Neutrino Physics

Joachim Kopp (CERN & JGU Mainz)

CERN Summer Student Lecture • 25 July 2024

CERN

Neutrino PLATFORM

QUANTUM TECHNOLOGY INITIATIVE

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

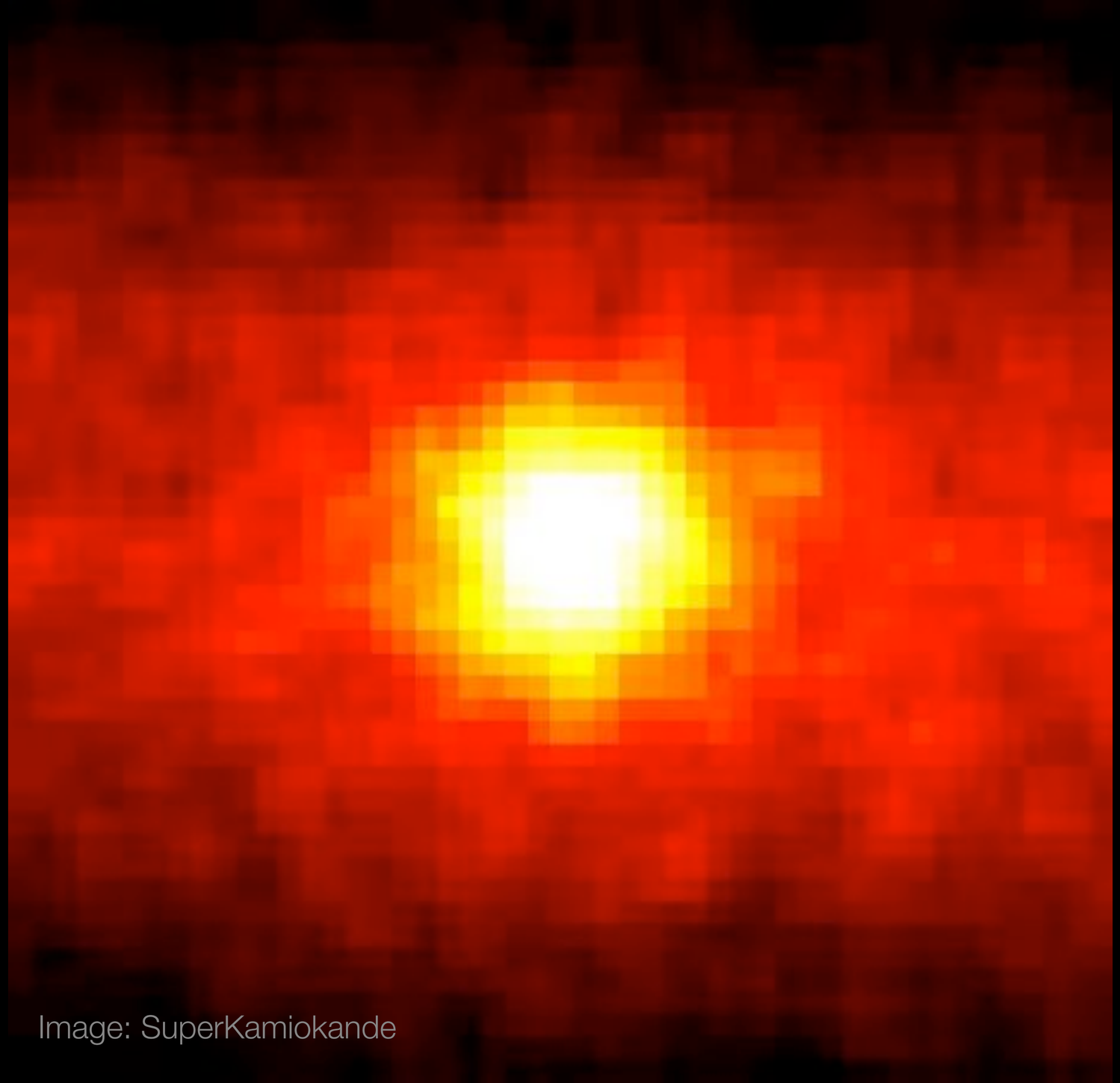
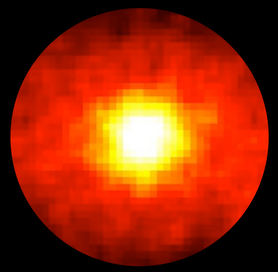
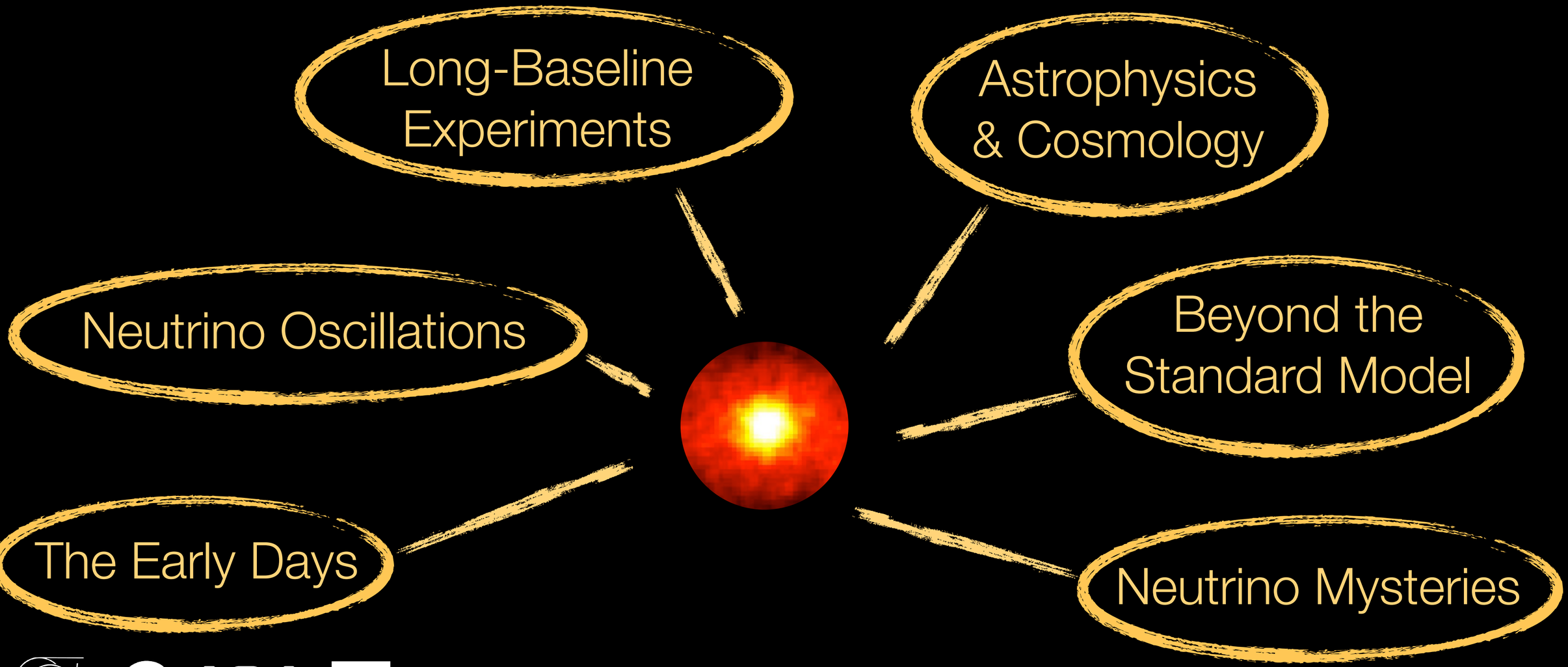


Image: SuperKamiokande

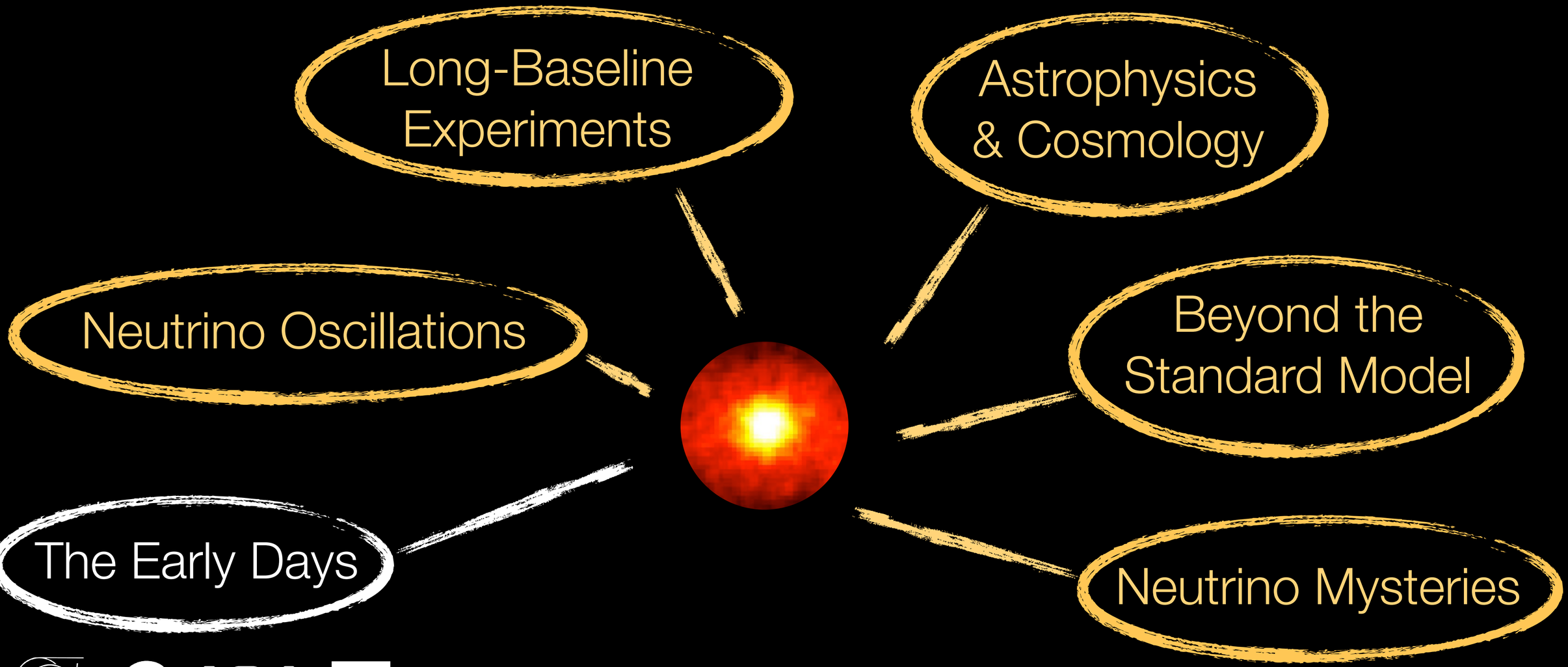
Outline

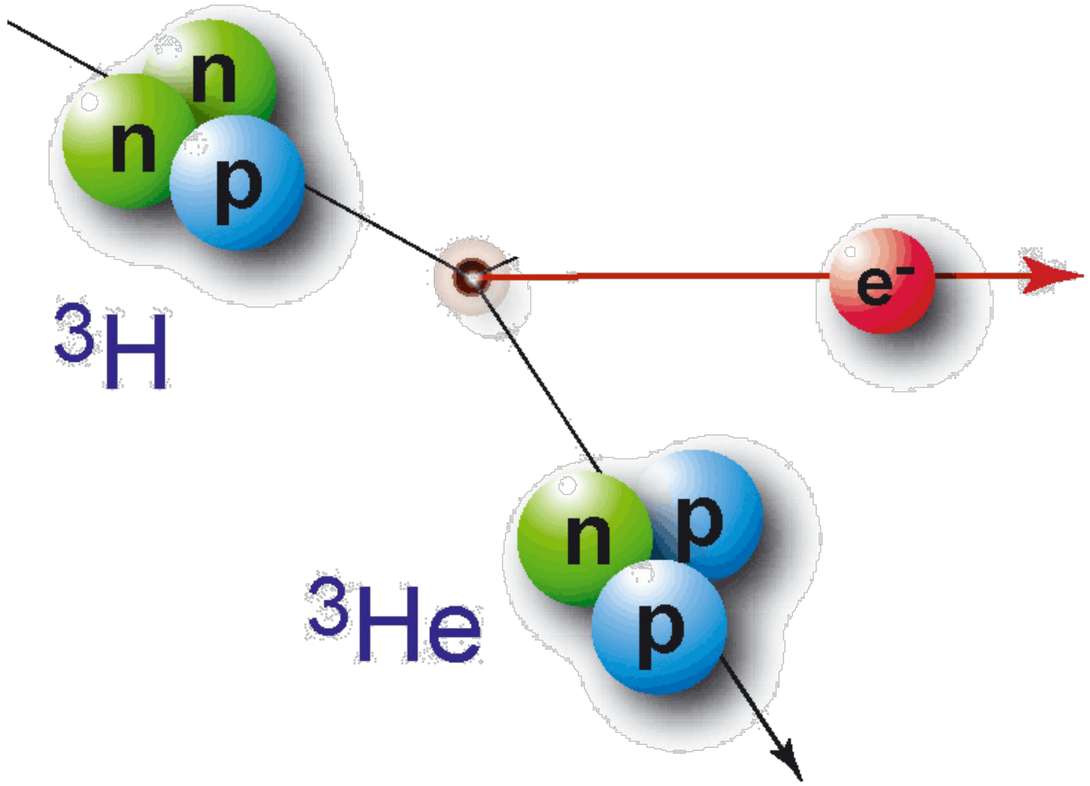


Outline

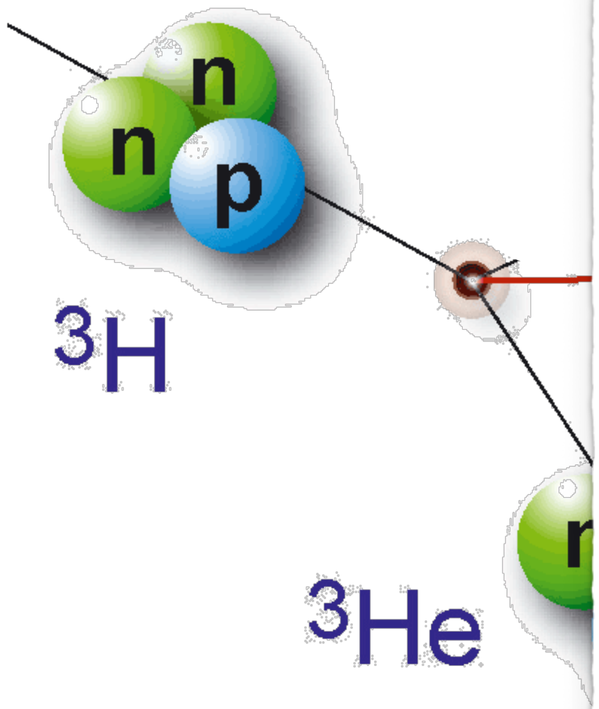

Long-Baseline Experiments
Astrophysics & Cosmology
Neutrino Oscillations
Beyond the Standard Model
The Early Days
Neutrino Mysteries

Outline


Long-Baseline Experiments
Astrophysics & Cosmology
Neutrino Oscillations
Beyond the Standard Model
The Early Days
Neutrino Mysteries



Wolfgang Pauli



Physical - Photocopie of PLC 0393

Abschrift/15.12.30 PW

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst ansuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

Wolfgang Pauli

Original - Photocopie of PLC 0393

Abschrift/15.12.30 PW

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

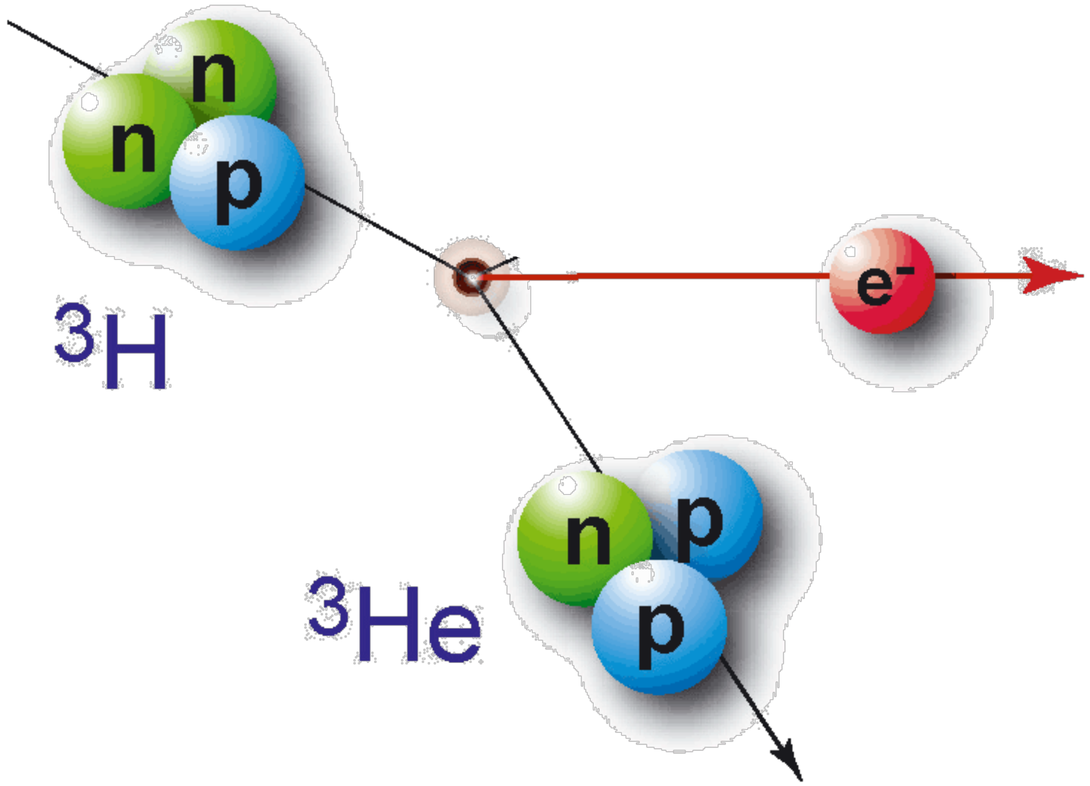
Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

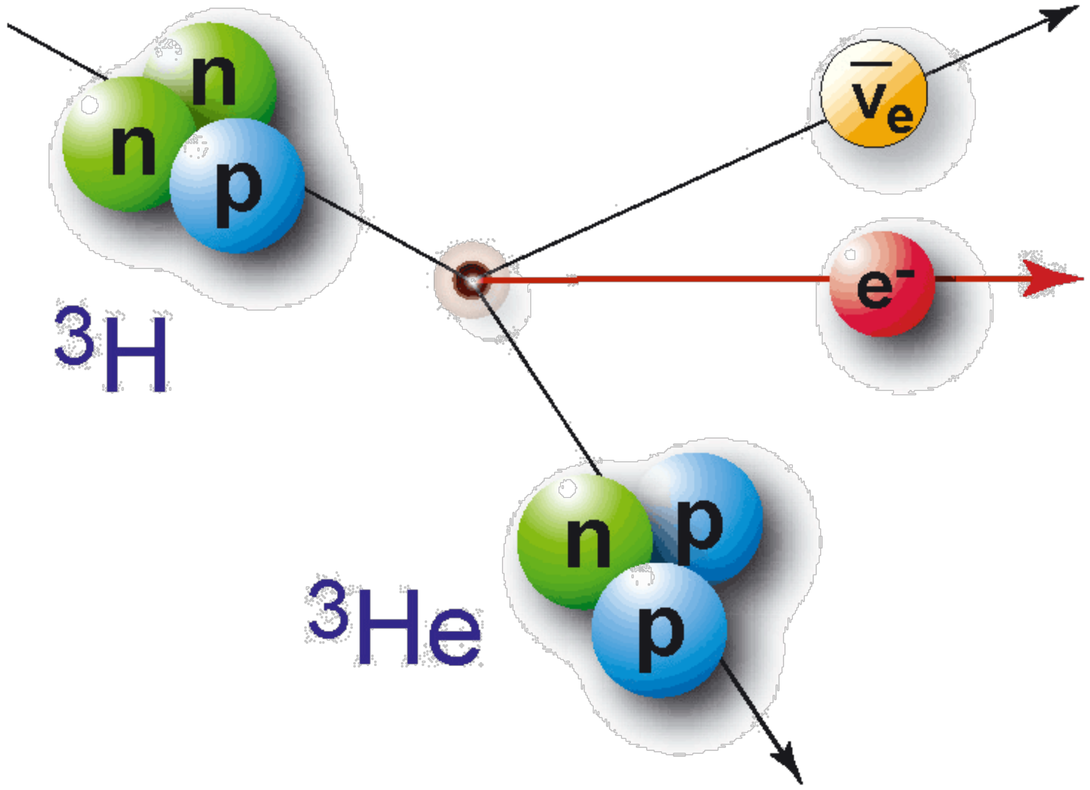
Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

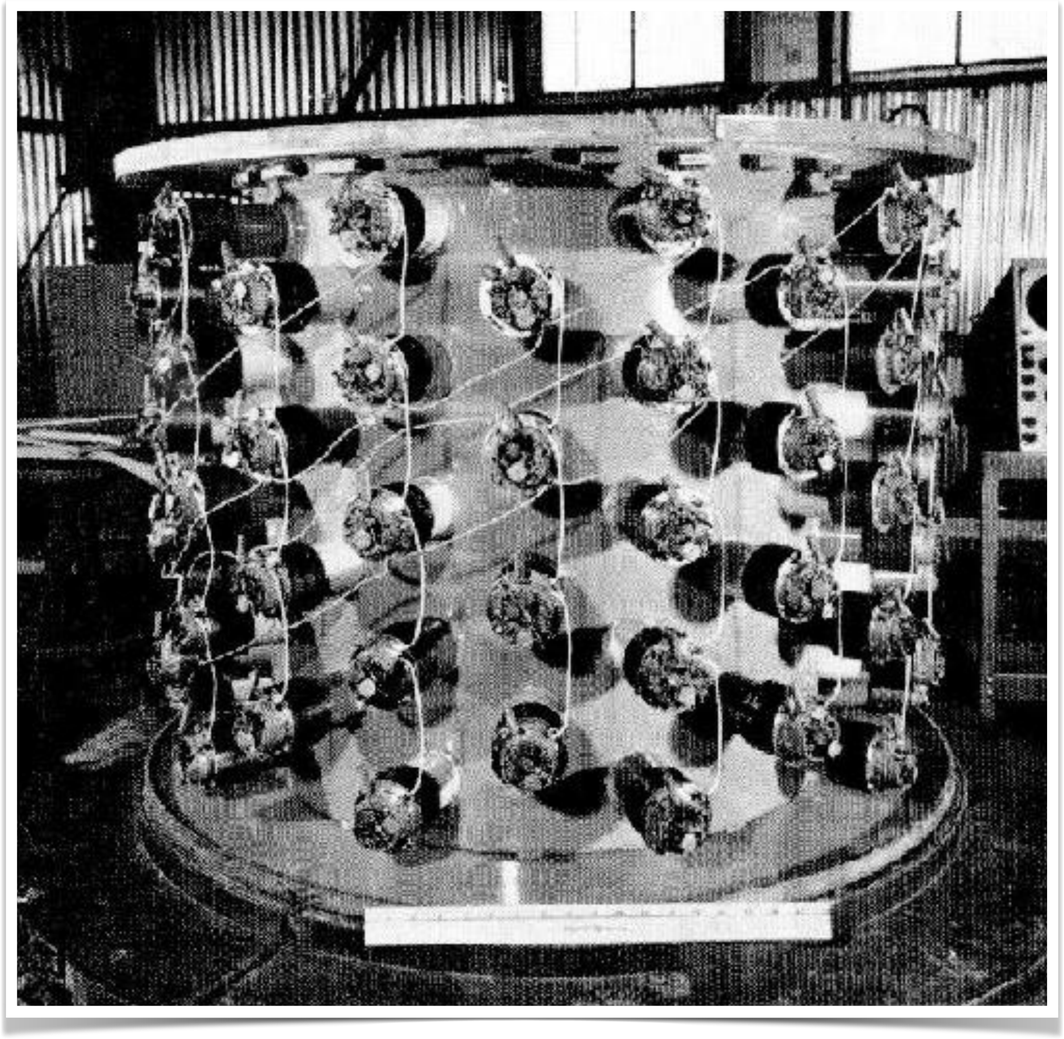
gez. W. Pauli



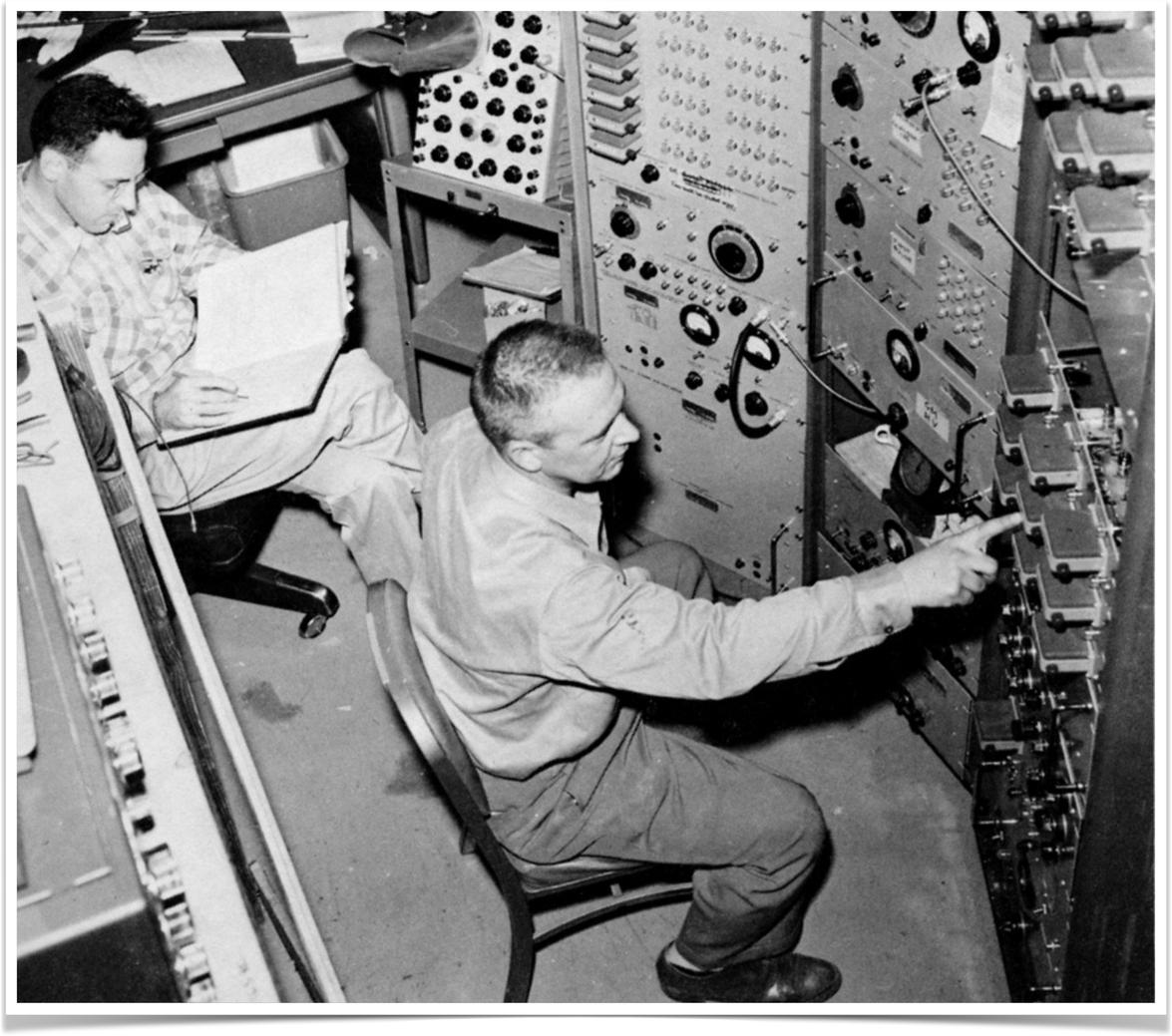
Wolfgang Pauli



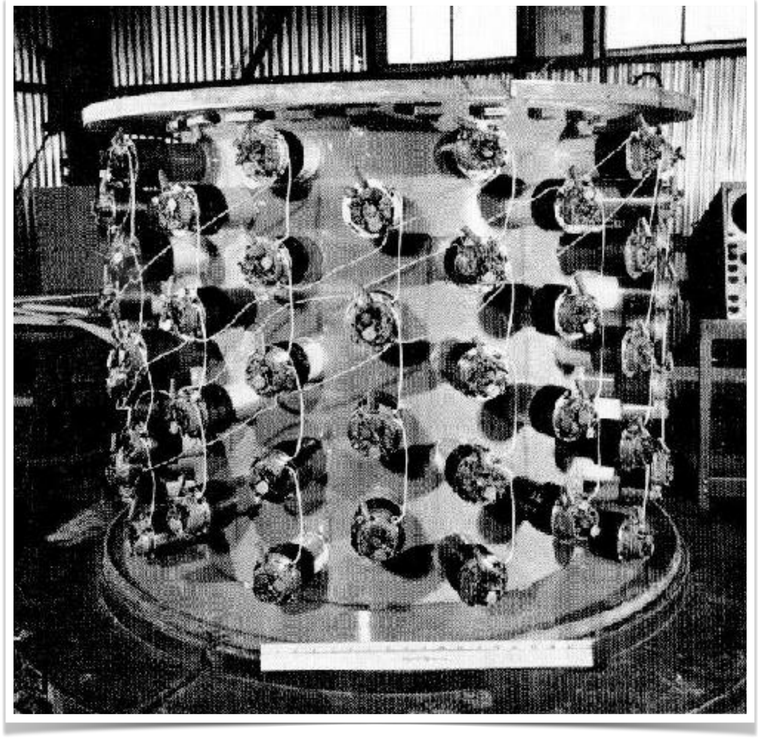
Wolfgang Pauli



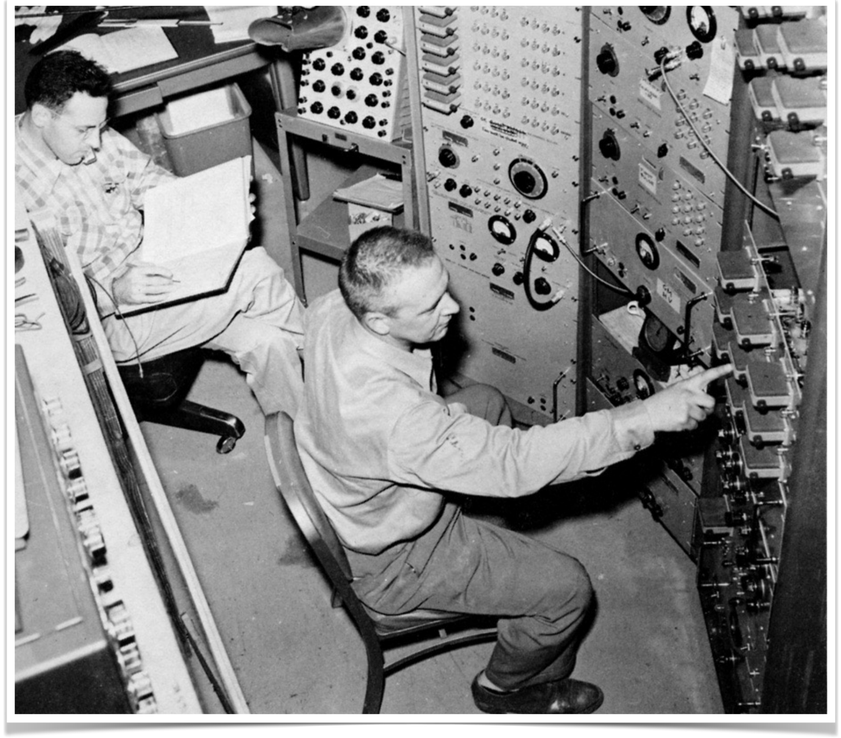
Poltergeist (1956)



Fred Reines, Clyde Cowan



Poltergeist (1956)



Fred Reines, Clyde Cowan

Nobel Prize in Physics 1995
“for the detection of the neutrino”

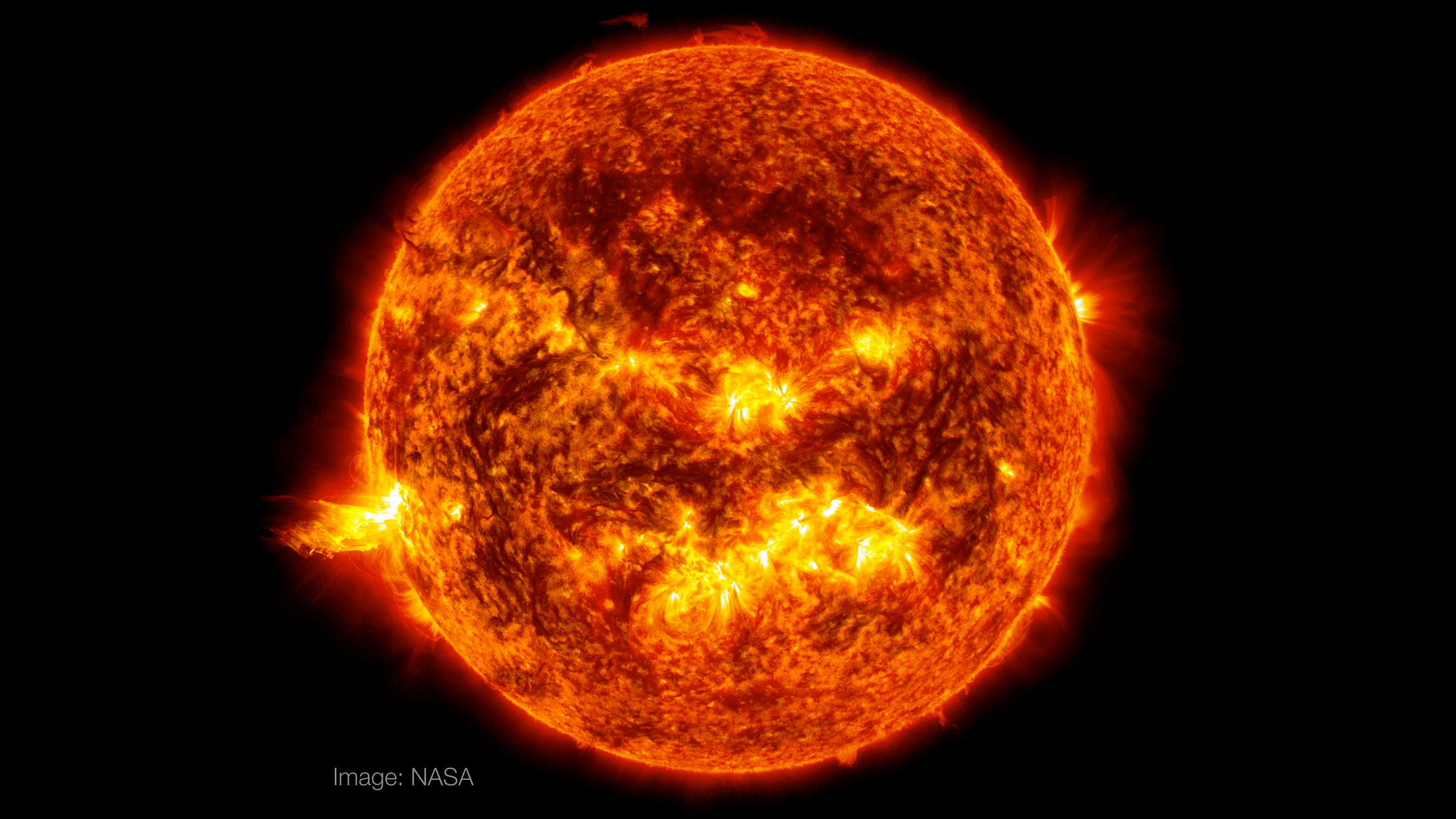


Image: NASA

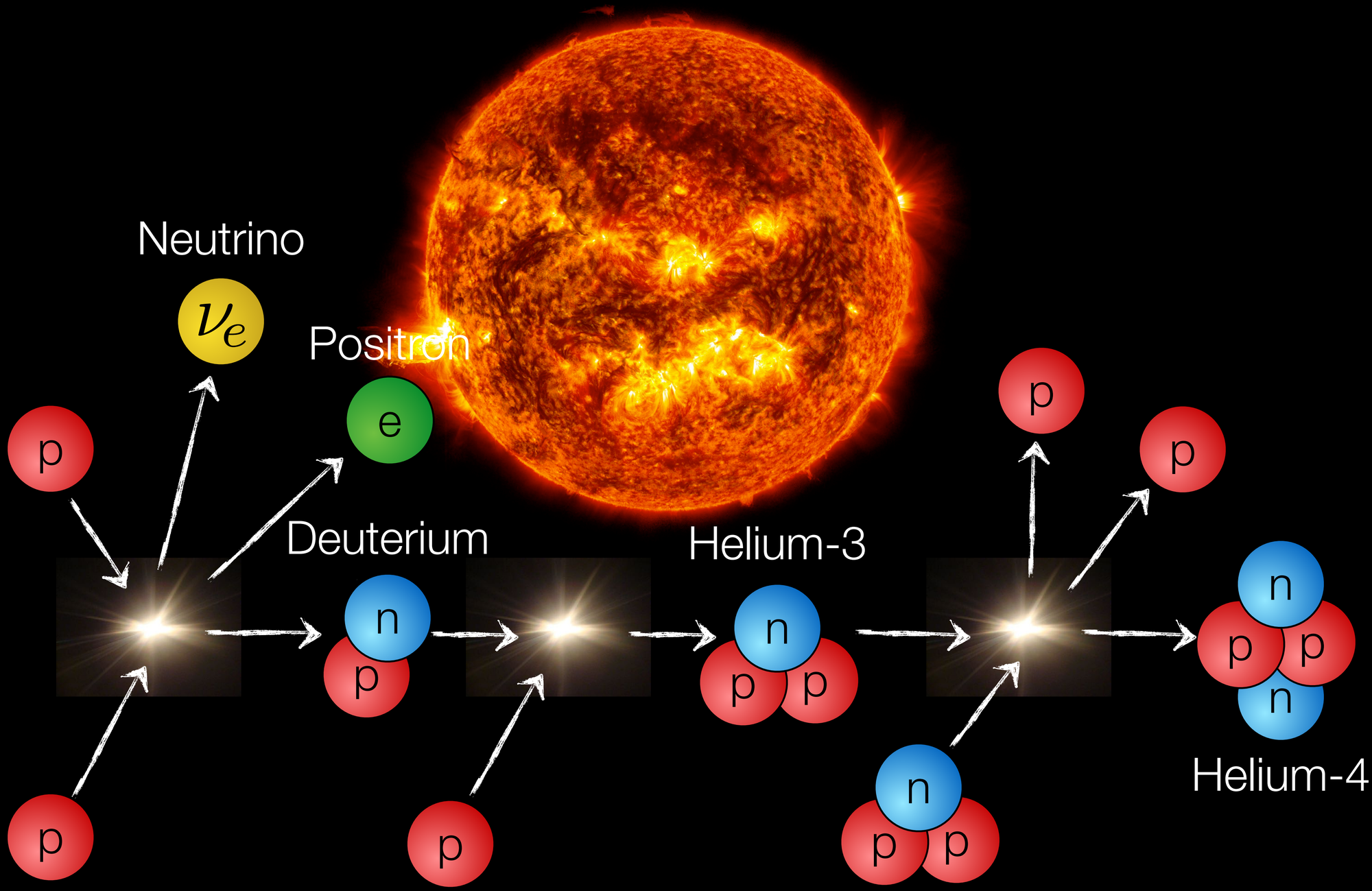
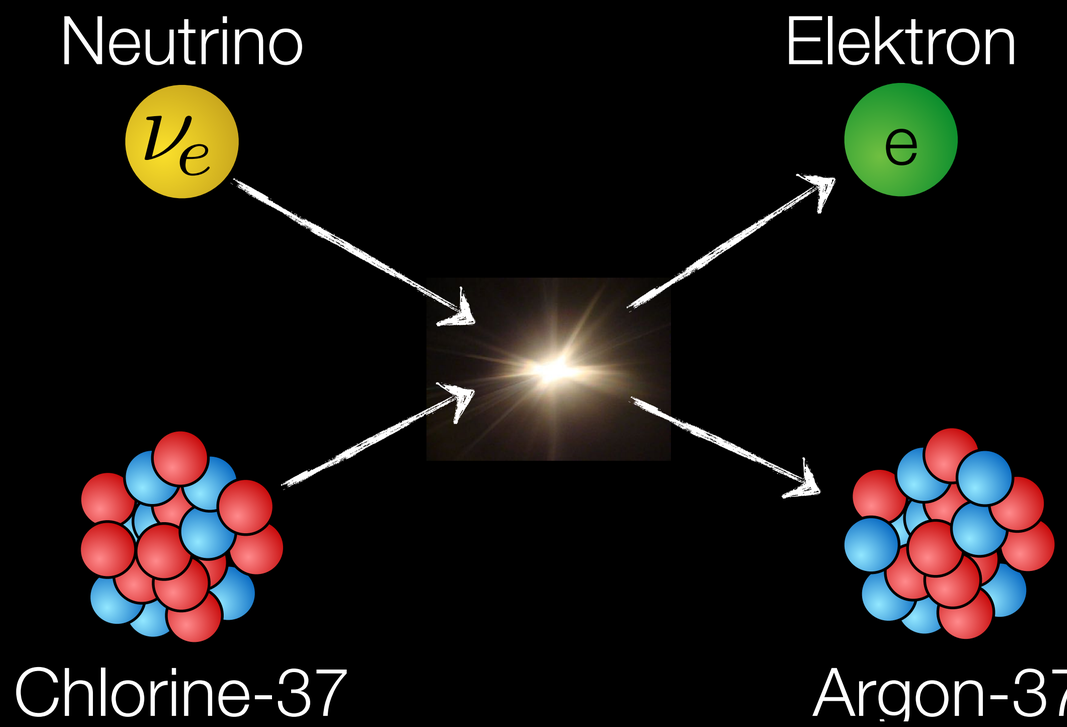
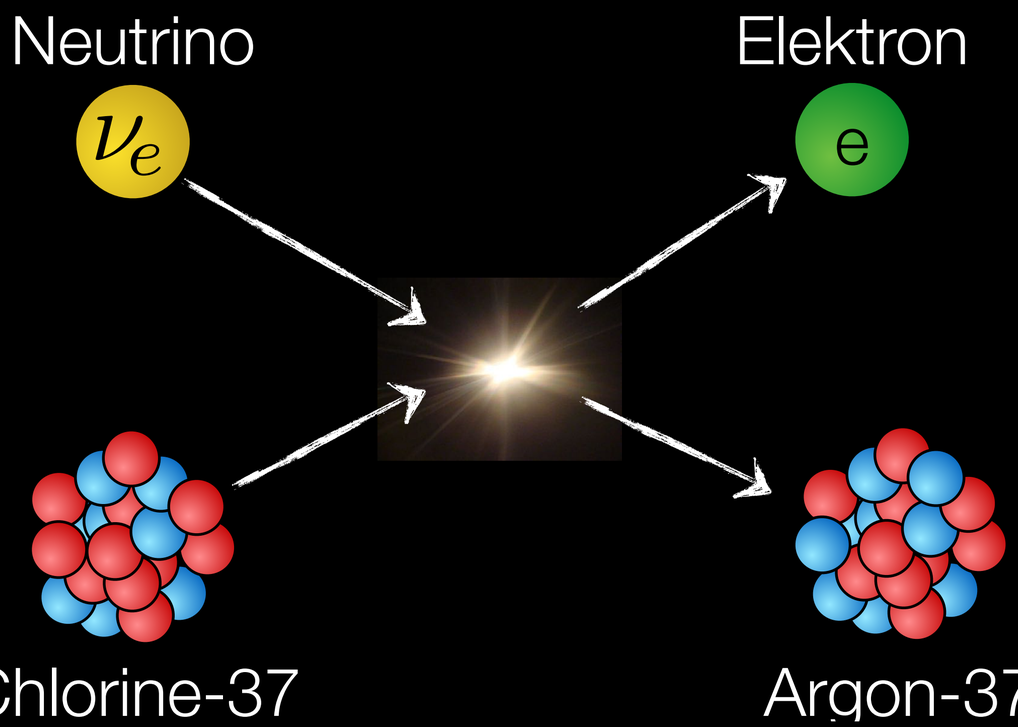

Neutrino
ν_e
Positron
e
p
p
Deuterium
n
p
Helium-3
n
p
p
p
p
p
n
p
p
n
p
p
n
p
p
n
Helium-4

Image: NASA

Nobel Prize in Physics 2002
“for pioneering contributions
to astrophysics,
in particular for the detection
of cosmic neutrinos”

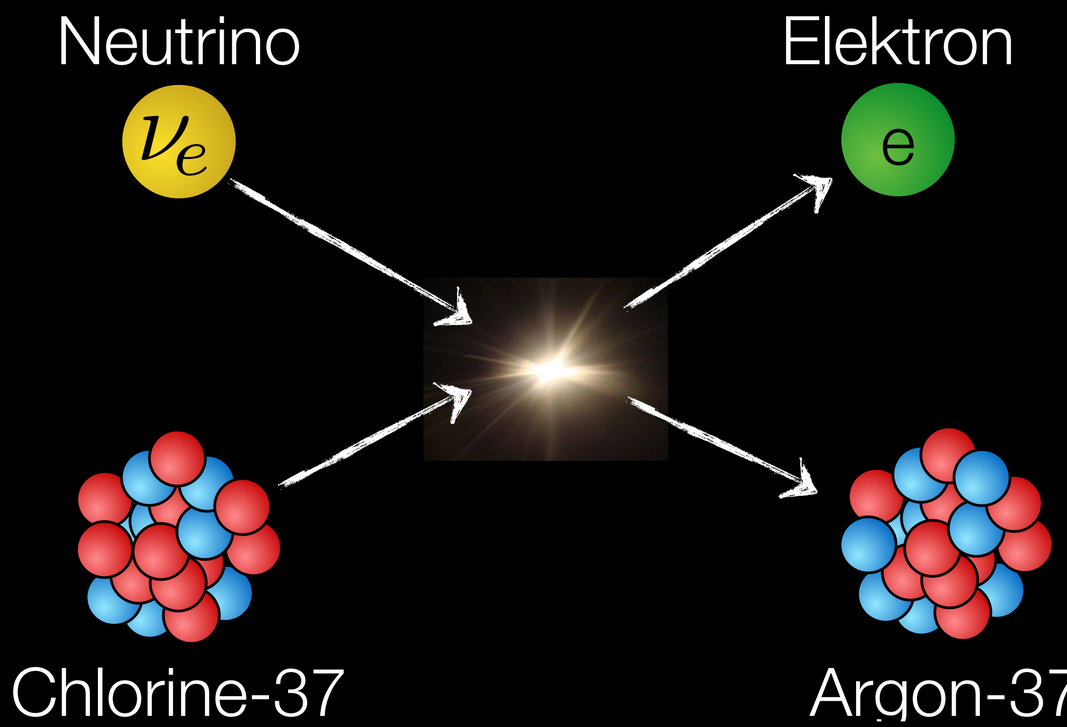

Neutrino
ν_e
Elektron
e
Chlorine-37
Argon-37

Ray Davis

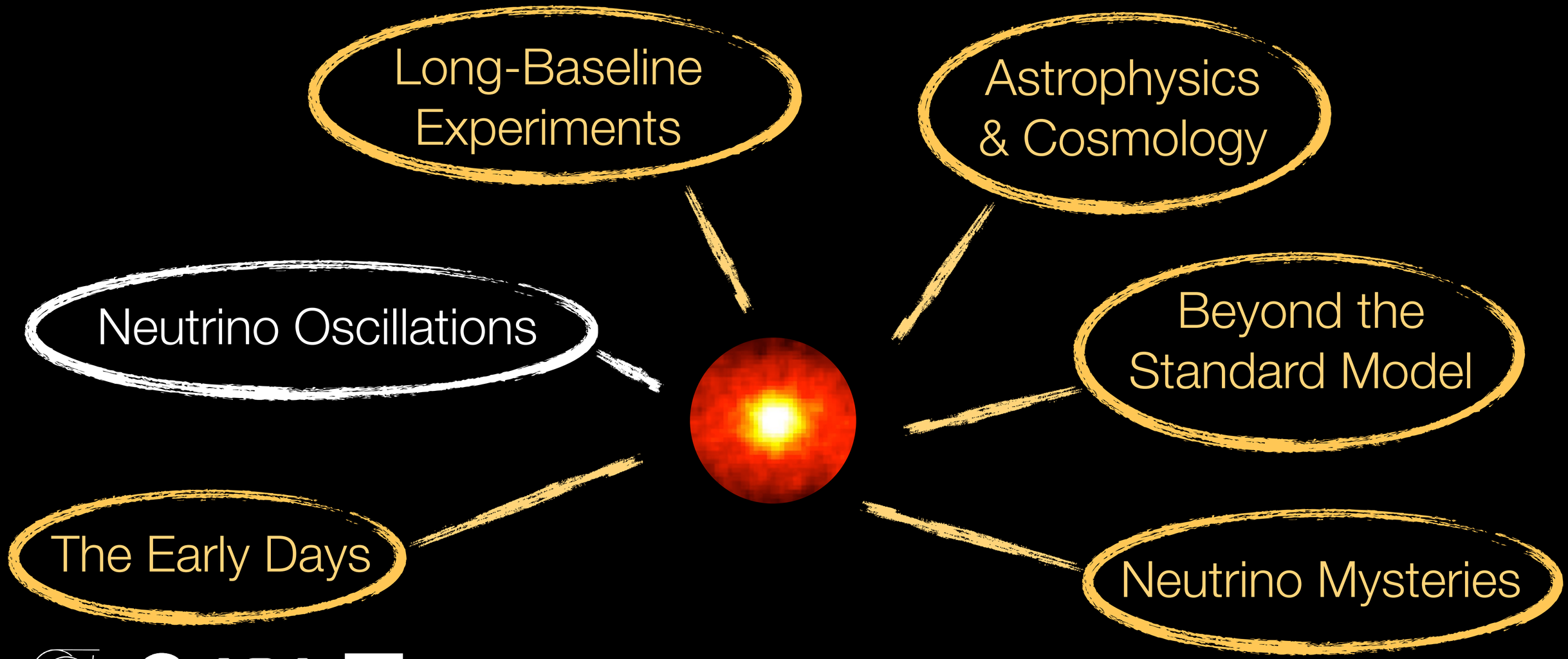


John Bahcall

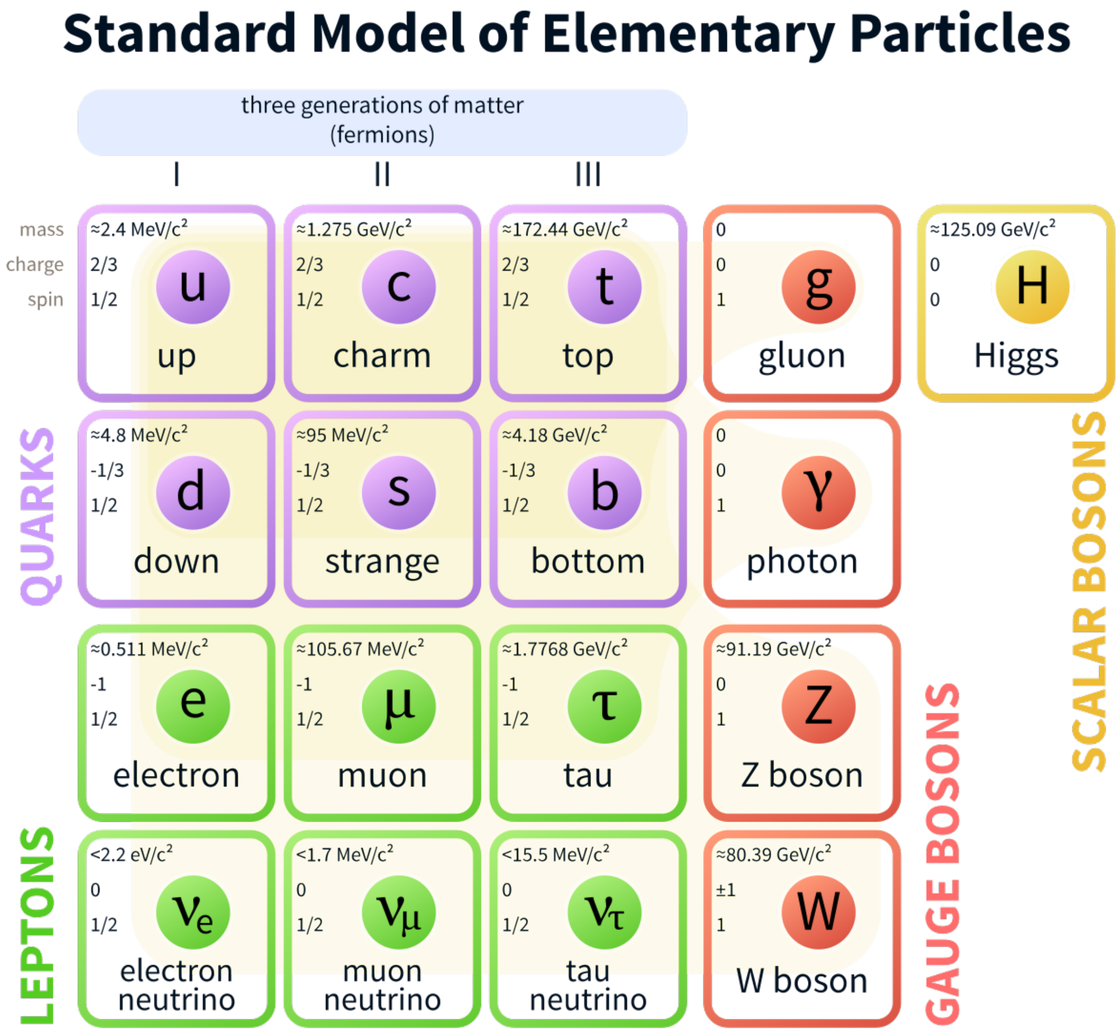
Ray Davis



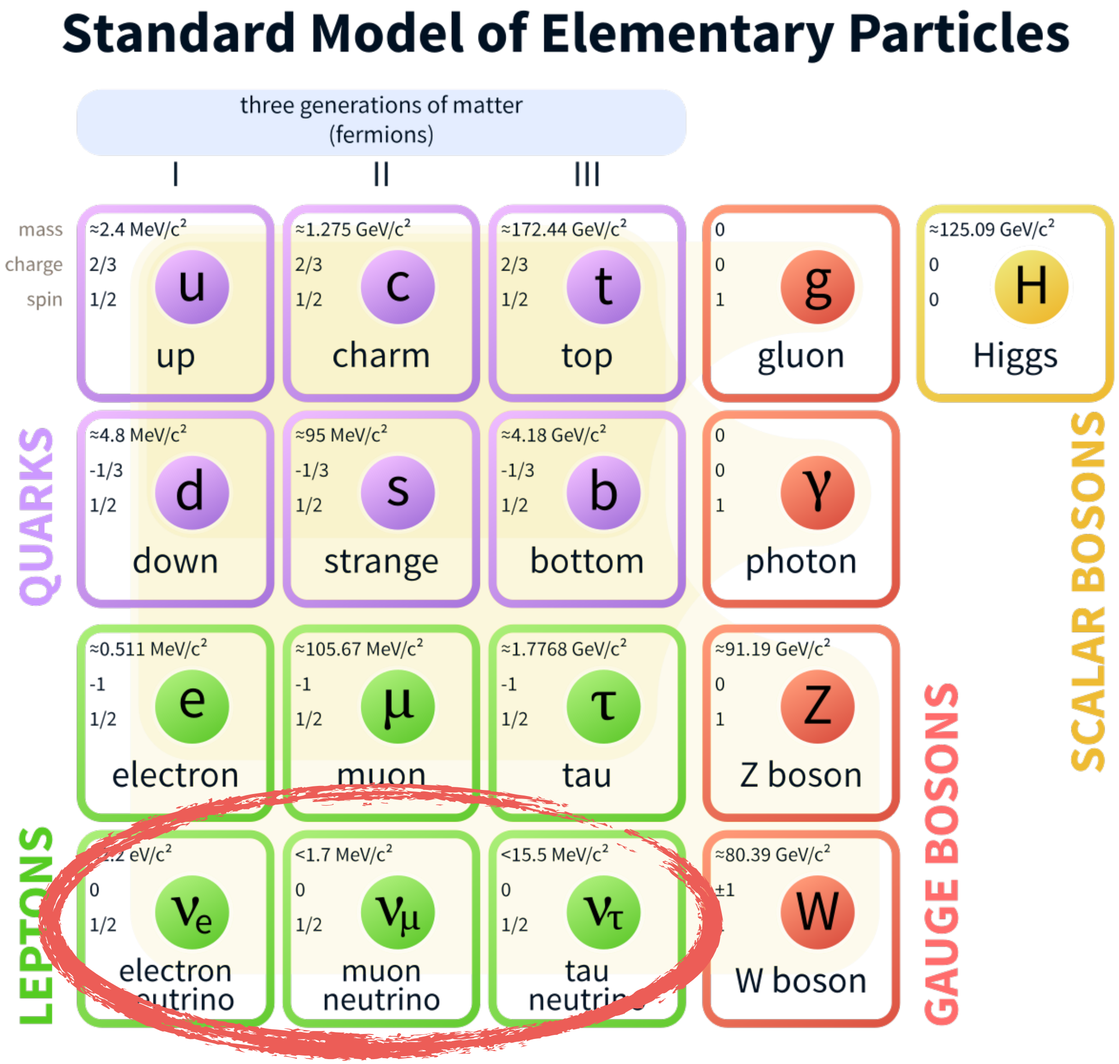
Outline


Long-Baseline Experiments
Astrophysics & Cosmology
Neutrino Oscillations
Beyond the Standard Model
The Early Days
Neutrino Mysteries

Particle Physicists' View of Neutrinos



Particle Physicists' View of Neutrinos



Neutrinos in the Standard Model

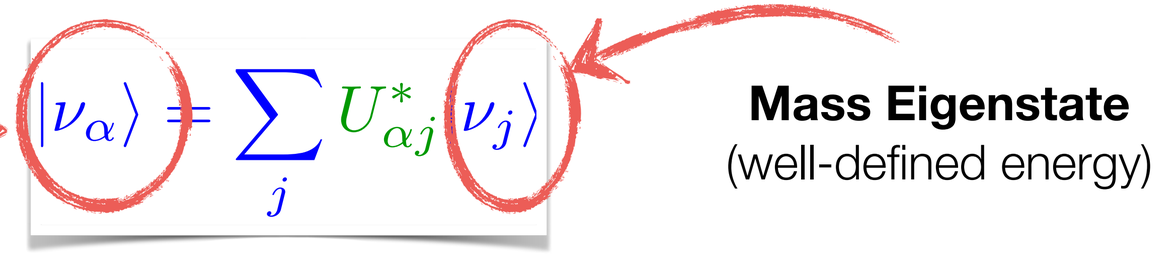
$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

Neutrinos in the Standard Model

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

Mass Eigenstate
(well-defined energy)

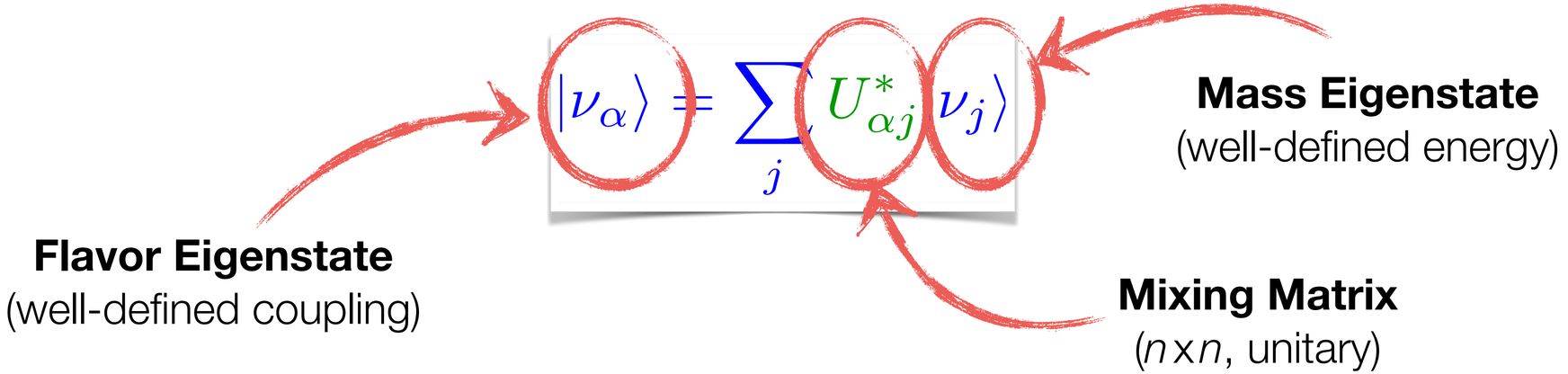
Neutrinos in the Standard Model



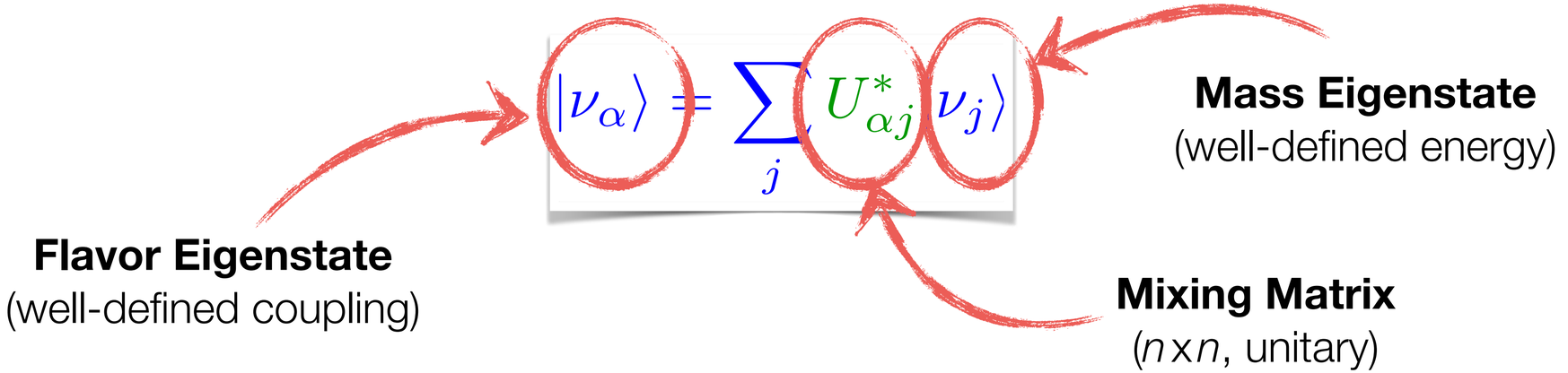
Flavor Eigenstate
(well-defined coupling)

Mass Eigenstate
(well-defined energy)

Neutrinos in the Standard Model



Neutrinos in the Standard Model



3-flavor mixing matrix:

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

Neutrinos in the Standard Model

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

Flavor Eigenstate
(well-defined coupling)

Mass Eigenstate
(well-defined energy)

Mixing Matrix
(nxn, unitary)

3-flavor mixing matrix:

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

Large
close to maximal

Neutrinos in the Standard Model

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

Flavor Eigenstate
(well-defined coupling)

Mass Eigenstate
(well-defined energy)

Mixing Matrix
(nxn, unitary)

3-flavor mixing matrix:

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

Large
close to maximal

Large
but non-maximal

Neutrinos in the Standard Model

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

Flavor Eigenstate
(well-defined coupling)

Mass Eigenstate
(well-defined energy)

Mixing Matrix
(*n*x*n*, unitary)

3-flavor mixing matrix:

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

Large
close to maximal

Small
but non-negligible (~0.1)

Large
but non-maximal

Neutrinos in the Standard Model

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

Flavor Eigenstate
(well-defined coupling)

Mass Eigenstate
(well-defined energy)

Mixing Matrix
(*n*x*n*, unitary)

3-flavor mixing matrix:

Unknown

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

Large
close to maximal

Small
but non-negligible (~0.1)

Large
but non-maximal

Neutrino Oscillations

- Initial state

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

- Transition probability

$$P_{\alpha\to\beta} = \left|\langle\nu_\beta| e^{-i\hat{H}T} |\nu_\alpha\rangle\right|^2$$

$$= \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \exp\left[-i\left(E_j - E_k\right)T\right]$$

- Two-flavor approximation

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \qquad P_{\alpha\to\beta} \simeq \sin^2 2\theta \sin^2 \frac{\Delta m^2 T}{4E}$$

Neutrino Oscillations

- Initial state

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

- Transition probability

$$P_{\alpha\to\beta} = \left|\langle\nu_\beta| e^{-i\hat{H}T} |\nu_\alpha\rangle\right|^2$$

$$= \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \exp\left[-i\left(E_j - E_k\right)T\right]$$

Mixing angle
controls oscillation amplitude

- Two-flavor approximation

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$P_{\alpha\to\beta} \simeq \sin^2 2\theta \sin^2 \frac{\Delta m^2 T}{4E}$$

Neutrino Oscillations

- Initial state

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

- Transition probability

$$P_{\alpha\to\beta} = \left|\langle\nu_\beta| e^{-i\hat{H}T} |\nu_\alpha\rangle\right|^2$$

$$= \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \exp\left[-i\left(E_j - E_k\right)T\right]$$

- Two-flavor approximation

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

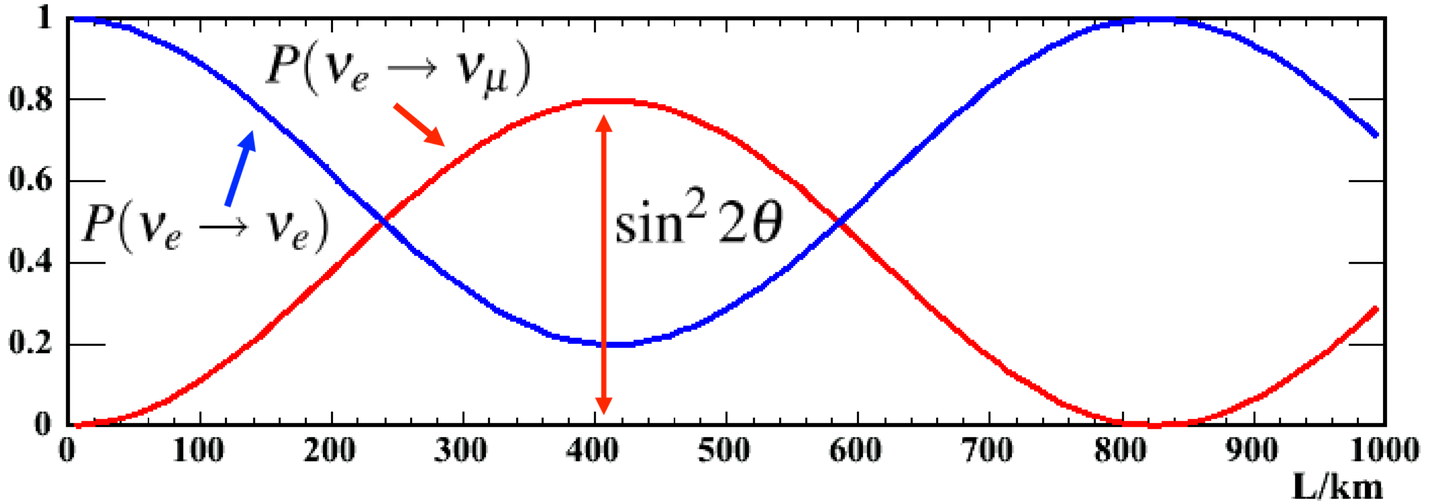
$$P_{\alpha\to\beta} \simeq \sin^2 2\theta \sin^2 \frac{\Delta m^2 T}{4E}$$

Mixing angle
controls oscillation amplitude

Mass squared difference
controls oscillation length

Neutrino Oscillations

- e.g. $\Delta m^2 = 0.003\,\mathrm{eV}^2, \quad \sin^2 2\theta = 0.8, \quad E_\nu = 1\,\mathrm{GeV}$



- wavelength

$$\lambda_{\mathrm{osc}} = \frac{4\pi E}{\Delta m^2}$$

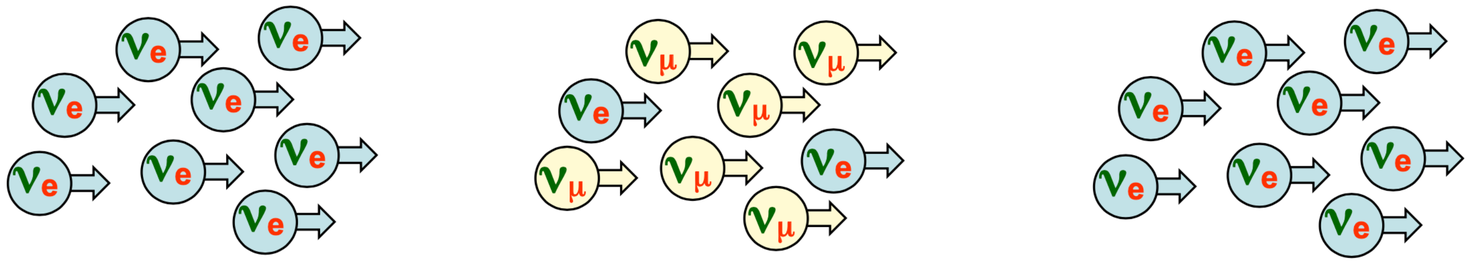
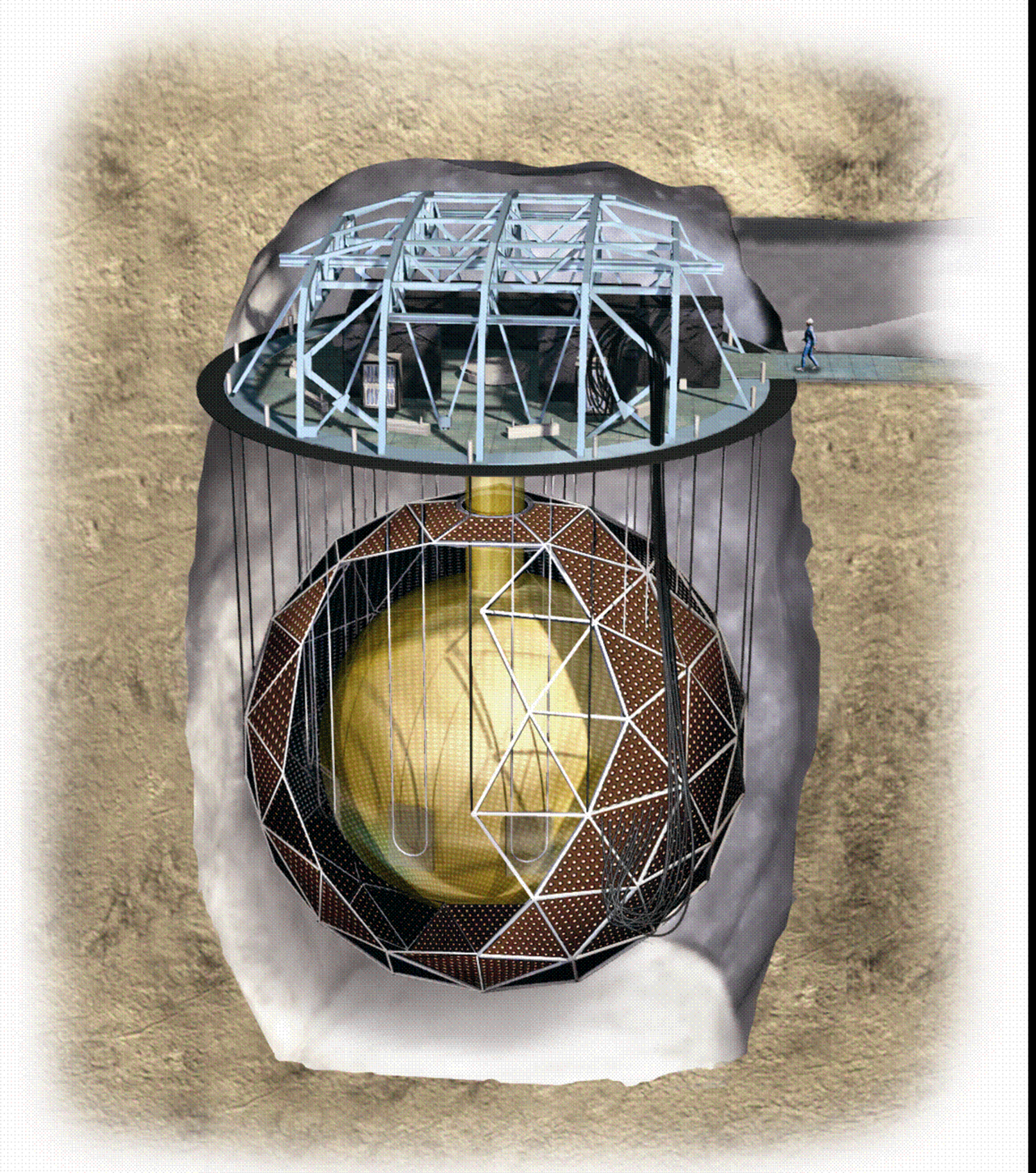
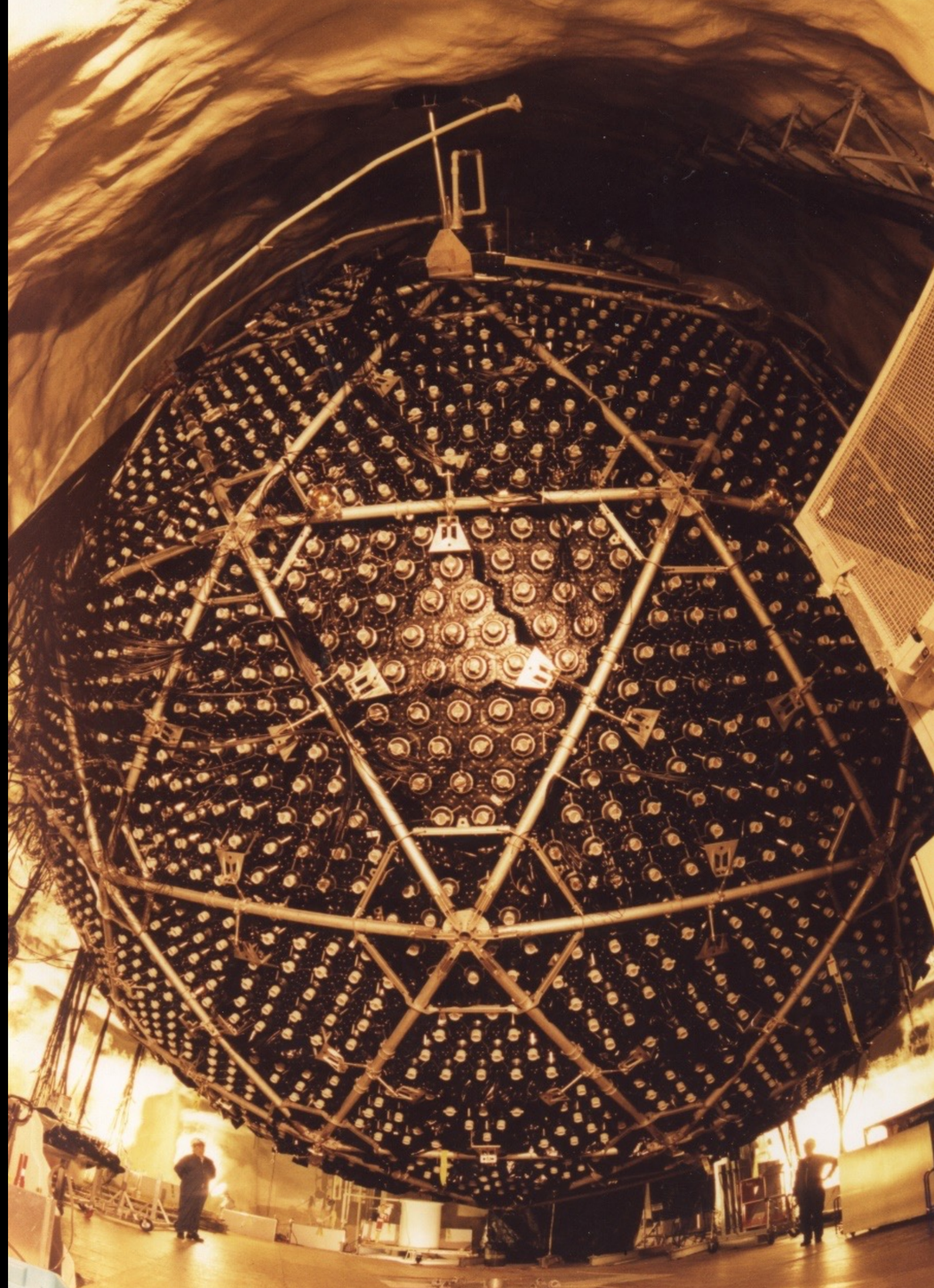
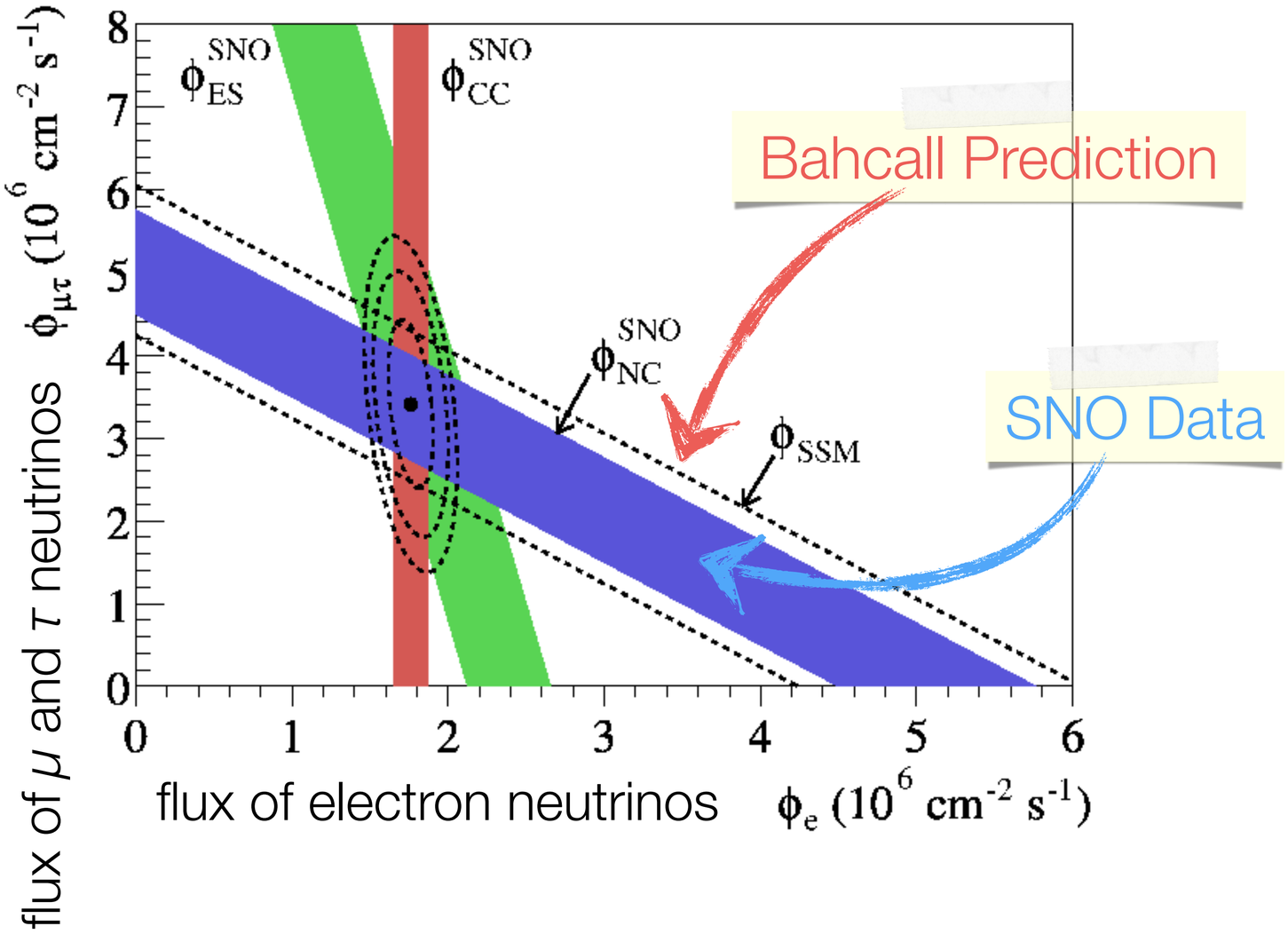


Image: Mark Thomson

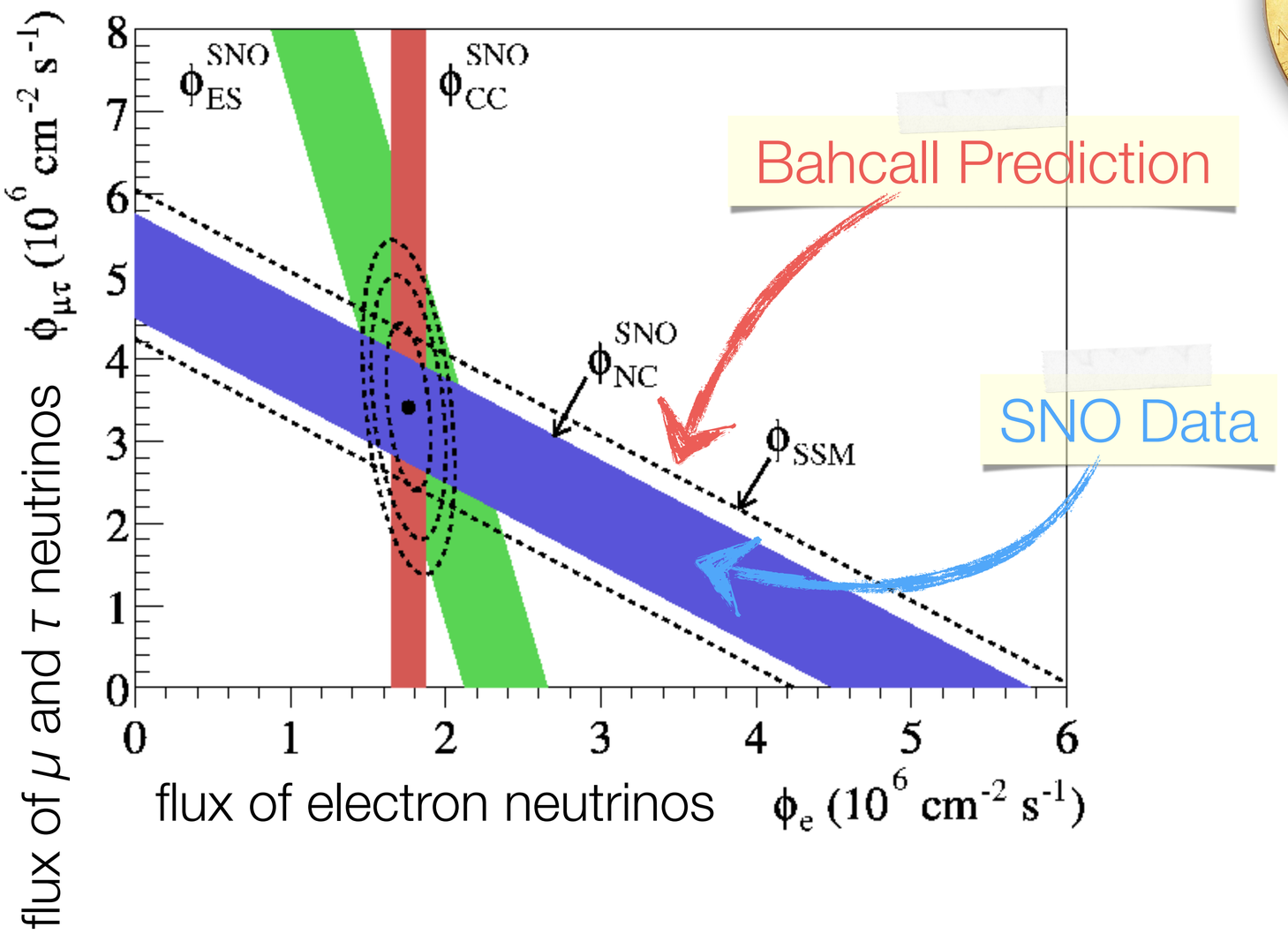




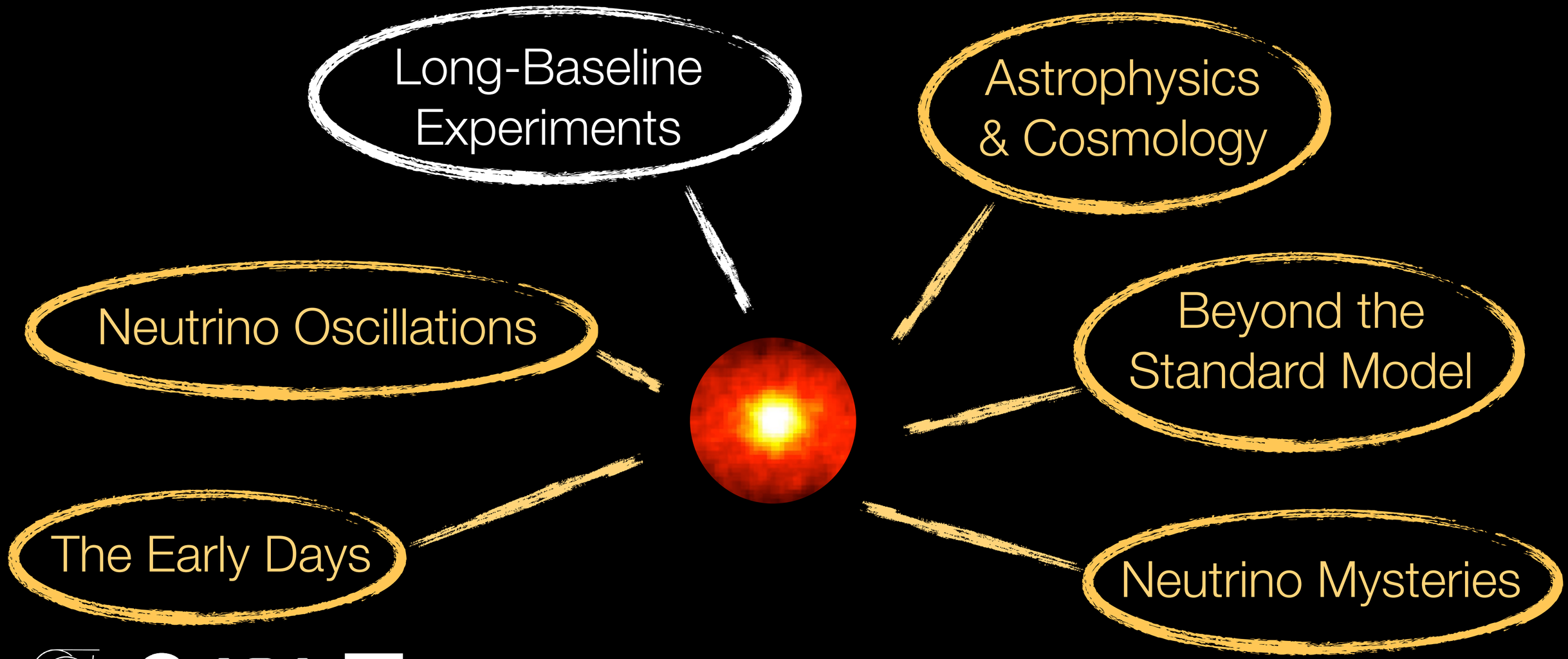
Resolving the Solar Neutrino Mystery



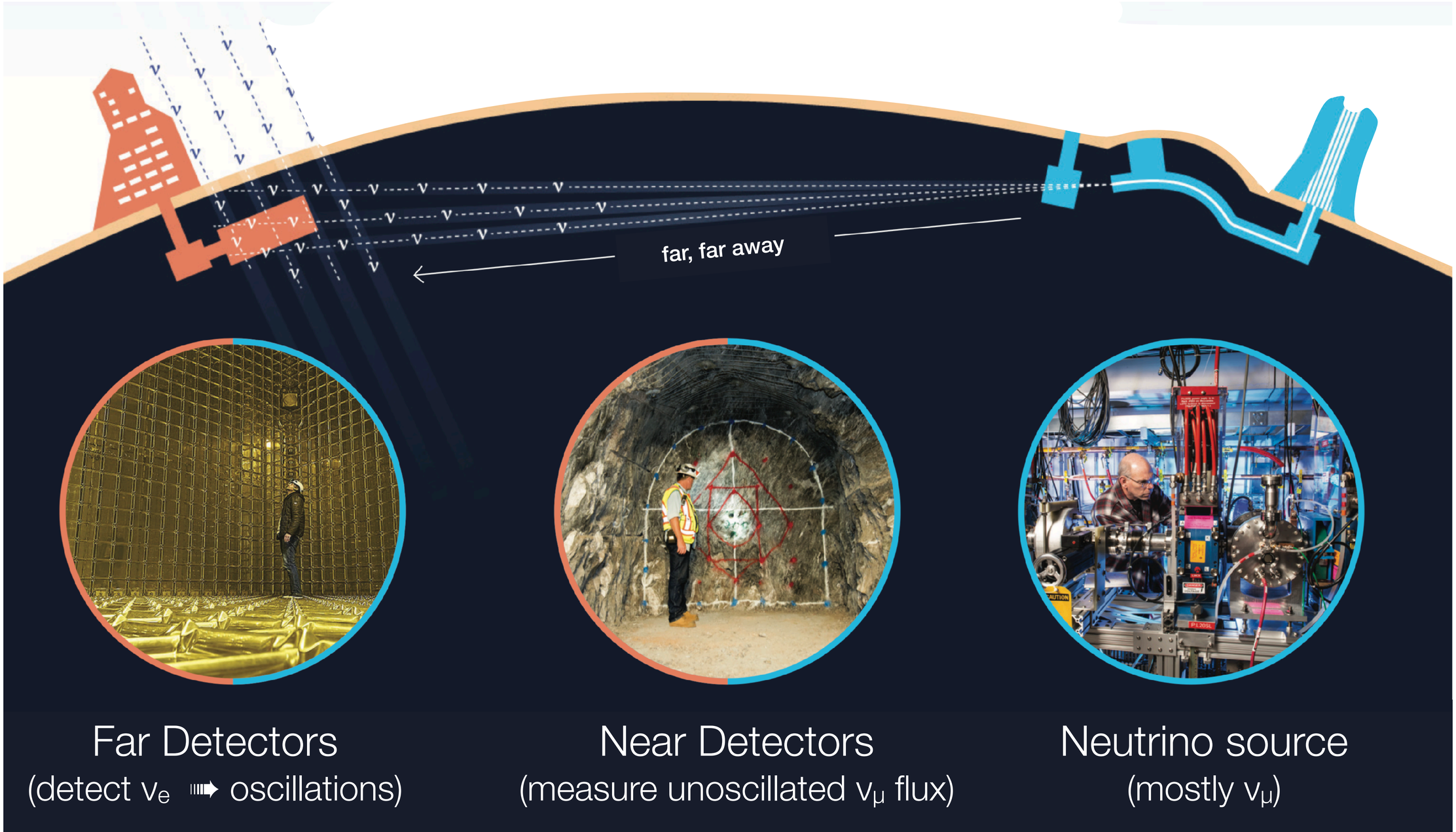
Resolving the Solar Neutrino Mystery



Outline


Long-Baseline Experiments
Astrophysics & Cosmology
Neutrino Oscillations
Beyond the Standard Model
The Early Days
Neutrino Mysteries

Long-Baseline Experiments



Making a Neutrino Beam

Image: MINOS Collaboration

Making a Neutrino Beam

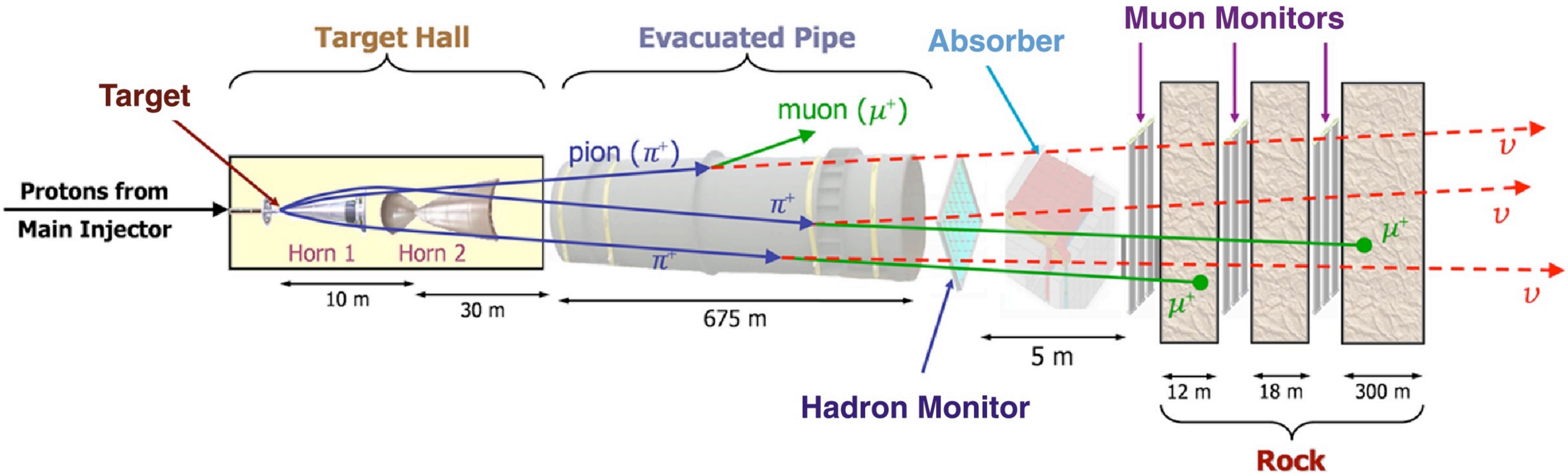
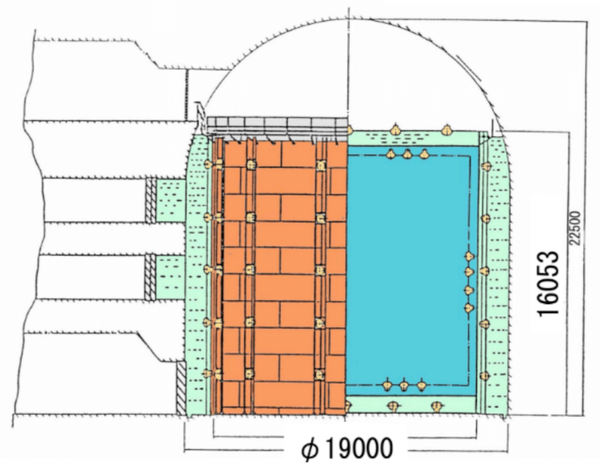
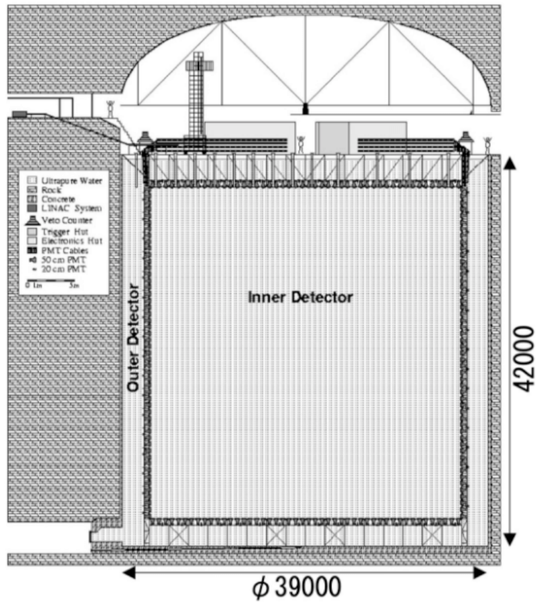
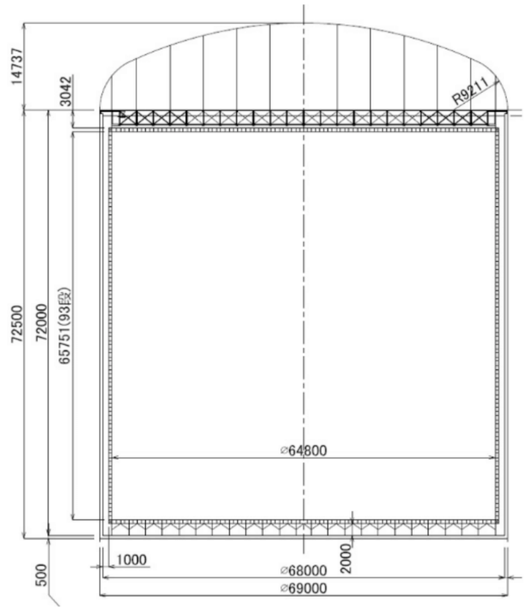


Image: MINOS Collaboration

Long-Baseline Experiments: Kamiokande

Kamiokande	Super-Kamiokande	Hyper-Kamiokande
1983～1996	1996~Present	Aiming to start observation in 2027
		
Size		
19m diameter x 16m hight	39m diameter x 42m hight	68m diameter x 71m hight

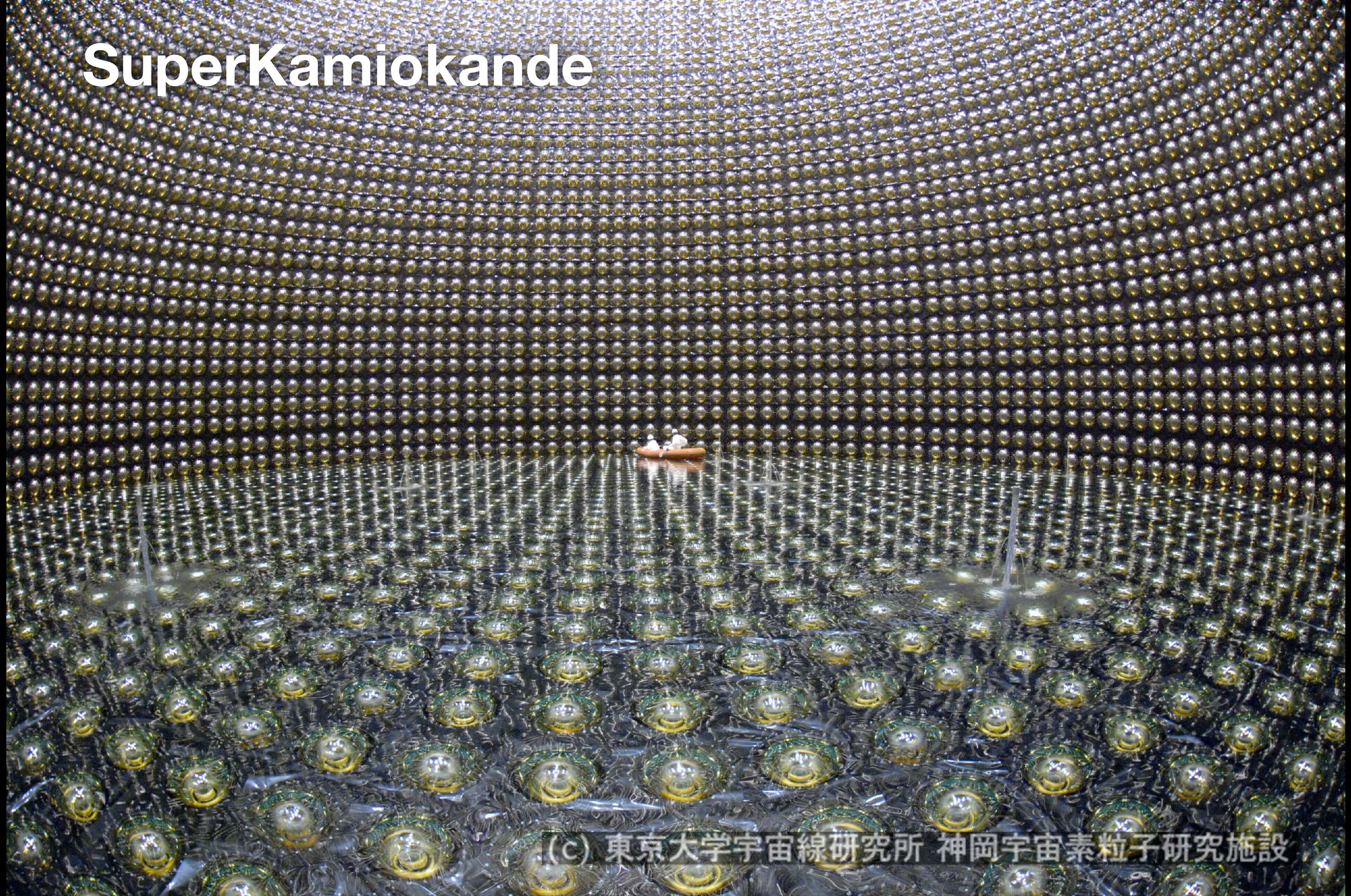
Long-Baseline Experiments: Kamiokande

Kamiokande	Super-Kamiokande	Hyper-Kamiokande
1983～1996	1996~Present	Aiming to start observation in 2027
Water mass (Fiducial mass)		
4500 ton※ (680~1040 ton) ※The waer mass in the tank(inner tank and, upper and bottom outer tank) is 3000 ton	50000 ton (22500 ton)	260000 ton (190000 ton)
Photomultiplier Tubes		
50cm diameter / 948	50cm diameter / 11146	50cm diameter / about 40000
Main and expected Results		

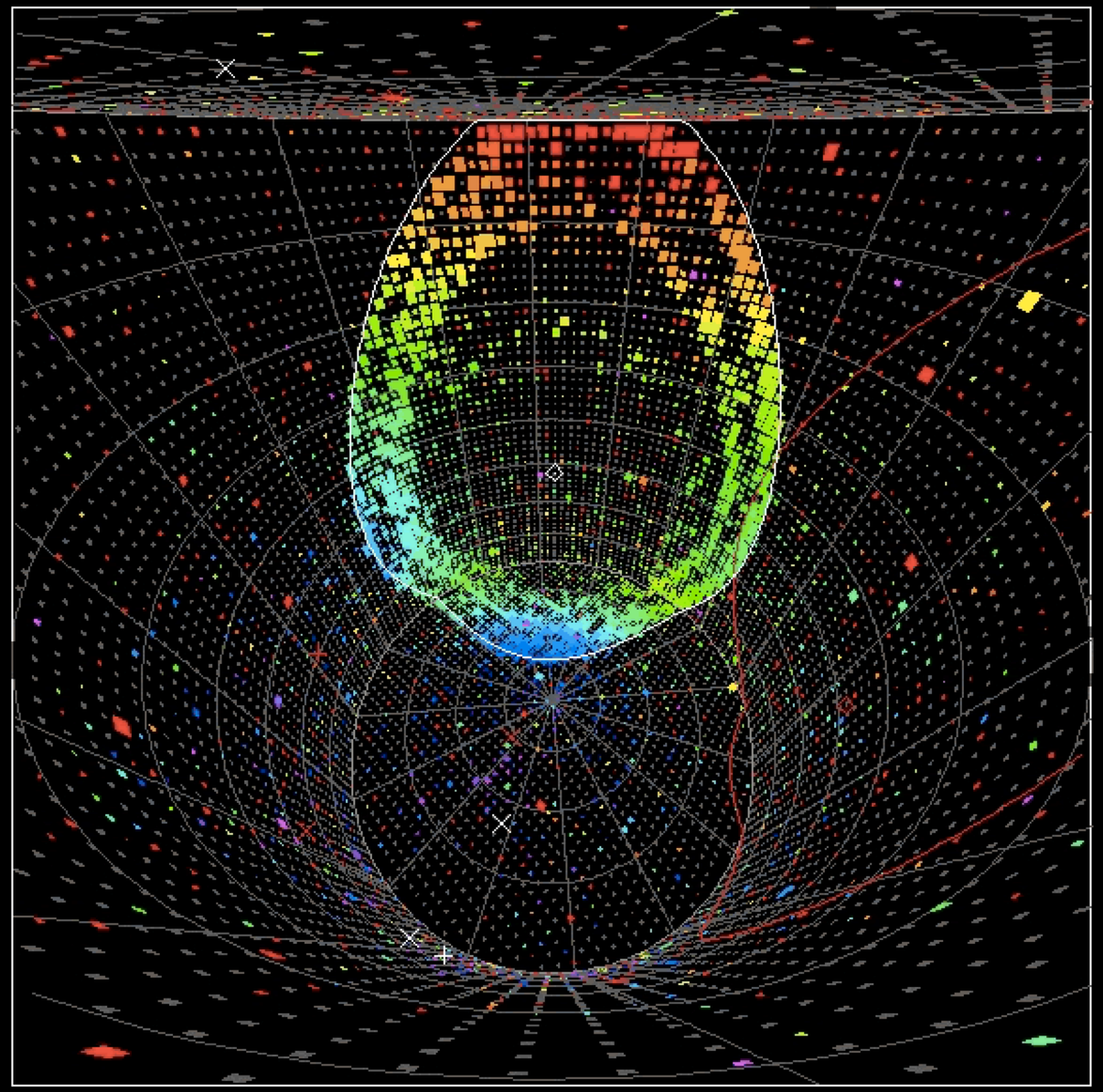
Long-Baseline Experiments: Kamiokande

Kamiokande	Super-Kamiokande	Hyper-Kamiokande
1983～1996	1996~Present	Aiming to start observation in 2027
Main and expected Results		
World's first observation of neutrinos from a supernova explosion and observation of solar neutrinos, leading to the creation of neutrino astronomy	Discovery of neutrino oscillations, showing that neutrinos have mass	1. Discovery of the difference between neutrino and antineutrino oscillations (CP violation) and precise measurements to elucidate the origin of matter in the universe 2. Further development of neutrino astronomy 3. Proof of "unification of elementary particles" and "unification of electromagnetic, weak and strong force" by the discovery of proton decay
Major awards		
The Nobel Prize in Physics 2002 Masatoshi Koshiba	The Nobel Prize in Physics 2015 Takaaki Kajita	

SuperKamiokande



A SuperKamiokande Event



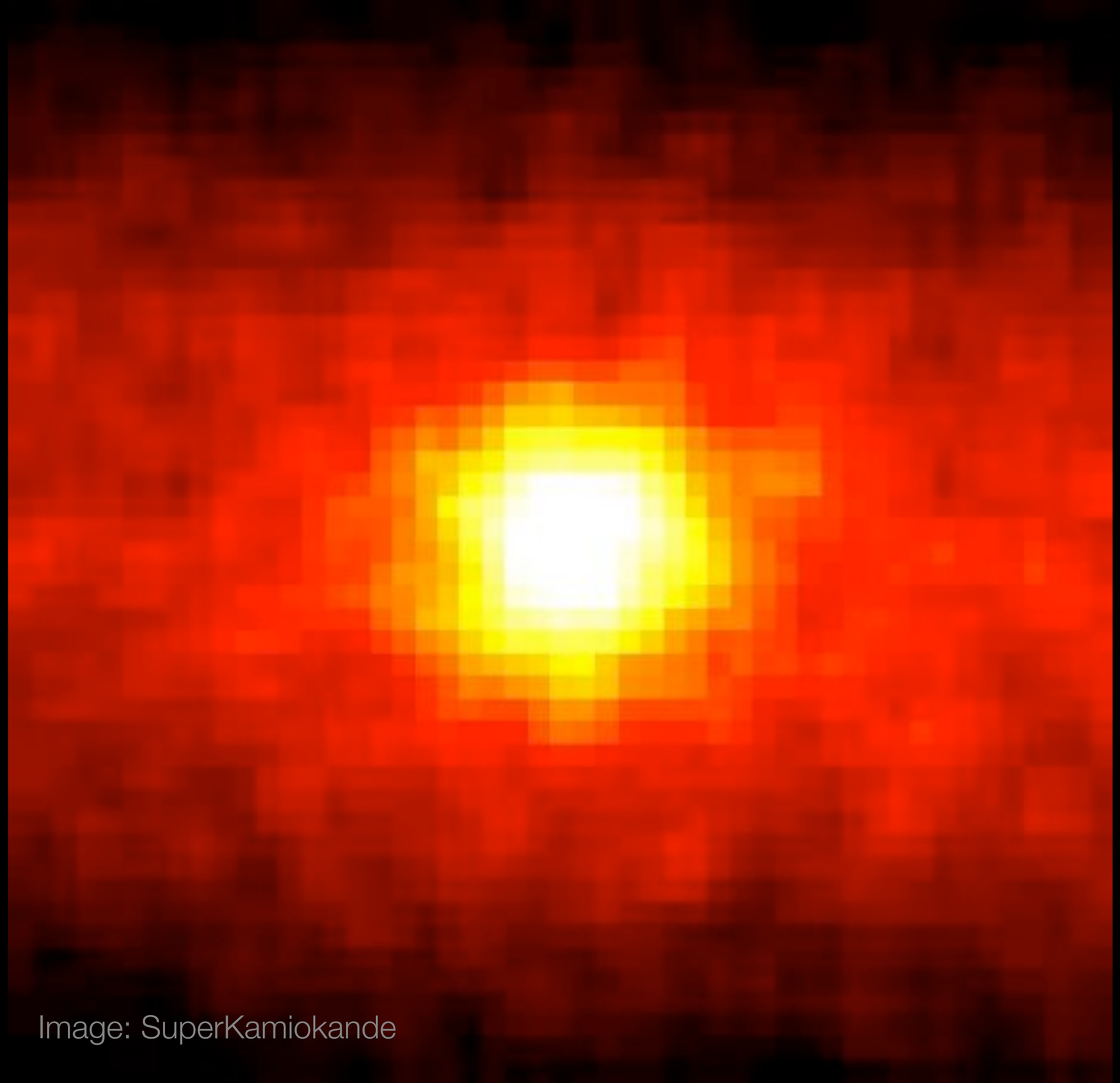
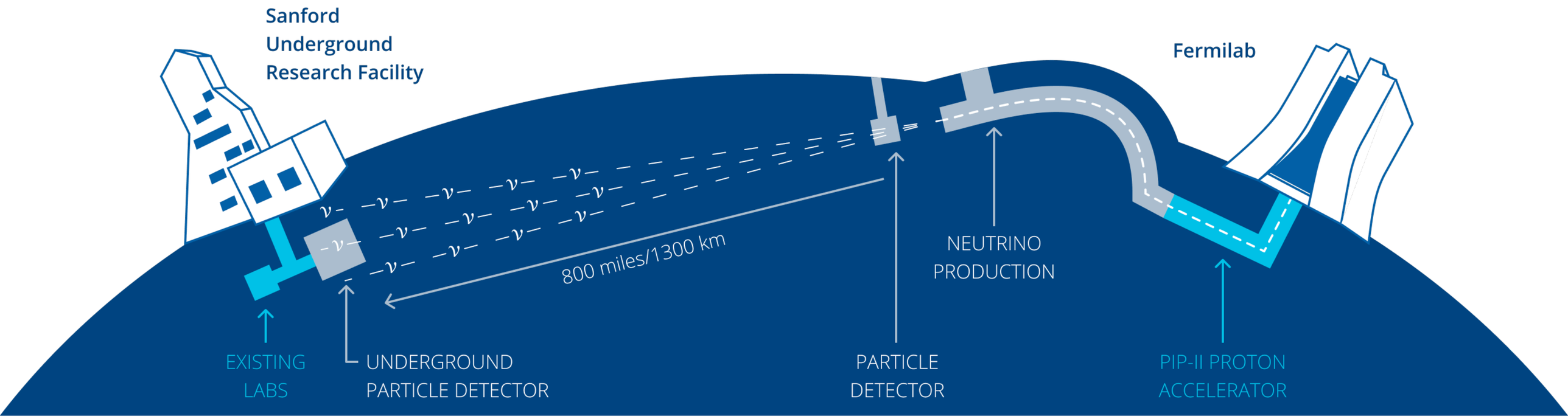
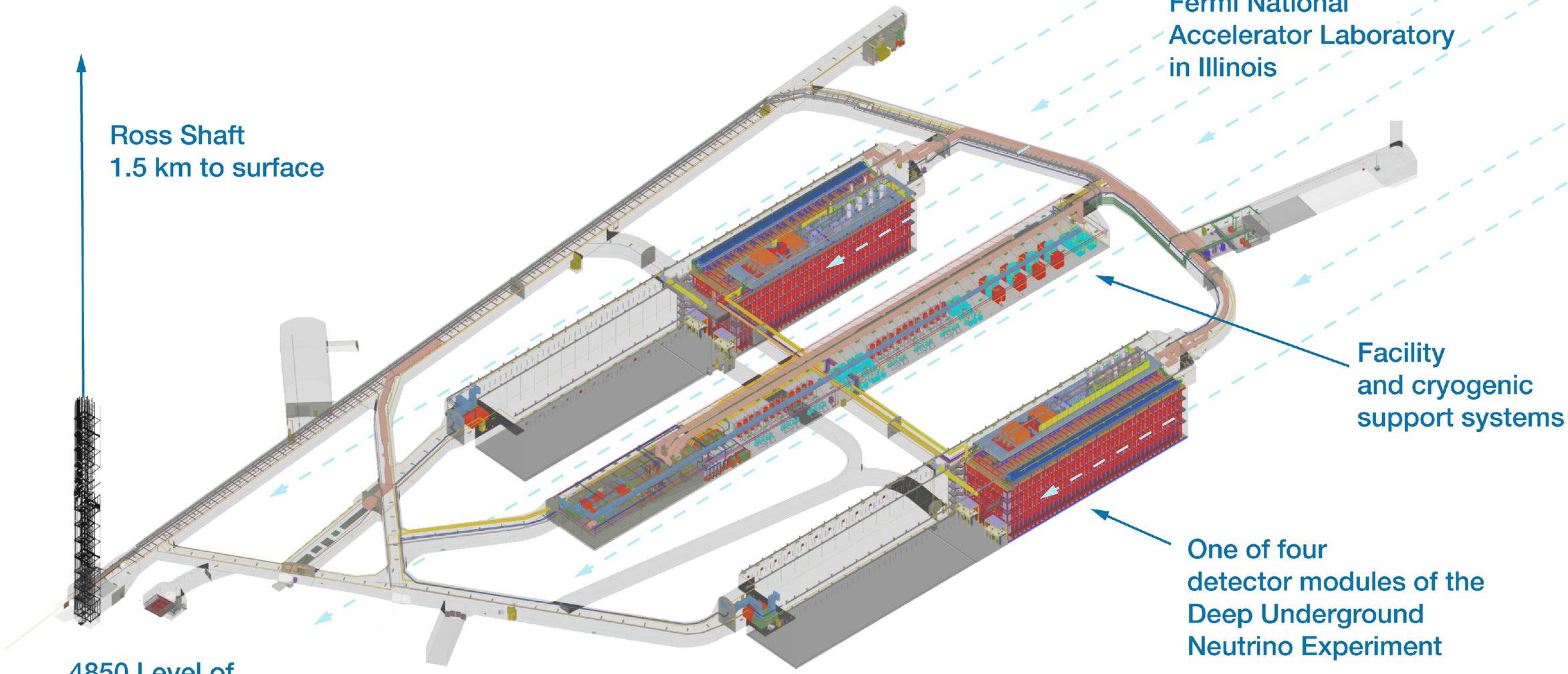


Image: SuperKamiokande

Long-Baseline Experiments: DUNE

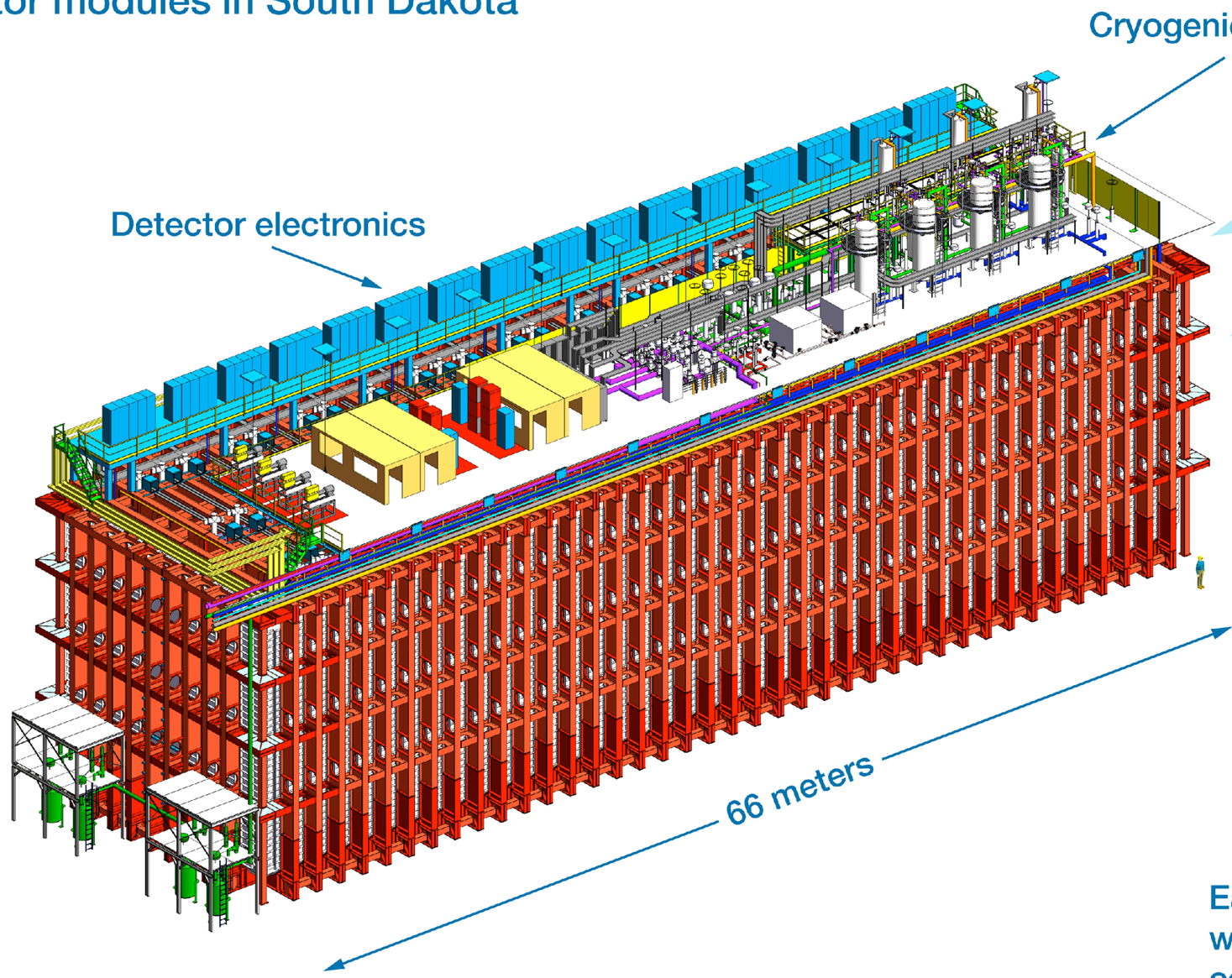


Long-Baseline Neutrino Facility
South Dakota Site



Deep Underground Neutrino Experiment

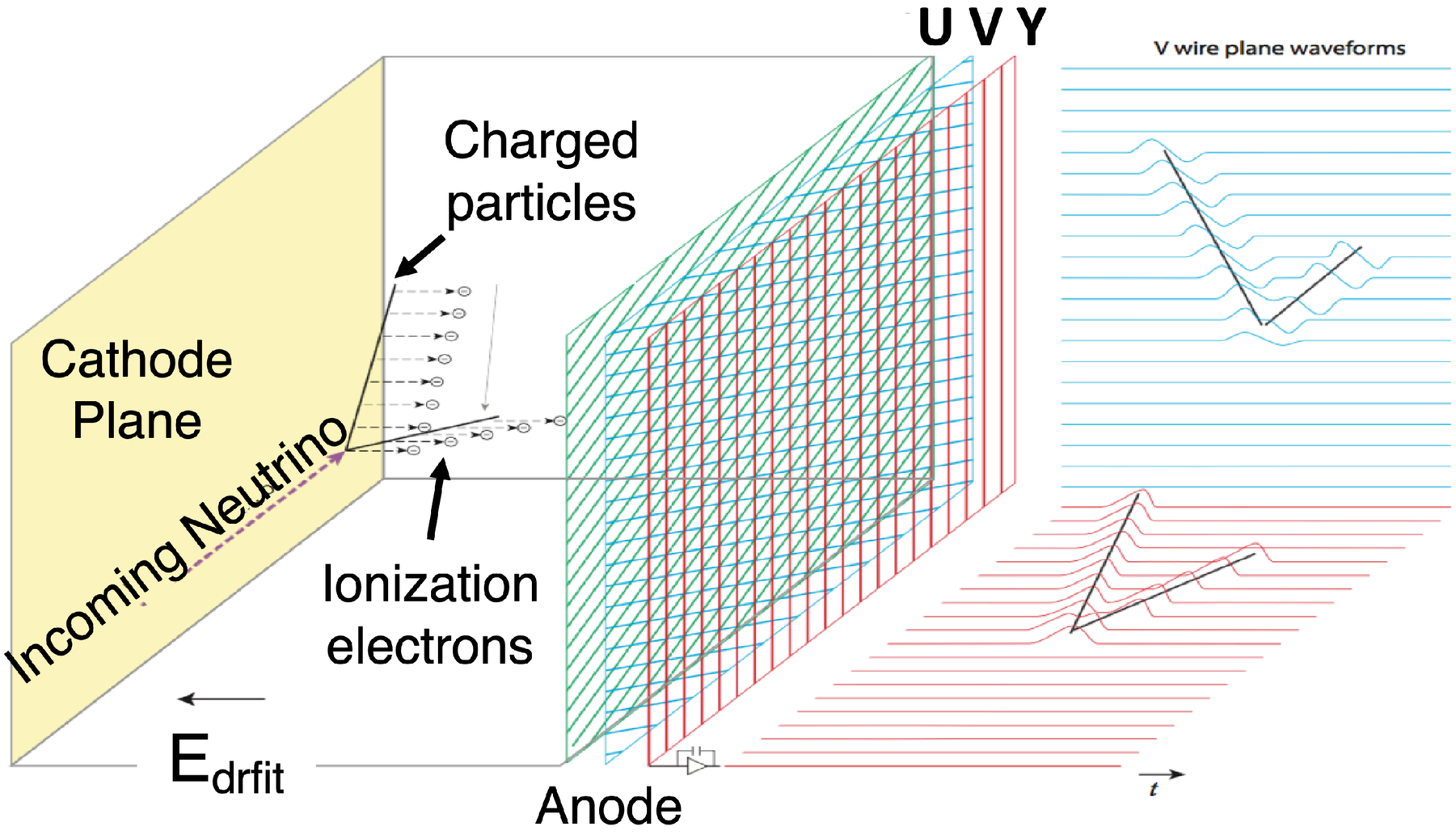
One of four detector modules in South Dakota



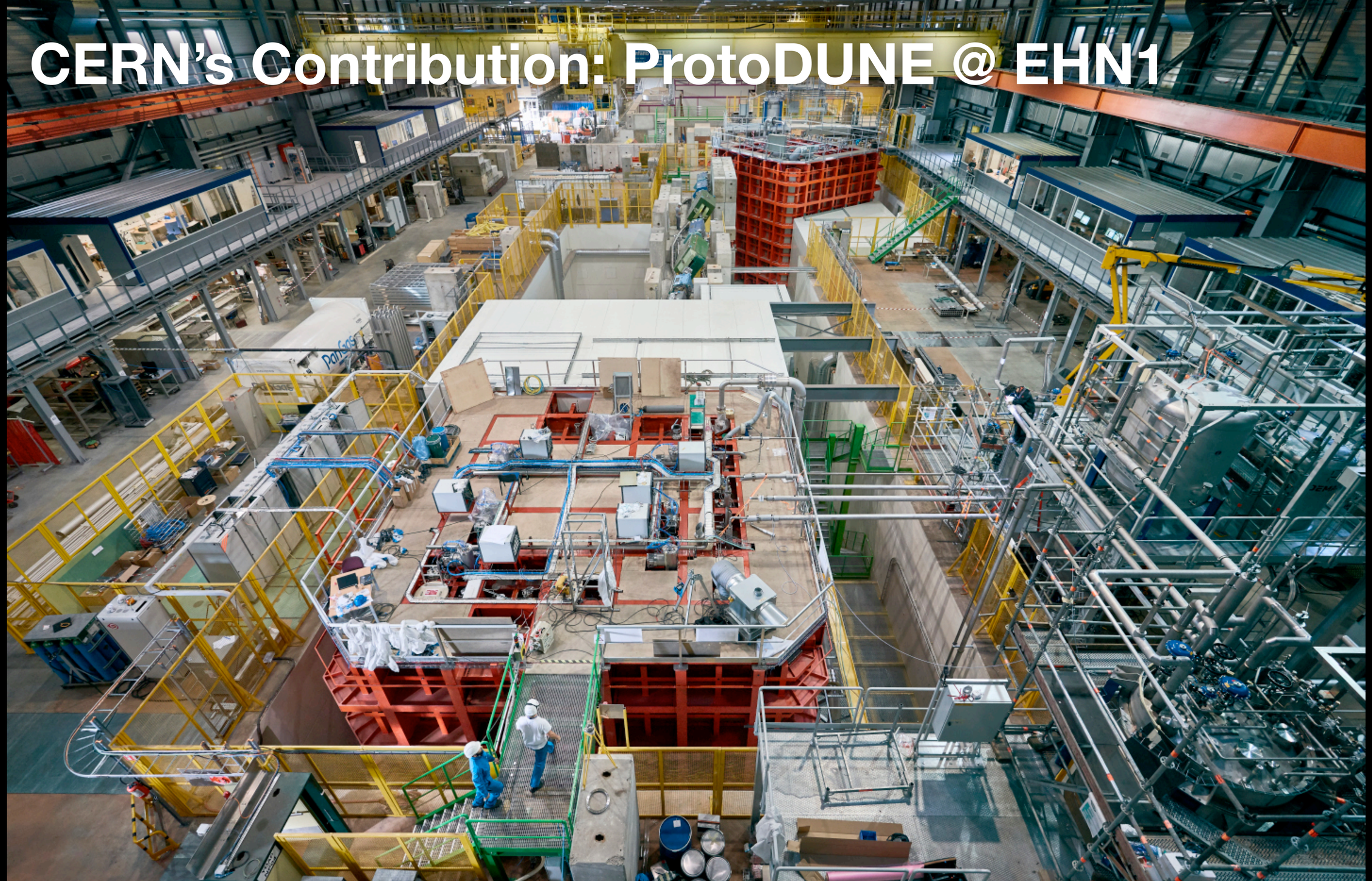
Detector located
1.5 kilometers
underground at
Sanford Lab

Each module will be filled
with 17,000 tons of argon,
cooled to minus 184°C

Neutrino Detection in Liquid Argon TPCs

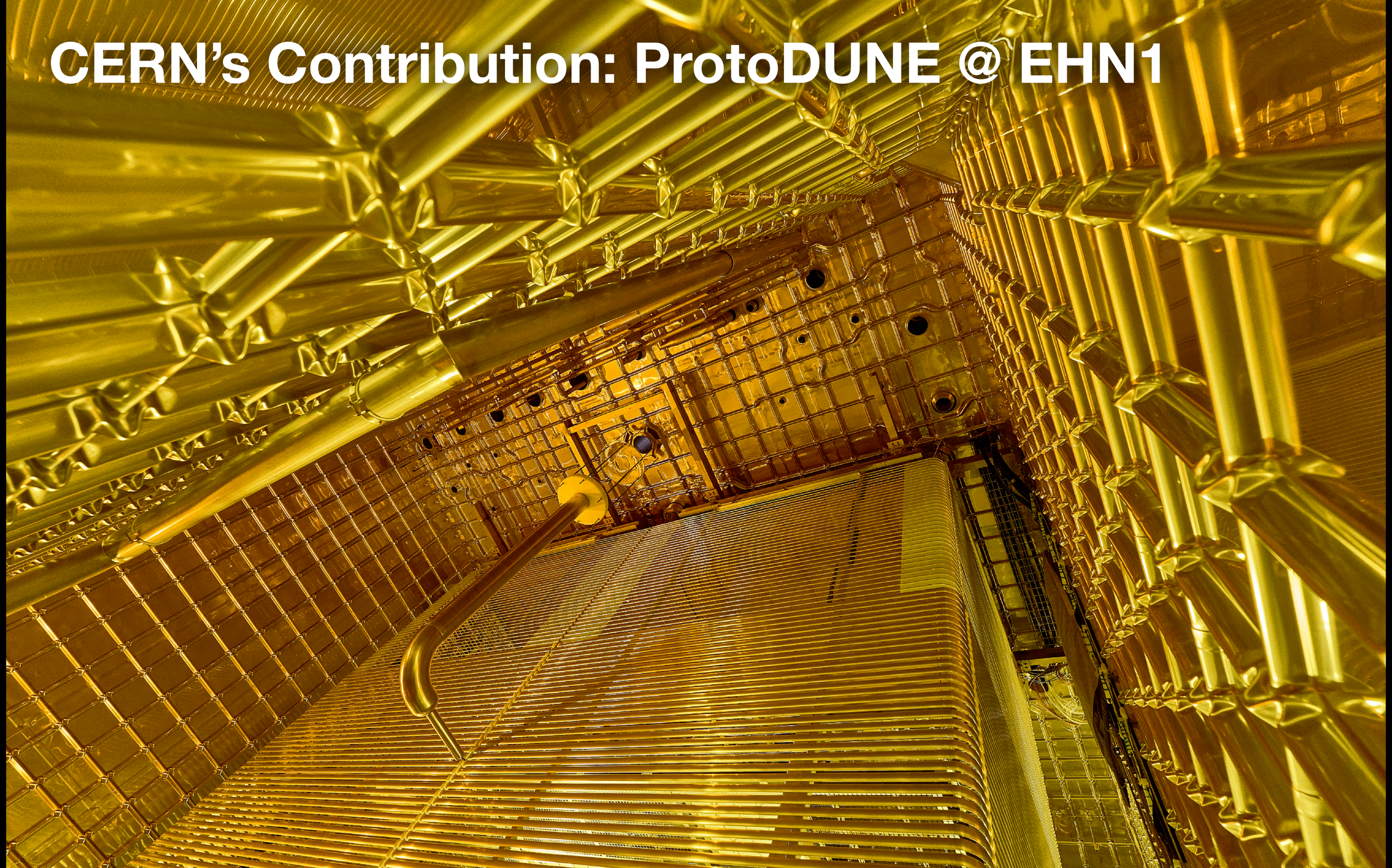


CERN's Contribution: ProtoDUNE @ EHN1



CERN’s Contribution: ProtoDUNE @ EHN1

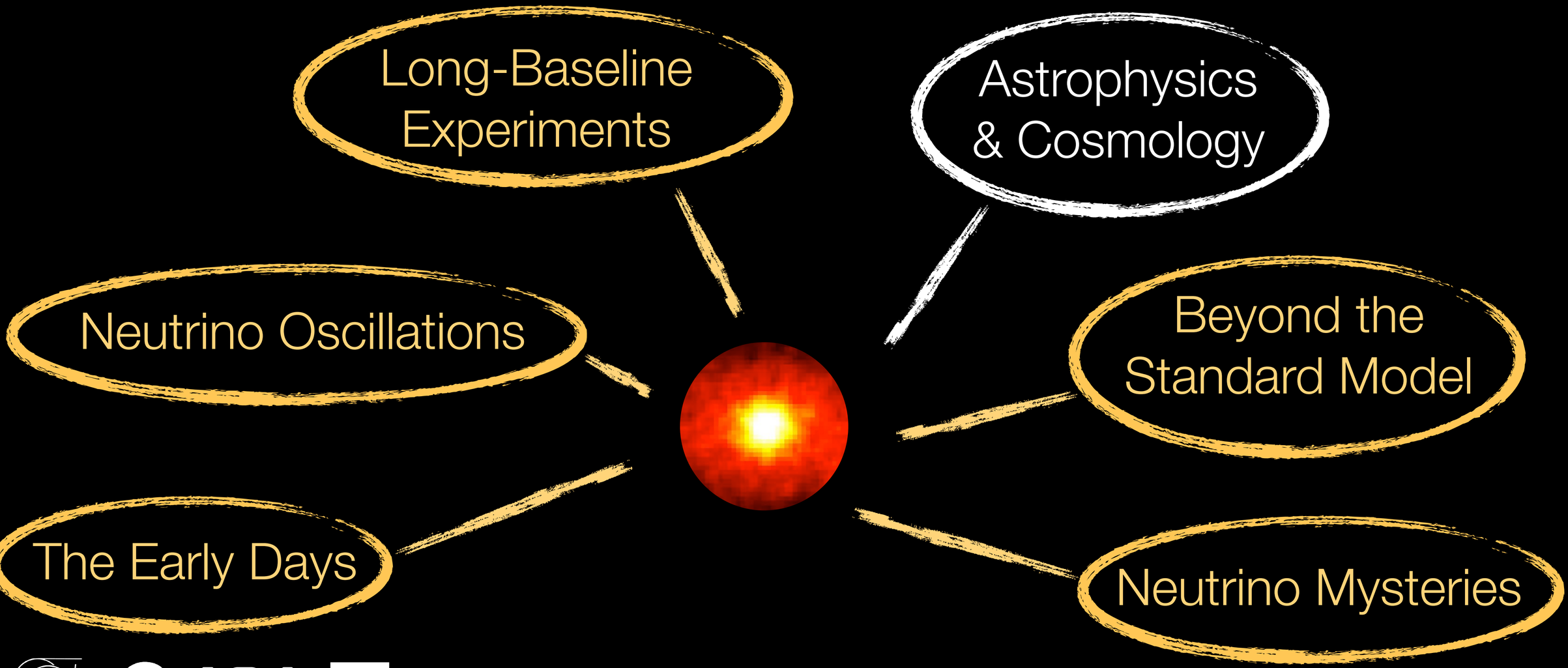
CERN's Contribution: ProtoDUNE @ EHN1



Yes, But Why?

- Connection between leptonic CP violation and baryogenesis
- Portal to new physics
- Precise knowledge of particle physics is indispensable for using neutrinos as astrophysical messengers
- Hints for the origin of flavour
- Multi-purpose detectors with lots of secondary opportunities
  (supernova neutrinos, light dark sectors, proton decay, …)
- …

Outline


Long-Baseline Experiments
Astrophysics & Cosmology
Neutrino Oscillations
Beyond the Standard Model
The Early Days
Neutrino Mysteries

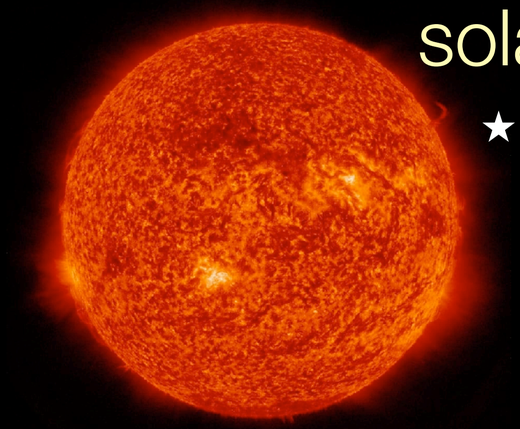
Neutrinos as Astrophysical Messengers

Neutrinos as Astrophysical Messengers

solar neutrinos

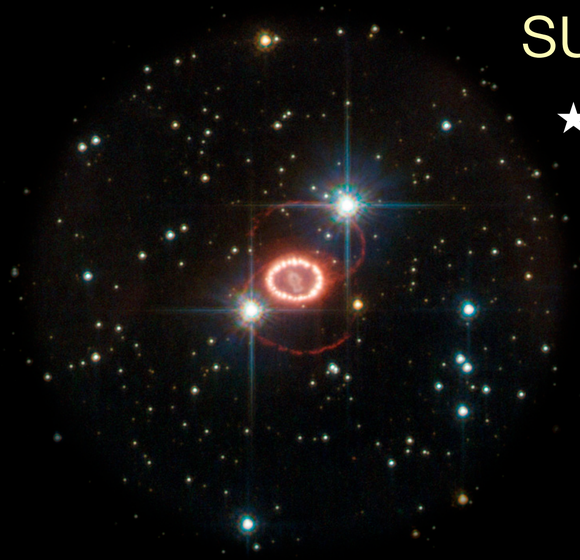
- ★ stellar evolution

Neutrinos as Astrophysical Messengers



solar neutrinos

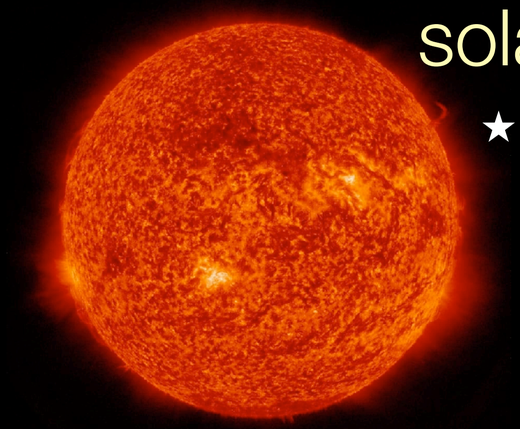
- ★ stellar evolution



supernova neutrinos

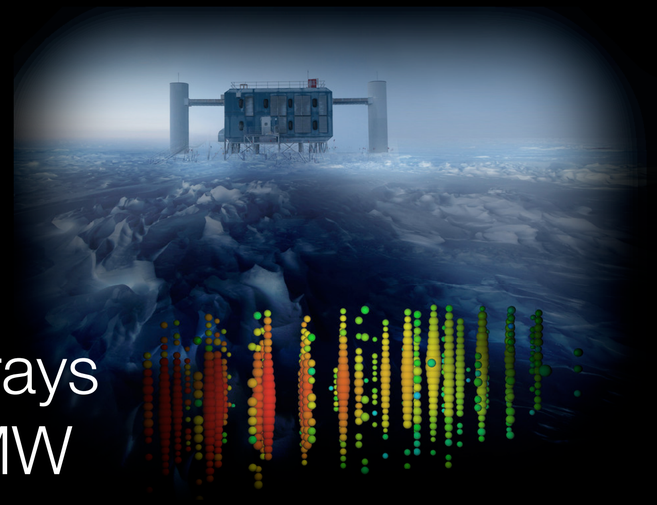
- ★ death throes of massive stars
- ★ nucleosynthesis
- ★ matter under extreme conditions

Neutrinos as Astrophysical Messengers



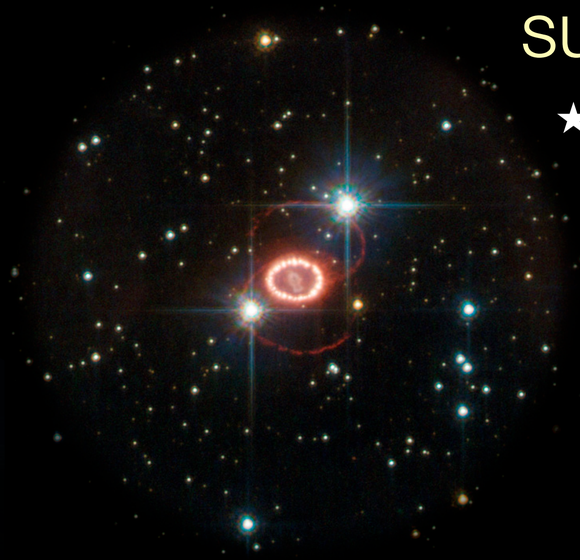
solar neutrinos

- ★ stellar evolution



high-*E* neutrinos

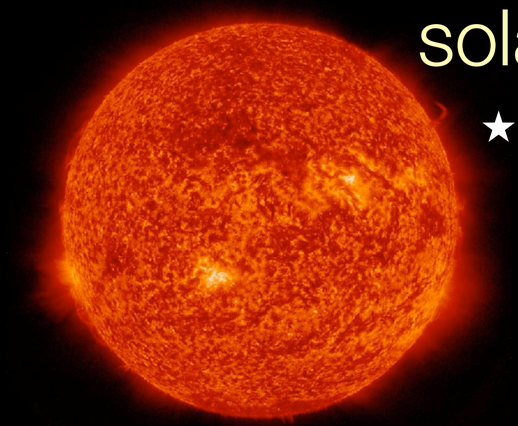
- ★ origin of cosmic rays
- ★ AGNs, blazars, MW



supernova neutrinos

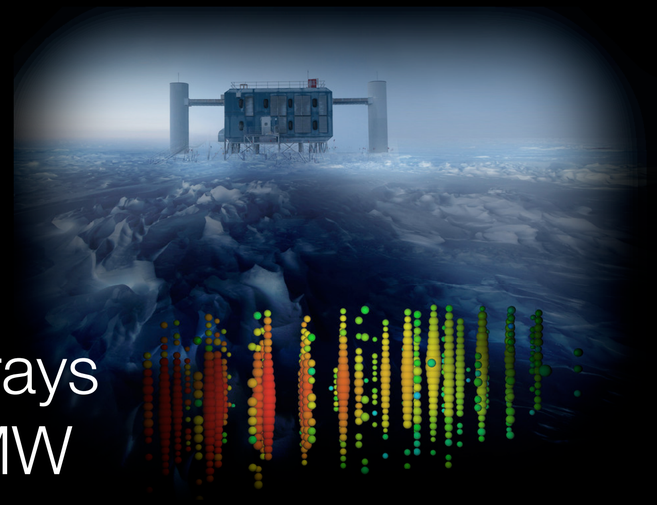
- ★ death throes of massive stars
- ★ nucleosynthesis
- ★ matter under extreme conditions

Neutrinos as Astrophysical Messengers



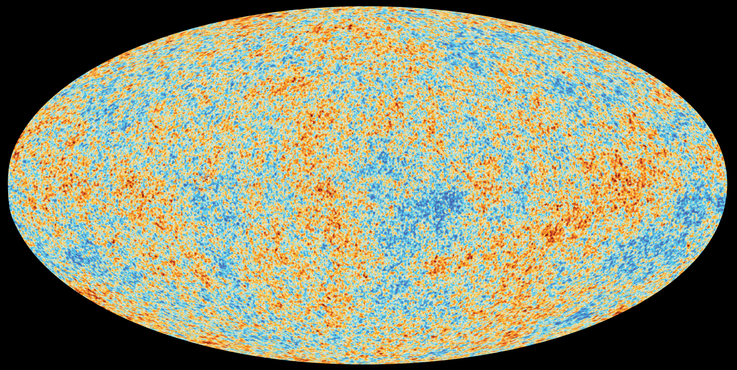
solar neutrinos

- ★ stellar evolution



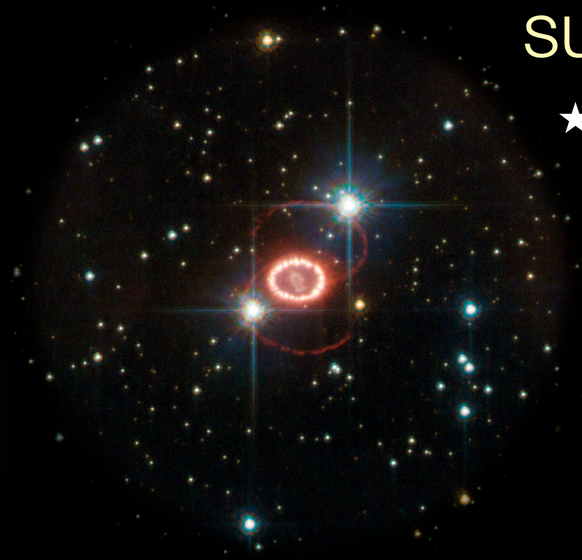
high-*E* neutrinos

- ★ origin of cosmic rays
- ★ AGNs, blazars, MW



cosmology

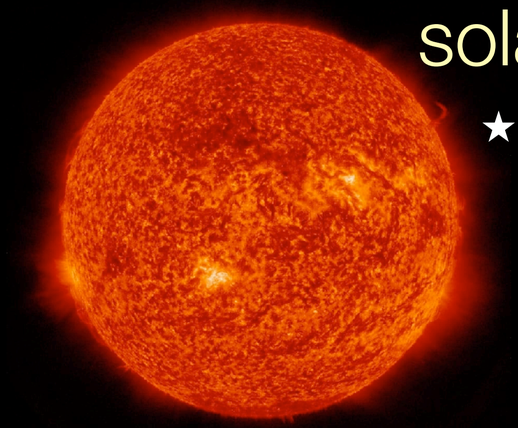
- ★ early Universe



supernova neutrinos

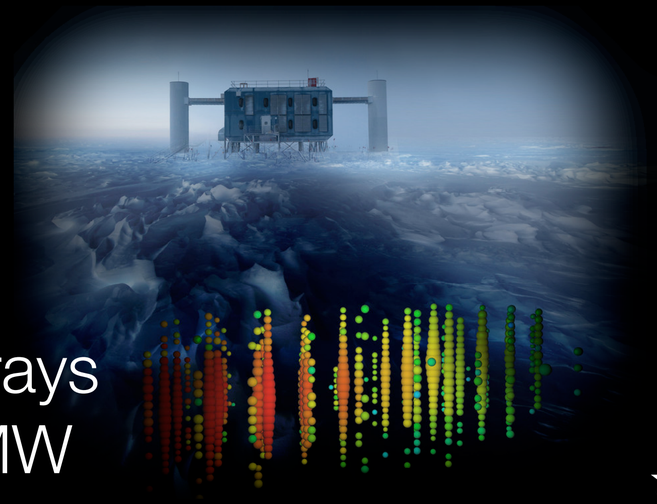
- ★ death throes of massive stars
- ★ nucleosynthesis
- ★ matter under extreme conditions

Neutrinos as Astrophysical Messengers



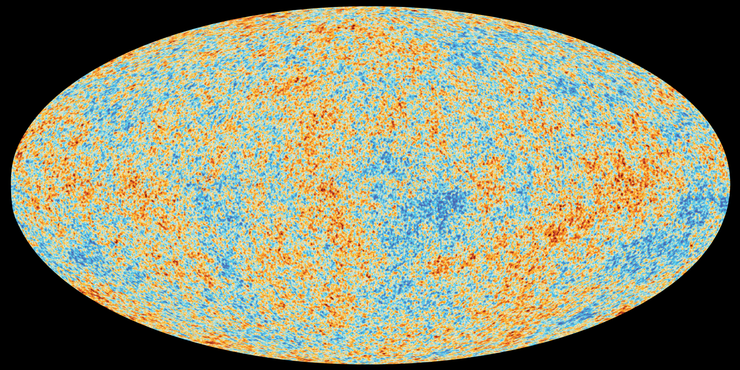
solar neutrinos

- ★ stellar evolution



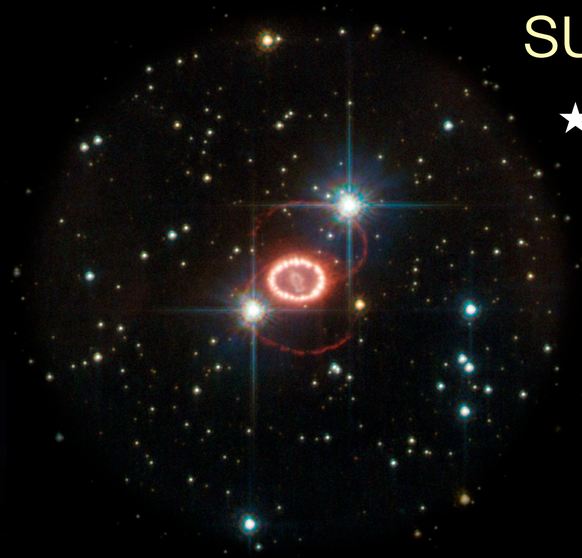
high-*E* neutrinos

- ★ origin of cosmic rays
- ★ AGNs, blazars, MW



cosmology

- ★ early Universe

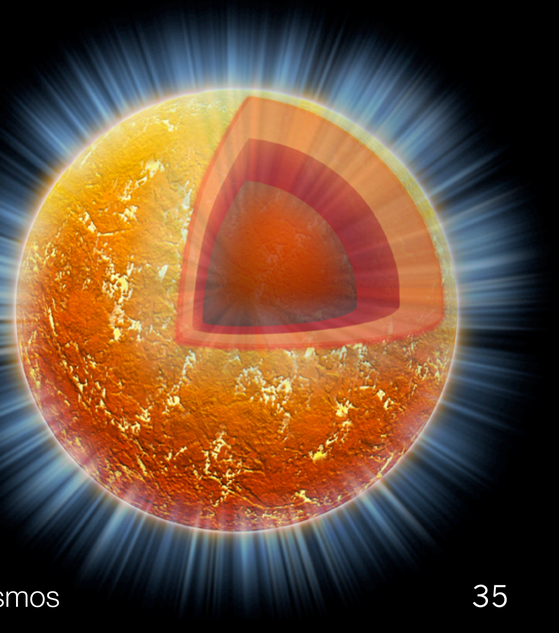


supernova neutrinos

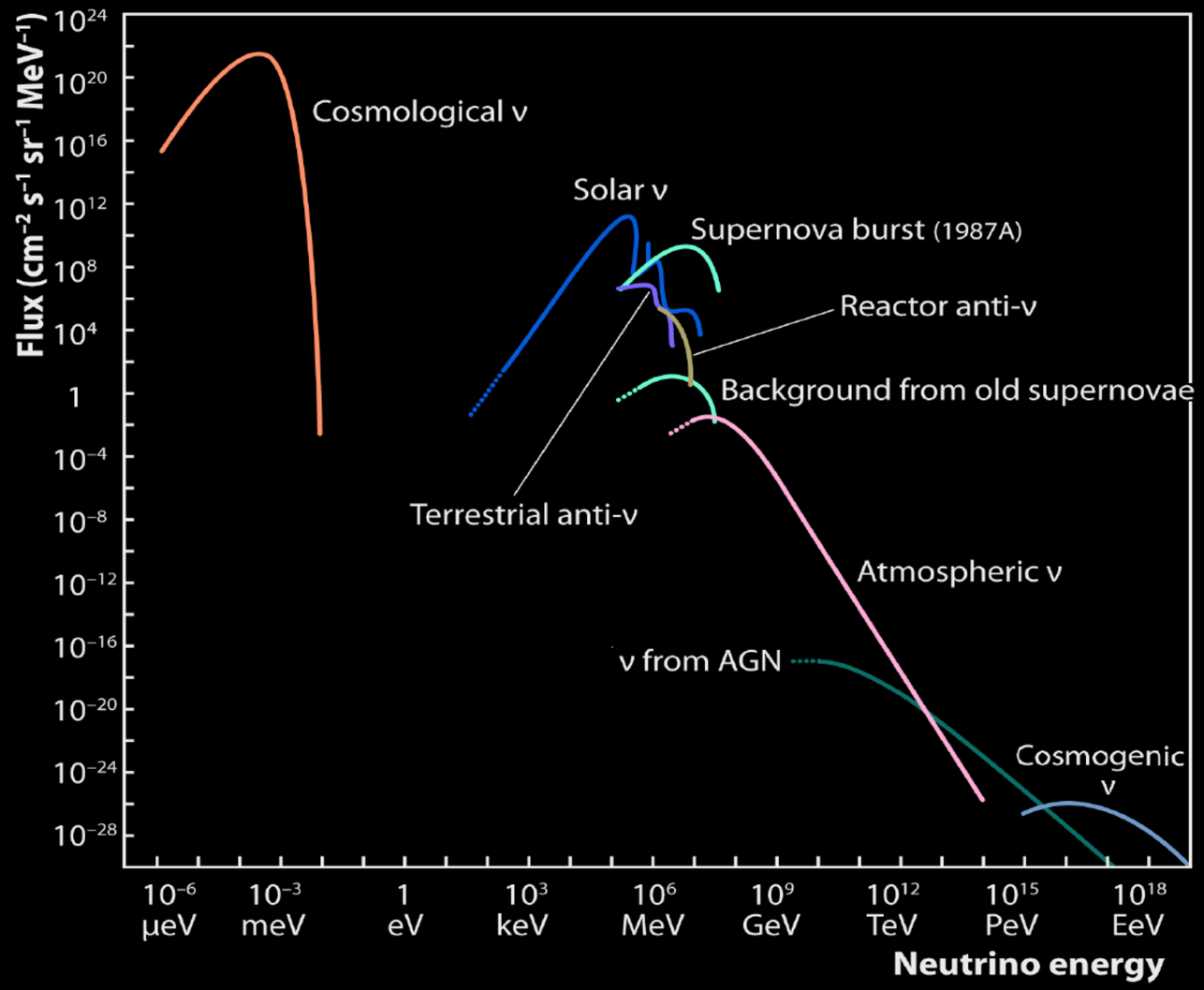
- ★ death throes of massive stars
- ★ nucleosynthesis
- ★ matter under extreme conditions

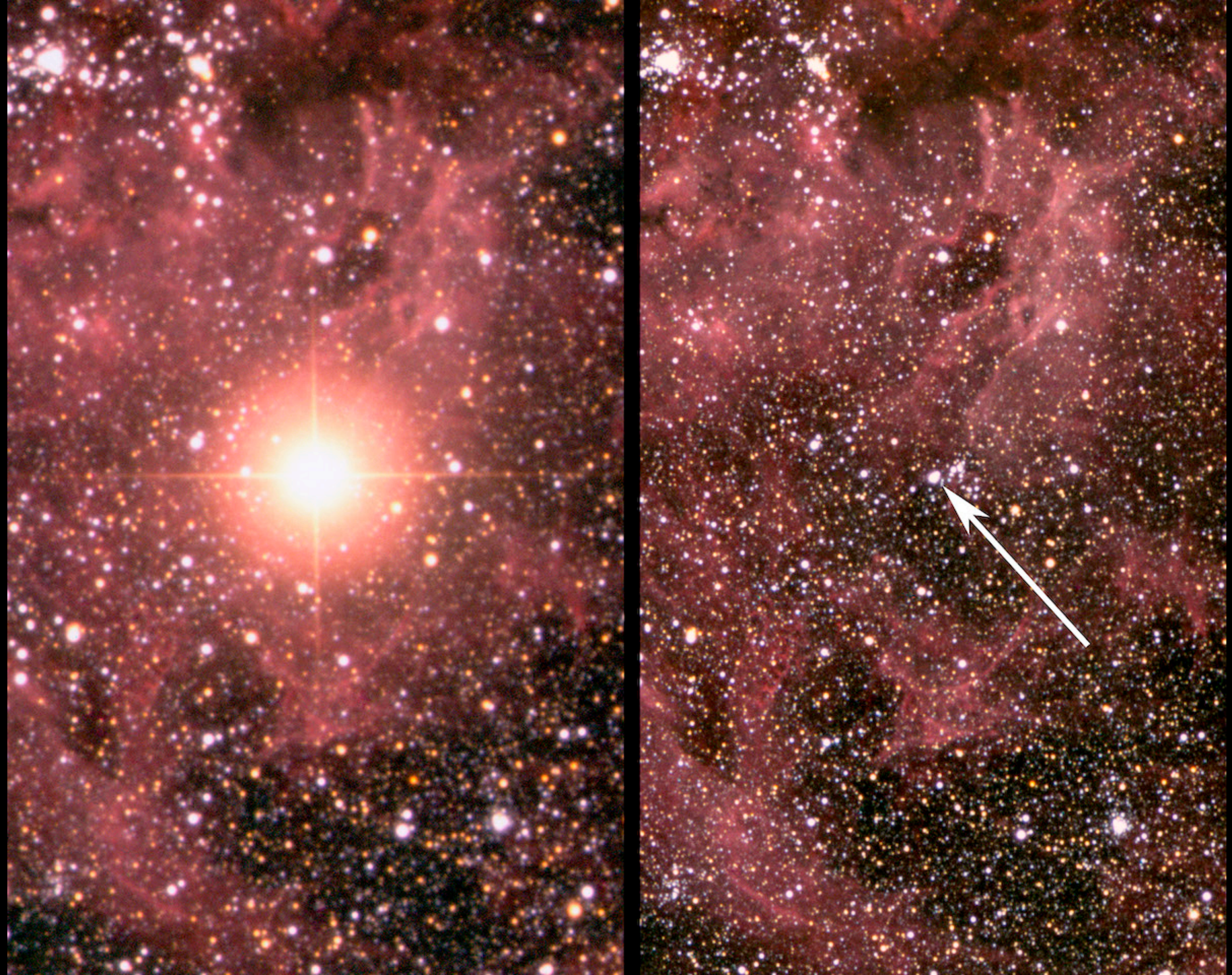
neutron stars

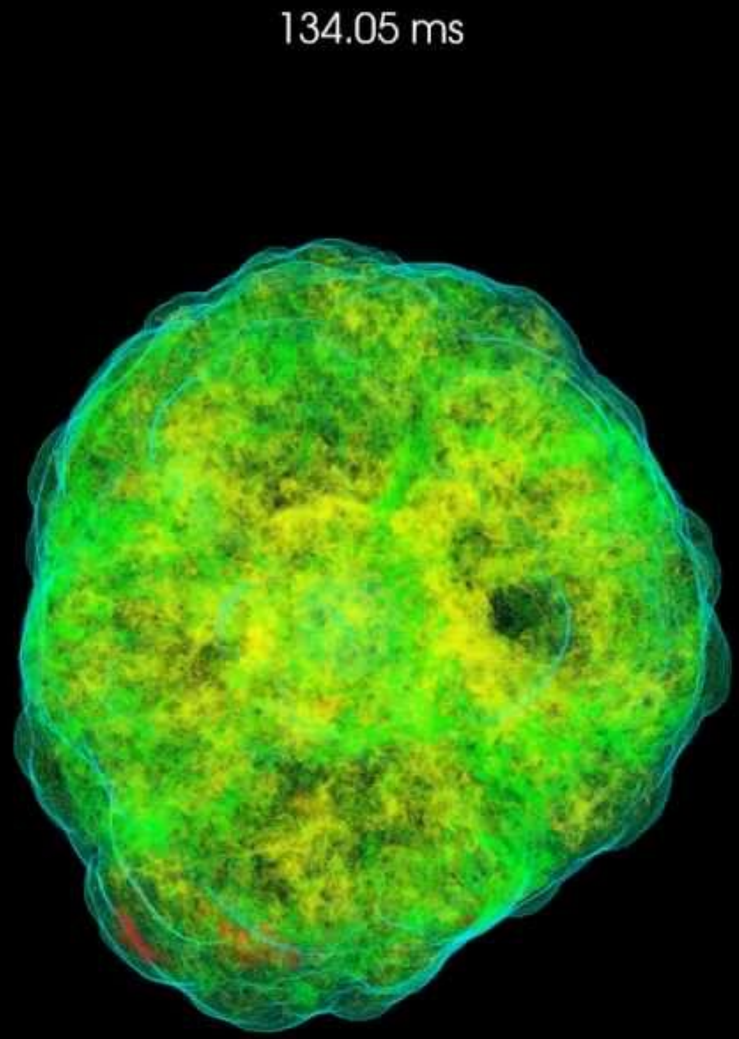
- ★ common-envelope systems
- ★ muon decays



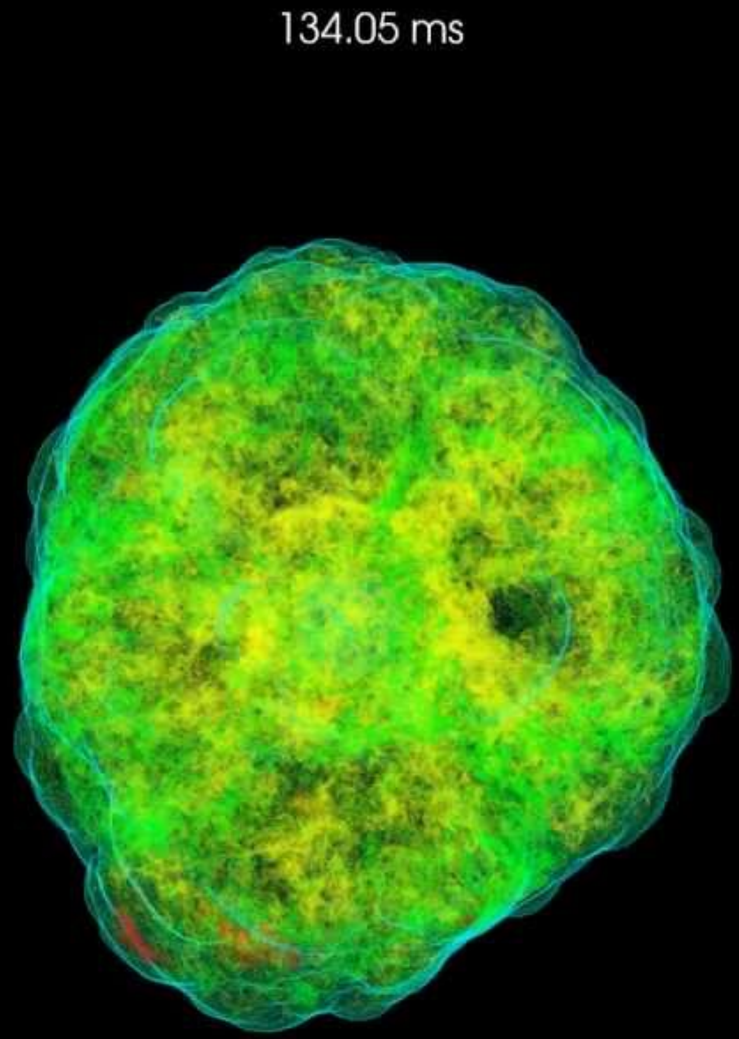
Neutrinos as Astrophysical Messengers







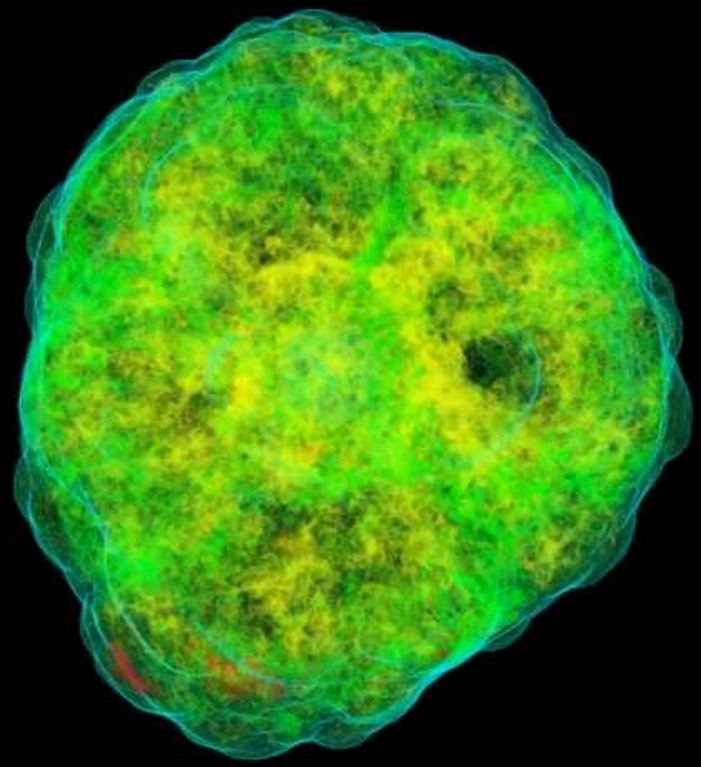
SXS Collaboration, Christian Ott *et al.*



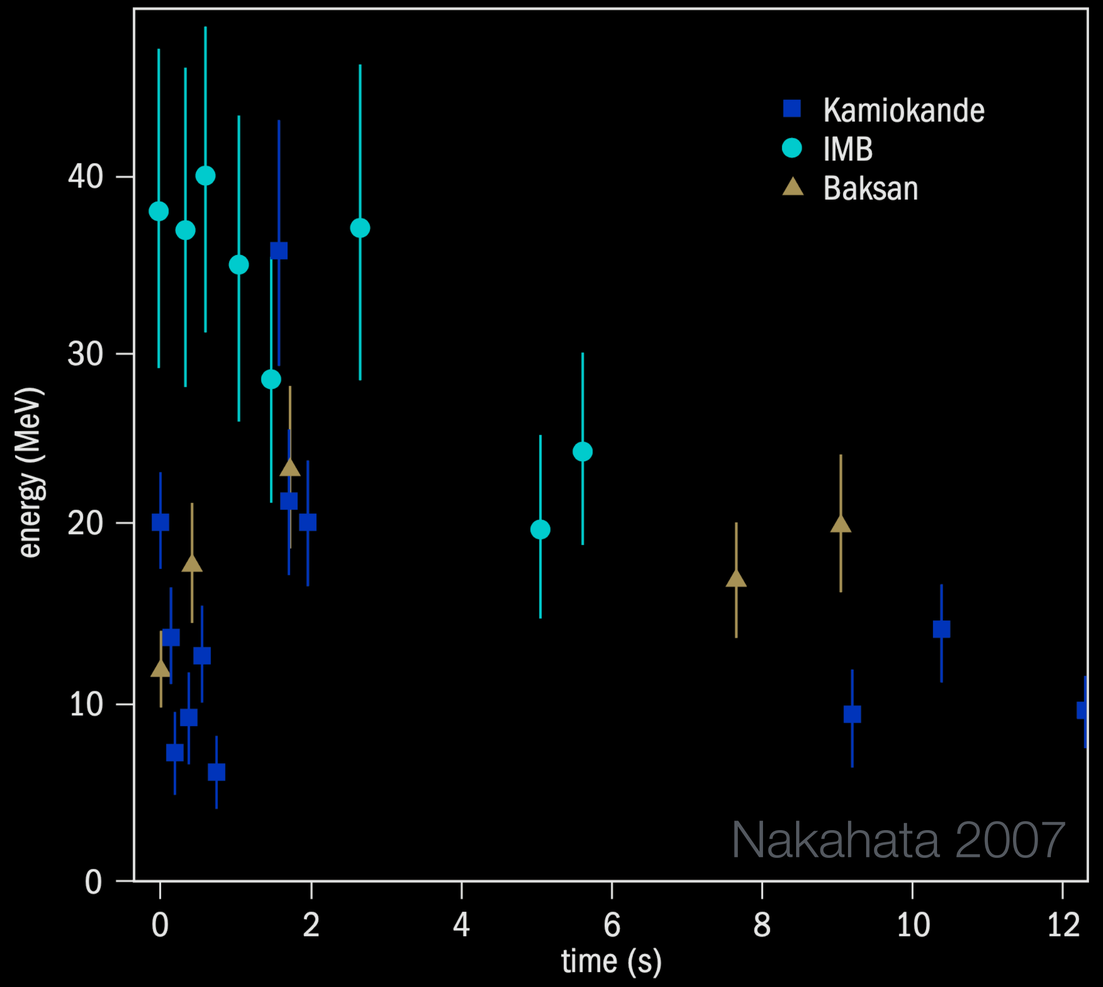
SXS Collaboration, Christian Ott *et al.*

Core-Collapse Supernovae

- explosion of massive star ($\gtrsim 8\,M_\odot$) that has run out of fuel
  - no more thermal pressure
  - core collapses
  - gigantic release of gravitational energy
- brighter than an entire galaxy
- ~10% of the star's mass converted to energy
  - 0.01% photons
  - 1% kinetic energy of ejecta
  - 99% neutrinos

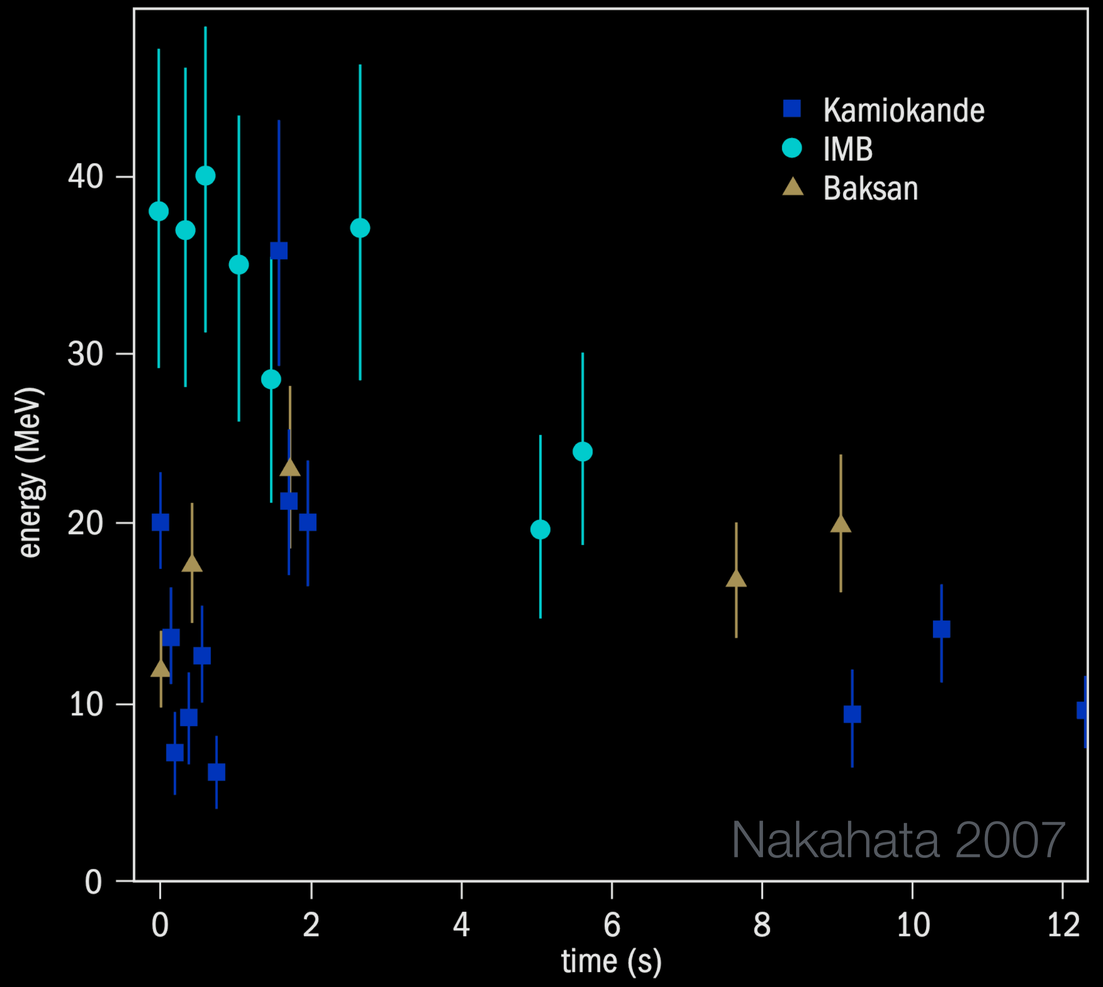


Supernova Neutrinos



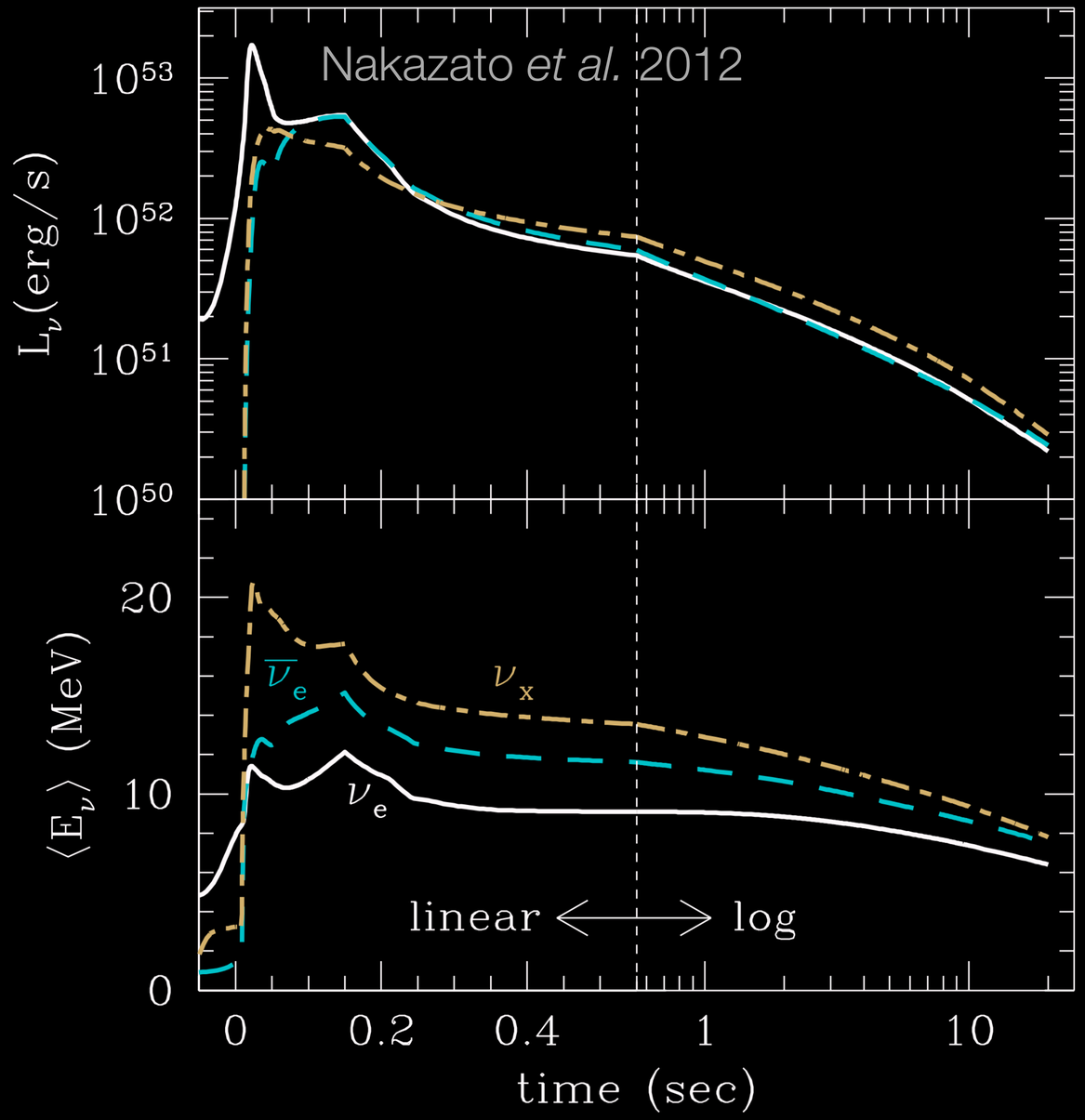
Supernova Neutrinos

- SN 1987A
  - 25 neutrino events



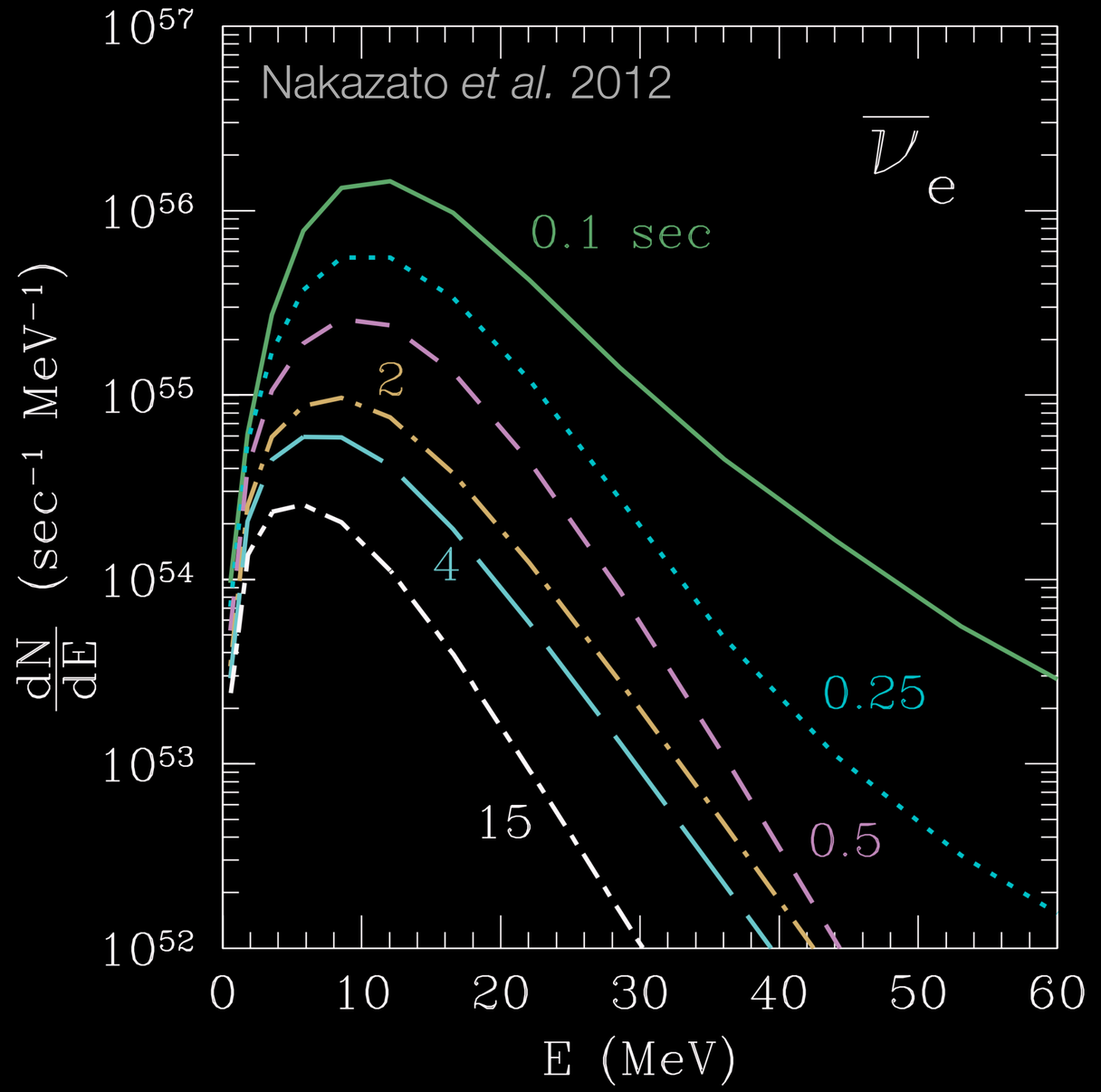
Supernova Neutrinos

- SN 1987A
  - 25 neutrino events
- the next galactic supernova
  - 10s of thousands of events
  - detailed spectra
  - high-resolution “light” curves
  - wealth of information on collapse dynamics, nucleosynthesis, …



Supernova Neutrinos

- SN 1987A
  - 25 neutrino events
- the next galactic supernova
  - 10s of thousands of events
  - detailed spectra
  - high-resolution “light” curves
  - wealth of information on collapse dynamics, nucleosynthesis, …



Supernova Neutrinos

- neutrino density $> 10^{30}\,\mathrm{cm}^{-3}$
  ➠ neutrinos induce MSW matter effects for themselves
- flavour evolution described by von Neumann equation

$$i(\partial_t + \vec{v} \cdot \vec{\nabla}_{\vec{r}})\rho_{\vec{r},\vec{p}} = [H_{\mathrm{vac}} + H_{\mathrm{MSW}} + H_{\nu\nu},\ \rho_{\vec{r},\vec{p}}]$$

Supernova Neutrinos

- neutrino density $> 10^{30}\,\mathrm{cm}^{-3}$
  ➠ neutrinos induce MSW matter effects for themselves
- flavour evolution described by von N[illegible]on

density matrix
in flavour space

$$i(\partial_t + \vec{v}\cdot\vec{\nabla}_{\vec{r}})\rho_{\vec{r},\vec{p}} = [H_{\mathrm{vac}} + H_{\mathrm{MSW}} + H_{\nu\nu}, \rho_{\vec{r},\vec{p}}]$$

vacuum oscillations

$$H_{\mathrm{vac}} = \frac{1}{2E} U_{\mathrm{PMNS}} M^2 U_{\mathrm{PMNS}}^\dagger$$

matter effects

$$H_{\mathrm{MSW}} = \sqrt{2} G_F n_e \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

self-interactions

$$H_{\nu\nu} = \sqrt{2} G_F \int \frac{d^3q}{(2\pi)^3} (1 - \cos\theta_{\vec{p}\vec{q}})(\rho_{\vec{r},\vec{q}} - \bar{\rho}_{\vec{r},\vec{q}})$$

Supernova Neutrinos

- neutrino density $> 10^{30}\,\mathrm{cm}^{-3}$
  ➠ neutrinos induce MSW matter effects for themselves
- flavour evolution described by von Neumann equation

$$i(\partial_t + \vec{v}\cdot\vec{\nabla}_{\vec{r}})\rho_{\vec{r},\vec{p}} = [H_{\mathrm{vac}} + H_{\mathrm{MSW}} + H_{\nu\nu},\ \rho_{\vec{r},\vec{p}}]$$

- at large n_ν:
  - same equation for all energies ➠ synchronization
  - non-trivial angular dependence
- non-linear equation ➠ dynamics highly non-trivial
- computationally intractable so far

Supernova Neutrinos

★ pure Standard Model problem

★ solution will be crucial for the next Galactic supernova

Supernova Neutrinos on a Quantum Computer

- highly entangled quantum system calls for simulation on a quantum system
- basic idea: flavour state of each neutrino mode represented by qubit q_i (in 2-flavour approximation)

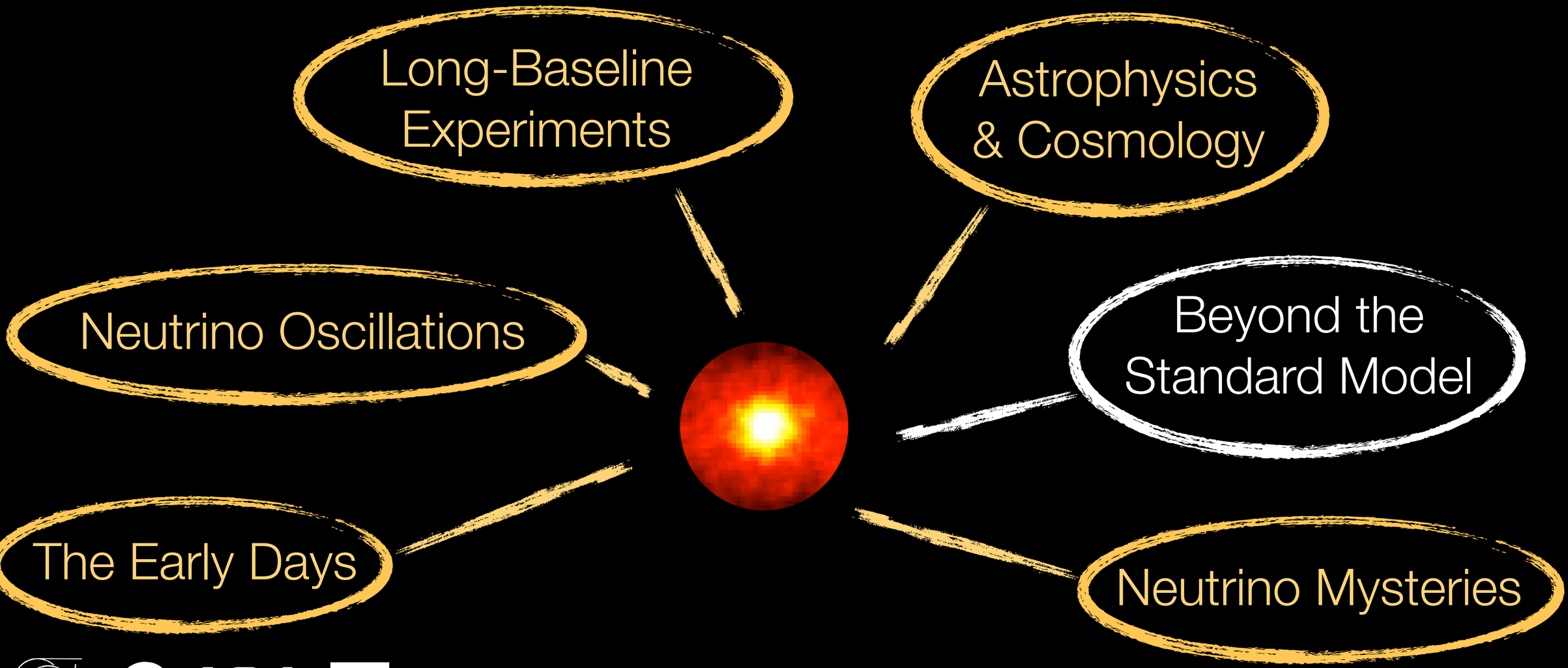
Hall et al. 2021, Amitrano et al. 2022, Siwach et al. 2023

states: $|\psi\rangle = |q_1\rangle \otimes |q_2\rangle \otimes \ldots \otimes |q_N\rangle$

Hamiltonian: $H = \sum_{k=1}^{N} \vec{b} \cdot \vec{\sigma}_k + \sum_{p<q}^{N} J_{pq} \vec{\sigma}_p \cdot \vec{\sigma}_q$

- time-evolution via Trotterization (discretisation in t + low-order expansion of $S = e^{i\hat{H}\delta t}$)

Outline


Long-Baseline Experiments
Astrophysics & Cosmology
Neutrino Oscillations
Beyond the Standard Model
The Early Days
Neutrino Mysteries

Example: Neutrino Magnetic Moments

Petcov 1977
Fujikawa Shrock 1980

Example: Neutrino Magnetic Moments

- Magnetic moment operator

$$\mathcal{L} \supset \frac{1}{2} \mu_\nu^{\alpha\beta} \, \bar{\nu}_L^\alpha \sigma^{\mu\nu} \nu_R^\beta F_{\mu\nu}$$

Petcov 1977
Fujikawa Shrock 1980

Example: Neutrino Magnetic Moments

- Magnetic n

Couples LH and RH neutrinos

$$\mathcal{L} \supset \frac{1}{2}\mu_\nu^{\alpha\beta}\bar{\nu}_L^\alpha \sigma^{\mu\nu} \nu_R^\beta F_{\mu\nu}$$

Petcov 1977
Fujikawa Shrock 1980

Example: Neutrino Magnetic Moments

- Magnetic n

Couples LH and RH neutrinos

$$\mathcal{L} \supset \frac{1}{2}\mu_\nu^{\alpha\beta}\bar{\nu}_L^\alpha \sigma^{\mu\nu} \nu_R^\beta F_{\mu\nu}$$

electromagnetic field strength tensor

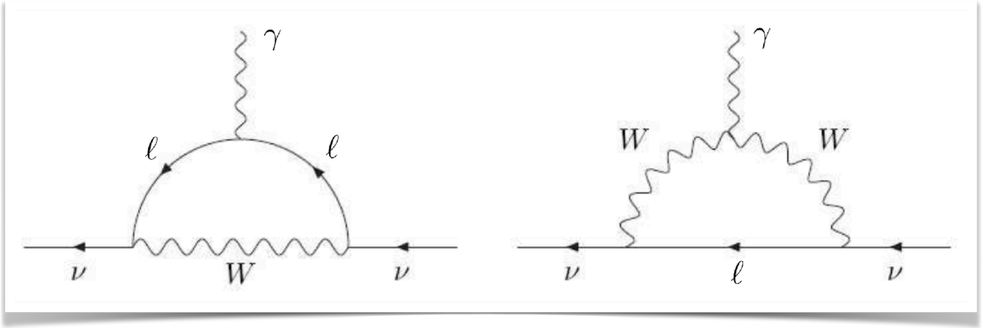
Petcov 1977
Fujikawa Shrock 1980

Example: Neutrino Magnetic Moments

- Magnetic moment operator

$$\mathcal{L} \supset \frac{1}{2}\mu_\nu^{\alpha\beta}\,\bar{\nu}_L^\alpha \sigma^{\mu\nu} \nu_R^\beta F_{\mu\nu}$$

- In the SM: generated by loop diagrams



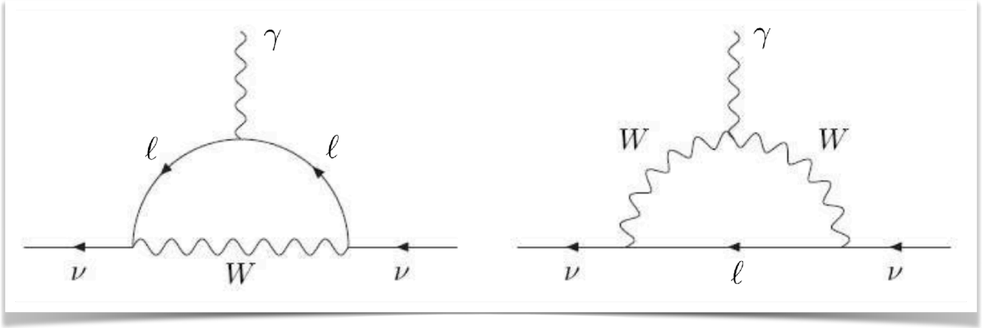
Petcov 1977
Fujikawa Shrock 1980

Example: Neutrino Magnetic Moments

- Magnetic moment operator

$$\mathcal{L} \supset \frac{1}{2}\mu_\nu^{\alpha\beta}\,\bar{\nu}_L^\alpha \sigma^{\mu\nu} \nu_R^\beta F_{\mu\nu}$$

- In the SM: generated by loop diagrams



- Numerically tiny: $10^{-19}\ \mu_B$

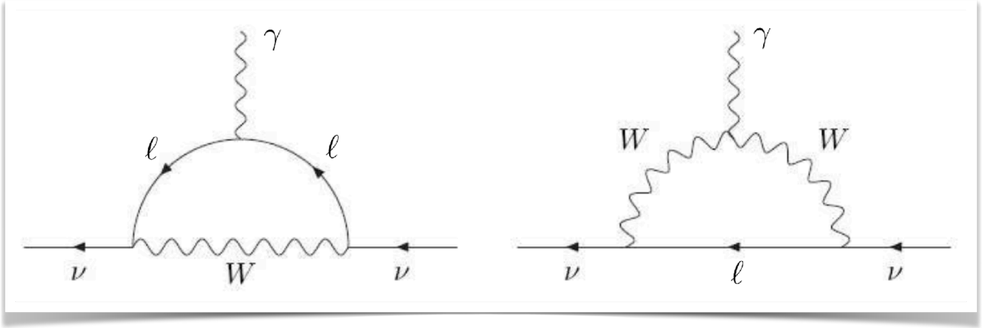
Petcov 1977
Fujikawa Shrock 1980

Example: Neutrino Magnetic Moments

- Magnetic moment operator

$$\mathcal{L} \supset \frac{1}{2}\mu_\nu^{\alpha\beta}\,\bar{\nu}_L^\alpha \sigma^{\mu\nu} \nu_R^\beta F_{\mu\nu}$$

- In the SM: generated by loop diagrams

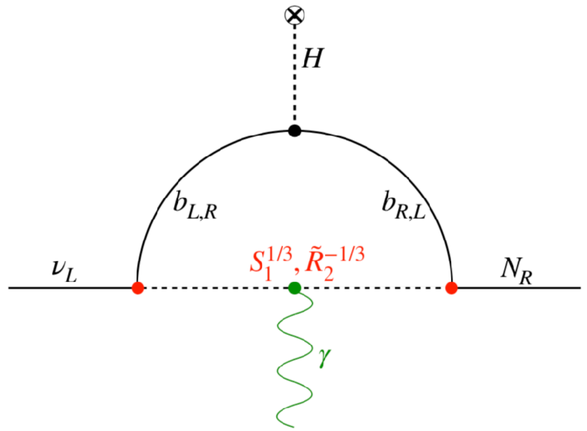


- Numerically tiny: $10^{-19}\ \mu_B$

Petcov 1977
Fujikawa Shrock 1980

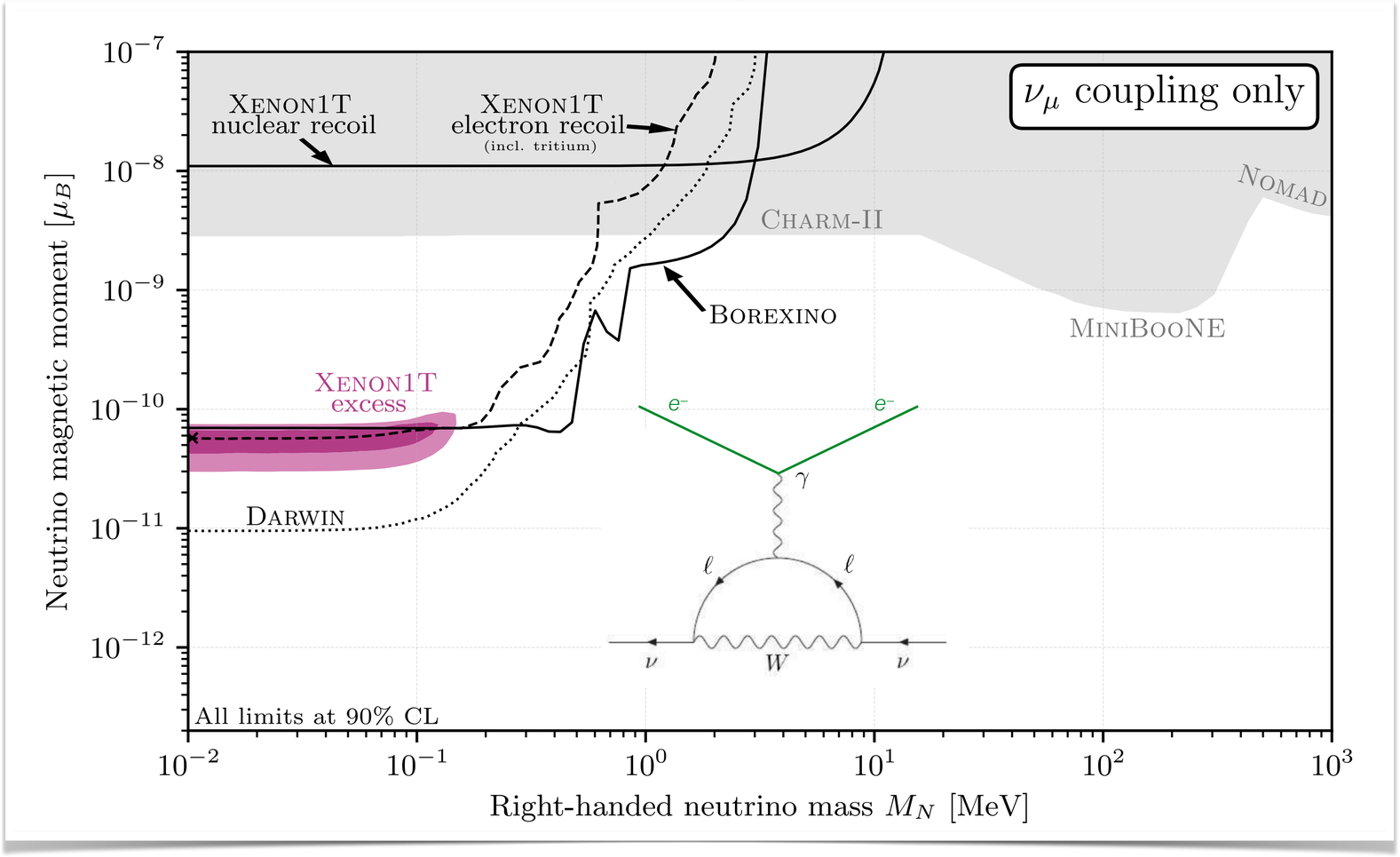
- Can be significantly enhanced in extensions of the SM

leptoquark model, inspired by B physics anomalies



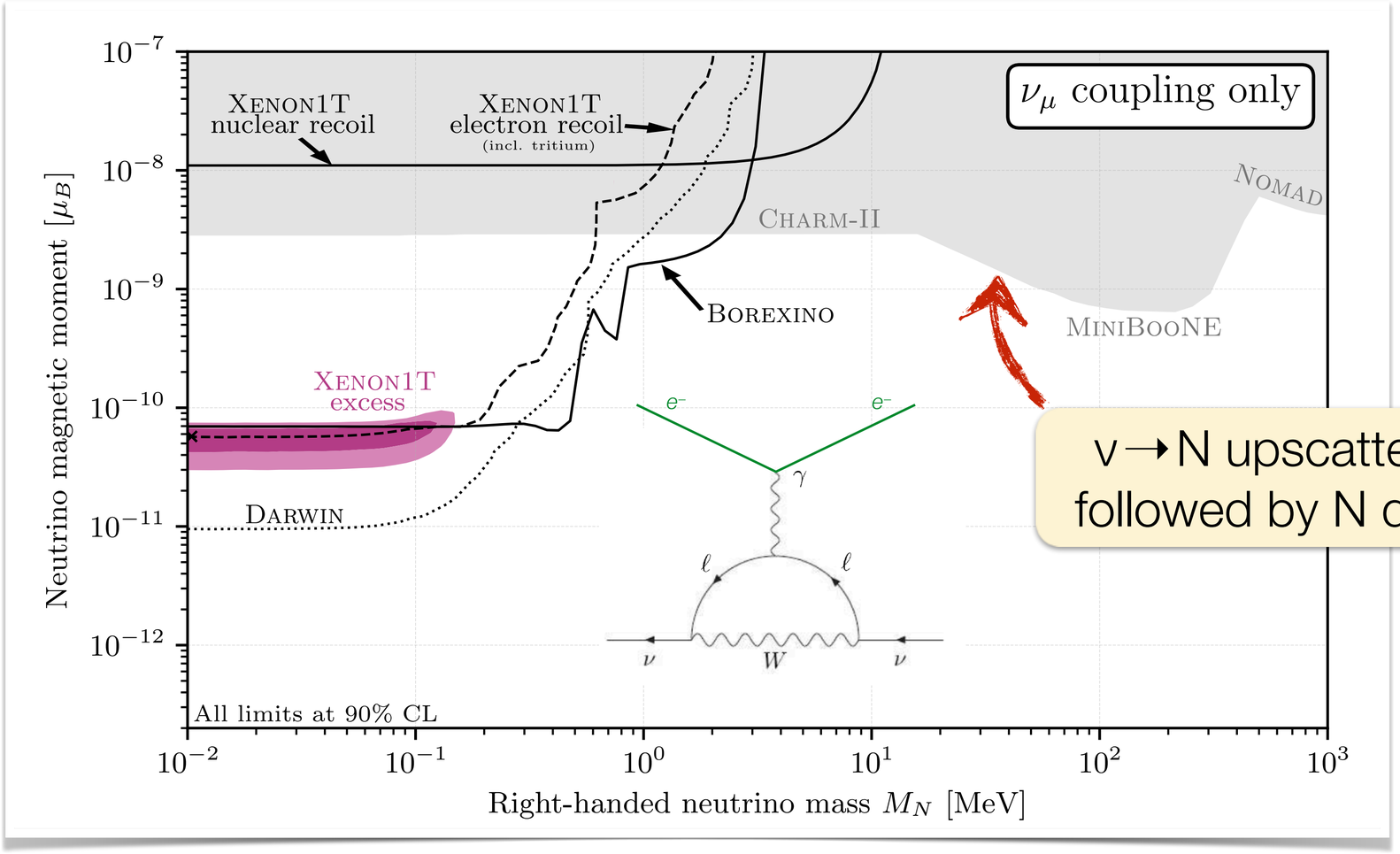
Brdar Greljo JK Opferkuch
2007.15563

Neutrino Magnetic Moments: Constraints



Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

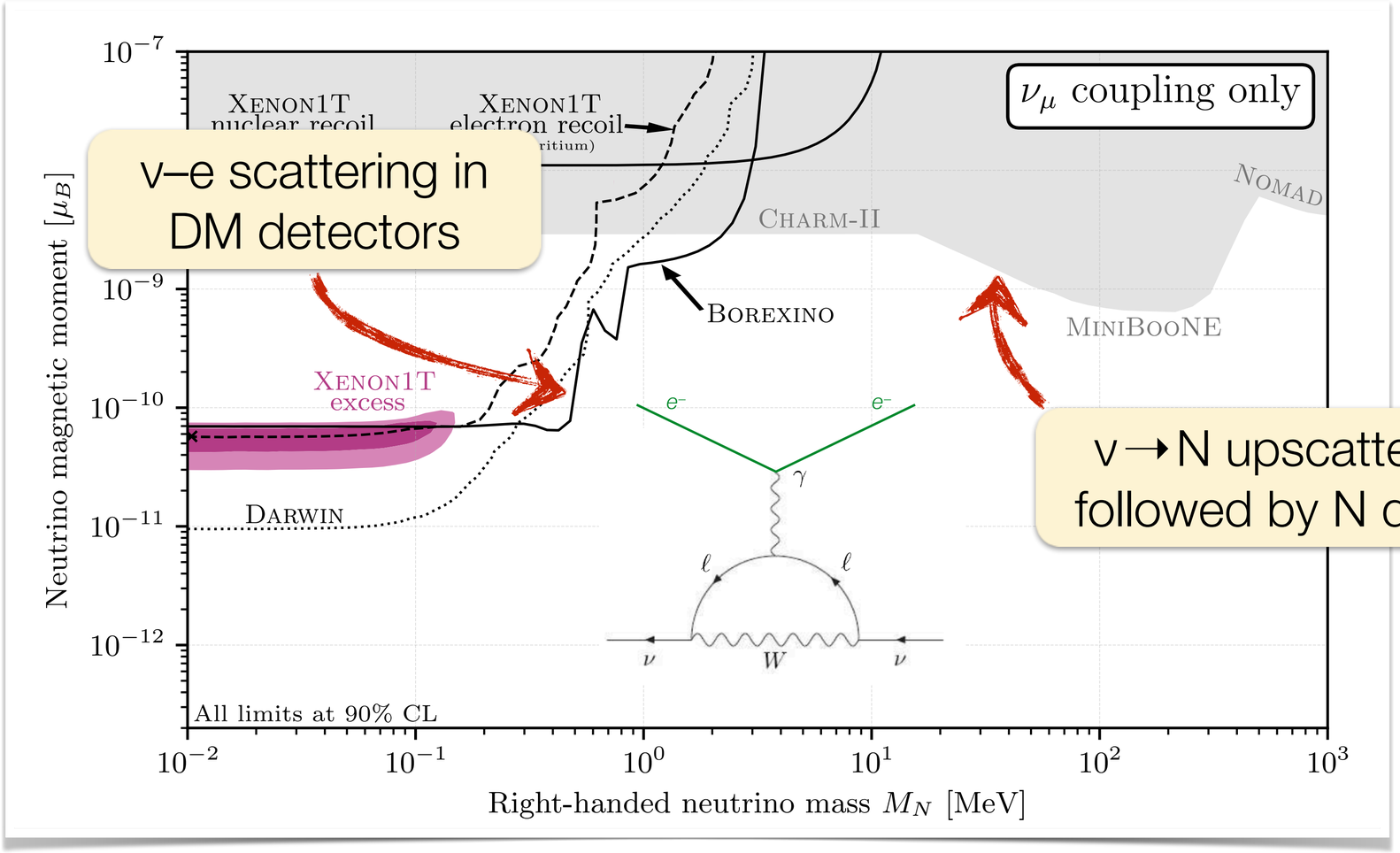
Neutrino Magnetic Moments: Constraints



ν → N upscattering followed by N decay

Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

Neutrino Magnetic Moments: Constraints

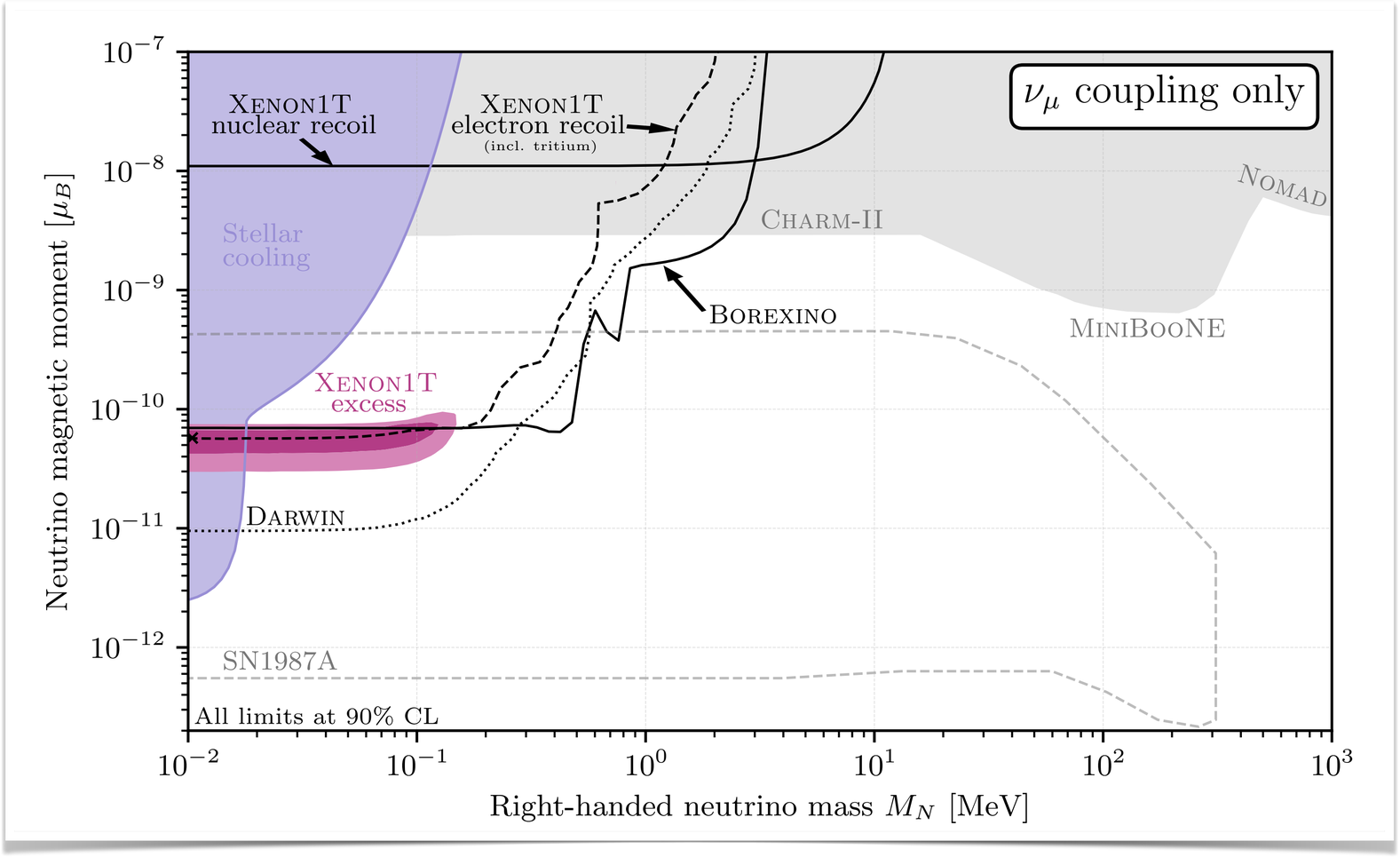


v–e scattering in DM detectors

v → N upscattering followed by N decay

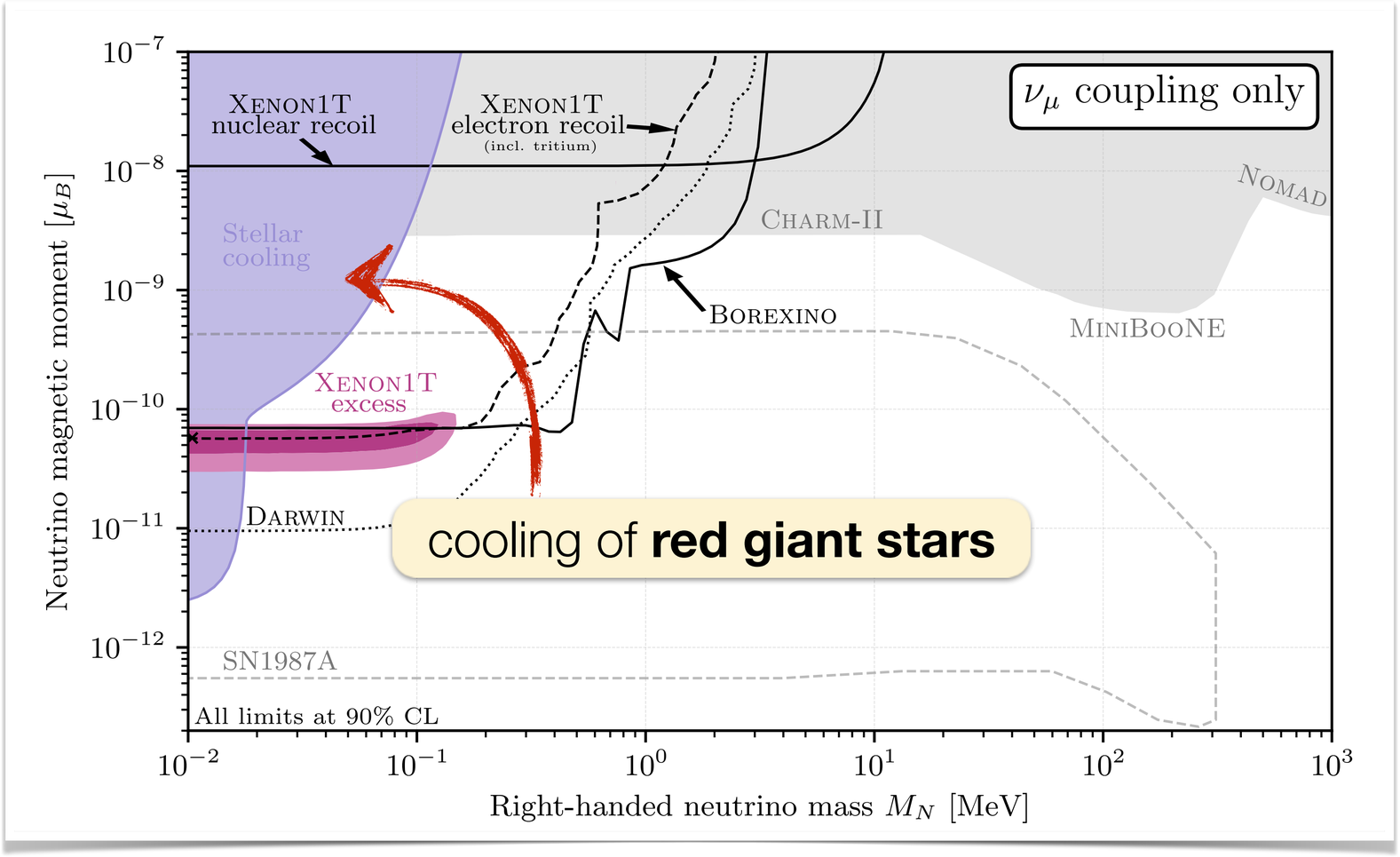
Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

Neutrino Magnetic Moments: Constraints



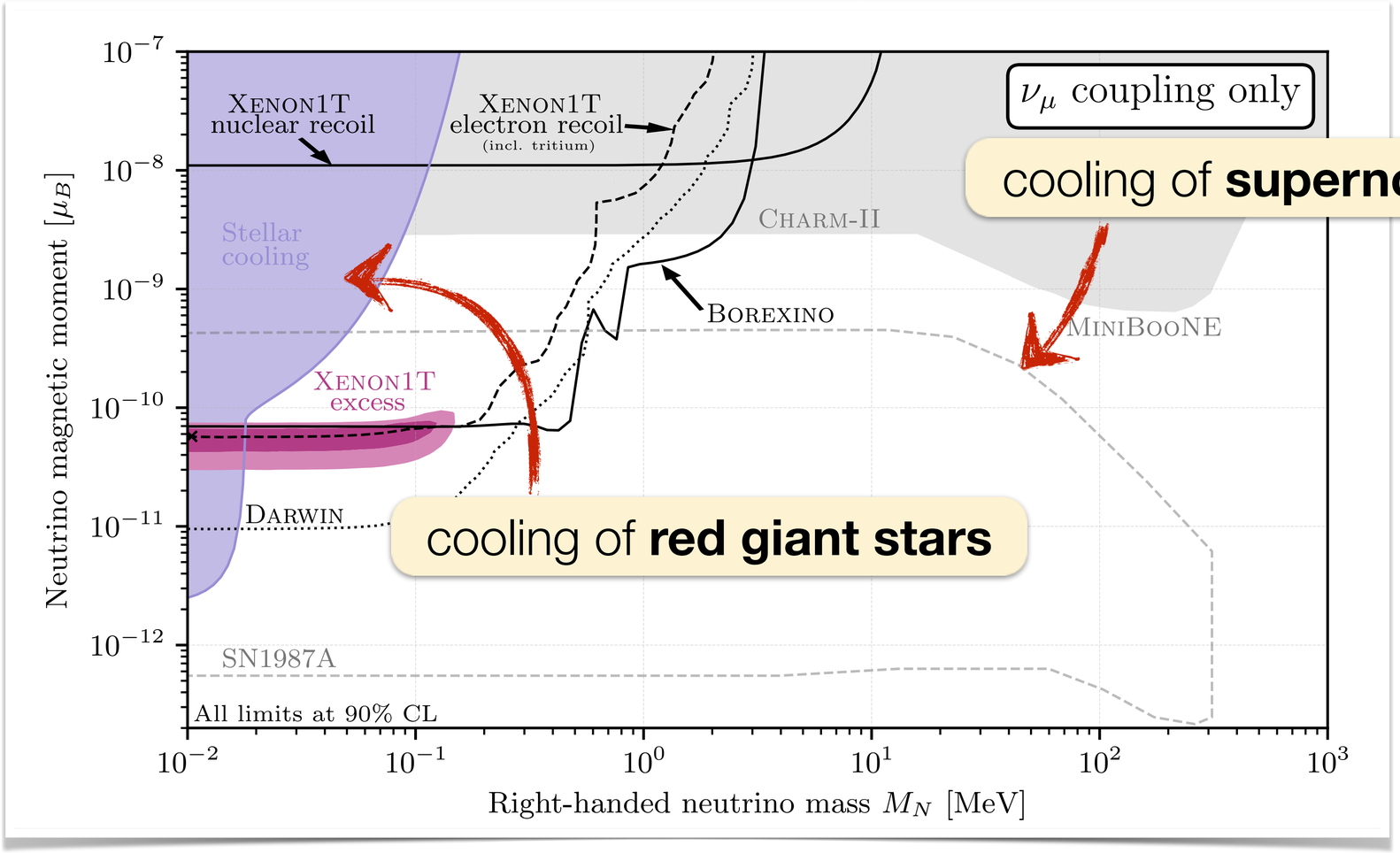
Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

Neutrino Magnetic Moments: Constraints



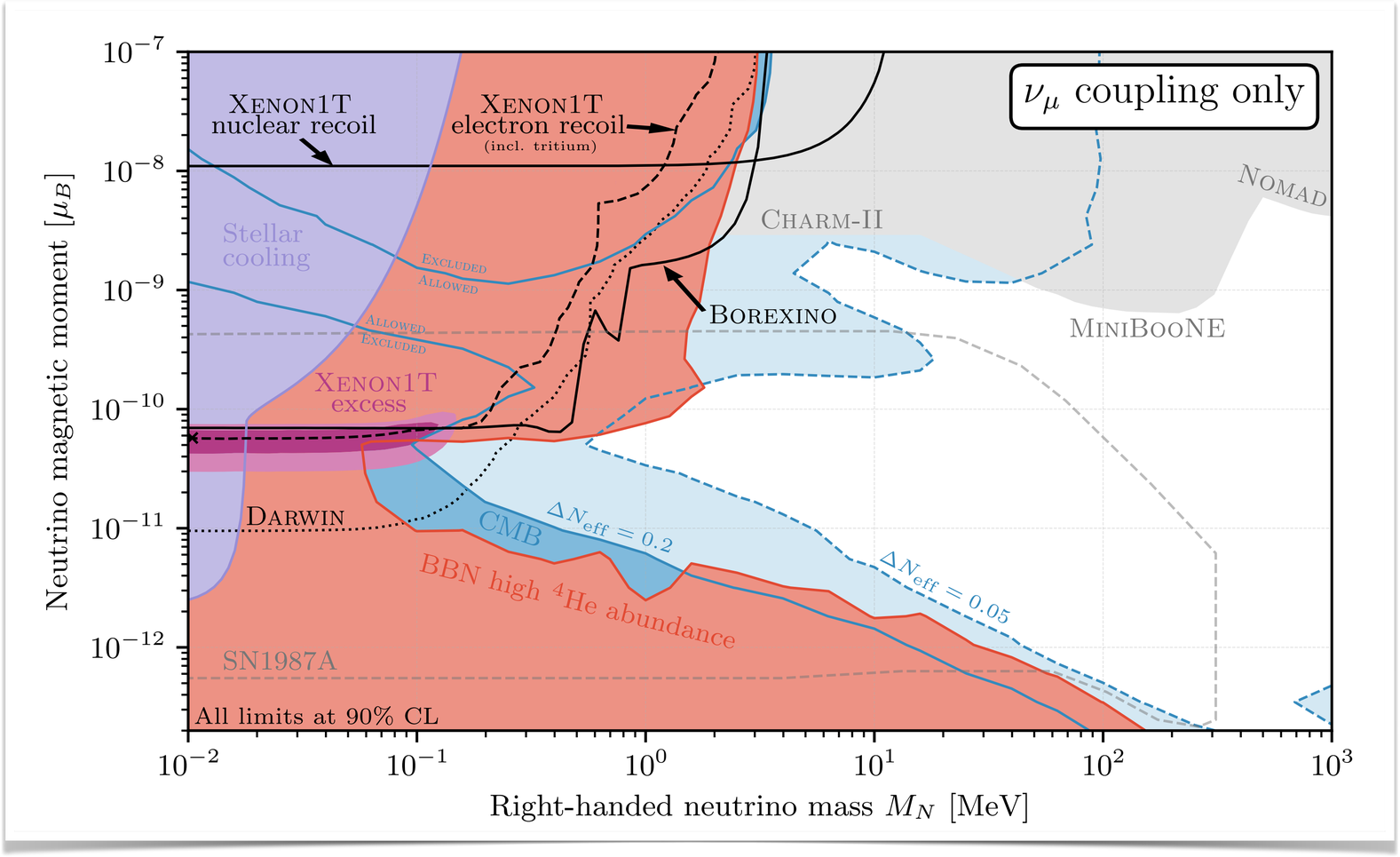
Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

Neutrino Magnetic Moments: Constraints



Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

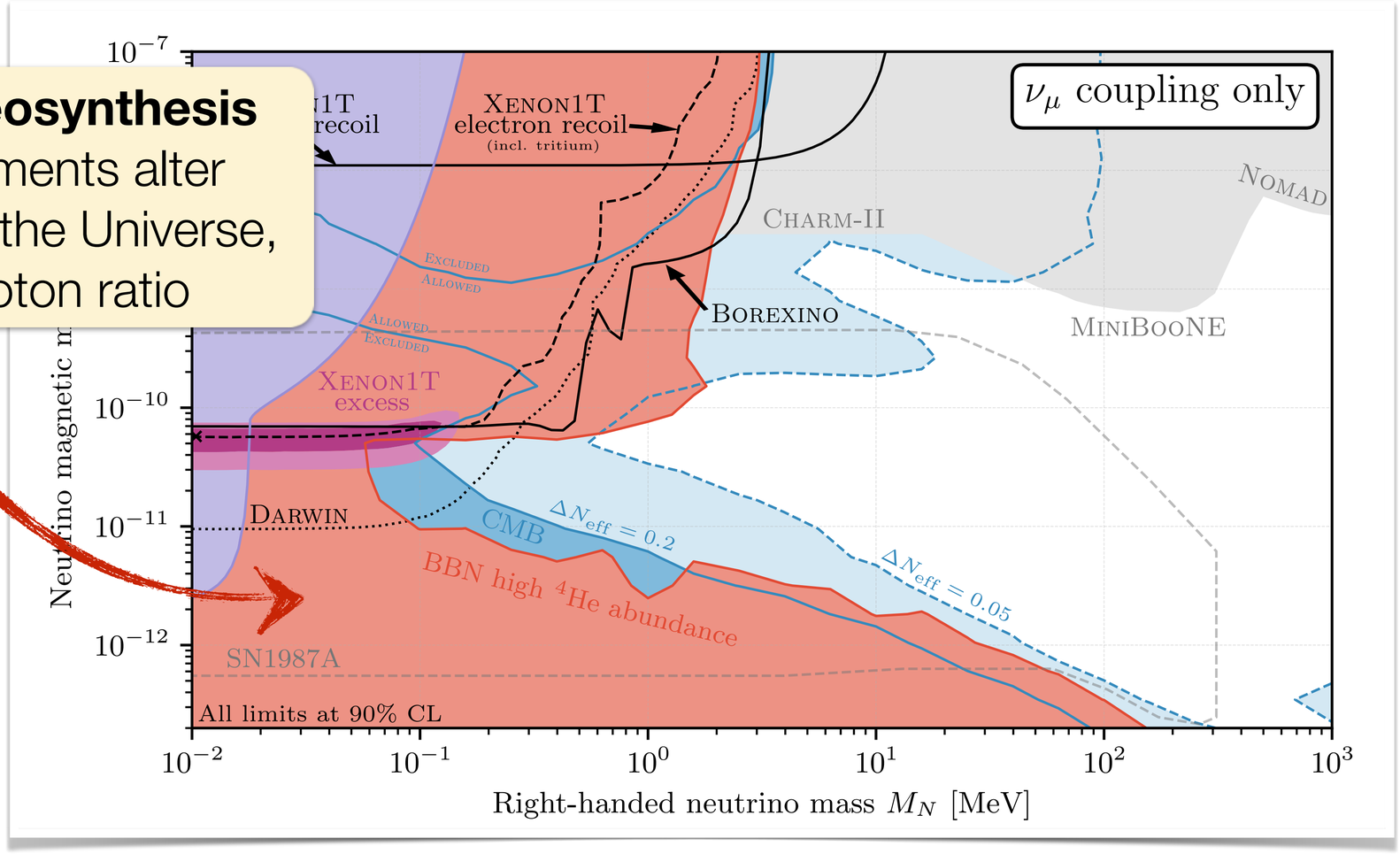
Neutrino Magnetic Moments: Constraints



Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

Neutrino Magnetic Moments: Constraints

Big Bang Nucleosynthesis
ν magnetic moments alter expansion rate of the Universe, baryon-to-photon ratio

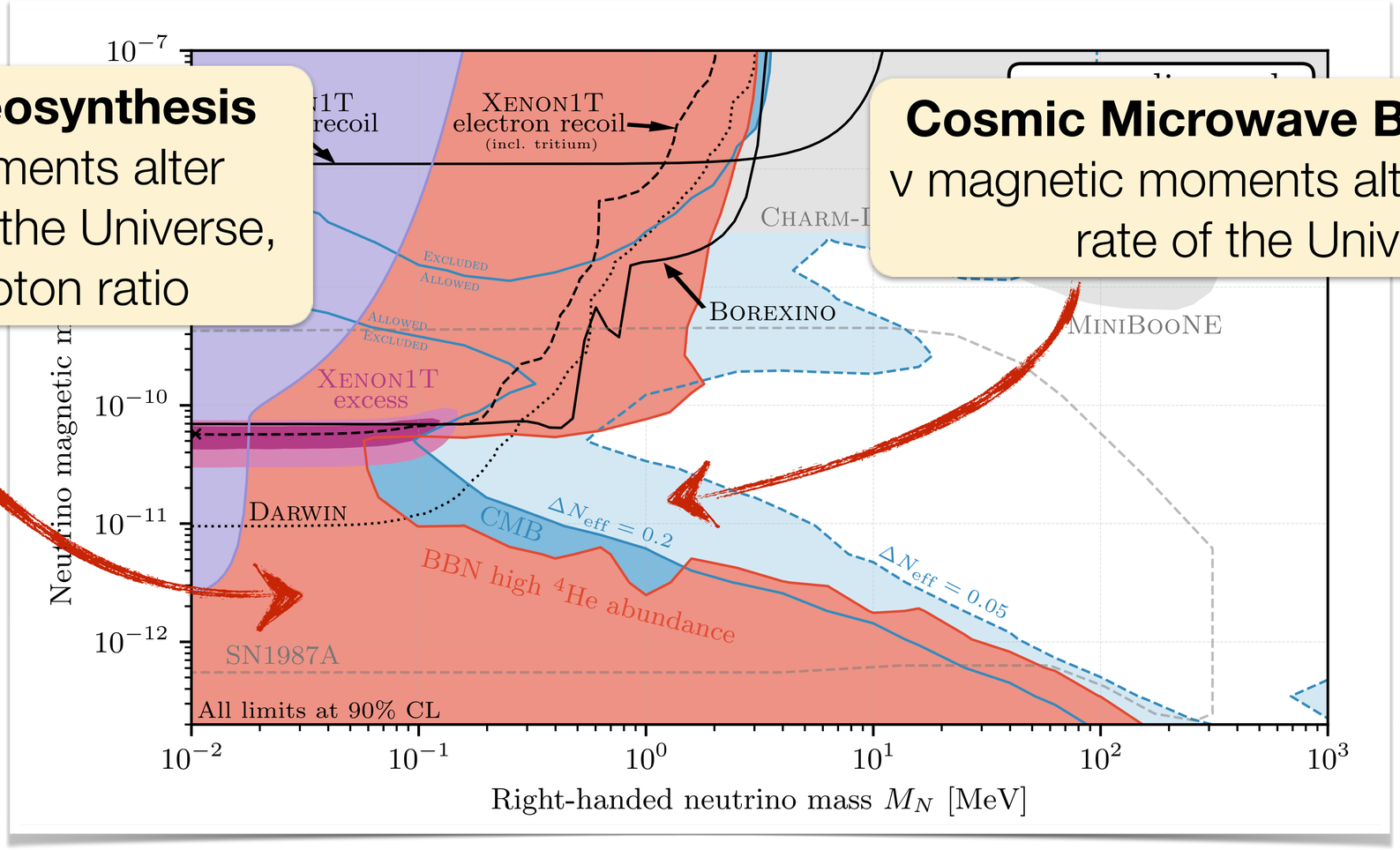


Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

Neutrino Magnetic Moments: Constraints

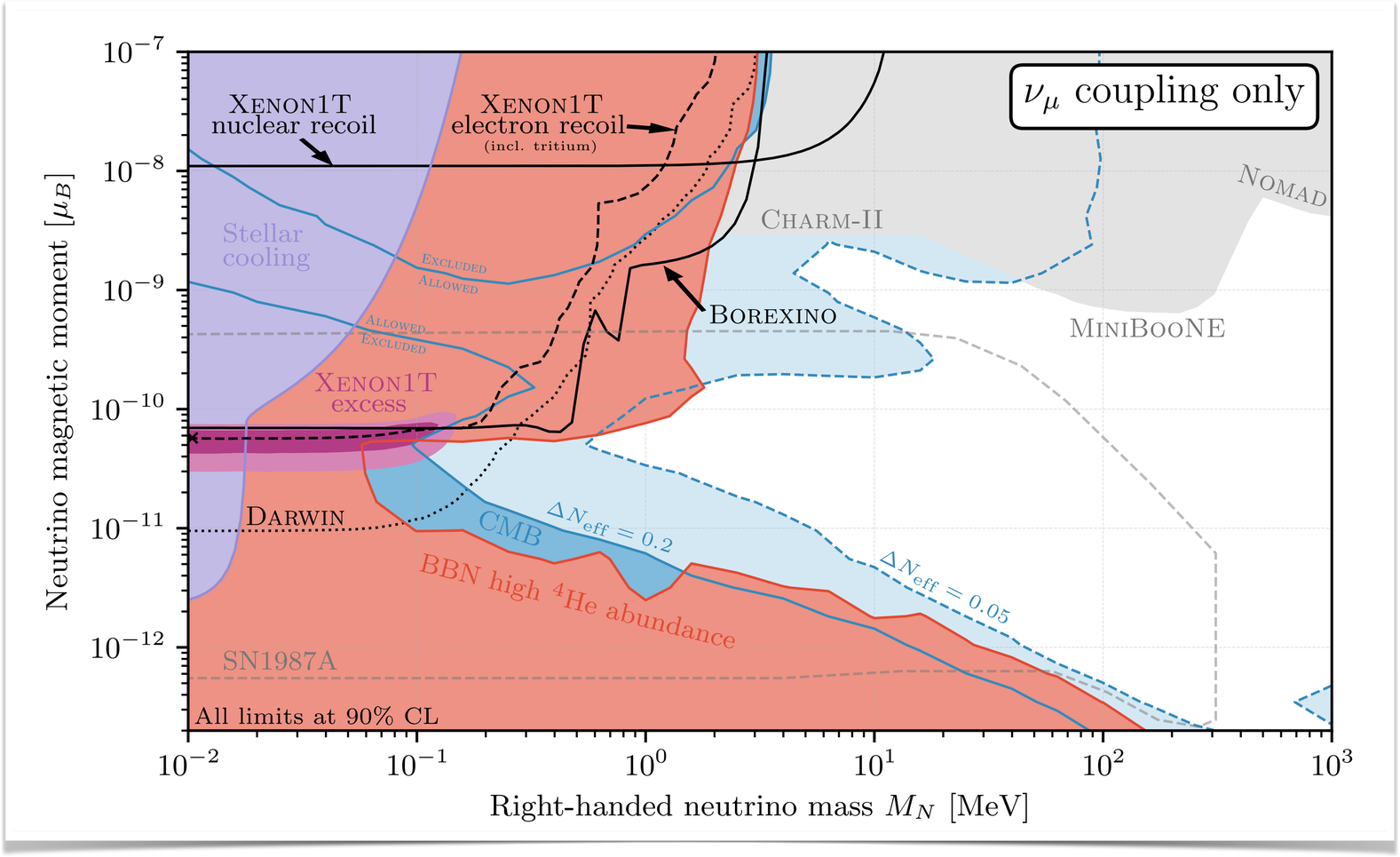
Big Bang Nucleosynthesis
ν magnetic moments alter expansion rate of the Universe, baryon-to-photon ratio

Cosmic Microwave Backrgound
ν magnetic moments alter expansion rate of the Universe



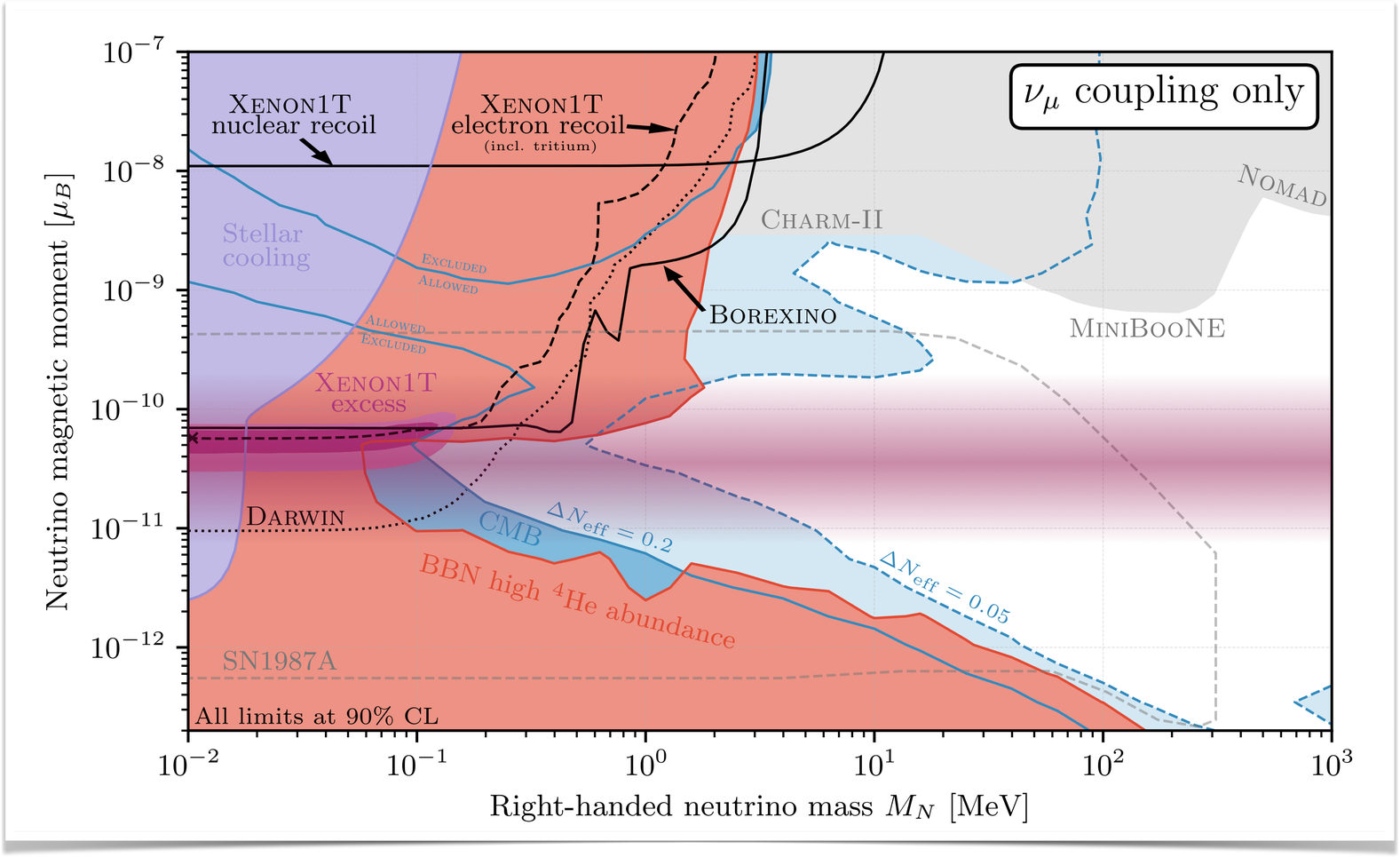
Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

Neutrino Magnetic Moments: Constraints



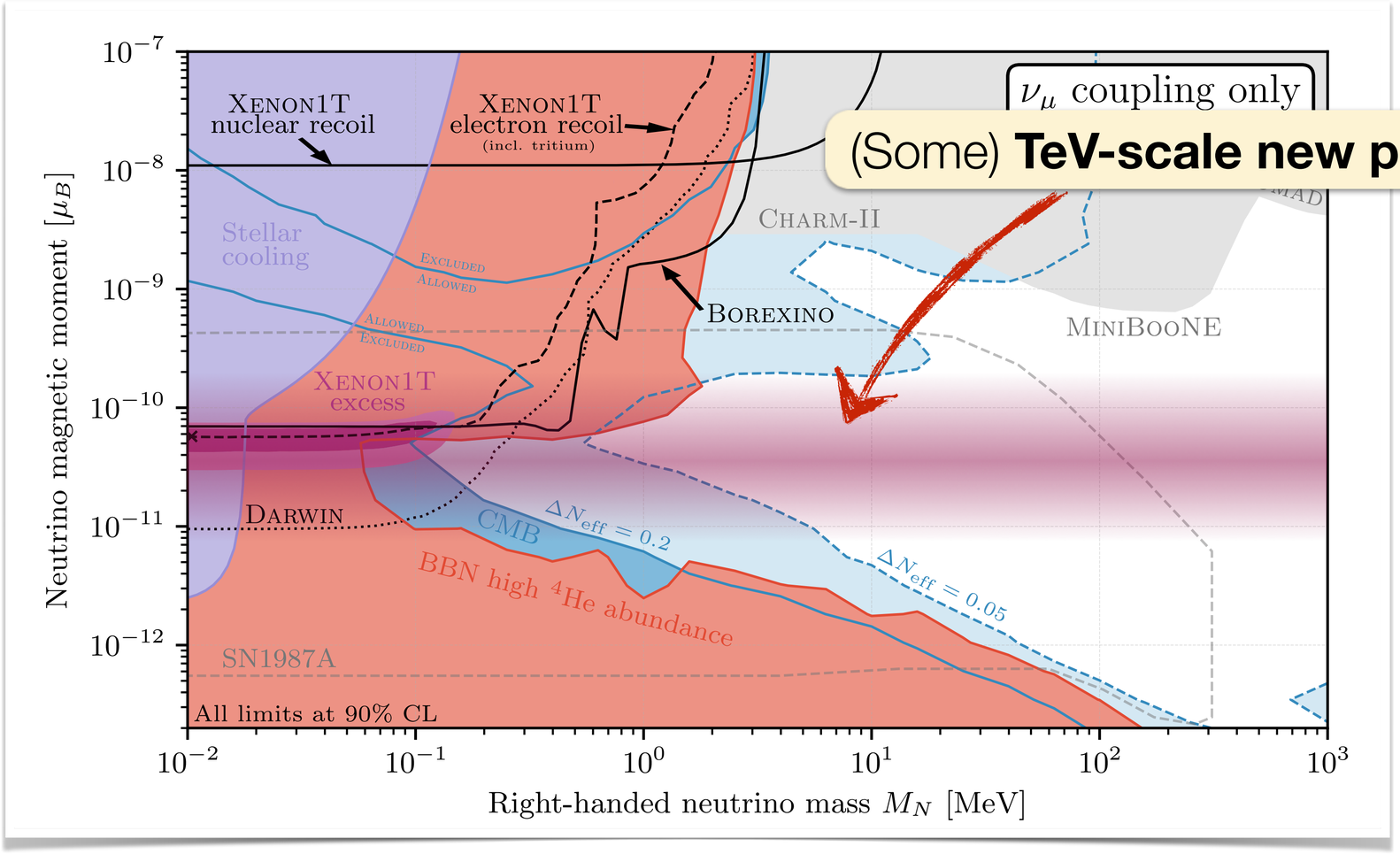
Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

Neutrino Magnetic Moments: Constraints



Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

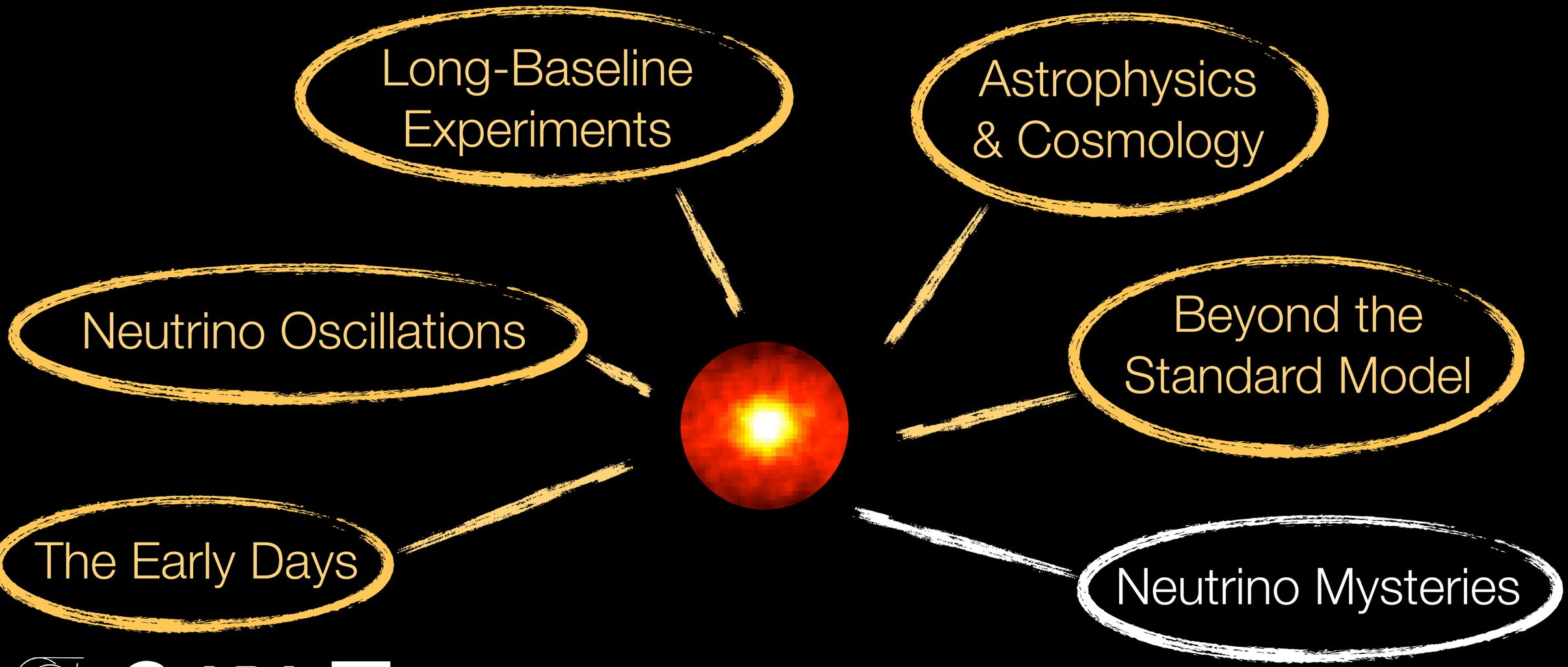
Neutrino Magnetic Moments: Constraints



(Some) **TeV-scale new physics** models

Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

Outline


Long-Baseline Experiments
Astrophysics & Cosmology
Neutrino Oscillations
Beyond the Standard Model
The Early Days
Neutrino Mysteries

MiniBooNE

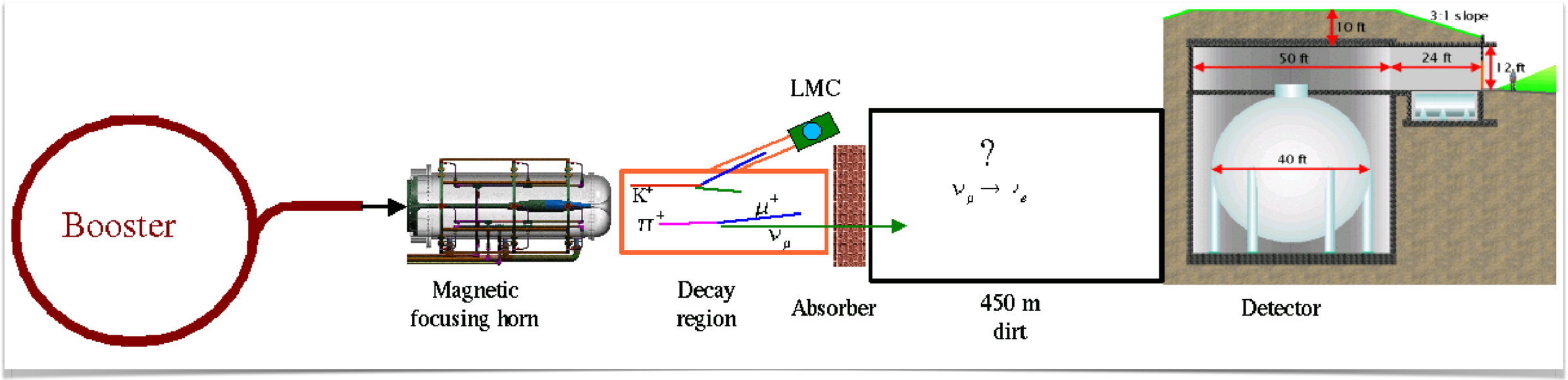
CERN

Neutrino PLATFORM

QUANTUM TECHNOLOGY INITIATIVE

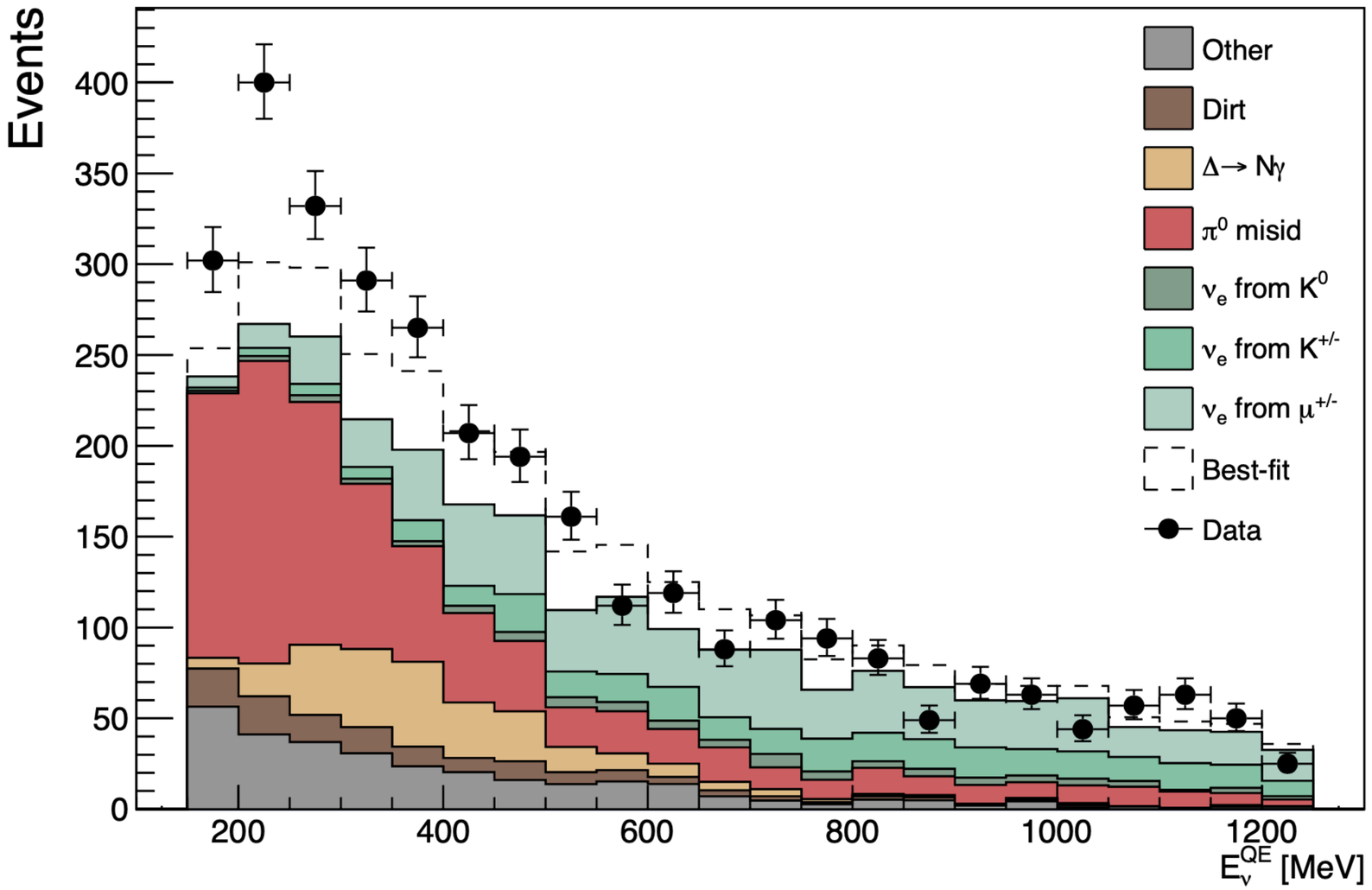
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

MiniBooNE

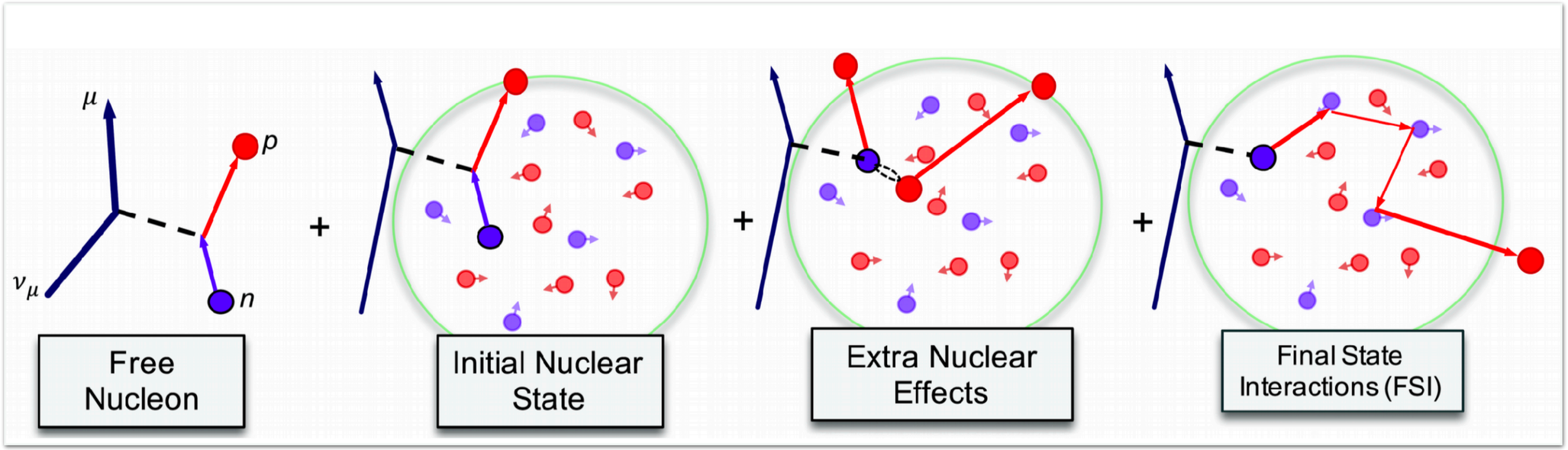

Booster
Magnetic
focusing horn
LMC
K+
π+
μ+
νμ
Decay
region
Absorber
?
νμ → νe
450 m
dirt
10 ft
3:1 slope
50 ft
24 ft
12 ft
40 ft
Detector

MiniBooNE

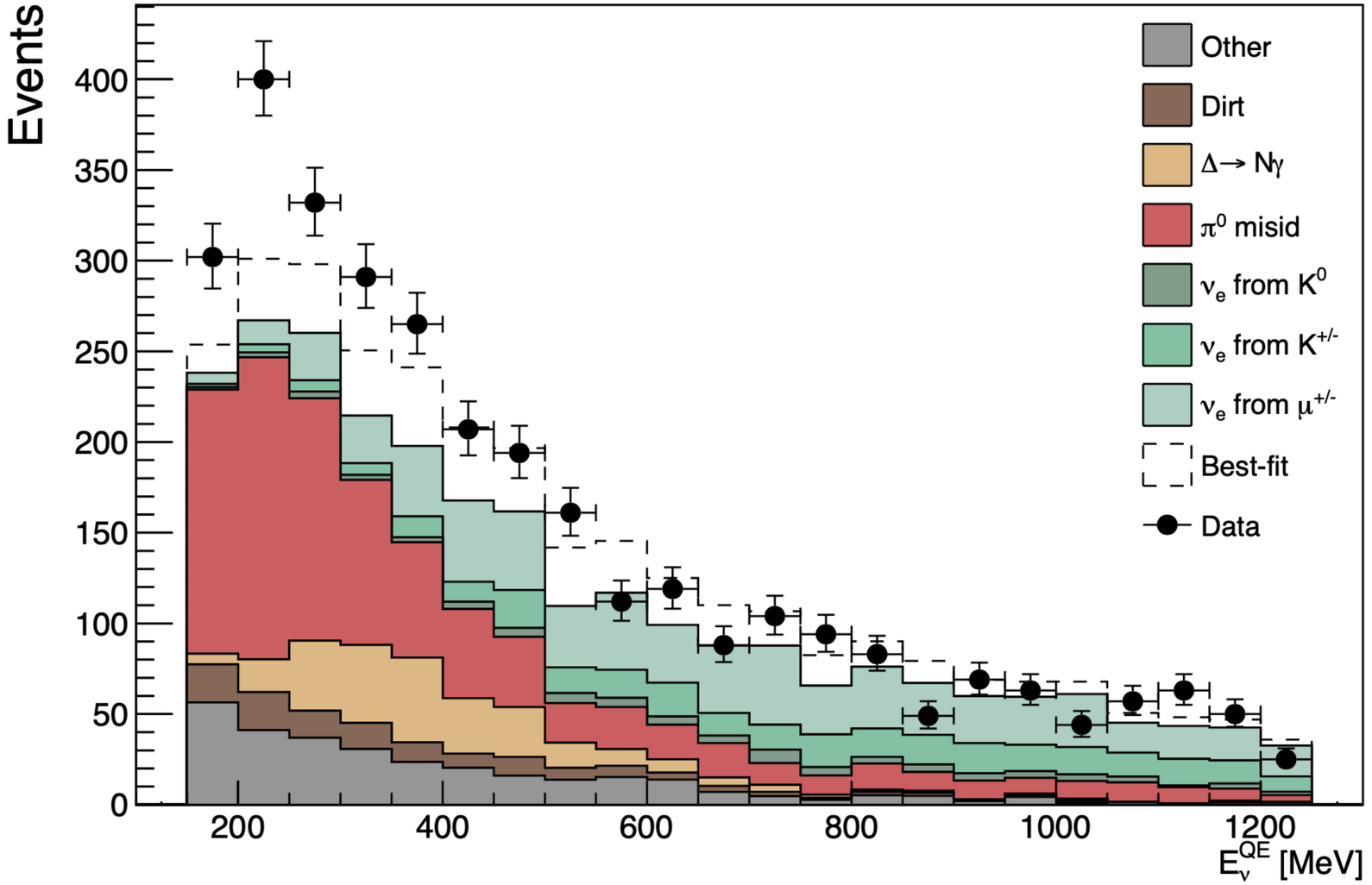
- ν_e excess in ν_μ beam (4.8σ significance)
- source–detector distance ~ 1 km (too short for standard oscillations)
- a possible hint for the existence of extra neutrino flavours ("sterile neutrinos")?



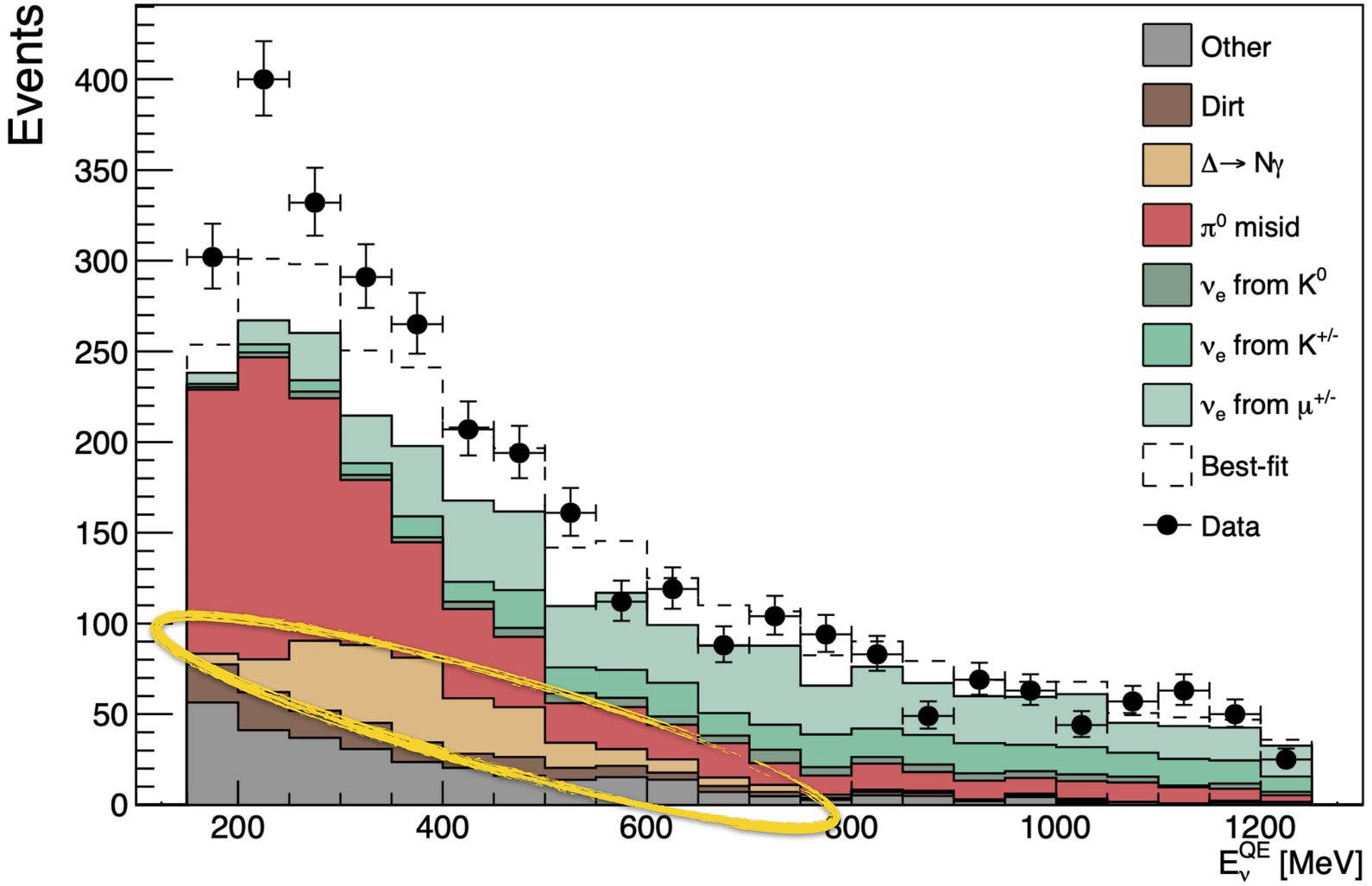
Neutrino Interactions are complicated



Example: $\Delta \rightarrow N + \gamma$

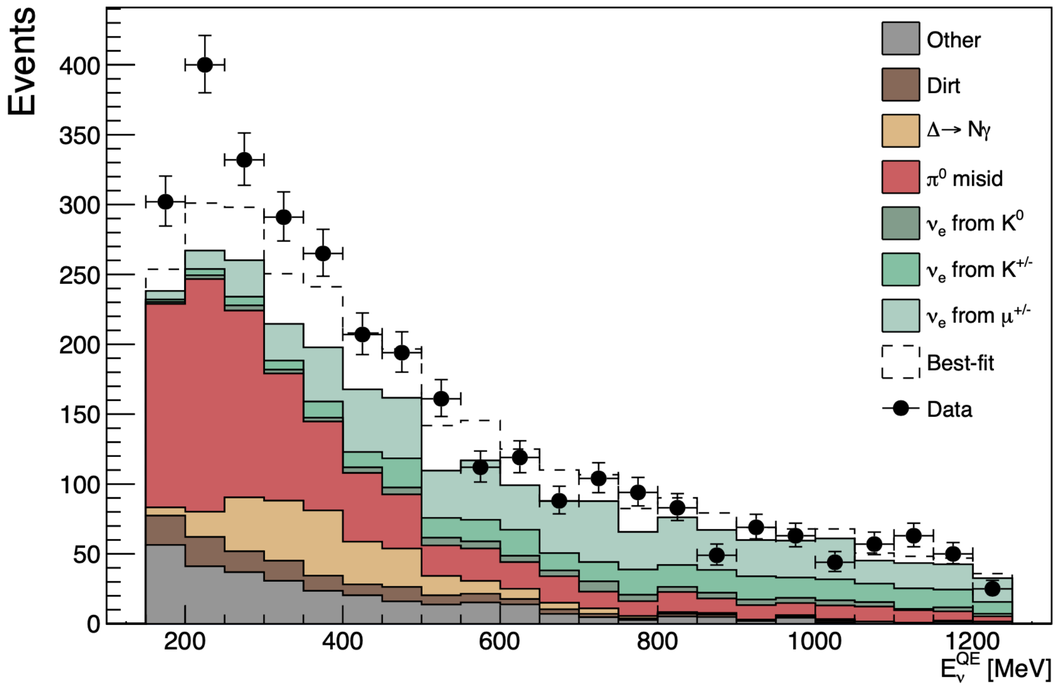


Example: $\Delta \rightarrow N + \gamma$



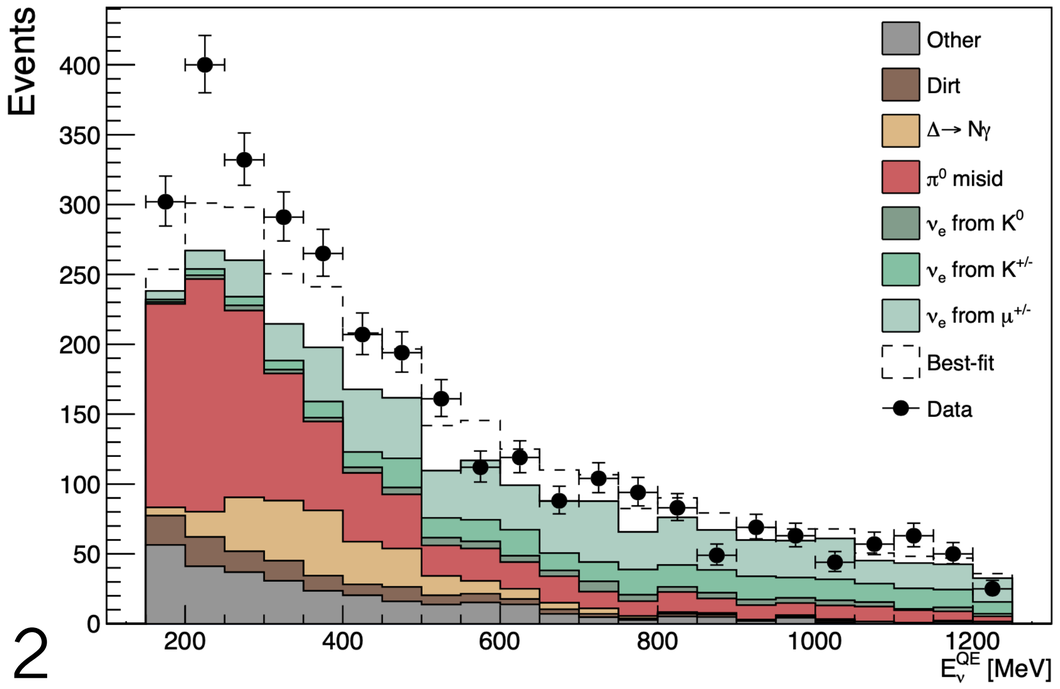
Example: $\Delta \rightarrow N + \gamma$

- Neutral current neutrino interaction:
  $\nu + N \rightarrow \nu + \Delta(1232)$
- $\Delta(1232)$ mostly decays to $\pi + N$
- But a rare decay exists to $\gamma + N$
- MiniBooNE cannot distinguish γ from e^-



Example: $\Delta \rightarrow N + \gamma$

- Δ production rate can be estimated from $\Delta \rightarrow \pi + N$
- Pions may be absorbed on their way out of the nucleus
- may excite another Δ resonance
  ➠ $\Delta \rightarrow N + \gamma$ enhanced by ~ factor 2
- or may be absorbed
  ➠ control region suppressed by ~ factor 2
- This factor 2 has been taken into account by MiniBooNE



The Gallium Anomaly

CERN

Neutrino PLATFORM

QUANTUM TECHNOLOGY INITIATIVE

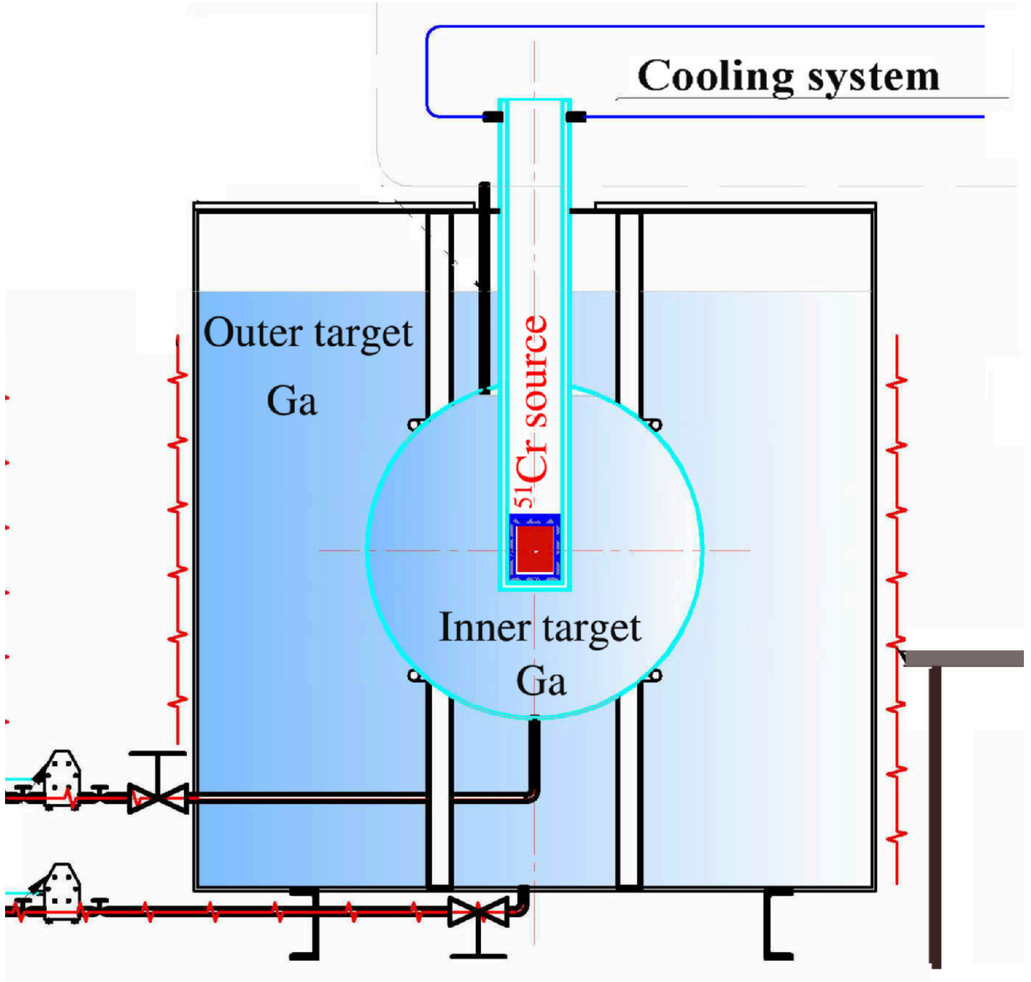
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

The Gallium Anomaly

- Experiments with intense radioactive sources
- Neutrino detection via

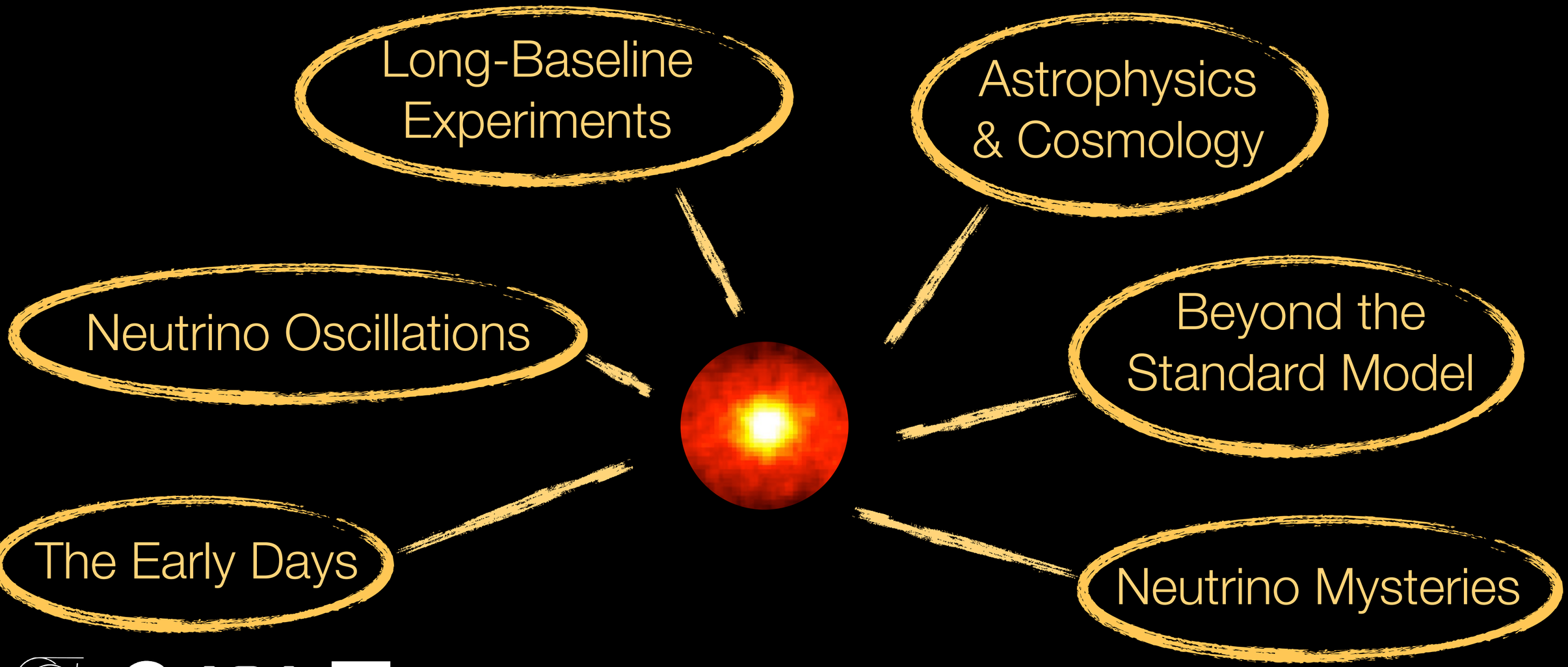
$$^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$$

- $> 5\sigma$ deficit
- seen by three experiments
- ν_e disappearance into sterile state?
- would require very large mixing (conflict with reactor observations)



Giunti Laveder 1006.3244
BEST arXiv:2109.11482
Barinov Gorbunov arXiv:2109.14654

Summary


Long-Baseline Experiments
Astrophysics & Cosmology
Neutrino Oscillations
Beyond the Standard Model
The Early Days
Neutrino Mysteries

Thank You!

CERN

Neutrino PLATFORM

QUANTUM TECHNOLOGY INITIATIVE

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ