Starting your journey into neutrino physics

Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

CaféConCiencia
August 07, 2025

Find these slides at

mbustamante.net/talks

Who am I?

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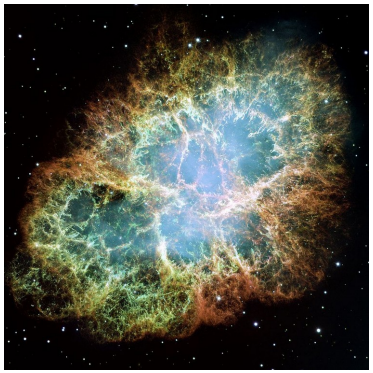

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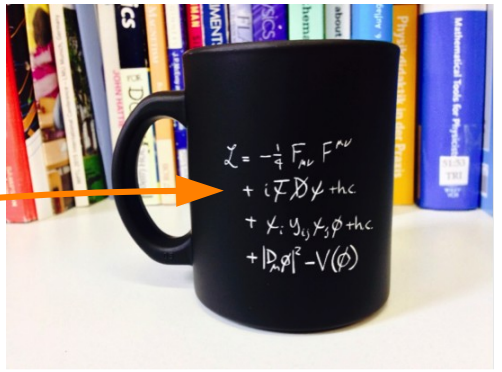

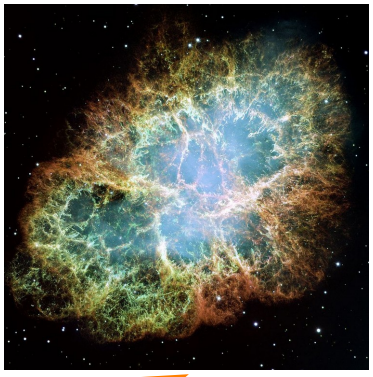

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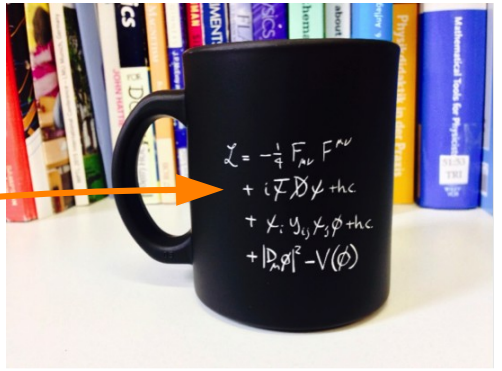

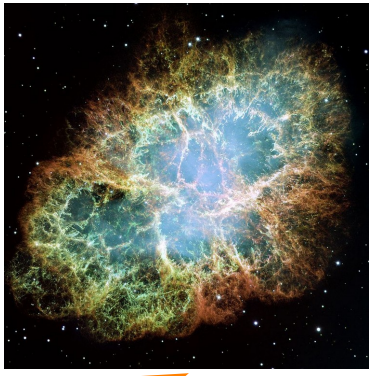

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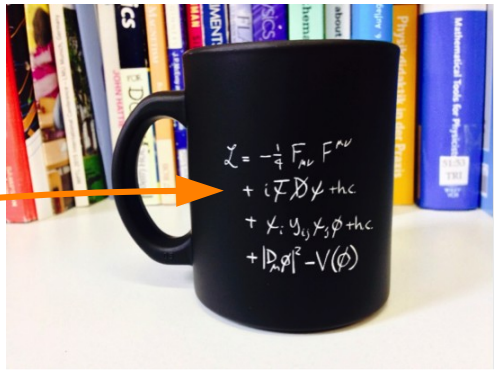

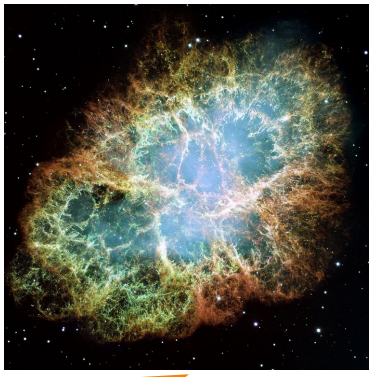

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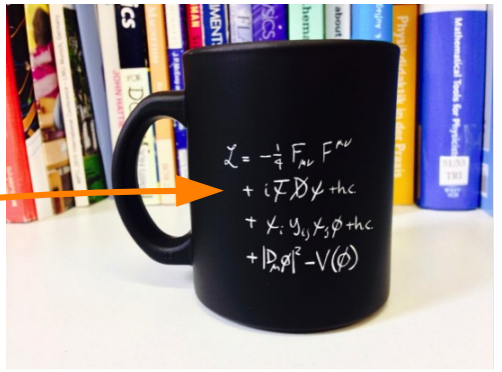

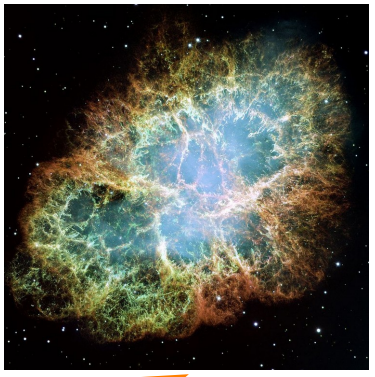

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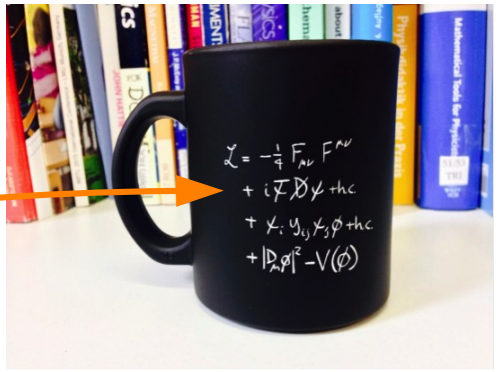

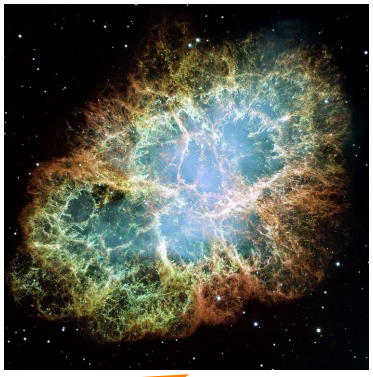

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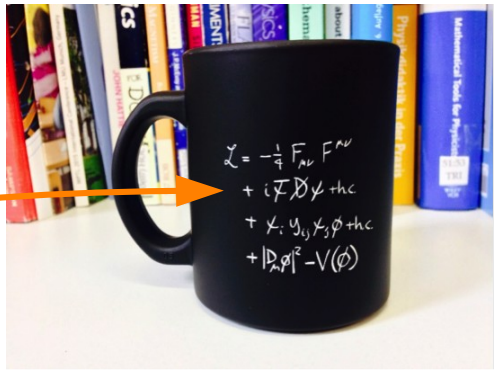

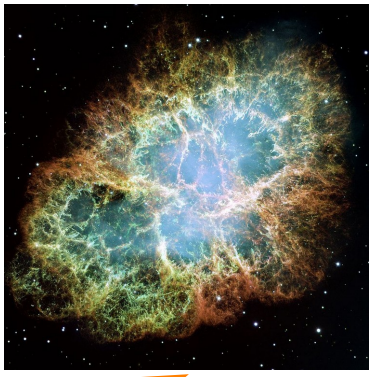

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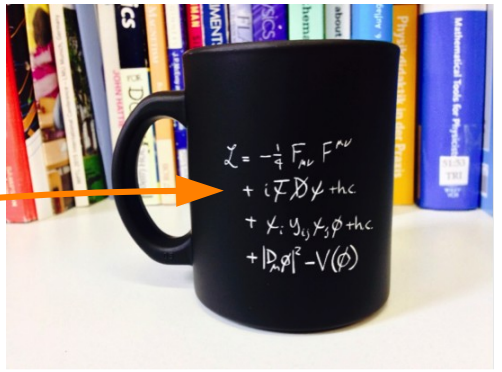
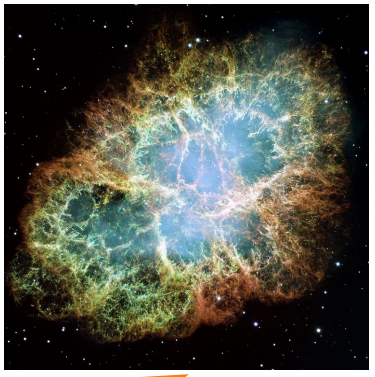
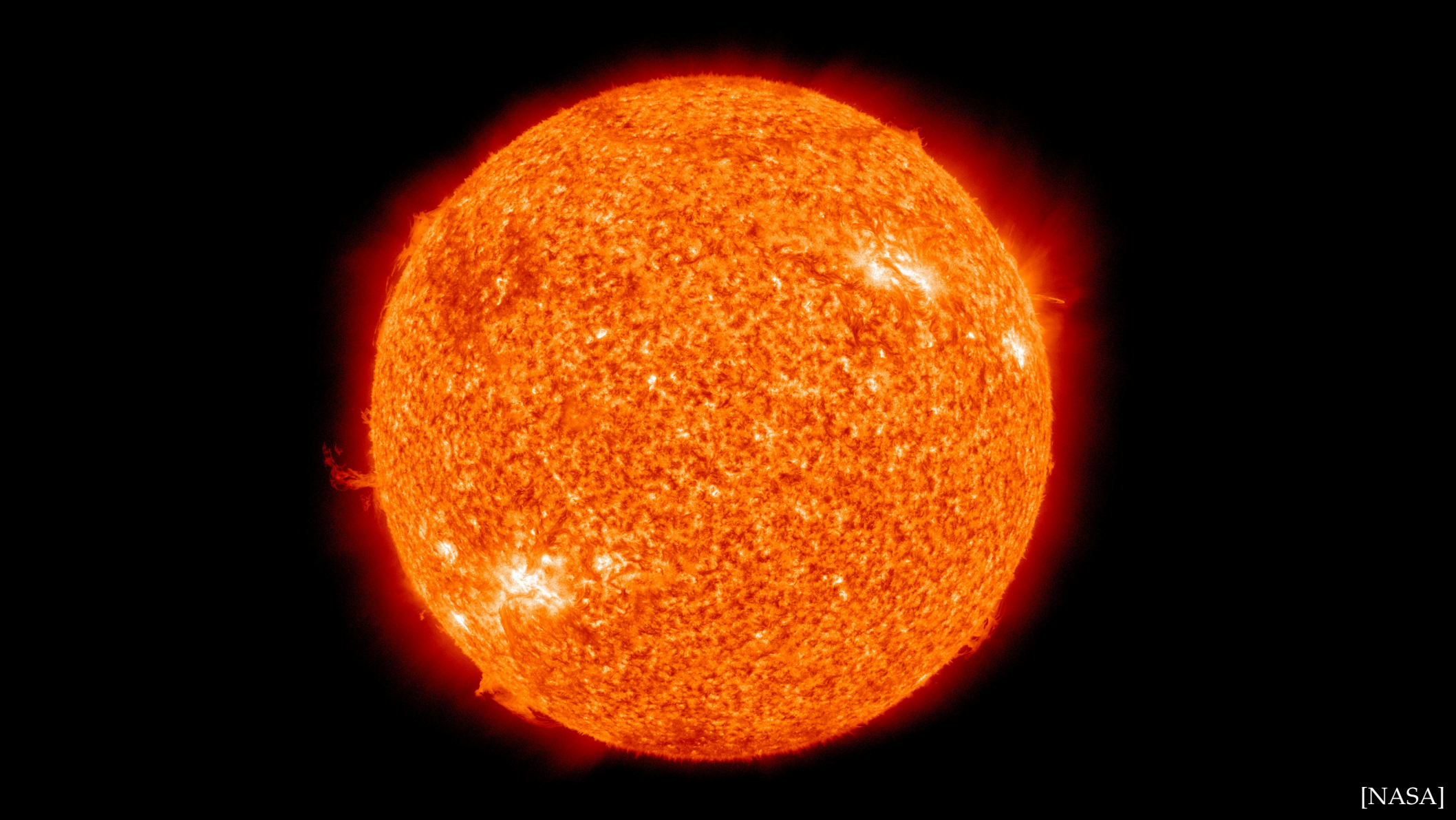
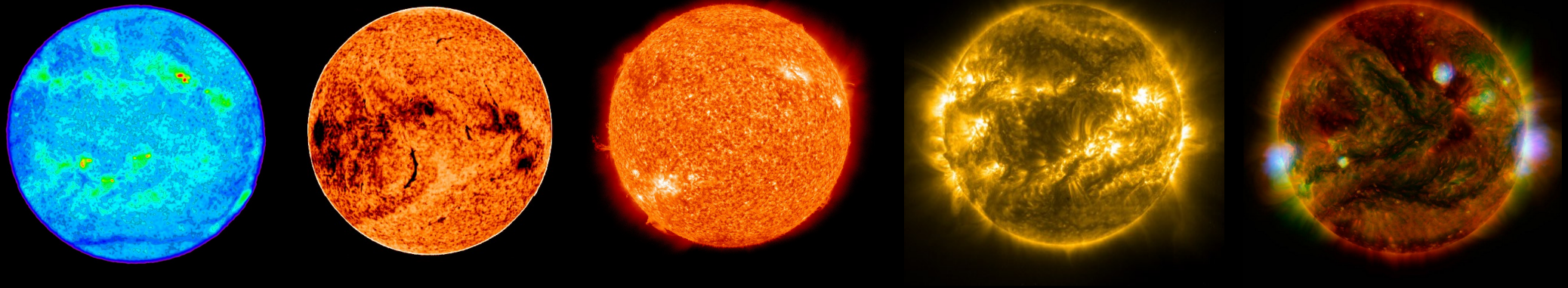






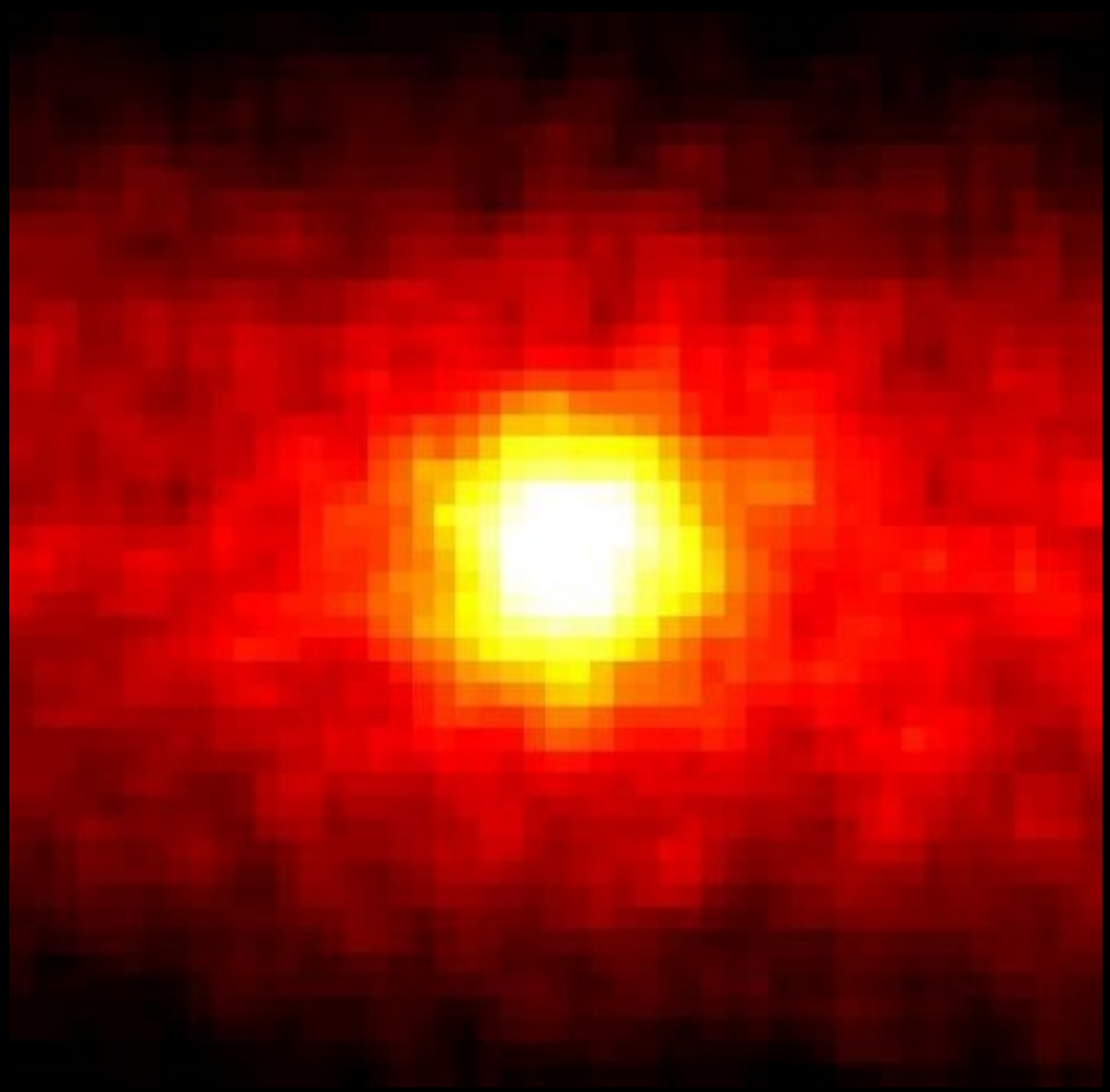
[NASA]

Light of longer wavelength (*i.e.*, less energetic)



Radio Infrared Optical Ultraviolet X-rays

[Kitt Peak / NASA / JPL-Caltech / GSFC / JAXA]



[Super-Kamiokande]

Also the Sun, but now seen in *neutrinos* (ν), not light!

~100 billion ν cross every cm^2 of your body every second

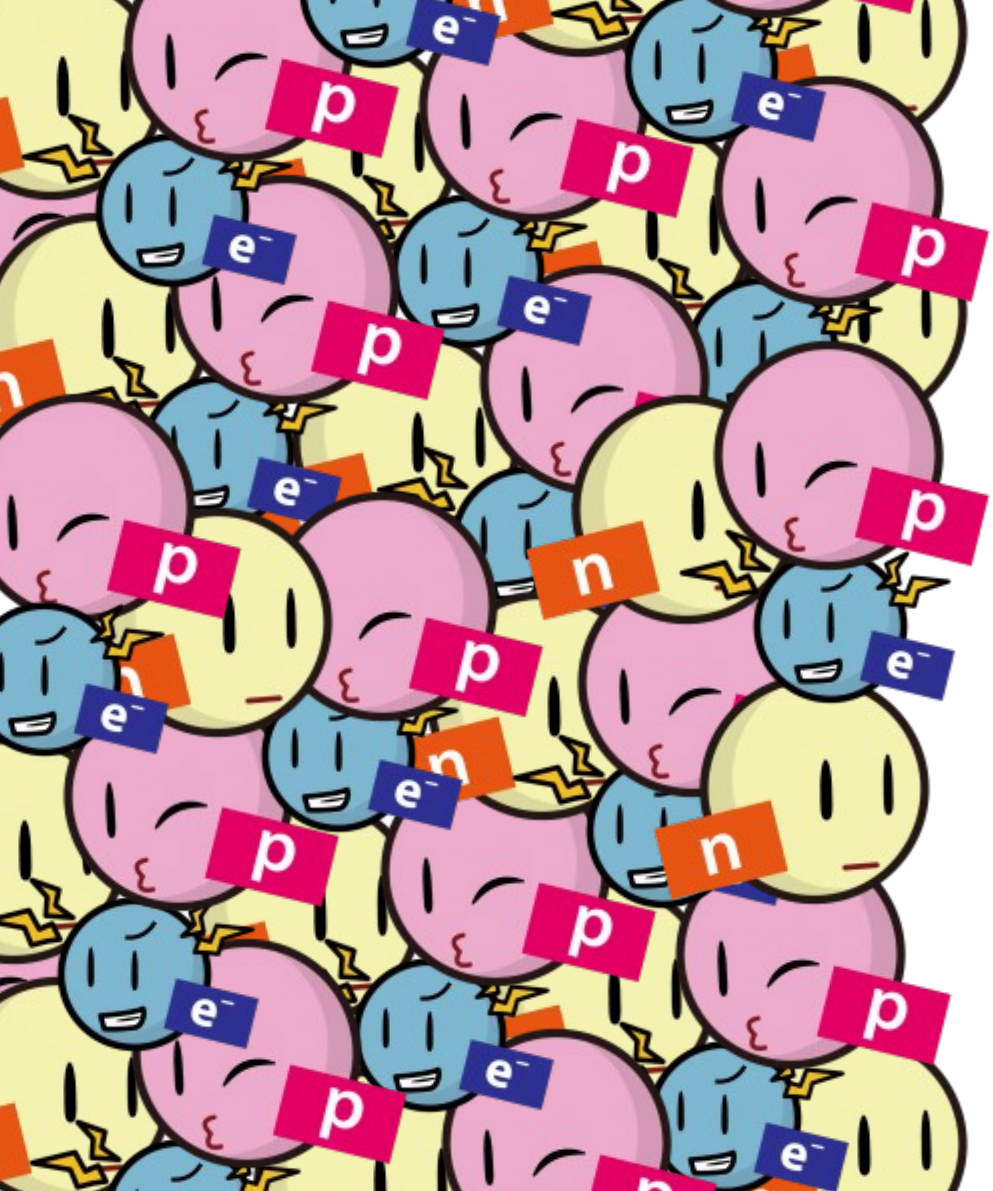
[Super-Kamiokande]

Also the Sun, but now seen in *neutrinos* (ν), not light!

~100 billion ν cross every cm^2 of your body every second

… but only a handful collide with our detectors!

[Super-Kamiokande]



Normal matter is made of

neutrons,

protons,

and electrons

Neutrinos are ***not*** part of normal matter

HiggsTan

Neutrinos are elementary particles,

electrically neutral,

very light,

and superbly antisocial

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= *indivisible*

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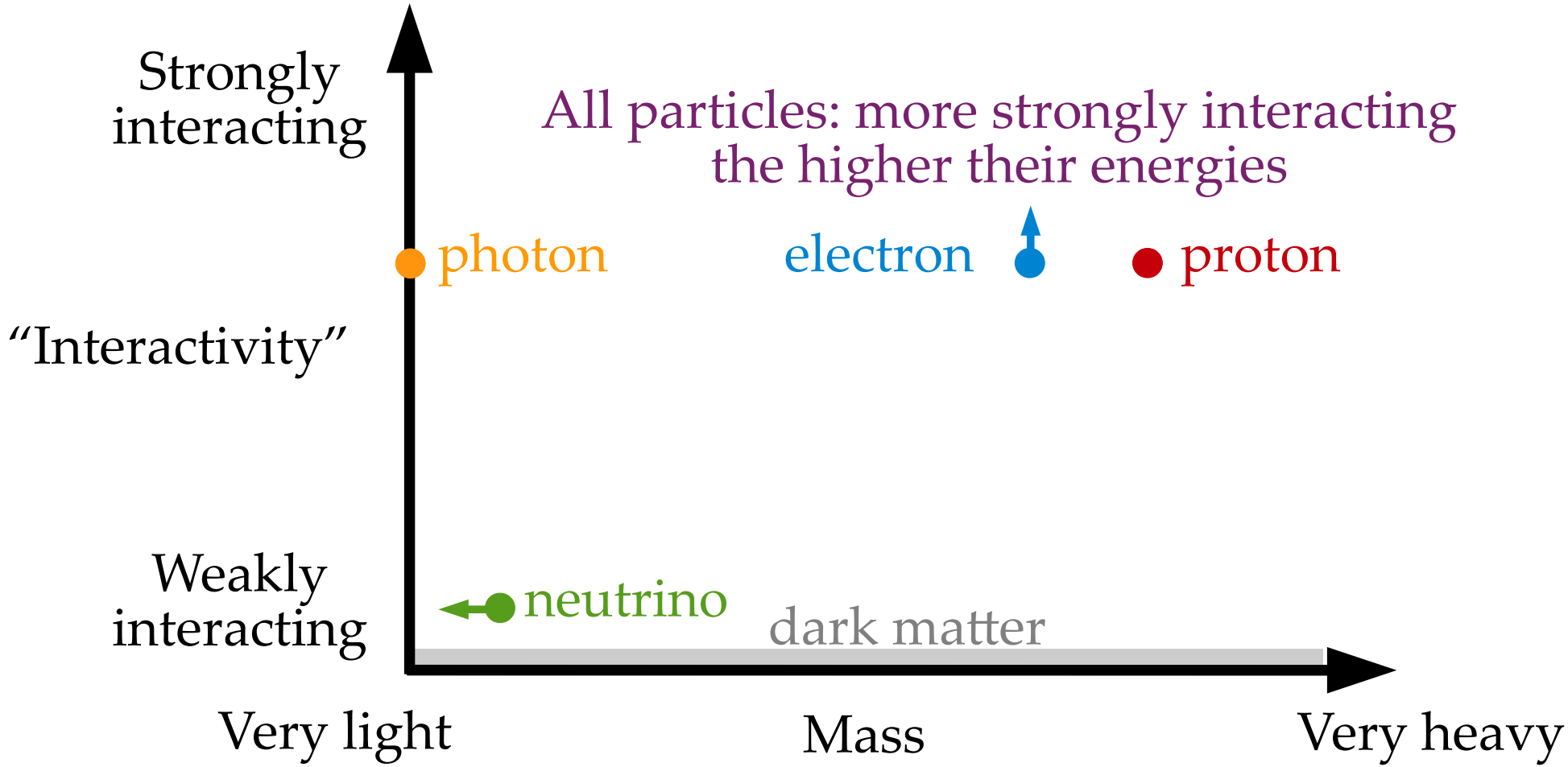
= *barely interact with matter*

Neutrinos are *very* light and *very* anti-social



Just how weak is *weak*

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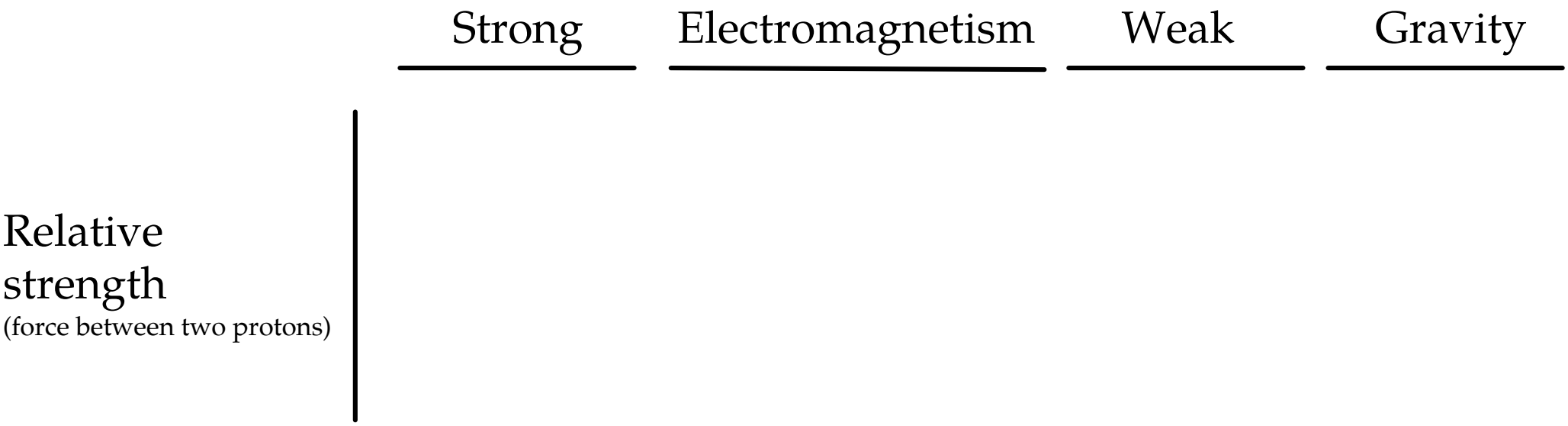
Strong	Electromagnetism	Weak	Gravity

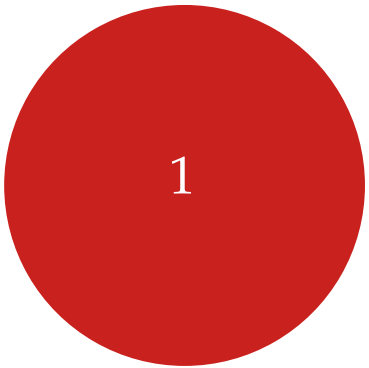
Just how weak is *weak*



Just how weak is *weak*

Strong	Electromagnetism	Weak	Gravity

Relative strength
(force between two protons)



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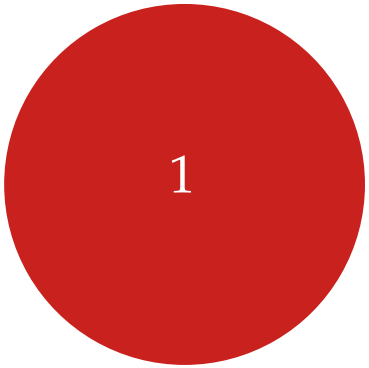

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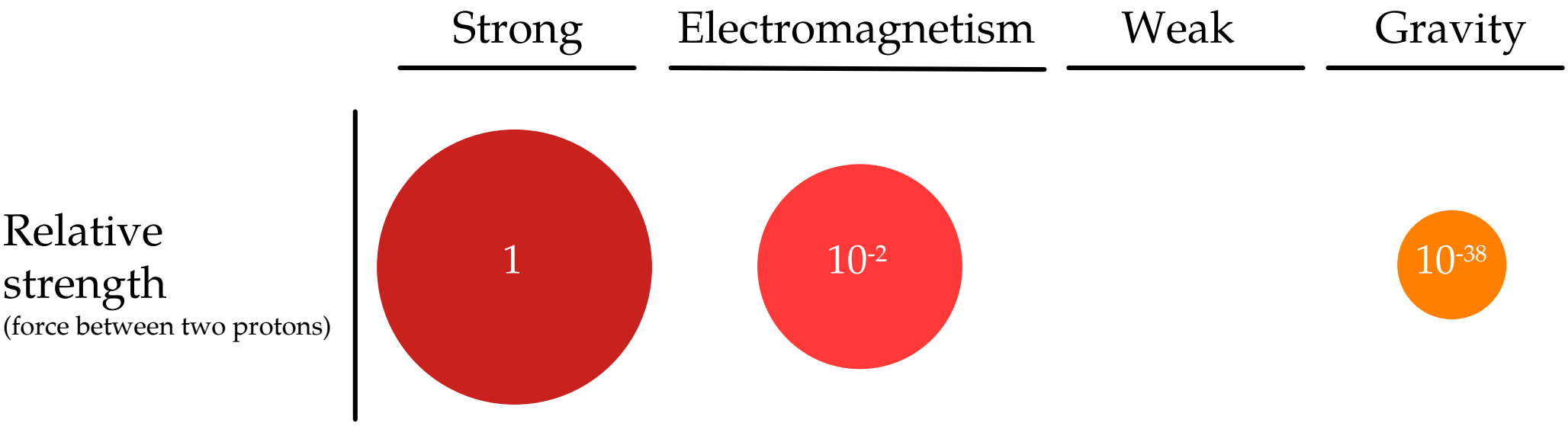

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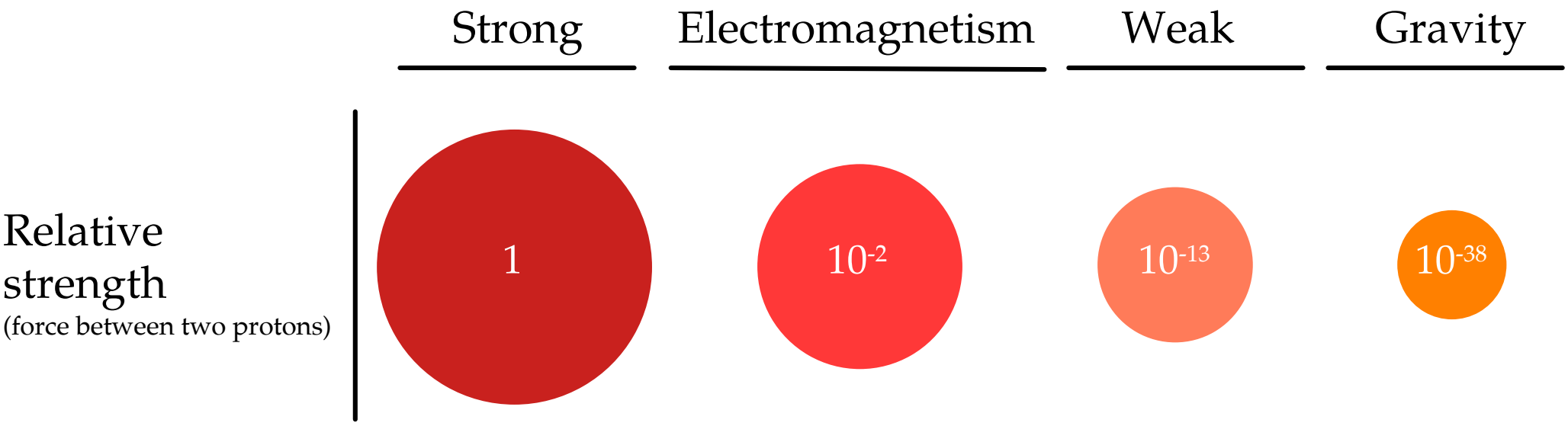

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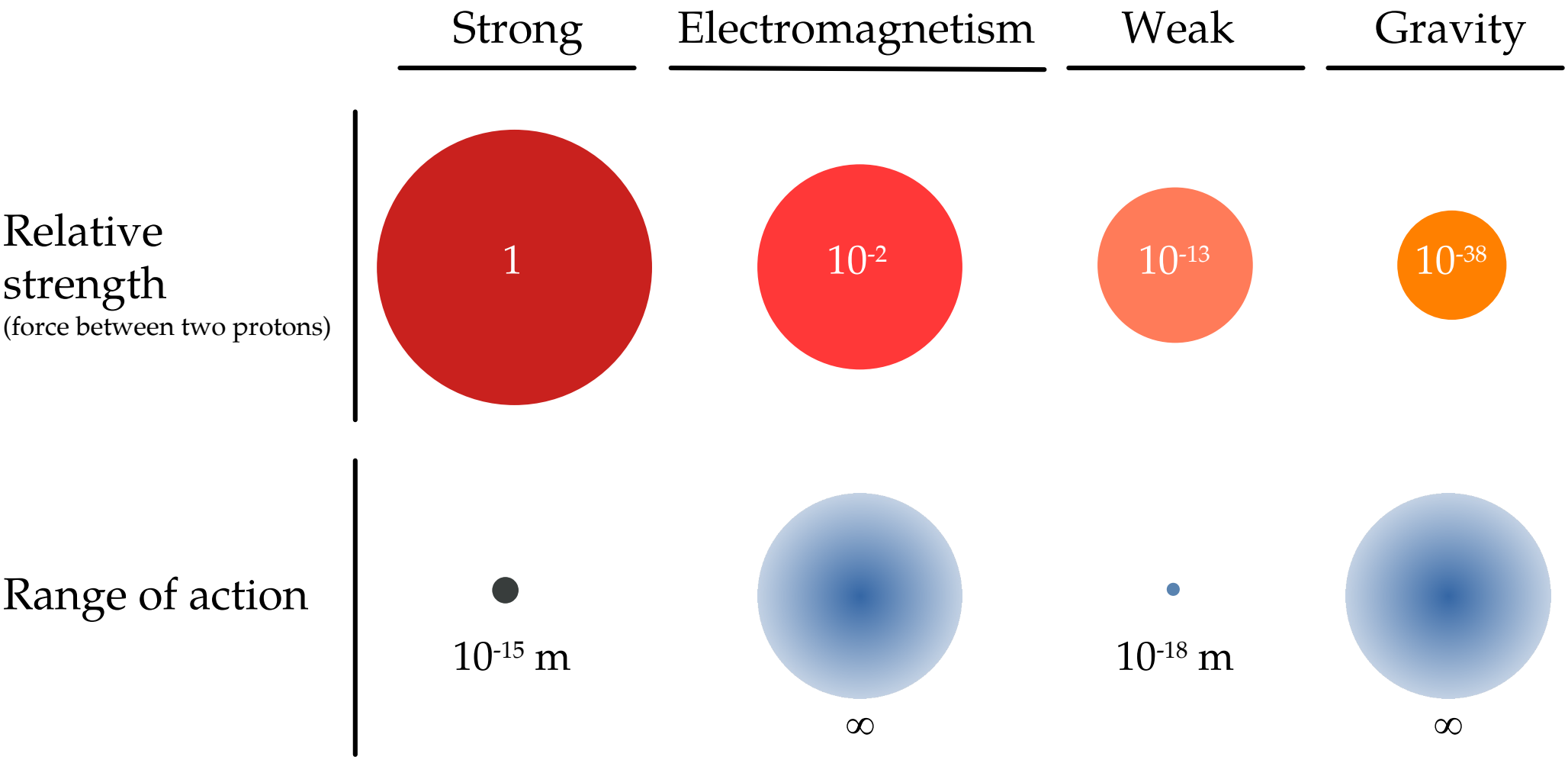

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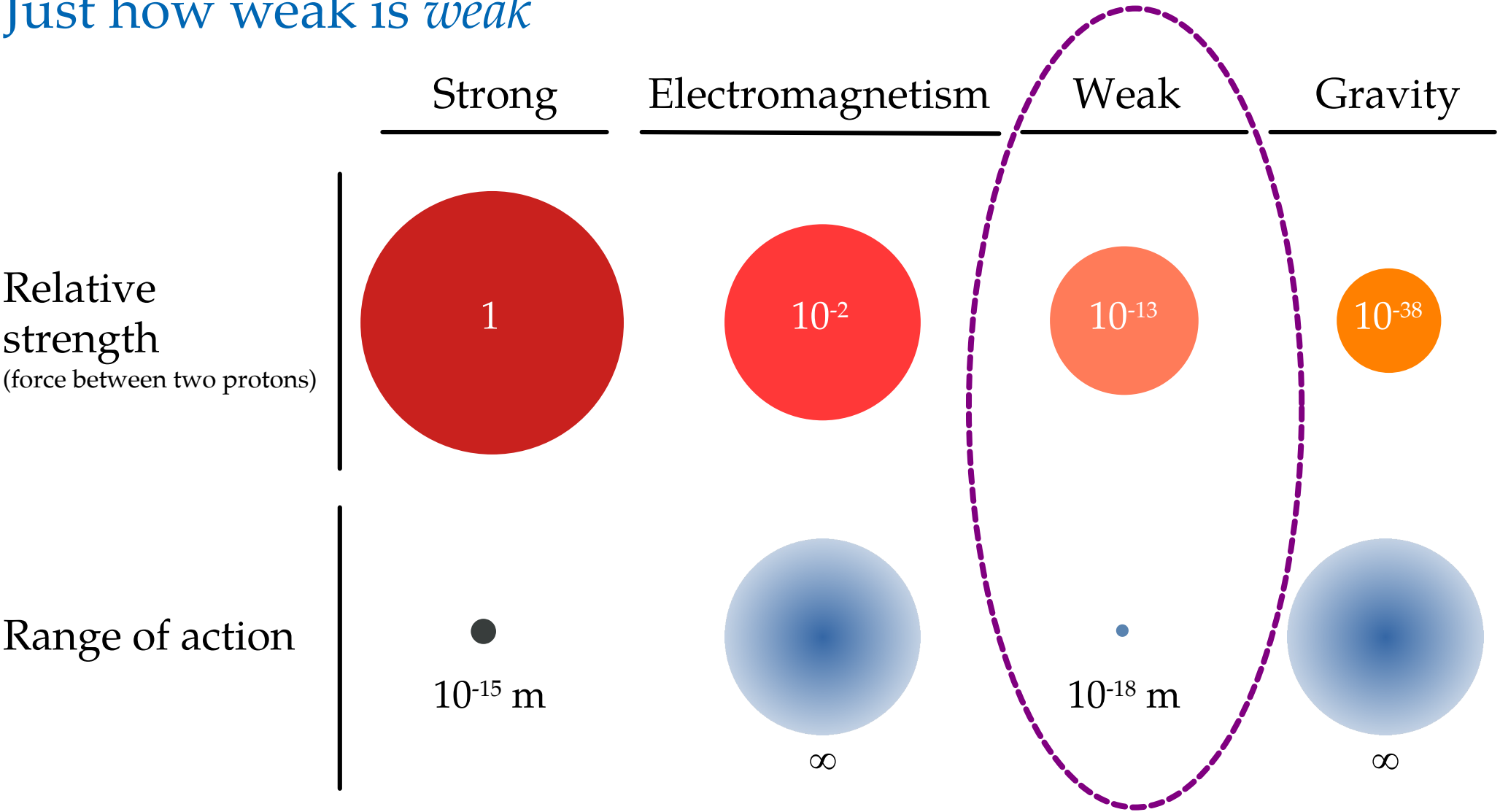
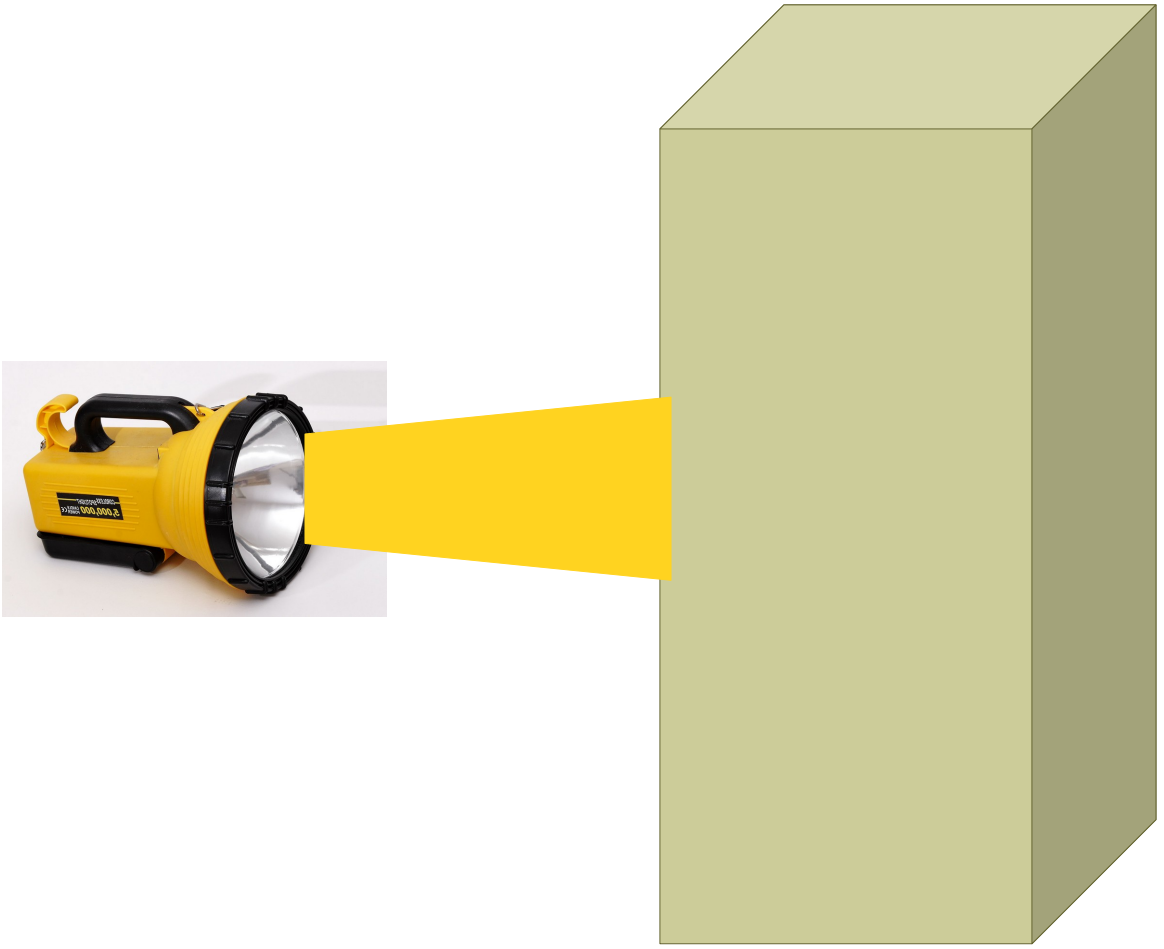


Stopping something that is *almost* not there



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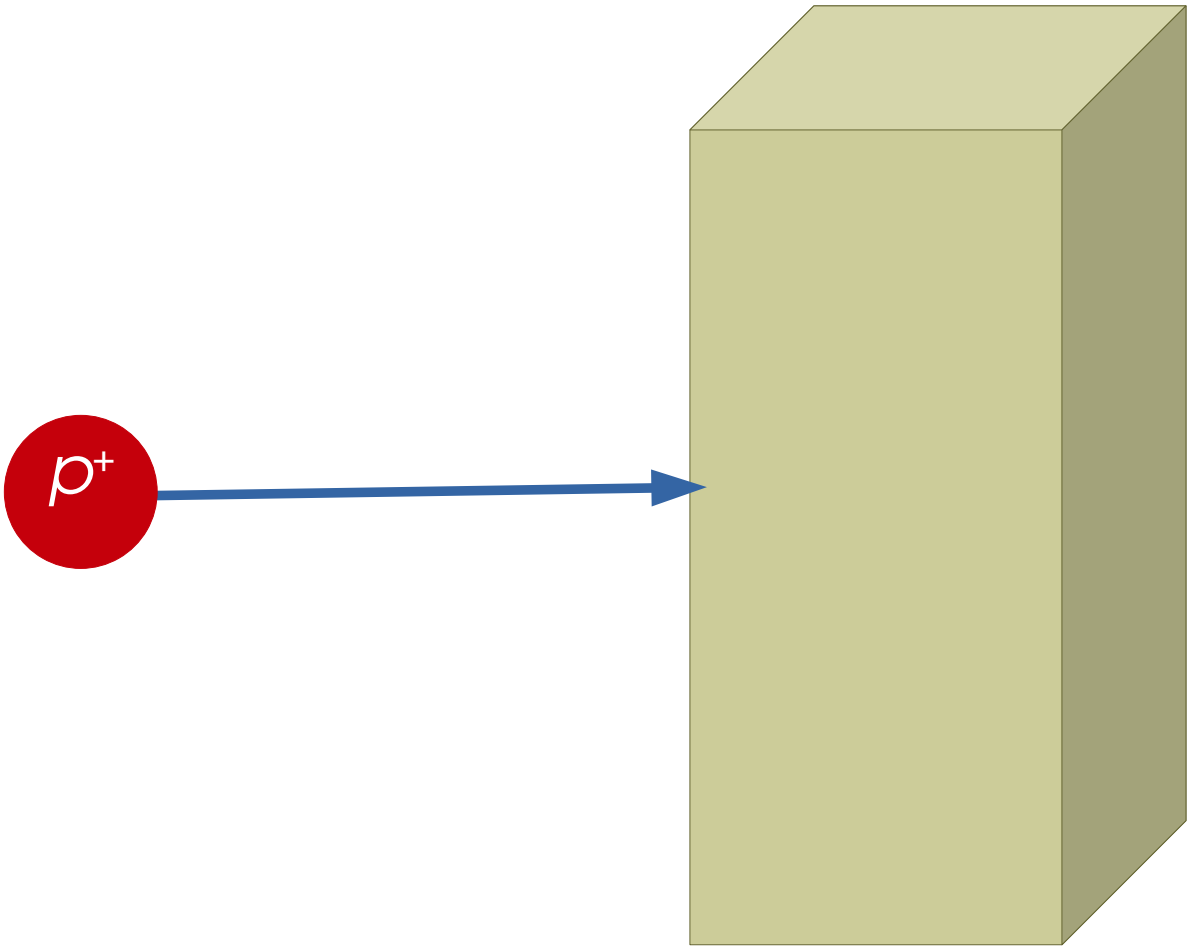

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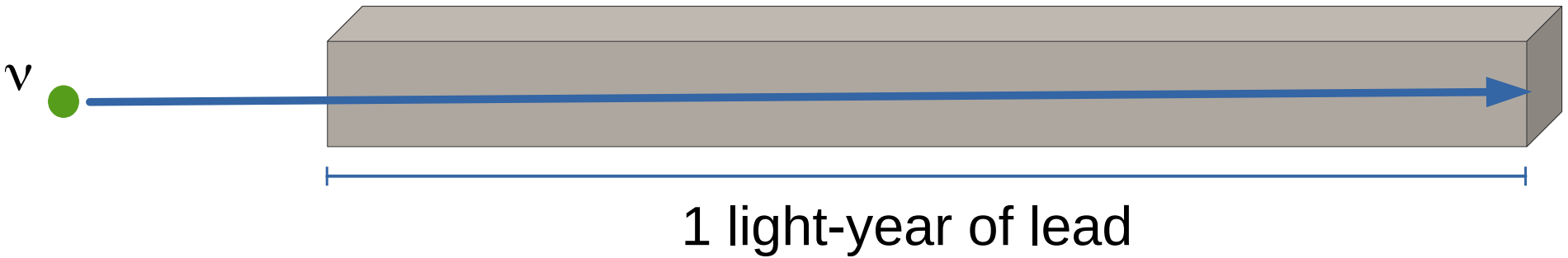
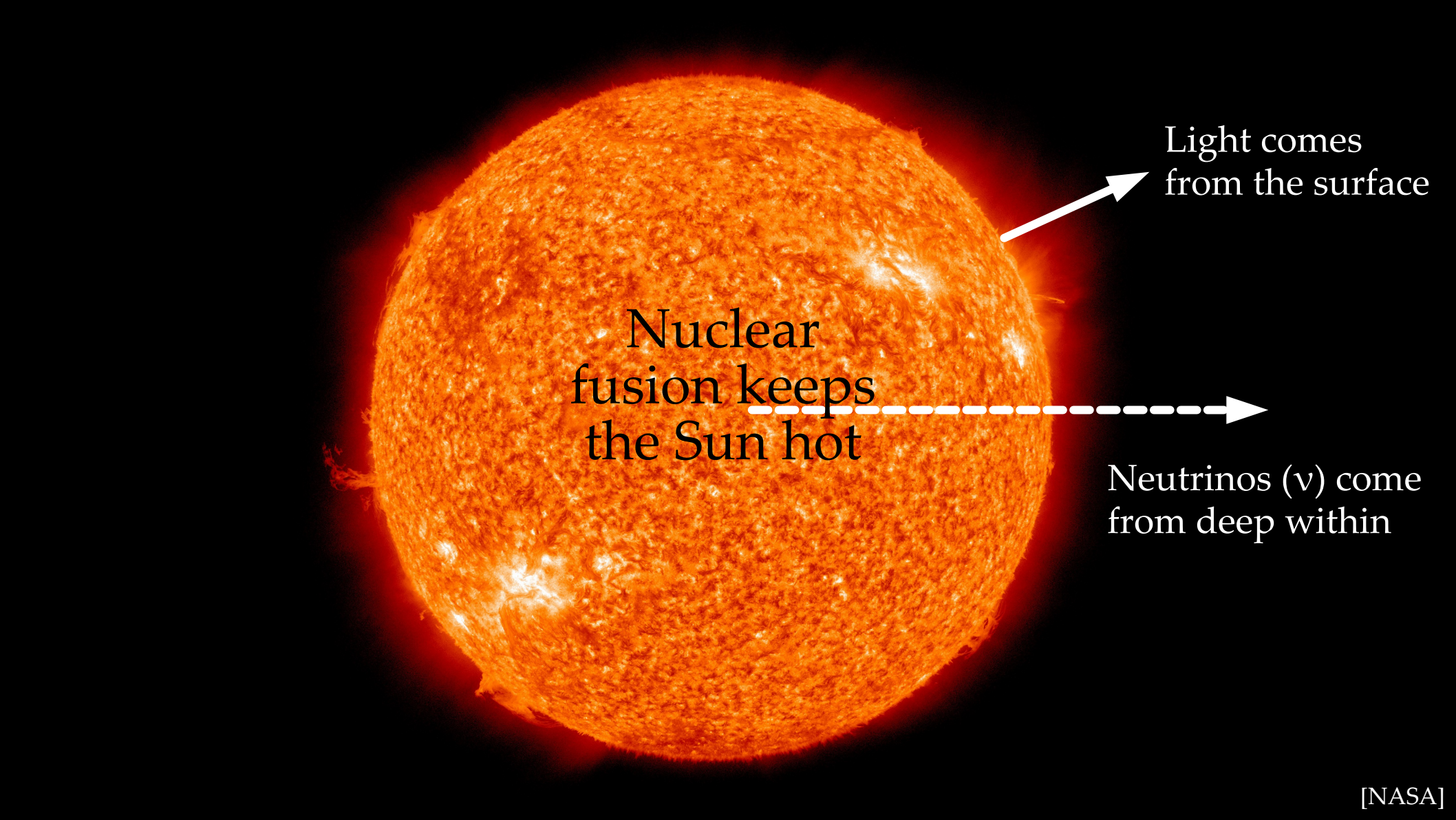


Stopping something that is *almost* not there

High-energy ν


Light comes
from the surface
Nuclear
fusion keeps
the Sun hot
Neutrinos (ν) come
from deep within
[NASA]

Neutrinos from the Sun

Nuclear fusion:

$$p + p + p + p \rightarrow \mathrm{He} + \mathrm{He} + \mathrm{energy}$$

Neutrinos from the Sun

Nuclear fusion:

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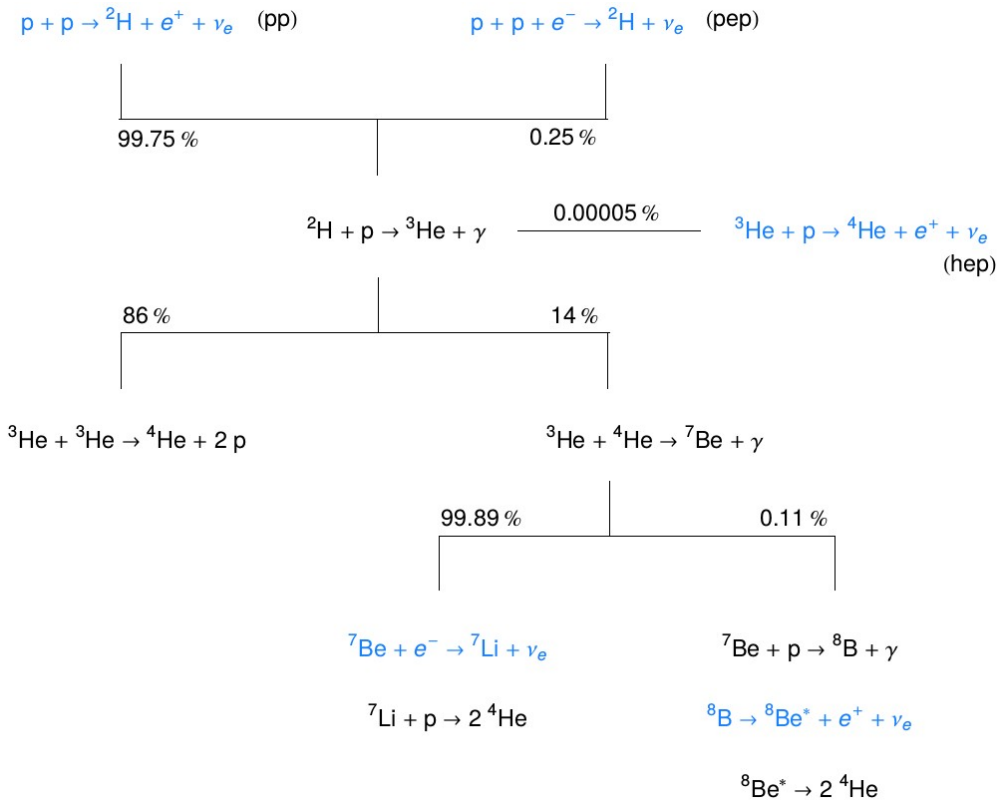

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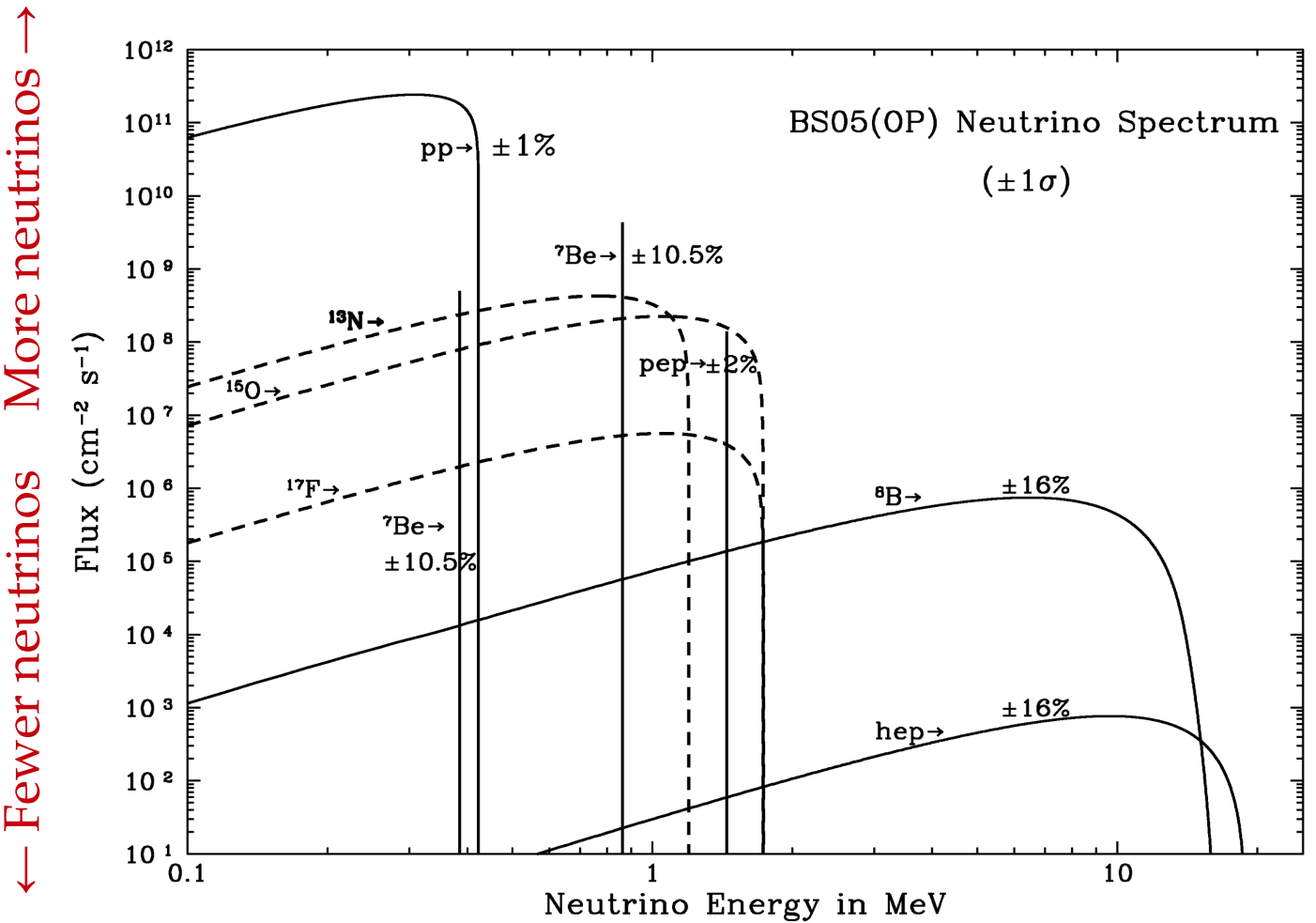
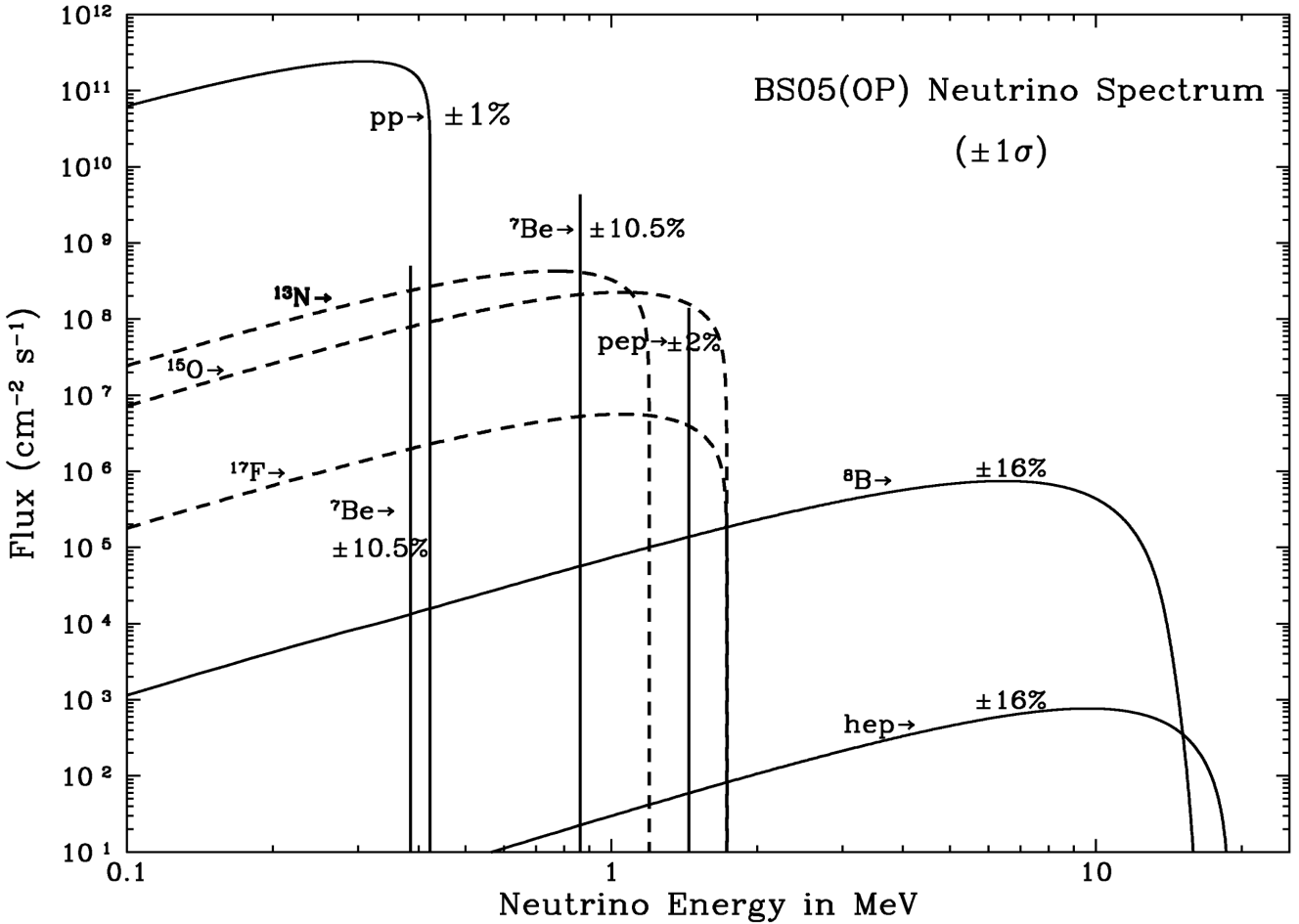
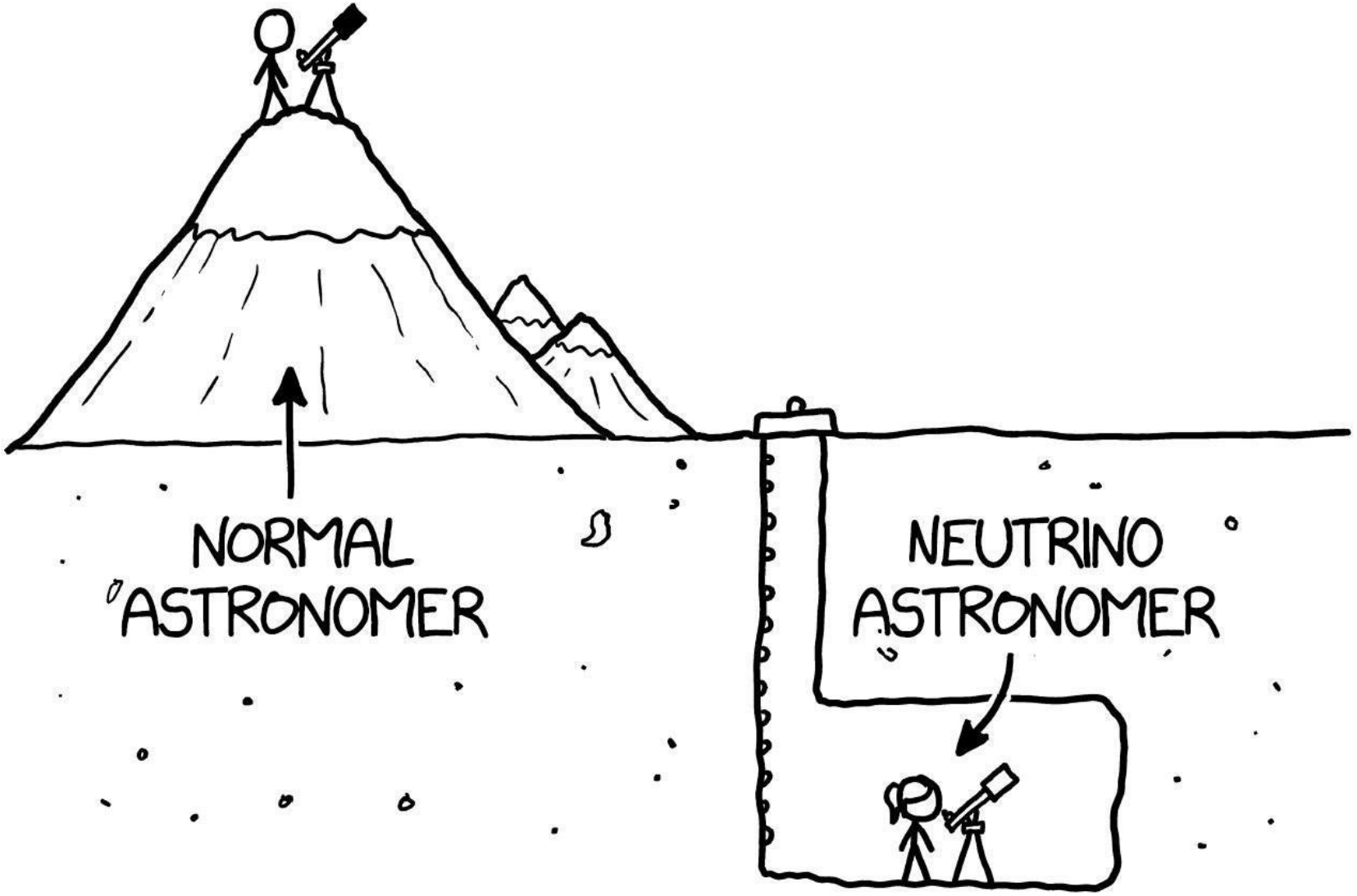


Neutrinos from the Sun

← Fewer neutrinos More neutrinos →



← Less energetic More energetic →

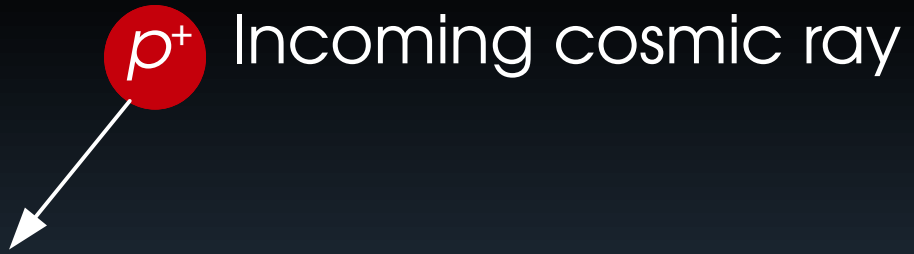


xkcd

Space

Atmosphere

Space



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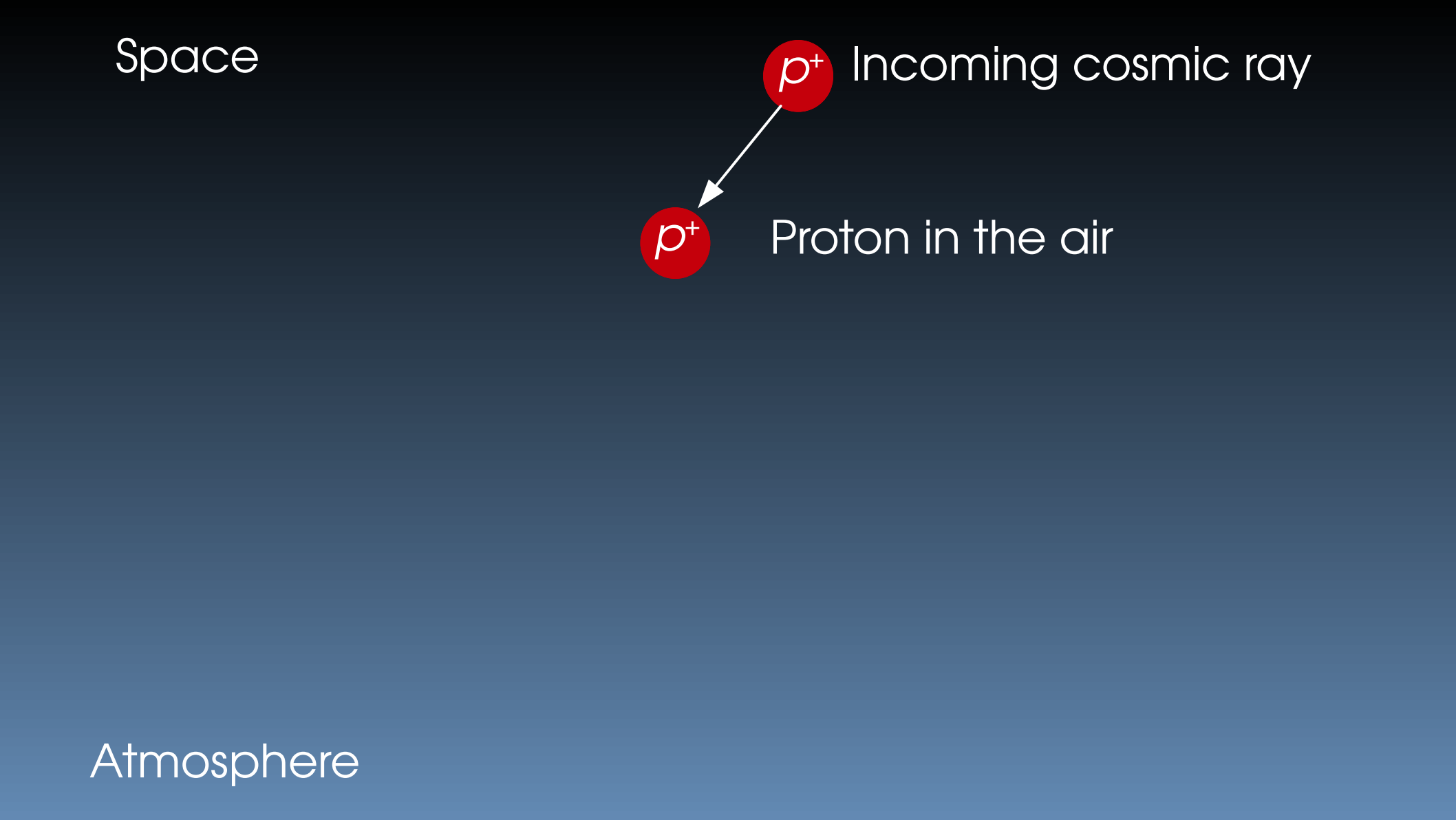
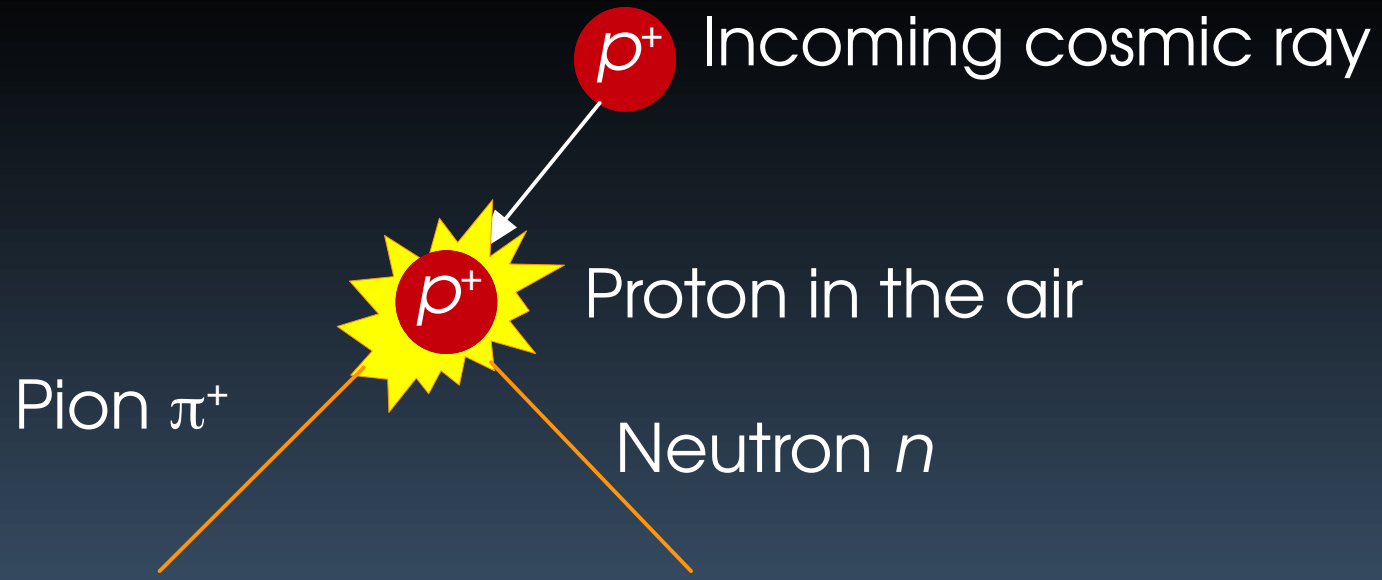

Space
p^+
Incoming cosmic ray
p^+
Proton in the air
Atmosphere

Space

Atmosphere

Space



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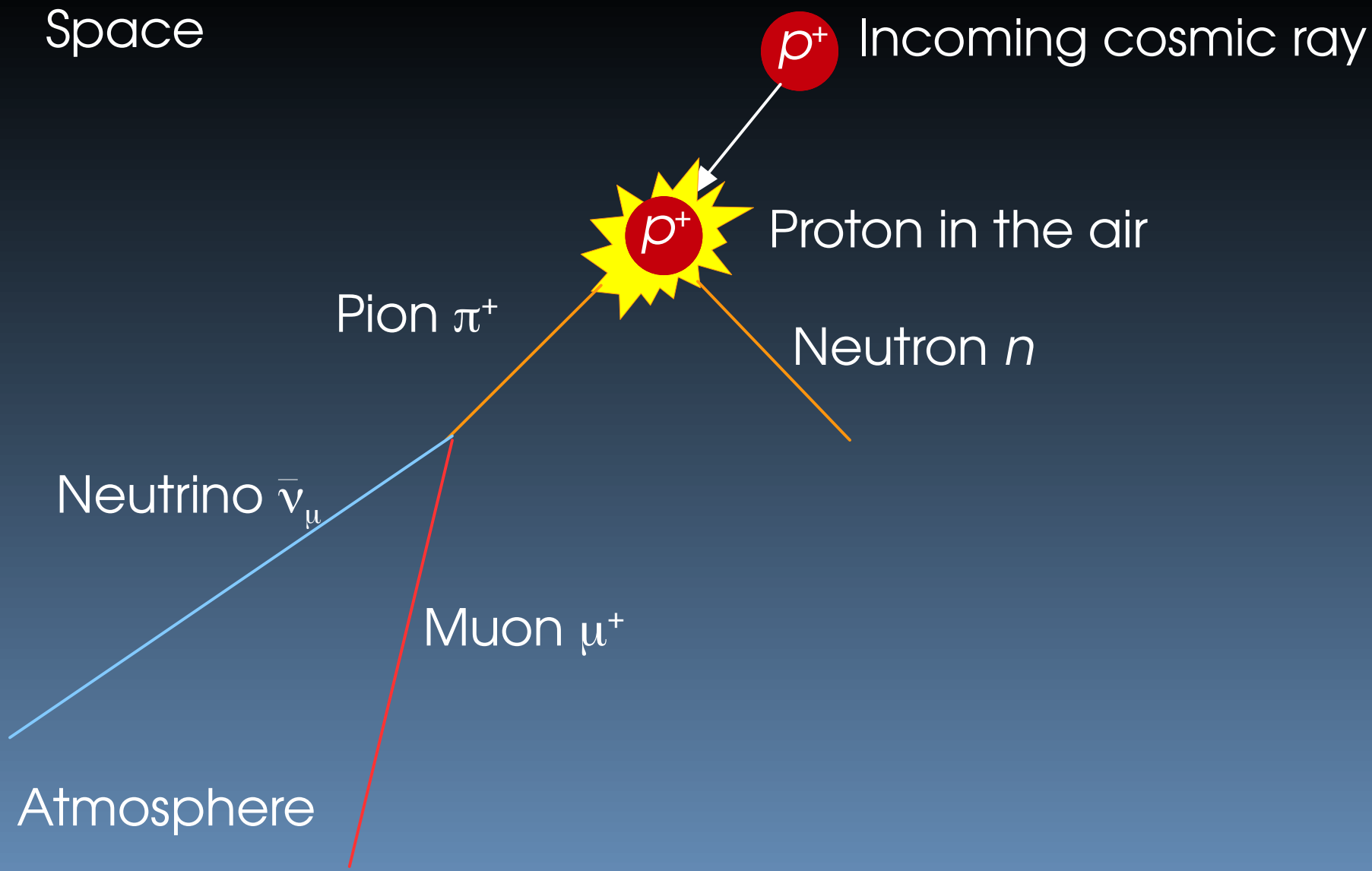
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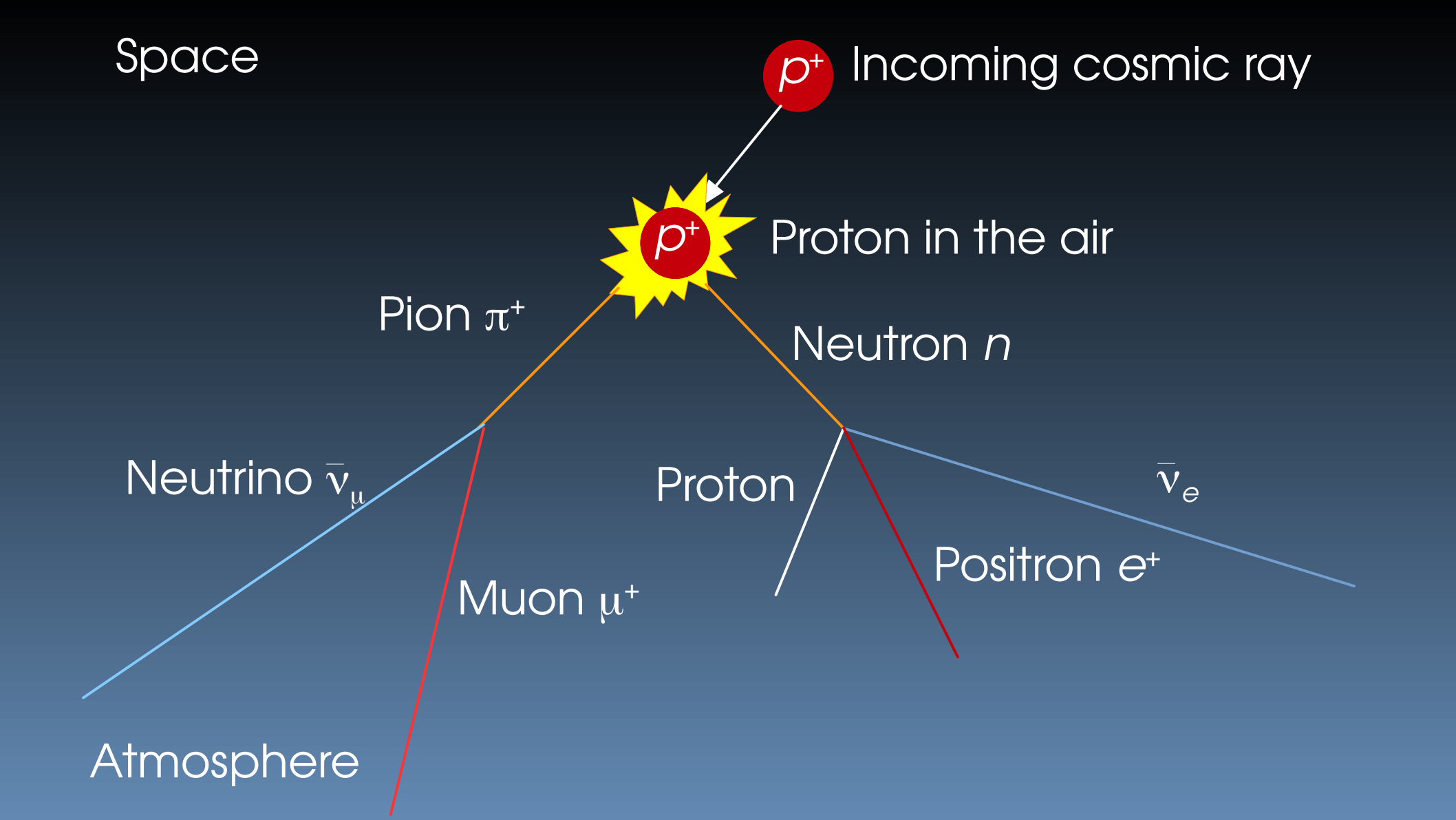
Pion π^+
Neutron n
Neutrino $\bar{\nu}_\mu$
Muon μ^+
Atmosphere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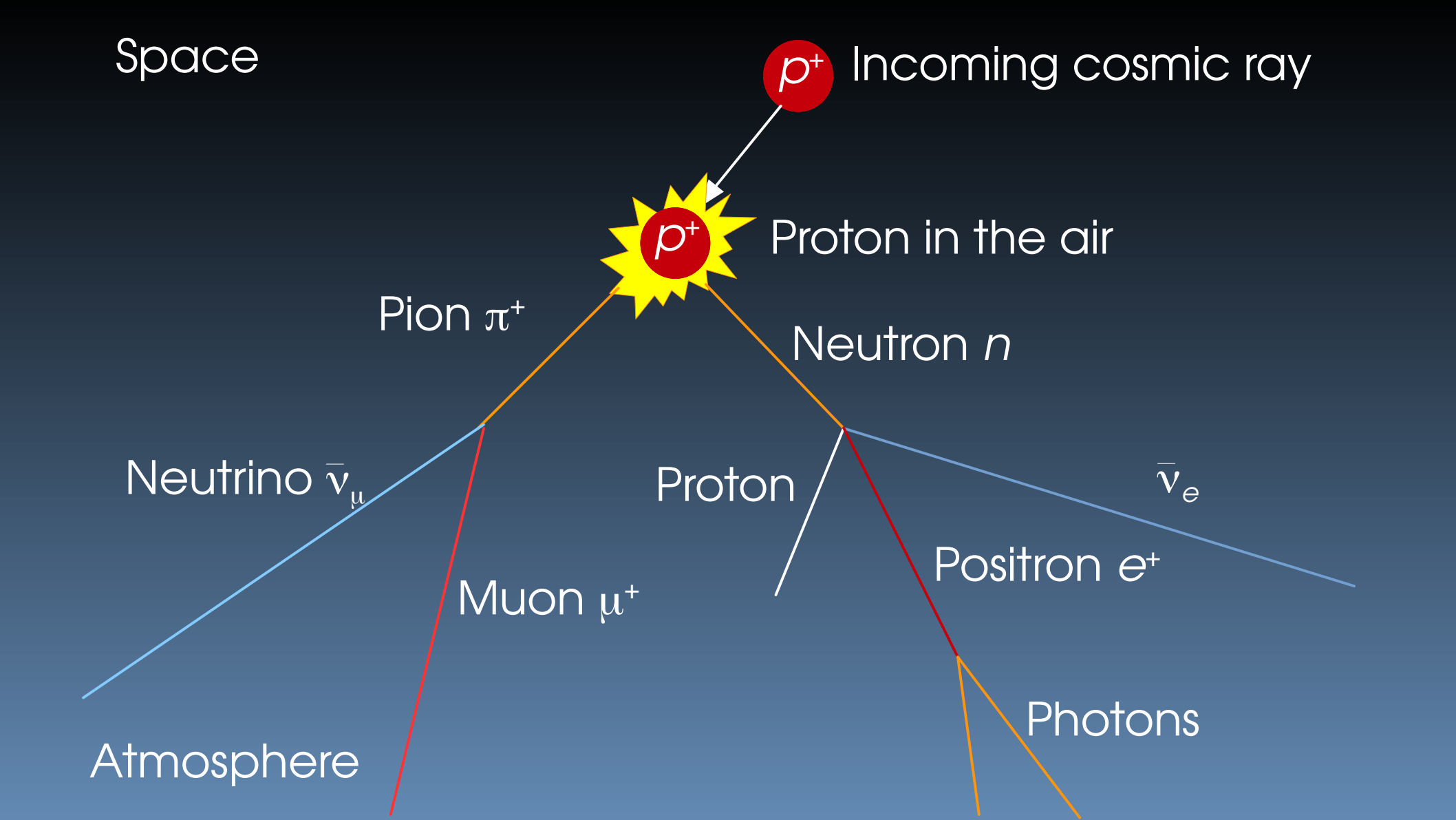
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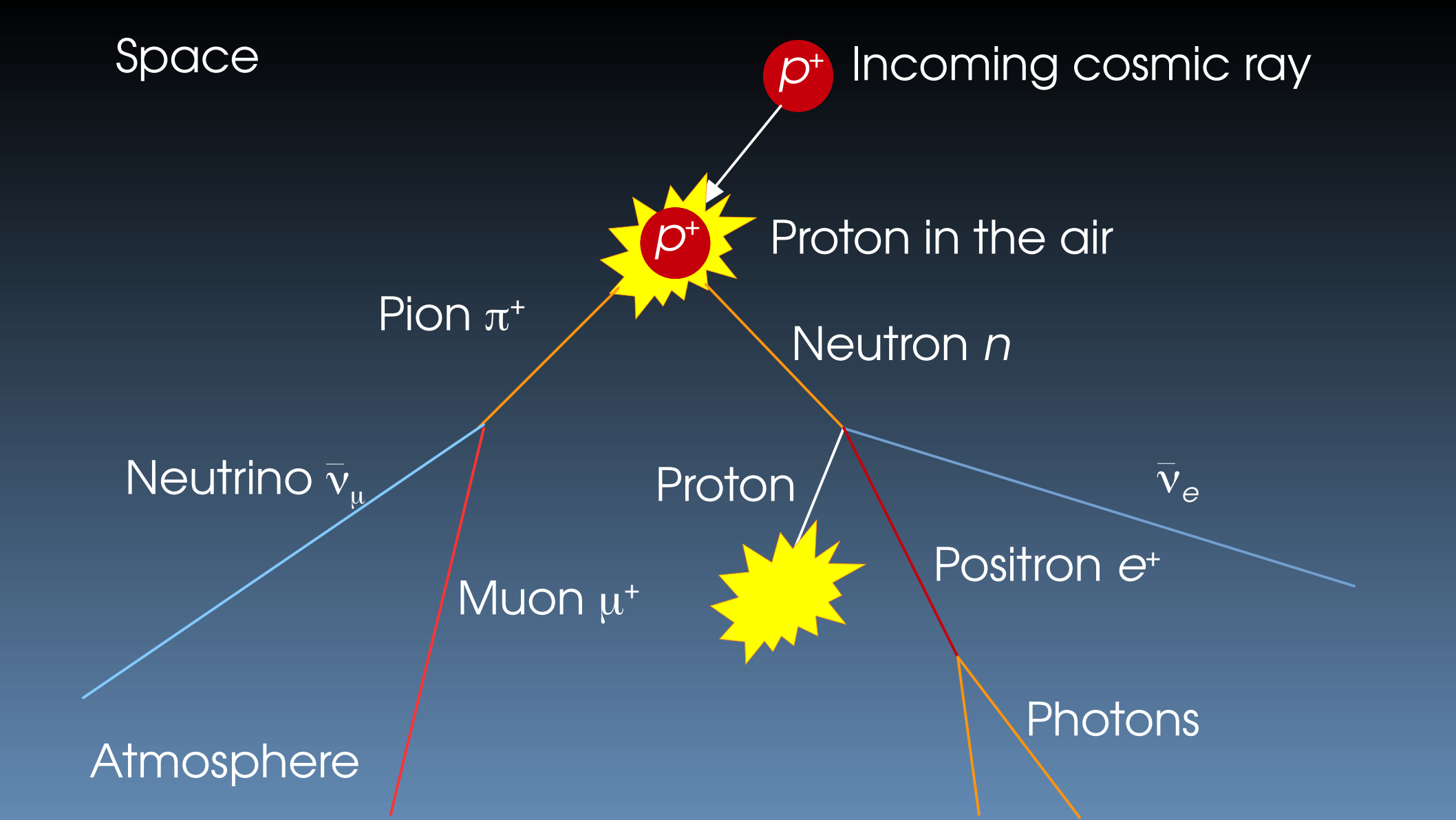
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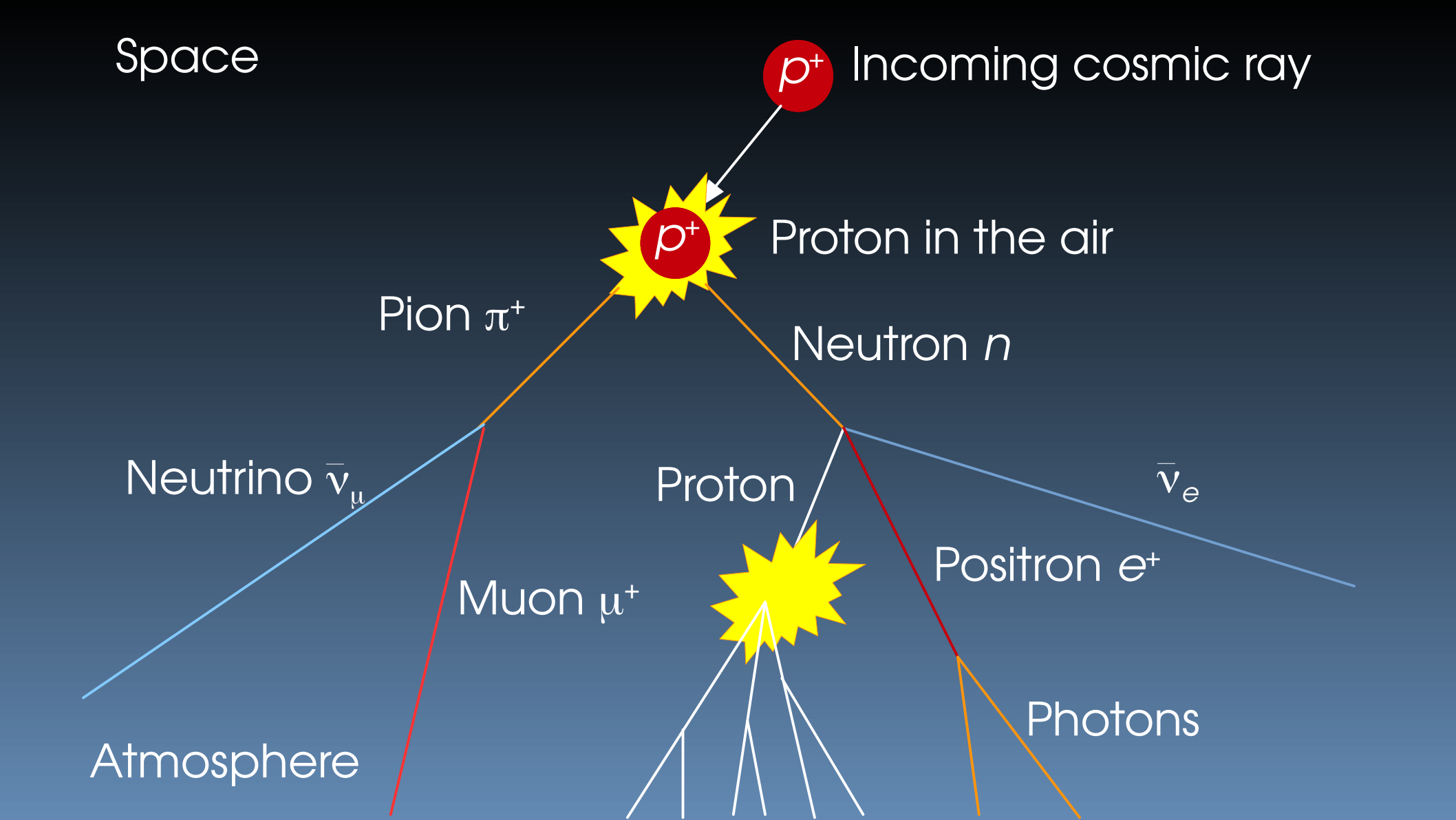
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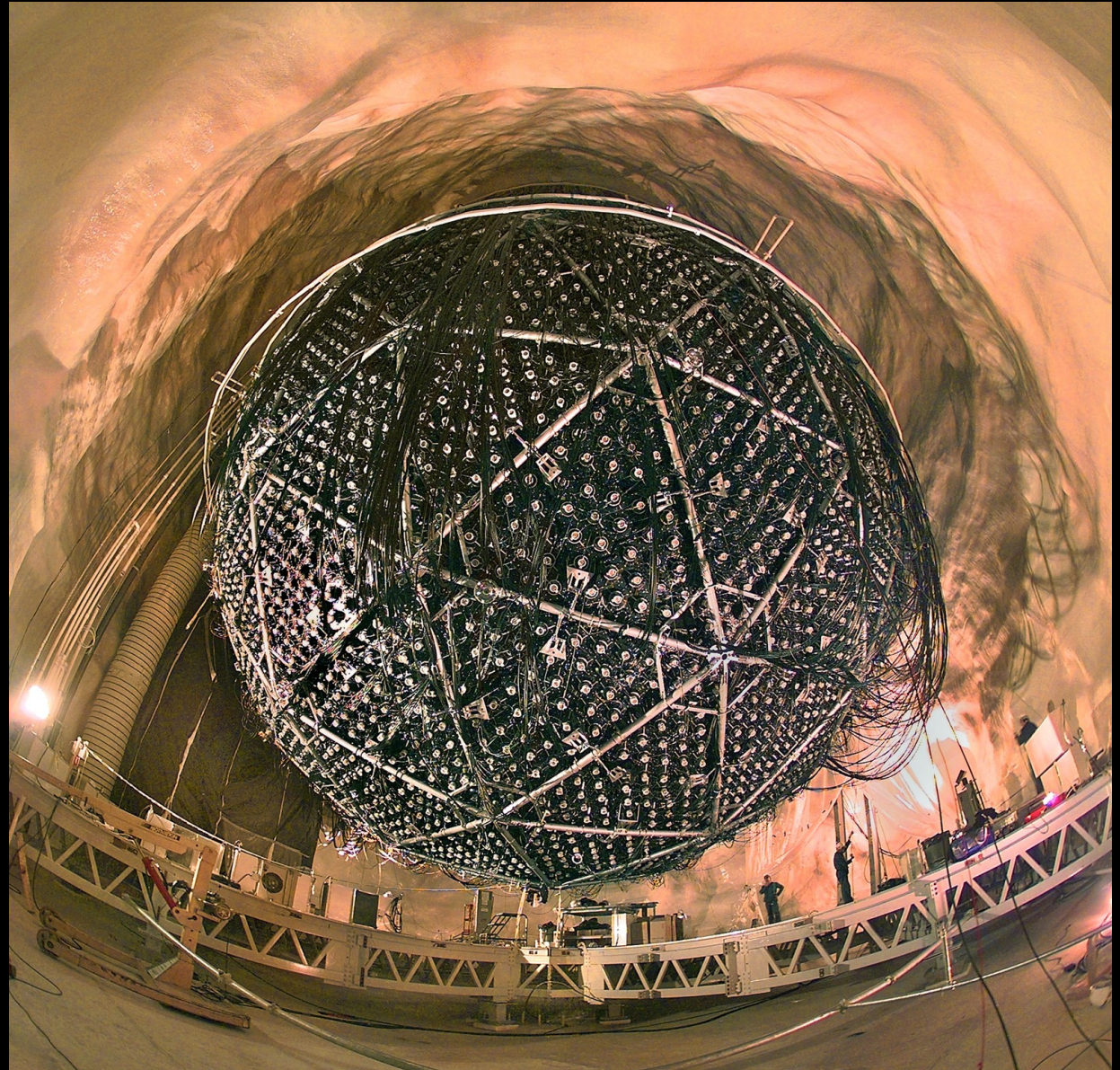
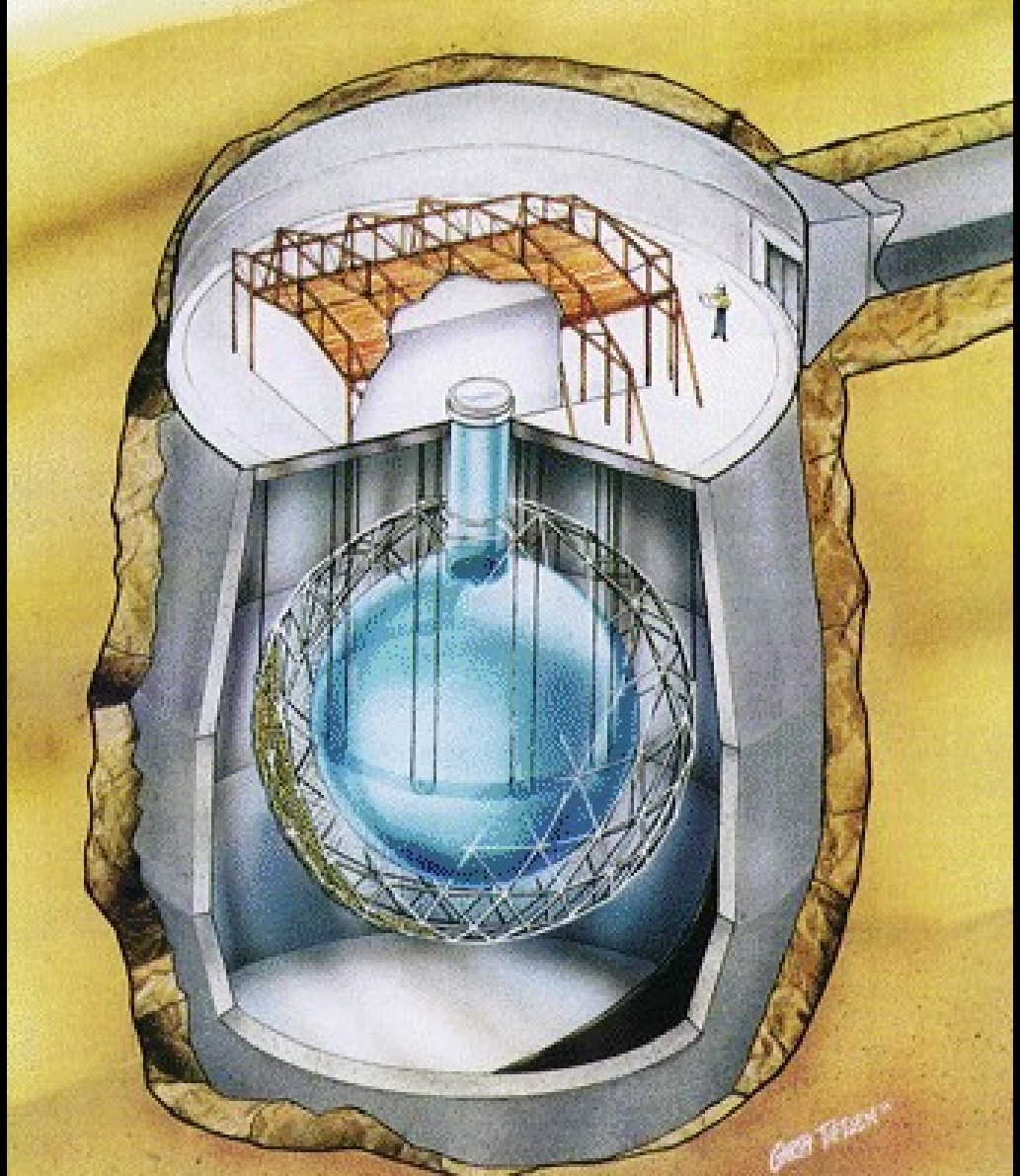
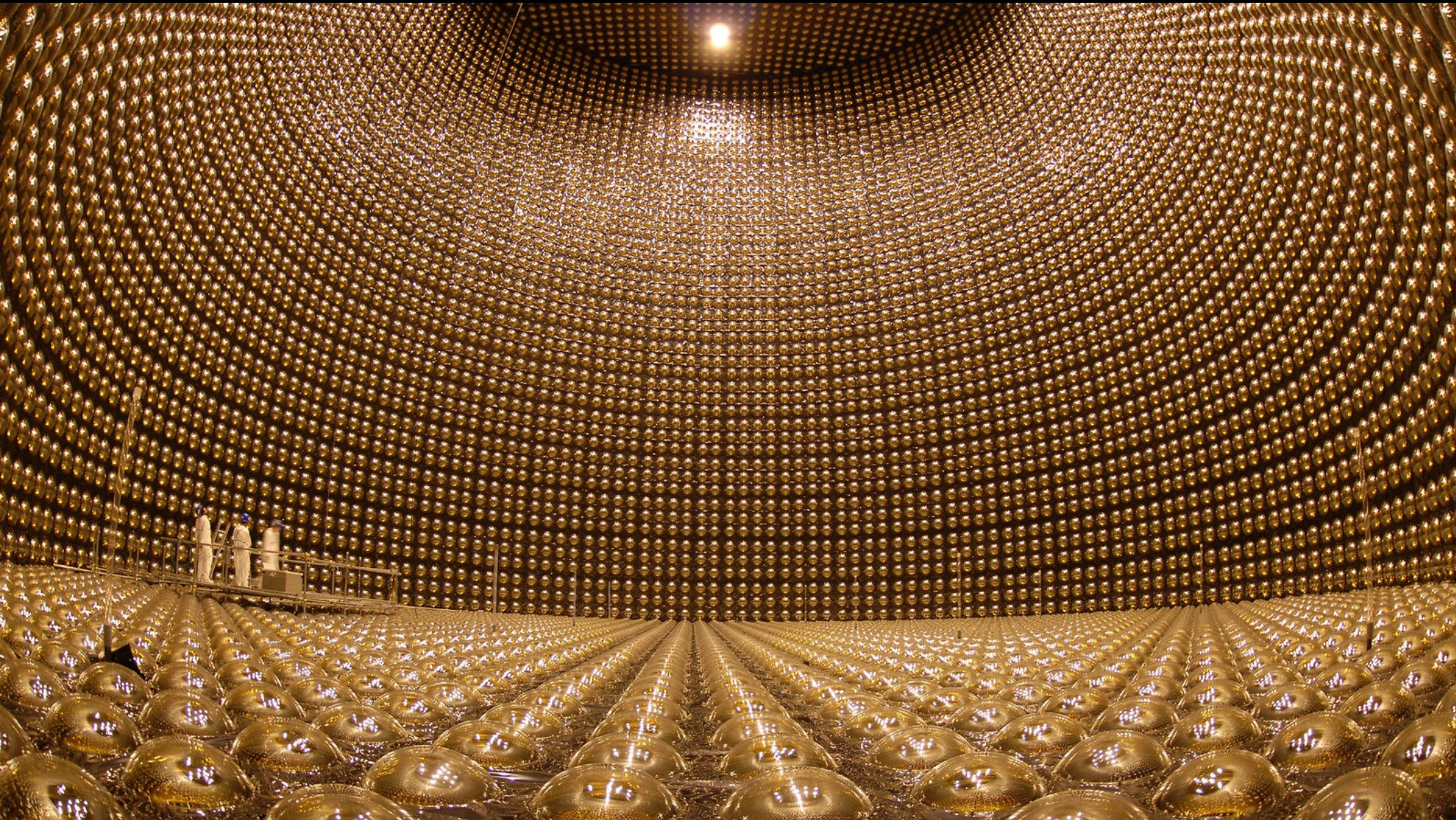
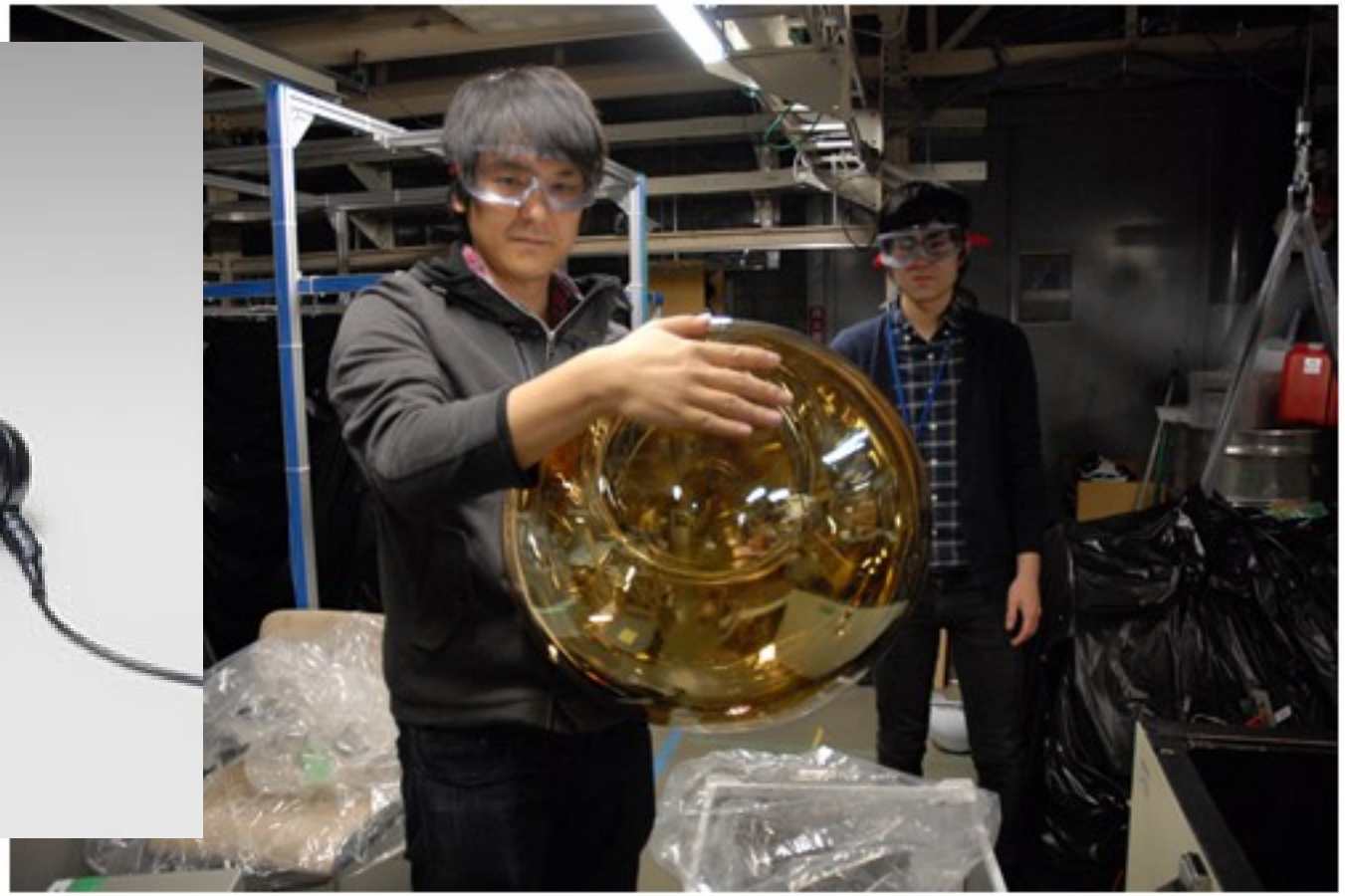
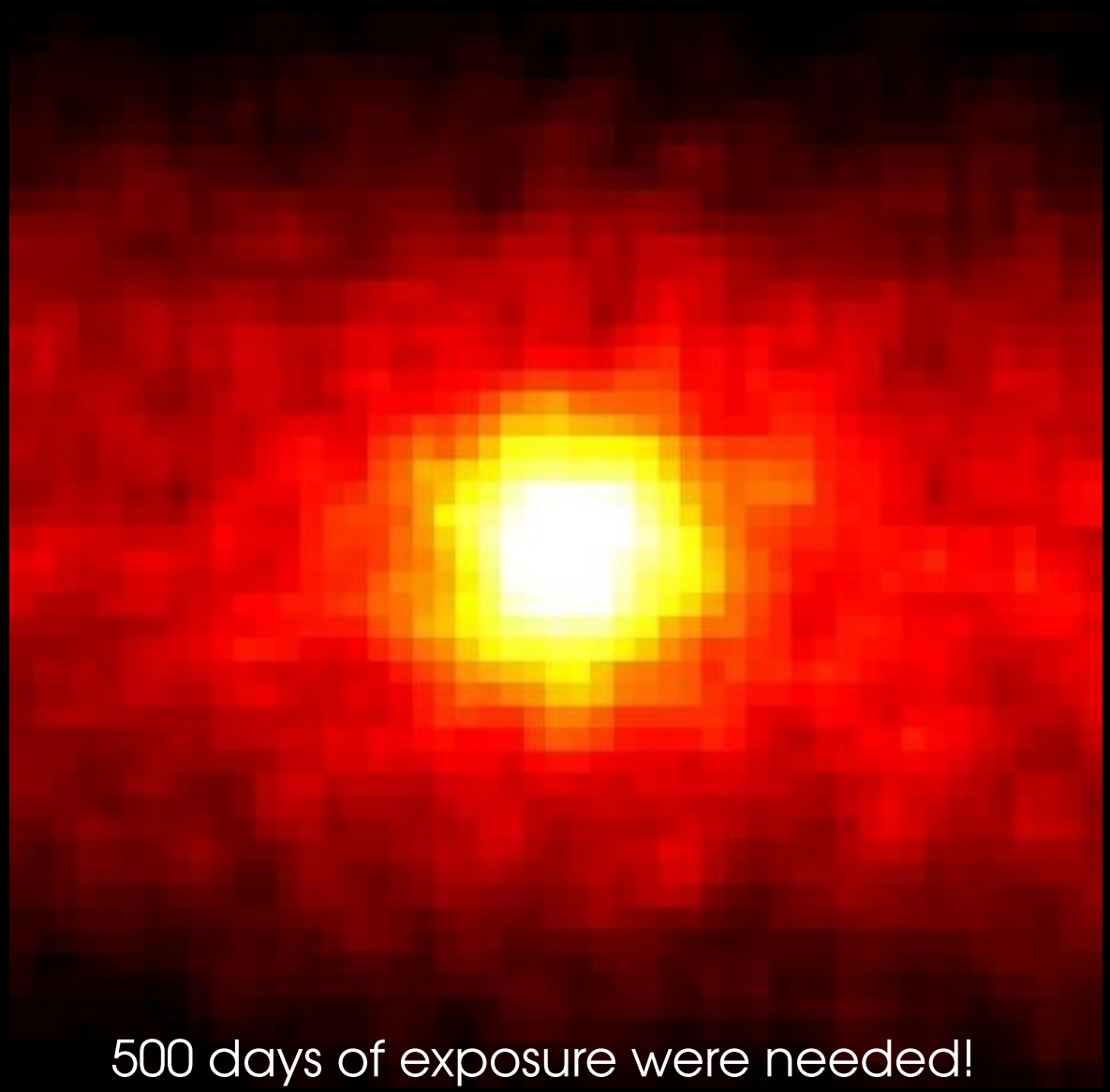






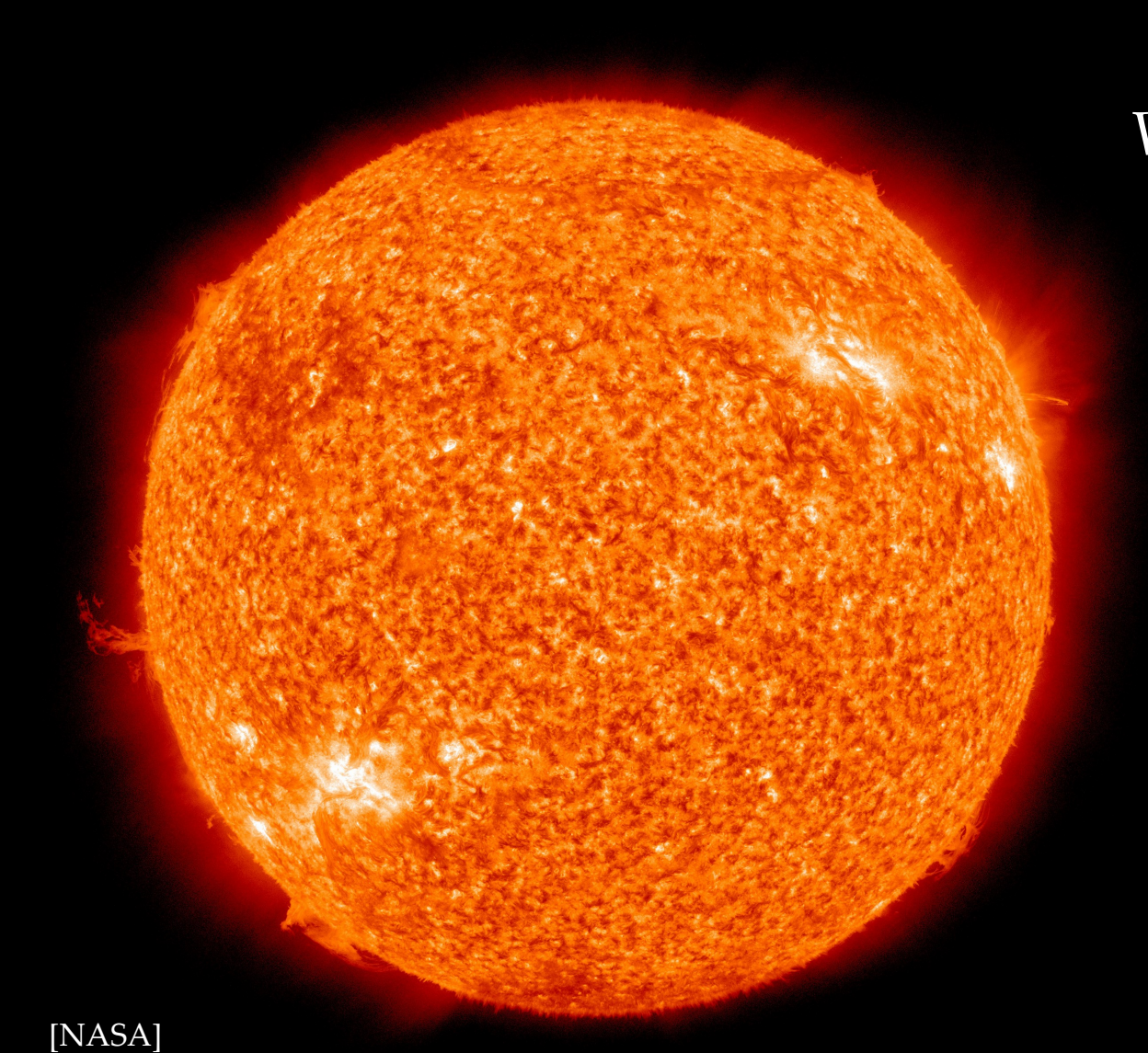




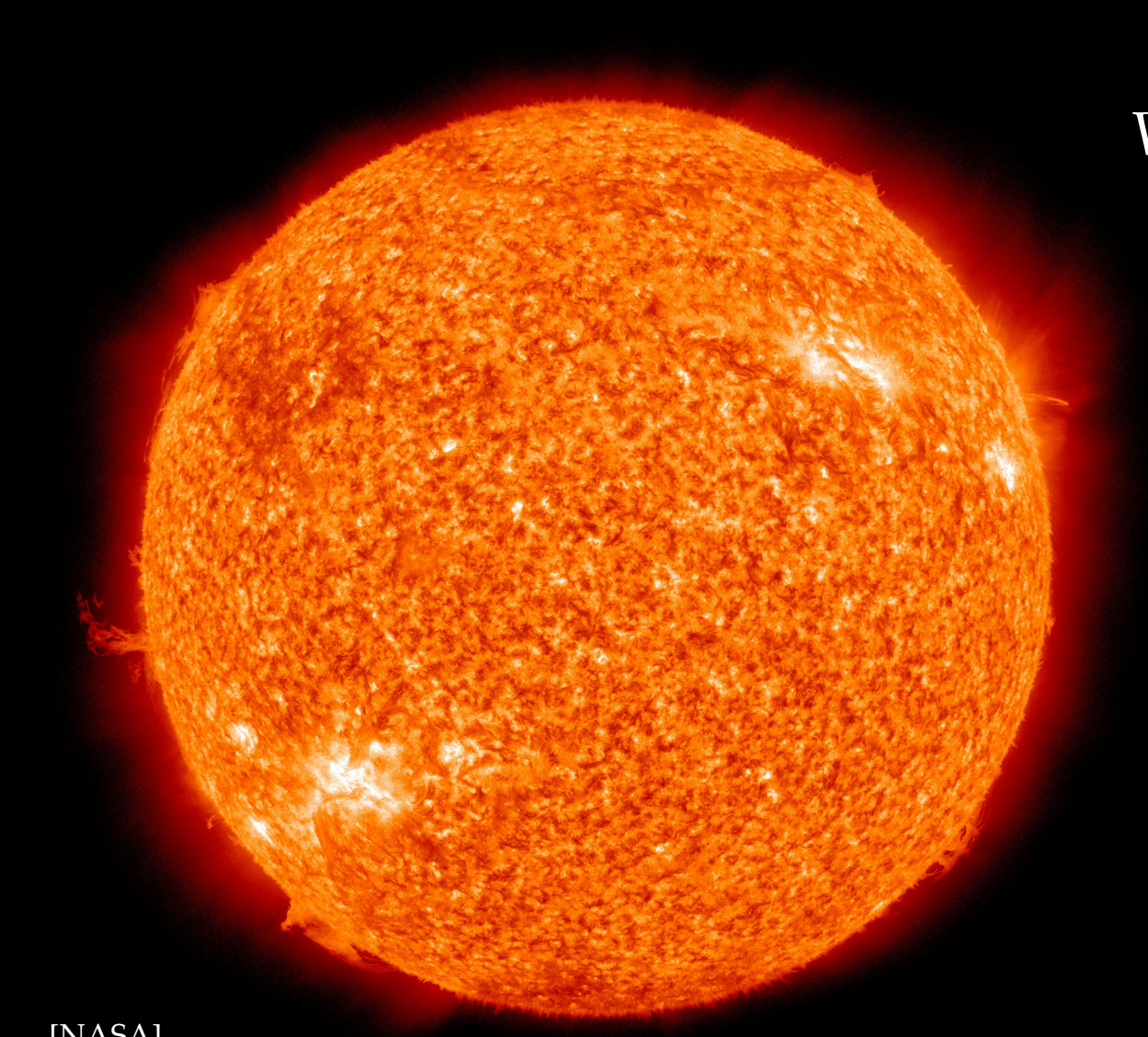
500 days of exposure were needed!

[Super-Kamiokande]

What did we learn?



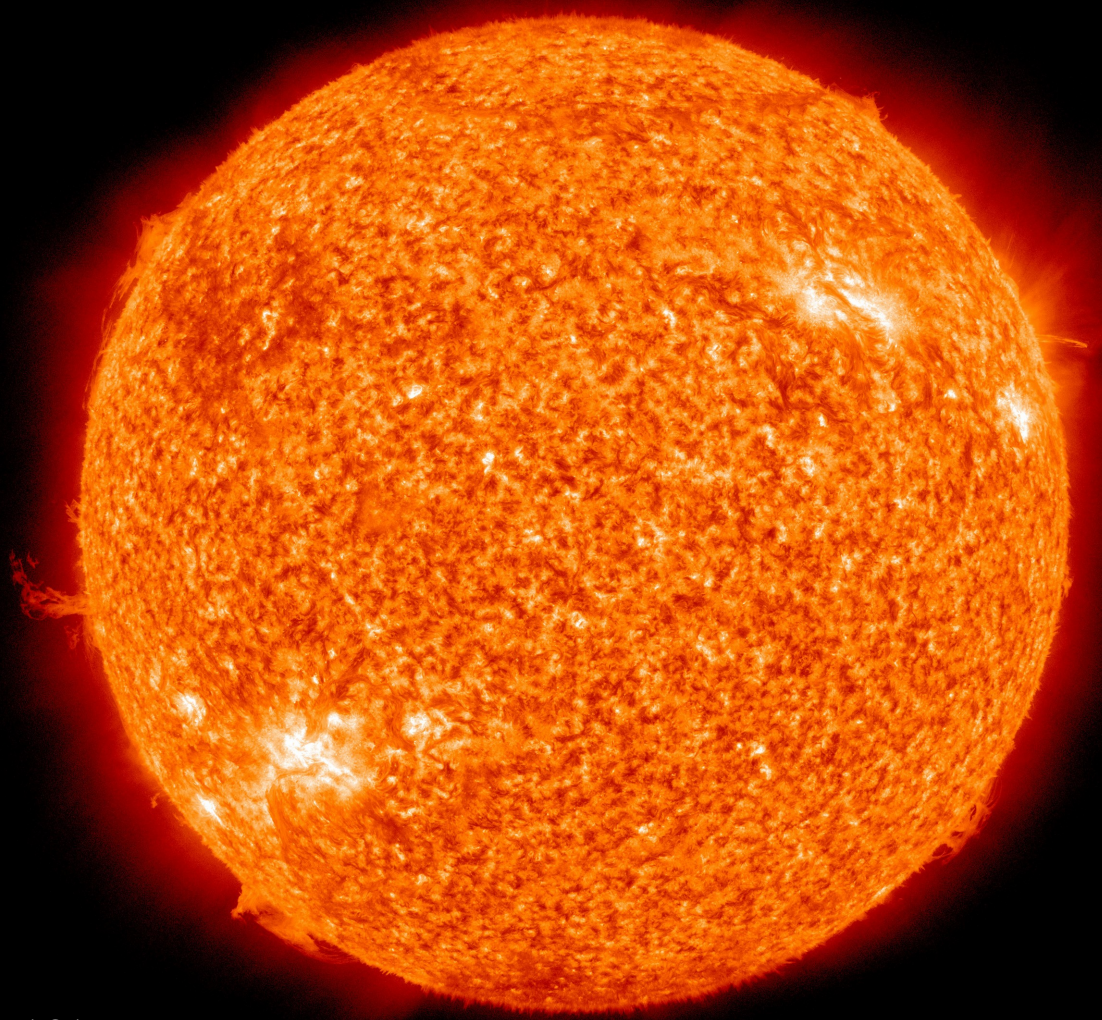
[NASA]



[NASA]

What did we learn?

- Nuclear fusion powers the Sun



[NASA]

What did we learn?

- Nuclear fusion powers the Sun
- The ν flux strongly depends on the core temperature T:

$$\nu \text{ flux} \propto T^{24}$$

By detecting ν, we found

$T \approx 15$ million K

2002 Nobel Prize in Physics

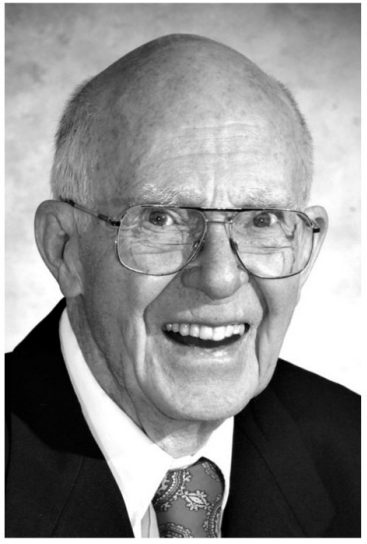


Photo from the Nobel Foundation archive.

Raymond Davis Jr.

Prize share: 1/4

Photo from the Nobel Foundation archive.

Masatoshi Koshiba

Prize share: 1/4

Photo from the Nobel Foundation archive.

Riccardo Giacconi

Prize share: 1/2

"… one half jointly to Raymond Davis Jr. and Masatoshi Koshiba ***'for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos'***"

2015 Nobel Prize in Physics

© Nobel Media AB. Photo: A. Mahmoud

Takaaki Kajita

Prize share: 1/2

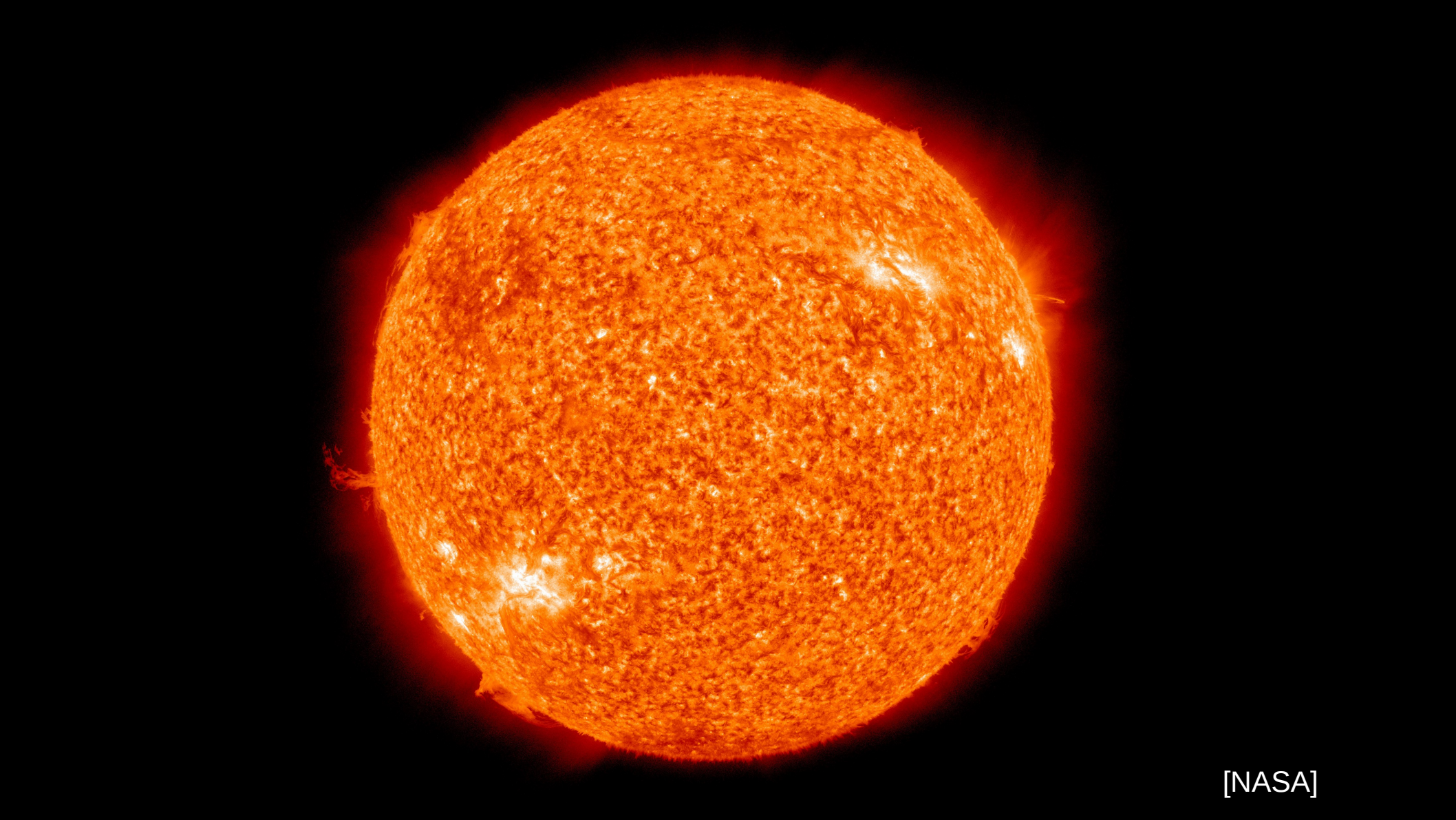
© Nobel Media AB. Photo: A. Mahmoud

Arthur B. McDonald

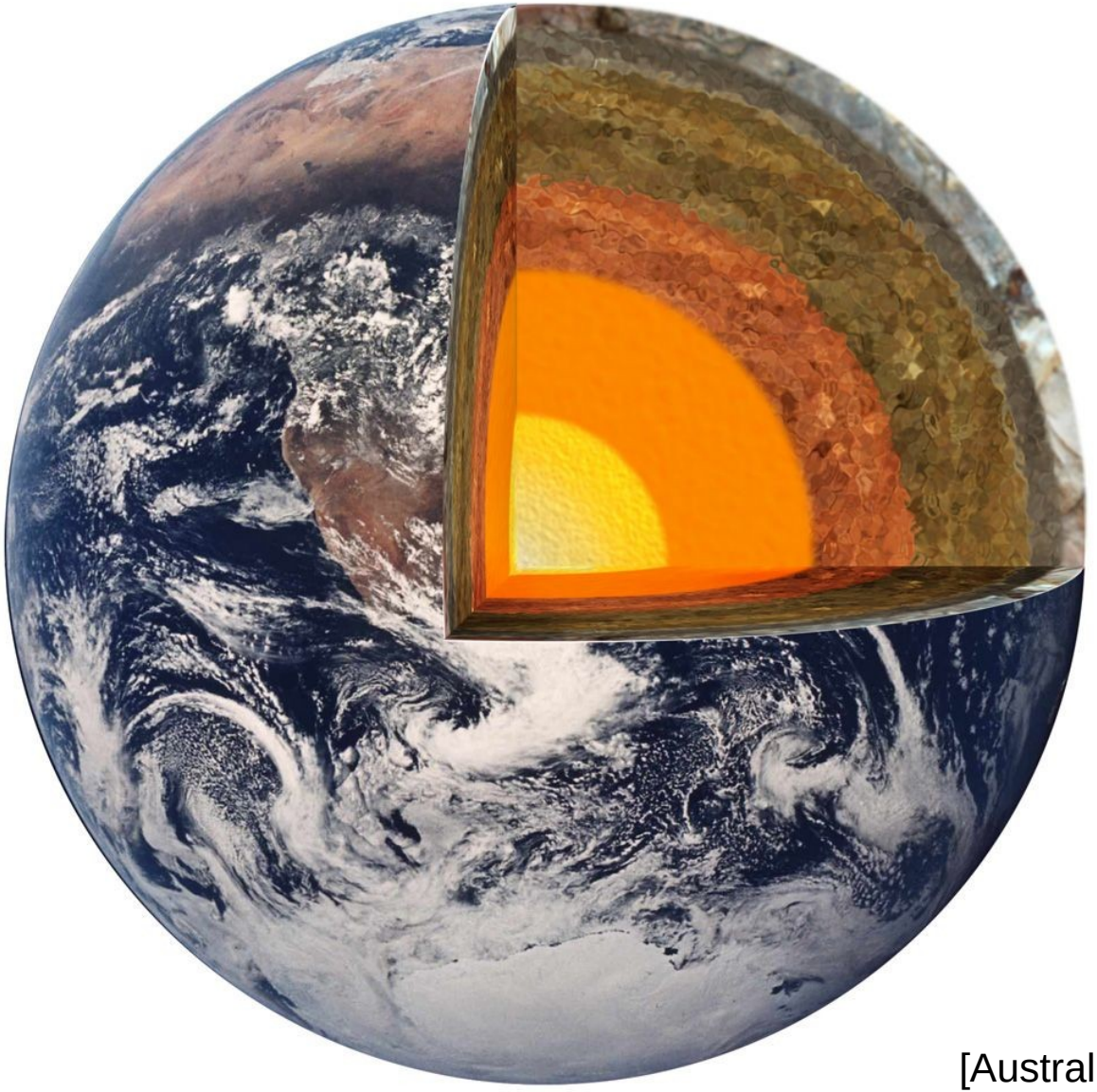
Prize share: 1/2

"… ***'for the discovery of neutrino oscillations, which shows that neutrinos have mass.'***"

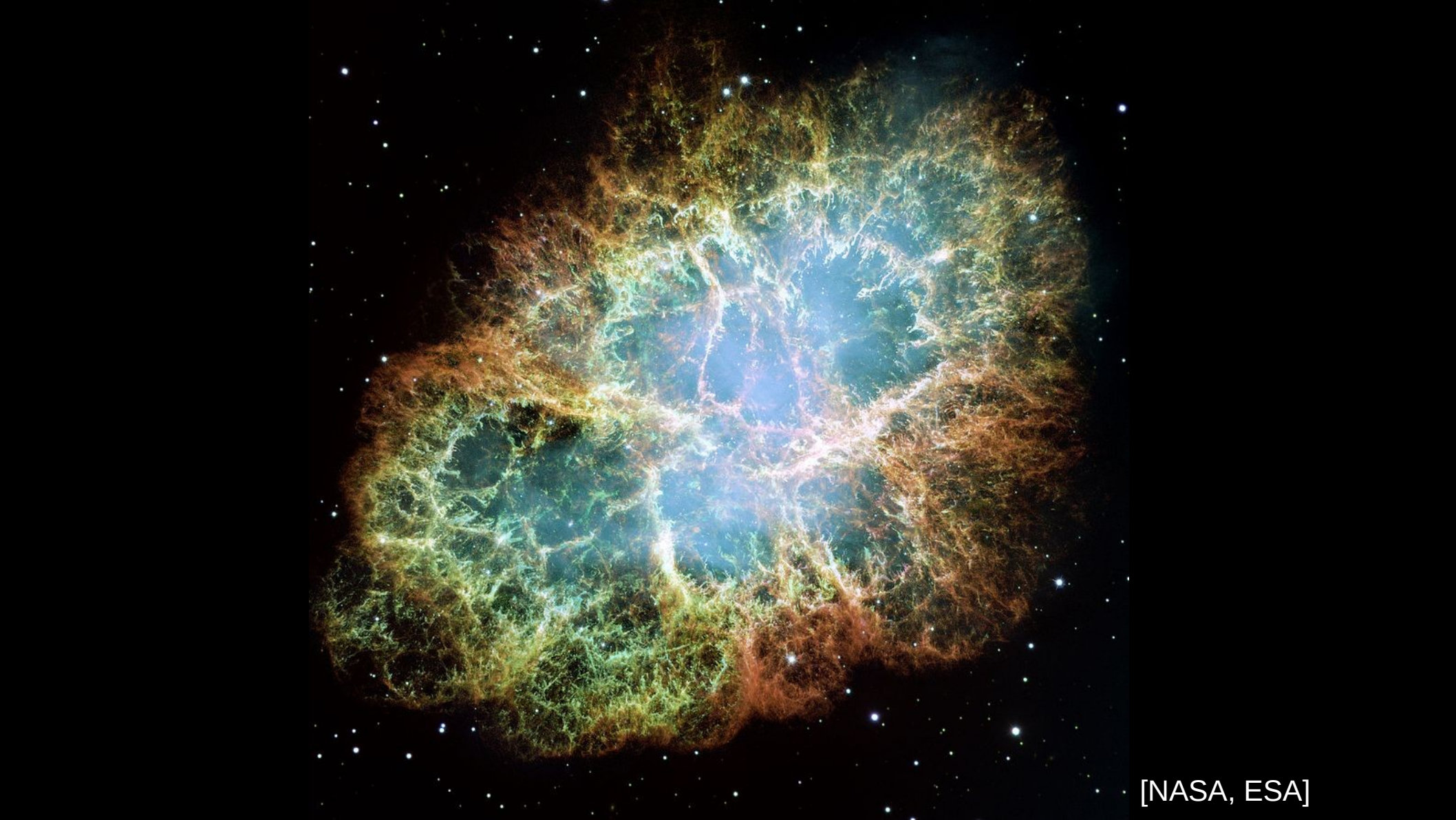

Congratulations to Dr. Takaaki Kajita
Director of the Institute for Cosmic Ray Research Kashiwa Campus at The University of Tokyo for being awarded The Nobel Prize


[NASA]

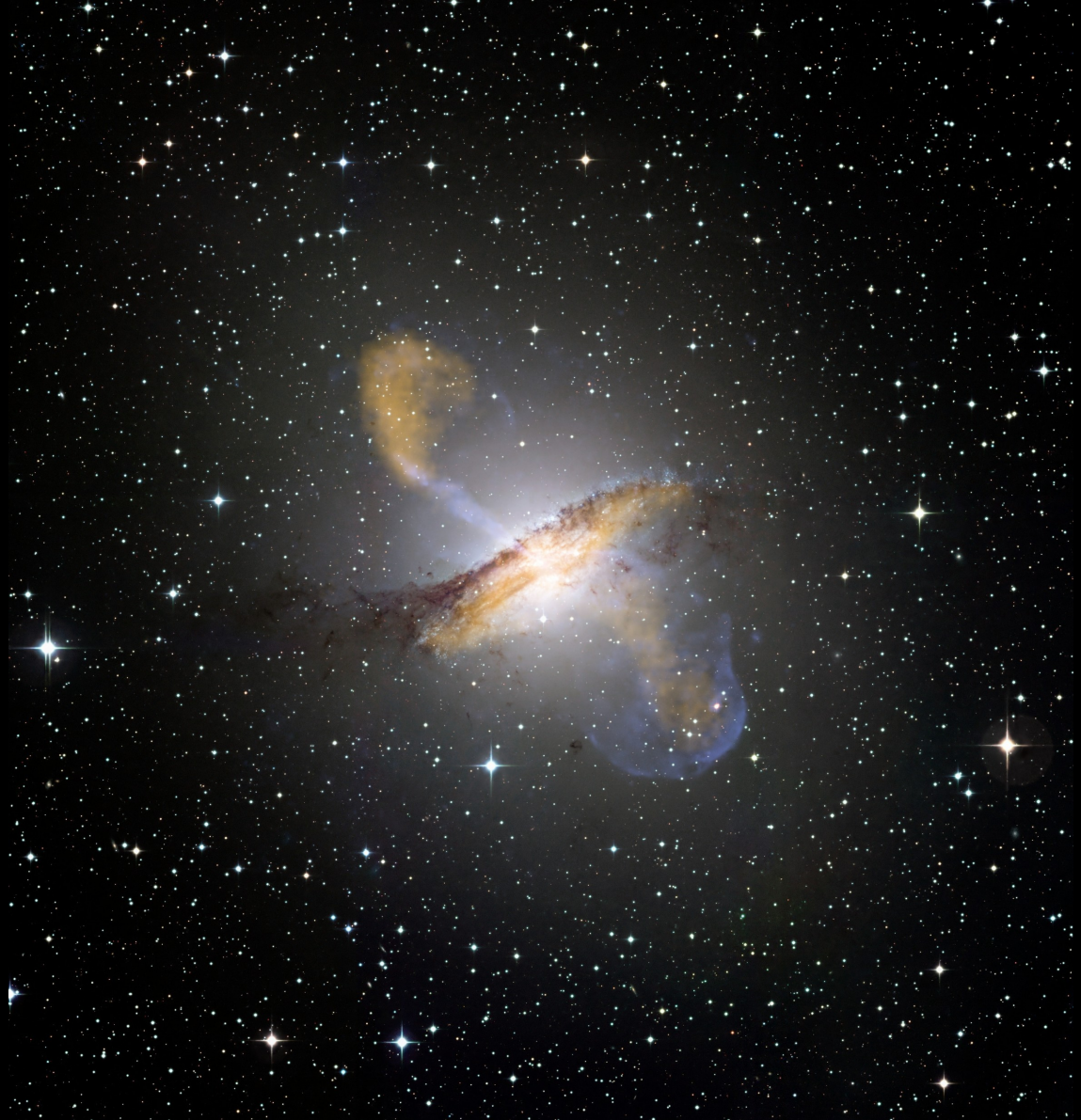

[Avda]



[Australian National University]



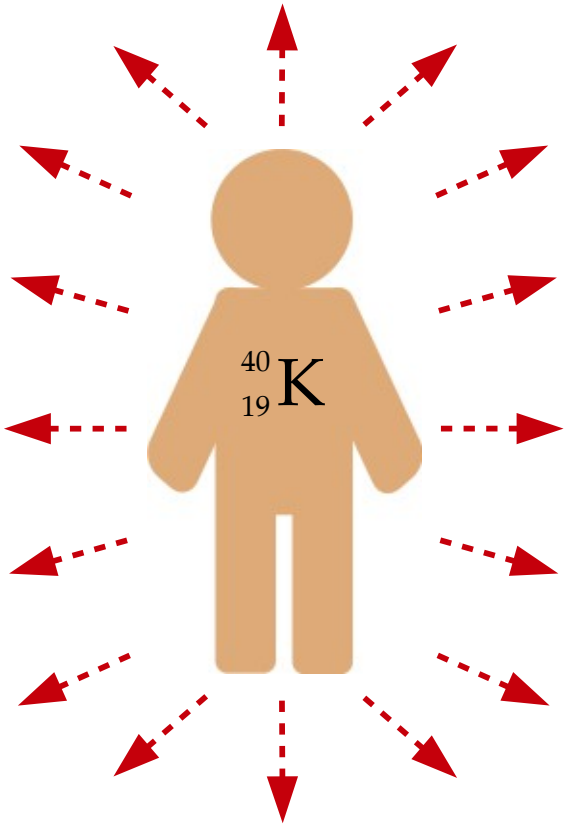
[NASA, ESA]



[NASA, ESO]

Neutrinos are everywhere: even *you* make them!

Some of the potassium in bananas is radioactive



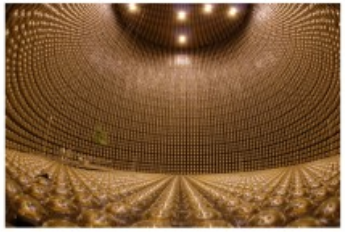
Potassium-40 has a half-life of ~ 1 billion years:

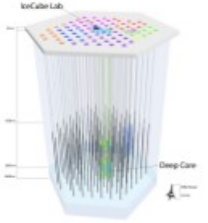
$$e^- + {}^{40}_{19}\mathrm{K} \rightarrow {}^{40}_{18}\mathrm{Ar} + \nu_e$$

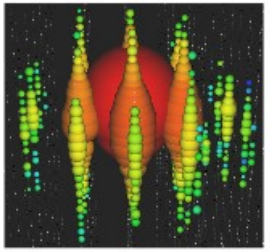
$${}^{40}_{19}\mathrm{K} \rightarrow {}^{40}_{18}\mathrm{Ar} + e^+ + \nu_e + \gamma$$

$${}^{40}_{19}\mathrm{K} \rightarrow {}^{40}_{20}\mathrm{Ca} + e^- + \bar{\nu}_e$$

4000+ neutrinos emitted each second by a 70-kg person







2013+

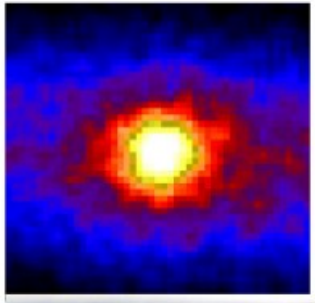
atmospheric

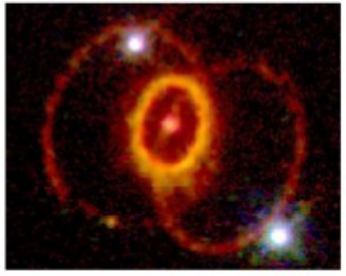
extragalactic

10^6 10^9 10^{12} 10^{15} 10^{18} 10^{21} E [eV]

solar reactor

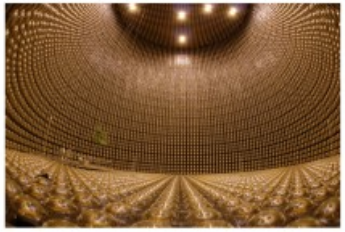
supernova accelerator

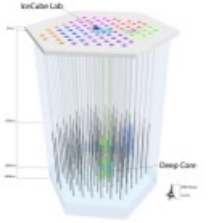


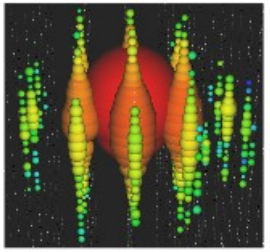


10^{12} eV →

6×10^{20} eV →







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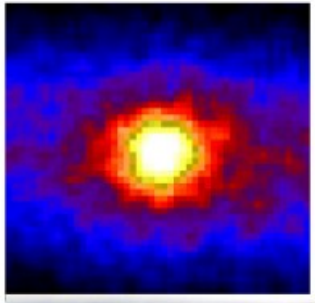

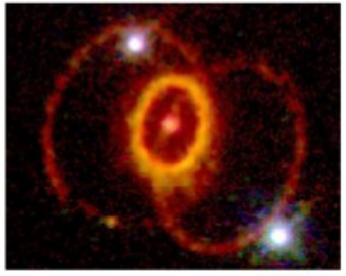

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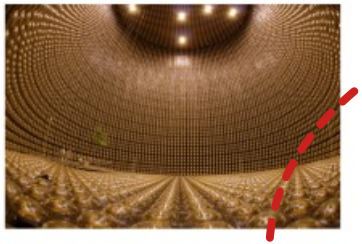
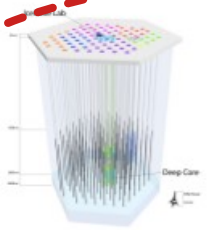
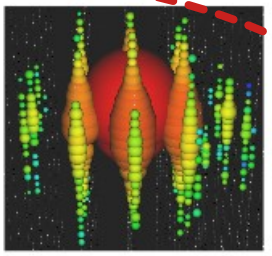
6×10^{20} eV →







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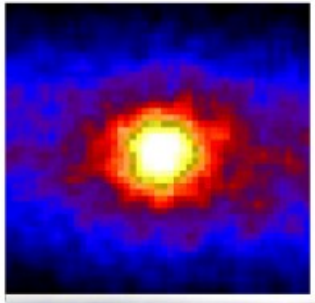

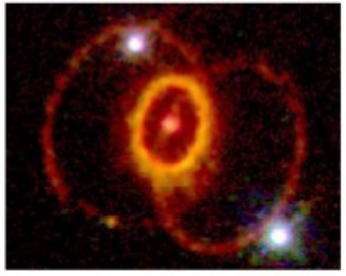

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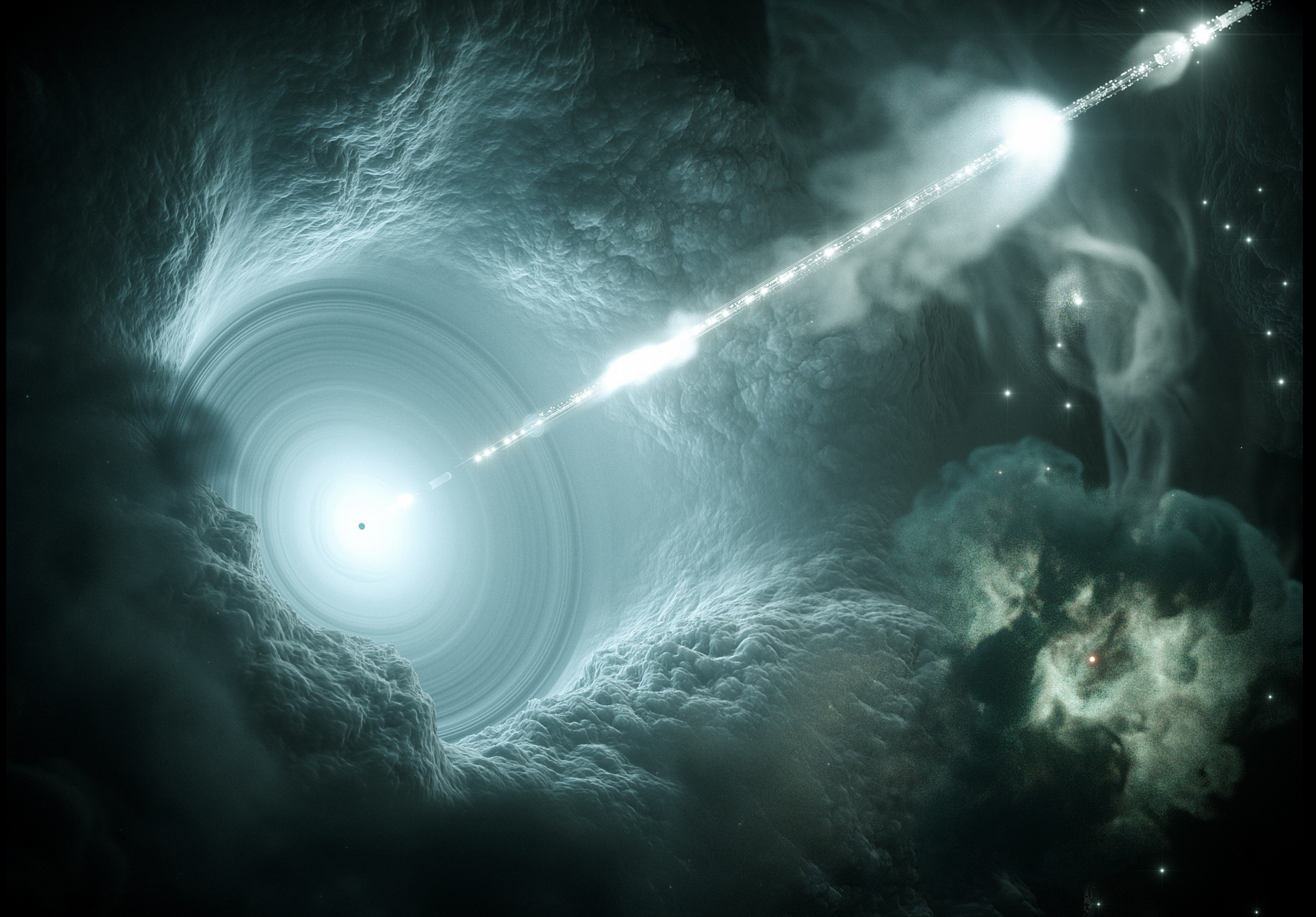
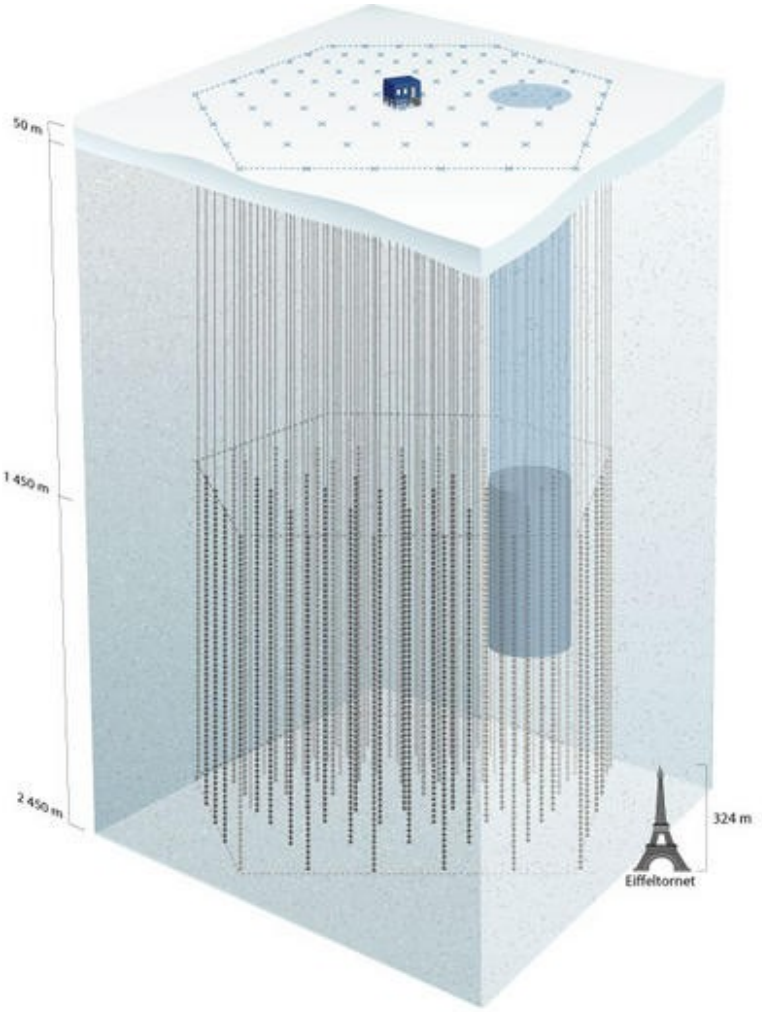


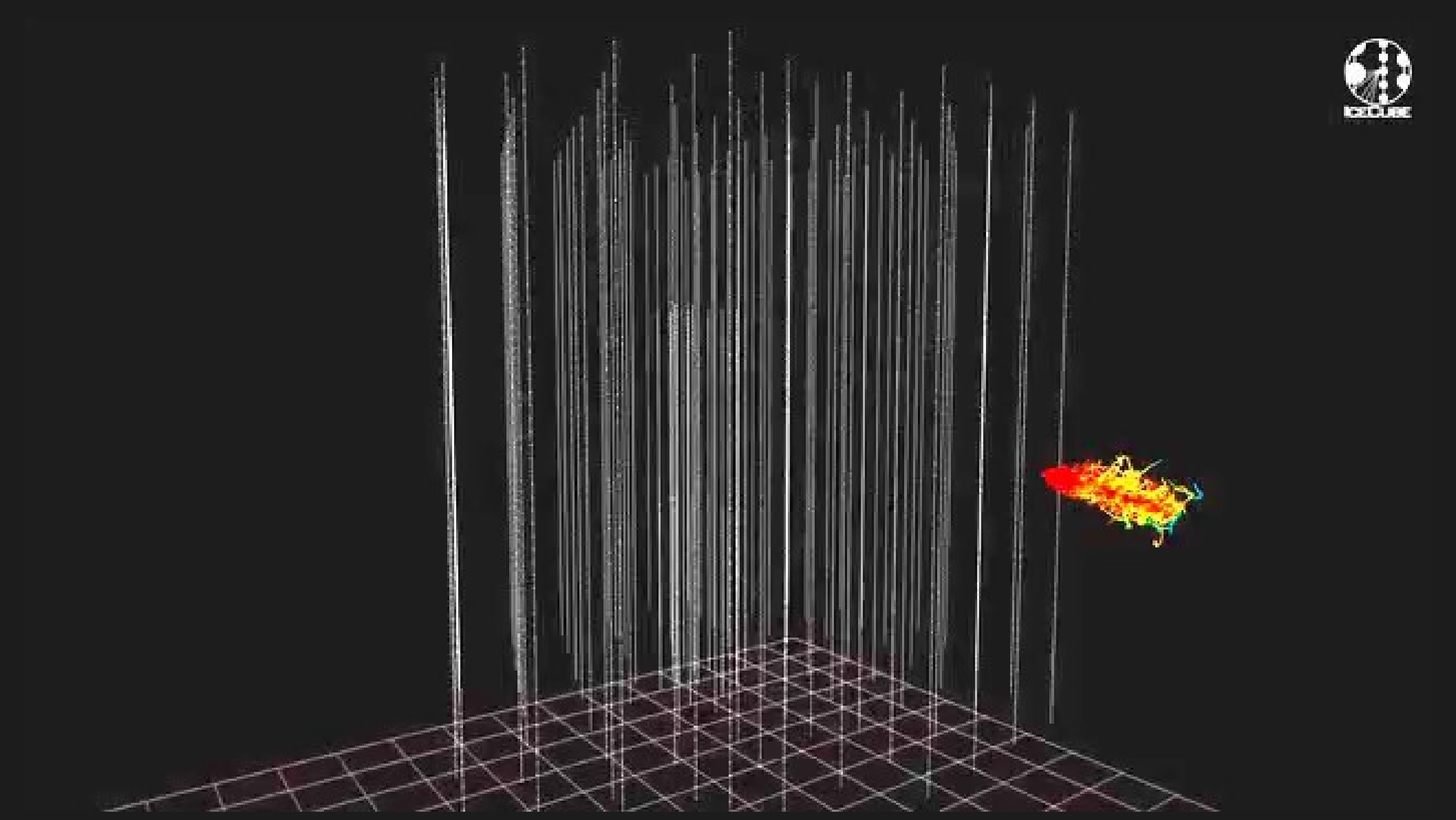
DESY

DESY

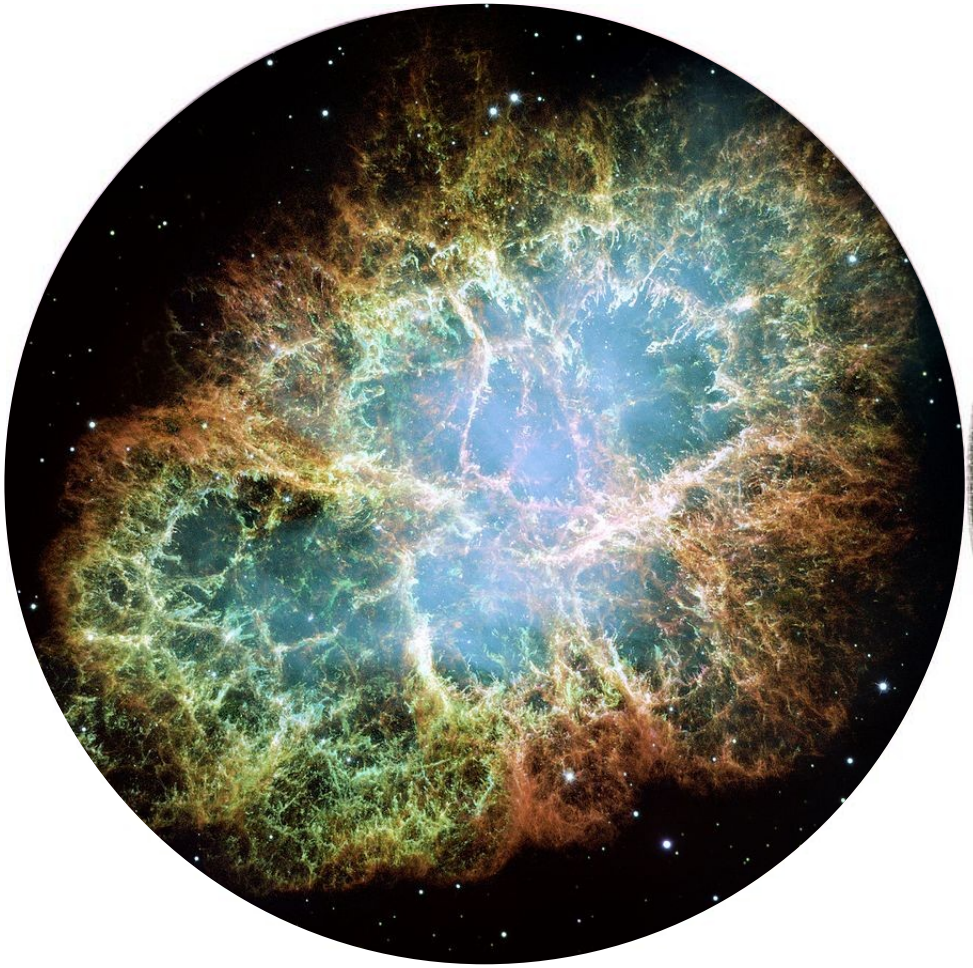
IceCube: The largest neutrino telescope



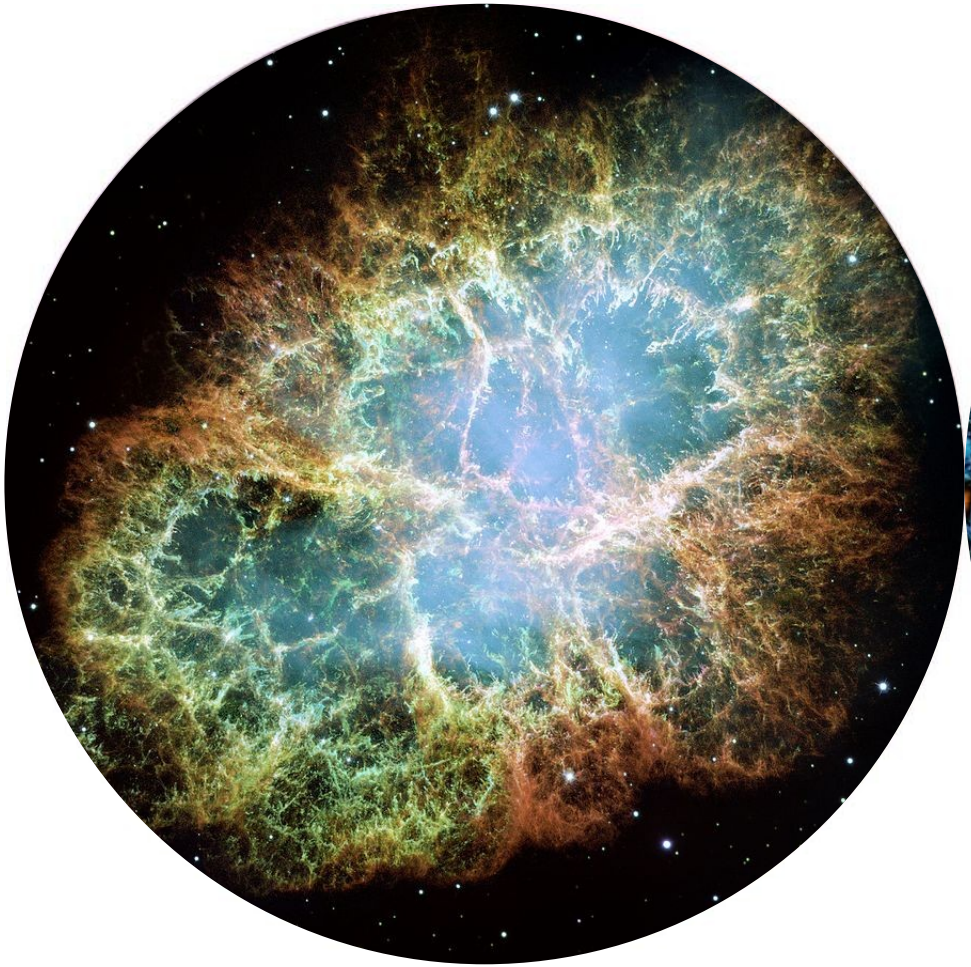
- Km^3 in-ice Cherenkov detector in Antarctica
- > 5000 PMTs at 1.5–2.5 km of depth

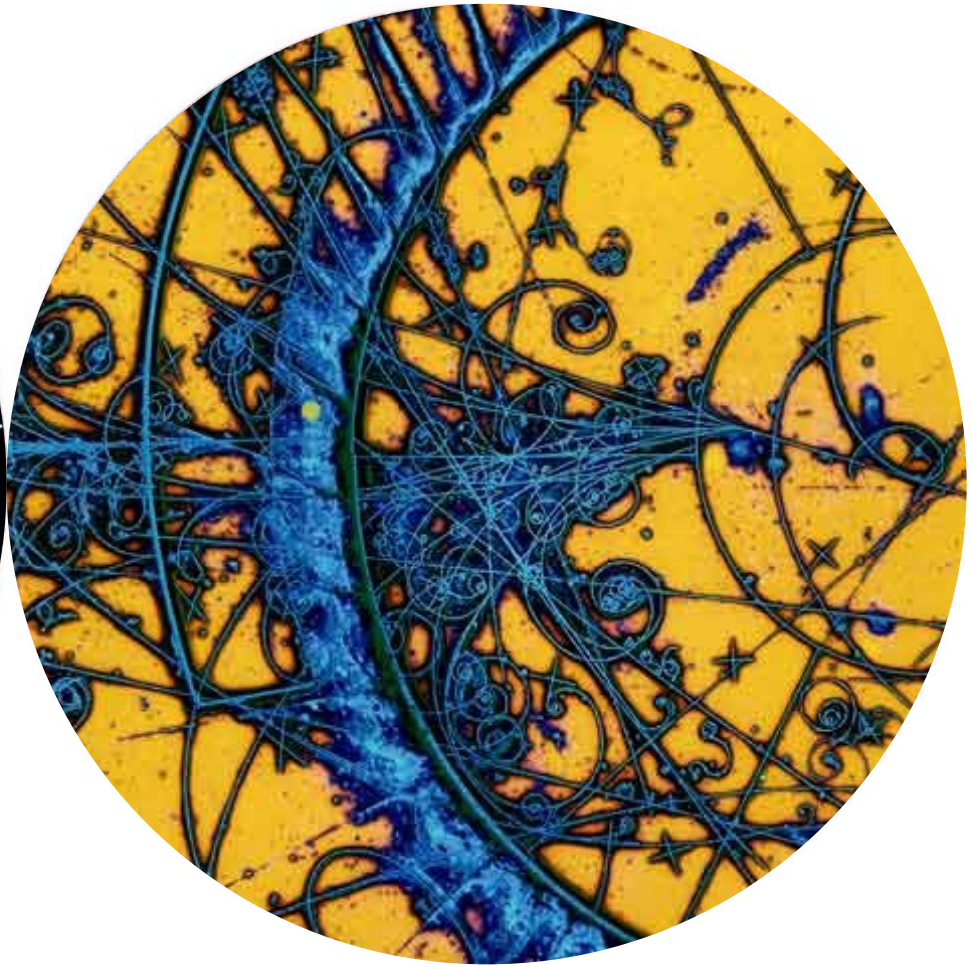


Banco Central de Reserva del Perú / NASA / ESA / CERN / Symmetry Magazine



Banco Central de Reserva del Perú / NASA / ESA / CERN / Symmetry Magazine





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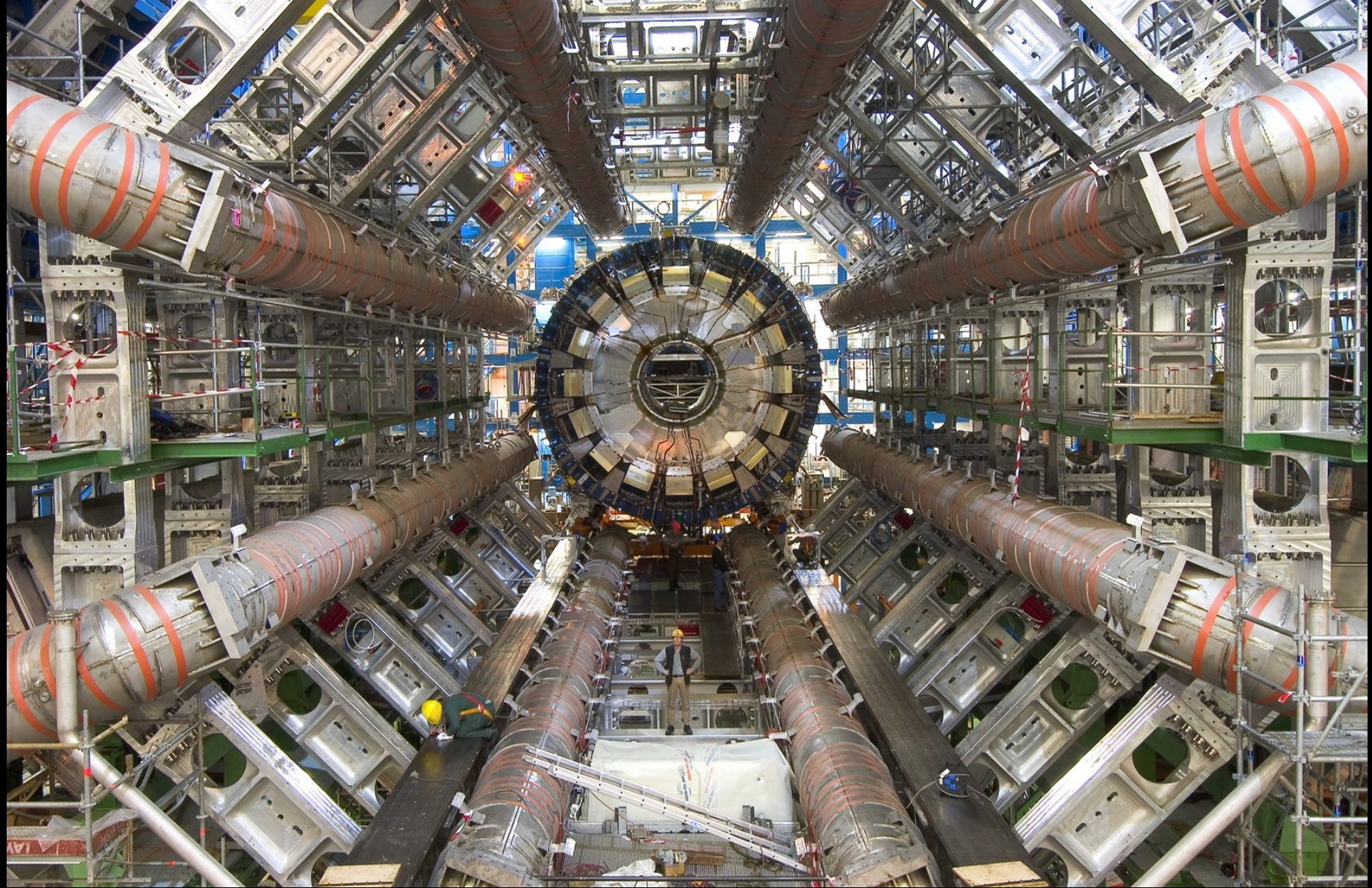
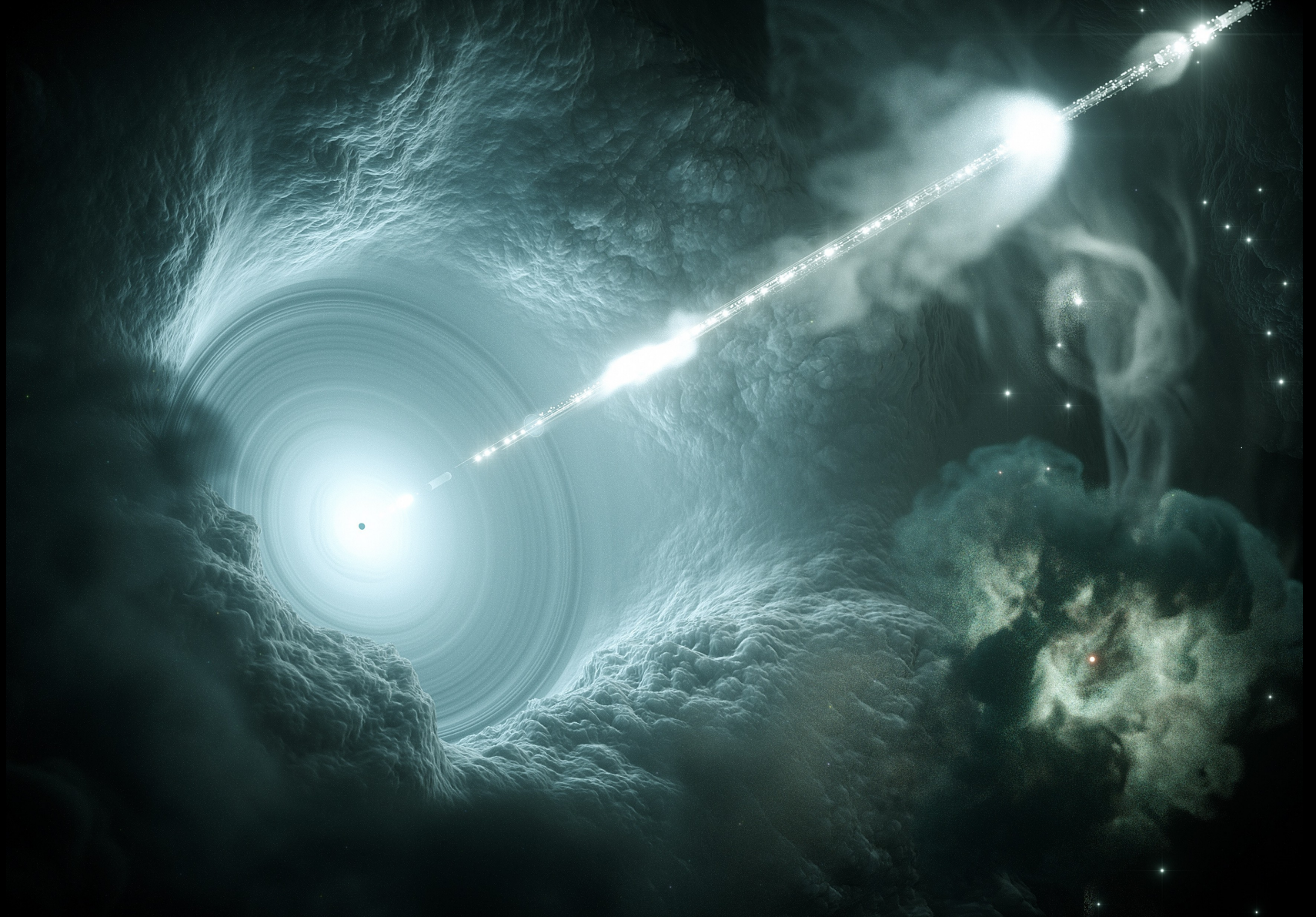


ATLAS



DESY

DESY


Photo by @aleozh


2021 (we are here):
TeV–PeV ν
discovered
First possible sources
Photo by @aleozh


2020s (we are getting there):
More source candidates
Characterize the ν flux precisely
2021 (we are here):
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2030s (under planning):
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More source candidates
Characterize the ν flux precisely
> 2040:
????
2021 (we are here):
TeV–PeV ν
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First possible sources
Photo by @aleozh

Undergrad & MSc: PUCP, 5+3 yr

- High Energy Physics Group
- 4 papers (+ proceedings) – key to apply to PhD
- 7 local & international conferences and schools
- 6–12-month research visits during MSc
  - Meet future colleagues
  - Meet future mentors
  - Learn the state of the art
  - Be exposed to other styles

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- Had a young, motivated PI as supervisor
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Working with experimental collaborations

I'm a theorist, but I work in close proximity to experimental collaborations

Theorist

Experimentalist

Working with experimental collaborations

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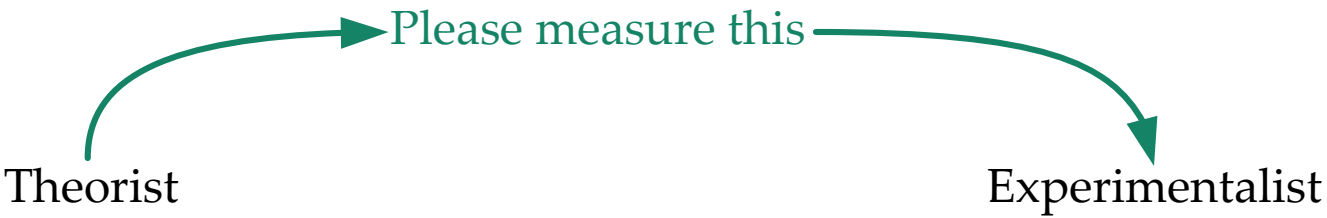

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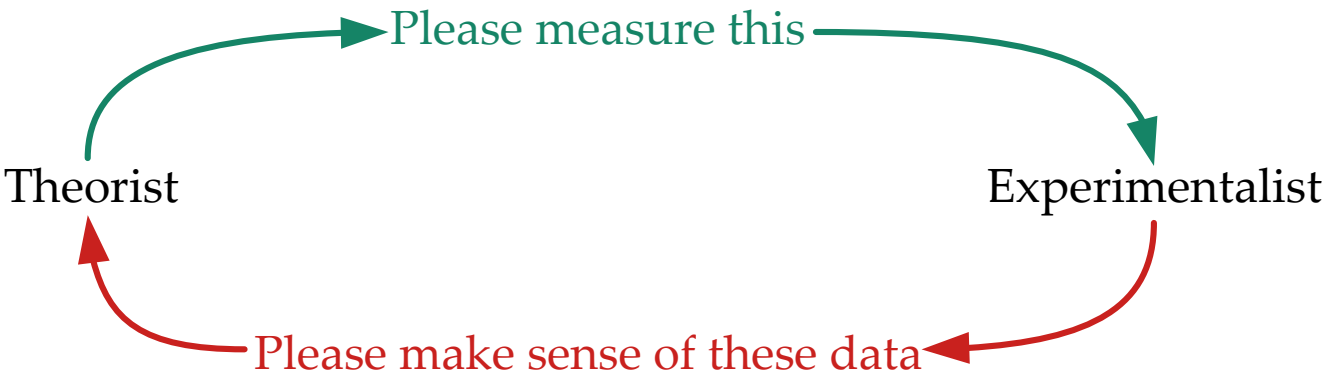

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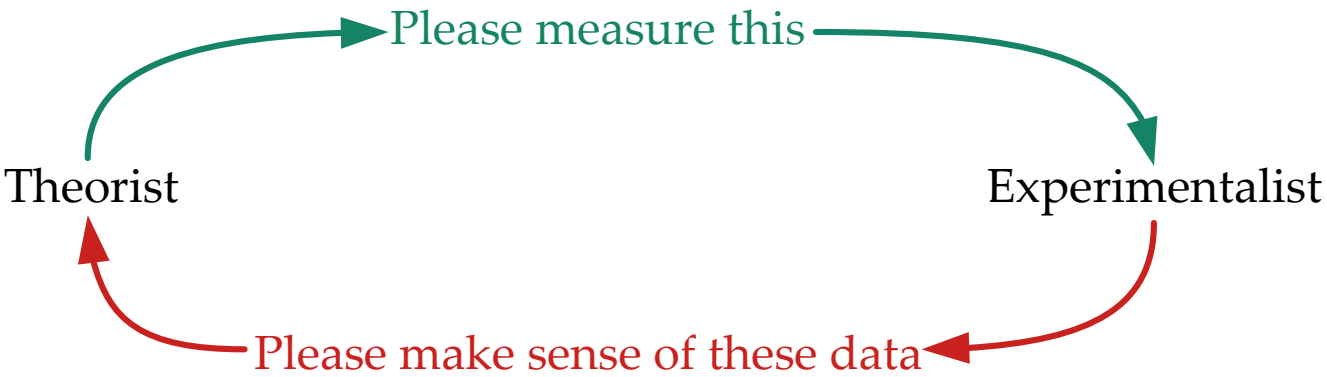

Plan the next generation of large-scale neutrino telescopes for the coming 10–20 years

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- Center for Cosmology and Astroparticle Physics
- Transitioned to more particle physics
- Started work with experimental collaborations
- Started refereeing papers: improves writing
- Gave lots of talks (~40 significant ones)!
- Started building my own researcher identity: experimentally minded theoretical perspective

Becoming an independent researcher

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UNIVERSITY OF COPENHAGEN

Today

Becoming an independent researcher

Today: Faculty position

- Assistant Professor, Niels Bohr Institute, U. of Copenhagen, Denmark
- Starting research grant from the Danish Villum Fonden (~1.5M USD)
- Building my own research group (students + postdocs)
- My time is divided between my students, my own research, and grant applications
- Key skill: Time management (too many things to do, too little time!)
- Working with students is a rewarding time investment

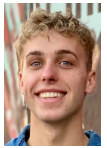
Students at NBI

Undergrads

- First direct exposure to research
- Well-defined project
- ~4 months
- Topics closely linked to content courses

2018
Siqiao Mu (Caltech)
Unitarity bounds of astrophysical neutrinos
PRD 2018

2020
Niels Gustav Willesen
Unitarity bounds of astrophysical neutrinos
JCAP 2021



2021
Jonathan Baltazar
Decay of high-energy cosmic neutrinos

2024
Franciszek Nawrocki
Investigating neutrino oscillations at astrophysical energy scales

2025
Julie Harder Gabrielsen
A method to compute neutrino oscillation probabilities for arbitrary time-dependent Hamiltonians

2025
Asmus Bo Klingemann
Neutrino tomography of the Earth in ESSnuSB

MSc

- Project led by student
- Well-defined goal
- Solutions defined by the student
- ~1 year
- Topics firmly beyond courses
- Paper

2019–2020
Charlotte Rosenstrøm
Bounds on secret neutrino interactions from high-energy astrophysical neutrinos
PRD 2020

2020–2021
Kjartan Másson
Secret interactions of ultra-high-energy neutrinos

2021-2022
Marie Hansen
Interactions between high-energy cosmic neutrinos and axions

2022-2024
Anirudh Bhatnagar
Probing quantum-gravity decoherence in high-energy neutrinos from the active galaxy NGC 1068

2023-2024
Federico Testagrossa
Two-detector flavor sensitivity to ultra-high-energy cosmic neutrinos

2024
Andreas Knage
Proton-dark matter interaction in the active galactic nucleus NGC 1068

2024-2025
Johannes Vos Jacobsen
Ultra-high-energy neutrinos from dark matter trapped inside the Earth

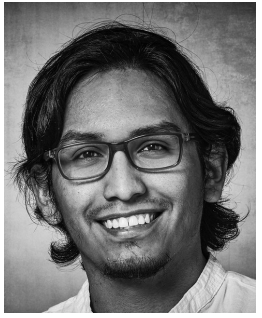
2025
Aske Matthiesen
Flavor measurements in TAMBO

2025
Yifei Li
Ultra-high-energy neutrino flux models in GRAND

Students at NBI

PhD

- State-of-the-art research
- Well-defined general plan
- Freedom to explore
- ~3 years
- Several papers
- Prepare for a career in academia if desired



2020–2023
Víctor Valera
Pushing neutrino physics to the cosmic frontiers
Undergrad: UNI
MSc: ICTP Trieste

2021-2025
Bernanda Telalovic
Novel tests of new physic with astrophysical neutrinos
Undergrad: U. Melbourne
Msc: U. Tübingen

Take-aways

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- Doing research is a craft: always improved, never perfected

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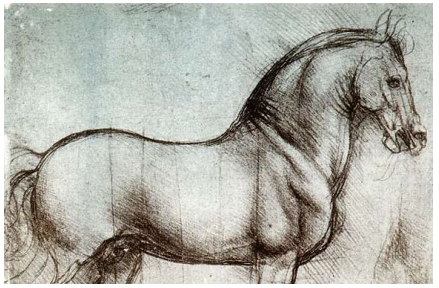

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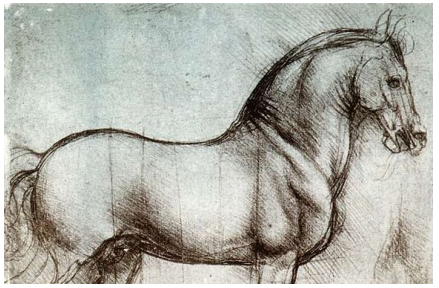

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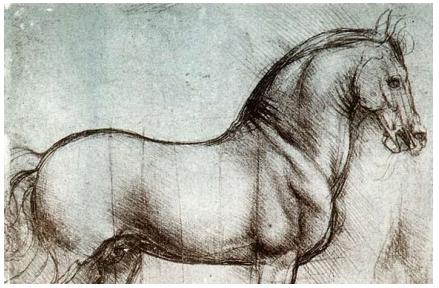

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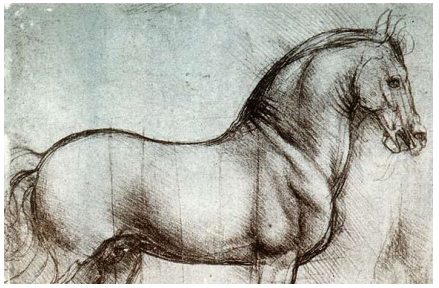
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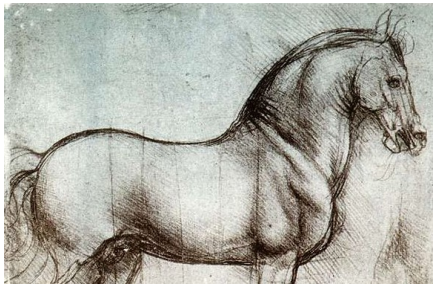
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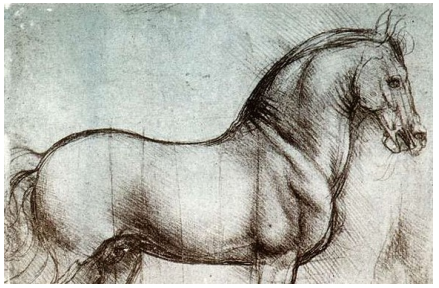
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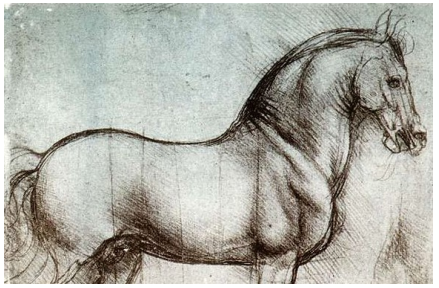
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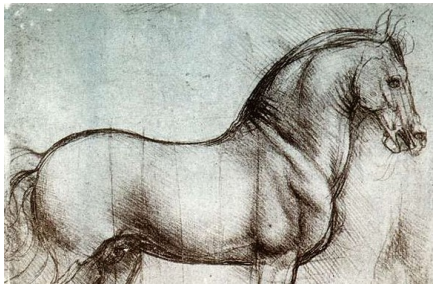
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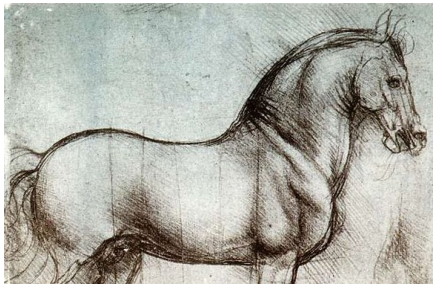
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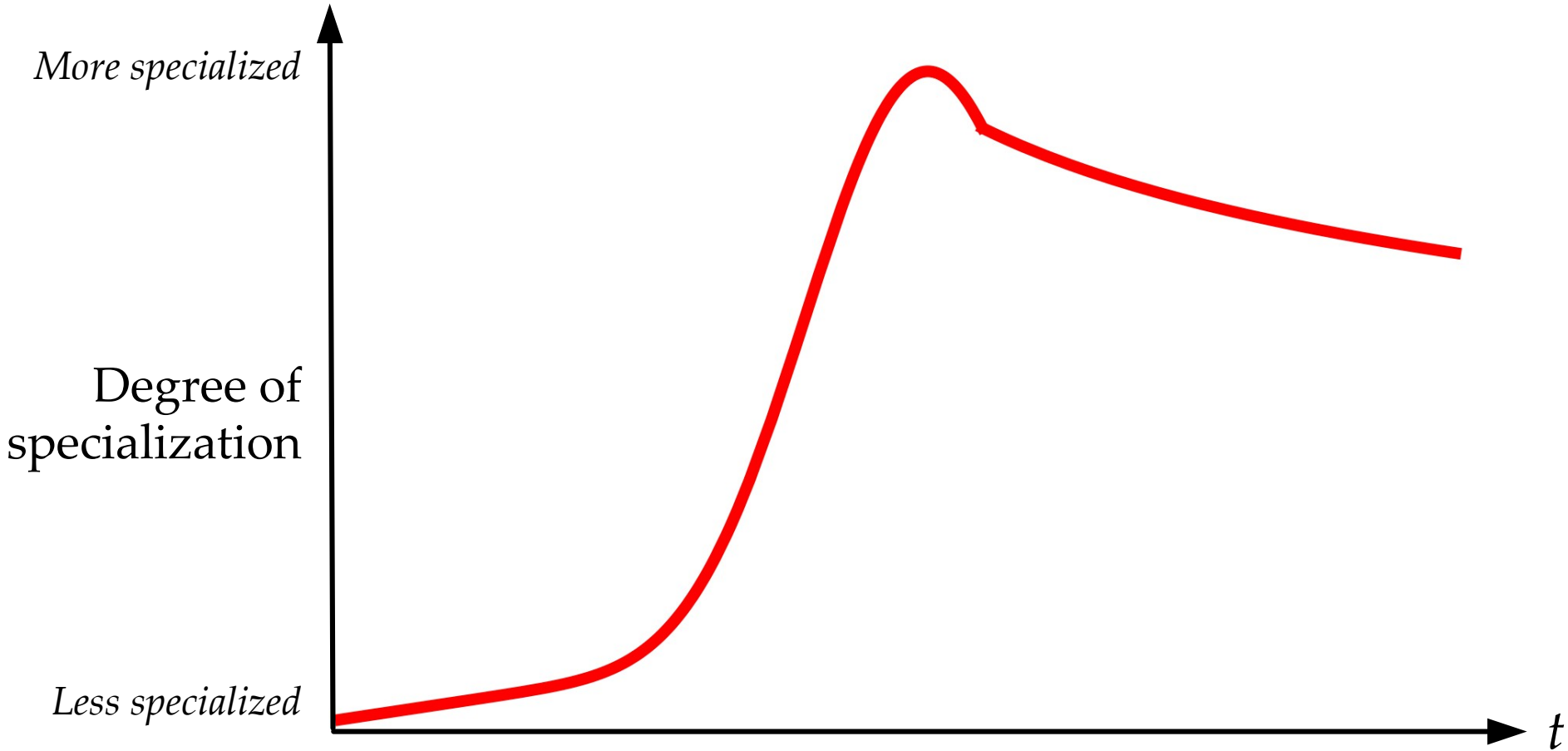
What interests you? What is your competitive advantage? What do people associate you with?


More specialized
Degree of specialization
Less specialized
t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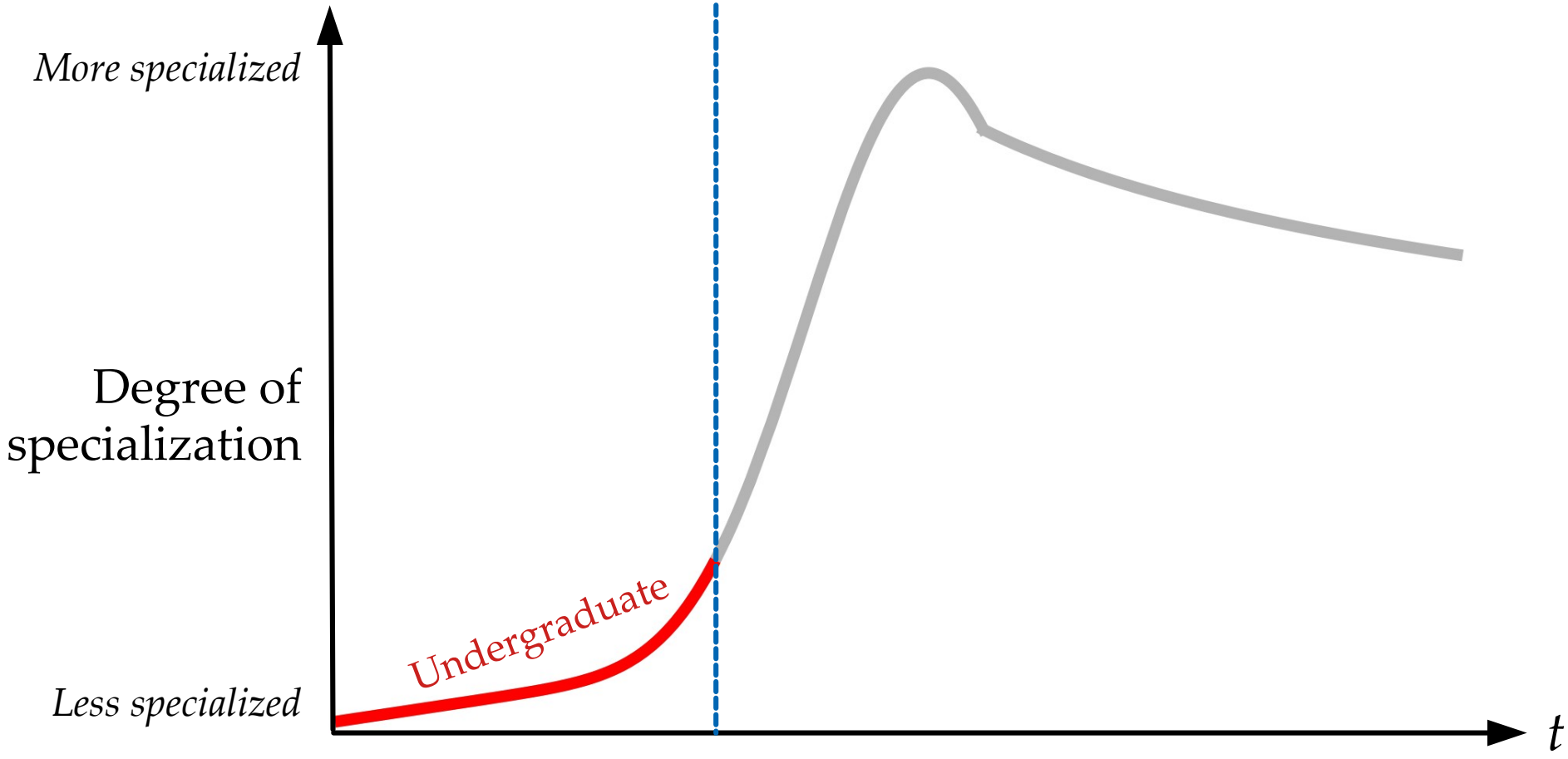
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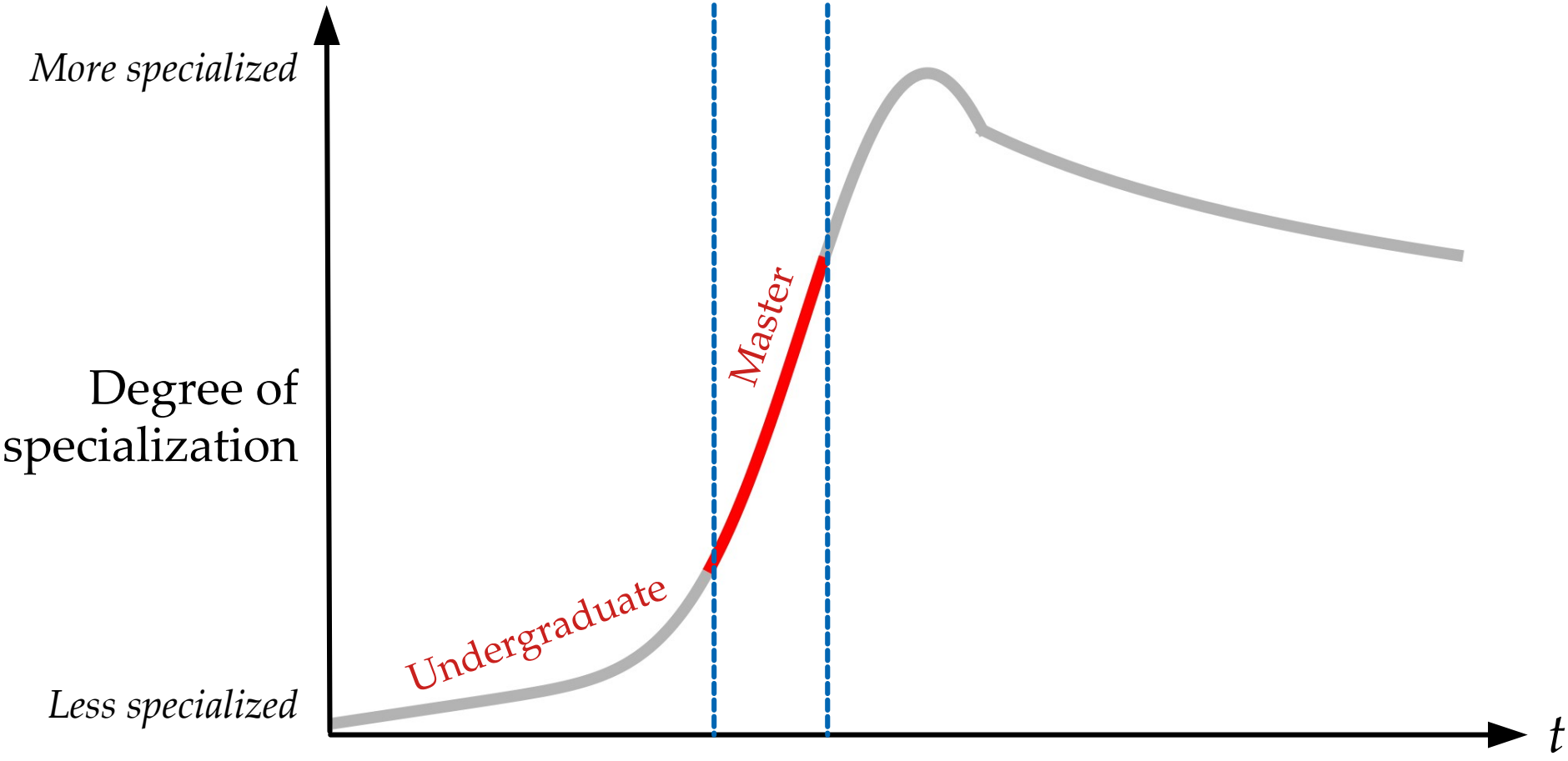
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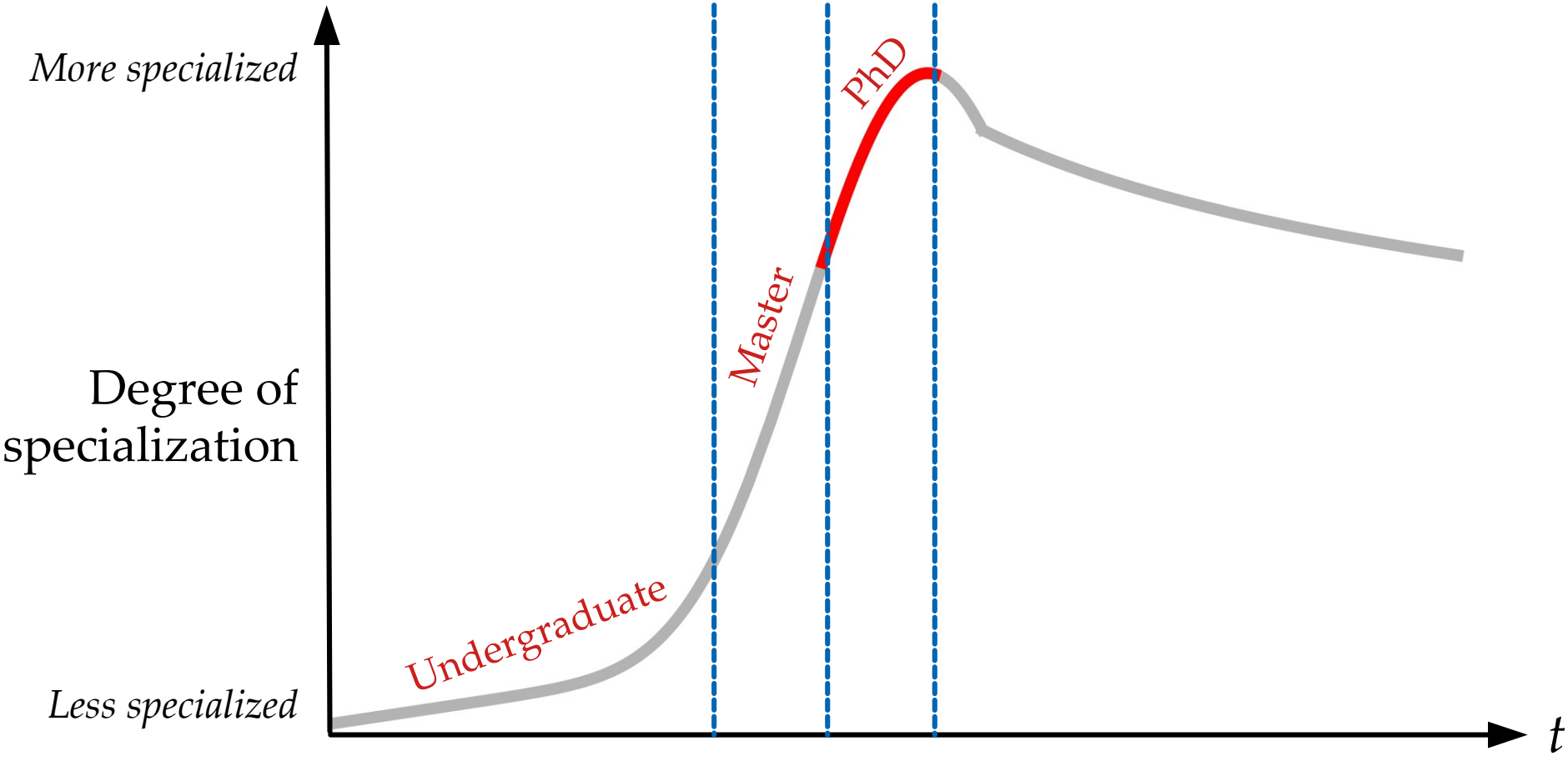
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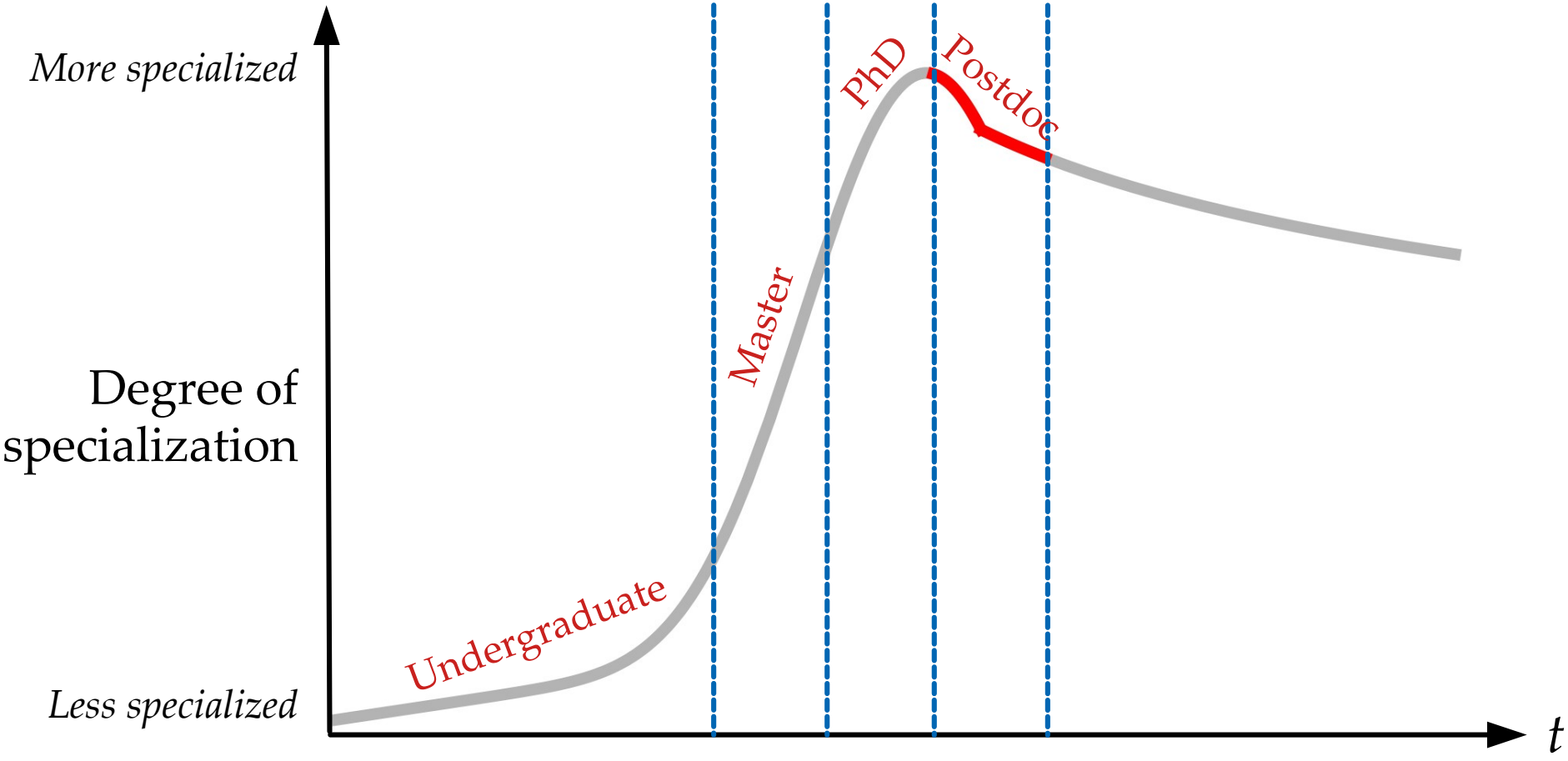
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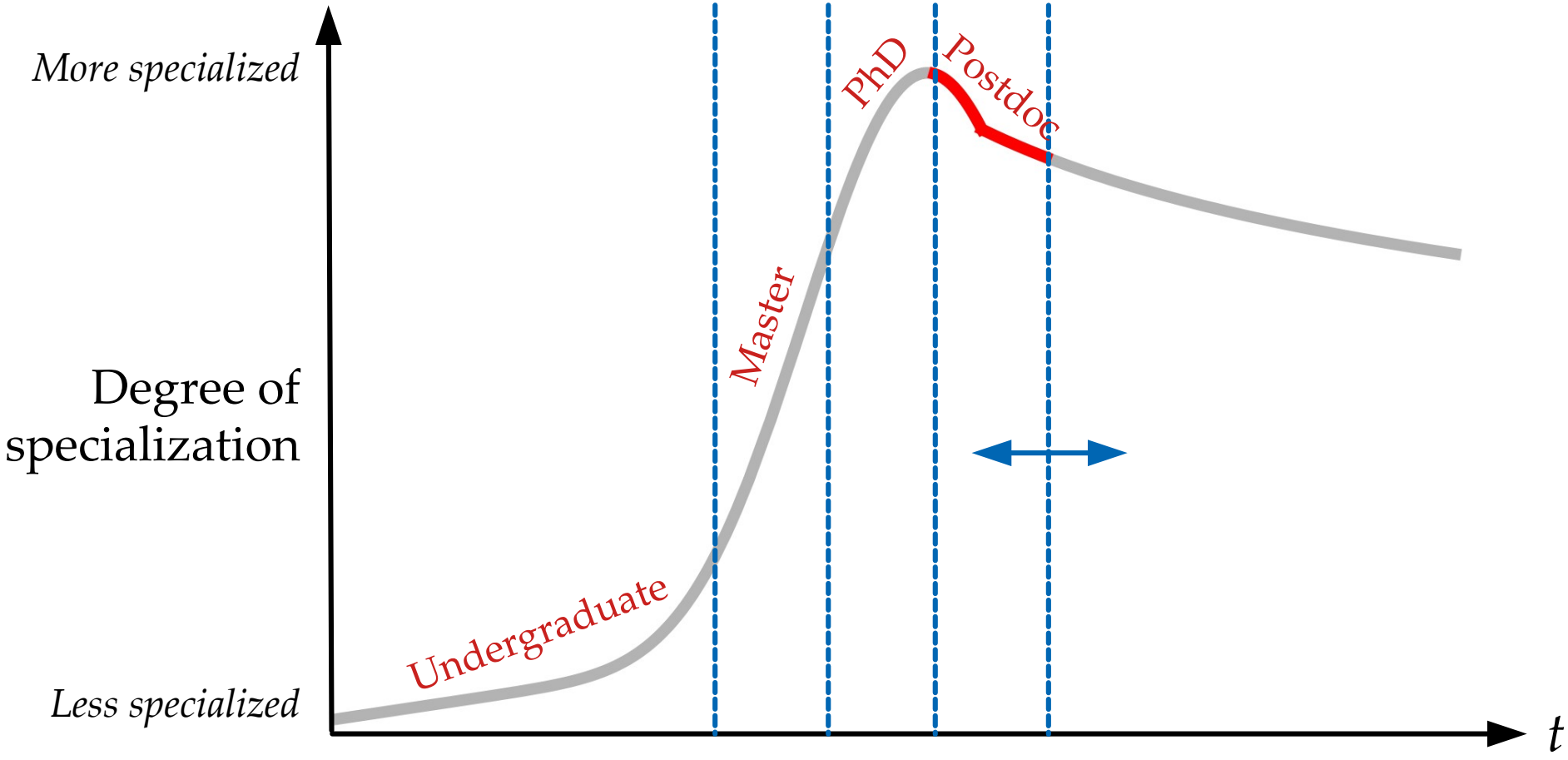
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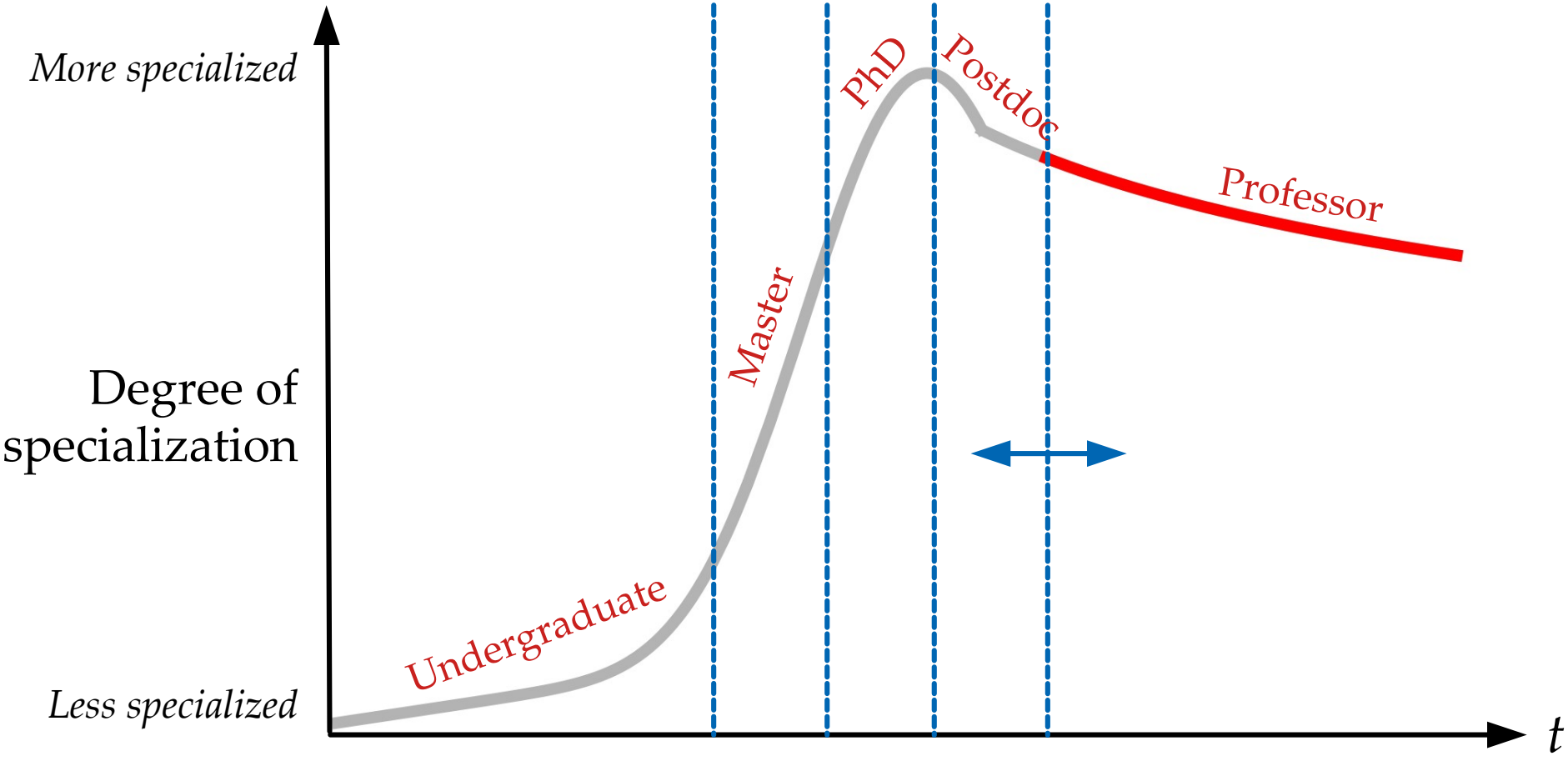
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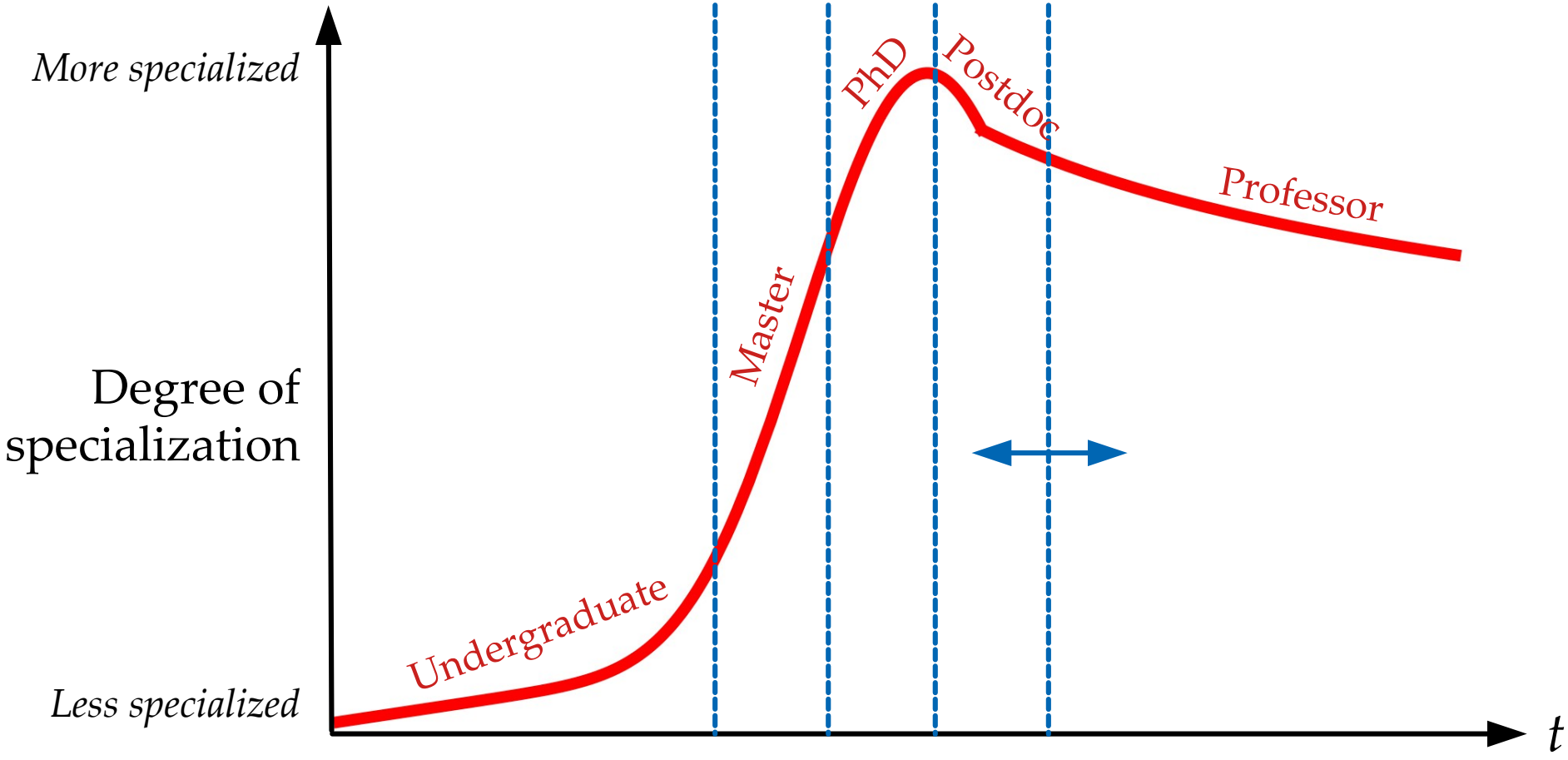
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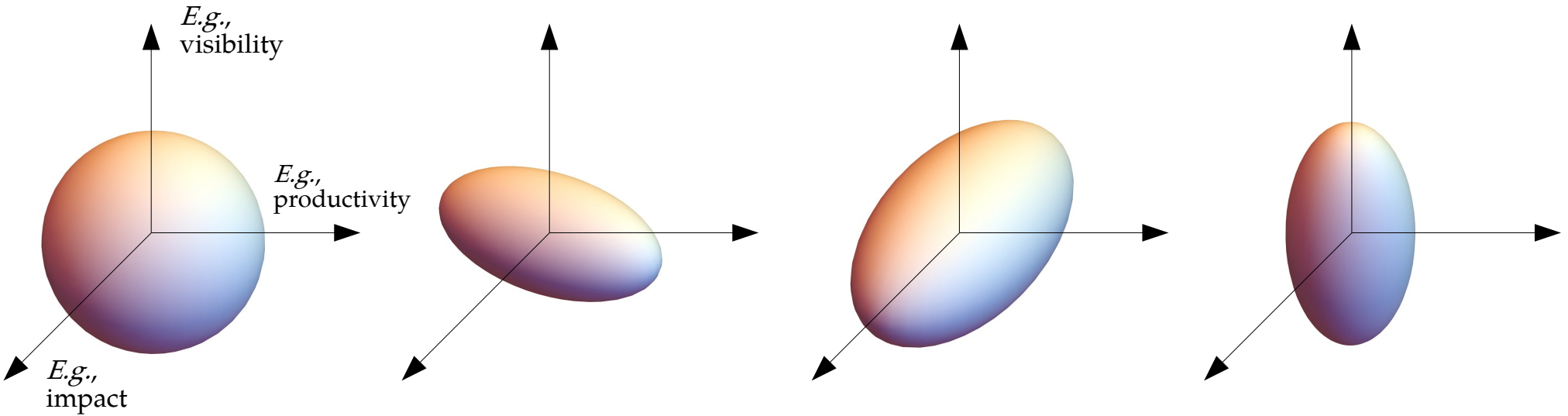
Academic success is a multidimensional function



$$\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 + \left(\frac{z}{c}\right)^2 = 1$$

Success: $V = \frac{4}{3}\pi abc$

If any of *a*, *b*, or *c* are zero, *V* is zero

Soft skills are crucial!

Most important: Make good science

Second most important: Communicate it effectively!

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  Explain the core of your work in the span of a minute

PHYSICAL REVIEW LETTERS

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Universe's Worth of Electrons to Probe Long-Range Interactions of High-Energy Astrophysical Neutrinos

Mauricio Bustamante and Sanjib Kumar Agarwalla

Phys. Rev. Lett. **122**, 061103 – Published 12 February 2019

Physics See Synopsis: Neutrino Probes of Long-Range Interactions

26

More

Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

2015/04/10

Back

Gamma-ray bursts as cosmic particle accelerators

Study provides new insights into the universe's most powerful explosions

This approach can not only explain the observed strong variations in the light curves of gamma-ray bursts. A consequence of this model is also that neutrinos, cosmic rays and gamma-rays must be produced in completely different regions of the jets. This can explain, why the expected flux of neutrinos could not be found. "We expect that the next generation of neutrino telescopes, such as IceCube-Gen-2, will be sensitive to this minimal flux that we're predicting", says Bustamante. In contrast to earlier models, this estimate is more robust and does only weakly depend on the characteristics of individual gamma-ray bursts.

CERNCOURIER | Reporting on international high-energy physics

NEUTRINOS | NEWS

The case of the disappearing neutrinos

15 January 2018

In an additional analysis of six years of IceCube data, Amy Connolly and Mauricio Bustamante of Ohio State University employ an alternative approach which uses 58 IceCube-contained events (in which the neutrino interaction took place within the detector) to measure the neutrino cross-section. Although these events mostly have well-measured energies, their neutrino zenith angles are less well known and they are also much less numerous, limiting the statistical precision.

EurekAlert! | AAAS

SEARCH ARCHIVE ADVANCED SEARCH

HOME NEWS RELEASES MULTIMEDIA MEETINGS PORTALS ABOUT LOGIN REGISTER

NEWS RELEASE 28-OCT-2019

Giant neutrino telescope to open window to ultra-high-energy universe

SCIENCE CHINA PRESS

Media Contact
Mauricio Bustamante
mbustamante@nbi.ku.dk

http://www.scichina.com/

PHYSICS

Astronomers Propose Huge New Telescope System to Understand the Most Energetic Particles Ever Detected

GIZMODO

Ryan F. Mandelbaum
10/29/18 4:20PM • Filed to: GRAND

14.3K 24 5

"Blazars could maybe make neutrinos in a wide energy range, or maybe it could be something else making these higher-energy neutrinos," Mauricio Bustamante, editor of the experiment's white paper and a postdoc at the Niels Bohr Institute in Copenhagen, told Gizmodo. "We hope it's as interesting as possible."

MIT Technology Review

Sustainable Energy

How Neutrino Beams Could Reveal Cavities Inside Earth

Geophysicists want to use neutrinos to 'x-ray' the Earth, a technique that could reveal undiscovered oil fields. But how practical is such a scheme?

by Emerging Technology from the arXiv Feb 1, 2012

SCIENTIFIC AMERICAN

PHYSICS

Bizarre Particles Keep Flying out of Antarctica's Ice, and They Might Shatter Modern Physics

"It was clear from the start that if the ANITA anomalous events are due to particles that had propagated through thousands of kilometers of Earth, then those particles were very likely not SM particles," said Mauricio Bustamante, an astrophysicist at the Niels Bohr Institute at the University of Copenhagen, who was not an author on the new paper.

Science outreach

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We dedicate this book
To our fellow citizens
Who, for love of truth,
Take from their own wants
By taxes and gifts,
And now and then send forth
One of themselves
As dedicated servant,
To forward the search
Into the mysteries and marvelous simplicities
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Our home

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- Down the road: consider a TEDx event

Funding opportunities in Peru

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PRONABEC (www.pronabec.gob.pe)

- Beca 18: For senior high-school students
- Beca Mujeres en Ciencia: For female senior high-school students
- Beca Inclusión: For people with disabilities
- Crédito Talento: Credit with comfortable payback times
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PUCP

- Programa de Apoyo a la Iniciación en la Investigación (PAIN): For undergraduate students
  investigacion.pucp.edu.pe/convocatoria/programa-apoyo-iniciacion-en-investigacion-pain
- Programa de Apoyo a la Investigación para Estudiantes de Posgrado (PAIP): For grad students
  investigacion.pucp.edu.pe/convocatoria/programa-apoyo-investigacion-para-estudiantes-de-posgrado-paip
- Beca Huiracocha: For PhD students
  posgrado.pucp.edu.pe/beca-fondo/beca-huiracocha

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- Programa de Apoyo a la Investigación para Estudiantes de Posgrado (PAIP): For grad students
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- Beca Huiracocha: For PhD students
  posgrado.pucp.edu.pe/beca-fondo/beca-huiracocha

Full list of undergraduate scholarships (State, private): www.pucp.edu.pe/pregrado/becas

Ten tips for beginner researchers 1/2

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1. Start doing research early
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Ten tips for beginner researchers 1/2

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5. Start reading scientific articles early (undergrad)
   - Different from reading a non-scientific text
   - Key skill: single out main results quickly

Ten tips for beginner researchers 2/2

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   - Python or Python + C
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10. Be mindful of your mental health
    As important as items 1–9

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  Towards the end of your undergraduate years

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  Yes! In finance (banks, stock market), software development, consulting, design of new materials, etc.

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webspace.science.uu.nl/~gadda001/goodtheorist/index.html

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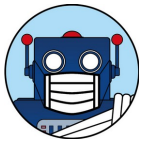

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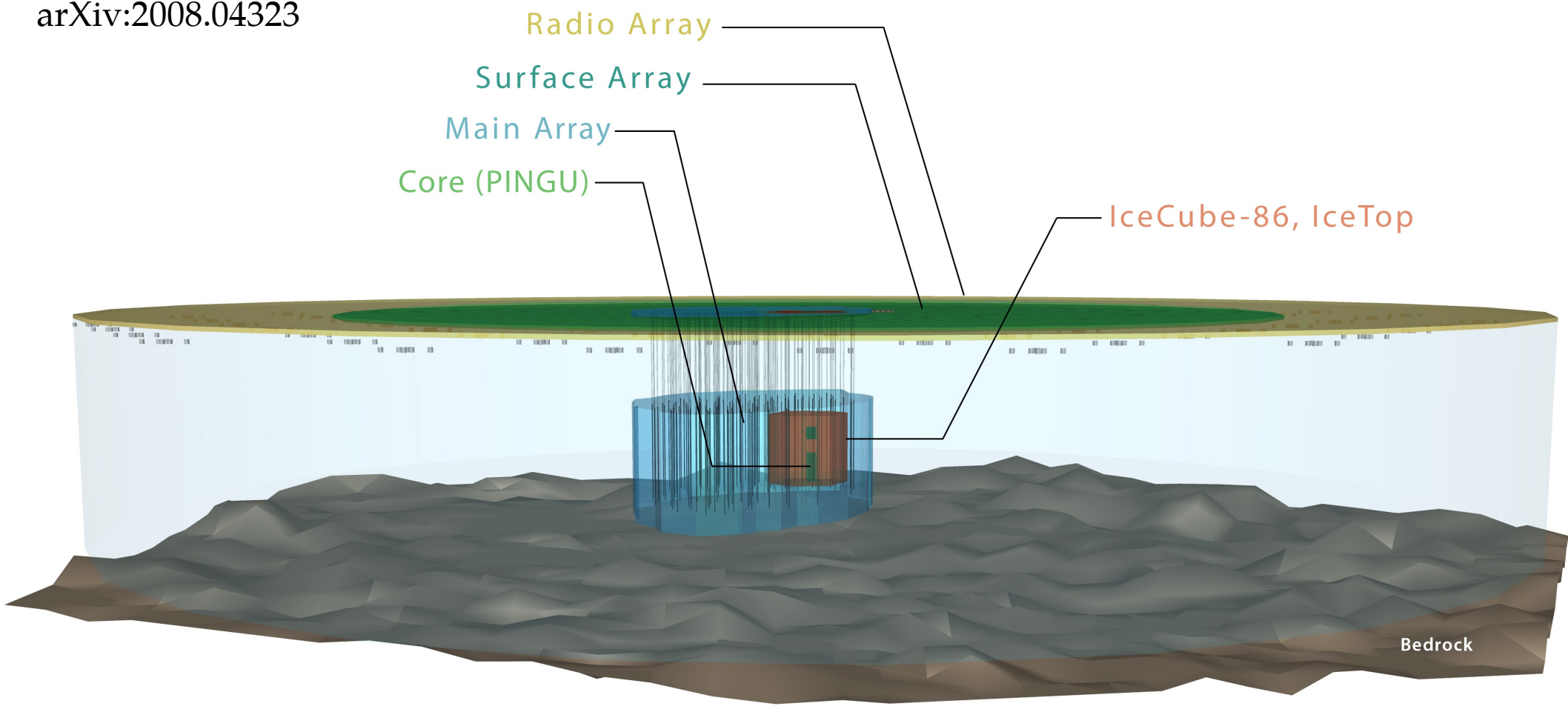
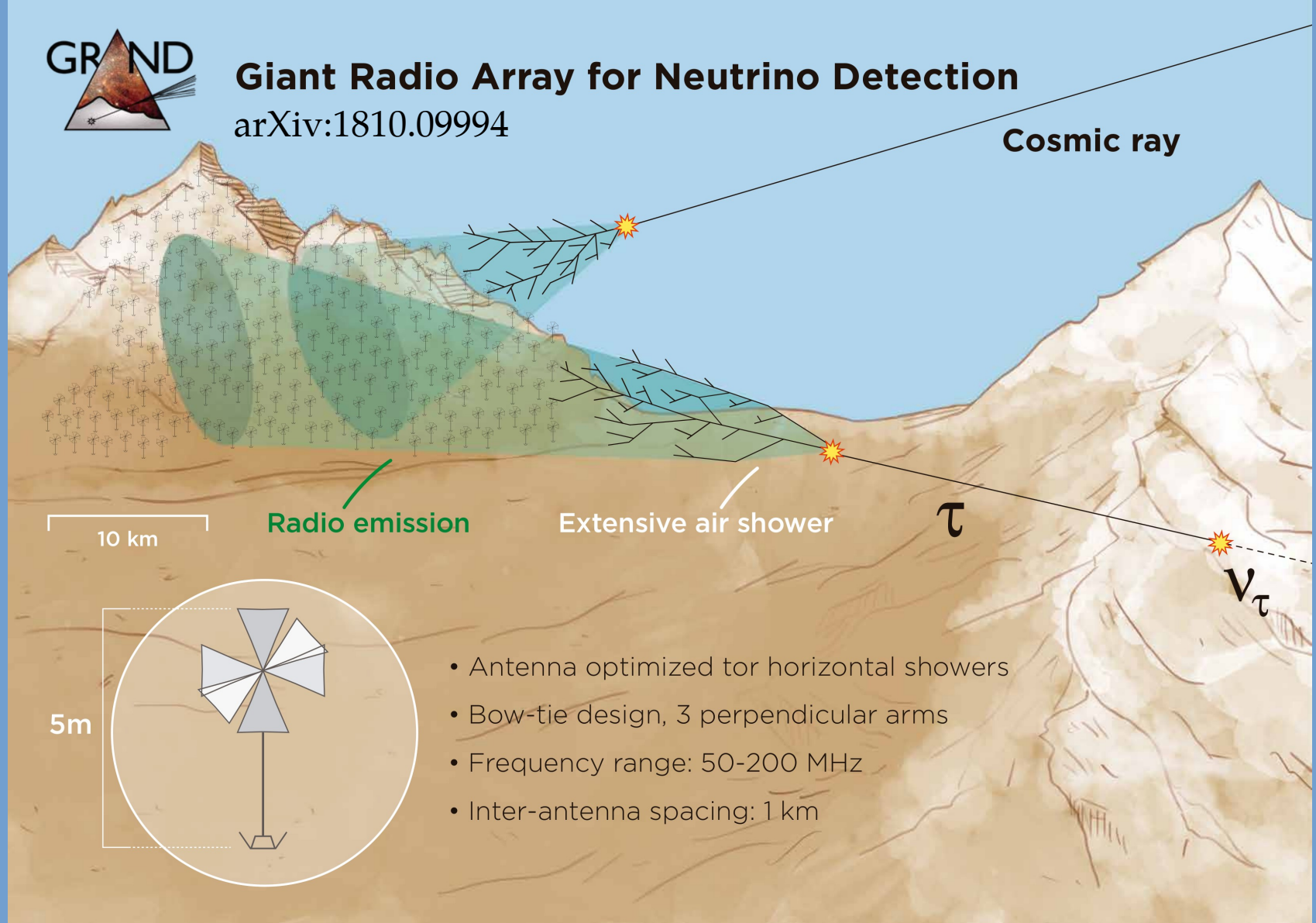
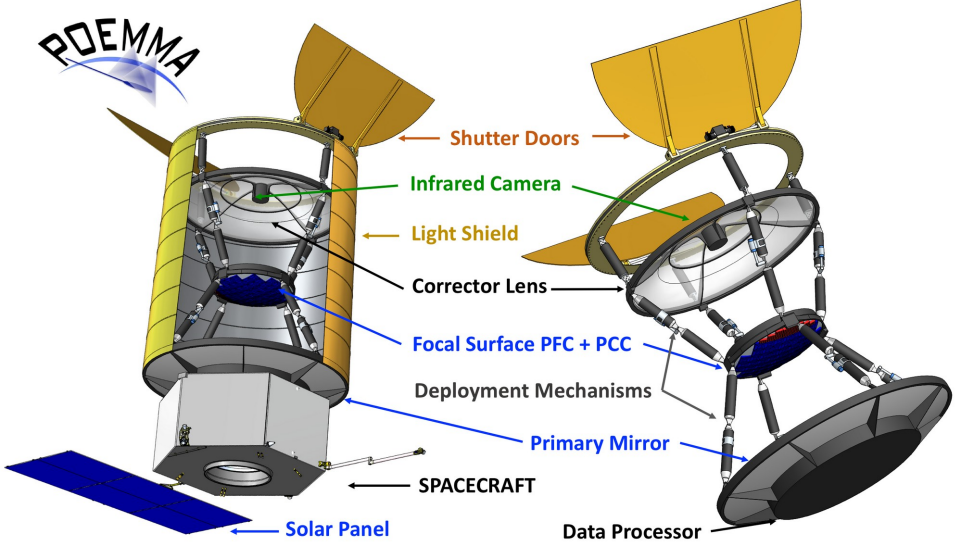



GRAND
Giant Radio Array for Neutrino Detection
arXiv:1810.09994
Cosmic ray
10 km
Radio emission
Extensive air shower
τ
ν_τ
5m
• Antenna optimized tor horizontal showers
• Bow-tie design, 3 perpendicular arms
• Frequency range: 50-200 MHz
• Inter-antenna spacing: 1 km

POEMMA:
Probe of Extreme Multi-Messenger Astrophysics

arXiv:2012.07945



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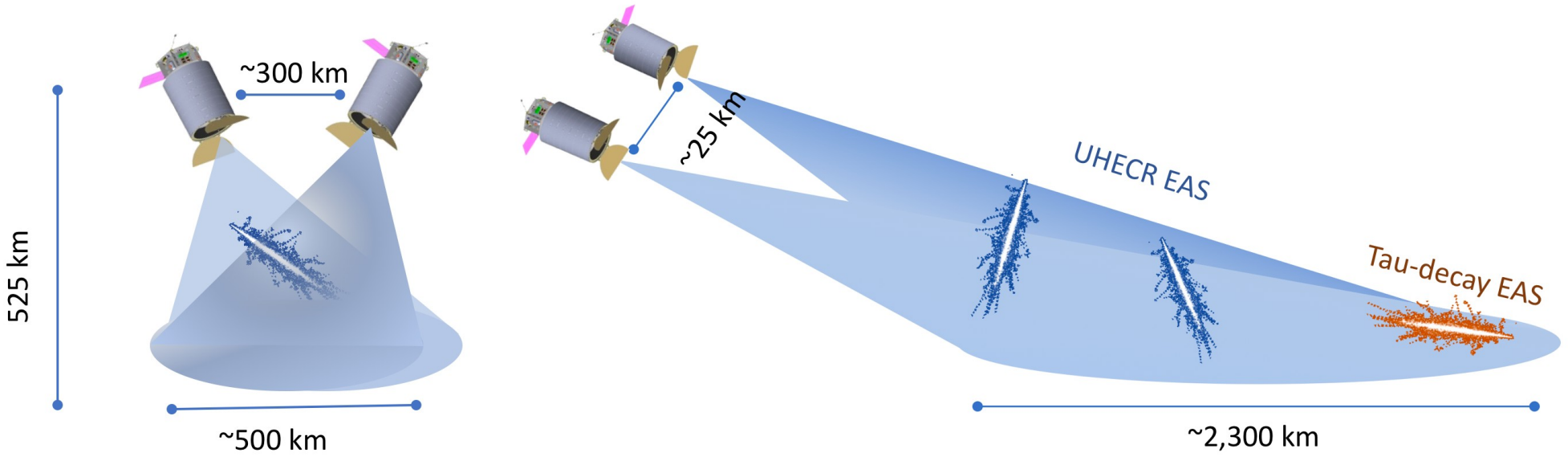

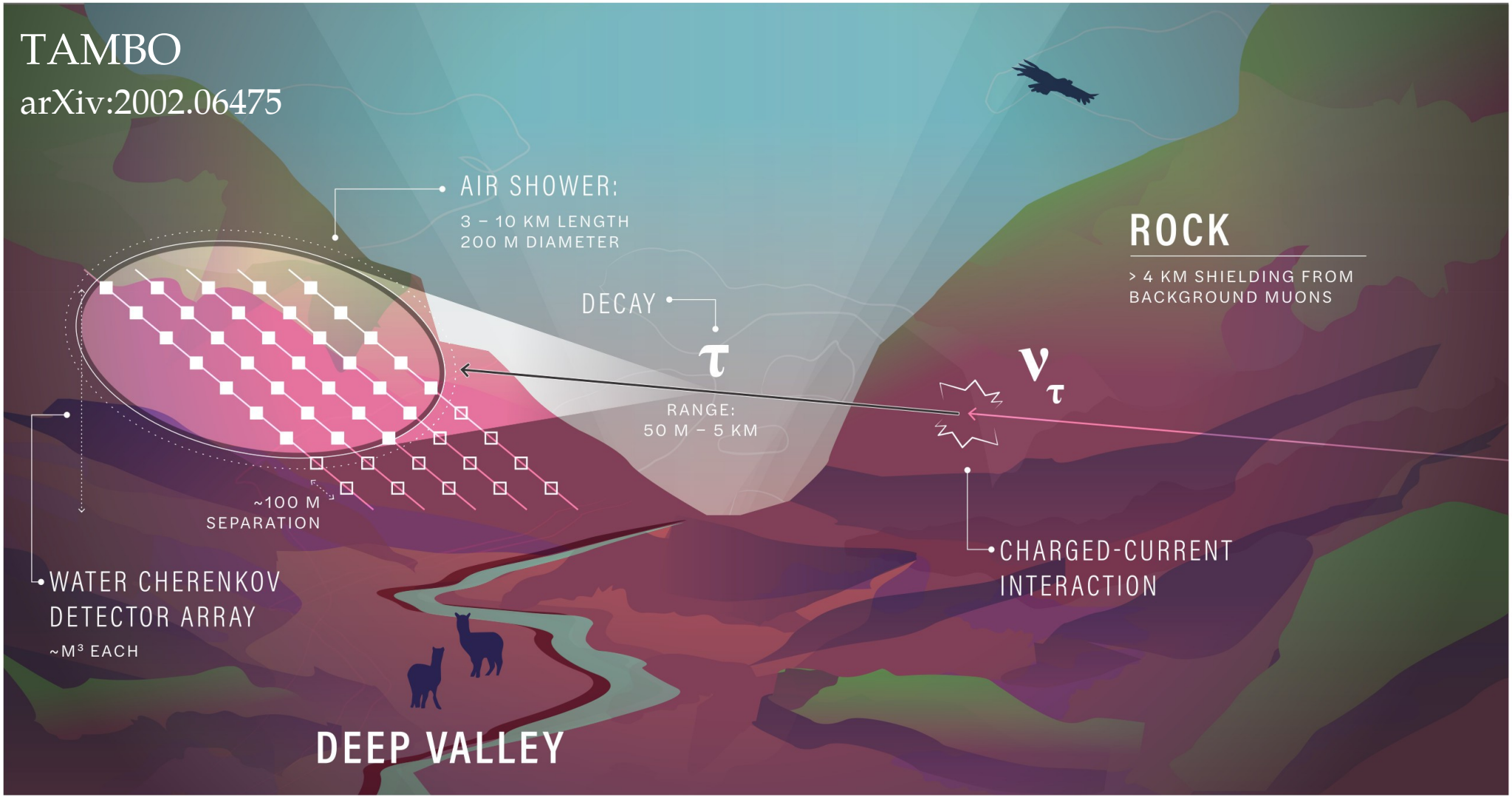

TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) · COLCA VALLEY, PERU

Find these slides at

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Feel free to contact me at mbustamante@nbi.ku.dk