Investigating the future of proton decay searches using paleo detectors

Cassandra Little
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The Final Frontier for Proton Decay

Sebastian Baum [1,*] Cassandra Little [2,†] Paola Sala [3,‡] Joshua Spitz [2,§] and Patrick Stengel [4,¶]

[1] *Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen University, D-52056 Aachen, Germany*
[2] *University of Michigan, Ann Arbor, Michigan 48109, USA*
[3] *INFN Milano, via Celoria 16, I-20133 Milano, Italy*
[4] *INFN Ferrara, via Giuseppe Saragat 1, I-44122 Ferrara, Italy*

We present a novel experimental concept to search for proton decay. Using paleo-detectors, ancient minerals acquired from deep underground which can hold traces of charged particles, it may be possible to conduct a search for $p \to \bar{\nu} K^+$ via the track produced at the endpoint of the kaon. Such a search is not possible on Earth due to large atmospheric-neutrino-induced backgrounds. However, the Moon offers a reprieve from this background, since the conventional component of the cosmic-ray-induced neutrino flux at the Moon is significantly suppressed due to the Moon's lack of atmosphere. For a 100 g, 10^9 year old (100 kton·year exposure) sample of olivine extracted from the Moon, we expect about 0.5 kaon endpoints due to neutrino backgrounds, including secondary interactions. If such a lunar paleo-detector sample can be acquired and efficiently analyzed, proton decay sensitivity exceeding $\tau_p \sim 10^{34}$ years may be achieved, competitive with Super-Kamiokande's current published limit ($\tau_p > 5.9 \times 10^{33}$ years at 90% CL) and the projected reach of DUNE and Hyper-Kamiokande in the $p \to \bar{\nu} K^+$ channel. This concept is clearly futuristic, not least since it relies on extracting mineral samples from a few kilometers below the surface of the Moon and then efficiently scanning them for kaon endpoint induced crystal defects with sub-micron-scale resolution. However, the search for proton decay is in urgent need of a paradigm shift, and paleo-detectors could provide a promising alternative to conventional experiments.

arXiv:2405.15845

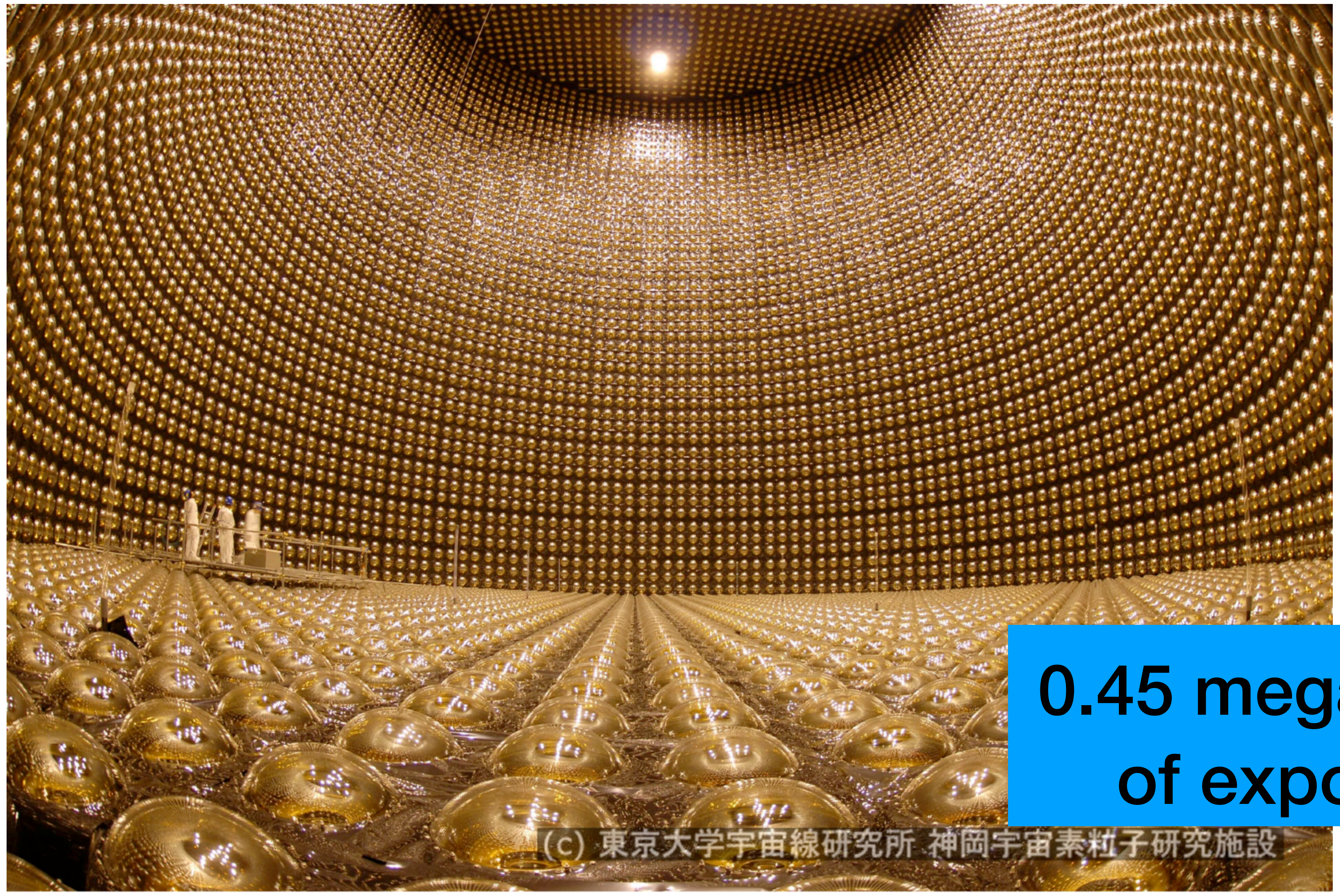
Proton Decay

- Proton decaying into lighter particles
    - In SM, conservation of baryon number (B) forbids proton decay
    - Many GUTs violate conservation of B
- A good, testable theory of physics beyond the SM and GUT models

Proton Searches

Experiments

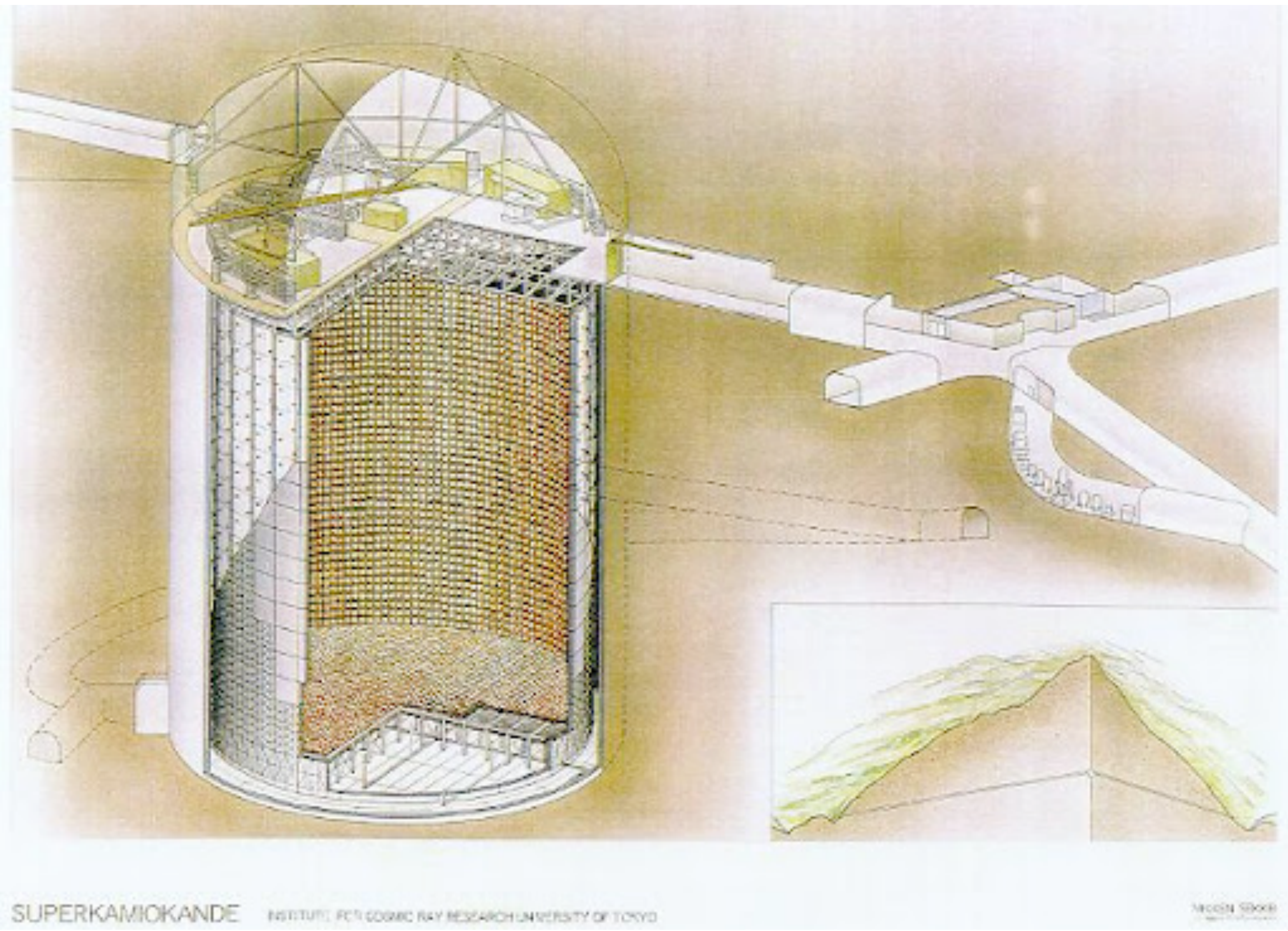
- Since the 80s
- Proton decay has not been observed

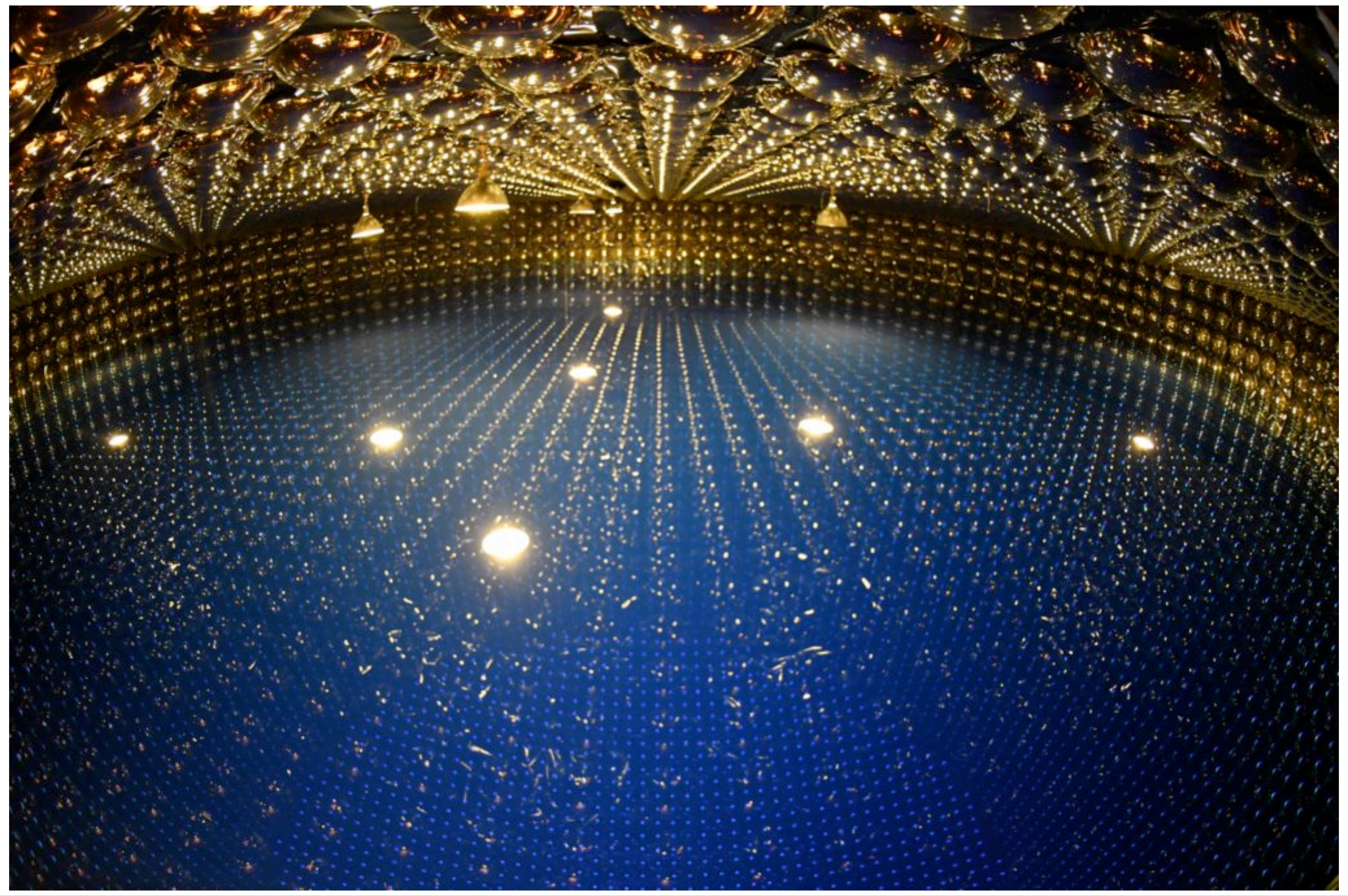


0.45 megaton·yrs of exposure!

(Super-)Kamiokande, 1982 - now

“No.SK3-13”; https://www-sk.icrr.u-tokyo.ac.jp/en/





Proton Searches

- Super-Kamiokande has the best published proton decay lifetime limits at 90% CL

$$\tau_p(p \rightarrow \bar{\nu}K^+) > 5.9 \times 10^{33} \text{ yrs}$$

K. Abe et al. (Super-Kamiokande), Phys. Rev. D 90, 072005 (2014), arXiv:1408.1195 [hep-ex]

- Hyper-K & DUNE will probe $\tau_p \sim 10^{34} - 10^{35}$ yrs

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Money…

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Technology…

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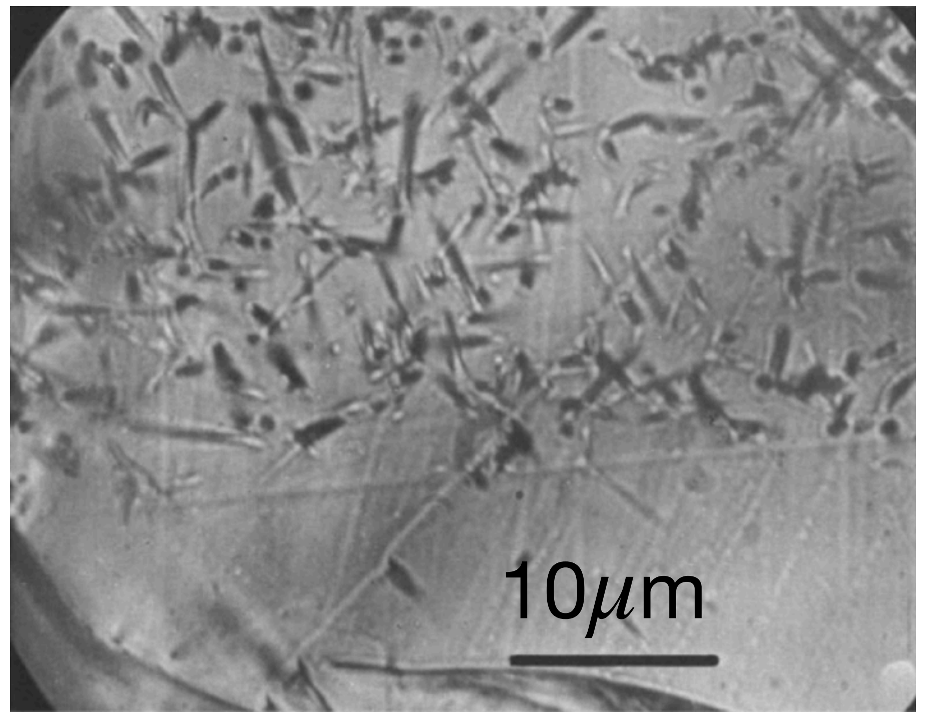
Money… Technology…

Is it time for a paradigm shift?

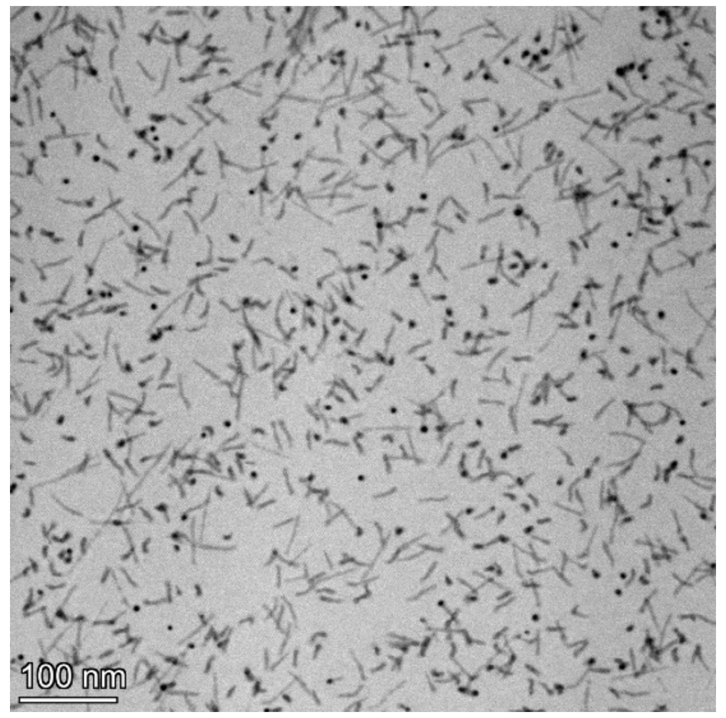
Paleo-detectors

- A kind of solid state (nuclear) track detector made of (natural) minerals
- Particle interactions cause deformations/damage in lattice structure.
- Observing these tracks since 1960s (material dating)

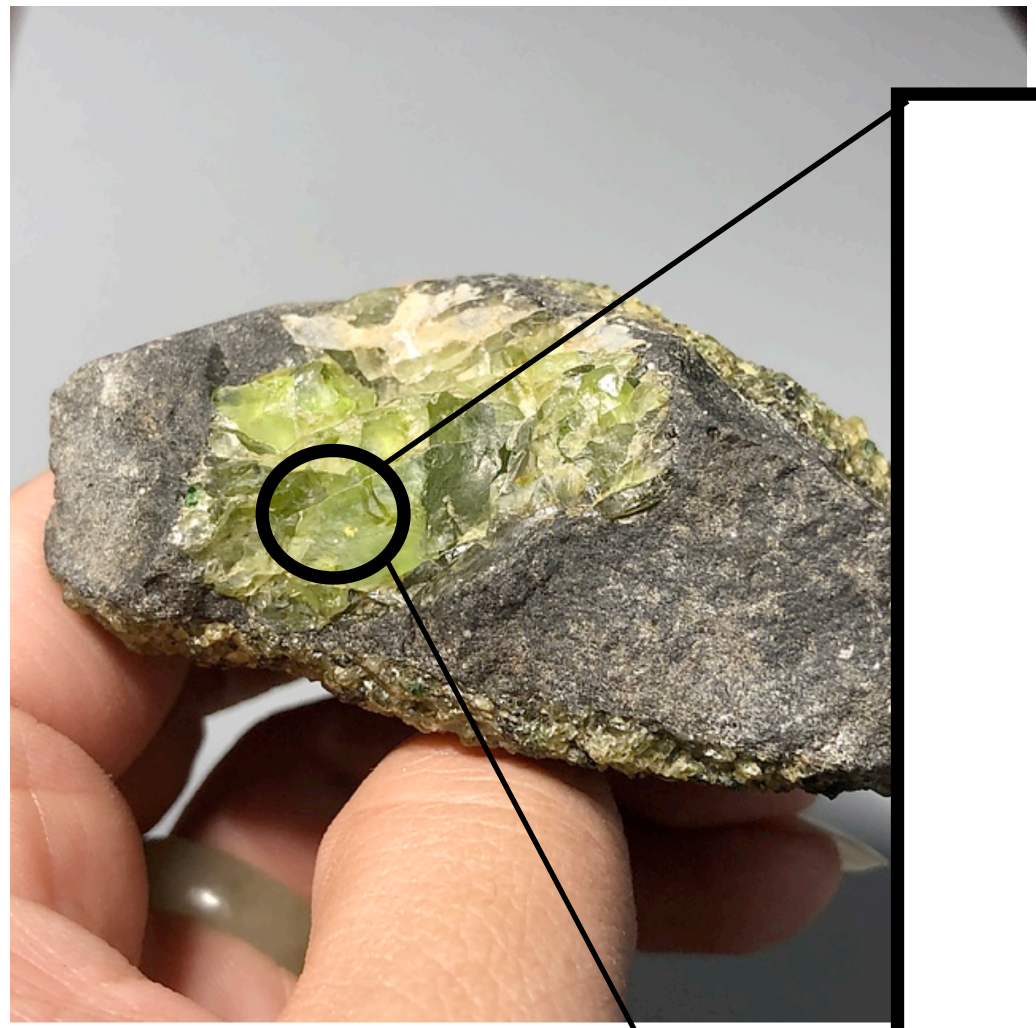


Uranium tracks in fossil, 1979

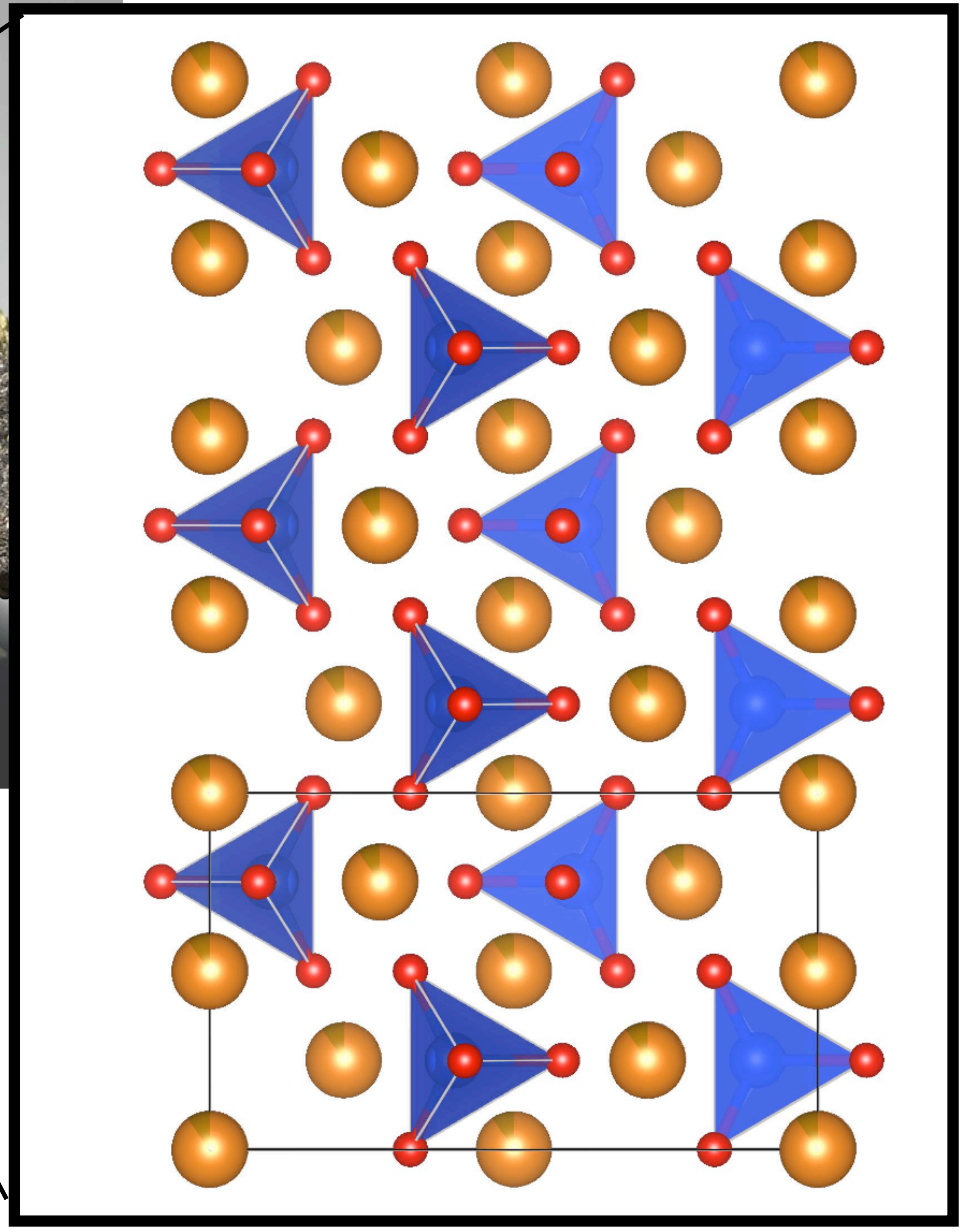
Naeser, C. W. "Fission-track dating and geologic annealing of fission tracks." *Lectures in isotope geology*. 1979



U. Mich. TEM image of Au ion tracks in olivine



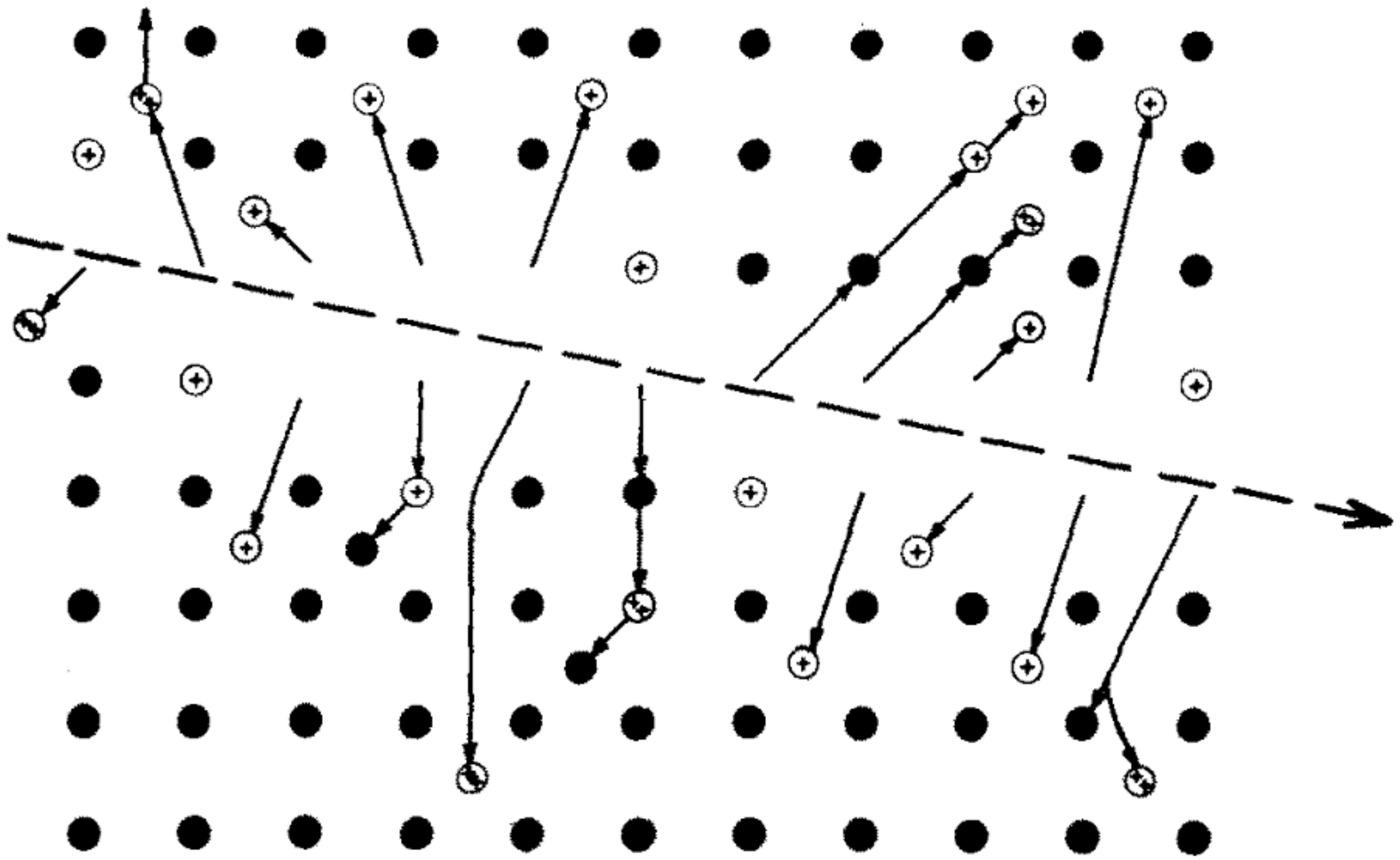
Olivine, mindat.org



Olivine lattice, Crystallography365

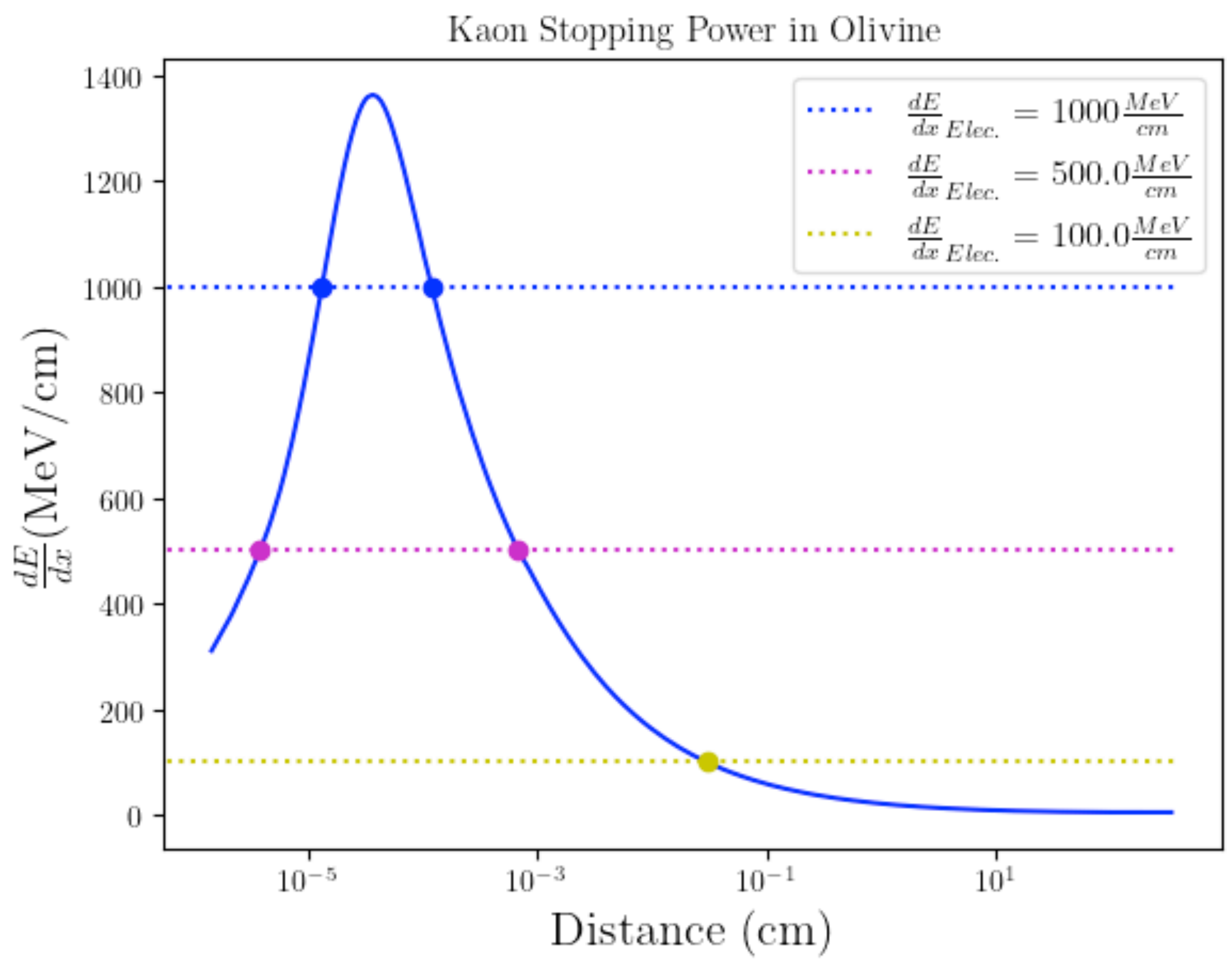
Paleo-detectors

Track Formation



R. L. Fleischer, P. B. Price, R. M. Walker; Ion Explosion Spike Mechanism for Formation of Charged-Particle Tracks in Solids. *J. Appl. Phys.* 1 November 1965; 36 (11): 3645–3652. https://doi.org/10.1063/1.1703059

- For high enough energy deposits, permanent lattice damage occurs
- But, what is the threshold?



Electronic stopping power -> proxy for "damage creation power"

Energy deposited as particle traverses material

Paleo-detectors

- Can retain tracks for >>10^9 yrs
- Natural minerals can be >10^9 yrs old
- Current microscopy technology has sub-nanometer-scale resolution

Paleo-detectors

Mikon Mineralienkontor, mikon-online.com

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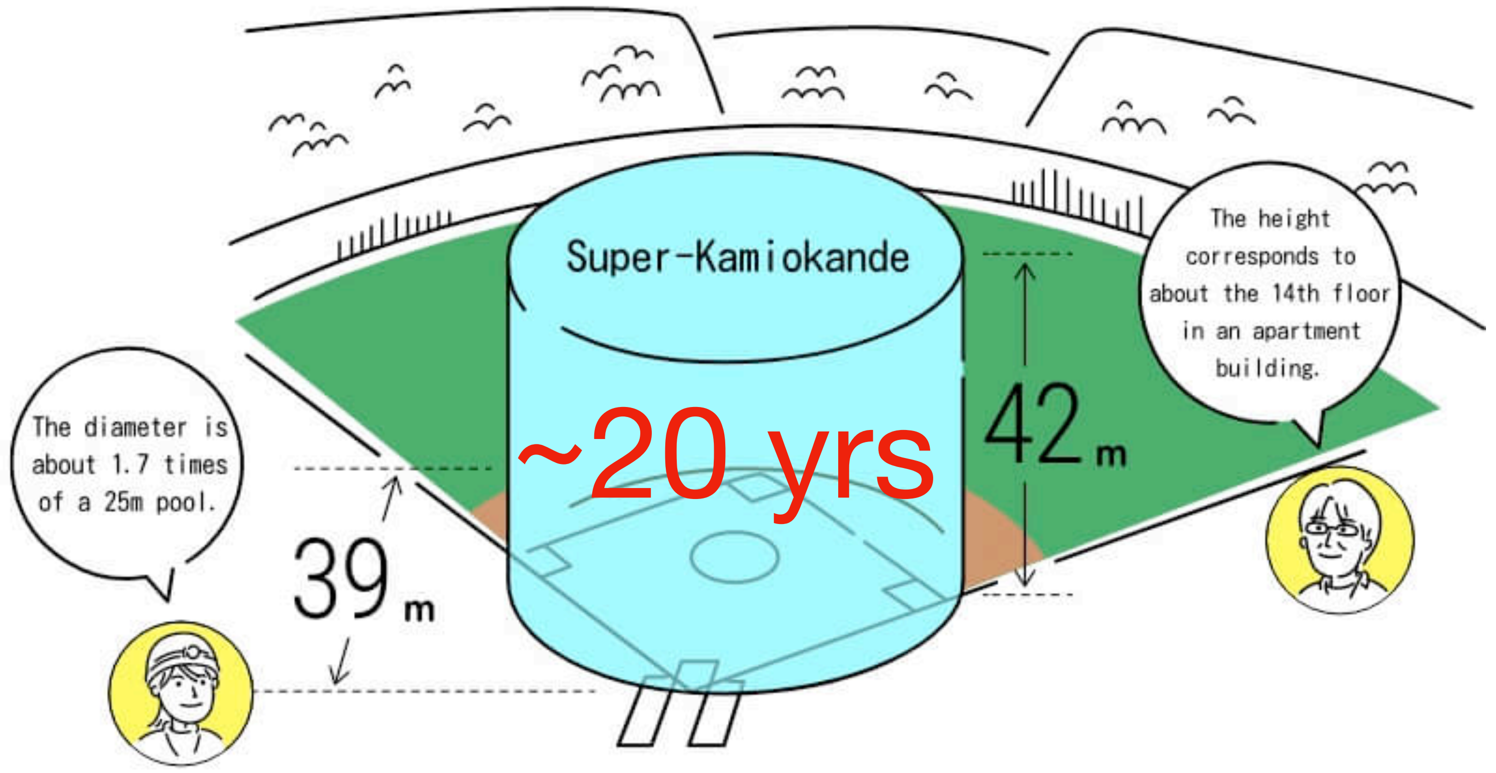

1 kg would match the Mton·yr exposure of Hyper-Kamiokande and DUNE!

- Can retain tracks for $>>10^9$ yrs
- Natural minerals can be $>10^9$ yrs old

} **Paleo-detector exposure**

100 g x 1G yr = 10 kton x 10 yr

- Current microscopy technology has sub-nanometer-scale resolution

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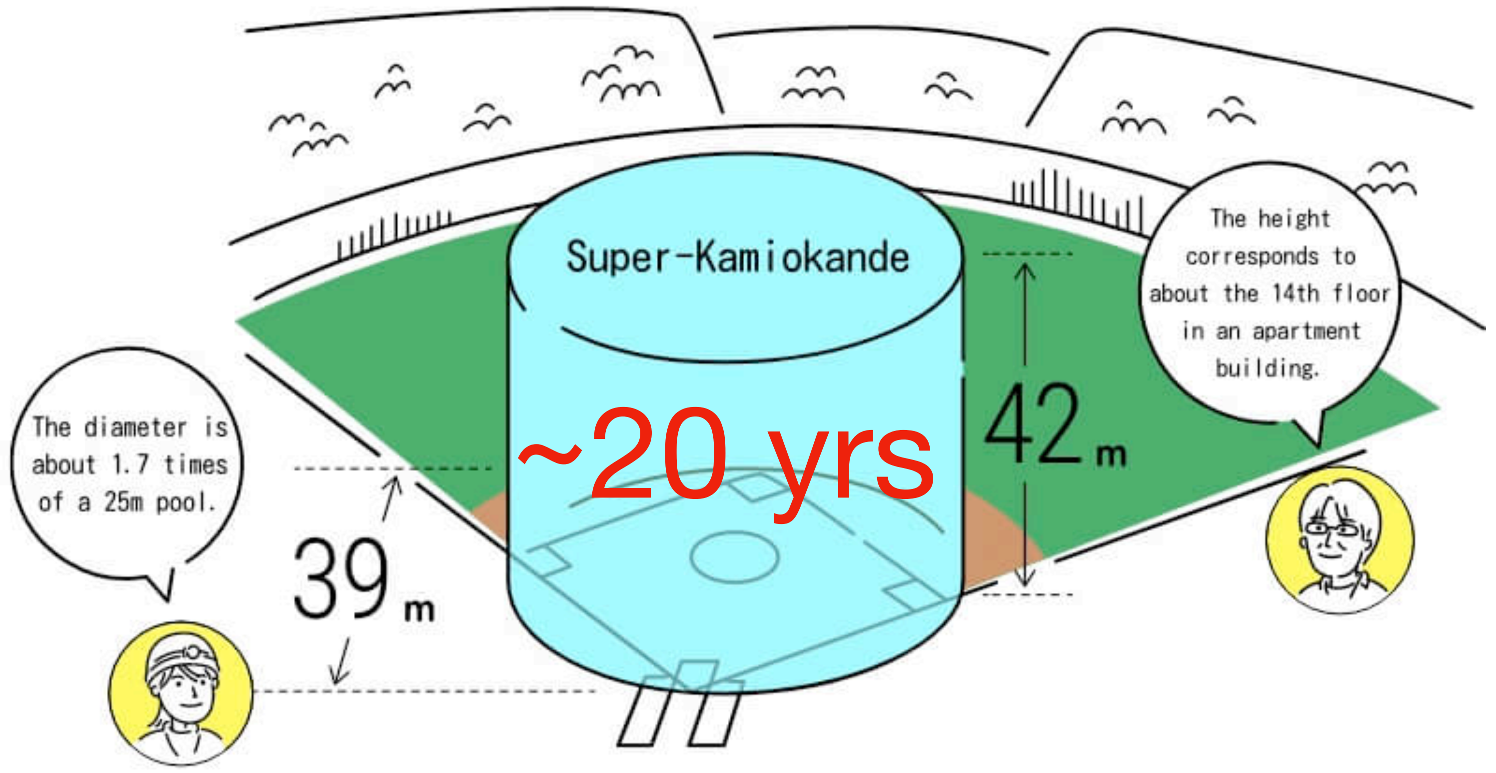

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- Current microscopy technology has sub-nanometer-scale resolution

$\lesssim$ KeV recoil thresholds in laboratory settings

Backgrounds

- Radiogenic
    - Neutrons
    - Radiative elements naturally occurring in minerals
- Cosmogenic
    - Prompt muons
    - Atmospheric neutrinos

Backgrounds

- Radiogenic → Find radiopure sample
    - Neutrons
    - Radiative elements naturally occurring in minerals
- Cosmogenic
    - Prompt muons
    - Atmospheric neutrinos

Backgrounds

- Radiogenic → Find radiopure sample
    - Neutrons
    - Radiative elements naturally occurring in minerals
- Cosmogenic → Get sample from deep underground
    - Prompt muons
    - Atmospheric neutrinos

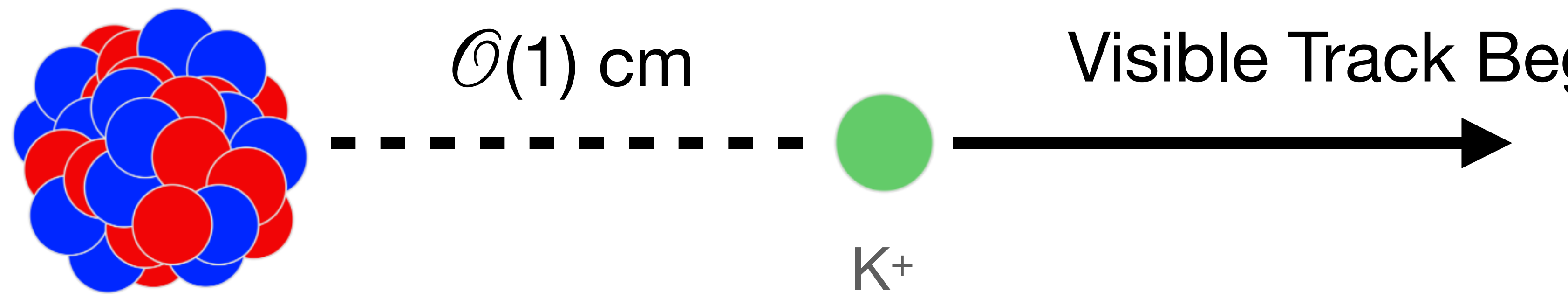
Proton Decay in a Paleo-detector

Detector Material

- Chose **Olivine [(Mg,Fe)2SiO4]** as our detector material
    - Abundant
    - Forms vacancies for tracks
    - Stable at high temperatures (robust to annealing)
    - Low concentrations of U & Th

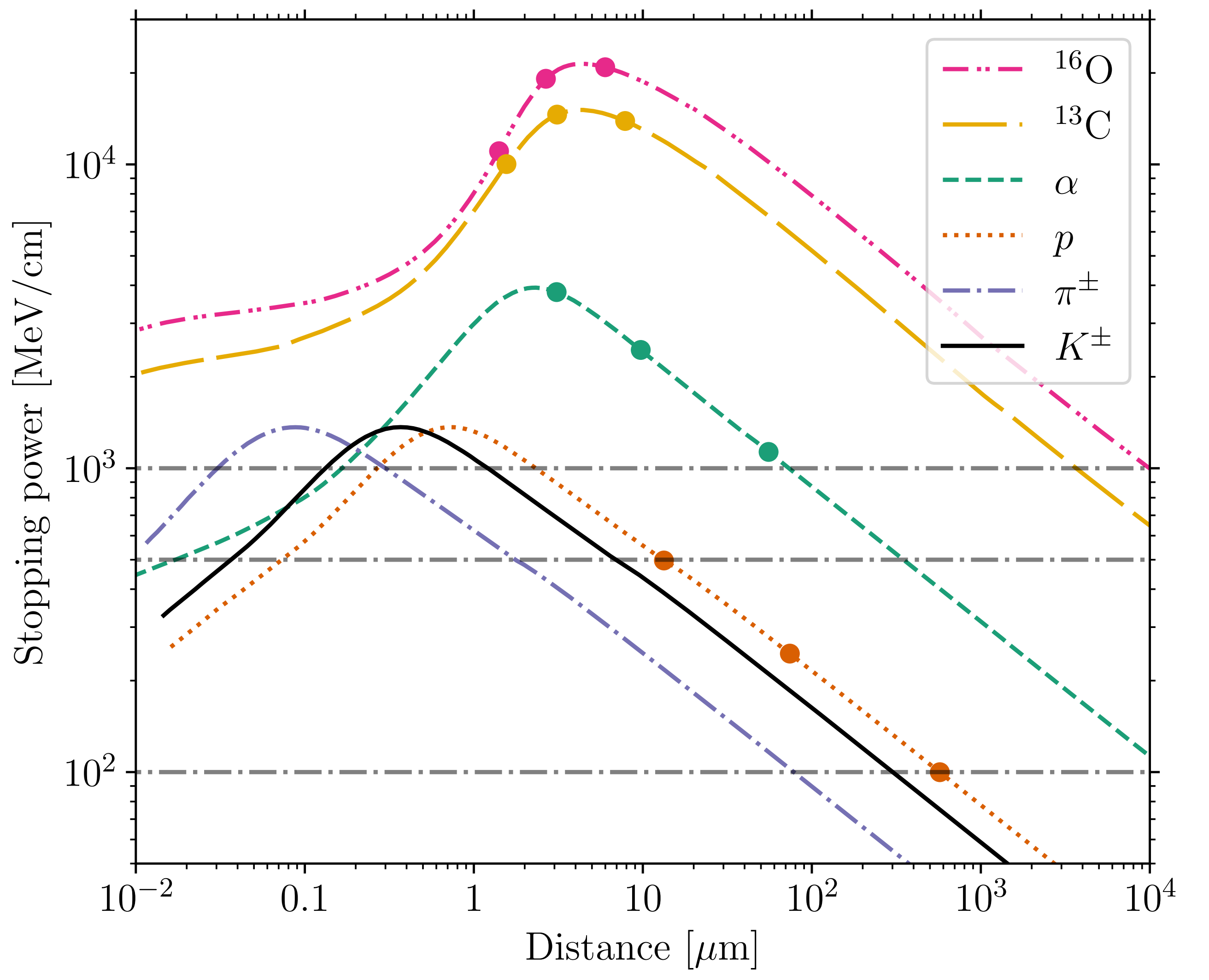
100g and 10^9 yrs old

Proton Decay in a Paleo-detector

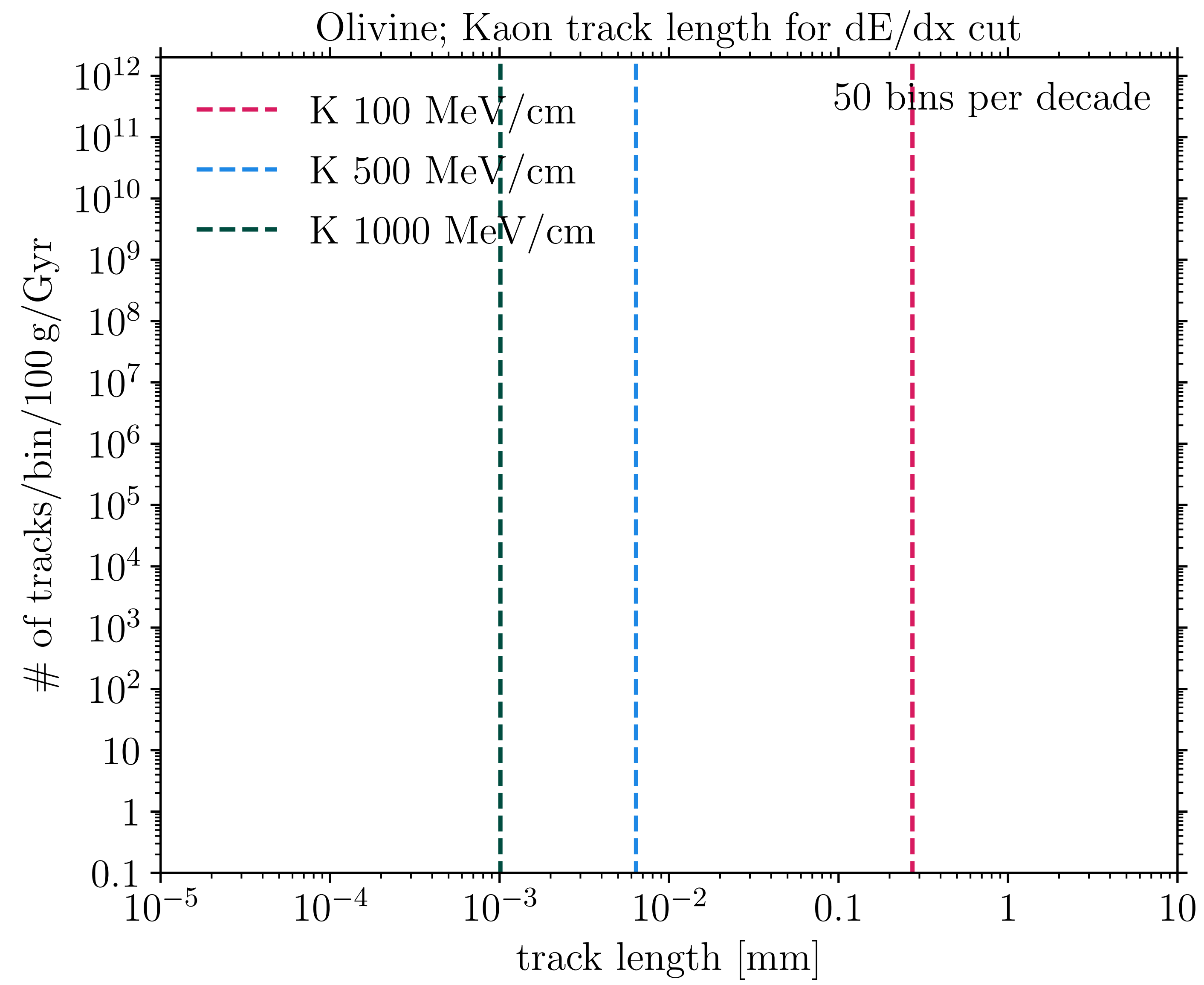


$$p \rightarrow \bar{\nu} K^{+}$$

- **Identify the kaon track**
    - Energy of $\mathcal{O}$(100) MeV
- Identify the proton decay nuclear remnant track?
    - ~2 μm
- Consider kaon track length at stopping power thresholds of
    - 100 MeV/cm: ~1 μm
    - 500 MeV/cm: $\gtrsim$ 6 μm
    - 1000 MeV/cm: ~ 100 μm



Black dotted lines represent 100, 500, & 1000 MeV/cm stopping power cutoffs.



Backgrounds

- Radiogenic
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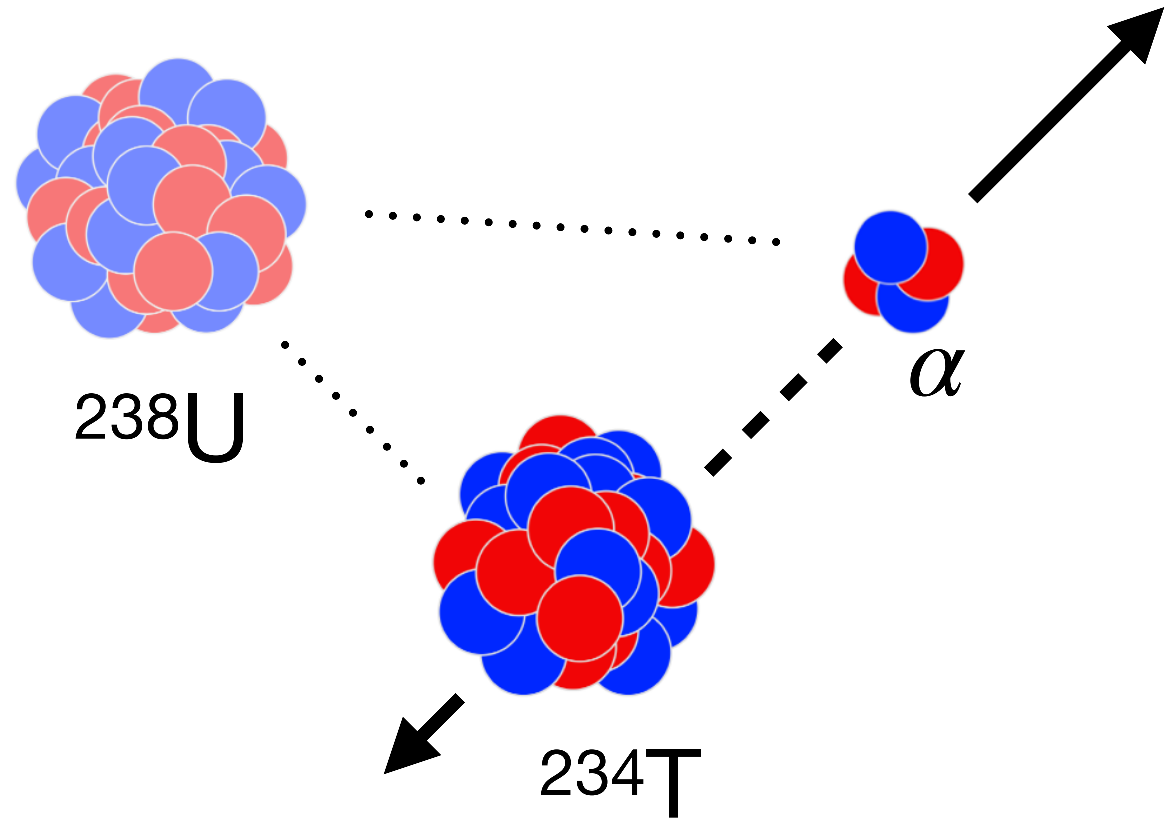
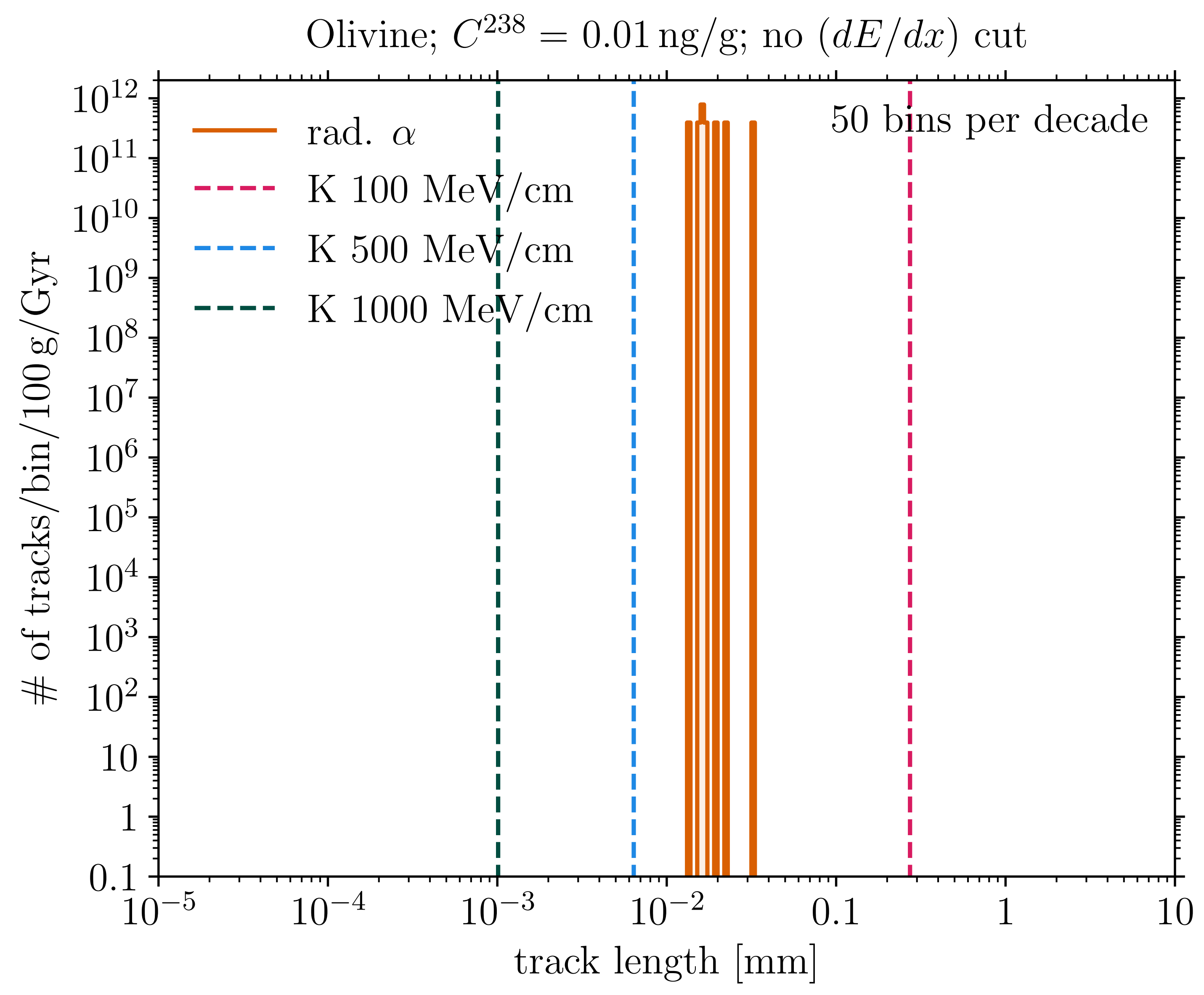
Radiogenic Backgrounds

Alpha particles from ^{238}U

Nucleus	$T_{1/2}$	Decay Mode
^{238}U	4.5×10^9 years	α
^{234}Th	24.1 days	β
^{234}Pa	1.17 minutes	β
^{234}U	2.5×10^5 years	α
^{230}Th	8.0×10^4 years	α
^{226}Ra	1,620 years	α
^{222}Rn	3.82 days	α
^{218}Po	3.05 minutes	α
^{214}Pb	26.8 minutes	β
^{214}Bi	19.7 minutes	β
^{214}Po	1.6×10^{-4} seconds	α
^{210}Pb	19.4 years	β
^{210}Bi	5.0 days	β
^{210}Po	138 days	α
^{206}Pb	Stable	-

- Natural olivine samples have a wide range of ^{238}U concentrations
    - We assume 10 ppt
- α-particle tracks $\mathcal{O}$**(10)** μ**m** || Nuclear remnant recoil tracks $\mathcal{O}$**(10) nm**
- α-particle and α-recoil tracks are **clustered**

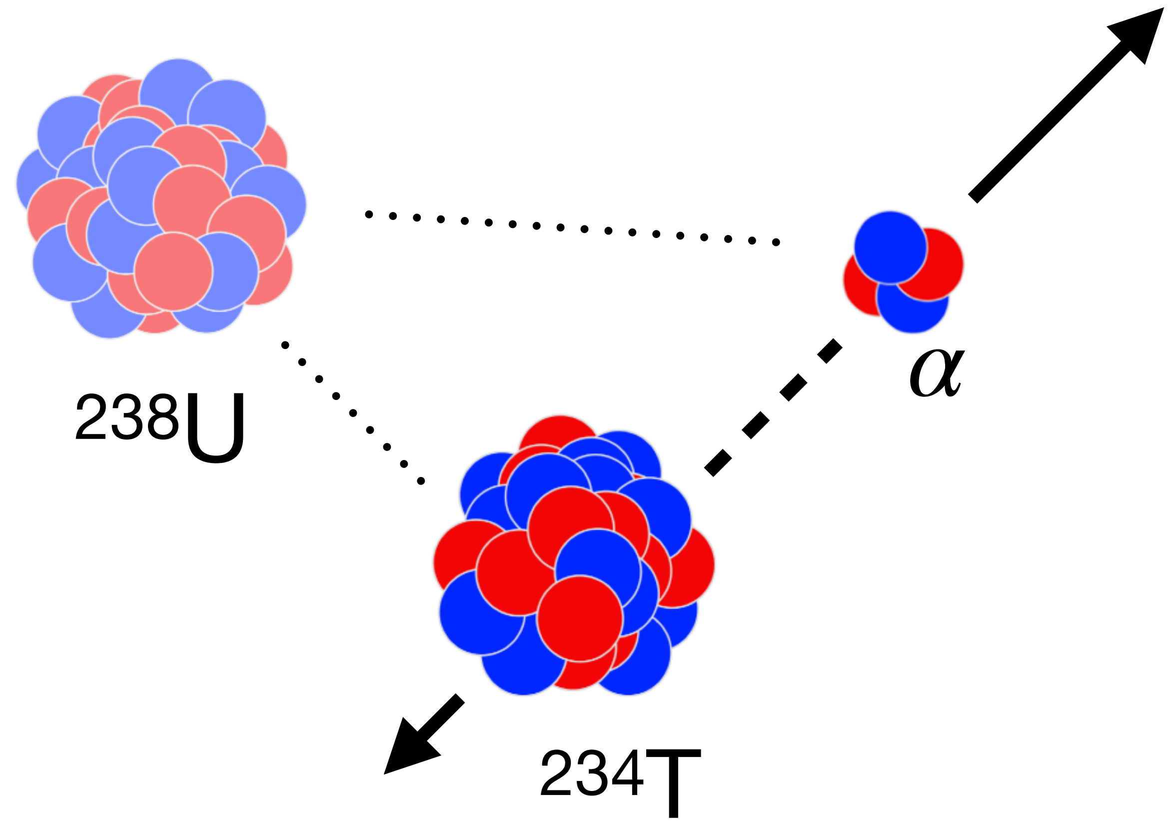


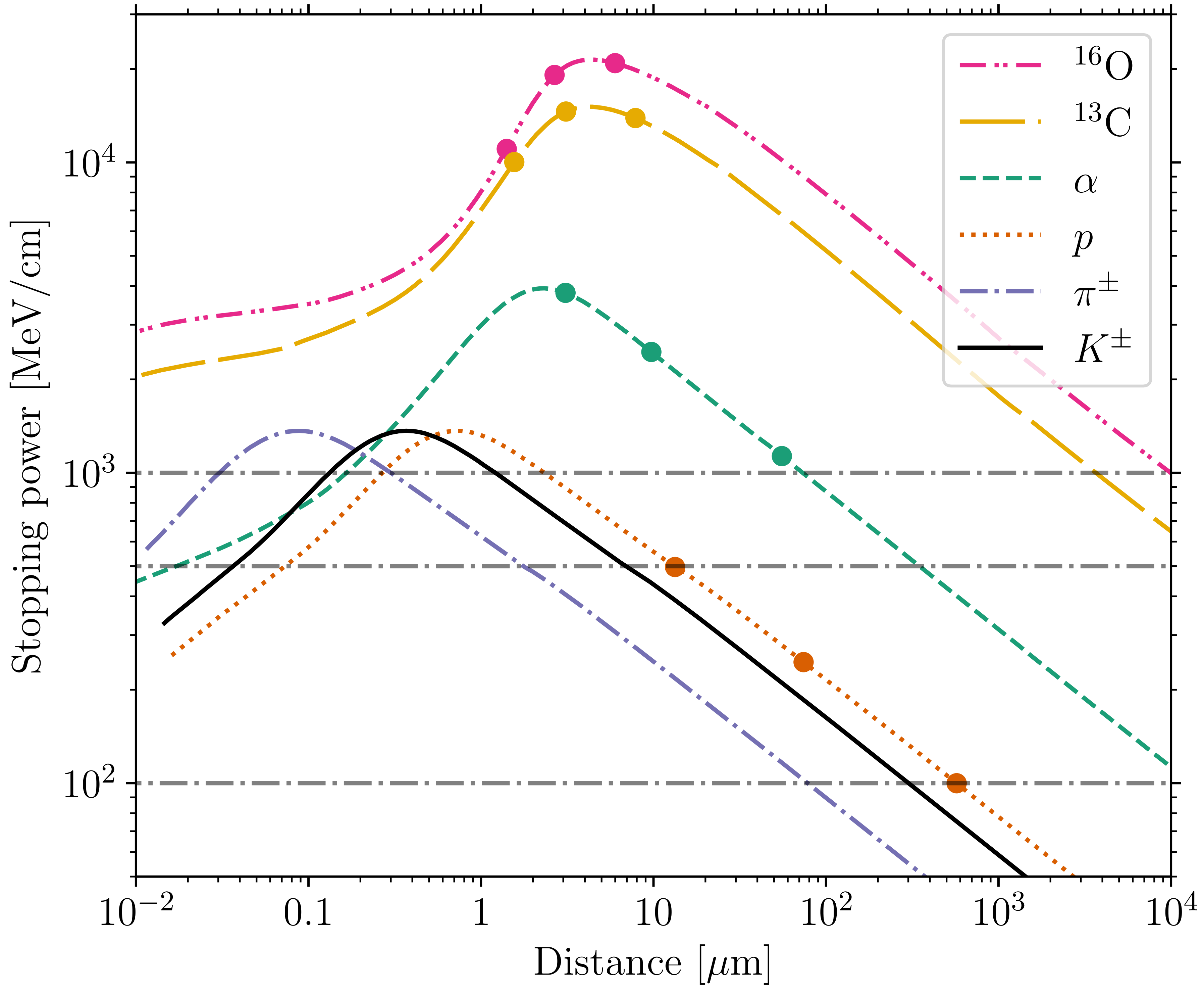


Radiogenic Backgrounds

Alpha particles from ^{238}U

- α stopping power distribution is different from K+
  - Different track characteristics?

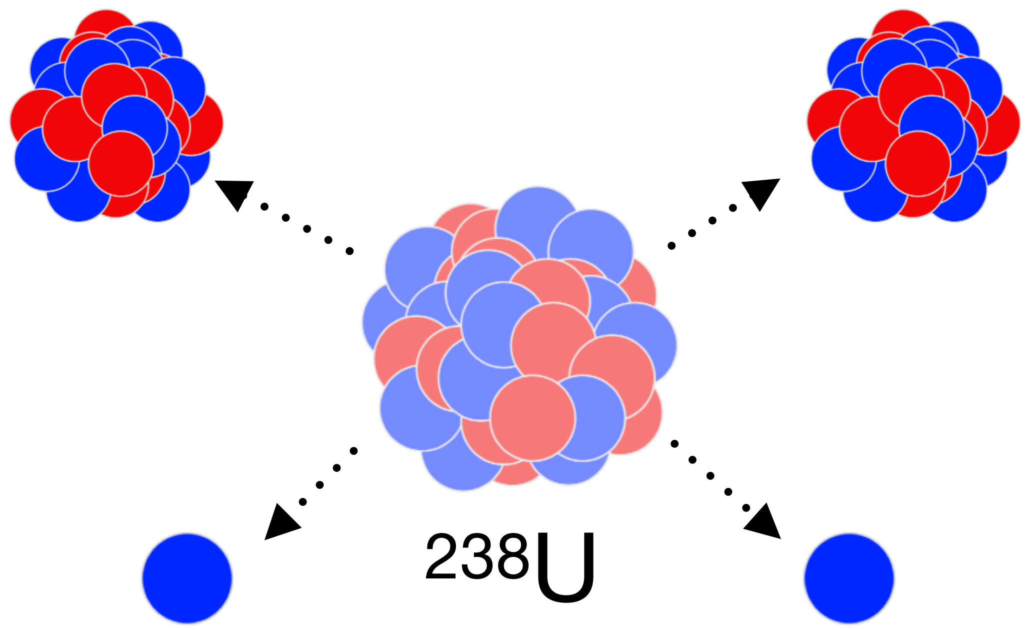




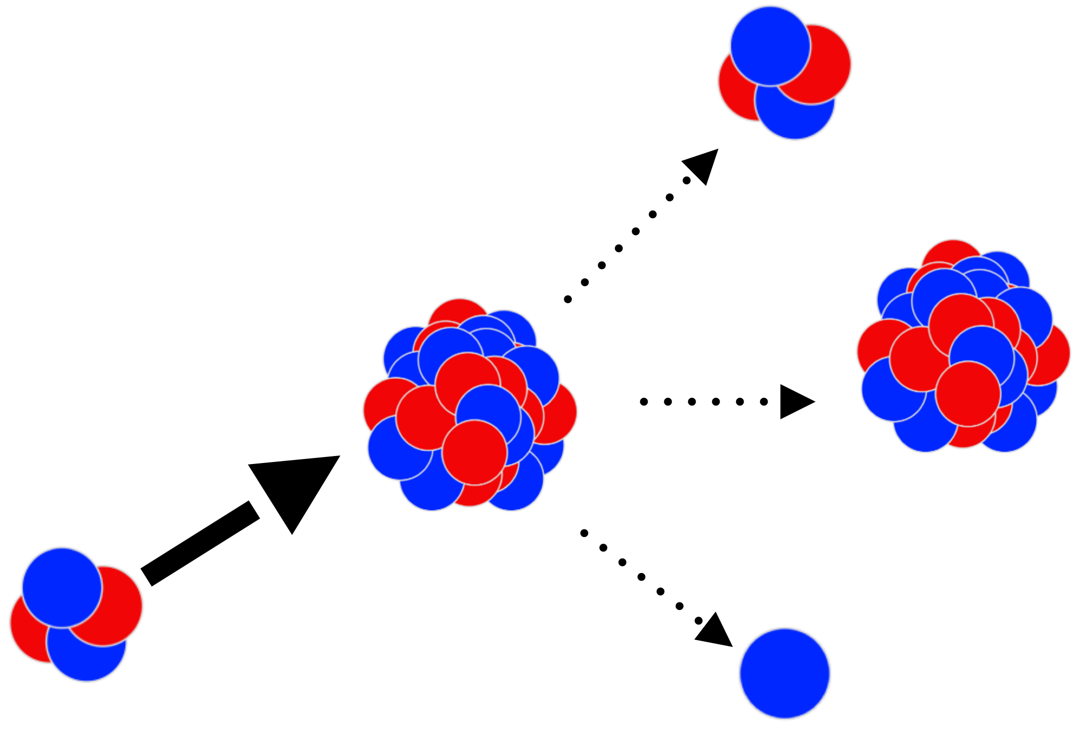
Dots mark where an ion with
1, 3, 10 MeV kinetic energy would “start”.

Radiogenic Backgrounds

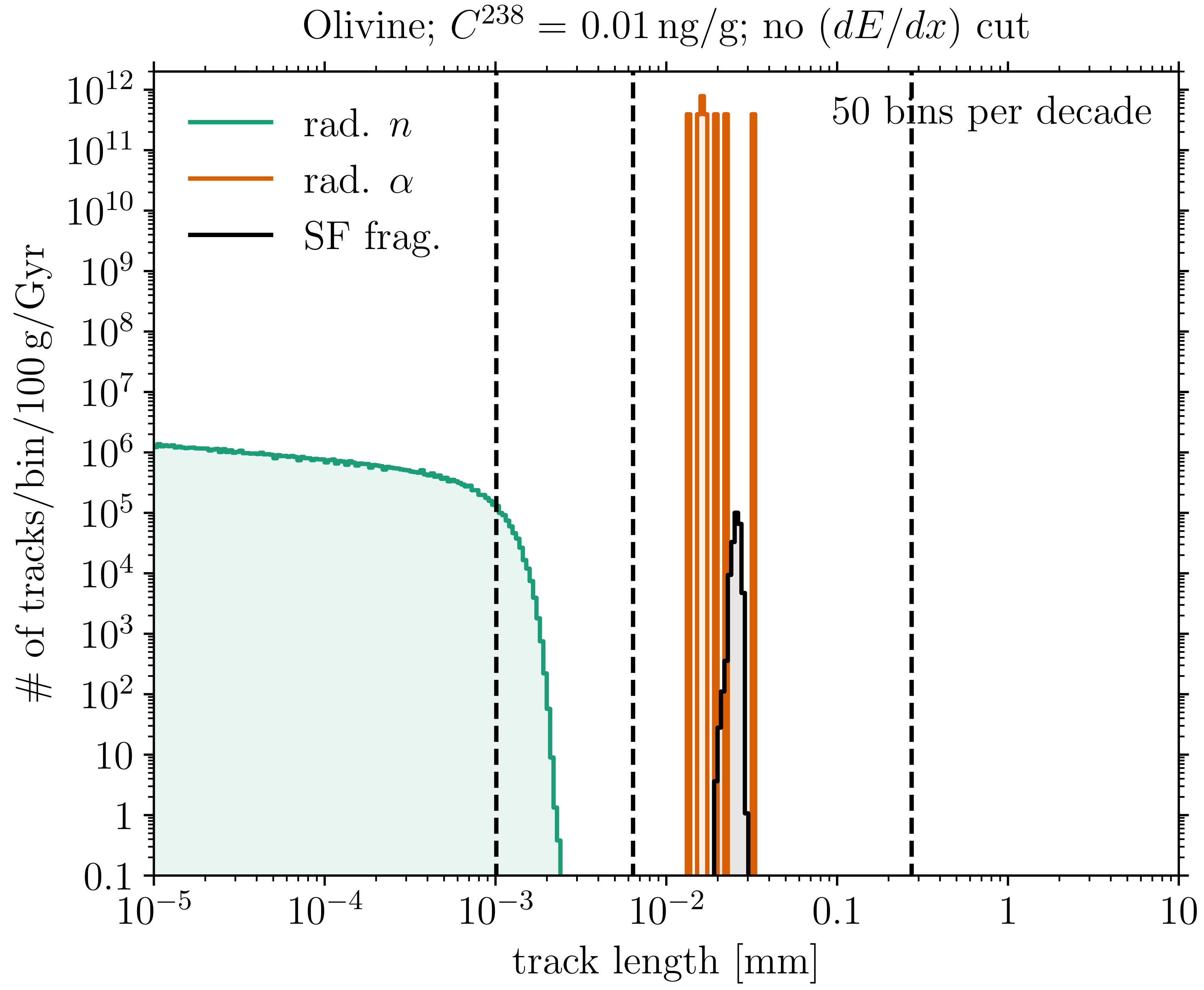
Neutrons



Spontaneous Fission



(n, α) - reactions



- Neutron induced nuclear recoil tracks < 3 μm
    - (Proton decay nuclear remnants are ~2 μm)

Backgrounds

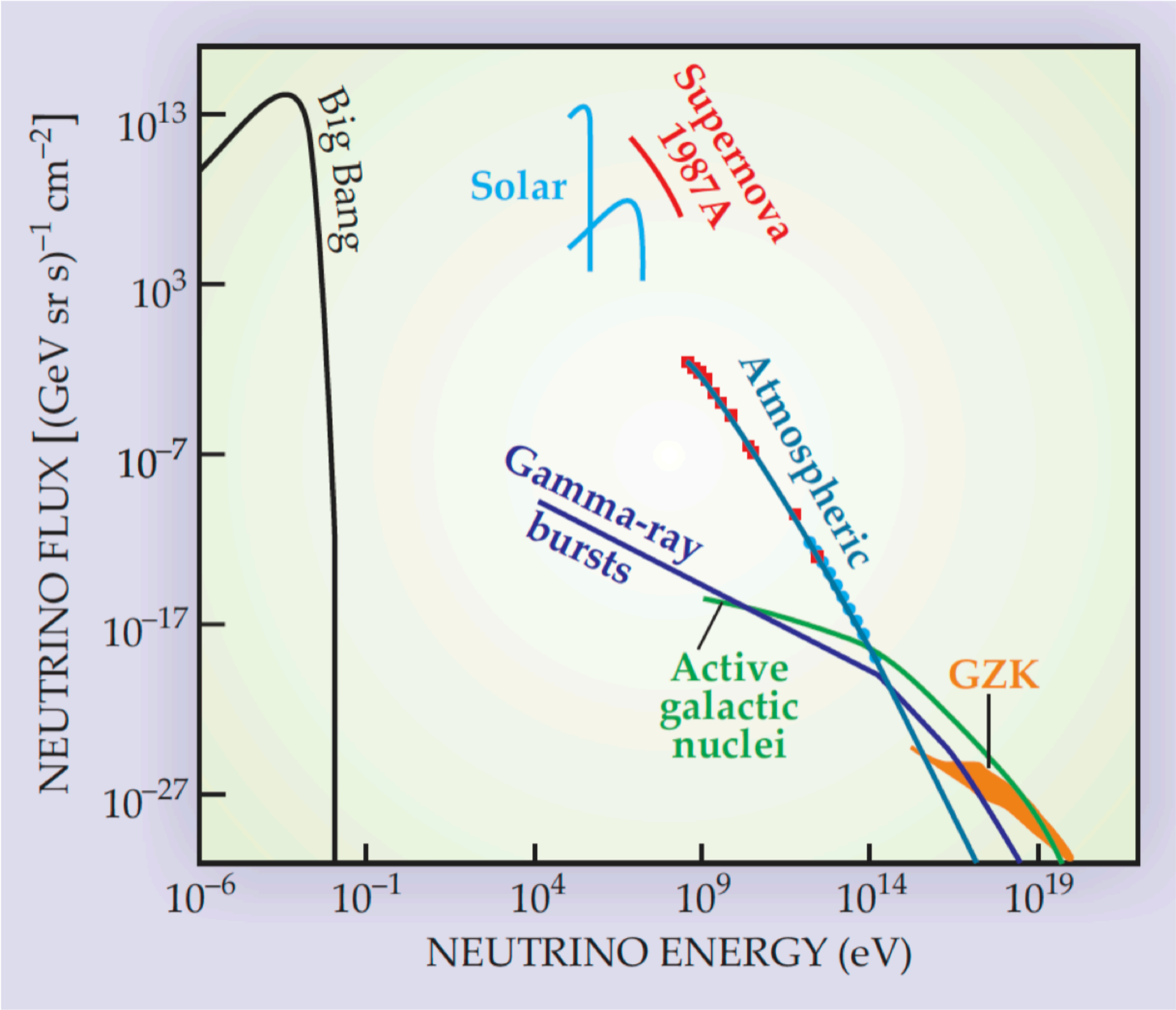
- Radiogenic
    - Neutrons
    - Radiative elements naturally occurring in minerals
- Cosmogenic
    - Prompt muons
    - Atmospheric neutrinos

Cosmic Backgrounds

Neutrinos

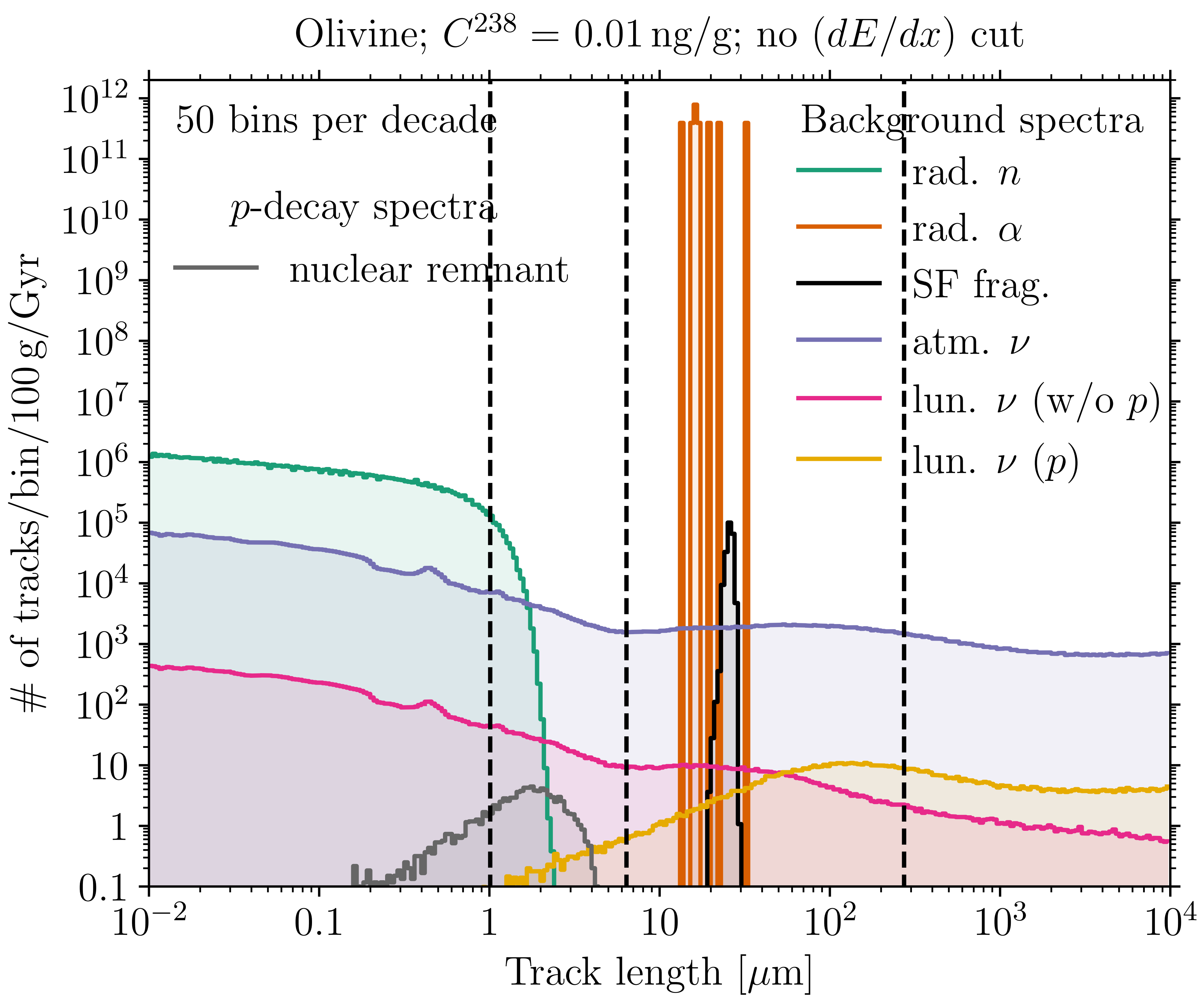
- Tracks from neutrinos > 0.1 GeV
  - Can produce a nuclear recoil remnant
  - Produce secondary particles that can then make their own tracks & secondary nuclear recoils

Including kaons



Physics Today

Atmospheric Neutrinos

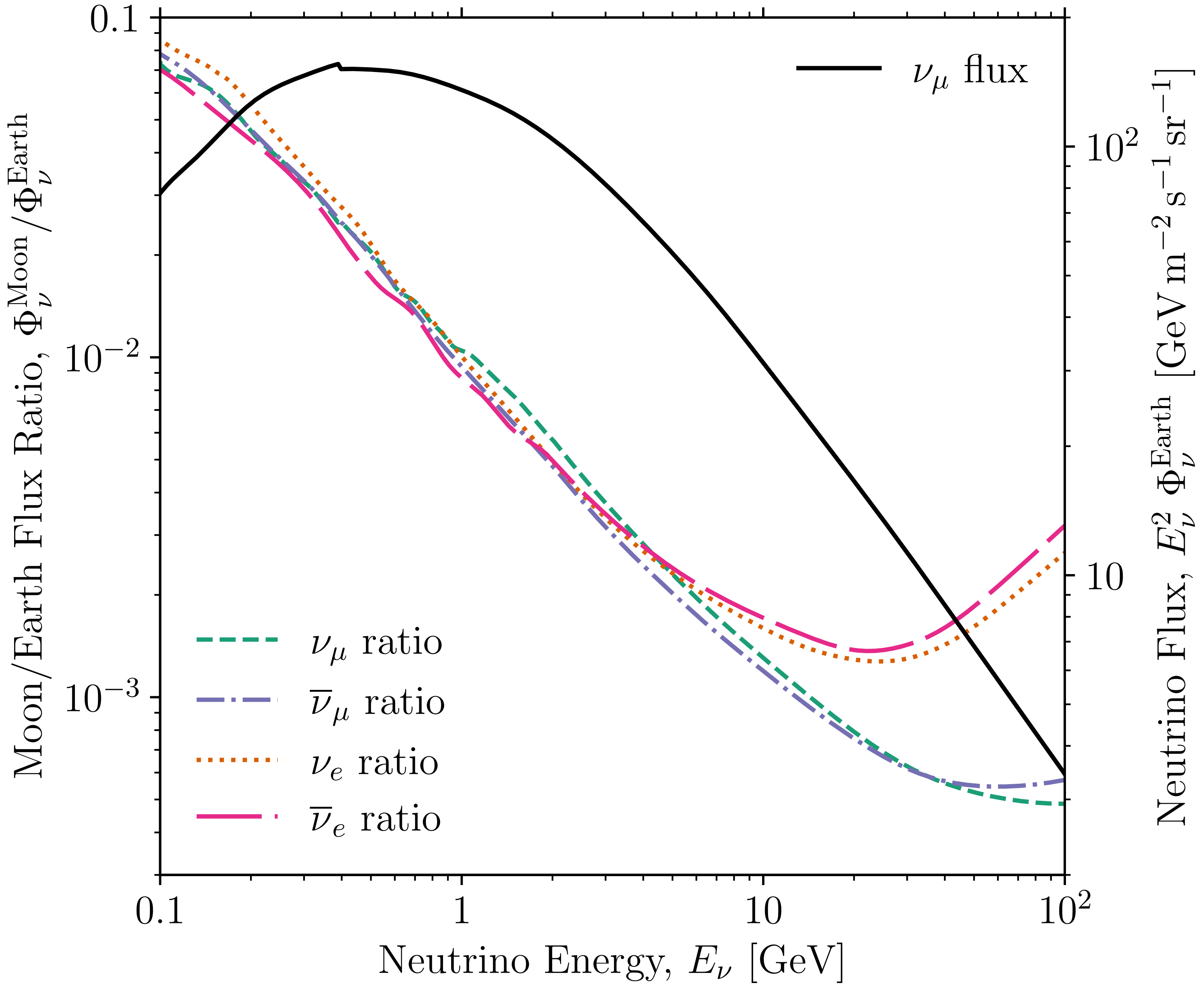


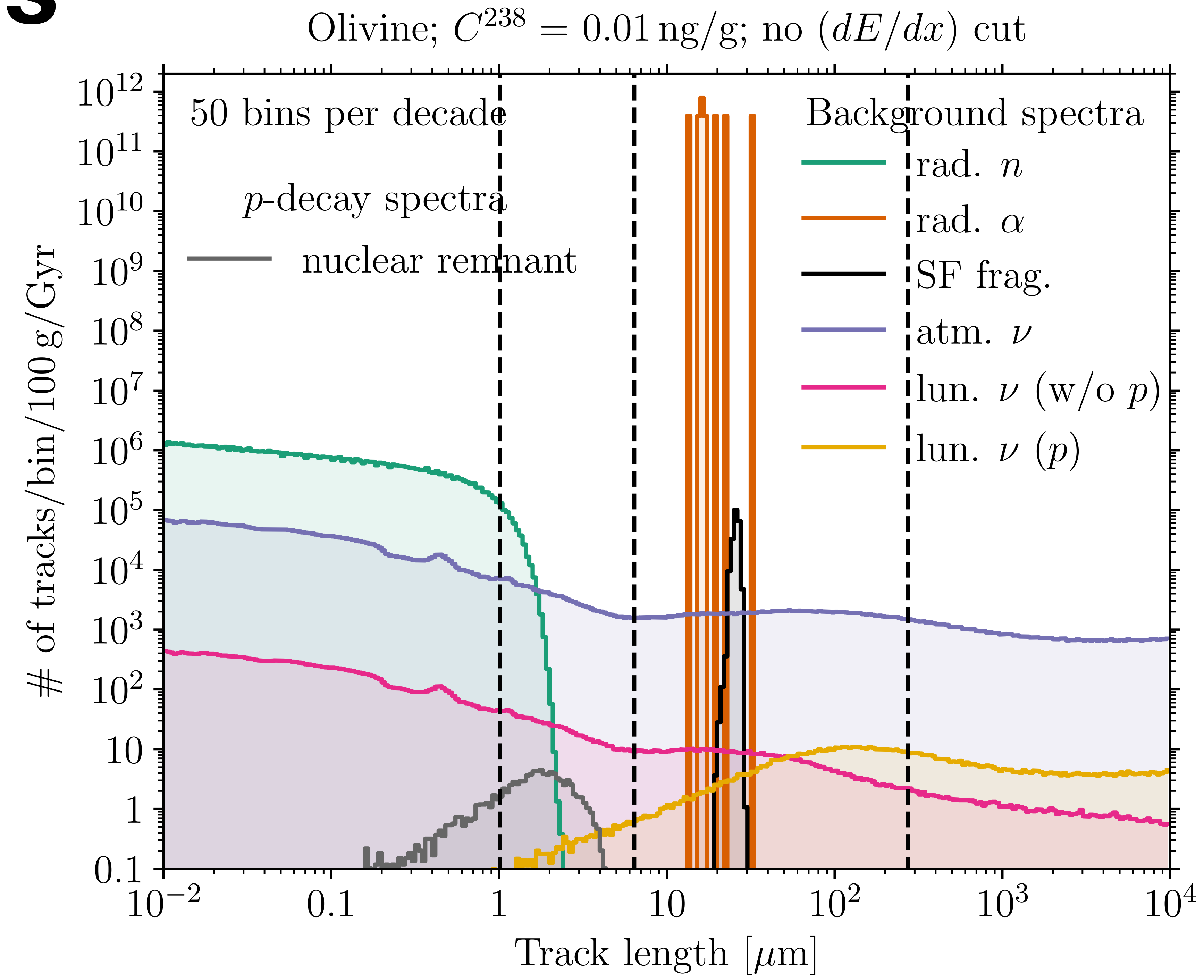
- Current τ_p limit corresponds to $\lesssim$ 6 kaons/100g/Gyr
- Atm. ν create ~400 kaons/100g/Gyr

What can we do?

To the Moon!

Atmospheric Neutrino Backgrounds





- Lunar ν create ~0.5 kaons/100g/Gyr

Cosmic Backgrounds

Muons

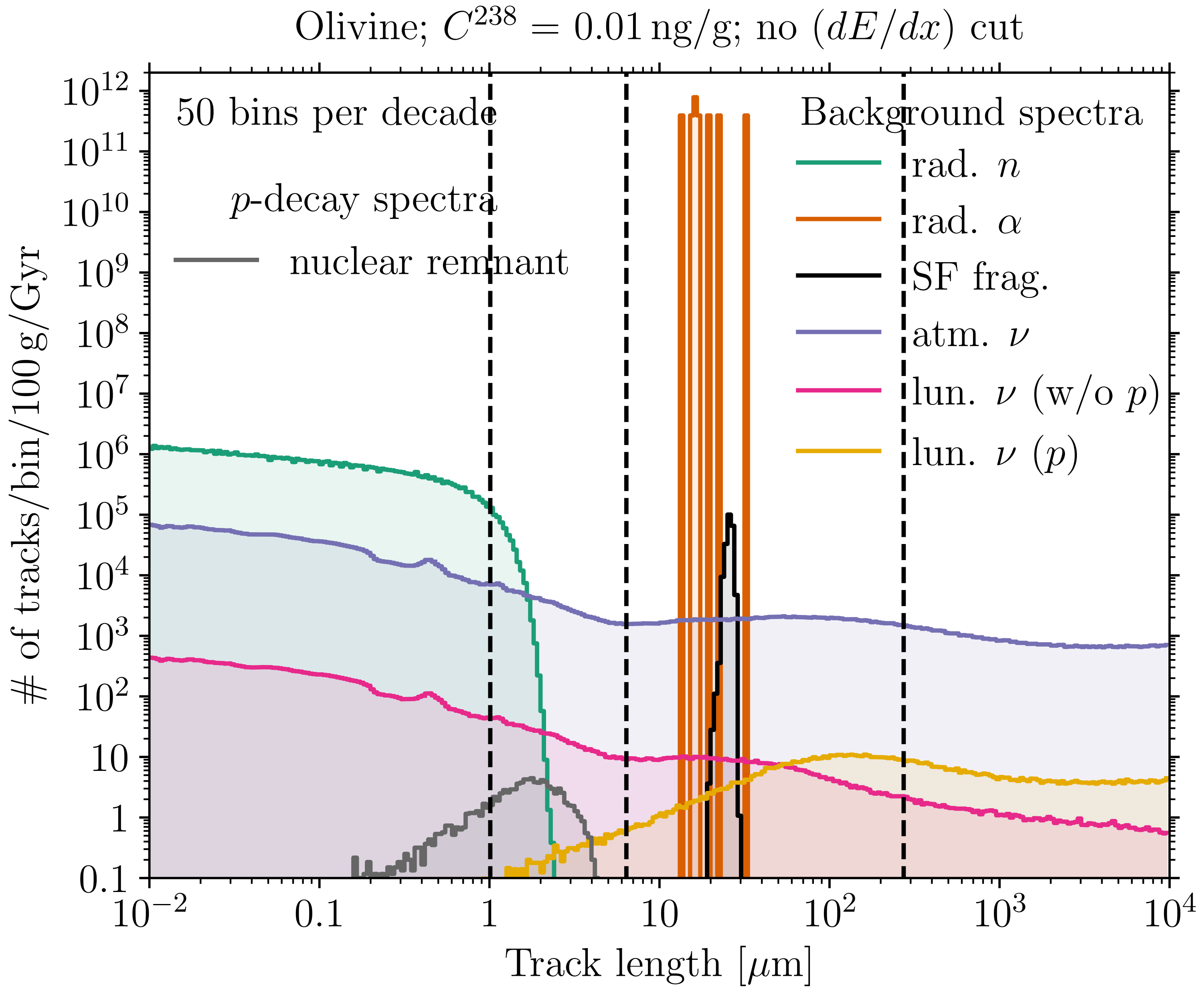
- From lunar regolith
- Produce energetic neutrons and spallation fragments (Including kaons)
- This flux depends on depth!

	5 km	**6 km**	$\gtrsim$ **10 km**
Lunar (prompt) Muon Flux	10^3 cm^{-2}Gyr^{-1}	10^2 cm^{-2}Gyr^{-1}	$< 10^{-2}$ cm^{-2}Gyr^{-1}
Lunar Fast Neutron Flux	~ 10^2 cm^{-2}Gyr^{-1}	~ 10 cm^{-2}Gyr^{-1}	~ 10^{-3} cm^{-2}Gyr^{-1}

- At 5 km, ~0.1 kaons/100g/Gyr on the moon

Background Summary

- ^{238}U induced tracks are clustered and have different $\frac{dE}{dx}$
- Can't see proton decay nuclear remnant tracks over the neutron background
- ν produce ~0.5 kaons/100g/Gyr
- At 5 km, ~0.1 kaons/100g/Gyr from muon flux. At 10 km, muon flux is < 10^{-2} $cm^{-2}Gyr^{-1}$



NewScientist

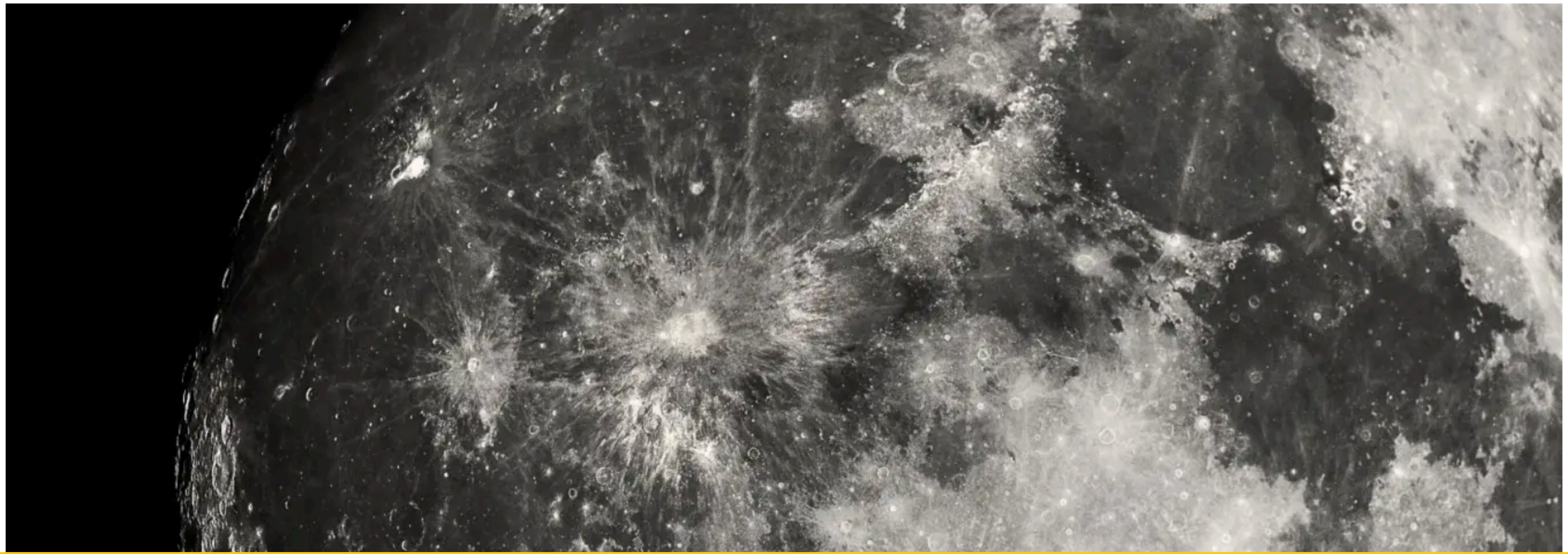
Space

Physicists want to drill a 5-kilometre-deep hole on the moon

Going deep into lunar rock could give us an opportunity to see if protons can decay into something else – a finding that could help us unify conflicting physics theories

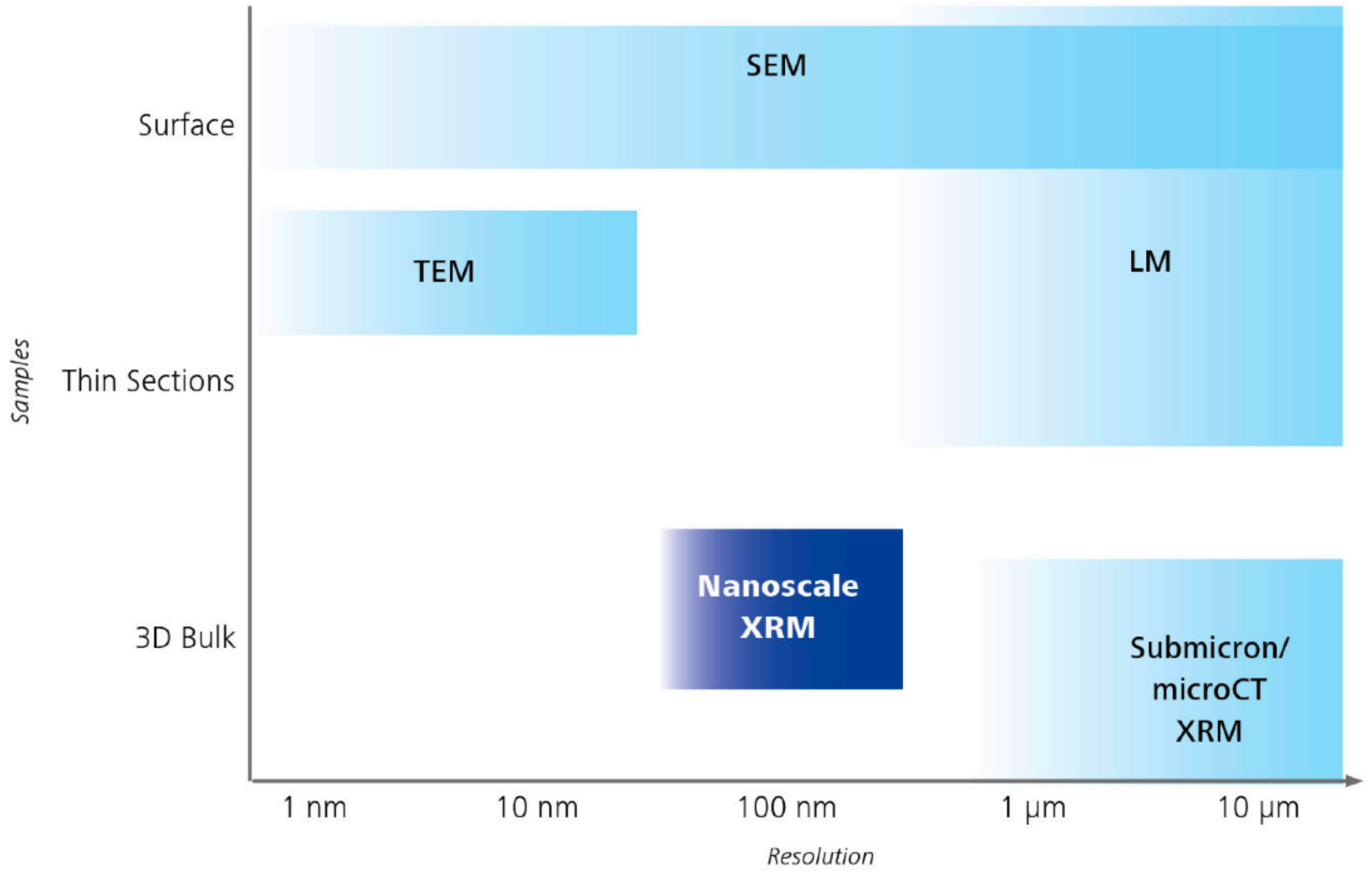
By Alex Wilkins

7 June 2024

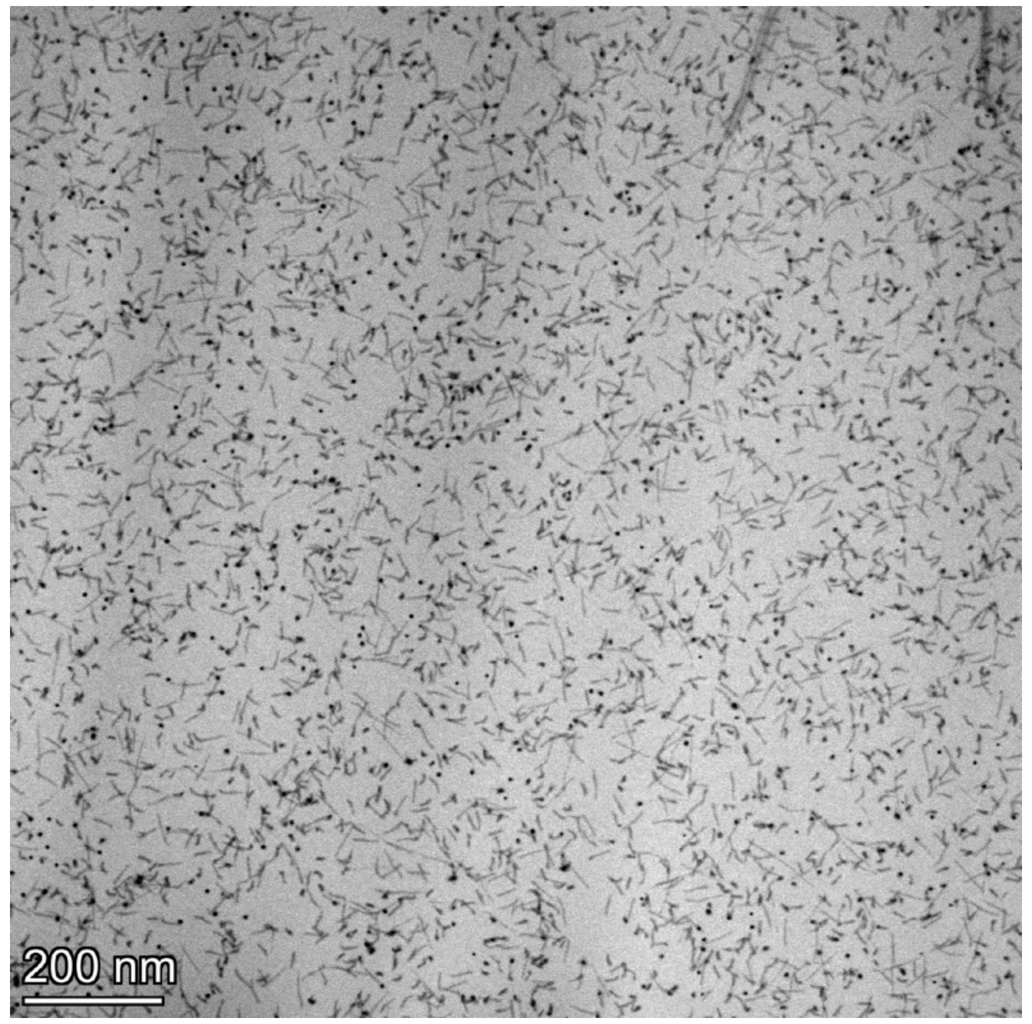


What the Future Holds

- Ongoing research into
    - Feasibility of identifying kaon tracks
    - $\frac{dE}{dx}$ effects on track characteristics



- There are many options in microscopy and the technology is always improving and evolving! Current pursuit: nano-CT (X-ray) techniques.



Michigan ion beam lab and recent track image

Backup