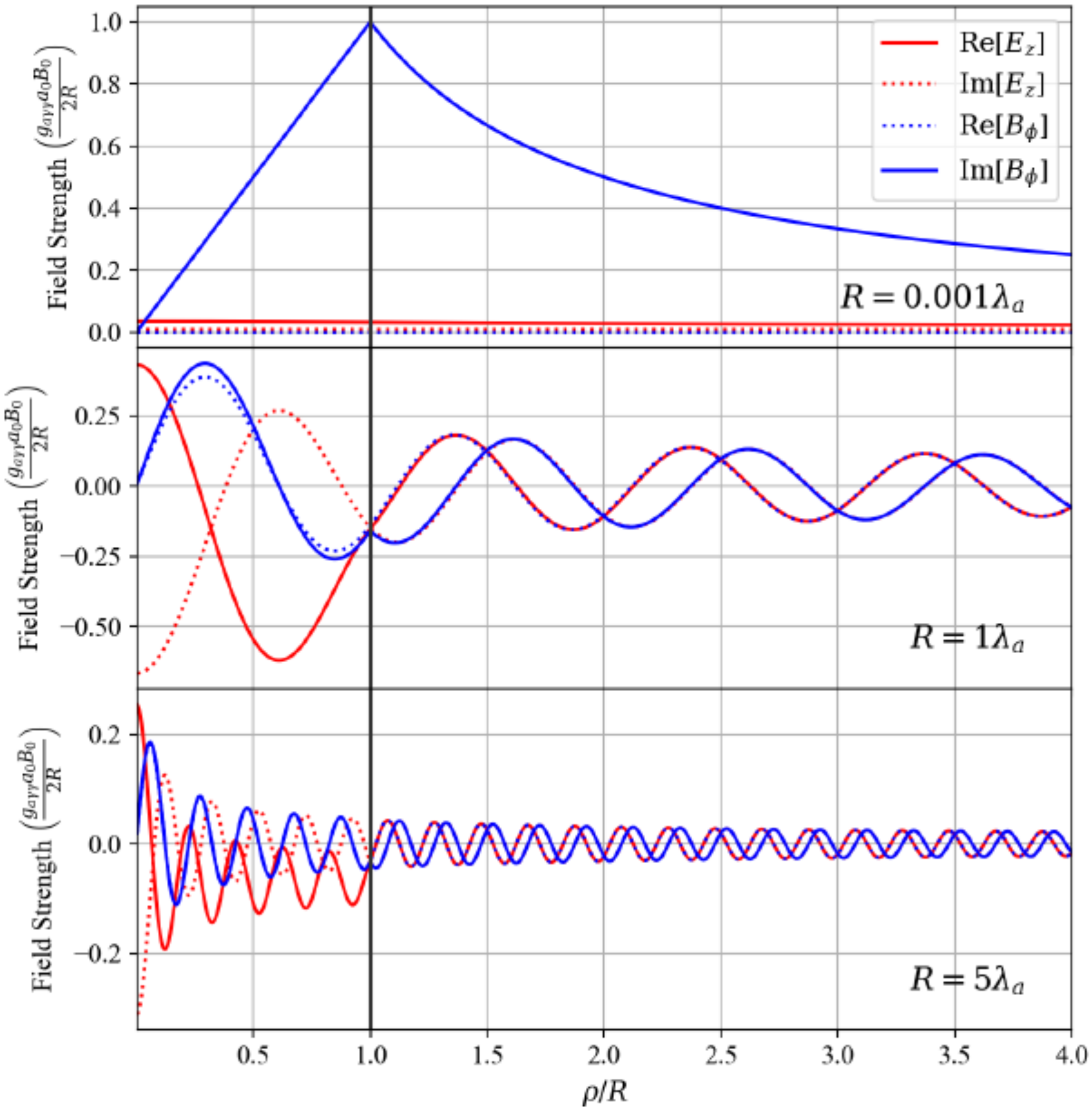
$$\nabla \cancel{\times} \mathbf{B}_r = \frac{\partial \mathbf{E}_r}{\partial t} + g_{a\gamma\gamma} \mathbf{B}_0 \frac{\partial a}{\partial t}$$

Radiation regime: $\lambda_{\mathrm{Comp}} \ll R_{\mathrm{exp}}$

MADMAX

A Calculation of the Axion Induced Fields

Solid lines indicate the axion induced fields, see also arXiv1812.0548 for a full QFT derivation.



$\lambda_{\text{Comp}} \gg R_{\text{exp}}$

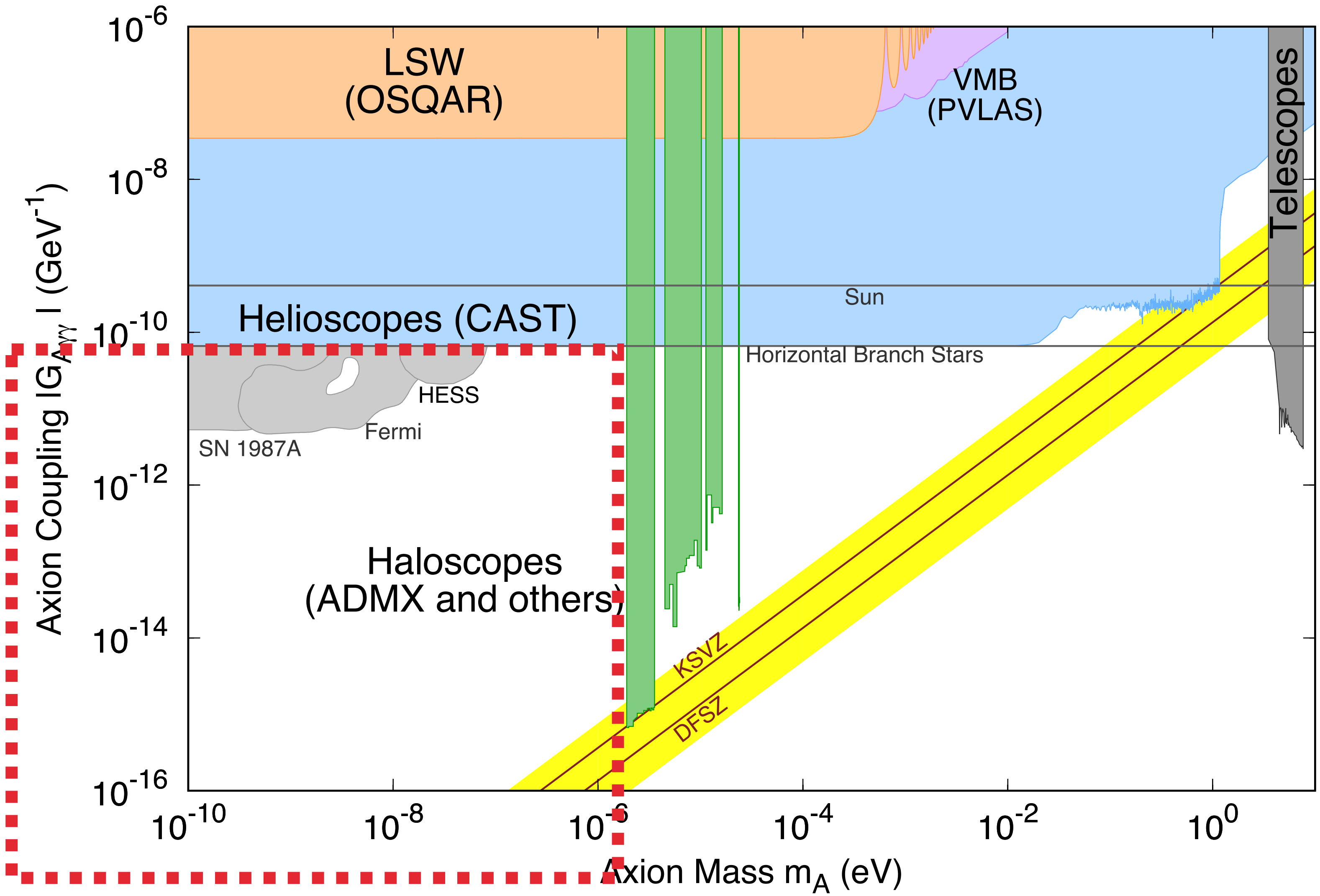
$\lambda_{\text{Comp}} \sim R_{\text{exp}}$

$\lambda_{\text{Comp}} \ll R_{\text{exp}}$

Ouellet and Bogorad, arXiv:1809.10709v1

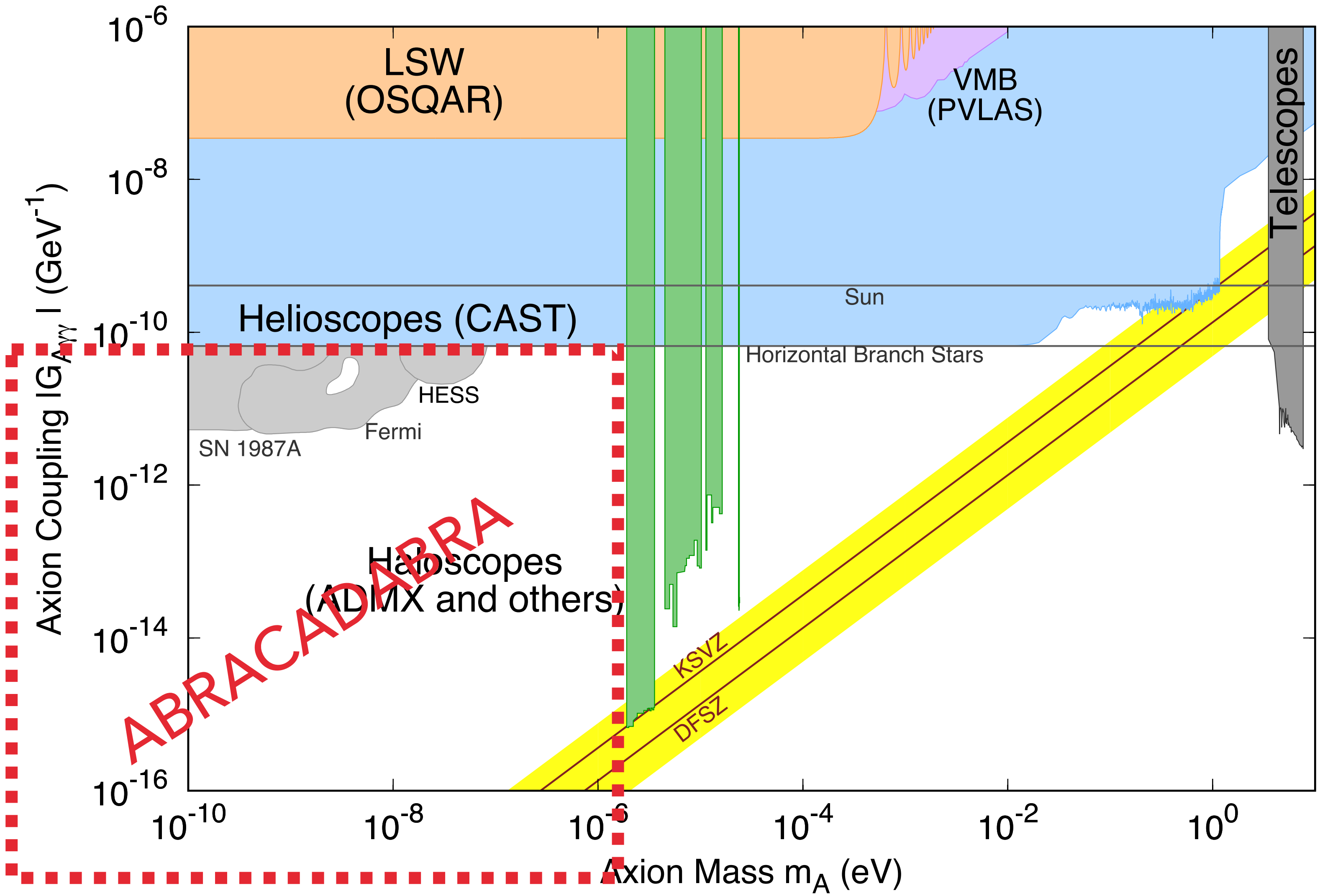
The Lumped Element Parameter Space

$\lambda_{\mathrm{Comp}} \gg R_{\mathrm{exp}}$



Sensitive to m_A between 10^{-14} to 10^{-6} eV, ~Hz to~GHz

The ABRA Parameter Space



Sensitive to m_A between 10^{-14} to 10^{-6} eV, ~Hz to~GHz

Some Details:

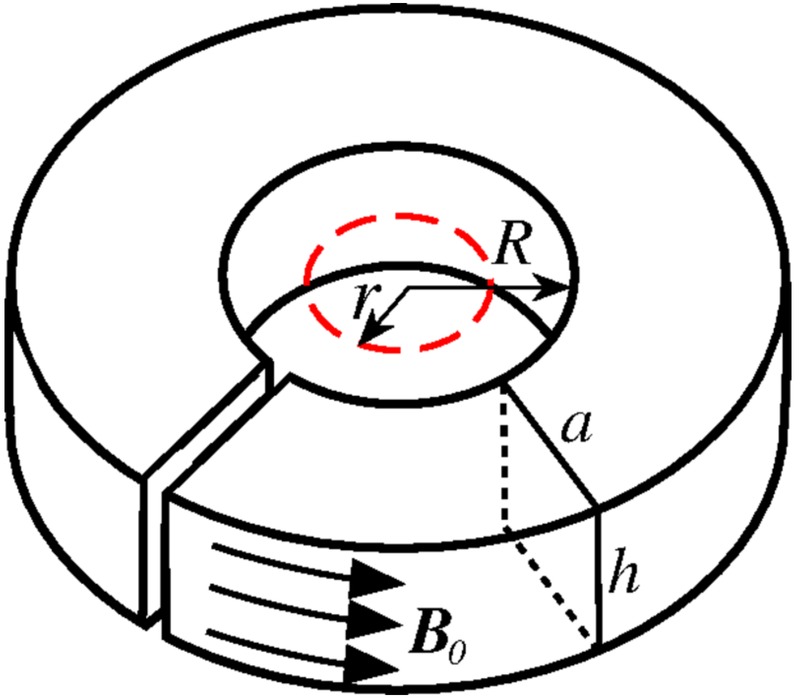
- The Strong CP Problem
- Axion Cosmology
- How do we detect them?
- ABRACADABRA

ABRACADABRA

A **B**roadband / **R**esonant **A**pproach to **C**osmic **A**xion **D**etection with an **A**mplifying **B**-field **R**ing **A**pparatus

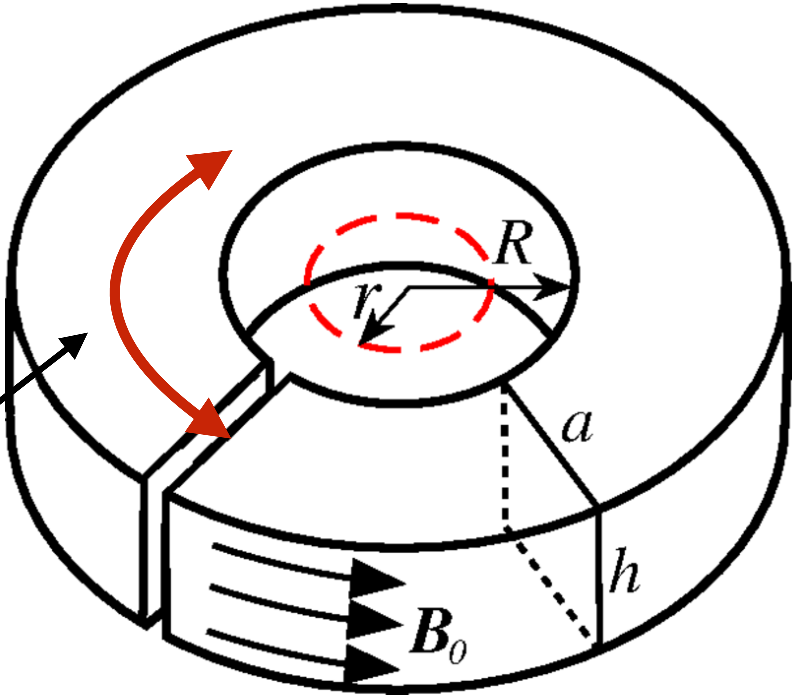
What is a B-field Ring Apparatus?

The cartoon experiment



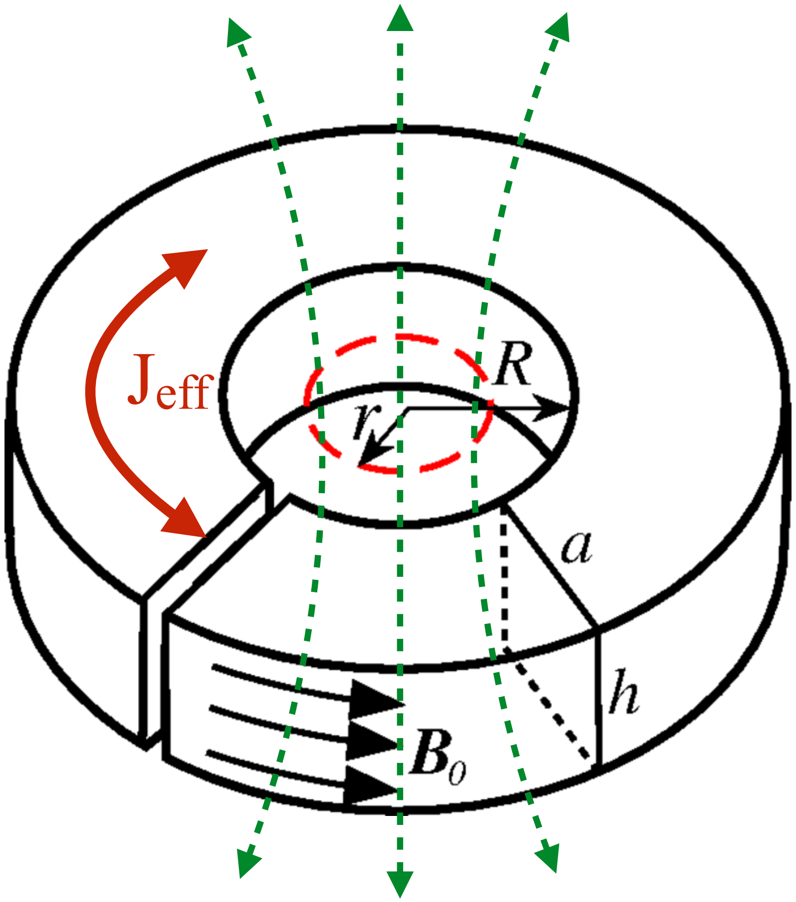
Based on Kahn, Safdi and Thaler, Phys.Rev.Lett. 117 (2016) no.14, 141801

The cartoon experiment



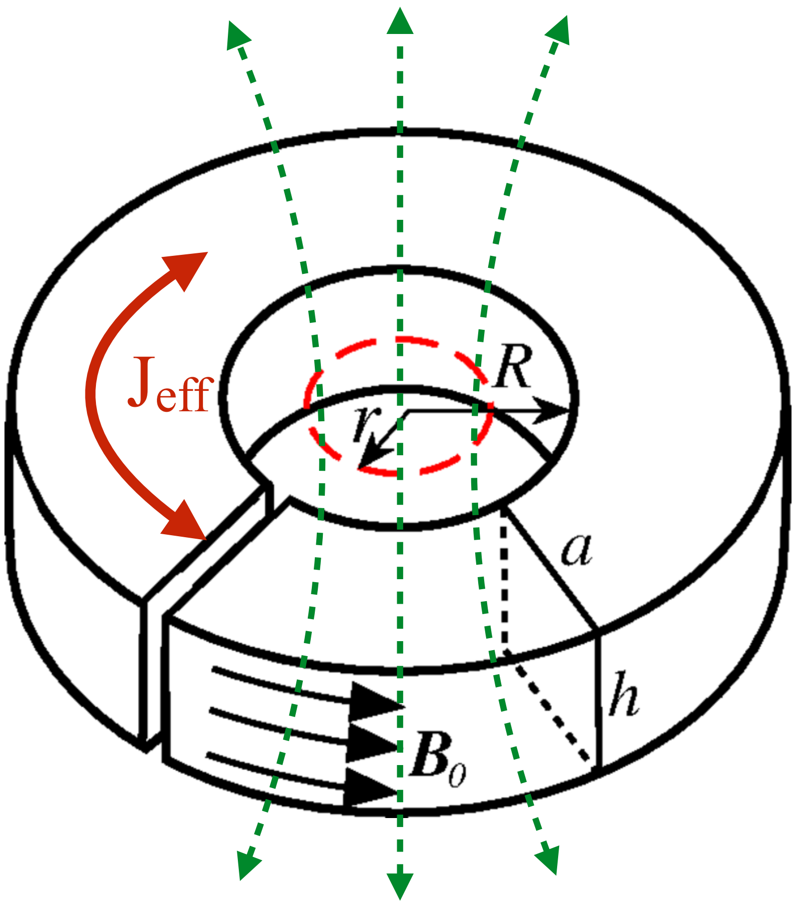
axion current

The cartoon experiment



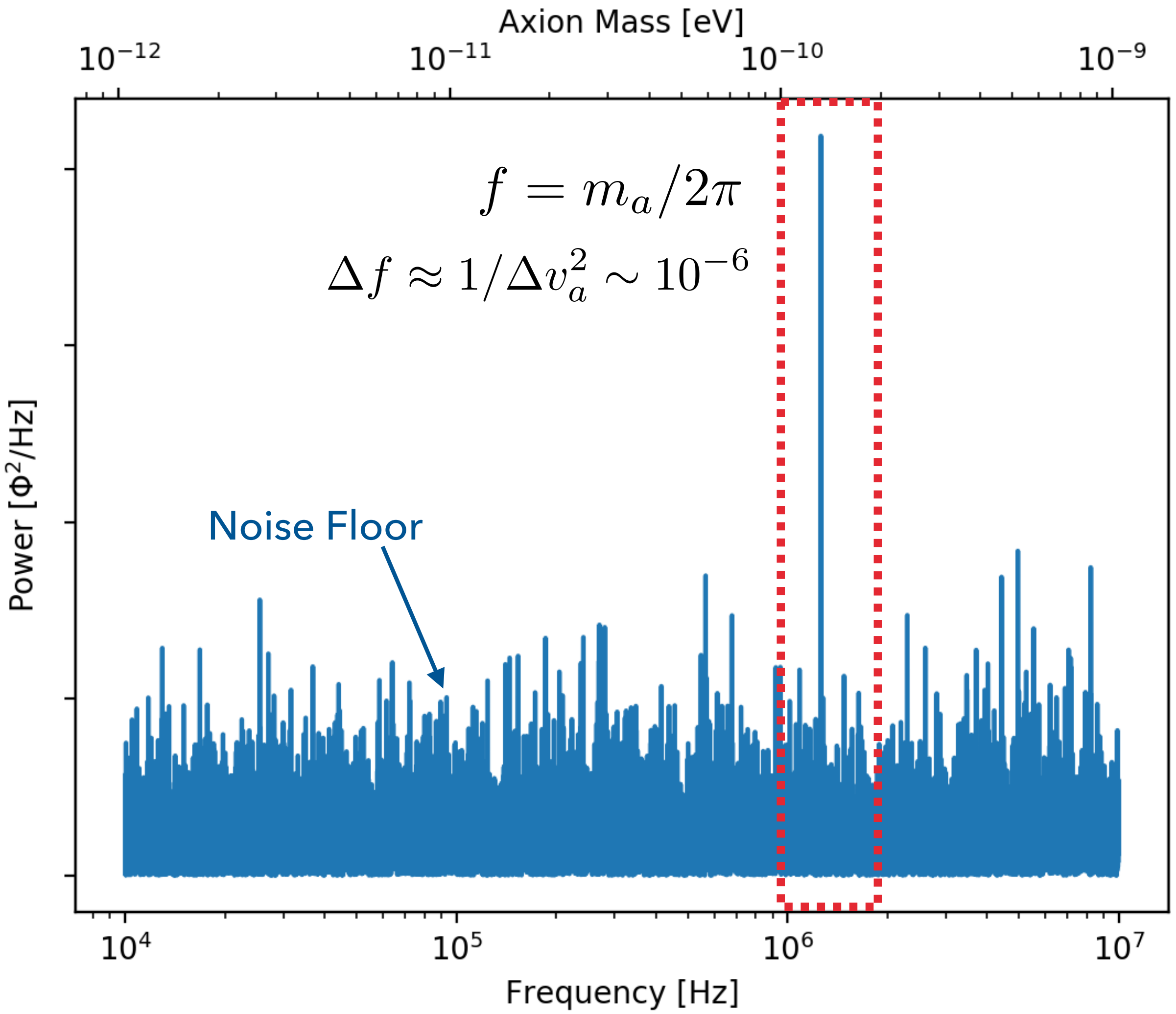
Real Magnetic Field!

The cartoon experiment



A real magnetic field induced in a zero field region.

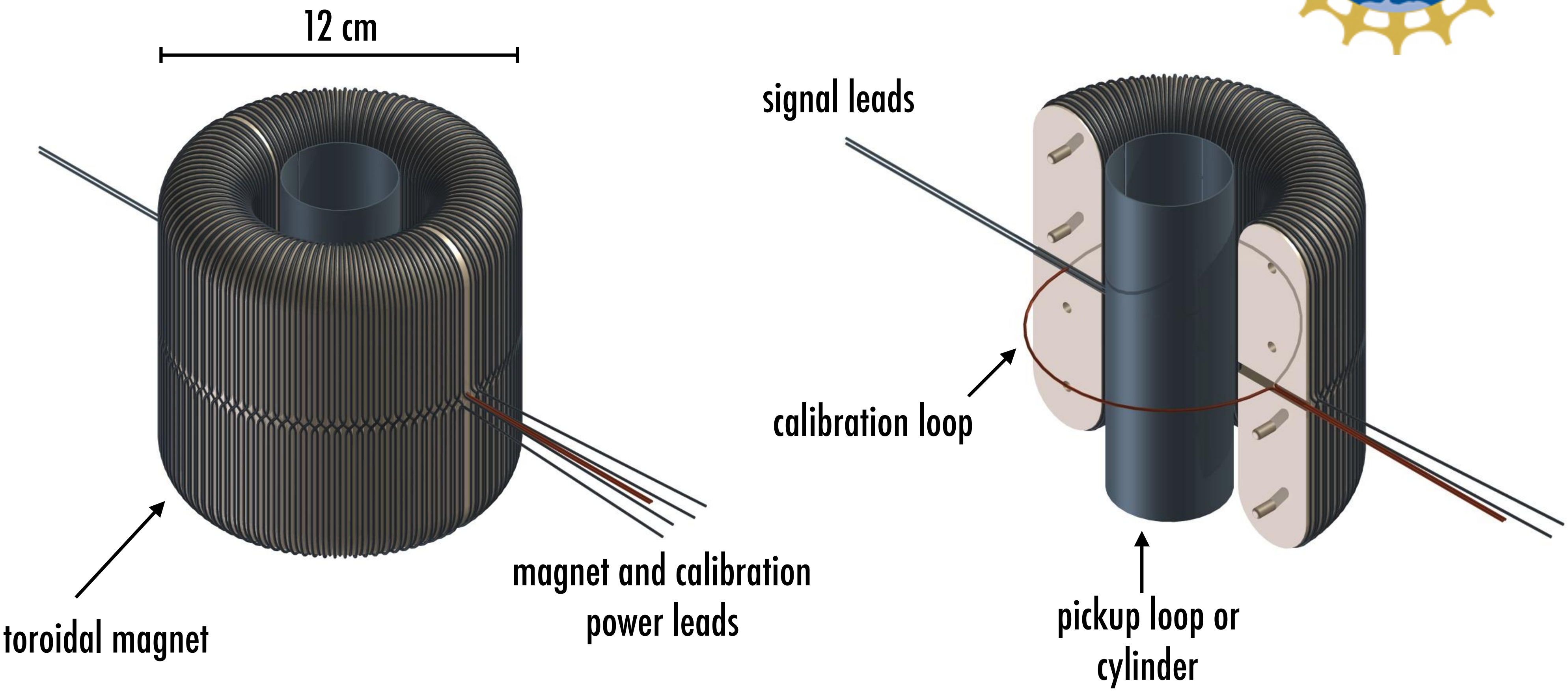
An Example Signal



$$f = m_a/2\pi$$

$$\Delta f \approx 1/\Delta v_a^2 \sim 10^{-6}$$

ABRACADABRA



ABRACADABRA-10cm Conceptual Design

ABRACADABRA

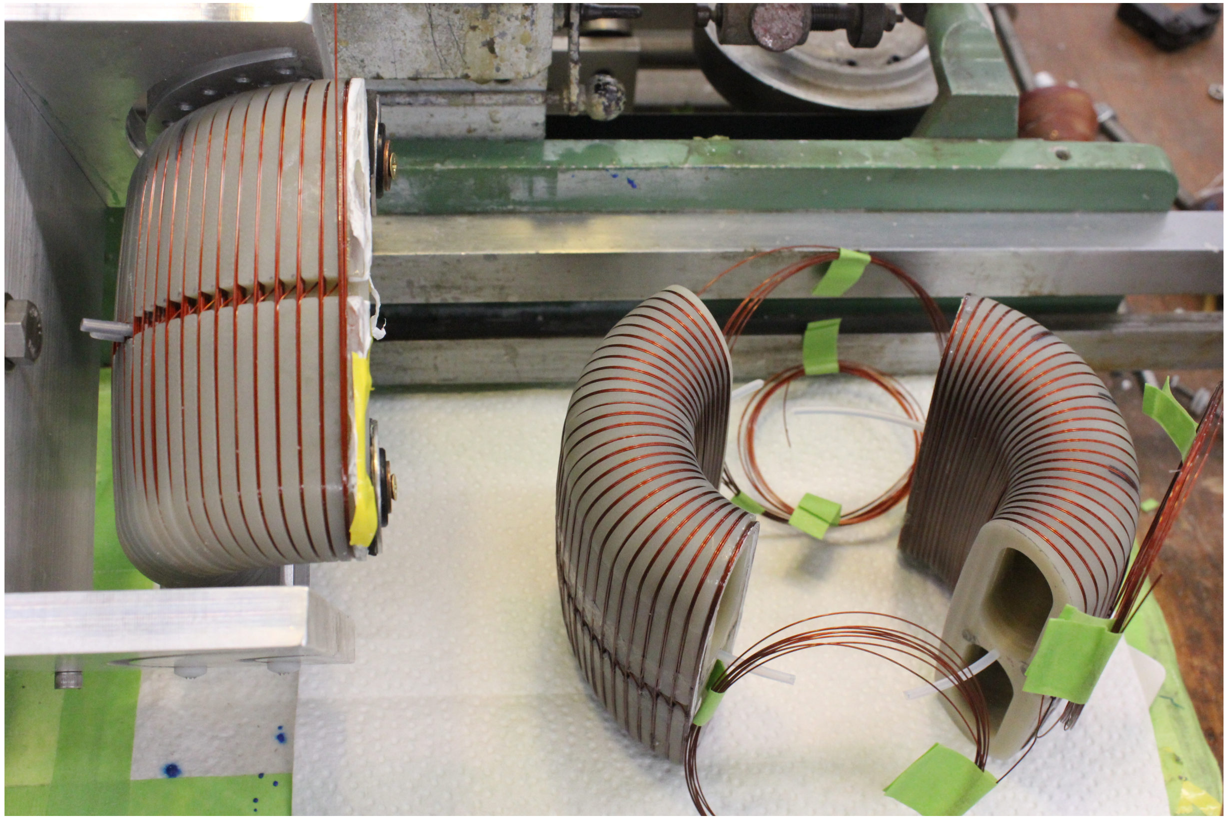
The Collaboration

MIT LNS	**Zachary Bogorad, Janet Conrad, Joe Formaggio, Jonathan Ouellet, Chiara Salemi, Jesse Thaler, Daniel Winklehner, Lindley Winslow (NSF PI)**
MIT PSFC	**Joe Minervini, Alexey Radovinsky**
Chicago/ UIUC	**Yonatan Kahn**
U of Michigan	**Joshua Foster, Ben Safdi**
UNC	**Reyco Henning**
LBNL	**Nick Rodd**

THE UNIVERSITY
of NORTH CAROLINA
at CHAPEL HILL

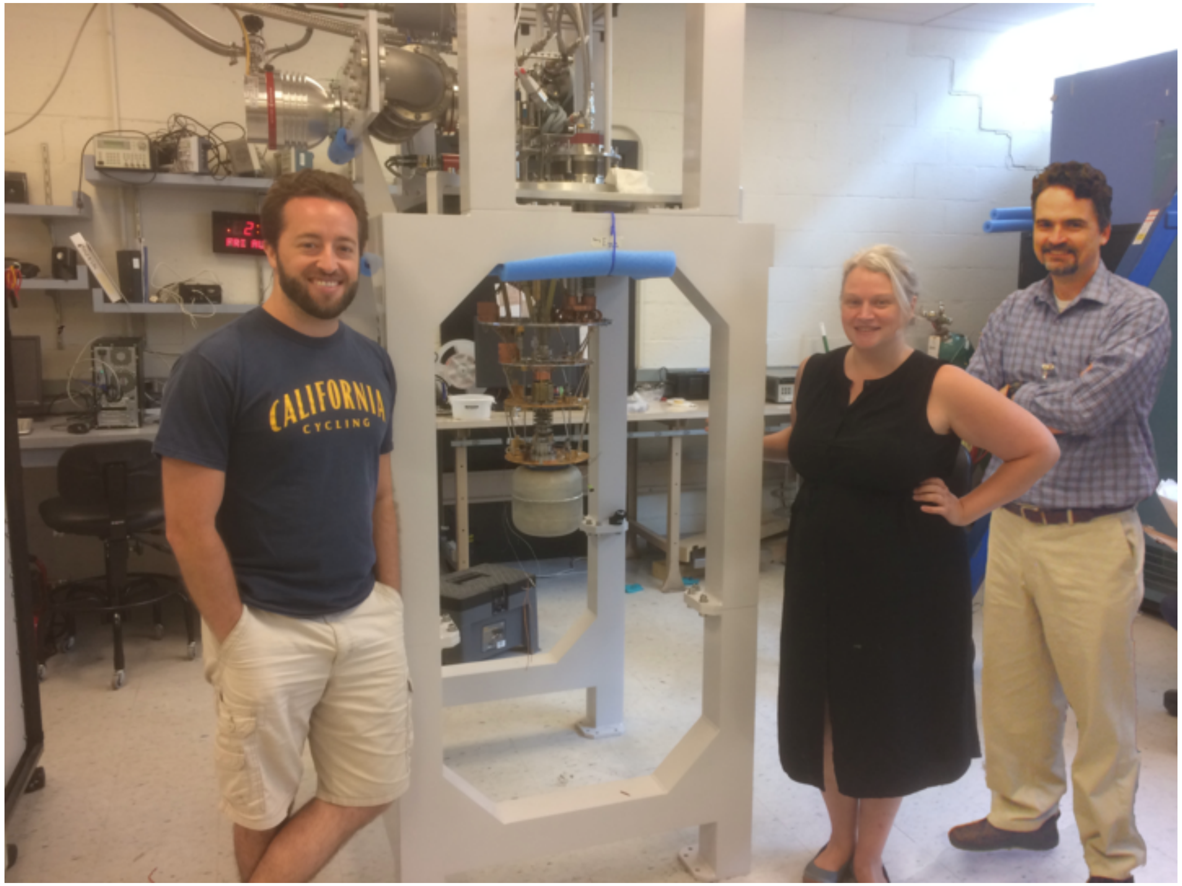
MICHIGAN

ABRACADABRA



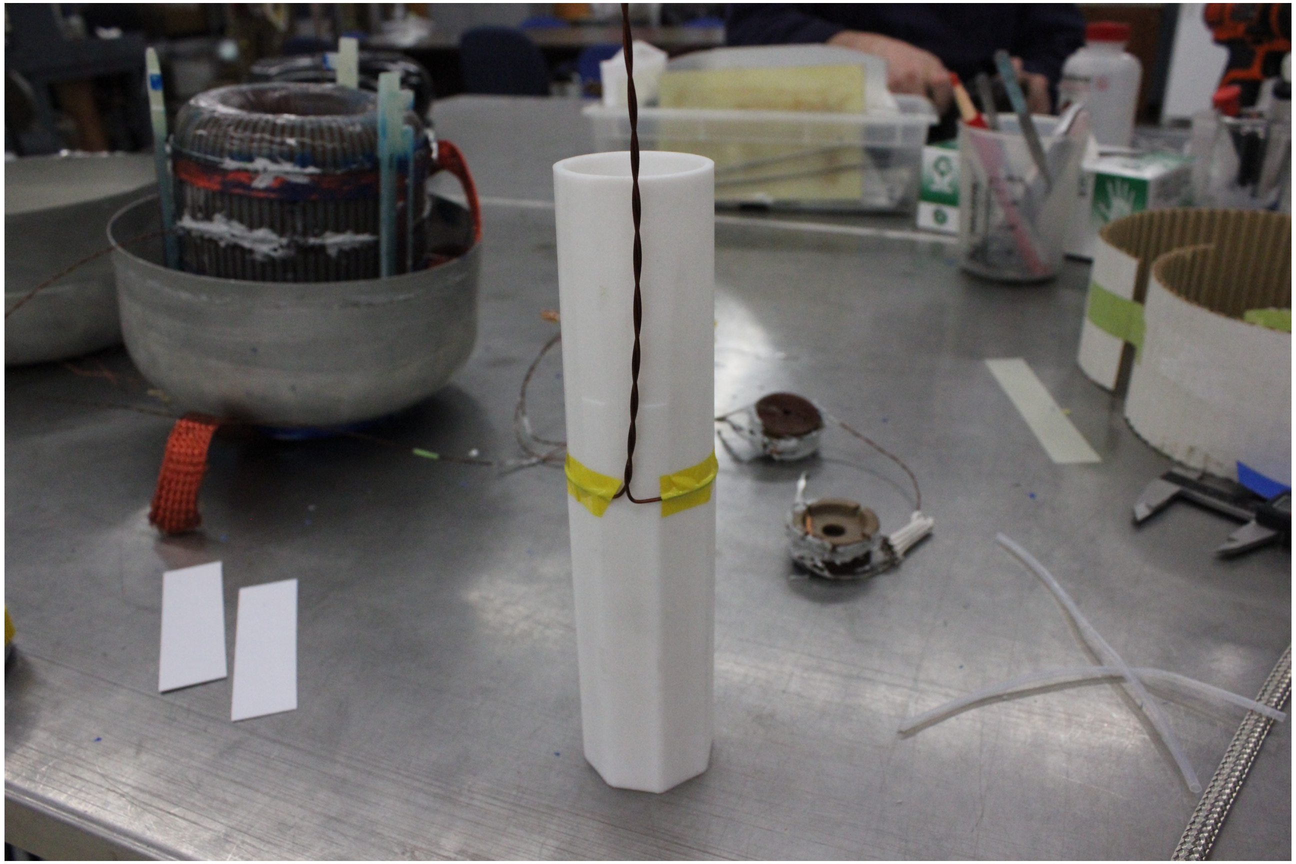
Magnet construction at Superconducting Systems Inc.
It was wrapped in 3 sections and then installed in a superconducting shield.

ABRACADABRA



ABRACADABRA-10cm installed Fall 2017.

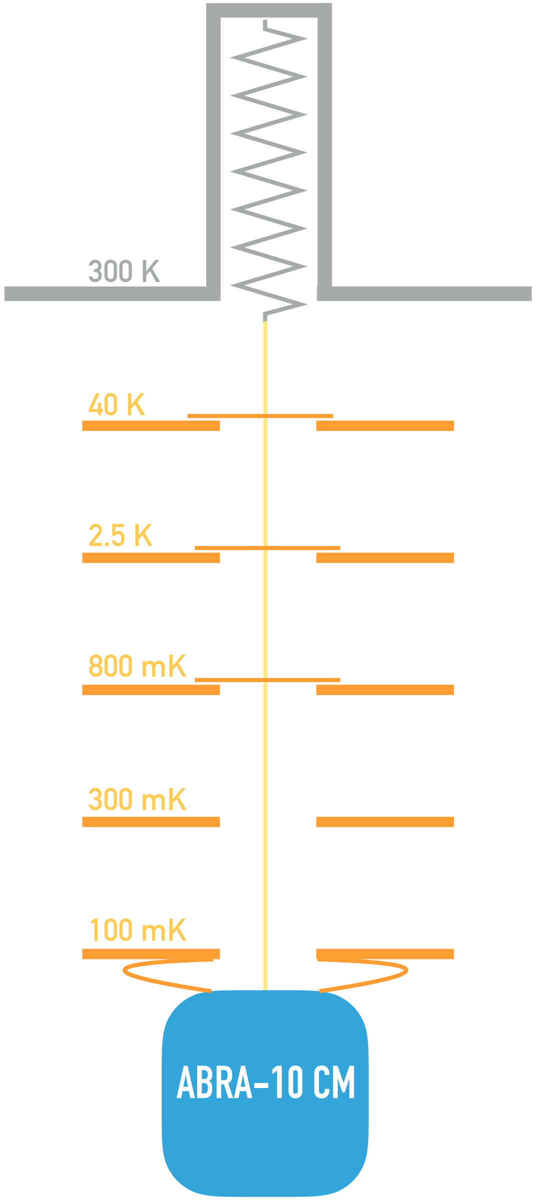
ABRACADABRA



Some improvements to the geometry were completed in January 2018.

Suspension System

- Vibration isolation suspension system
  - 150 cm pendulum, with a resonance frequency of ~2 Hz
  - In the Z direction, a spring with a resonance frequency of ~8 Hz
- Supported by a thin Kevlar thread with very poor thermal conductivity
- Can be upgraded with minus-K isolation



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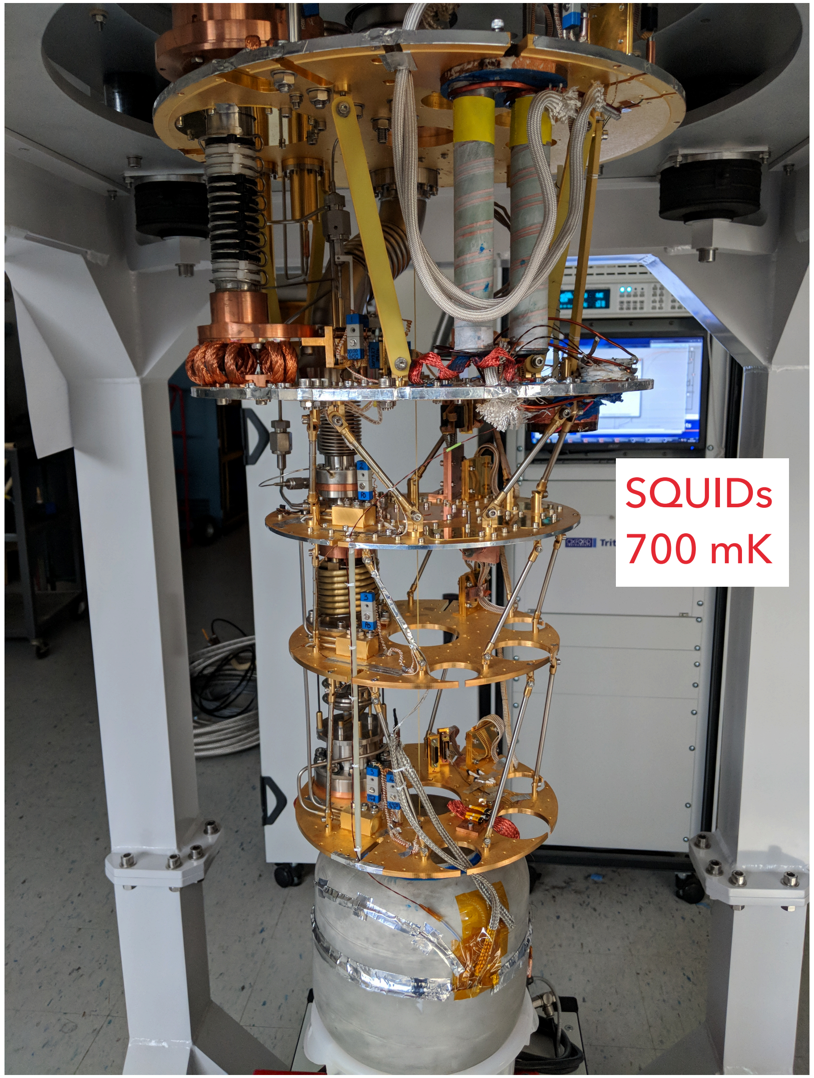
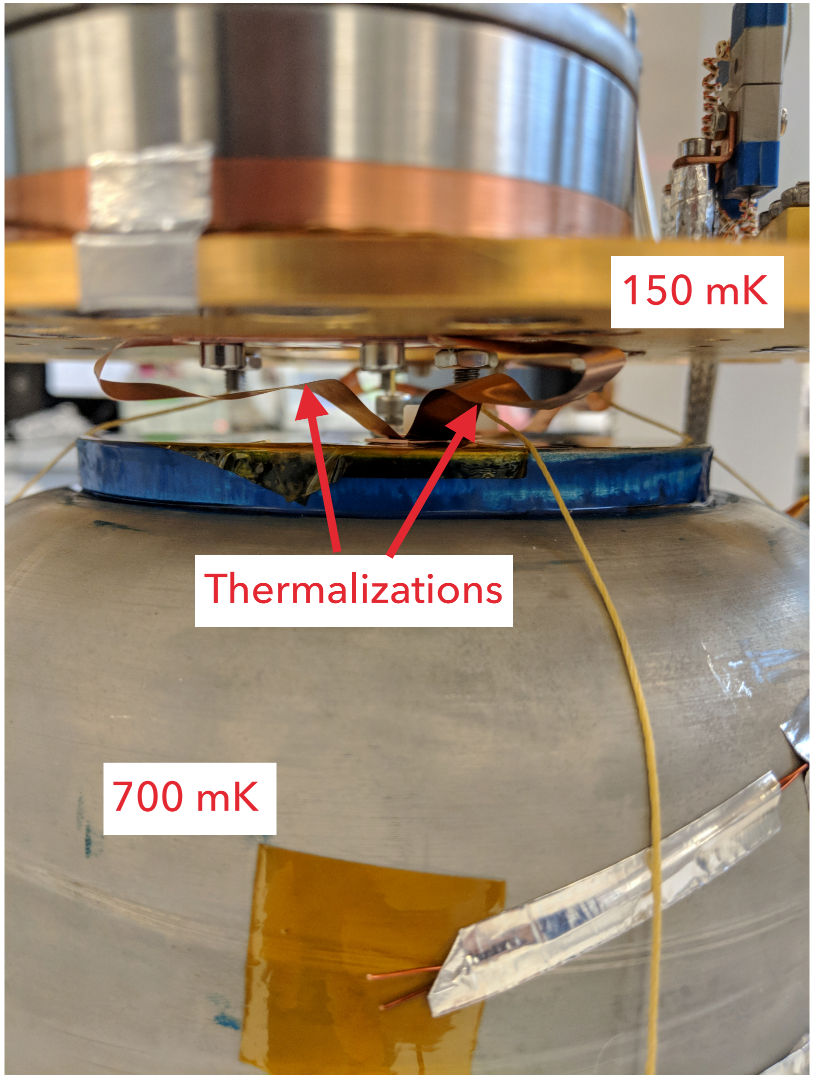
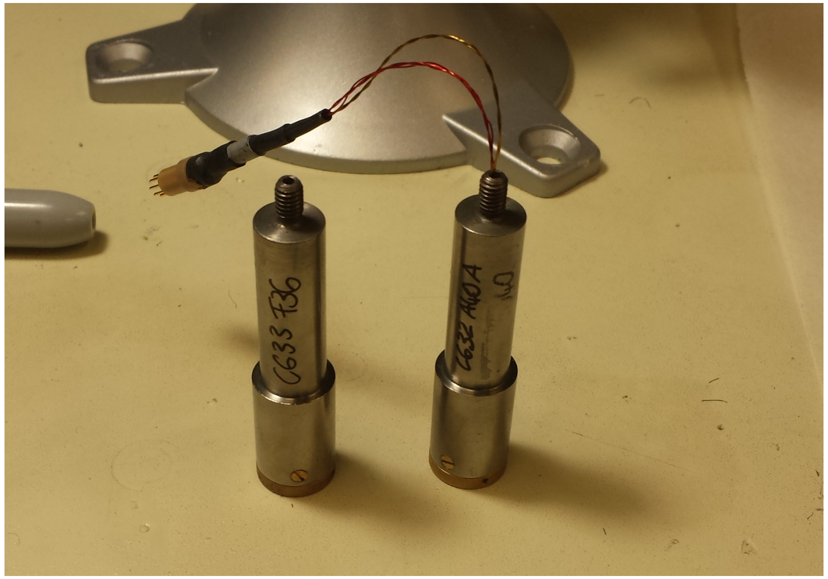
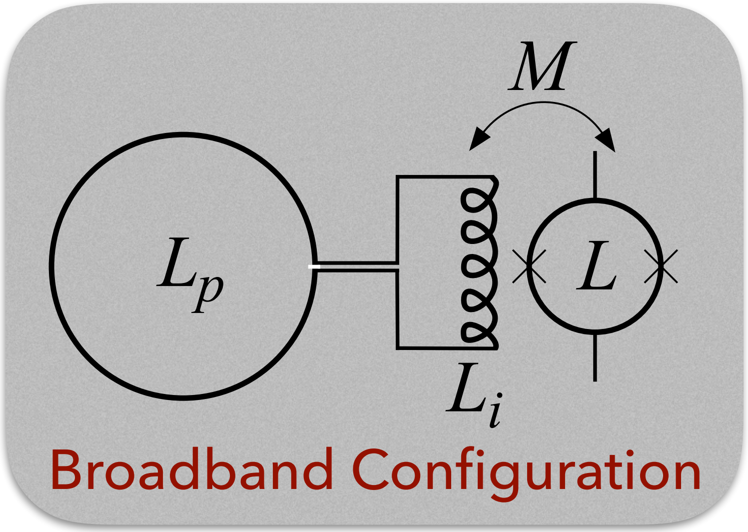




SQUID Current Sensors

- Off the shelf SQUIDs from Magnicon
  - Two stage current sensor + series array amplifier
  - Optimal temperature: ~700 mK
  - Input inductance: 150 nH
  - Noise floor: ~1.2 $\mu\Phi_0/\mathrm{Hz}^{1/2}$
  - 1/f corner: ~50 Hz
  - Bandwidth Limit: ~6MHz
- Additional filters limit bandwidth to 2kHz-2MHz





Broadband Configuration

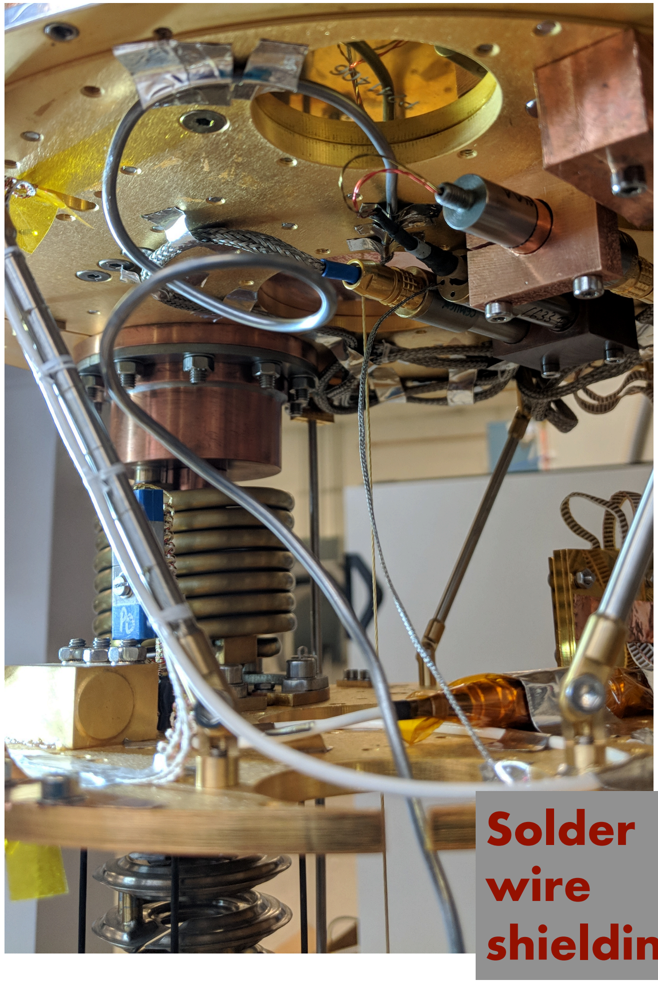
ABRACADABRA

Magnetic Shielding

- Two layers of mu-metal shielding
- Possibility of third layer later
- (Still need to measure the attenuation)

Wiring and Shielding

Superconducting crimps



Solder wire shielding

ABRACADABRA

First Results October 2018!

arXiv:1810.12257

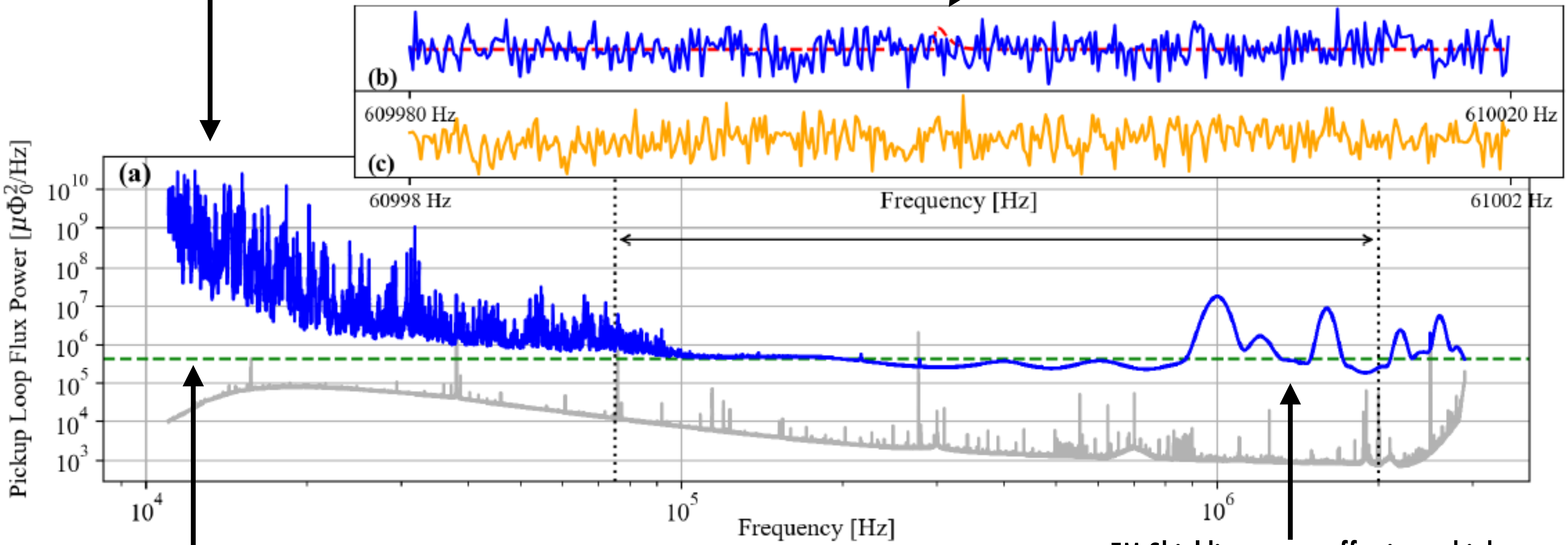
Long Technical Paper

arXiv:1901.10652

ABRACADABRA

Mechanically cooled fridge so vibration dominate at low frequency.

Example signal

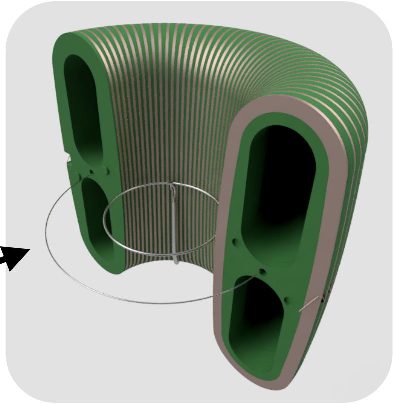


EM Shielding not as effective at high frequency or large sources.

SQUID Noise Floor!

Data taken from July 16, 2018 to August 14, 2018, continuous digitization and data transfer was a major accomplishment in itself!

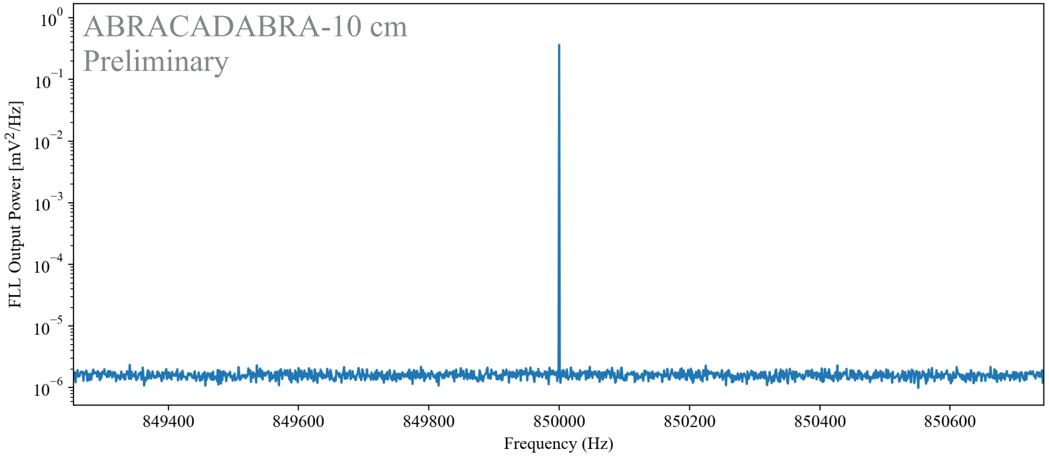
ABRACADABRA

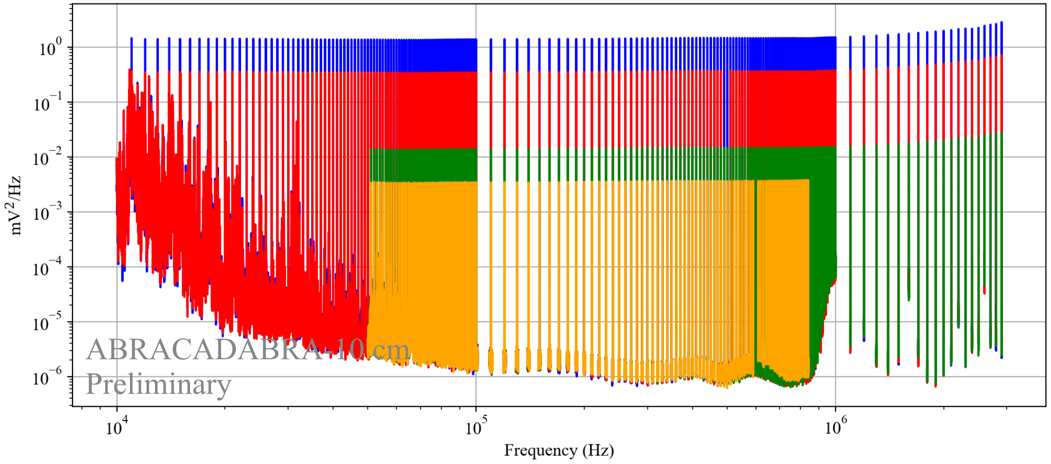


One of the key experimental details is how you calibrate the system?

Calibration Loop

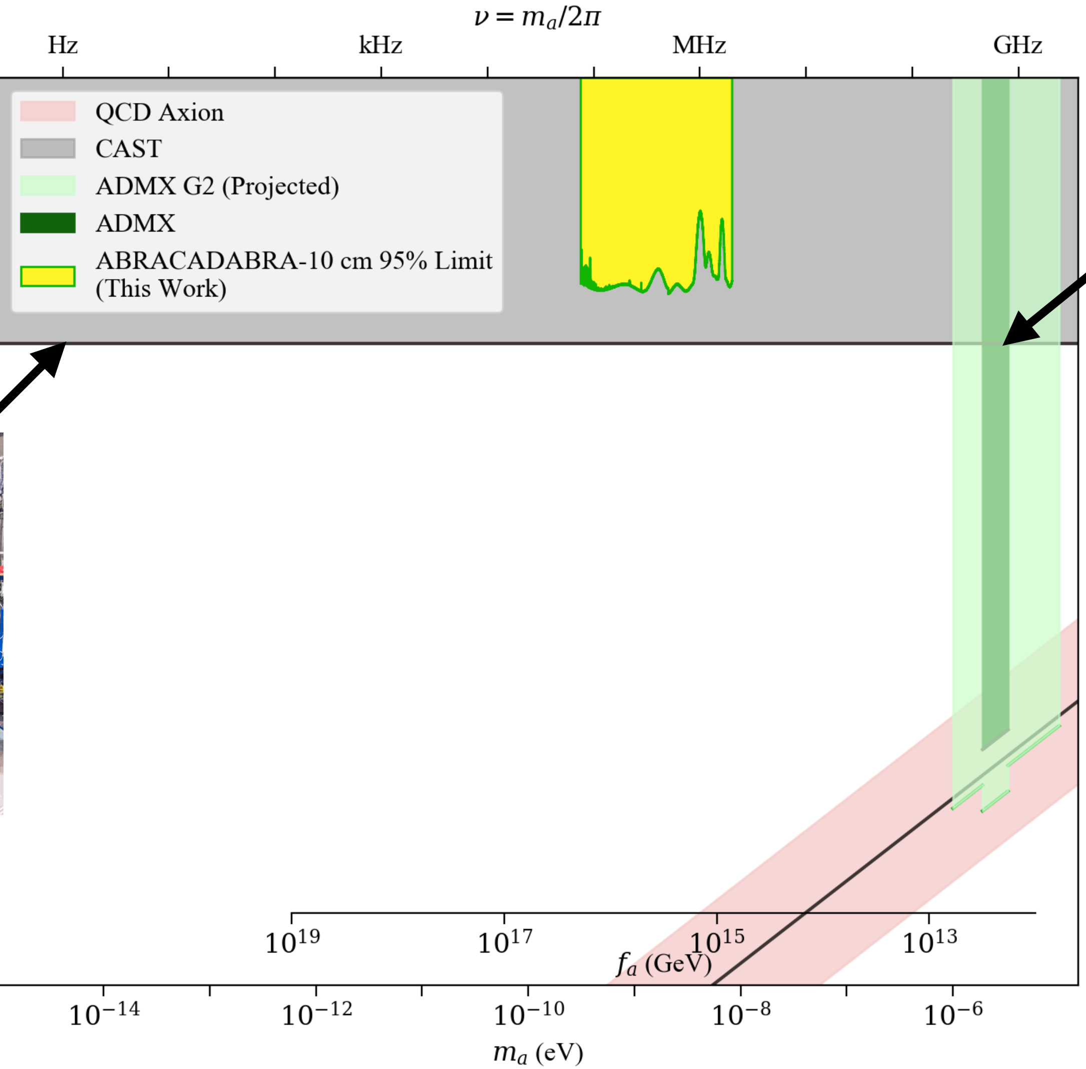
We performed detailed scans to determine that our efficiency was flat over a broadband of frequencies. Unfortunately, the gain was low by a factor of 6.5 low, most likely due to neglecting parasitic inductances. Work is underway now to regain this factor.





ABRACADABRA

First search for axion dark matter below 1µeV, and we are just beginning!



ADMX

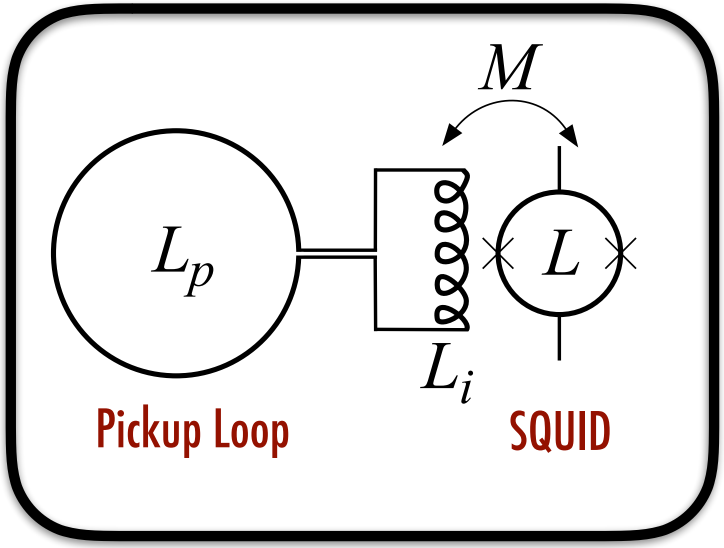
CAST
Solar Axion Experiment

What next?

ABRA Readout

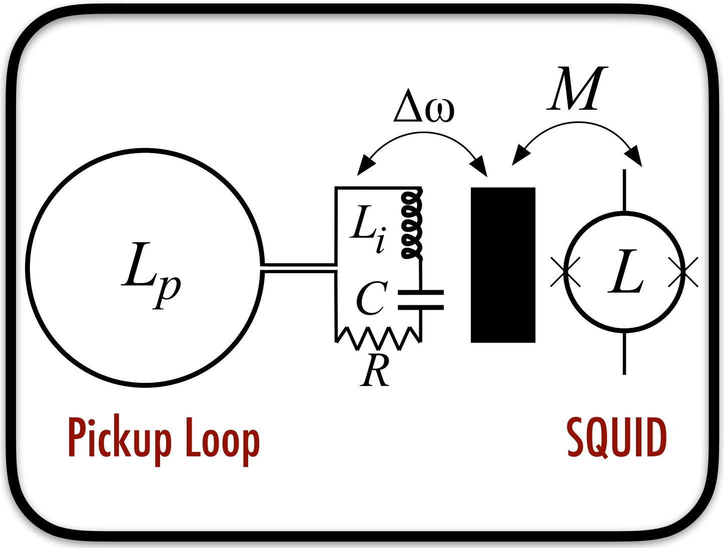
Option #1 - Broadband Readout

- pickup loop directly coupled to the SQUID
- simultaneous scan of all frequencies
- simple and fast



Option #2 - Resonant Readout

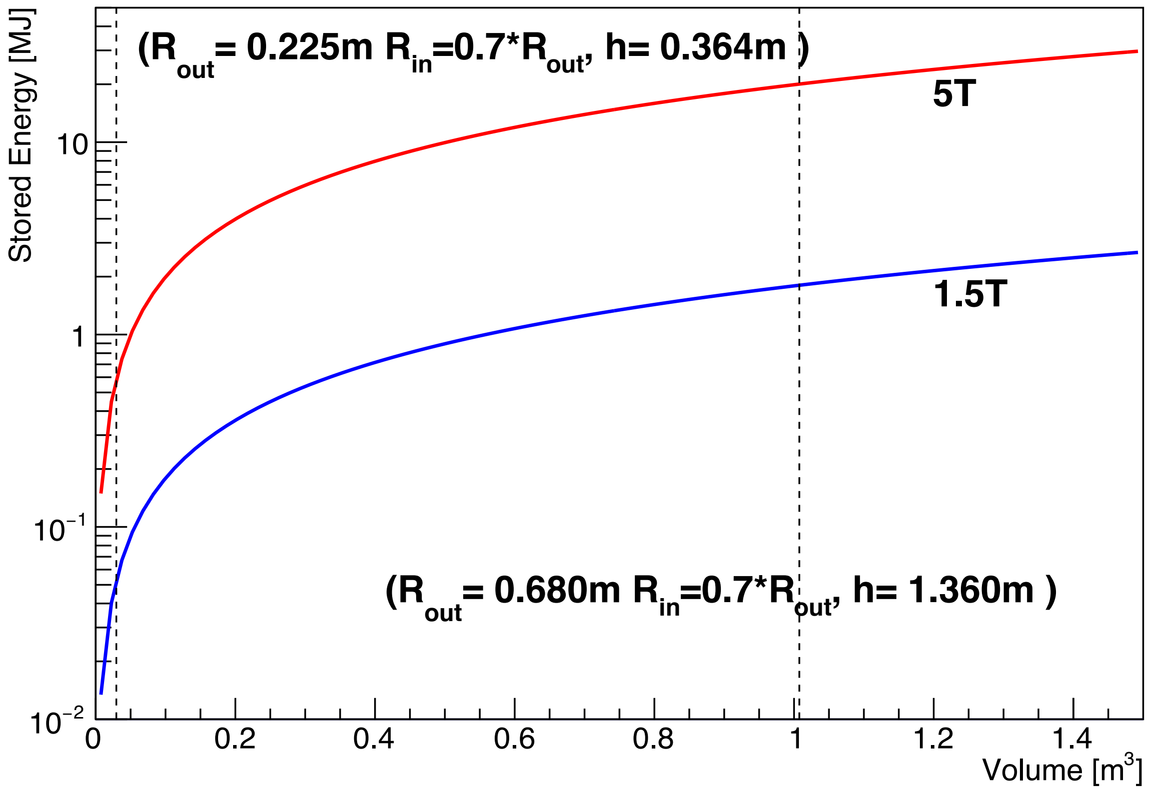
- pickup loop coupled to the SQUID through a resonant circuit
- scan across all frequencies
- signal enhancement by Q_{value} ~10^6 on resonance but significant enhancement of sidebands as well
- better ultimate sensitivity



For a review of this issue see Chaudhuri, Irwin et al. arXiv:1803.01627

A Bigger Magnet with Higher Field

Higher Cost
$$$

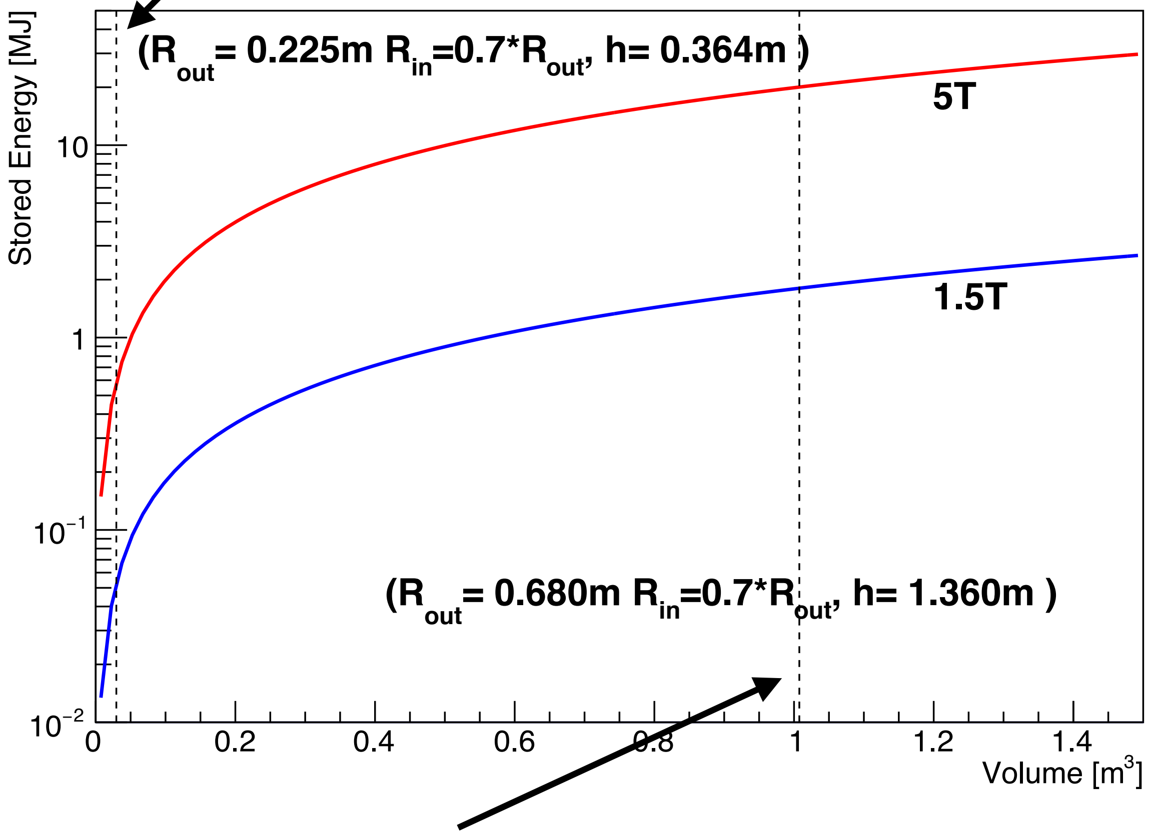


Bigger Field = More Sensitive

More Volume = More Sensitive

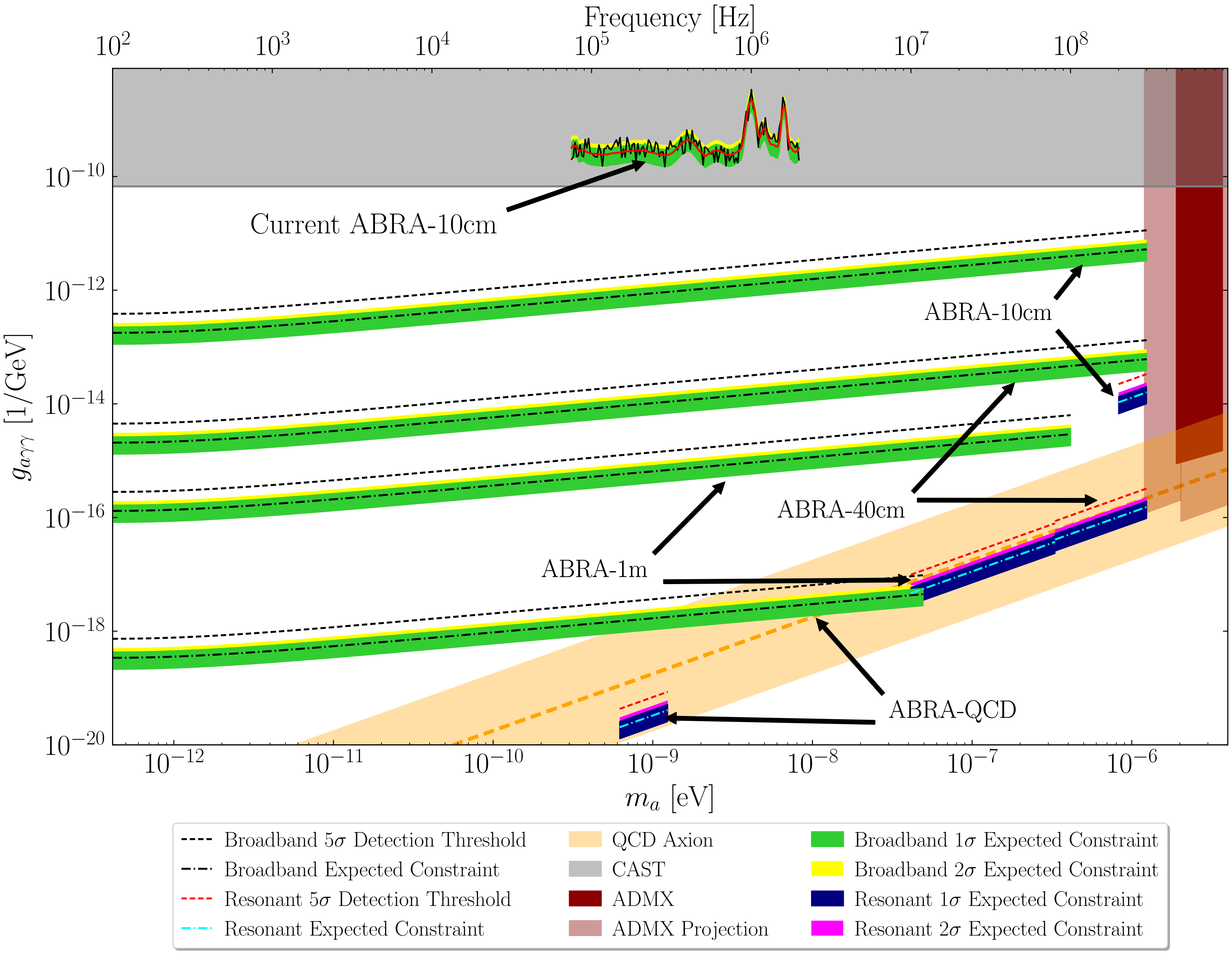
A Bigger Magnet with Higher Field

A 40cm-Scale experiment is good for engineering → Especially if you run two of them.



A 1m-scale experiment is the goal from the science perspective.

ABRACADABRA



Note: ABRA-40cm is two magnets, 1 year integration assumed for all except ABRA-10cm which is 1 month.

And now for neutrinoless double-beta decay!

Things my group searches for:

Axions

Neutrinoless Double-Beta Decay

Big Questions:

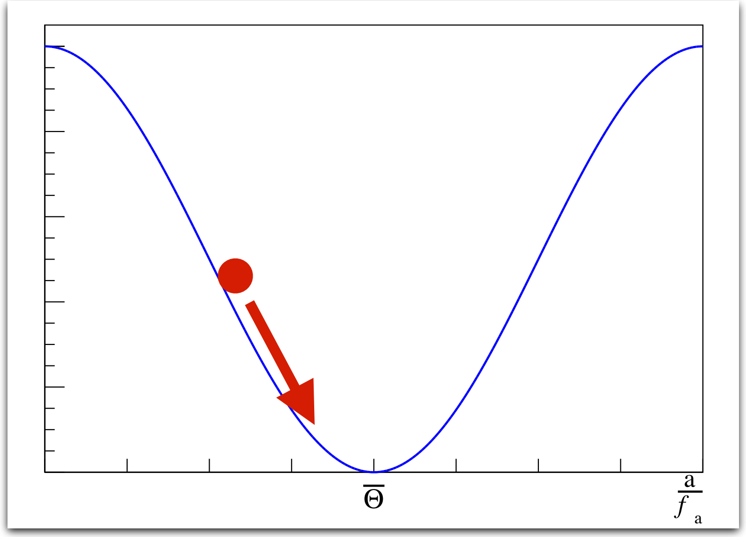
What is Dark Matter?

Why is there only matter in the universe?

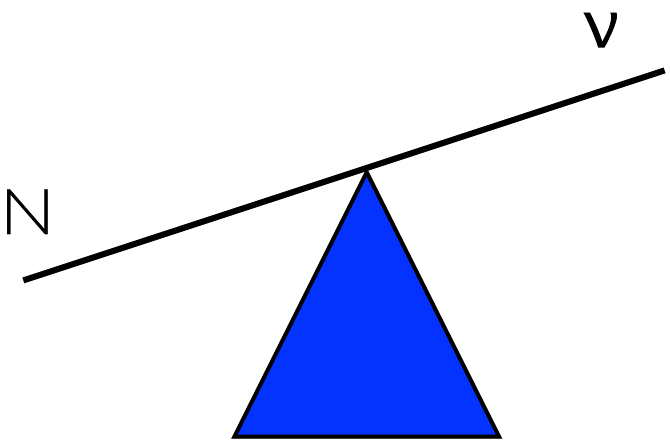
Why are the neutrinos so light?

What unites these two topics?

Peccei-Quinn Mechanism



See-Saw Mechanism



$$m_a \sim \frac{m_\pi f_\pi}{f_a} 10^{-9}\,\mathrm{eV}\left(\frac{10^{16}\,\mathrm{GeV}}{f_a}\right)$$

nano-eV mass

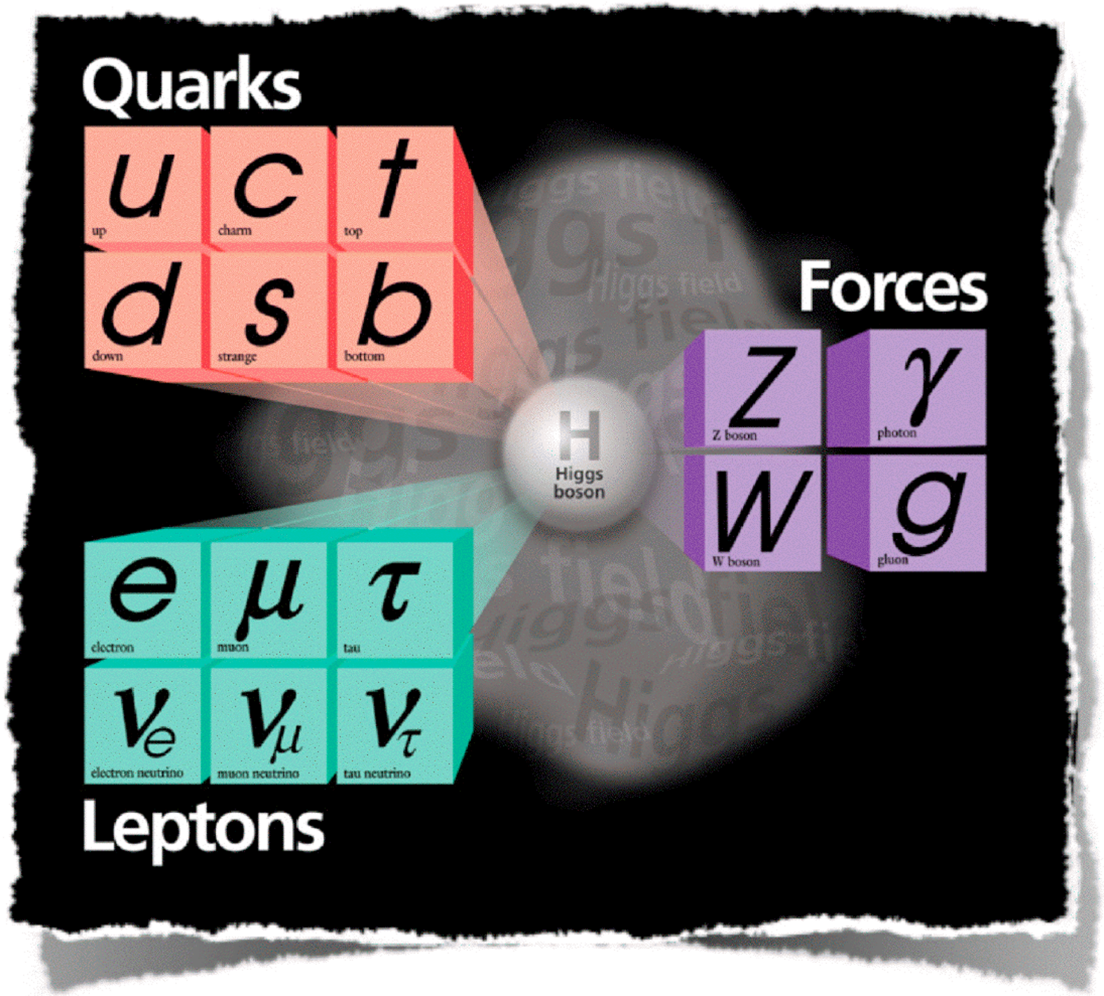
GUT scale axion

$$L_m = -\frac{1}{2}\frac{m_D^2}{m_R}\bar{\nu}\nu - \frac{1}{2}m_R\bar{N}N$$

Our
Standard
Light ν

GUT scale ν

This is the Standard Model



The Neutrino:

- *Fermions (spin 1/2)*
- *Three Flavors*
- *No Electric Charge*
- *No Strong Charge*
- *Weakly Interacting*
- *Left-Handed*
- *Small masses*

Dirac Neutrinos

neutrino and antineutrino
different particles

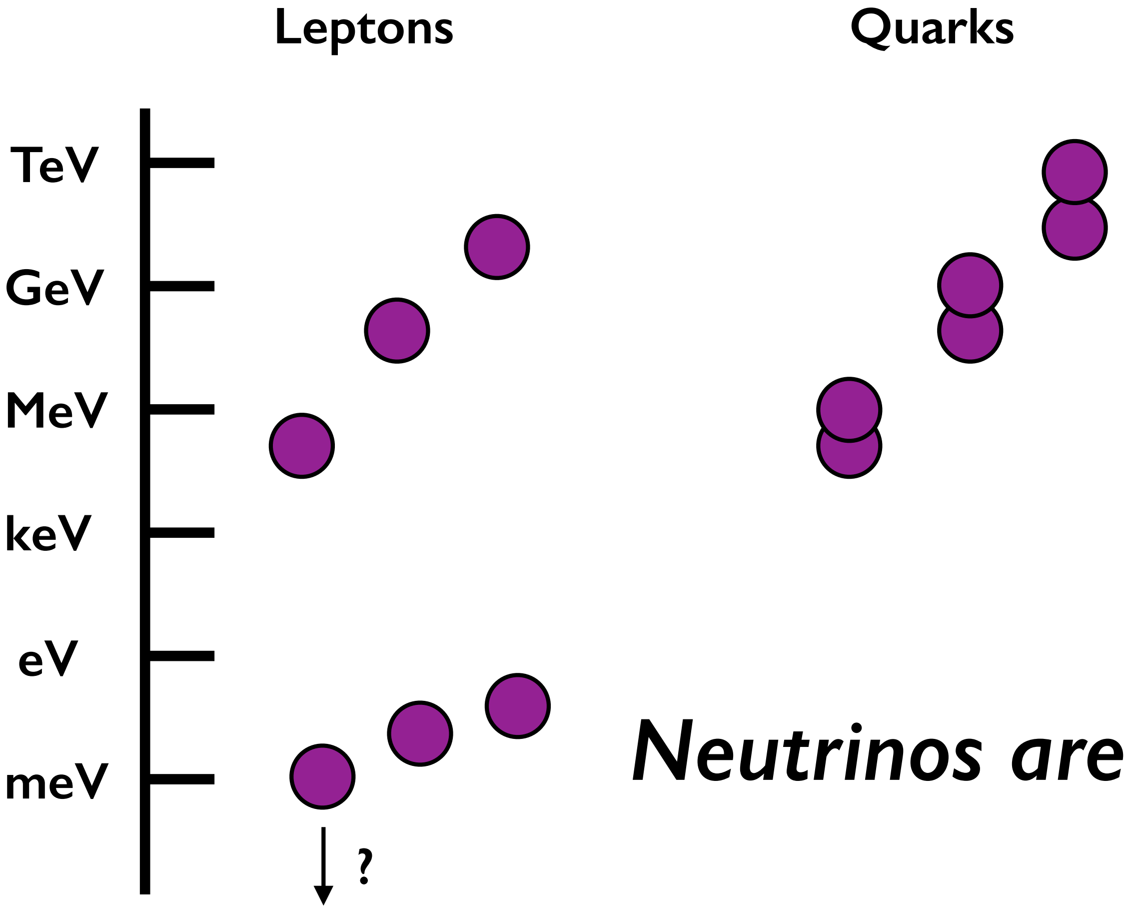
Majorana Neutrinos

neutrino and antineutrino different
helicity state of the same particle

This is the last missing piece of the Standard Model.

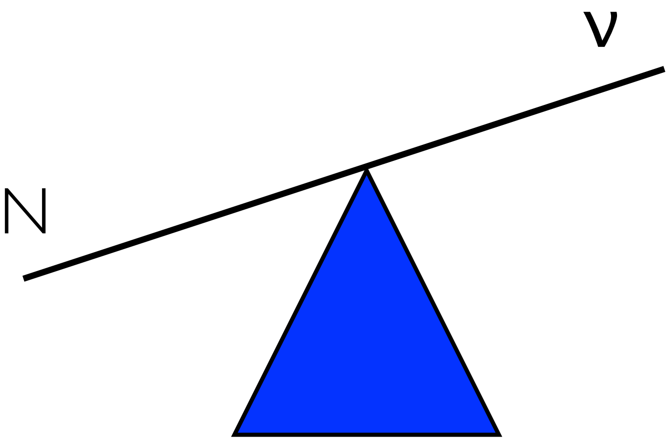
Majorana neutrinos are really nice.

Masses of the Standard Model Particles



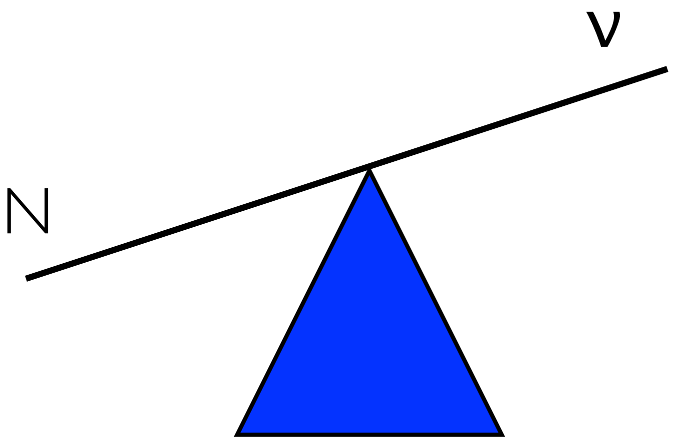
Neutrinos are very light!

See-Saw Mechanism



A **big** Majorana mass splits the Dirac neutrino into two neutrinos: the light neutrino **ν** and a heavy neutrino N.

See-Saw Mechanism



The m_D is normal Dirac mass and should be about the same order as the quarks or charged leptons.

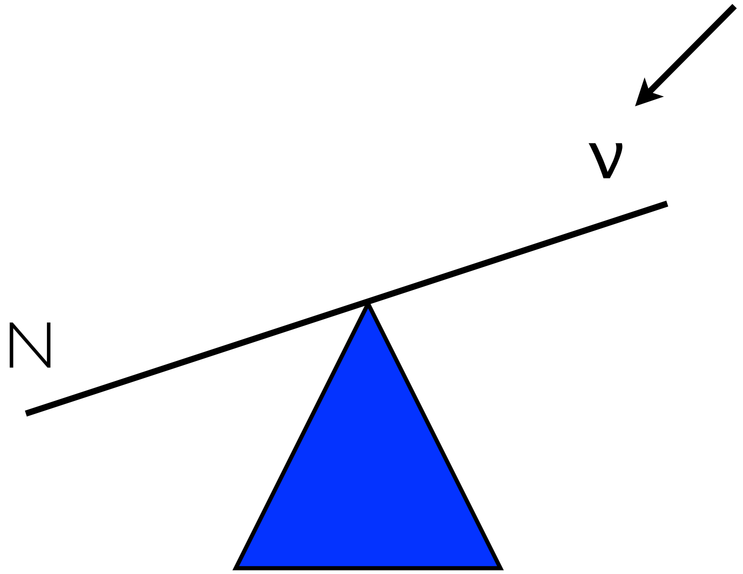
$$L_m = -\frac{1}{2}\boxed{\frac{m_D{}^2}{m_R}}\bar{\nu}\nu - \frac{1}{2}m_R\overline{N}N$$

The m_R is the Majorana mass and can be much heavier.

Our Standard Light ν

Its much heavier big sister

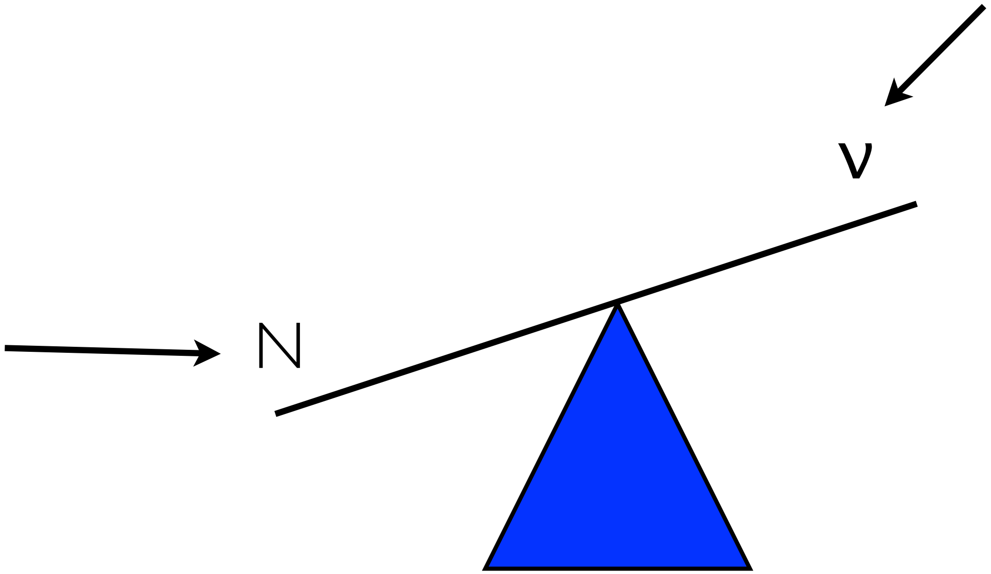
And now for some hand waving.....



Its these that we can make and detect.

And now for some hand waving.....

Its these guys that will be made in the Big Bang and it’s CP Violation and Lepton number violation in their decays that can be turned into the matter antimatter asymmetry.



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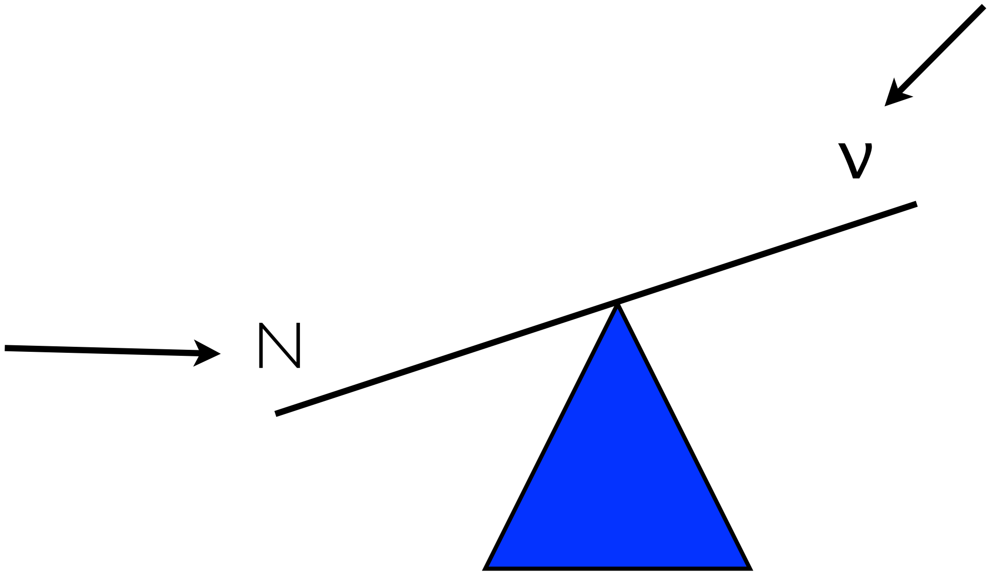
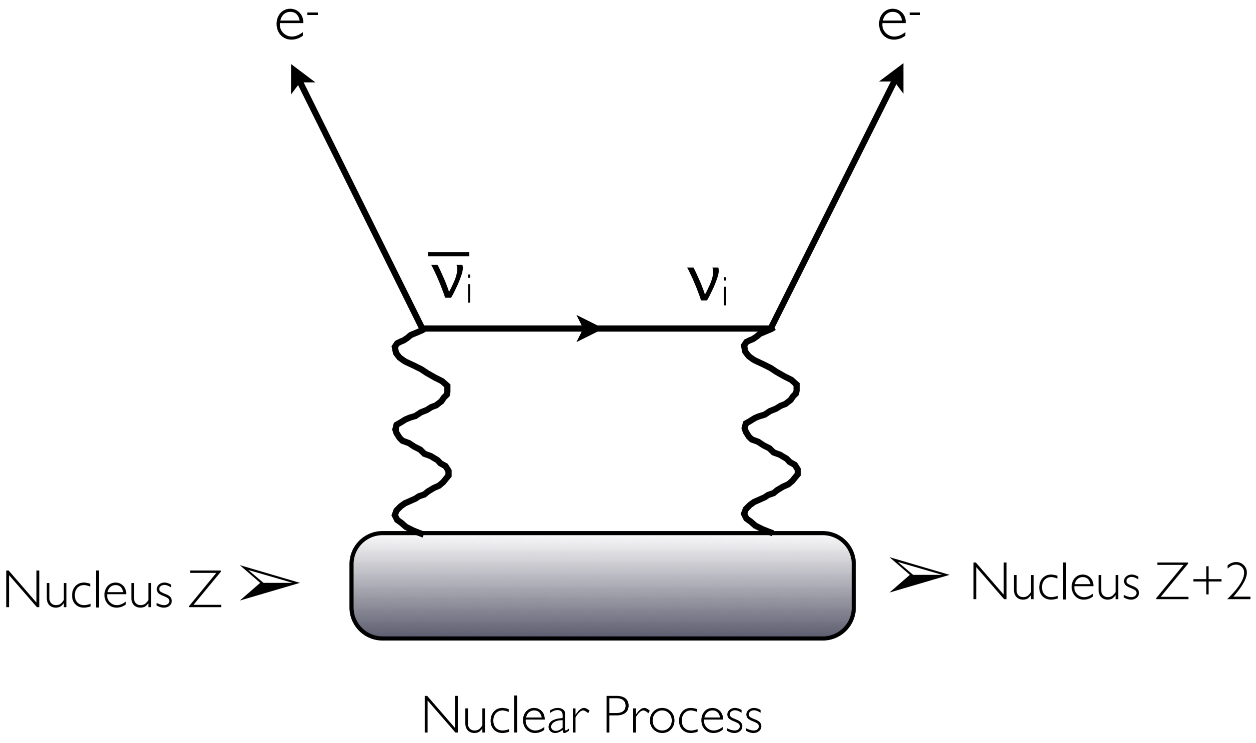


Its these that we can make and detect.

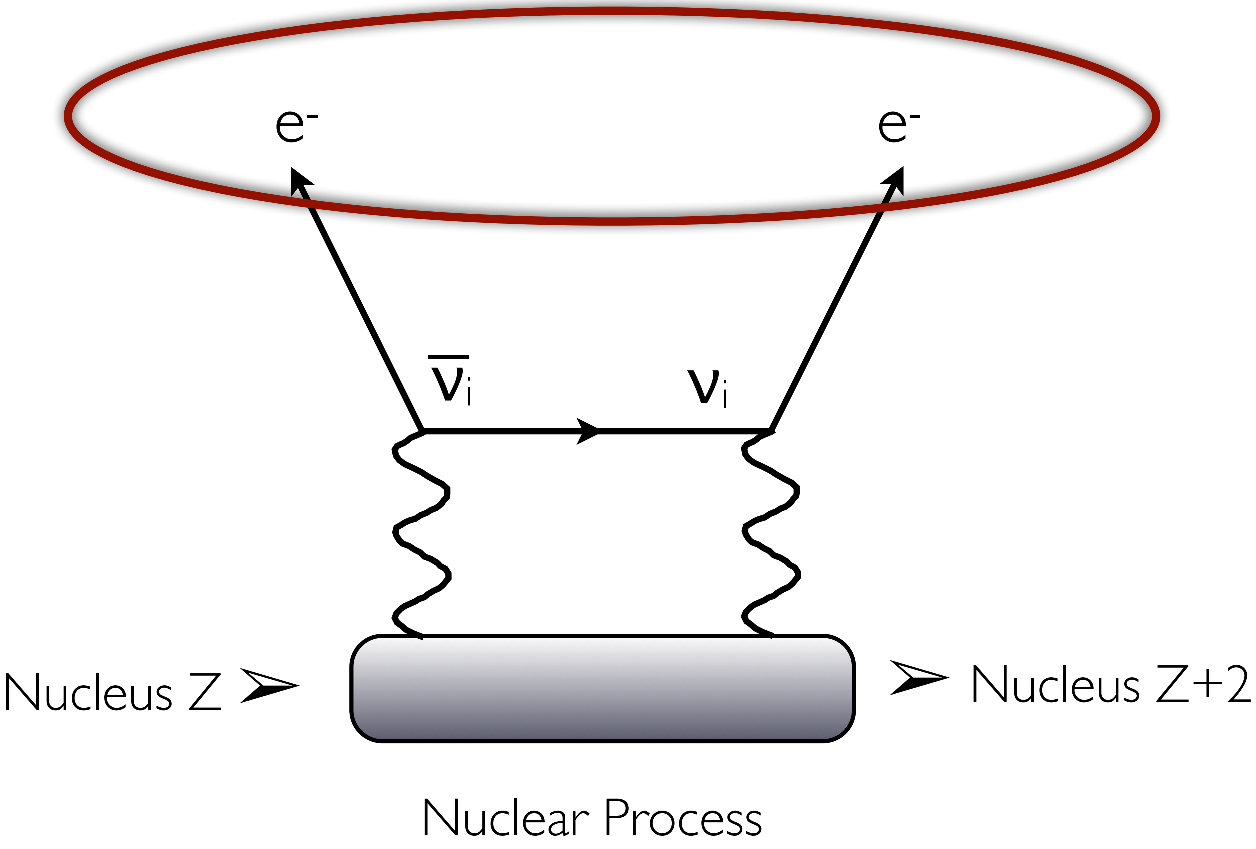
Its these guys that will be made in the Big Bang and it's CP Violation and Lepton number violation in their decays that can be turned into the matter antimatter asymmetry.

So if we detect CP violation and Lepton number violation in the ν then it would be difficult to construct a theory of the N that do not have the same properties.

How do we find out if neutrinos are Majorana?



Neutrinoless Double Beta Decay



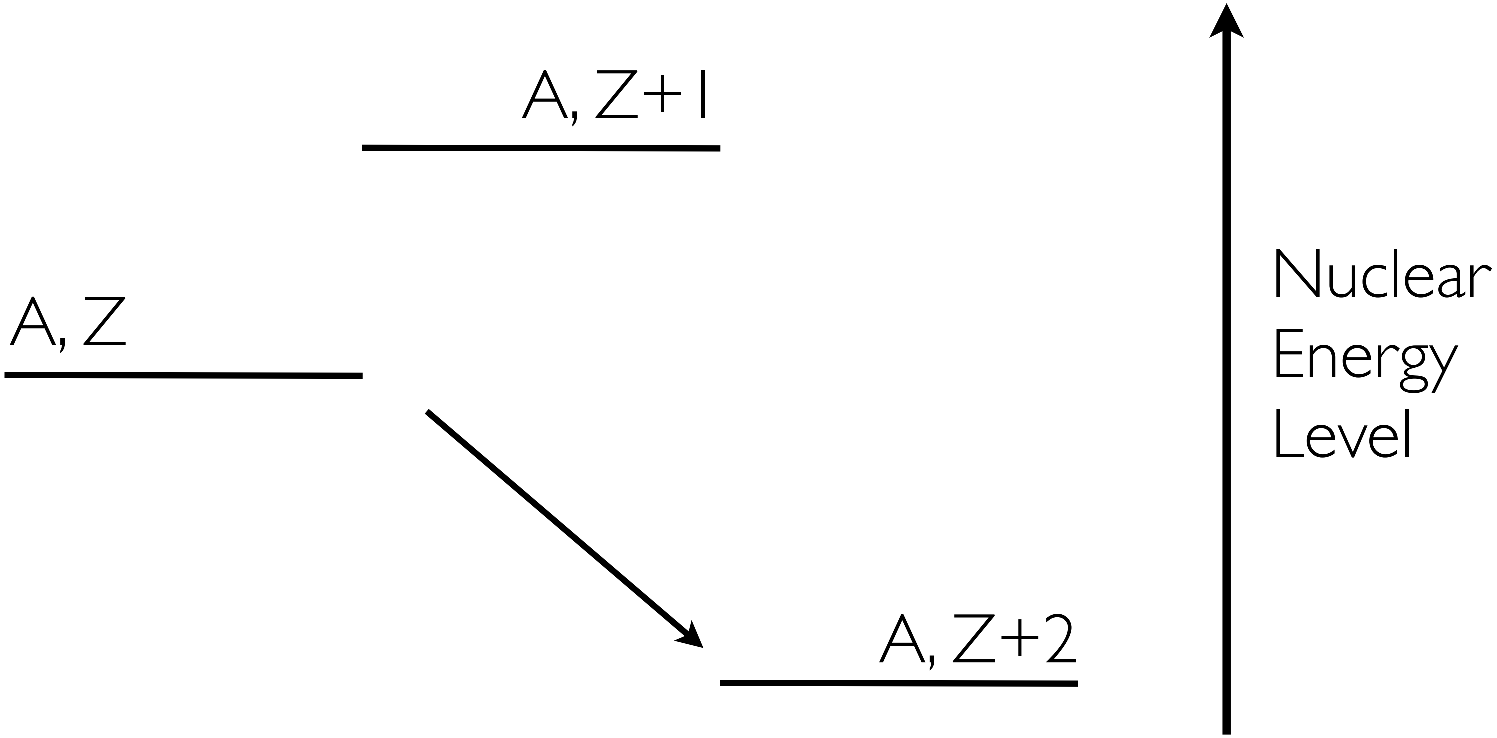
Lepton Number Violation!

Neutrinoless Double Beta Decay

Light Majorana Neutrino Exchange

The Process of Double Beta Decay

Due to energy conservation some nuclei can’t decay to their daughter nucleus, but can skip to their granddaughter nucleus.



A, Z+1

A, Z

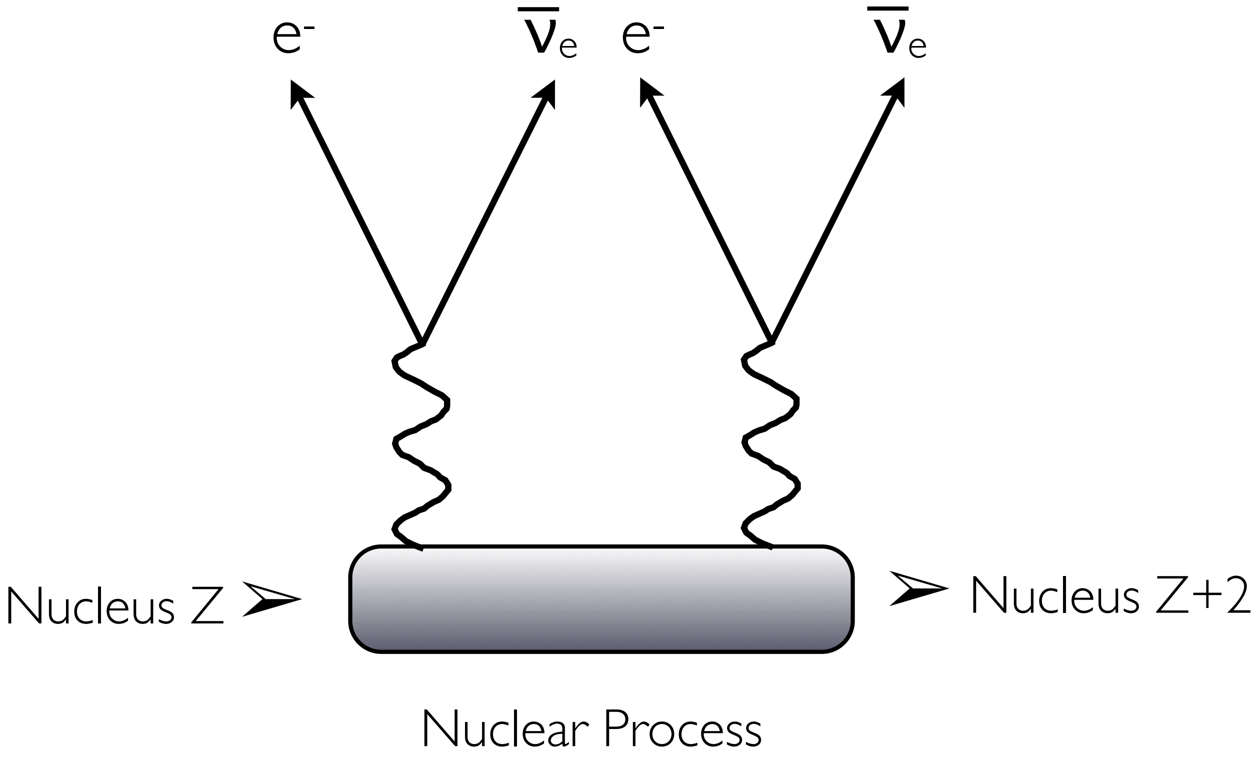
A, Z+2

Nuclear
Energy
Level

Just a few isotopes!

The Standard Model Process

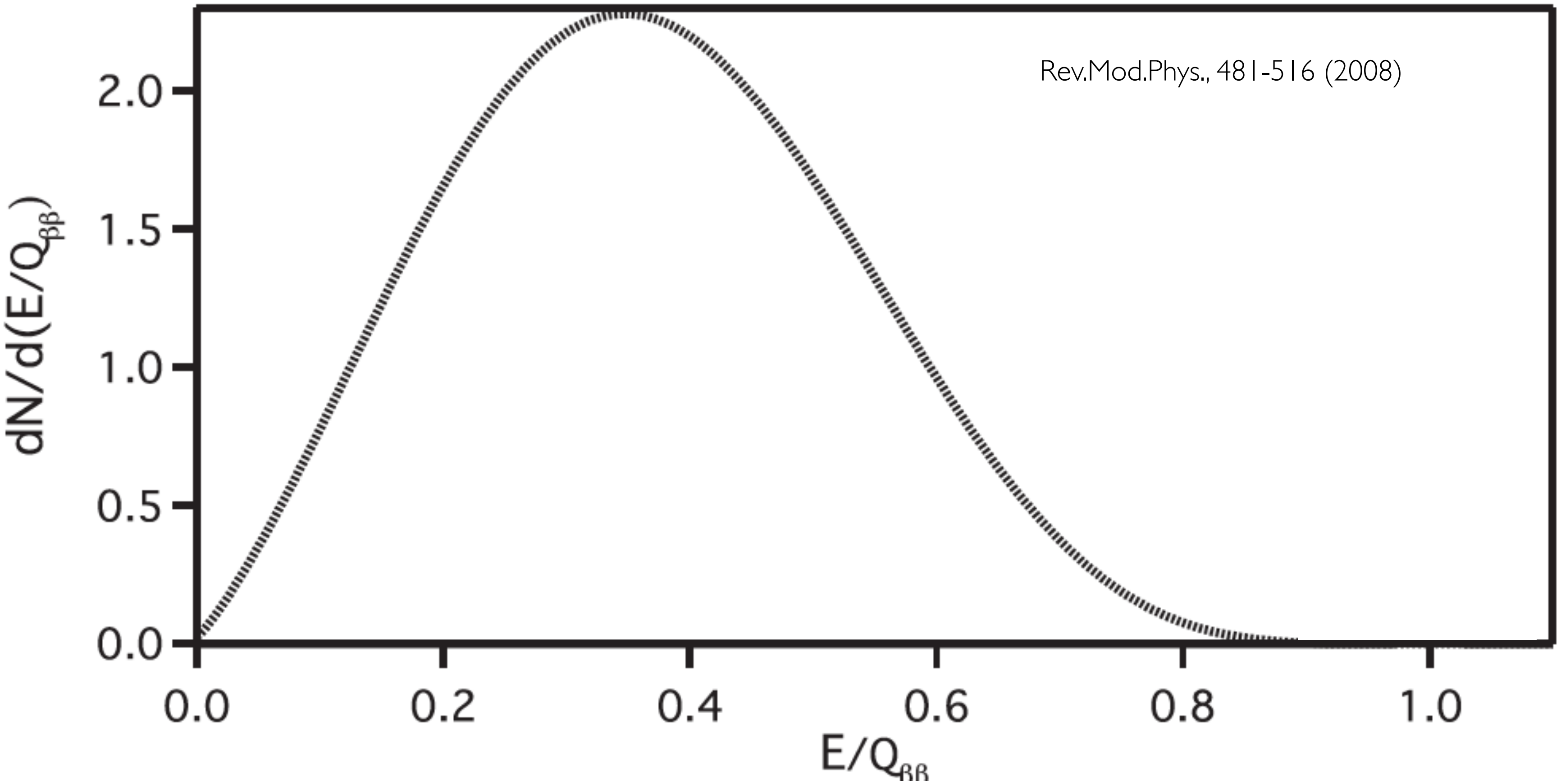
This 2ν process is completely allowed and the rate was first calculated by Maria Goeppert-Mayer in 1935.



Phys. Rev. 48, 512-516 (1935)

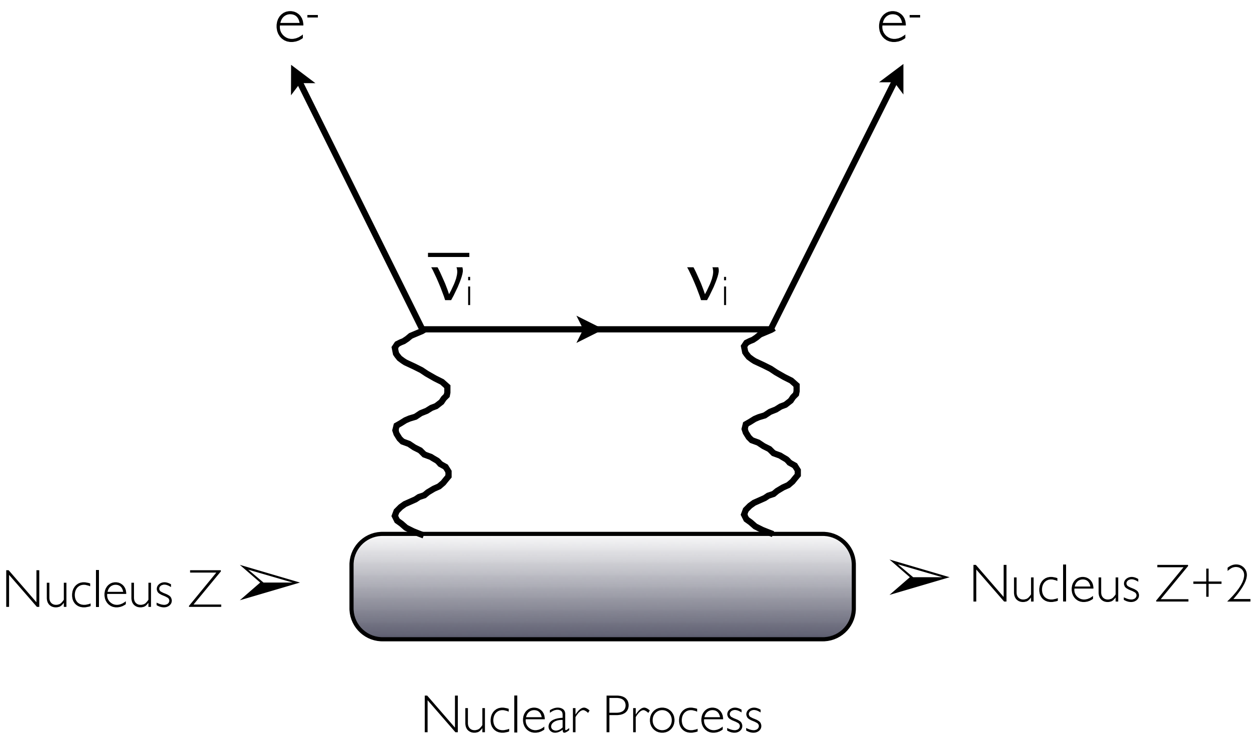
Double Beta Decay (2ν)

The sum of the electron energies gives a spectrum similar to the standard beta decay spectrum.



This has been observed in isotopes such as ^{130}Te and ^{116}Cd.

Neutrinoless Double Beta Decay

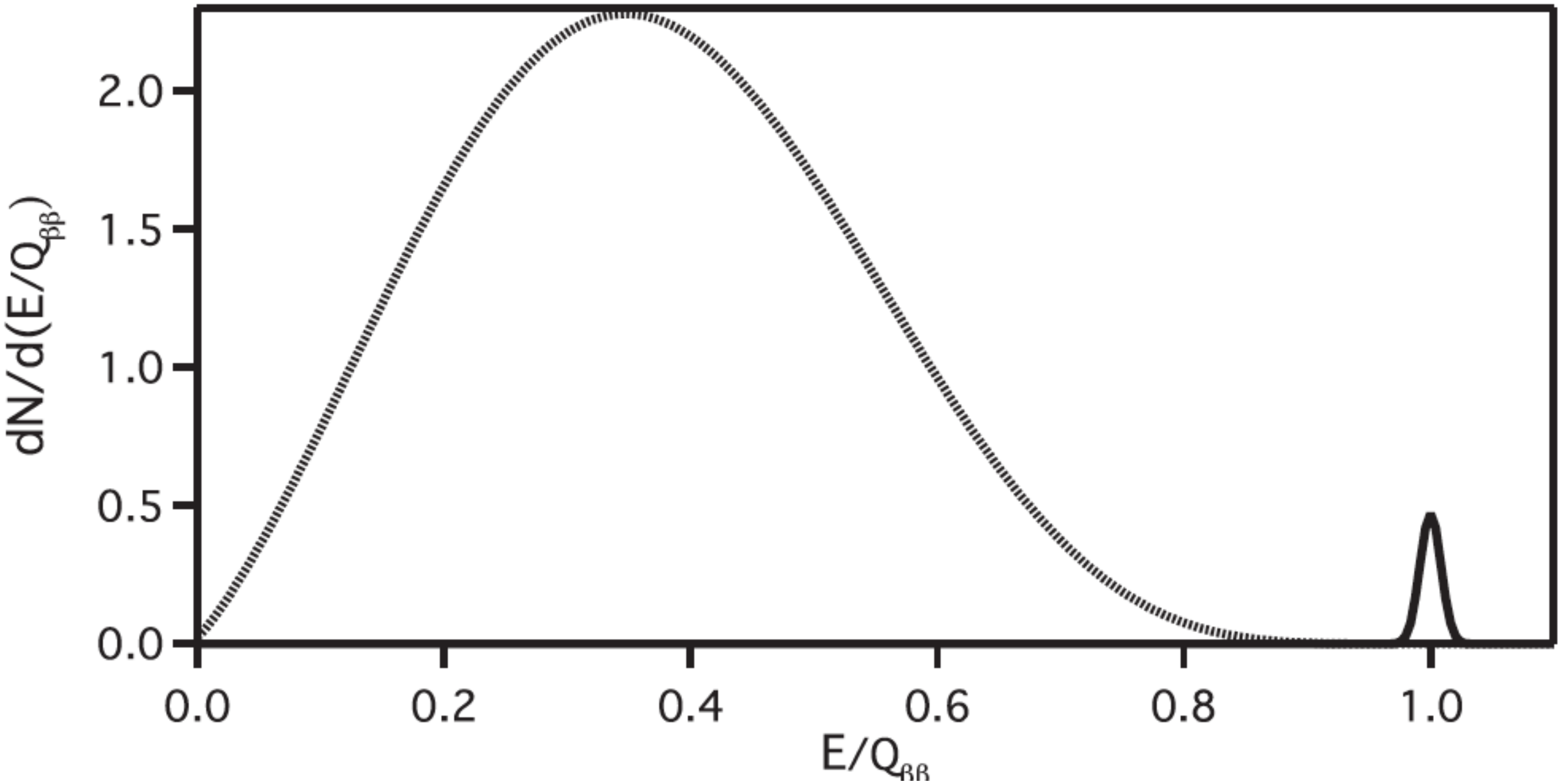


Light Majorana Neutrino Exchange

Neutrinoless Double Beta Decay

The sum of the electron energies gives a spike at the endpoint of the "neutrino-full" double beta decay.

REVIEWS OF MODERN PHYSICS, VOLUME 80, APRIL–JUNE 2008



Neutrinoless Double Beta Decay

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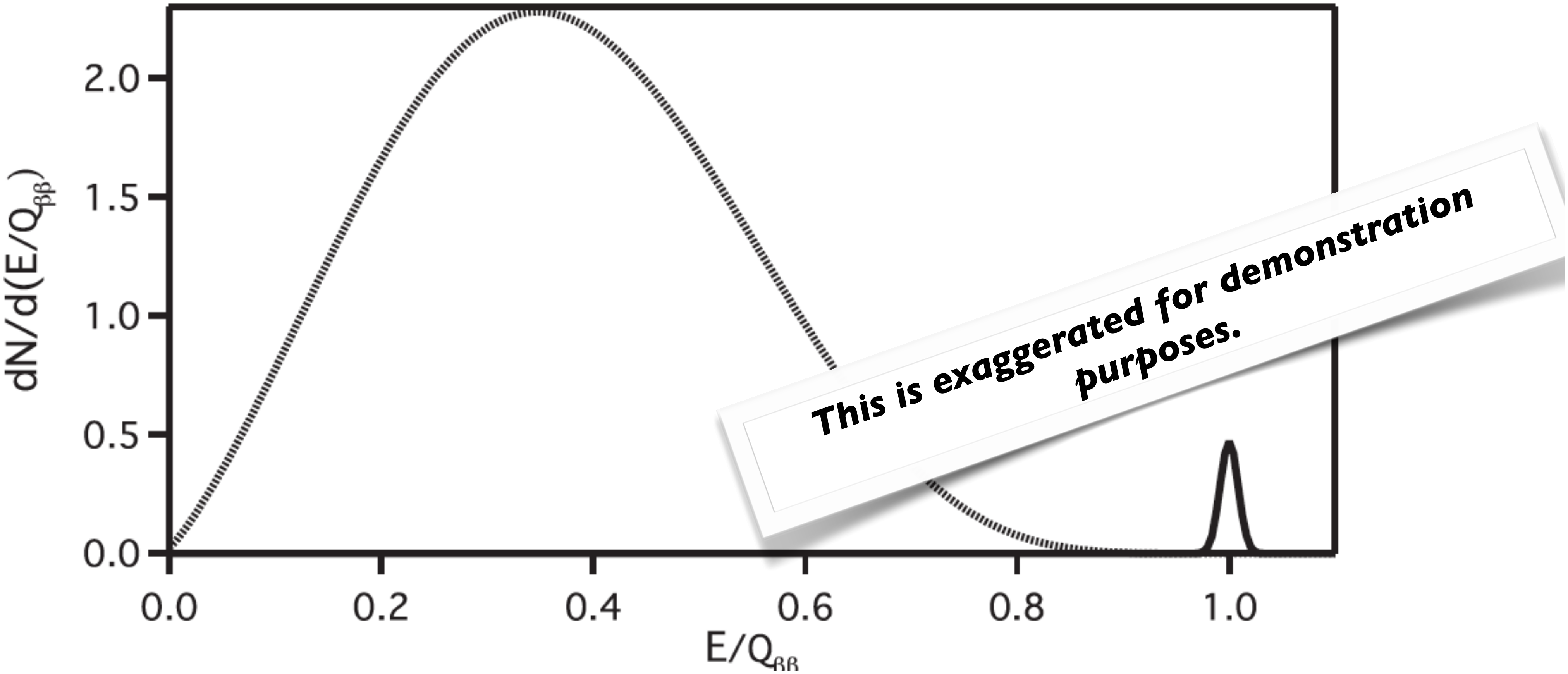


This is exaggerated for demonstration purposes.

How do we measure this?

What is measured is a half-life...

The half-life of the neutrinoless decay:

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

Phase space factor
Notice higher endpoint means faster rate.

What is measured is a half-life:

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)\left|\underset{\uparrow}{M_{0\nu}}\right|^2 \langle m_{\beta\beta}\rangle^2$$

Nuclear Matrix Element

This is a difficult calculation with large errors and substantial variation between isotopes...motivates searches with multiple isotopes.

What is measured is a half-life:

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

Effective Majorana Mass of the neutrino

Effective Majorana Mass:

$$m_{\beta\beta} = \sum_i V_{ei}^2 m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha} sin^2\theta_{12}) + m_3\sin^2\theta_{13}$$

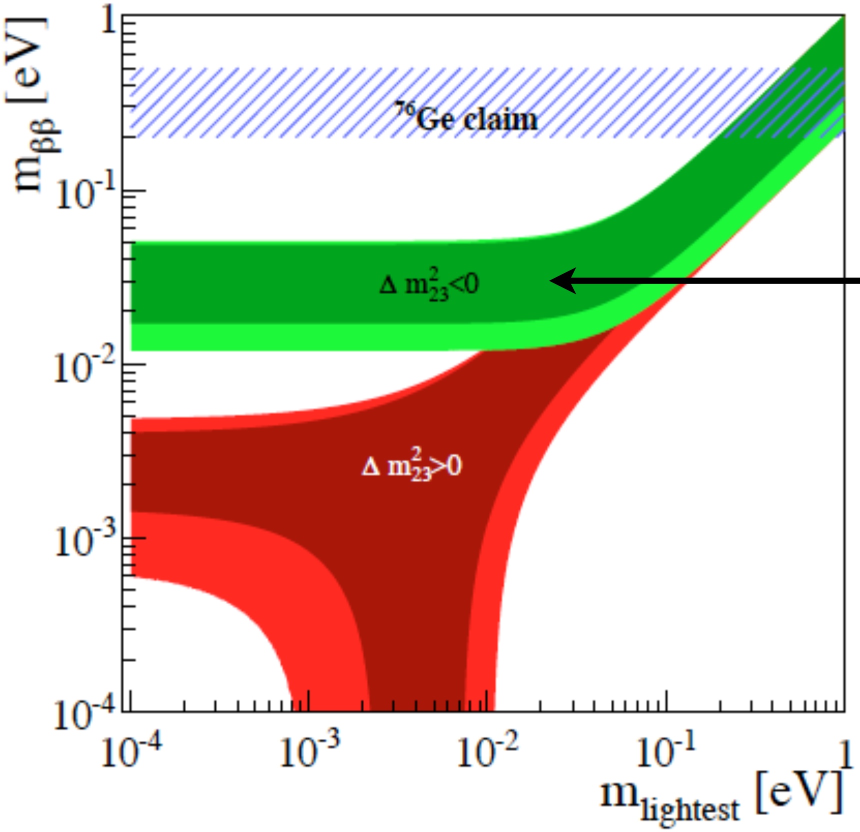
Two more phases!

Electron Neutrino Mass:

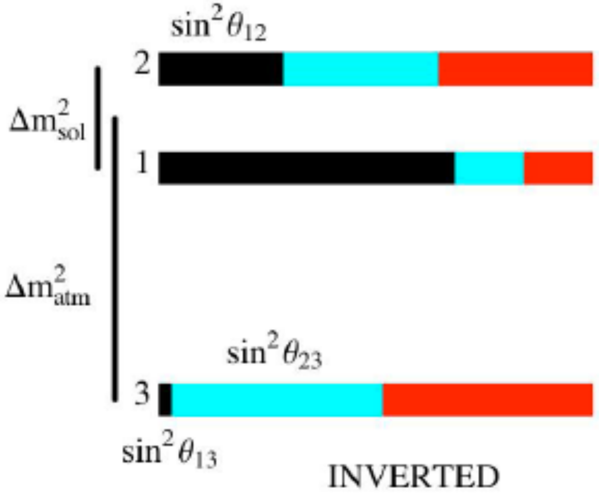
$$m_{\nu_e}^2 = \sum_i |V_{ei}^2| m_i^2 = \cos^2\theta_{13}(m_1^2\cos^2\theta_{12} + m_2^2\sin^2\theta_{12}) + m_3^2\sin^2\theta_{13}$$

Double Beta Decay Visualizing the Equations:

$$m_{\beta\beta} = \sum_i V_{ei}^2 m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha} sin^2\theta_{12}) + m_3 \sin^2\theta_{13}$$

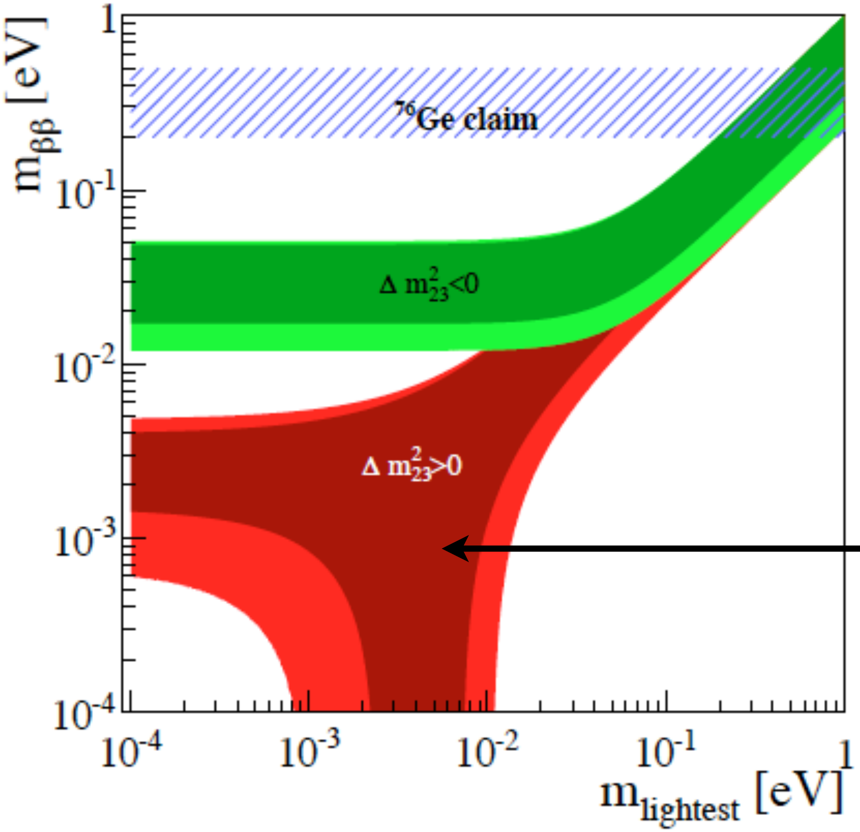


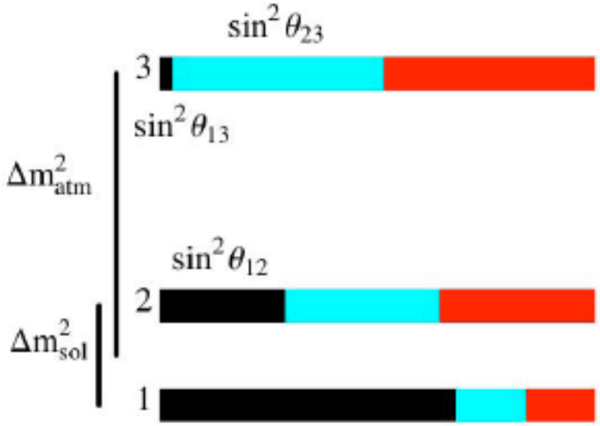
Inverted



Double Beta Decay Visualizing the Equations:

$$m_{\beta\beta} = \sum_i V_{ei}^2 m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha} sin^2\theta_{12}) + m_3\sin^2\theta_{13}$$

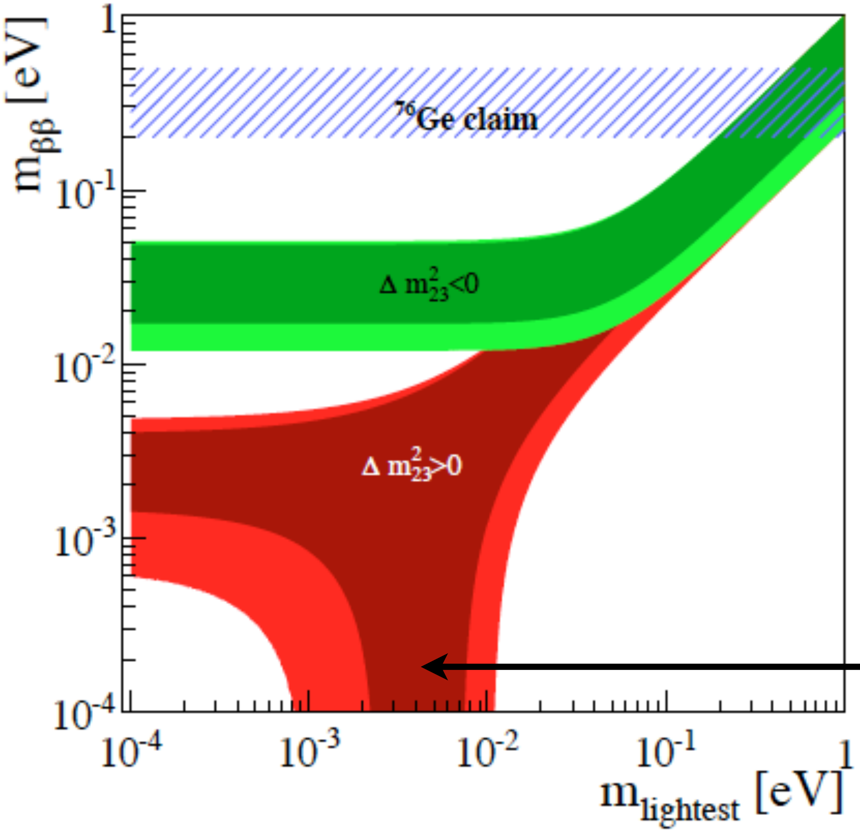




Normal

Double Beta Decay Visualizing the Equations:

$$m_{\beta\beta} = \sum_i V_{ei}^2 m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha} sin^2\theta_{12}) + m_3\sin^2\theta_{13}$$



The dark part of the width of these bands is real and if nature is cruel there could be some very nasty interference.

Comparing Experiments' Sensitivity:

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16 \times 10^{26}\ \mathrm{yr}}{n_\sigma}\left(\frac{\varepsilon a}{W}\right)\sqrt{\frac{Mt}{b\Delta(E)}}$$

Isotopic abundance

$$T^{0\nu}_{1/2}(n_\sigma) = \frac{4.16 \times 10^{26}\ \text{yr}}{n_\sigma}\left(\frac{\varepsilon a}{W}\right)\sqrt{\frac{Mt}{b\Delta(E)}}$$

Isotope	Endpoint	Abundance
^{48}Ca	4.271 MeV	0.187%
^{150}Nd	3.367 MeV	5.6%
^{96}Zr	3.350 MeV	2.8%
^{100}Mo	3.034 MeV	9.6%
^{82}Se	2.995 MeV	9.2%
^{116}Cd	2.802 MeV	7.5%
^{130}Te	2.527 MeV	34.5%
^{136}Xe	2.457 MeV	8.9%
^{76}Ge	2.039 MeV	7.8%

Total Mass

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16 \times 10^{26}\ \text{yr}}{n_\sigma} \left(\frac{\varepsilon a}{W} \right) \sqrt{\frac{Mt}{b\Delta(E)}}$$

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16 \times 10^{26}\ \text{yr}}{n_\sigma} \left(\frac{\varepsilon a}{W} \right) \sqrt{\frac{Mt}{b\Delta(E)}}$$

Background rate

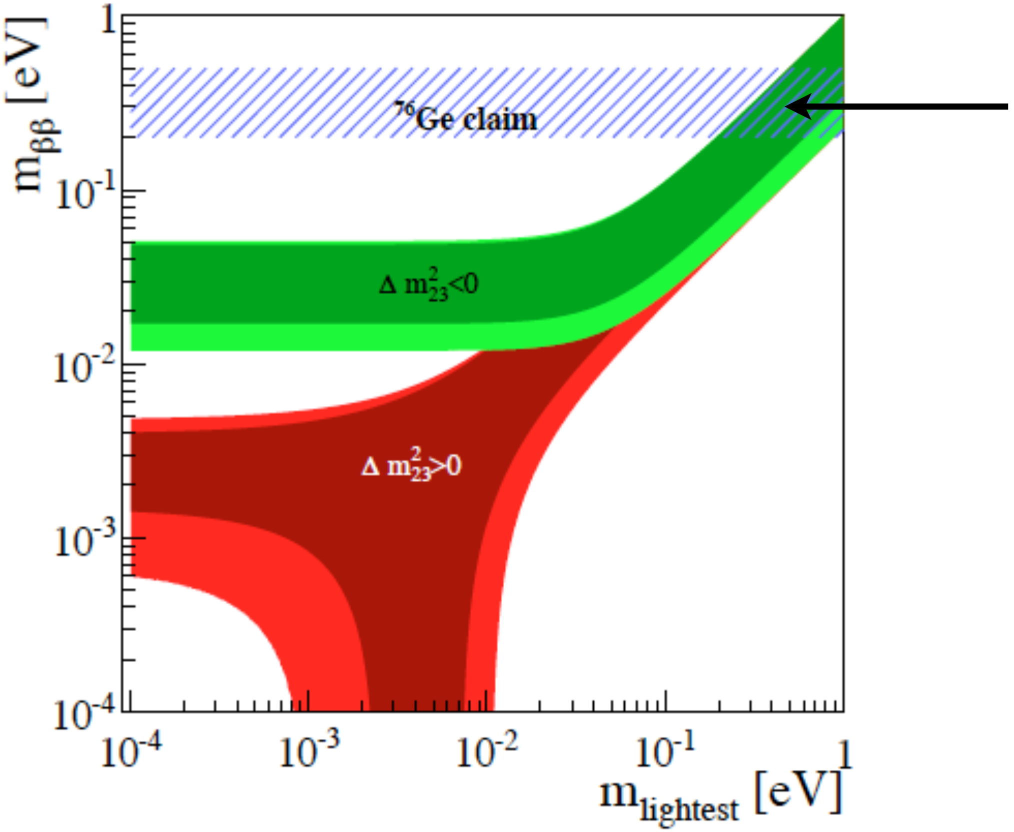
$$T^{0\nu}_{1/2}(n_\sigma) = \frac{4.16 \times 10^{26}\ \mathrm{yr}}{n_\sigma}\left(\frac{\varepsilon a}{W}\right)\sqrt{\frac{Mt}{b\Delta(E)}}$$

Energy resolution
(Most important for separating neutrinoless from two neutrino double beta decay).

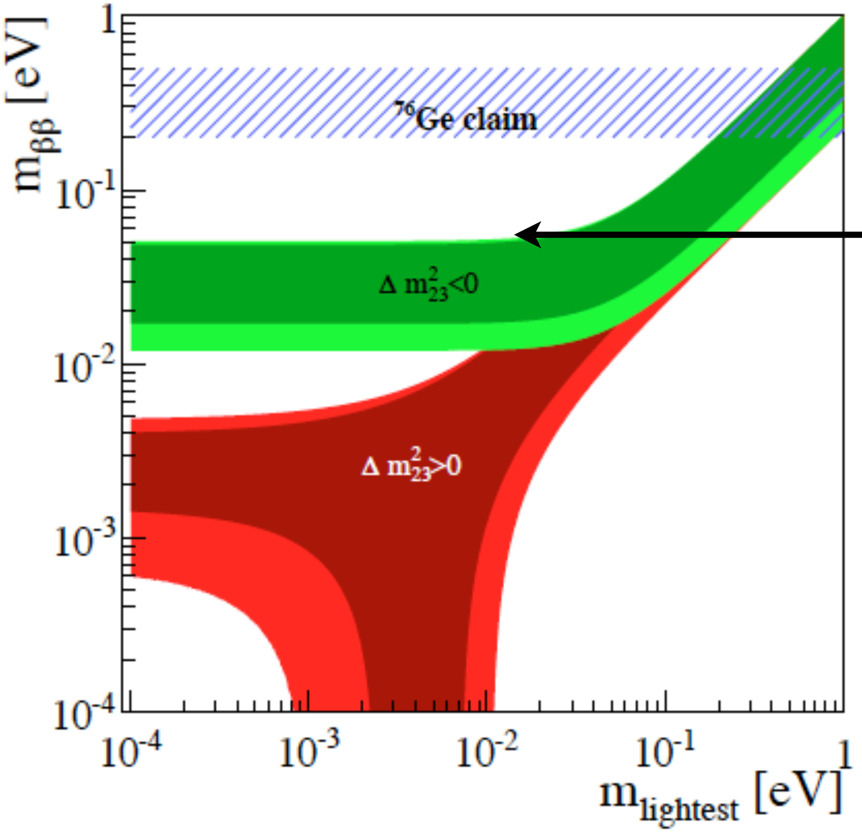
Big

Good
Energy
Resolution

What has been happening lately...



The last few years have focused on experiments sensitive to addressing this claim.



Actually, we are about here now, $\sim 10^{26}$ years.

Rough Time Scales

^{14}C - 10^4 years

^{40}K - 10^9 years

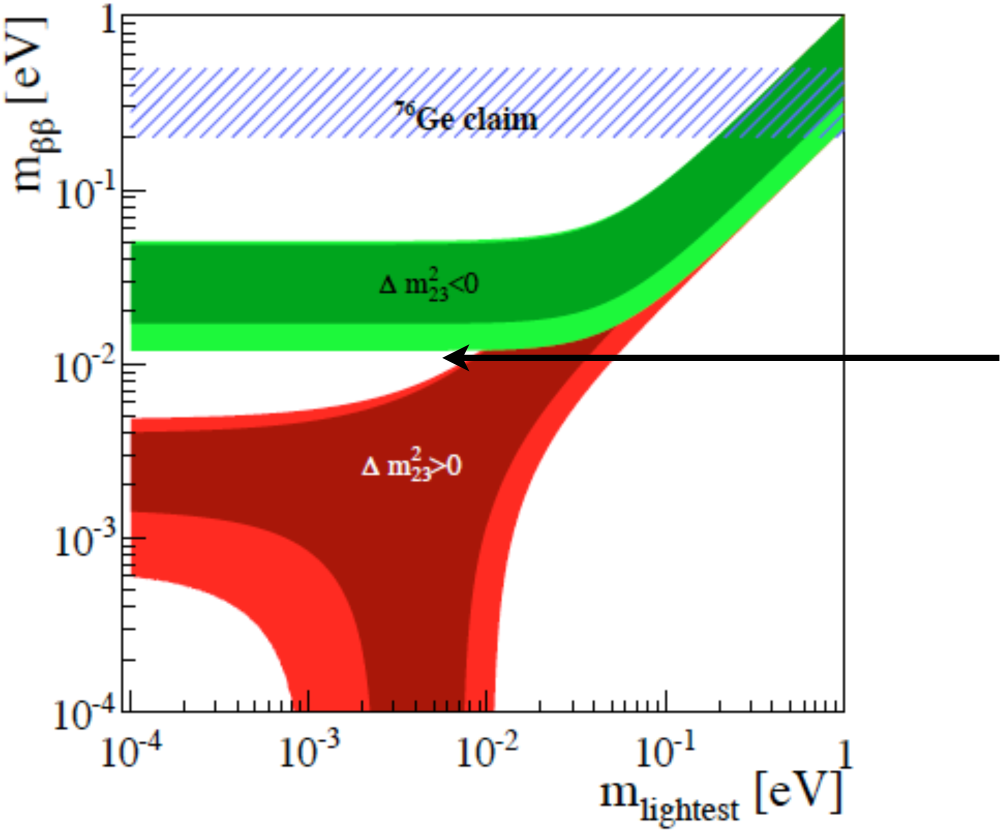
^{232}Th - 10^{10} years

The Universe - 10^{10} years

Two Neutrino Double Beta ~ 10^{20} years

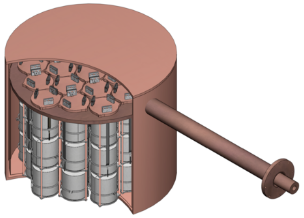
Neutrinoless Double Beta $>10^{26}$ years

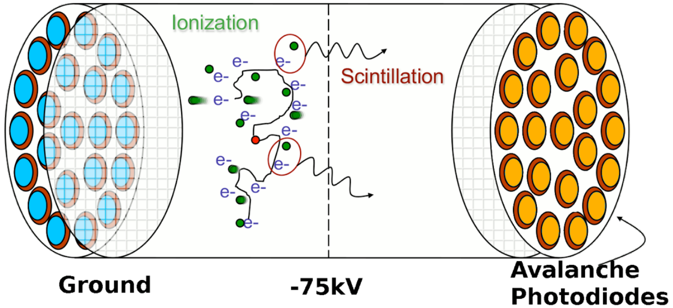
Proton Decay $>10^{30}$ years

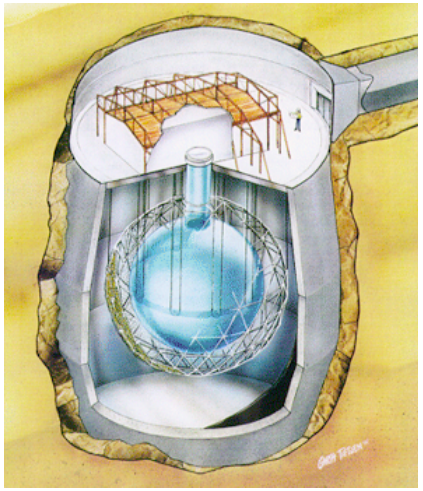


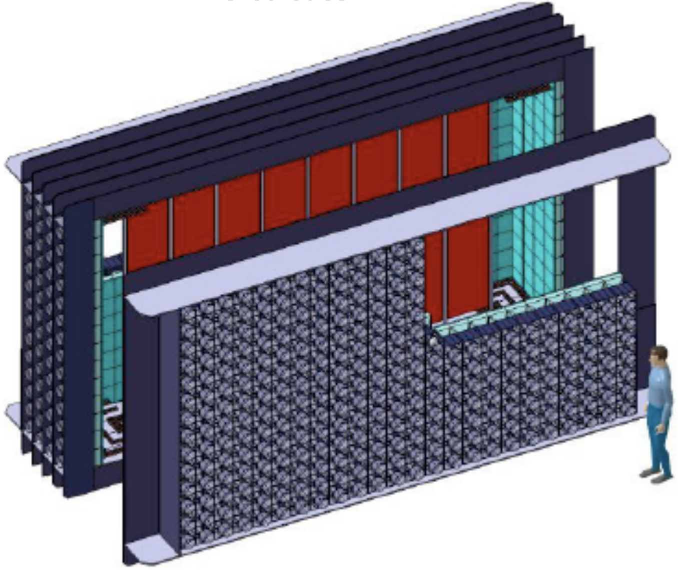
We have been trying to figure out what is needed for a definitive search over the parameter space corresponding to the inverted hierarchy.

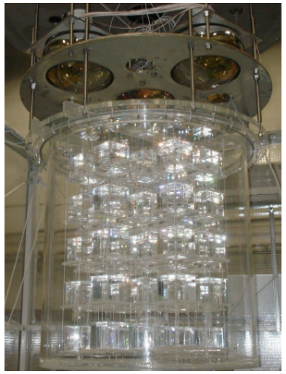
A lot of detector ideas:

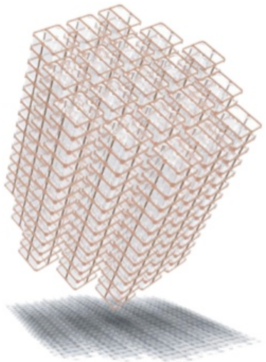


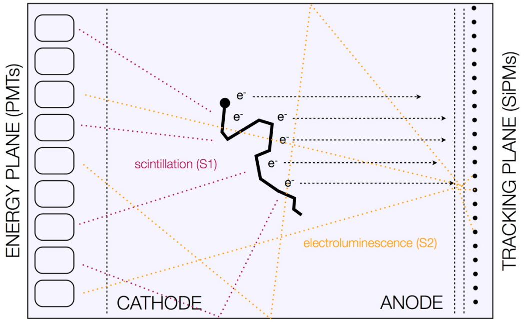


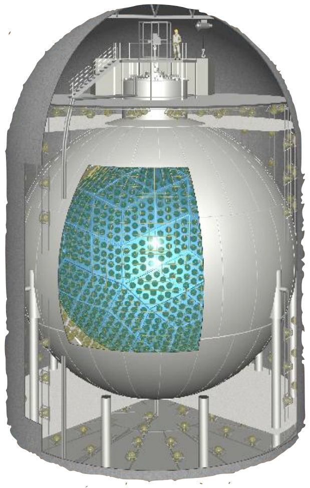




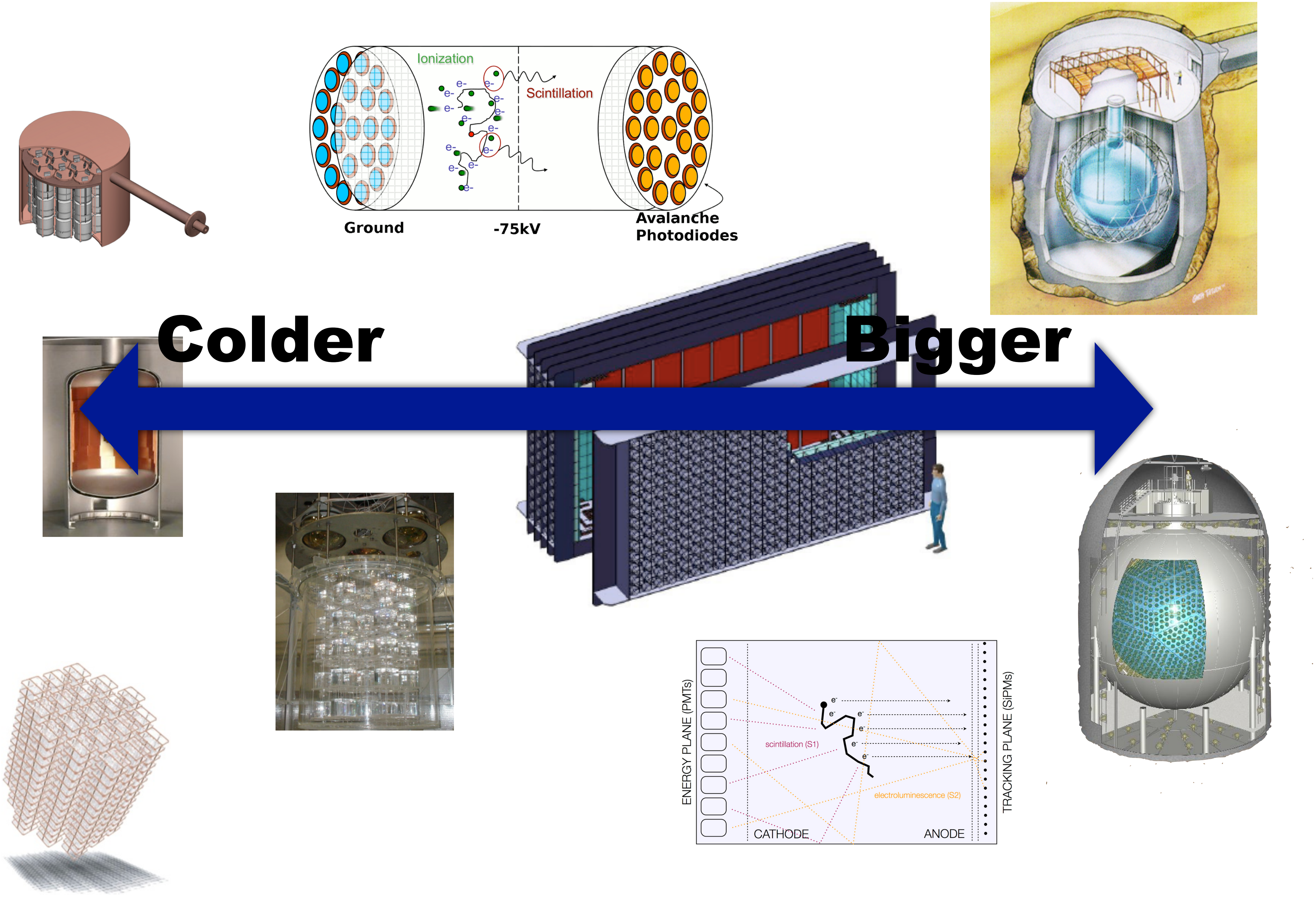








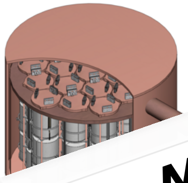
A lot of detector ideas:

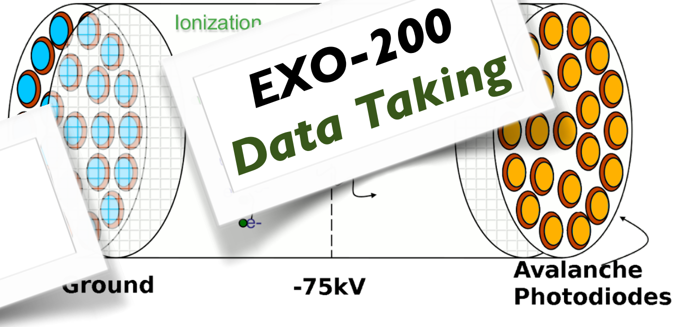


Colder

Bigger

A lot of detector ideas:


Majorana
Data Taking



EXO-200
Data Taking

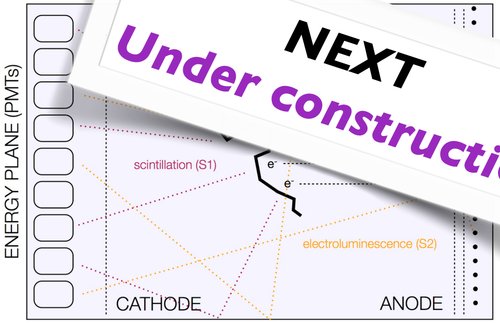

SNO+
Commissioning


SuperNEMO
Under construction


GERDA
Data Taking


CANDLES
Complete


KamLAND-Zen
Data Taking

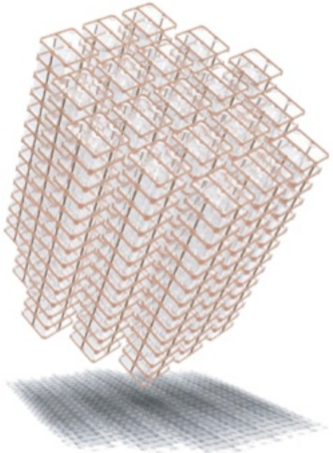


NEXT
Under construction


CUORE
Data Taking

What did I choose?

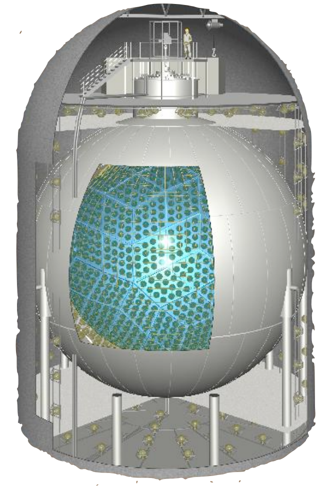
Good Energy Resolution



Bolometers

More Difficult to make big.

Good at Size

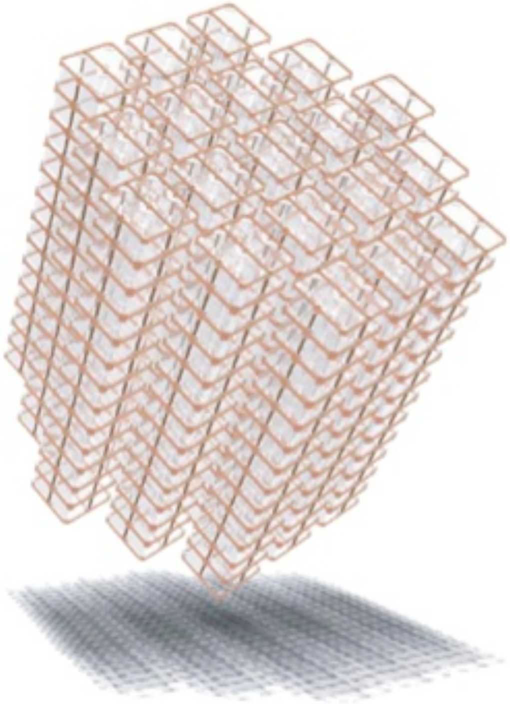


Scintillator

Bad Energy Resolution

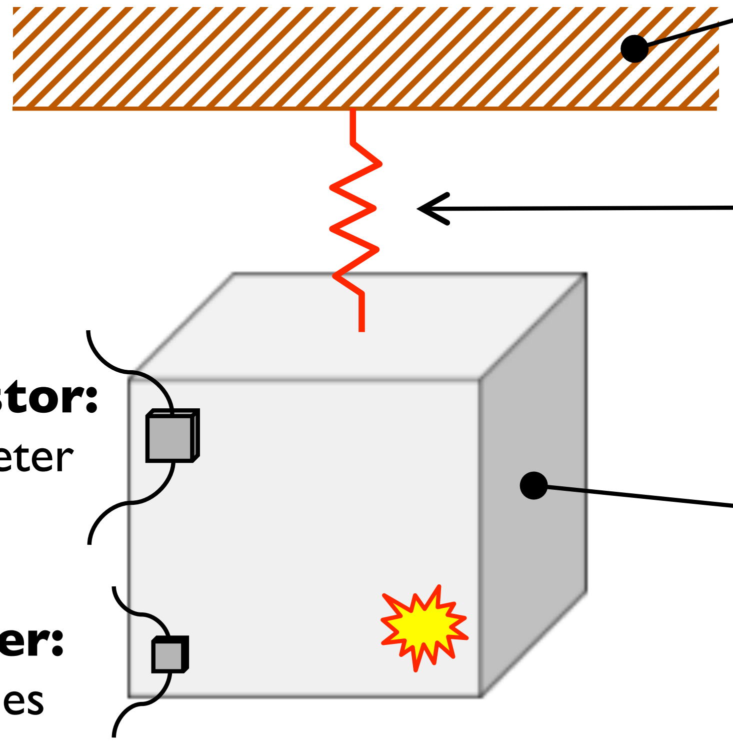
CUORE:

Cryogenic Underground Observatory for Rare Events



Super Cool

How Bolometers work:



Copper frame:
10 mK heat sink

PTFE holders:
weak thermal coupling

NTD Ge thermistor:
resistive thermometer

TeO_2 crystal:
energy absorber

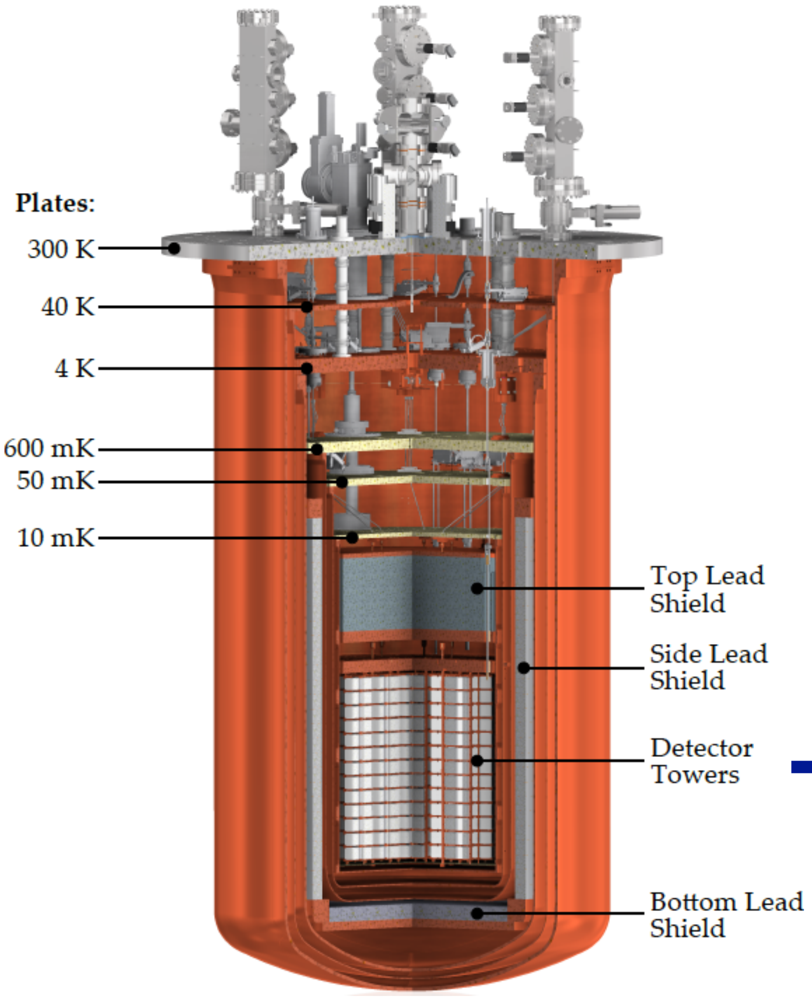
Si joule heater:
reference pulses

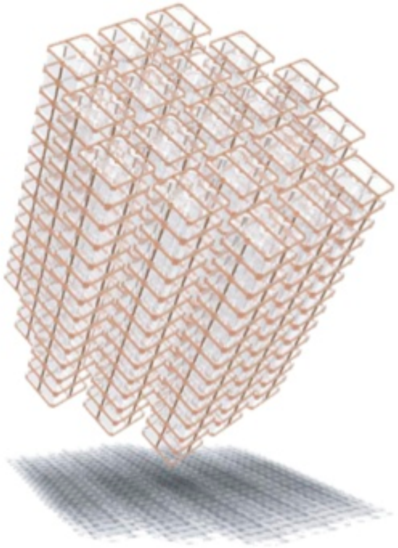
Radiation:
energy deposit

CUORE:

Cryogenic Underground Observatory for Rare Events

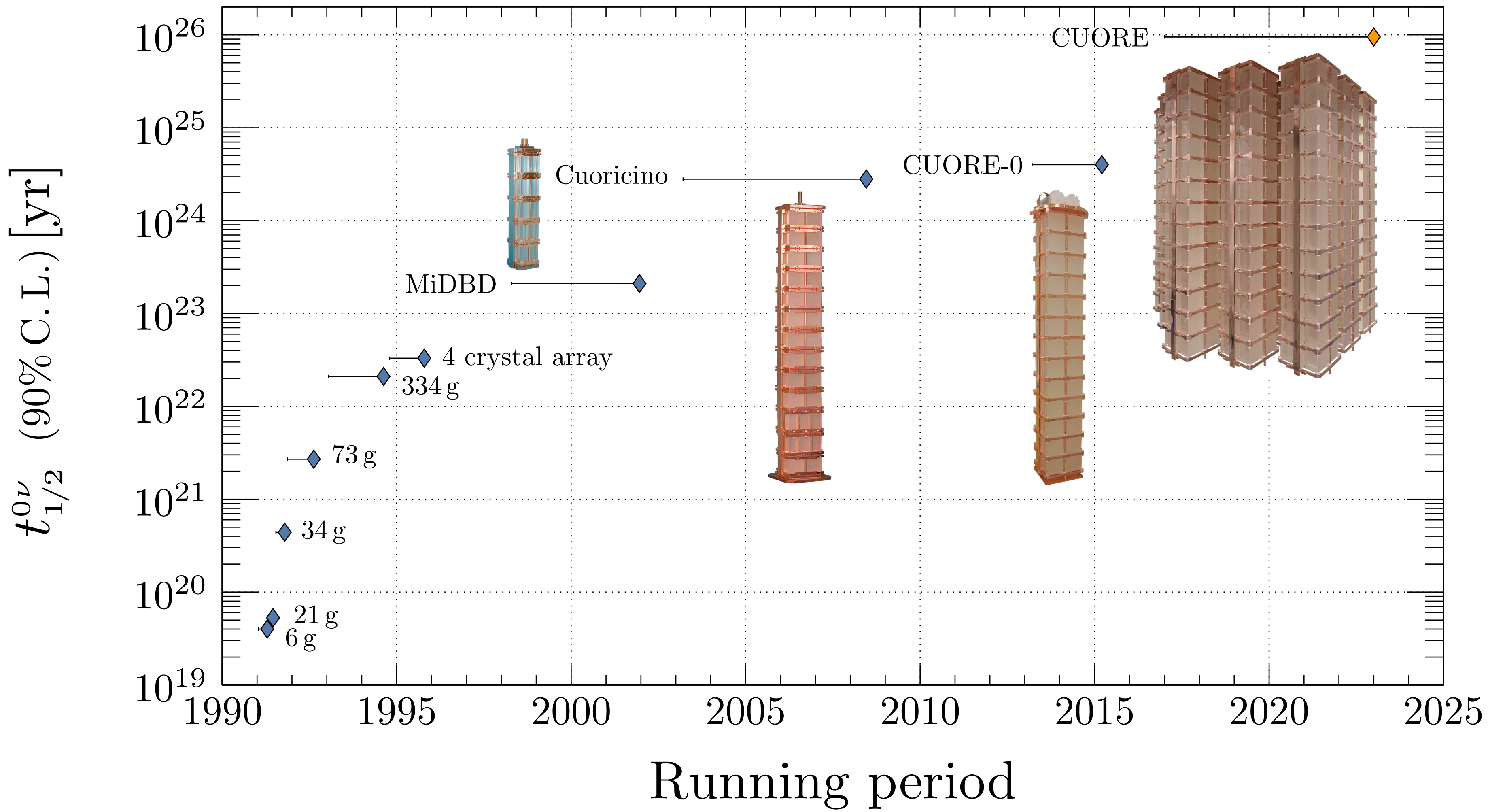
- 19 Towers, 988 TeO_2 crystals operated as bolometers.
- We are the “Coldest cubic meter in the known universe”, arXiv:1410.1560





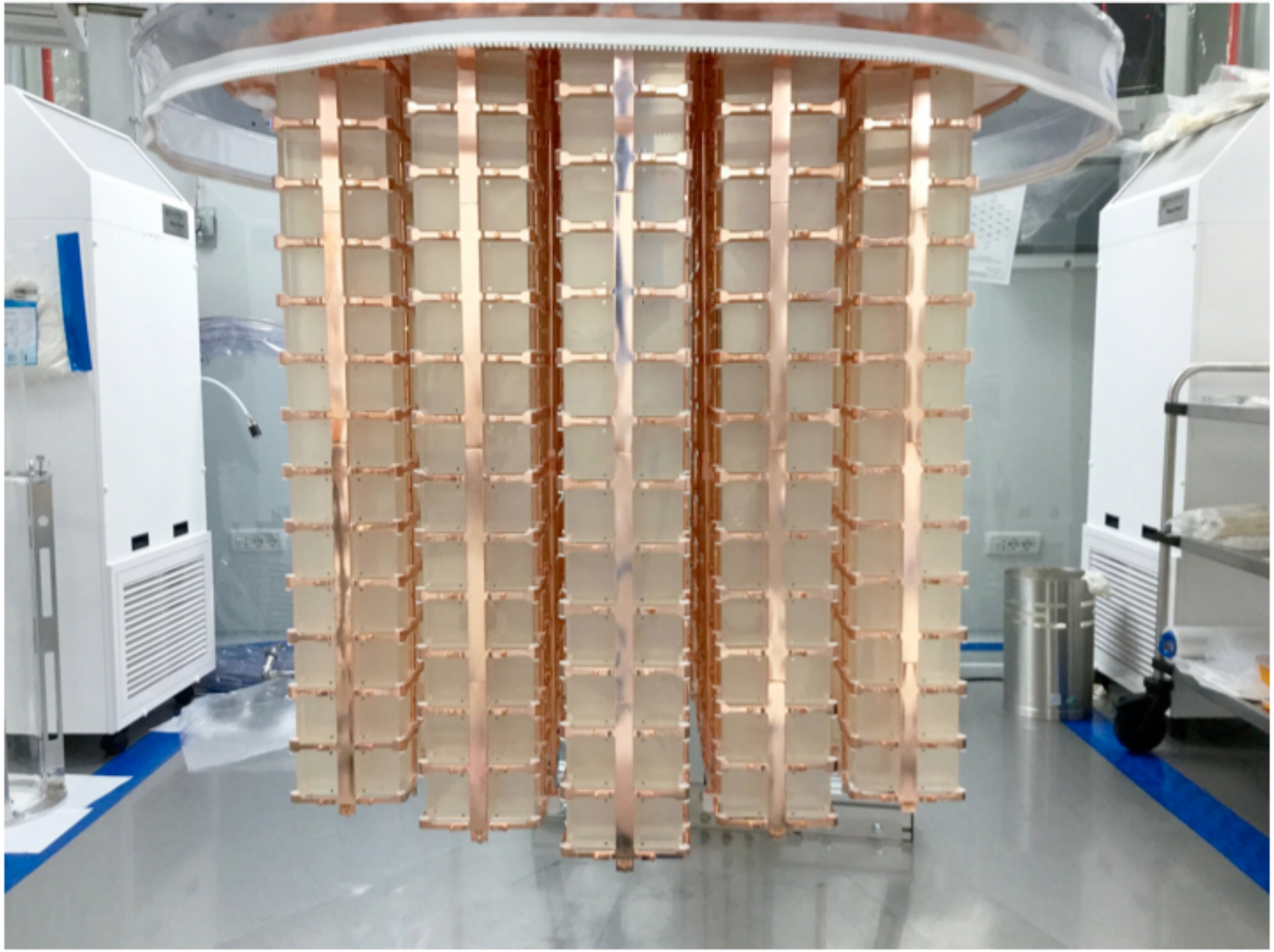
CUORE:

Cryogenic Underground Observatory for Rare Events



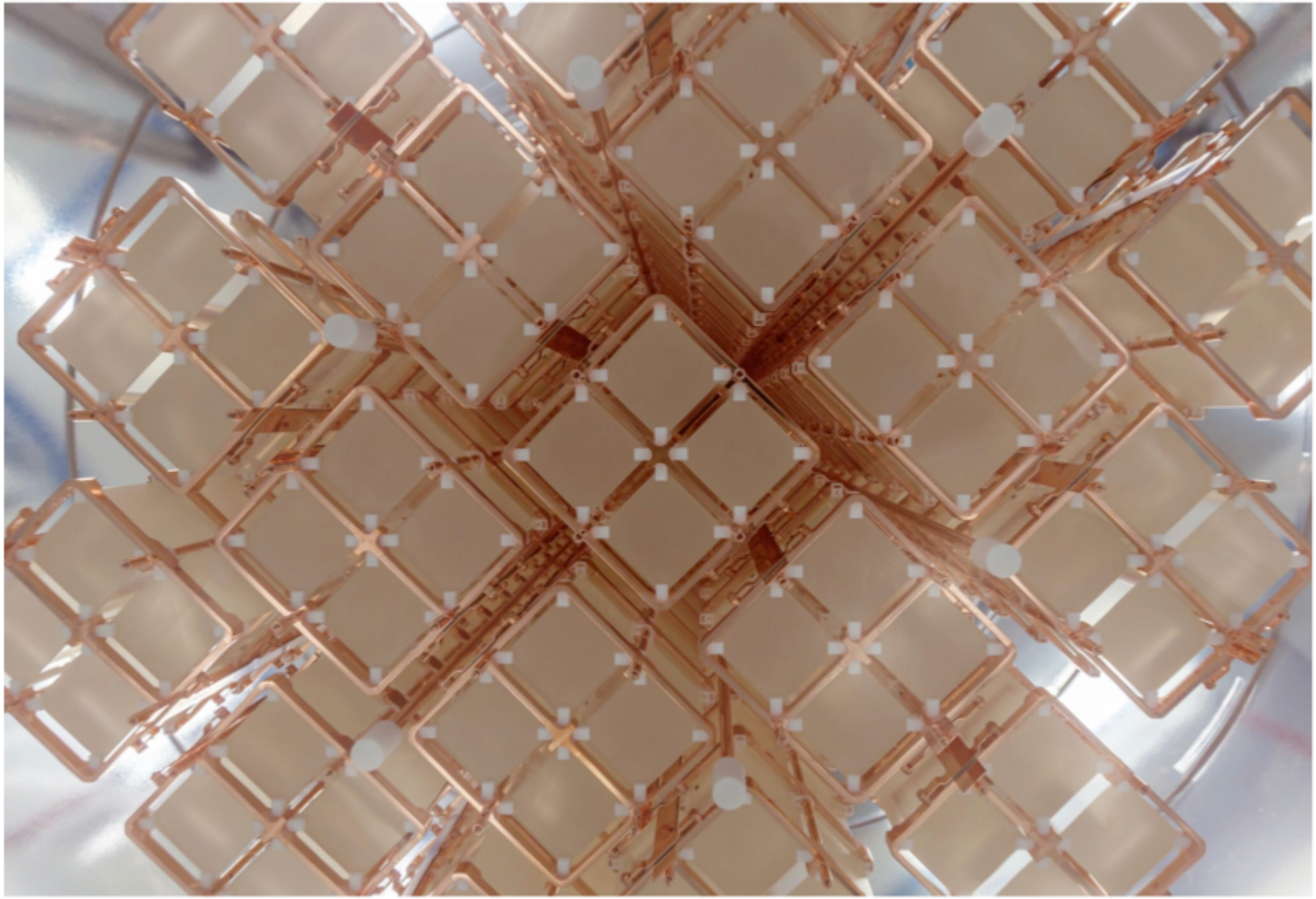
CUORE:

Cryogenic Underground Observatory for Rare Events

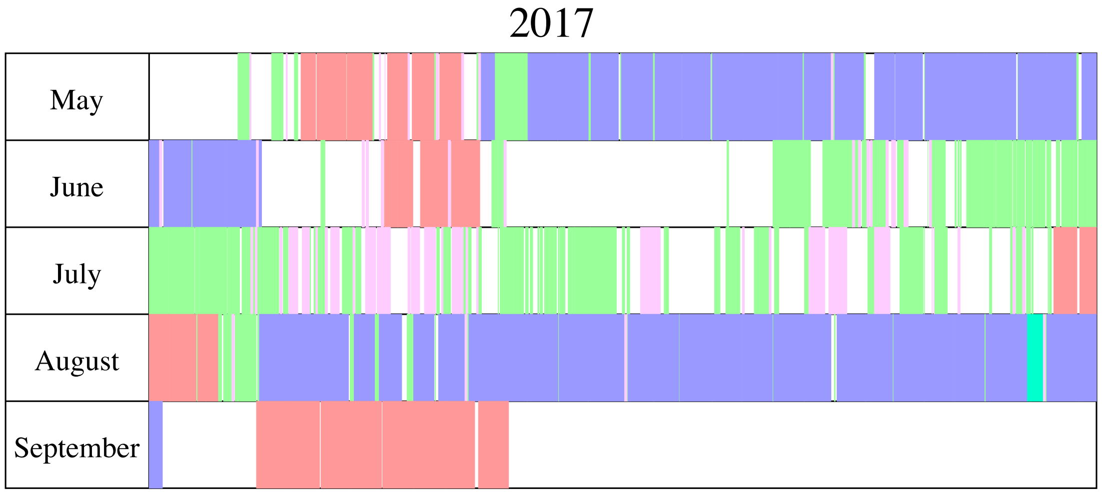


CUORE:

Cryogenic Underground Observatory for Rare Events



Physics Data Taking 2017



Dataset 1: May - June

Detector Optimization Campaign

Dataset 2: August - September

Blue = Physics

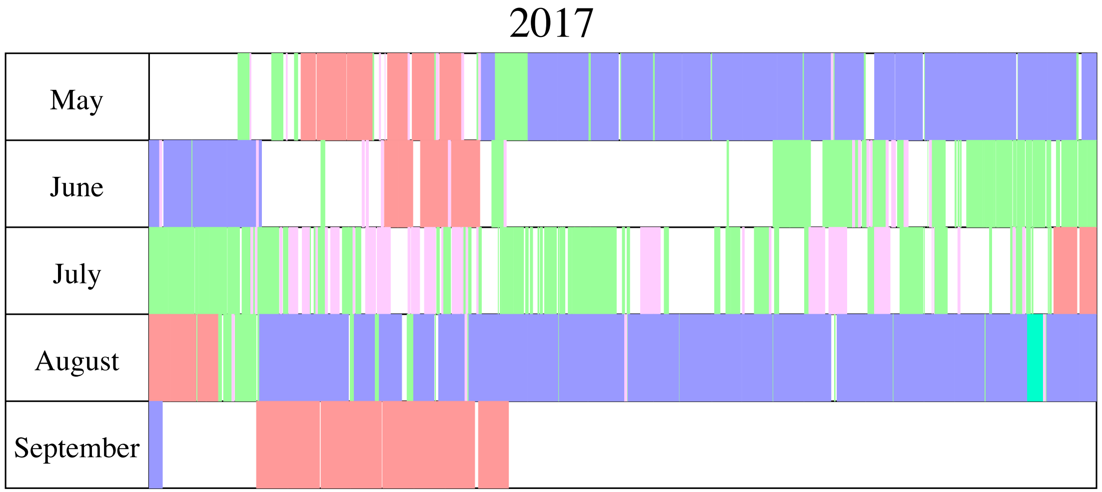
Red = Calibration

Pink = Setup/Configuration

Green = Test

All physics runs bracketed
by a calibration run.

Physics Data Taking 2017



Dataset 1: May - June

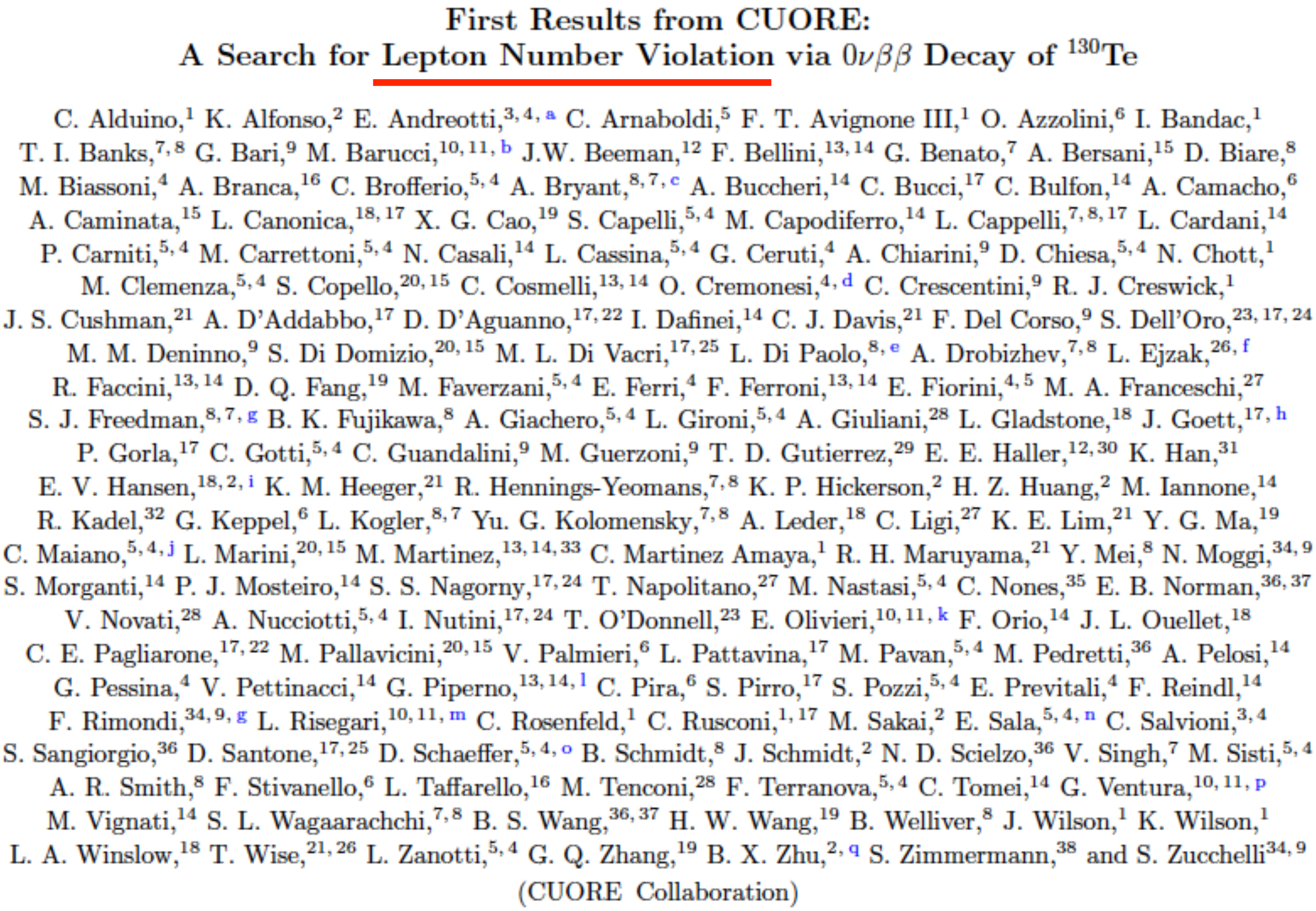
Detector Optimization Campaign

Dataset 2: August - September

Acquired statistics used for this 0vDBD decay search:
(Dataset 1 + Dataset 2):

- $^{nat}TeO_2$ exposure: 86.3 kg yr (37.6 kg yr + 48.7 kg yr)
- ^{130}Te exposure: 24.0 kg yr

CUORE:
Cryogenic Underground Observatory for Rare Events



First Results from CUORE:
A Search for Lepton Number Violation via $0\nu\beta\beta$ Decay of ^{130}Te

C. Alduino,[1] K. Alfonso,[2] E. Andreotti,[3,4,a] C. Arnaboldi,[5] F. T. Avignone III,[1] O. Azzolini,[6] I. Bandac,[1] T. I. Banks,[7,8] G. Bari,[9] M. Barucci,[10,11,b] J.W. Beeman,[12] F. Bellini,[13,14] G. Benato,[7] A. Bersani,[15] D. Biare,[8] M. Biassoni,[4] A. Branca,[16] C. Brofferio,[5,4] A. Bryant,[8,7,c] A. Buccheri,[14] C. Bucci,[17] C. Bulfon,[14] A. Camacho,[6] A. Caminata,[15] L. Canonica,[18,17] X. G. Cao,[19] S. Capelli,[5,4] M. Capodiferro,[14] L. Cappelli,[7,8,17] L. Cardani,[14] P. Carniti,[5,4] M. Carrettoni,[5,4] N. Casali,[14] L. Cassina,[5,4] G. Ceruti,[4] A. Chiarini,[9] D. Chiesa,[5,4] N. Chott,[1] M. Clemenza,[5,4] S. Copello,[20,15] C. Cosmelli,[13,14] O. Cremonesi,[4,d] C. Crescentini,[9] R. J. Creswick,[1] J. S. Cushman,[21] A. D'Addabbo,[17] D. D'Aguanno,[17,22] I. Dafinei,[14] C. J. Davis,[21] F. Del Corso,[9] S. Dell'Oro,[23,17,24] M. M. Deninno,[9] S. Di Domizio,[20,15] M. L. Di Vacri,[17,25] L. Di Paolo,[8,e] A. Drobizhev,[7,8] L. Ejzak,[26,f] R. Faccini,[13,14] D. Q. Fang,[19] M. Faverzani,[5,4] E. Ferri,[4] F. Ferroni,[13,14] E. Fiorini,[4,5] M. A. Franceschi,[27] S. J. Freedman,[8,7,g] B. K. Fujikawa,[8] A. Giachero,[5,4] L. Gironi,[5,4] A. Giuliani,[28] L. Gladstone,[18] J. Goett,[17,h] P. Gorla,[17] C. Gotti,[5,4] C. Guandalini,[9] M. Guerzoni,[9] T. D. Gutierrez,[29] E. E. Haller,[12,30] K. Han,[31] E. V. Hansen,[18,2,i] K. M. Heeger,[21] R. Hennings-Yeomans,[7,8] K. P. Hickerson,[2] H. Z. Huang,[2] M. Iannone,[14] R. Kadel,[32] G. Keppel,[6] L. Kogler,[8,7] Yu. G. Kolomensky,[7,8] A. Leder,[18] C. Ligi,[27] K. E. Lim,[21] Y. G. Ma,[19] C. Maiano,[5,4,j] L. Marini,[20,15] M. Martinez,[13,14,33] C. Martinez Amaya,[1] R. H. Maruyama,[21] Y. Mei,[8] N. Moggi,[34,9] S. Morganti,[14] P. J. Mosteiro,[14] S. S. Nagorny,[17,24] T. Napolitano,[27] M. Nastasi,[5,4] C. Nones,[35] E. B. Norman,[36,37] V. Novati,[28] A. Nucciotti,[5,4] I. Nutini,[17,24] T. O'Donnell,[23] E. Olivieri,[10,11,k] F. Orio,[14] J. L. Ouellet,[18] C. E. Pagliarone,[17,22] M. Pallavicini,[20,15] V. Palmieri,[6] L. Pattavina,[17] M. Pavan,[5,4] M. Pedretti,[36] A. Pelosi,[14] G. Pessina,[4] V. Pettinacci,[14] G. Piperno,[13,14,l] C. Pira,[6] S. Pirro,[17] S. Pozzi,[5,4] E. Previtali,[4] F. Reindl,[14] F. Rimondi,[34,9,g] L. Risegari,[10,11,m] C. Rosenfeld,[1] C. Rusconi,[1,17] M. Sakai,[2] E. Sala,[5,4,n] C. Salvioni,[3,4] S. Sangiorgio,[36] D. Santone,[17,25] D. Schaeffer,[5,4,o] B. Schmidt,[8] J. Schmidt,[2] N. D. Scielzo,[36] V. Singh,[7] M. Sisti,[5,4] A. R. Smith,[8] F. Stivanello,[6] L. Taffarello,[16] M. Tenconi,[28] F. Terranova,[5,4] C. Tomei,[14] G. Ventura,[10,11,p] M. Vignati,[14] S. L. Wagaarachchi,[7,8] B. S. Wang,[36,37] H. W. Wang,[19] B. Welliver,[8] J. Wilson,[1] K. Wilson,[1] L. A. Winslow,[18] T. Wise,[21,26] L. Zanotti,[5,4] G. Q. Zhang,[19] B. X. Zhu,[2,q] S. Zimmermann,[38] and S. Zucchelli[34,9]
(CUORE Collaboration)

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

CSNSM

SINAP

UNIVERSITAS STUDII PADUANI MCCXXII

Massachusetts Institute of Technology

Lawrence Livermore National Laboratory

VirginiaTech 1872 *Invent the Future*®

INFN

ALMA MATER STUDIORUM A.D. 1088 UNIVERSITA DI BOLOGNA

UNIVERSITÀ DEGLI STUDI DI CASSINO E DEL LAZIO MERIDIONALE SOL PER NOCTEM 1979

Yale

SHANGHAI JIAO TONG UNIVERSITY 1896

CAL POLY SAN LUIS OBISPO

CUORE

BERKELEY LAB

UNIVERSITY OF SOUTH CAROLINA 1801

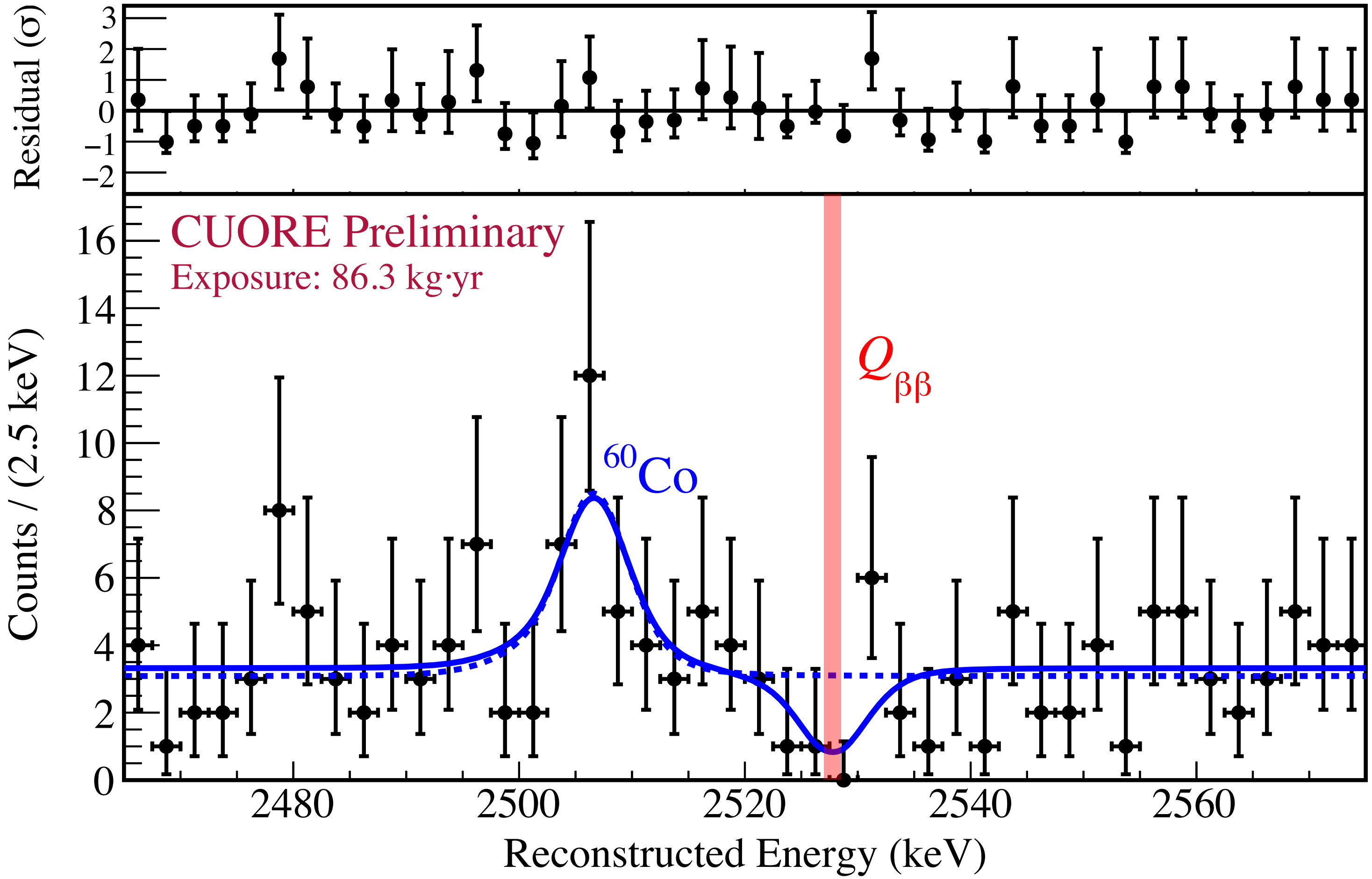
STVDIVM VRBIS

SAPIENZA UNIVERSITÀ DI ROMA

UCLA

THE UNIVERSITY OF CALIFORNIA LET THERE BE LIGHT 1868

The Result

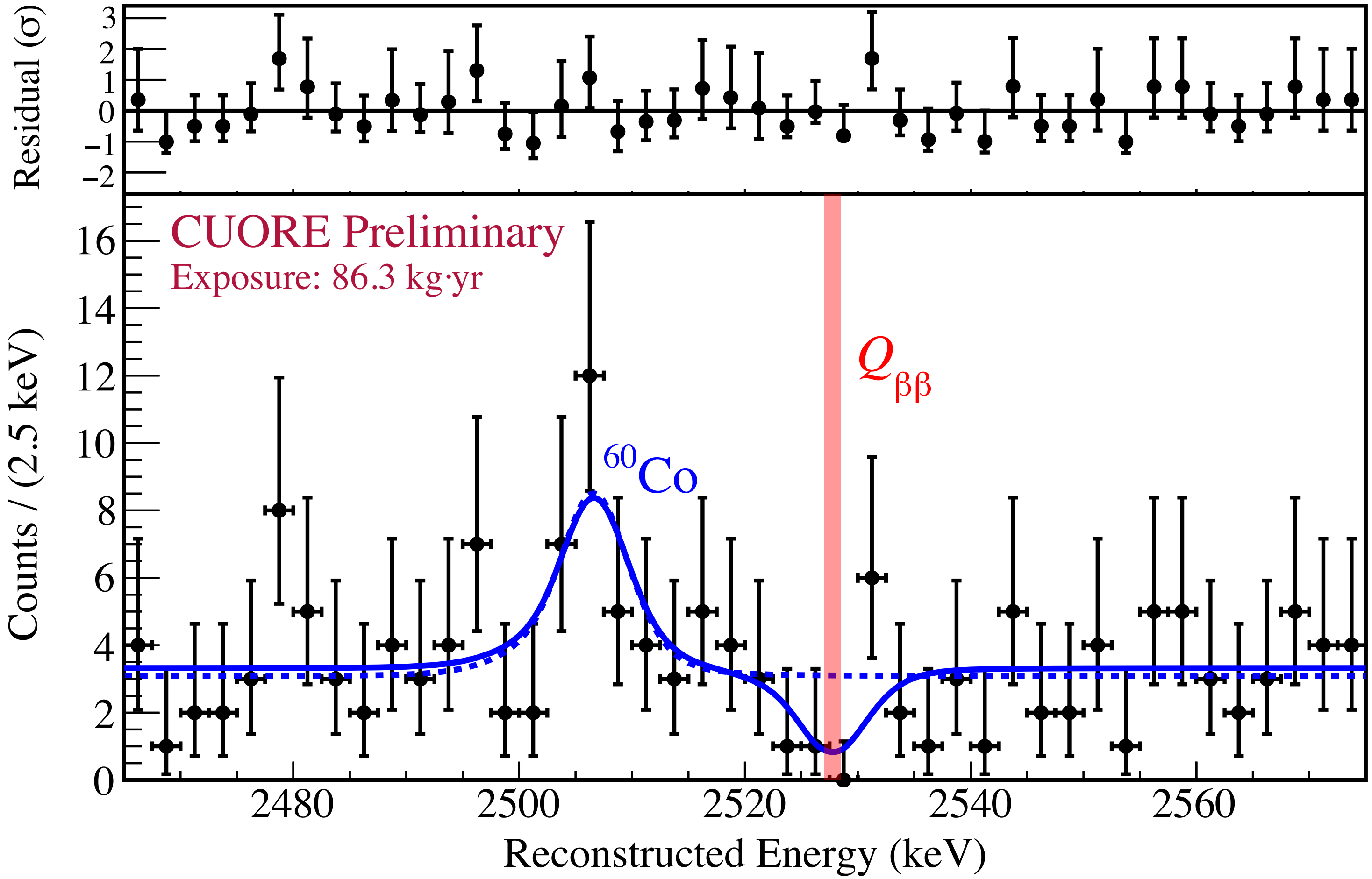


ROI background index: $(1.49_{-0.17}^{+0.18}) \times 10^{-2}$ c/(keV·kg·yr)

$(1.35_{-0.18}^{+0.20}) \times 10^{-2}$ c/(keV·kg·yr)

Best fit for ^{60}Co mean: (2506.4 ± 1.2) keV

The Result



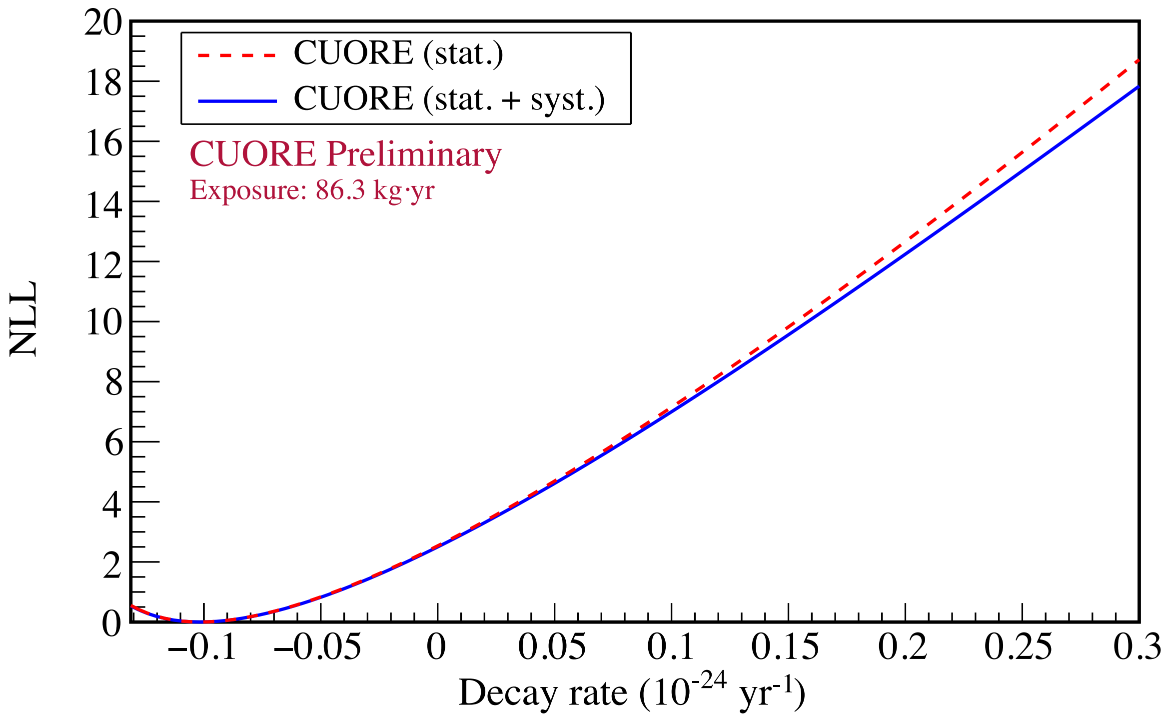
Best fit decay rate: $(-1.0_{-0.3}^{+0.4}$ (stat.) ± 0.1 (syst.)$)\times10^{-25}$ / yr

The Result

No evidence of signal

Limit calculation

Profile likelihood integrated on the physical region ($\Gamma^{0\nu} > 0$)



Decay rate limit (90% CL, including systematics): 0.51×10^{-25} / yr

Half-life limit (90% CL, including systematics): 1.3×10^{25} yr

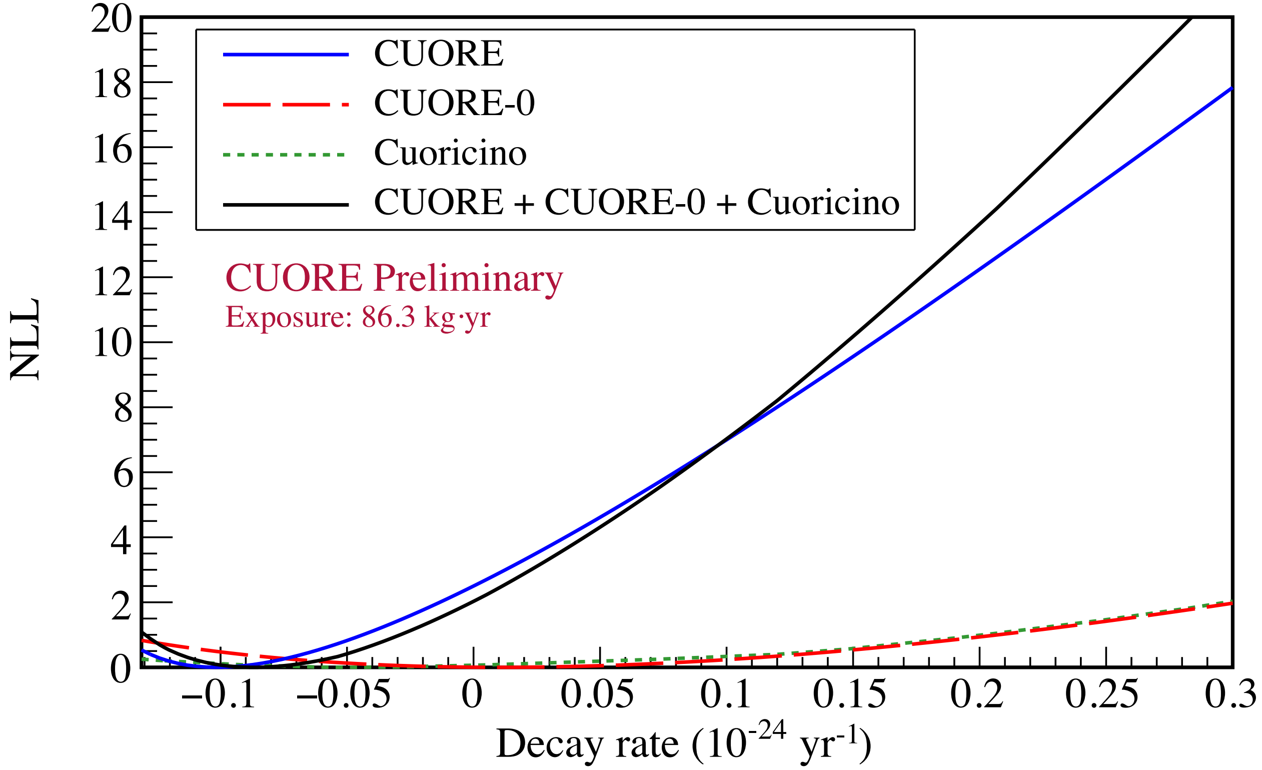
Median expected sensitivity: 7.0×10^{24} yr

Combination with Previous Results

We combined the CUORE result with the existing ^{130}Te

- 19.75 kg·yr of Cuoricino
- 9.8 kg·yr of CUORE-0

The combined 90% C.L. limit is
$T_{0\nu} > 1.5 \times 10^{25}$ yr

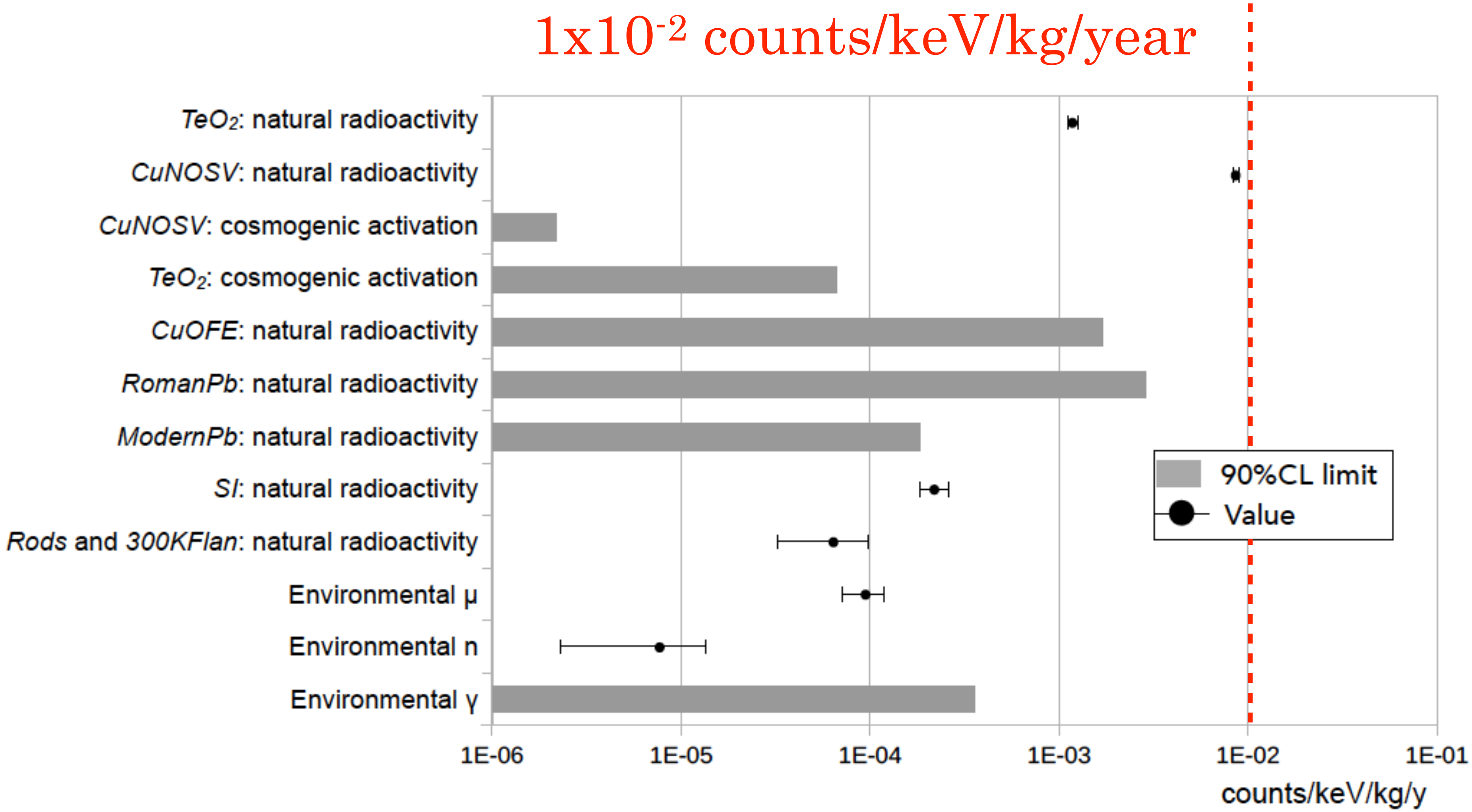


CUORE:

Cryogenic Underground Observatory for Rare Events

CUORE Goal:

$1x10^{-2}$ counts/keV/kg/year

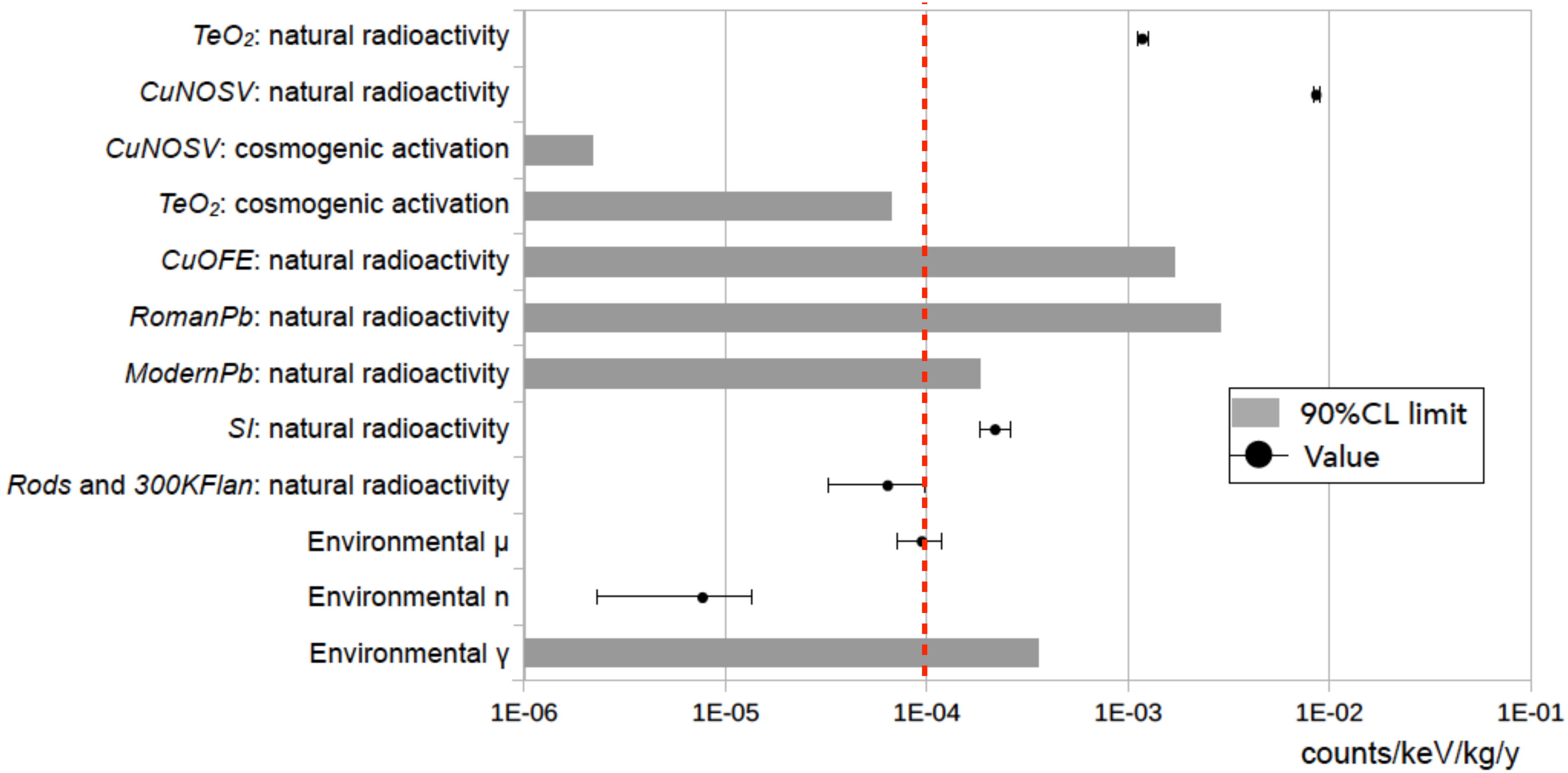


CUORE:

Cryogenic Underground Observatory for Rare Events

CUPID Goal:

1×10^{-4} counts/keV/kg/year

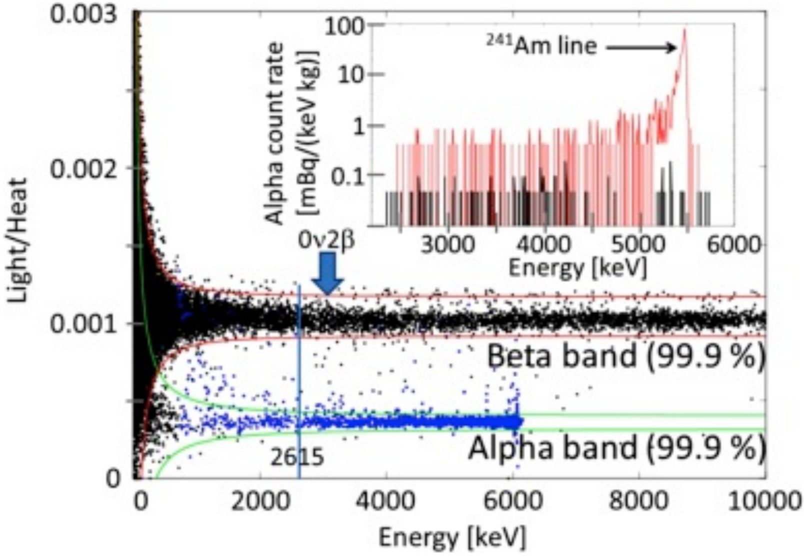


CUPID:

CUORE with Particle ID

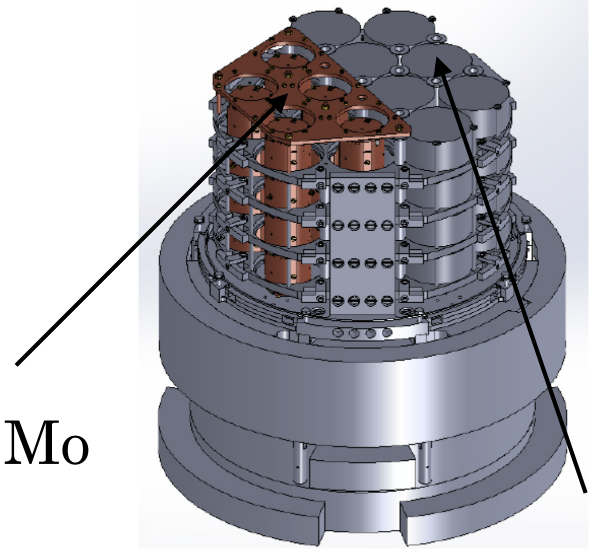
- Scintillating bolometers provide active alpha rejection by comparing heat and light signals.
- Moving to Li_2MoO_4 (LMO) enriched in ^{100}Mo moves above all gamma backgrounds.
- Re-uses CUORE infrastructure so is an easily staged upgrade.
- Active crystal R&D effort at MIT with RMD Inc.

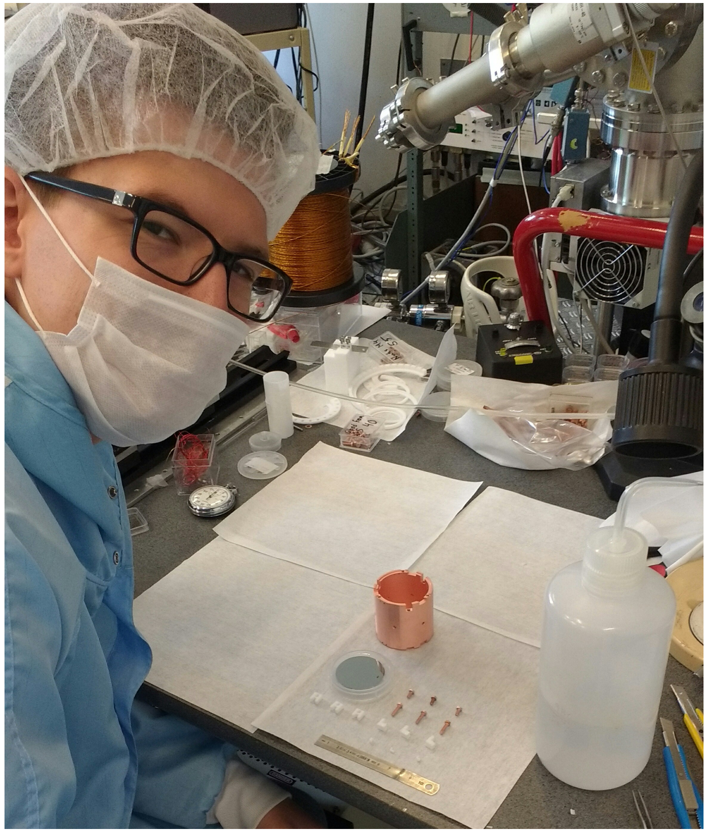
RMD Inc.
$Na_2Mo_2O_7$ Crystal



LUMINEU:
Physics Letters B, Volume 710, Issue 2, 2012, Pages 318-323

CUPID-Mo Demonstrator



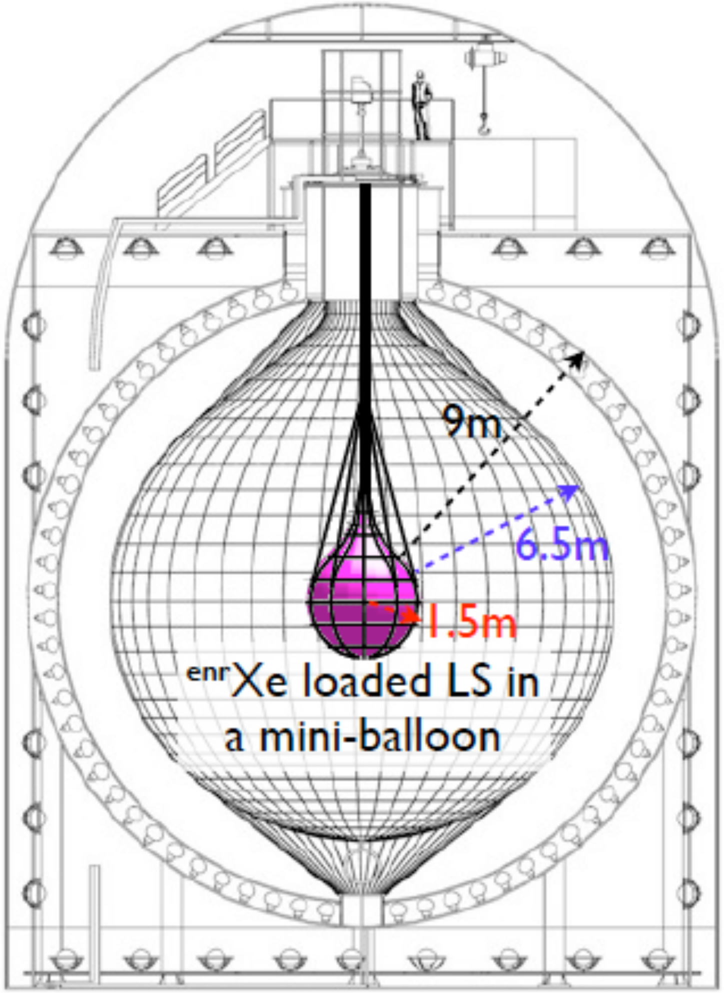


MIT Graduate Student Joe Johnston assembling the CUPID-Mo bolometric test tower, funding through MISTI-France.

- We are working closely with the Orsay group both on crystal testing and the realization of a demonstrator experiment.
- The 20 Li_2MoO_4 crystal phase-I demonstrator is now taking data.

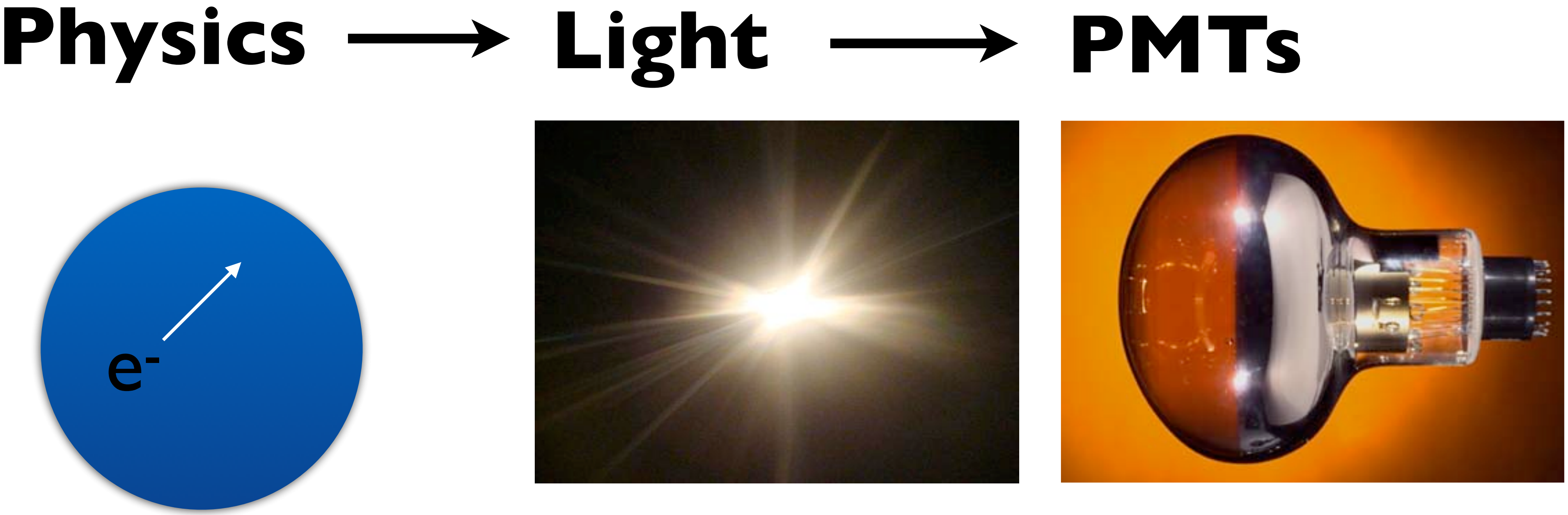
KamLAND-Zen

Zero Neutrino
double beta decay search



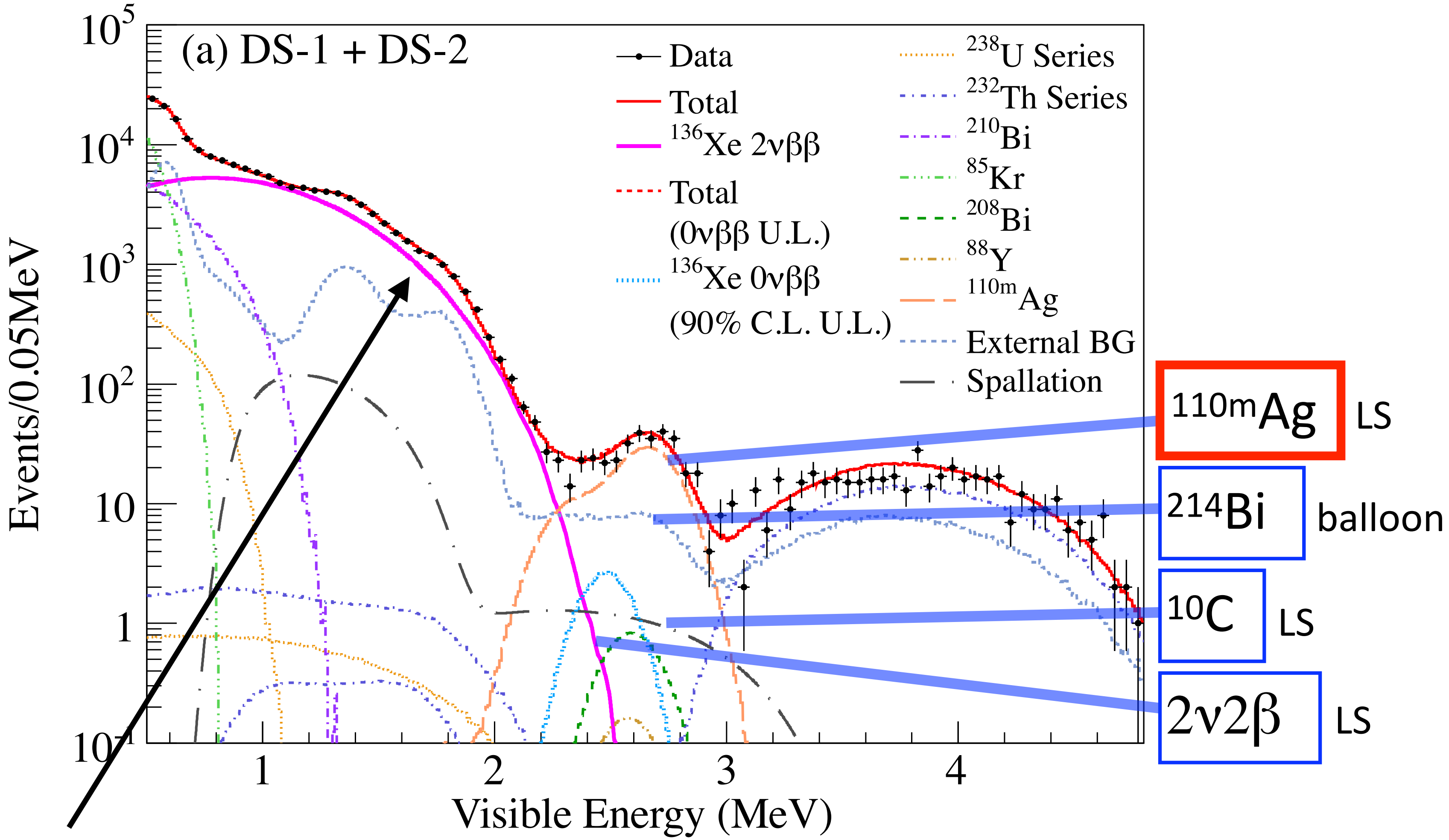
~320kg 90% enriched ^{136}Xe installed so far

Basic Principle of Liquid Scintillator Detector


Physics ⟶ **Light** ⟶ **PMTs**

A charged particle vibrates molecules making light that is detected by photomultiplier detectors (PMT).

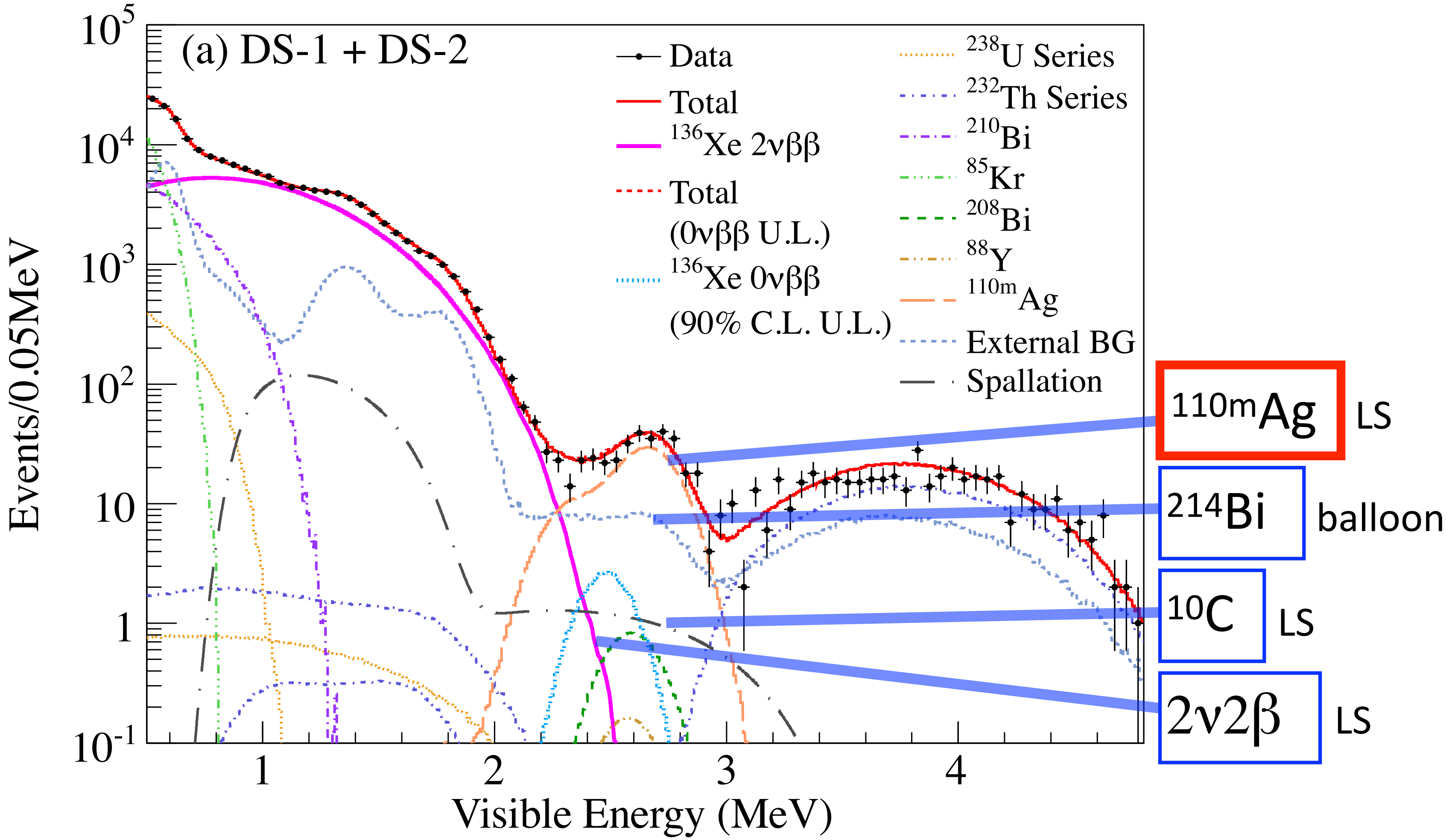
KamLAND-Zen started in 2011:



$T_{1/2}(2\nu) = 2.32+/-0.12\times10^{21}$ yr

Currently the slowest process directly measured.

KamLAND-Zen started in 2011:



^{110m}Ag LS

^{214}Bi balloon

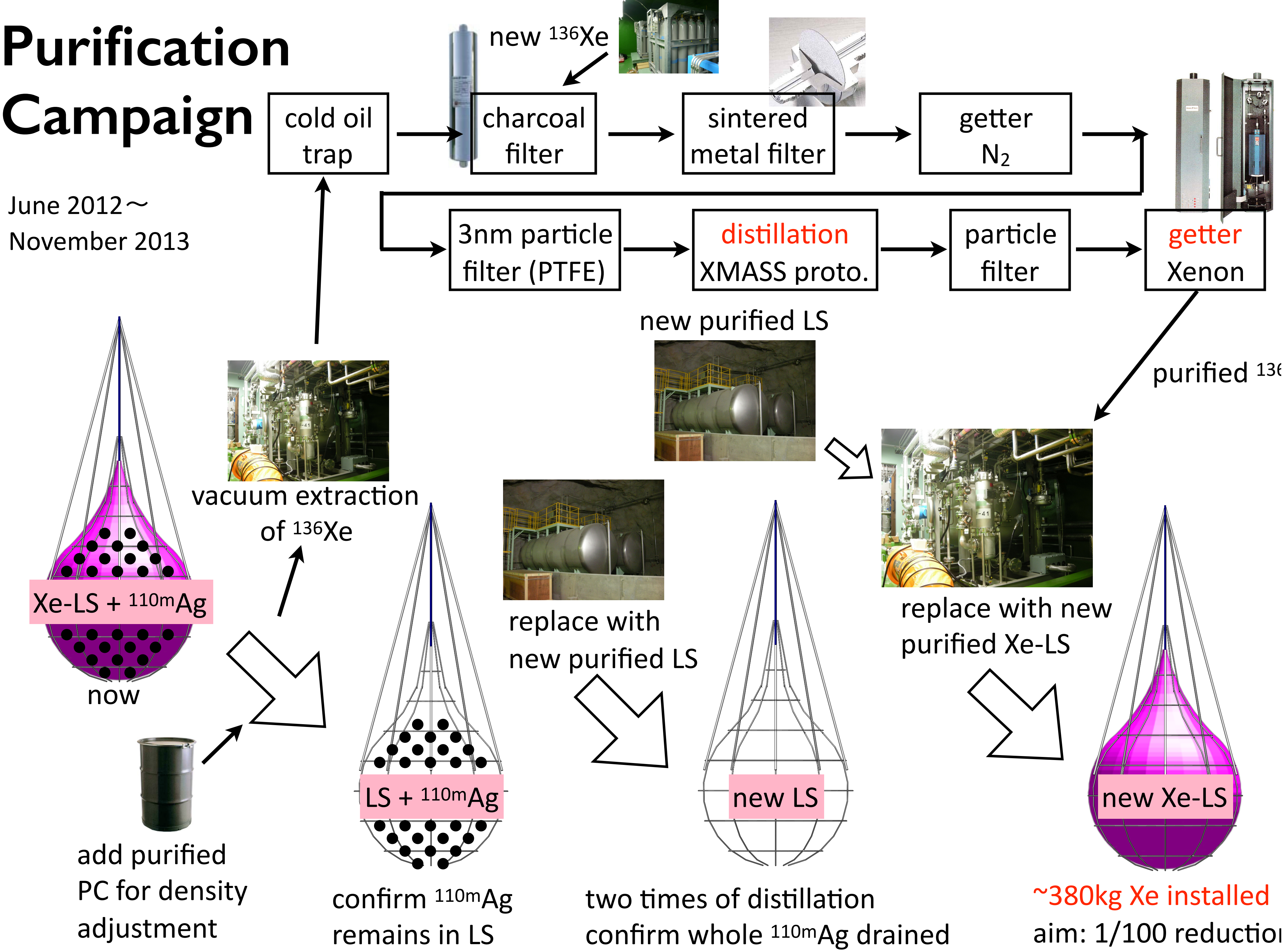
^{10}C LS

2ν2β LS

An Unexpected BG was found!

Purification Campaign

June 2012～
November 2013



cold oil trap → charcoal filter → sintered metal filter → getter N_2 → 3nm particle filter (PTFE) → distillation XMASS proto. → particle filter → getter Xenon

new ^{136}Xe

vacuum extraction of ^{136}Xe

add purified PC for density adjustment

confirm ^{110m}Ag remains in LS

replace with new purified LS

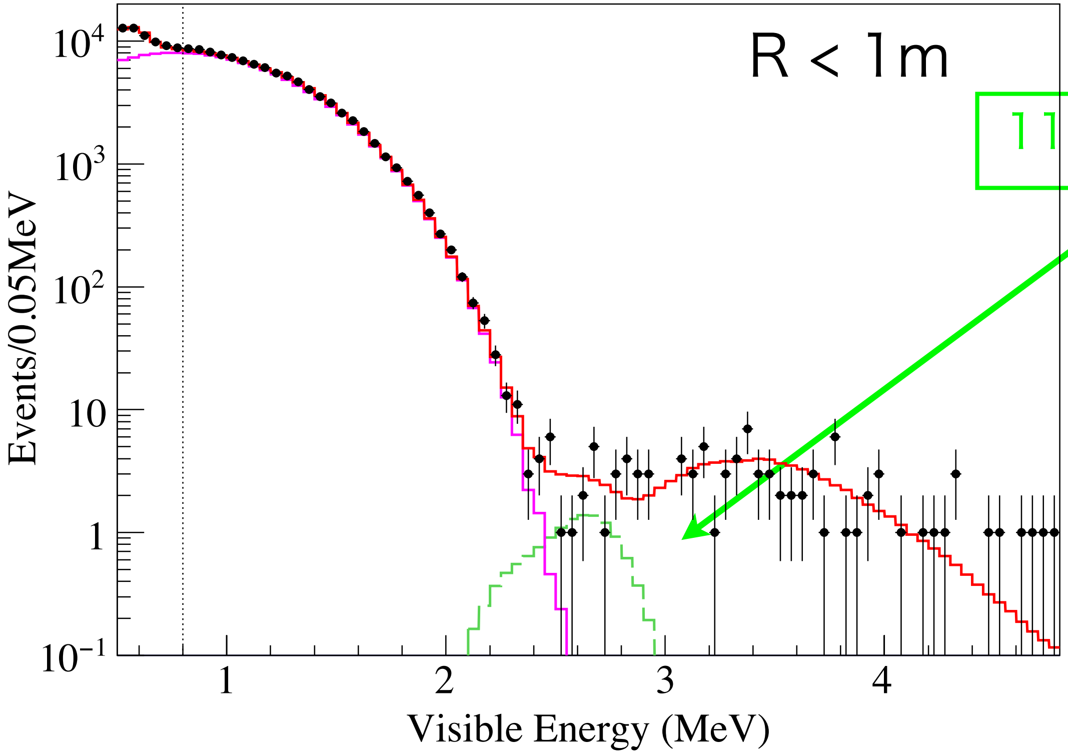
two times of distillation
confirm whole ^{110m}Ag drained

replace with new purified Xe-LS

~380kg Xe installed
aim: 1/100 reductio

Full phase-2 data-set

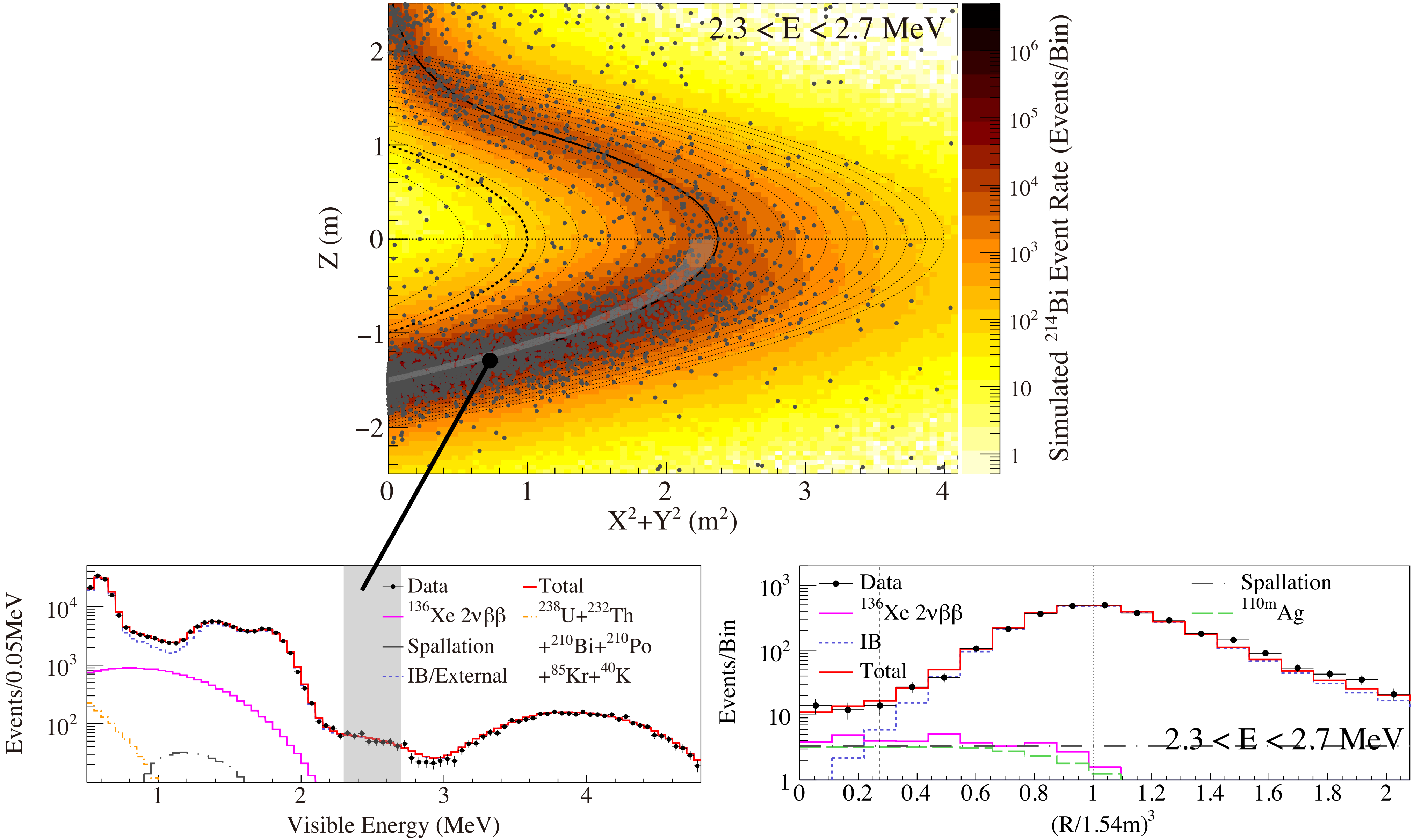
- After Purification
- December 2013 - October 2015
- Livetime 534.5 days, exposure 504 kg-yr
- For Reference: $T_{1/2}(^{110m}Ag)$ = 250 days.



^{110m}Ag still exists?

We might have scrubbed and dropped “dust” during extraction of the LS supply tube.

Analysis:
40 equal-volume bins



Energy and radial distributions are well-reproduced by known BGs.

Phase 2 - Results on $0\nu2\beta$

	period-1	period-2
livetime	270.7 days	263.8 days
^{136}Xe $0\nu2\beta$ decay rate	< 5.5 /kton/day	< 3.5 /kton/day

combined < 2.4 /kton/day (90%C.L.)

^{136}Xe $0\nu2\beta$ half-life > 9.2×10^{25} yr (90%C.L.)

sensitivity > 4.9×10^{25} yr (11% probability)

Combined datasets gives

$T_{1/2}>1.07\times10^{26}$ yr

Mini-Balloon Construction:

Summer 2015:
MIT IROP Students
Emmett Krupczak and Gailin Pease

Outer Detector Refurbishment:

January 2016

New Mini-Balloon Leak Checking and Installation

MIT Undergraduates Hannah Taylor and Andrea Herman

Summer 2016

A New New Mini-Balloon Construction for Summer 2017

MIT graduate student
Suzannah Fraker

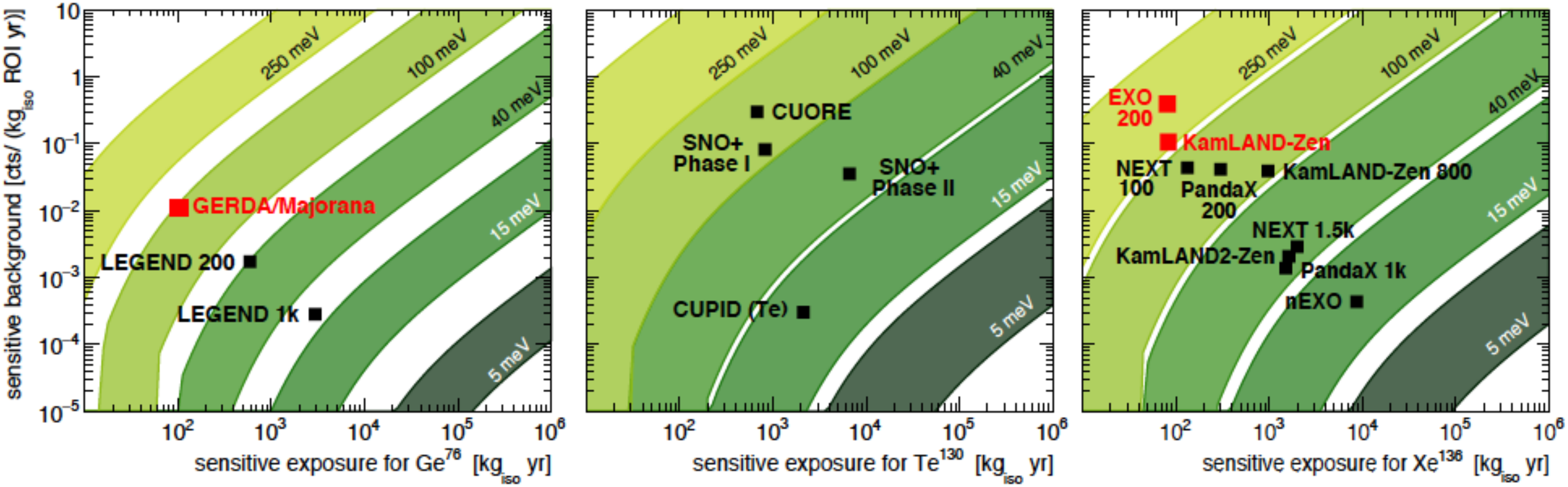
KamLAND-Zen 800 is now running!!!

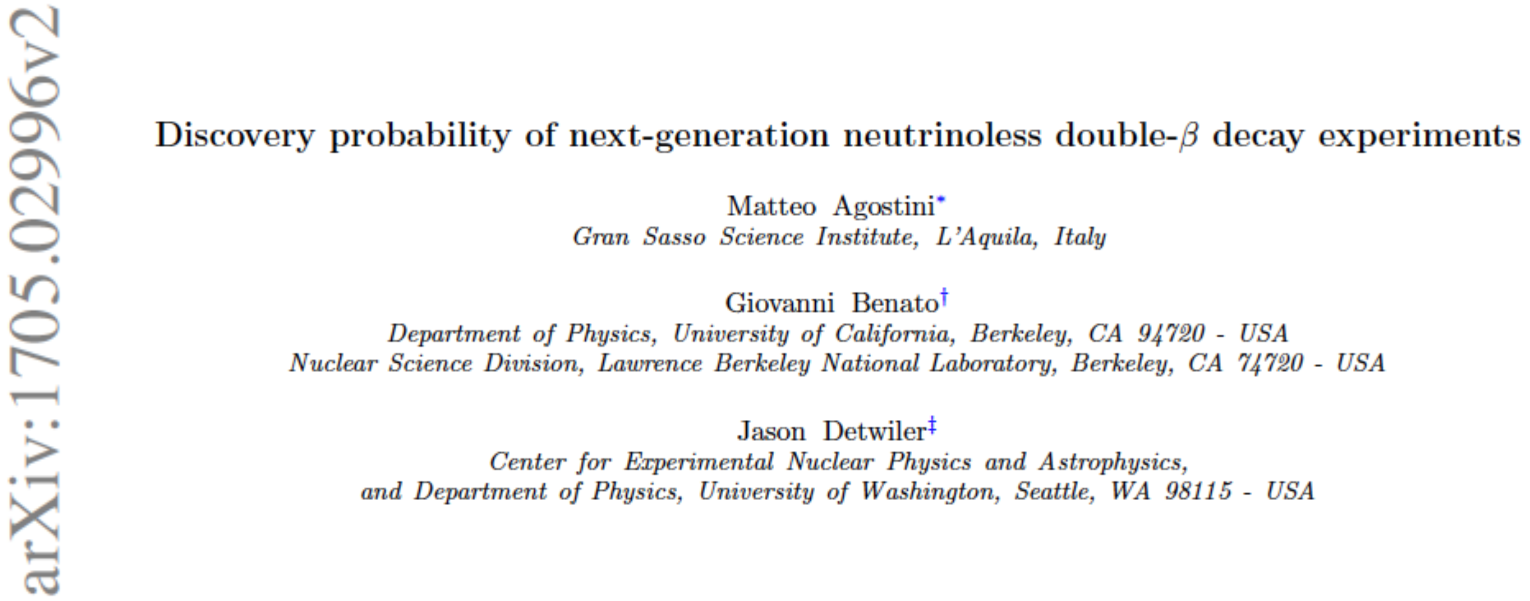
Discovery probability of next-generation neutrinoless double-β decay experiments

Matteo Agostini[*]
Gran Sasso Science Institute, L'Aquila, Italy

Giovanni Benato[†]
Department of Physics, University of California, Berkeley, CA 94720 - USA
Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 74720 - USA

Jason Detwiler[‡]
Center for Experimental Nuclear Physics and Astrophysics,
and Department of Physics, University of Washington, Seattle, WA 98115 - USA





arXiv:1705.02996v2

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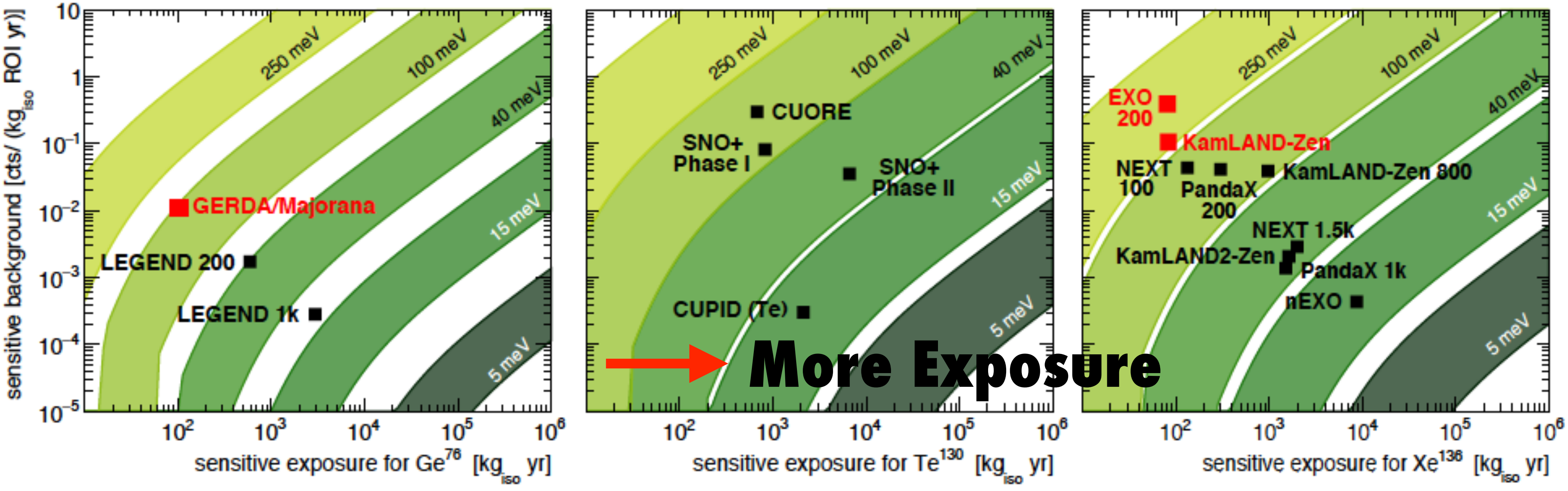
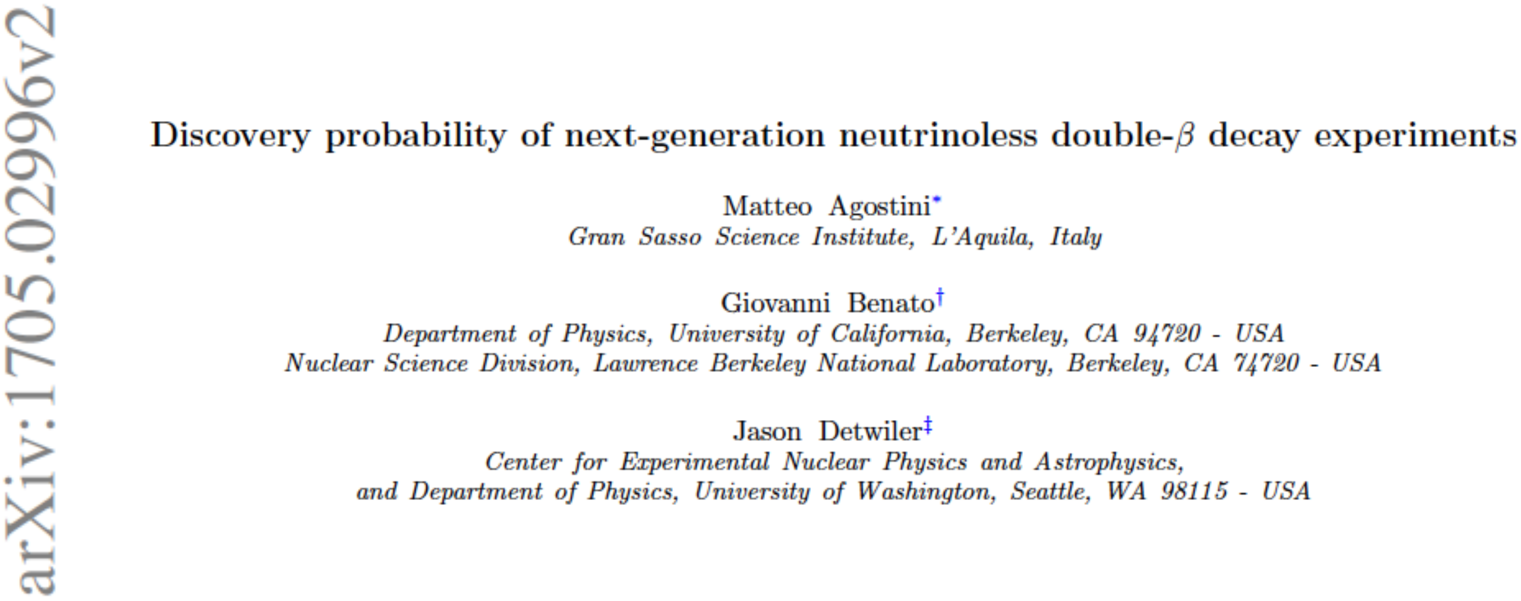


More Exposure



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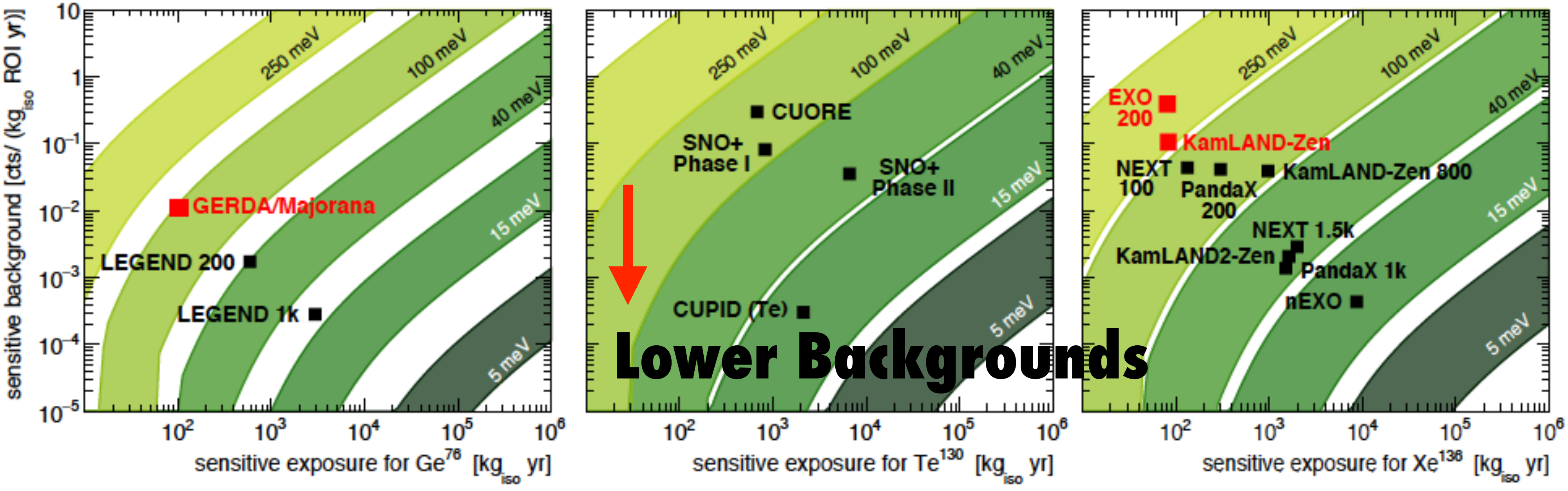
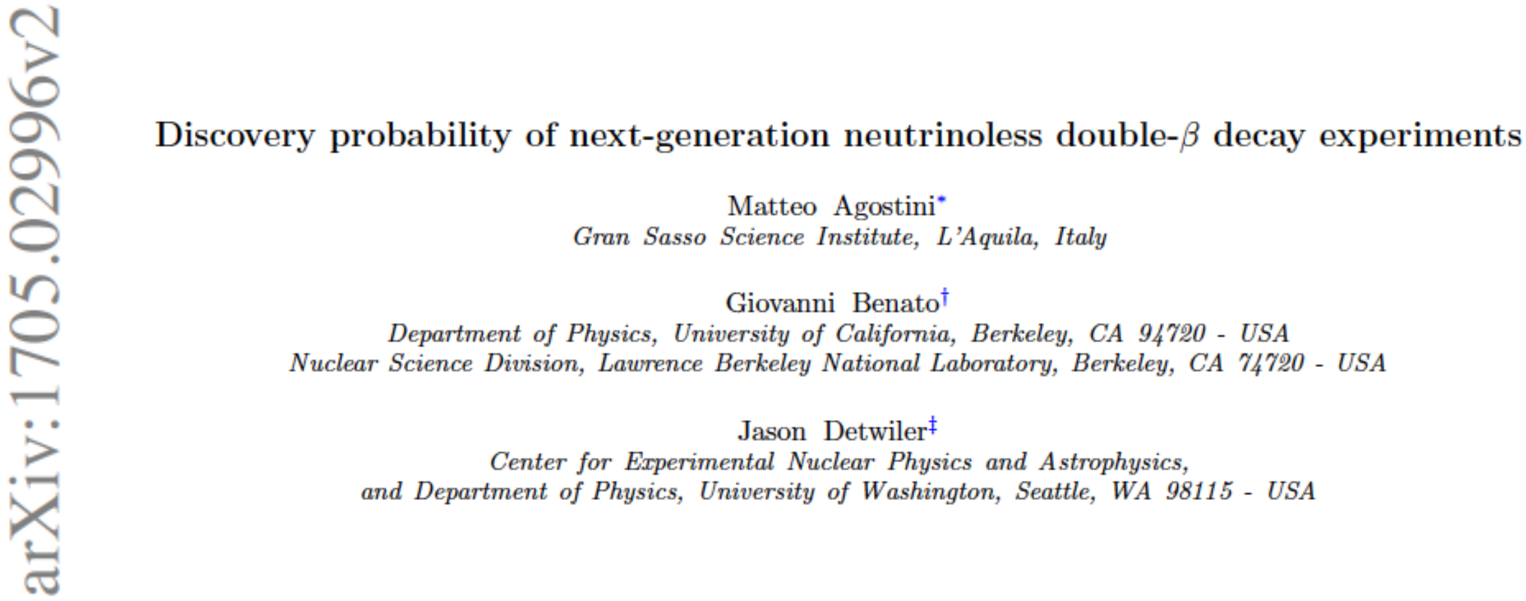


Lower Backgrounds



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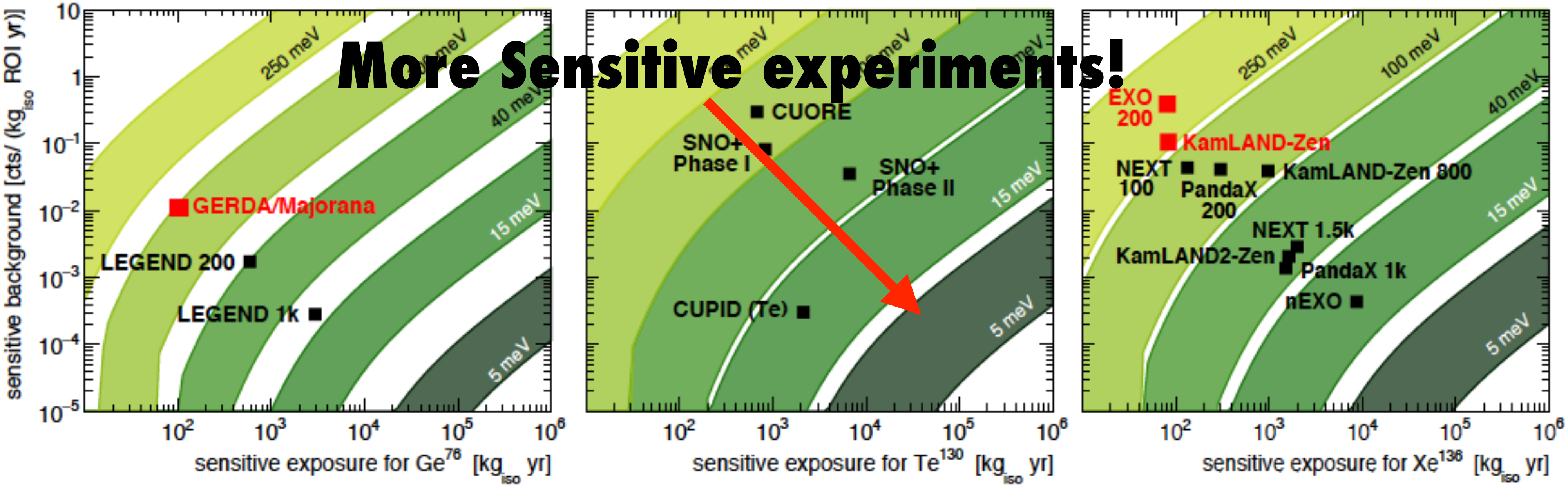

More Sensitive experiments!

Discovery probability of next-generation neutrinoless double-β decay experiments

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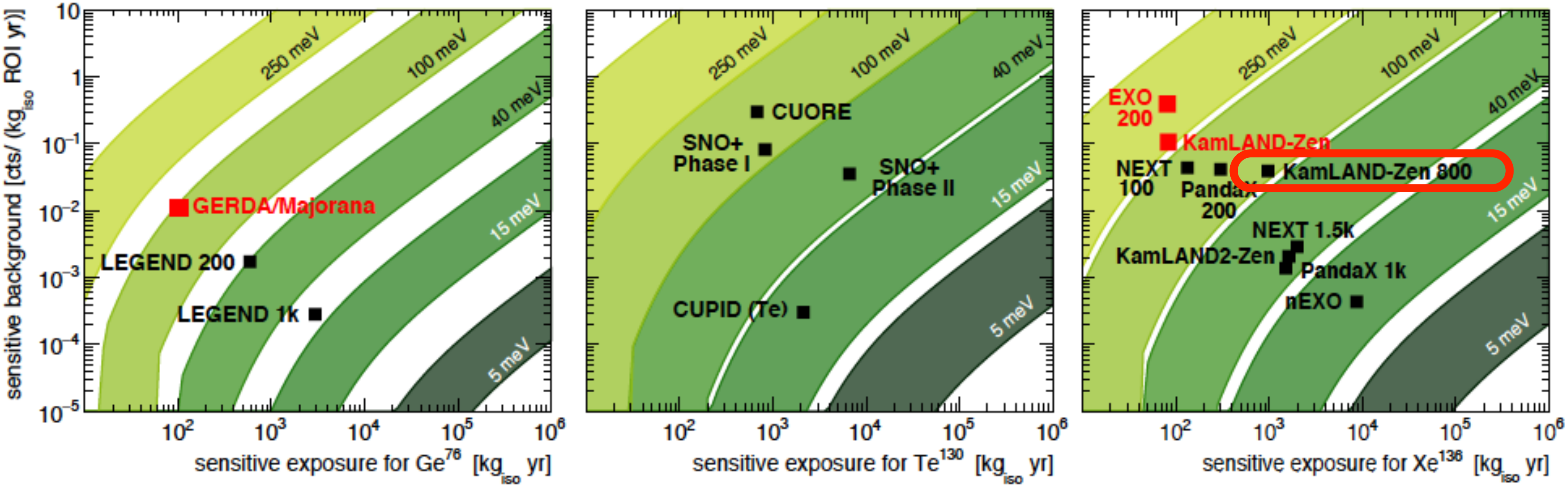
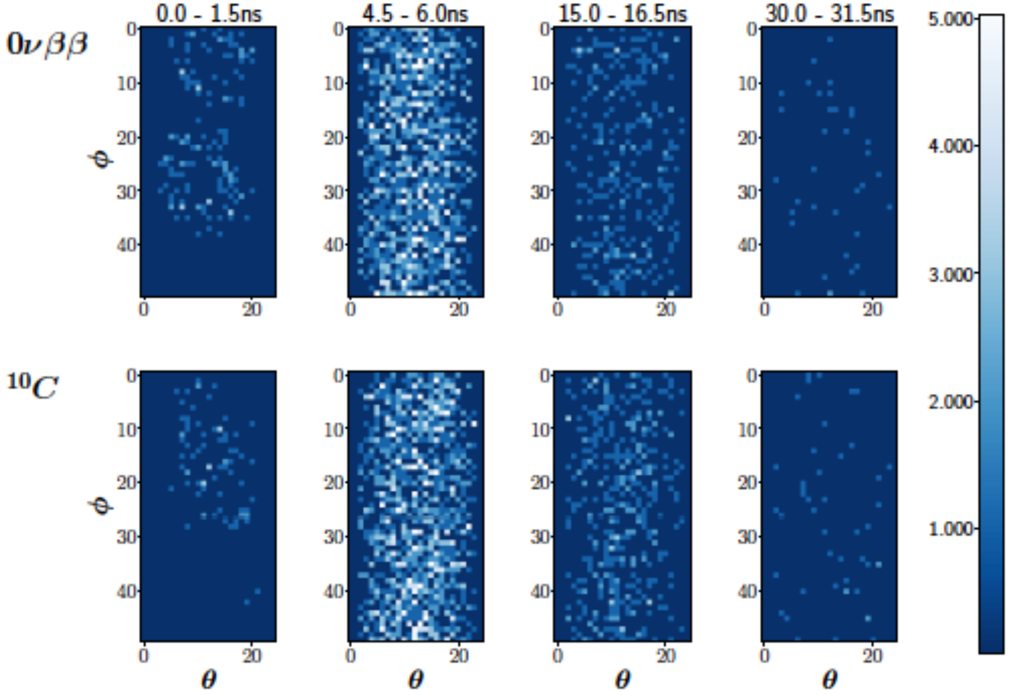
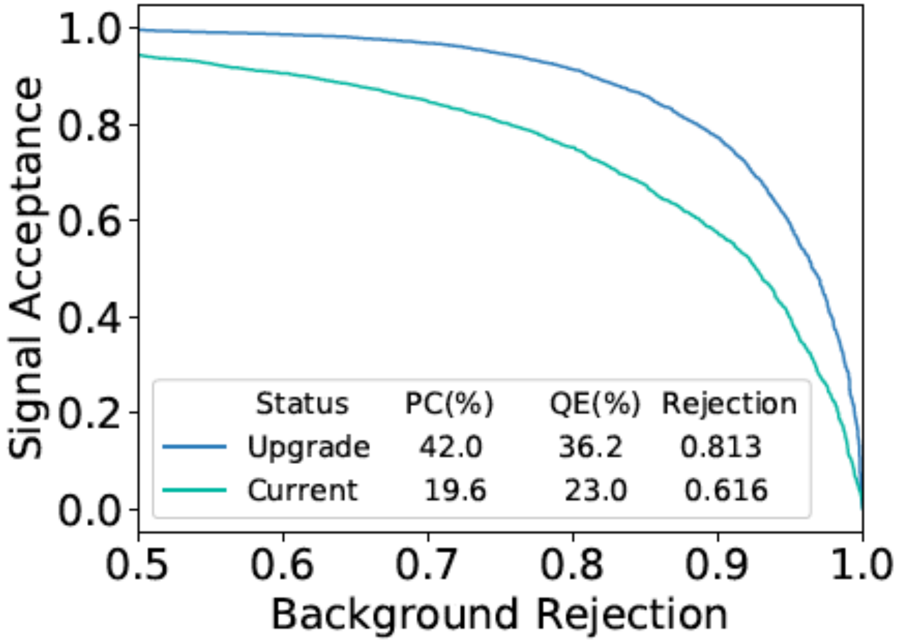


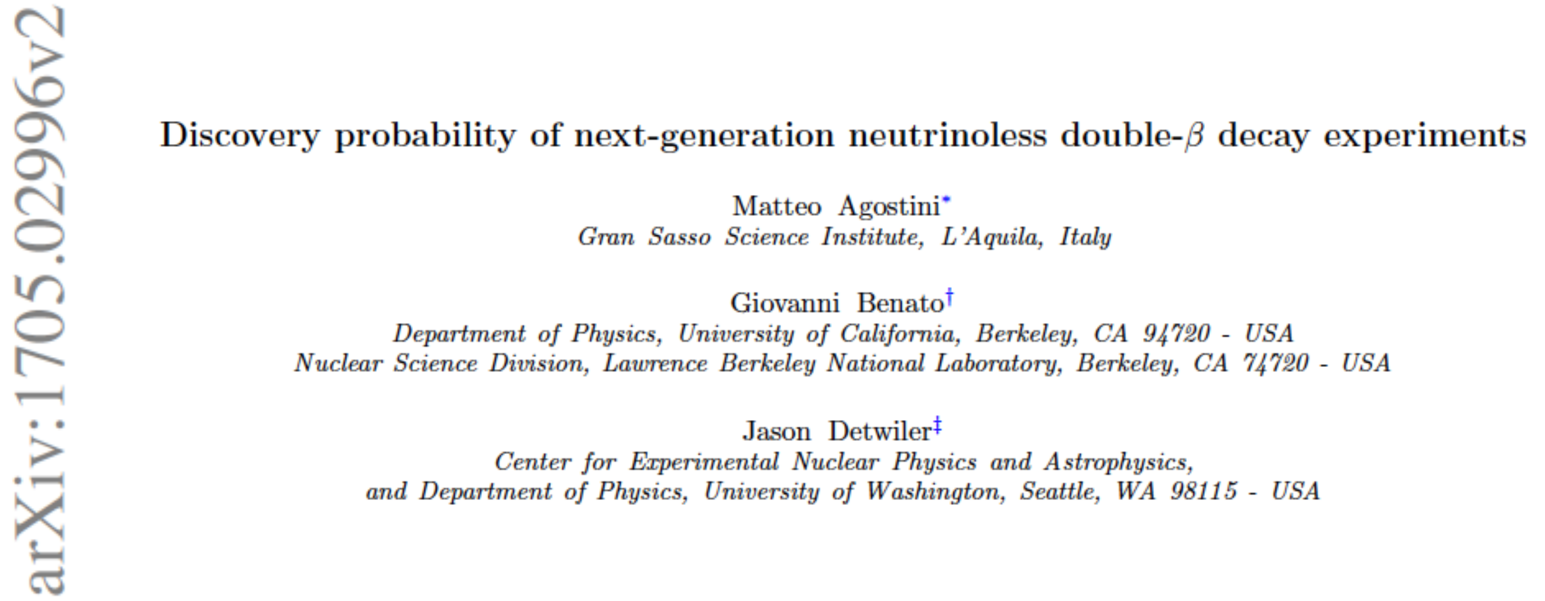
Deep Learning to Reduce Backgrounds!

The topology and time structure of events can be used to separate backgrounds from NDBD.
A generic CNN-based algorithm can already reduce the background by more than half!





See arXiv:1812.02906v1, submitted to NIMA



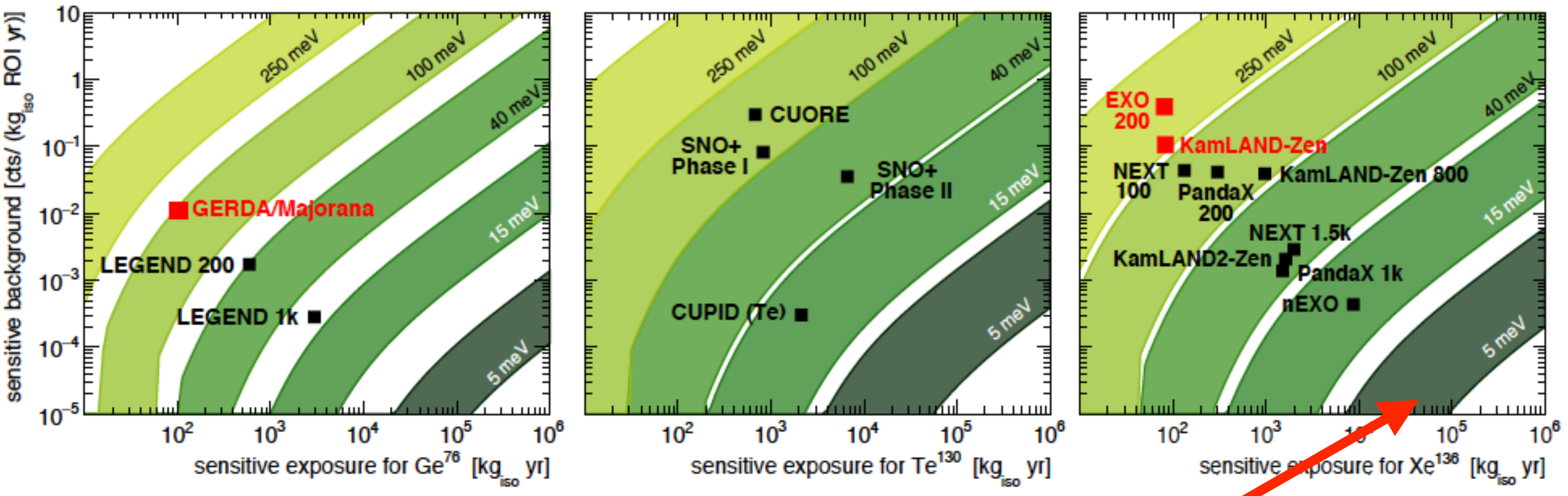
arXiv:1705.02996v2

Discovery probability of next-generation neutrinoless double-β decay experiments

Matteo Agostini*
Gran Sasso Science Institute, L'Aquila, Italy

Giovanni Benato†
Department of Physics, University of California, Berkeley, CA 94720 - USA
Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 74720 - USA

Jason Detwiler‡
Center for Experimental Nuclear Physics and Astrophysics,
and Department of Physics, University of Washington, Seattle, WA 98115 - USA



How do you get down here?

National Science Foundation
WHERE DISCOVERIES BEGIN

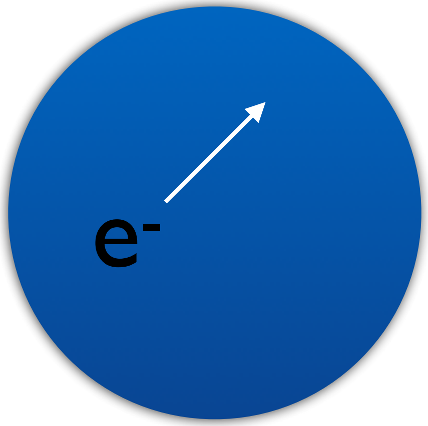
NuDot:
A Prototype Directional Liquid Scintillator

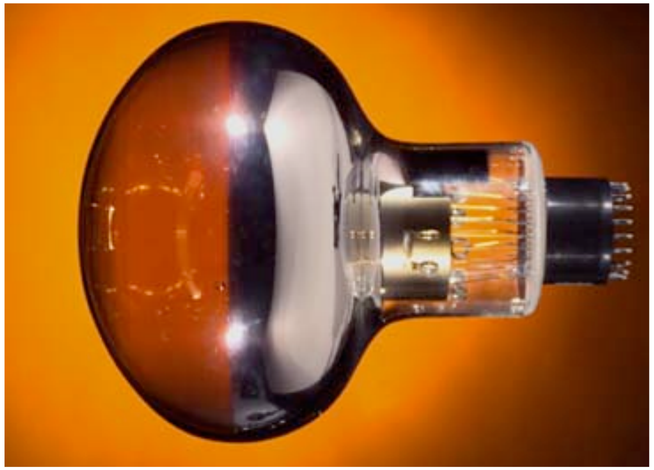
UCLA

THE UNIVERSITY OF
CHICAGO

Basic Principle of Liquid Scintillator Detector

Physics ⟶ **Light** ⟶ **PMTs**

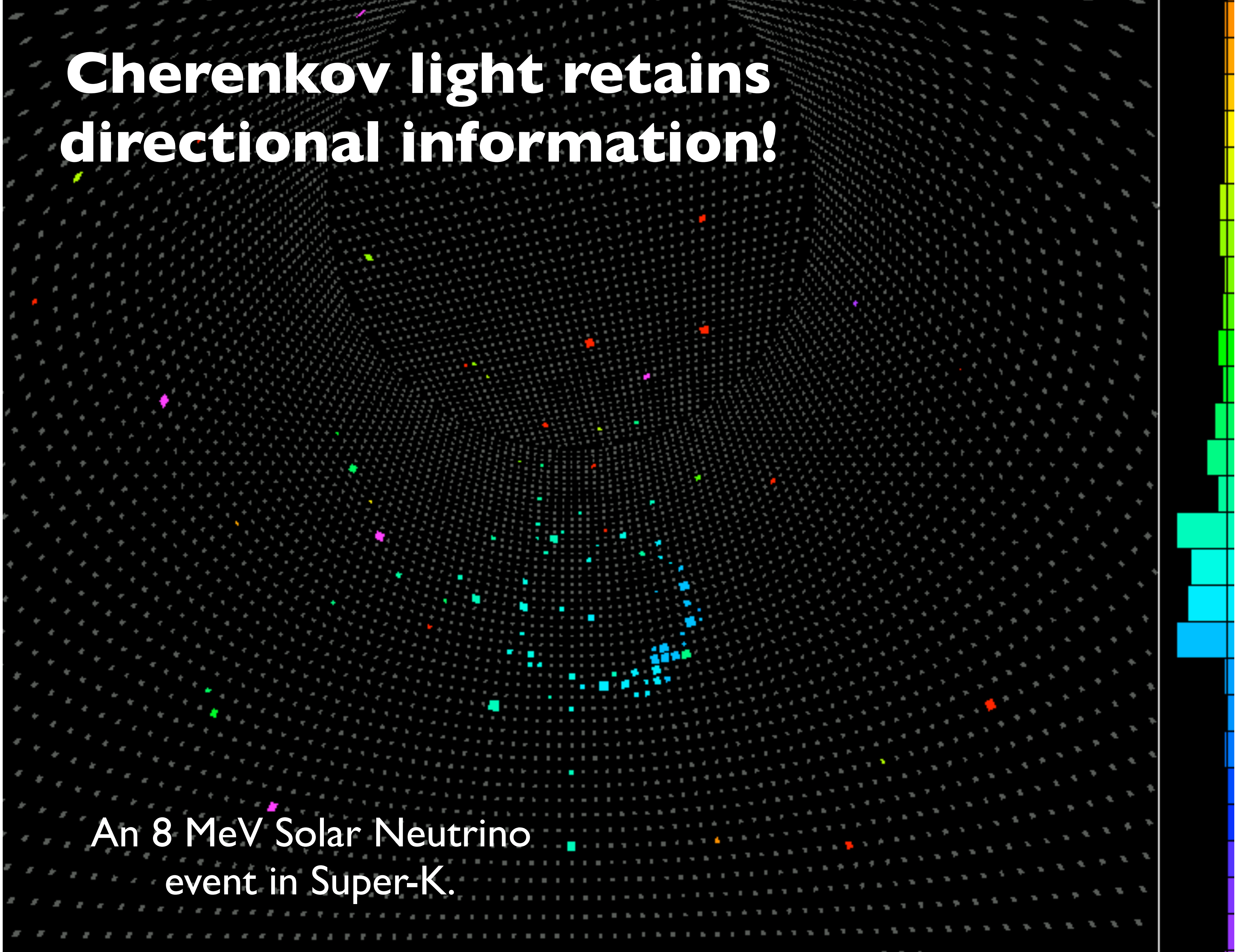




A charged particle vibrates molecules making light that is detected by photomultiplier detectors (PMT).

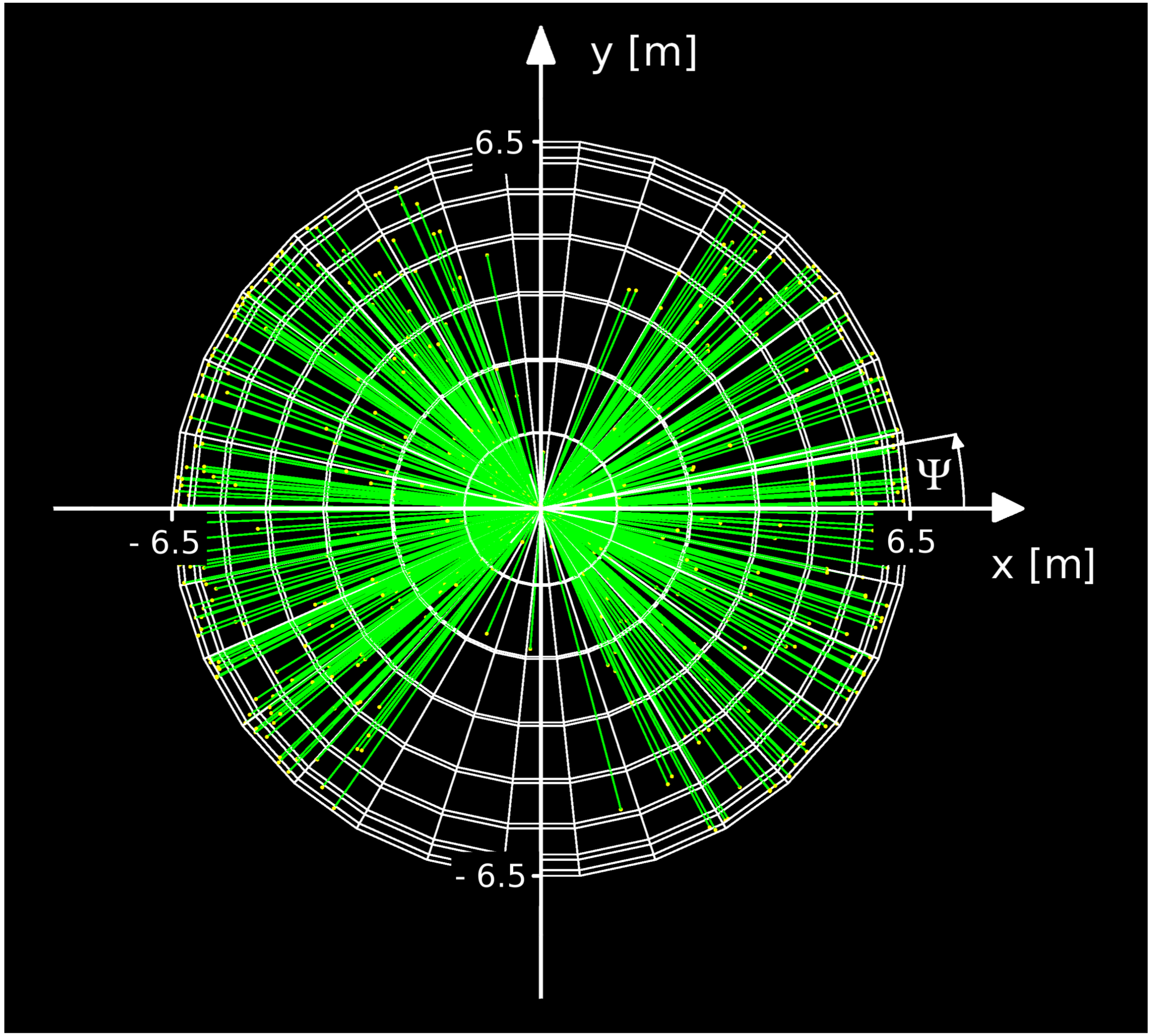
Problem:
Scintillation light
is isotropic.

Cherenkov light retains directional information!



An 8 MeV Solar Neutrino
event in Super-K.

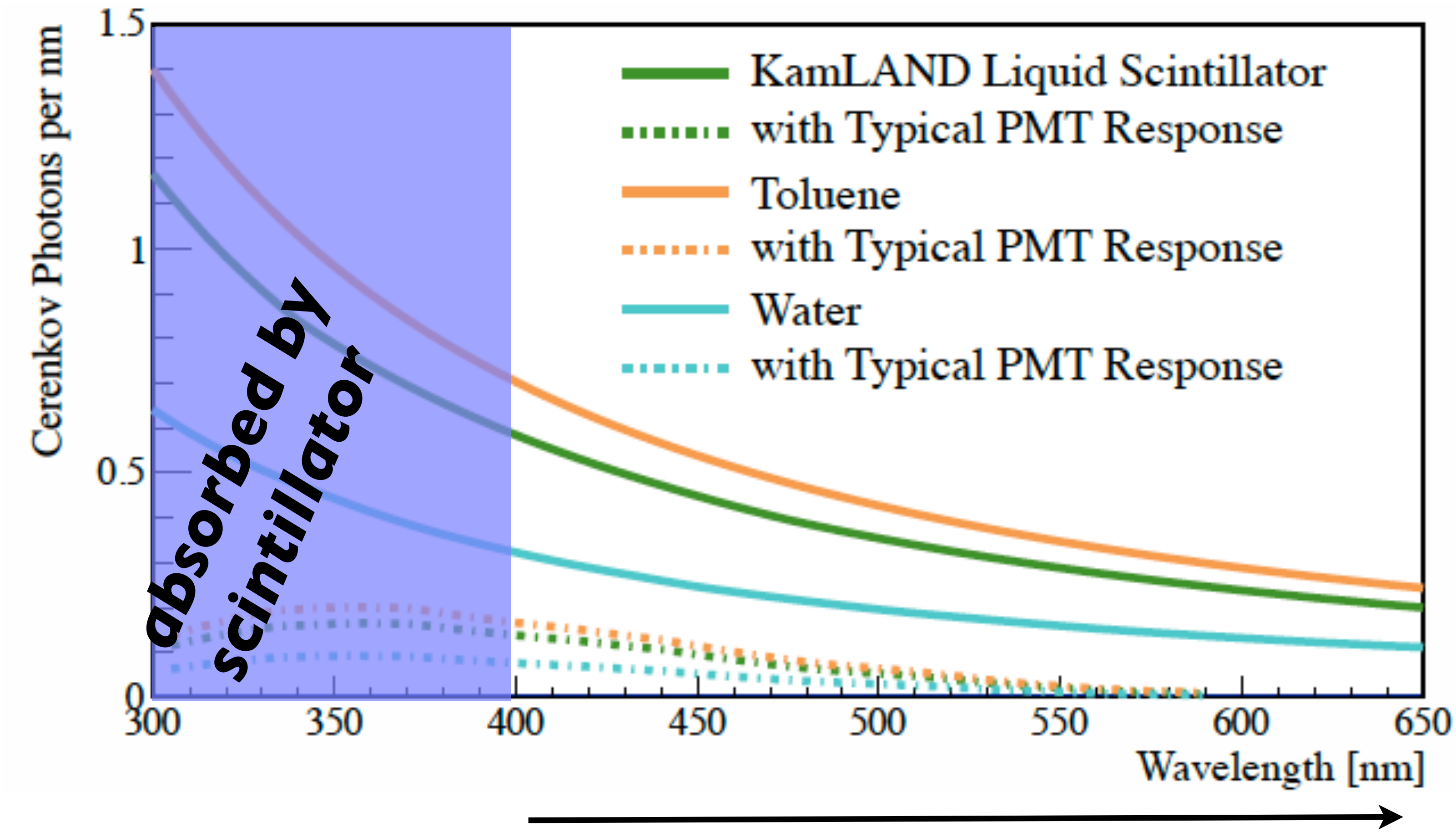
Neutrinoless Double Beta Decay



(Cherenkov Only)

How does it work?

Number of Cherenkov Photons for a 1MeV e-



Retains directional information!

Important in Big Detector.

Longer wavelengths travel faster in scintillator

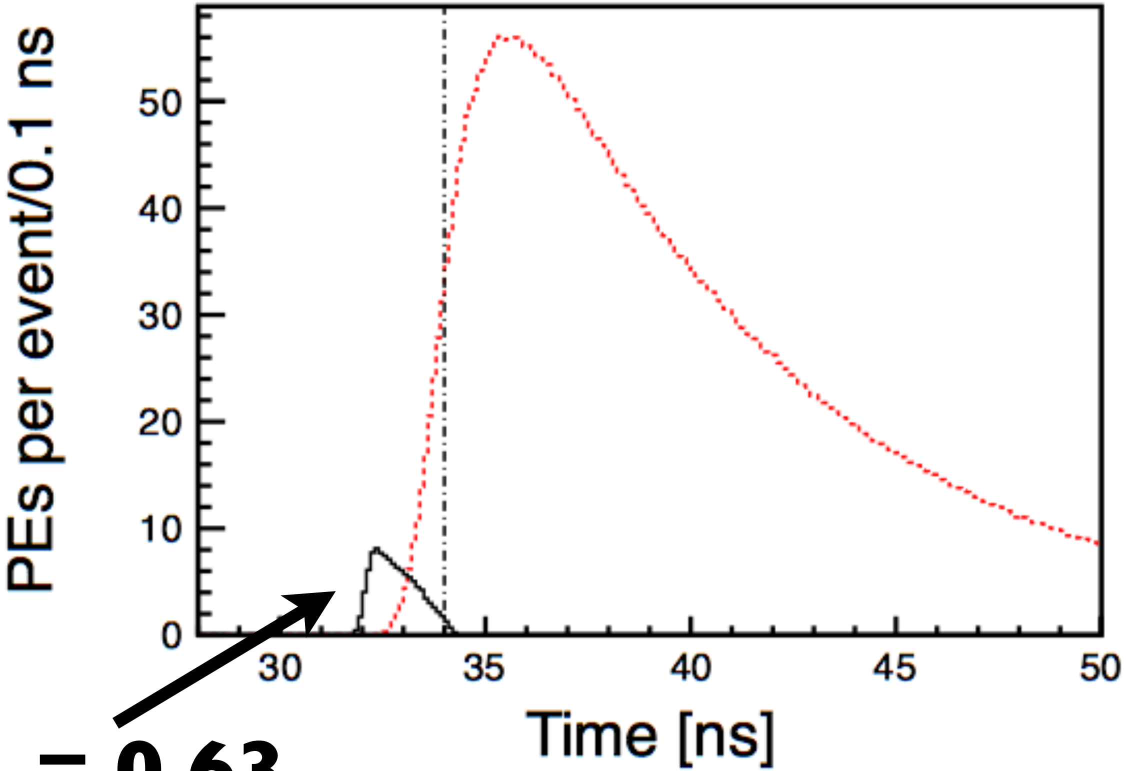
and

Scintillation processes have inherent time constants.

Always Important

JINST 9 (2014) P06012

So if you have good enough timing....

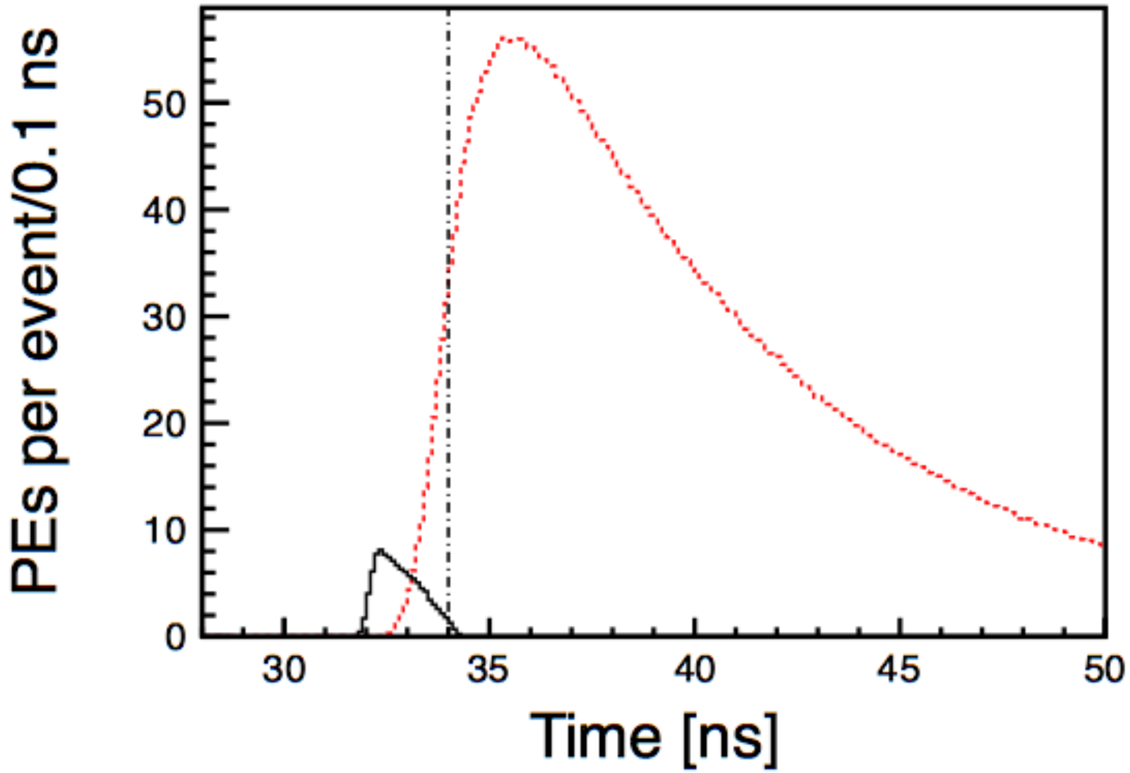


$R_{c/s}$ = 0.63

.... you should be able to separate the scarce Cherenkov from the abundant scintillation light.

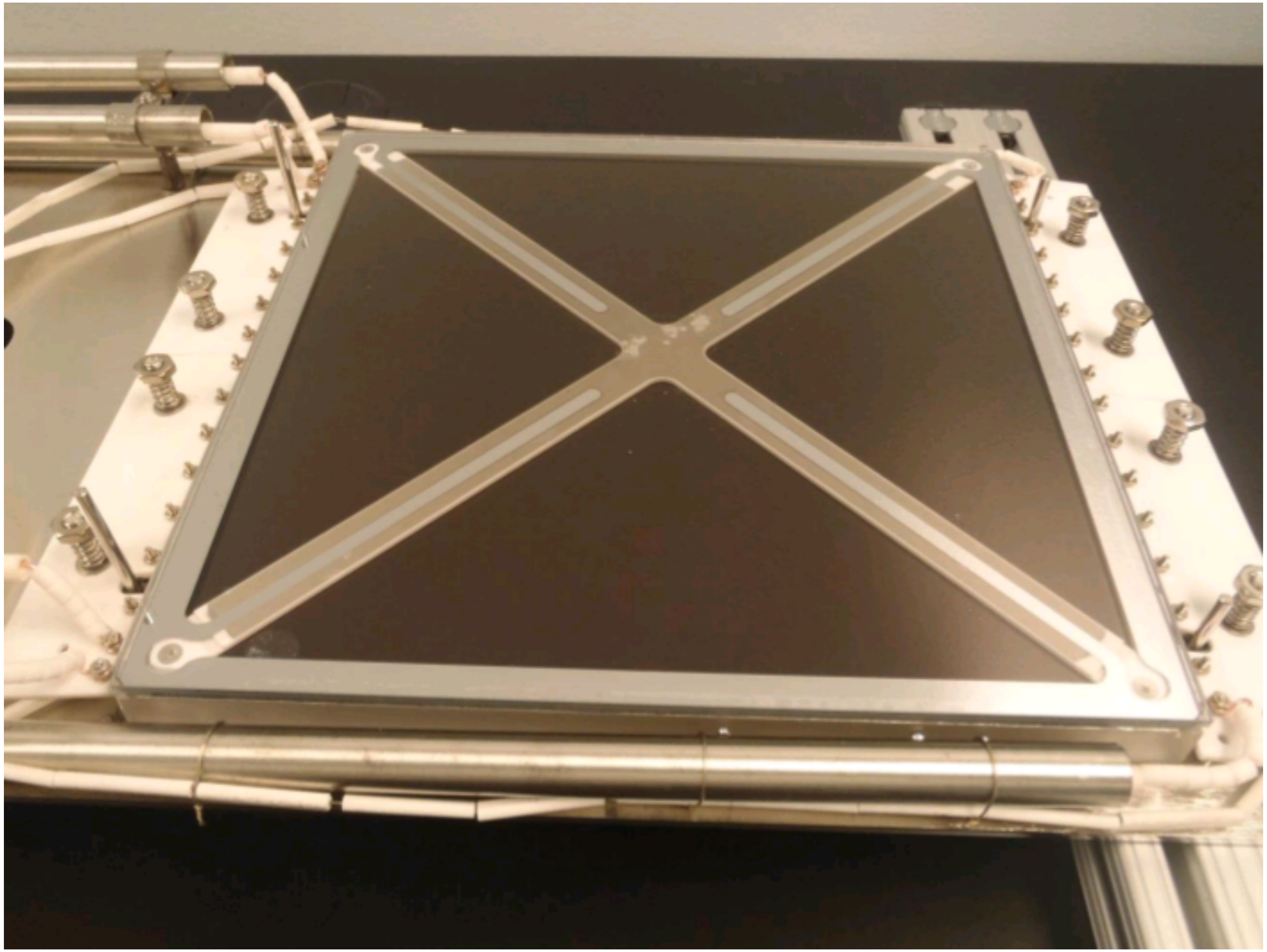
JINST 9 (2014) P06012

This corresponds to 0.1 ns.



This sort of timing is available in very tiny MCP-based PMT's/SiPMs...for now.

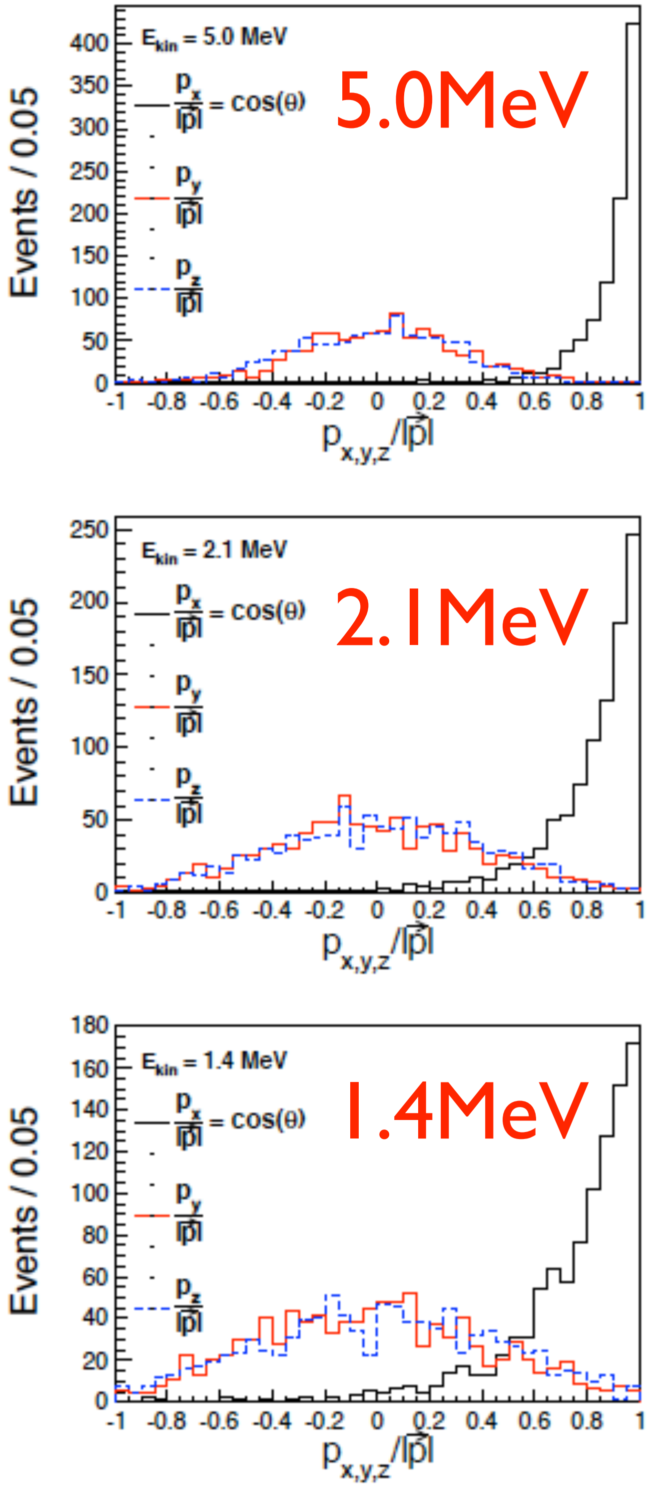
The LAPPD:



INCOM
Bright Ideas in Fiberoptics

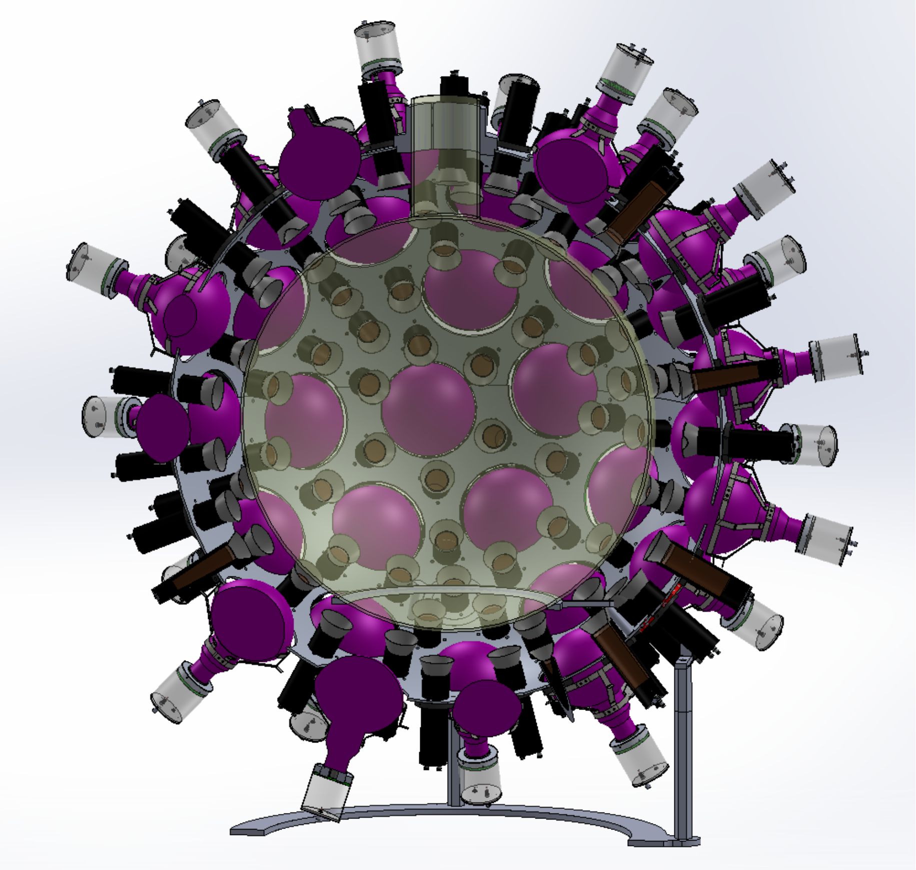
THE UNIVERSITY OF
CHICAGO

JINST 9 (2014) P06012



With a basic algorithm, we can reconstruct the direction of single electrons!

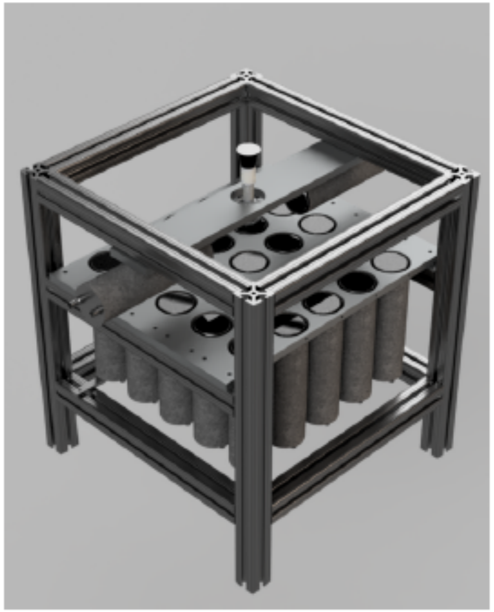
NuDot:
A Prototype Directional Liquid Scintillator Detector



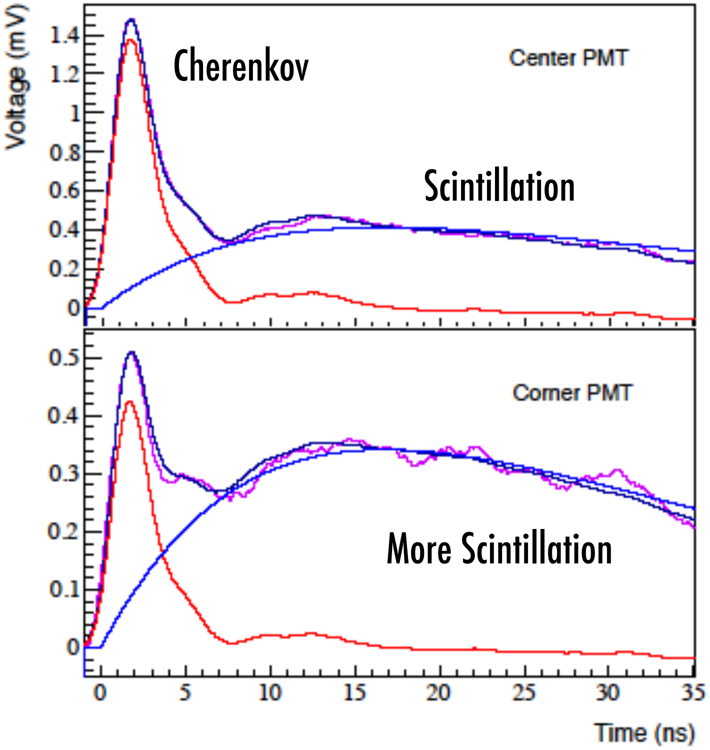
- NuDot mechanical design completed by MIT-Bates Engineering Center.
- All components are ordered and many have arrived.
- Construction beginning imminently and first results expected by the summer!

First Demonstration of Cherenkov Separation in MeV β's

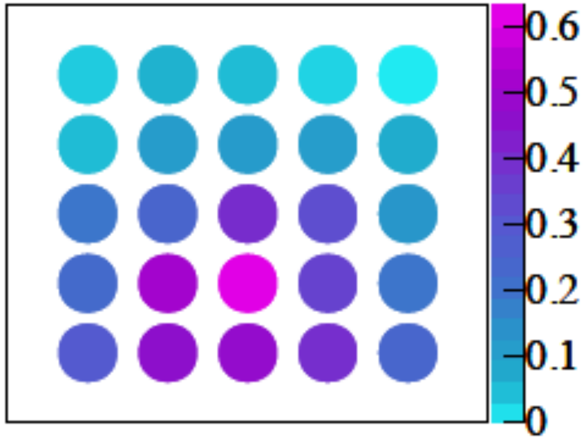
FlatDot



Time Profile



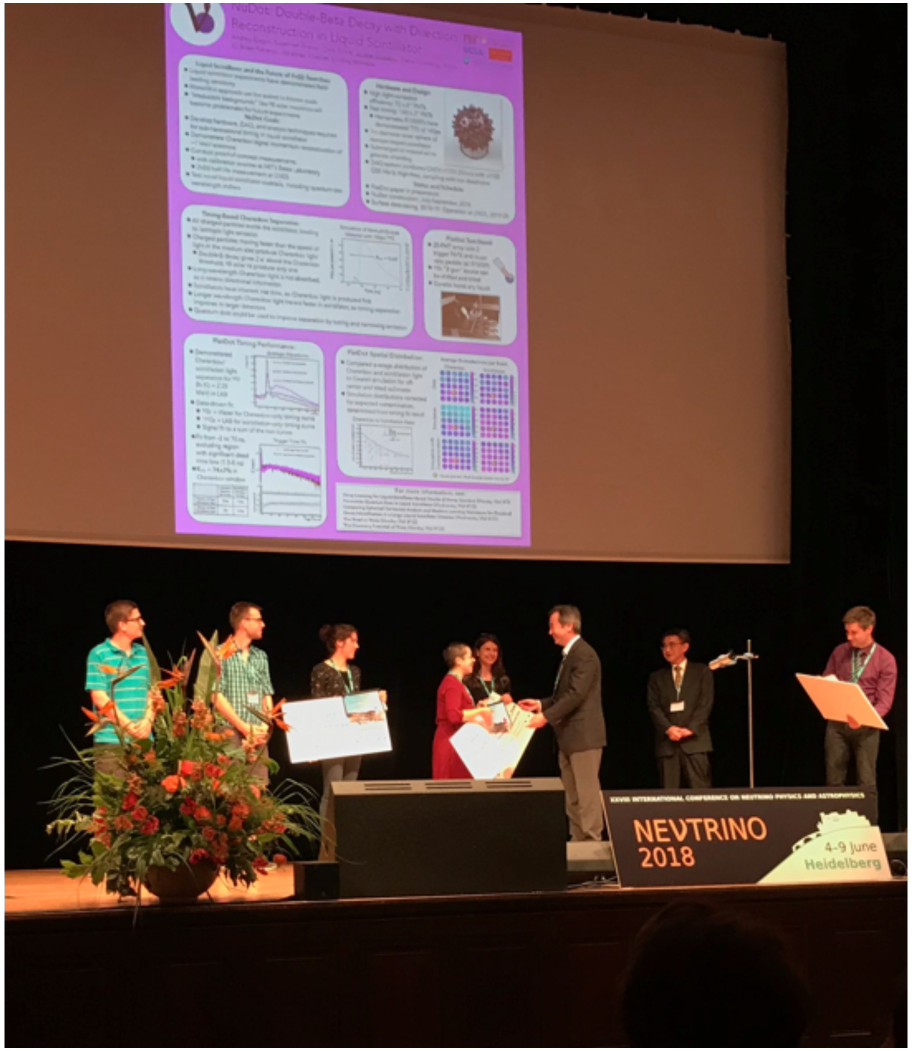
Cherenkov "Ring"



More Scintillation

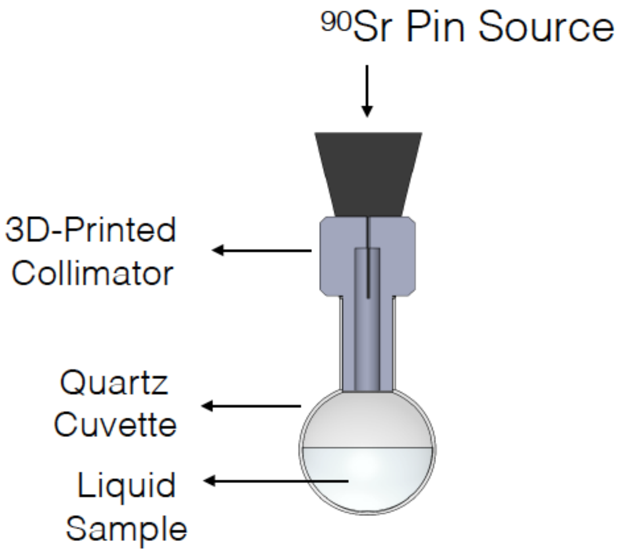
See arXiv:1811.11144, accepted by JINST.

NuDot:
A Prototype Directional Liquid Scintillator Detector

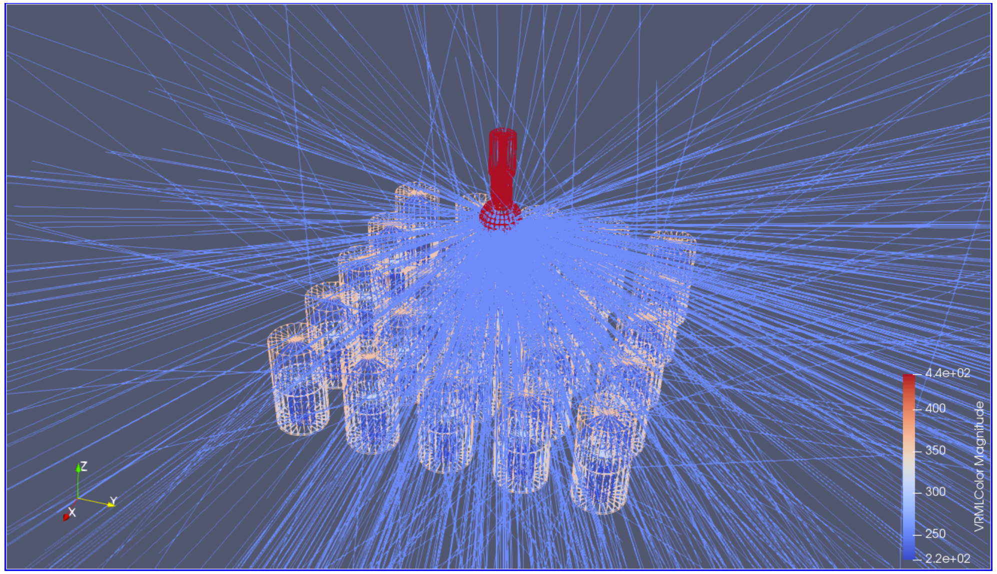


Pappalardo Fellow Julieta Gruszko finalist for Neutrino2018 poster session with this result (more than 500 posters).

The Directional Calibration Source



Source Geometry



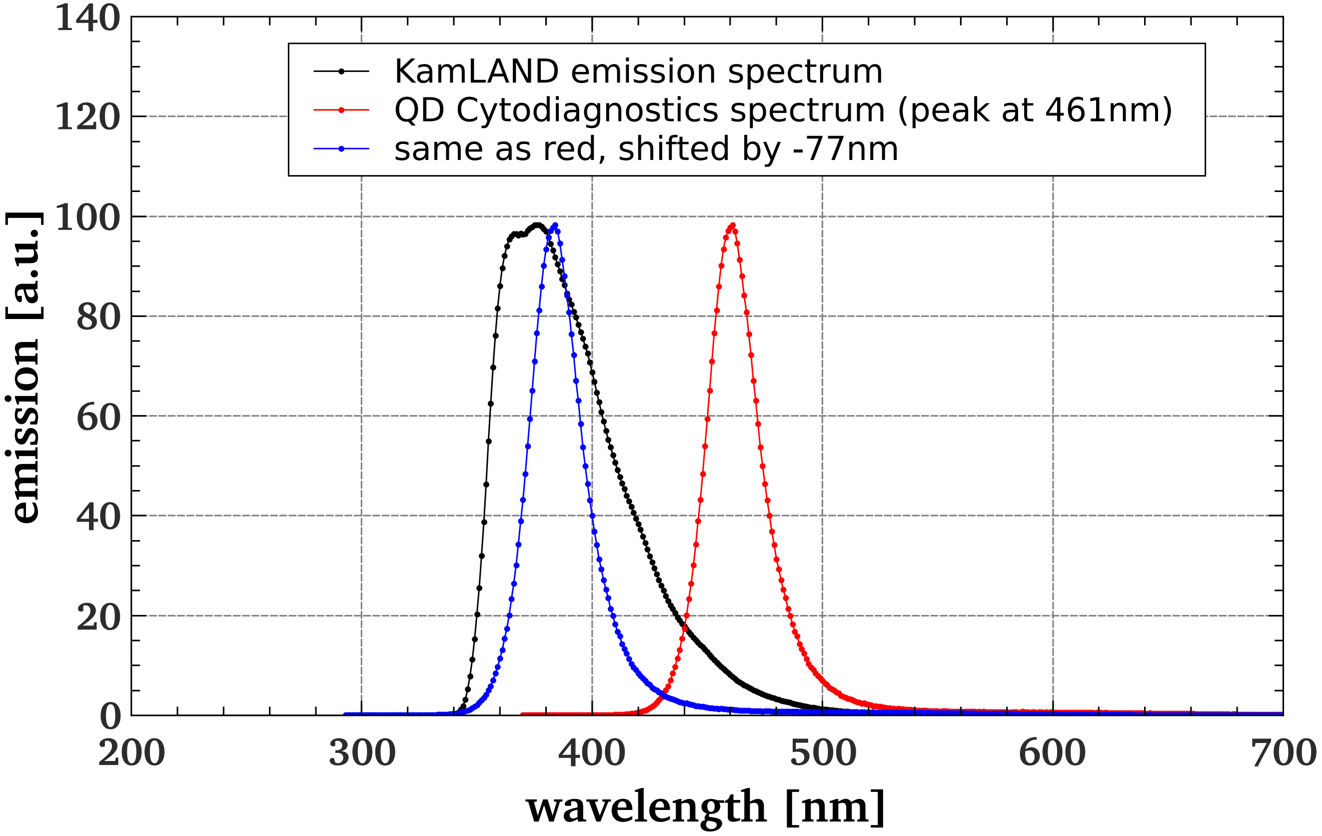
MC Simulation

Two realizations came together: 3D printing of nylon to interface with the quartz cuvette and that a collimated ^{90}Sr beta-source had sufficient rate for calibration.

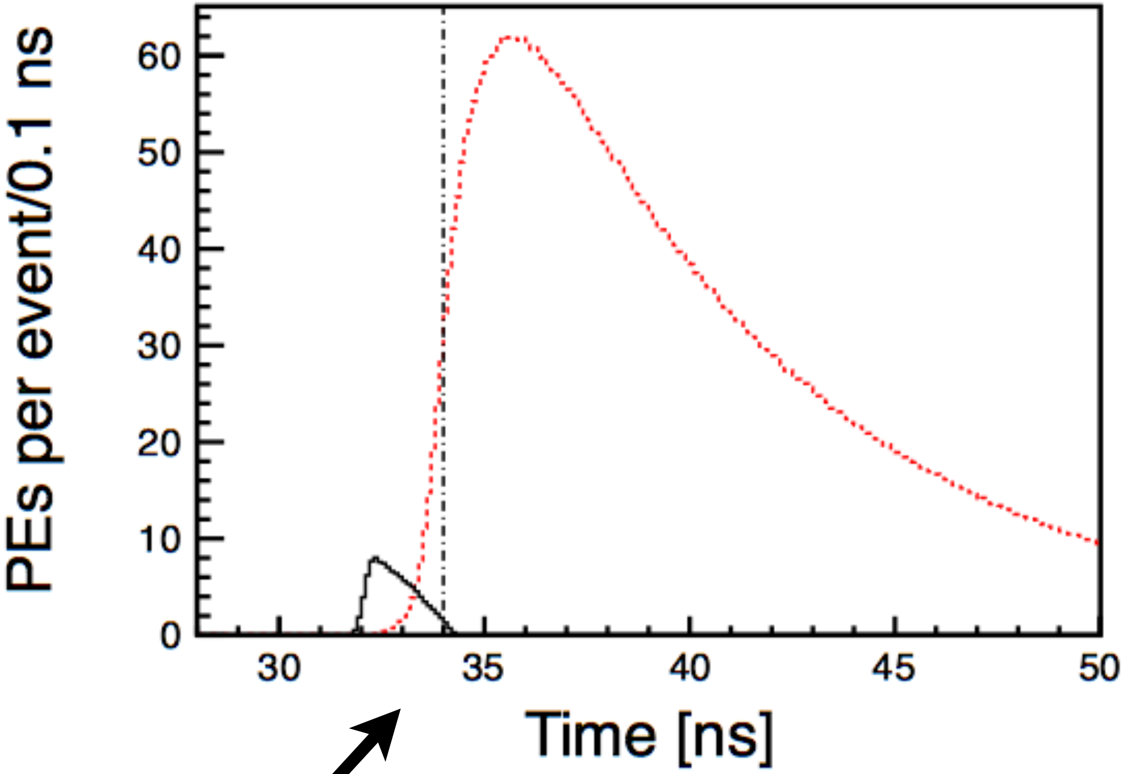
Stay tuned for more results!
ABRACADABRA
KamLAND-Zen 800
CUPID-Mo and CUORE
NuDot

Did you say something about quantum dots?

What if I could narrow the emission spectrum?



Narrowed emission spectrum with traditional PMTs and 0.1ns timing.



$R_{c/s}$ = 0.86

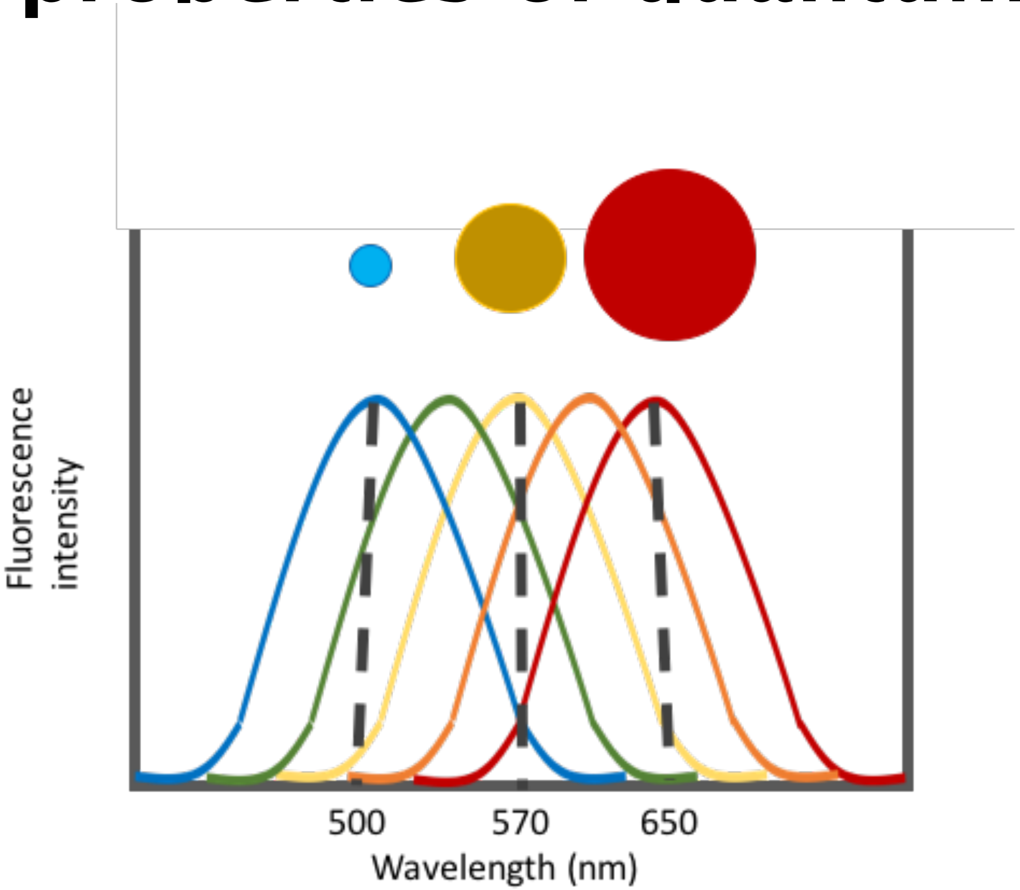
What are Quantum Dots?

Quantum Dots are semiconducting nanocrystals.

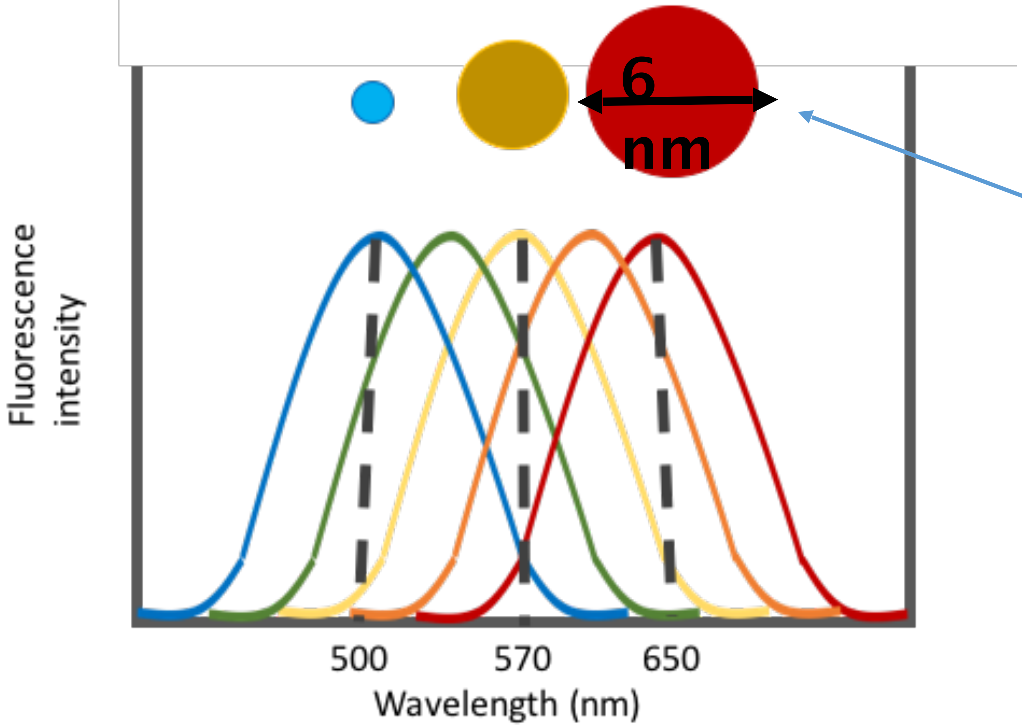
Candidate Isotopes Are Quantum Dot Materials!

Isotope	Endpoint	Abundance
^{48}Ca	4.271 MeV	0.187%
^{150}Nd	3.367 MeV	5.6%
^{96}Zr	3.350 MeV	2.8%
^{100}Mo	3.034 MeV	9.6%
^{82}Se	2.995 MeV	9.2%
^{116}Cd	2.802 MeV	7.5%
^{130}Te	2.533 MeV	34.5%
^{136}Xe	2.479 MeV	8.9%
^{76}Ge	2.039 MeV	7.8%
^{128}Te	0.868 MeV	31.7%

Optical properties of quantum dots are

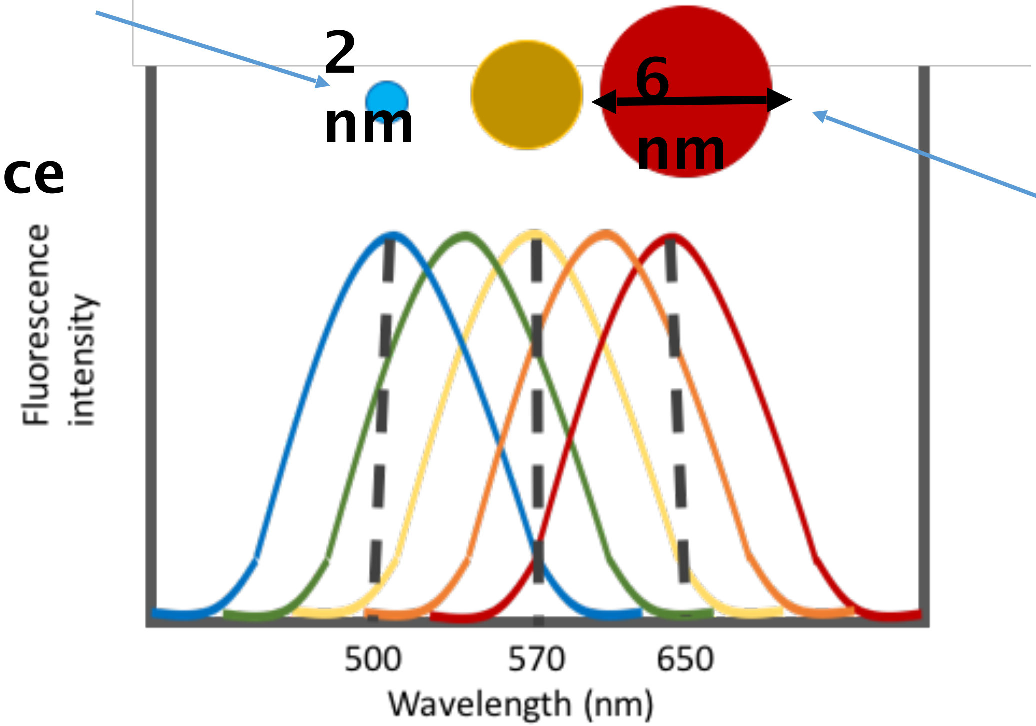


Optical properties of quantum dots are size-dependent



electrons confined to an effective box

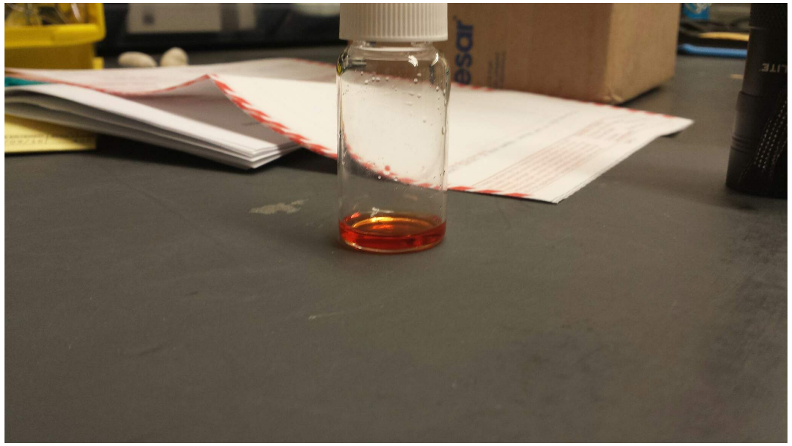
Optical properties of quantum dots are size-dependent

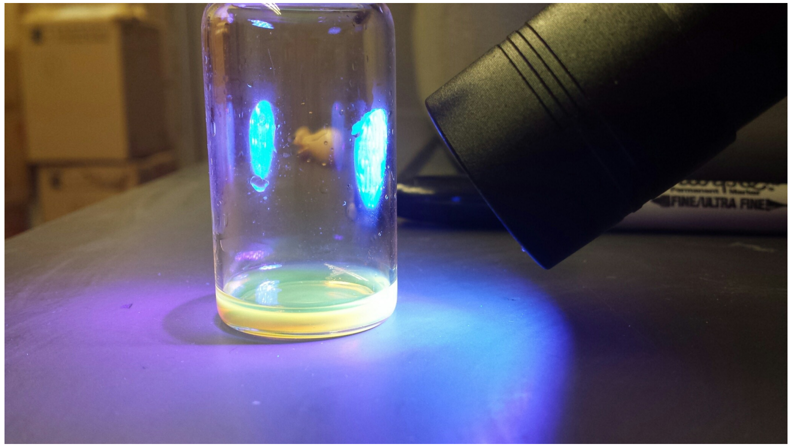


Causes blue-shift in fluorescence

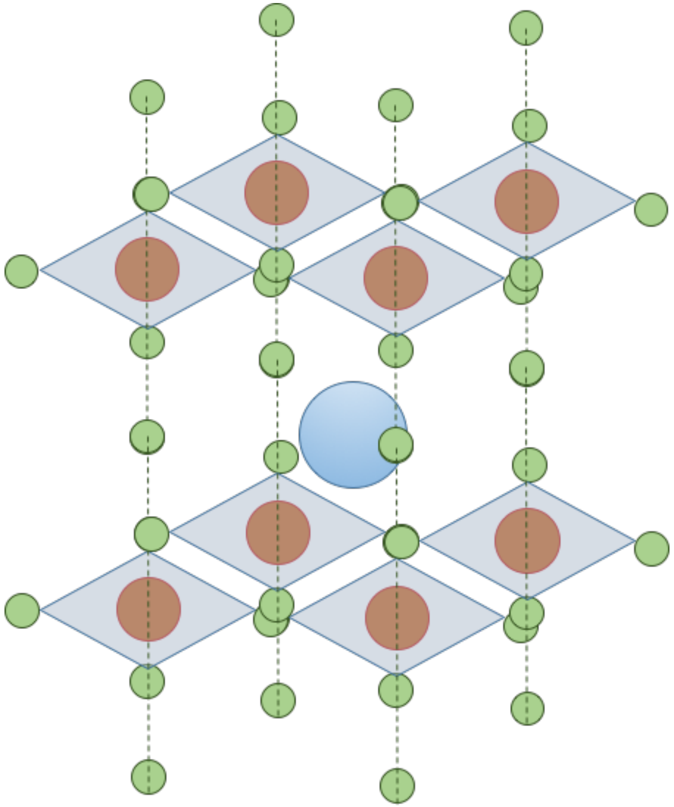
electrons confined to an effective box

We can tune fluorescence by tuning the reaction!

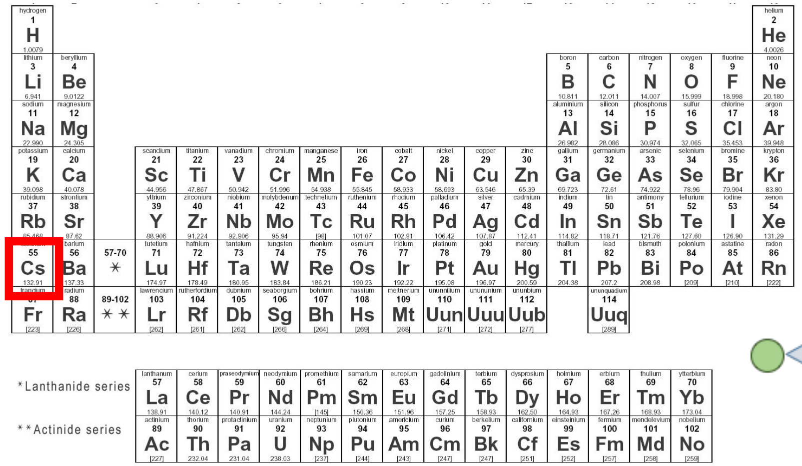


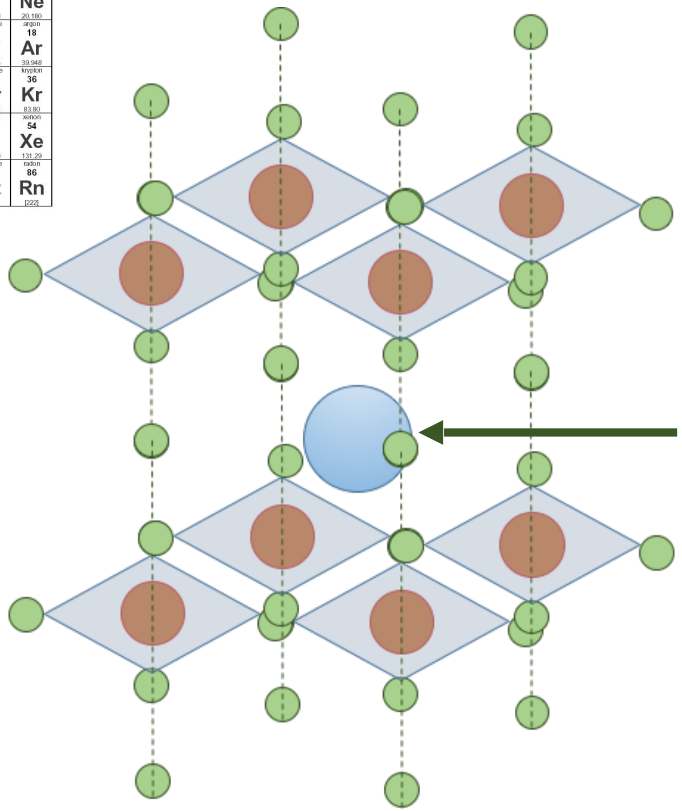


Can we make UV-emitting quantum dots?



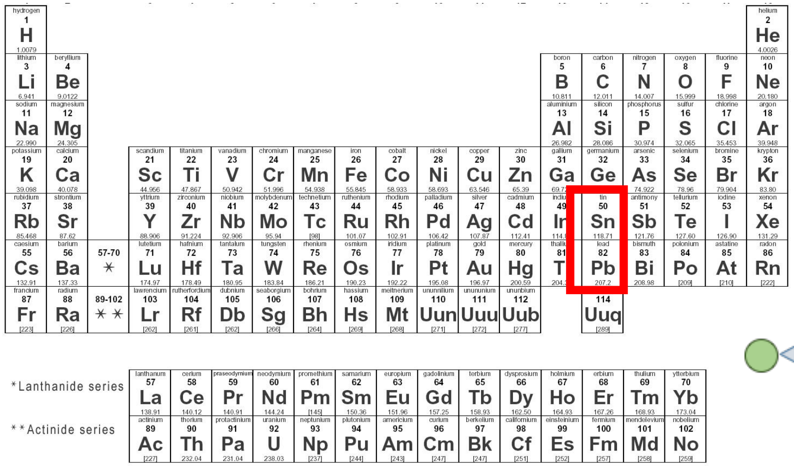
Perovskites are a possibility!

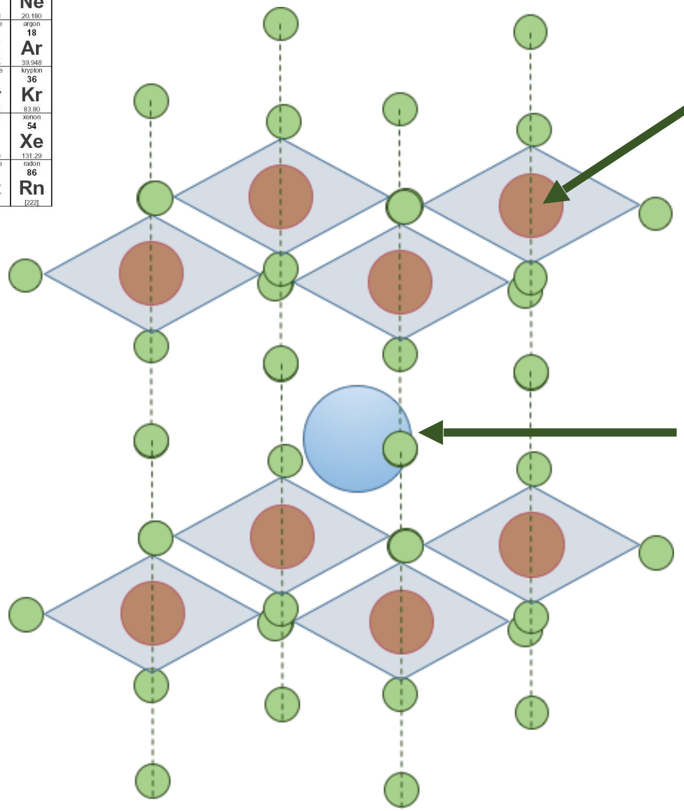




Organic or metal cation (Methyl ammonium or Cs+)

Perovskite crystal structure

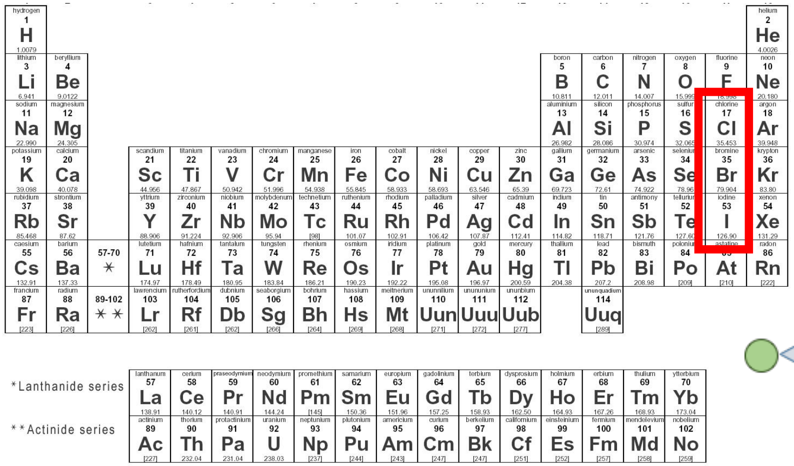


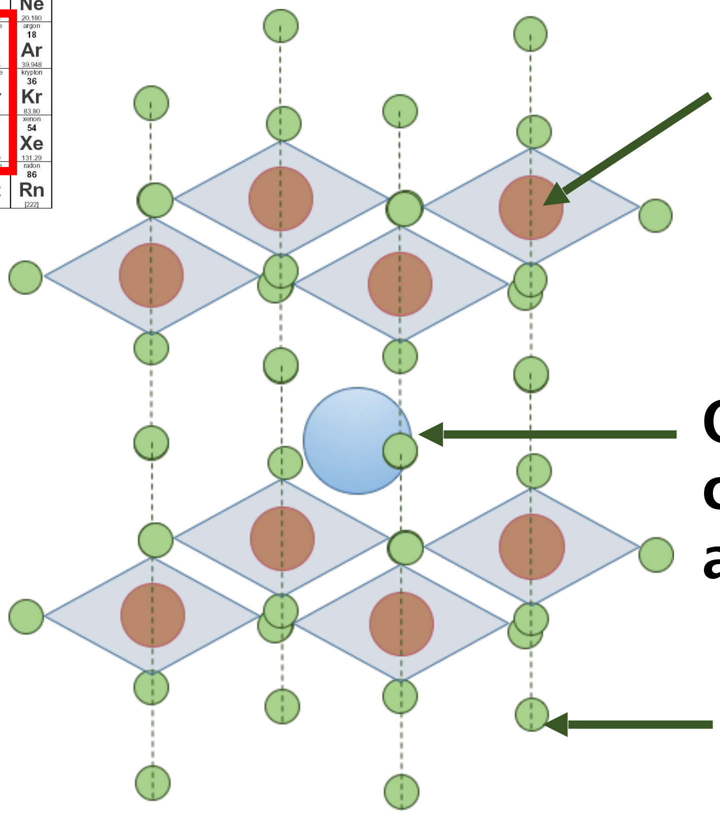


Divalent cation (Pb(II) or Sn(II))

Organic or metal cation (Methyl ammonium or Cs+)

Perovskite crystal structure



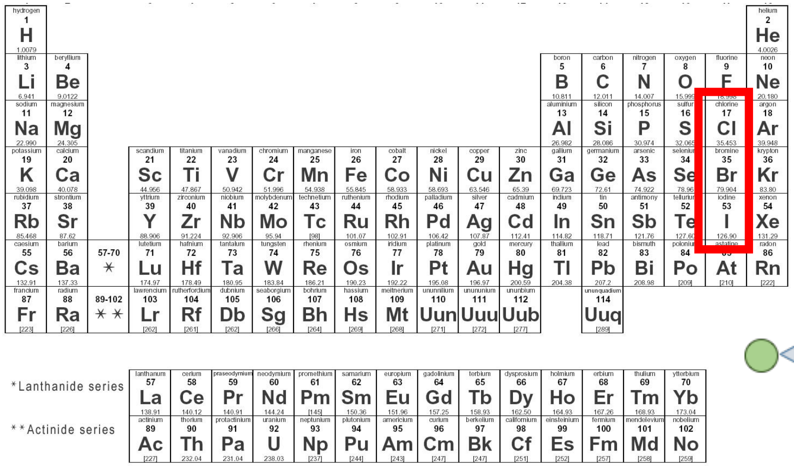


Divalent cation (Pb(II) or Sn(II))

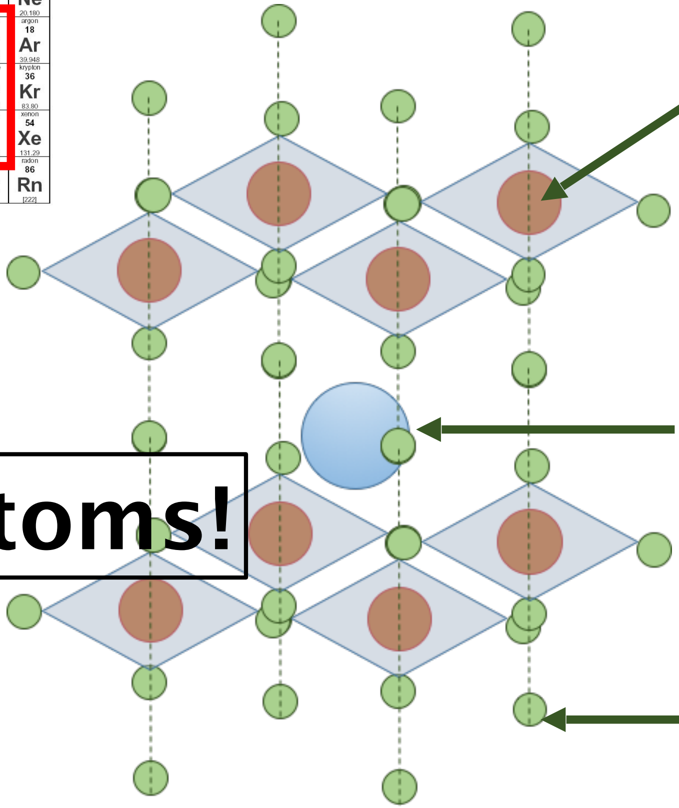
Organic or metal cation (Methyl ammonium or Cs+)

Halide anion (Cl–, Br–, I–)

Perovskite crystal structure



Mix and match atoms!



Divalent cation (Pb(II) or Sn(II))

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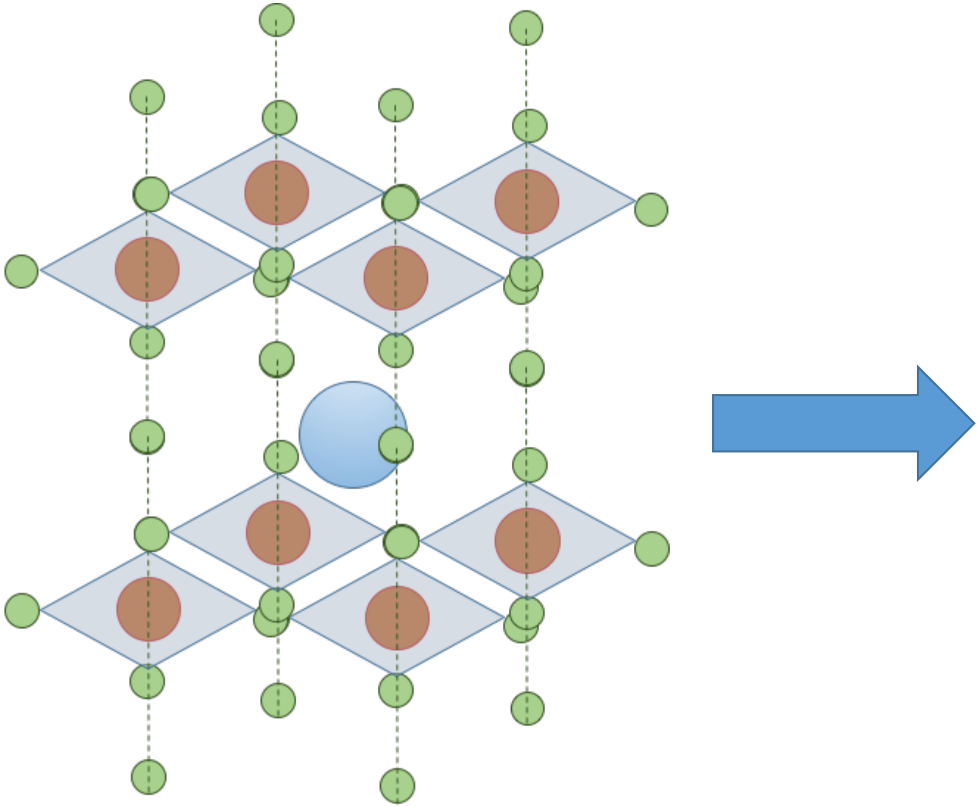
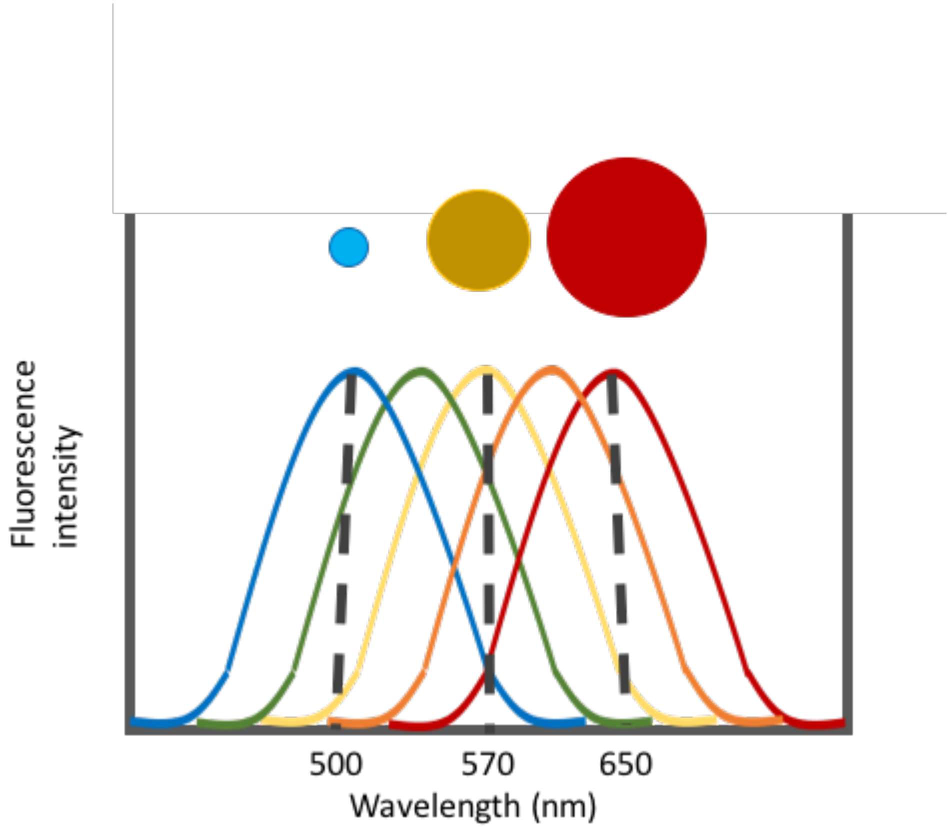
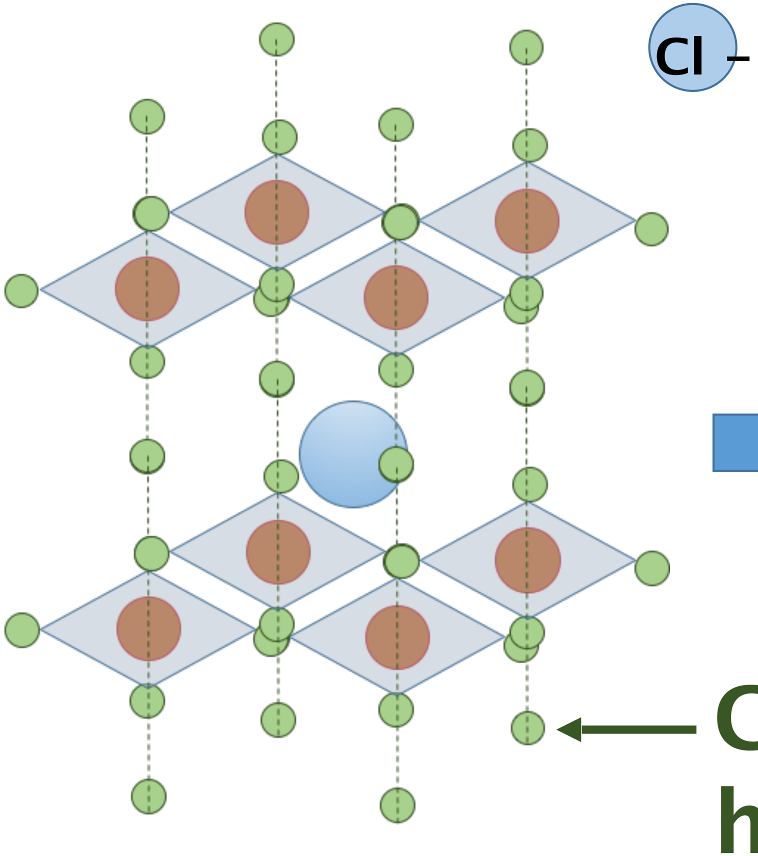
Perovskite crystal structure

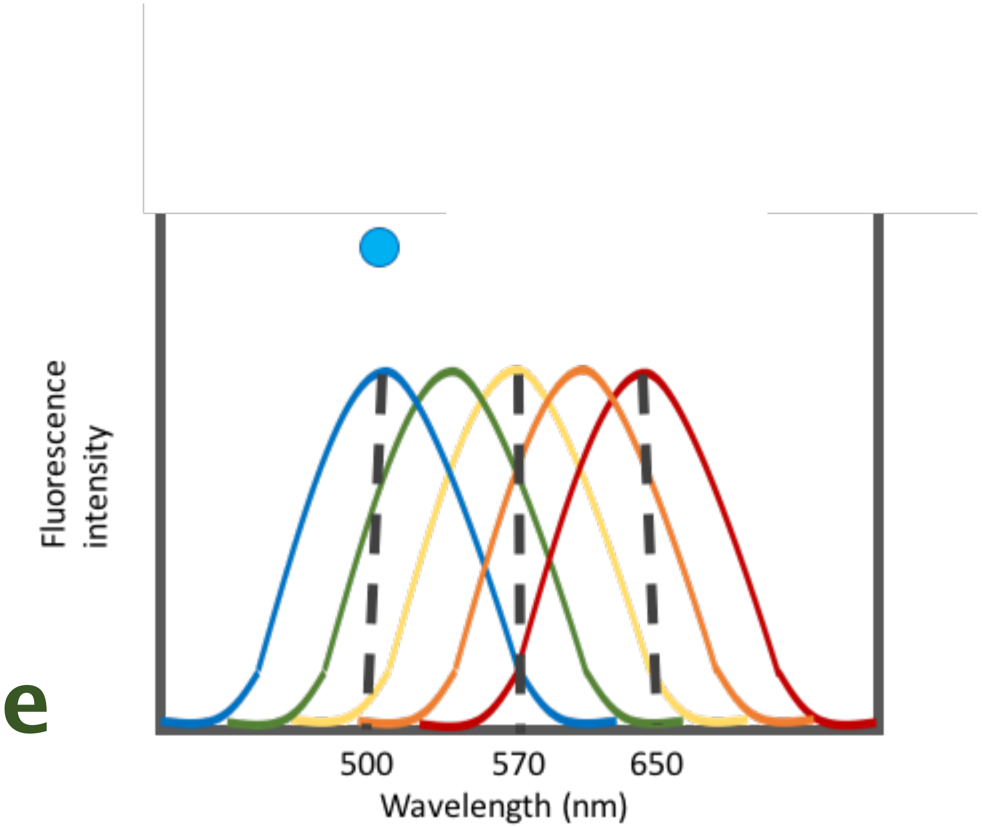




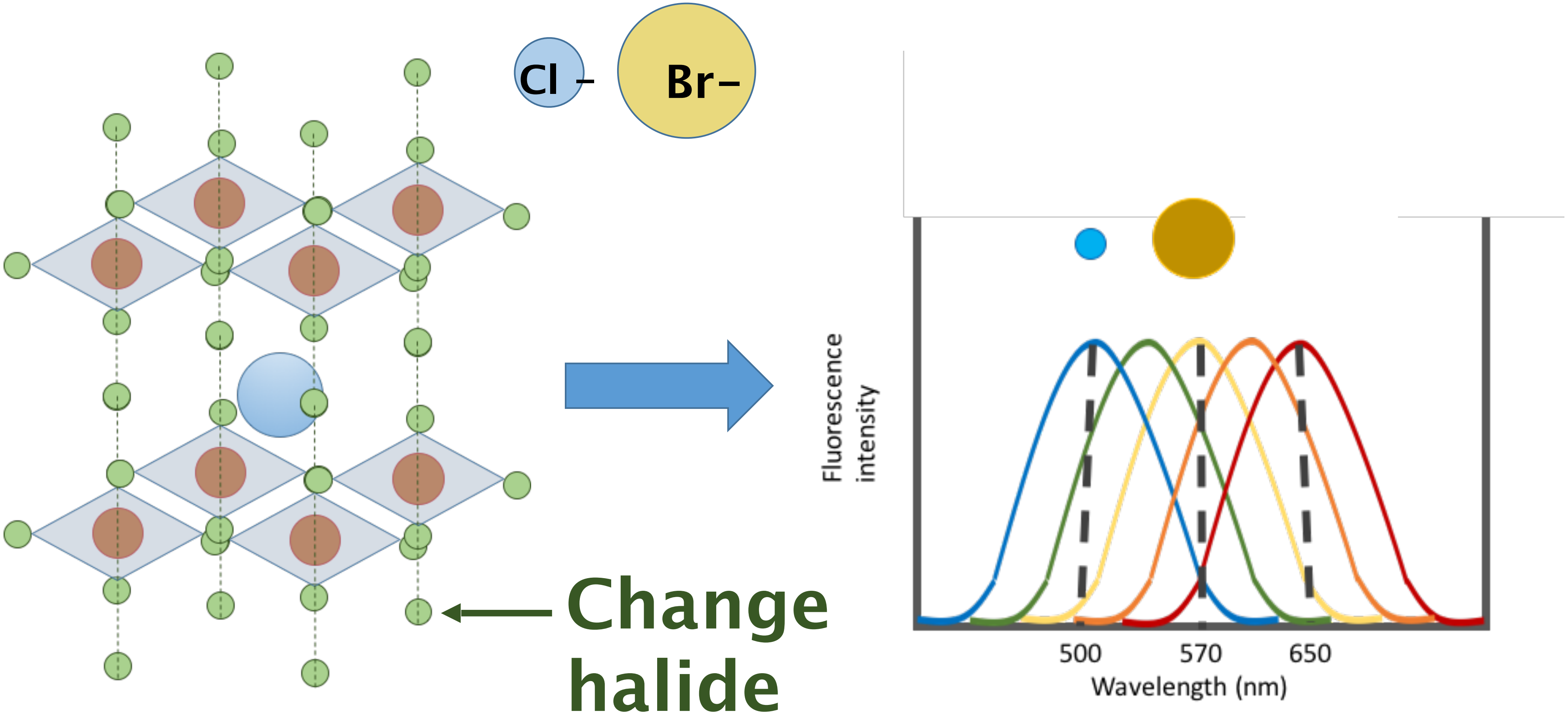
We can make quantum dots out of these!



Change halide

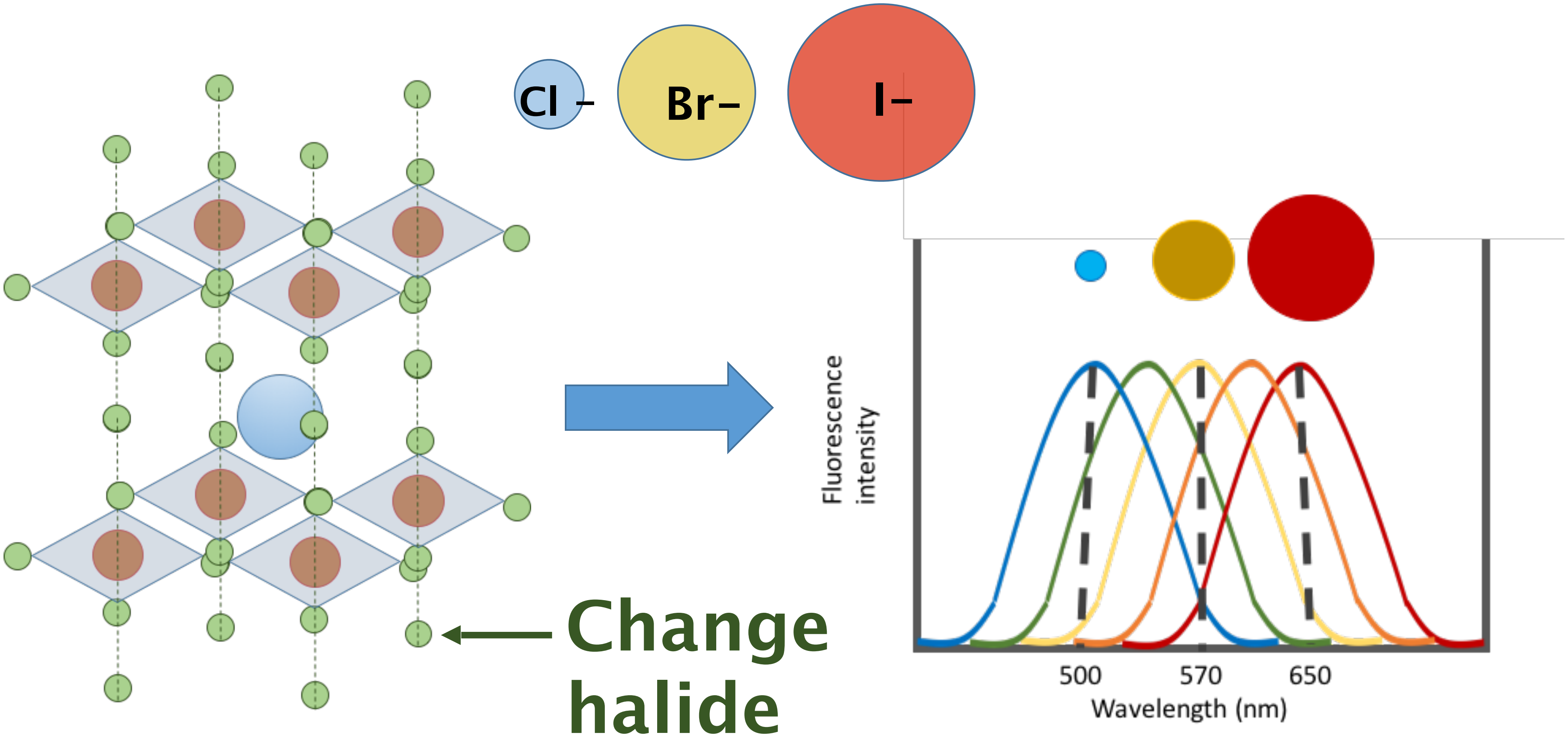


Recall: we can tune the size and fluorescence

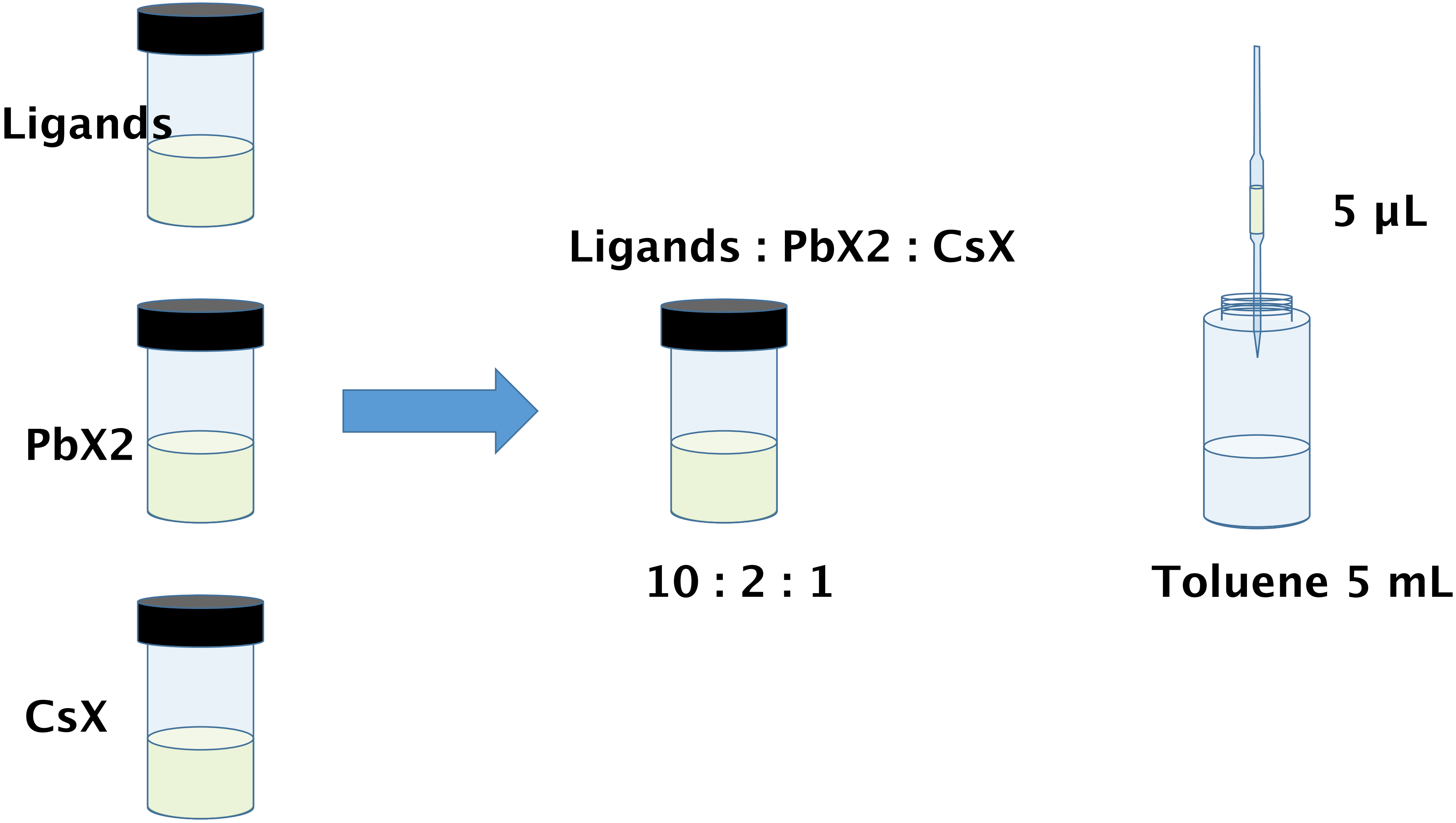


Change halide

Recall: we can tune the size and fluorescence



Recall: we can tune the size and fluorescence



Ligands

PbX2

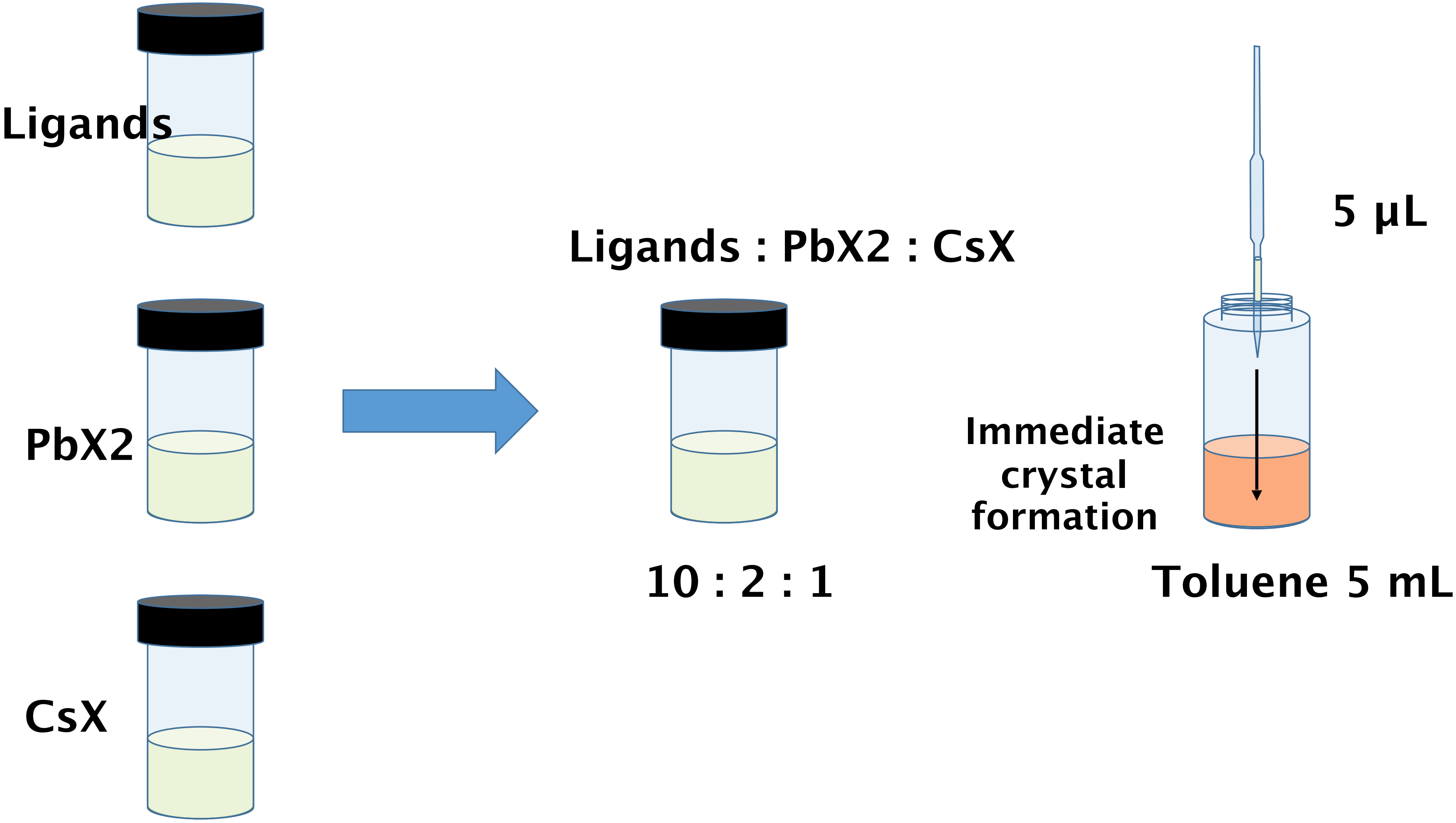
CsX

Ligands : PbX2 : CsX

10 : 2 : 1

5 µL

Toluene 5 mL



Ligands

PbX2

CsX

Ligands : PbX2 : CsX

10 : 2 : 1

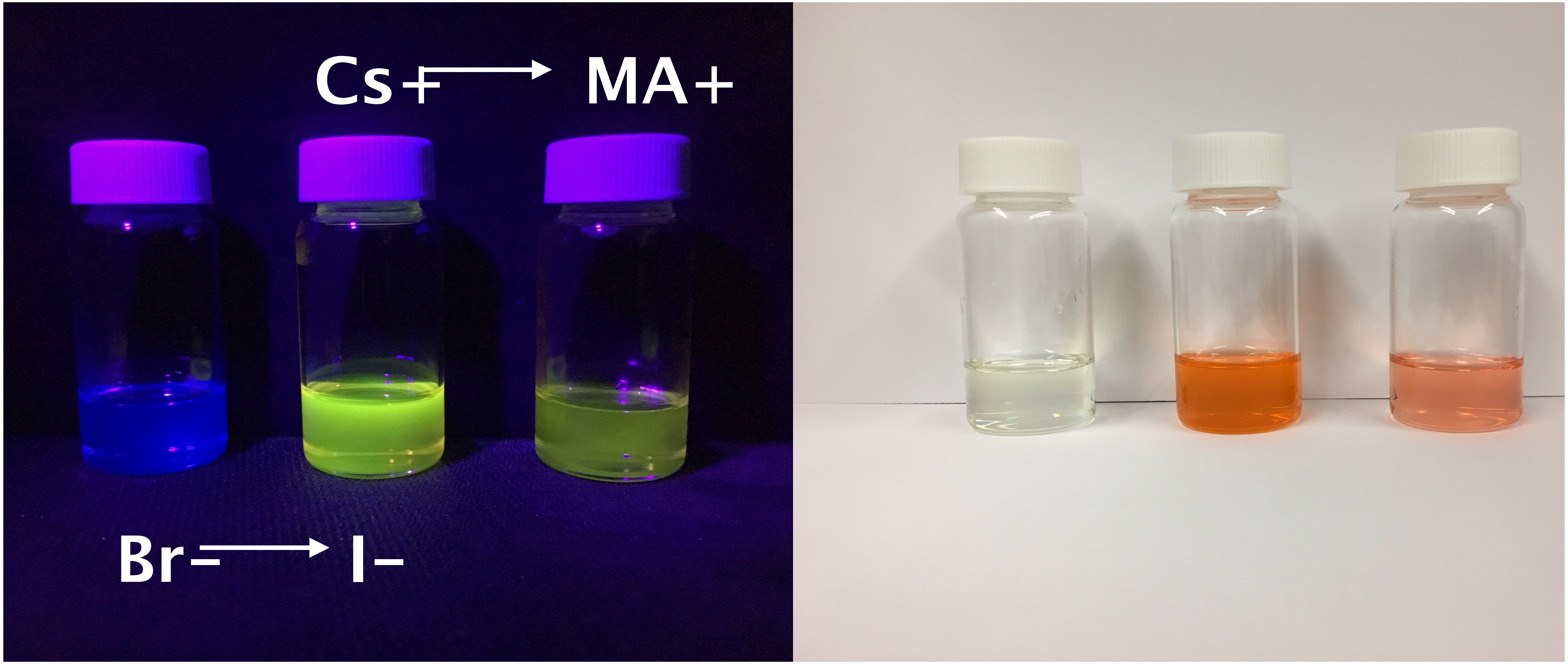
5 µL

Immediate crystal formation

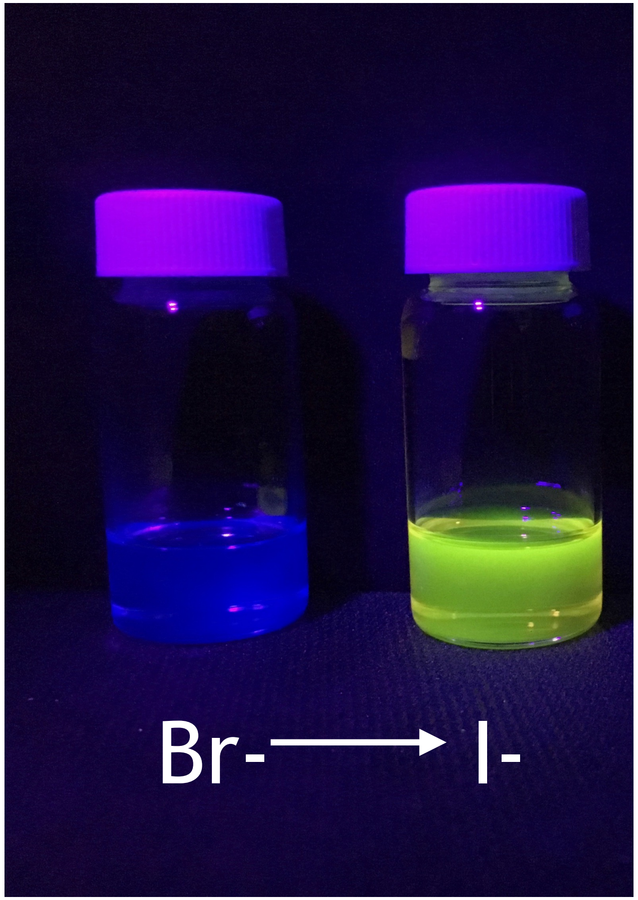
Toluene 5 mL

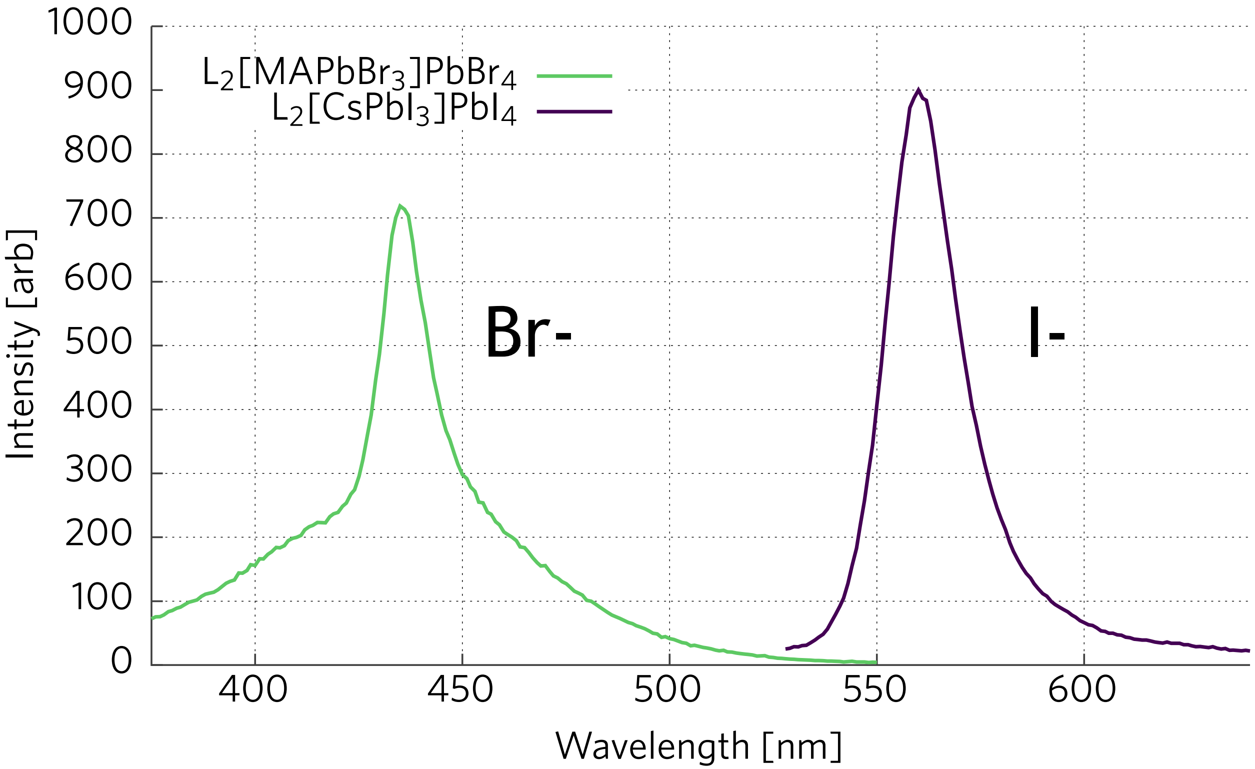
Synthesis is as easy as mixing solvent!

Perovskite quantum dots



Perovskite quantum dots

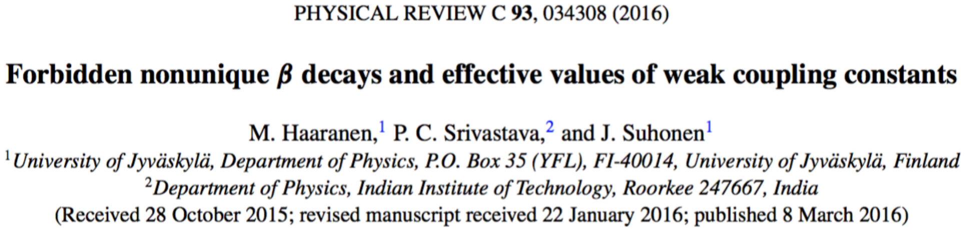




Fluorescence red shifts with growing halide

More results coming soon!

First Crystals: $LiInSe_2$

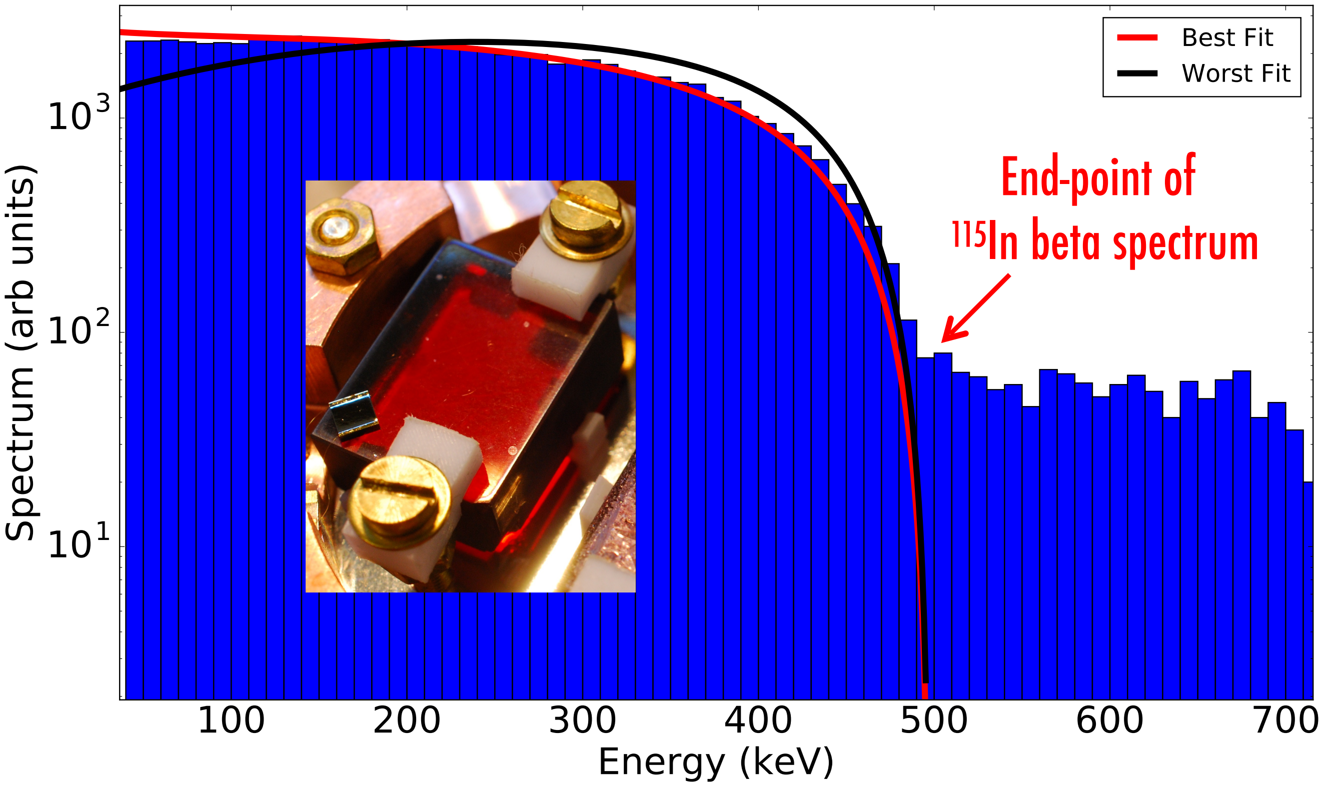


PHYSICAL REVIEW C **93**, 034308 (2016)

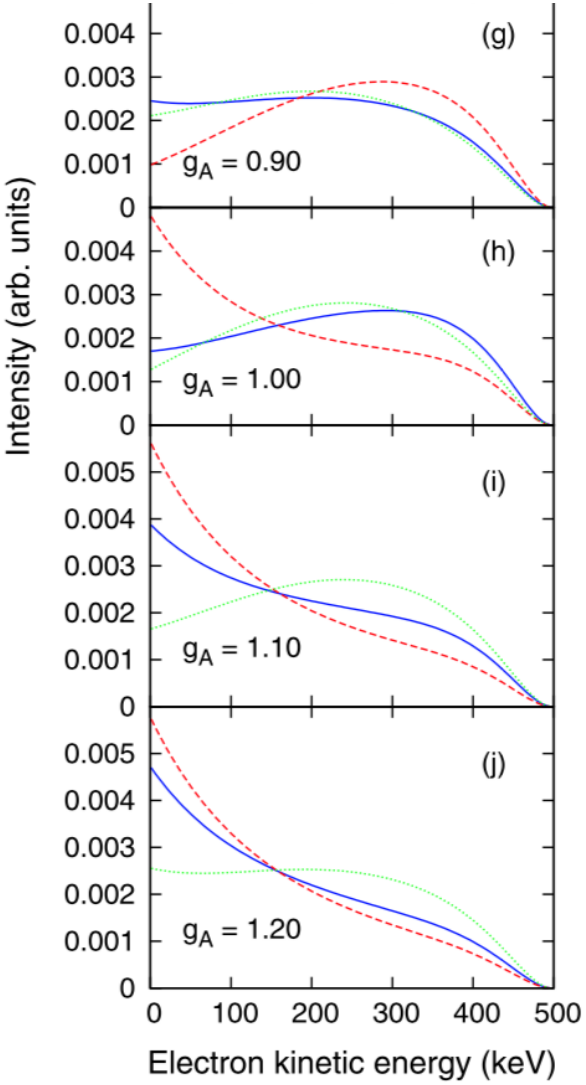
Forbidden nonunique β decays and effective values of weak coupling constants

M. Haaranen,[1] P. C. Srivastava,[2] and J. Suhonen[1]
[1]*University of Jyväskylä, Department of Physics, P.O. Box 35 (YFL), FI-40014, University of Jyväskylä, Finland*
[2]*Department of Physics, Indian Institute of Technology, Roorkee 247667, India*
(Received 28 October 2015; revised manuscript received 22 January 2016; published 8 March 2016)

^{115}In, 4-fold forbidden non-unique β decay
(Q_β = 496 keV, $T_{1/2}$ = 4.4×10^{14} y)

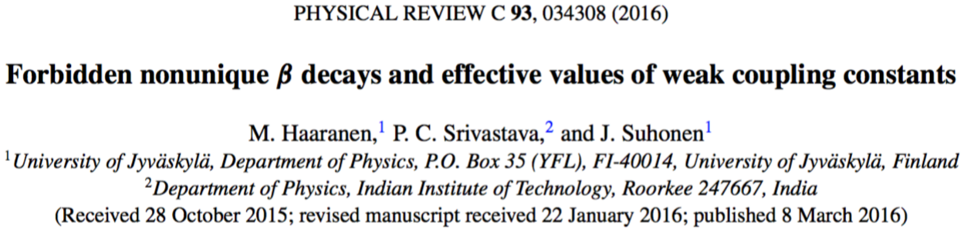


End-point of
^{115}In beta spectrum



The crystal doesn't work for double-beta experiments because of the In, but can help with theoretical uncertainties in the nuclear physics (quenching of g_A) that could severely impact the sensitivity of experiments.

First Crystals: $LiInSe_2$



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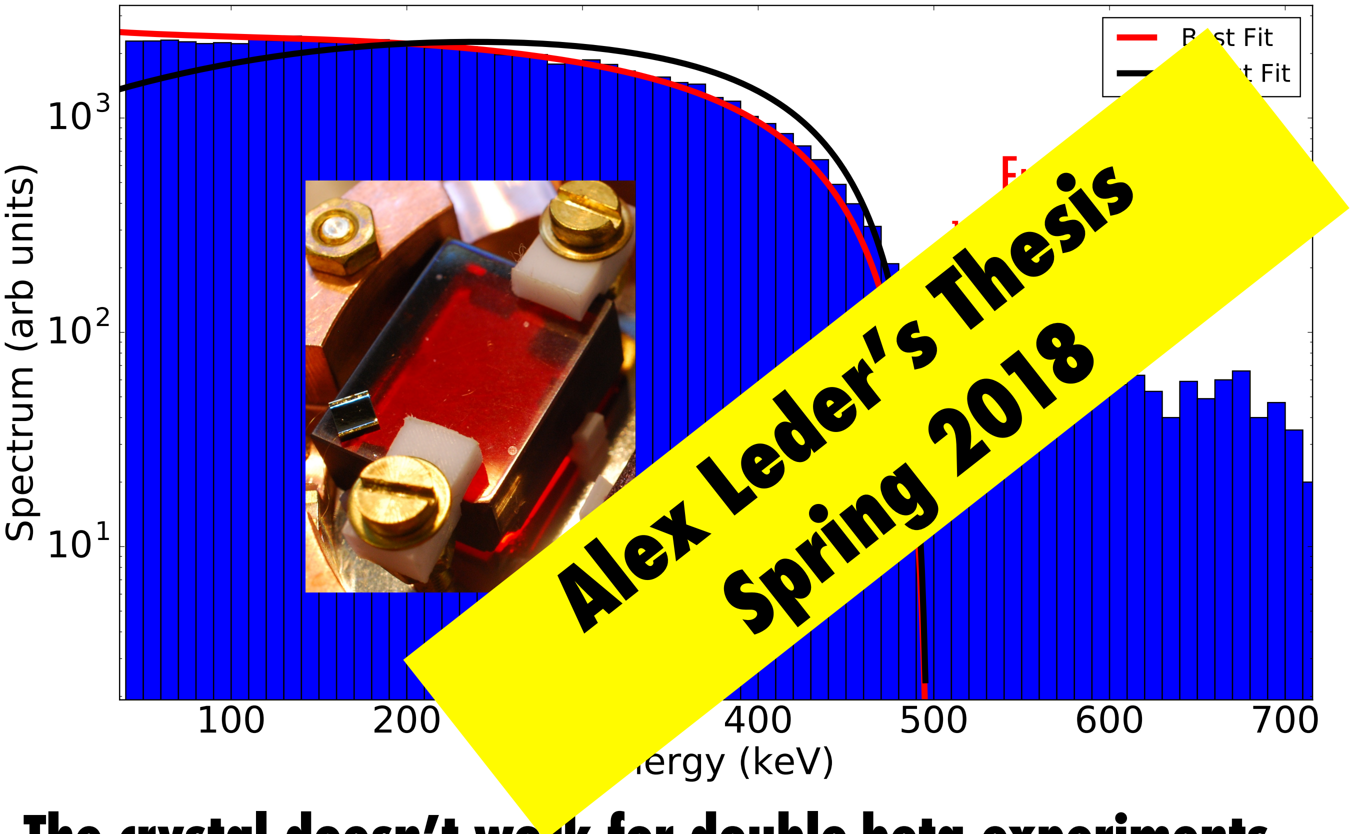
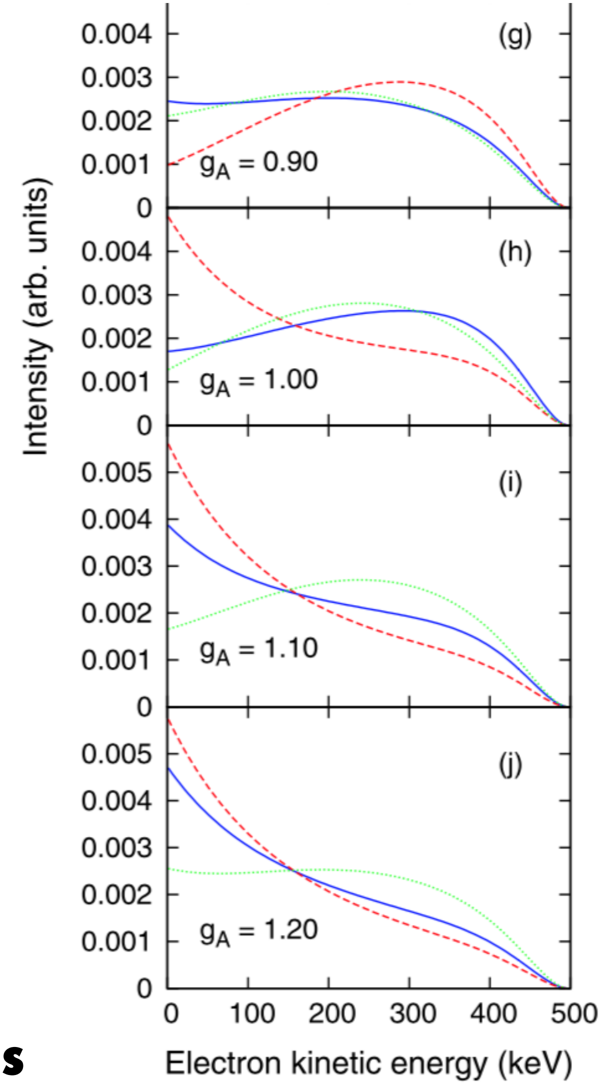


Alex Leder's Thesis
Spring 2018



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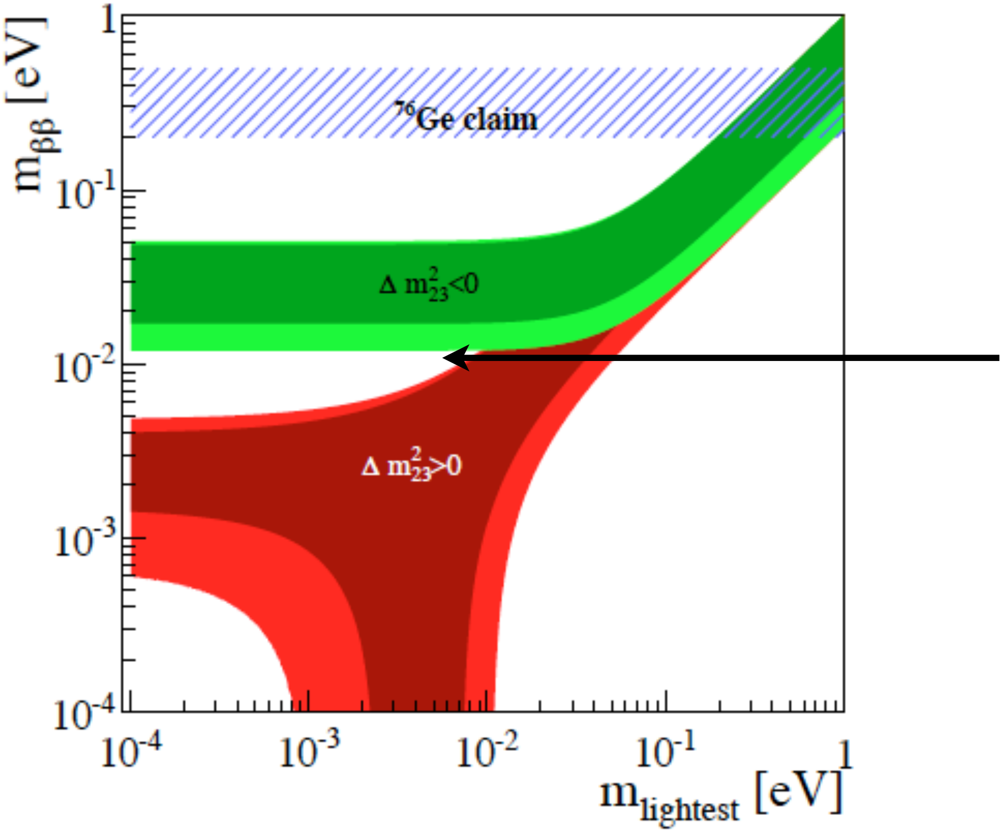
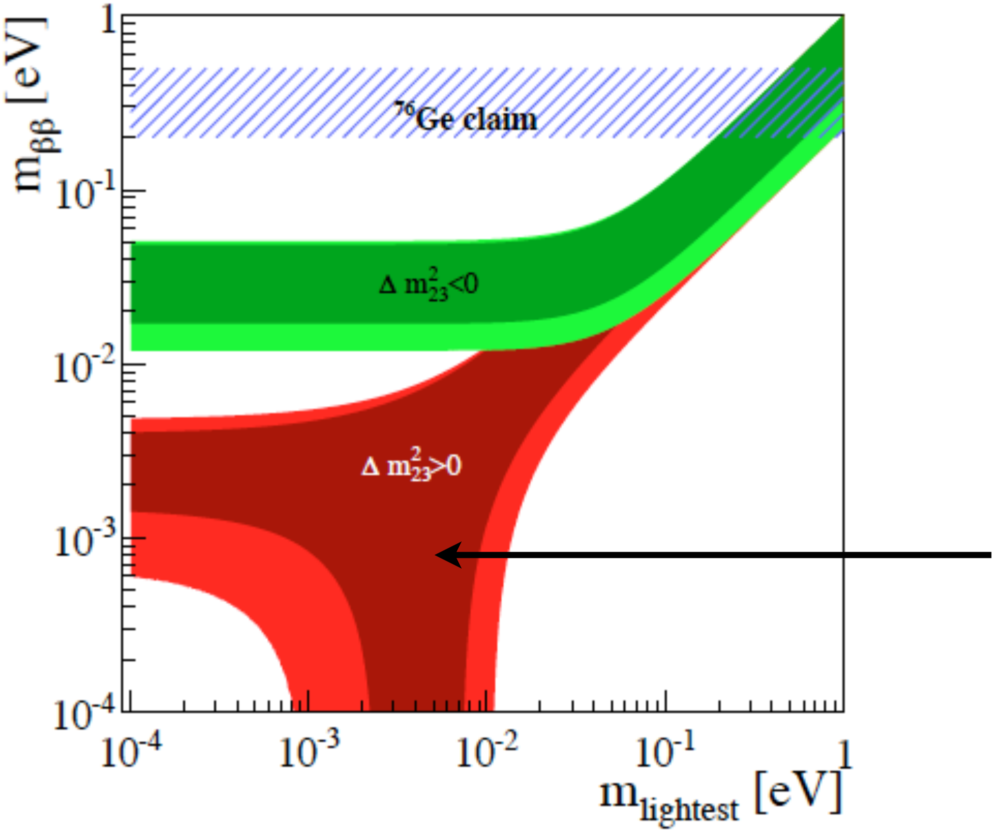


The field is ready to build experiments capable of reaching ~10^{27} years.



How do we build an experiment for the normal hierarchy, ~10^{28} years?

Thinking Big….

see Brunner and Winslow, Nucl.Phys.News 27 (2017) no.3, 14-19

The next-next generation?

Axions

Neutrinoless Double-Beta Decay

What is Dark Matter?

Why is there only matter in the universe?

Why are the neutrinos so light?

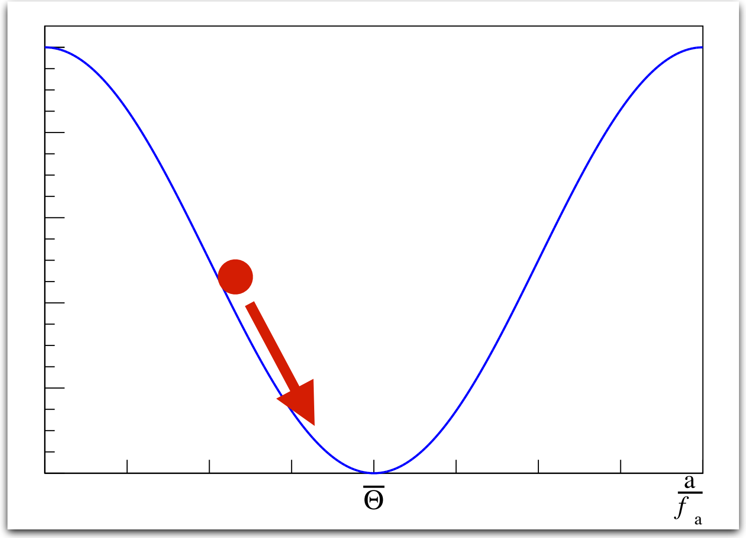
Strong CP Problem

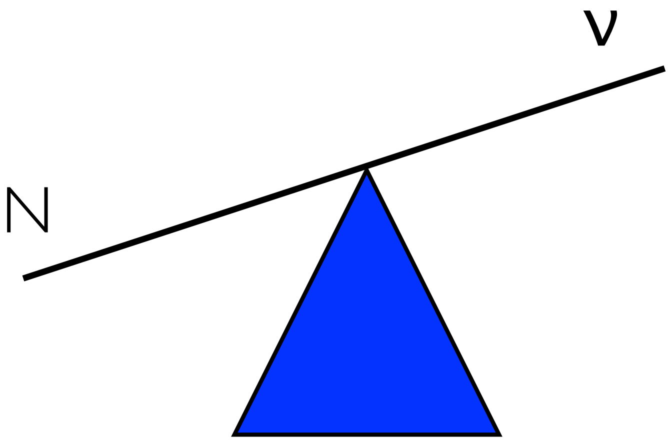
Majorana vs. Dirac Neutrinos

What unites these two topics?

Peccei-Quinn Mechanism

See-Saw Mechanism





$$m_a \sim \frac{m_\pi f_\pi}{f_a} 10^{-9}\,\mathrm{eV}\left(\frac{10^{16}\,\mathrm{GeV}}{f_a}\right)$$

nano-eV mass

GUT scale axion

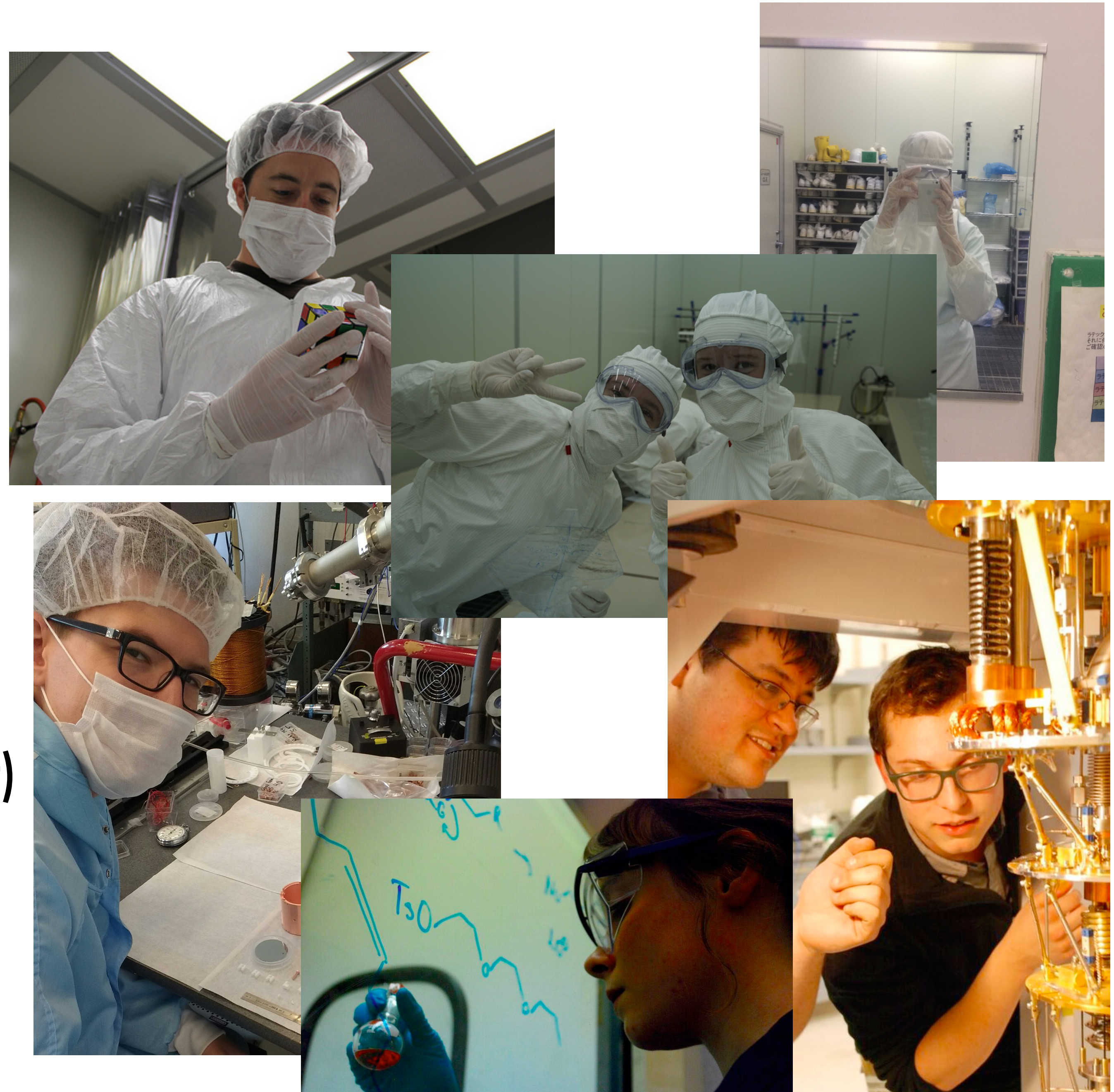
$$L_m = -\frac{1}{2}\frac{m_D^2}{m_R}\bar{\nu}\nu - \frac{1}{2}m_R\bar{N}N$$

Our
Standard
Light ν

GUT scale ν

Thank you to my wonderful group!

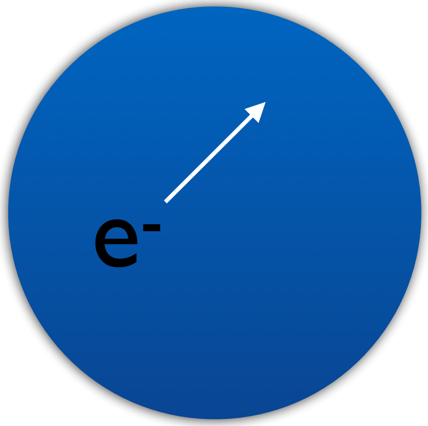
The Winslow Group
Lindley Winslow
Jon Ouellet (Postdoc)
Lucia Canonica (Postdoc - Italy)
Julieta Gruszko(Pappalardo Fellow)
Alex Leder (Grad Student)
Joe Johnston (Grad Student)
Suzannah Fraker (Grad Student)
Chiara Salemi (Grad Student)
Zhenghao Fu (Grad Student)
Brian Naranjo (UCLA Staff Researcher)
Diana Gooding (BU Grad Student)
Many Wonderful UROPs

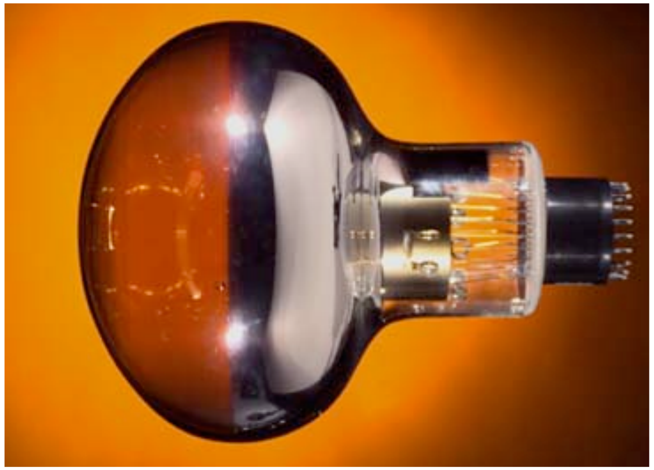


Can we do something better with Liquid Scintillator detectors?

Basic Principle of Liquid Scintillator Detector

Physics ⟶ **Light** ⟶ **PMTs**

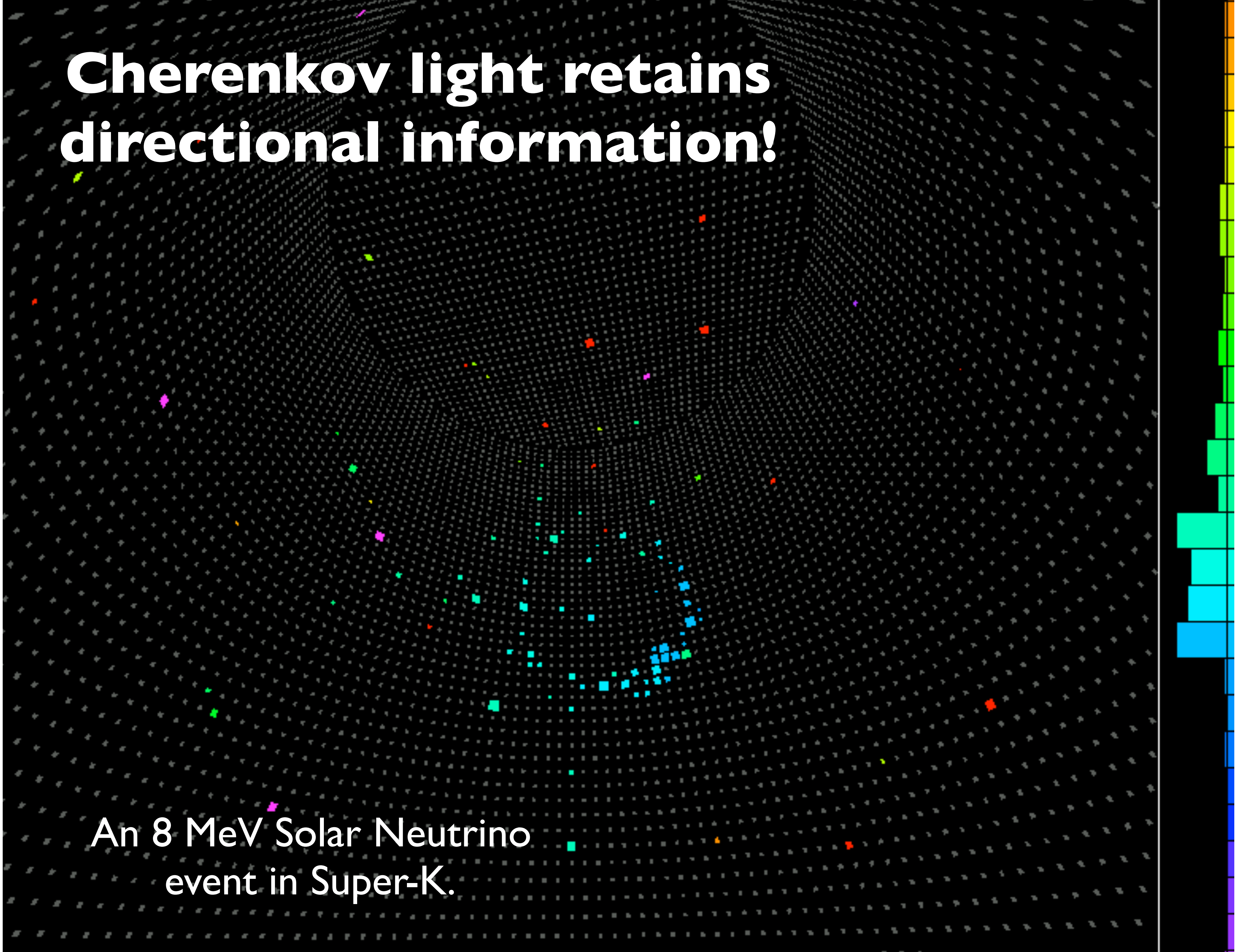




A charged particle vibrates molecules making light that is detected by photomultiplier detectors (PMT).

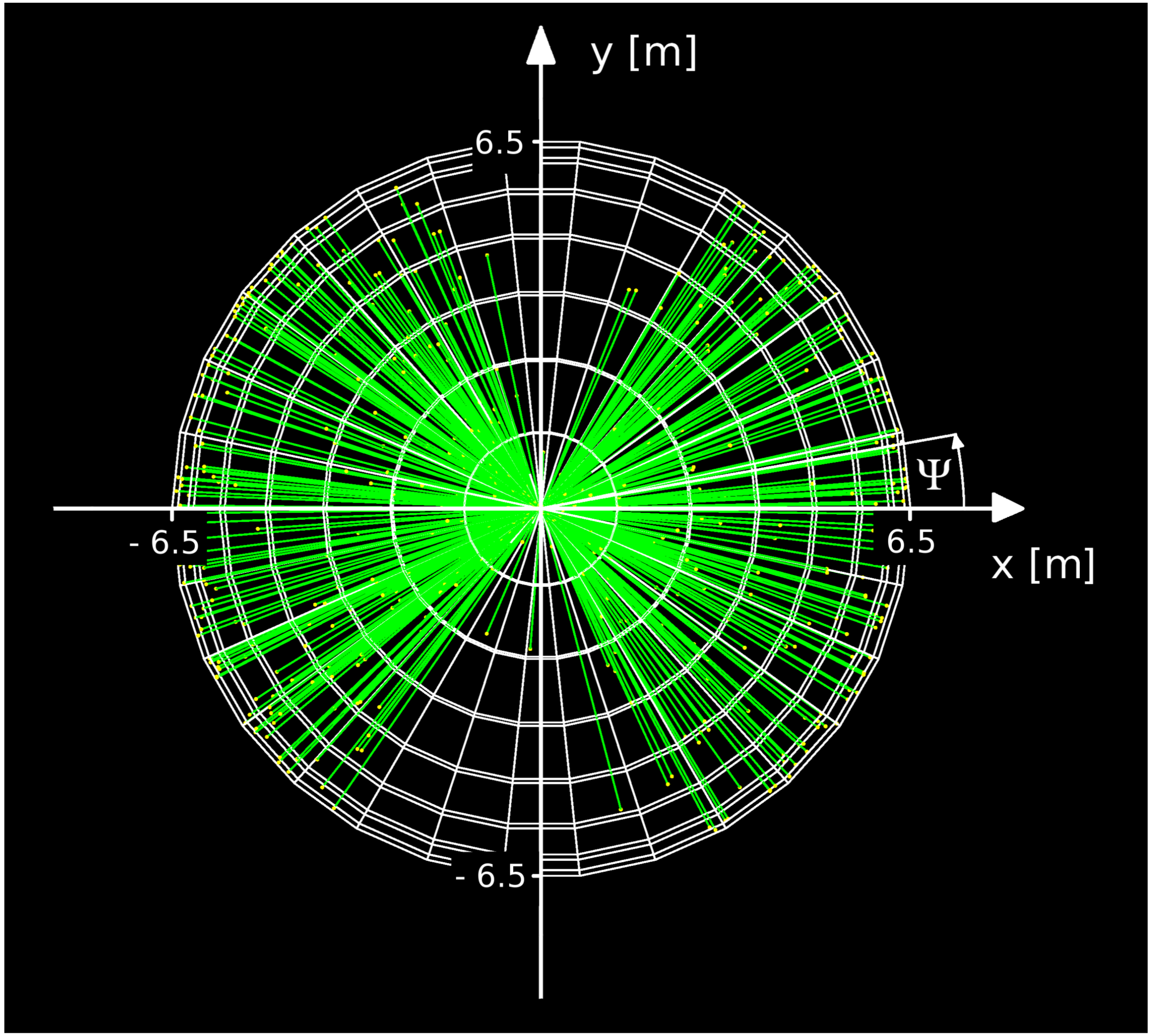
**Problem:
Scintillation light
is isotropic.**

Cherenkov light retains directional information!



An 8 MeV Solar Neutrino
event in Super-K.

Neutrinoless Double Beta Decay



(Cherenkov Only)

National Science Foundation
WHERE DISCOVERIES BEGIN

NuDot:
A Prototype Directional Liquid Scintillator

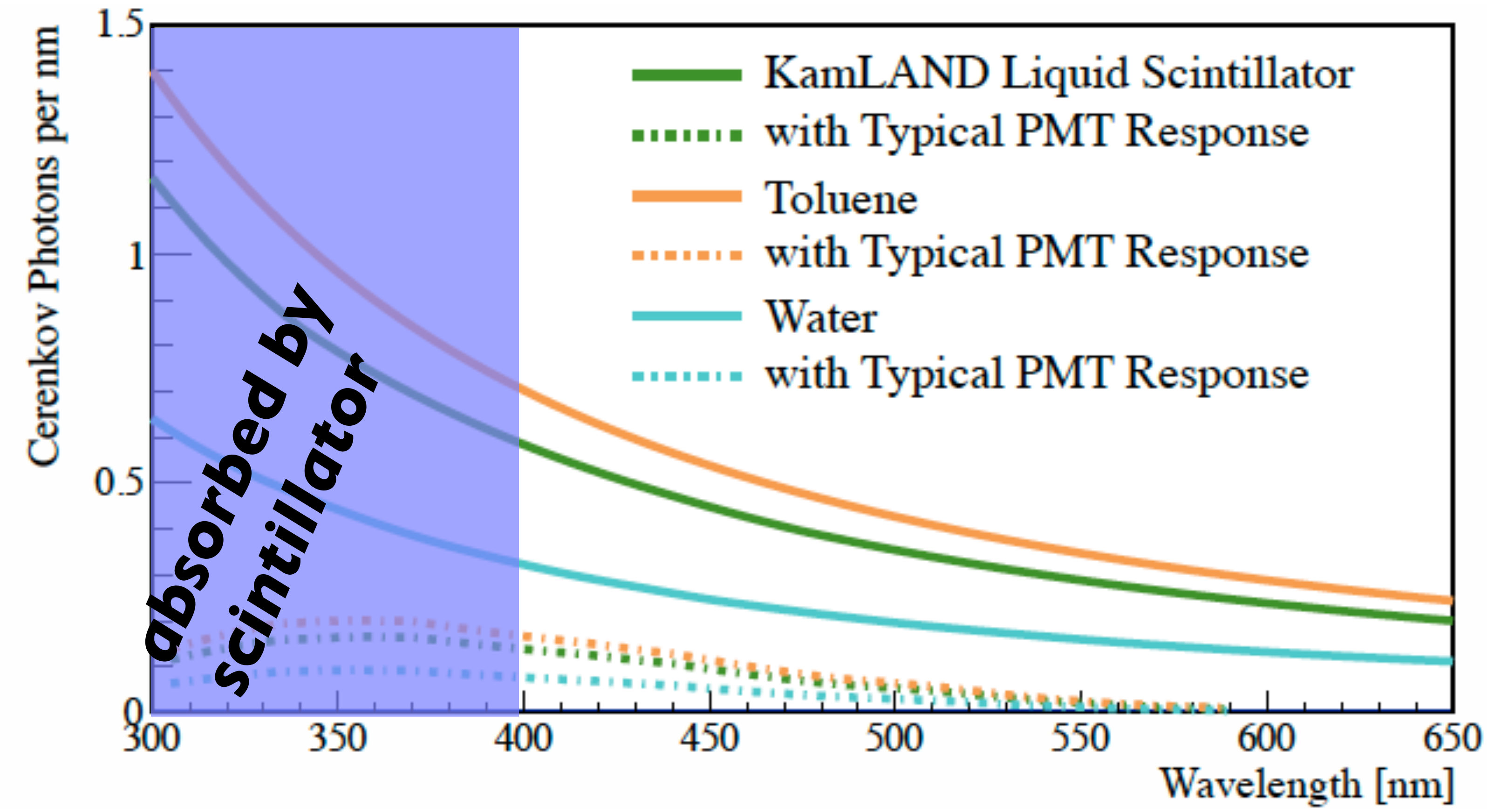
MIT

UCLA

THE UNIVERSITY OF CHICAGO

How does it work?

Number of Cherenkov Photons for a 1MeV e-



Retains directional information!

Important in Big Detector.

Longer wavelengths travel faster in scintillator

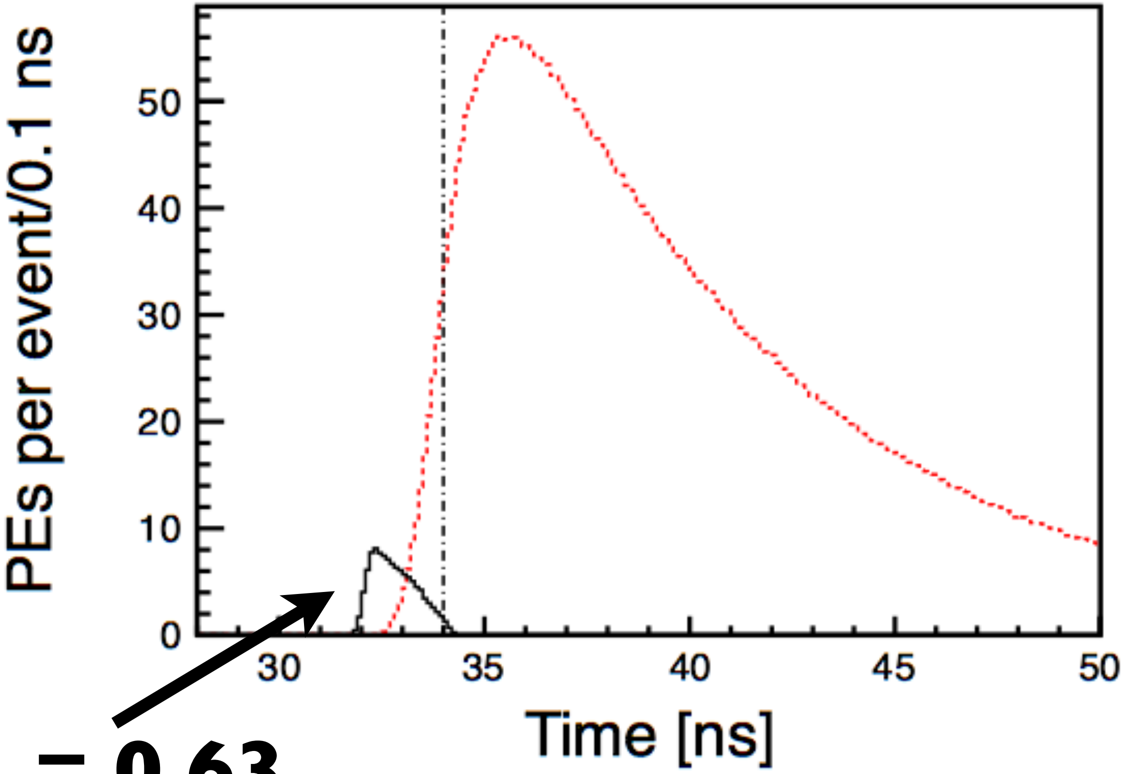
and

Scintillation processes have inherent time constants.

Always Important

JINST 9 (2014) P06012

So if you have good enough timing....

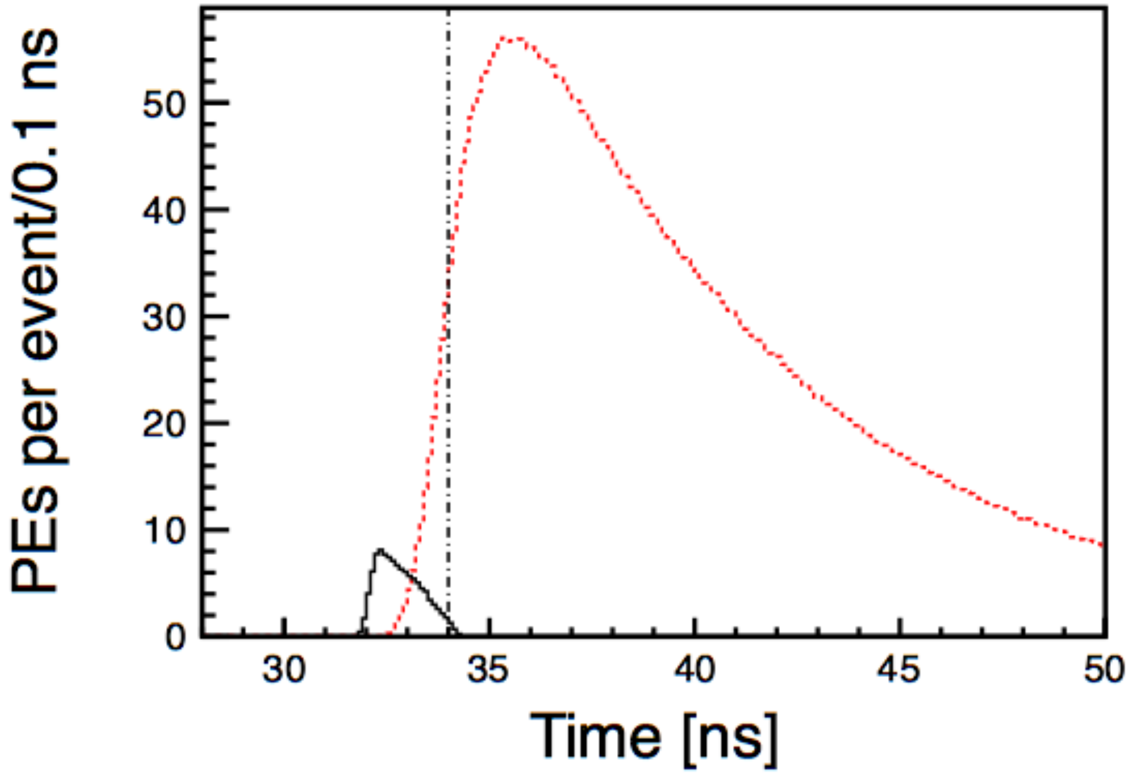


$R_{c/s}$ = 0.63

.... you should be able to separate the scarce Cherenkov from the abundant scintillation light.

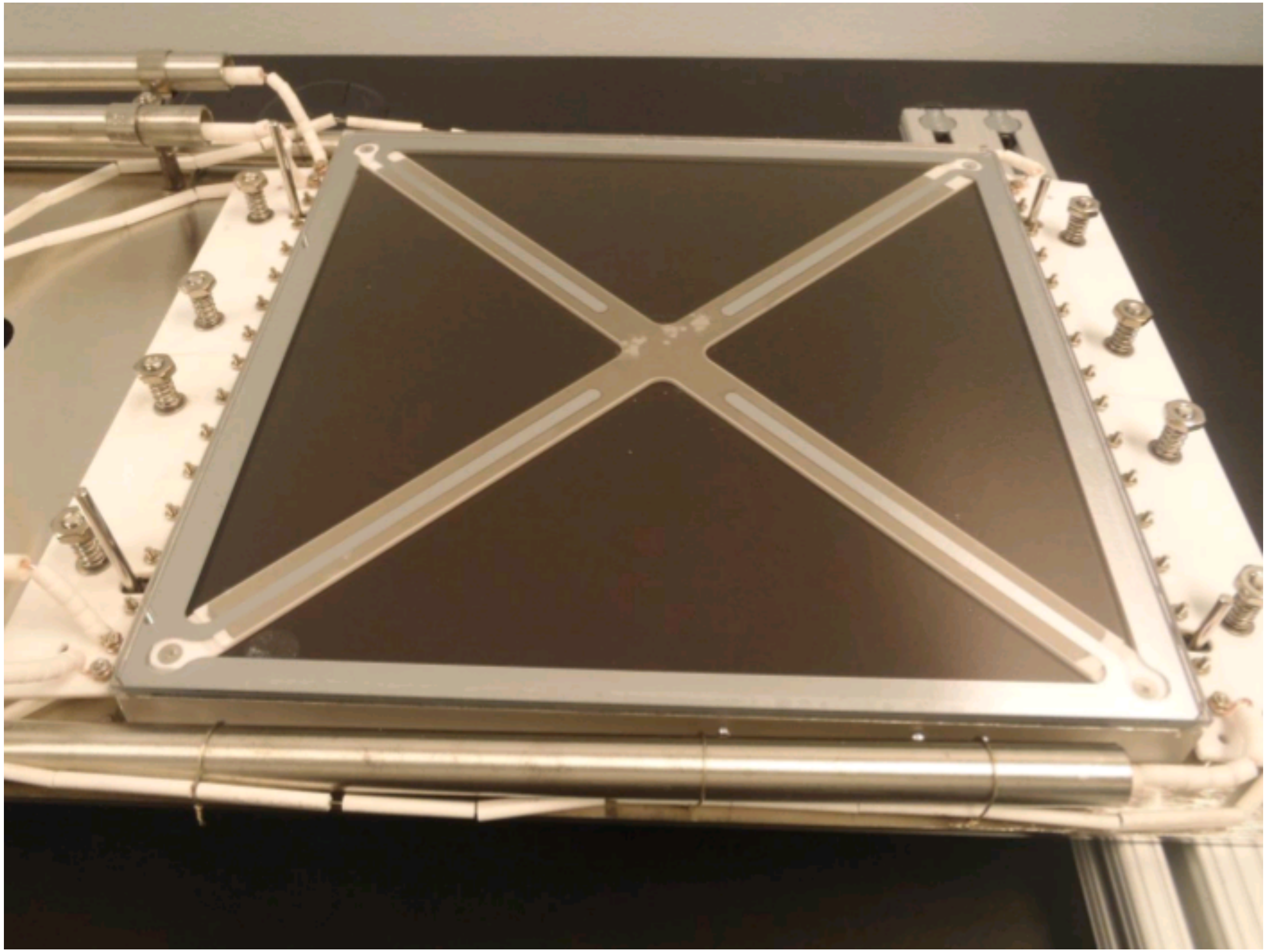
JINST 9 (2014) P06012

This corresponds to 0.1 ns.

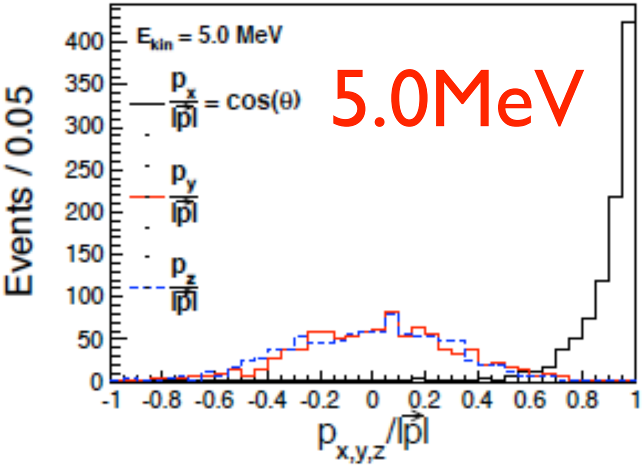


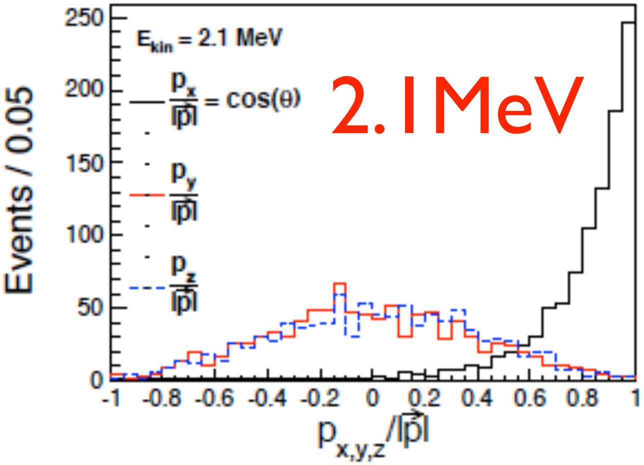
This sort of timing is available in very tiny MCP-based PMT’s/SiPMs…for now.

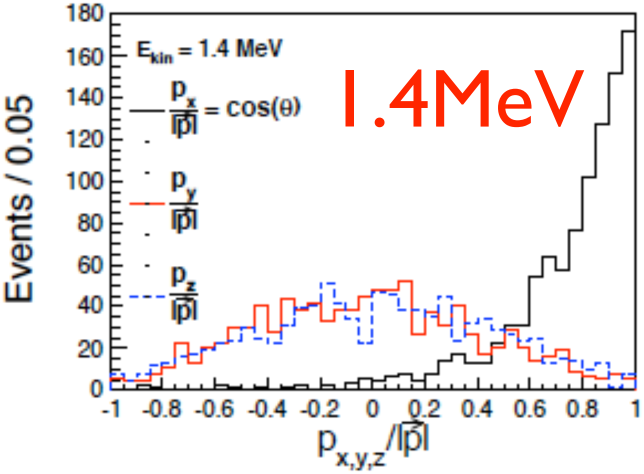
The LAPPD:



JINST 9 (2014) P06012

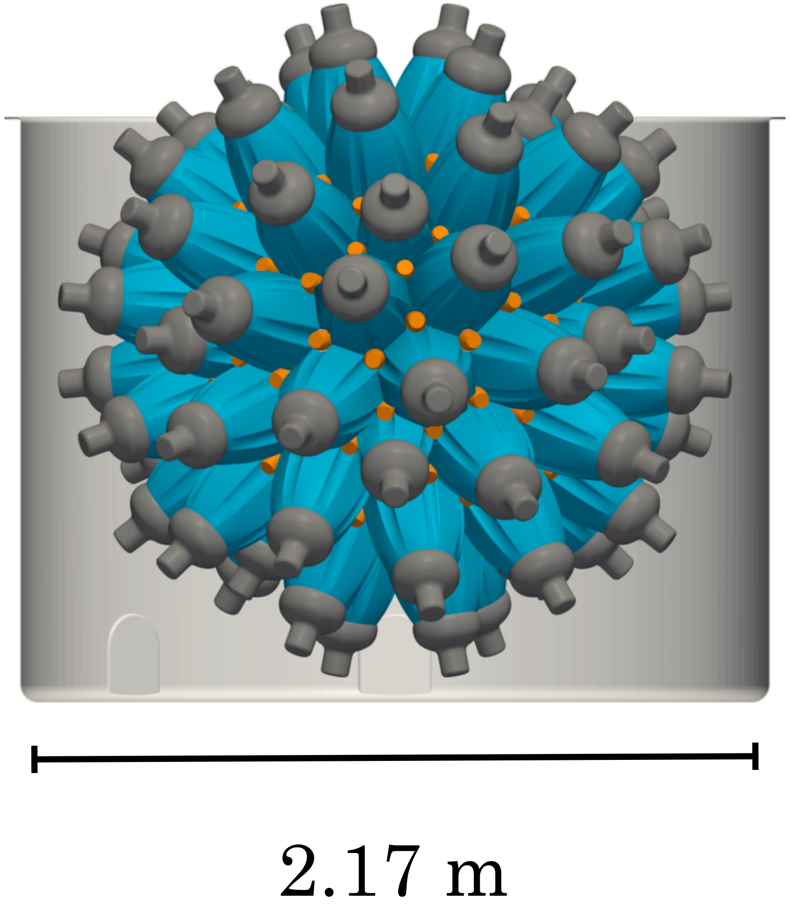






With a basic algorithm, we can reconstruct the direction of single electrons!

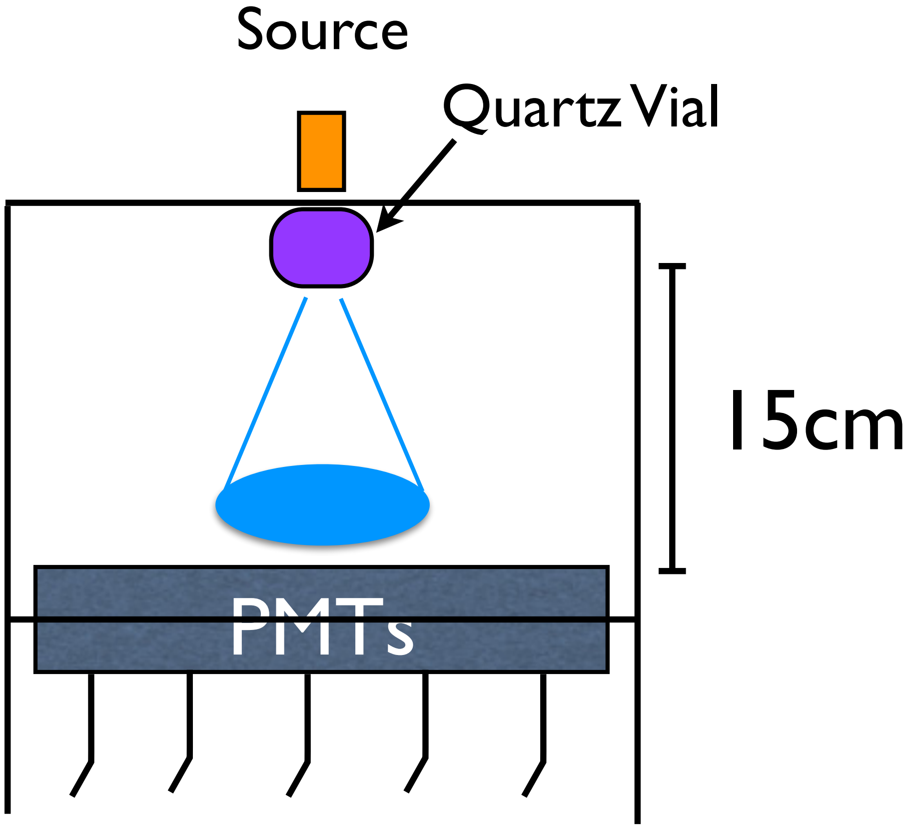
NuDot: A Prototype Directional Liquid Scintillator Detector

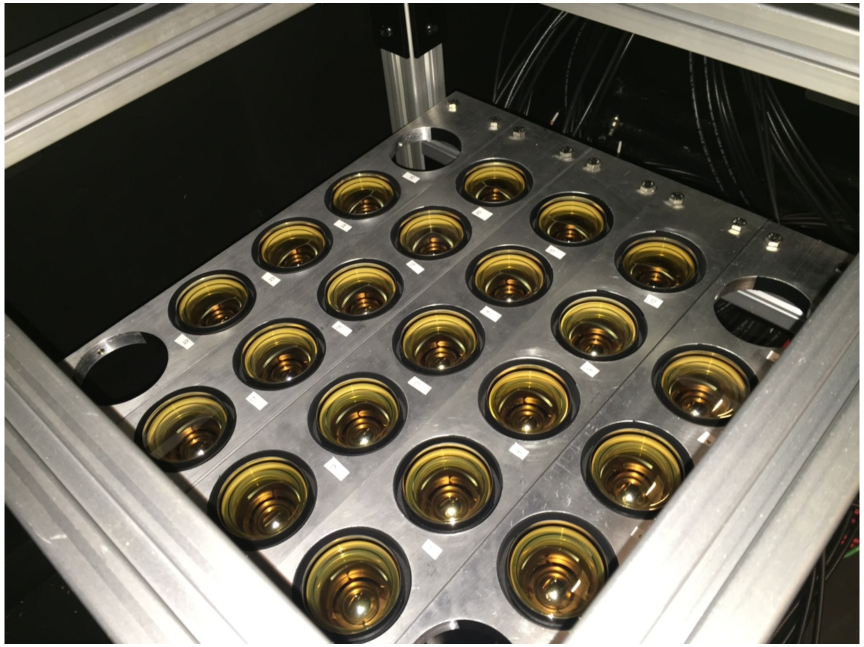


- NuDot has 140 2” PMTs (300 ps timing, shown in orange).
- Construction delayed last summer by Hamamatsu, so…
- Working on smaller 25 PMT setup.

FlatDot:

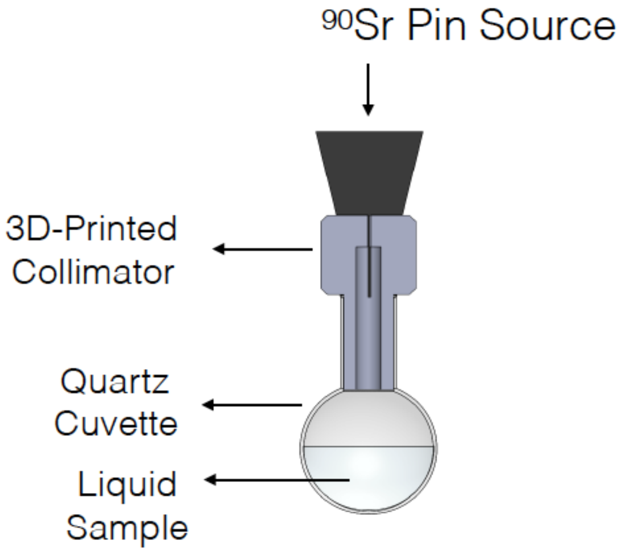
Prototype of the Prototype





Excellent system for testing new data acquisition system and testing different scintillator cocktails (including quantum dots)!

FlatDot:
Progress!



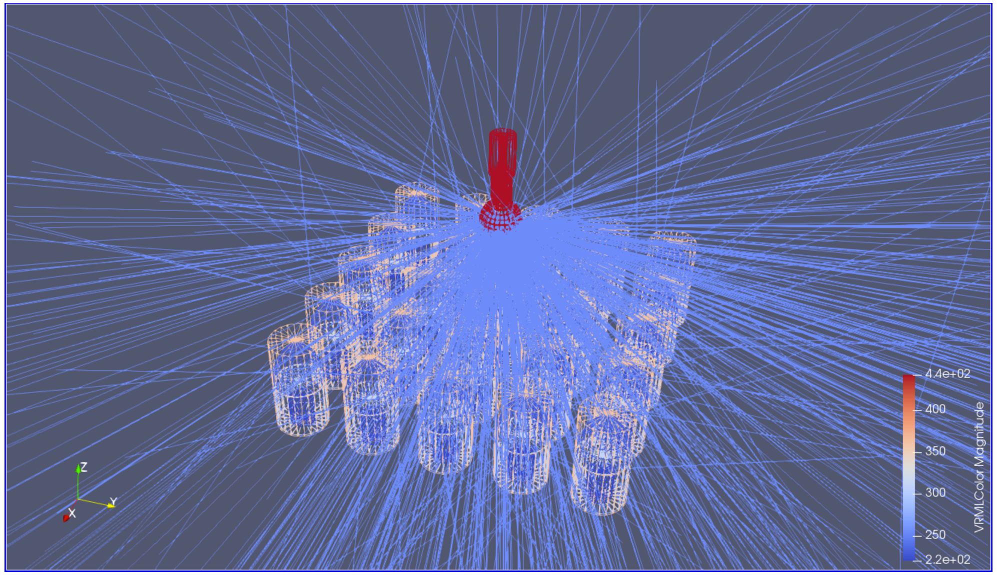
^{90}Sr Pin Source

3D-Printed Collimator

Quartz Cuvette

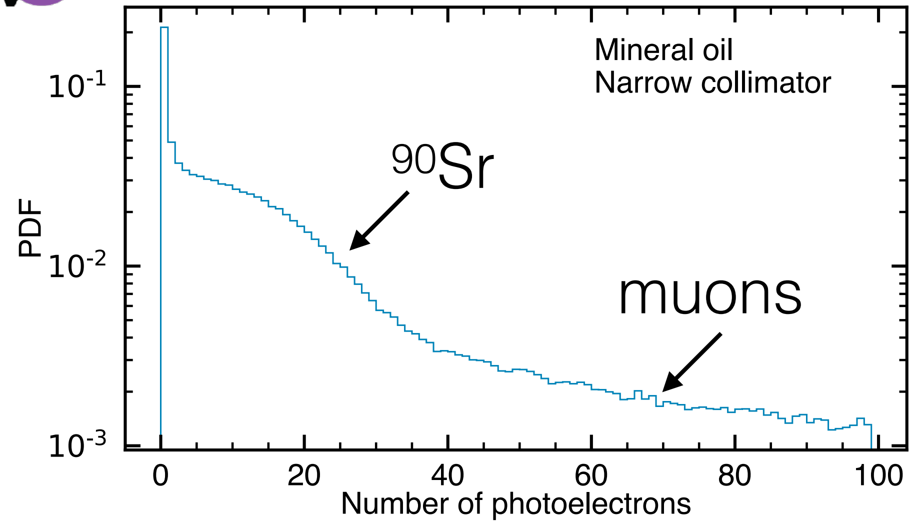
Liquid Sample

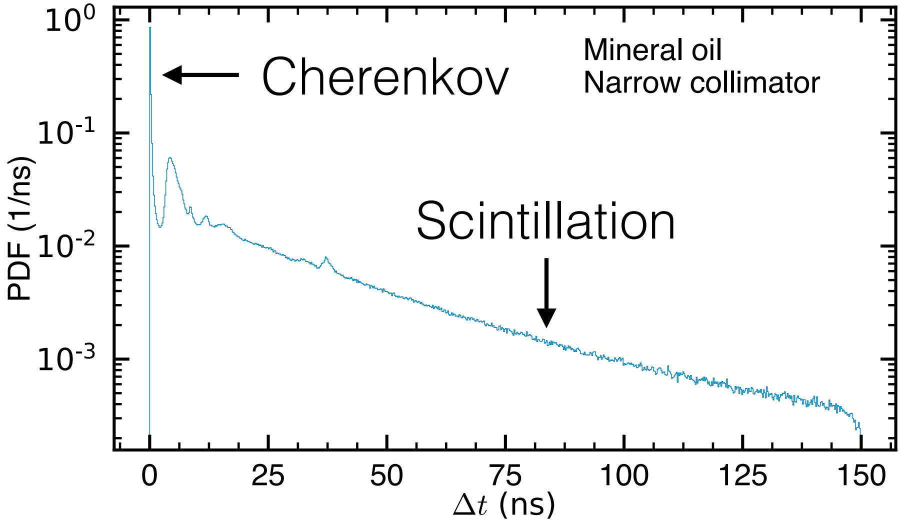
Source Geometry

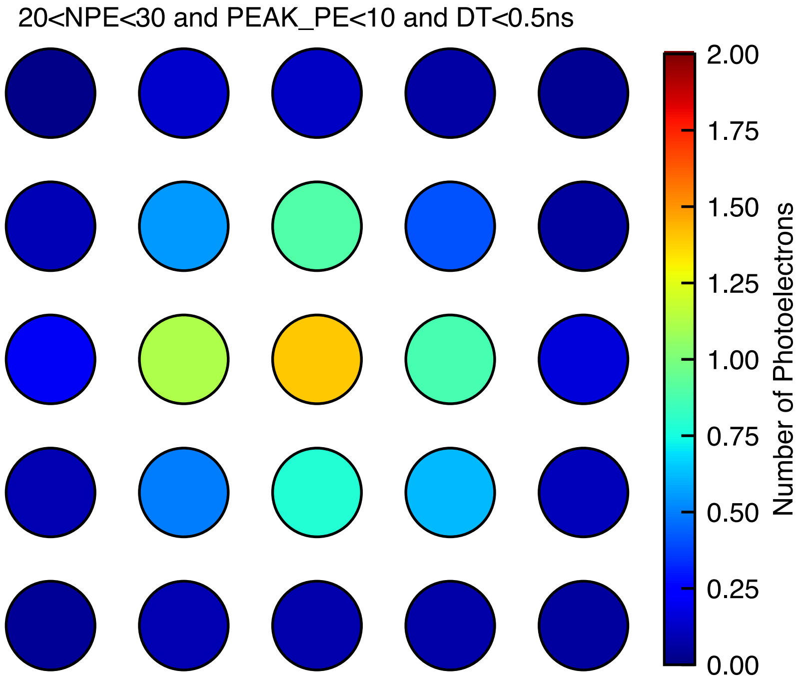


MC Simulation

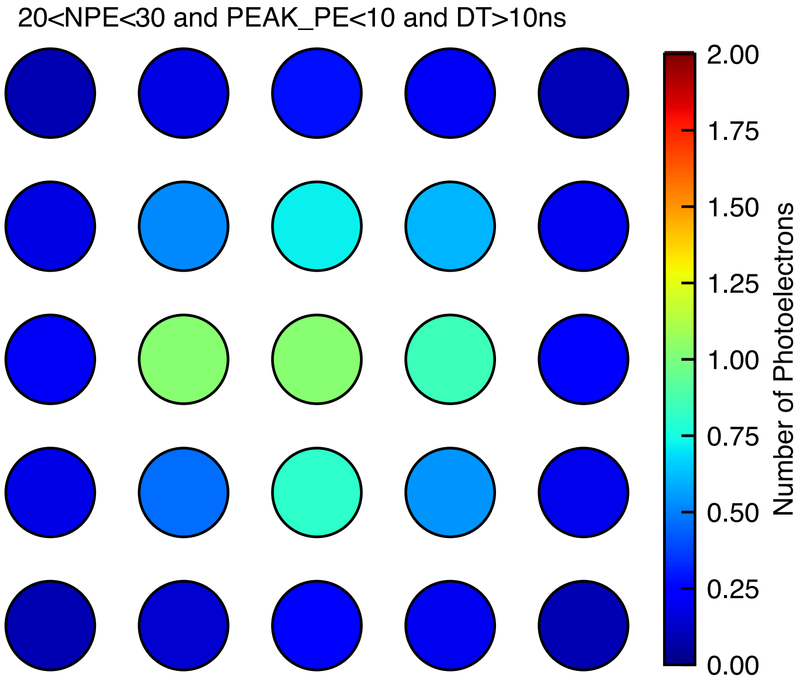
FlatDot Mineral Oil Data







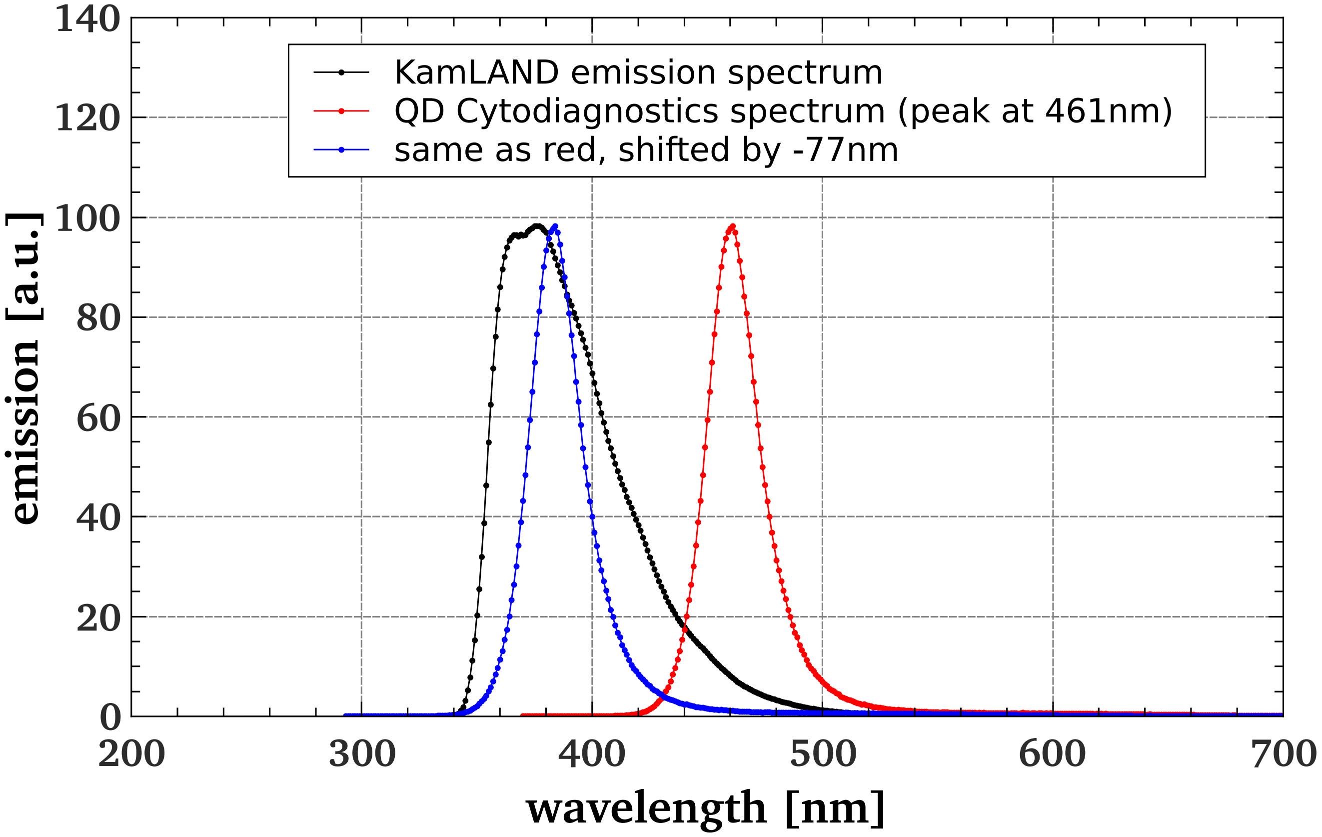
Cherenkov



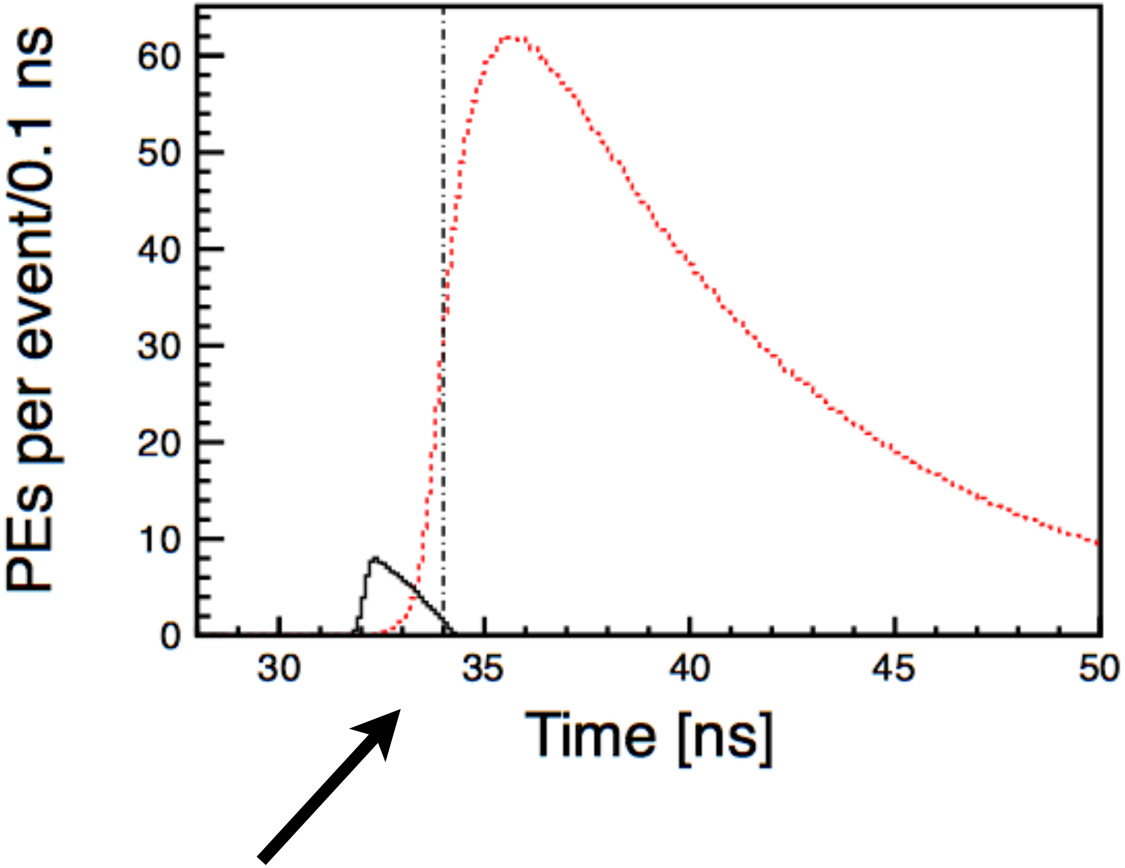
Scintillation

Did you say something about quantum dots?

What if I could narrow the emission spectrum?



Narrowed emission spectrum with traditional PMTs and 0.1ns timing.



$R_{c/s}$ = 0.86

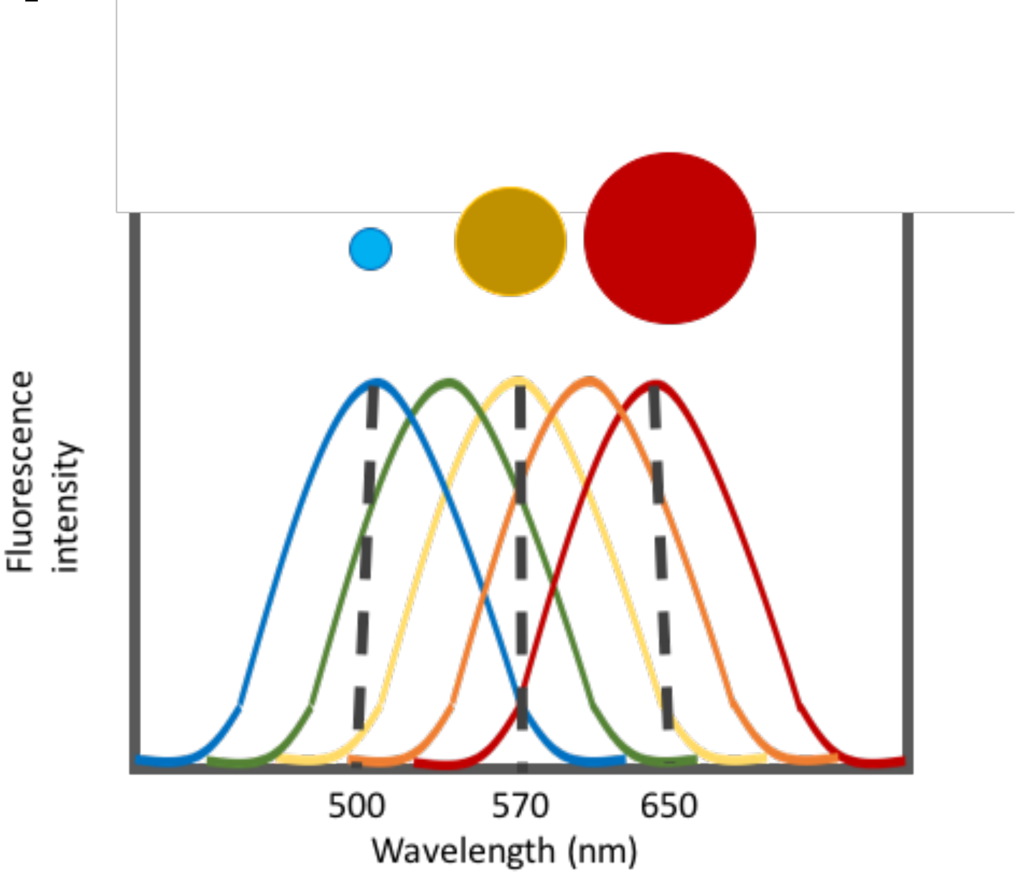
What are Quantum Dots?

Quantum Dots are semiconducting nanocrystals.

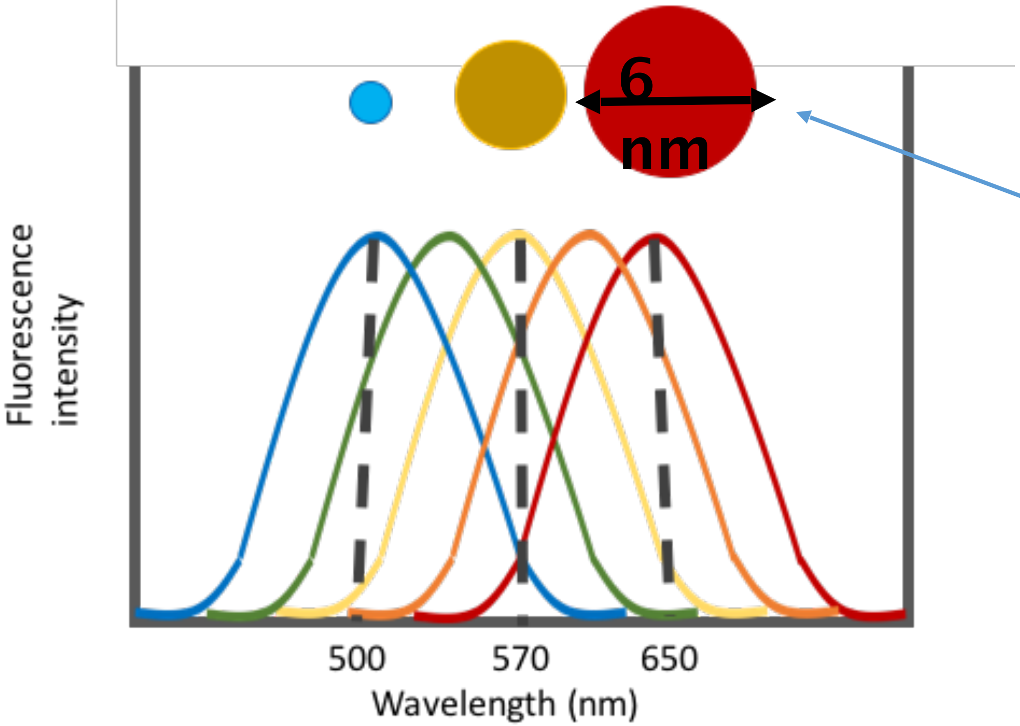
Candidate Isotopes Are Quantum Dot Materials!

Isotope	**Endpoint**	**Abundance**
^{48}Ca	4.271 MeV	0.187%
^{150}Nd	3.367 MeV	5.6%
^{96}Zr	3.350 MeV	2.8%
^{100}Mo	3.034 MeV	9.6%
^{82}Se	2.995 MeV	9.2%
^{116}Cd	2.802 MeV	7.5%
^{130}Te	2.533 MeV	34.5%
^{136}Xe	2.479 MeV	8.9%
^{76}Ge	2.039 MeV	7.8%
^{128}Te	0.868 MeV	31.7%

Optical properties of quantum dots are



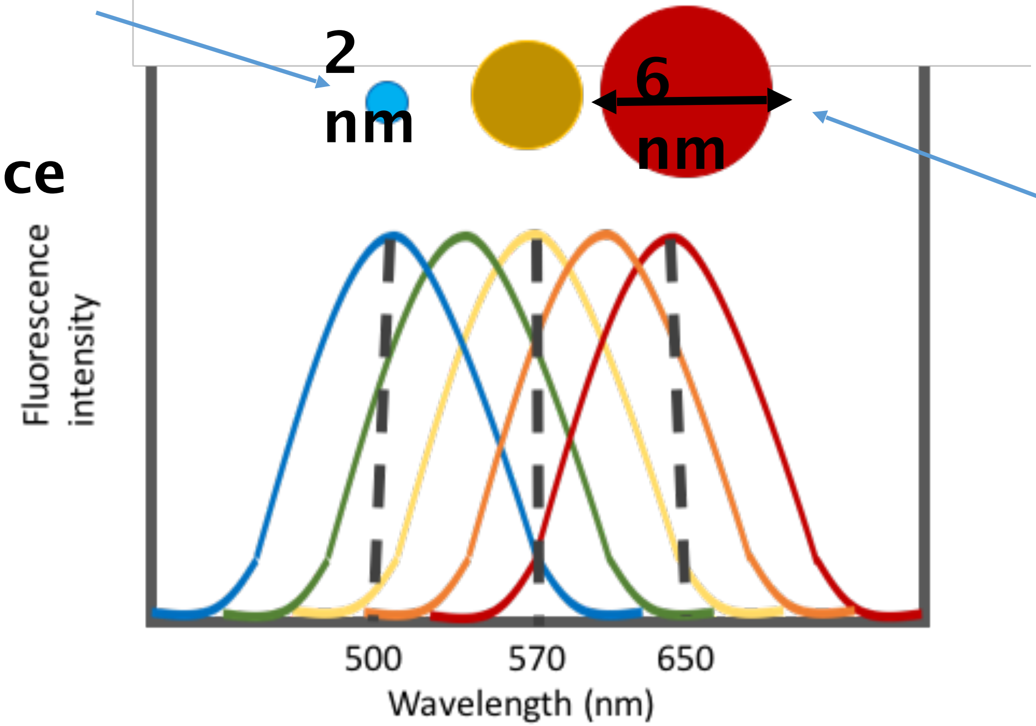
Optical properties of quantum dots are size-dependent



electrons confined to an effective box

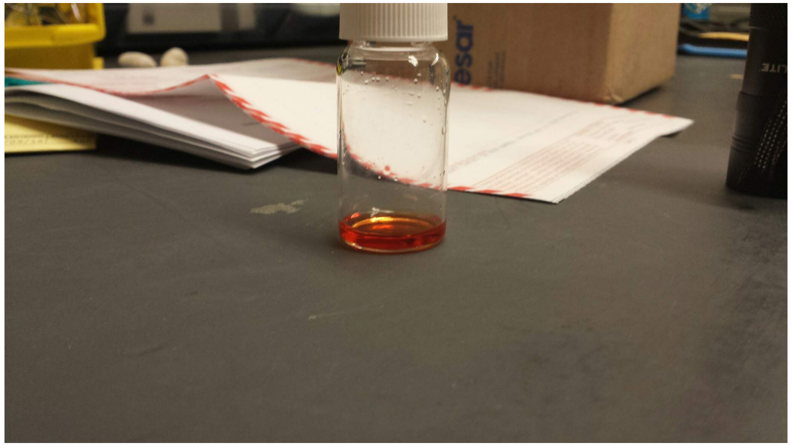
Optical properties of quantum dots are size-dependent

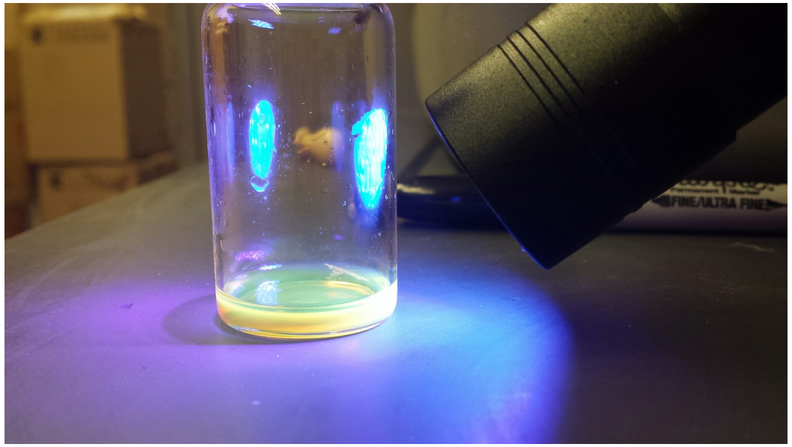
Causes blue-shift in fluorescence



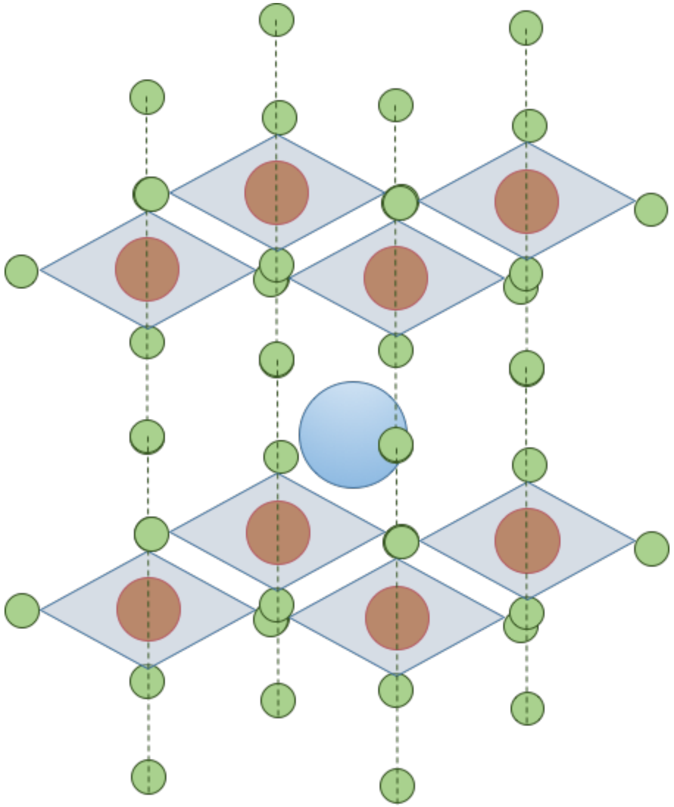
electrons confined to an effective box

We can tune fluorescence by tuning the reaction!

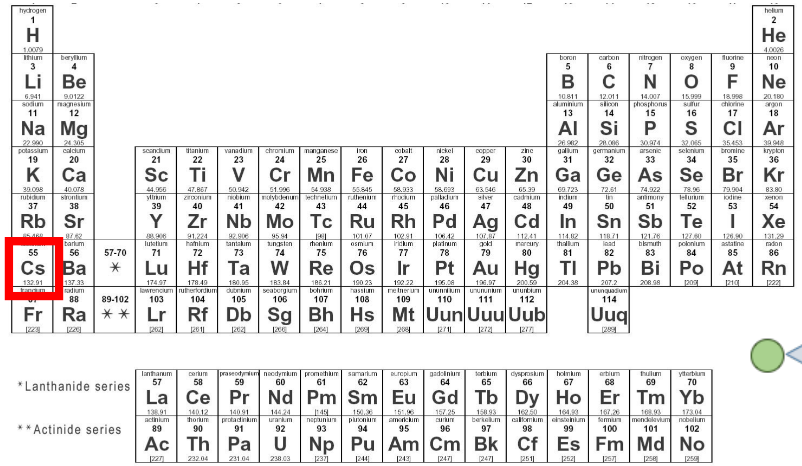


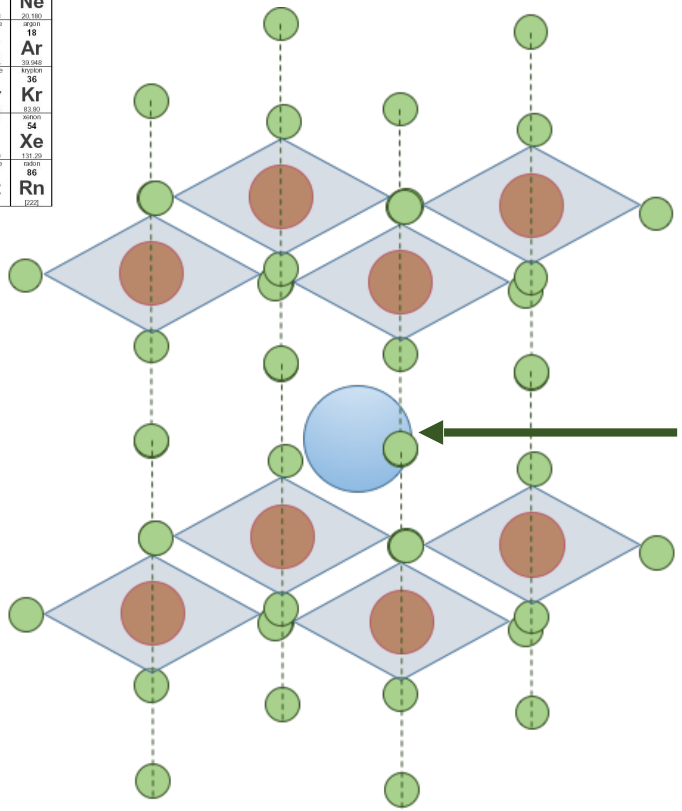


Can we make UV-emitting quantum dots?



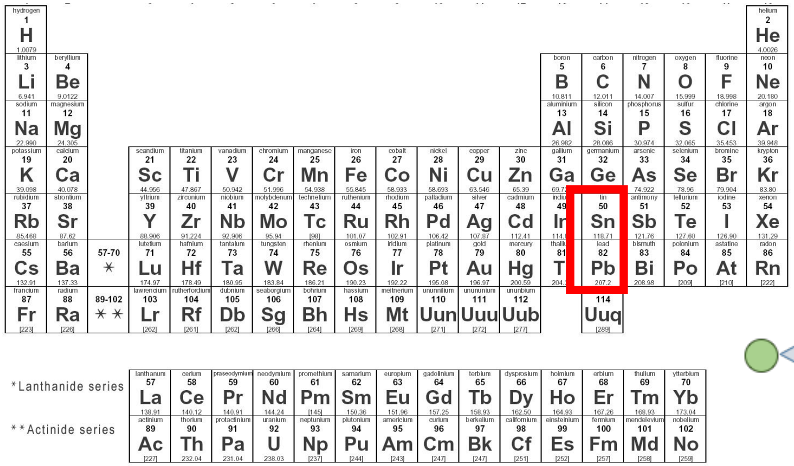
Perovskites are a possibility!

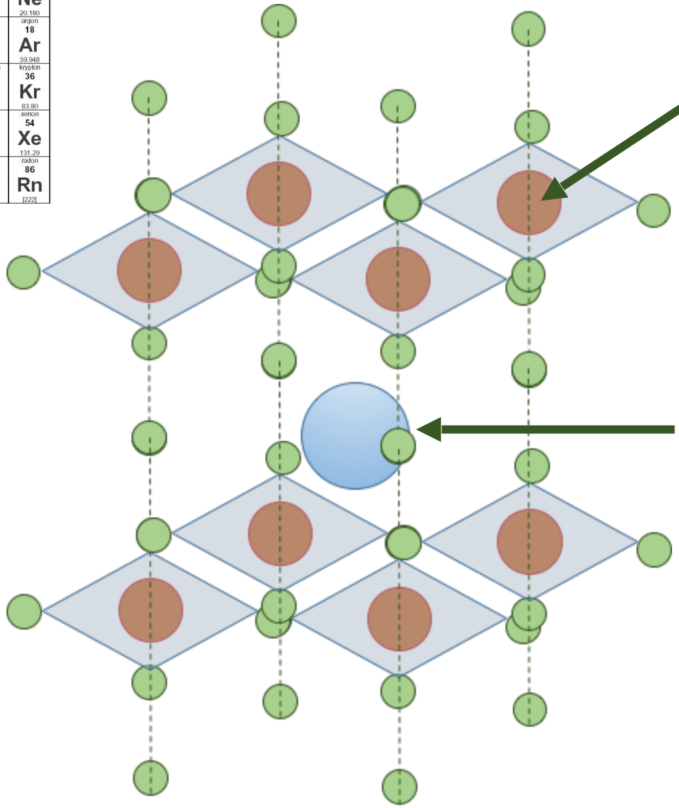




Organic or metal cation (Methyl ammonium or Cs+)

Perovskite crystal structure

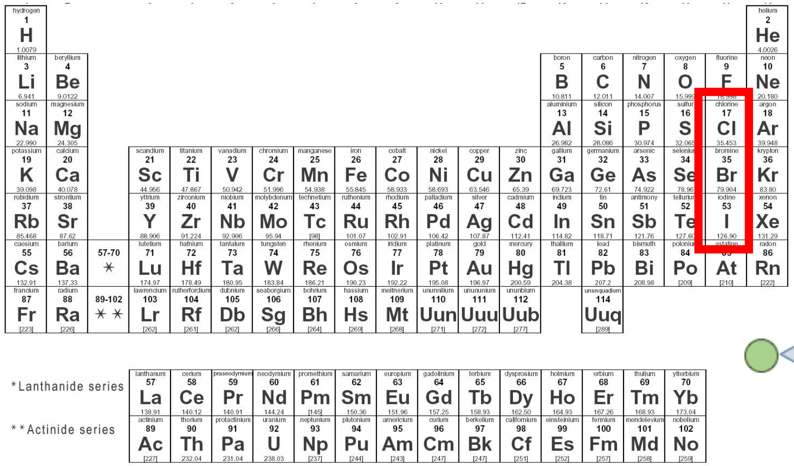


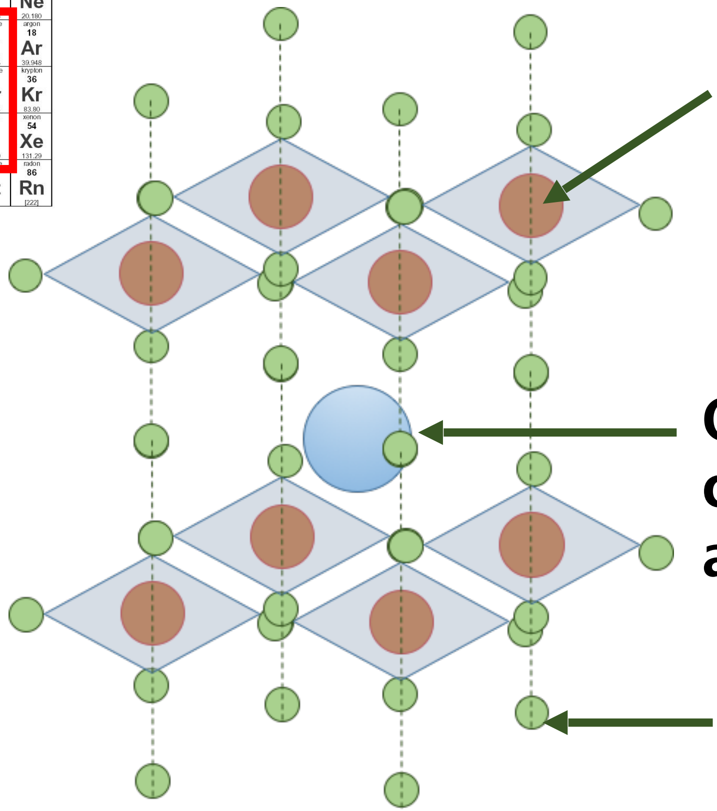


Divalent cation (Pb(II) or Sn(II))

Organic or metal cation (Methyl ammonium or Cs+)

Perovskite crystal structure



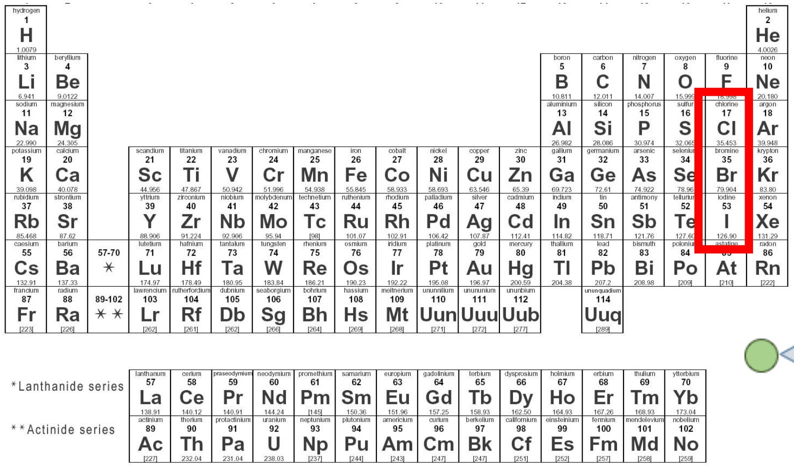


Divalent cation (Pb(II) or Sn(II))

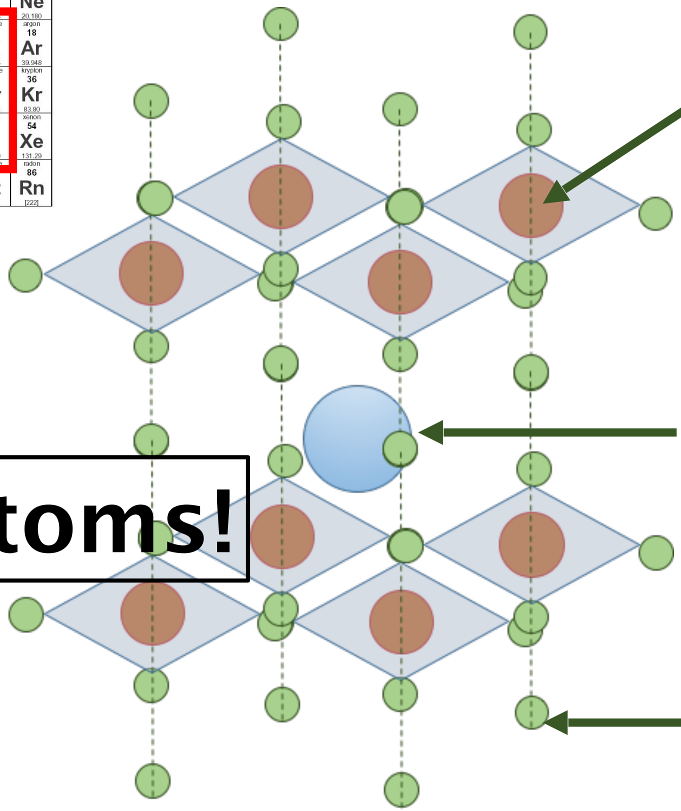
Organic or metal cation (Methyl ammonium or Cs+)

Halide anion (Cl−, Br−, I−)

Perovskite crystal structure



Mix and match atoms!

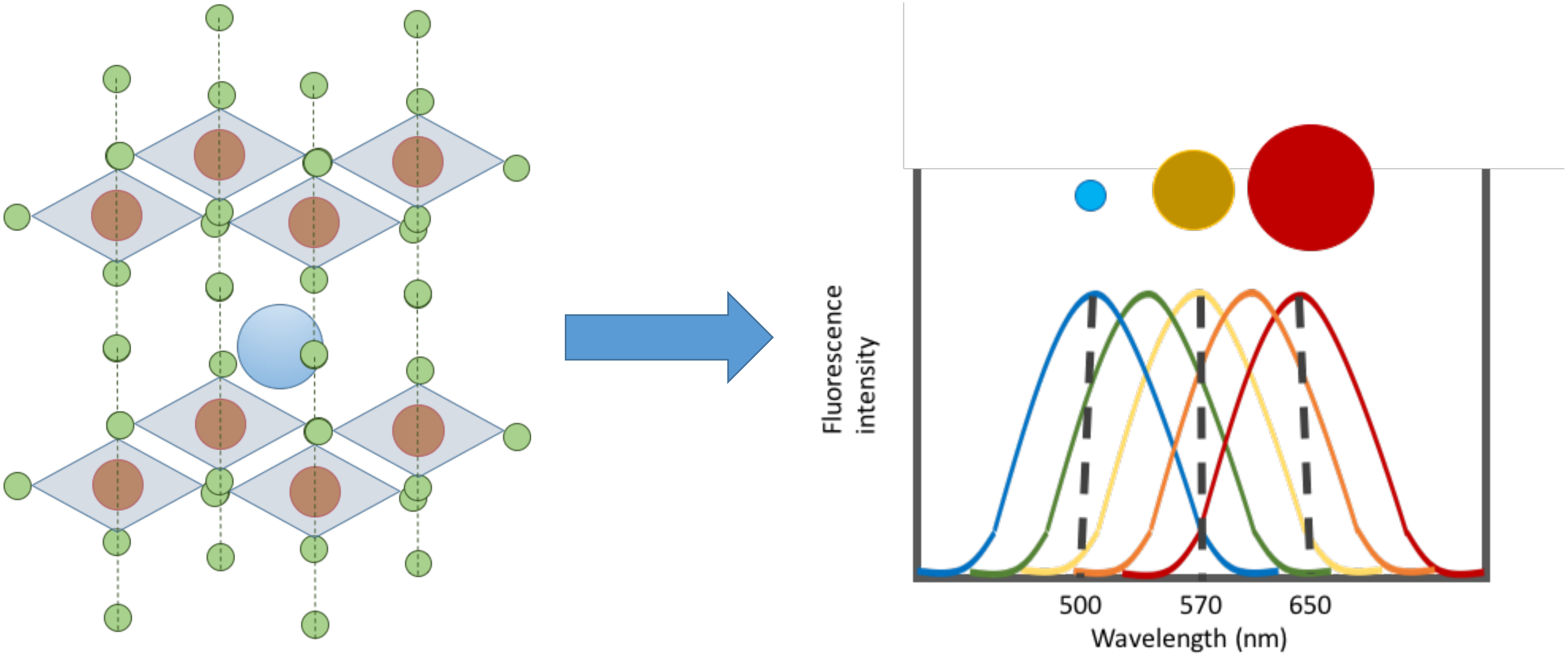


Divalent cation (Pb(II) or Sn(II))

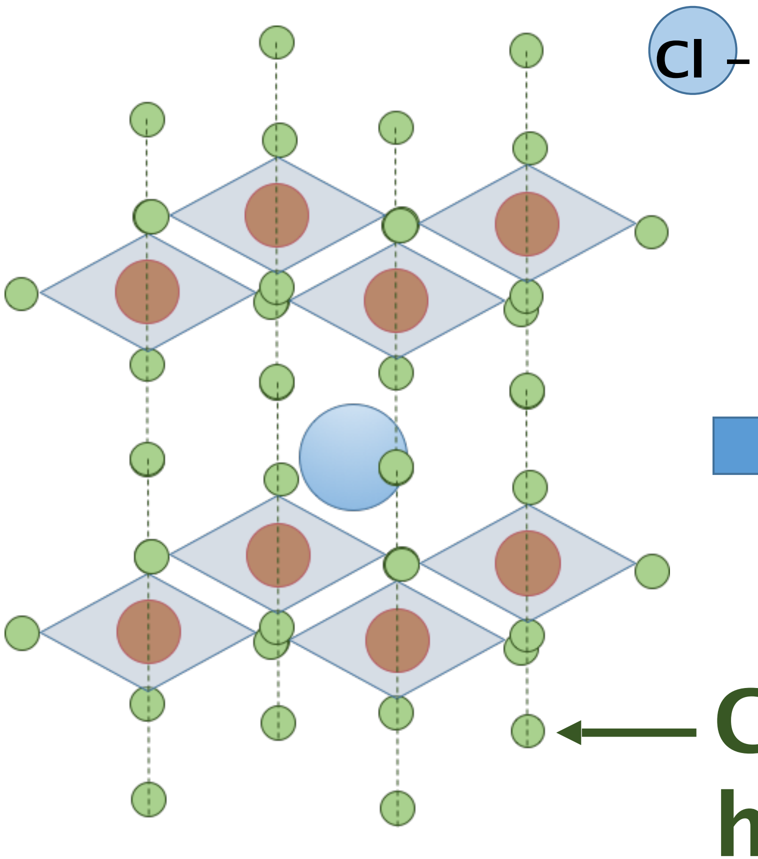
Organic or metal cation (Methyl ammonium or Cs+)

Halide anion (Cl–, Br–, I–)

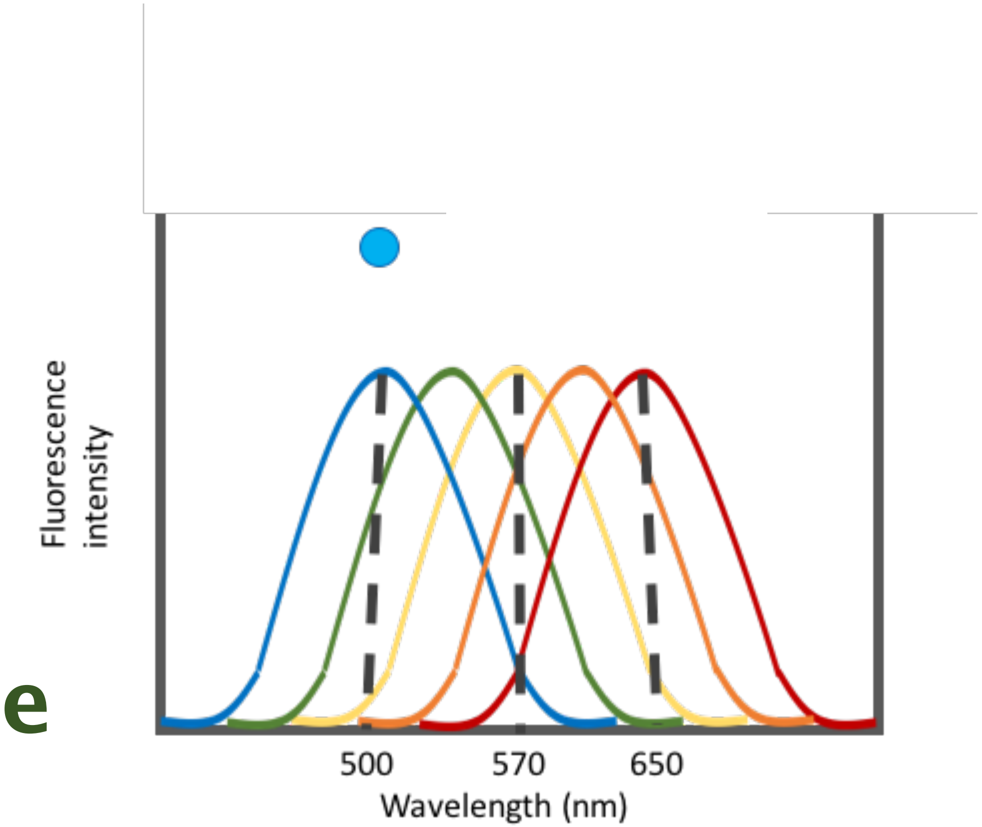
Perovskite crystal structure



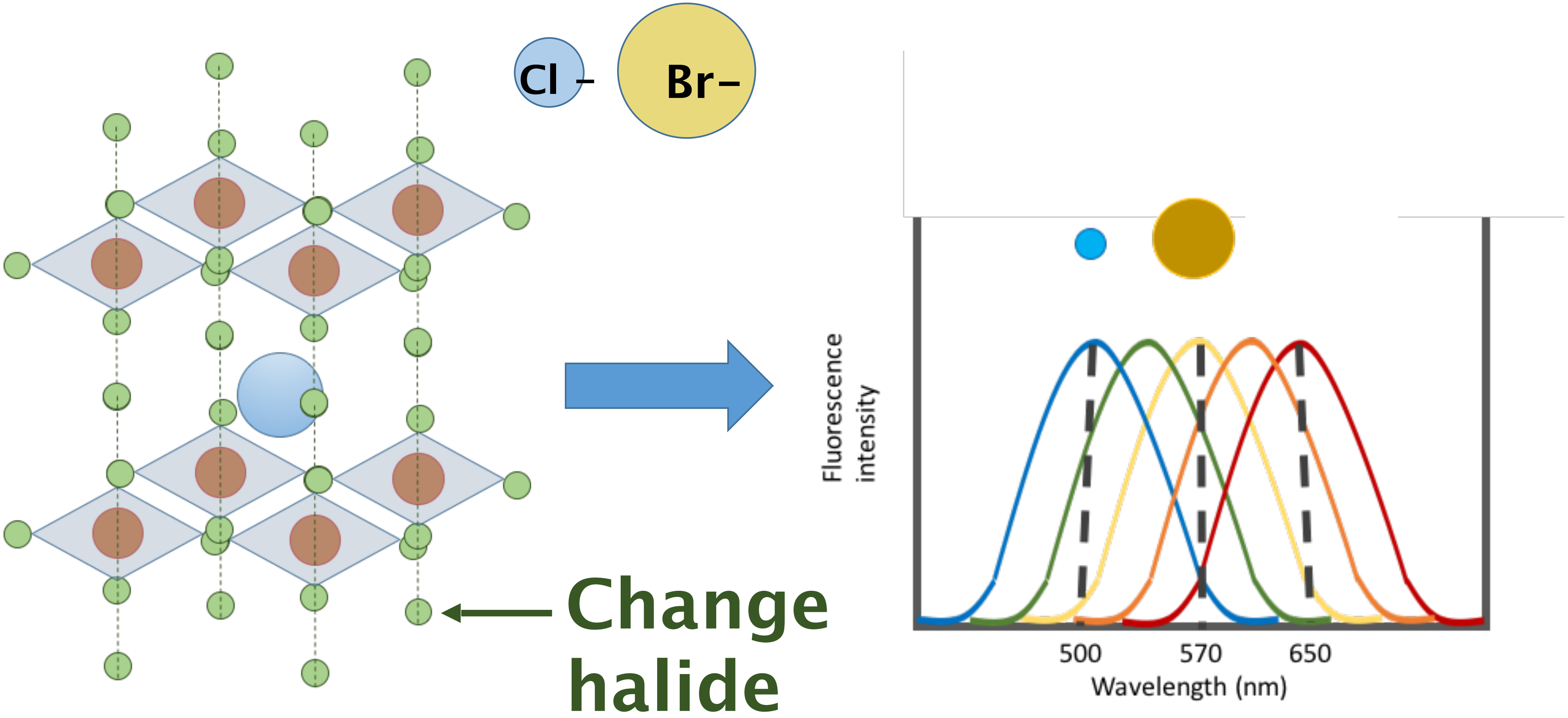
We can make quantum dots out of these!



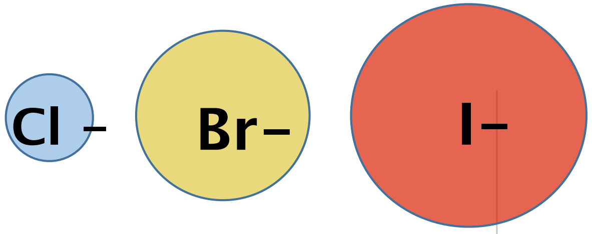
Change halide

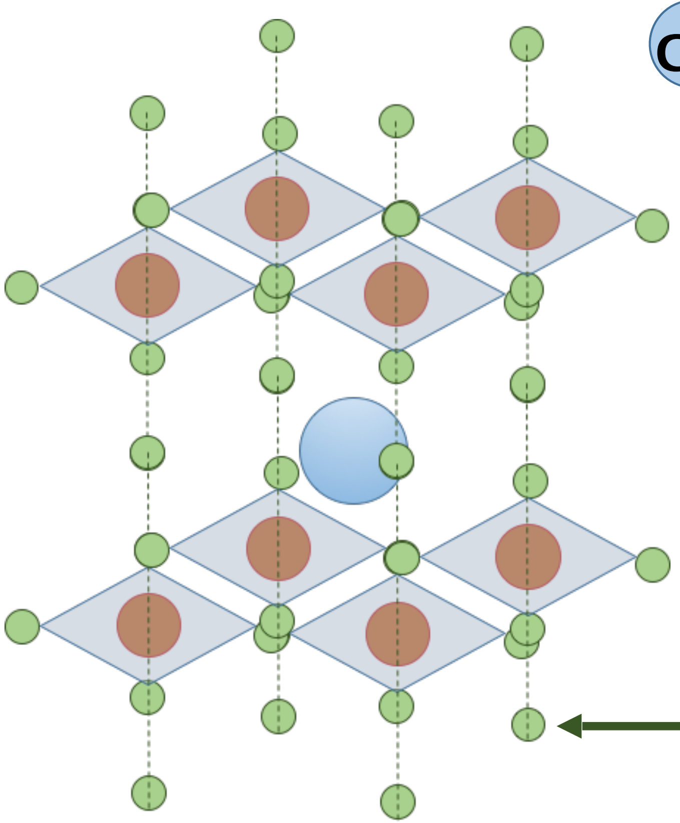


Recall: we can tune the size and fluorescence

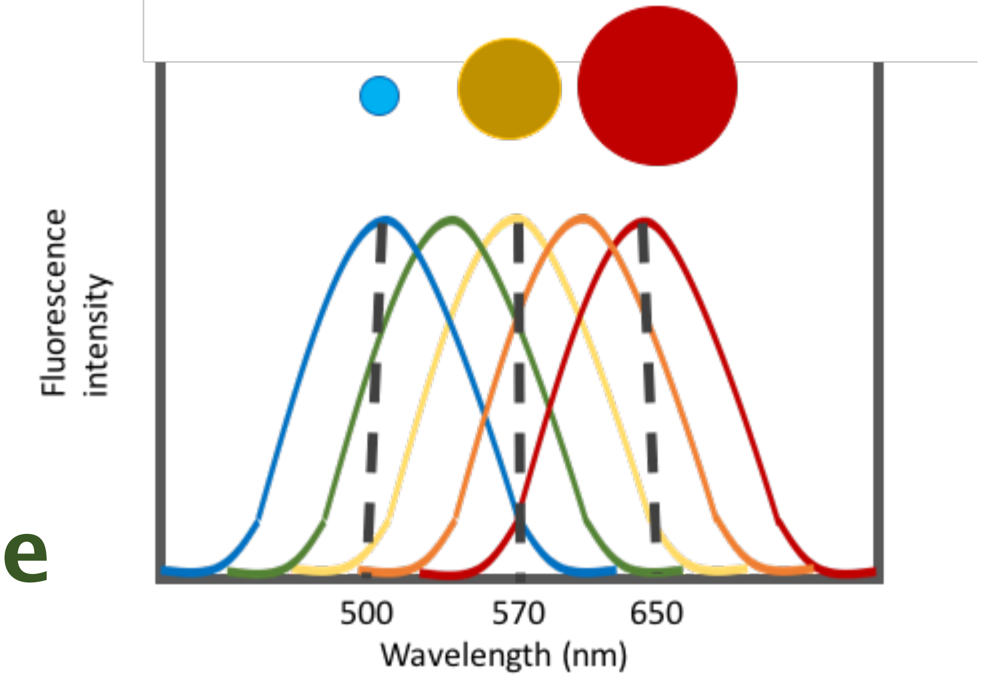


Recall: we can tune the size and fluorescence

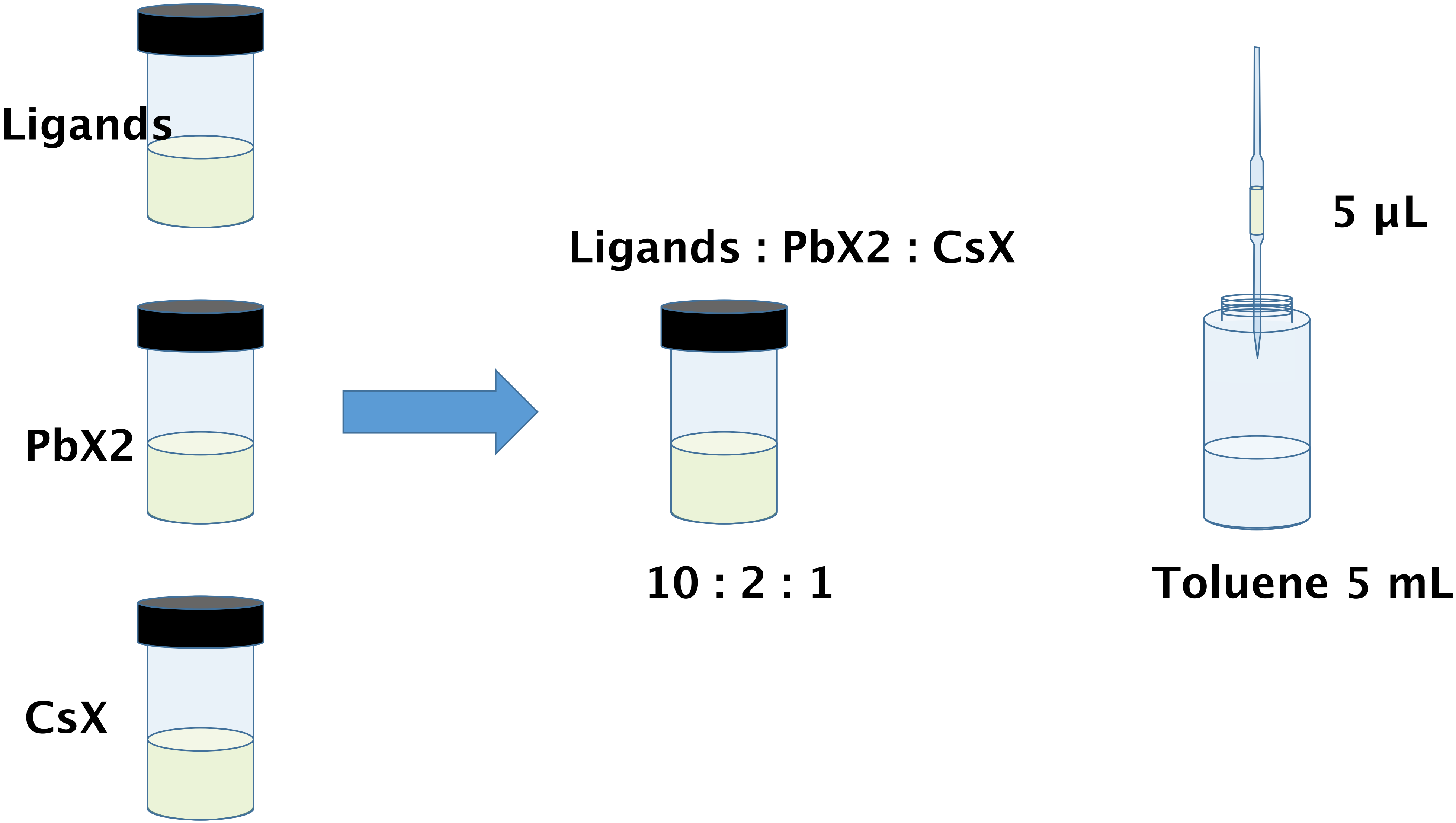




Change halide



Recall: we can tune the size and fluorescence



Ligands

PbX2

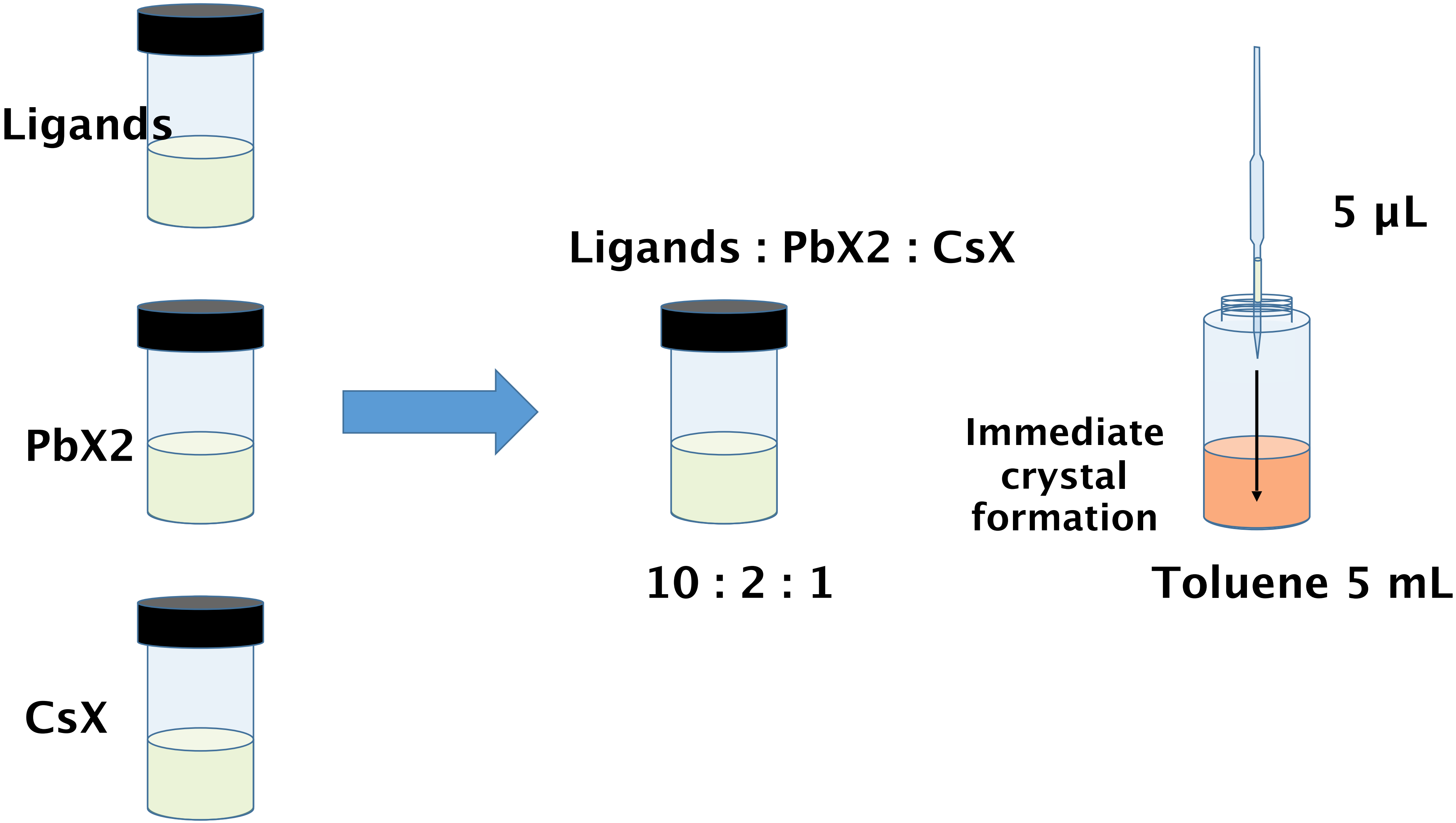
CsX

Ligands : PbX2 : CsX

10 : 2 : 1

5 µL

Toluene 5 mL



Ligands

PbX2

CsX

Ligands : PbX2 : CsX

10 : 2 : 1

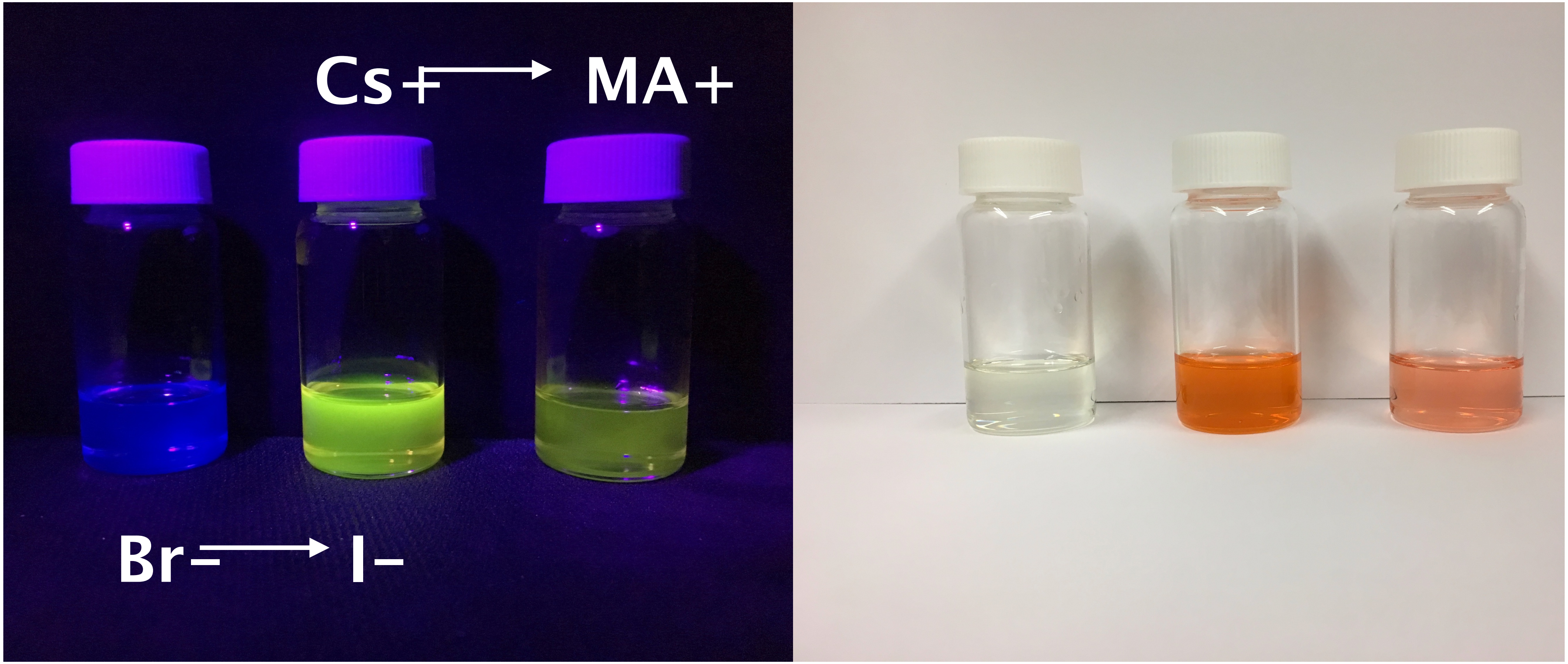
5 μL

Immediate crystal formation

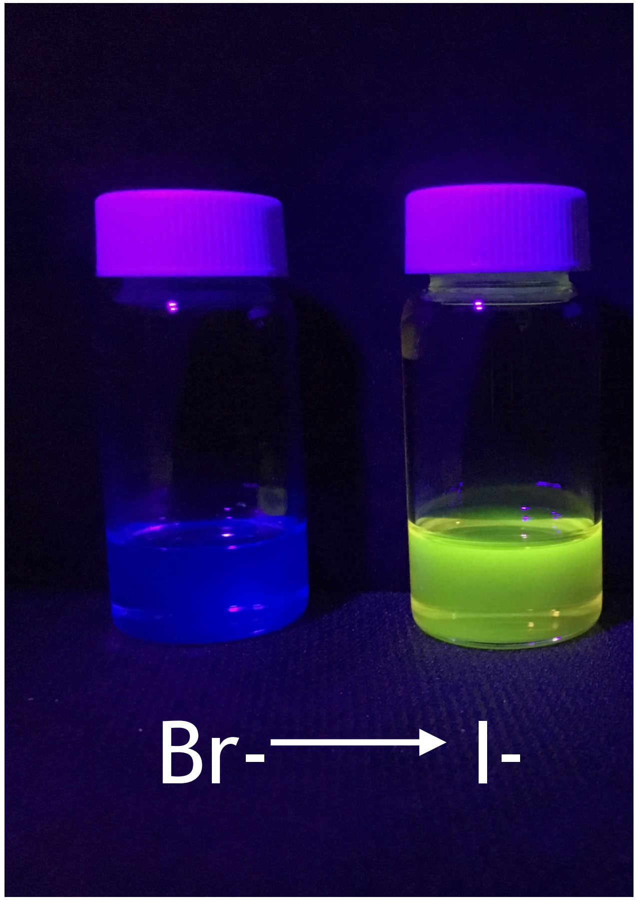
Toluene 5 mL

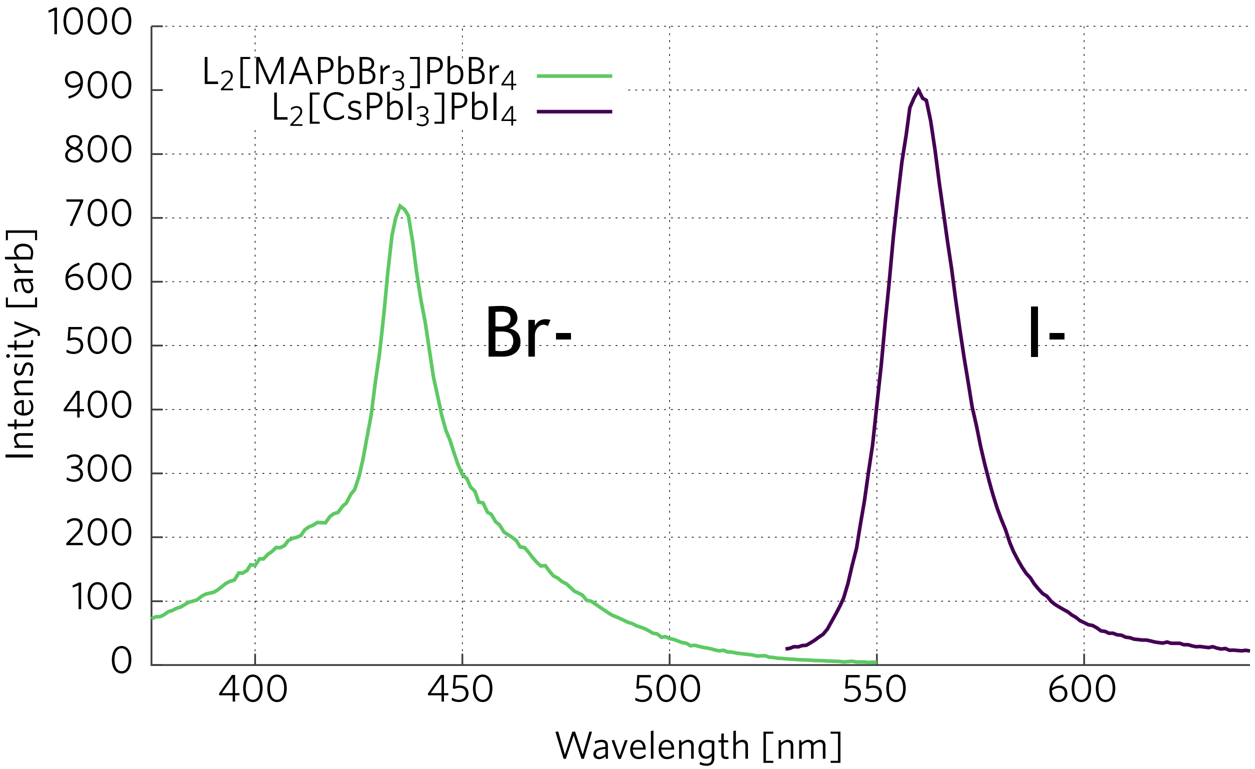
Synthesis is as easy as mixing solvent!

Perovskite quantum dots



Perovskite quantum dots





Fluorescence red shifts with growing halide

More results coming soon!

The End