July 13, 2023

FSPA Early Career Seminar Series

Antineutrinos for Nuclear Safeguards

Ohana Benevides Rodrigues obenevidesrodrigues@iit.edu Illinois Institute of Technology

Who am I?

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- PROSPECT
- Mobile Antineutrino Demonstrator (MAD)

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Aside From Research…

- Career-wise…
  - Teaching and Mentoring
  - EDI

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Aside From Research…

- Career-wise…
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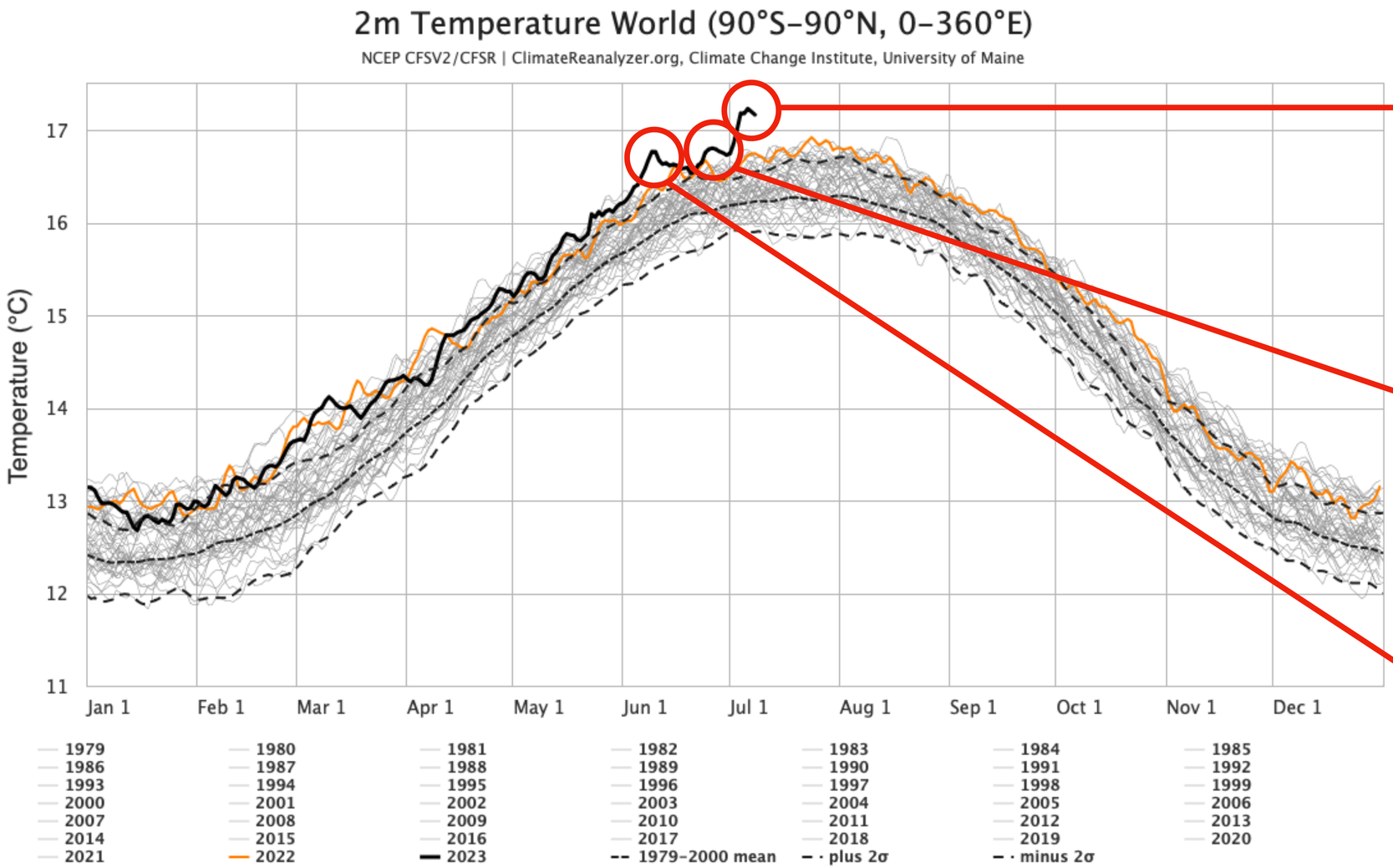
- On my free time…
  - Explore National parks with my dogs, Rum and Quanta
  - Learn about political/social science and philosophy of science
  - Read classic literature
  - Crochet

Getting into the topic of today's talk…

Why we should have more nuclear reactors?

Climate change



Mon Jun 26, 2023

Obs Temp: 16.81 °C
Clim Mean: 16.13 °C
Anomaly: +0.68 °C

Fri Jun 9, 2023

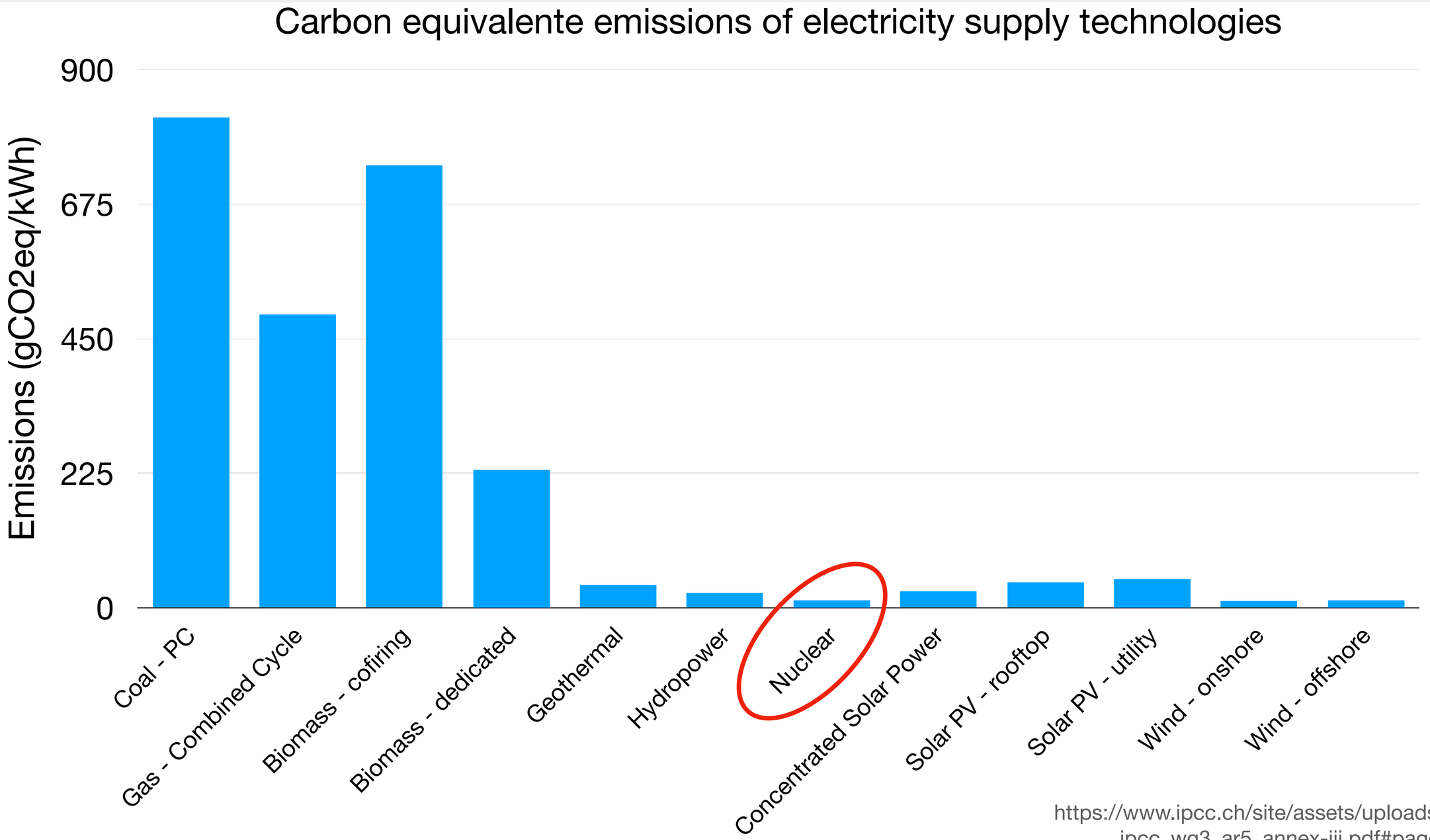
Obs Temp: 16.77 °C
Clim Mean: 15.86 °C
Anomaly: +0.90 °C

Thu Jul 6, 2023

Obs Temp: 17.23 °C
Clim Mean: 16.22 °C
Anomaly: +1.02 °C

https://www.climatereanalyzer.org/clim/t2_daily/

Nuclear Power



https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf#page=7

However…

Nuclear Power - Barriers and risks

Barriers to and risks associated with an increasing use of nuclear energy include operational risks and the associated safety concerns, uranium mining risks, financial and regulatory risks, unresolved waste management issues, nuclear weapon proliferation concerns, and adverse public opinion (*robust evidence, high agreement*). New fuel cycles and reactor technologies addressing some of these issues are under development and progress has been made concerning safety and waste disposal (*medium evidence, medium agreement*). [7.5.4, 7.8.2, 7.9, 7.11]

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Nuclear Power - Barriers and risks

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2

1

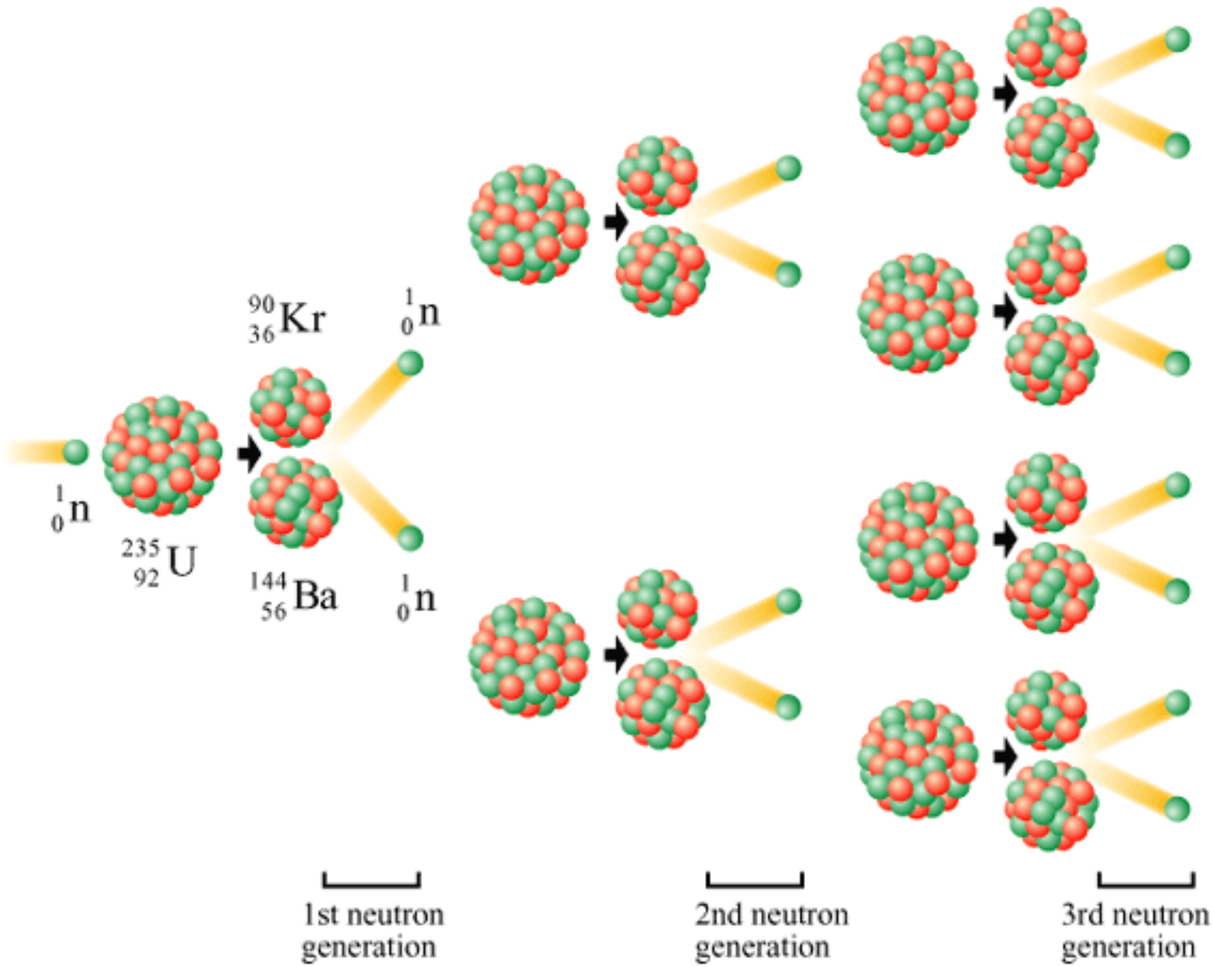
We've been exploring using antineutrino detectors to be applied to these points

https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter7.pdf

Lets revisit some key concepts regarding nuclear weapons

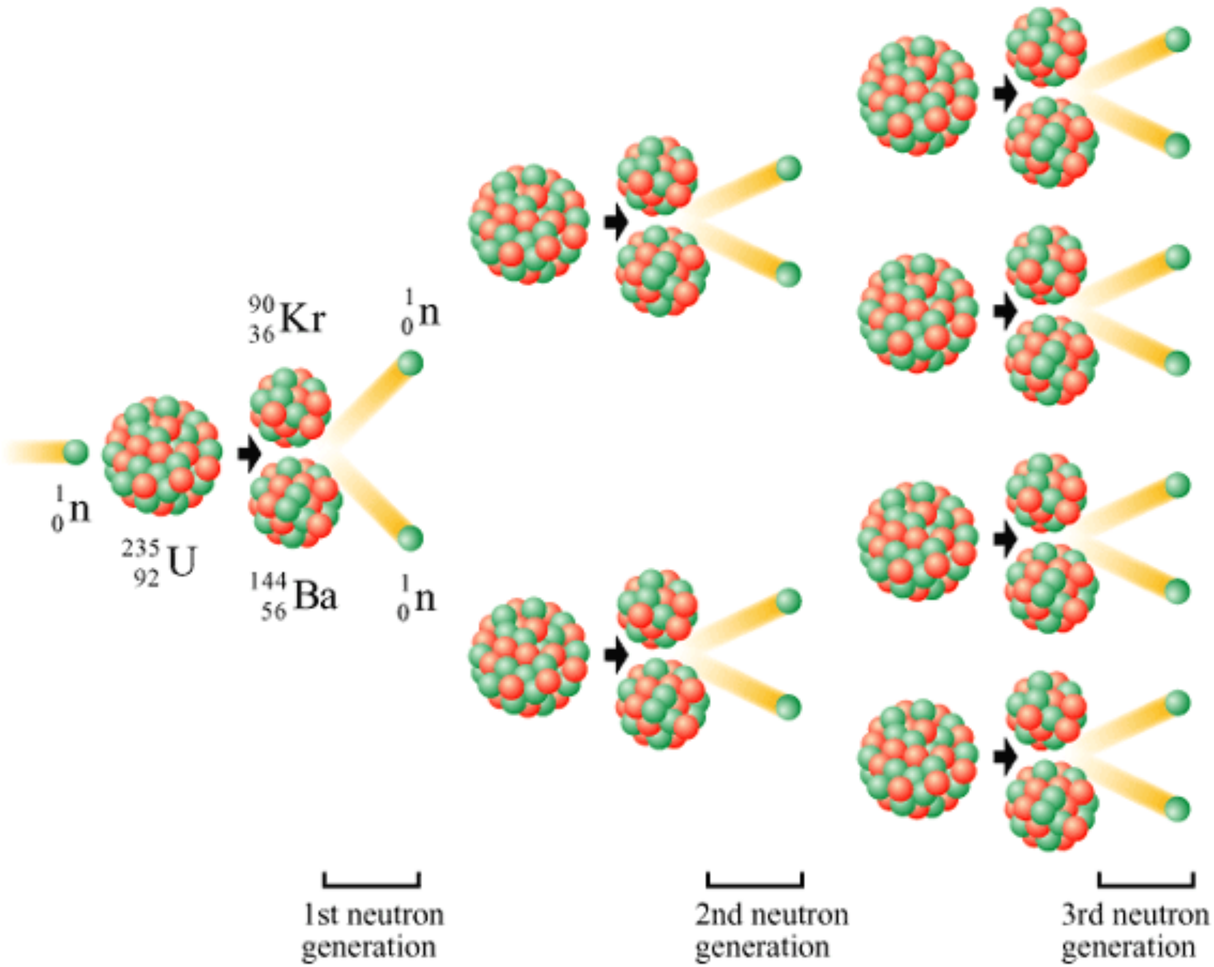
Nuclear Explosion

- Neutron-induced fission chain reactions



Nuclear Explosion

- Neutron-induced fission chain reactions
- Essential ingredients: ^{235}U or ^{239}Pu
  - Nearby neutron likely to cause fission and release >1 neutron as a product



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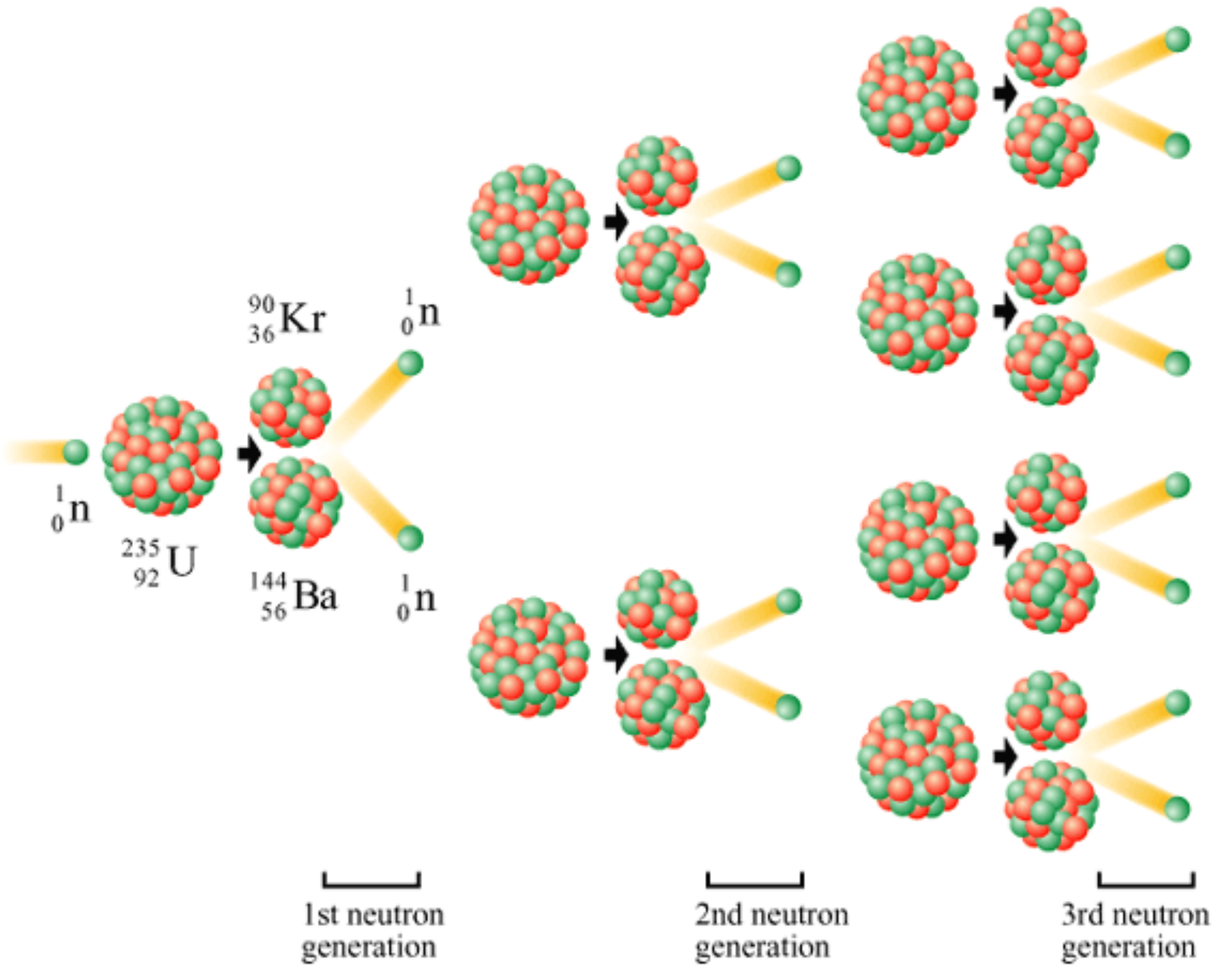

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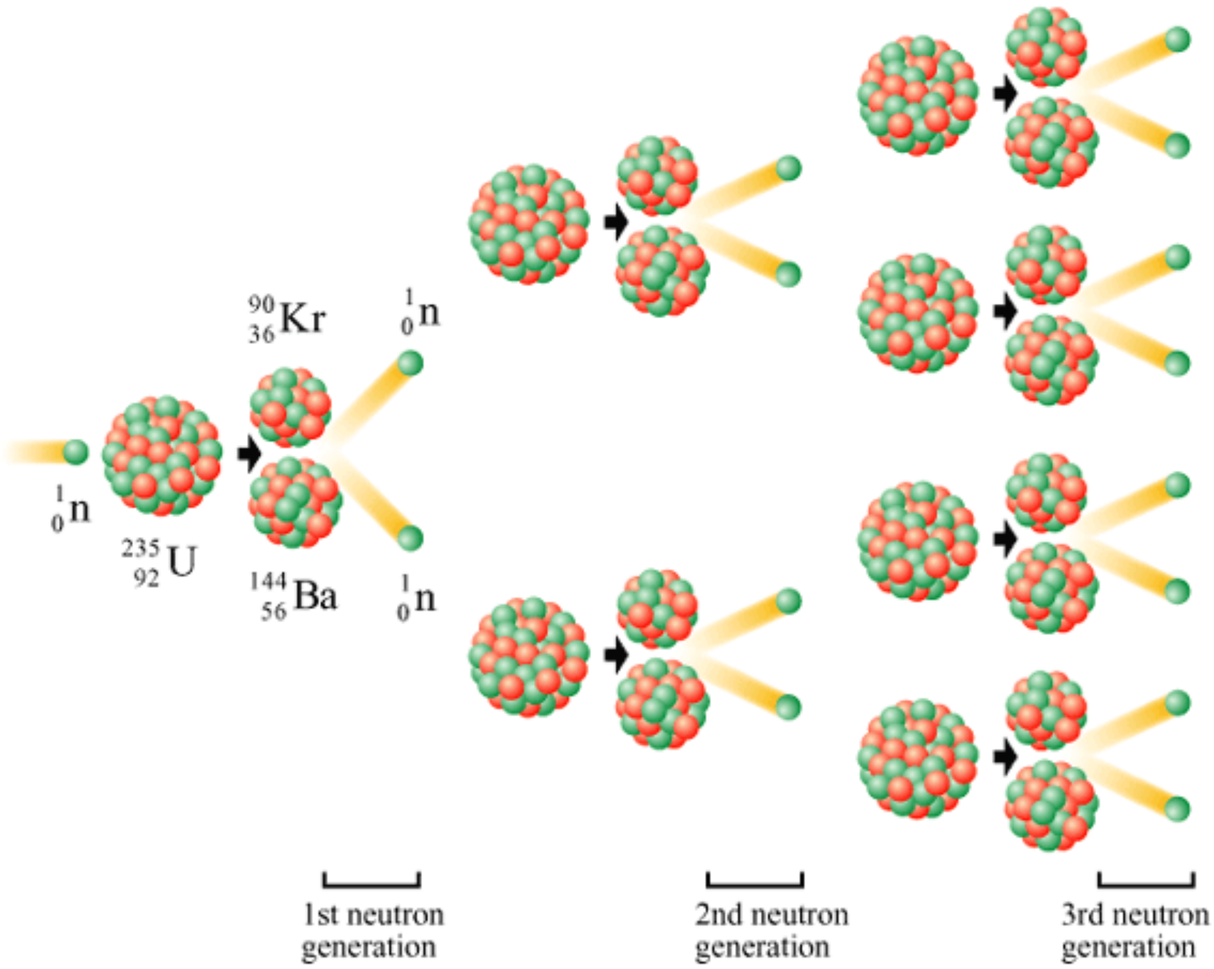

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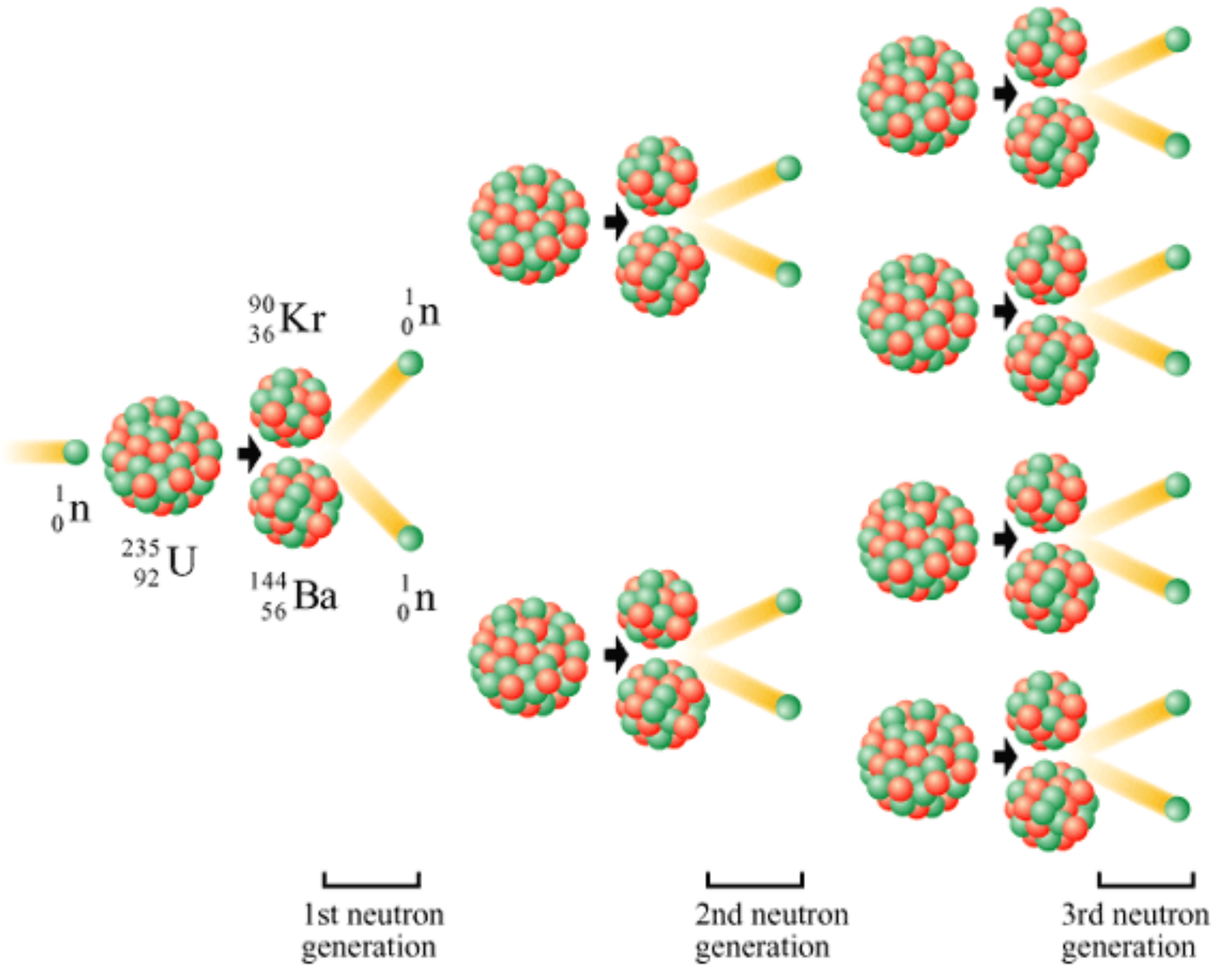
  - We (humans) make them
  - We can also control the production



Nuclear Control

- To control the production of nuclear weapons -> control/catalog ^{235}U and ^{239}Pu

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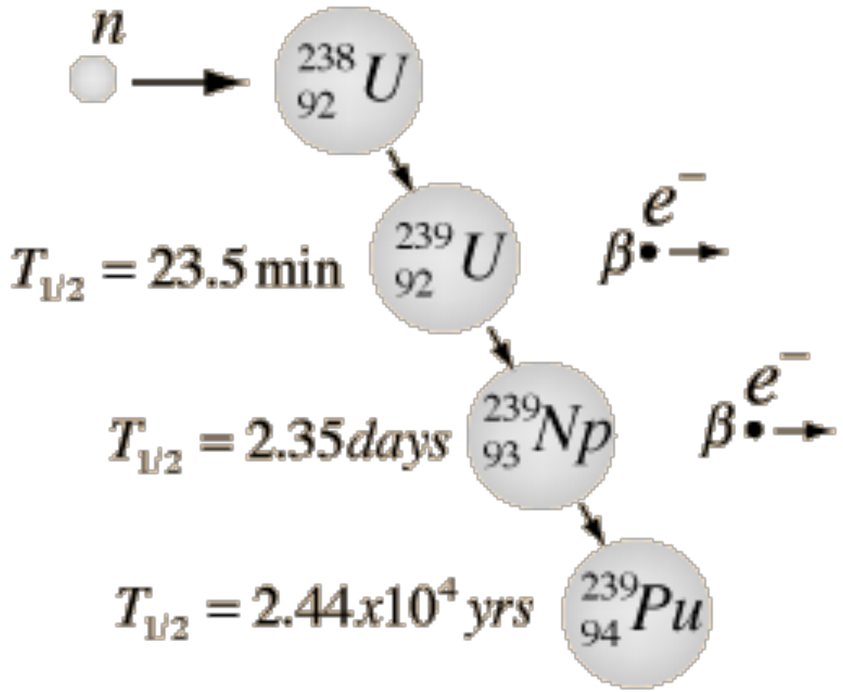

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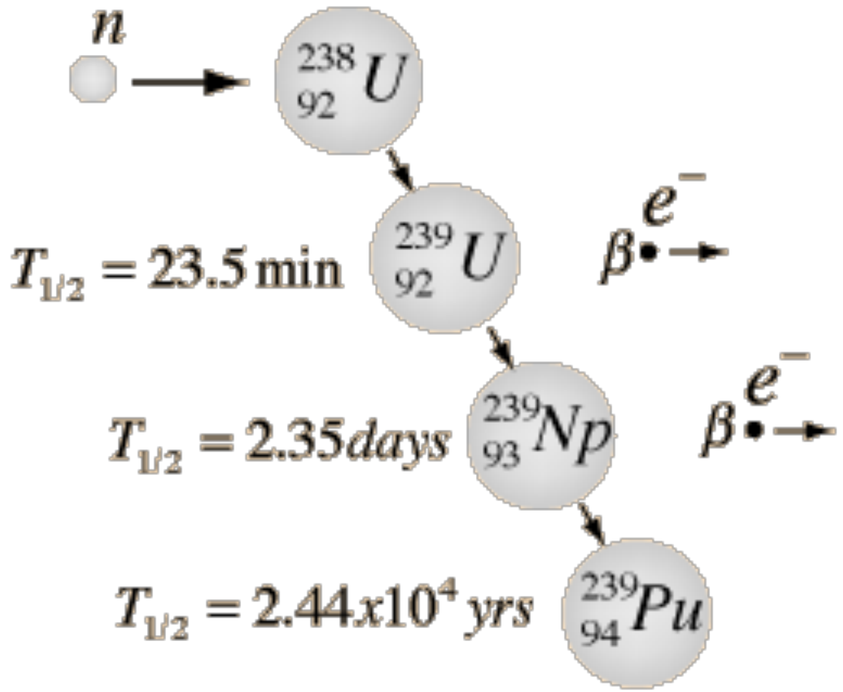
- ALL reactors make ^{239}Pu
- We need to monitor and control nuclear reactors



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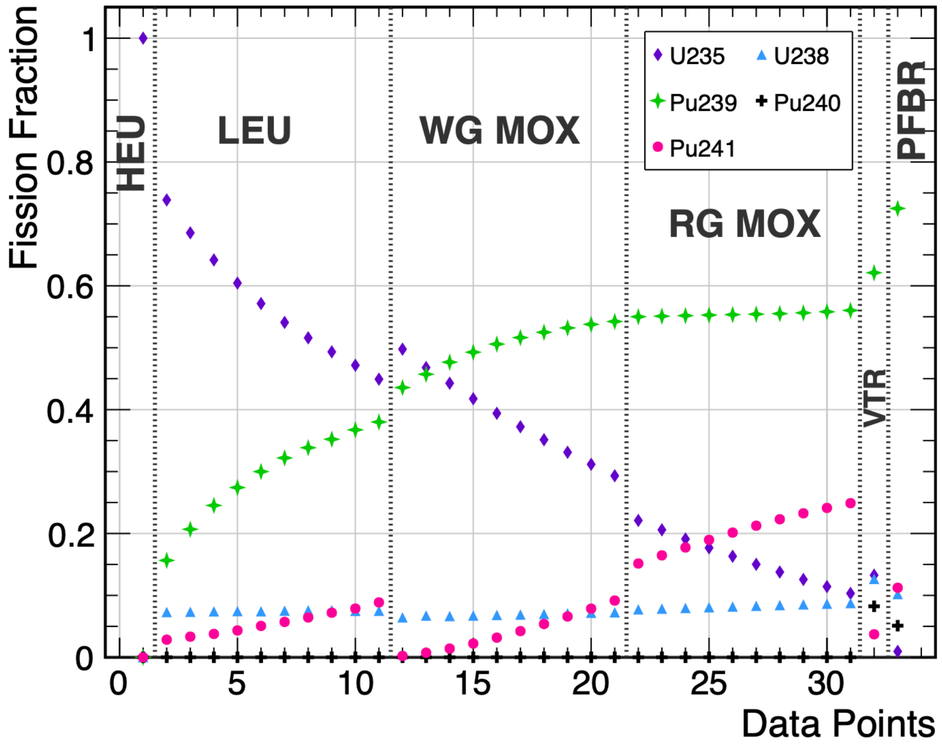
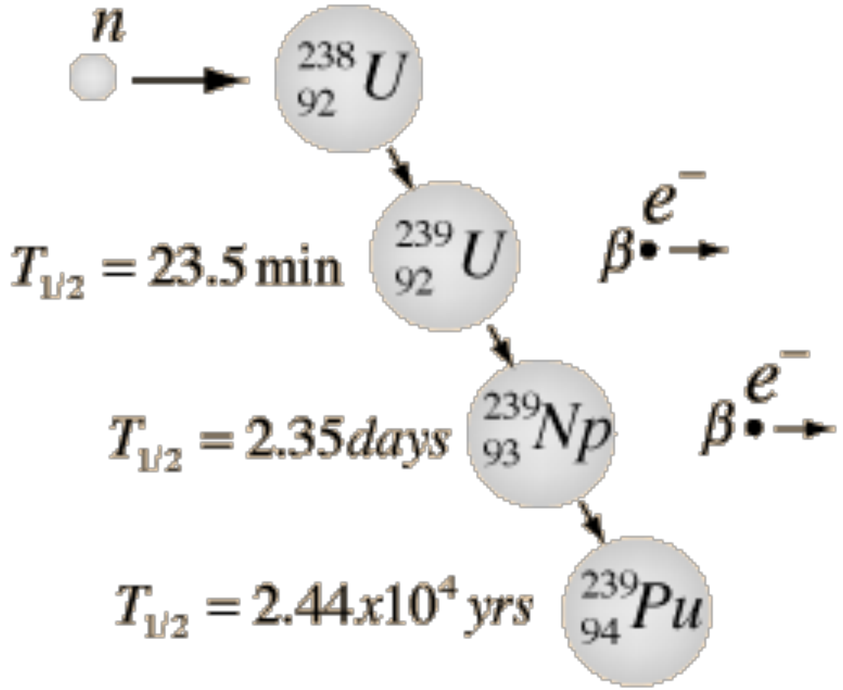
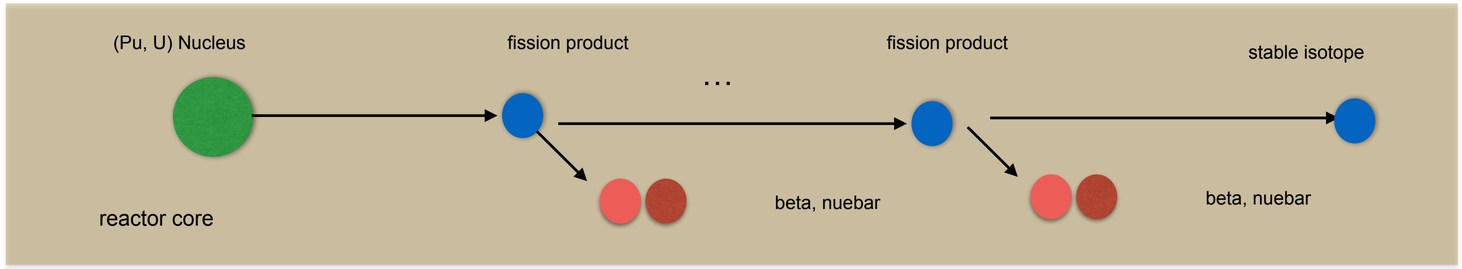


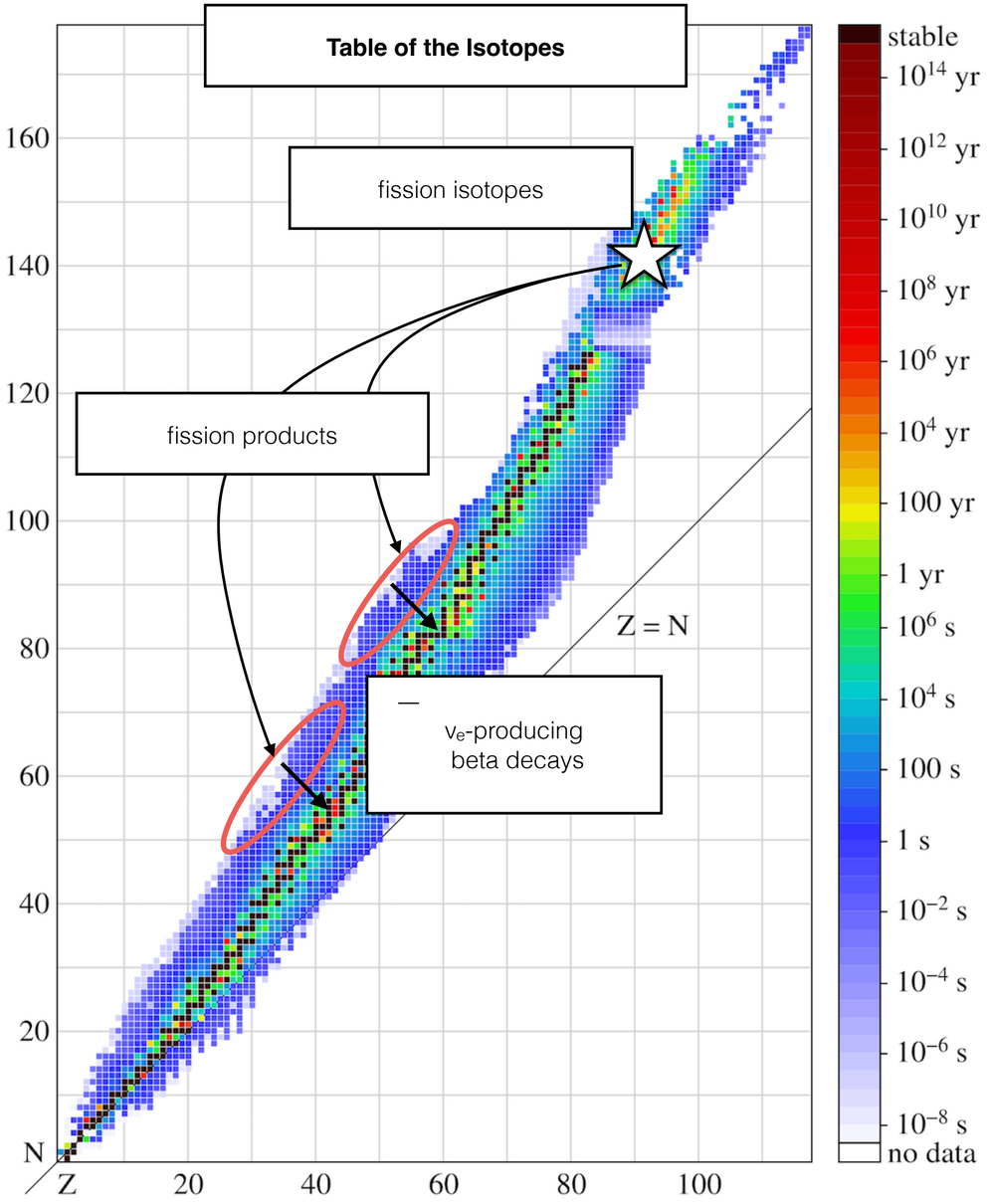


https://journals.aps.org/prd/pdf/10.1103/PhysRevD.107.092010

Reactor Antineutrino Production

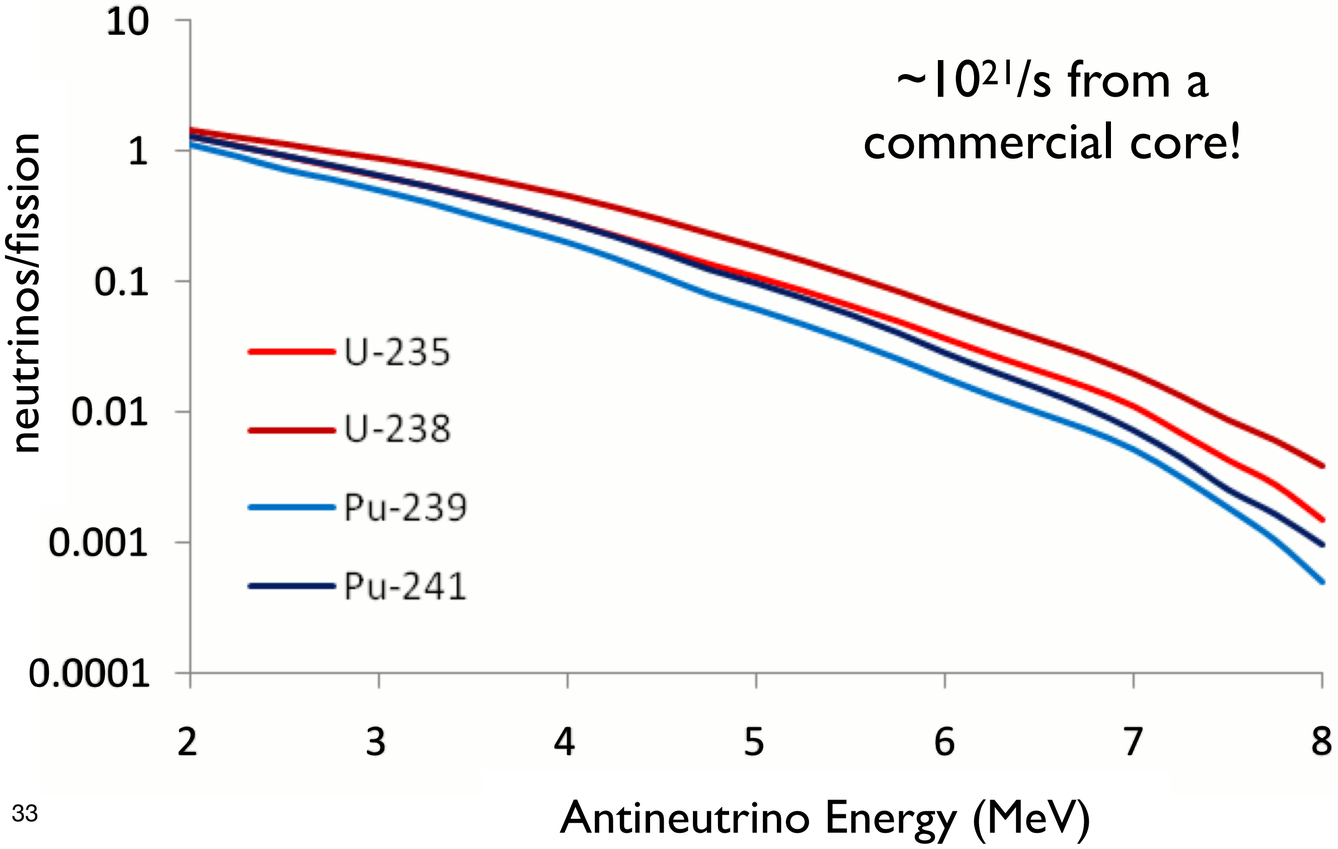
$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} + \bar{\nu}_{e} $$



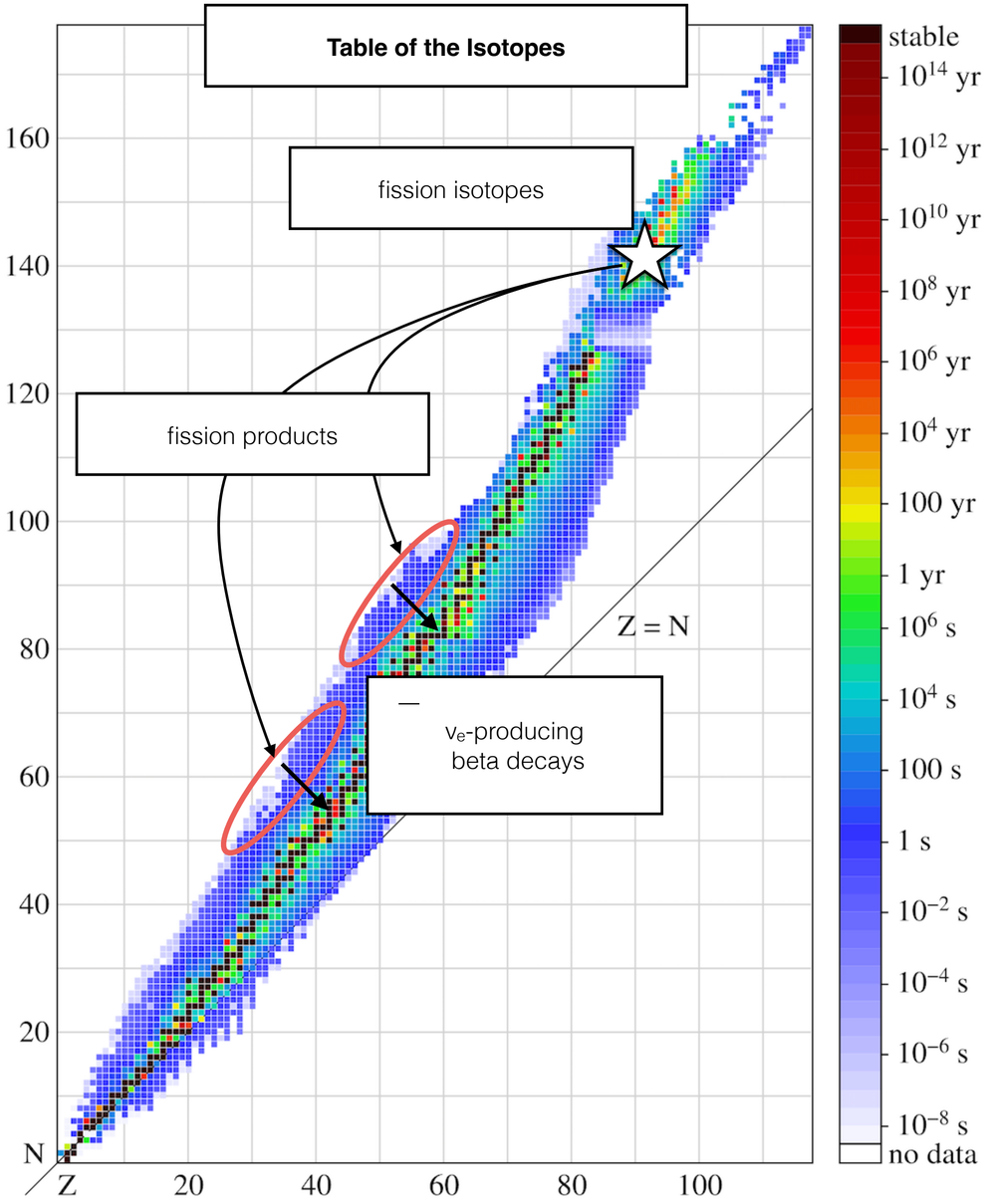


Reactor Antineutrino Production

- Reactor $\bar{\nu}_e$: made in beta-decay of ^{239}Pu, ^{235}U fission products
- Each isotope: different branches -> slightly different $\bar{\nu}_e$ energies



~10^{21}/s from a commercial core!



We can use neutrinos to monitor:

1 - Reactor Power
2 - Rate-Based ^{239}Pu
3 - Energy-Based ^{239}Pu

1 Reactor Power Monitoring

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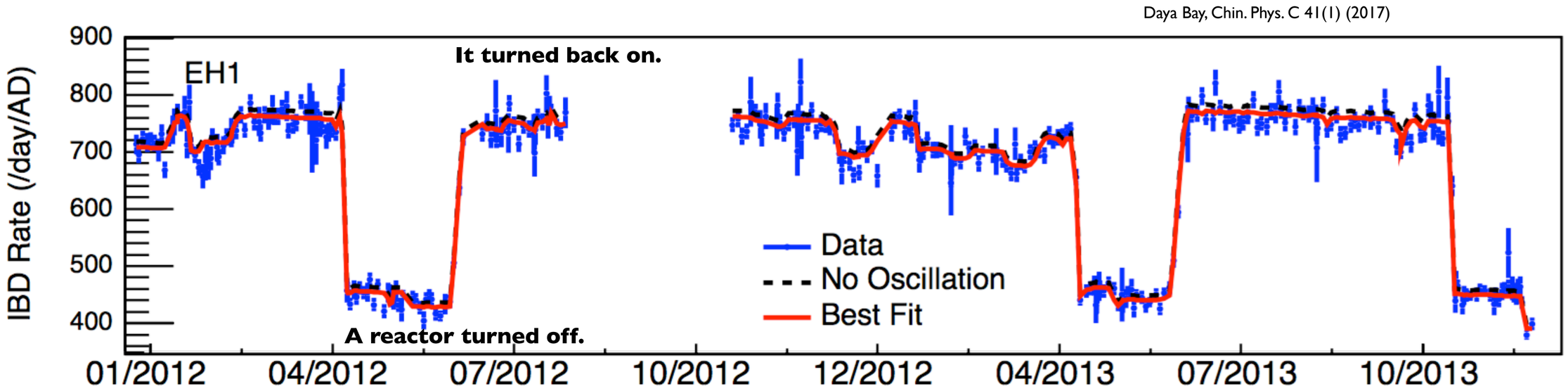

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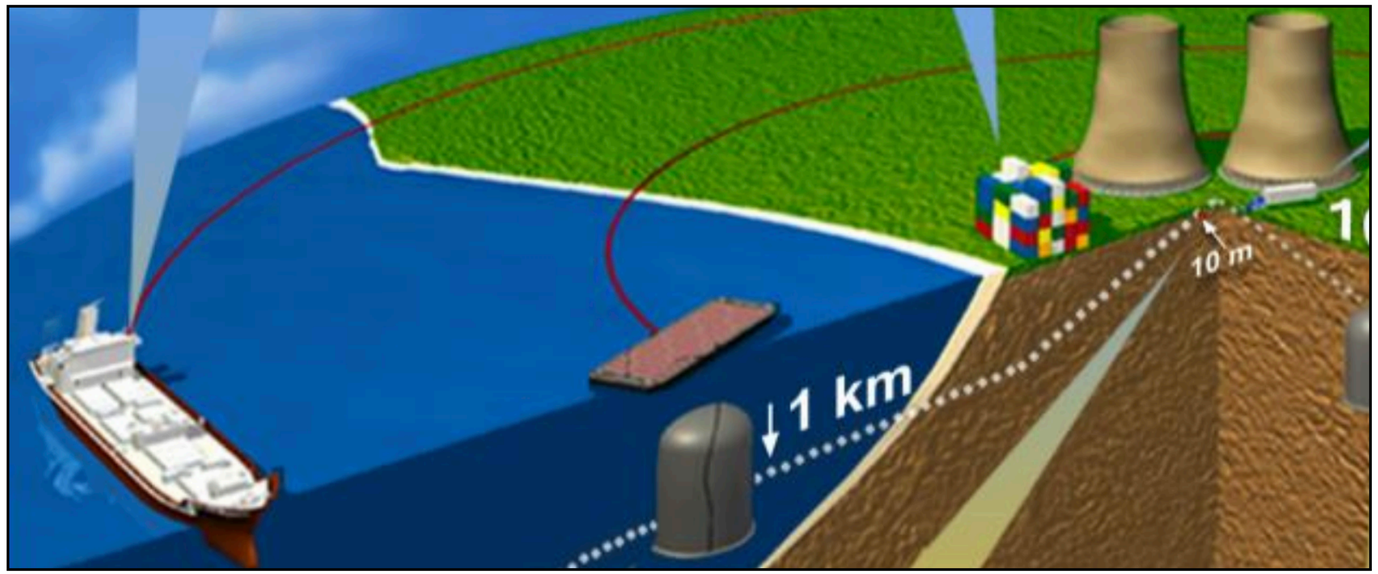
- Monitor operational status, even from very far away (50+ km)



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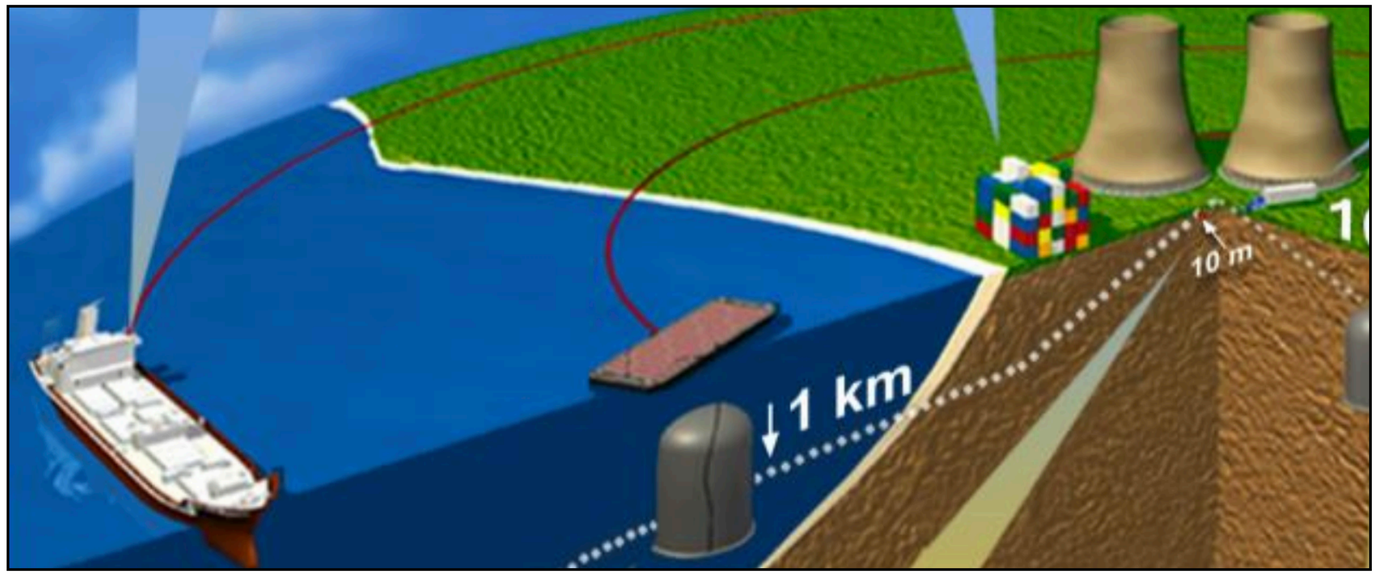
Barriers to and risks associated with an increasing use of nuclear energy inclu 4 **operational risks and the associated safety concerns, uranium mining risks, financial and regulatory risks, unresolved waste management issues, nuclear weapon proliferation concerns, and adverse public opinion** (*robust evidence, high agreement*). New fuel cycles and reactor technologies addressing some of these issues are under development and progress has been made concerning safety and waste disposal (*medium evidence, medium agreement*). [7.5.4, 7.8.2, 7.9, 7.11]



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1 Reactor Power Monitoring

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- There are advanced reactors and new technologies that can benefit

  - Small Modular Reactors -> Not meant to be opened ever

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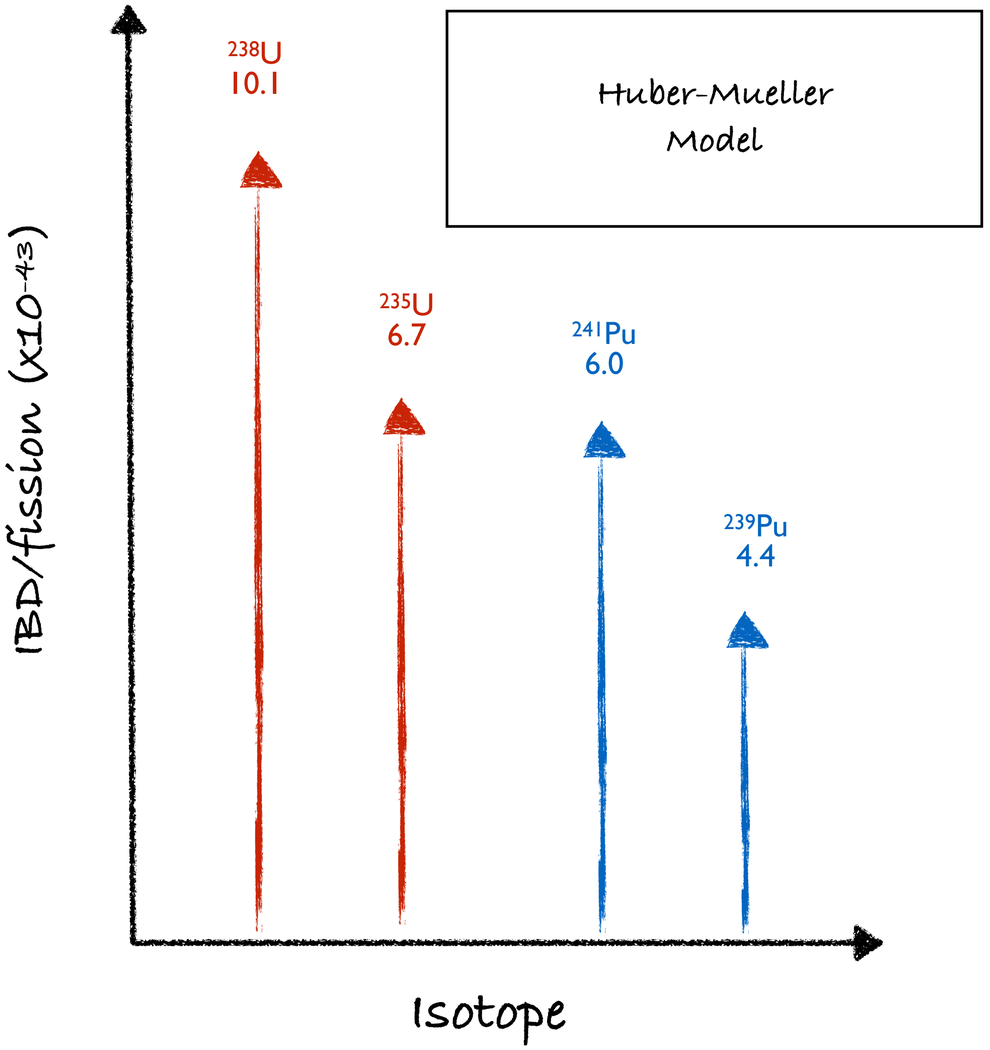
https://www.energy.gov/ne/advanced-small-modular-reactors-smrs

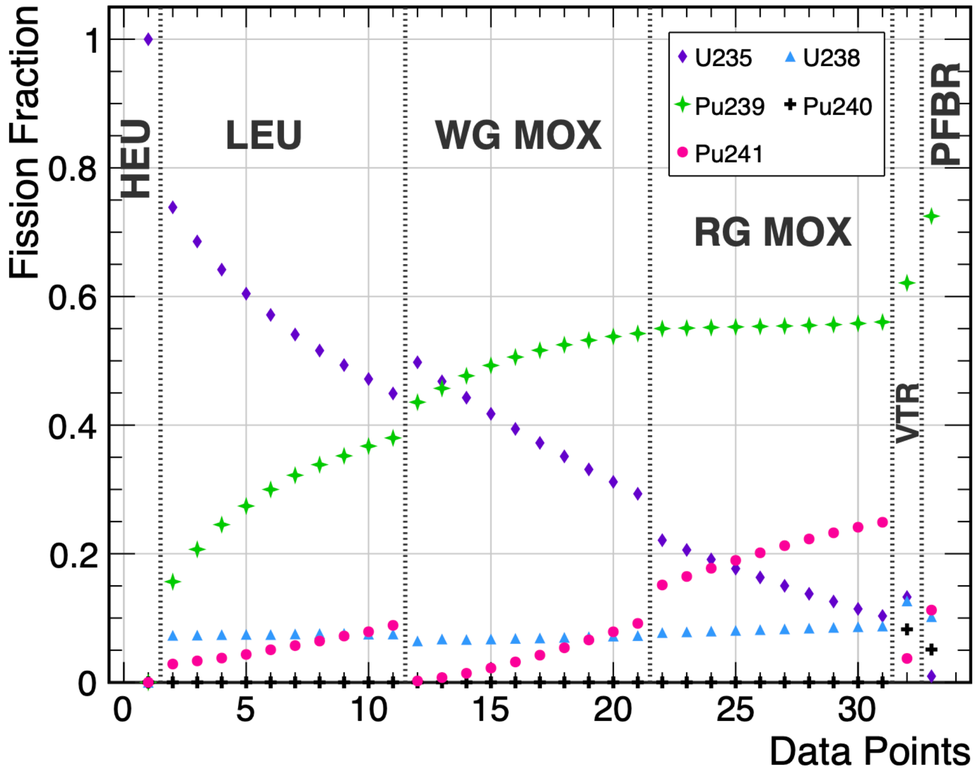
2 Rate-Based ^{239}Pu Monitoring

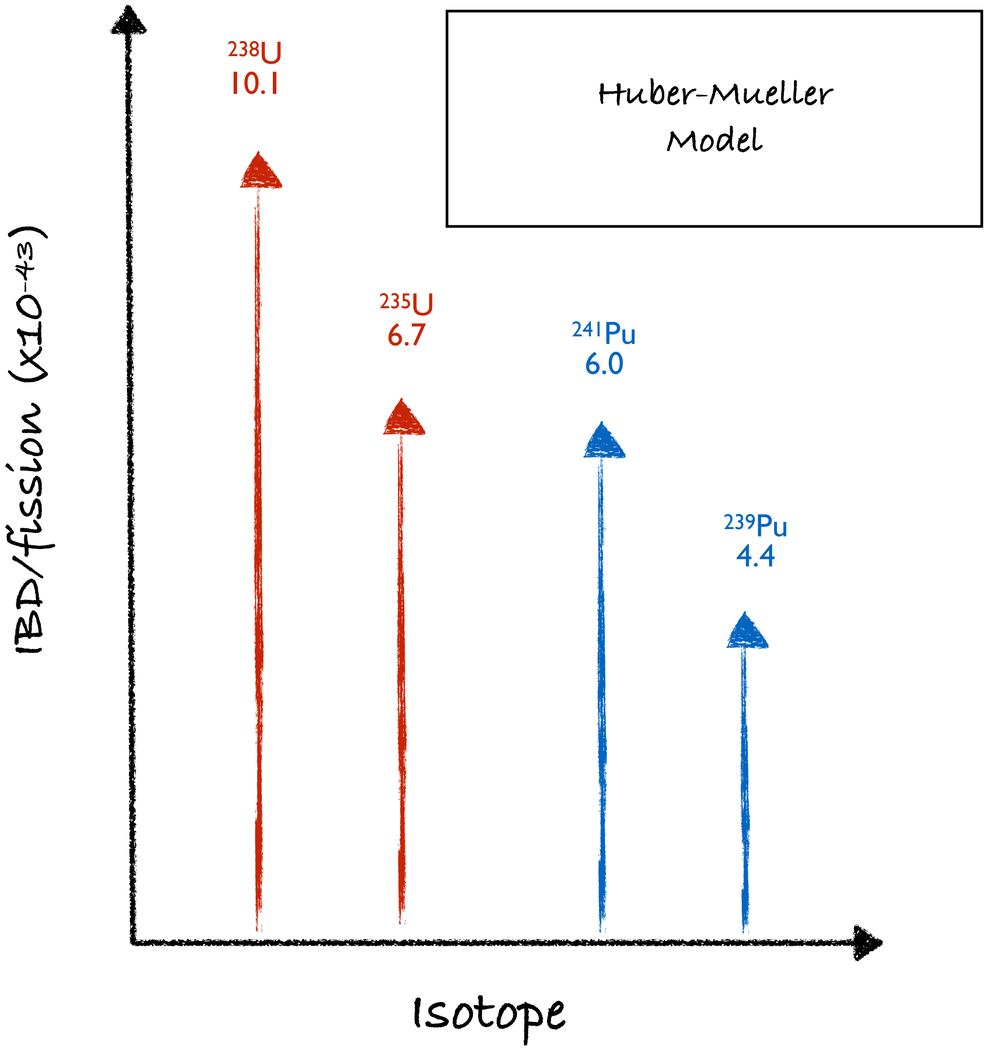
- ^{239}Pu makes fewer neutrinos than ^{235}U



2 Rate-Based ^{239}Pu Monitoring

- ^{239}Pu makes fewer neutrinos than ^{235}U
- Change in detected antineutrino/day is a direct measure of amount of ^{239}Pu bred into fuel





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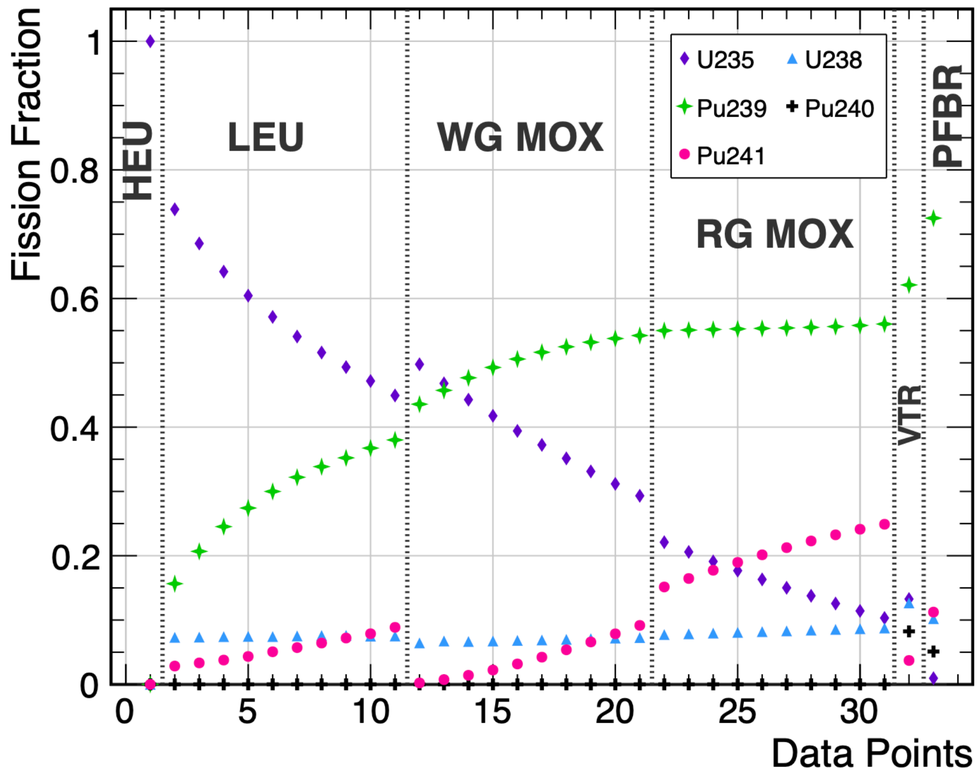

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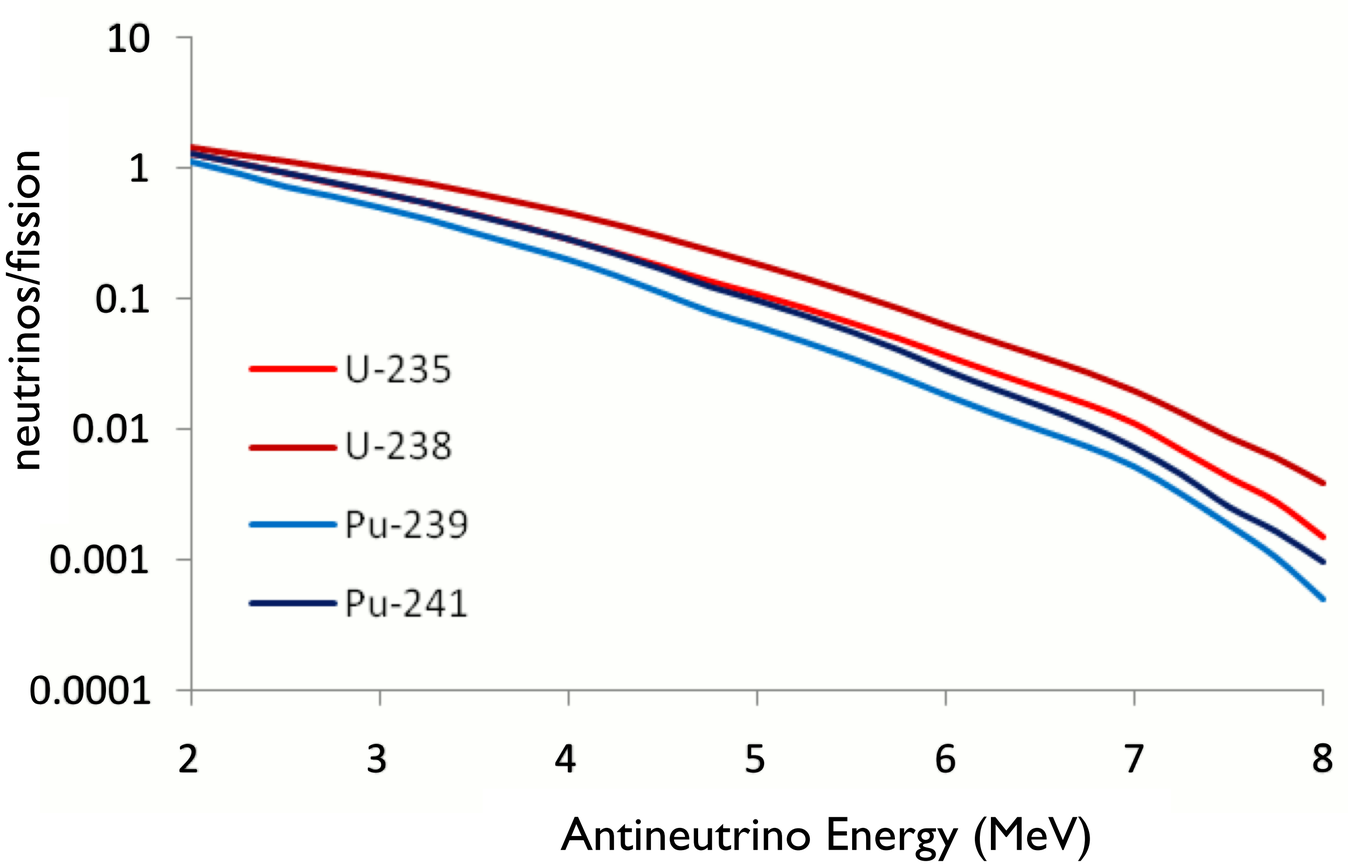
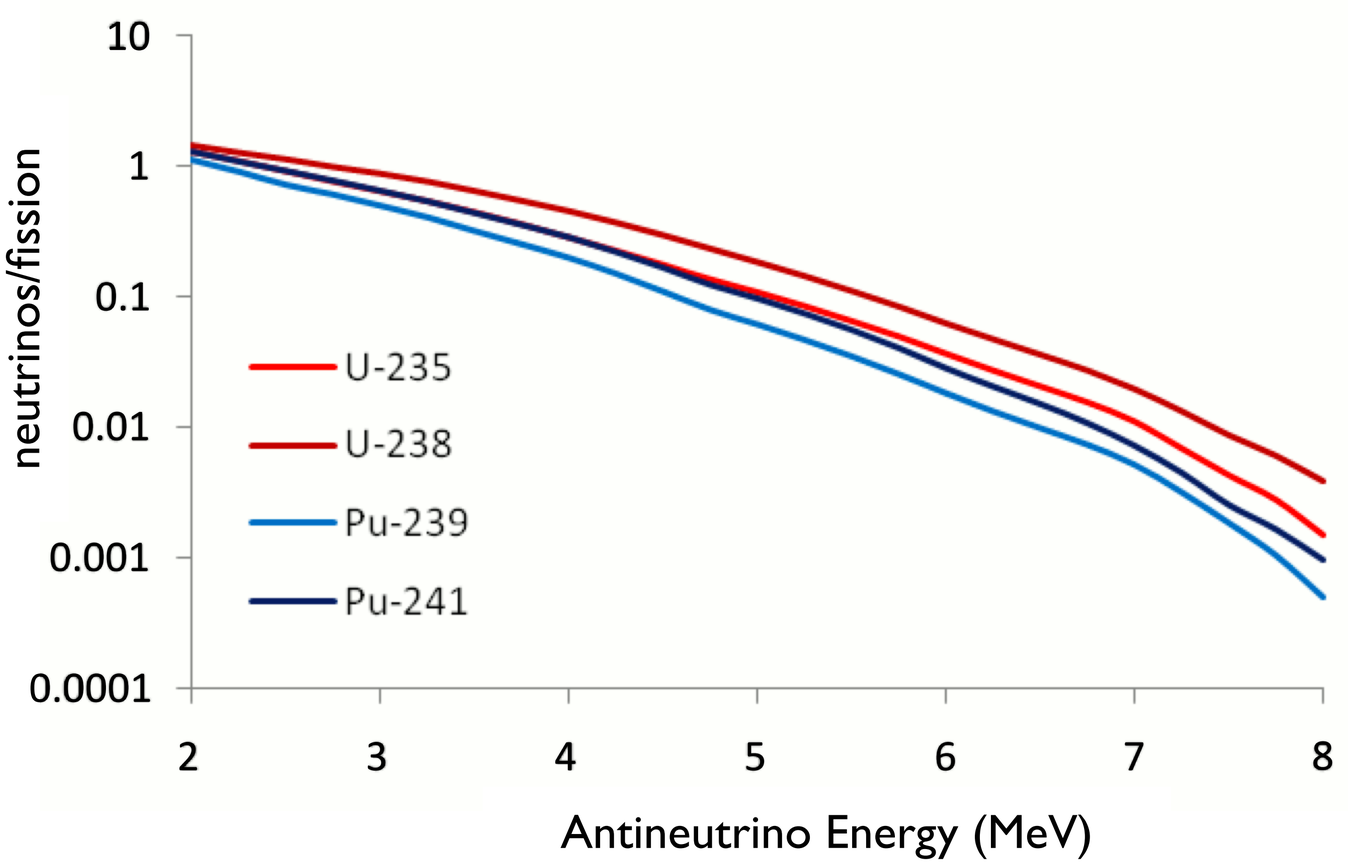
3 Energy-Based ^{239}Pu Monitoring

- We know ^{239}Pu makes lower energy neutrinos than ^{235}U



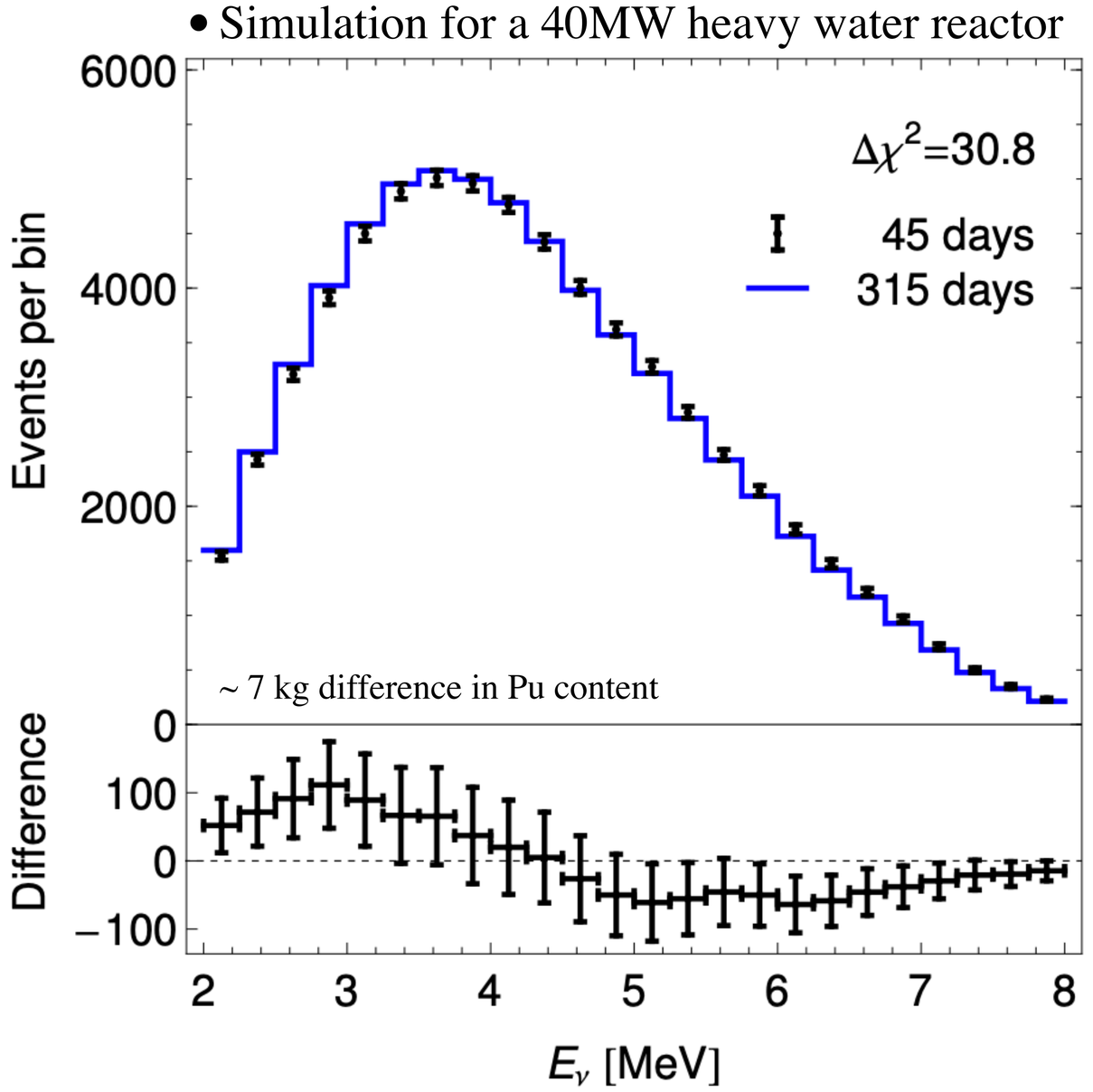
3 Energy-Based ^{239}Pu Monitoring

- We know ^{239}Pu makes lower energy neutrinos than ^{235}U
- Detected antineutrino energy is a direct measure of kg of ^{239}Pu bred into fuel



3 Energy-Based ^{239}Pu Monitoring

- We know ^{239}Pu makes lower energy neutrinos than ^{235}U
- Detected antineutrino prompt energy is a direct measure of kg of ^{239}Pu bred into fuel
- Daya Bay has observed this change in spectrum



^{239}Pu Monitoring

- Case studies:

1. Monitoring of plutonium production and investigation of a possible diversion from declared inventories at a Iranian reactor at Arak

   https://arxiv.org/pdf/1403.7065.pdf

2. How antineutrino detectors could have been used for safeguards in the context of the North Korean nuclear crisis in 1994

   https://arxiv.org/pdf/1312.1959.pdf

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Final remarks and Conclusion

- Need alternative energy sources ASAP
- Nuclear power presents as a valuable alternative
  - Need precautions to use it safely and ethically
- Antineutrino monitoring can help keep track of:
  - Status (on/off)
  - Power
  - Fuel content
- Advantages of:
  - Detectors located outside of the reactor building or even the facility -> Minimally invasive.
  - There are no known ways to shield, suppress, or fake a neutrino signal
  - Unattended and remote operation

Check this report for detailed info on practical applications:
https://nutools.ornl.gov/wp-content/uploads/securepdfs/2022/01/Nu_Tools_Report_Final_20211220.pdf

Mobile Antineutrino Demonstrator

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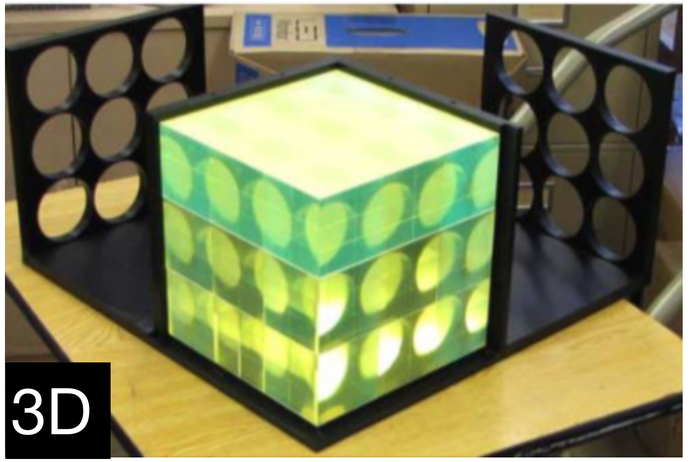
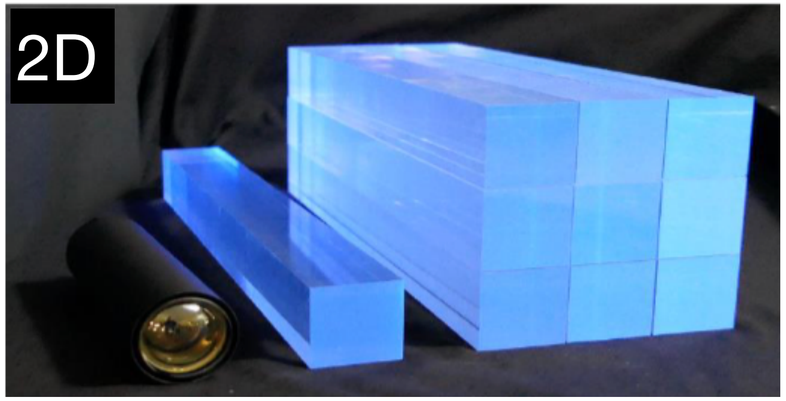
Mobile Antineutrino Demonstrator

- NNSA sponsored project
- ~ 1Ton-scale segmented scintillator detector
- Moveable platform
- Standard shipping container

- Two designs being explored:

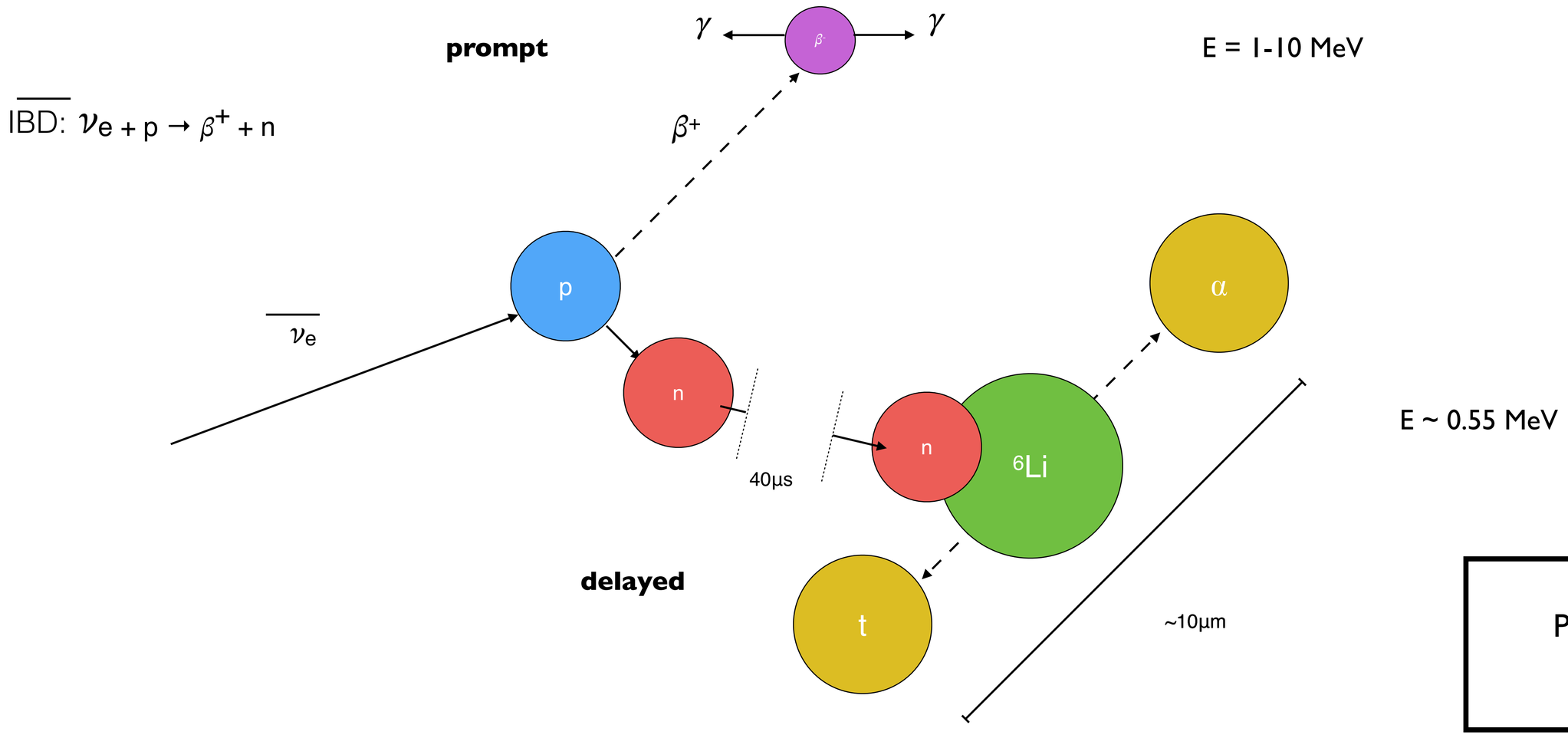




Questions?

Backup

IBD Detection in ^{6}Li-doped Detector



PROSPECT example