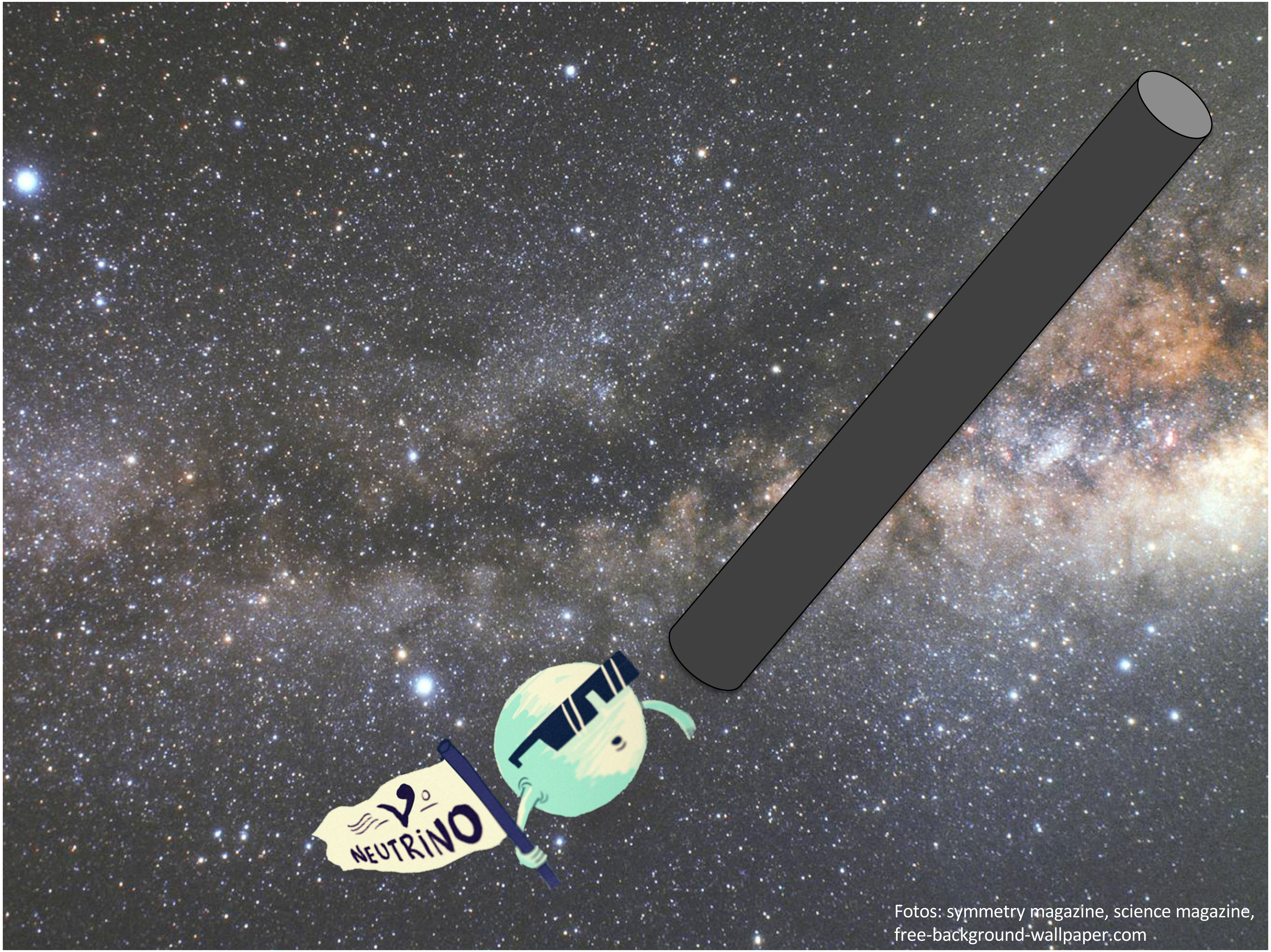
New Physics with Coherent Neutrino-Nucleus Scattering

Raimund Strauss
Technical University of Munich
Bormio Winter Meeting,
21.01.2020

Fotos: symmetry magazine, science magazine,
free-background-wallpaper.com



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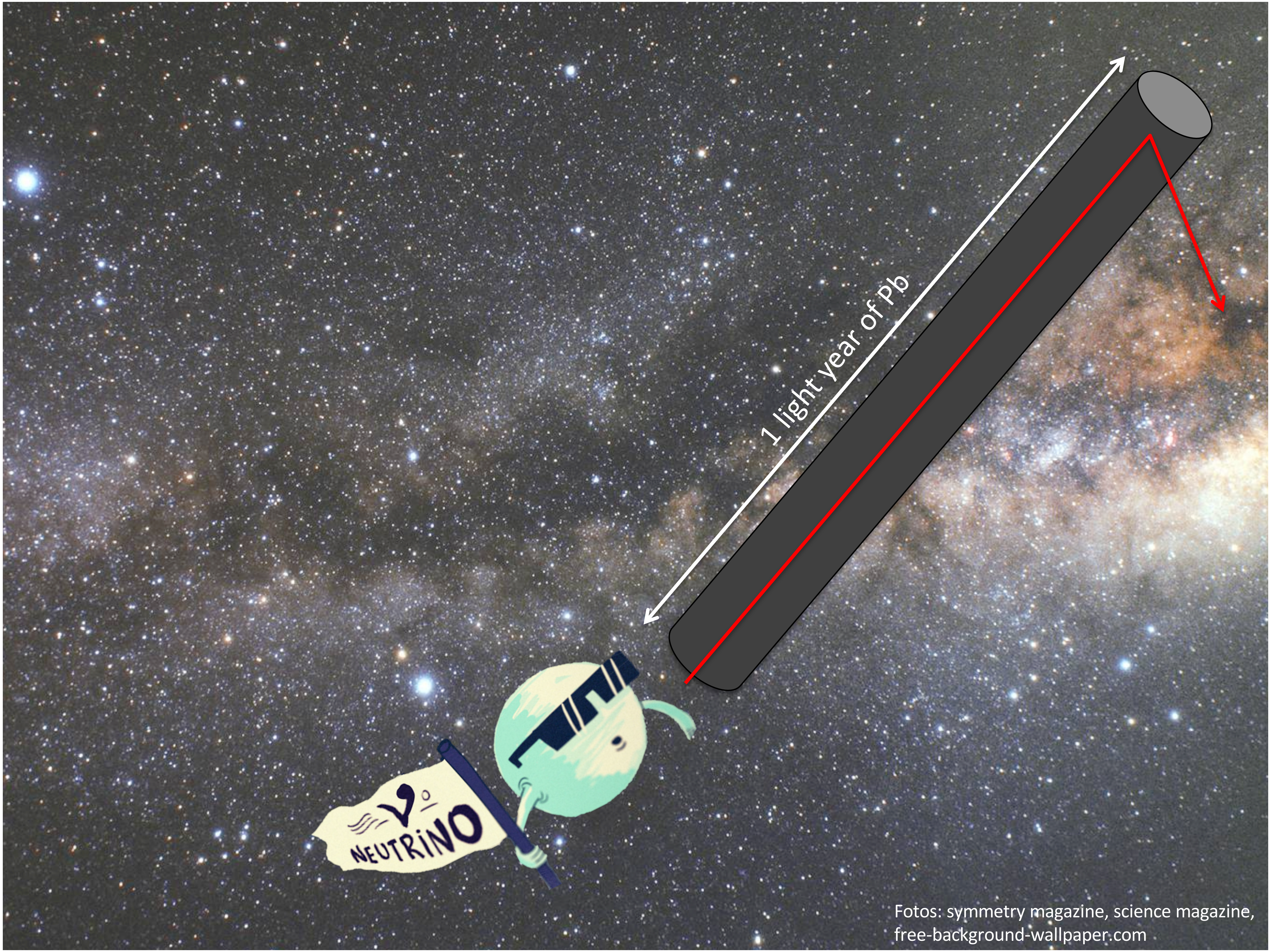
1 light year of Pb
NEUTRINO
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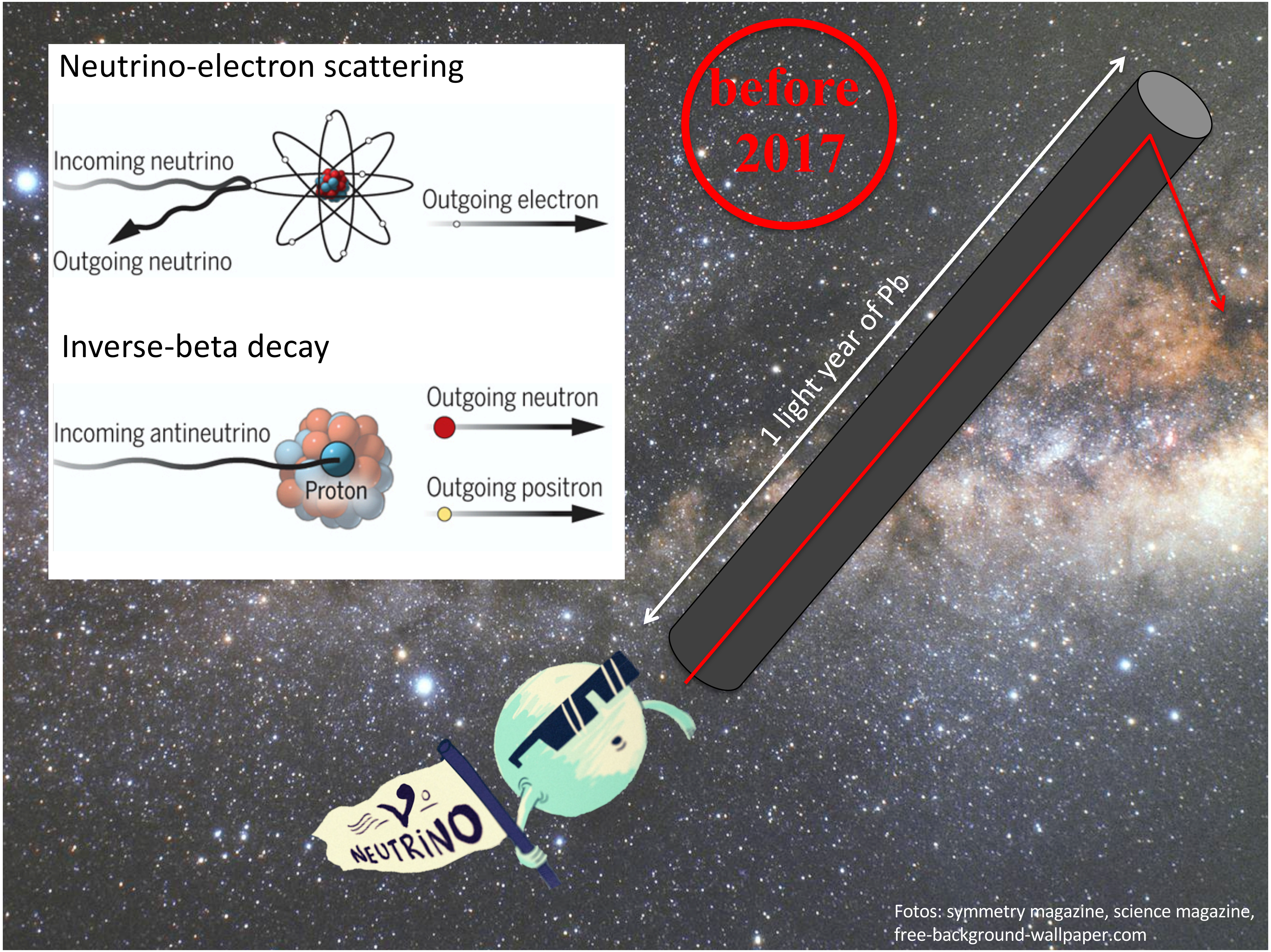
Neutrino-electron scattering
Incoming neutrino
Outgoing neutrino
Outgoing electron
Inverse-beta decay
Incoming antineutrino
Proton
Outgoing neutron
Outgoing positron
before 2017
1 light year of Pb
NEUTRINO
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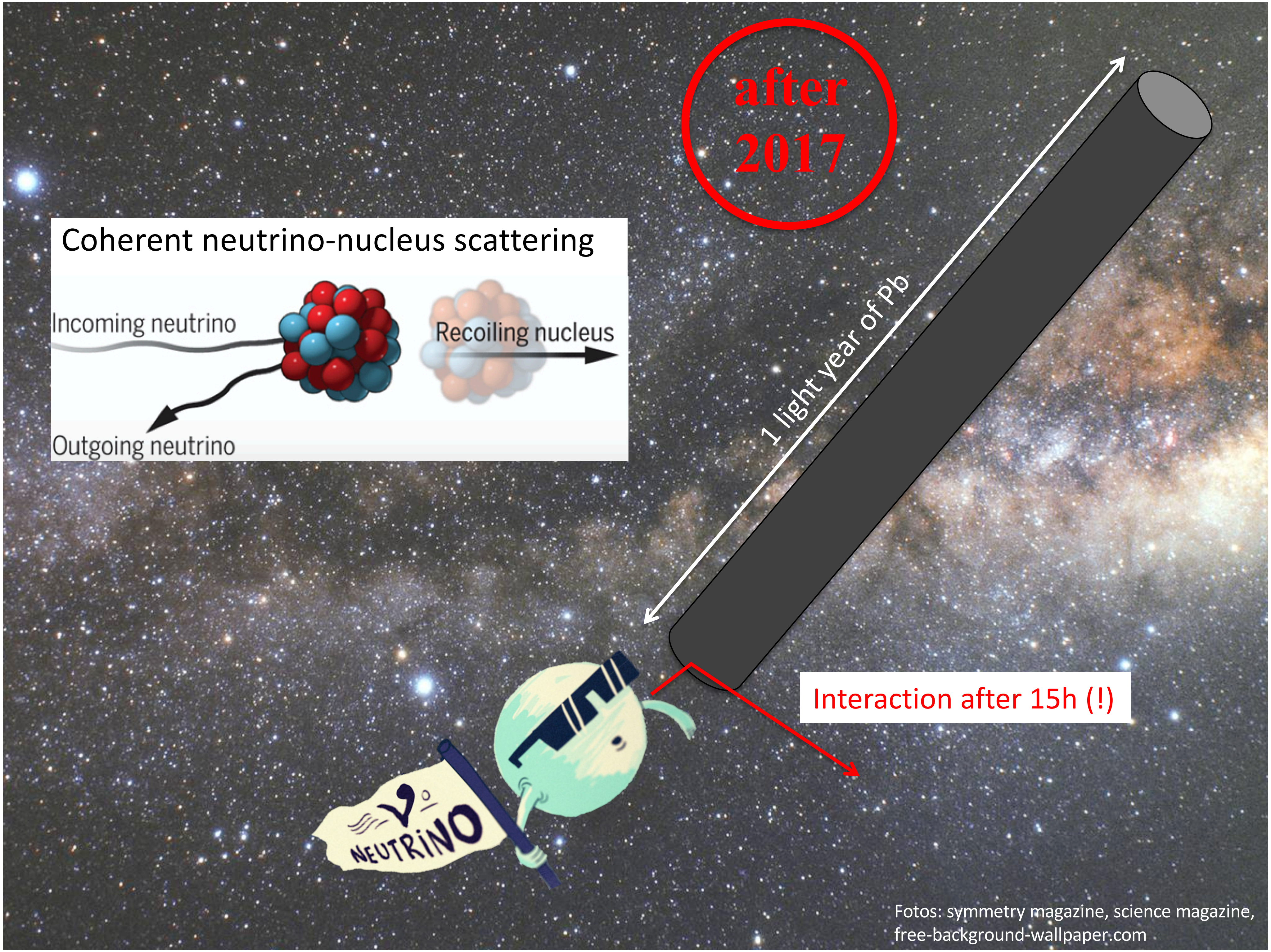
after 2017
Coherent neutrino-nucleus scattering
Incoming neutrino
Recoiling nucleus
Outgoing neutrino
1 light year of Pb
Interaction after 15h (!)
NEUTRINO
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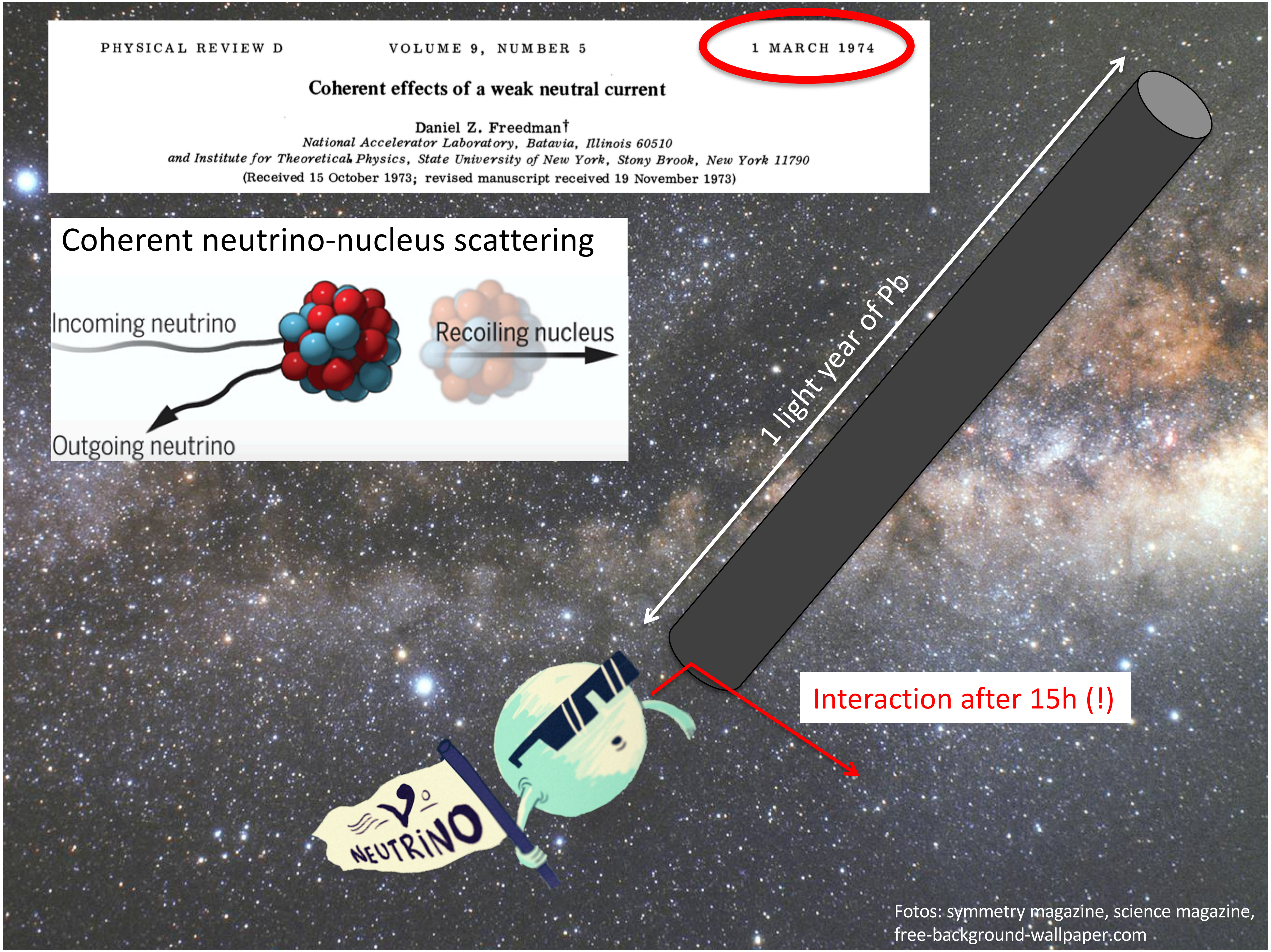
PHYSICAL REVIEW D
VOLUME 9, NUMBER 5
1 MARCH 1974
Coherent effects of a weak neutral current
Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)
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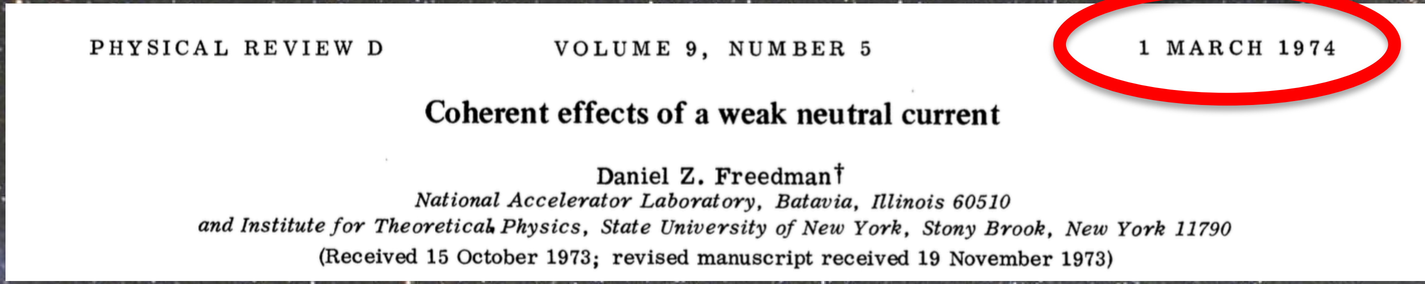
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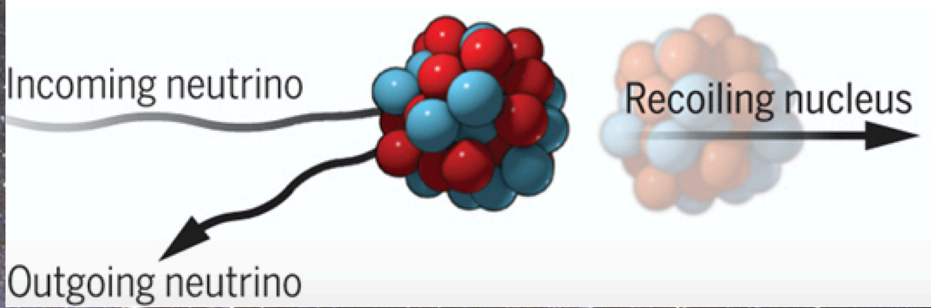
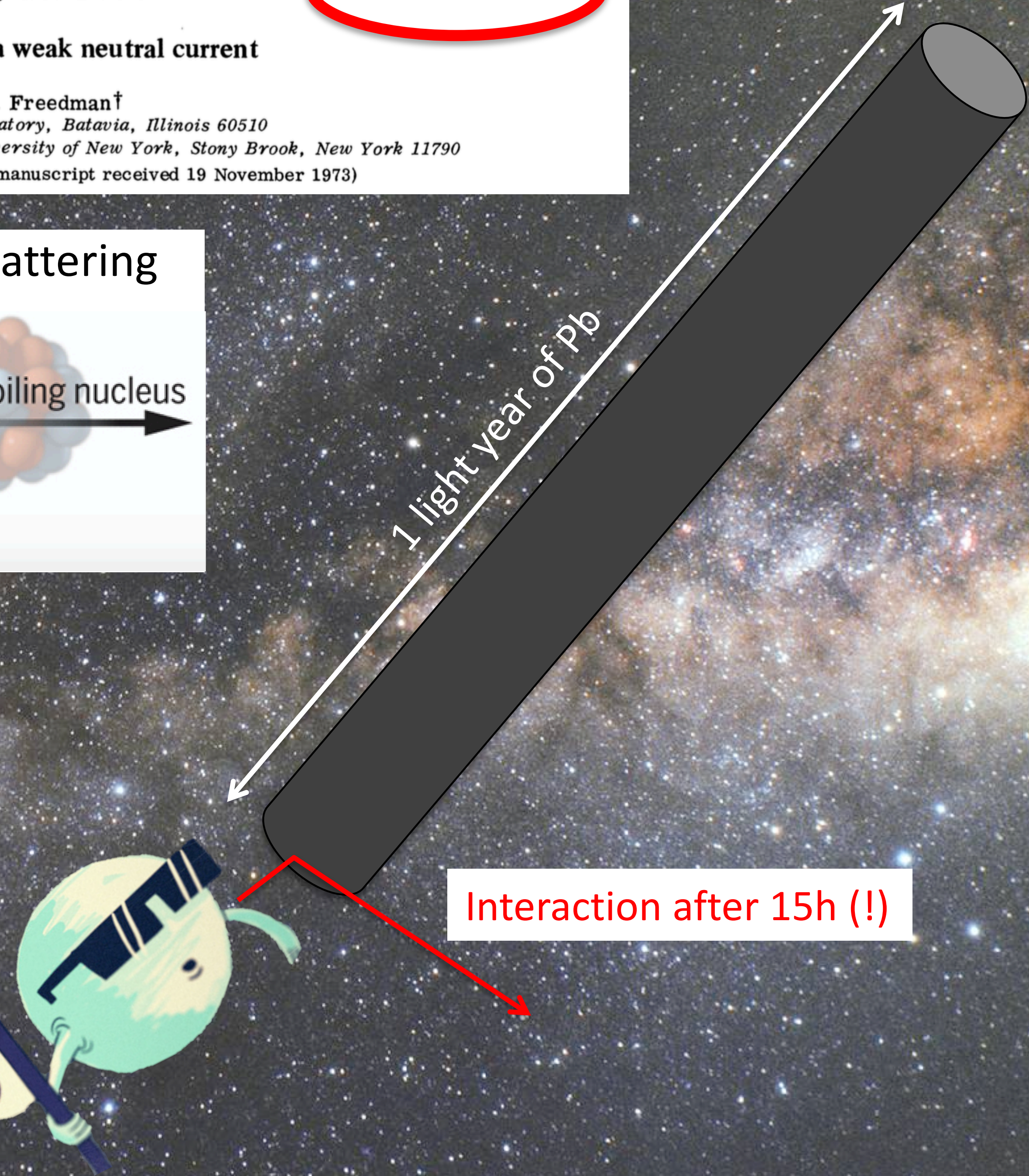


Potential:

- Precision test of SM
- Portal to new physics
- Miniaturization of neutrino detectors



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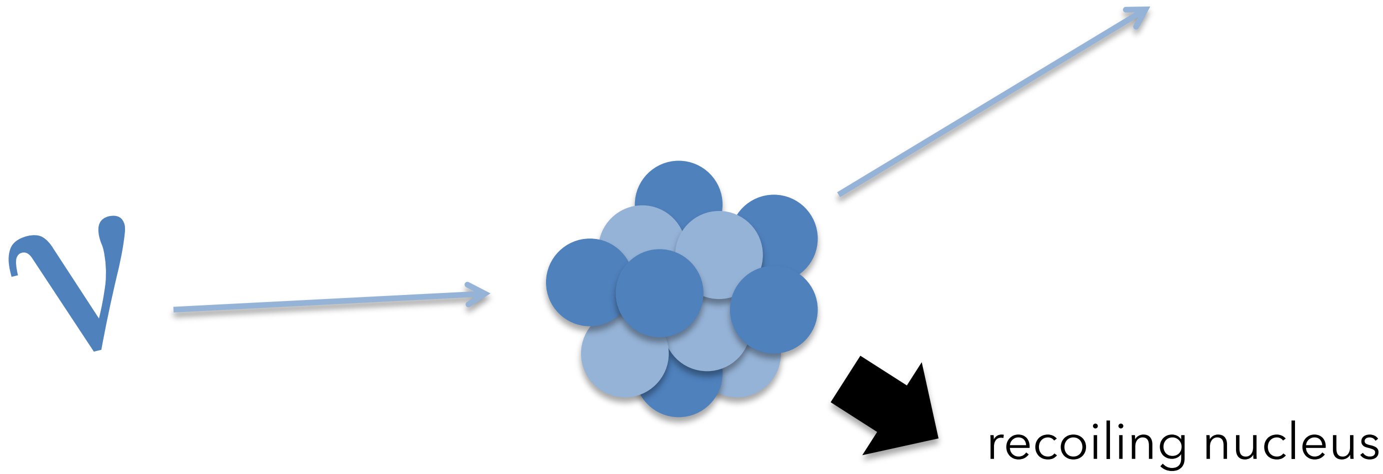
Coherent Neutrino-Nucleus Scattering



- Elastic <u>coherent</u> scattering off nuclei

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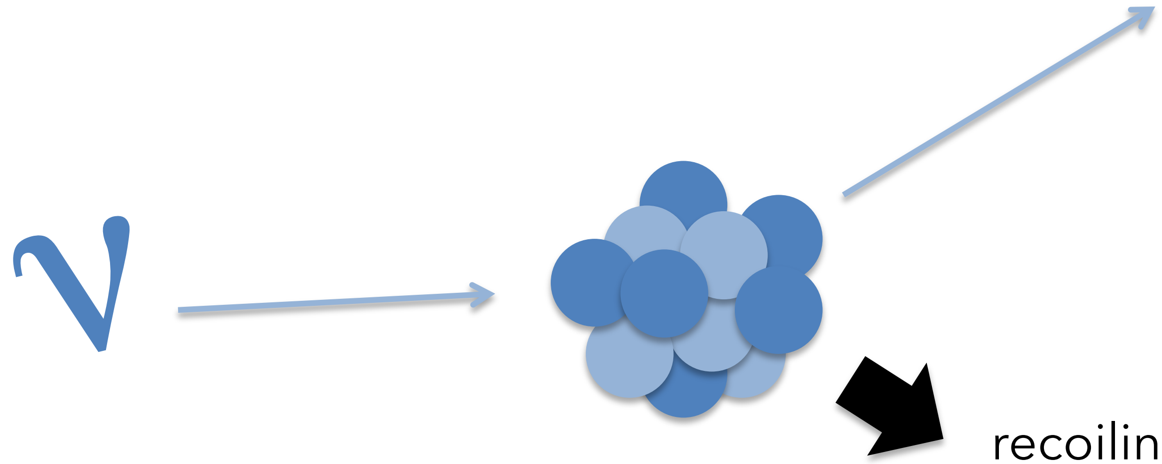

recoiling nucleus

- Elastic coherent scattering off nuclei

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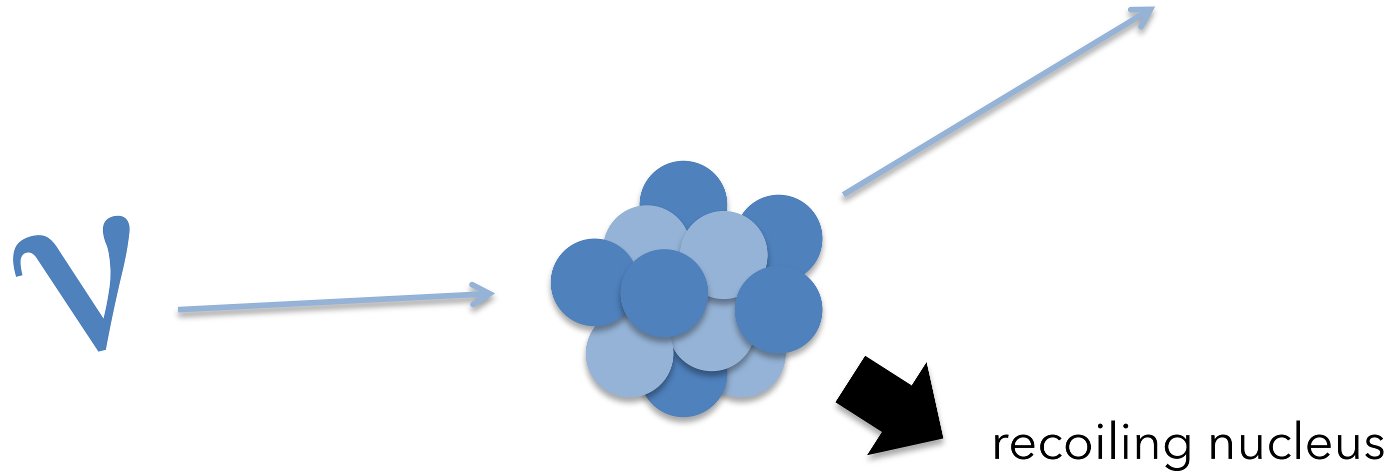


- Elastic <u>coherent</u> scattering off nuclei

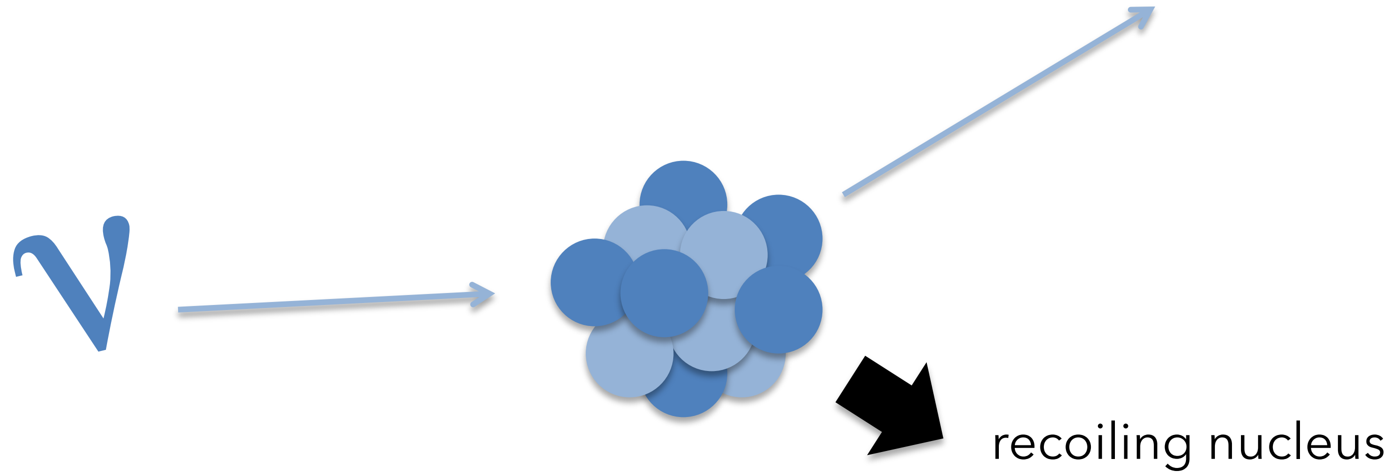
- Weak neutral current process

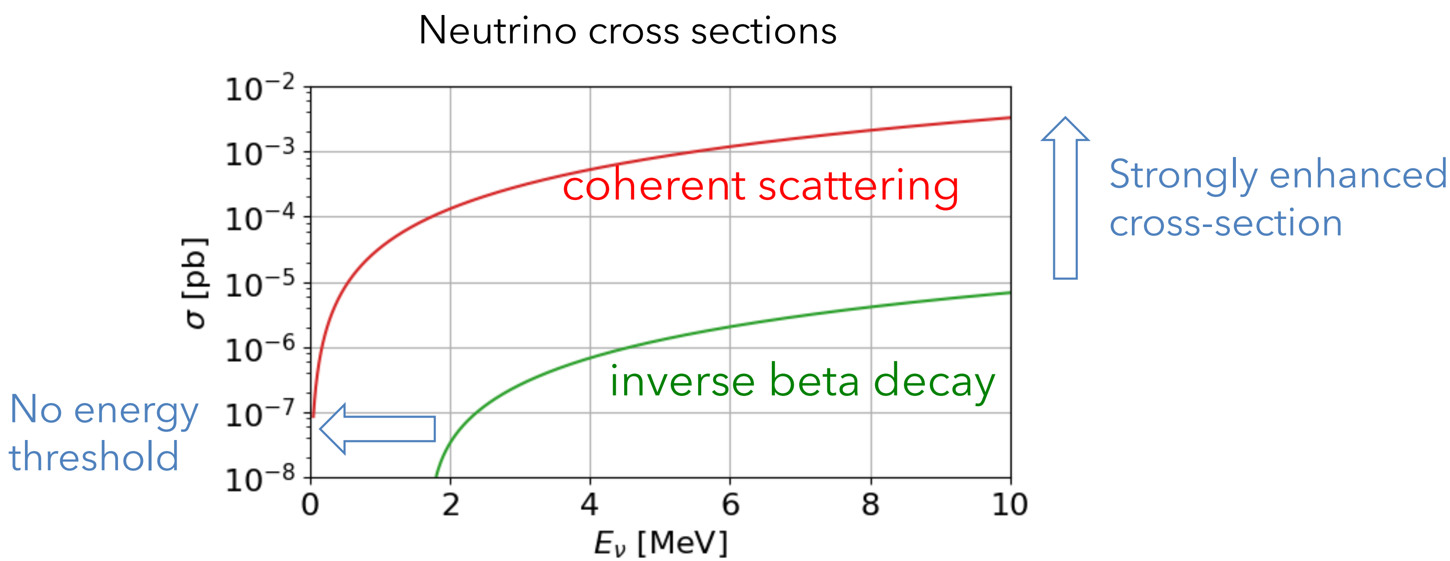
$$\sigma \propto N^2$$

cross-section

neutron number

Coherent Neutrino-Nucleus Scattering





Raimund Strauss (Bormio Winter Meeting)

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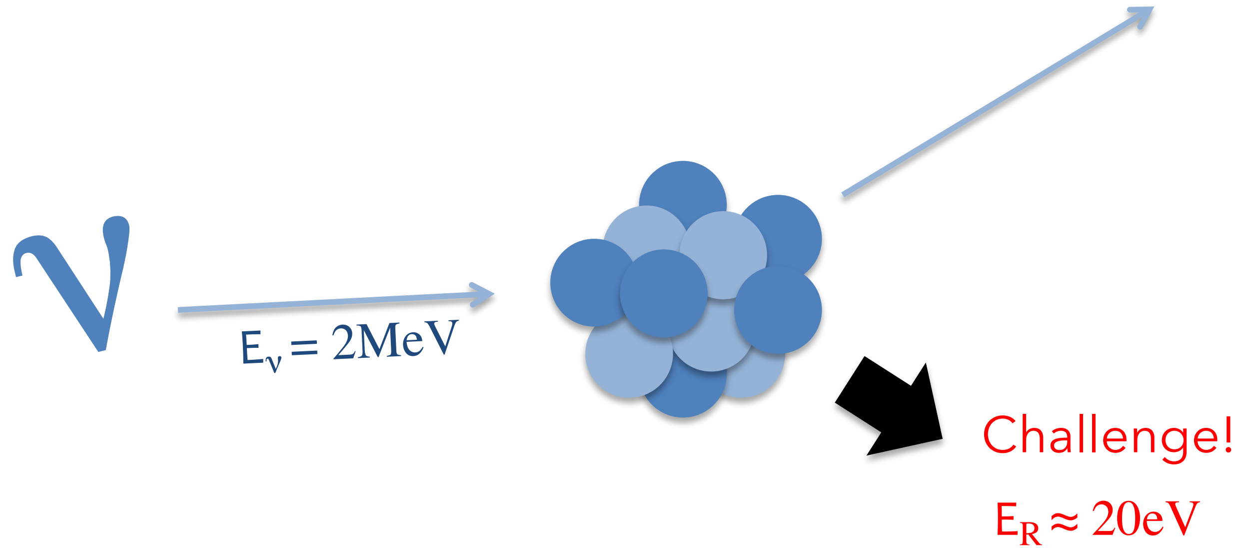

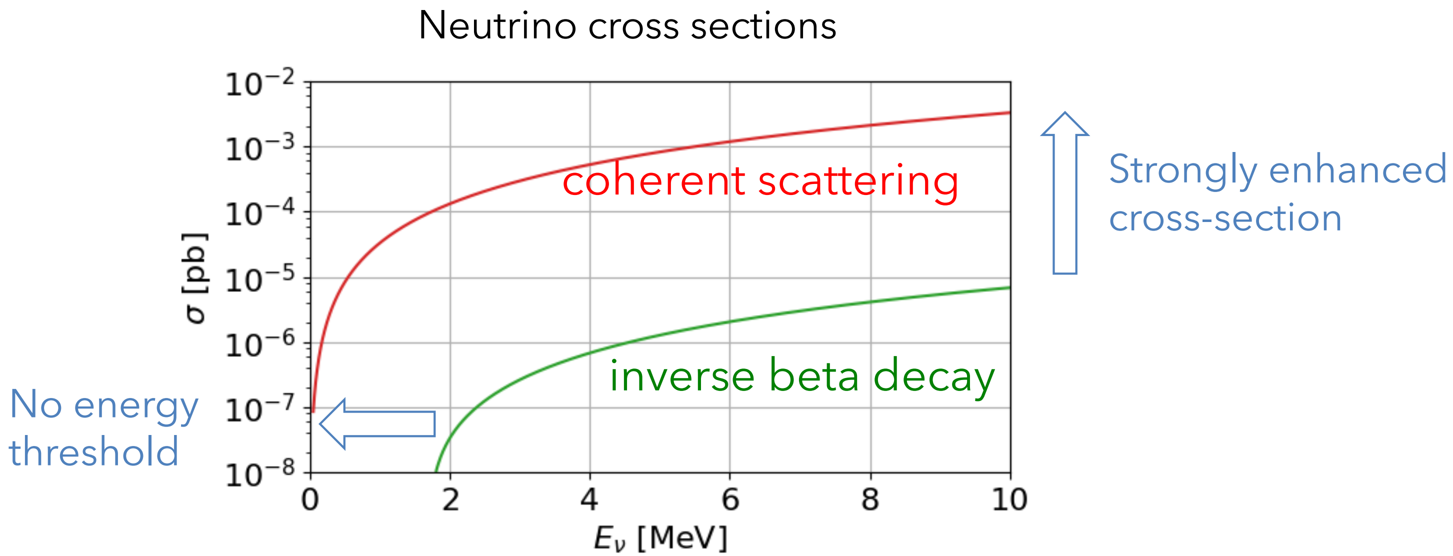

What to do with *Coherent Elastic Neutrino-Nucleus Scattering* ?

What to do with *CEvNS*?

What to do with *7s*?

What to do with *7s*?

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany
(Received 21 November 1983)

Advantages of CEvNS:

- Cross-sections orders of magnitude larger
- Equal response to all known neutrino flavours
- Response to neutrinos of all energies (threshold-less)
- Known (target) material dependence

Experiments and applications of CEvNS:

- Spallation-source neutrinos
- Supernova bursts
- Reactor neutrinos
- Solar neutrinos
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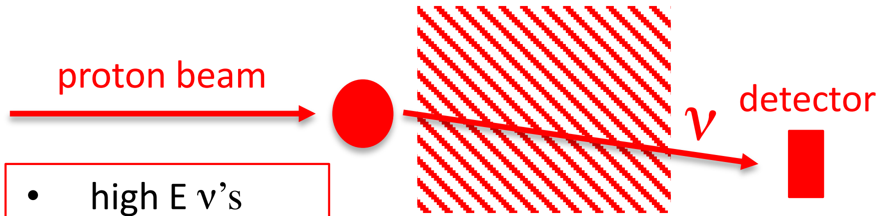
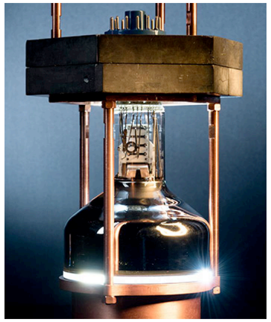
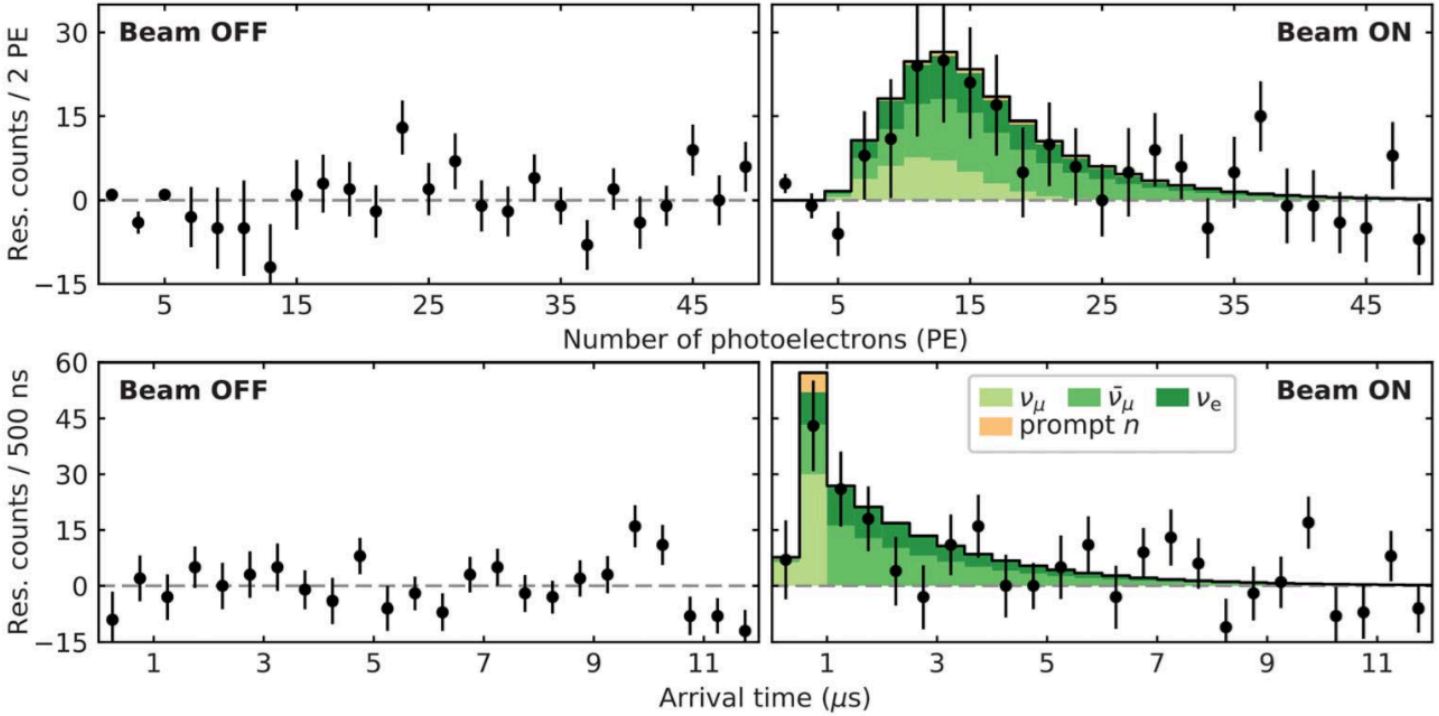


- high E ν's
- timing
- backgrounds!



Results of COHERENT 2017

308 live-days



6.7 sigma evidence for a CNNS signal

Observed:	134±22 events
Expected (SM):	173±48 events

Akimov *et al.*, *Science* **357**, 1123–1126 (2017)   15 September 2017

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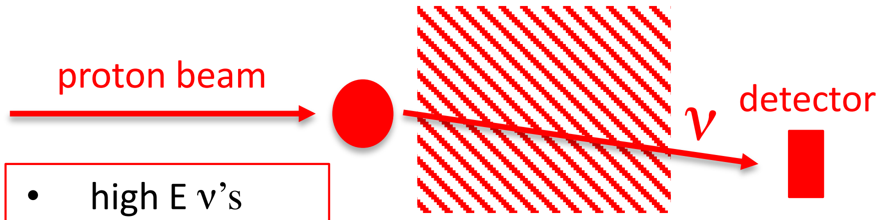
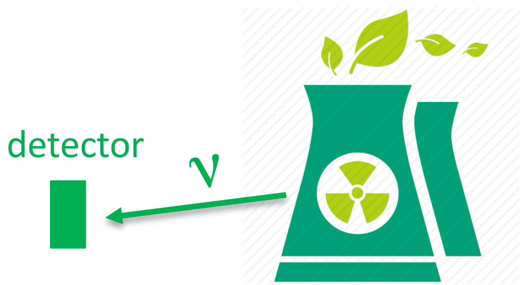


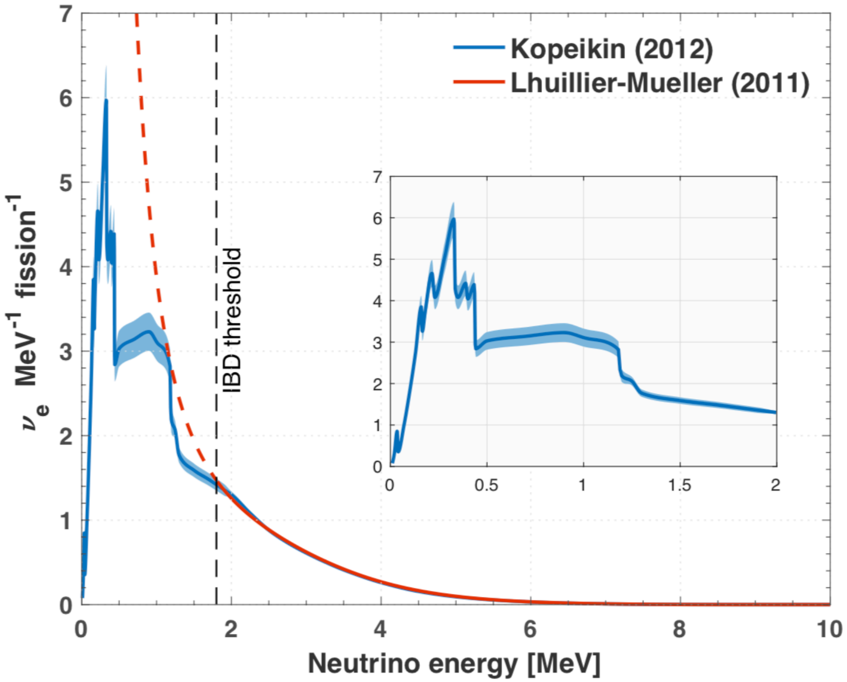
- high E ν's
- timing
- backgrounds!

- low E ν's
- Intense source
- no timing
- low systematics?



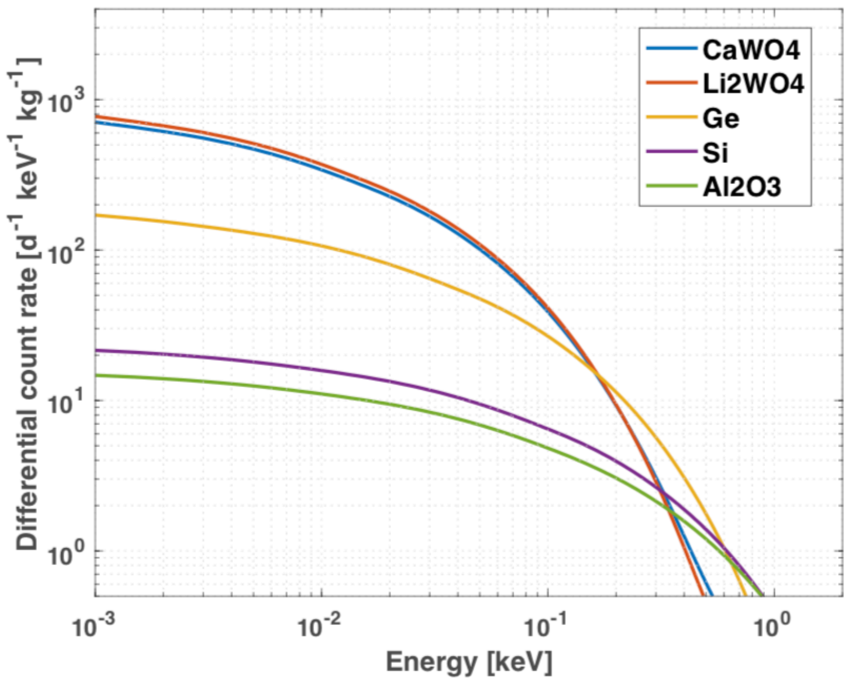
CEvNS at Reactors

Reactor antineutrino spectrum



- High flux: 10^{12}-10^{13} cm^{-2} s^{-1}
- Intense at low energies

Recoil spectrum in detector from CEvNS



- Low threshold required (<1keV)
- Strong Material dependence (N^2)
- Full coherence

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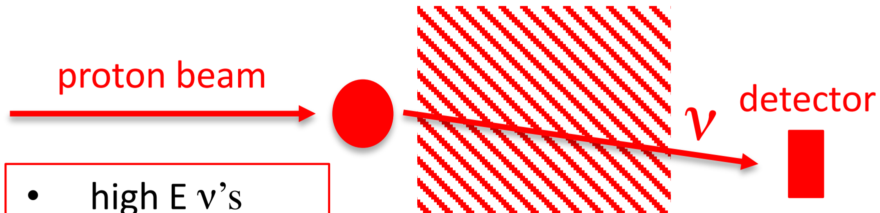

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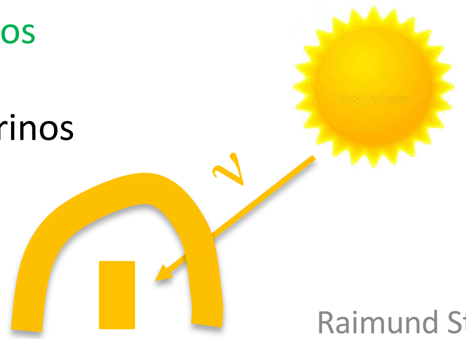

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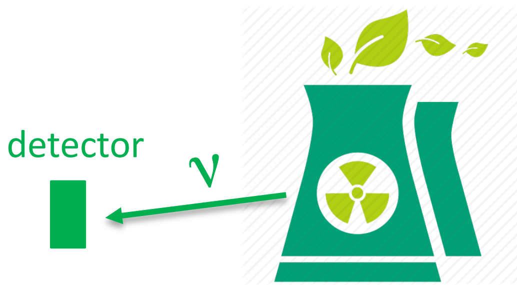
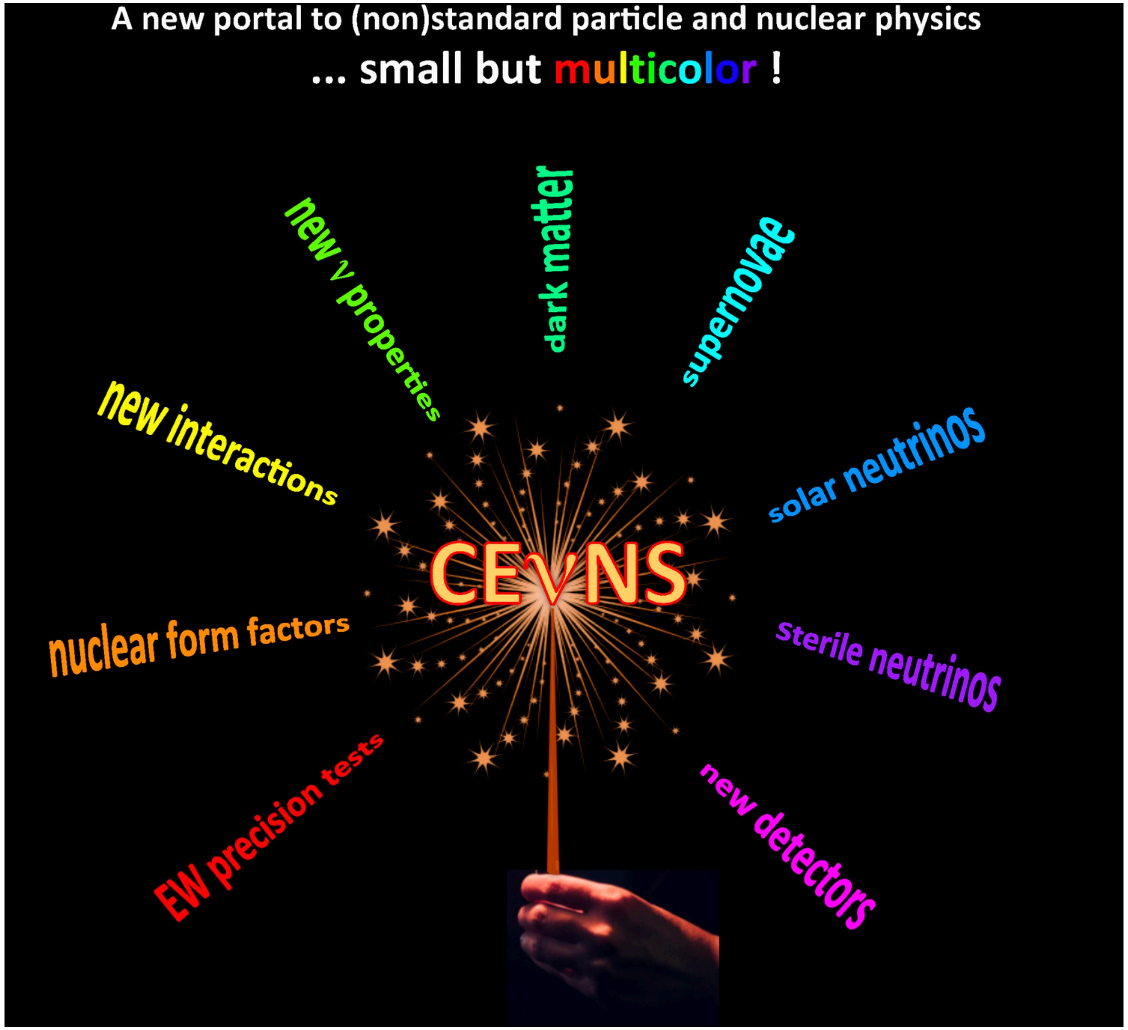


CEvNS Physics Potential



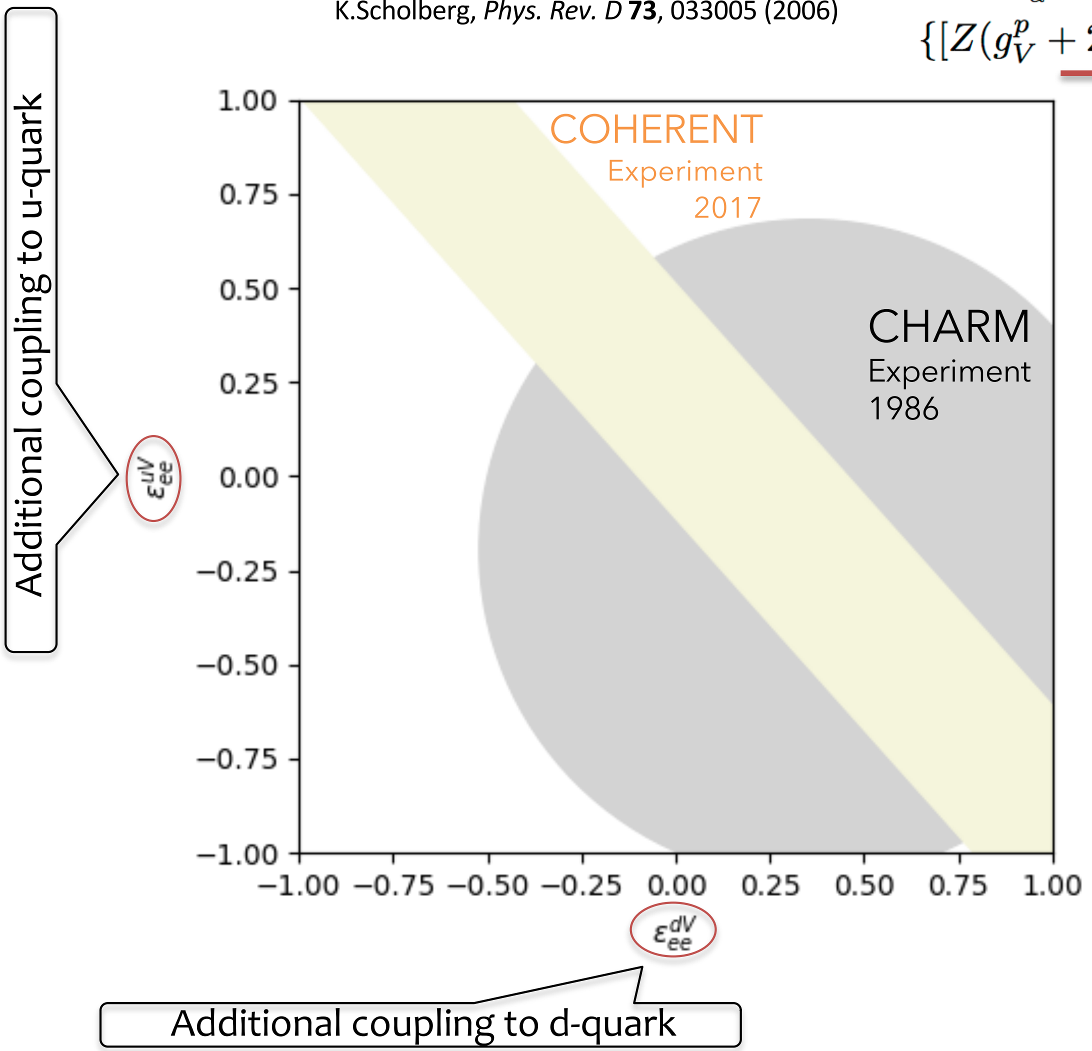
From E. Lisi,
Neutrino2018 Opening Talk

Neutrino Non-Standard Interactions

Standard parametrization of modified CNNS cross-section:
K.Scholberg, *Phys. Rev. D* **73**, 033005 (2006)

$$\left(\frac{d\sigma}{dE}\right)_{\nu_\alpha A} = \frac{G_F^2 M}{\pi} F^2(2ME)\left[1 - \frac{ME}{2k^2}\right] \times \qquad (4)$$
$$\{[Z(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}) + N(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})]^2$$

With $g_V^p = (\frac{1}{2} - 2\sin^2\theta_W)$
and $g_V^n = -\frac{1}{2}$



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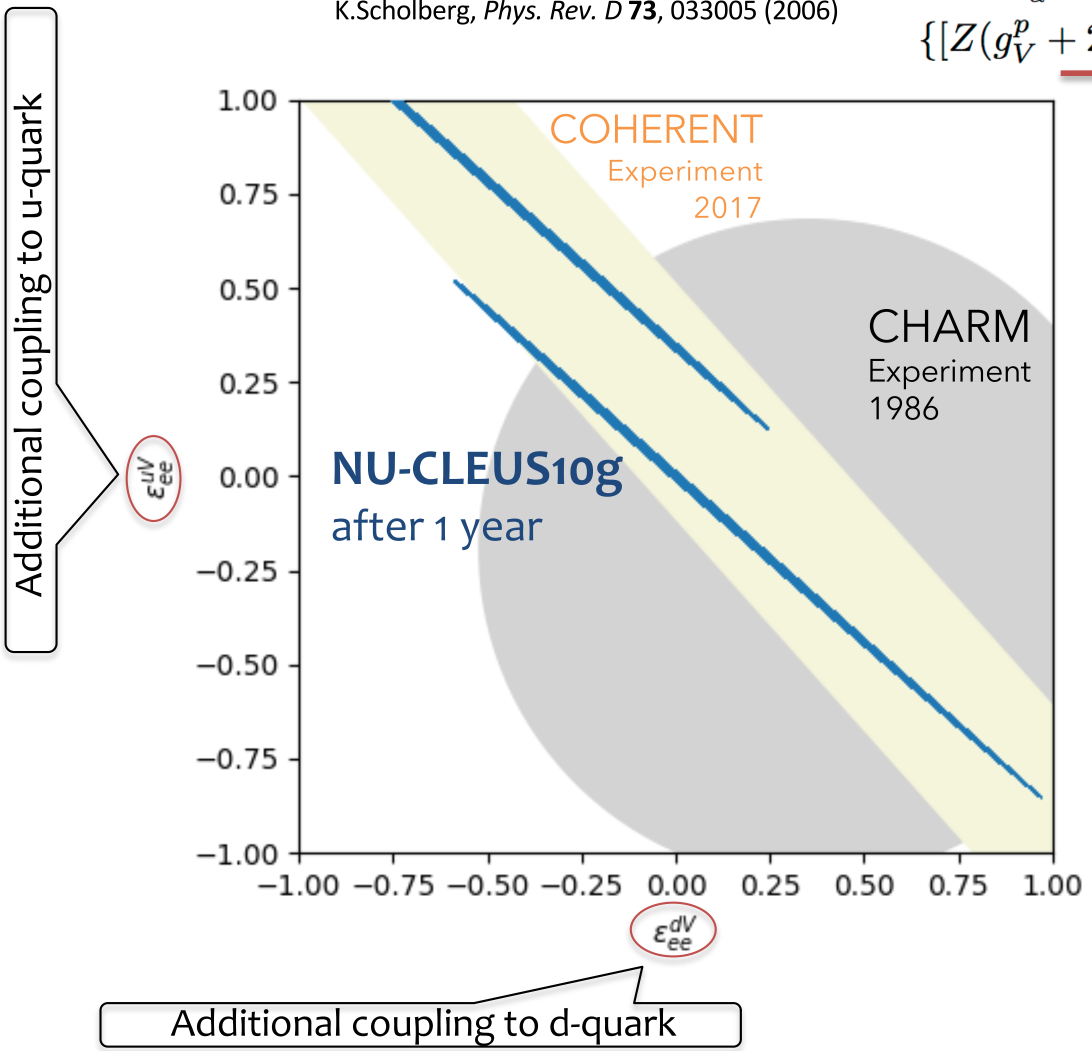
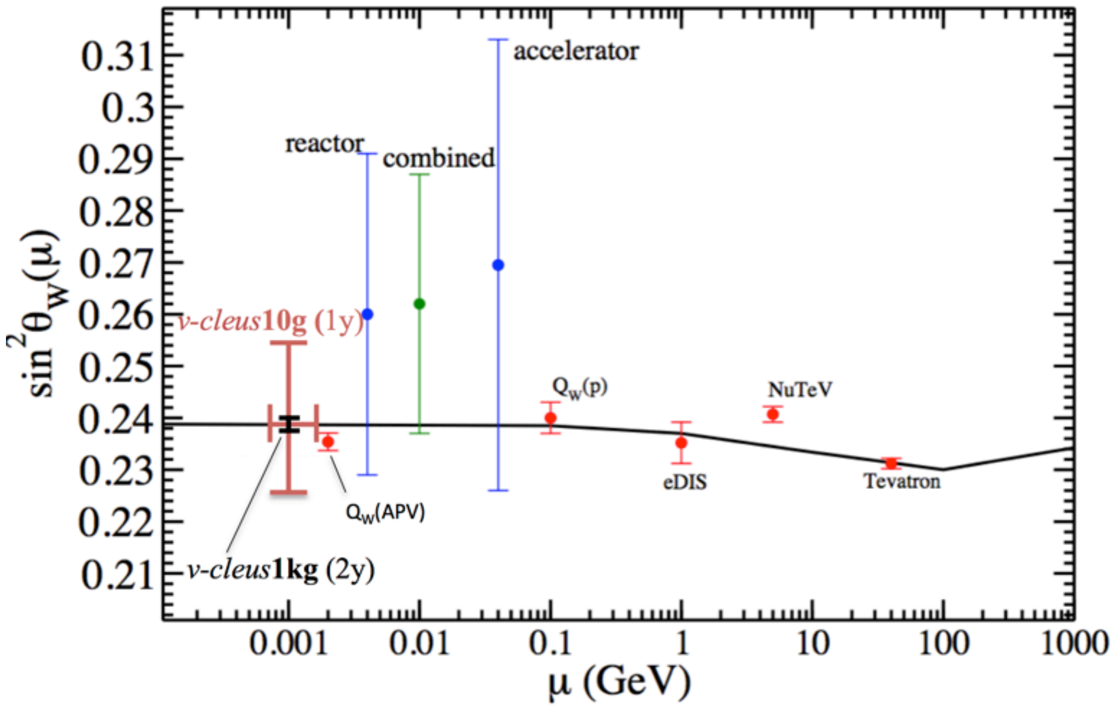


Exceed present precision of the COHERENT experiment after 4 month.

Weinberg Angle

"Running" of Weinberg Angle



Plot adopted from: B.C. Canas, Phys.Lett. B 761 (2016) 450-455

$$\left(\frac{d\sigma}{dE}\right)_{\nu_\alpha A} = \frac{G_F^2 M}{\pi} F^2(2ME)\left[1 - \frac{ME}{2k^2}\right] \times$$
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With $g_V^p = (\frac{1}{2} - 2\sin^2\theta_W)$ and $g_V^n = -\frac{1}{2}$

First determination of the Weinberg angle at q = 1MeV/c after 6 weeks of measurement with 10g!

Nuclear Physics with “Coherent” Scattering

Coherence valid for neutrino energies < 20 MeV
(e.g. for CsI)

Nuclear Physics with “Coherent” Scattering

from J. Rhyne

Coherence valid for neutrino energies < 20 MeV (e.g. for CsI)

$$\frac{d\sigma_{\nu-\mathcal{N}}}{dT}(E,T) \simeq \frac{G_F^2 M}{4\pi}\left(1-\frac{MT}{2E^2}\right)[NF_N(q^2)-\epsilon Z F_Z(q^2)]^2$$

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neutron **Form factor**

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neutron **Form factor**

e.g. Helm Form factor

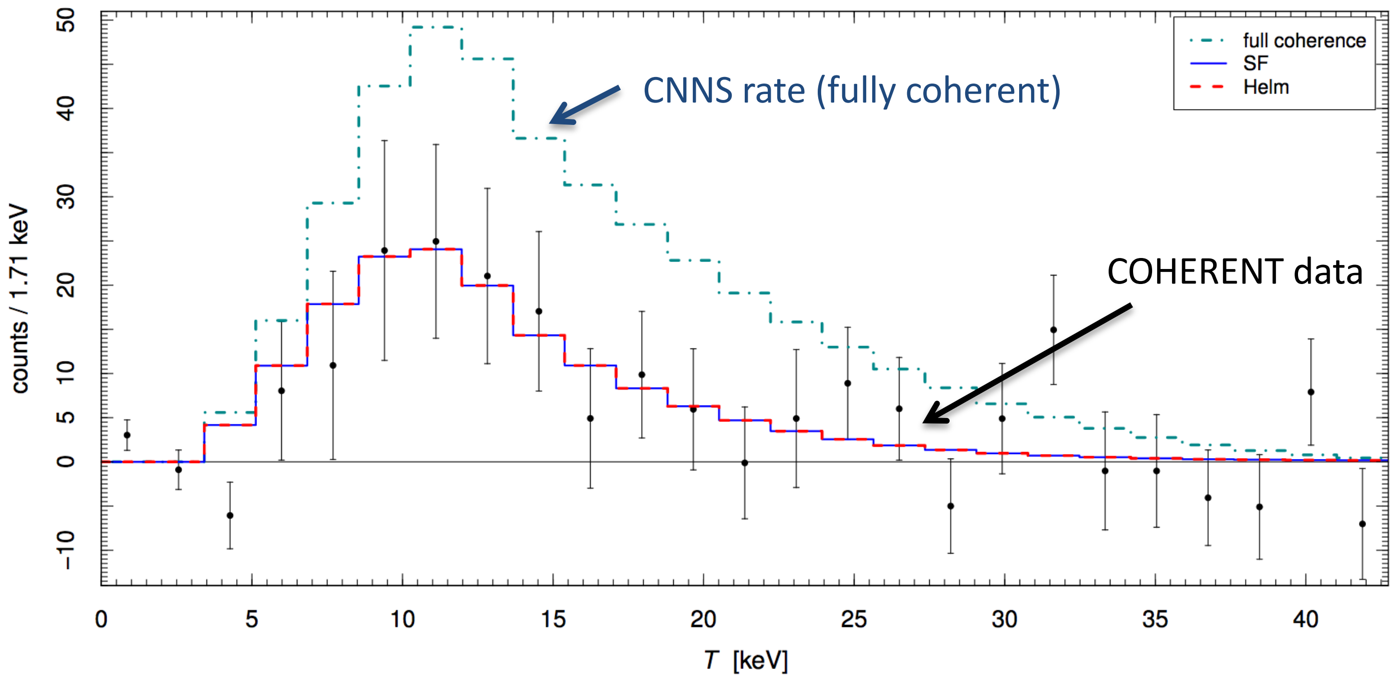
$$F_N^{\mathrm{Helm}}(q^2) = 3\,\frac{j_1(qR_0)}{qR_0}\,e^{-q^2 s^2/2}$$

Neutron rms radius

$$R_n^2 = \frac{3}{5}R_0^2 + 3s^2$$

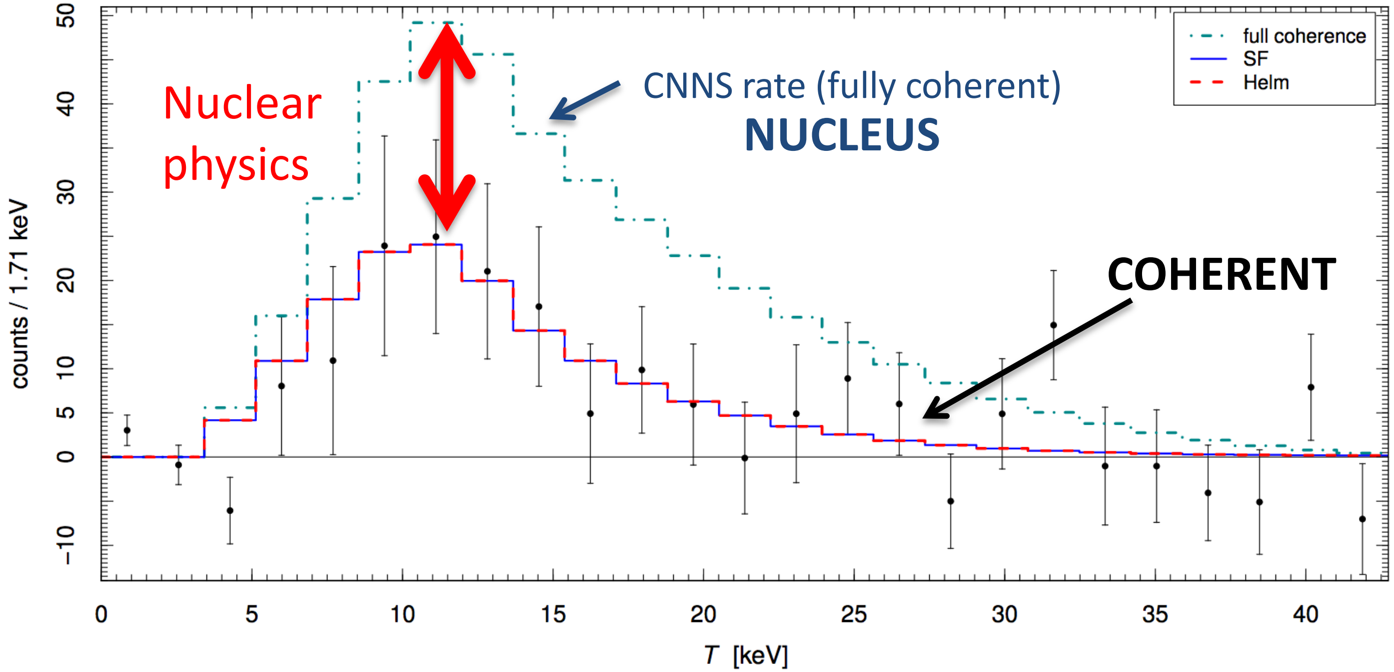
Neutron RMS Radius with CEvNS

Phys. Rev. Lett. **120** 071501, arXiv:1710.02730



Neutron RMS Radius with CEvNS

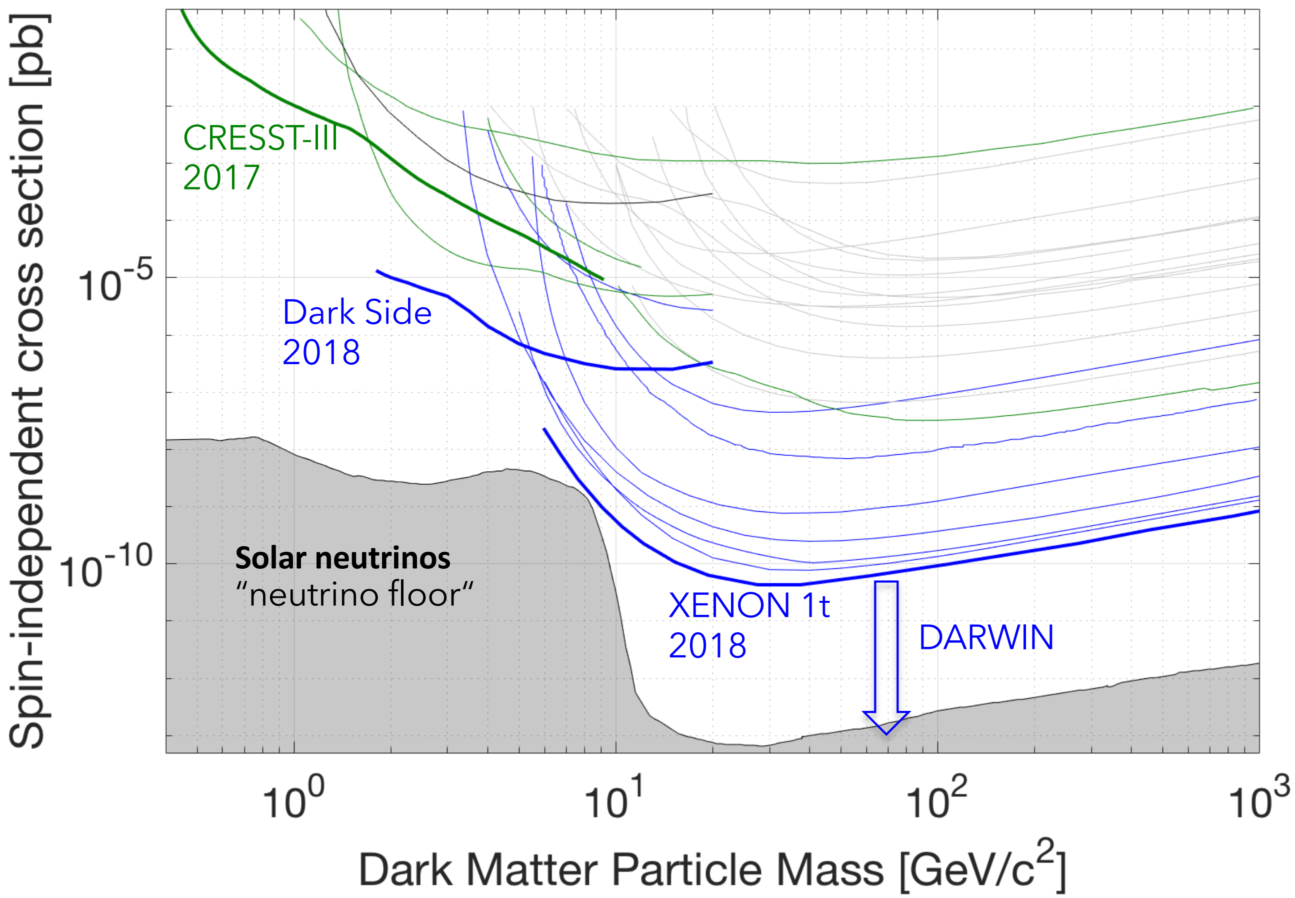
Phys. Rev. Lett. **120** 071501, arXiv:1710.02730



$$R_n = 5.5^{+0.9}_{-1.1}\ \mathrm{fm.} \qquad \Delta R_{np} \simeq 0.7^{+0.9}_{-1.1}\ \mathrm{fm.}$$

Cross-Disciplinary: Dark Matter Search

Current experimental limits on Dark Matter



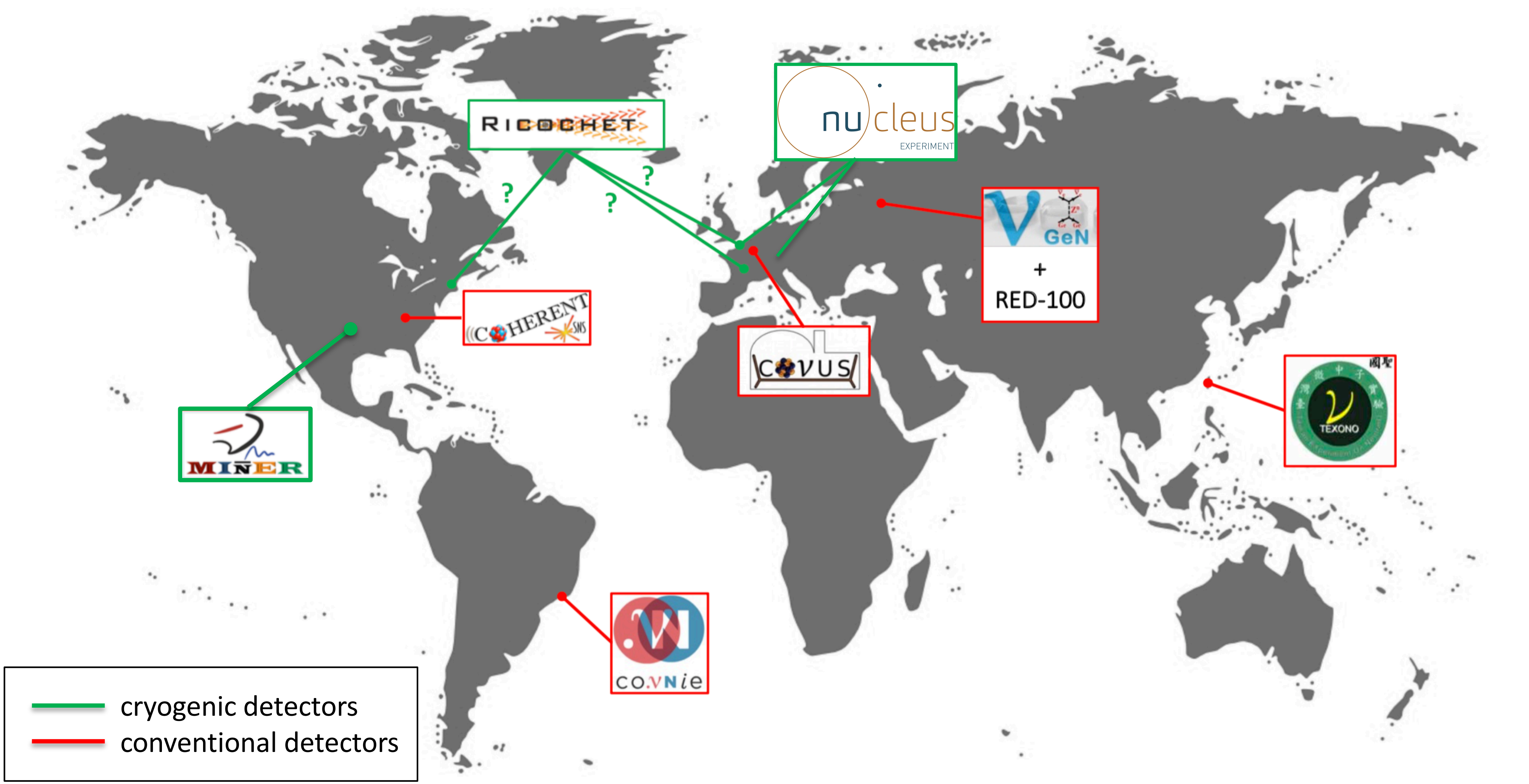
Coherent scattering of solar neutrinos as **ultimate background** for Dark Matter searches ?

or

Study **solar neutrinos** with direct Dark Matter experiments ?

Precise knowledge of **coherent neutrino scattering cross-section** and **Form factors** required by independent experiments!

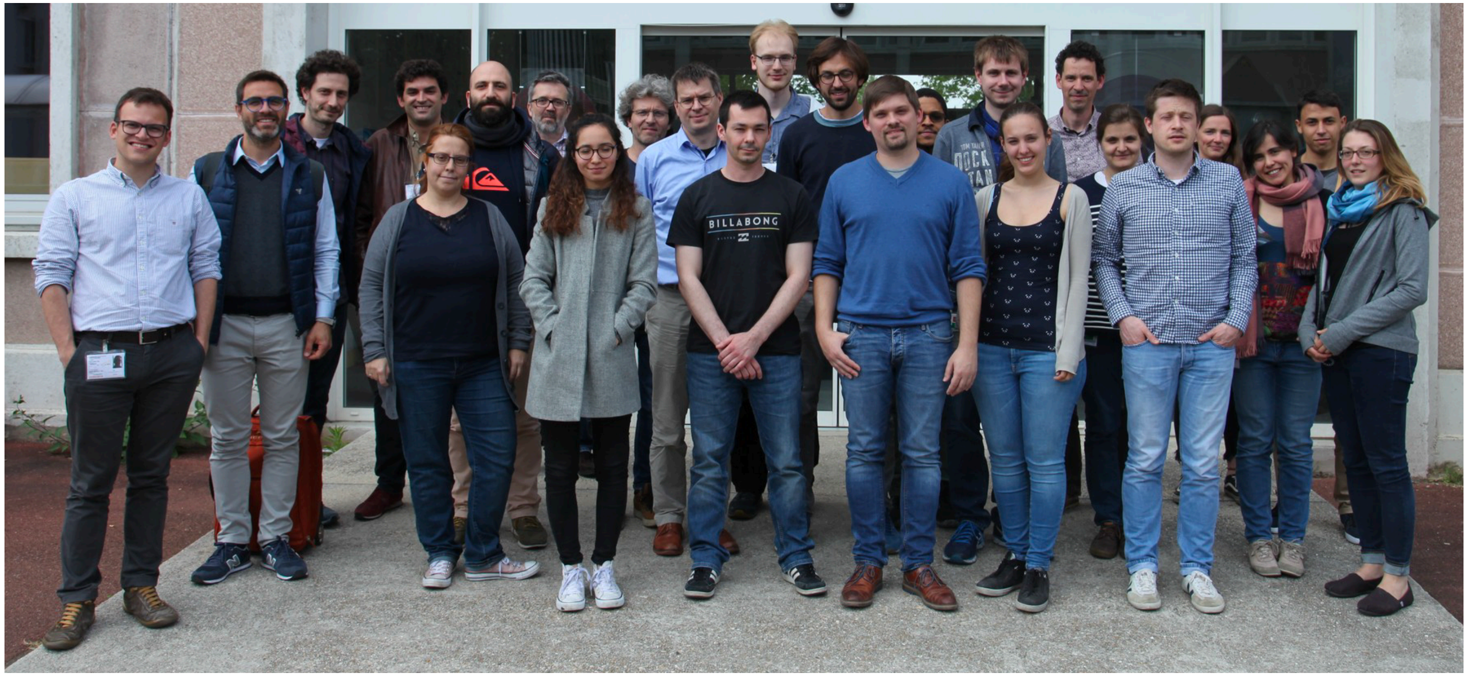
CEvNS Experiments Worldwide



Map courtesy M. Vivier, CEA

NUCLEUS Collaboration

- 6 institutions
- 40 members



HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

TU WIEN

SFB 1258 Neutrinos Dark Matter Messengers

INFN Roma1 Roma2 Ferrara

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

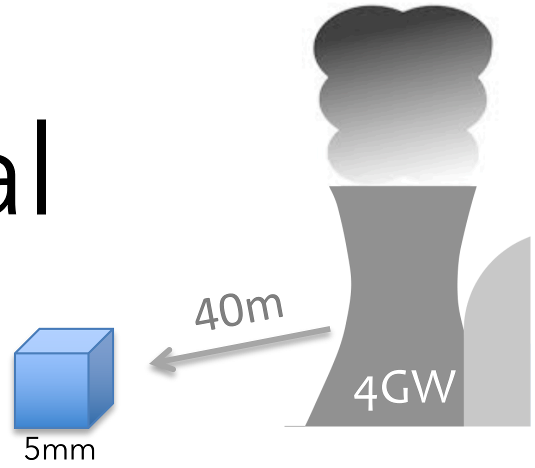
ORIGINS Excellence Cluster

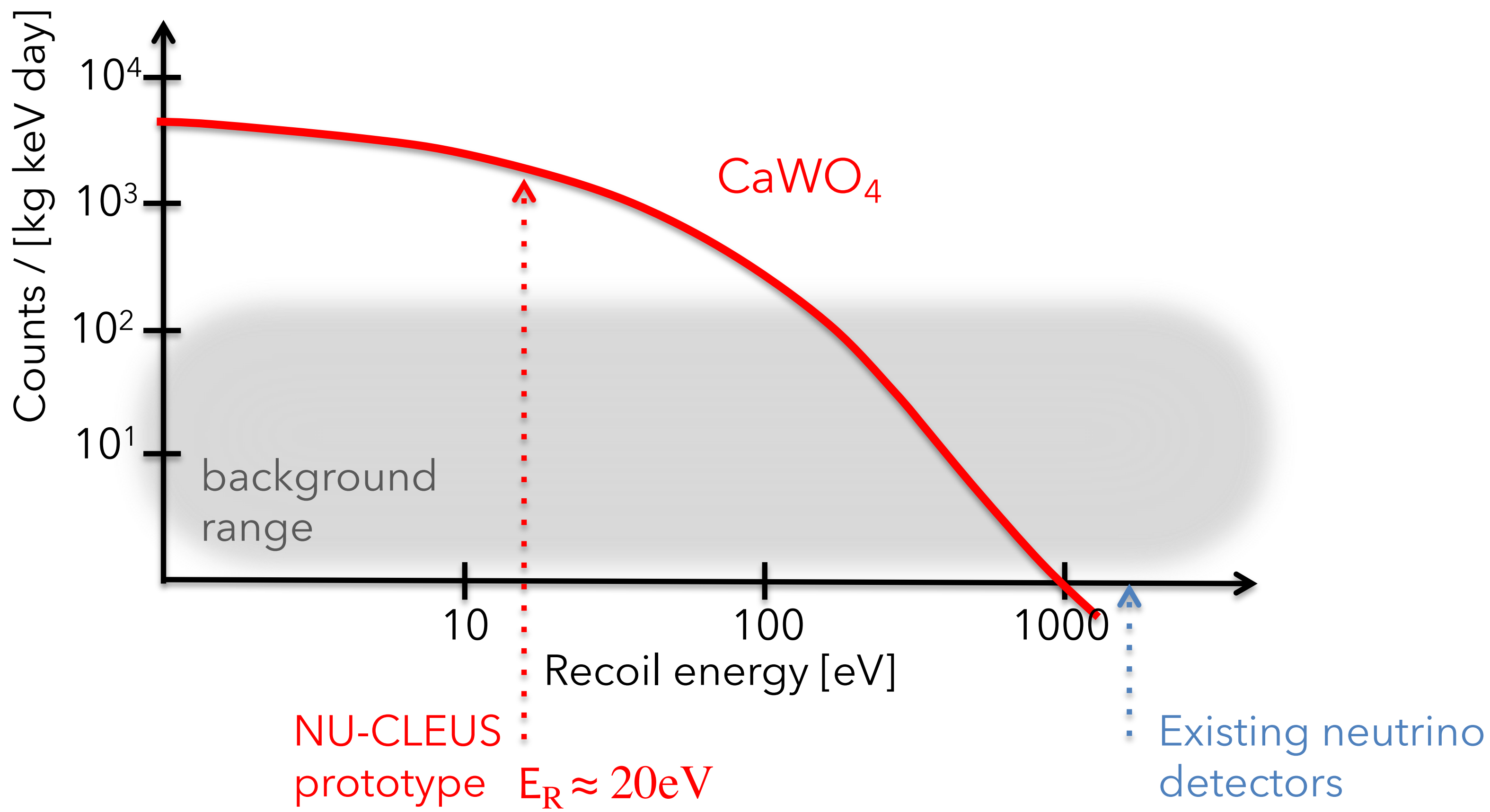
TECHNISCHE UNIVERSITÄT MÜNCHEN

erc

cea

NUCLEUS Potential





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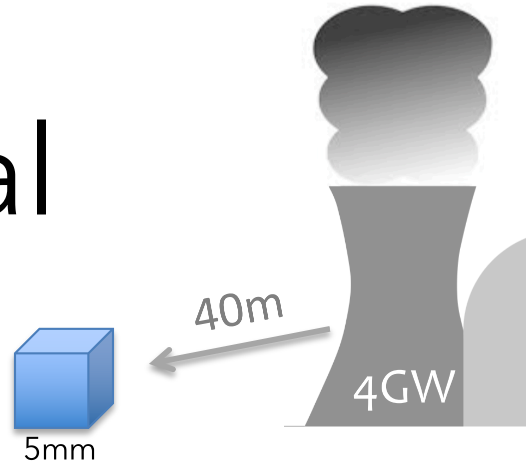
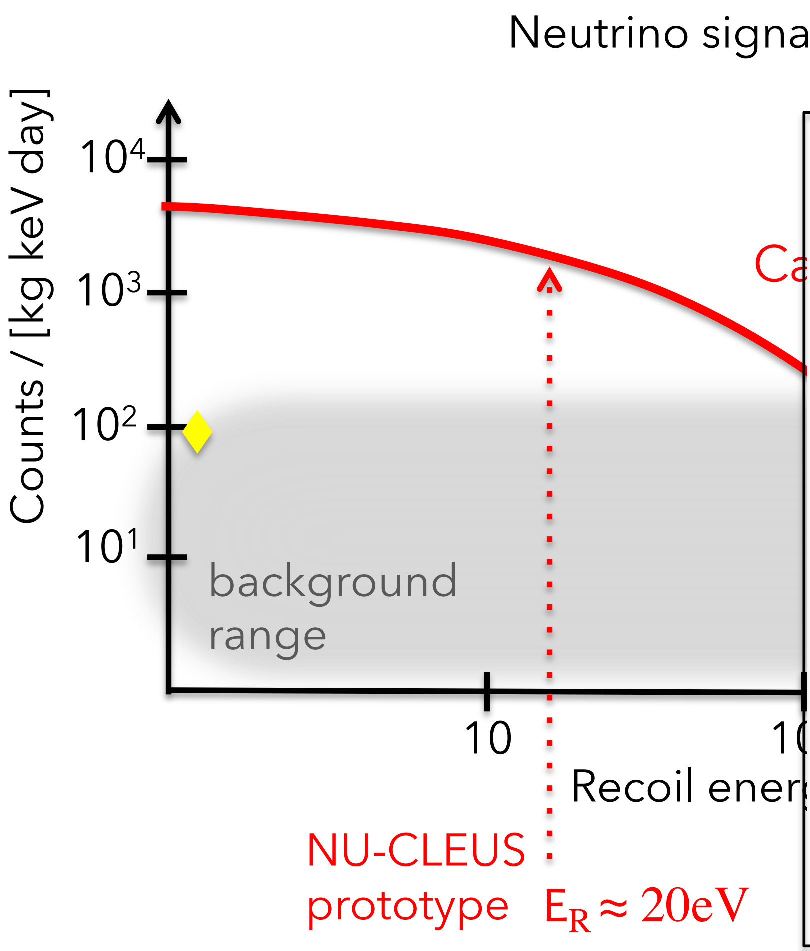
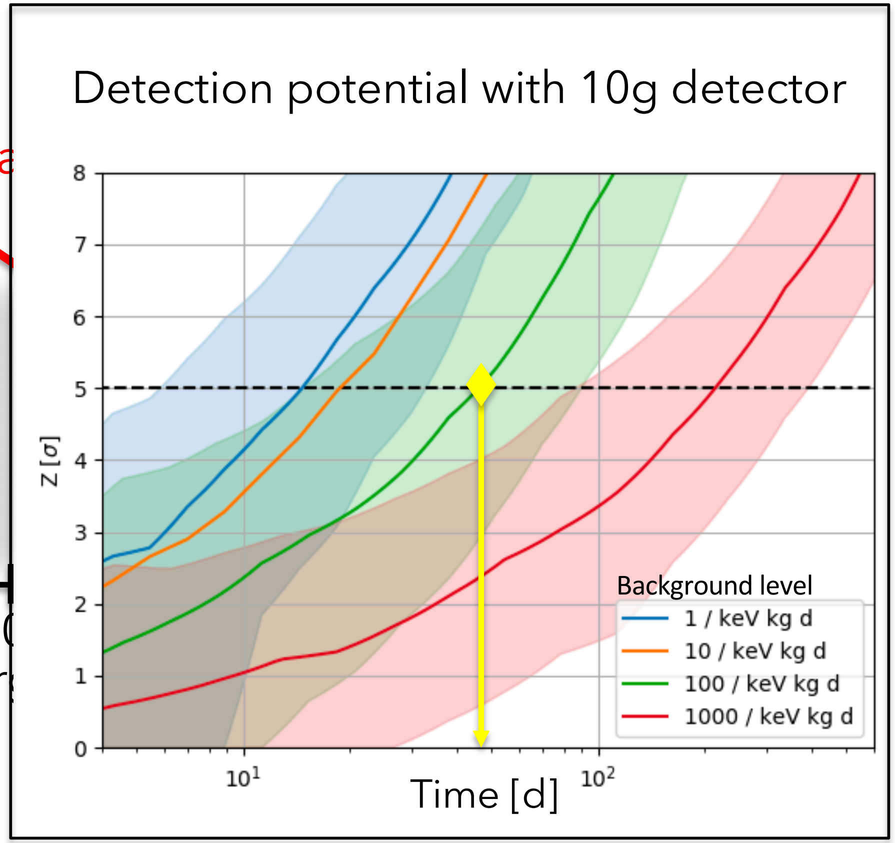




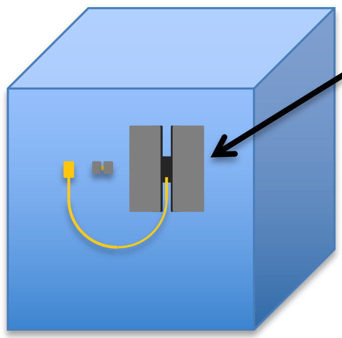


The NUCLEUS Detector Concept

Gram-Scale Cryogenic Calorimeters

Single crystal
Si, Ge, Al_2O_3, $CaWO_4$

Thermometer
Transition-edge-sensor



Operation at mK temperatures

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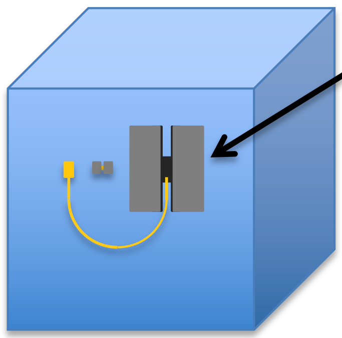

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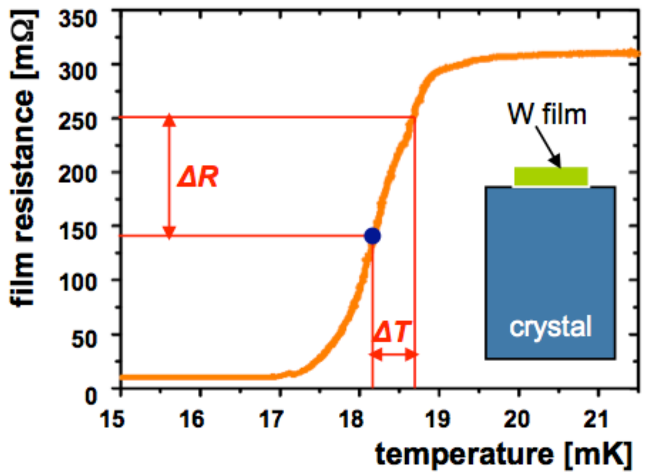
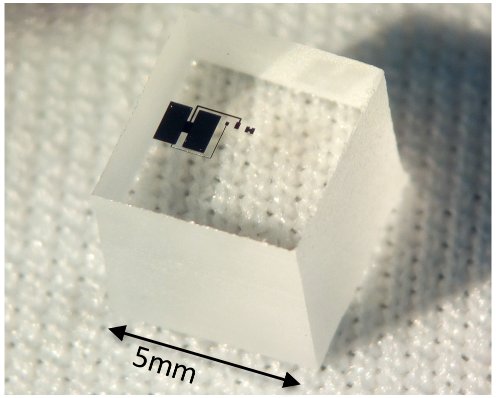


based on CRESST technology

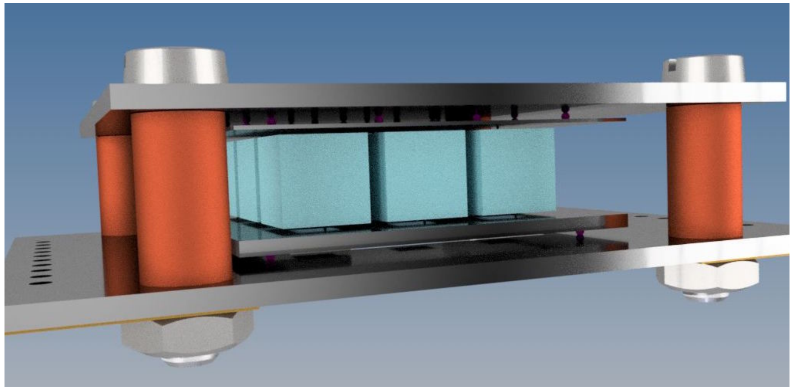
The NUCLEUS Detector Concept

StG2018 NU-CLEUS

The first prototype



NUCLEUS 10g detector



Technology for neutrino detection demonstrated

RS et al., *Phys. Rev. D* **96**, 022009 (2017)

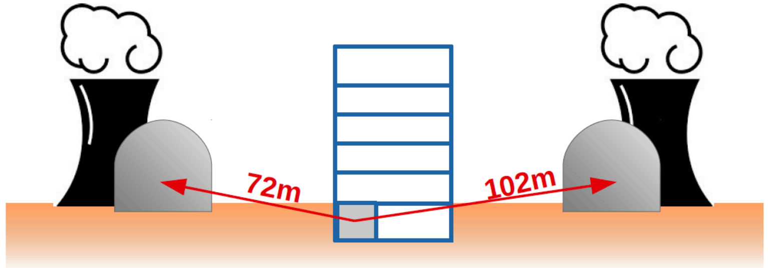
- World-best energy threshold for nuclear recoils, $\mathbf{E_{th} = (19.7 \pm 0.8)\ eV}$
- Low systematics – precise knowledge of energy scale – no quenching

The CHOOZ Nuclear Power Plant

- Full access to inner zone of power plant
- Support from on-site personnel
- Background measurements done
- Convention (CEA-EDF) for NU-CLEUS in preparation

The CHOOZ Nuclear Power Plant

"Very Near Site" - VNS



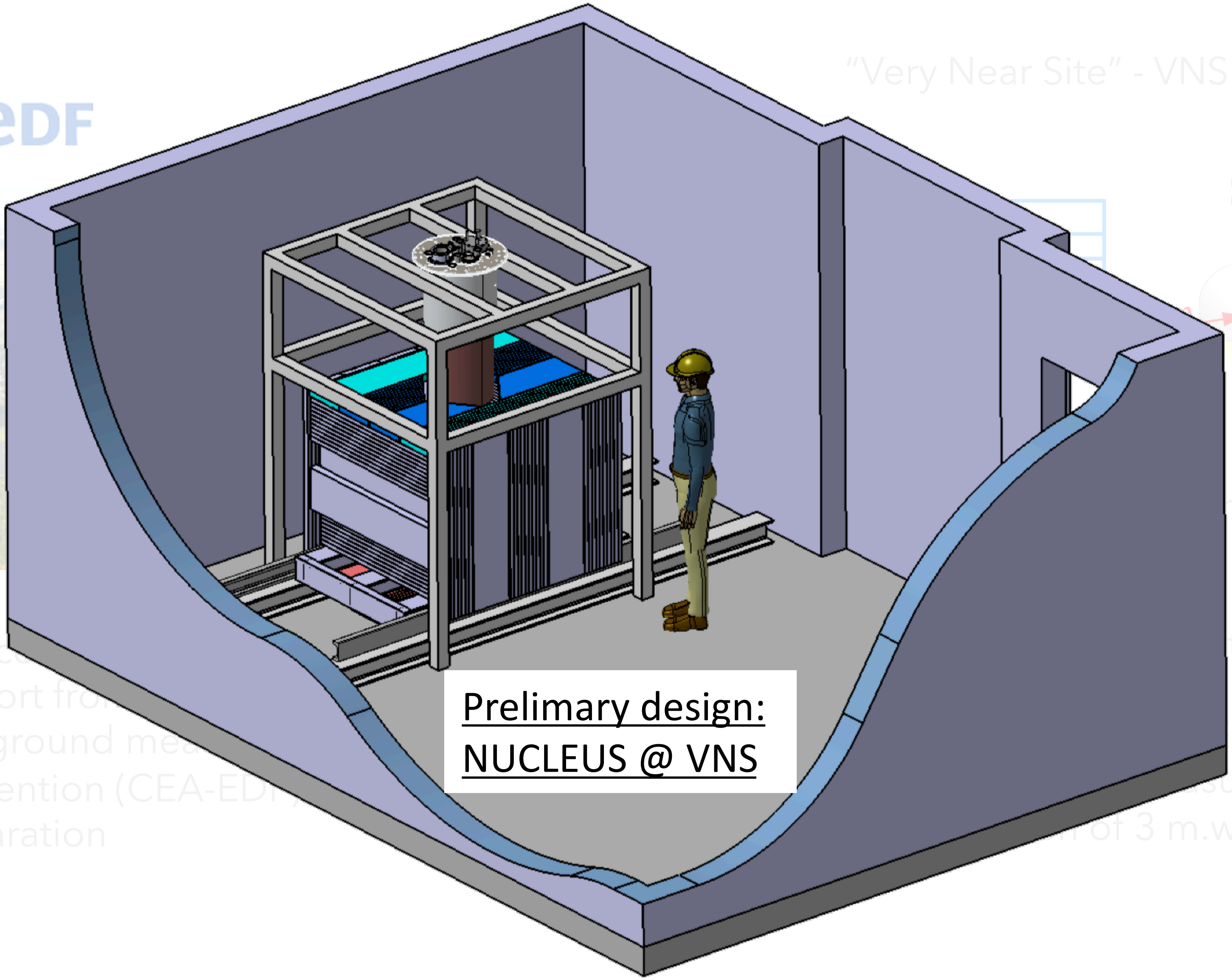
New experimental site in a 24m^2 room in an administrative building

- Full access to inner zone of power plant
- Support from on-site personnel
- Background measurements done
- Convention (CEA-EDF) for NU-CLEUS in preparation

- In-between the two 4.25 GWth reactor cores
- Expected nu-flux: 10^{12} (s cm^2)$^{-1}$
- Muon rate measurements on-site: overburden of 3 m.w.e
- Extensive simulation campaign

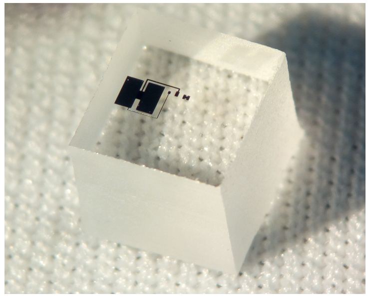
G. Angloher et al. (NUCLEUS Collaboration), arXiv:1905.10258 accepted by EPJ-C

The CHOOZ Nuclear Power Plant



Status&Future of NUCLEUS

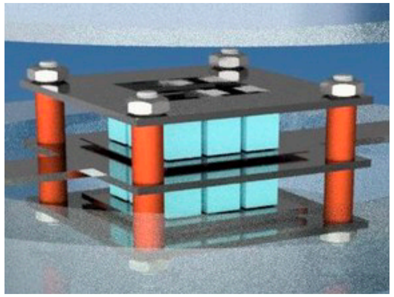
NUCLEUS 1g



2017-2019

straight
forward

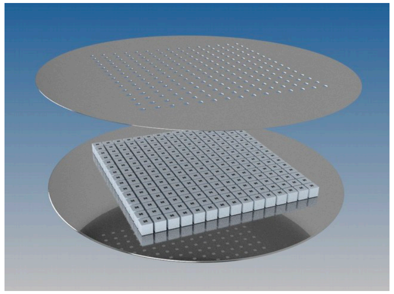
NUCLEUS 10g



2020-2022

major
R&D

NUCLEUS 1kg

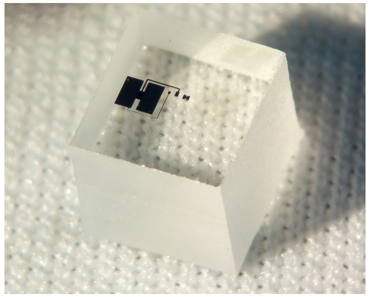


>2024

✓ Proof-of-principle
✓ Reactor site
✓ Collaboration

Status&Future of NUCLEUS

NUCLEUS 1g

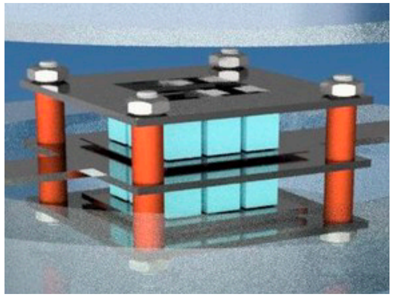


2017-2019

- ✓ Proof-of-principle
- ✓ Reactor site
- ✓ Collaboration

straight forward

NUCLEUS 10g



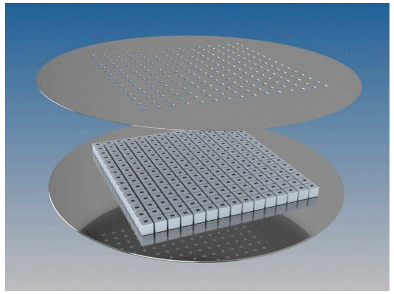
2020-2022

- **Jan 2020:** Cryostat delivered to Munich
- **Late 2020:** NUCLEUS 10g cryodetectors commissioned
- **Early 2021:** "Blank assembly" of all subsystems in TUM underground lab
- **Late 2021:** setup relocation to Chooz + commissioning

➢ **Early 2022:** NUCLEUS-10g data taking

major R&D

NUCLEUS 1kg



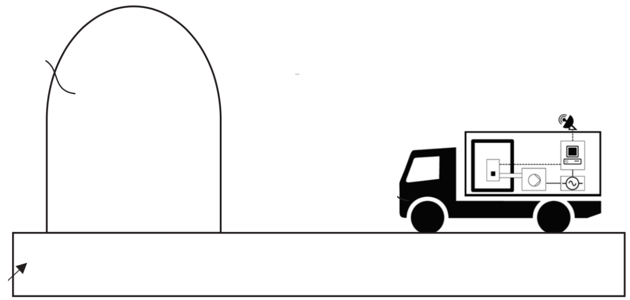
>2024

Application of NU-CLEUS Technology

Mobile cryogenic detector

Use neutrinos to monitor nuclear reactors

Surveillance of power plants world-wide



IAEA
International Atomic Energy Agency
Atoms for Peace

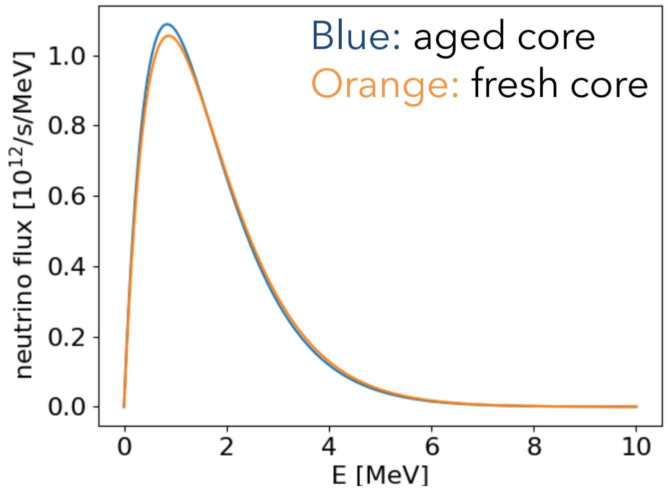
Nuclear non-proliferation

e.g. Phys. Rev. Lett. 113, 042503 (2014)

Nuclear Non-Proliferation

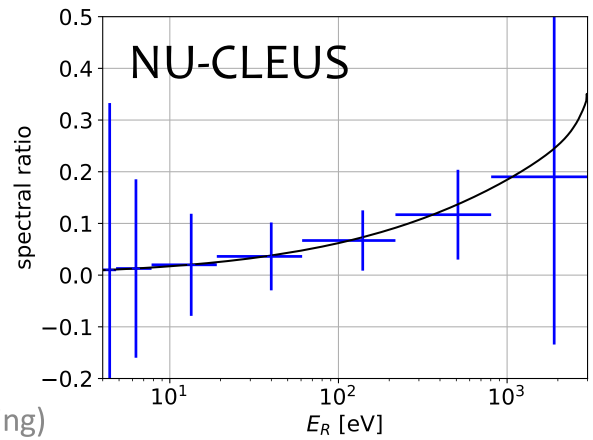
http://www.lefigaro.fr/assets/pdf/AIEA-neutrino.pdf

Fuel content modifies antineutrino spectrum



Following the scenario of
Phys. Rev. Lett. 113, 042503 (2014)

<u>At 40m distance:</u>
Significance for diversion of fuel elements after 8 days (90%conf.)



Conclusion

Coherent neutrino-nucleus scattering:

Portal to new physics

The COHERENT Experiment:

First results from CEvNS

CEvNS at nuclear reactors:

Explore low-energy and precision frontier

Mobile CEvNS detectors:

Reactor safety and non-proliferation of nuclear material

Workshop announcement:

MUNICH

SEPT 16-18, 2020

BACKUP SLIDES

Worldwide CEvNS efforts: comparison

Experiment	ν source	ν flux [cm^{-2} s^{-1}]	Overburden [m w.e.]	Technology E_{th} + mass
COHERENT	Spallation Neutron Source, Oakridge (USA) Baseline ≈ 20 m	10^7	≈ 8	Multiple targets & detectors $E_{th} \geq O(keV)$ – M ≈ 40 kg
CONUS	Brokdorf Power Plant (Germany), 3.9 GW_{th} Baseline = 17 m	2.2 x 10^{13}	10 → 45	Ge ionization $E_{th} \geq 1\ keV_{NR}$ – M =4 kg
CONNIE	Angra dos Reis Power Plant (Brazil) 3.8 GW_{th} Baseline = 30 m	7 x 10^{12}	Surface	Si charged couple devices $E_{th} \approx 300\ eV_{NR}$ – M ≈ 0.1 kg
TEXONO	Kuo-Sheng Power Plant (Taiwan), 2.7 GW_{th} Baseline = 28 m	5 x 10^{12}	30	Ge ionization CsI[Tl] scintillation $E_{th} \geq 1\ keV_{NR}$ – M≈ kg scale
ν-GEN	Kalinin Power Plant (Russia), 3 GW_{th} Baseline = 10 m	5 x 10^{13}	≈ 10	Ge ionization $E_{th} \geq 1\ keV_{NR}$ – M = 2 kg
RED-100	Kalinin Power Plant (Russia), 3 GW_{th} Baseline = 19 m	10^{13}	≈ 10	Liquid Xe TPC $E_{th} \approx O(1\ keV_{NR})$ – M = 100 kg
MINER	TAMU research reactor (Texas), 1 MW_{th} Baseline = 2-10 m	4 x 10^{11}	15	Ge/Si CDMS techno. Aim at $E_{th} \approx 40\ eV_{NR}$ – M ≈ 10 kg
ν-CLEUS	Chooz (France) 2 x 4.25 GW_{th} @ VNS Baseline = 70-100 m	2 x 10^{12}	≤ 4	$CaWO_4, Al_2O_3, Li_2WO_4$ cryo. cal. $E_{th} \approx 20\ eV_{NR}$ – M = 0.01 → 1 kg
RICOCHET	Chooz (France) 2 x 4.25 GW_{th} @ NS ? [400 m] MIT research reactor 6 MW_{th} ? ILL research reactor 58 MW_{th} ? [10 m]	8 x 10^{10} 10^{11} 9 x 10^{11}	120 ≈ 10 ≈ 10	Ge/Zn cryo. cal. $E_{th} \approx O(50\ eV_{NR})$ - M ≈ 0.5 kg

Ionization and/or scintillation

Phonons

Courtesy M. Vivier

COHERENT – great! | Why **NU–CLEUS** ?

Error budget

Observed:	134±22 events
Expected (SM):	173±48 events

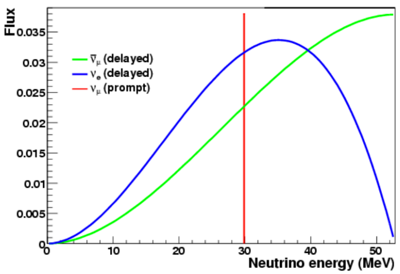
stat. **16%**

syst. **30%**

Aims for few percent level

Neutrino source

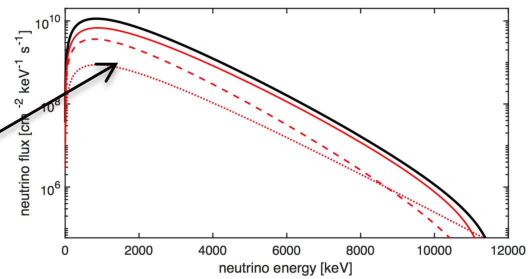
Stopped-pion-source



Nuclear power reactor

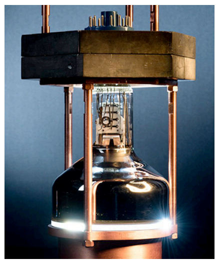
Reactor neutrino physics!

Low energy neutrinos



Detector

“conventional“



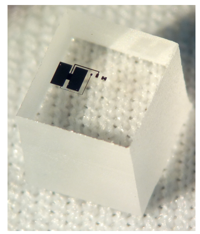
15cm

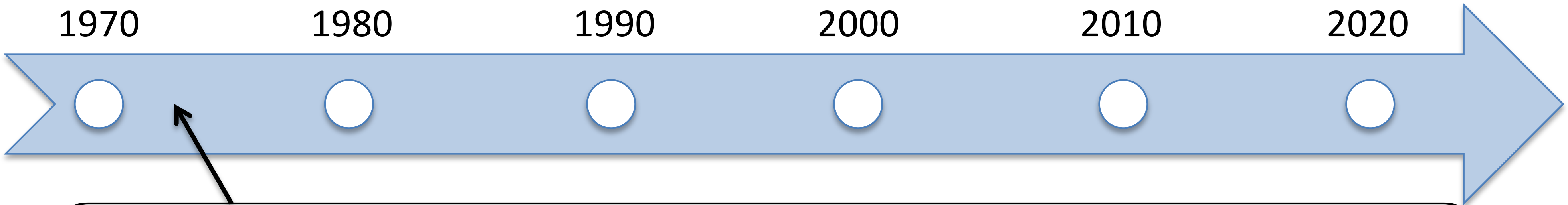
Threshold: A few keV

cryogenic detector

Threshold: A few 10’s of eV

5mm



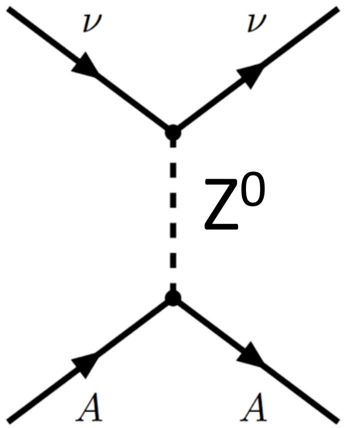


PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

(Received 15 October 1973; revised manuscript received 19 November 1973)



Coherent scattering for ***λ$_\nu$ >> 2R***
→ ***E$_\nu$ < 30*** **MeV**

Fermi constant

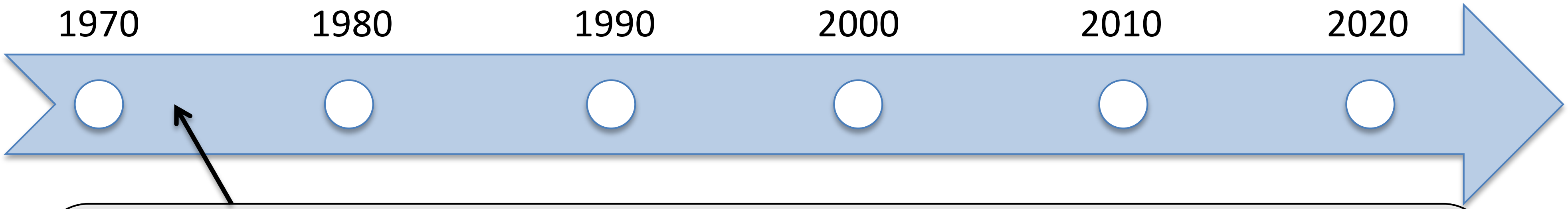
$$\frac{d\sigma}{dz} \approx a_0^2 \frac{G^2}{2\pi} A^2 E^2 (1+z)$$

atomic number

neutrino energy

$$\sigma \simeq 0.42 \times 10^{-44} N^2 (E/1\ \mathrm{MeV})^2\ \mathrm{cm}^2$$

→ enhancement by roughly ***N*²**



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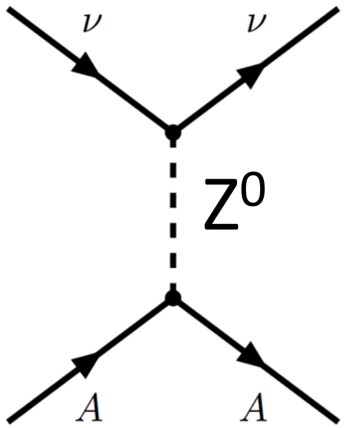
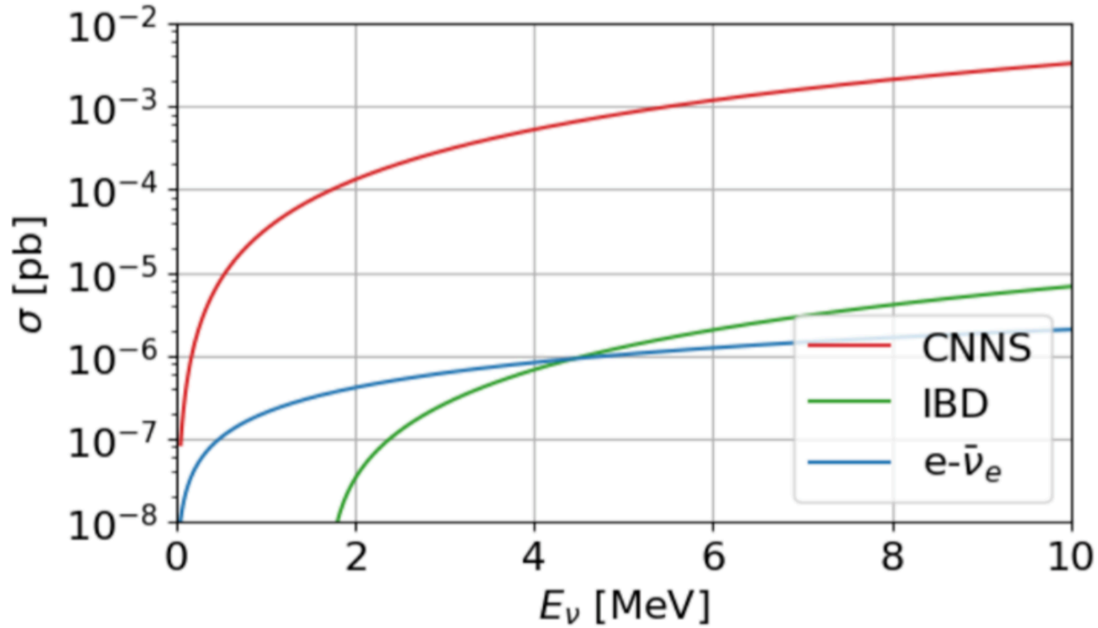
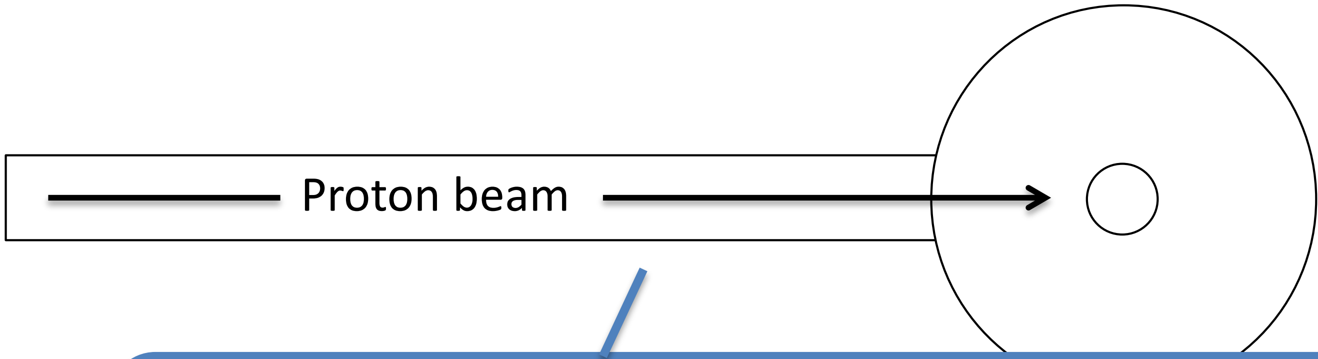
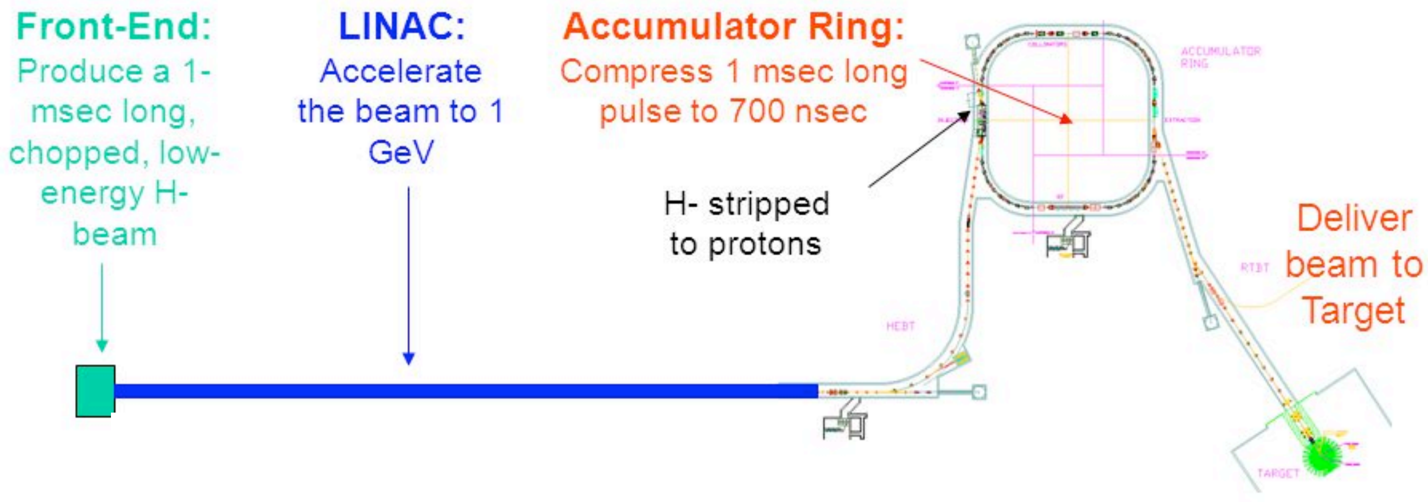


Coherent scattering for ***λ_ν >> 2R***
→ *E_ν < 30* MeV





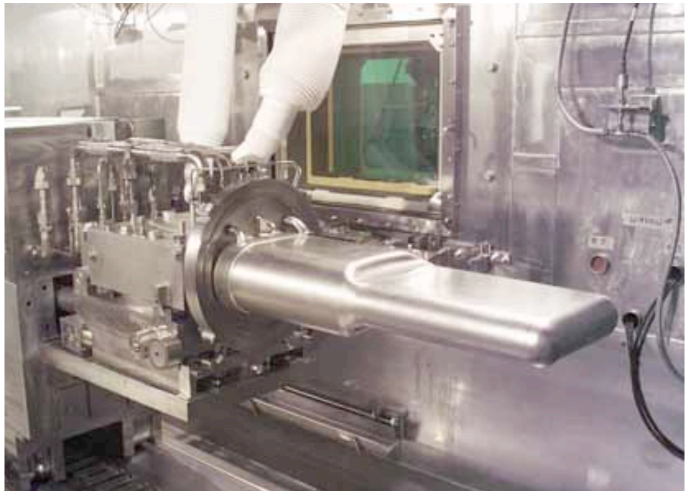


- Intense proton beam: 5×10^{20} protons-on-target / day
- Energy: 1GeV
- Pulsed beam: 60Hz

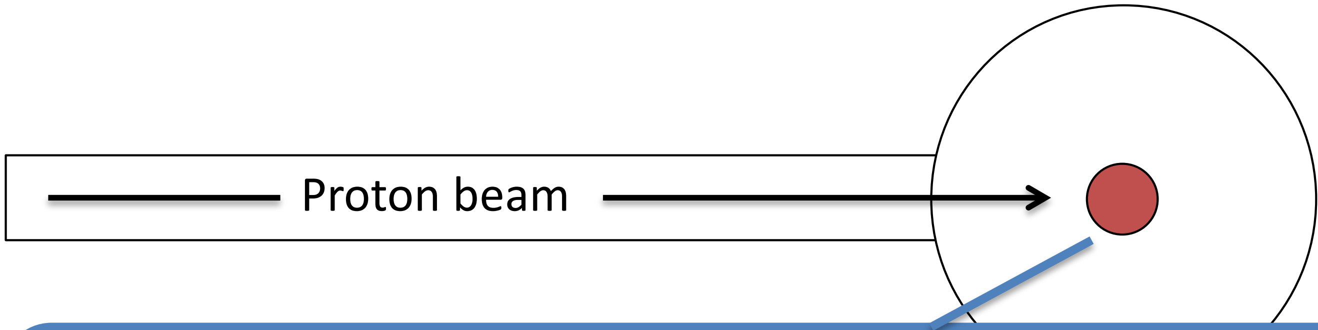
OAK RIDGE
National Laboratory

SNS
SPALLATION NEUTRON SOURCE

Protons on mercury target



- Most intense neutron beam in the world
- Cross-disciplinary science

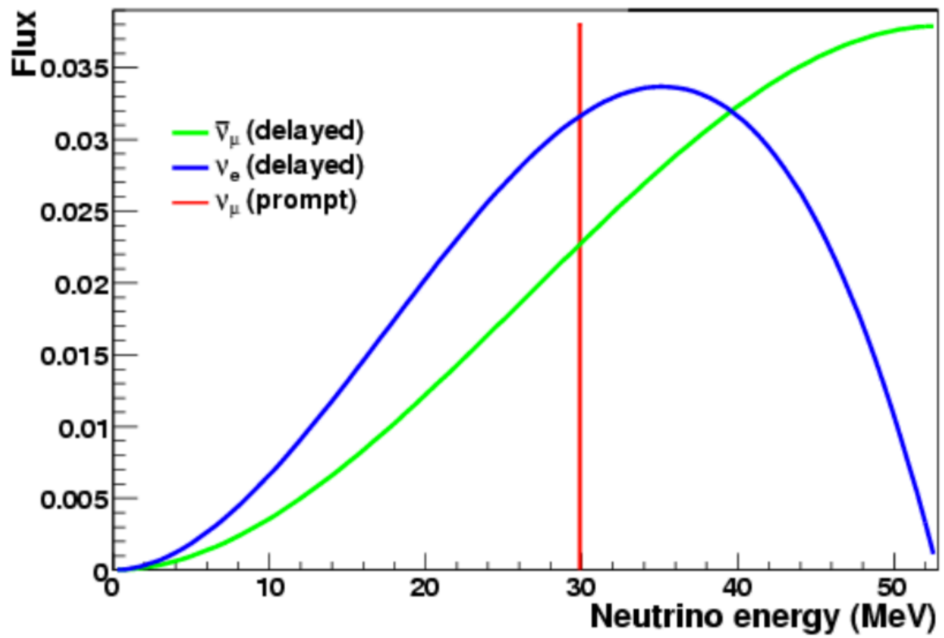


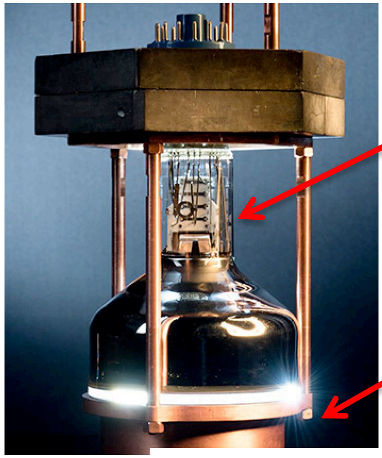
Neutrino production

- Pion production and stopping
- π^+ decay at rest
- μ^+ decay at rest
- 0.08 ν's / flavor / proton
- Isotropic production

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

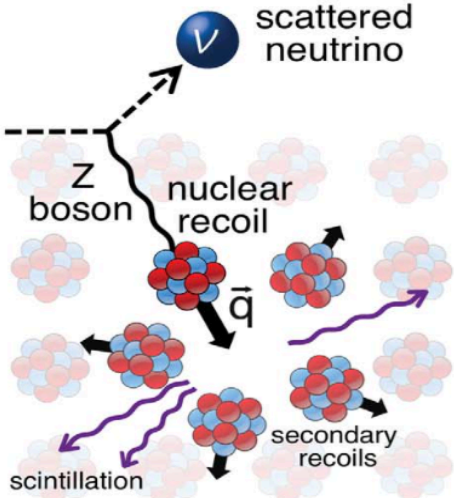
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$



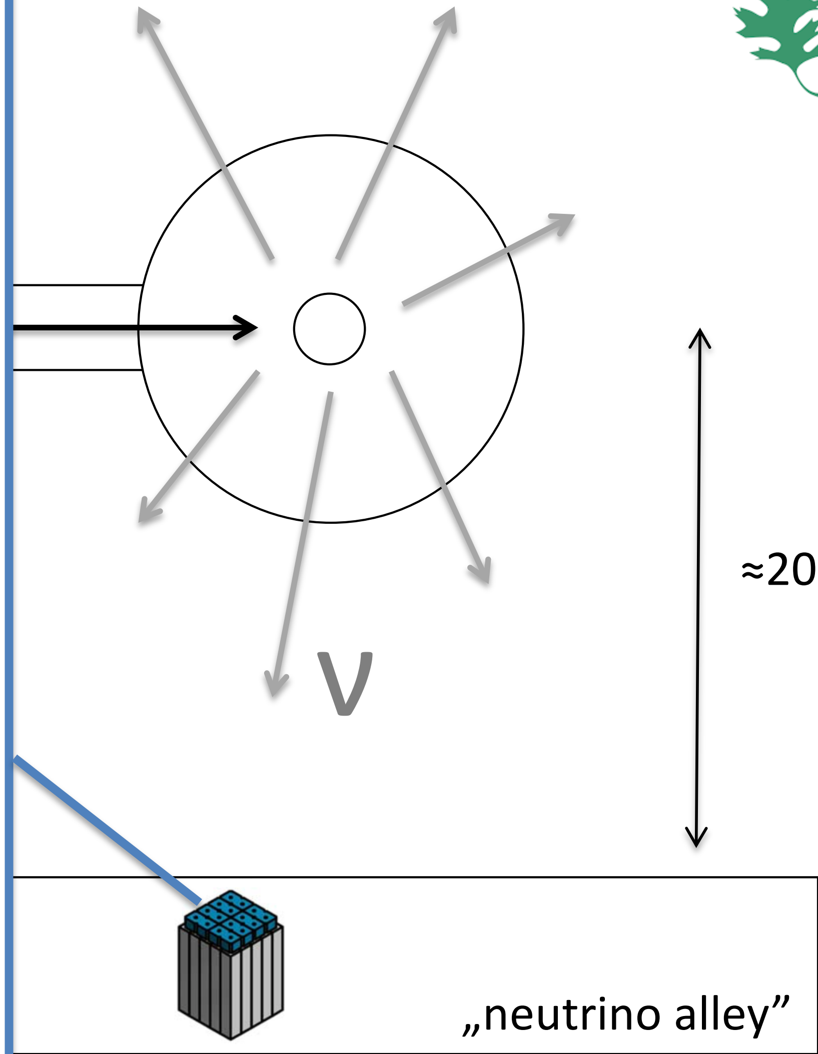


Photomultiplier

CsI crystal
(15kg)

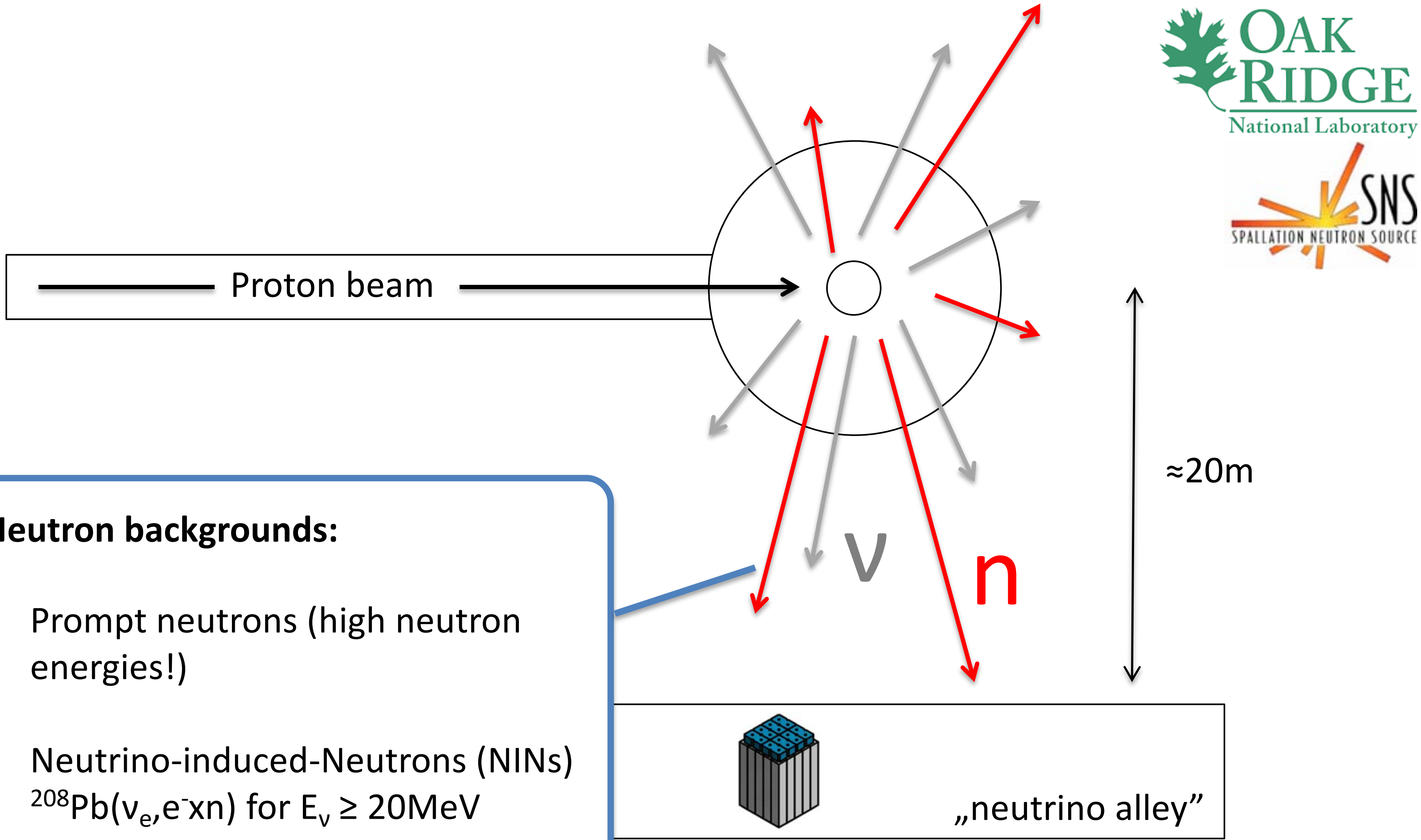


Nuclear-recoil threshold: ≈4.3keV
Light quenching(!)



Oak Ridge National Laboratory

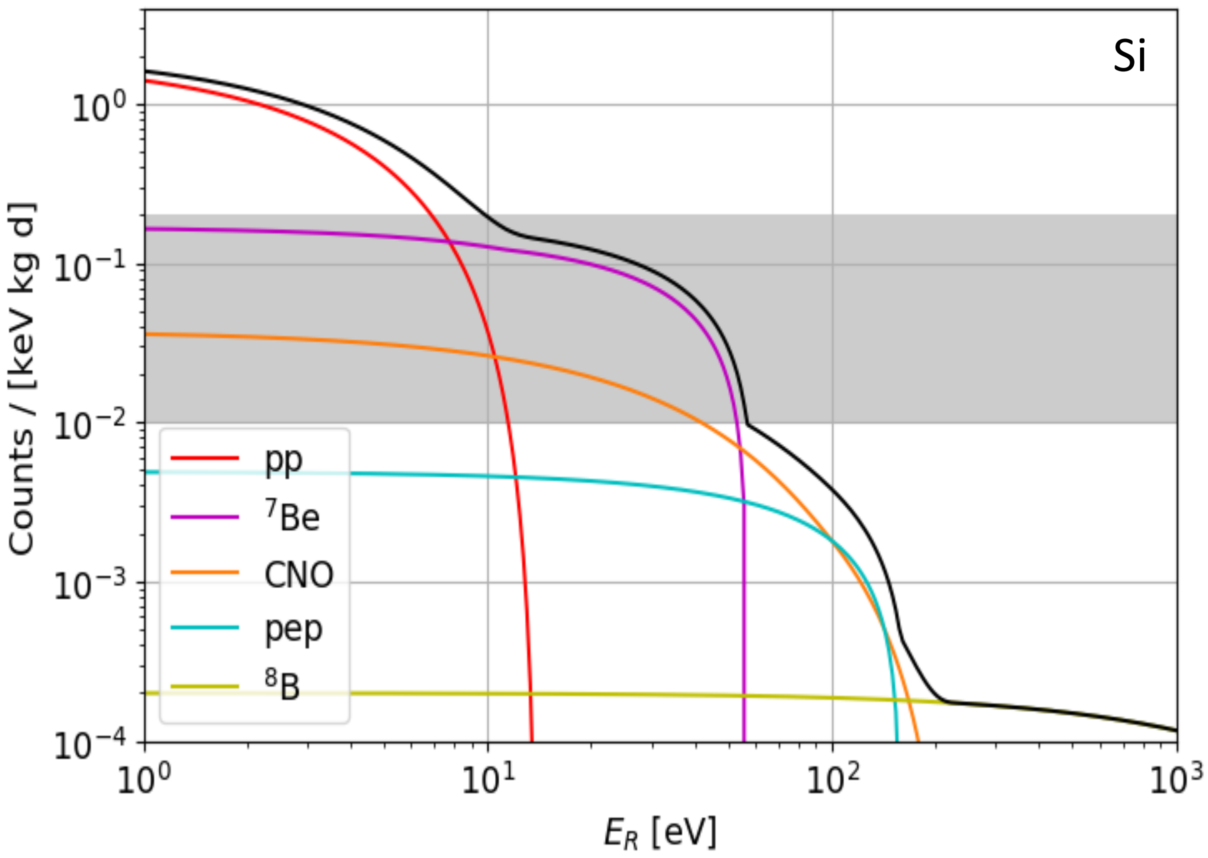
SNS Spallation Neutron Source



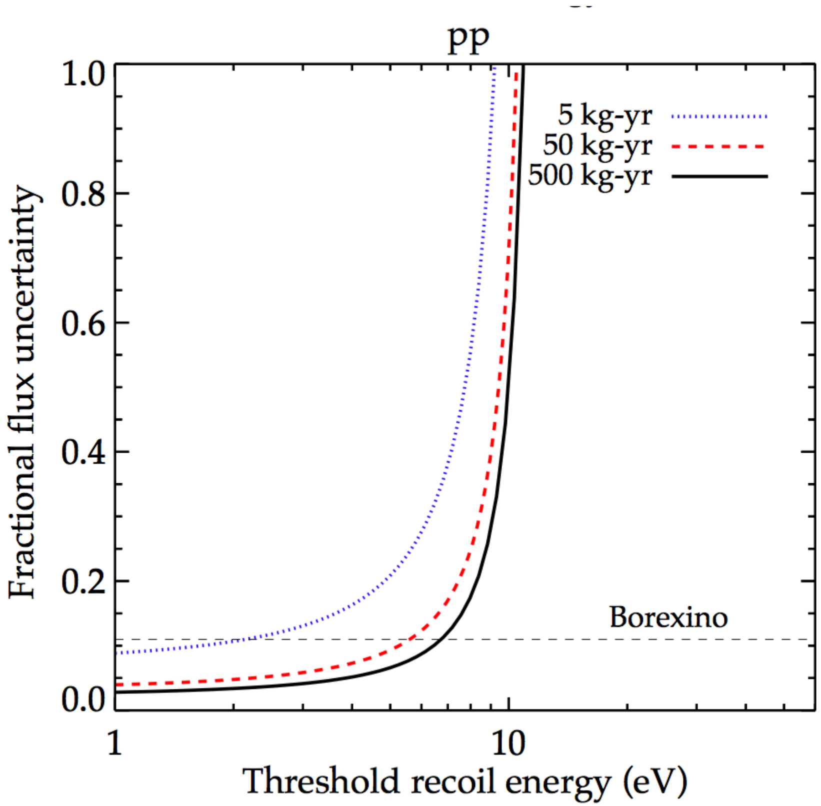
Neutron backgrounds:

- Prompt neutrons (high neutron energies!)
- Neutrino-induced-Neutrons (NINs) $^{208}Pb(\nu_e,e^- xn)$ for $E_\nu \geq 20MeV$

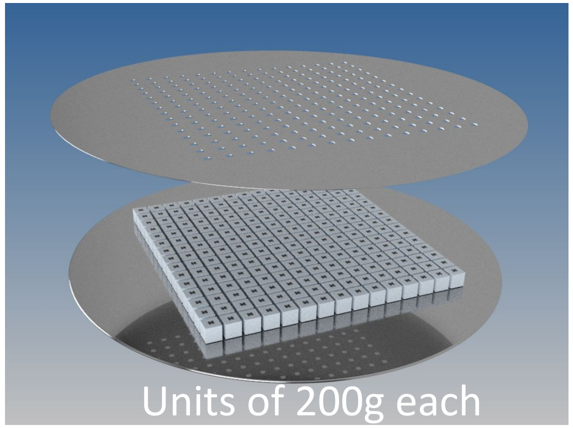
Solar neutrinos with NU-CLEUS



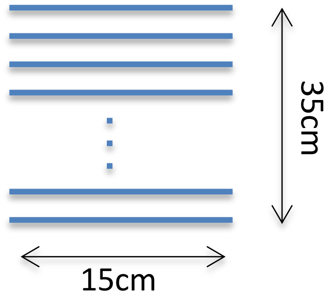
Solar neutrinos with table-top experiment!



L.E. Strigari, Phys. Rev. D 93, 103534 (2016)

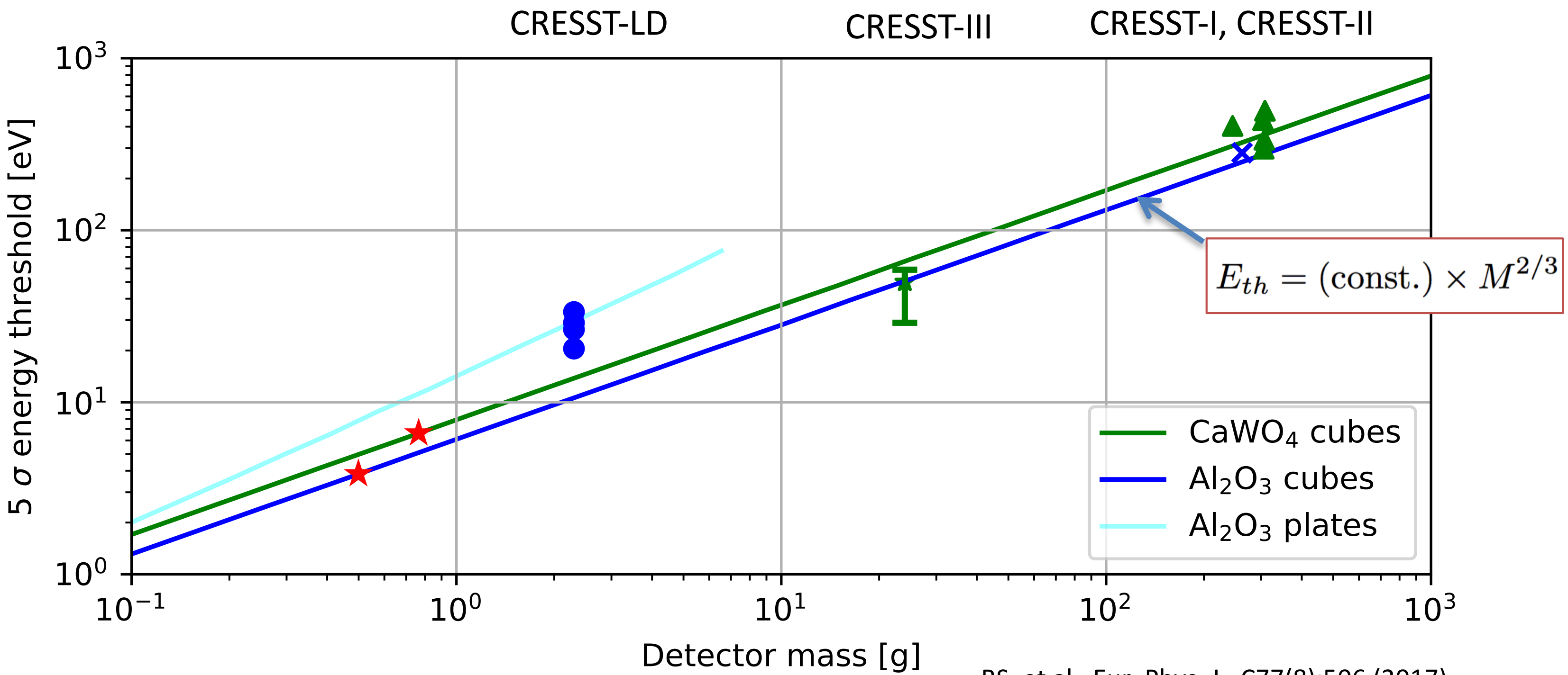


10kg still table-top



ν-cleus 1kg will be sensitive to pp neutrinos!

Scaling law for calorimeters

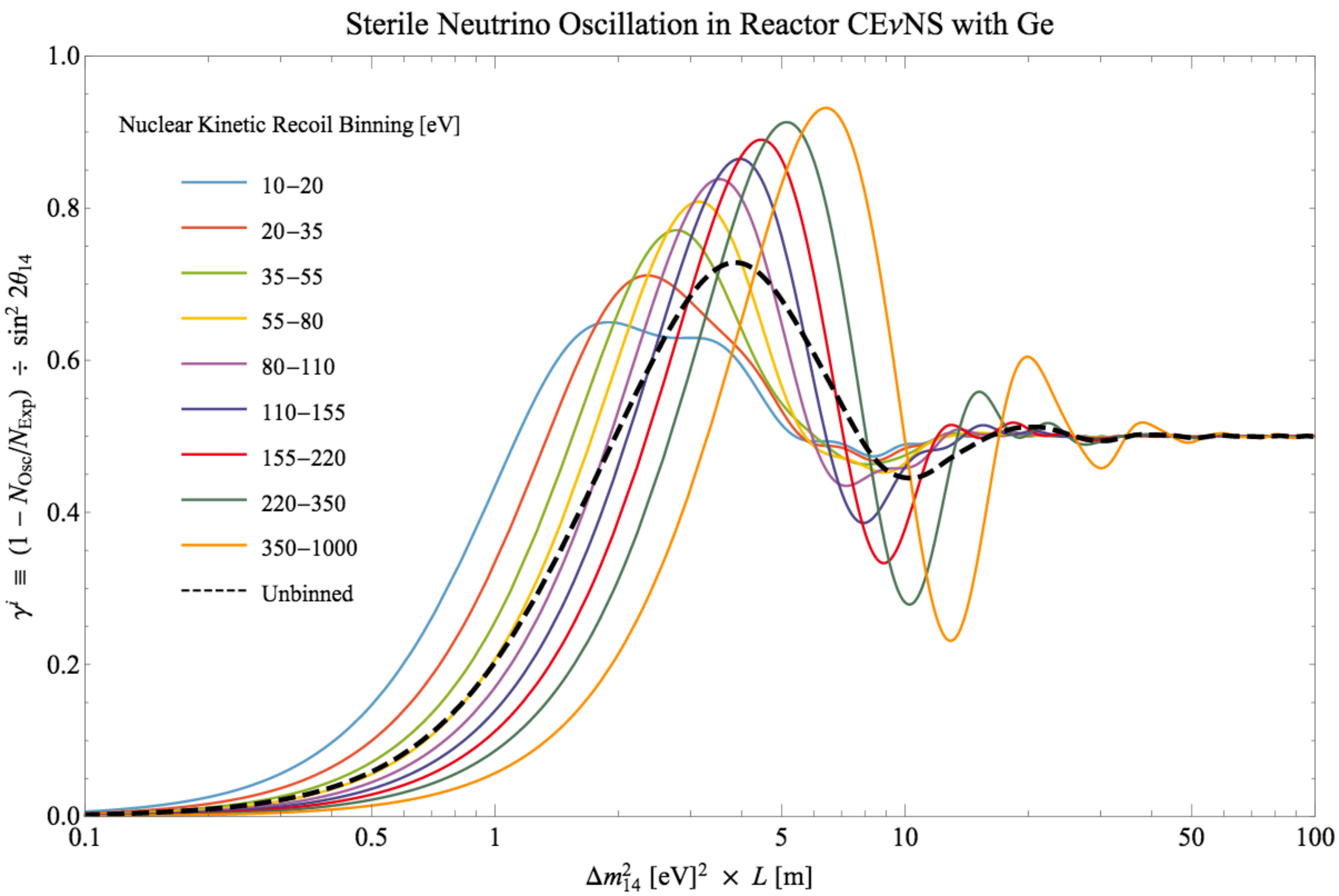


RS, et al.. Eur. Phys. J., C77(8):506 (2017)
arXiv: 1704.04320

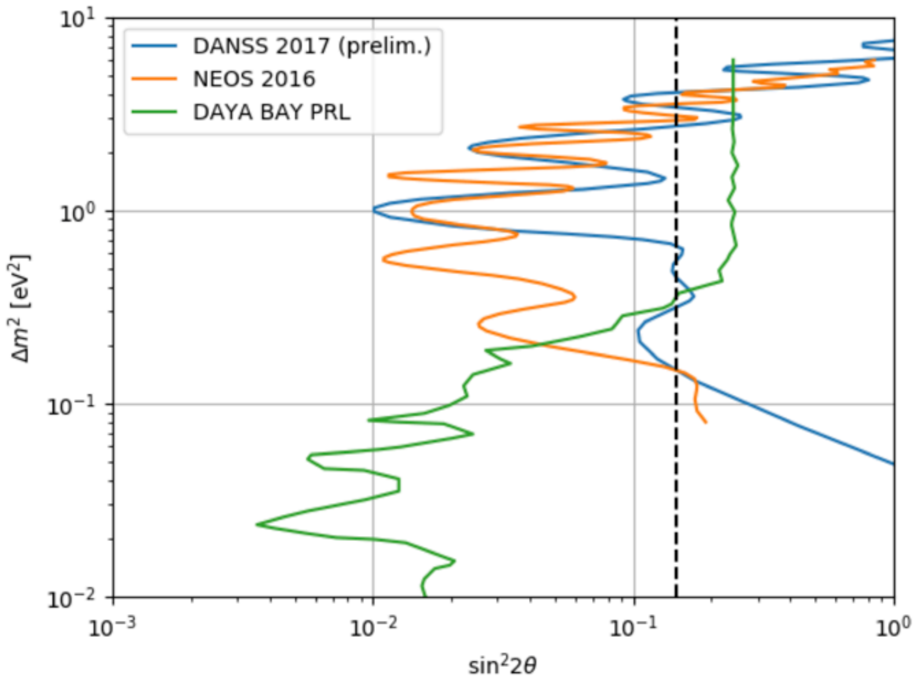
Validation of model with existing devices!

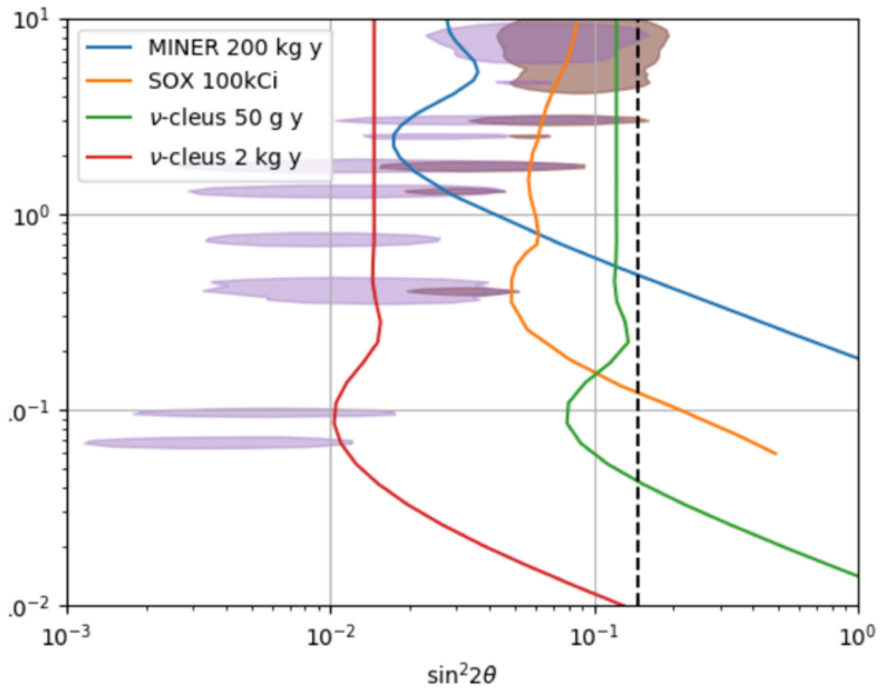
→ Predicitions for gram-scale detectors

News: Sensitivity Studies – Sterile Neutrinos



News: Sensitivity Studies – Sterile Neutrinos





News: Sensitivity Studies – Reactor physics