Updates from the Coherent Neutrino-Nucleus Interaction Experiment - CONNIE

Martín Makler
for the CONNIE collaboration

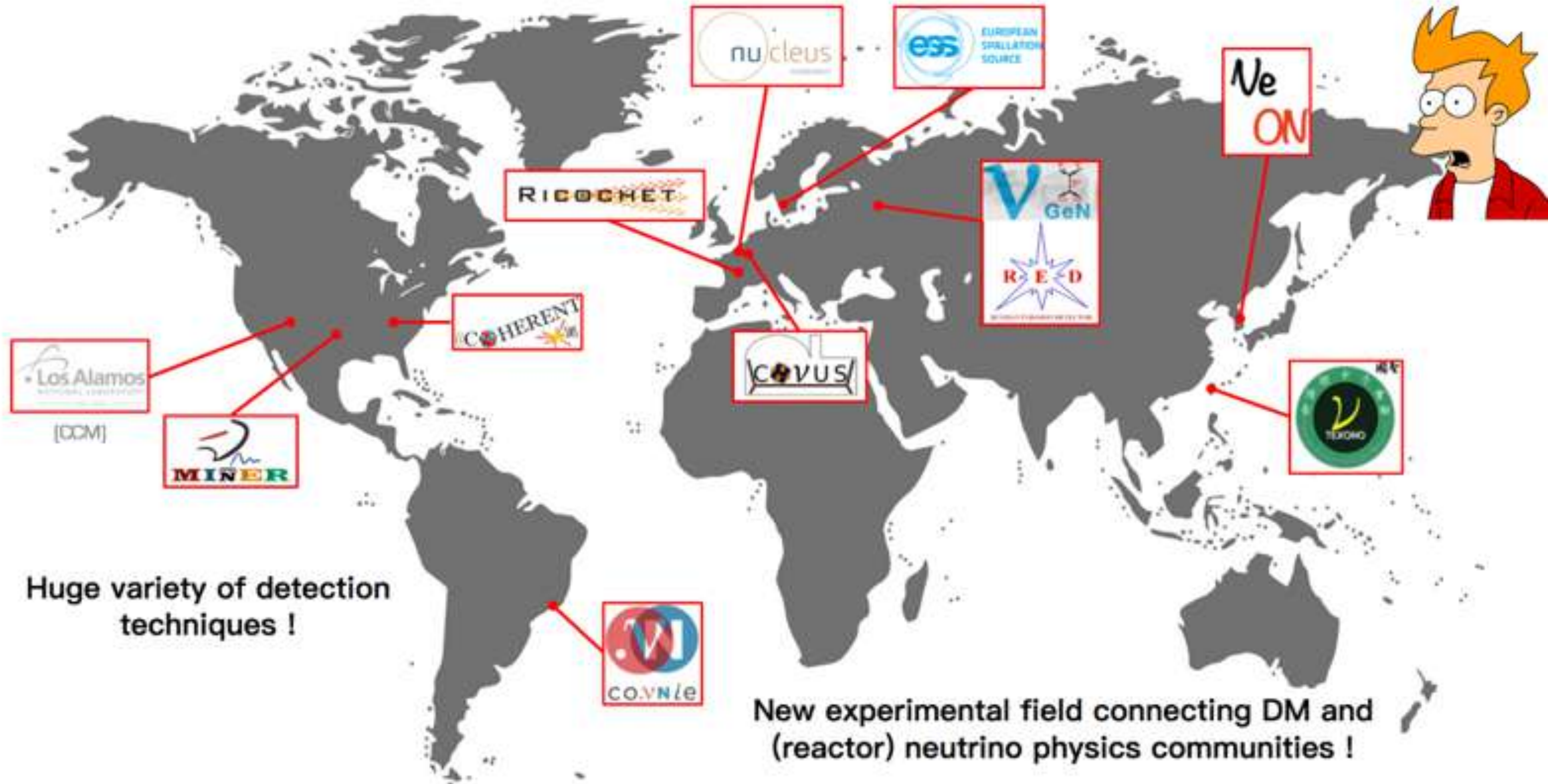
ICTP SAIFR International Centre for Theoretical Physics South American Institute for Fundamental Research

3rd SOUTH AMERICAN DARK MATTER WORKSHOP

CONNIE and Dark Matter

- CONNIE is a neutrino detector operating at the ground
- What are you doing here?!
- **Search for DM inspired physics BSM**
- Reactor
  - (anti-)neutrinos: light mediators modify cross section
  - new particle production at the reactor:
    - Axions and axion-like particles
- On the ground
  - Strongly Interacting Massive Particles
- Sterile neutrinos (very short baseline oscillation experiments – low energy)
- Any particle physics experiment has been turned into a search for dark sector
  - **Low energy threshold:** coherent interaction, neutral current

Proliferation of experimental efforts worldwide !



from Matthieu VIVIER@Magnificent CEvNS workshop 2020

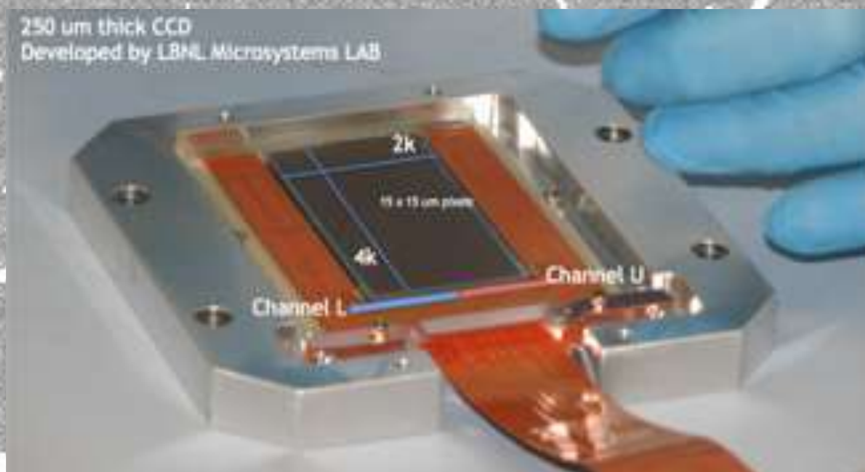
CEvNS ⇔ low threshold DM detector

CONNIE ⇔ DAMIC MINER ⇔ CDMS RICOCHET ⇔ EDELWEISS

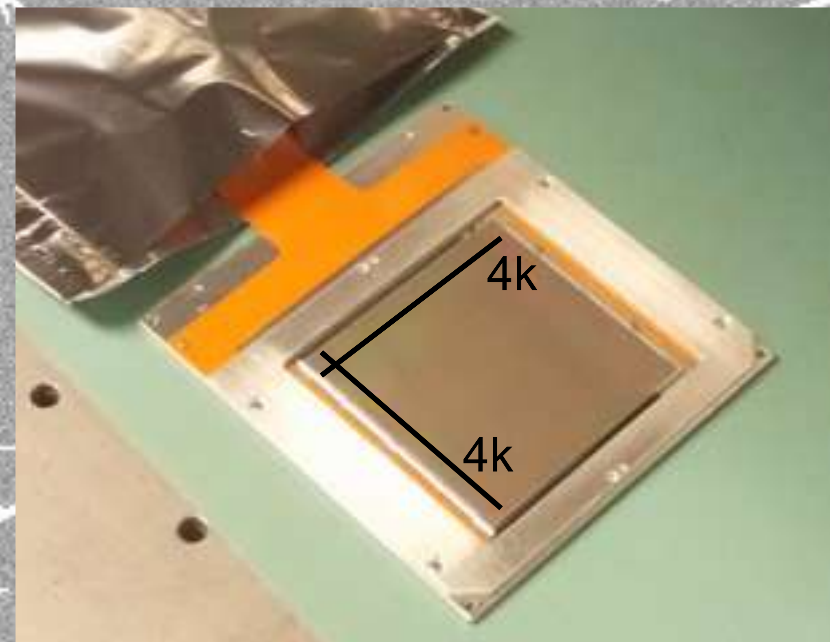
νCLEUS ⇔ CRESST Etc.

CONNIE Experiment

Coherent Neutrino-Nucleus Interaction Experiment



CONNIE 2014 Engineering run
250 μm CCDs, 1 g
1 CCD for physics analysis
Exposure ~ 15 g-day



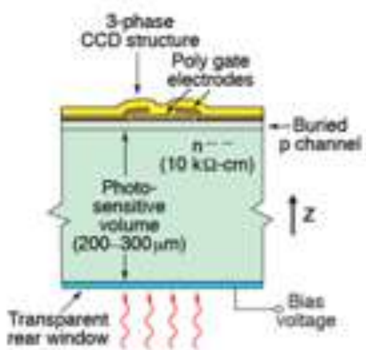
CONNIE 2016 Detector upgrade
675 μm CCDs, 5.8 g each
8 CCD for physics analysis
Running since Aug 2016
Exposure ~ 2000 g-day

JINST 11 (2016) P07024

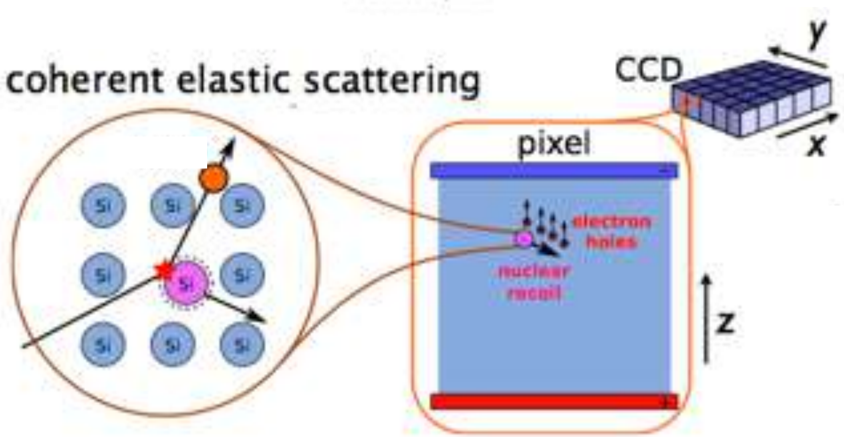
Phys. Rev. D 100 (2019) 092005

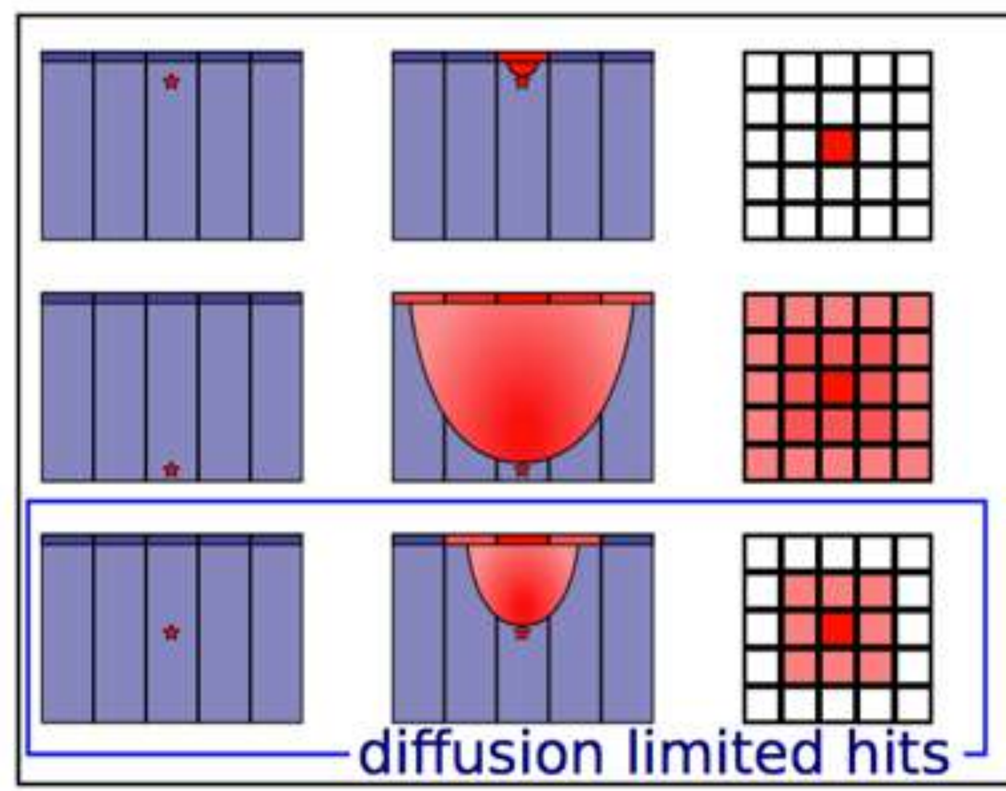
CCDs – Charge Coupled Device

- Characteristics
  - high-resistivity CCDs created at LBNL and used in the DAMIC experiment
  - threshold of ~40 eV for ionization energy of the nuclear recoil (quenching factor)
  - large mass compared to regular CCDs (now 675 μm, 5.25 g, 4k x 4k)
  - "3D" information (diffusion): rejection of surface events

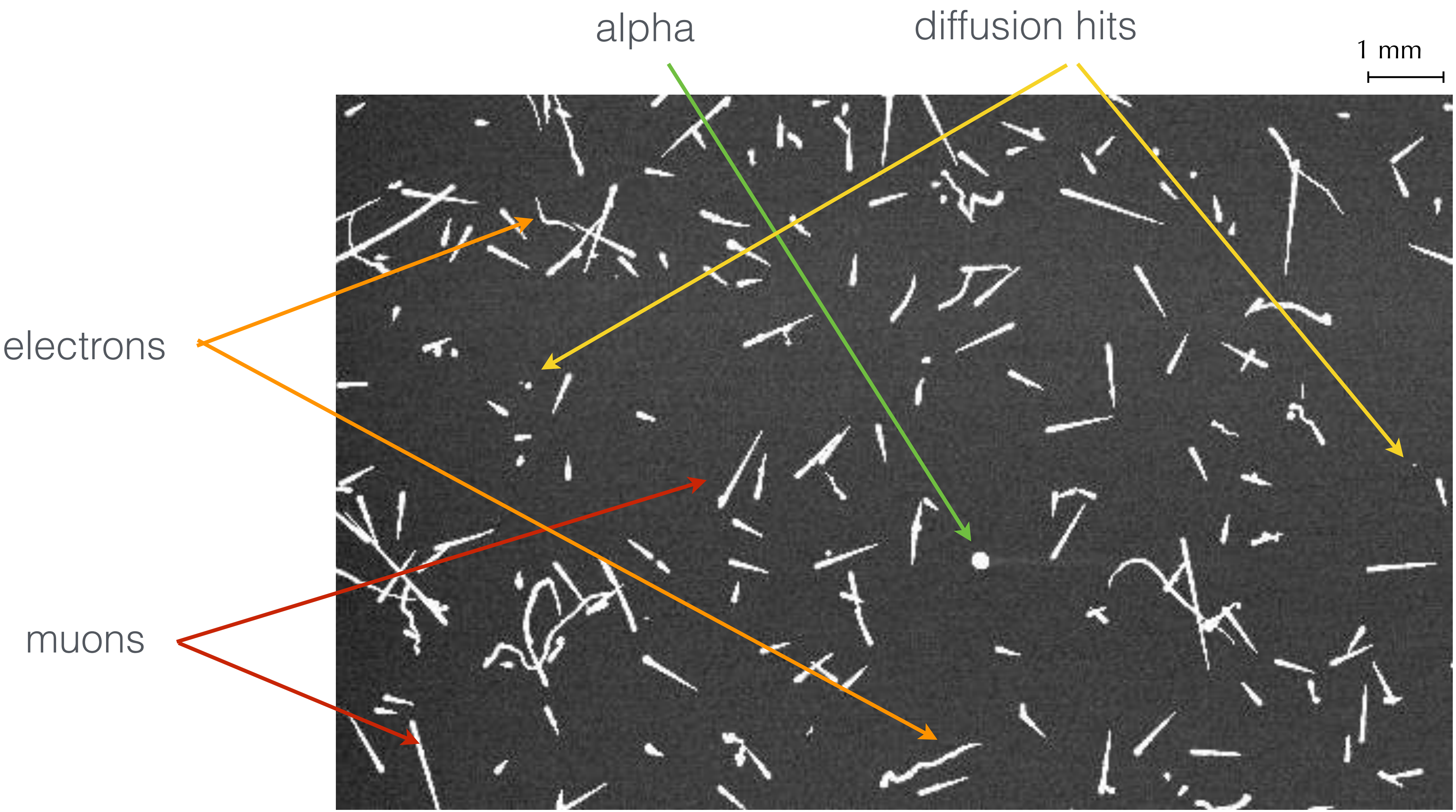


(a) A CCD pixel





Particle identification CCD



The detector

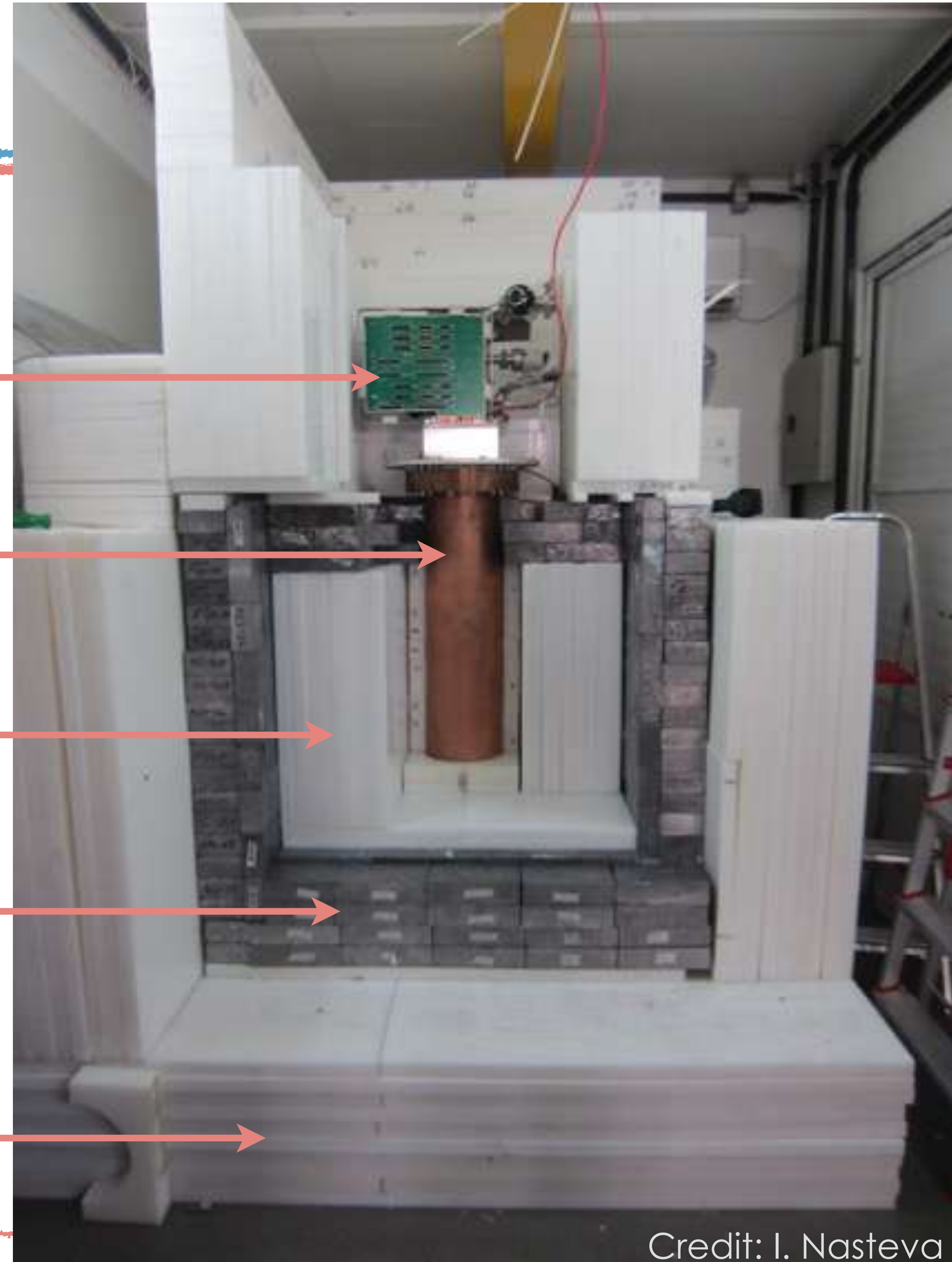
ViB board
(signals transport)

Dewar
(hold vacuum)

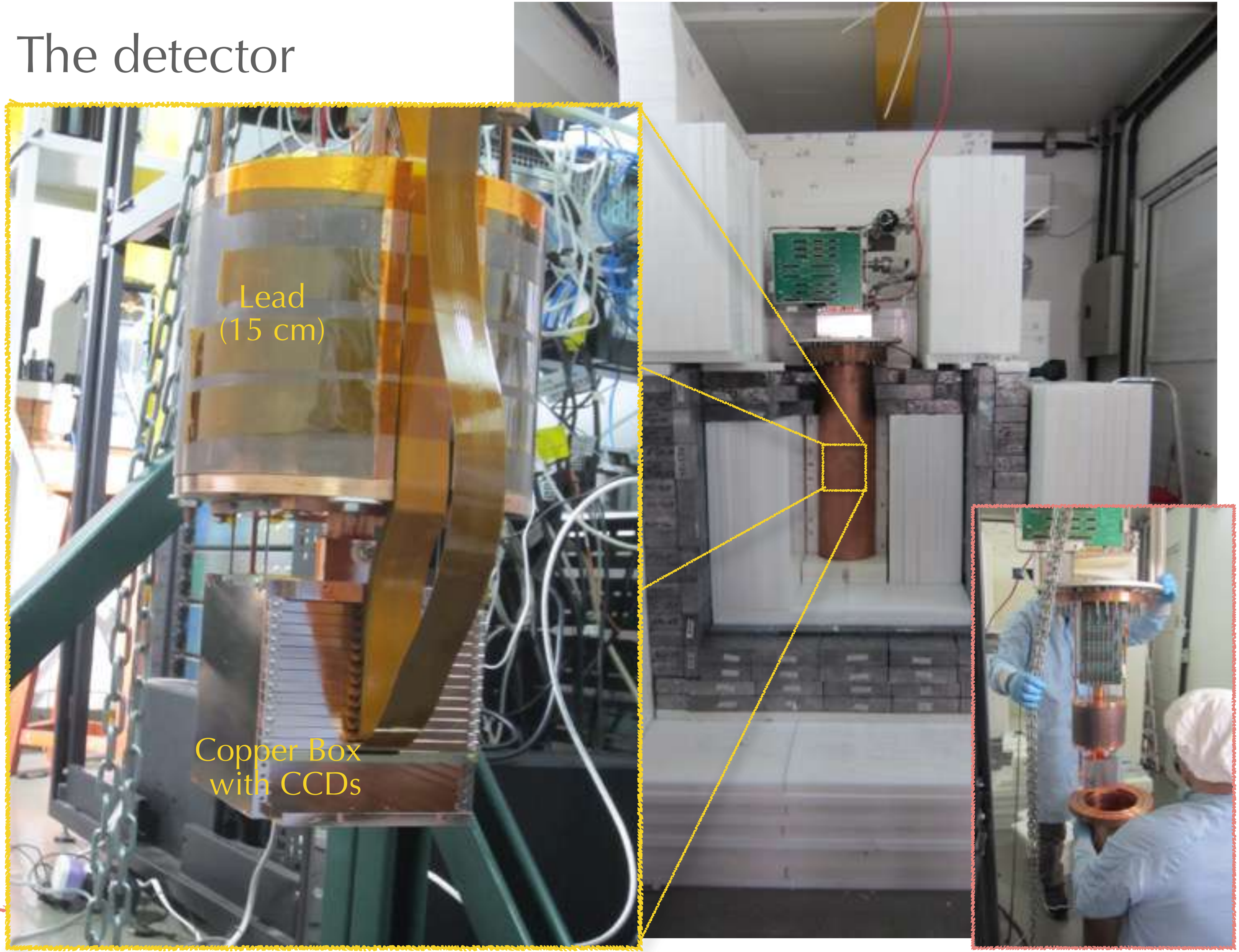
Inner
polyethylene (30 cm)

Lead (15 cm)
~ 800 bricks (Fermilab, USP, CBPF
and bought to Aurea)

Outer
polyethylene (30 cm)



The detector



Location

30 m from the Angra 2 nuclear power plant reactor core,
Rio de Janeiro – Brazil

antineutrino source of 3.8 GW_{th}

estimated flux of 7.8 x 1012 $\nu\ s^{-1}cm^{-2}$ at the detector position.

Two experiments on the Neutrinos Lab

- Neutrinos Angra
- CONNIE

Analysis of 2016 + 2017 data

Stability is controlled through:

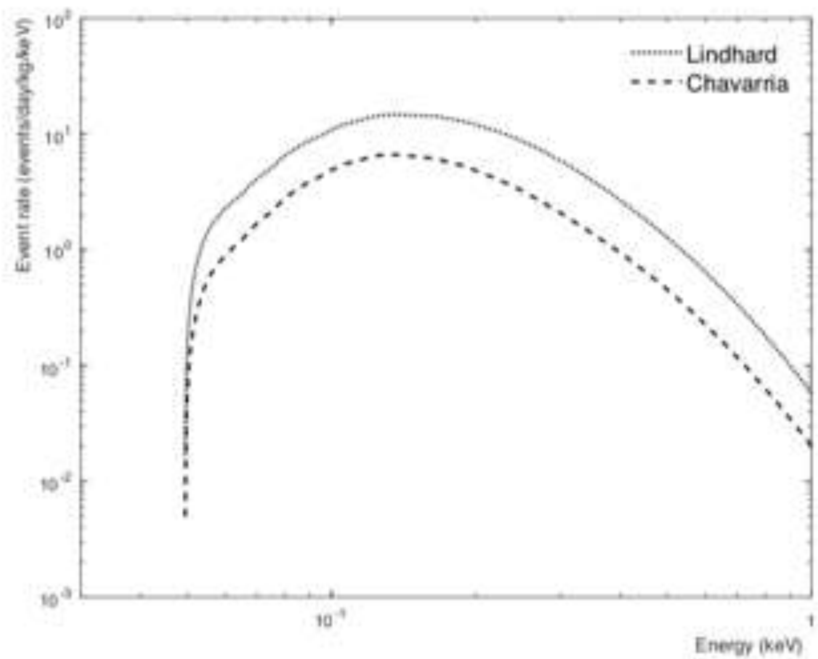
- read-out noise and dark current
- calibration of Cu and Si peaks
- high-energy event rates

- Event selection
  - Good CCDs (noise & DC)
  - Edge effect & hot pixels removal
  - Total exposure: 2.1kg-day reactor ON
    1.6 kg-day reactor OFF
- Search for the SM CEvNS signal
  - Background is not modelled
  - Compare the rates with the reactor ON and reactor OFF

Efficiency computation:

- simulate low-energy neutrino events in each image and process the full event reconstruction analysis

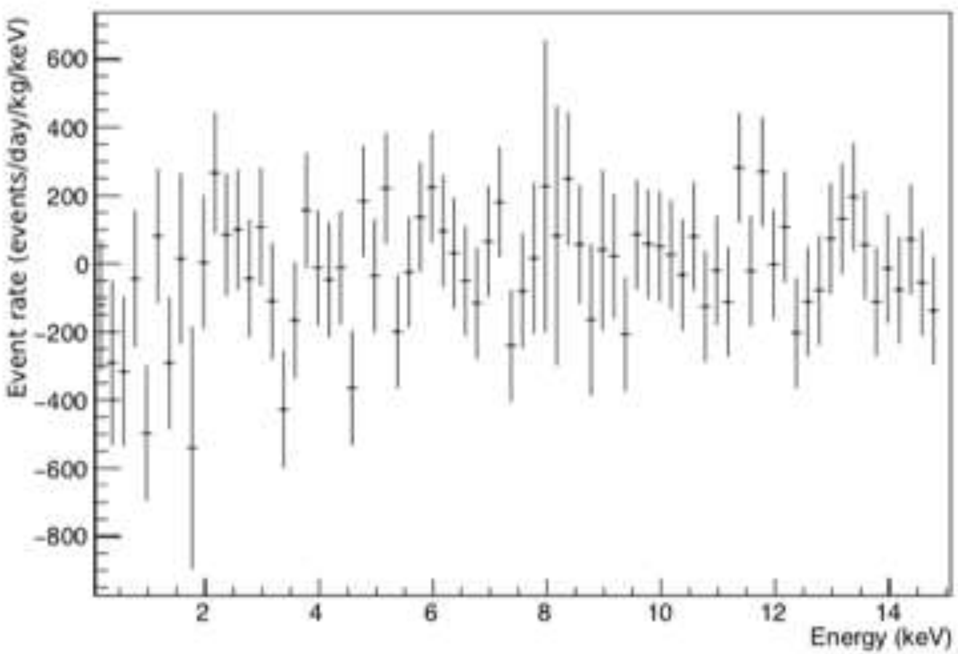
- Expected neutrino event rate



Phys. Rev. D 100, 092005 (2019); arXiv:1906.02200

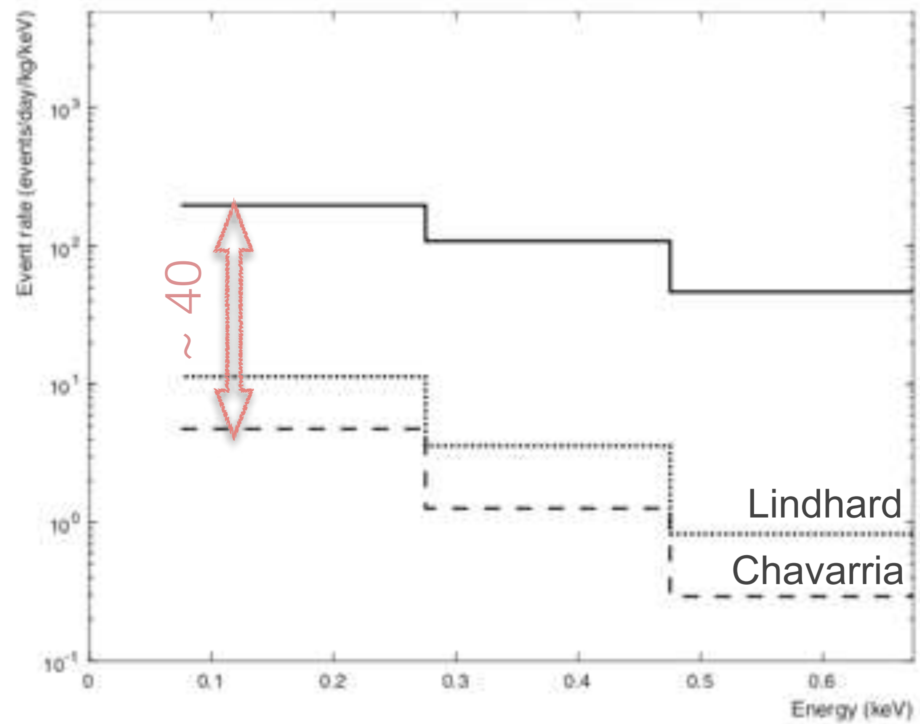
Reactor ON/OFF - 2016 + 2017 data

- Energy spectrum difference



First search for CEνNS at a nuclear reactor reaching recoil energies down to 1 keV (0.1 keV_{ee})

- CEνNS event rate: 95% confidence level limit from the reactor on - off measurement



Phys. Rev. D 100, 092005 (2019)
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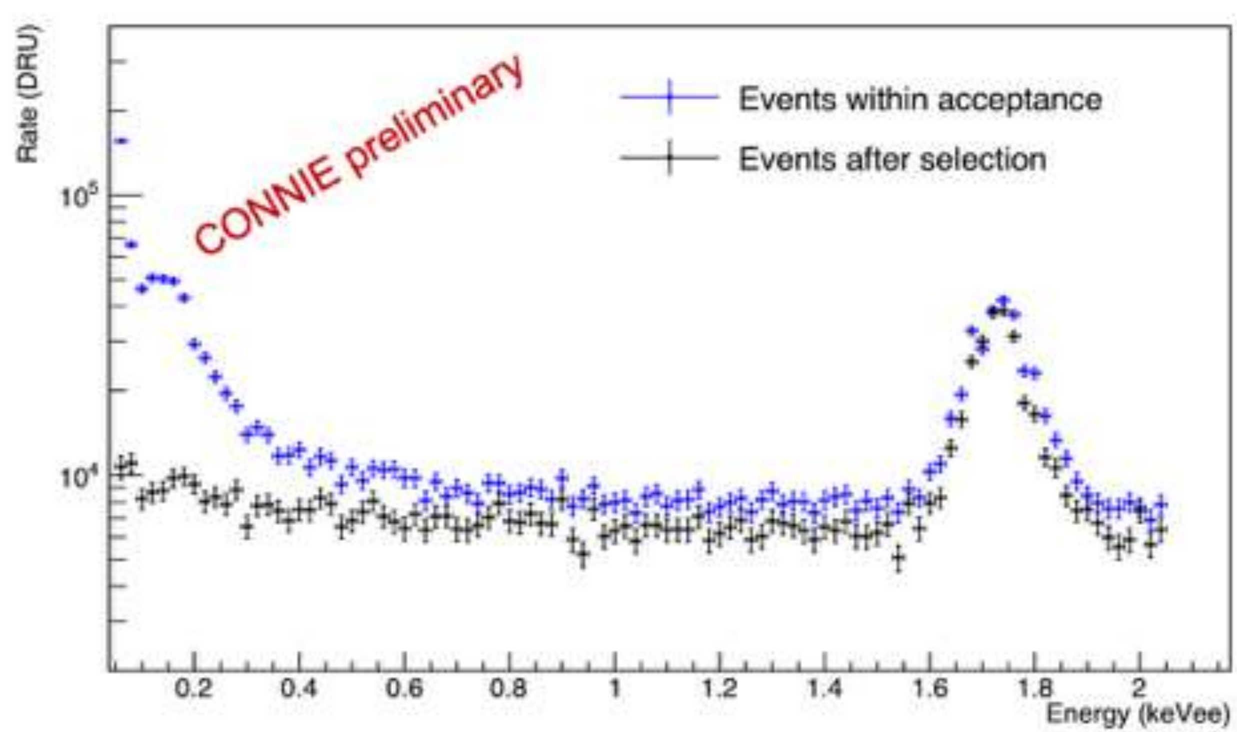
2019 - 2020 Data

- A hardware binning of data reduces the effect of readout noise at low energies. (CONNIE 19/20)
- understanding and controlling the low energy background
- improvement in calibrations and event selection
- revised neutrino signal selection

blind analysis

- adjust all analyses using only the reactor OFF data
- unblind the mid to high energy reactor ON data for stability check-ups

rate of events corrected by efficiency for reactor OFF



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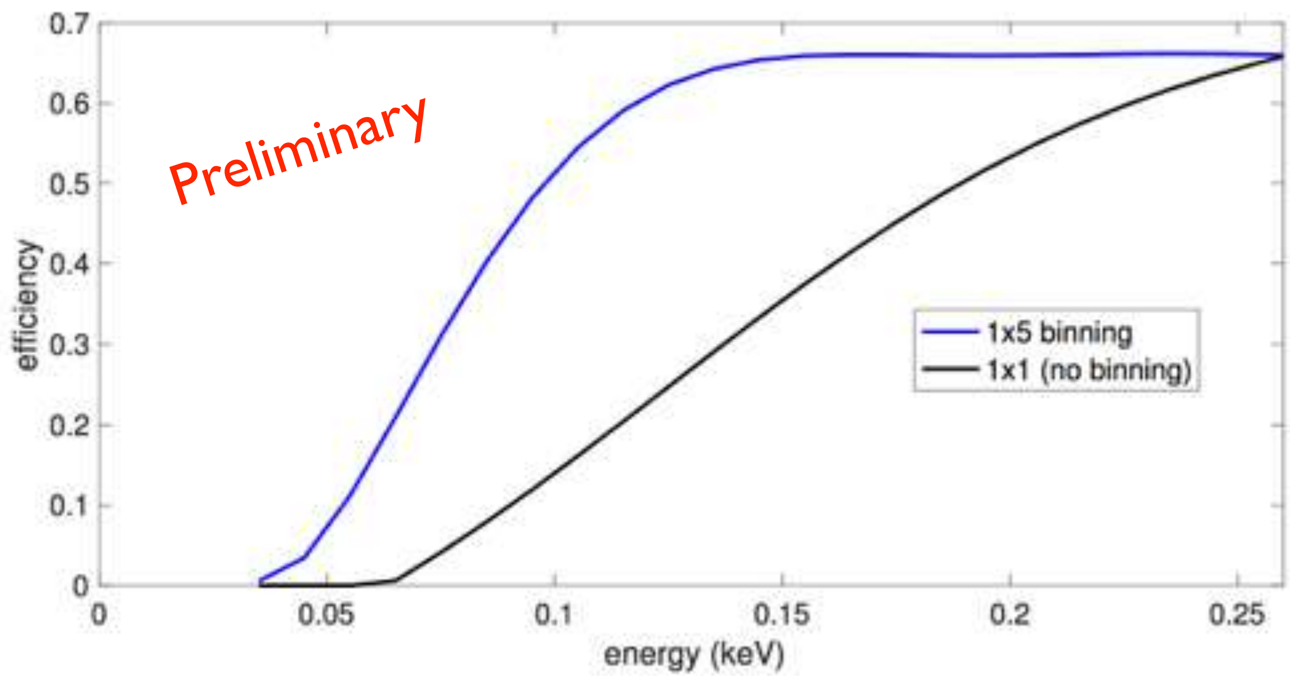
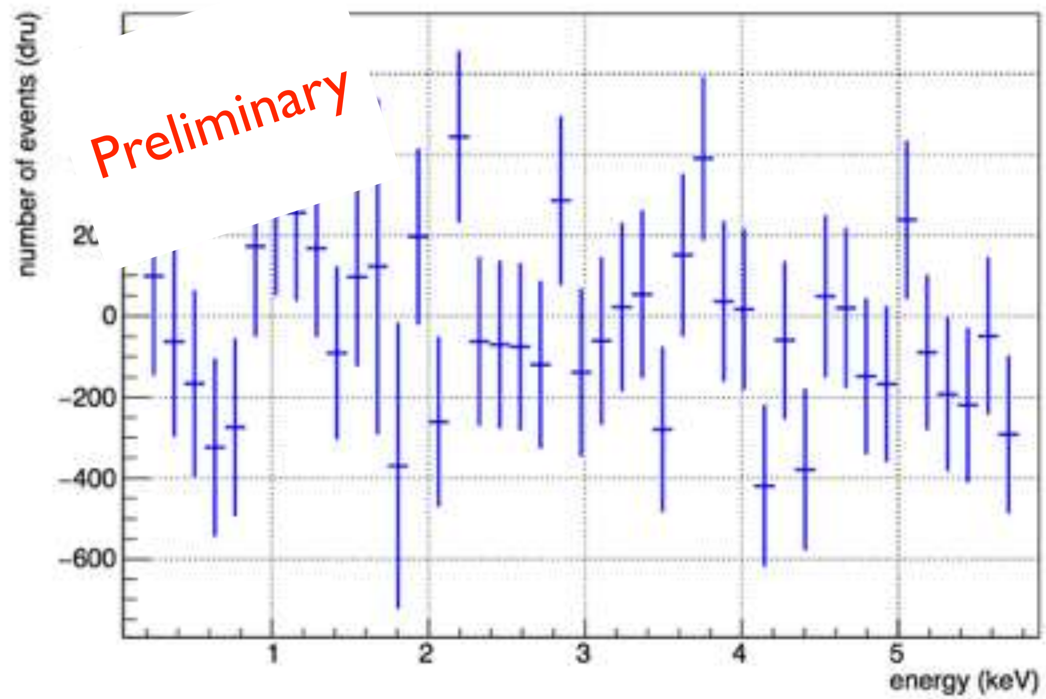
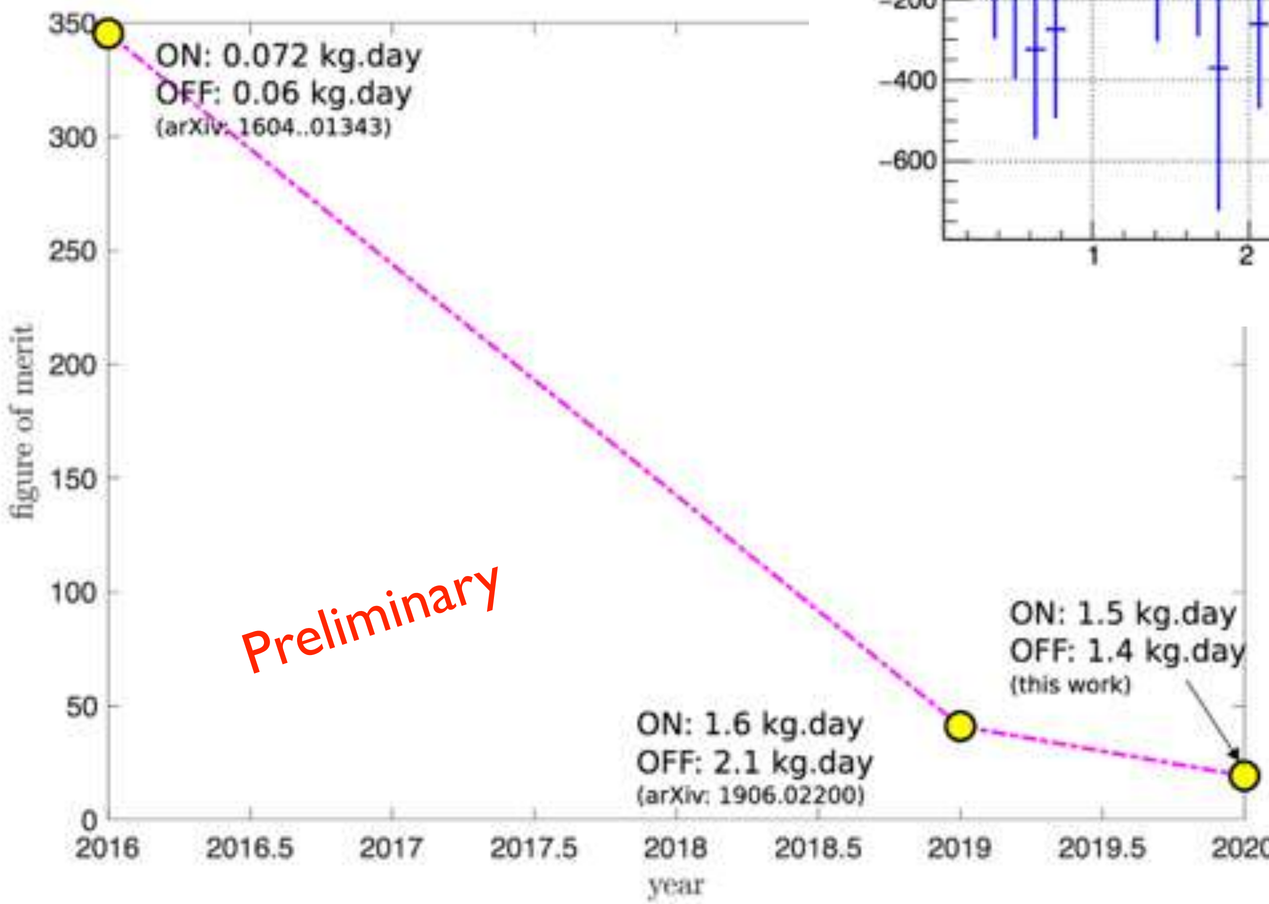


2019 - 2020 Data

blind analysis

- just unblinded the reactor ON 2019 data
- reactor ON 1.52 kg·day
- reactor OFF 1.35 kg·day





From G. Moroni
Fermilab W&C today

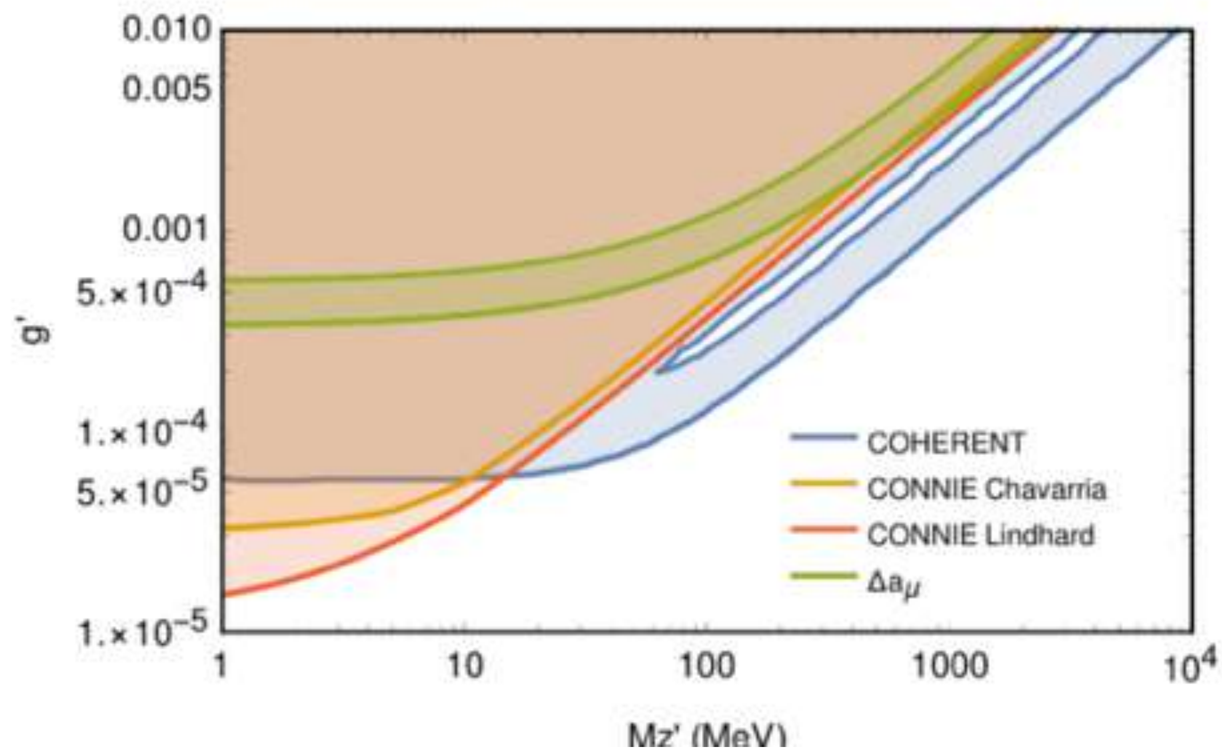
Implications for BSM physics: light mediators

Event rates in the lowest-energy bin yield limits on non-standard neutrino interactions:

- light vector (Z') mediator
- most stringent limits for low mediator masses $M_{Z'} < 10$ MeV
- first competitive BSM constraint from CEvNS in reactors!

$$\frac{d\sigma_{SM+Z'}}{dE_R}(E_{\bar{\nu}_e}) = \left(1 - \frac{Q_{Z'}}{Q_W}\right)^2 \frac{d\sigma_{SM}}{dE_R}(E_{\bar{\nu}_e})$$

$$Q_{Z'} = \frac{3(N+Z)g'^2}{\sqrt{2}G_F\left(2ME_R + M_{Z'}^2\right)}\,.$$



J. High Energ. Phys. 2020, 54 (2020); arXiv:1910.04951

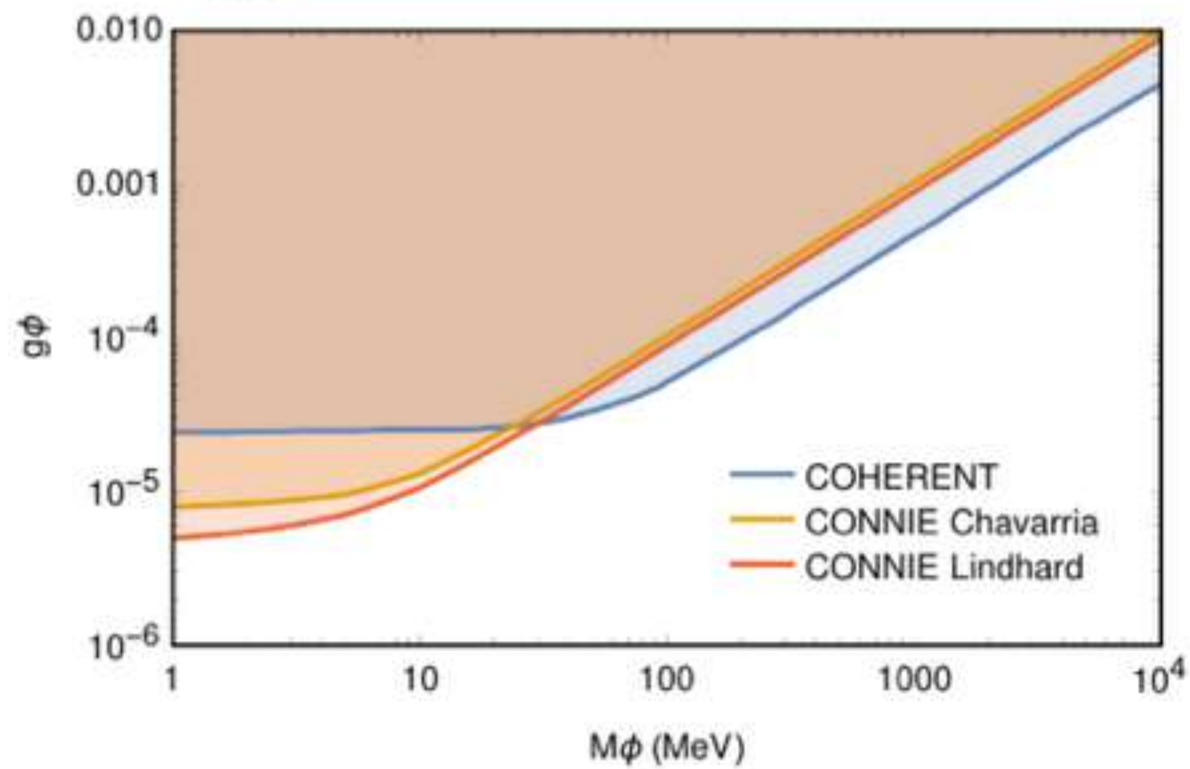
Implications for BSM physics: light mediators

Event rates in the lowest-energy bin yield limits on non-standard neutrino interactions:

- light scalar (ϕ) mediator.
- most stringent limits for low mediator masses $M_\phi < 30$ MeV
- first competitive BSM constraint from CEvNS in reactors!

$$\frac{d\sigma_{SM+\phi}}{dE_R}(E_{\bar{\nu}_e}) = \frac{d\sigma_{SM}}{dE_R}(E_{\bar{\nu}_e}) + \frac{G_F^2}{4\pi}Q_\phi^2\left(\frac{2ME_R}{E_{\bar{\nu}_e}^2}\right)MF^2(q)$$

$$Q_\phi = \frac{(14N+15.1Z)g_\phi^2}{\sqrt{2}G_F\left(2ME_R+M_\phi^2\right)}$$



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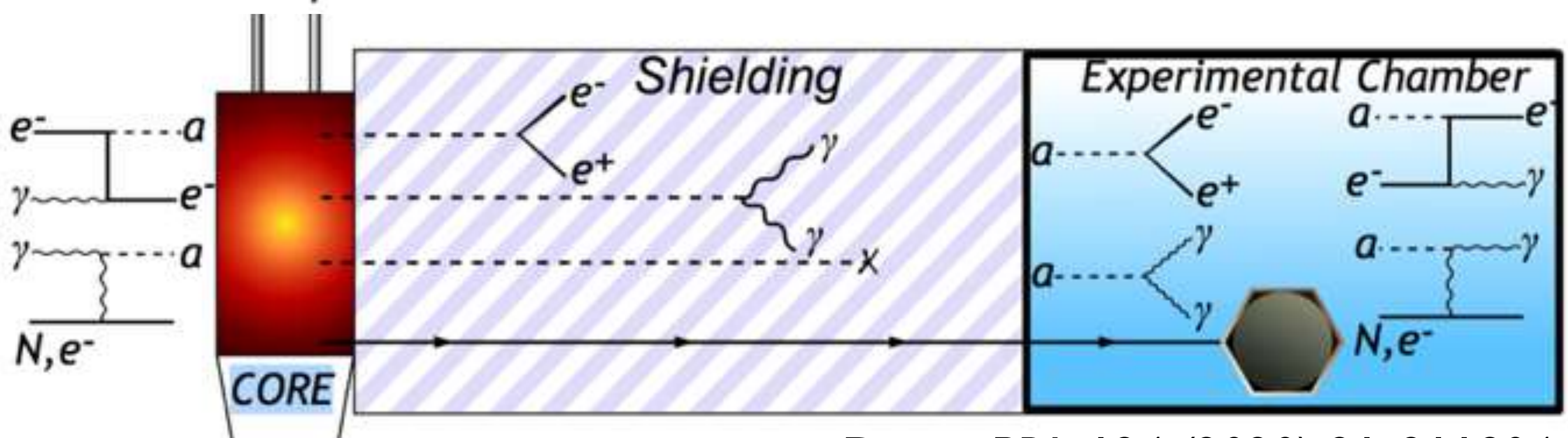
Axion Like Particles

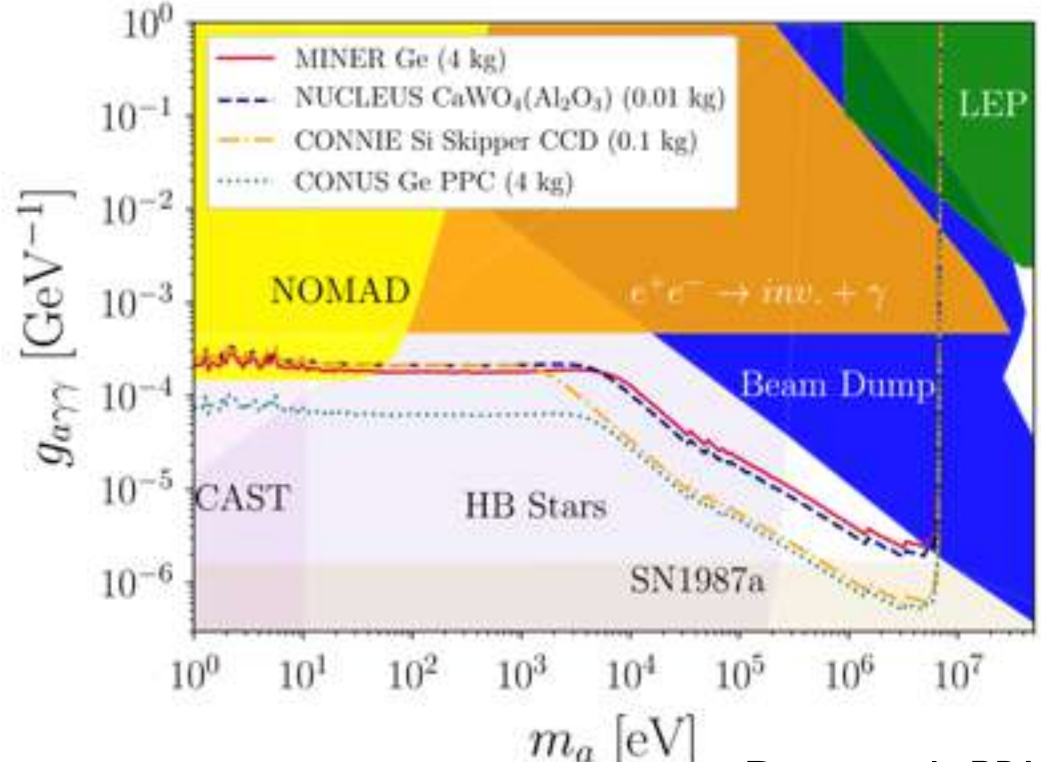
- Nuclear reactors are high intensity low energy γ sources:
  - γ are produced in the core in large amounts (10^{23} γ per day at 1 MW)
  - high-Z material in the core ^{235}U, ^{231}Th → convert to ALPs via Primakoff, Compton channels or nuclear de-exitation
- Detected via the inverse Compton and Primakoff channels, as well as decays, inside detector housing

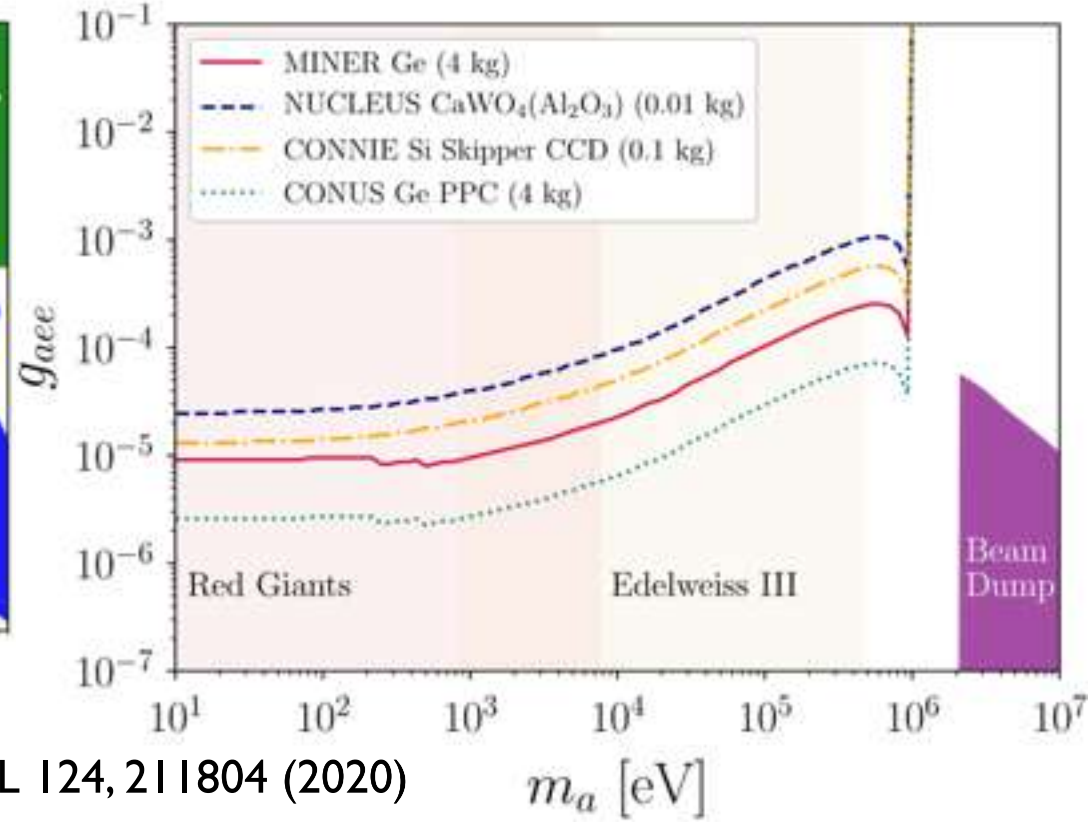
$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma}\, a F_{\mu\nu}\widetilde{F}^{\mu\nu} - i g_{aee}\, a\, \bar{e}\gamma_5 e - i a \bar{n}\gamma_5 \left(g^{(0)}_{ann} + \tau_3 g^{(1)}_{ann}\right) n$$



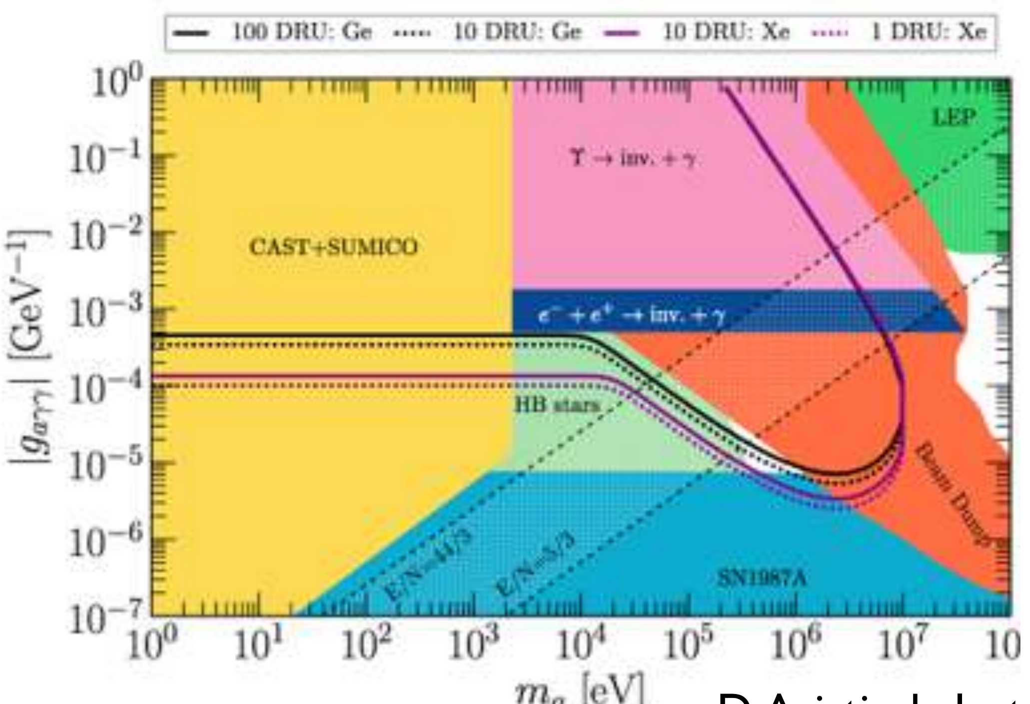
Dent+ PRL 124 (2020) 21, 211804

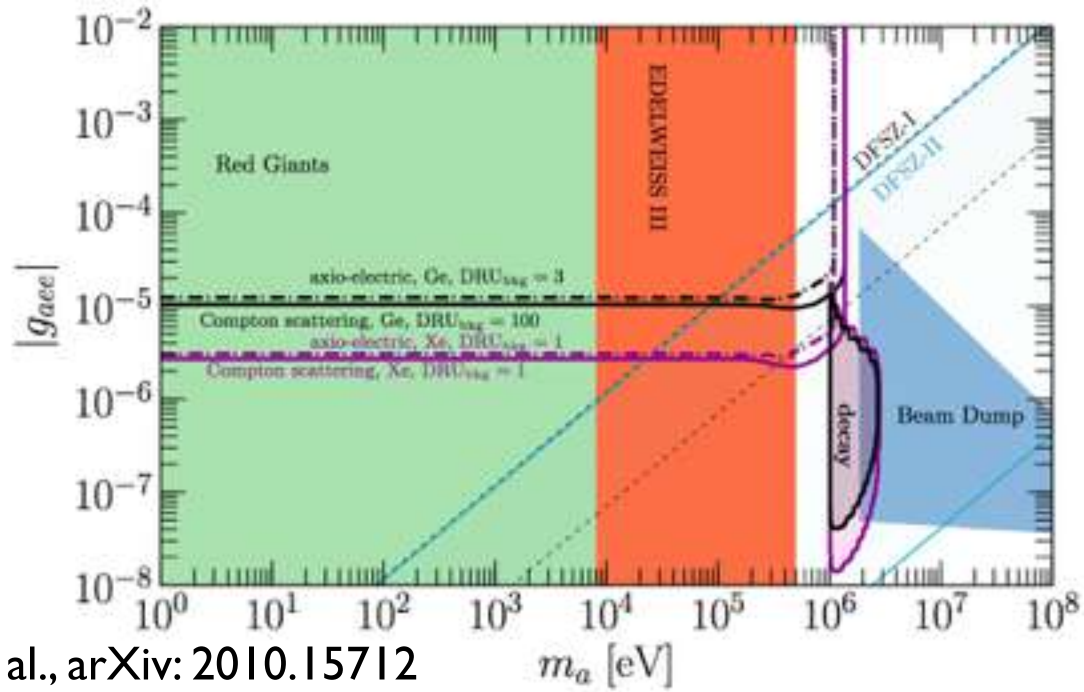
See also D. Aristizabal, et al., arXiv: 2010.15712





Dent et al., PRL 124, 211804 (2020)





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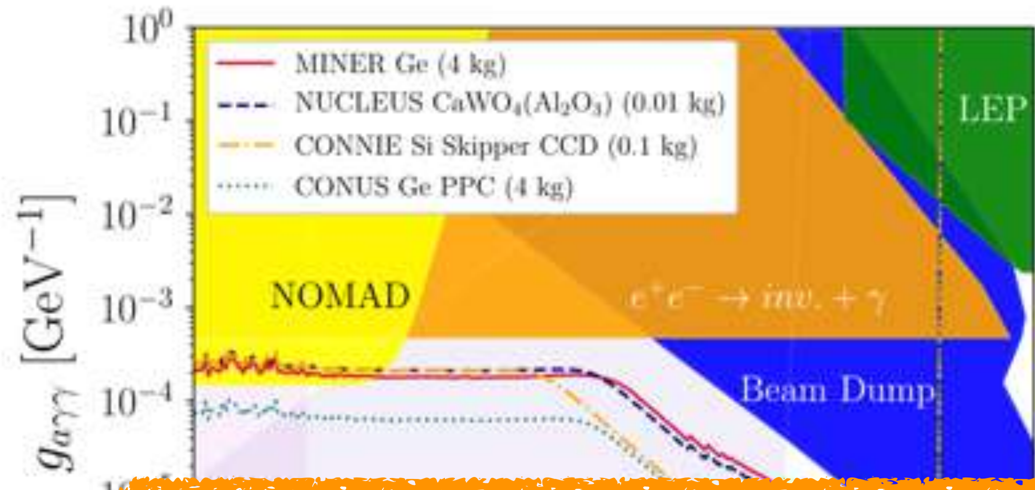
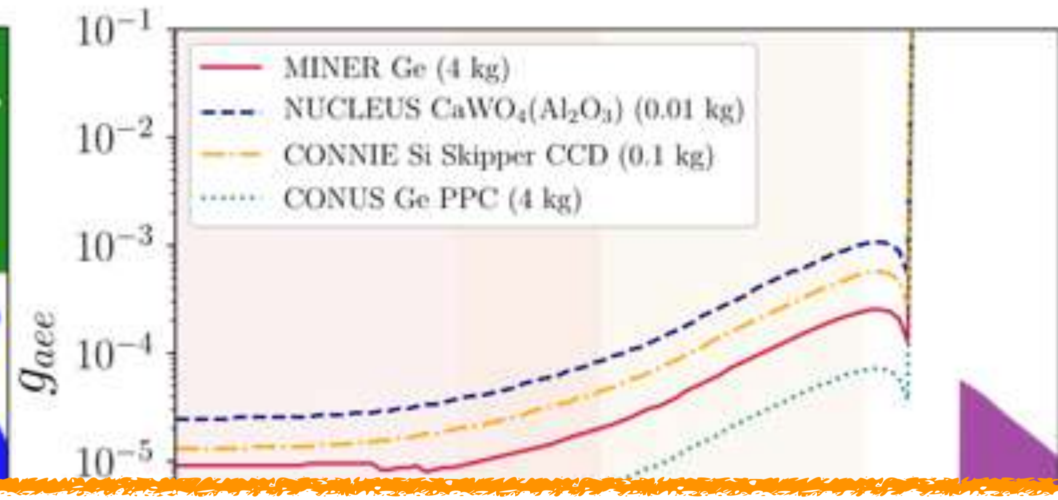
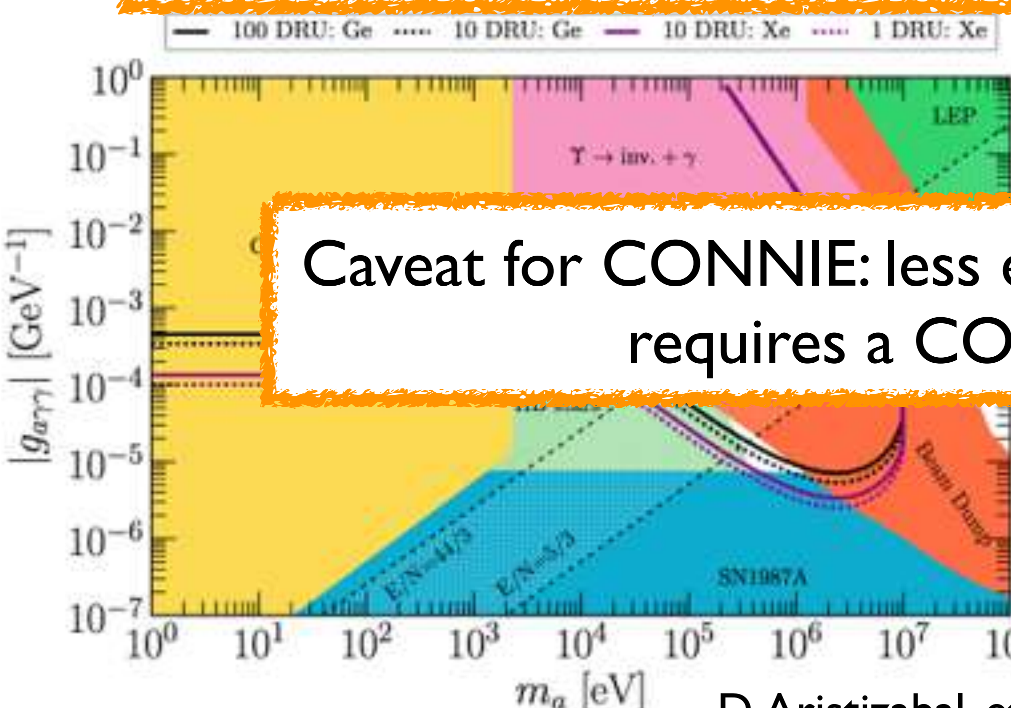
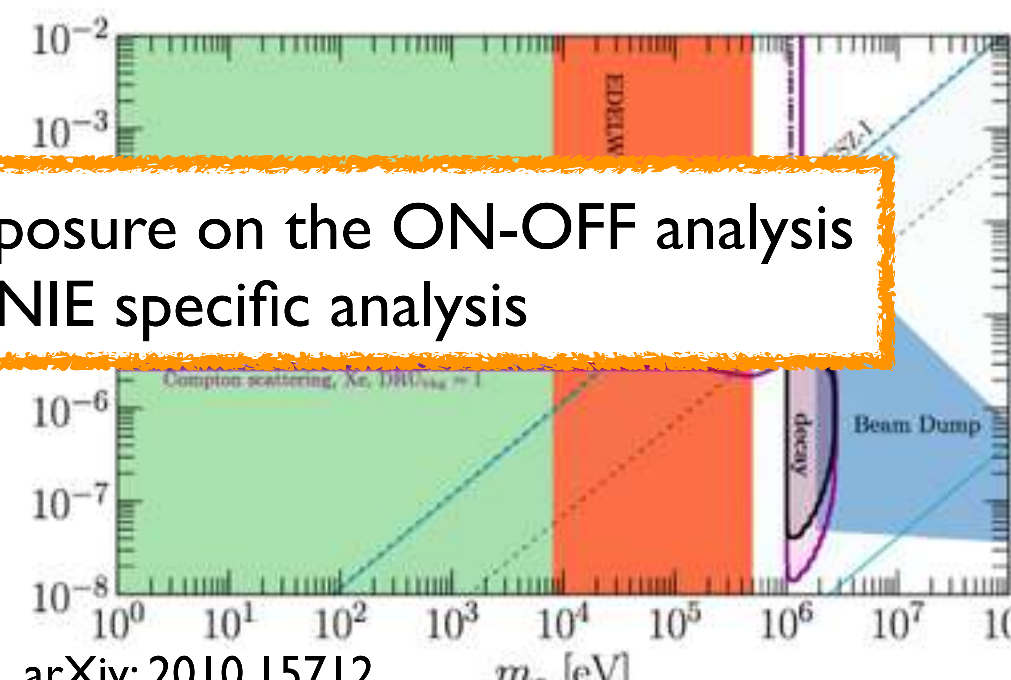




CEvNS experiments can become the most sensitive laboratory-based detectors to $g_{a\gamma\gamma}$ within an ALP mass range ~(1–10^6) eV





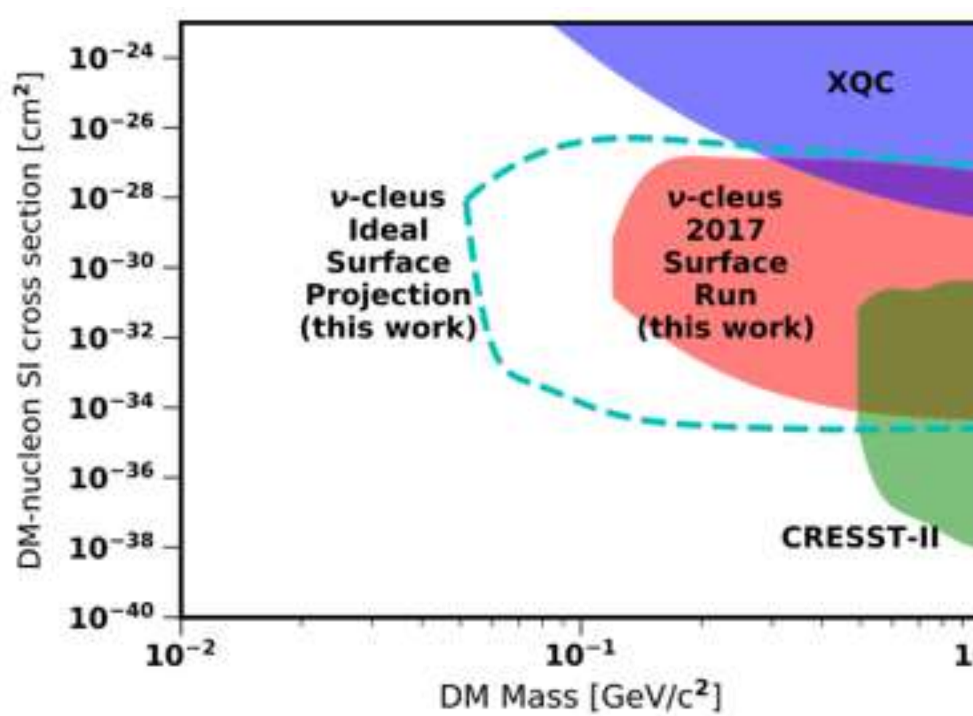
Caveat for CONNIE: less exposure on the ON-OFF analysis requires a CONNIE specific analysis

D. Aristizabal, et al., arXiv: 2010.15712

Strongly Interacting Massive Particles (SIMPs)

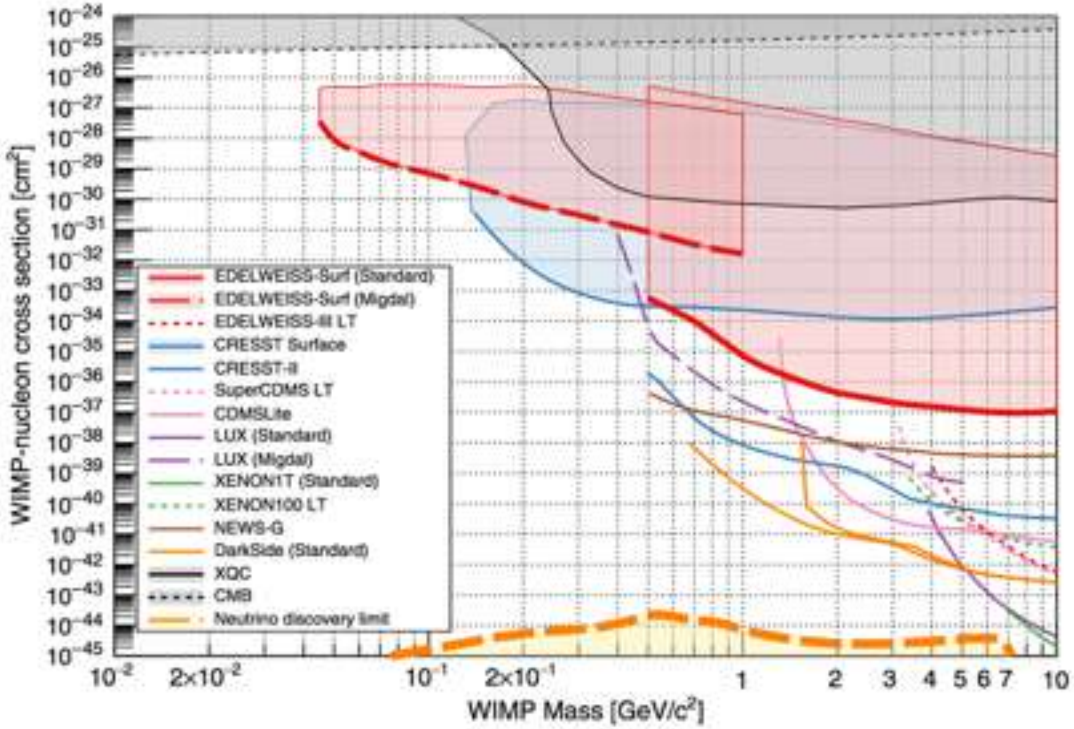
- DM particle candidates that interact with nucleons via nuclear-scale cross sections
- SIMPs interact with Earth, atmosphere and shielding, modifying their distribution in the lab
- For large SIMP-nucleon cross sections the sensitivity of traditional direct dark matter searches using underground experiments is limited by the energy loss experienced by SIMPs.
- **Surface-based experiments are ideal for a SIMP search!**

- Constraints on sub-GeV mass SIMPs: 2017 Surface Run of the ν-cleus prototype, obtained by the CRESST collaboration, **0.49 g** Al_2O_3 target running for a total live time of **2.27 h**, with a low-energy threshold of **20 eV**



JH Davis, PRL 119, 211302 (2017)

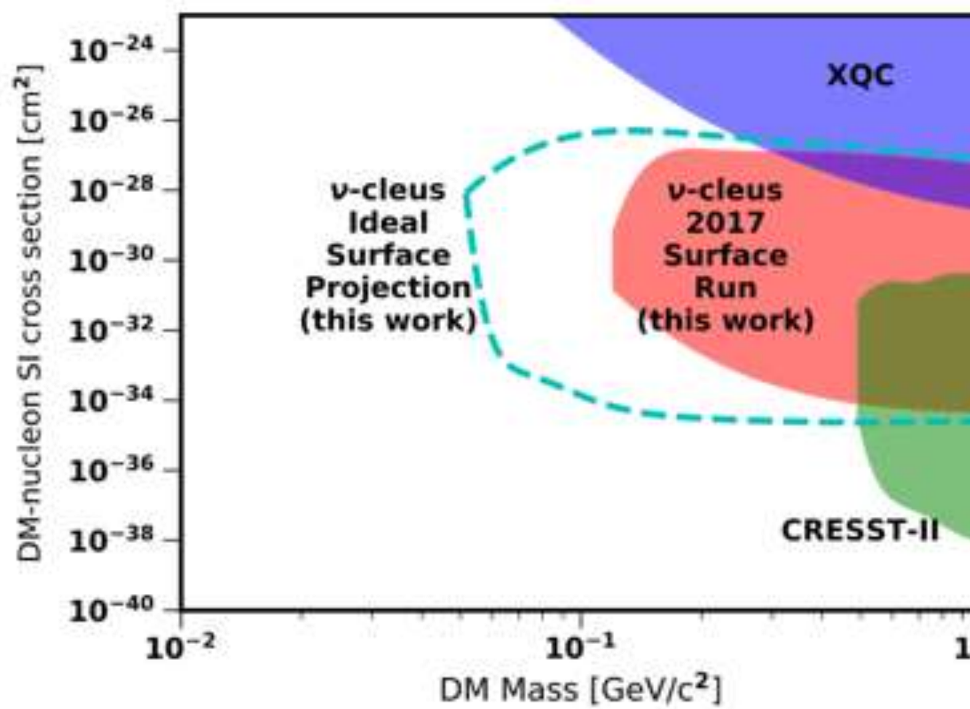
EDELWEISS collaboration, PRD 99, 082003 (2019)



SIMPS

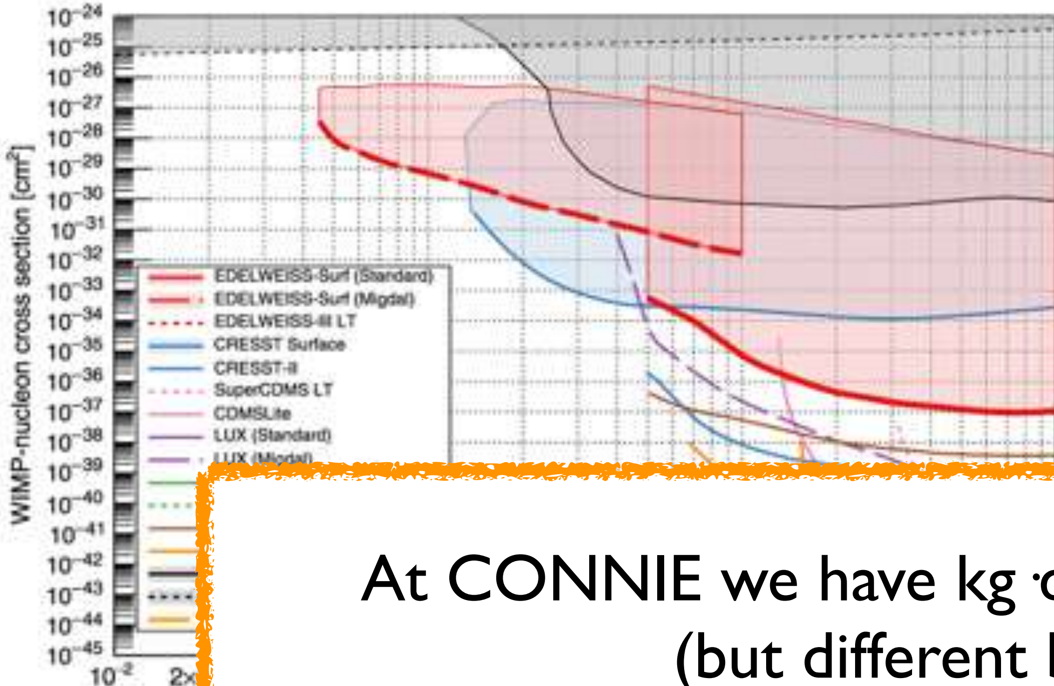
EDELWEISS **33.4 g** Ge cryogenic detector operated in a surface lab. **One day** exposure and a **60 eV** analysis energy threshold

- Constraints on sub-GeV mass SIMPs: 2017 Surface Run of the ν-cleus prototype, obtained by the CRESST collaboration, **0.49 g** Al_2O_3 target running for a total live time of **2.27 h**, with a low-energy threshold of **20 eV**



JH Davis, PRL 119, 211302 (2017)

EDELWEISS collaboration, PRD 99, 082003 (2019)



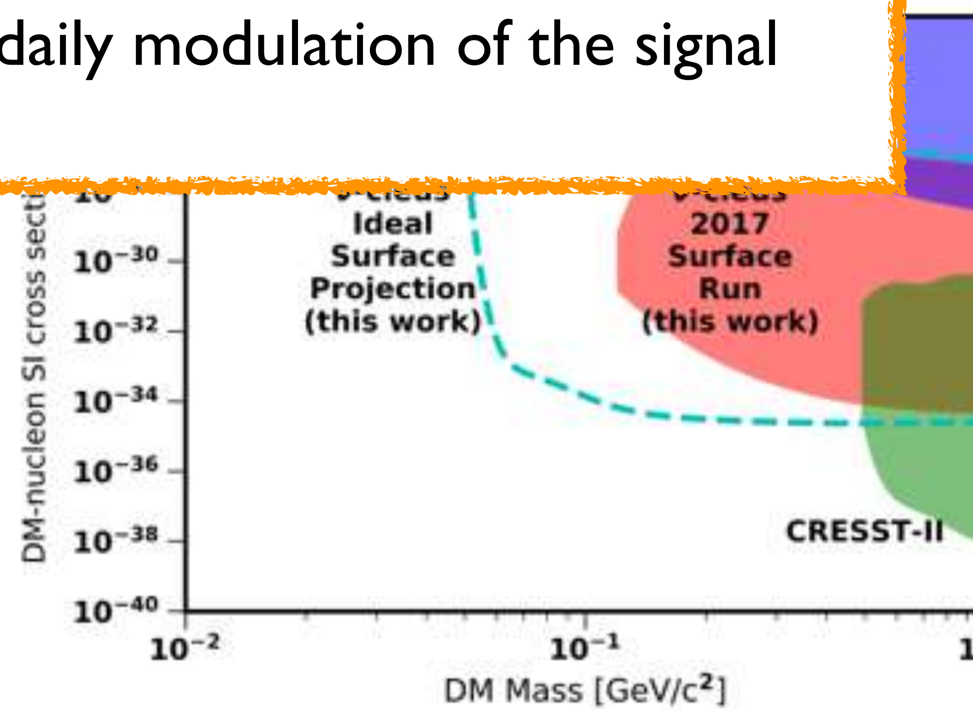
SIMPS

EDELWEISS **33.4 g** Ge cryogenic detector operated in a surface lab. **One day** exposure and a **60 eV** analysis energy threshold

At CONNIE we have kg·day exposures or higher
(but different background)

Moreover, explore the daily modulation of the signal

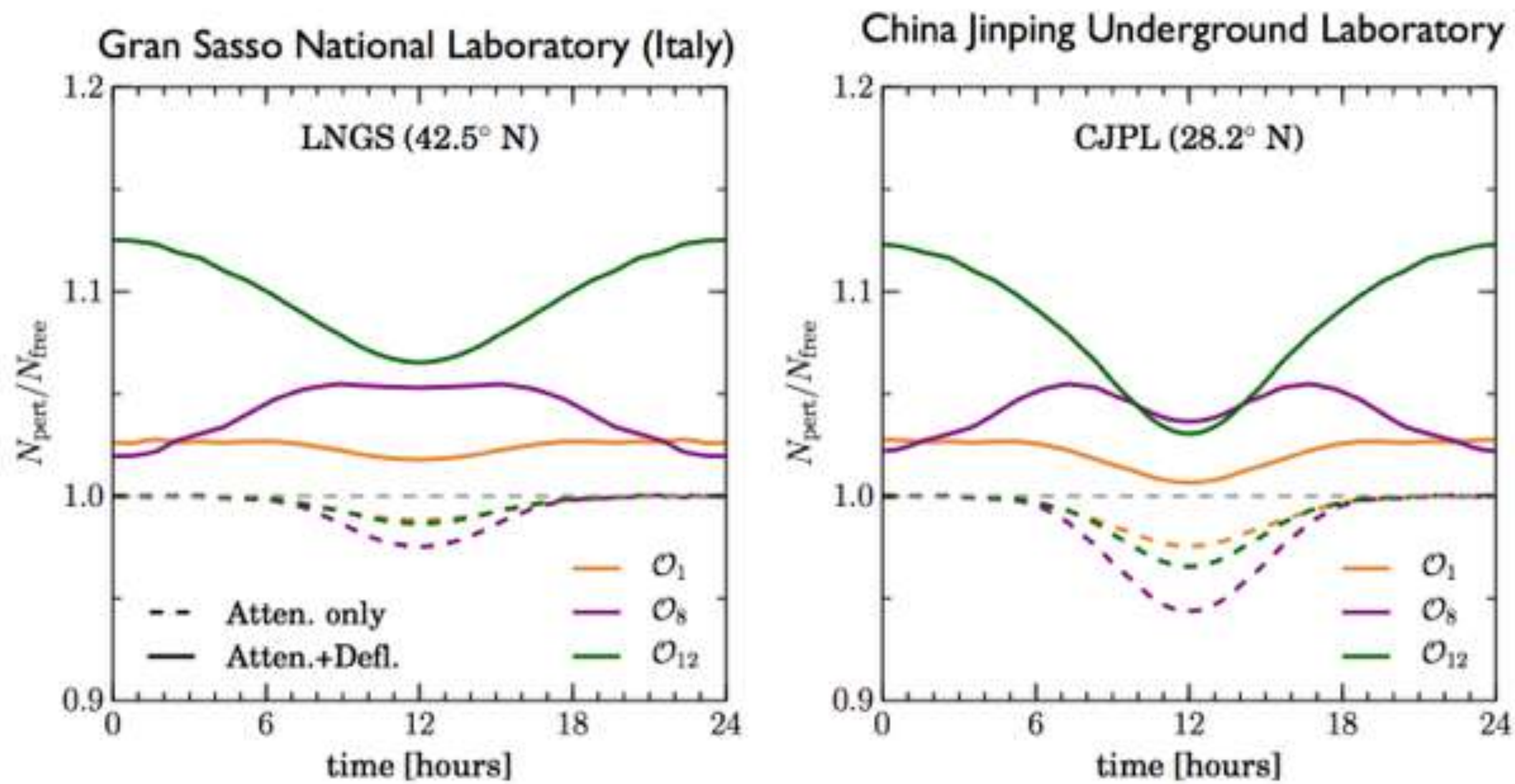
- Cons
  2017
  prototype, obtained by the CRESST collaboration, **0.49 g** Al_2O_3 target running for a total live time of **2.27 h**, with a low-energy threshold of **20 eV**



JH Davis, PRL 119, 211302 (2017)

Modulation Signatures

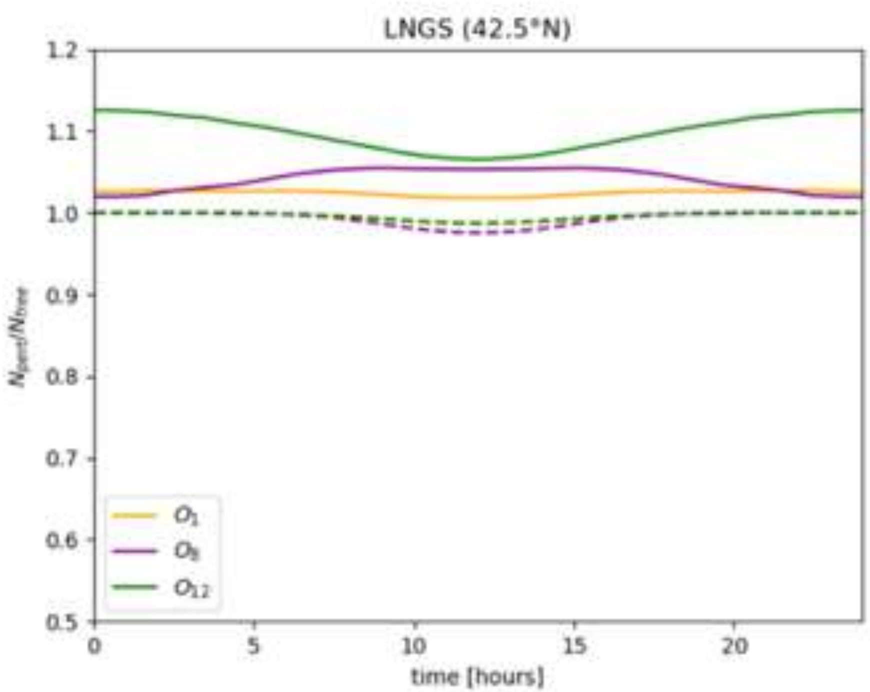
- Effect of attenuation of the Earth and Deflection
- The Earth rotation induces a **daily modulation** in the rate, which is highly sensitive to the detector latitude (+ DM mass and interactions and detector)

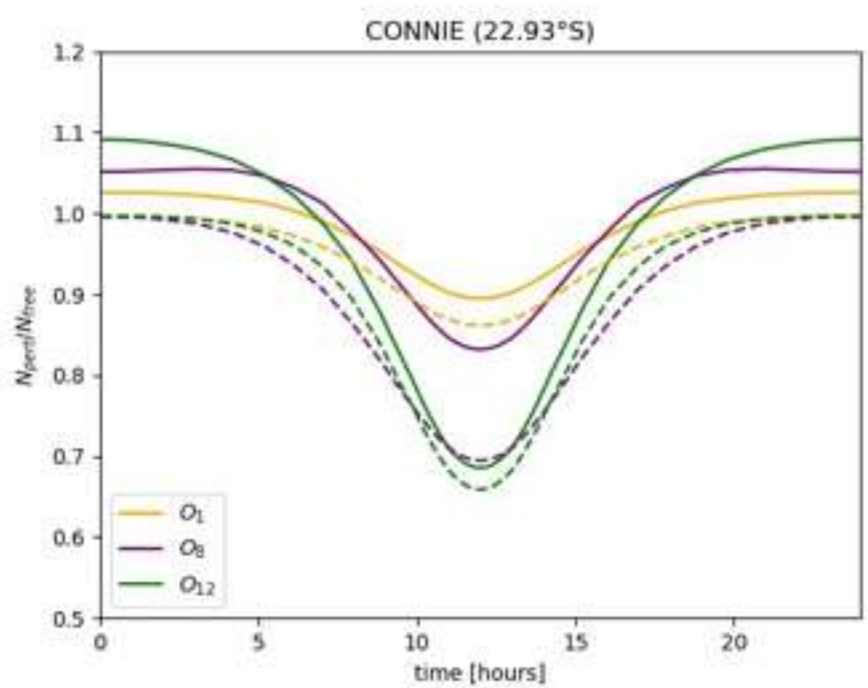


Kavanagh+JCAP **01** (2017), CRESST-II-like detector $p_{scat} = 10\%$ $m_\chi = 0.5$ GeV

Modulation Signatures

- Look for daily modulations at CONNE:
  - Higher modulation expected at Angra!
  - Very stable detector
  - Sidereal time: average over the year to minimize seasonal effects
  - Much larger exposure, but higher background
  - Working at higher energies will allow us to have almost continuous coverage for a couple of years



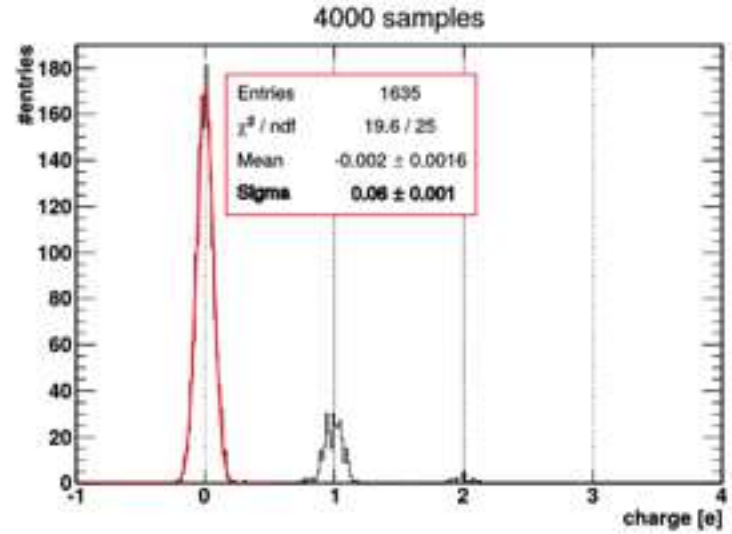


from Ana Foguel

EarthShadow (Kavanagh et al., 2016), CRESST-II-like detector $p_{\mathrm{scat}} = 10\%$ $m_\chi = 0.5$ GeV

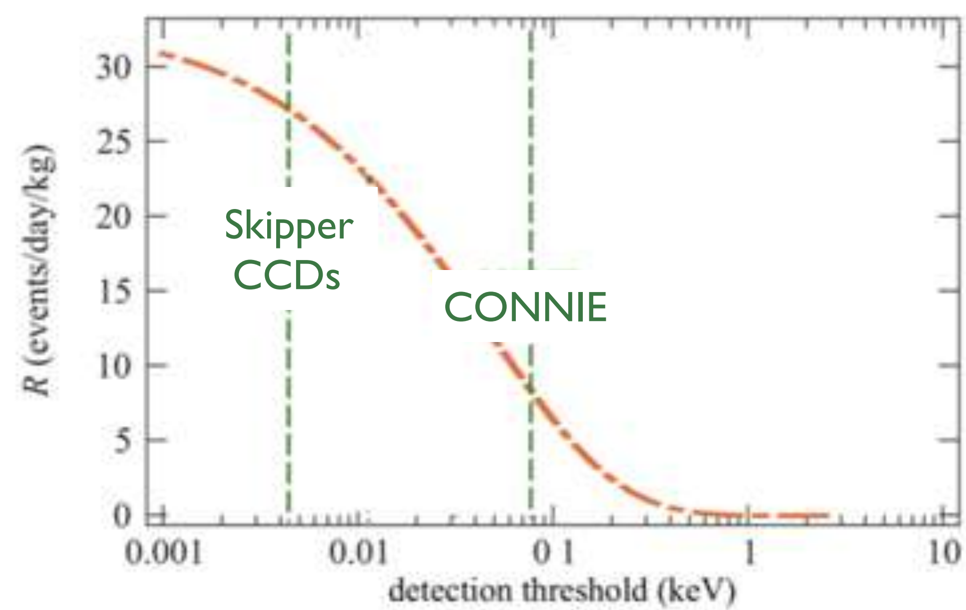
Prospects for the future

- Upgrade CONNIE with 1-2 new skipper–CCDs:
  - Reduction in electronic noise
  - Individual electron detection
  - Promising for neutrino and dark matter detection
- Goals:
  - Reduce CONNIE energy threshold to **~ 15 eV**
  - Better understanding of the background experiment
  - In coordination with vIOLETA R&D effort



J. Tiffenberg et al, PRL 119 (2017)

- Carry out the analysis with ALPs, SIMPs, and other BSM physics



Summary

- **CCDs** can be used **as particle detectors** with **good spatial and energy resolution** and **very low electronic noise**
- Capability to **detect nuclear recoils**
- CONNIE now **operating at Angra 2** nuclear power plant: source of **neutrinos** and photons, with **possible production of ALPs and other BSM particles**
- **First competitive BSM constraint from CEvNs** at reactors
- Low threshold detector at the ground: promising for **SIMPs**
- **2019-2020 data:** improvements in data taking and analysis (will be published soon)
- Data will eventually be made public
- Next year: **installation of 1-2 skipper-CCDs, greatly reduce the noise**

CONNIE has helped to develop the Latin American expertise in reactor neutrino experiments and CCDs as particle detectors (instrumentation and data analysis)

Neutrino Laboratory could host other experiments