Neutrinos in the Lab and in the Cosmos

Joachim Kopp (CERN & JGU Mainz)

CERN Academic Training Lectures • 16–19 October 2023

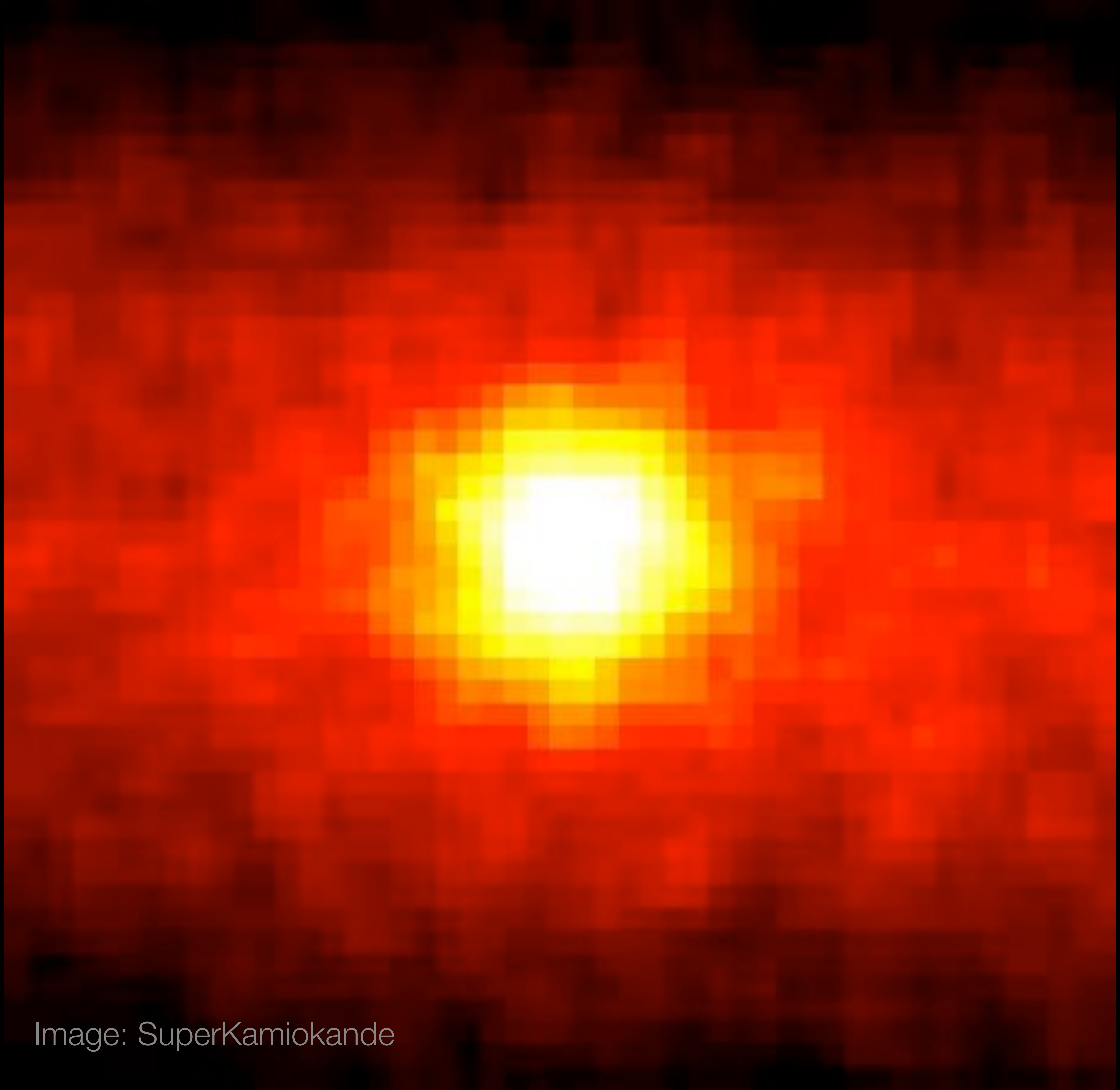
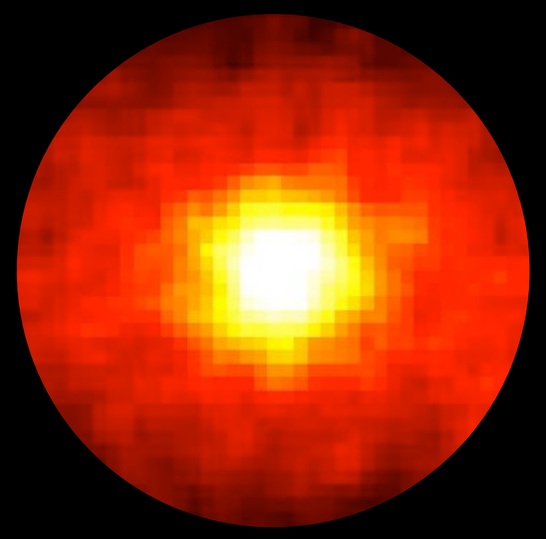
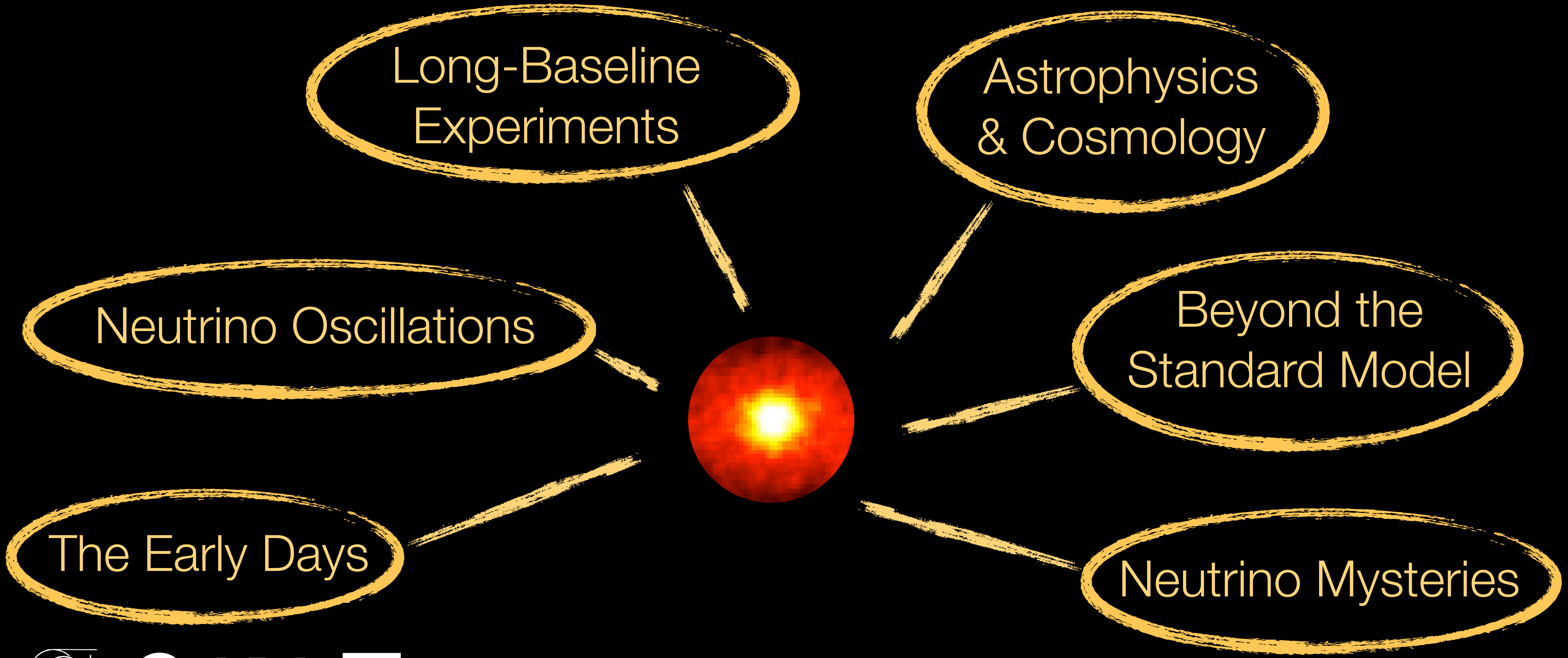


Image: SuperKamiokande

Outline

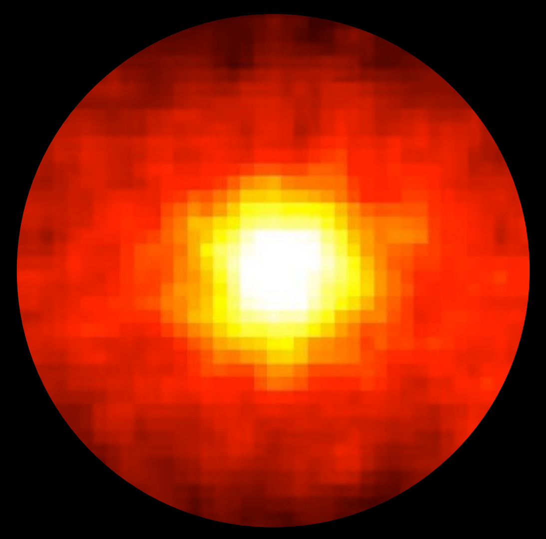


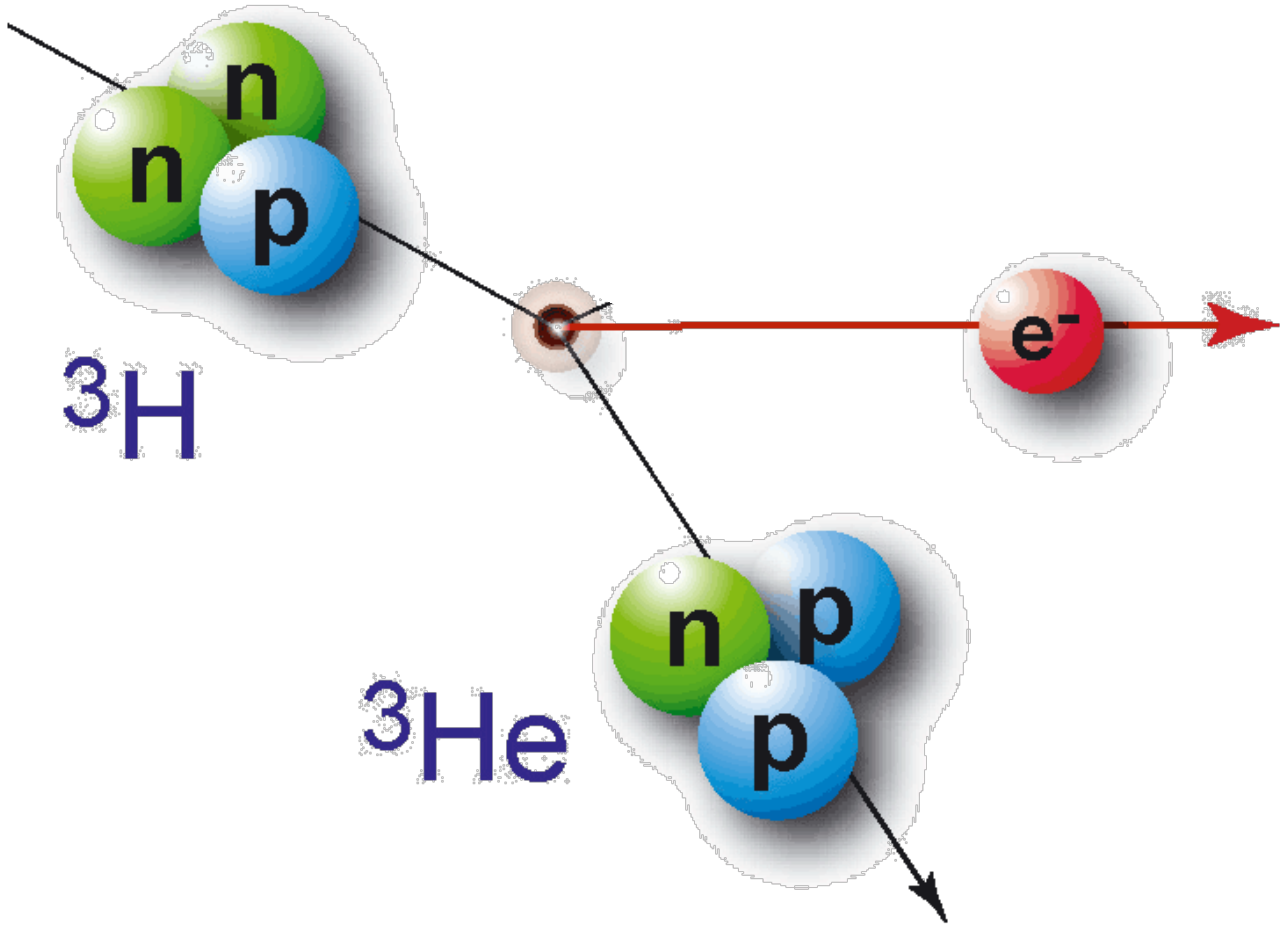
Outline


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

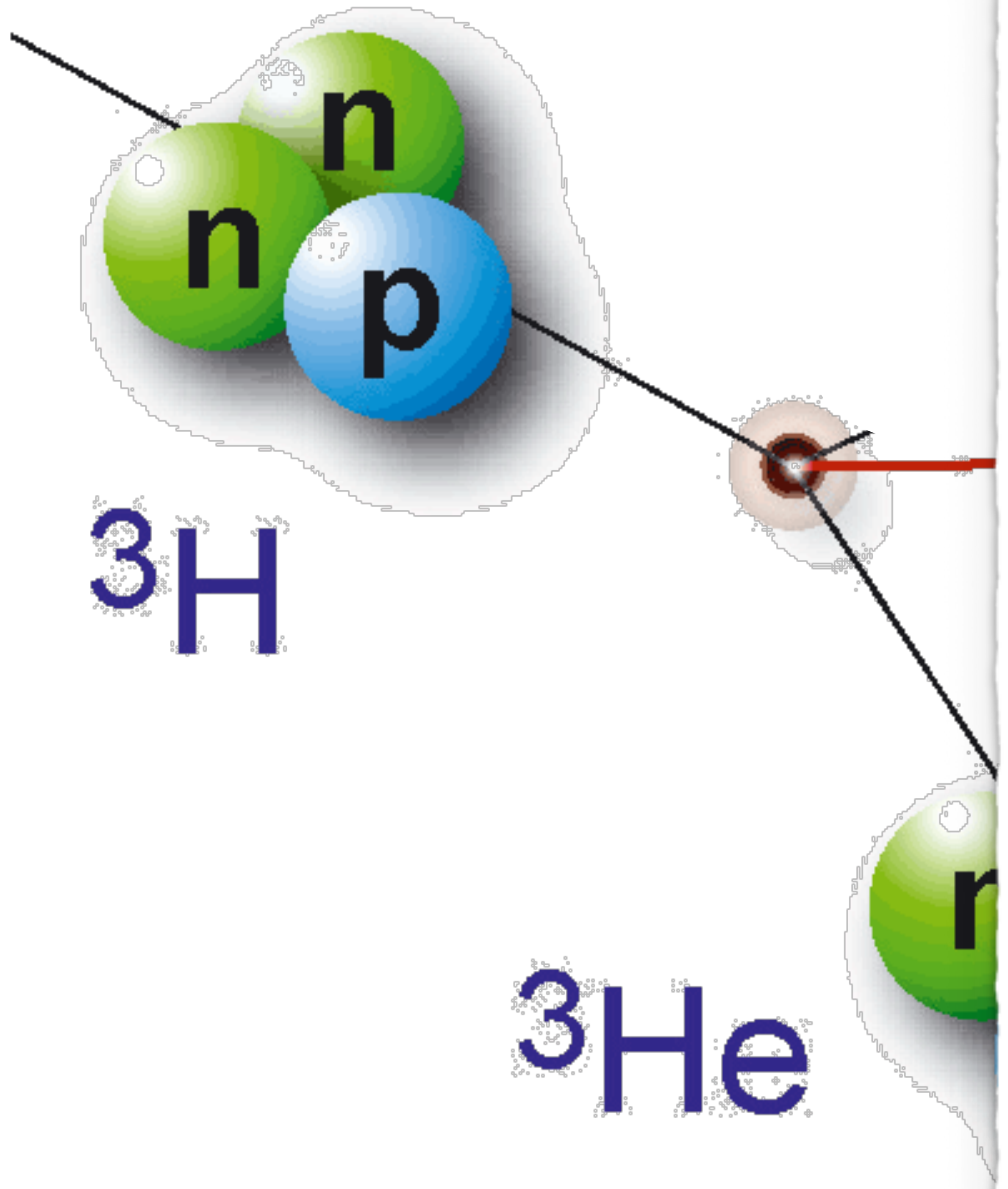
Outline

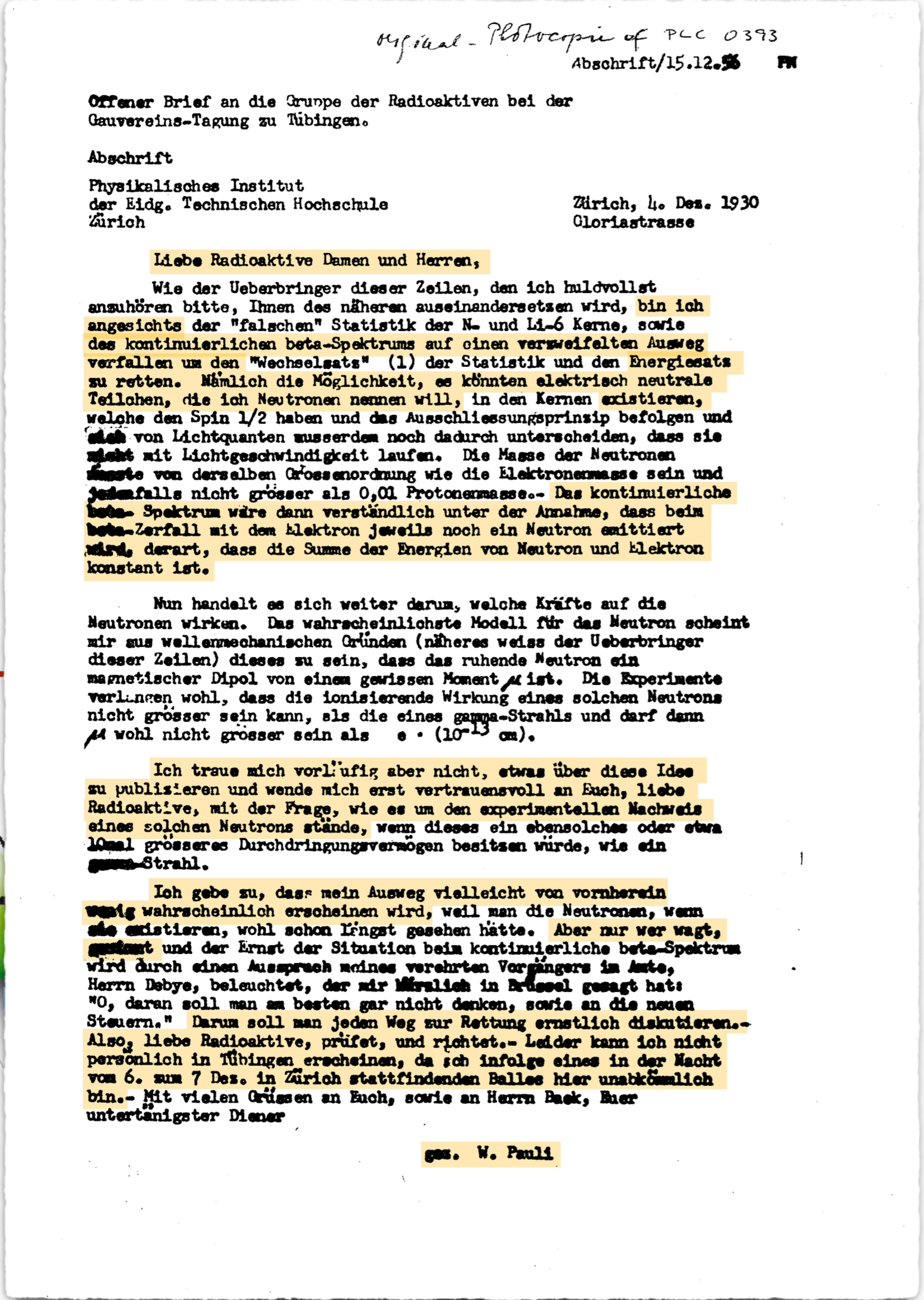
- Long-Baseline Experiments
- Astrophysics & Cosmology
- Neutrino Oscillations
- Beyond the Standard Model
- The Early Days
- Neutrino Mysteries





Wolfgang Pauli





Original - Photocopie of PLC 0393

Abschrift/15.12.56 FM

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 Grossenordnung 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/15.12.56 PM

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 Grossenordnung 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.

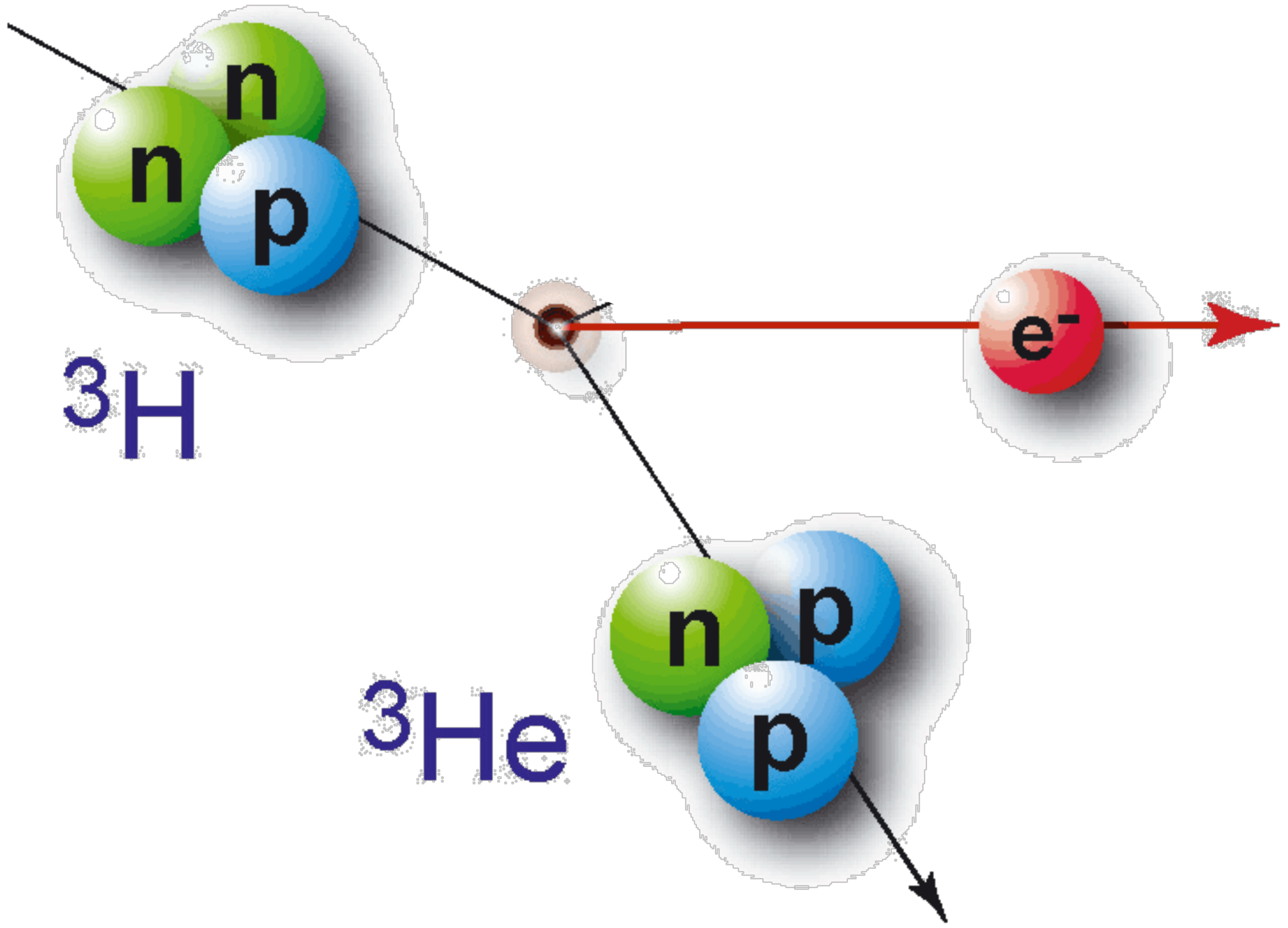
Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint

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 $e \cdot (10^{-13}\ cm)$.

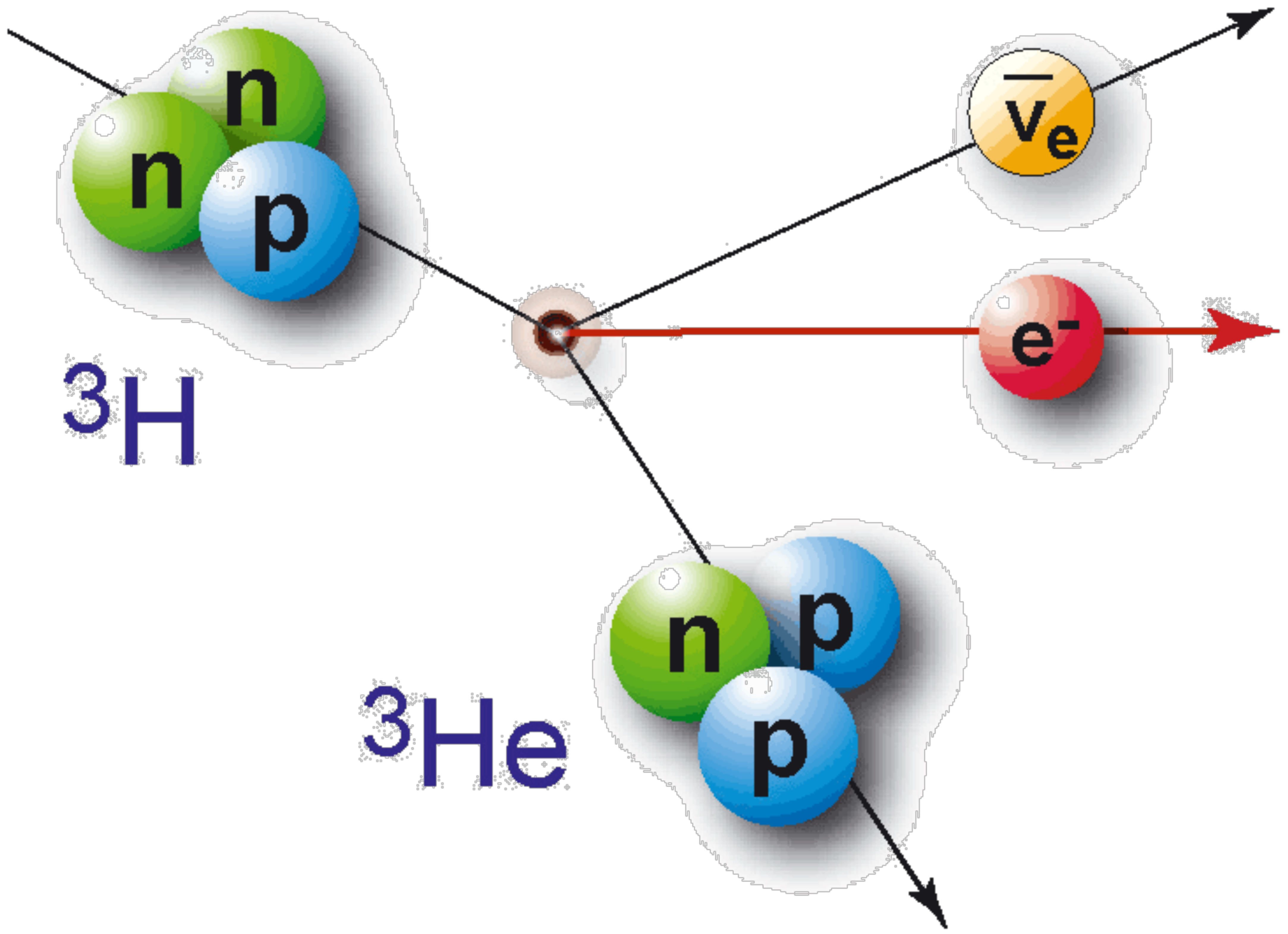
Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen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

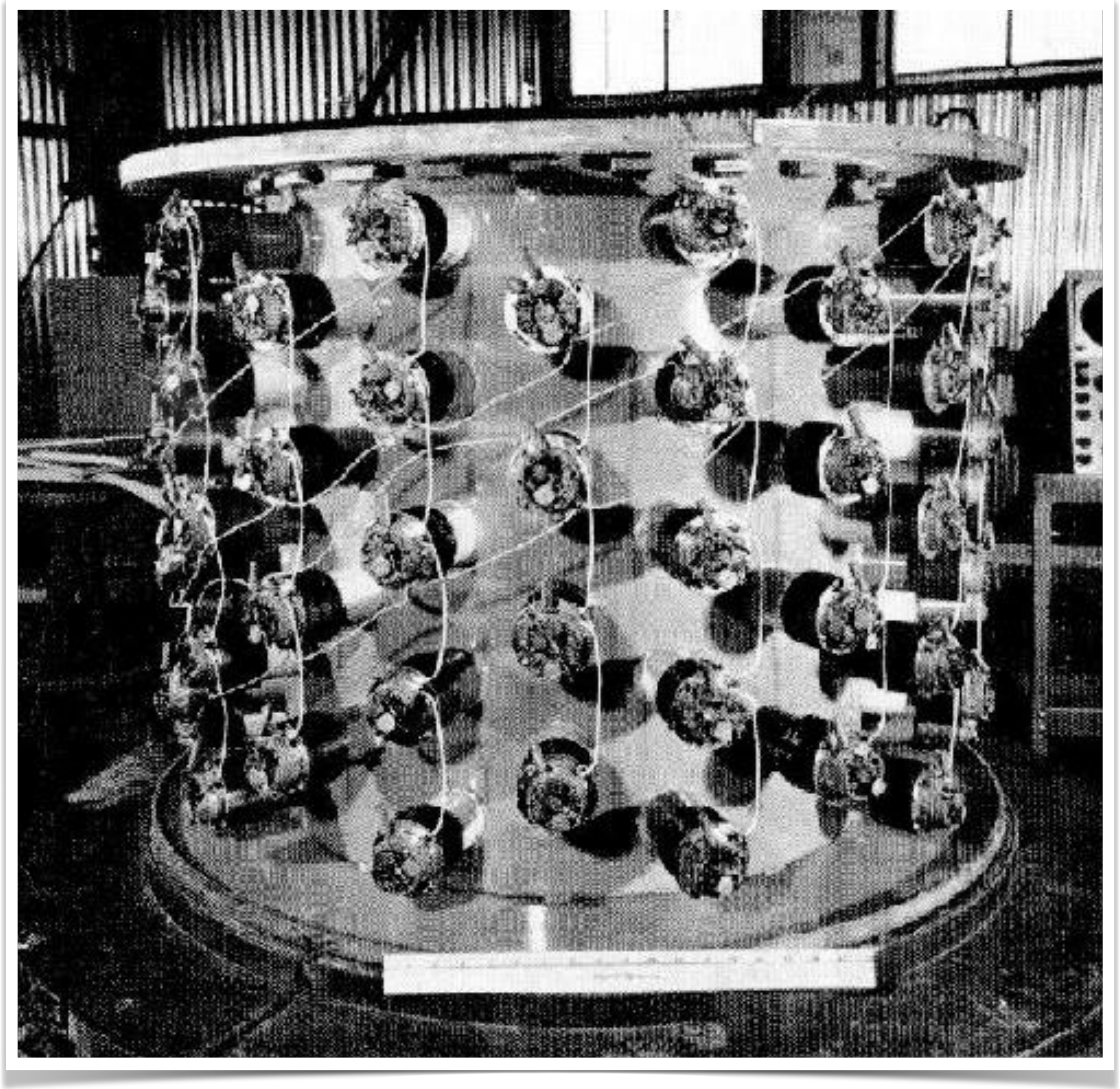
ges. W. Pauli



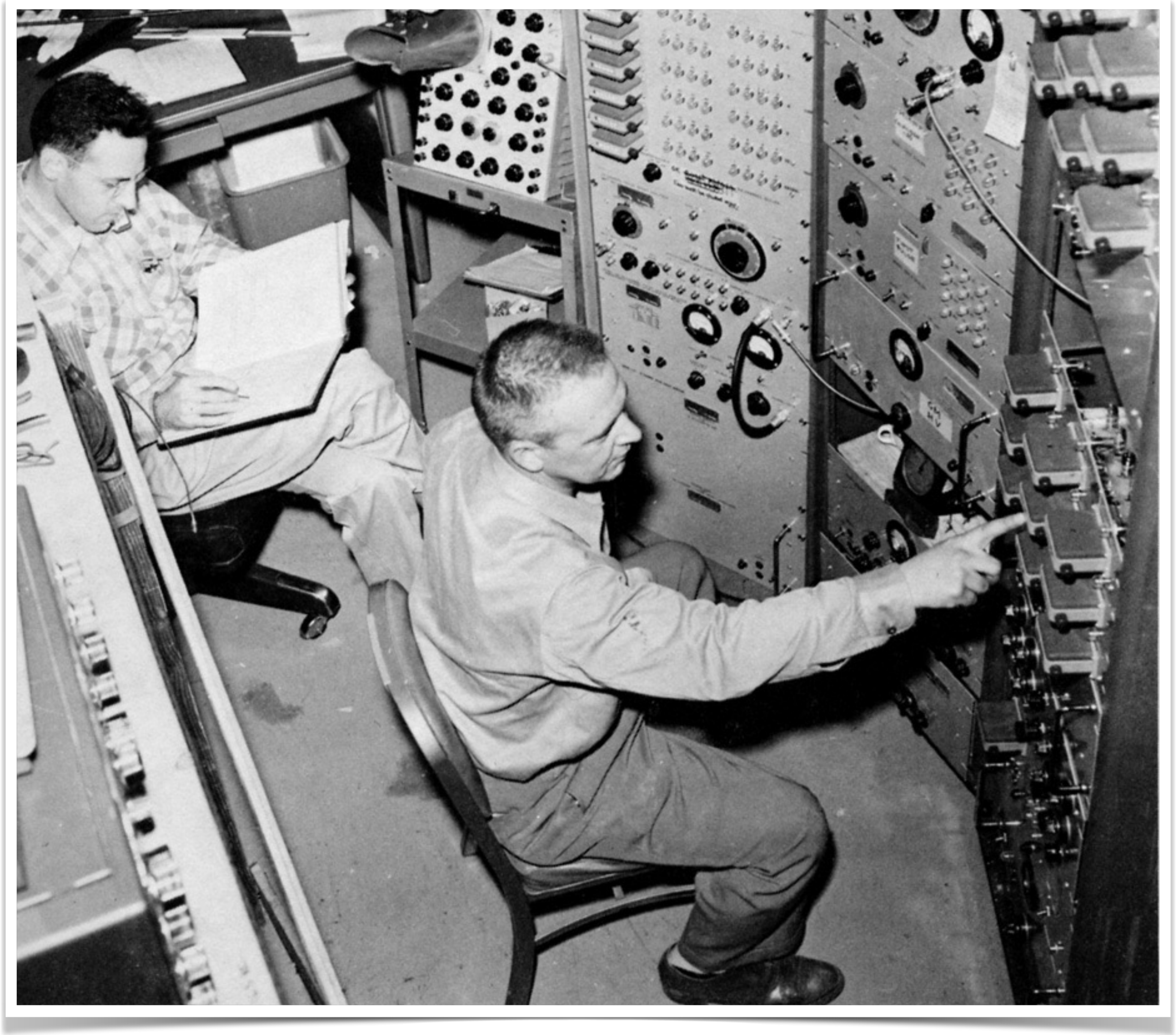
Wolfgang Pauli



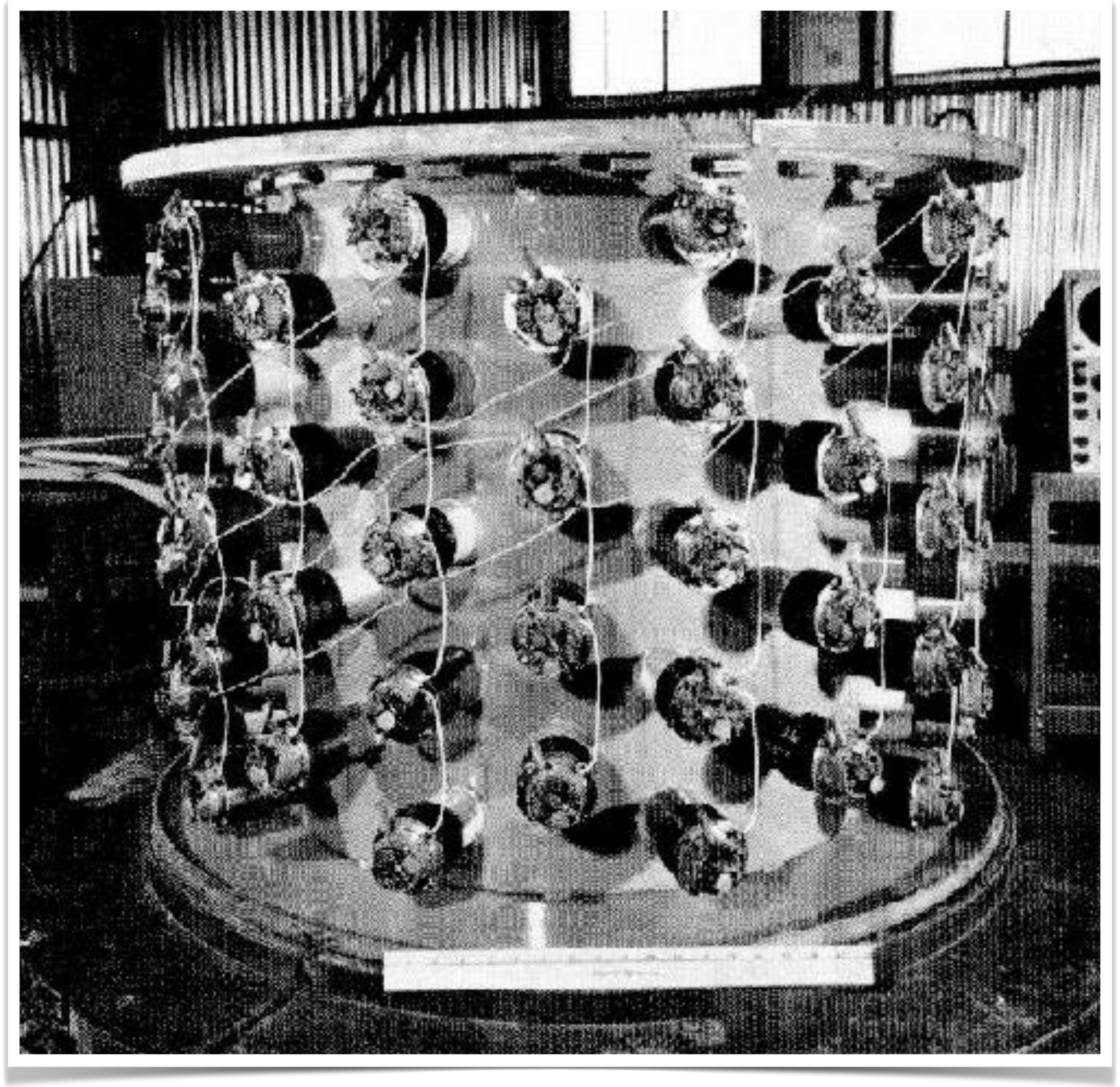
Wolfgang Pauli



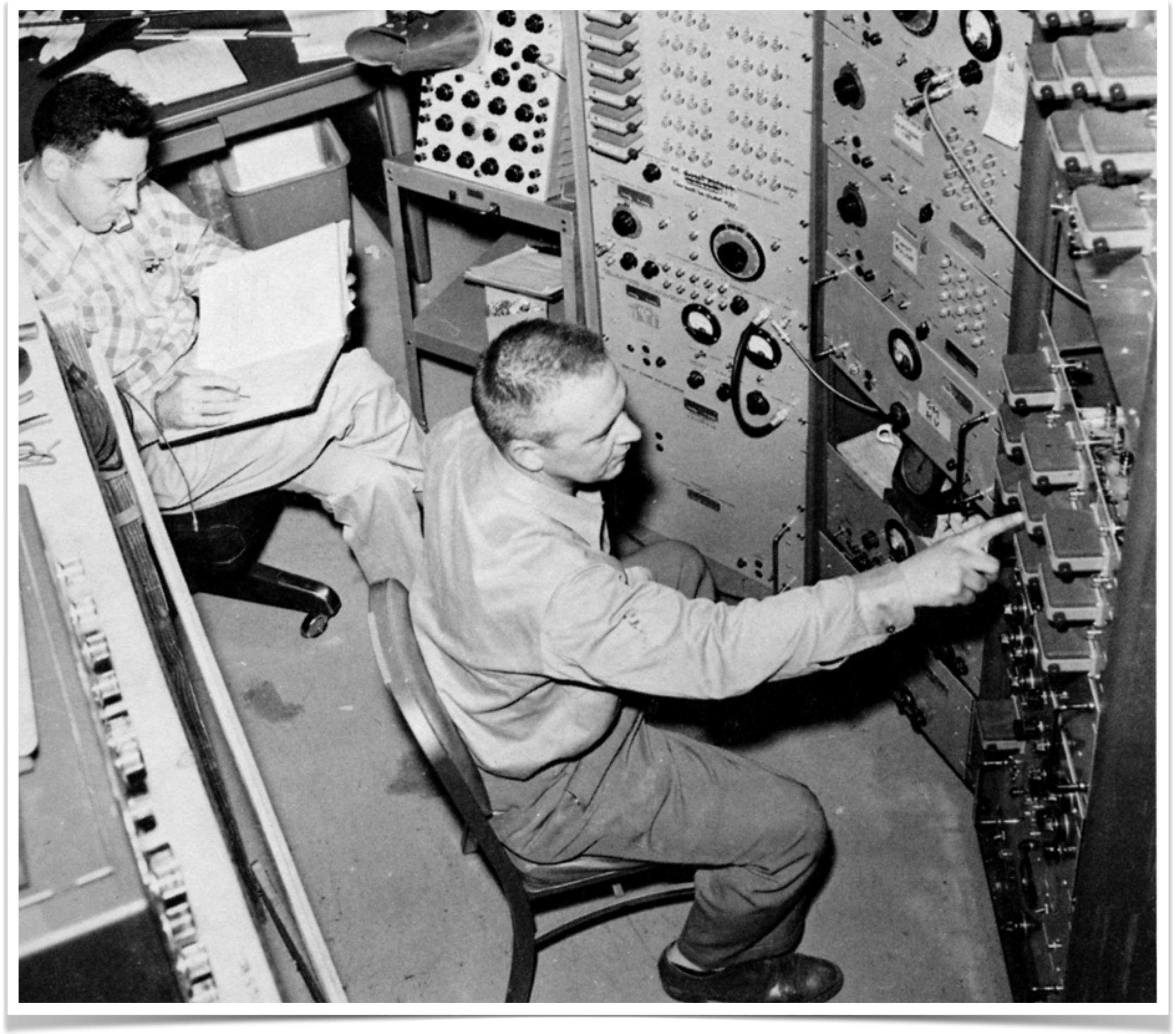
Poltergeist (1956)



Fred Reines, Clyde Cowan



Poltergeist (1956)



Fred Reines, Clyde Cowan

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

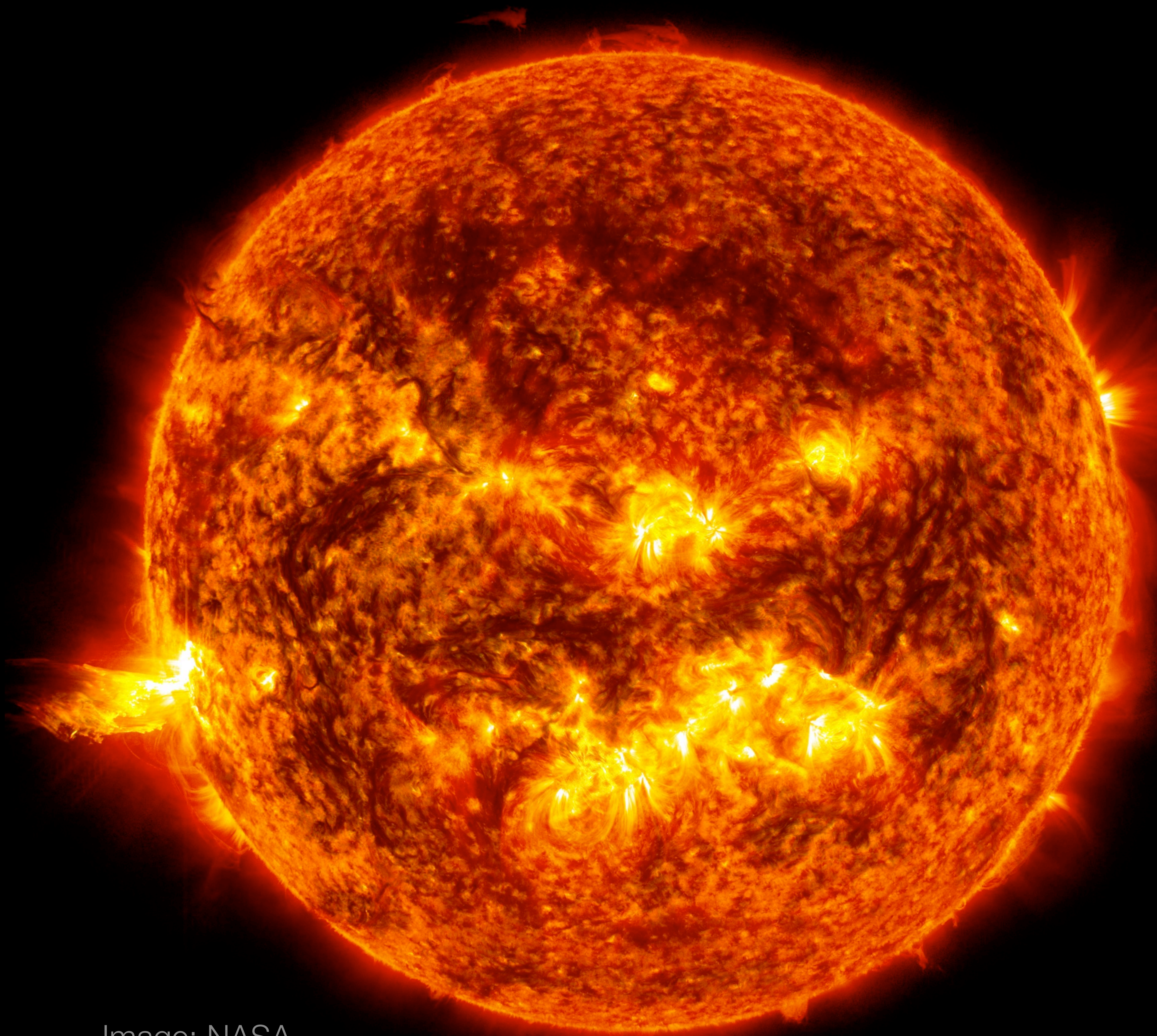
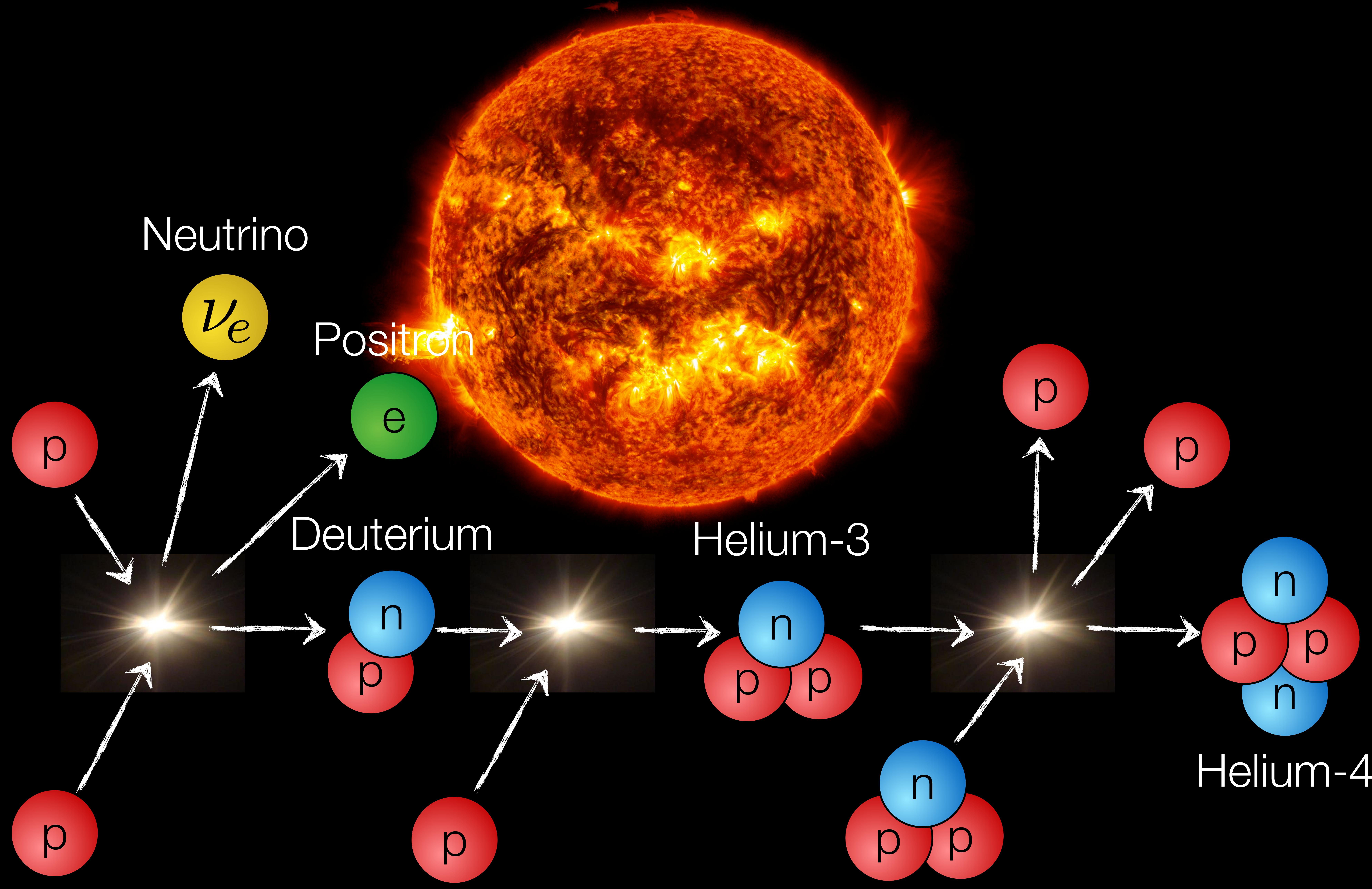
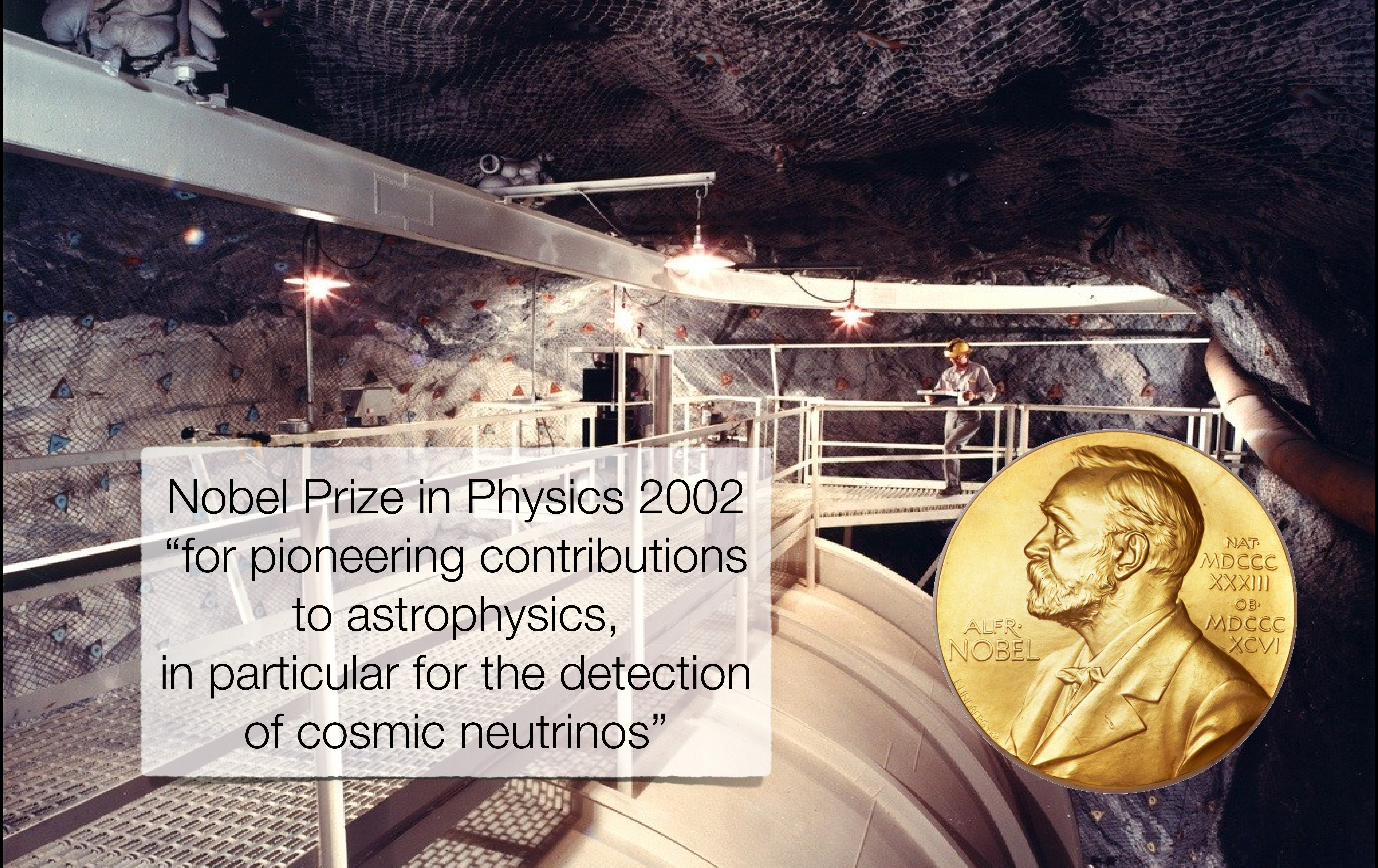
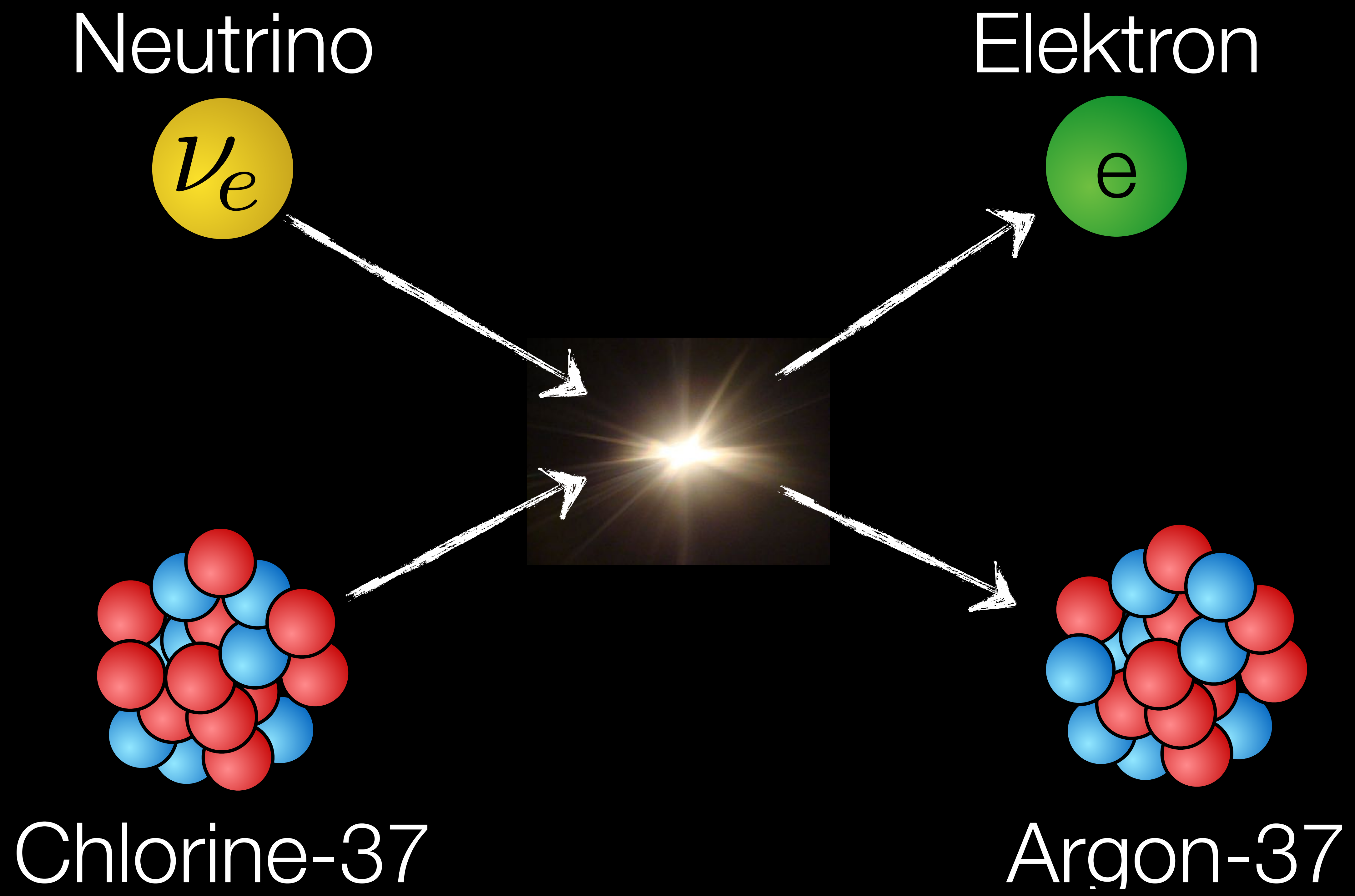


Image: NASA

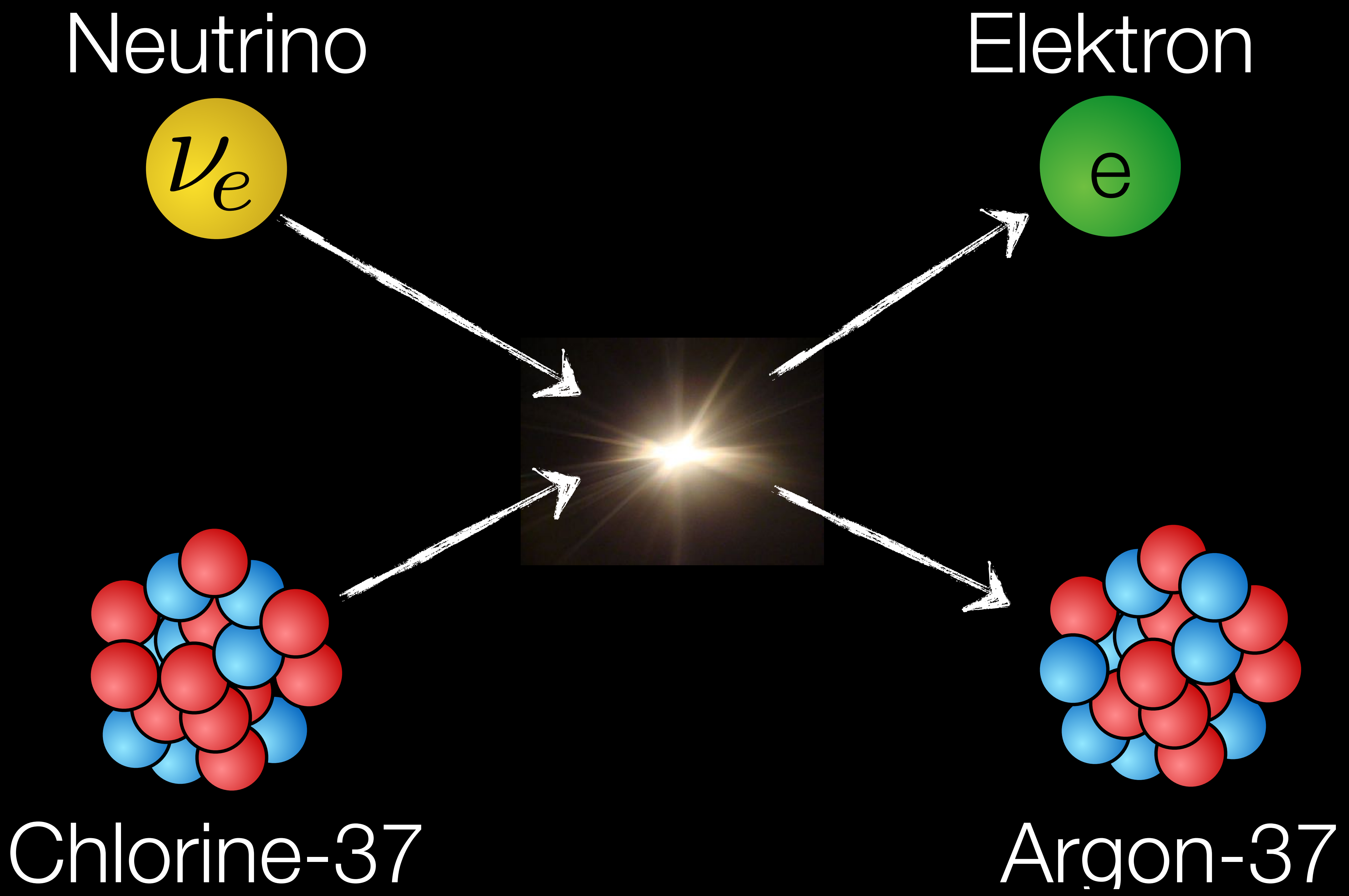

Neutrino
ν_e
Positron
e
p
p
Deuterium
n
p
p
Helium-3
n
p
p
n
p
p
p
p
n
p
p
n
Helium-4
Image: NASA



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

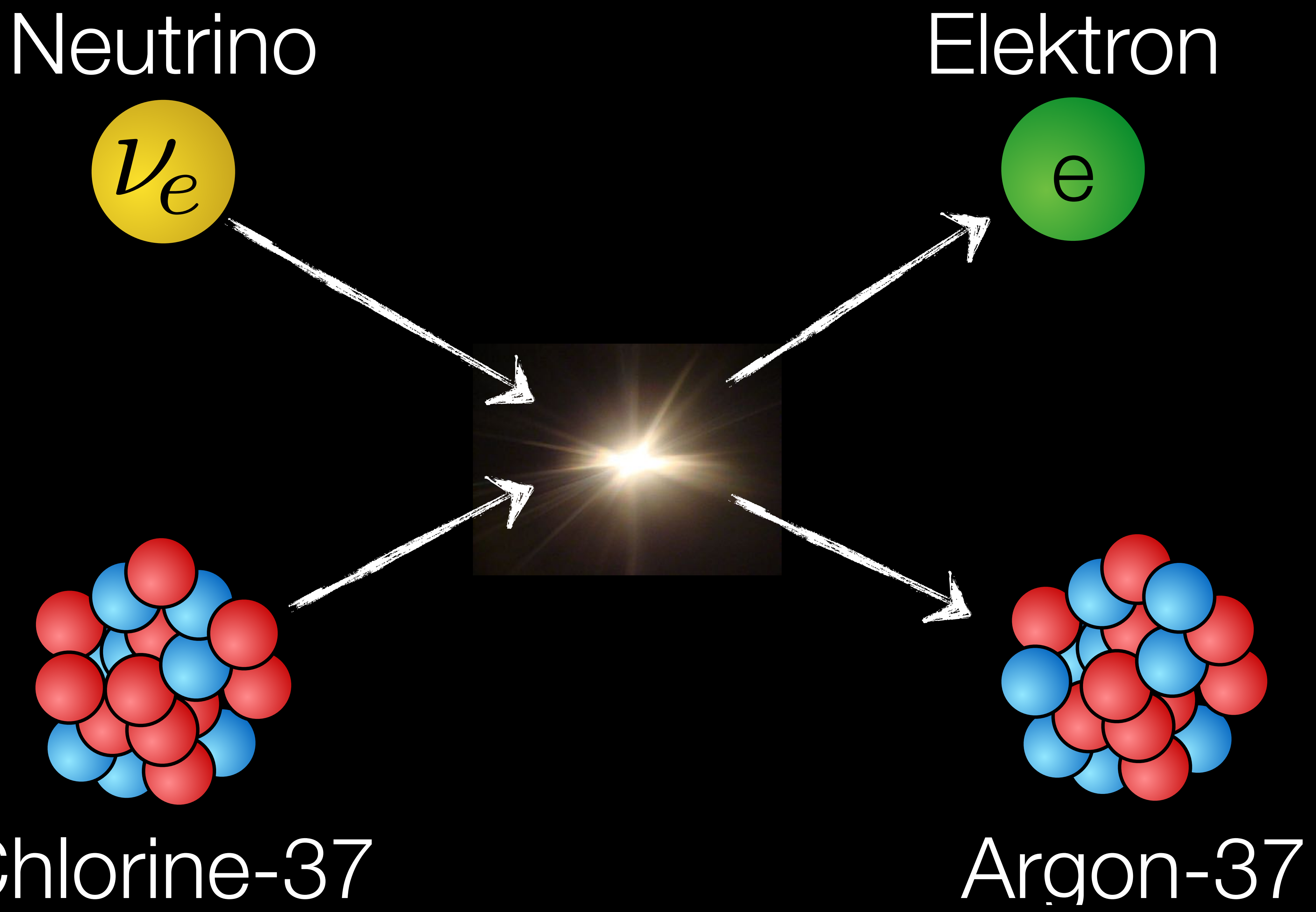

Neutrino
ν_e
Elektron
e
Chlorine-37
Argon-37

Ray Davis

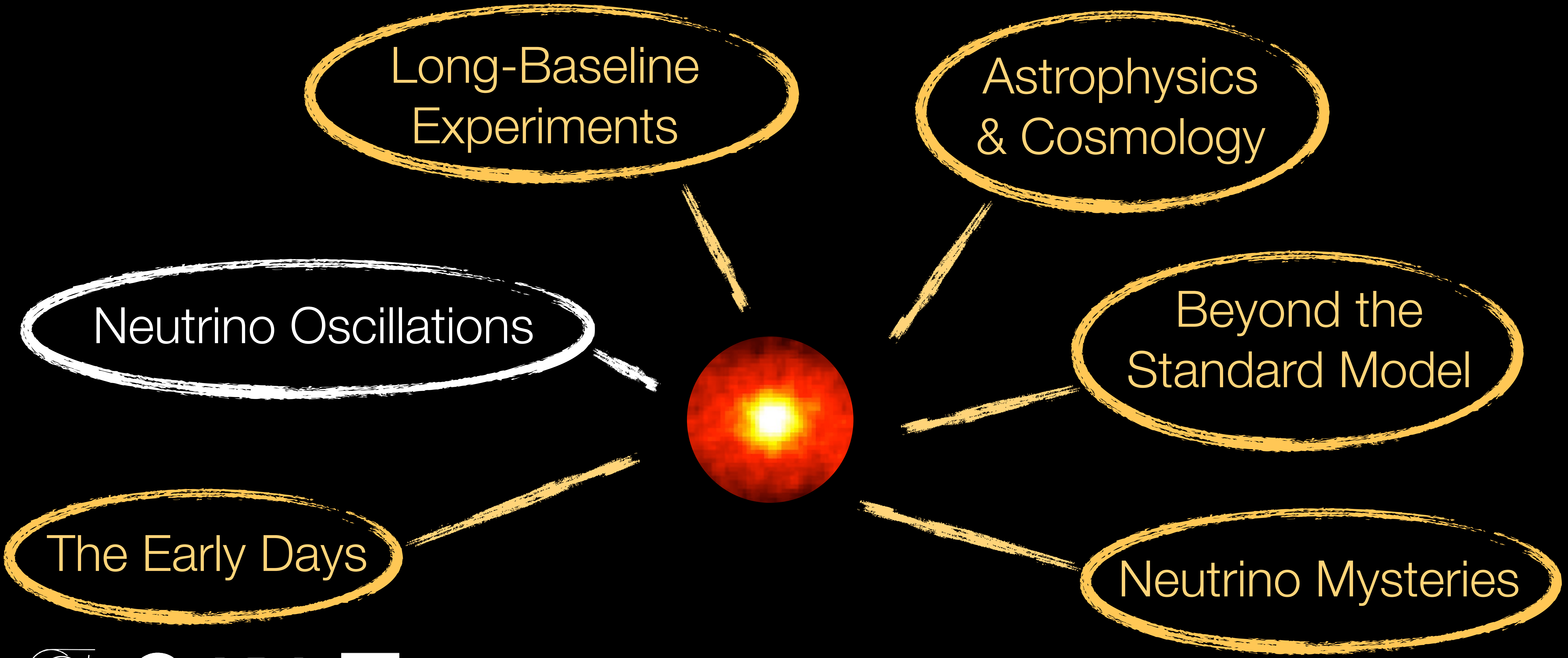


John Bahcall

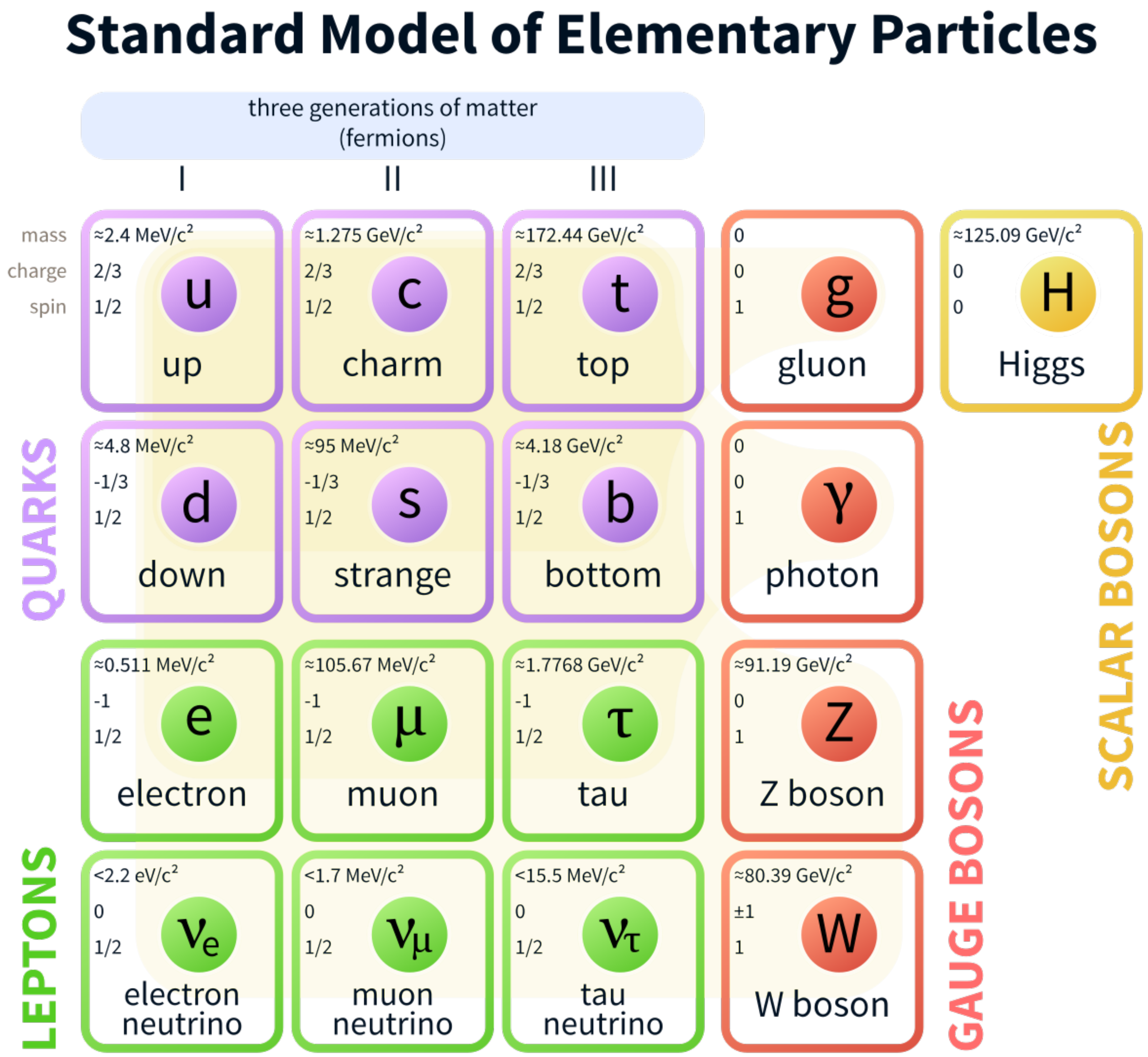
Ray Davis



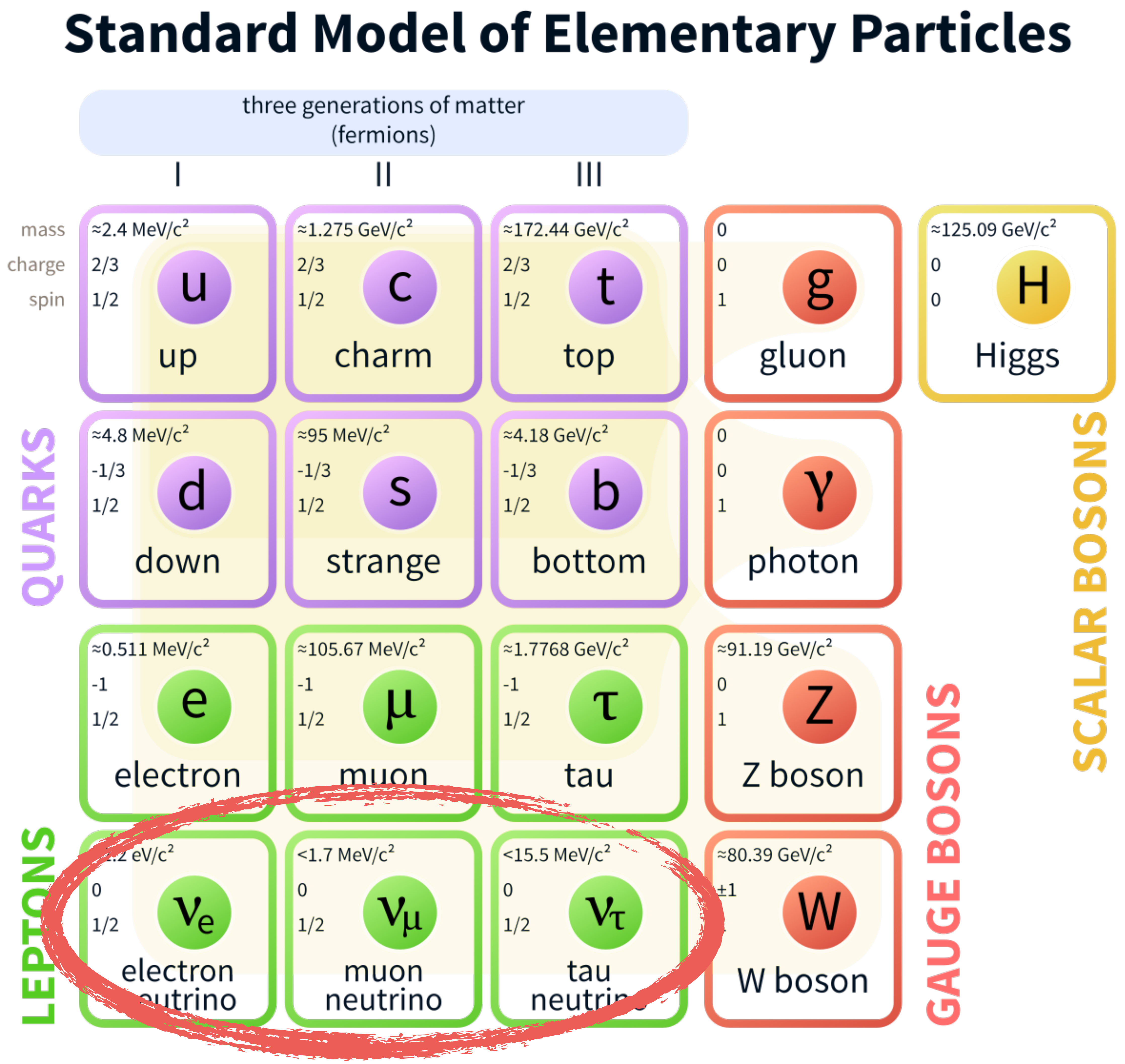
Outline


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

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

Mass Eigenstate
(well-defined energy)

Flavor Eigenstate
(well-defined coupling)

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
($n \times n$, unitary)

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
($n \times n$, unitary)

3-flavor mixing matrix:

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

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
($n \times n$, 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

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
($n \times n$, 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

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
($n \times n$, 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
($n \times n$, 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

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

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

- 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

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

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

- 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

Neutrino Oscillations

- Initial state

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

- Transition probability

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

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

- 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

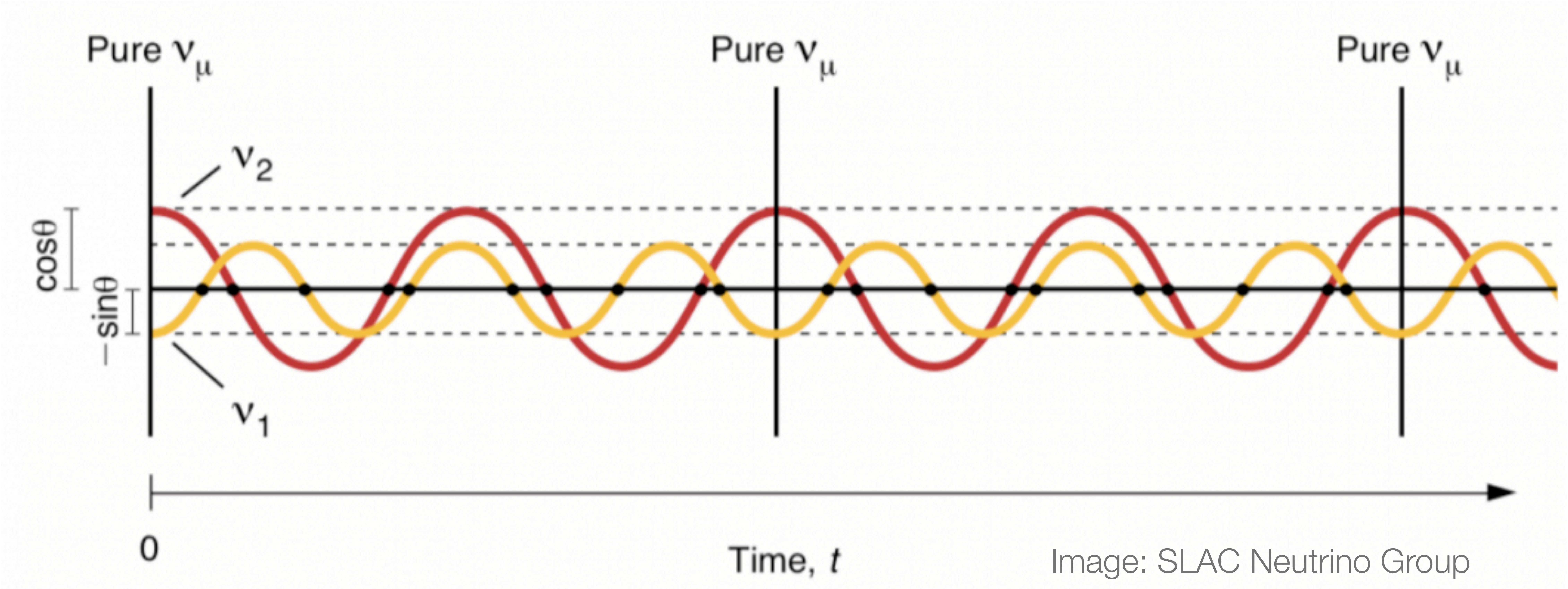
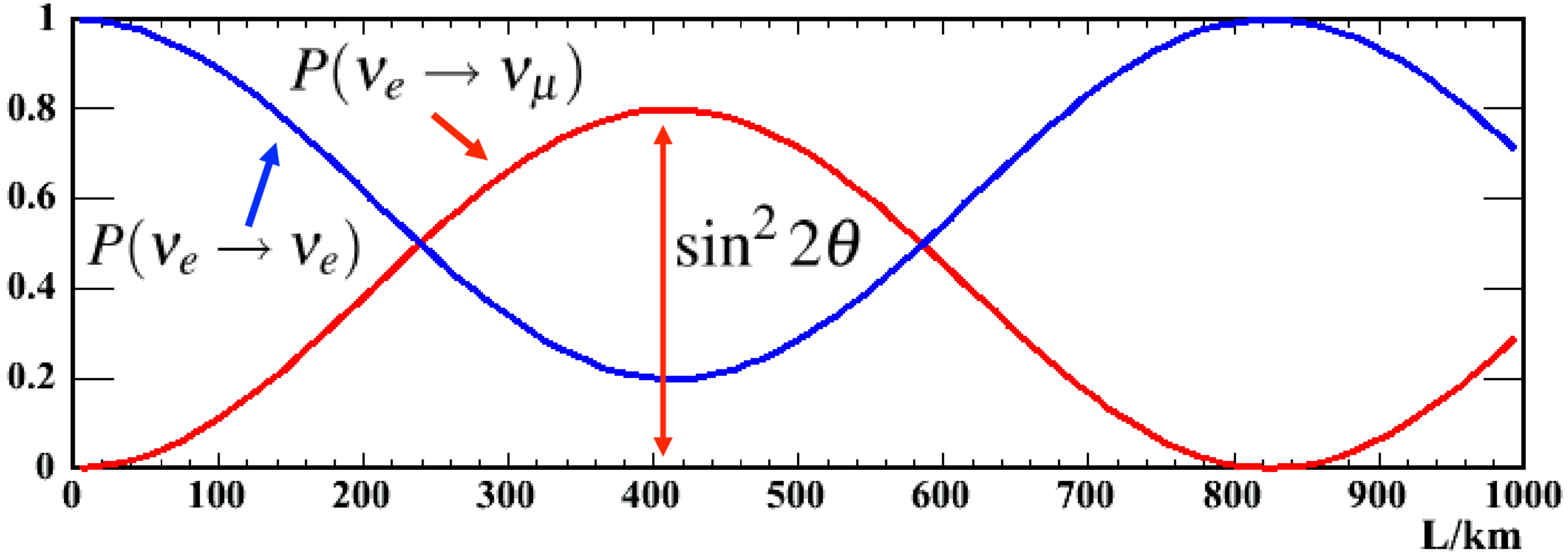


Image: SLAC Neutrino Group

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

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

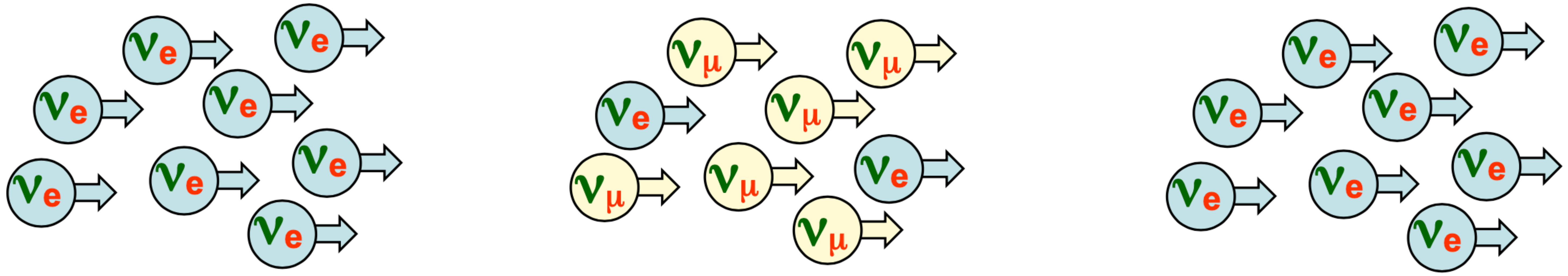
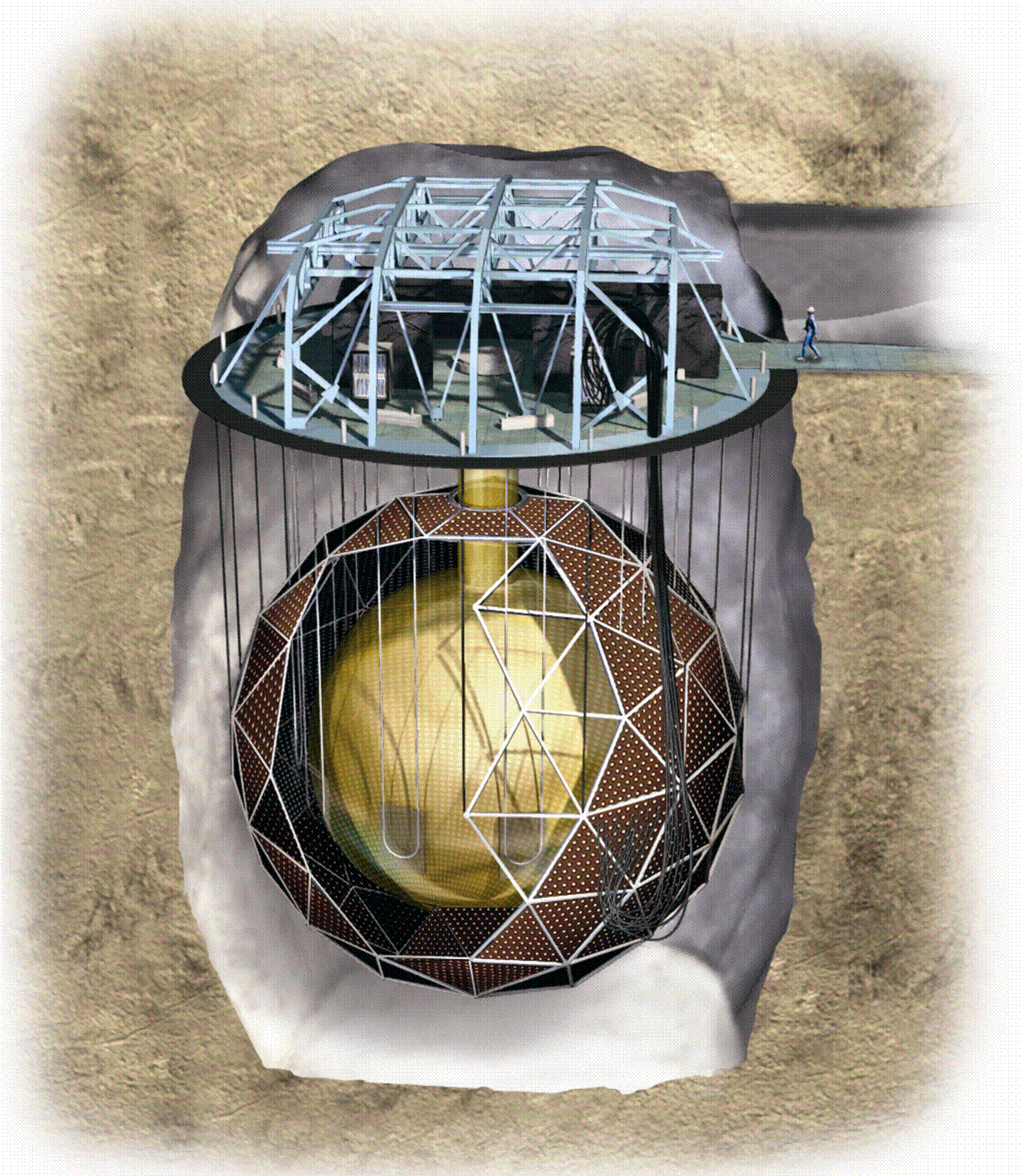
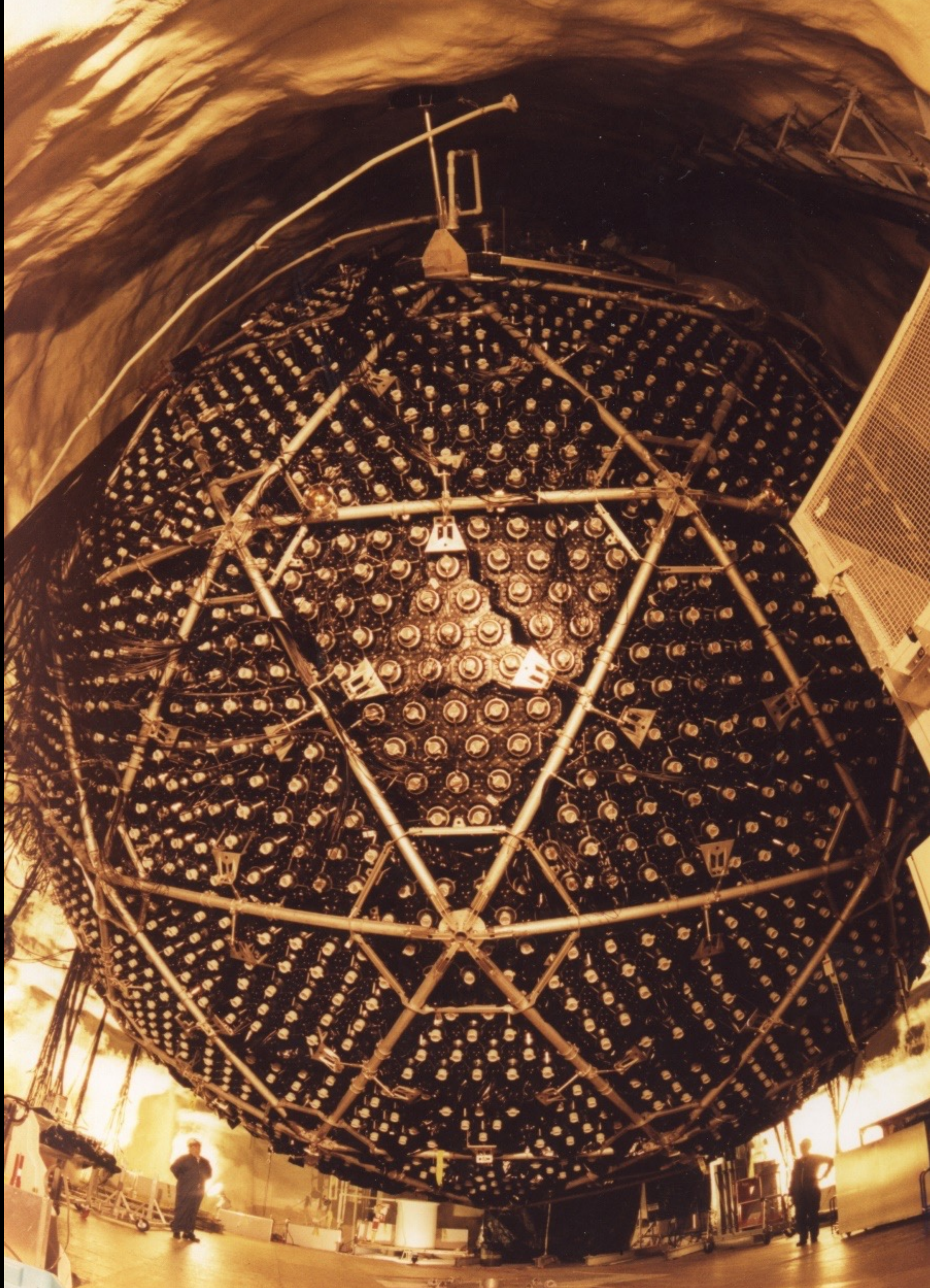
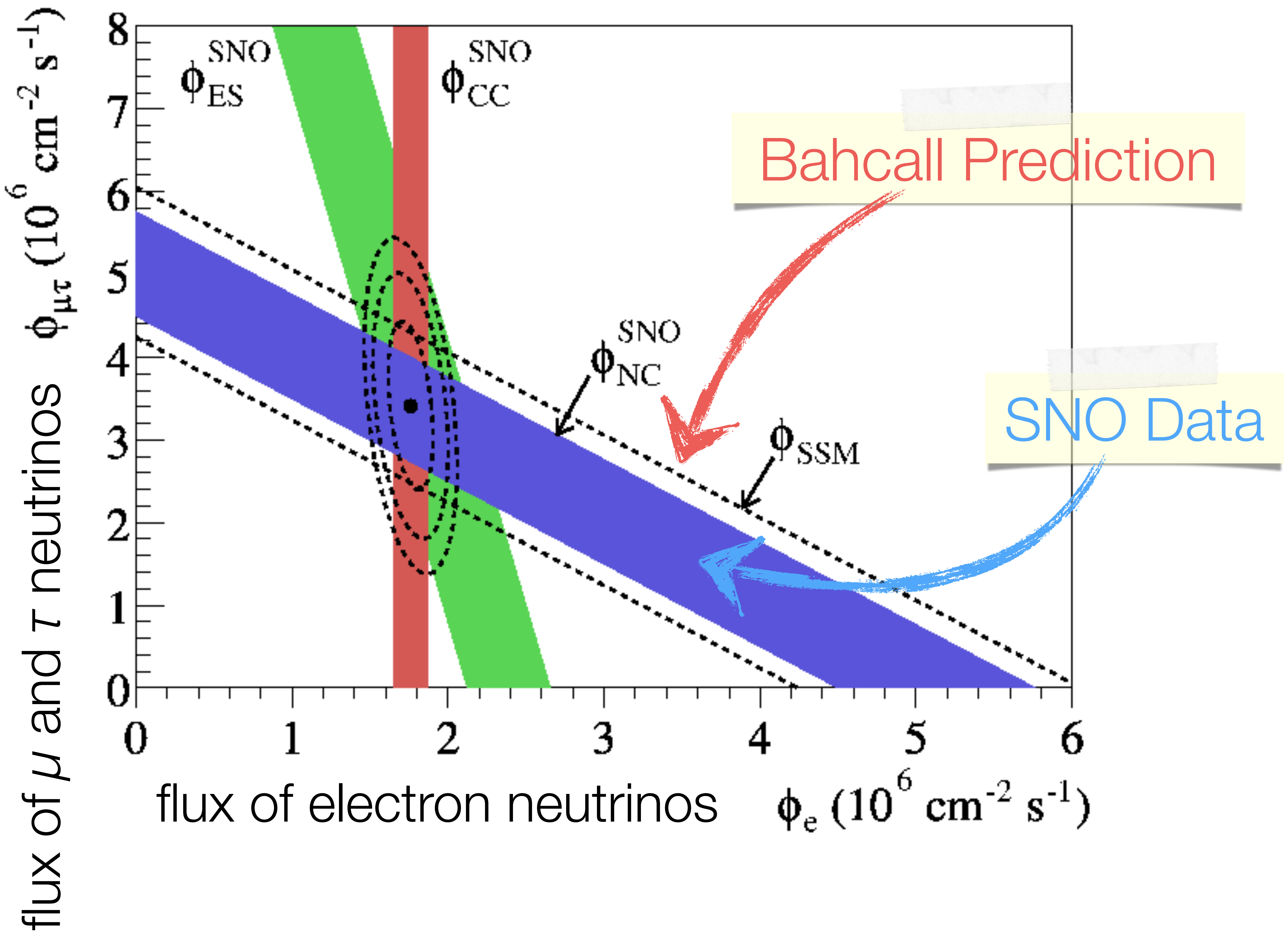


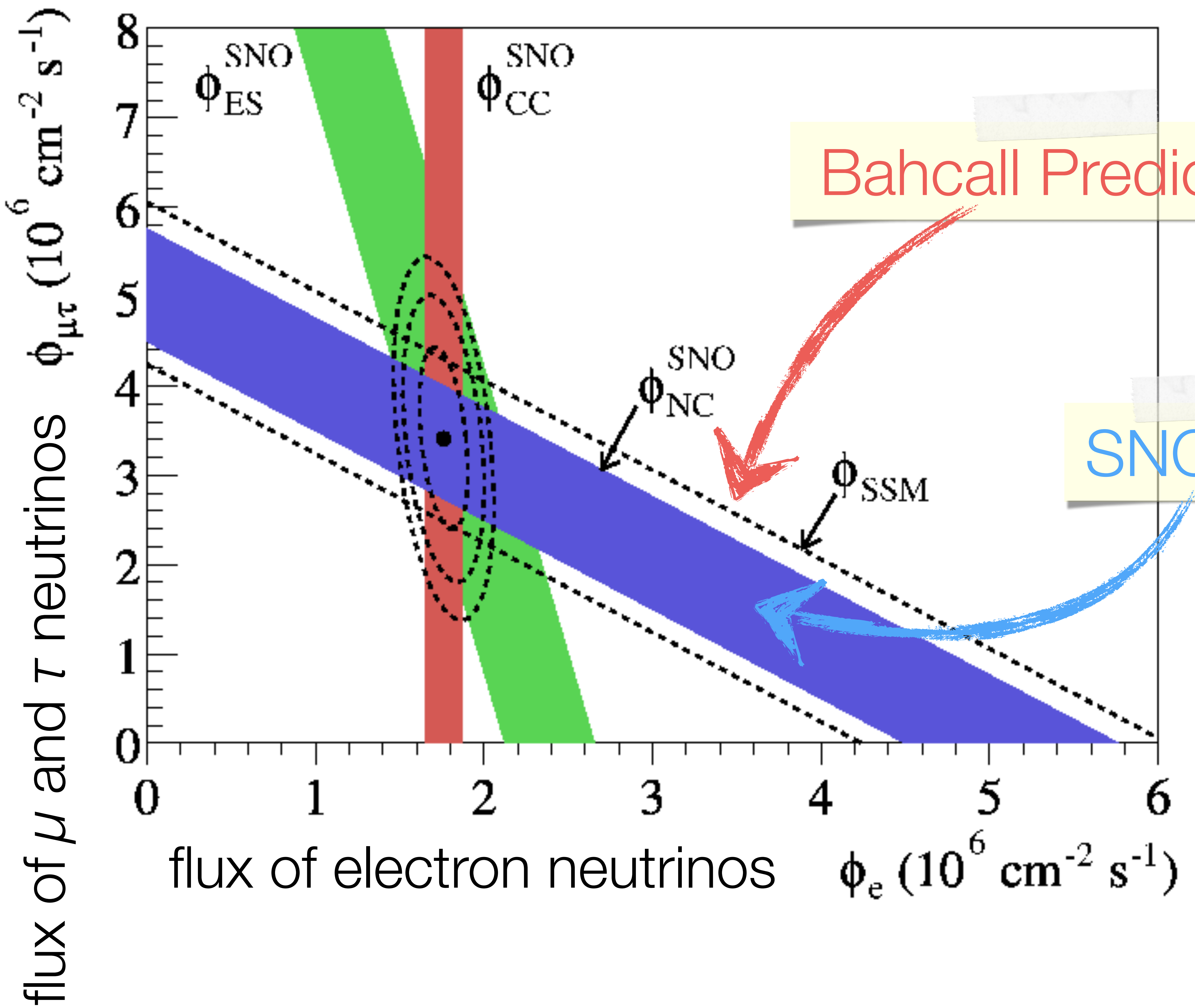
Image: Mark Thomson

Resolving the Solar Neutrino Mystery



Resolving the Solar Neutrino Mystery

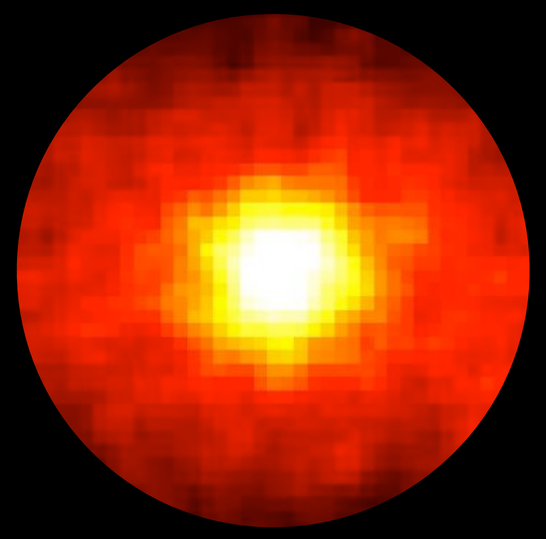


Outline

Long-Baseline Experiments

Astrophysics & Cosmology

Neutrino Oscillations



Beyond the Standard Model

The Early Days

Neutrino Mysteries

Motivation

The Neutrino Mixing Matrix

The Neutrino Mixing Matrix

3-flavor mixing matrix:

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

The Neutrino Mixing Matrix

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

The Neutrino Mixing Matrix

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

The Neutrino Mixing Matrix

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

The Neutrino Mixing Matrix

3-flavor mixing matrix:

Unknown

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

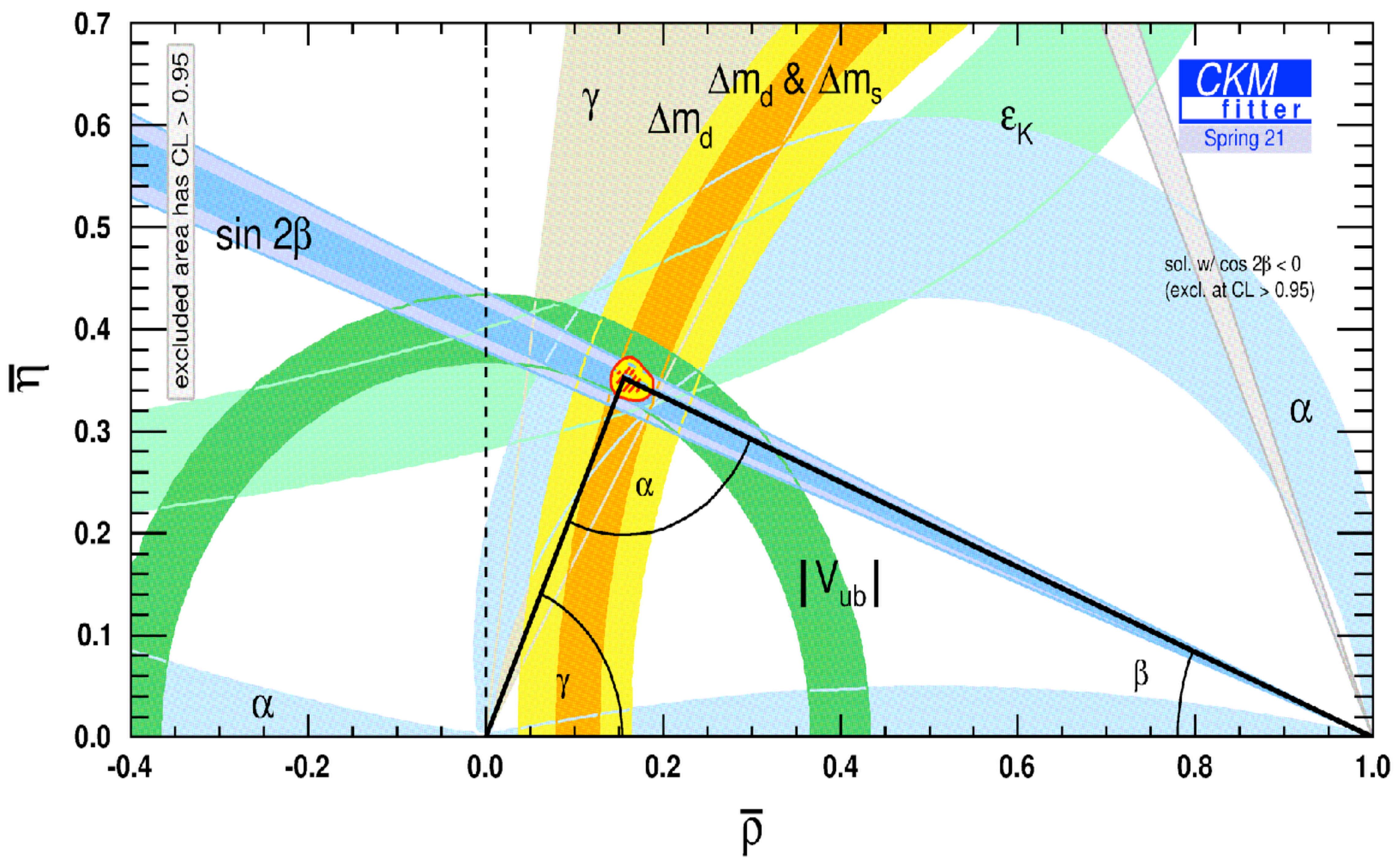
Large
close to maximal

Small
but non-negligible (~0.1)

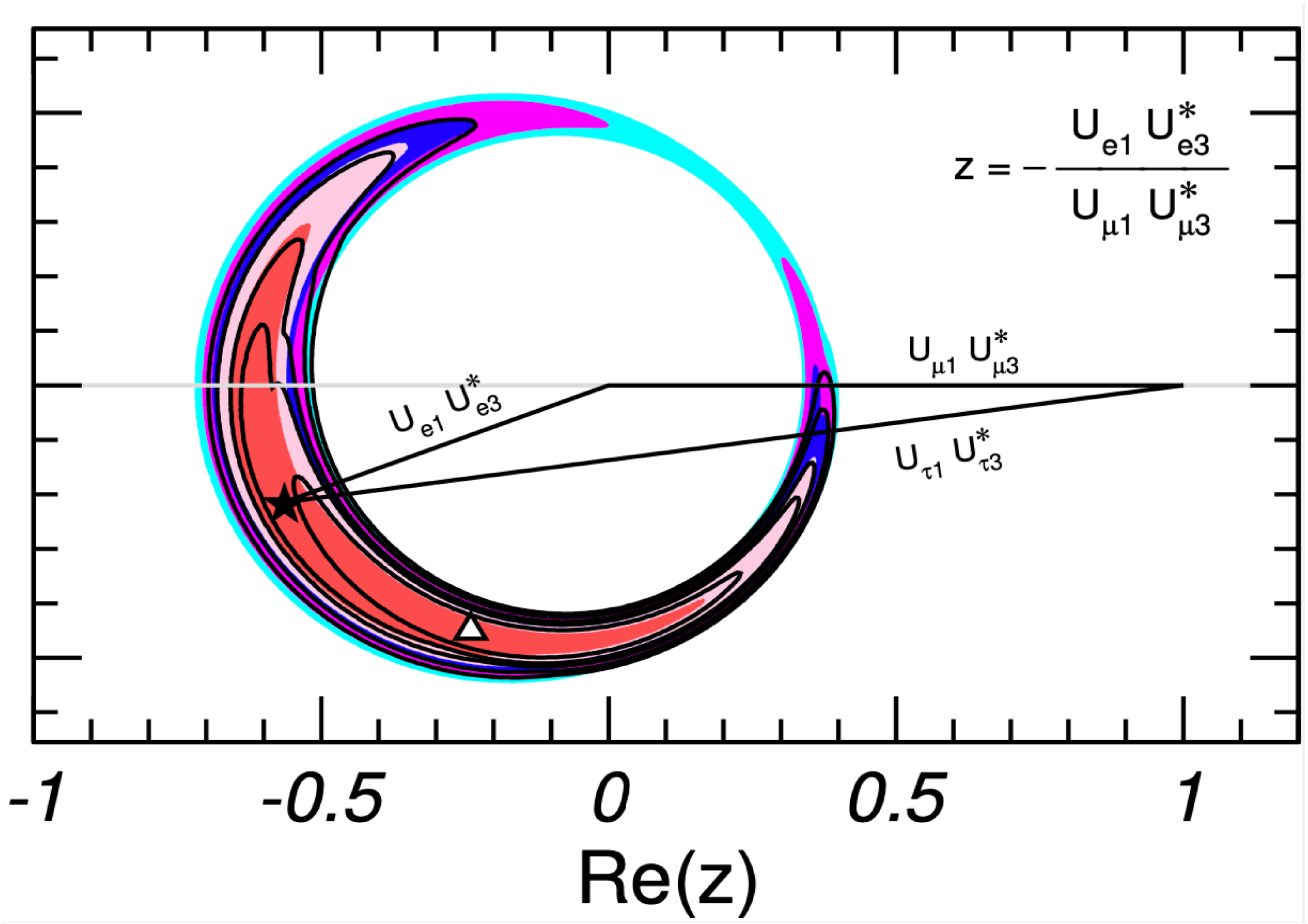
Large
but non-maximal

Flavor Triangles

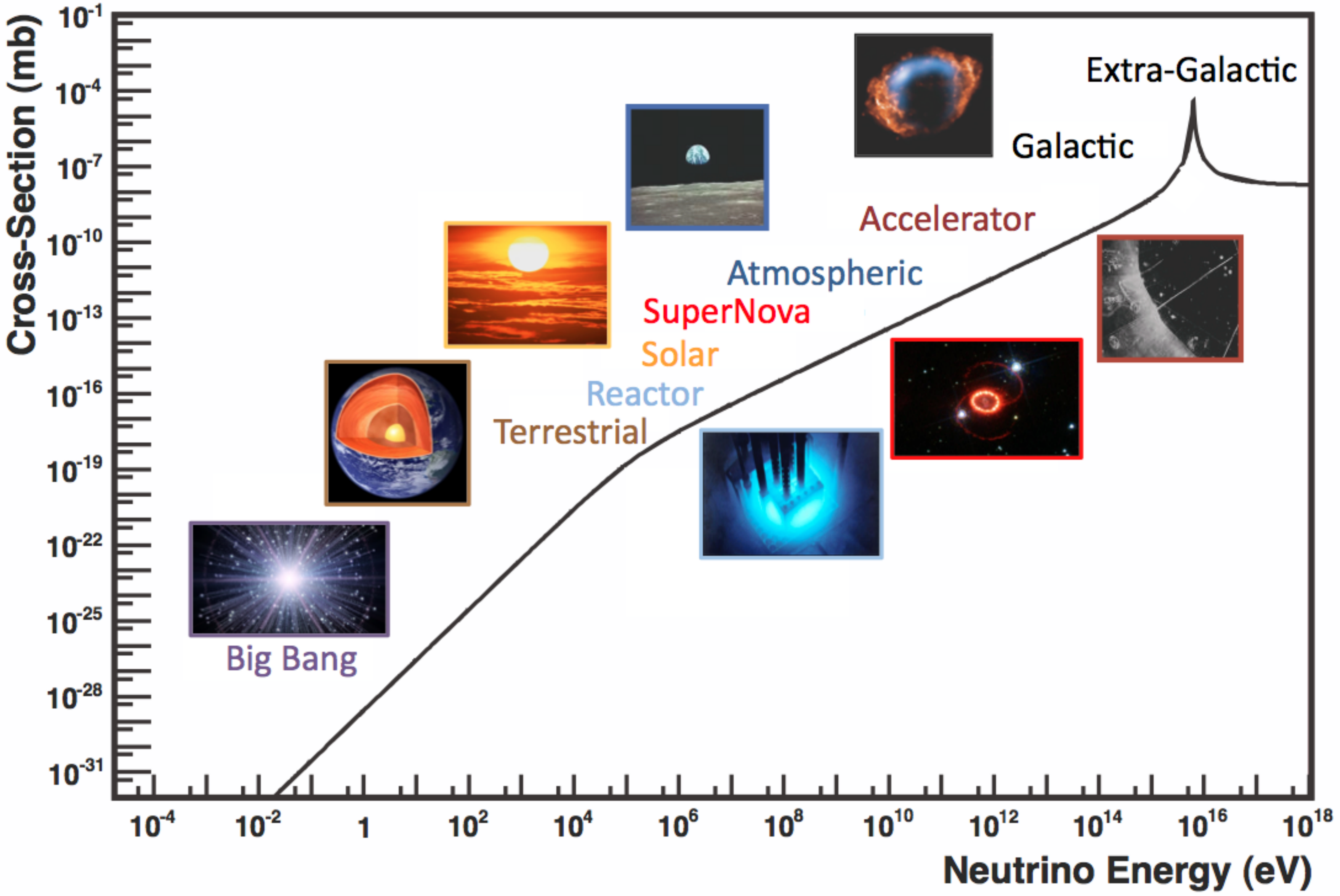
Quarks



Leptons



Neutrino Sources



Making a Neutrino Beam

Image: MINOS Collaboration

Making a Neutrino Beam

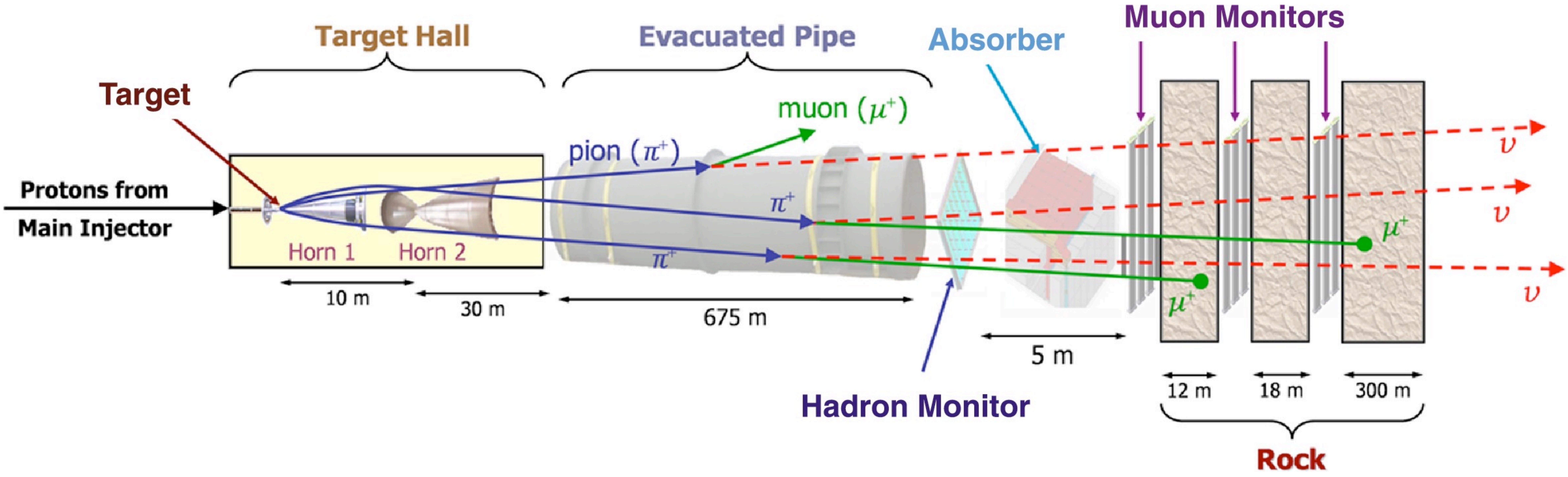
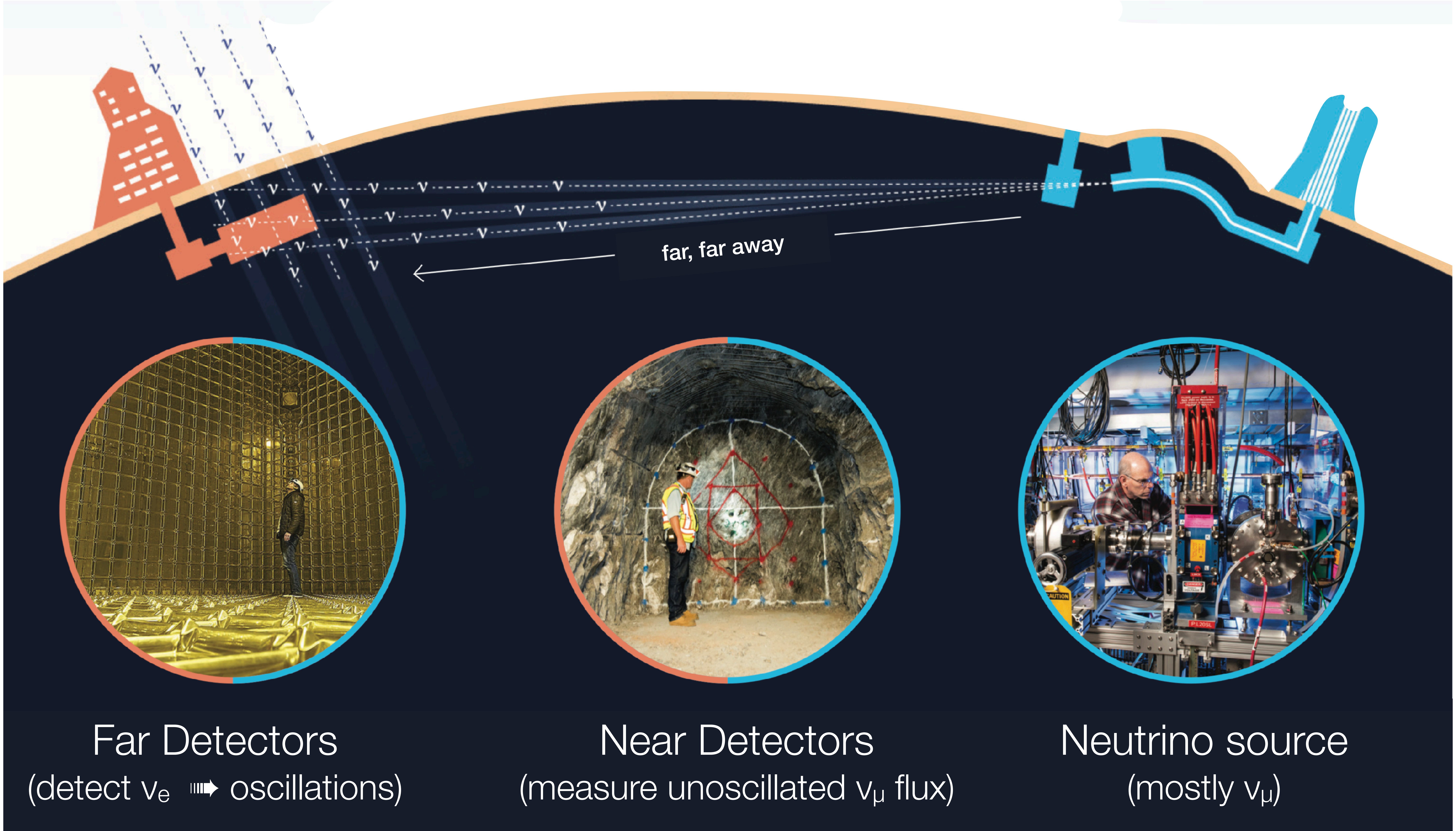


Image: MINOS Collaboration

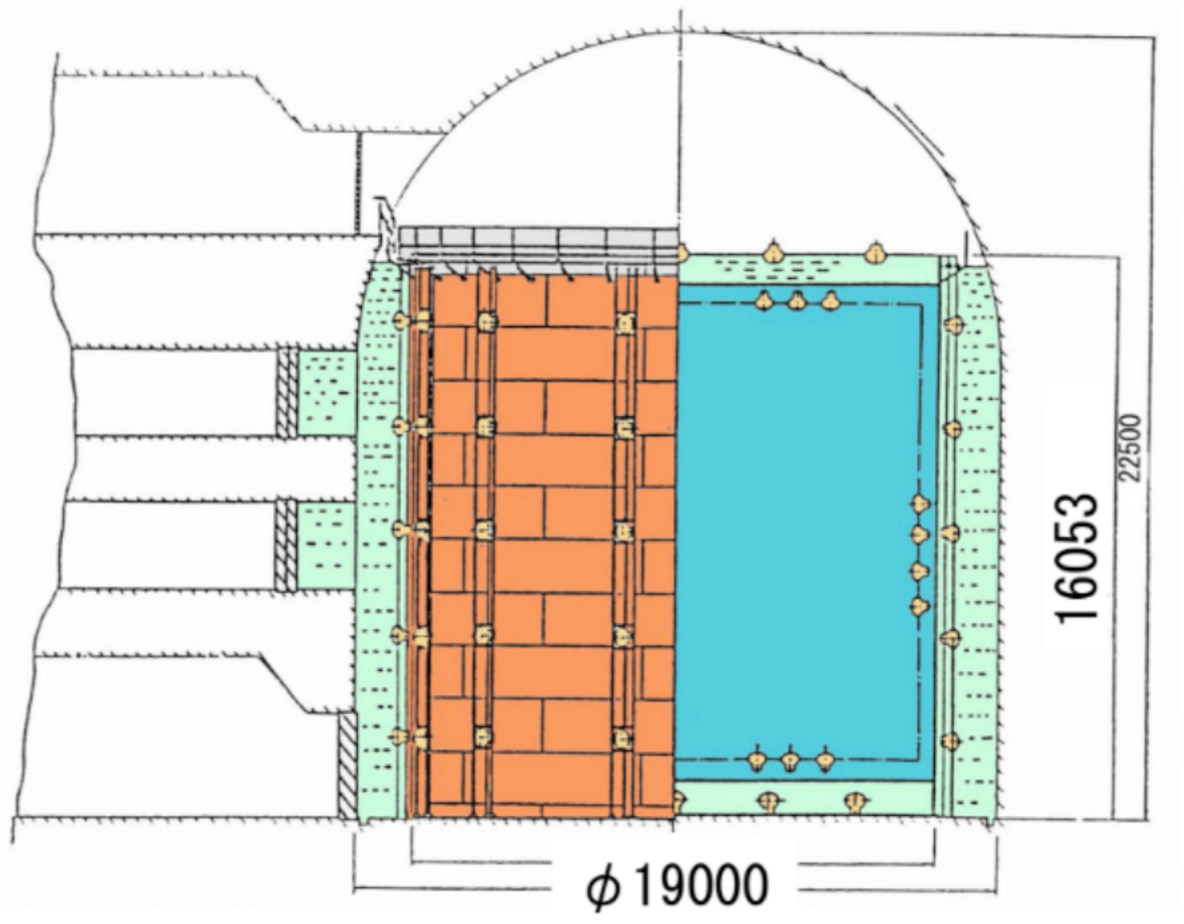
Long-Baseline Experiments

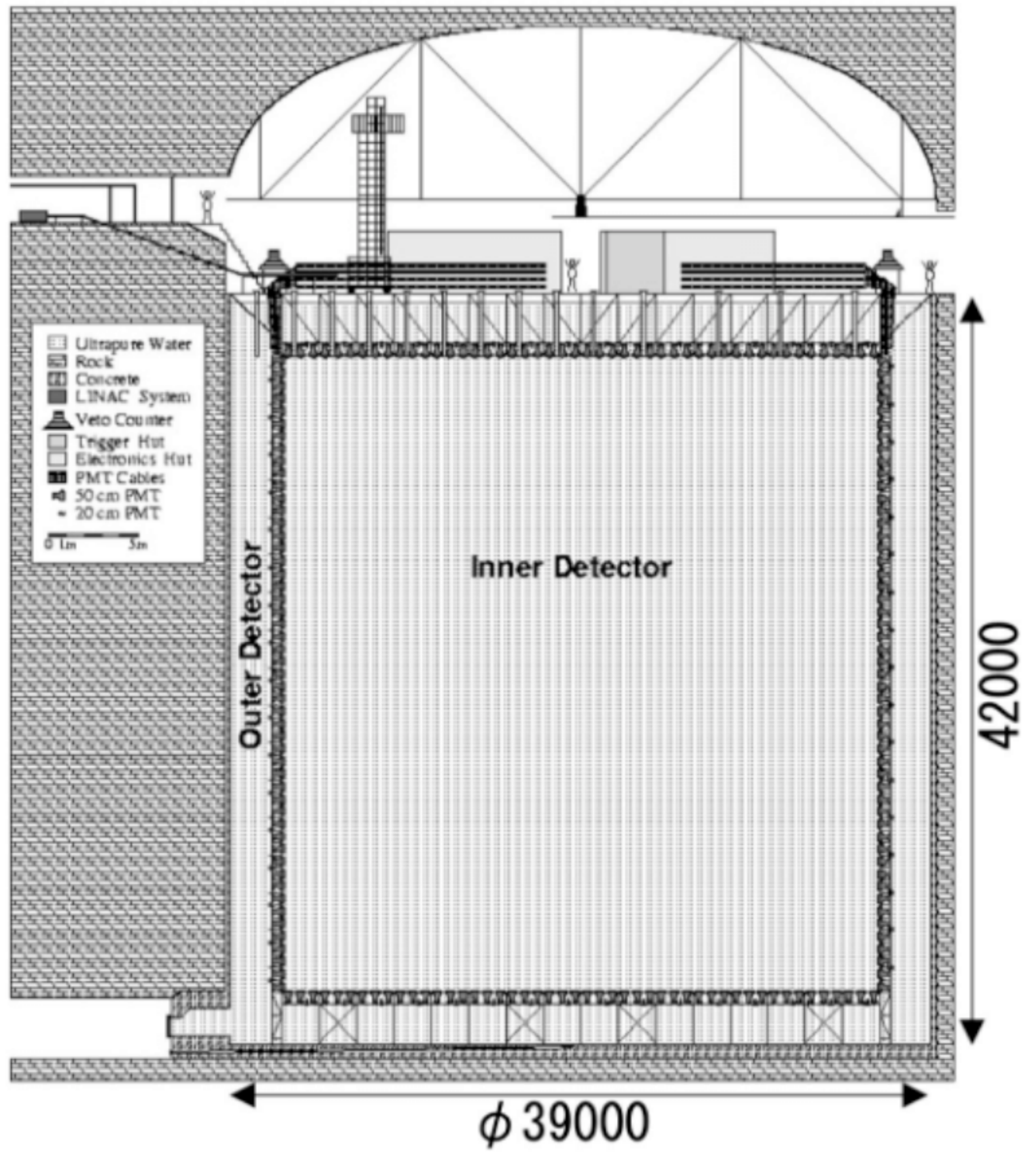


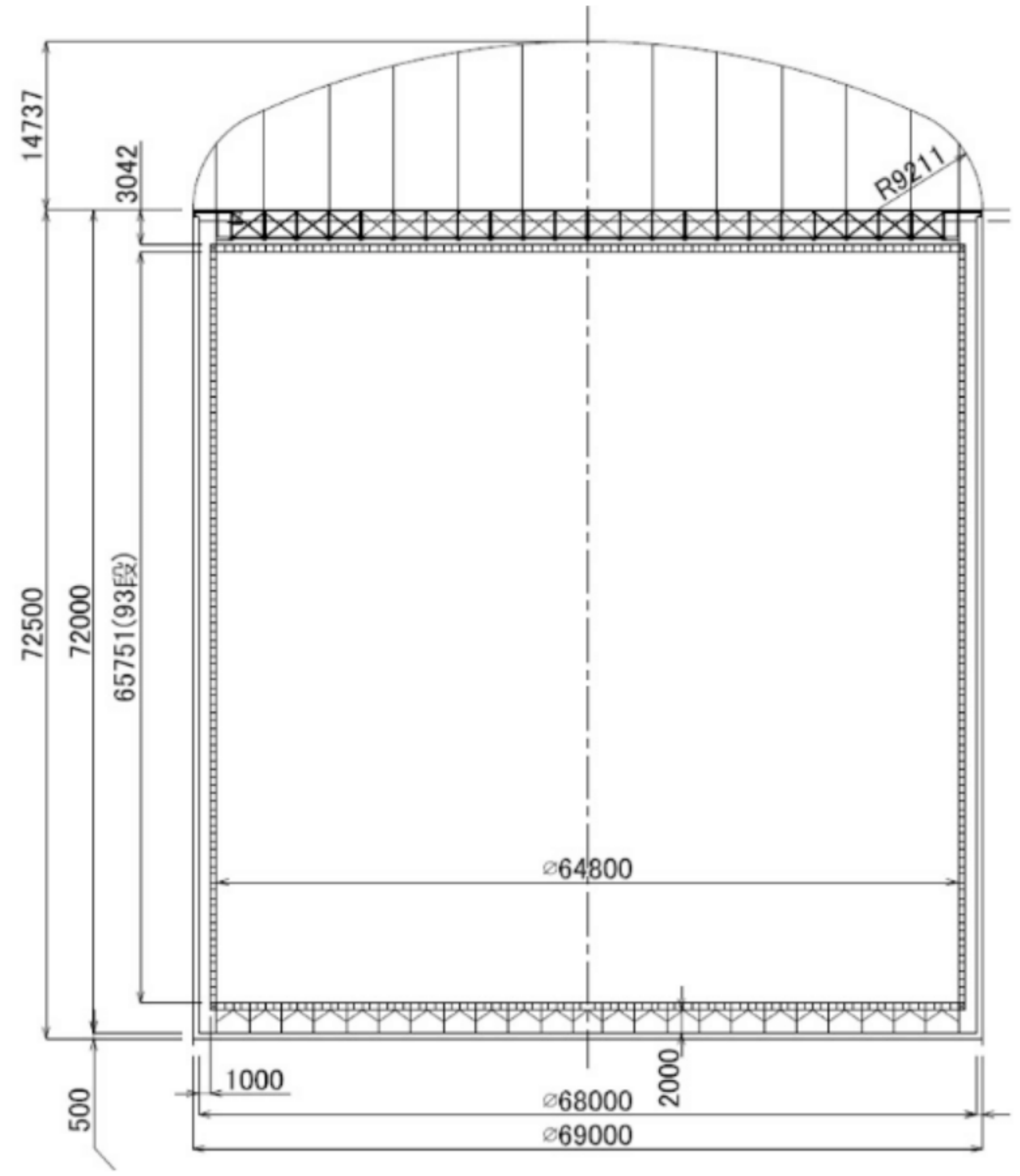
Kamiokande

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

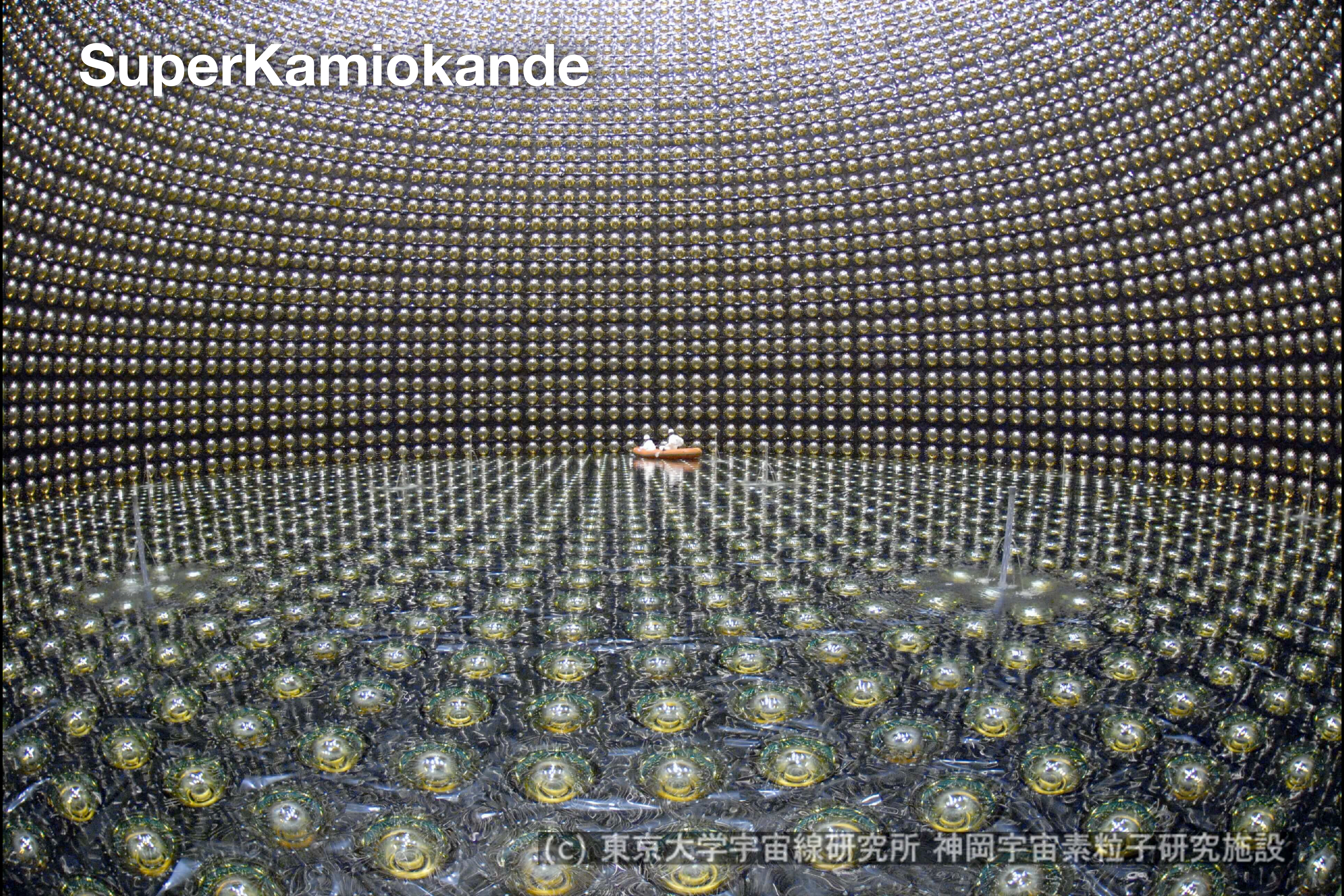
Long-Baseline Experiments: Kamiokande

Kamiokande 1983～1996	**Super-Kamiokande** 1996~Present	**Hyper-Kamiokande** 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

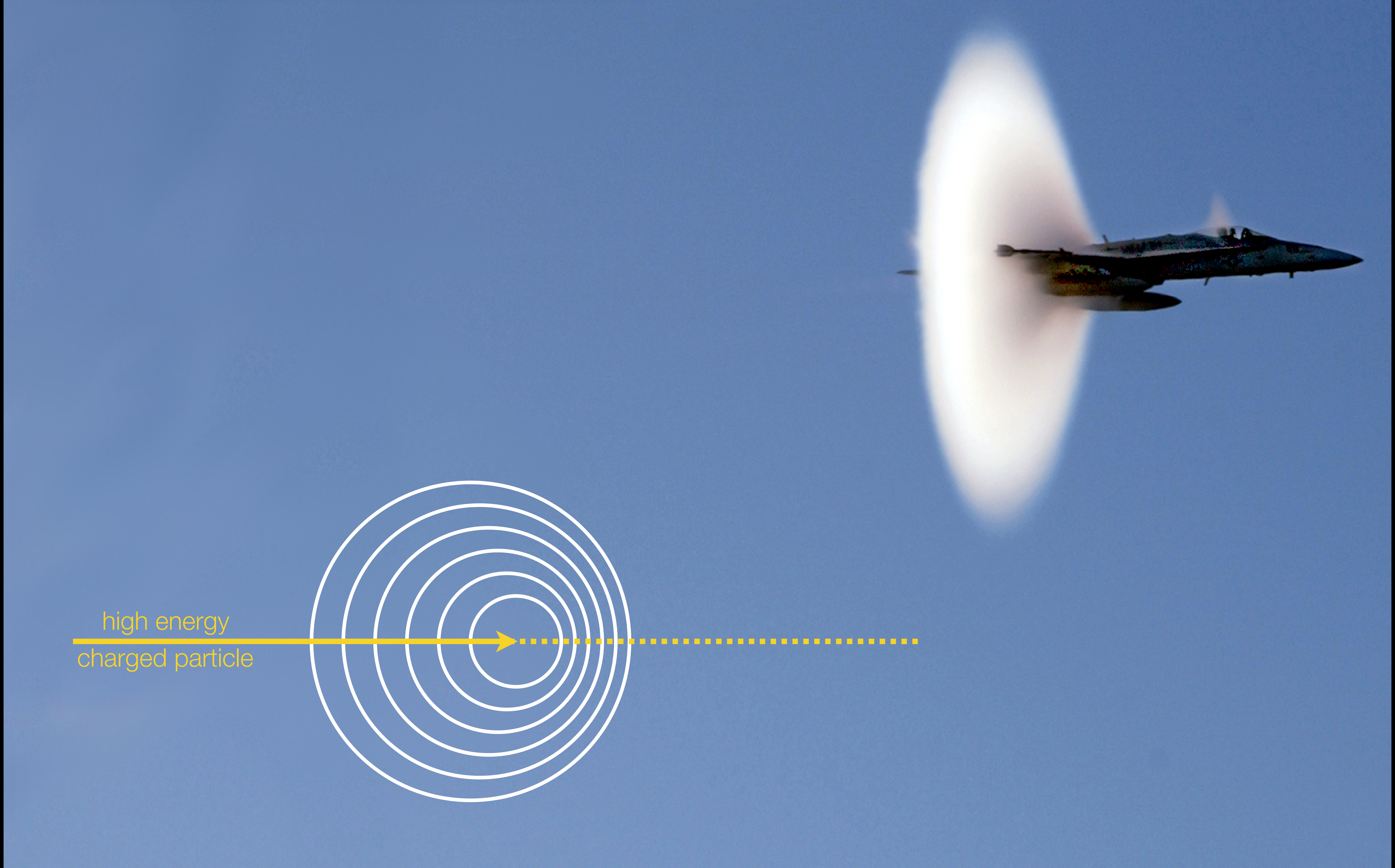
Kamiokande	Super-Kamiokande	Hyper-Kamiokande
1983～1996	1996~Present	Aiming to start observation in 2027
Main and expected Results		
World's first observation of neutrinos from a supernova explosion and observation of solar neutrinos, leading to the creation of neutrino astronomy	Discovery of neutrino 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

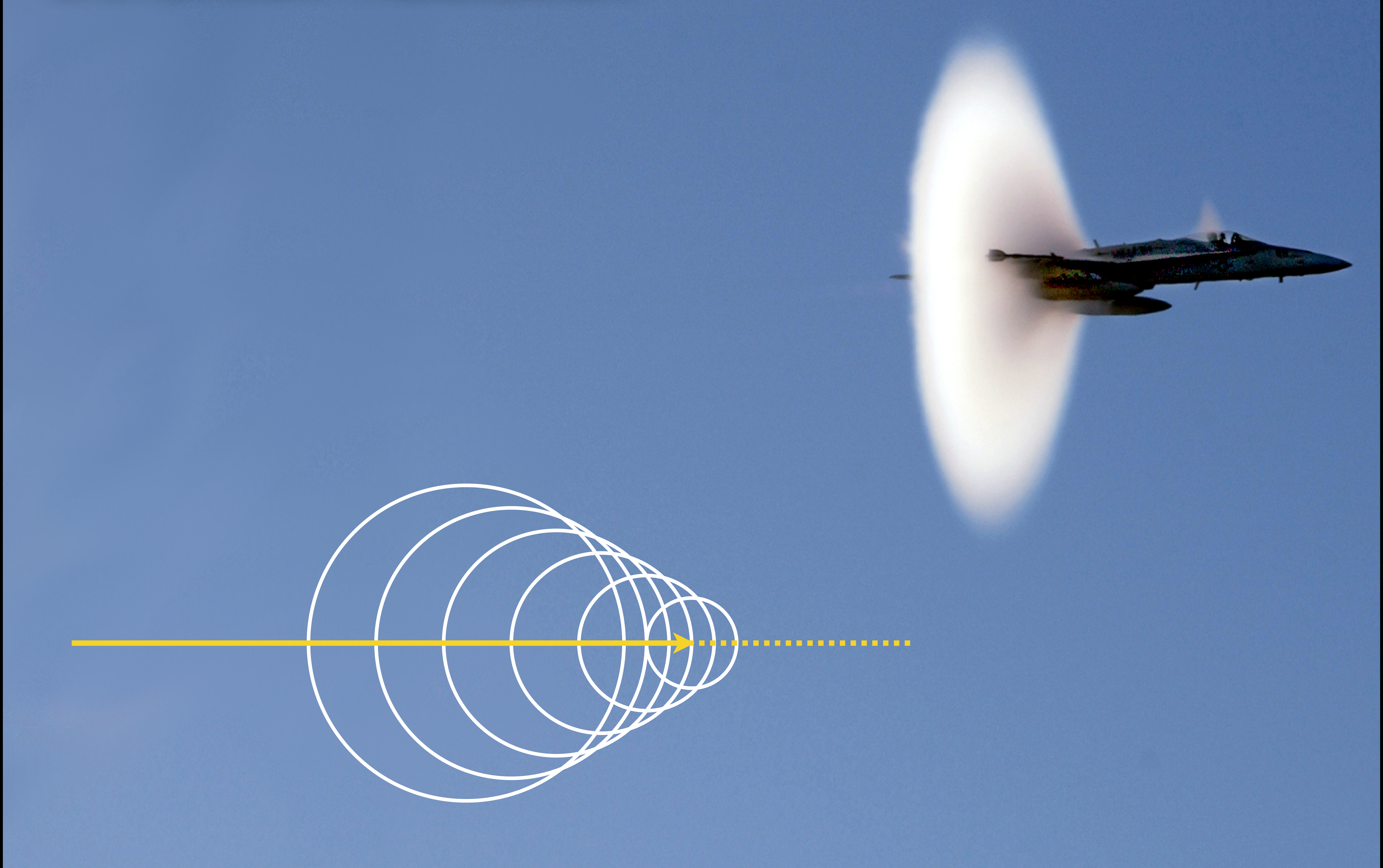



Čerenkov Radiation

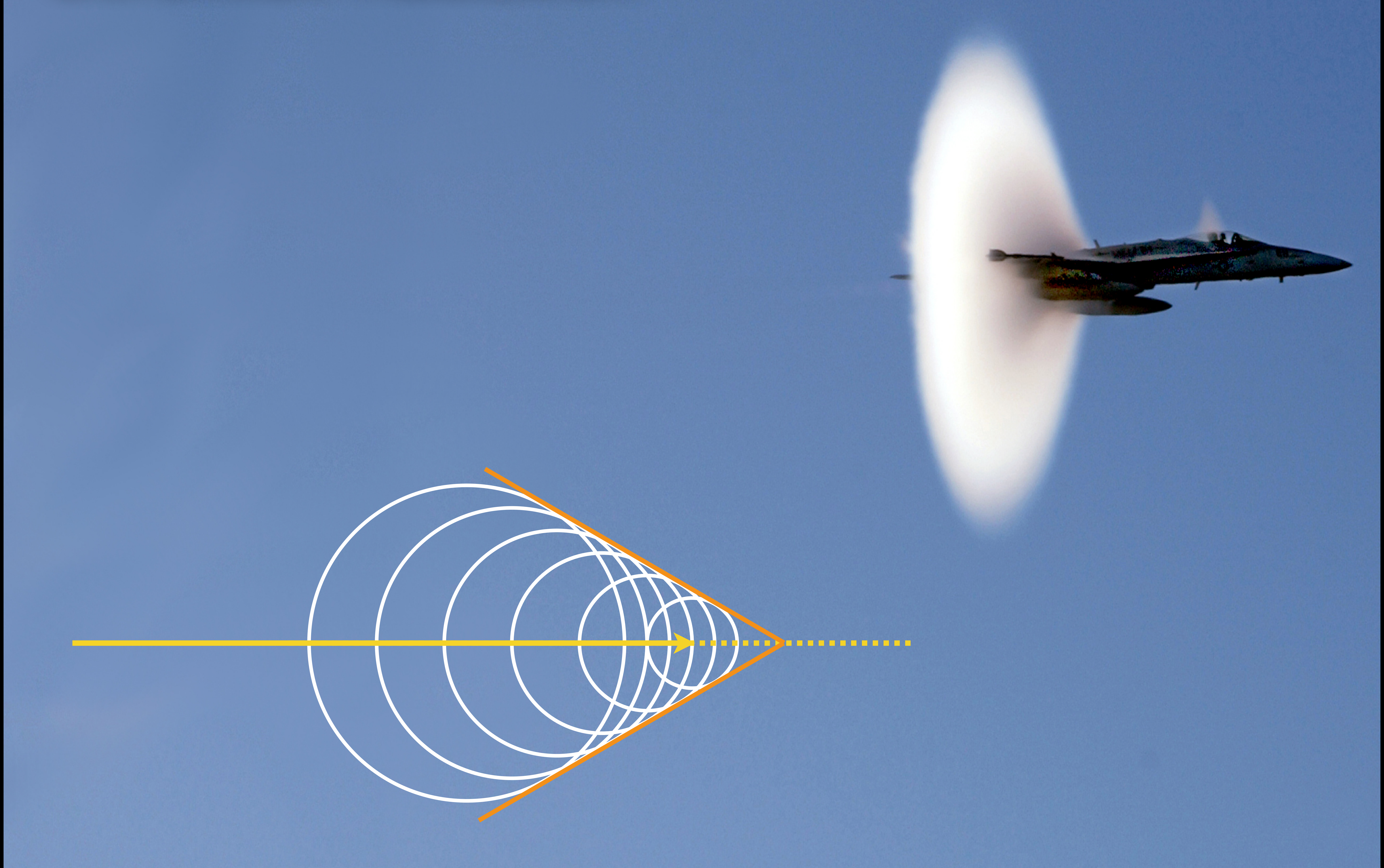
Čerenkov Radiation



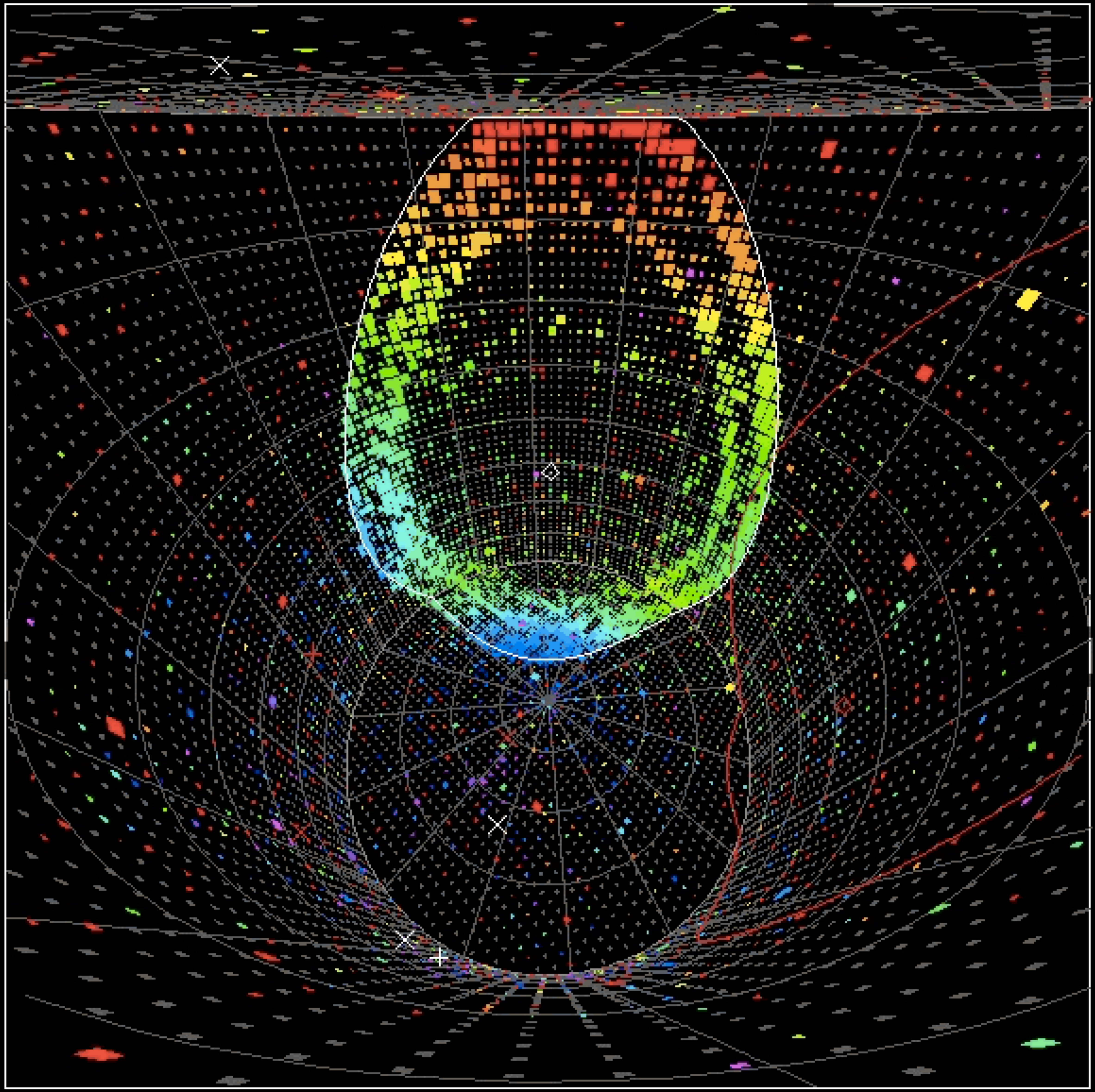
Čerenkov Radiation



Čerenkov Radiation



A SuperKamiokande Event



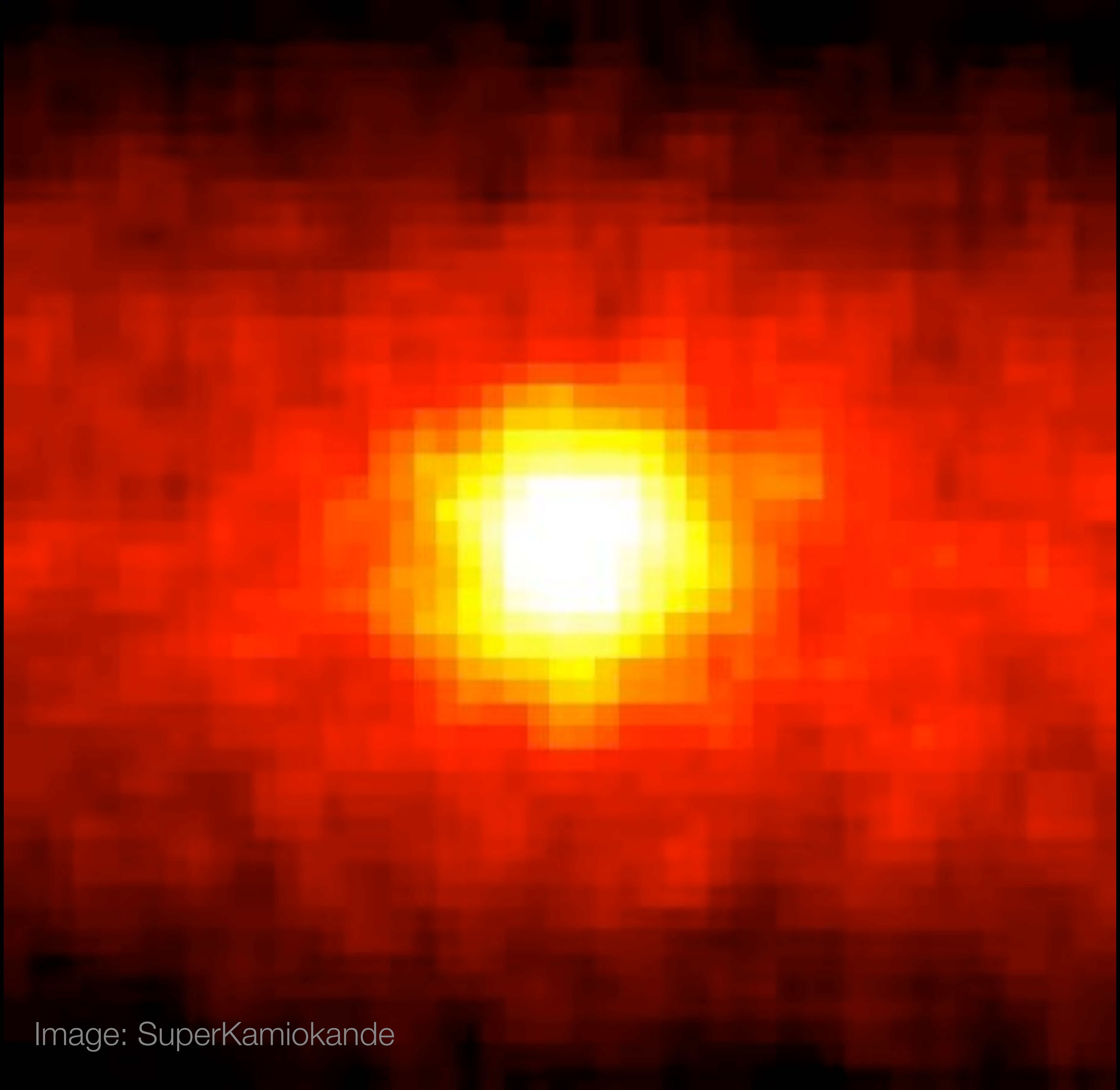
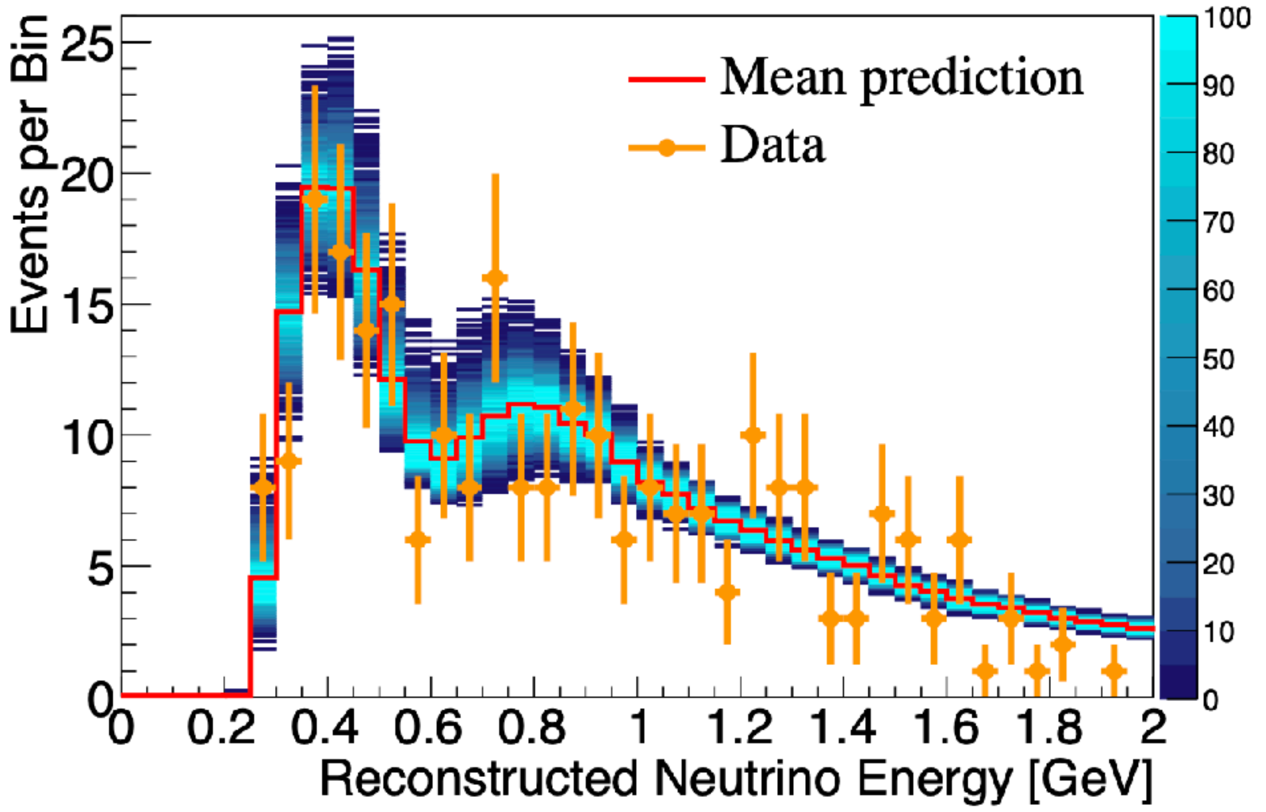
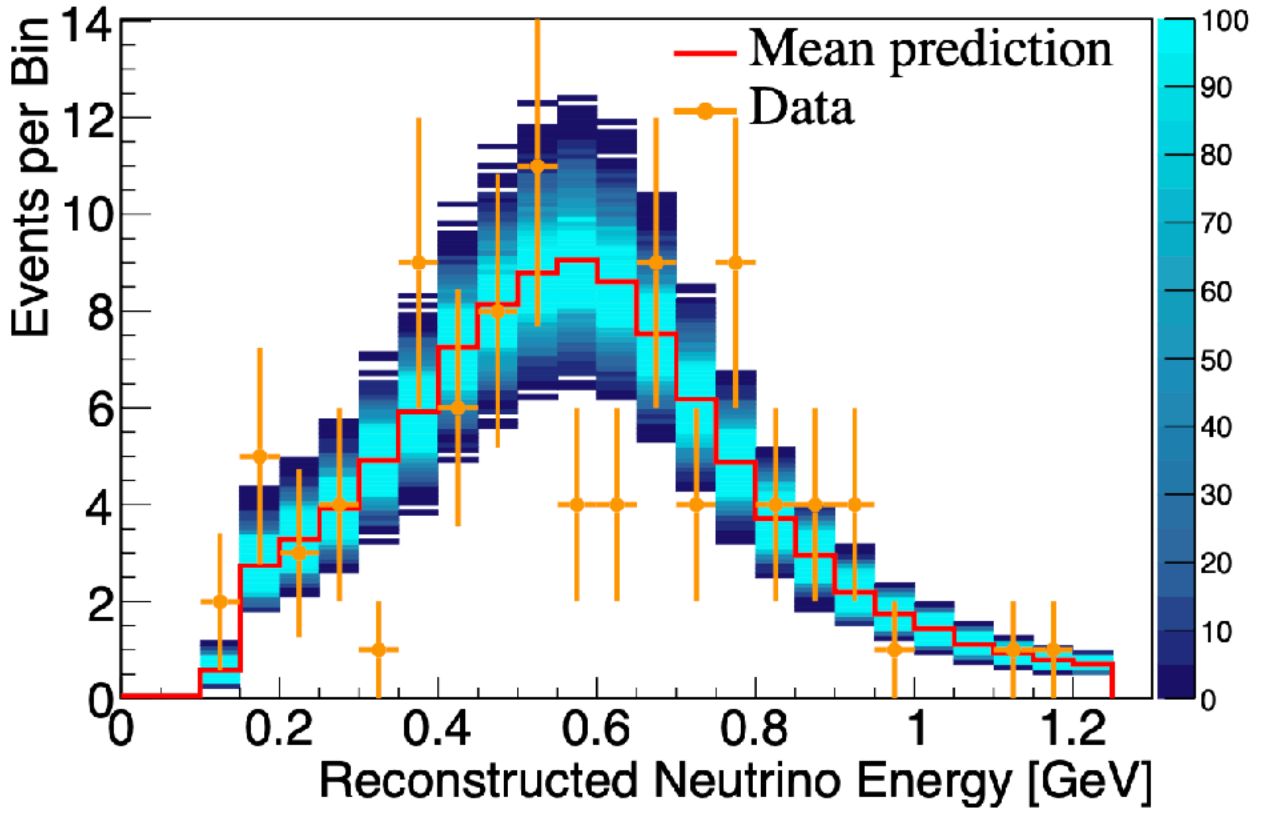


Image: SuperKamiokande

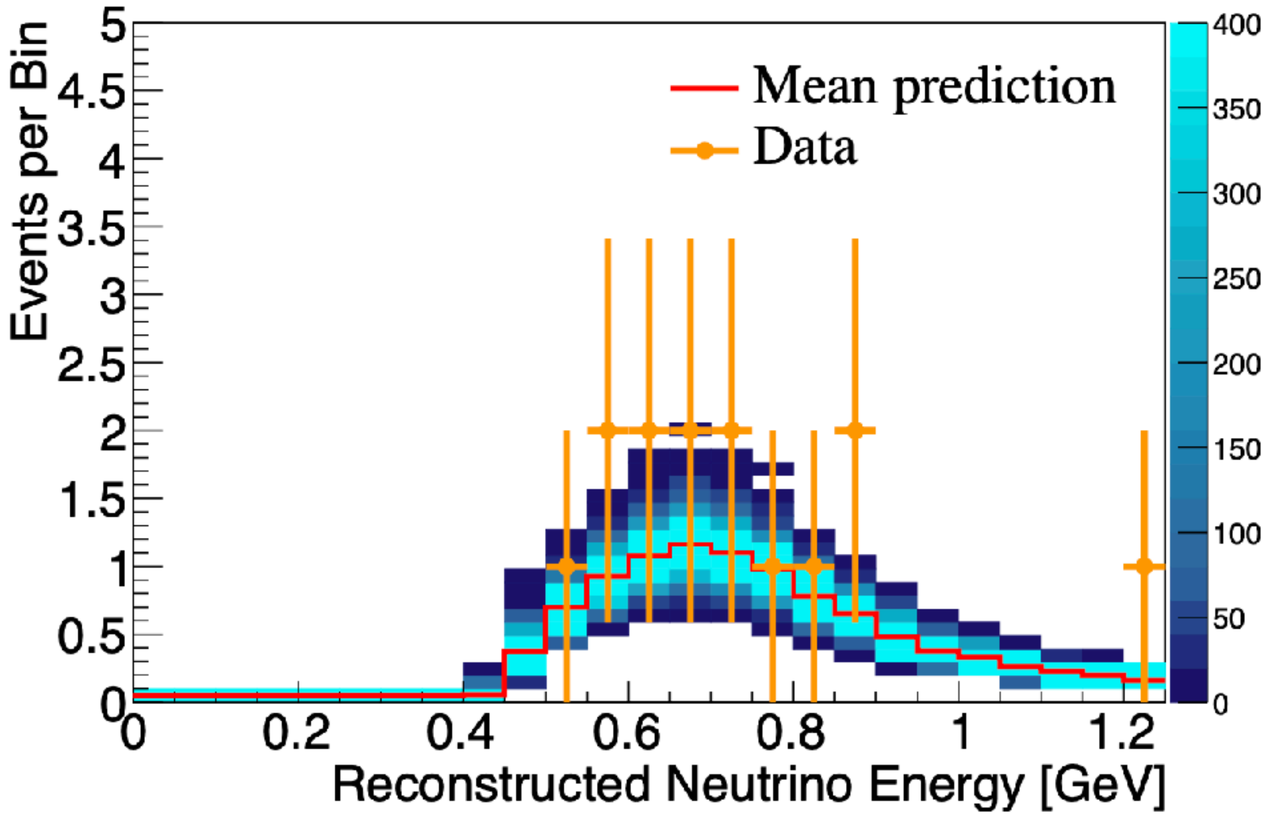
SuperKamiokande Long-Baseline Results



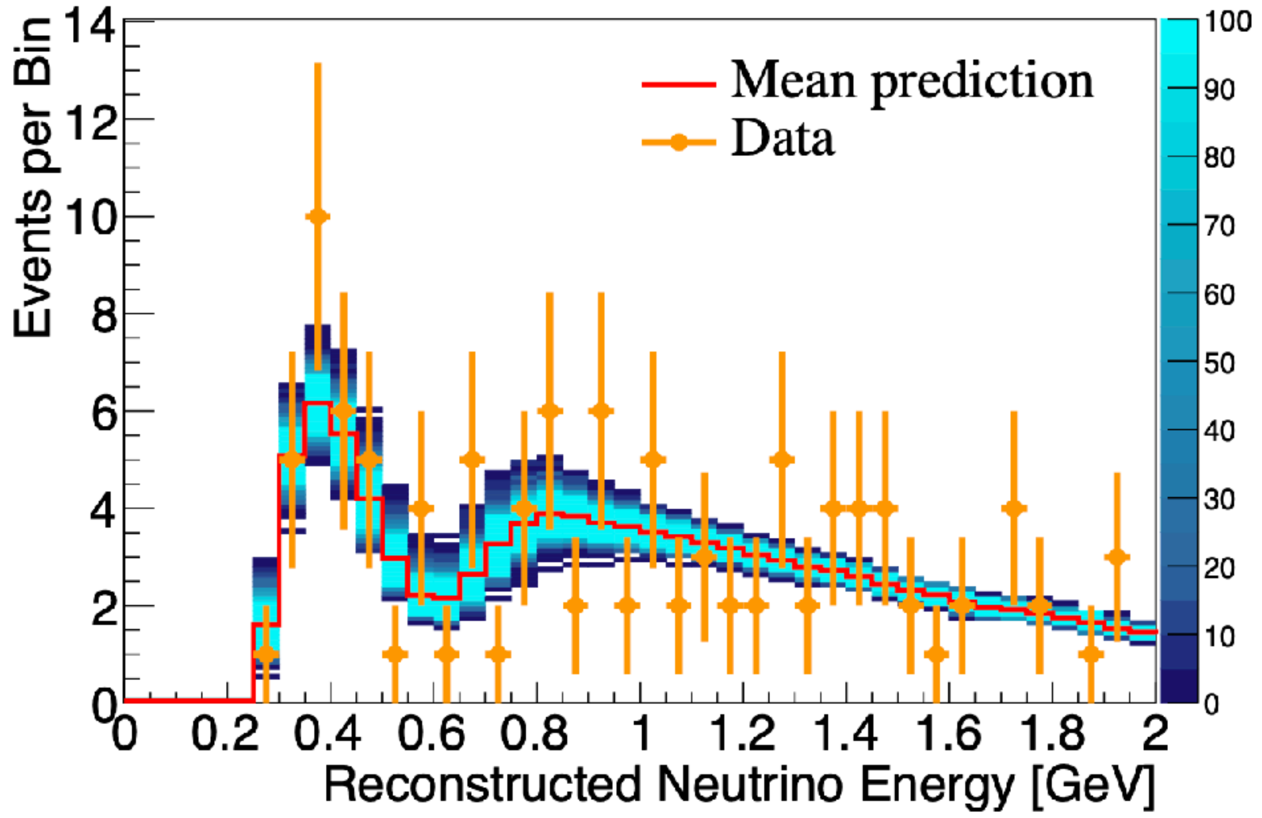
(a) ν-mode 1Rμ



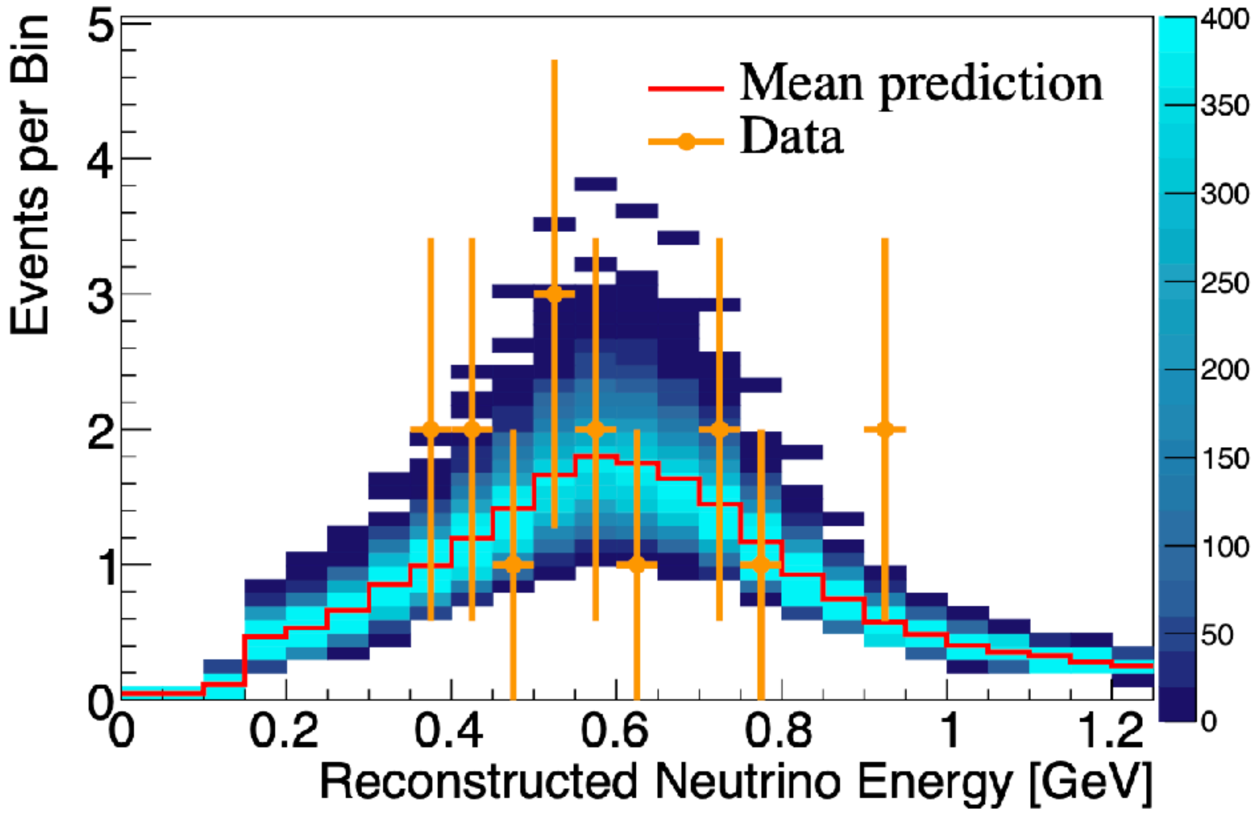
(b) ν-mode 1Re



(c) ν-mode 1Re1de

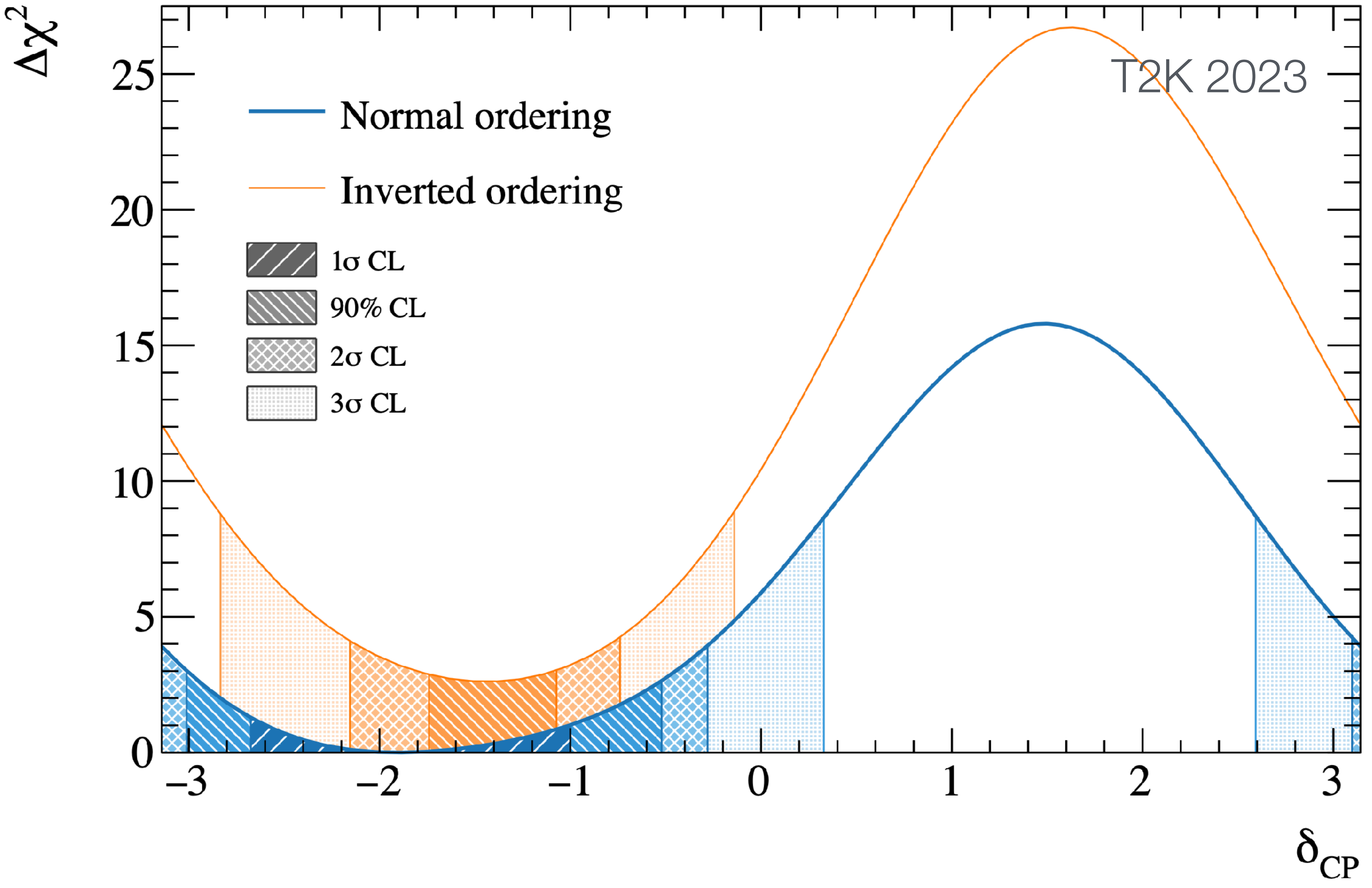


(d) $\bar{\nu}$-mode 1Rμ



(e) $\bar{\nu}$-mode 1Re

SuperKamiokande Long-Baseline Results



Neutrino Interactions

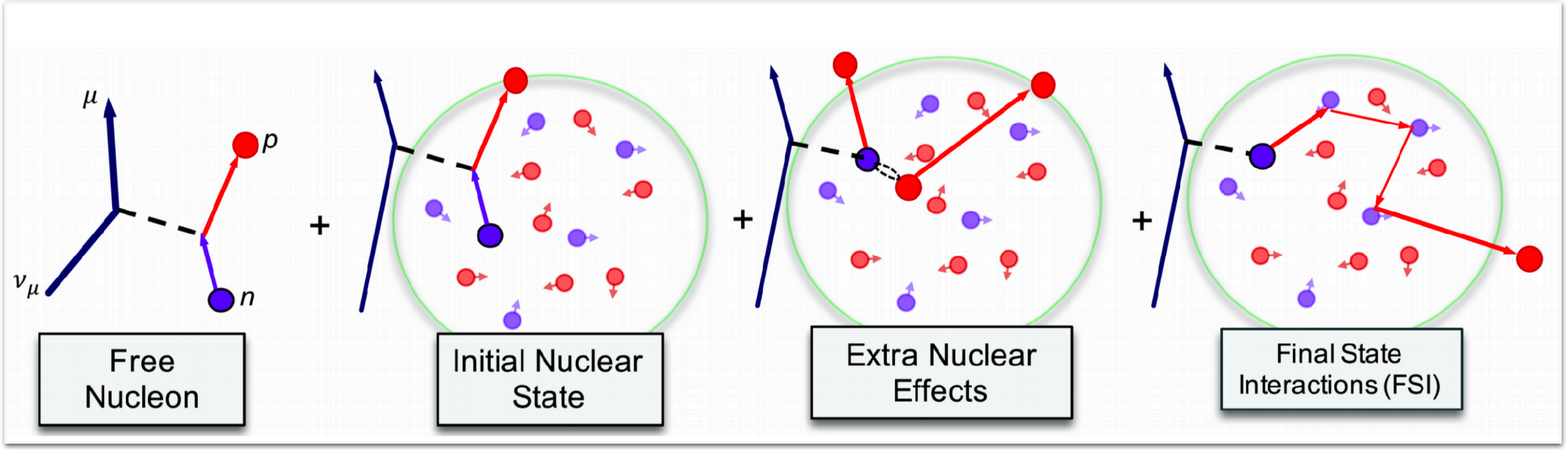


Image Credit: Callum Wilkinson

Neutrino Interactions

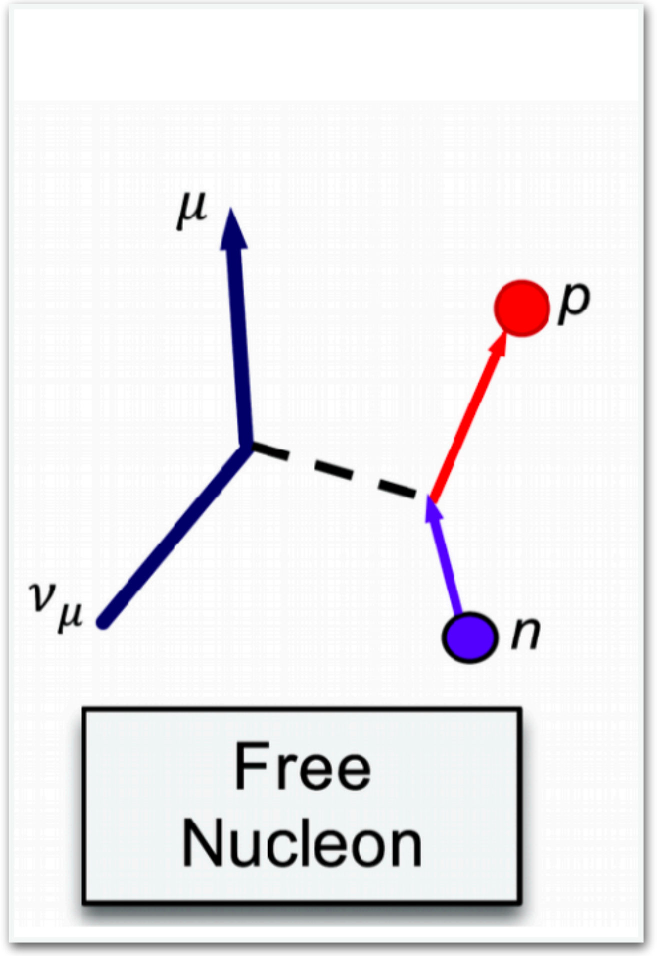


Image Credit: Callum Wilkinson

Neutrino Interactions

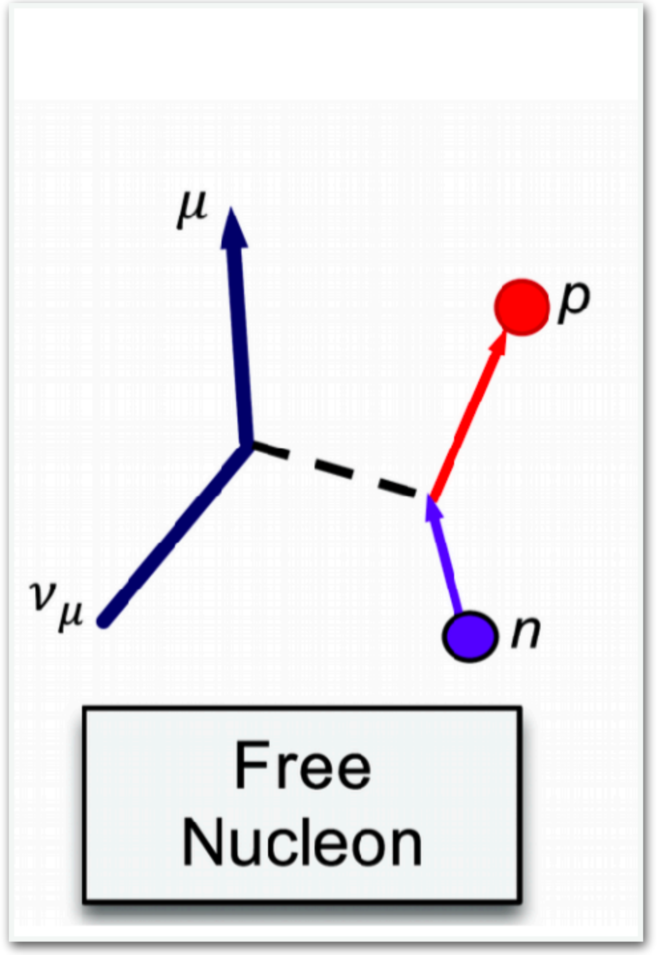
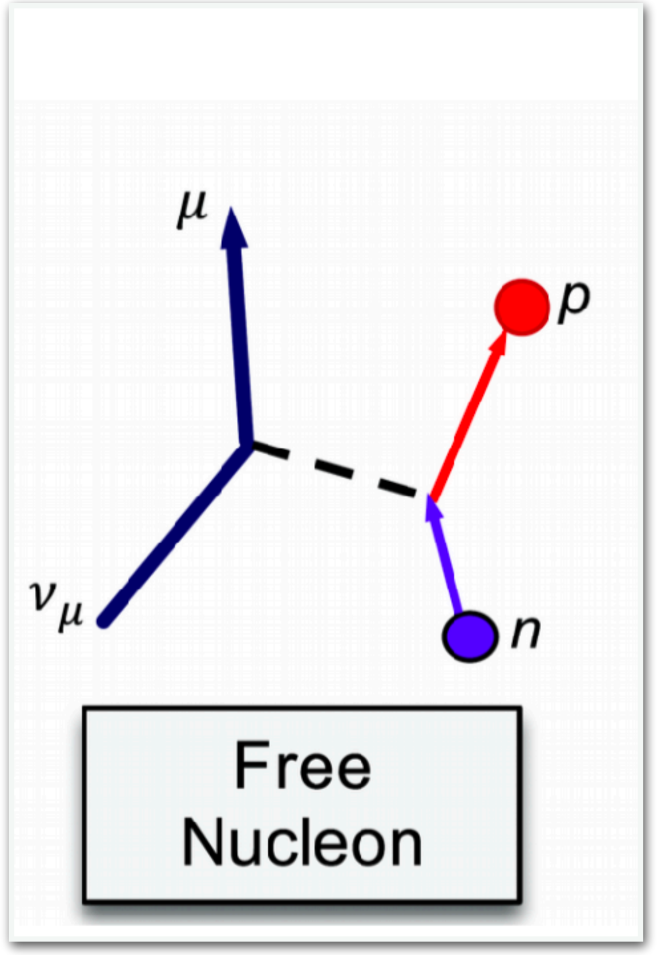


Image Credit: Callum Wilkinson

Neutrino Interactions



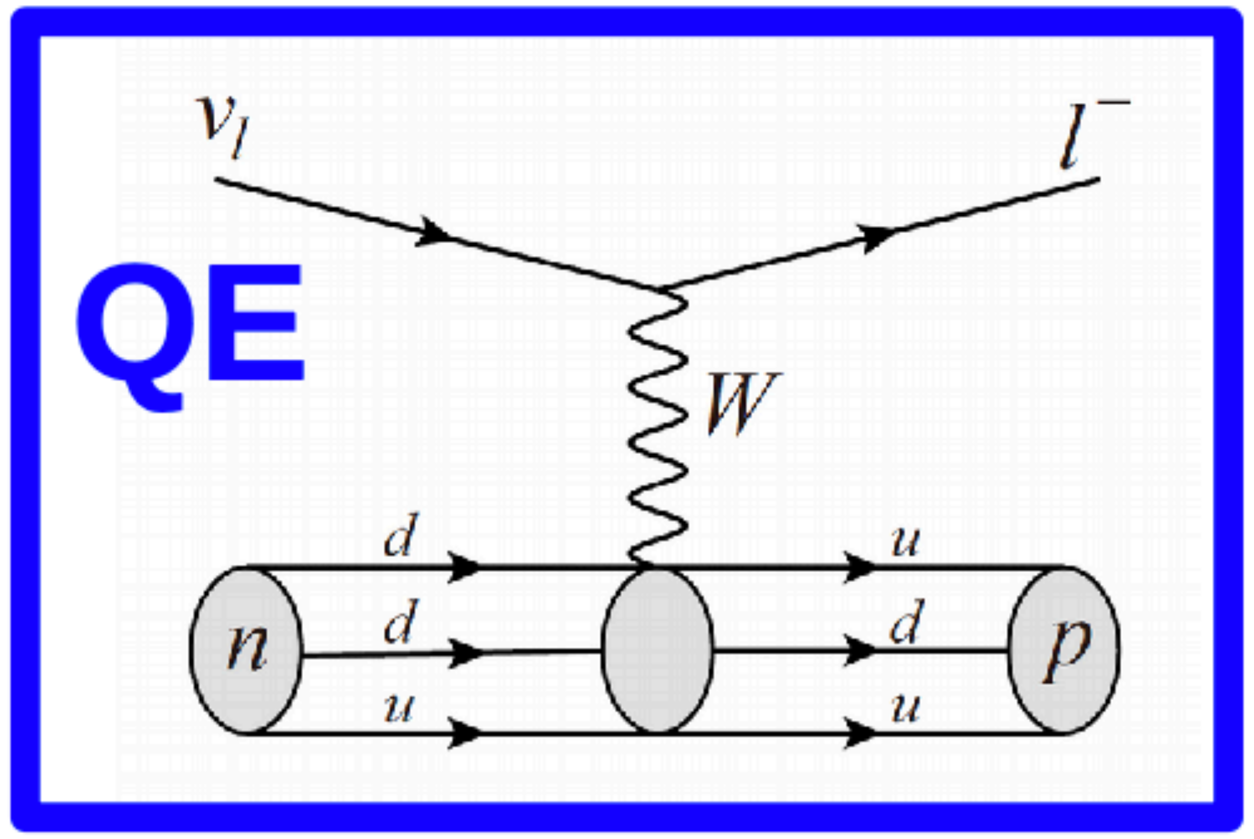
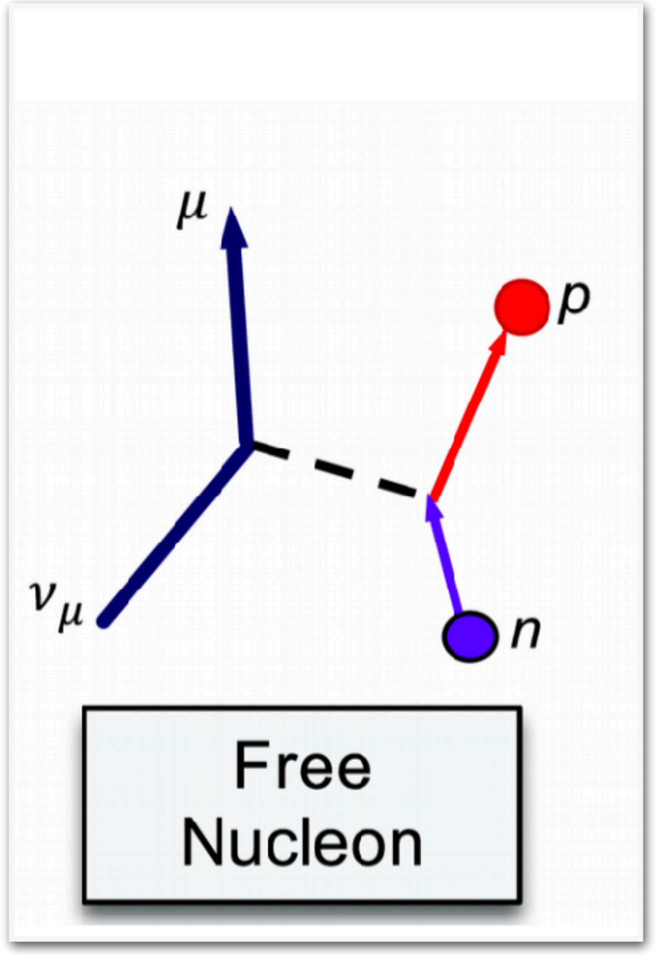
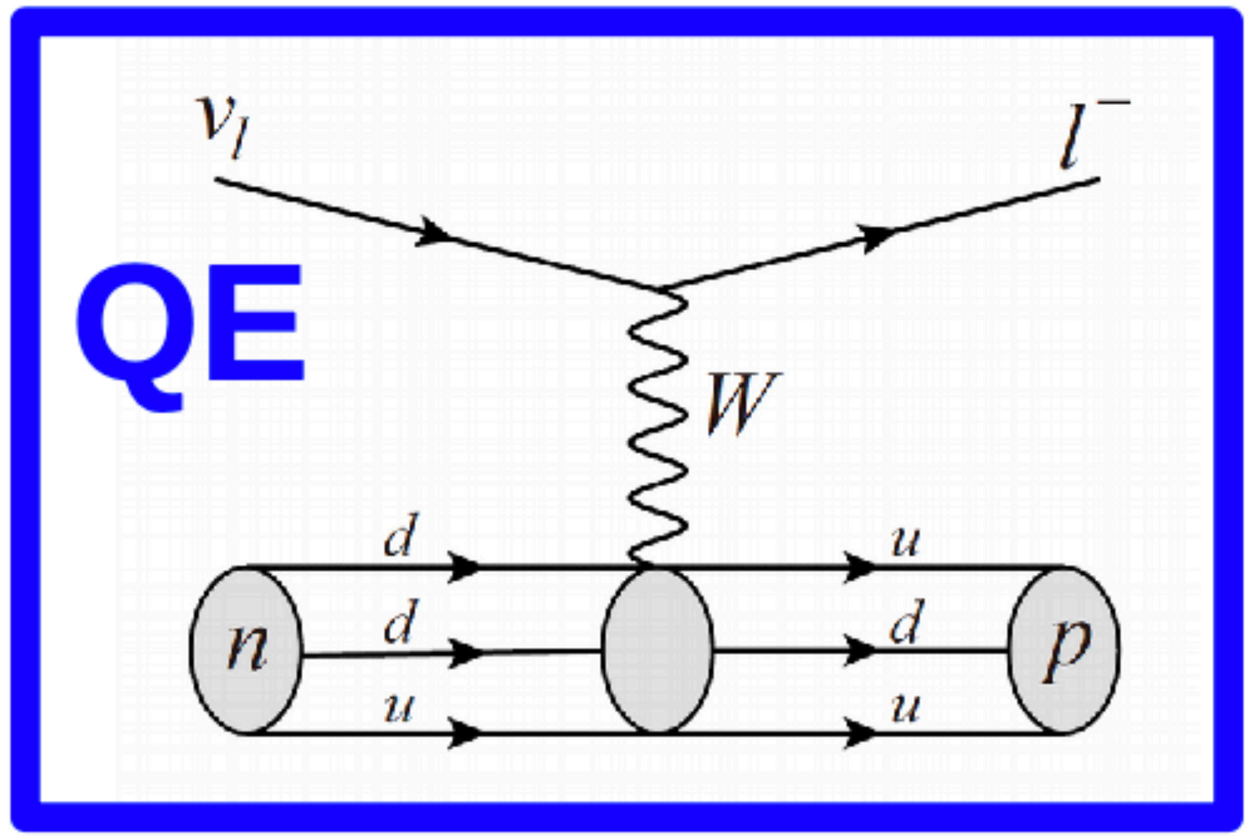


Image Credit: Callum Wilkinson

Neutrino Interactions





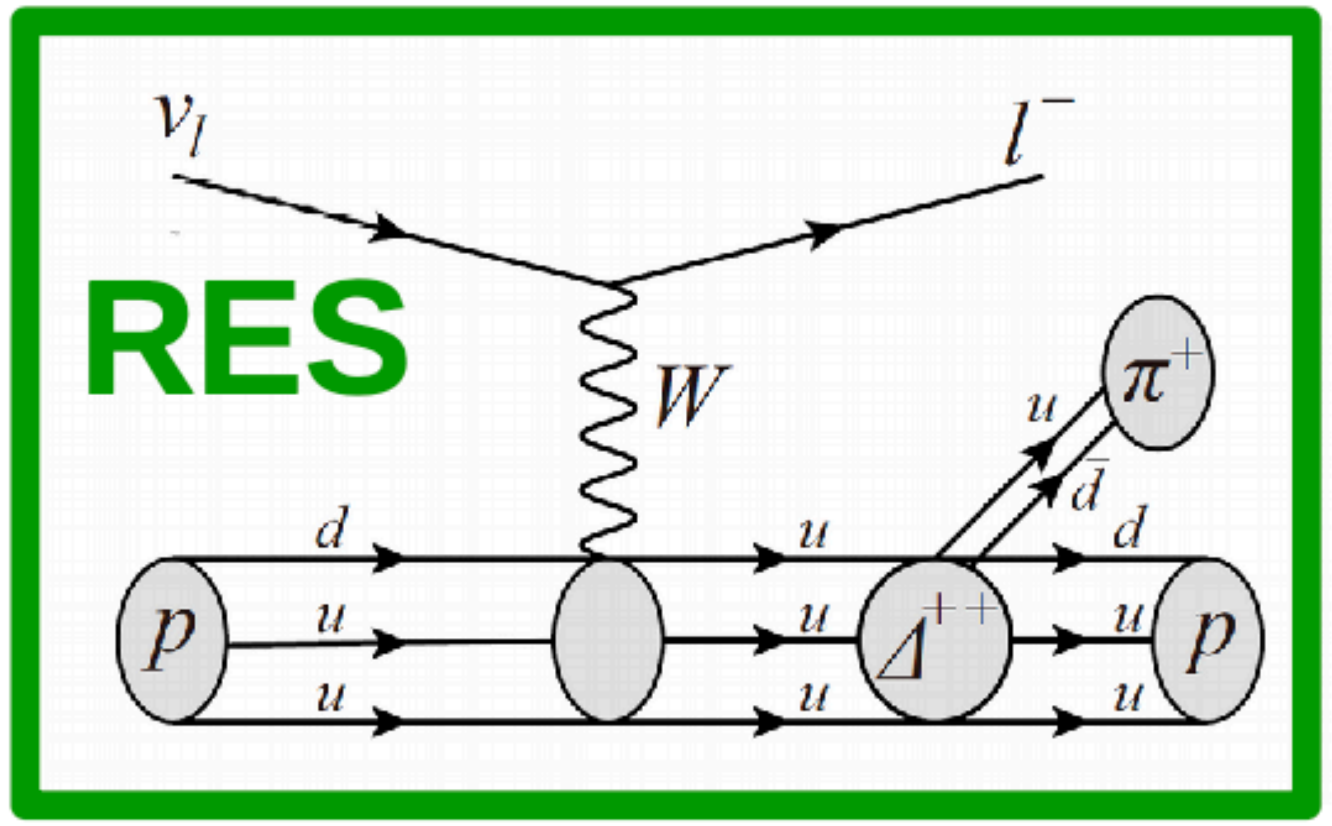
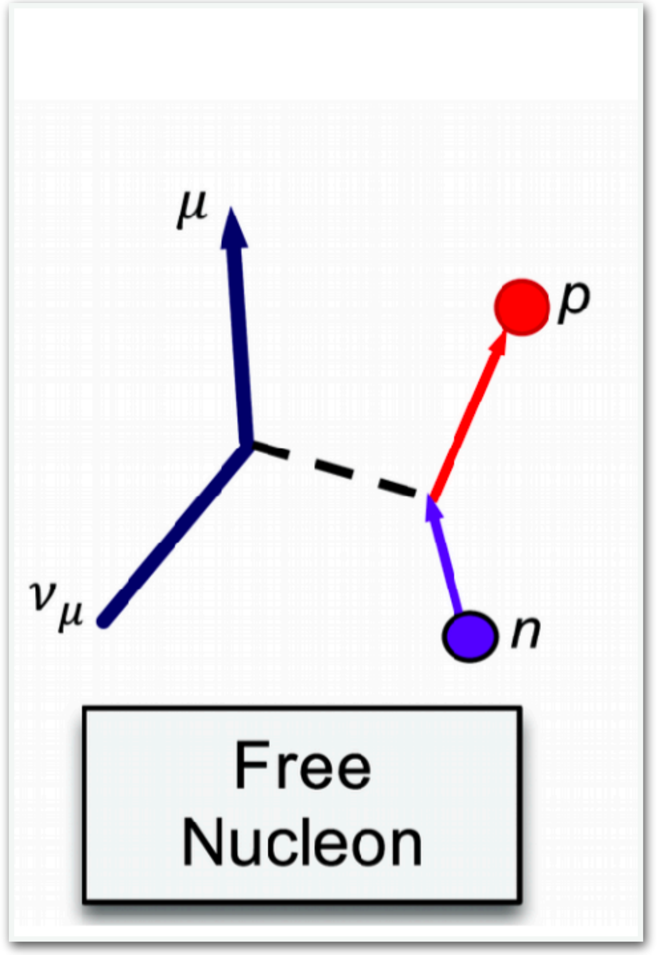
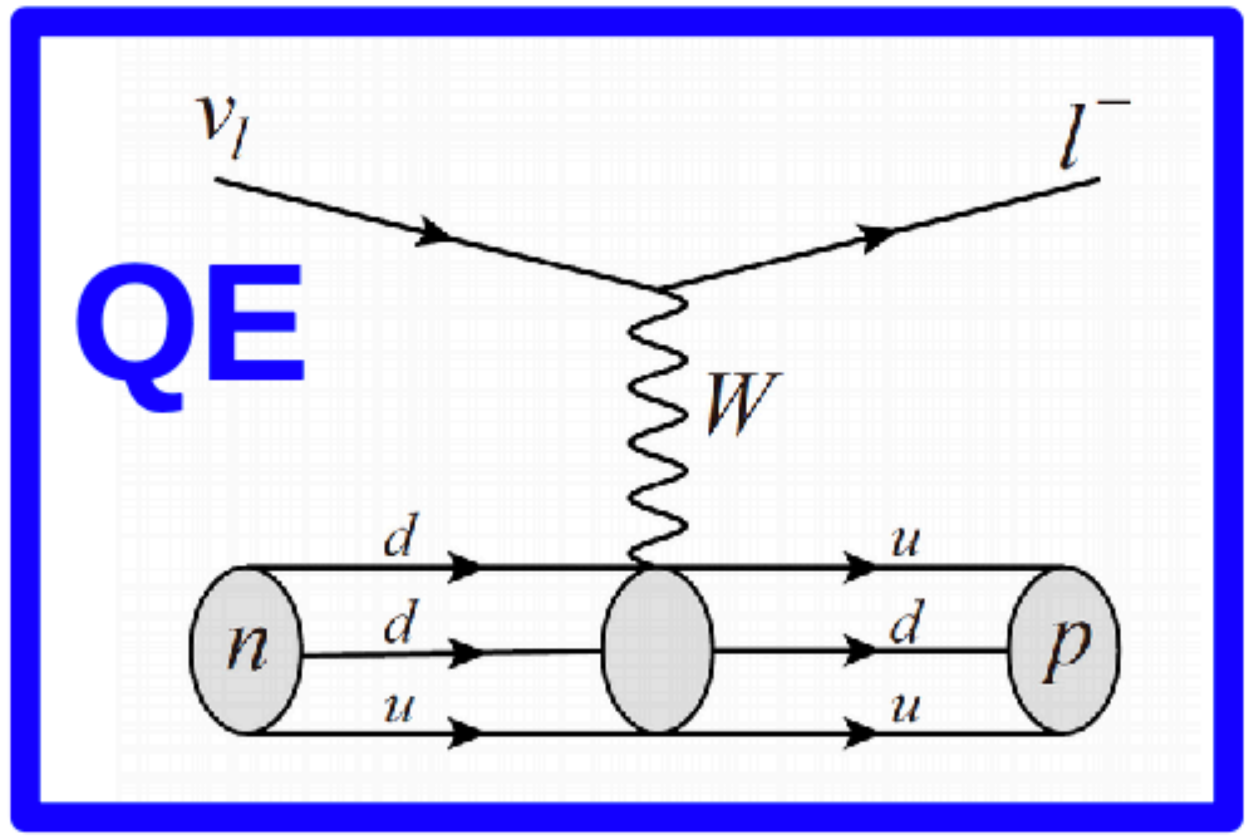
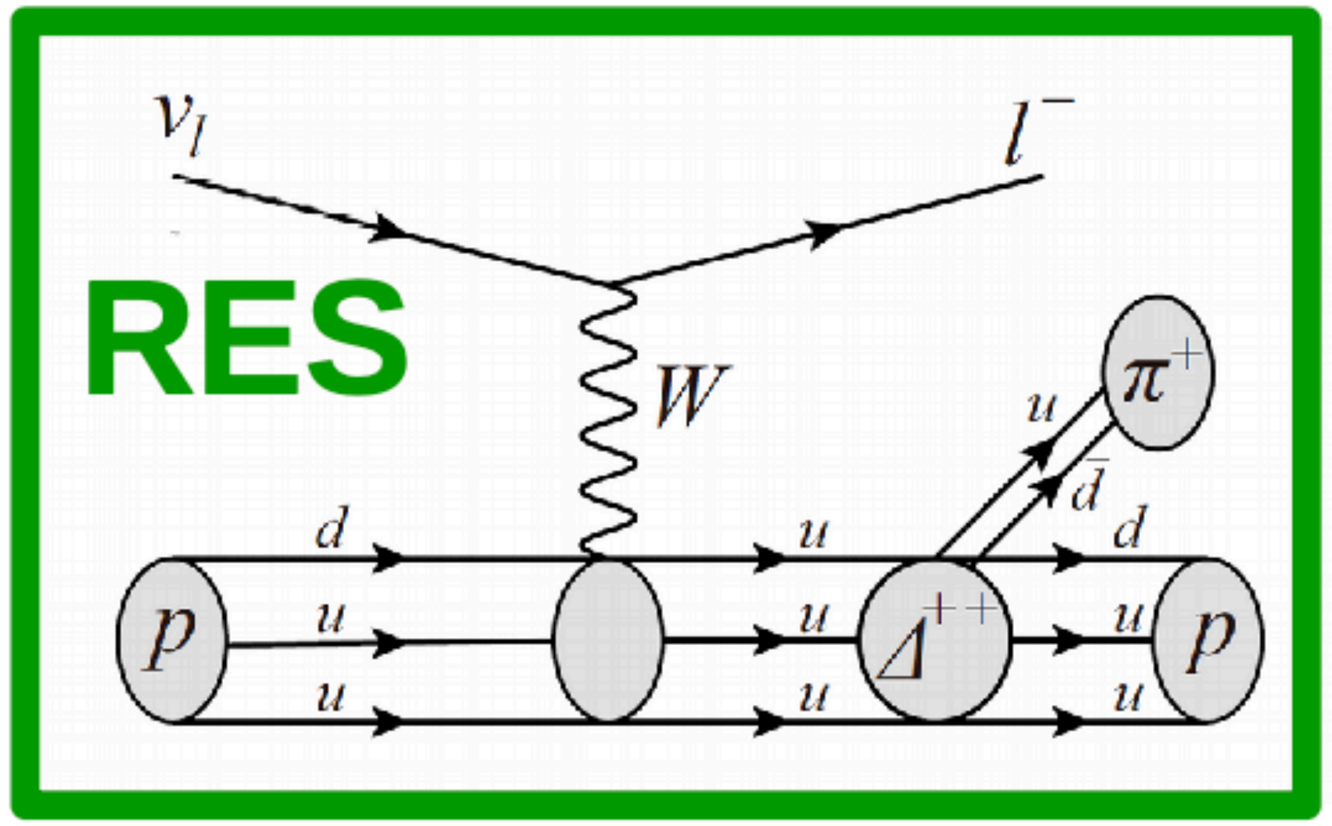


Image Credit: Callum Wilkinson

Neutrino Interactions







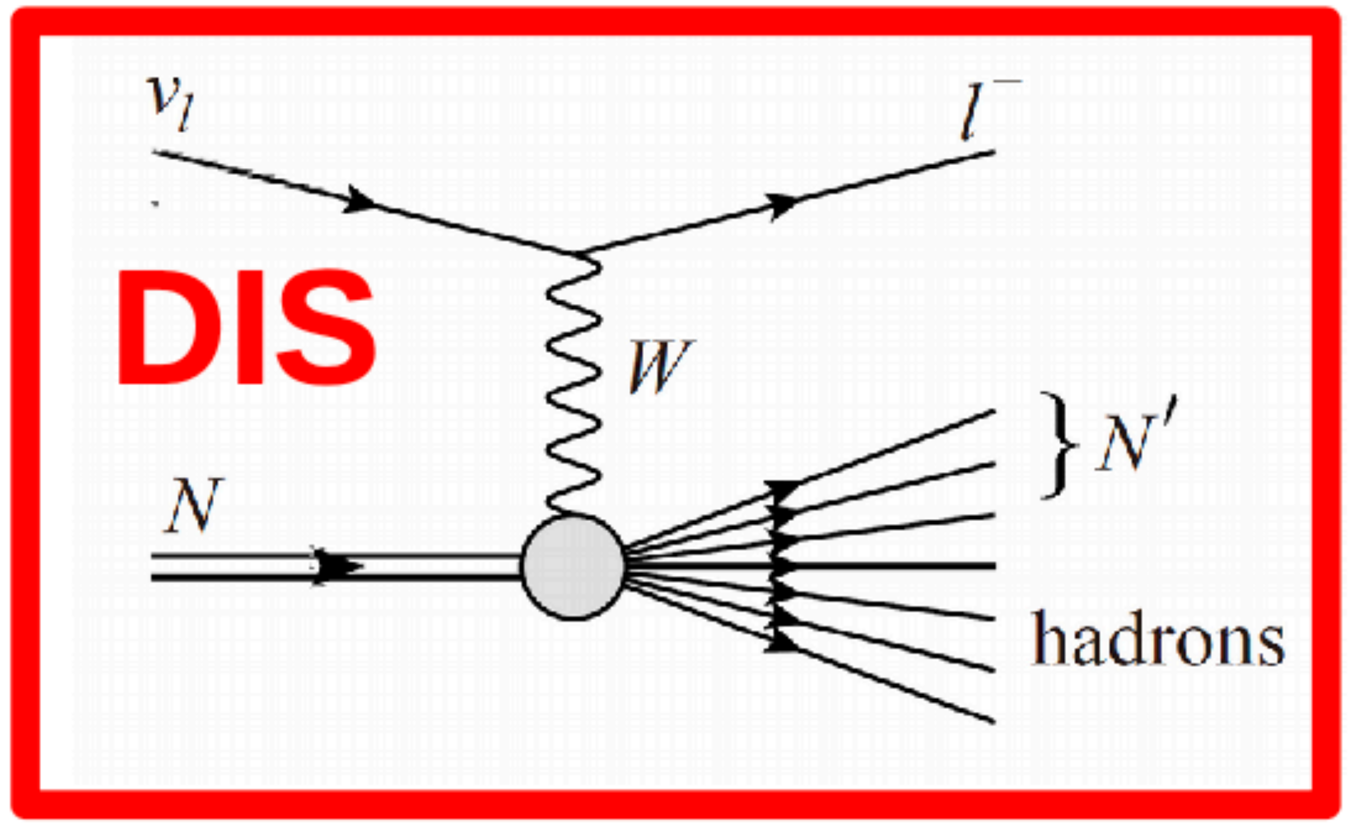


Image Credit: Callum Wilkinson

Neutrino Interactions

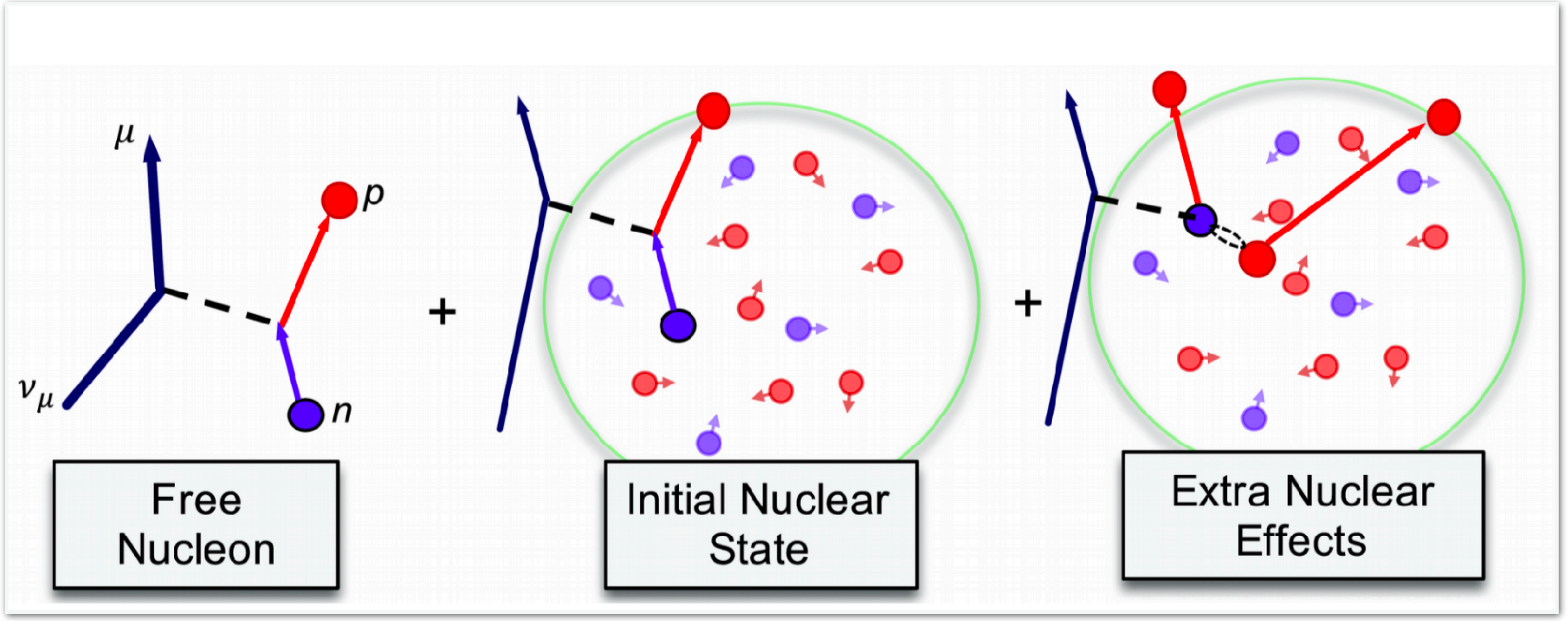
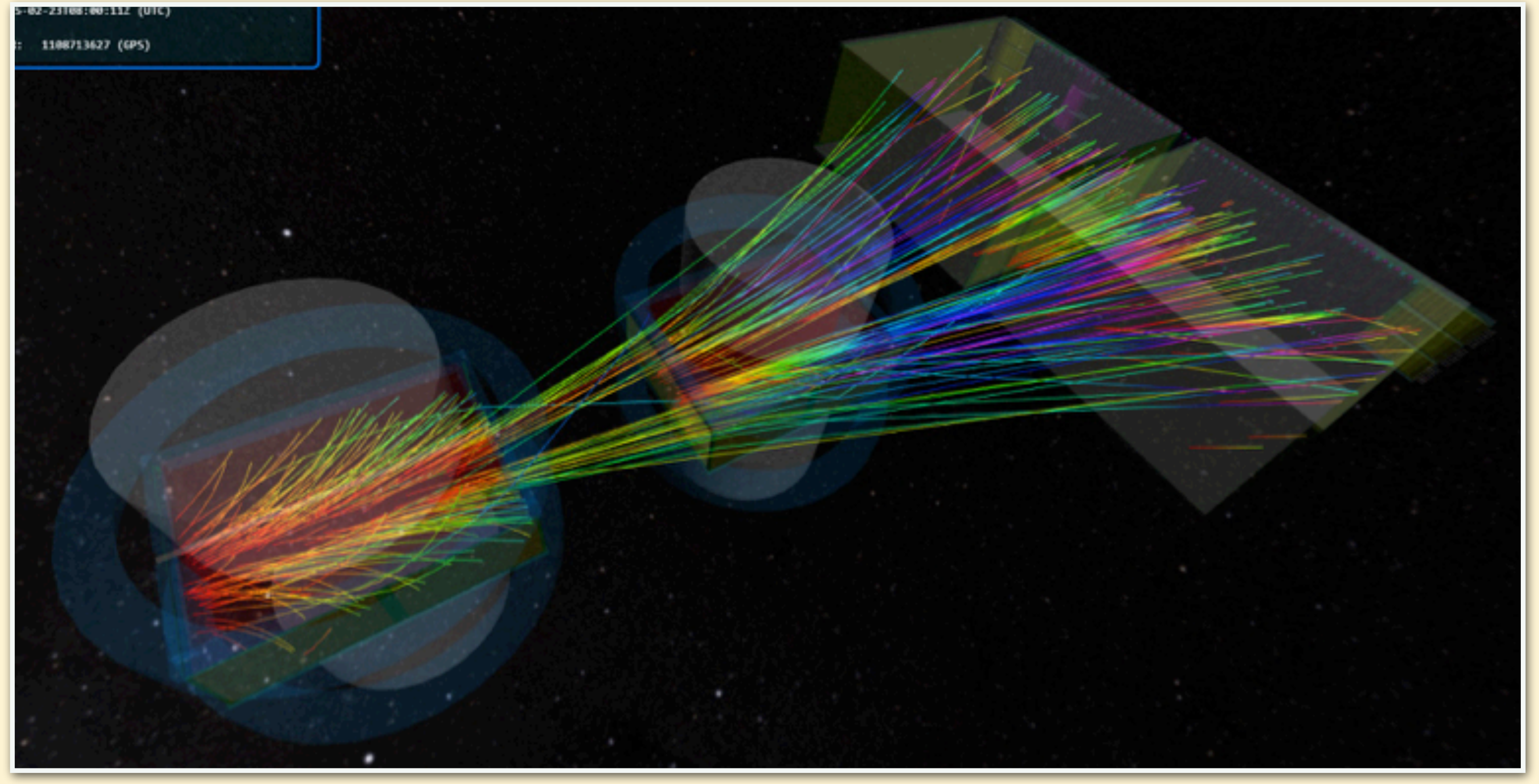


Image Credit: Callum Wilkinson

Mitigation of Systematic Uncertainties

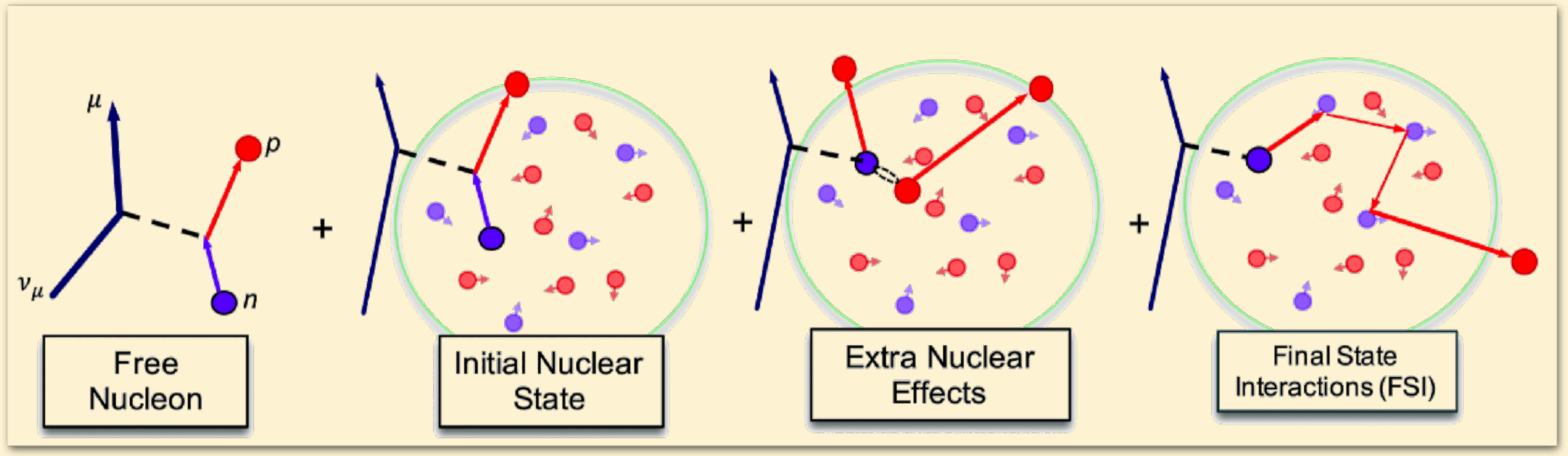
Experimental Mitigation

- near detectors
  (on-axis and off-axis)
- hadroproduction experiments
  (NA61/SHINE, ENUBET)

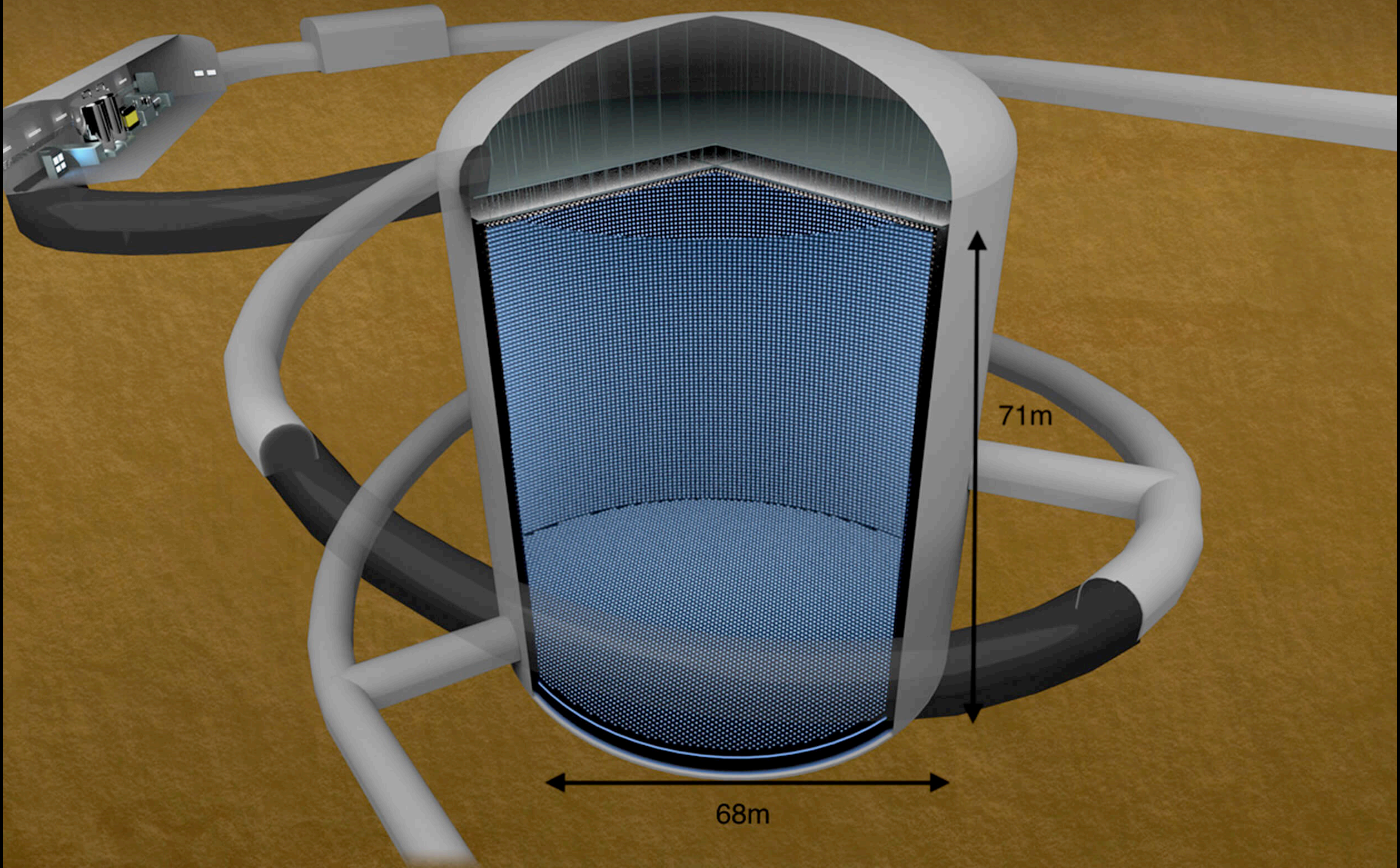


Theory Needs

- better modelling of neutrino interactions
- new strategies for optimally exploiting near detector data
  (e.g. DUNE-PRISM)



HyperKamiokande



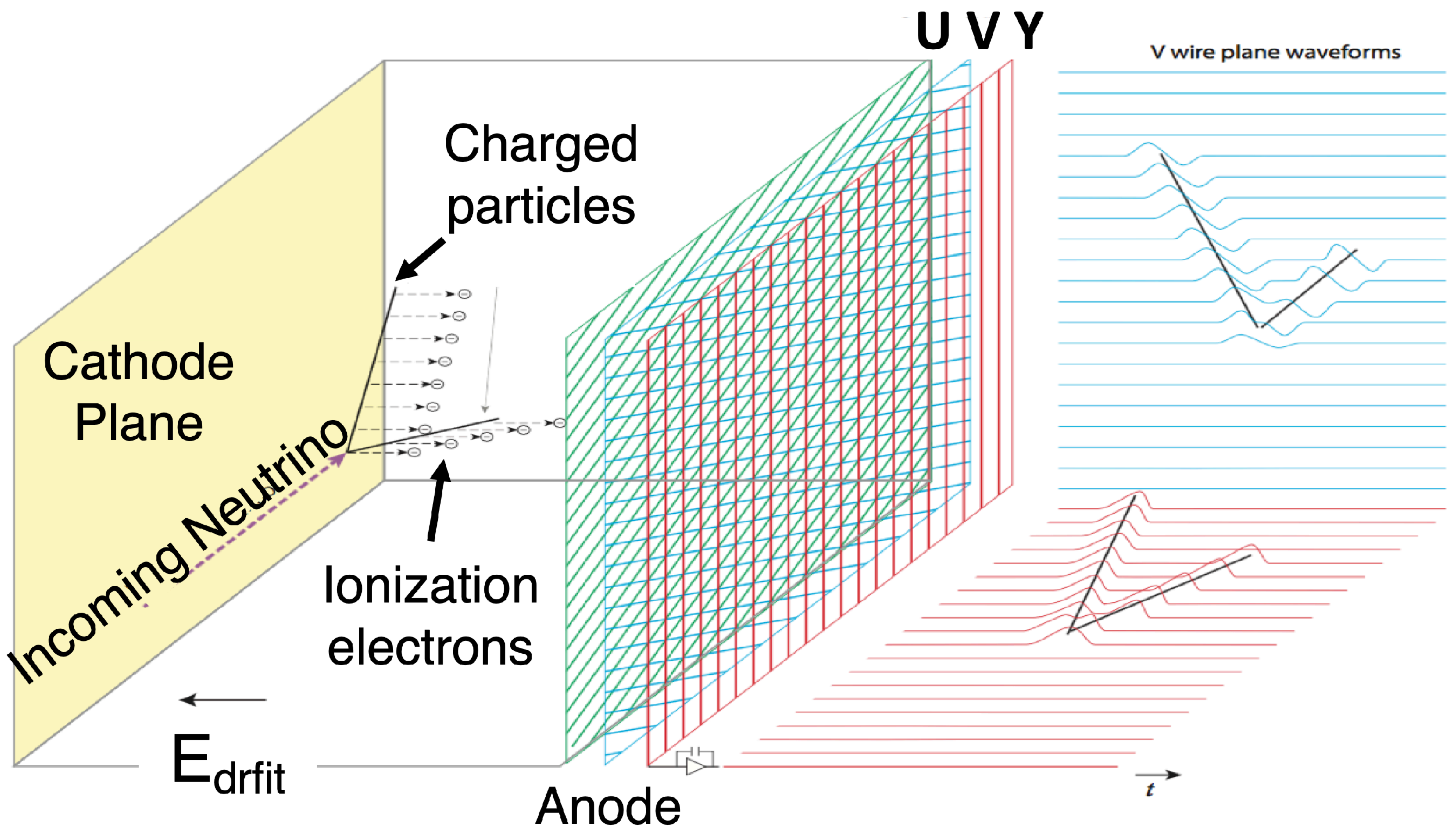
HyperKamiokande

DUNE

HyperK's North American Competitor: DUNE

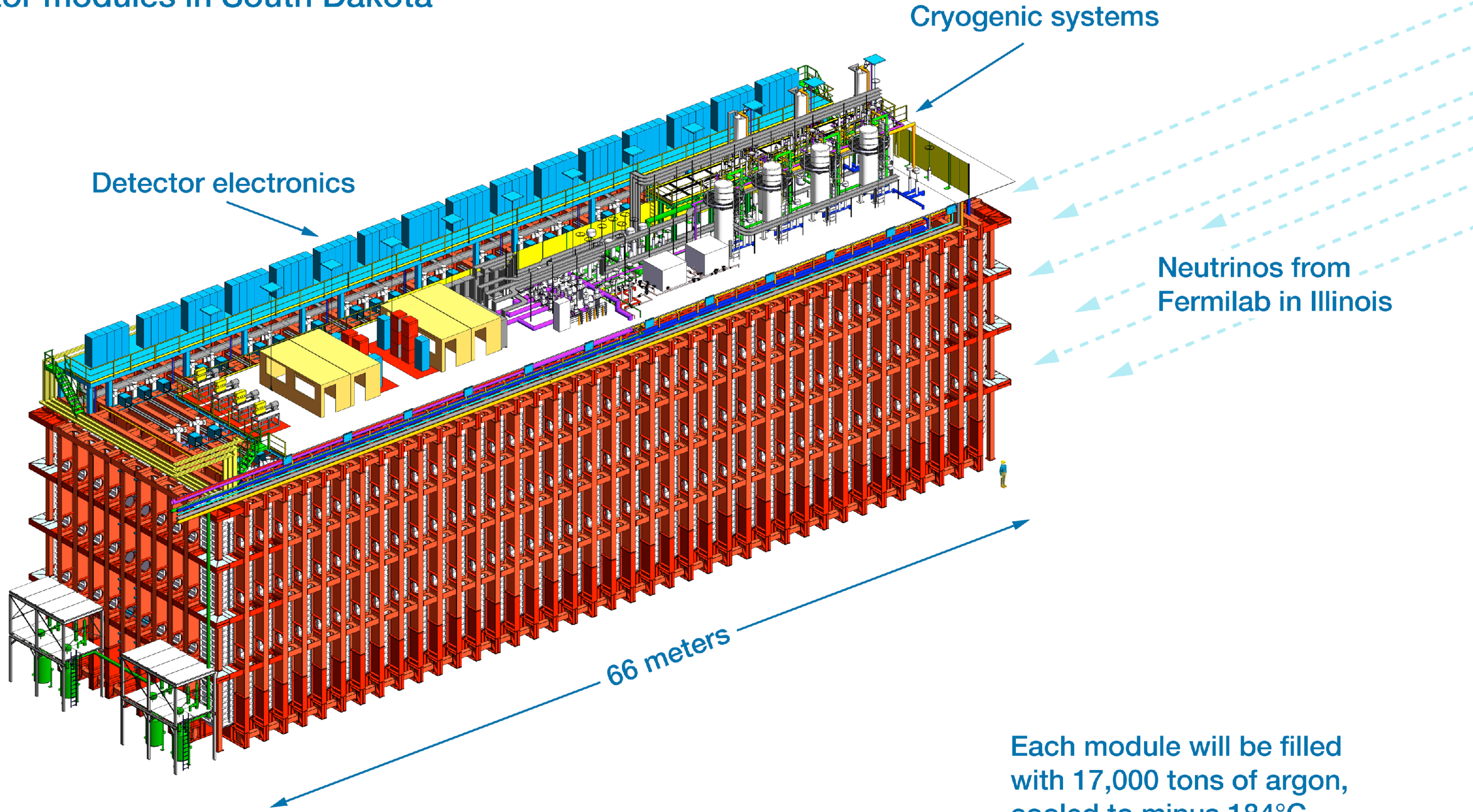
The DUNE Beam

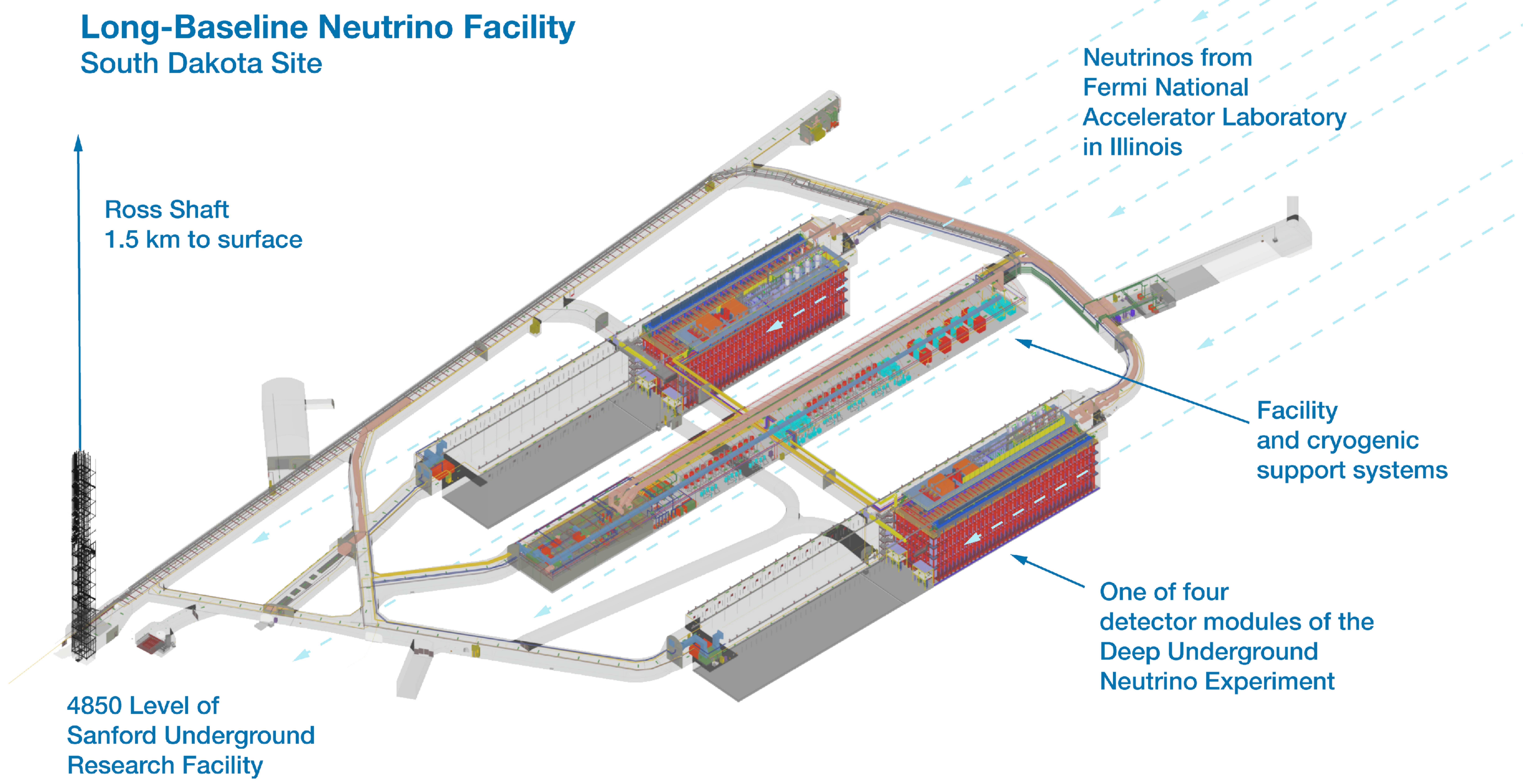
Neutrino Detection in Liquid Argon TPCs



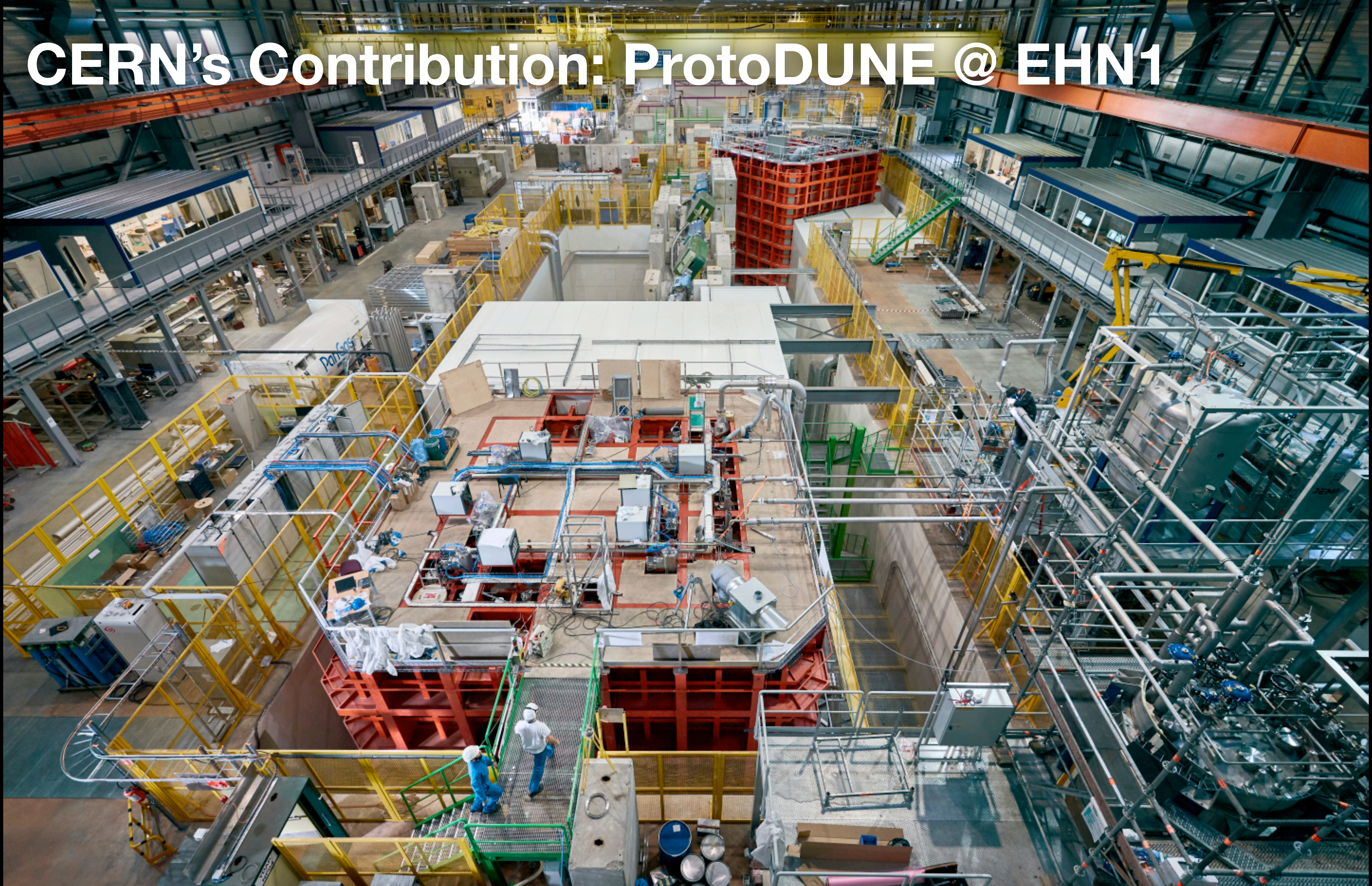
Deep Underground Neutrino Experiment

One of four detector modules in South Dakota



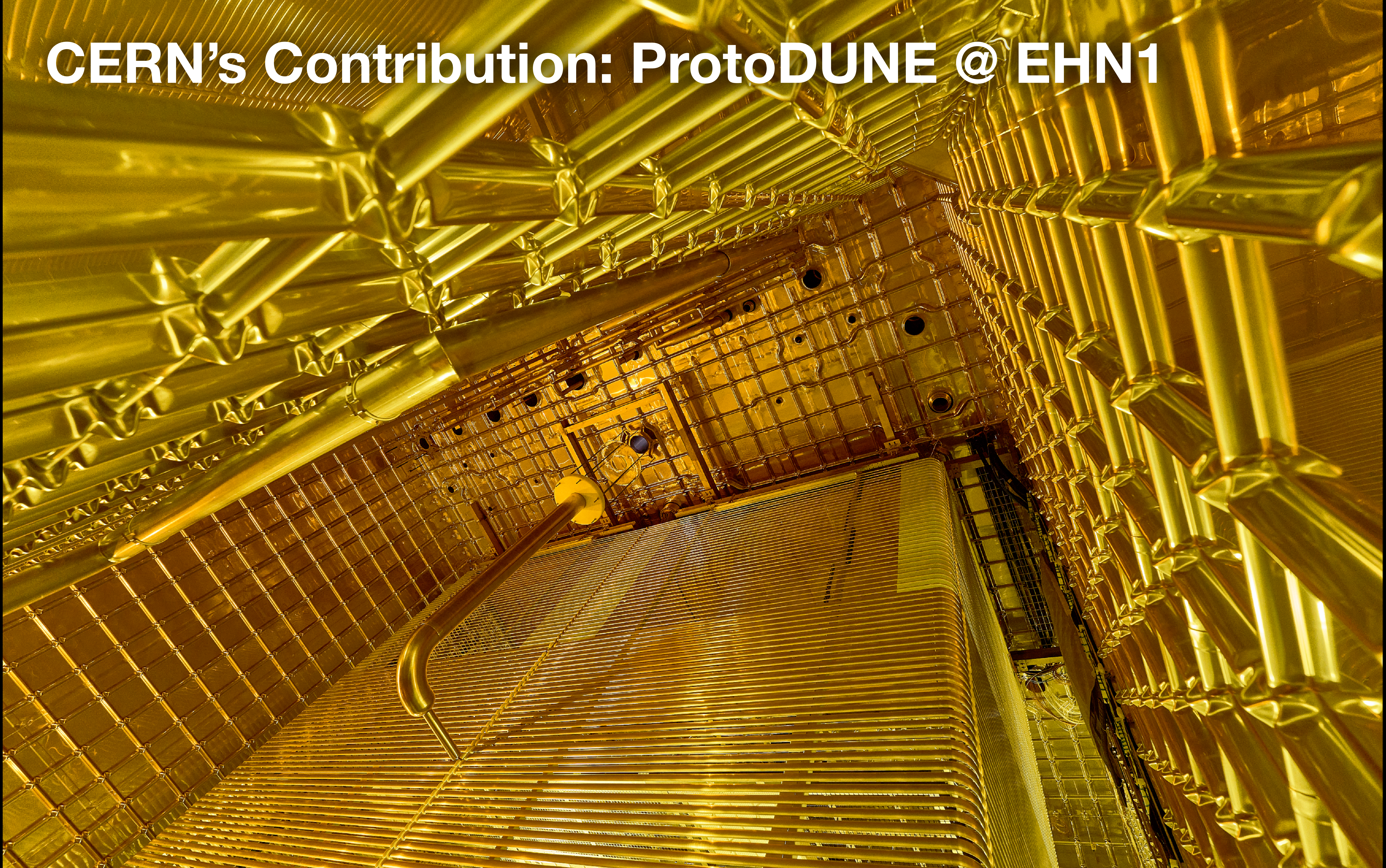

Long-Baseline Neutrino Facility
South Dakota Site
Neutrinos from Fermi National Accelerator Laboratory in Illinois
Ross Shaft 1.5 km to surface
Facility and cryogenic support systems
One of four detector modules of the Deep Underground Neutrino Experiment
4850 Level of Sanford Underground Research Facility

CERN's Contribution: ProtoDUNE @ EHN1



CERN’s Contribution: ProtoDUNE @ EHN1

CERN's Contribution: ProtoDUNE @ EHN1



Yes, But Why?

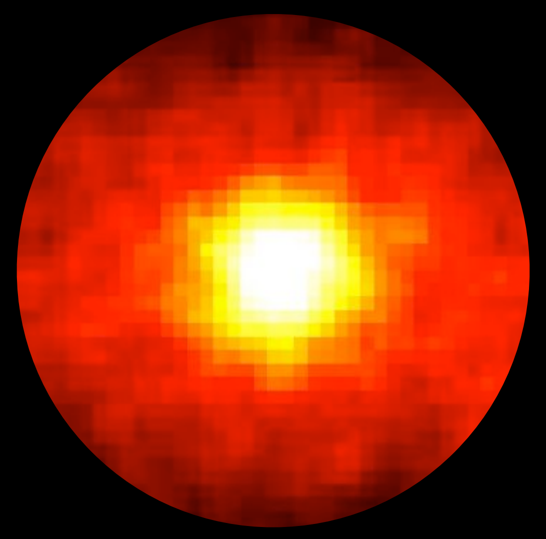
- ☐ Connection between leptonic CP violation and baryogenesis
- ☐ Portal to new physics
- ☐ Precise knowledge of particle physics is indispensable for using neutrinos as astrophysical messengers
- ☐ Hints for the origin of flavour
- ☐ Multi-purpose detectors with lots of secondary opportunities (supernova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

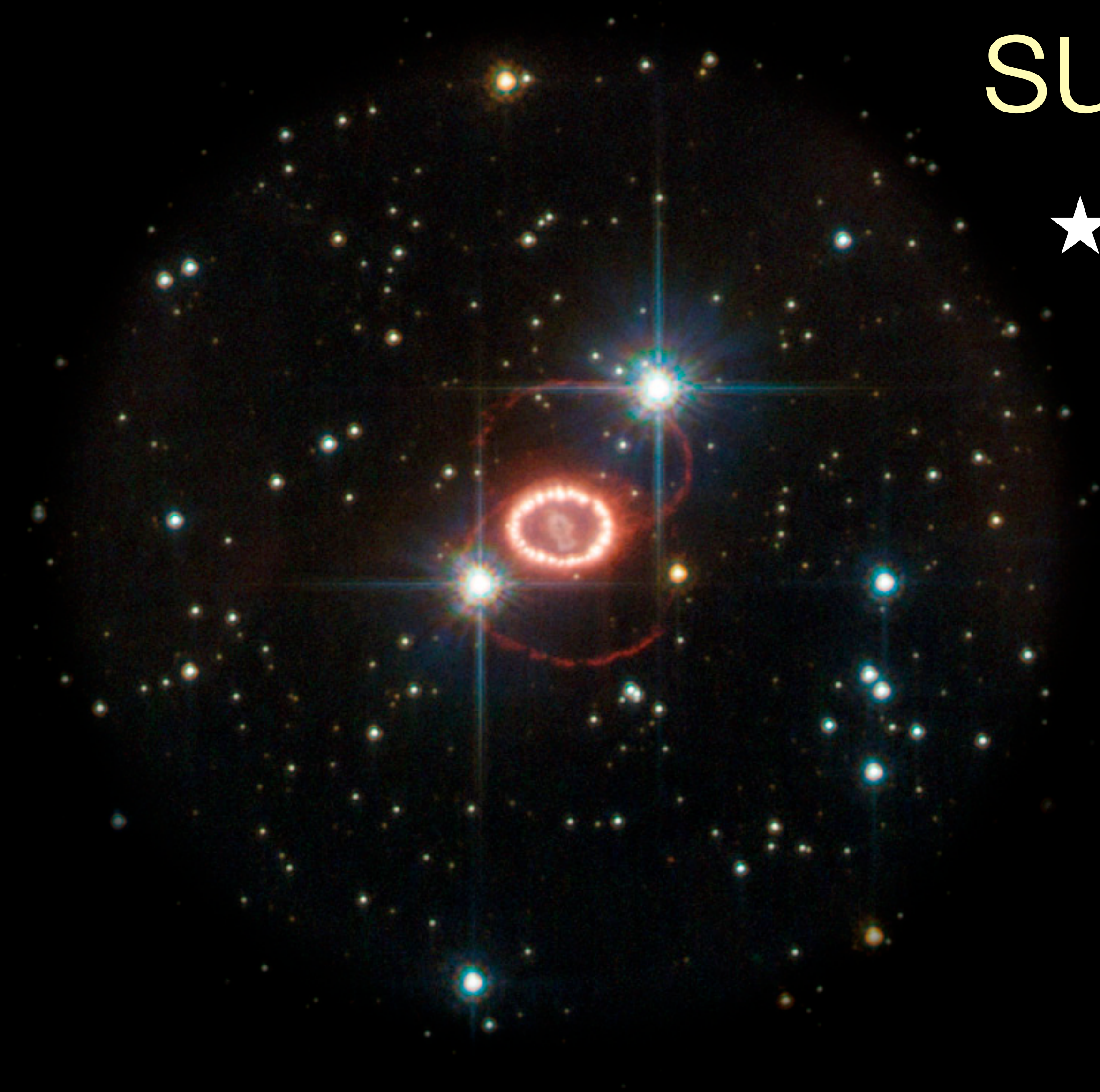
solar neutrinos

- ⋆ stellar evolution

Neutrinos as Astrophysical Messengers

solar neutrinos

- ⋆ stellar evolution



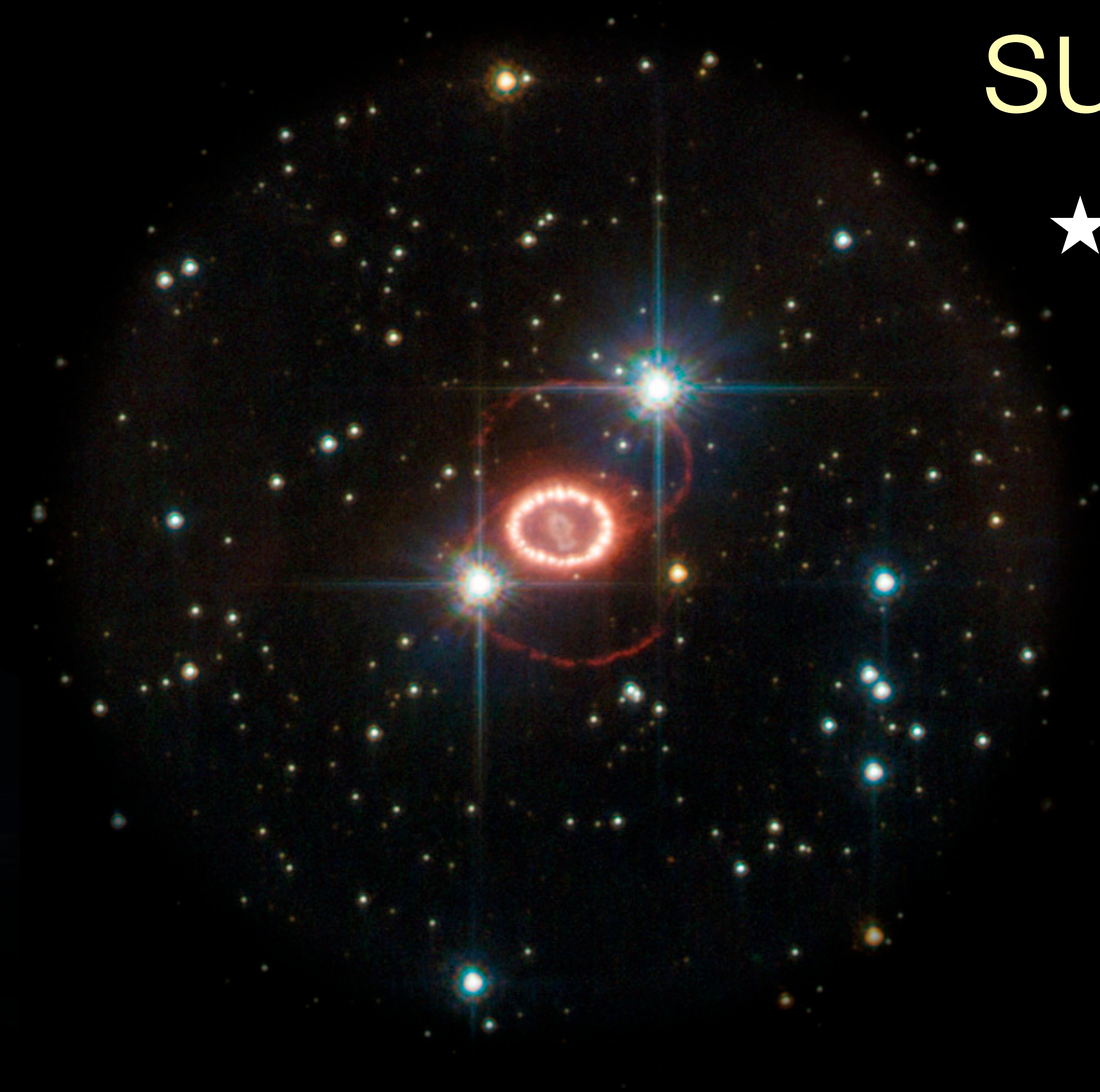
supernova neutrinos

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

Neutrinos as Astrophysical Messengers

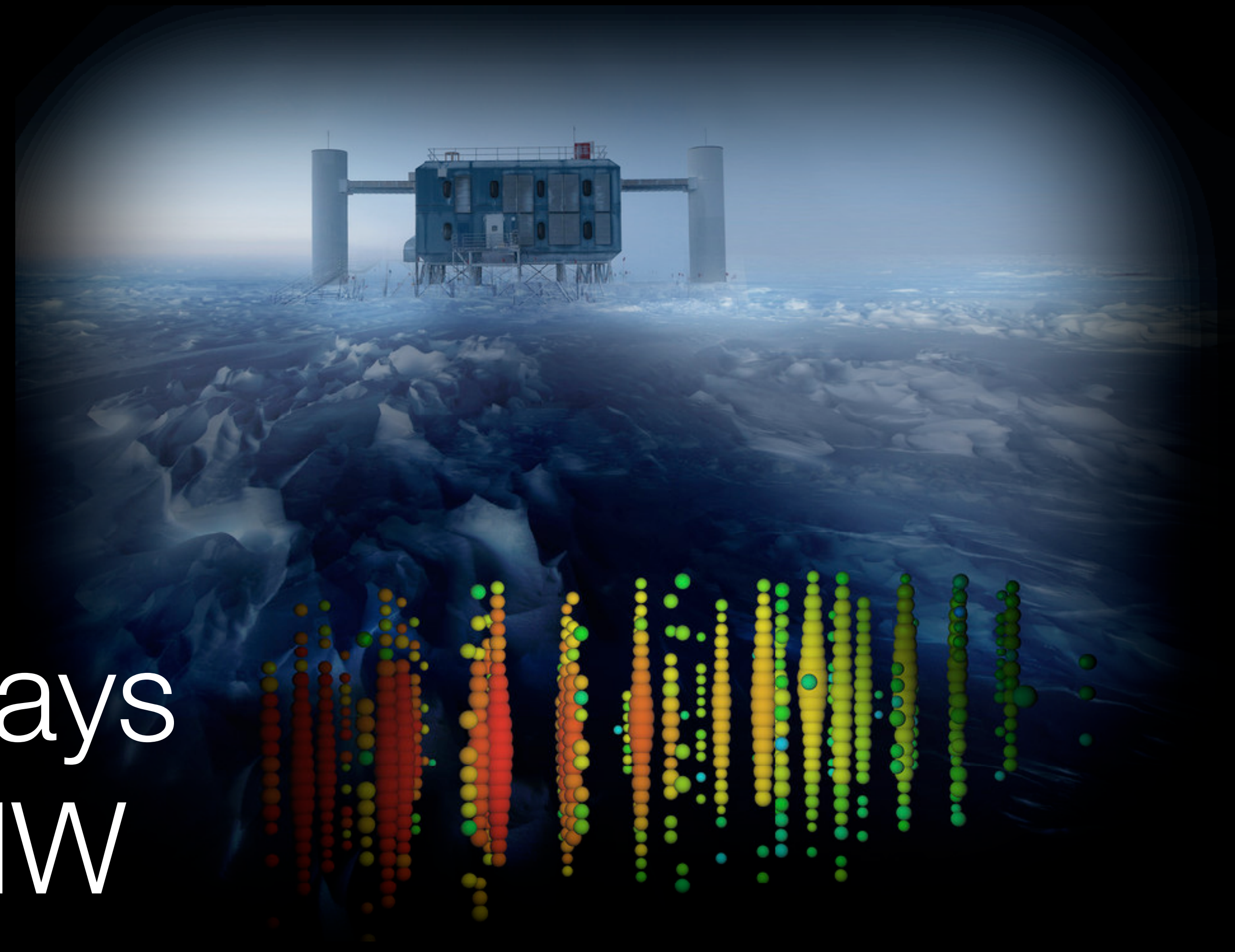
solar neutrinos

- ★ stellar evolution



supernova neutrinos

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



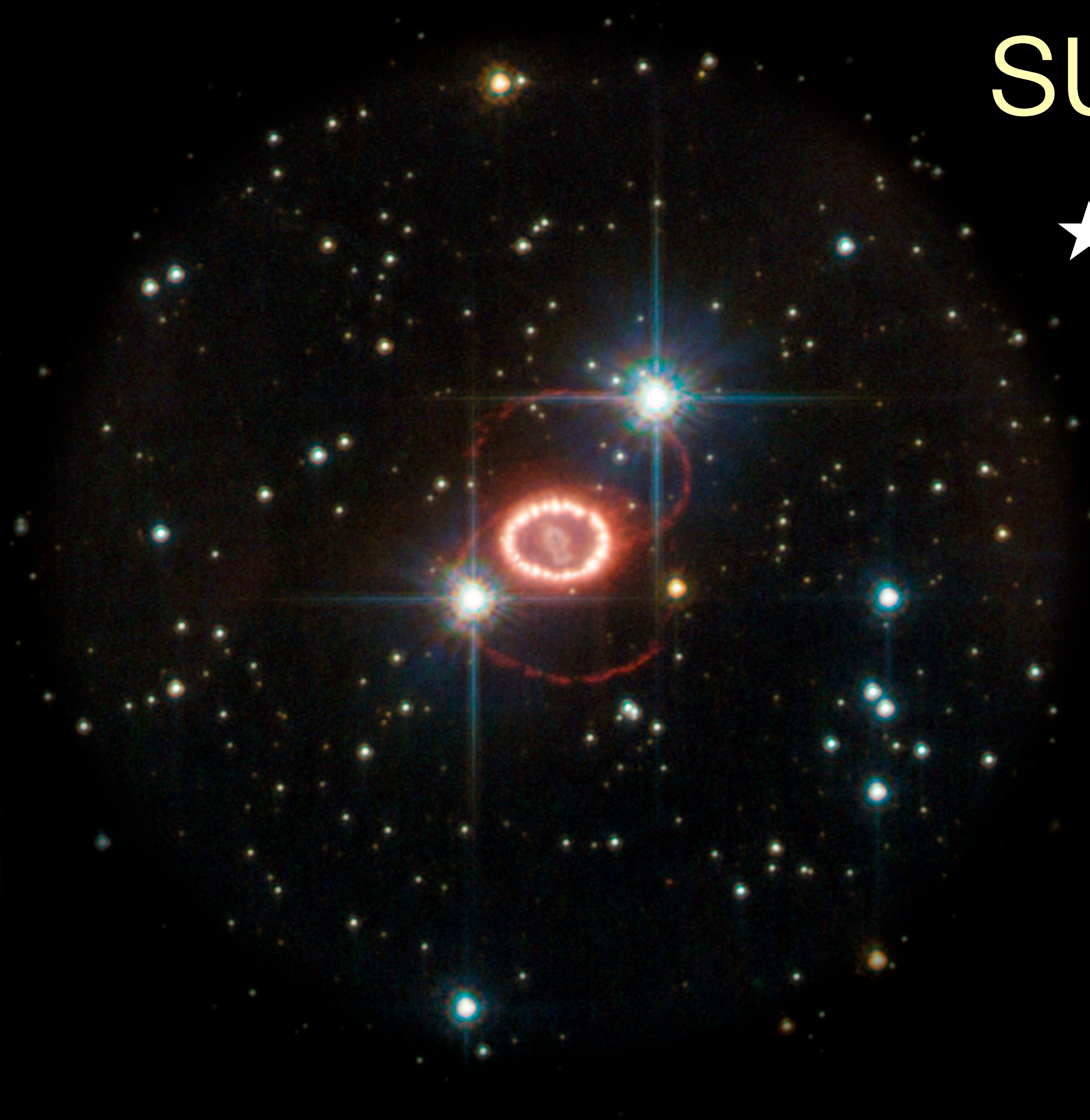
high-*E* neutrinos

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

Neutrinos as Astrophysical Messengers

solar neutrinos

★ stellar evolution

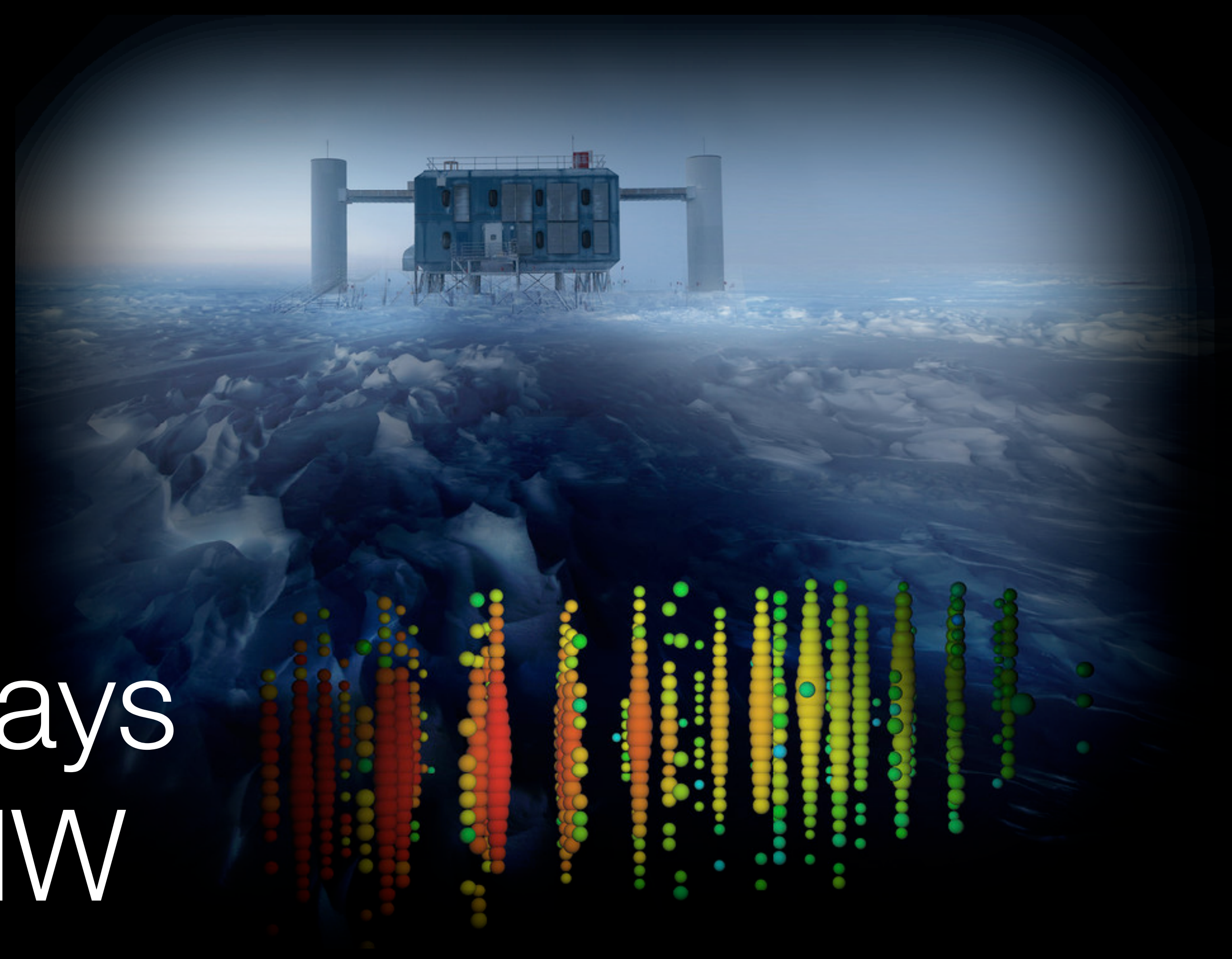


supernova neutrinos

★ death throes of massive stars

★ nucleosynthesis

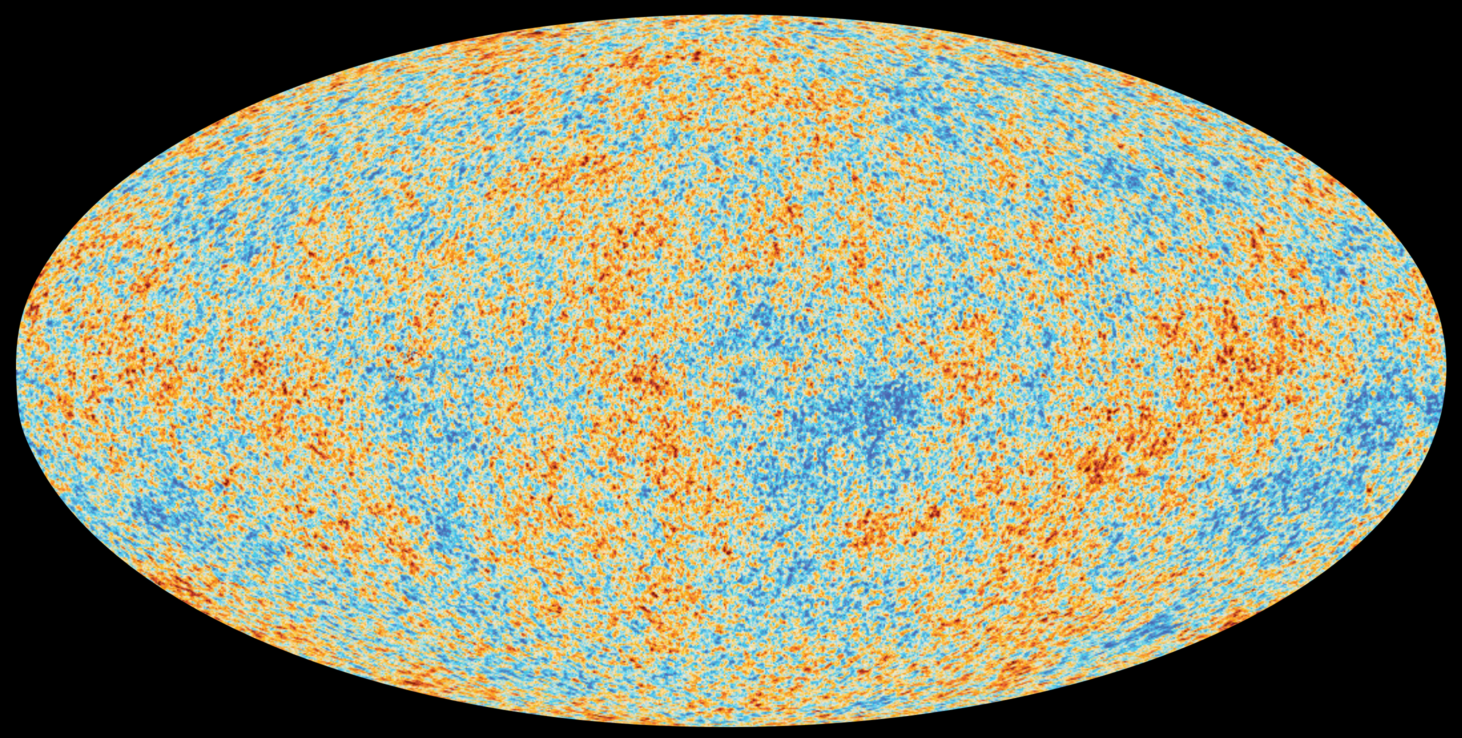
★ matter under extreme conditions



high-*E* neutrinos

★ origin of cosmic rays

★ AGNs, blazars, MW

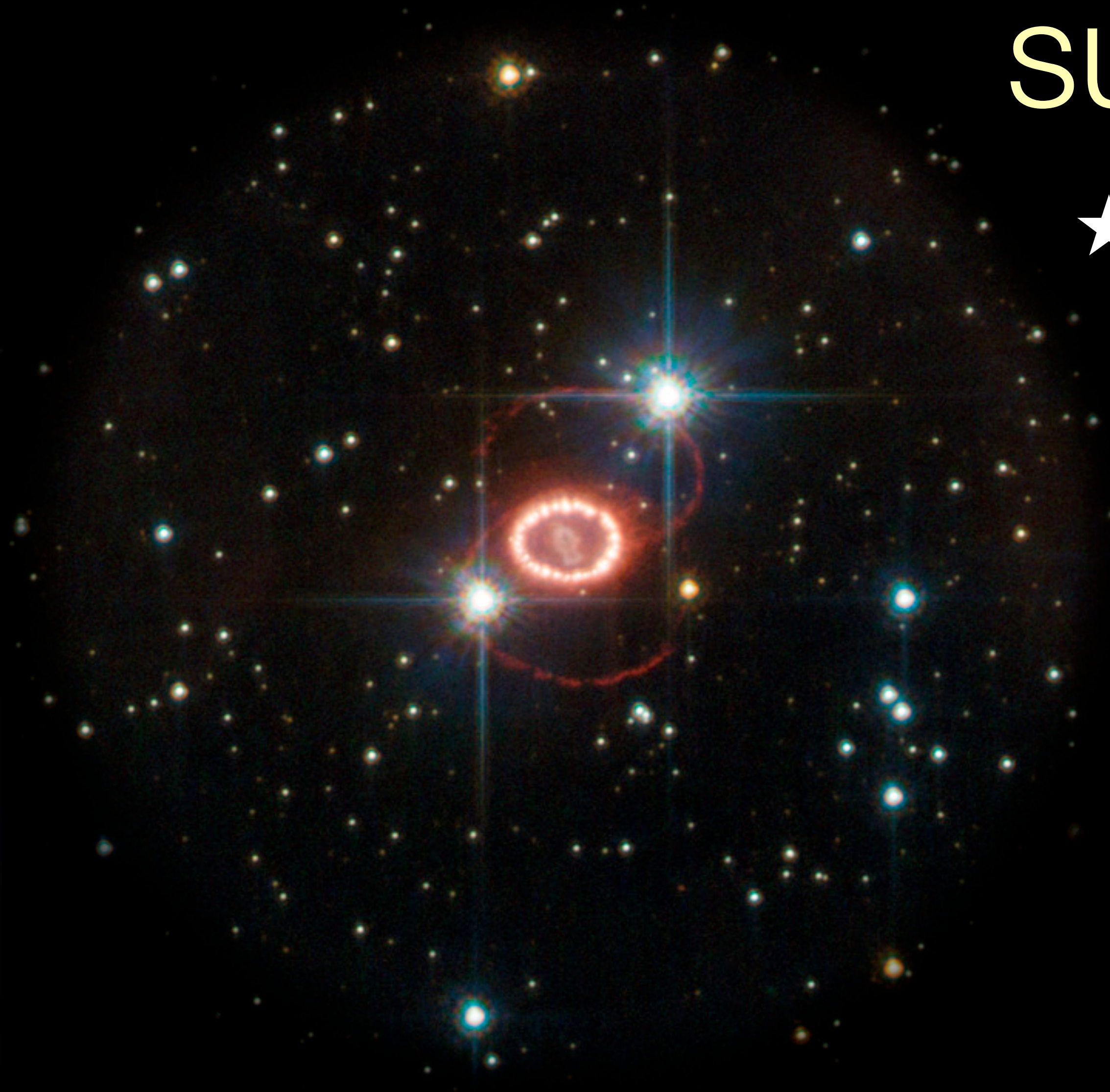


cosmology

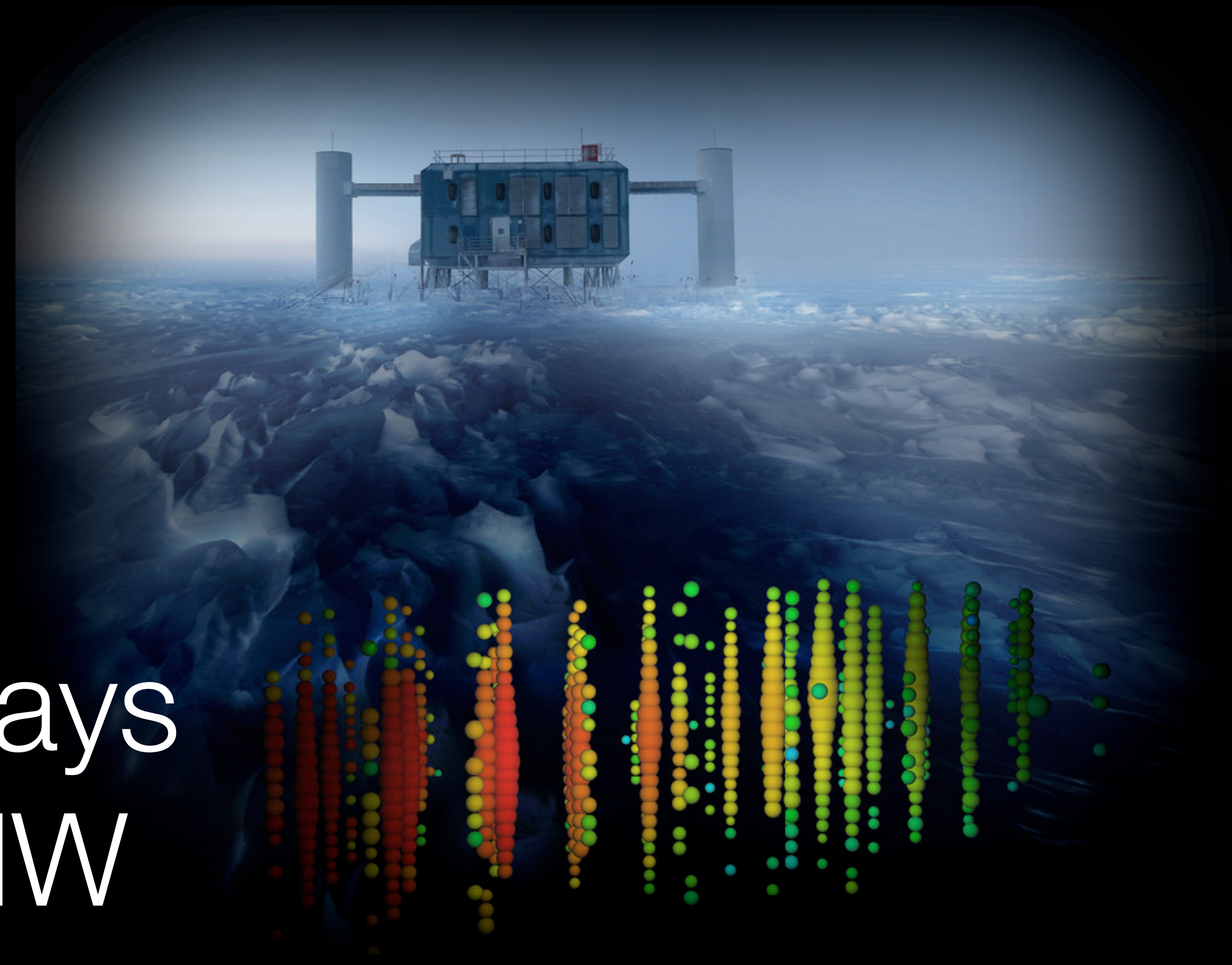
★ early Universe

Neutrinos as Astrophysical Messengers

solar neutrinos
- ★ stellar evolution

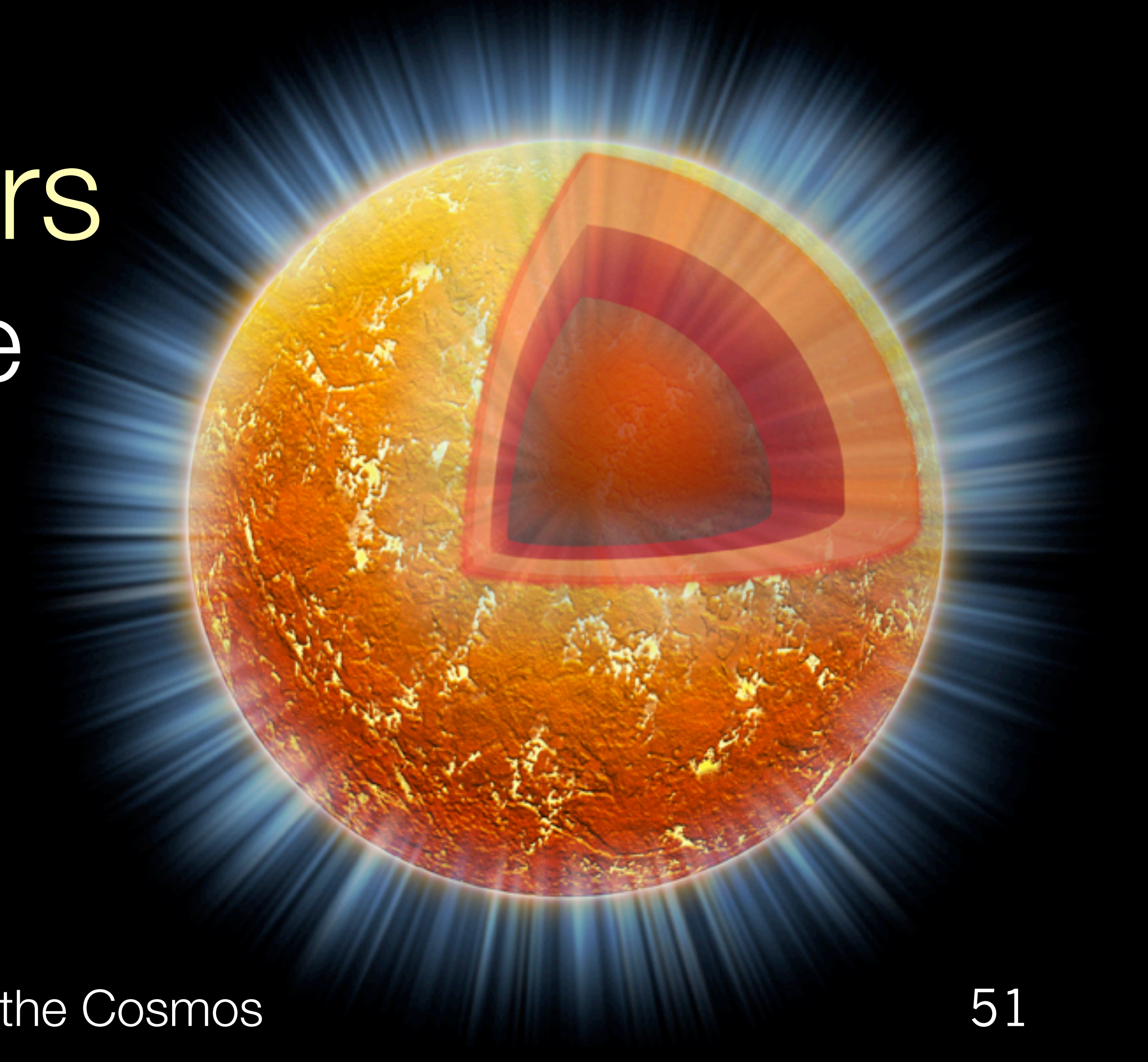


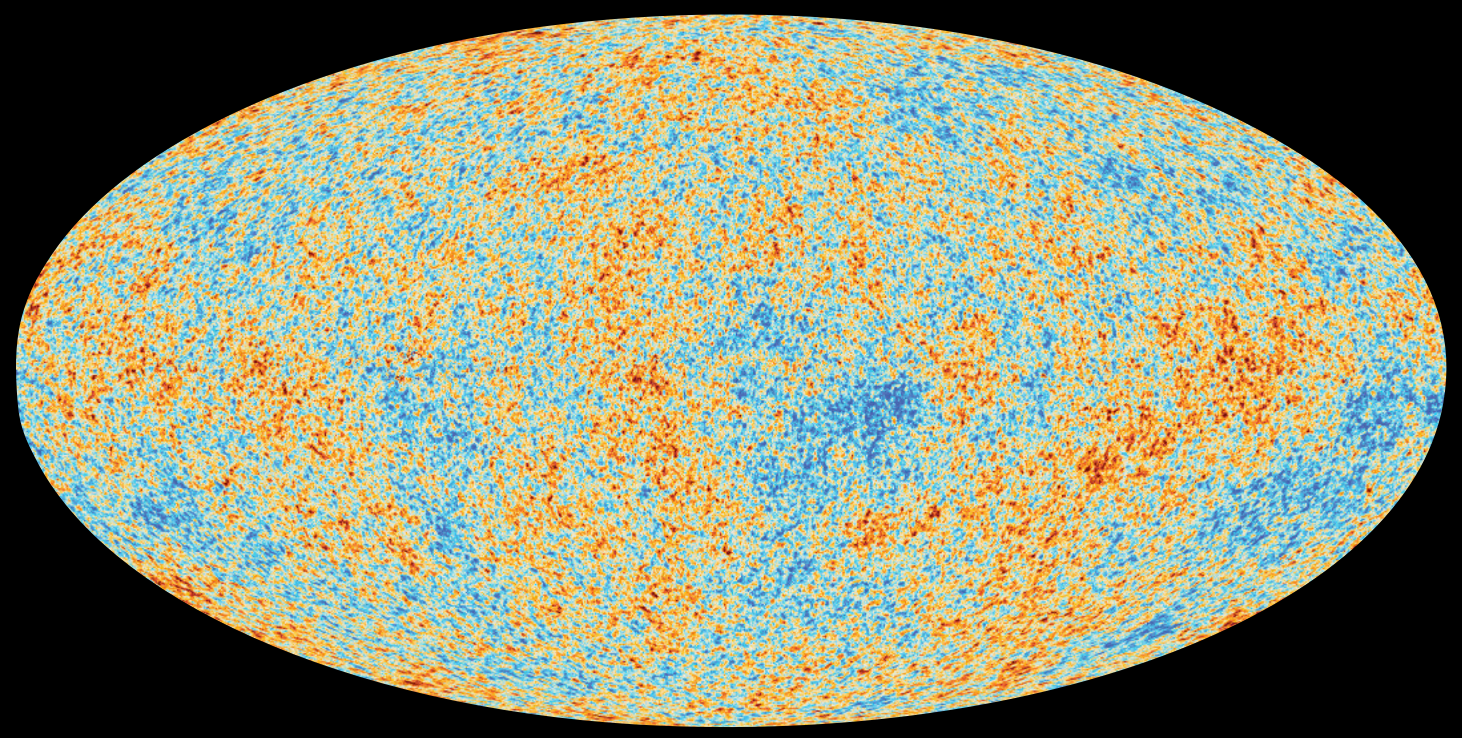
supernova neutrinos
- ★ death throes of massive stars
- ★ nucleosynthesis
- ★ matter under extreme conditions



high-*E* neutrinos
- ★ origin of cosmic rays
- ★ AGNs, blazars, MW

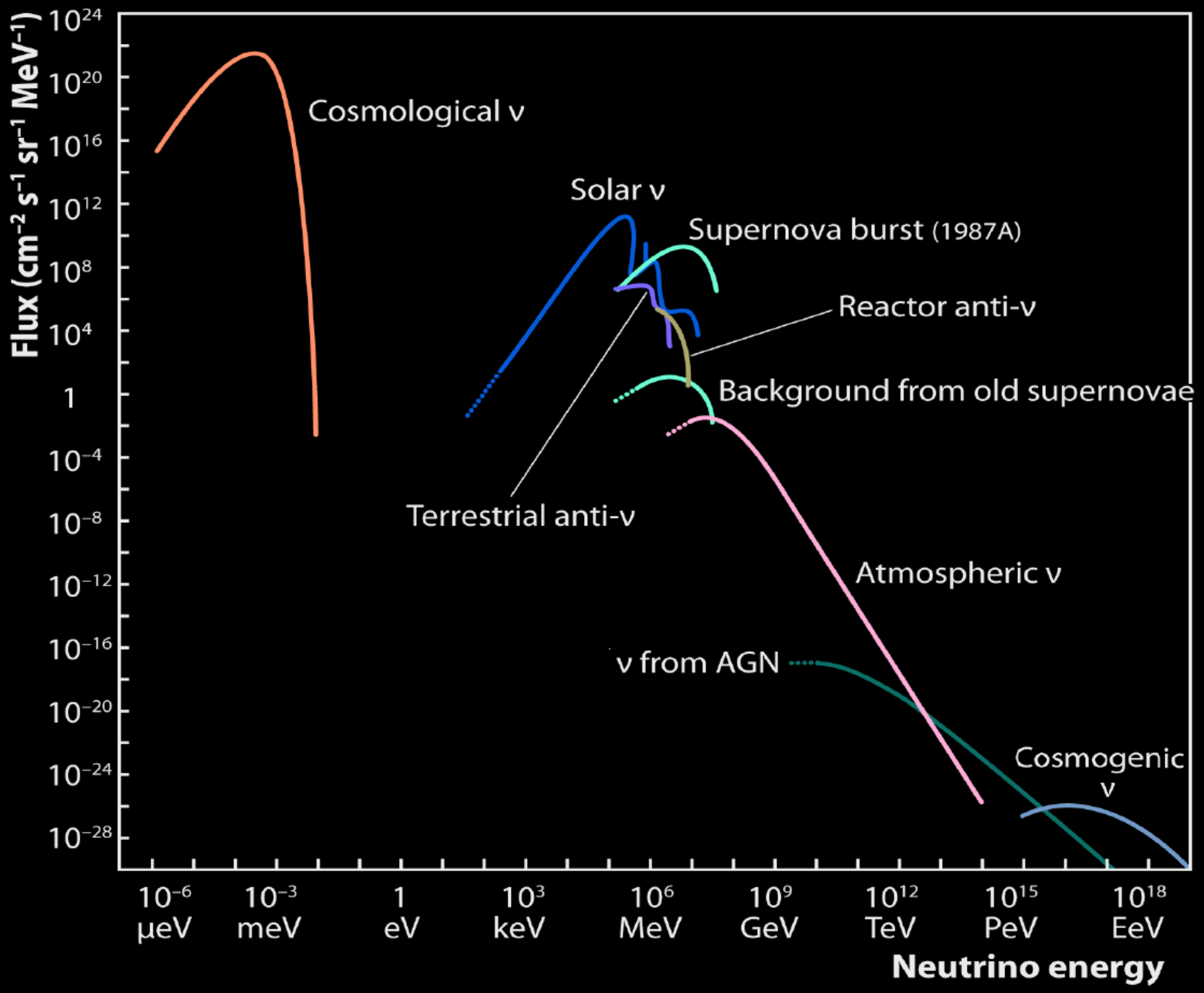
neutron stars
- ★ common-envelope systems
- ★ muon decays





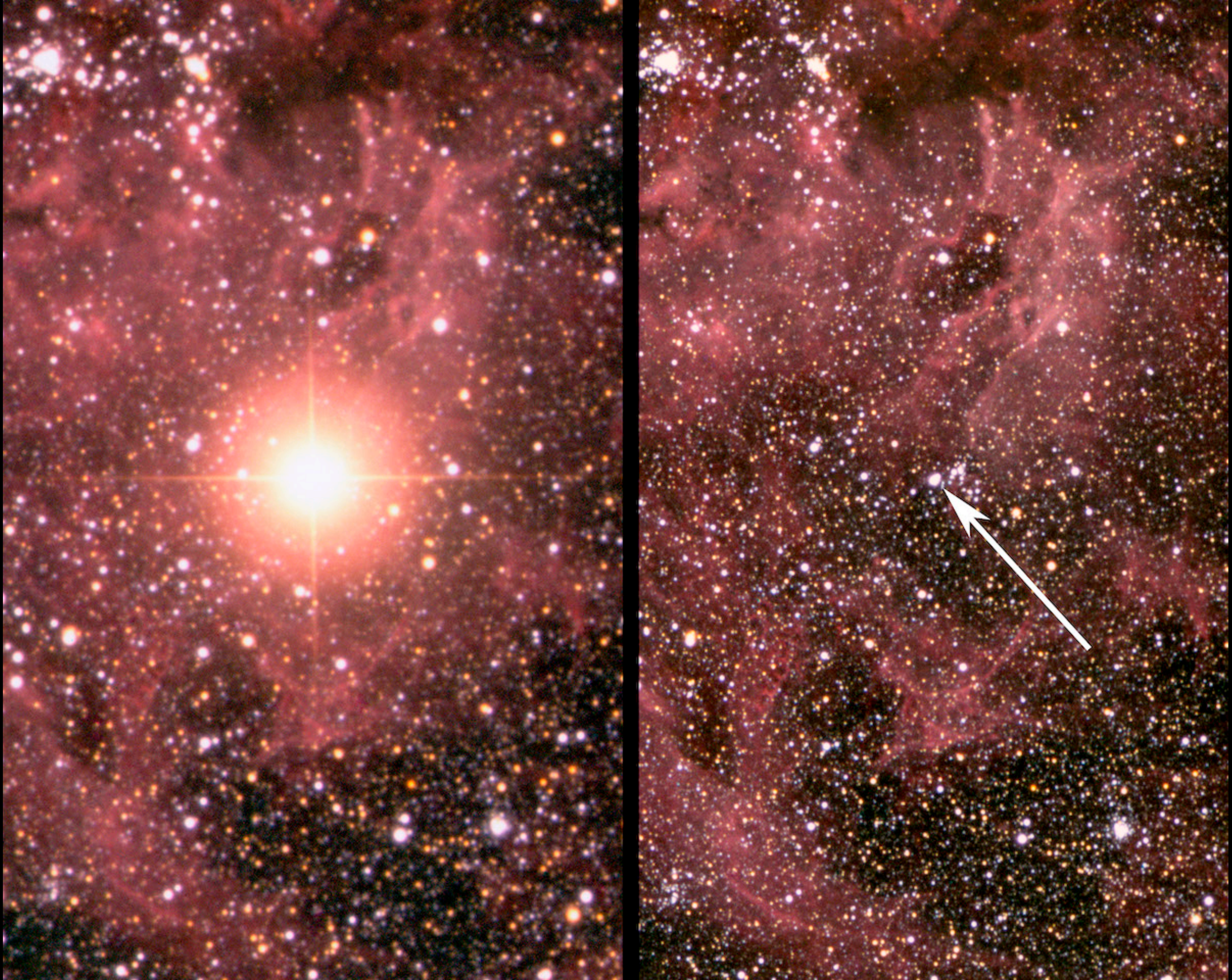
cosmology
- ★ early Universe

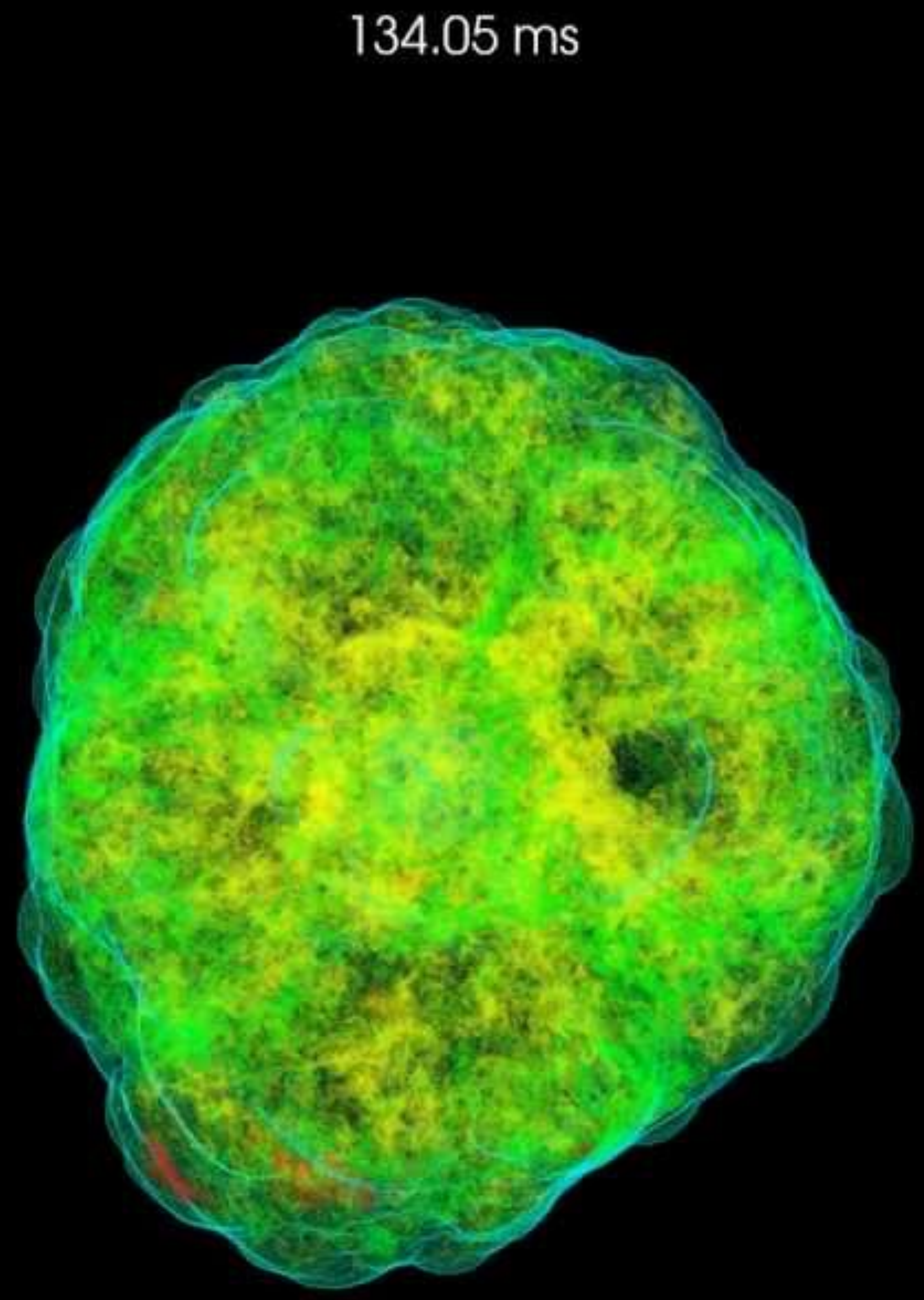
Neutrinos as Astrophysical Messengers



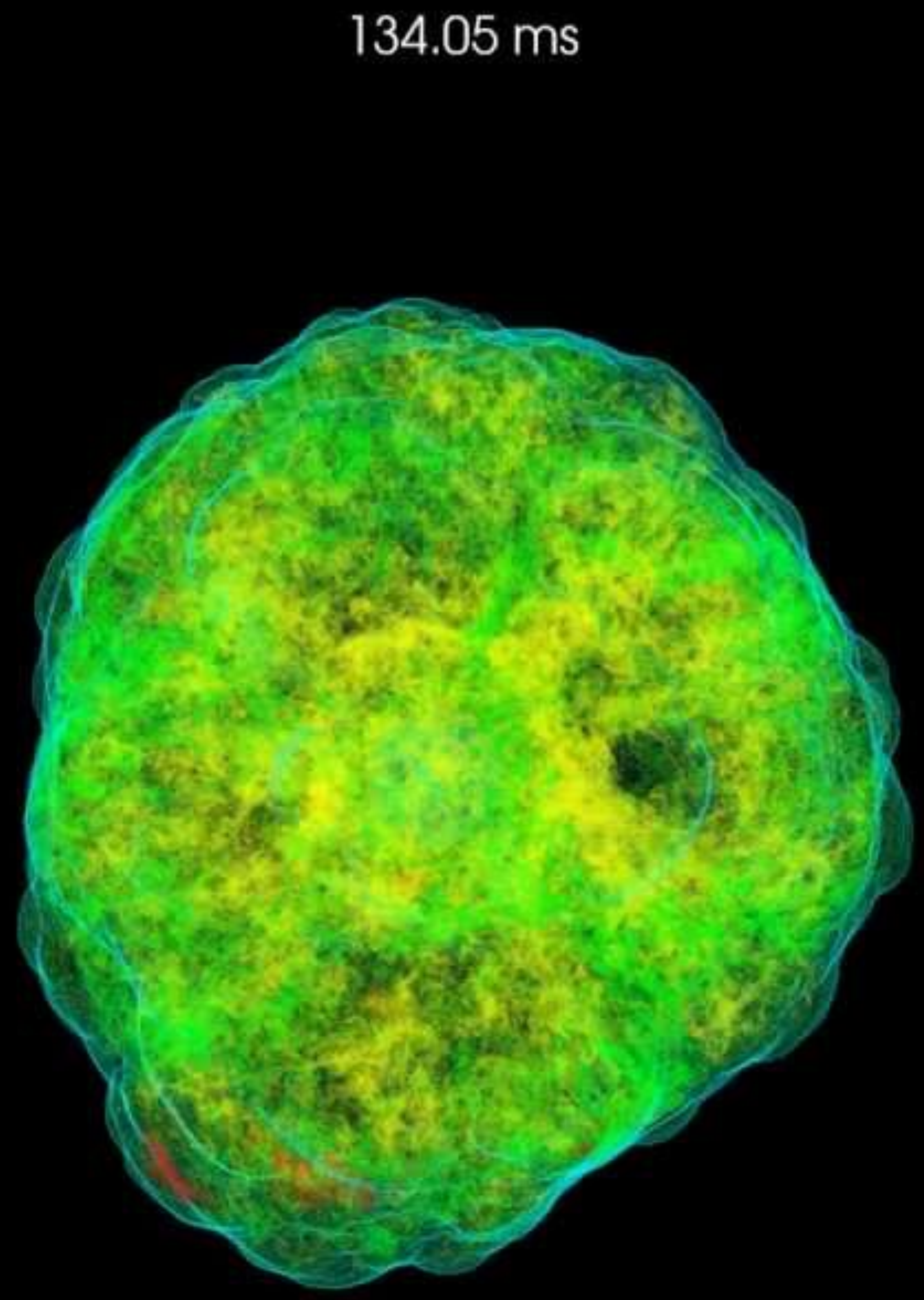
Supernovae

CERN Neutrino PLATFORM QUANTUM TECHNOLOGY INITIATIVE JOHANNES GUTENBERG UNIVERSITÄT MAINZ





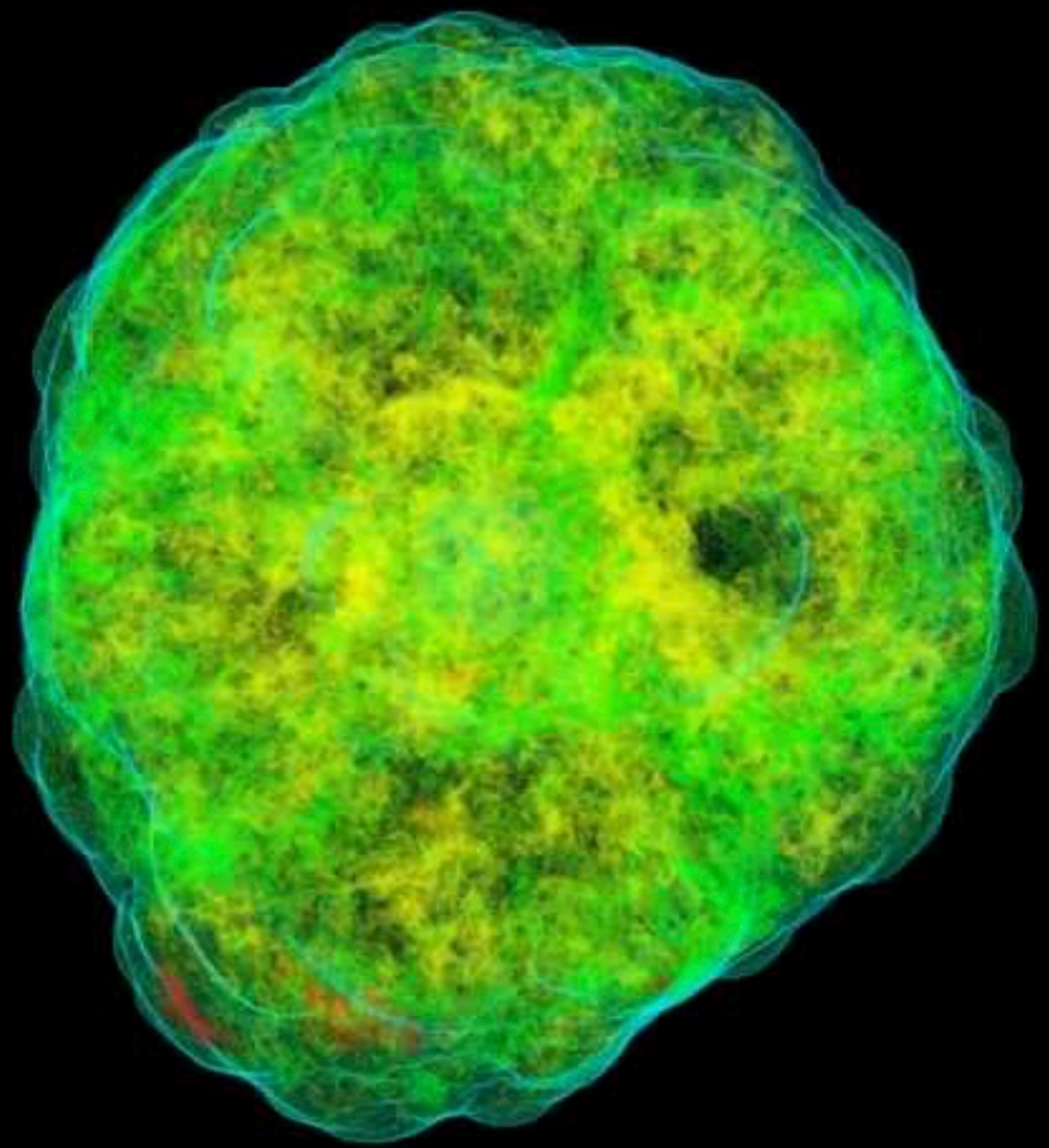
SXS Collaboration, Christian Ott *et al.*



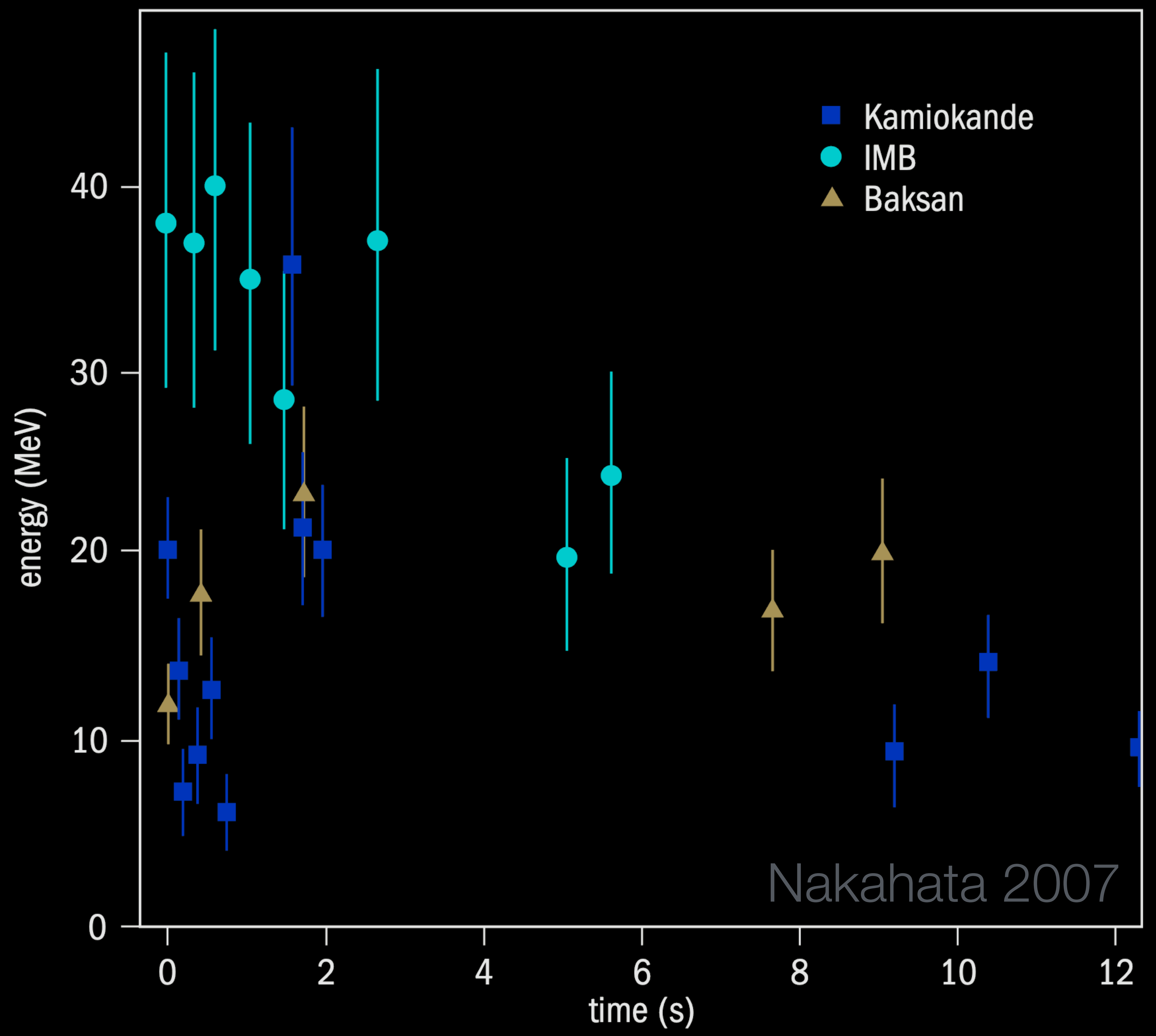
SXS Collaboration, Christian Ott *et al.*

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

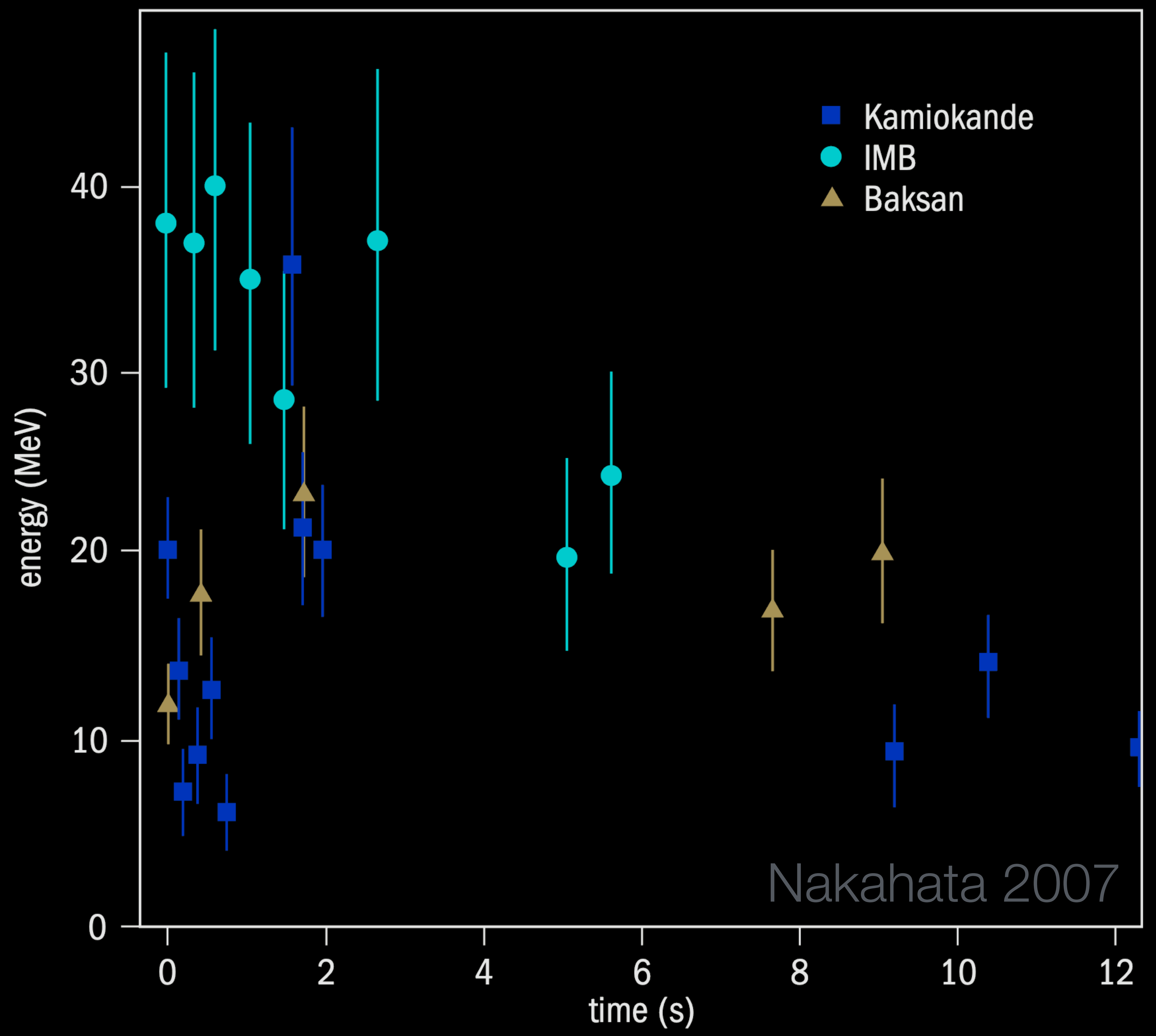


Supernova Neutrinos



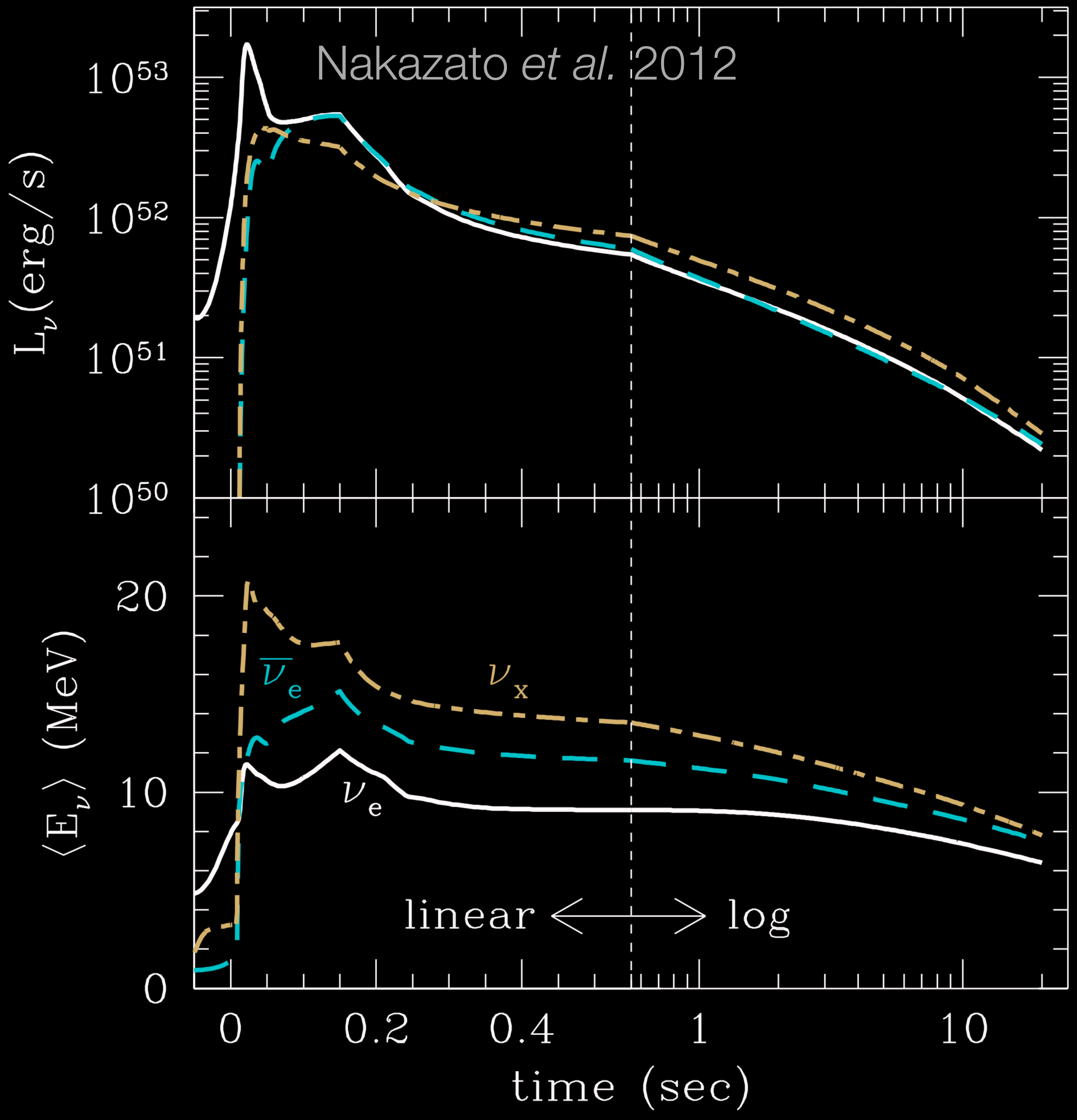
Supernova Neutrinos

- SN 1987A
  - 25 neutrino events



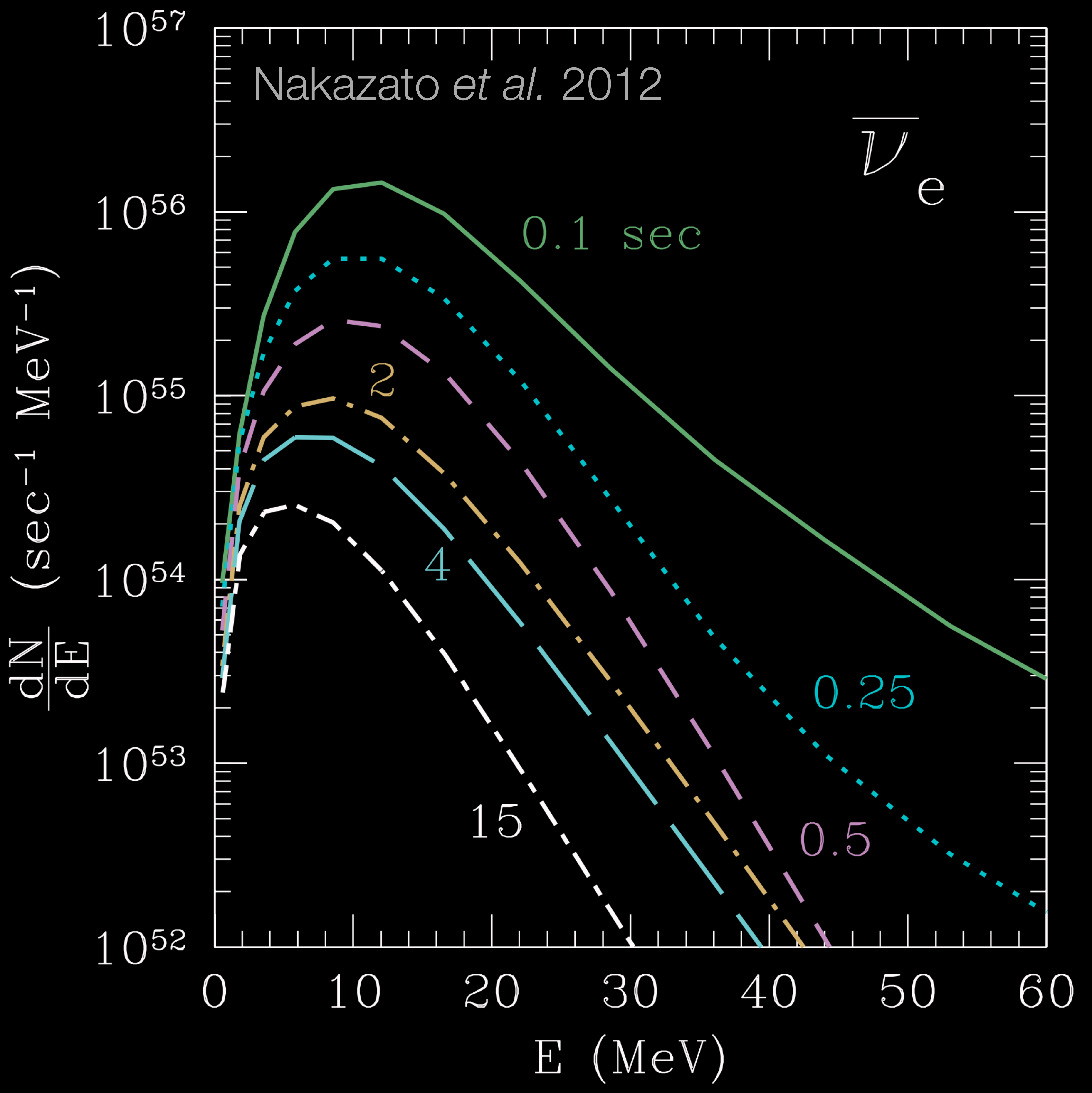
Supernova Neutrinos

- 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, …



Ultra-High Energy Neutrinos

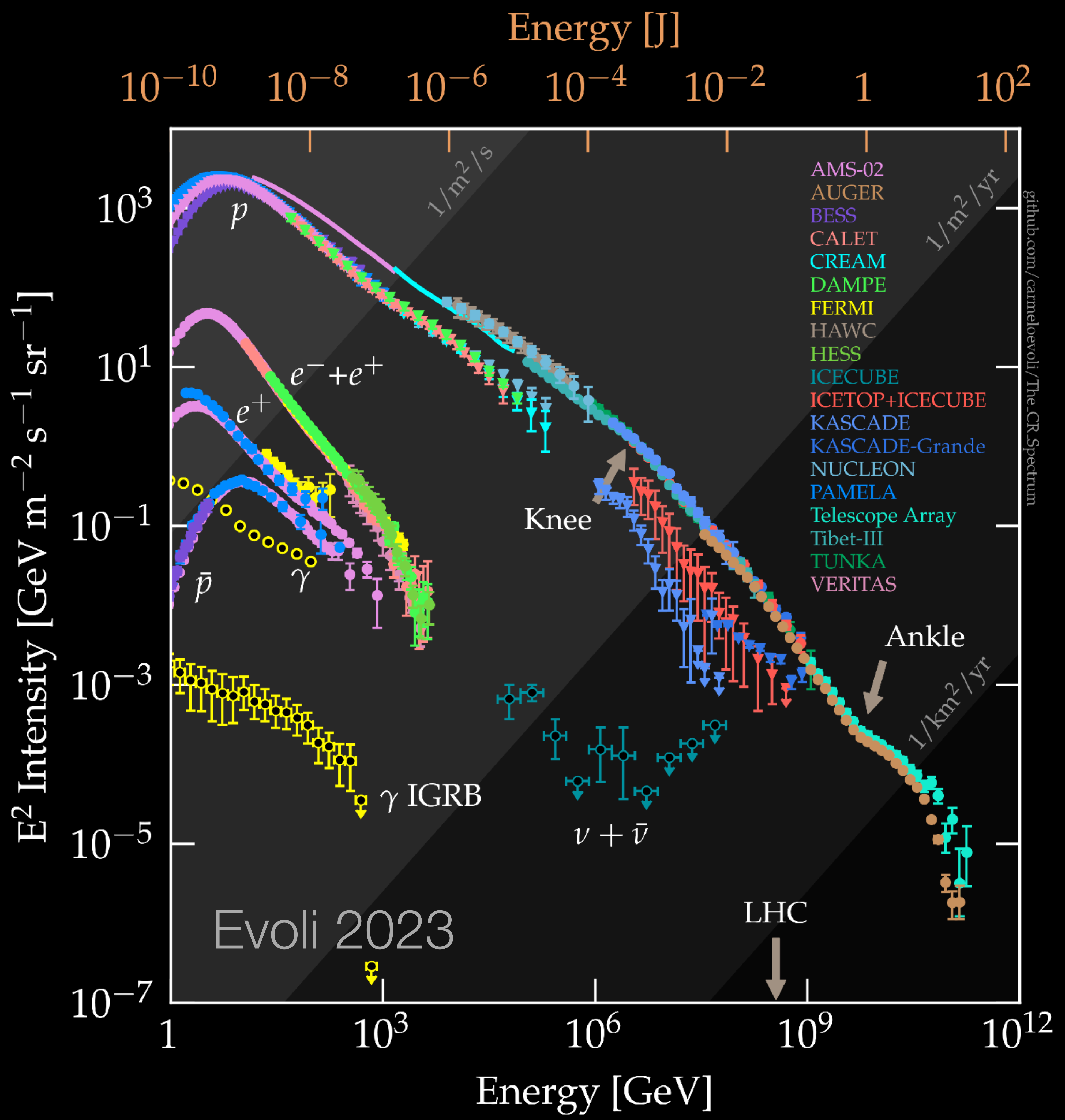
CERN

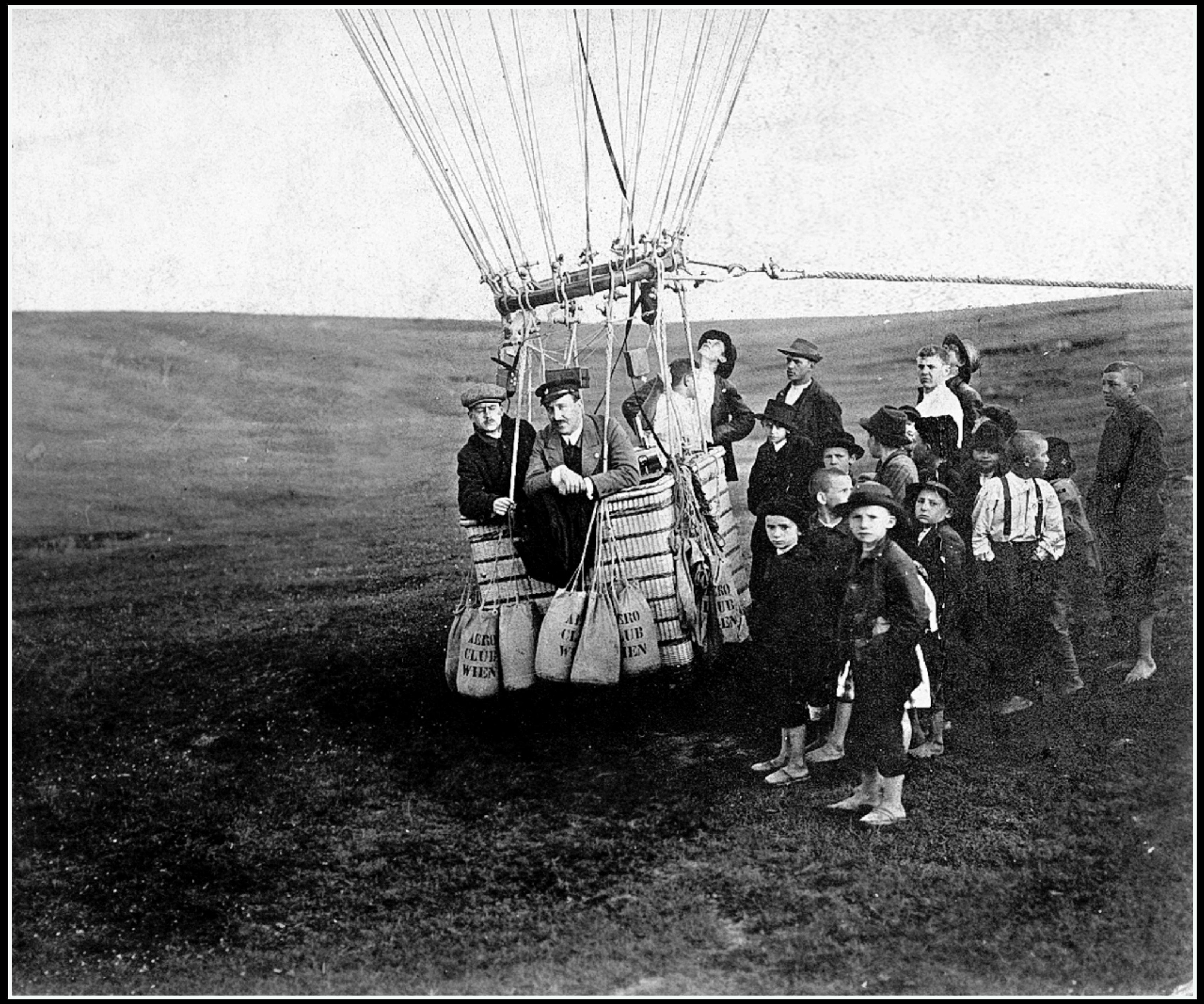
Neutrino PLATFORM

QUANTUM TECHNOLOGY INITIATIVE

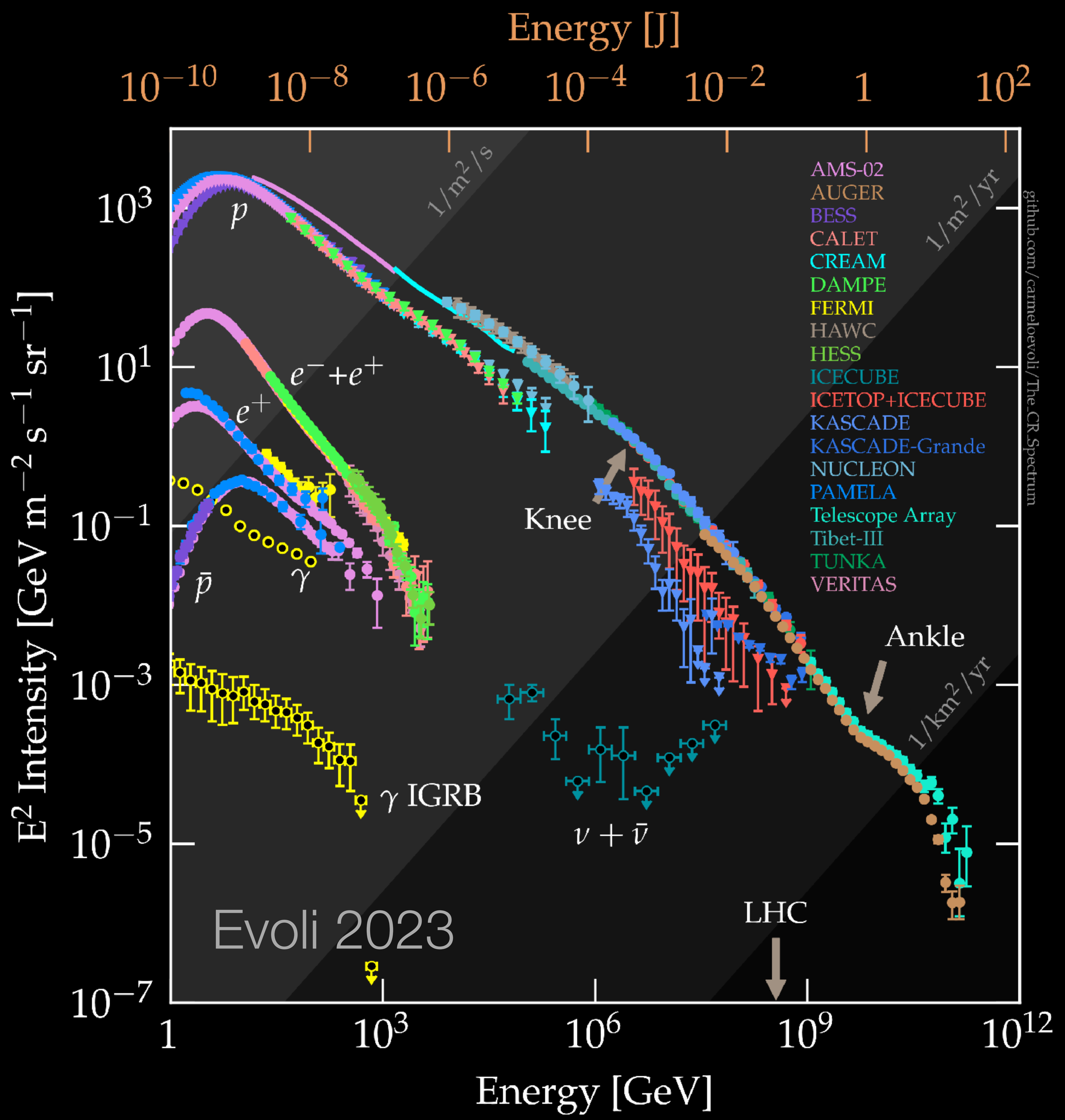
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

High Energy Neutrinos and Cosmic Rays

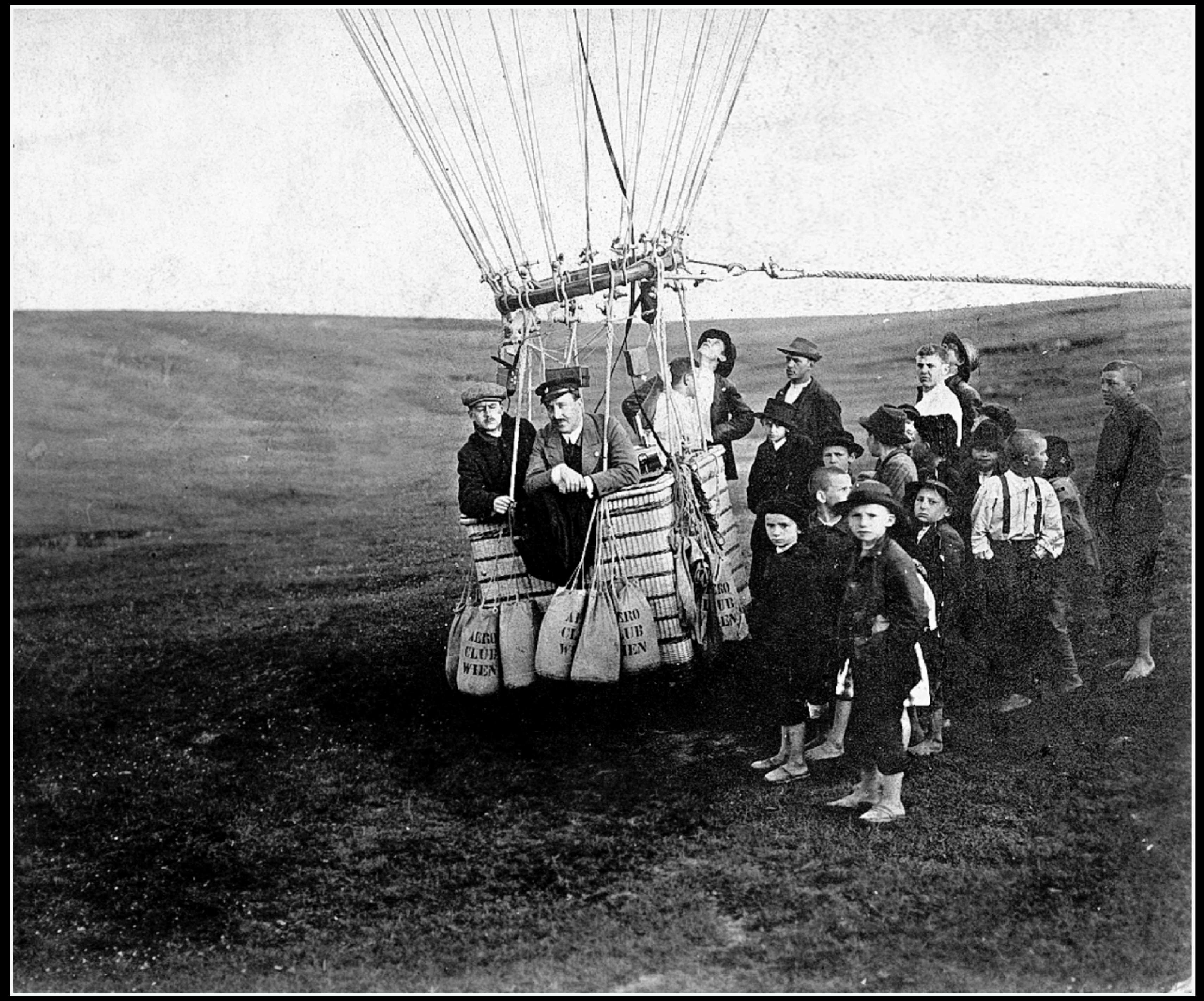




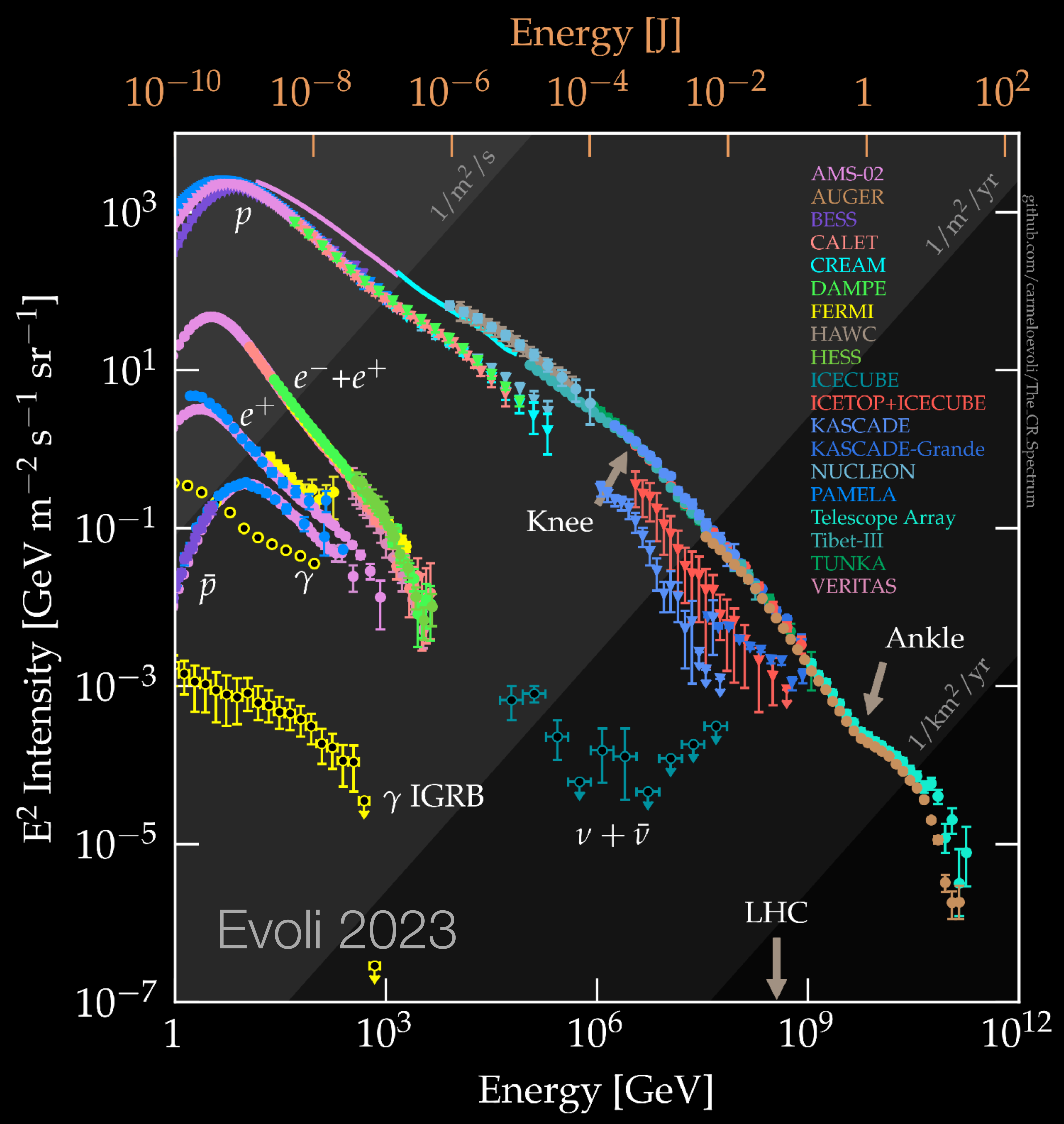
High Energy Neutrinos and Cosmic Rays



- discovered by Victor Hess in 1912

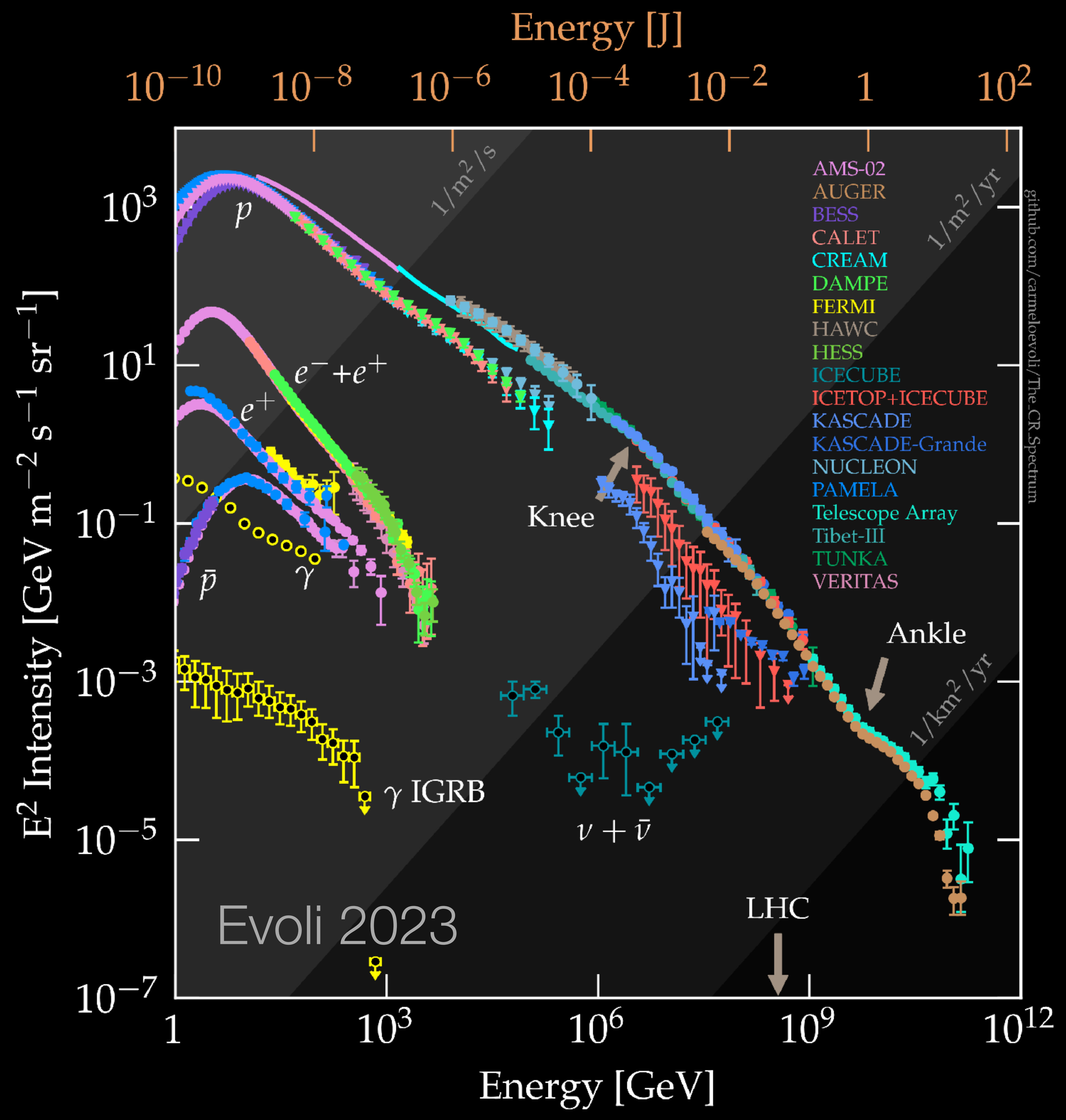


High Energy Neutrinos and Cosmic Rays



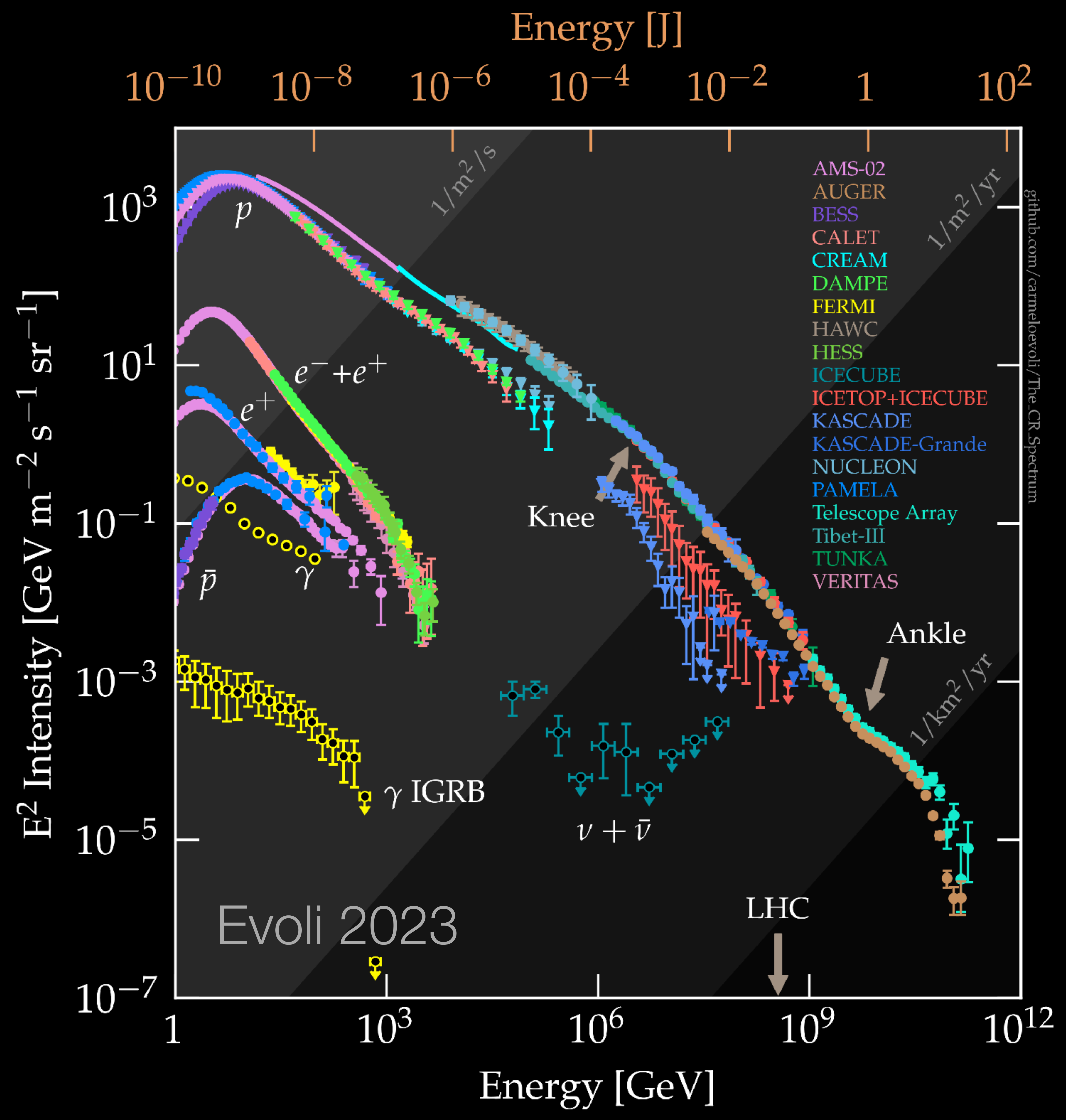
- discovered by Victor Hess in 1912
- origin still not fully understood today

High Energy Neutrinos and Cosmic Rays

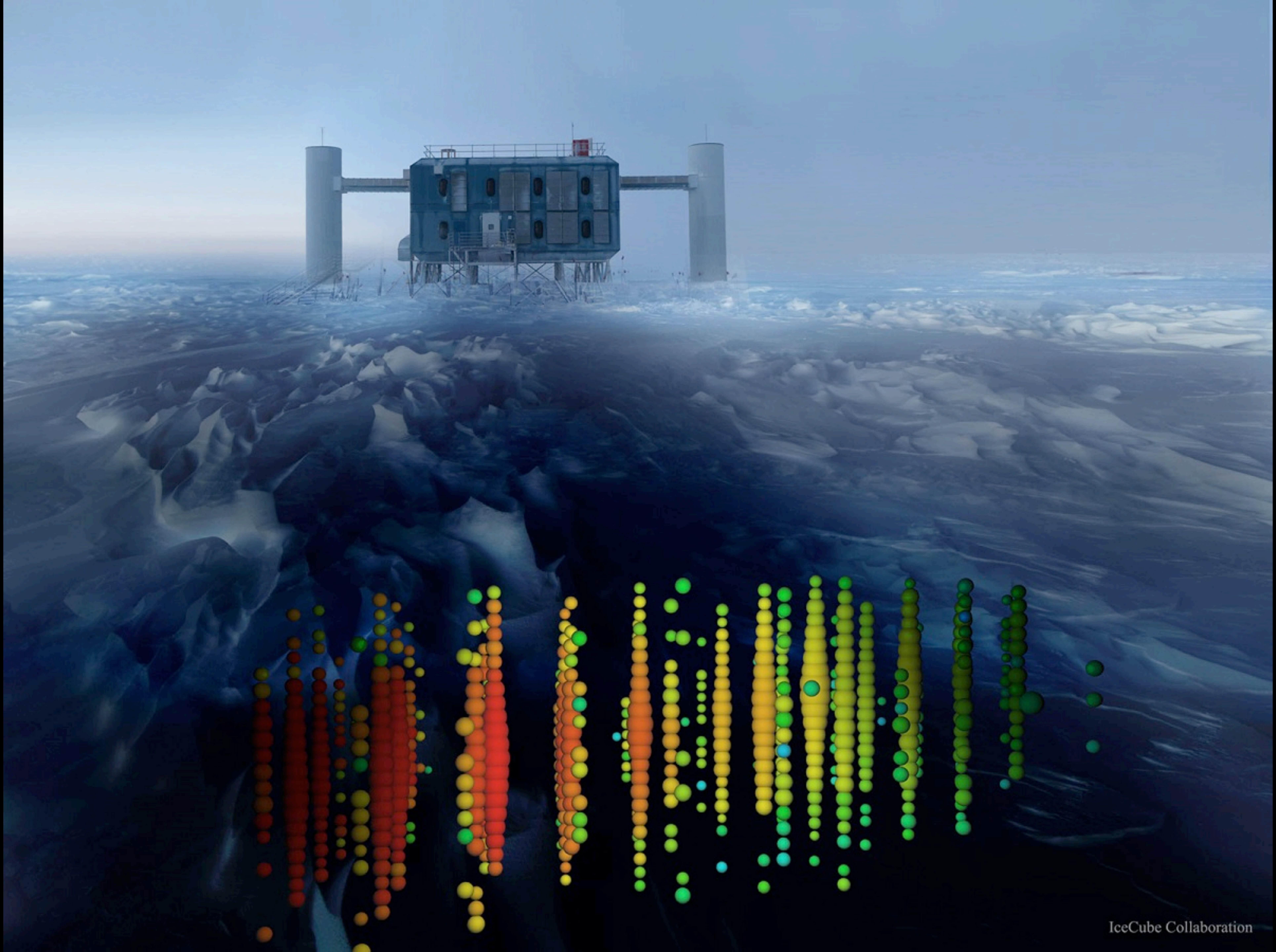


- discovered by Victor Hess in 1912
- origin still not fully understood today
- neutrinos to the rescue!
  - protons accelerated in astrophysical magnetic fields
  - some protons hit ambient hydrogen gas
  - production of pions, which decay to neutrinos
  - look for these neutrinos!

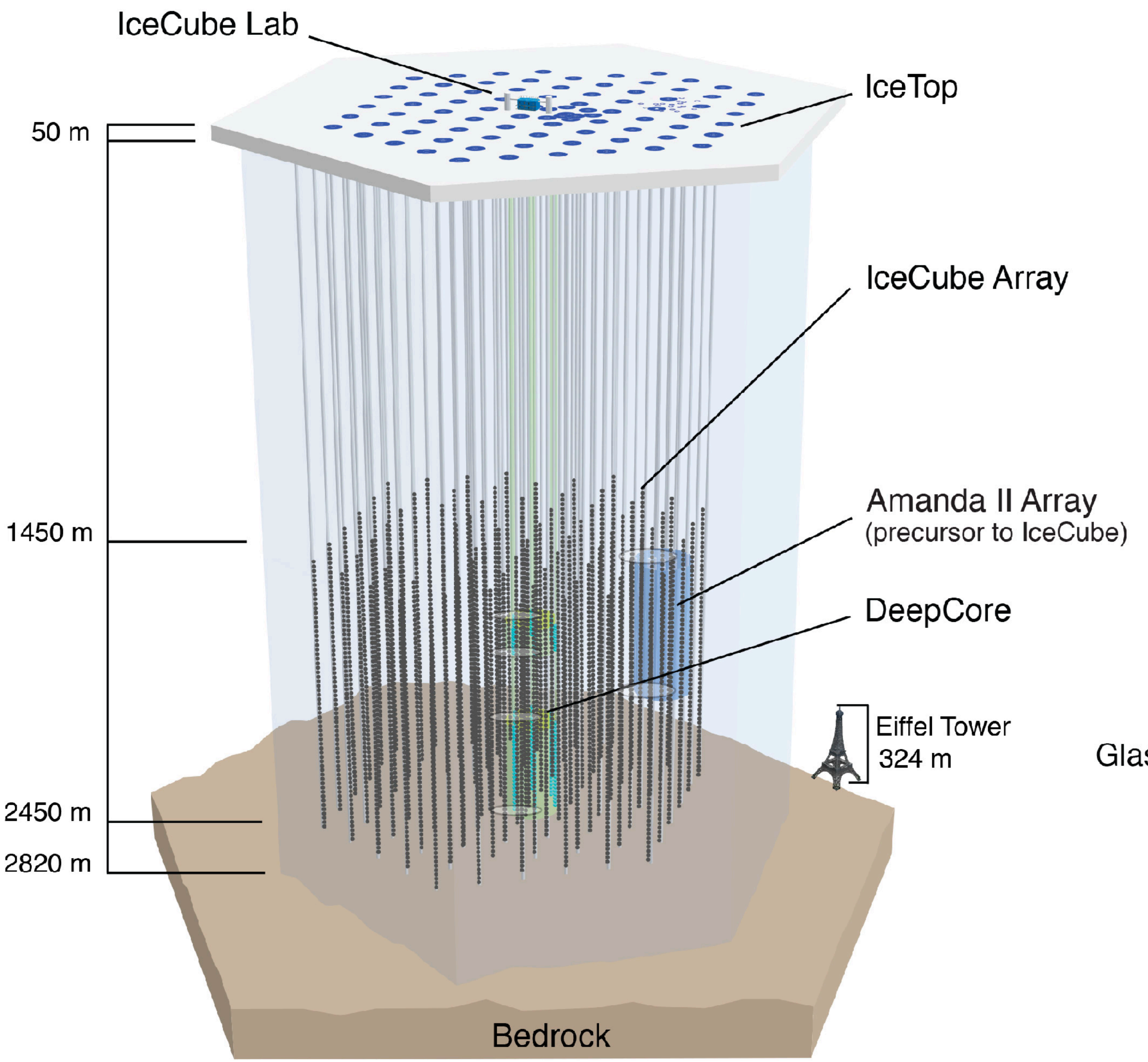
High Energy Neutrinos and Cosmic Rays

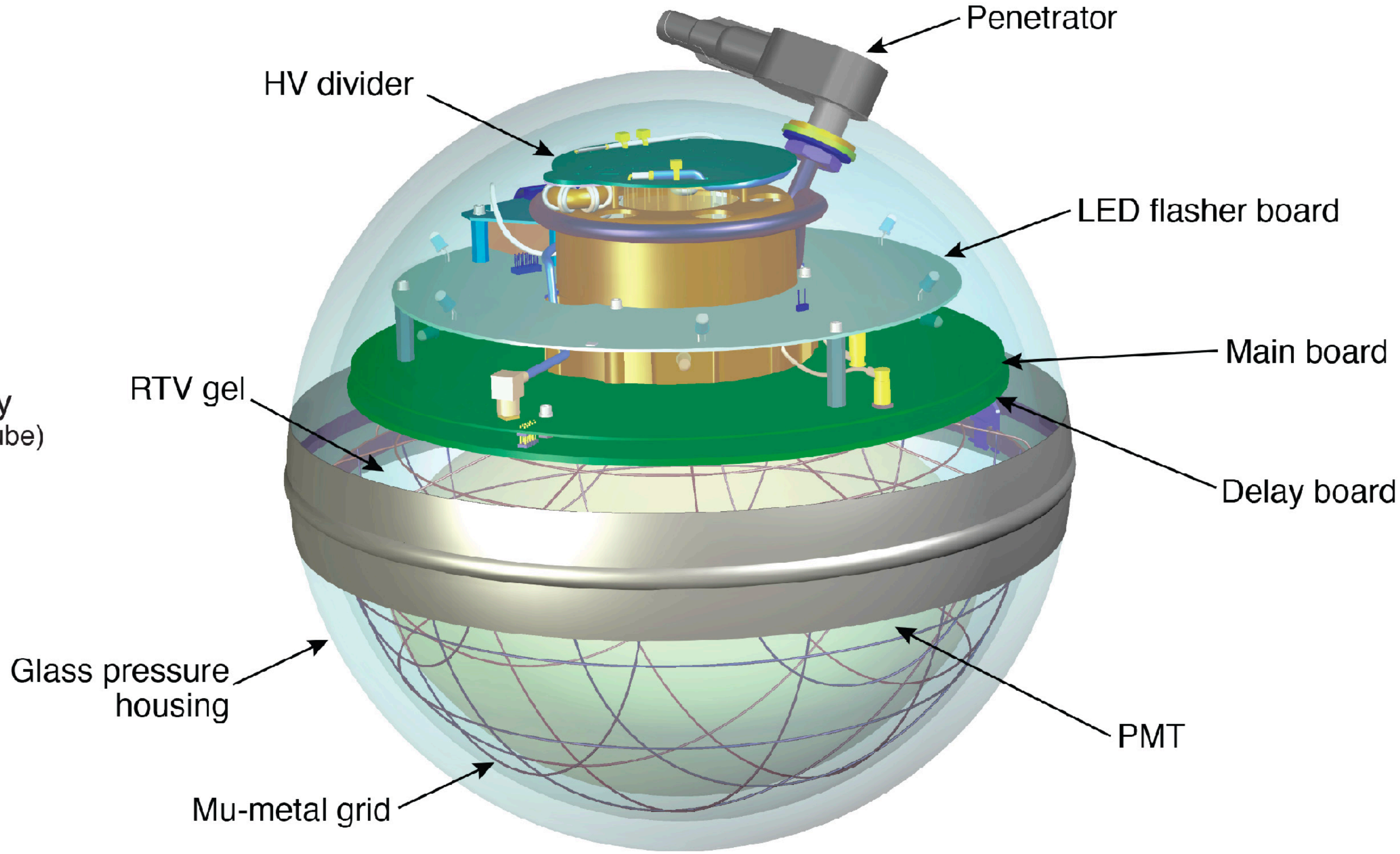


- discovered by Victor Hess in 1912
- origin still not fully understood today
- neutrinos to the rescue!
  - protons accelerated in astrophysical magnetic fields
  - some protons hit ambient hydrogen gas
  - production of pions, which decay to neutrinos
  - look for these neutrinos!
- advantages:
  - neutrinos are not absorbed
  - neutrinos are not deflected
    ➠ point back to the source


IceCube Collaboration

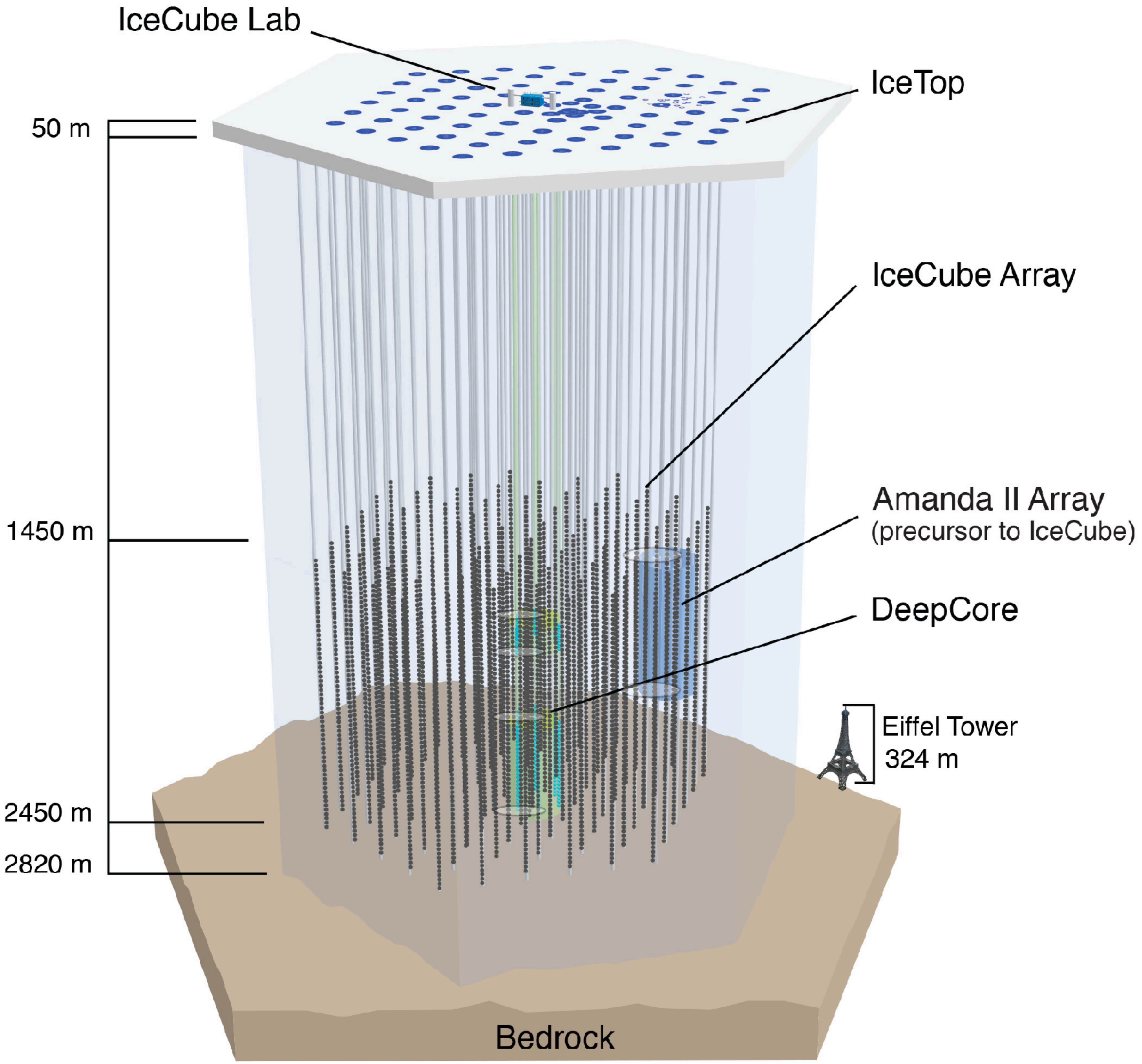
The IceCube Detector at the South Pole



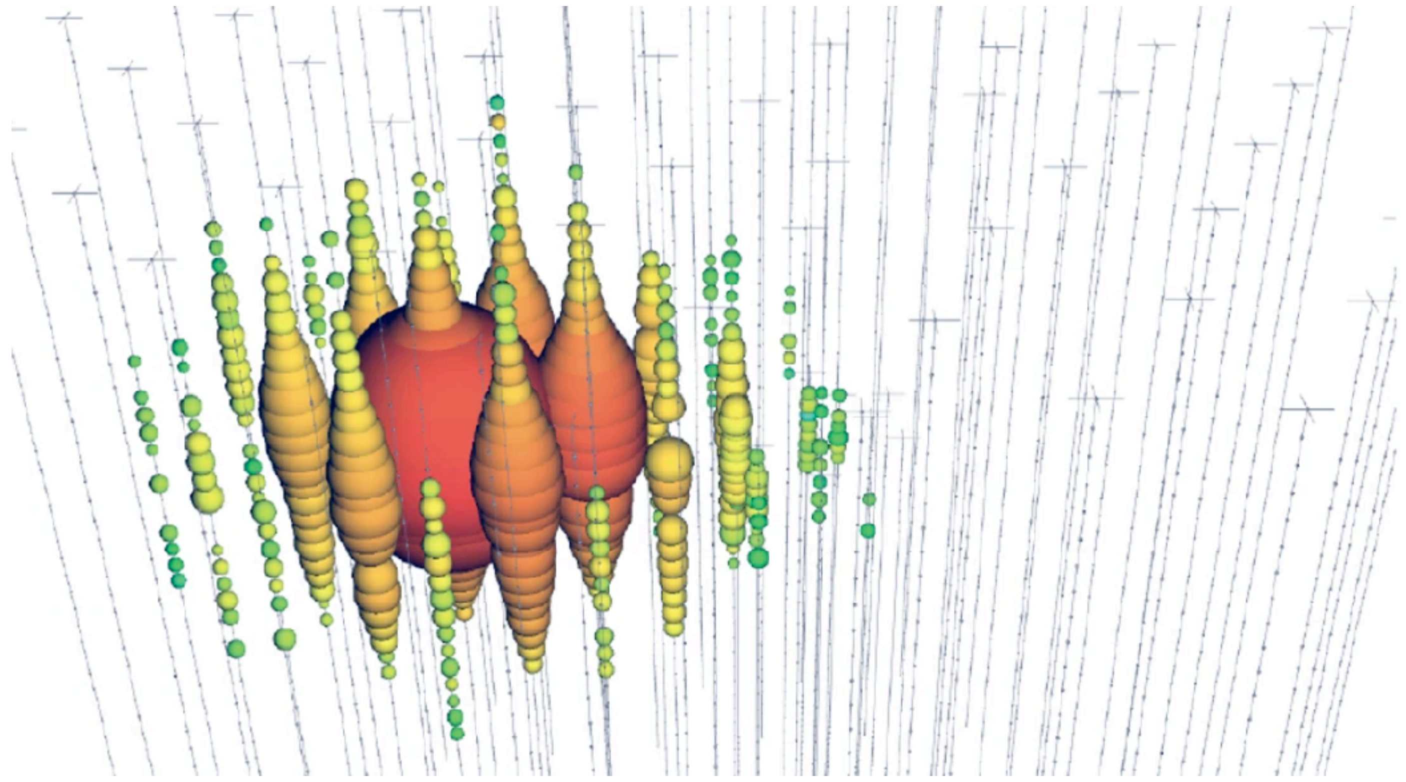


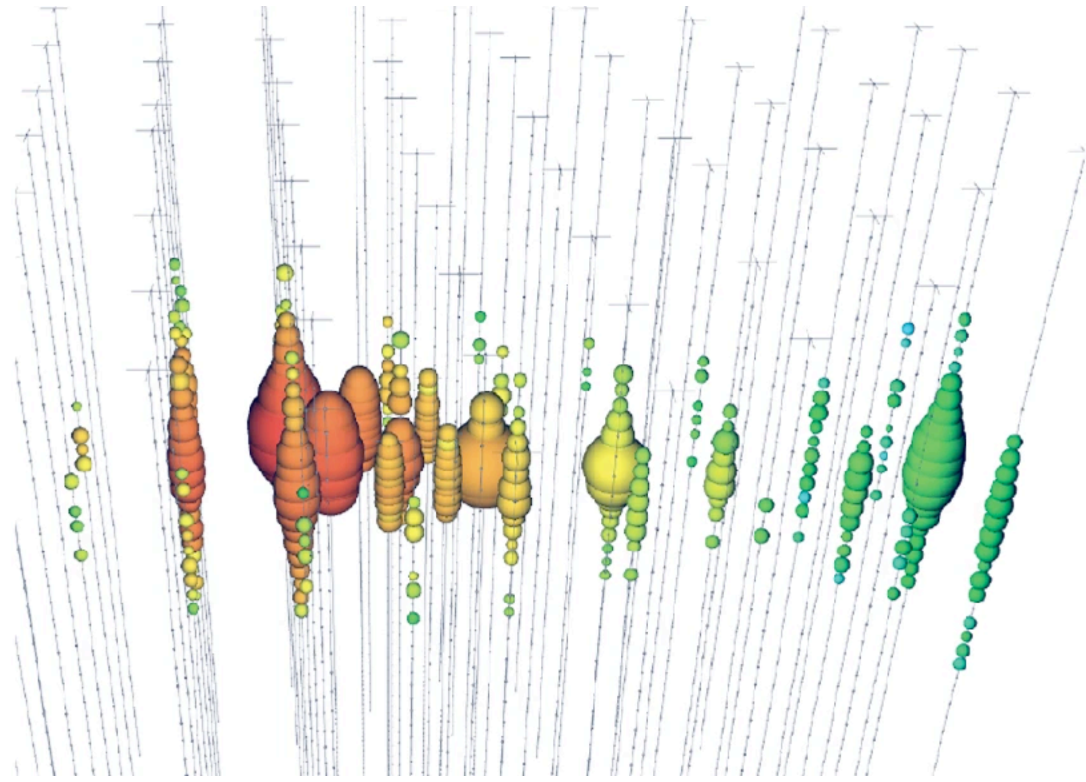
Halzen Kheirandish 2022

The IceCube Detector at the South Pole



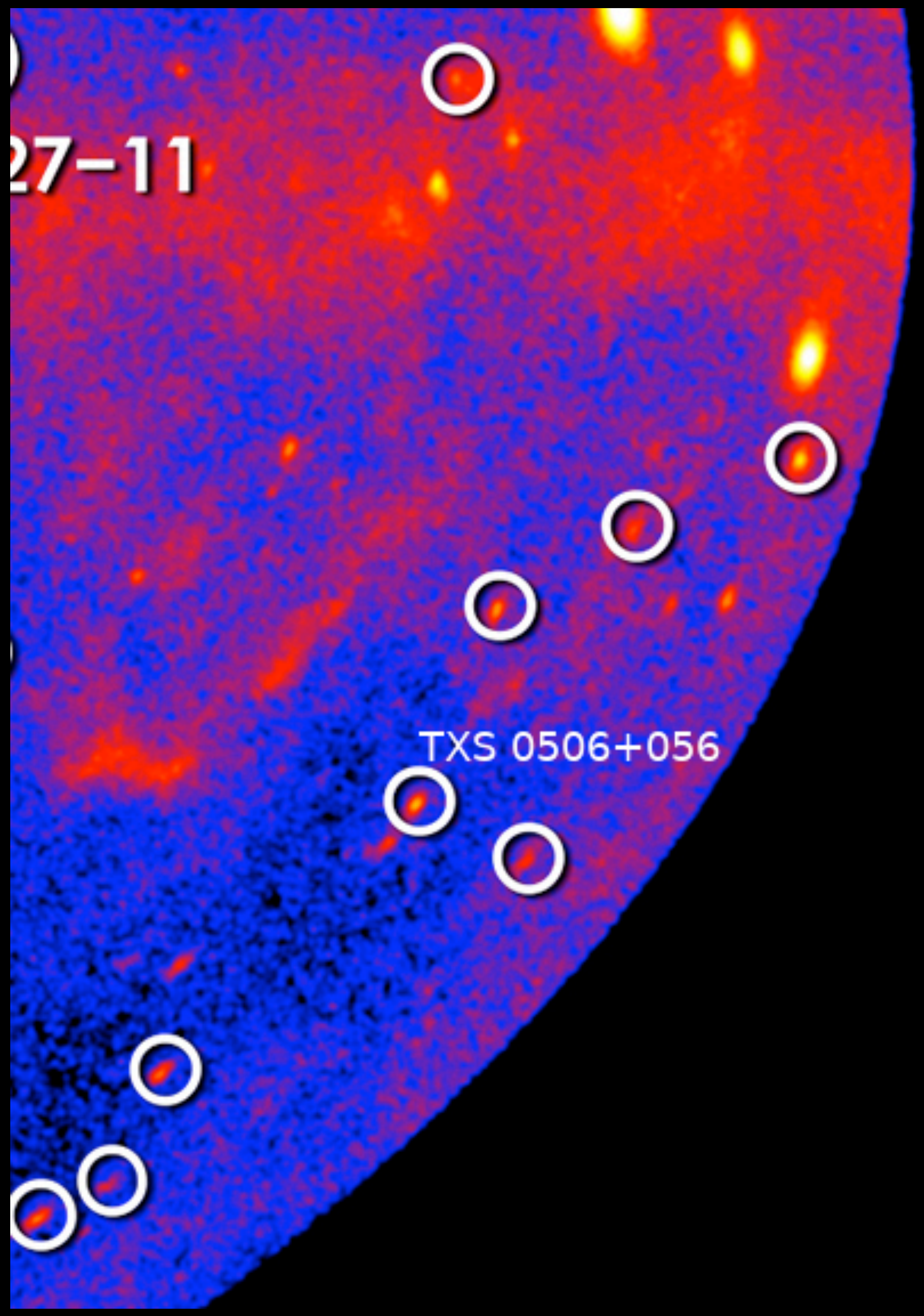
- detection via Čerenkov effect
- 4D event information
  (PMT locations + timing)
- main event categories:
  - showers: near-spherical blob (ν_e, ν_τ, NC)
  - tracks: elongated energy deposit (ν_μ)
    (contained tracks, starting tracks, throughgoing tracks)



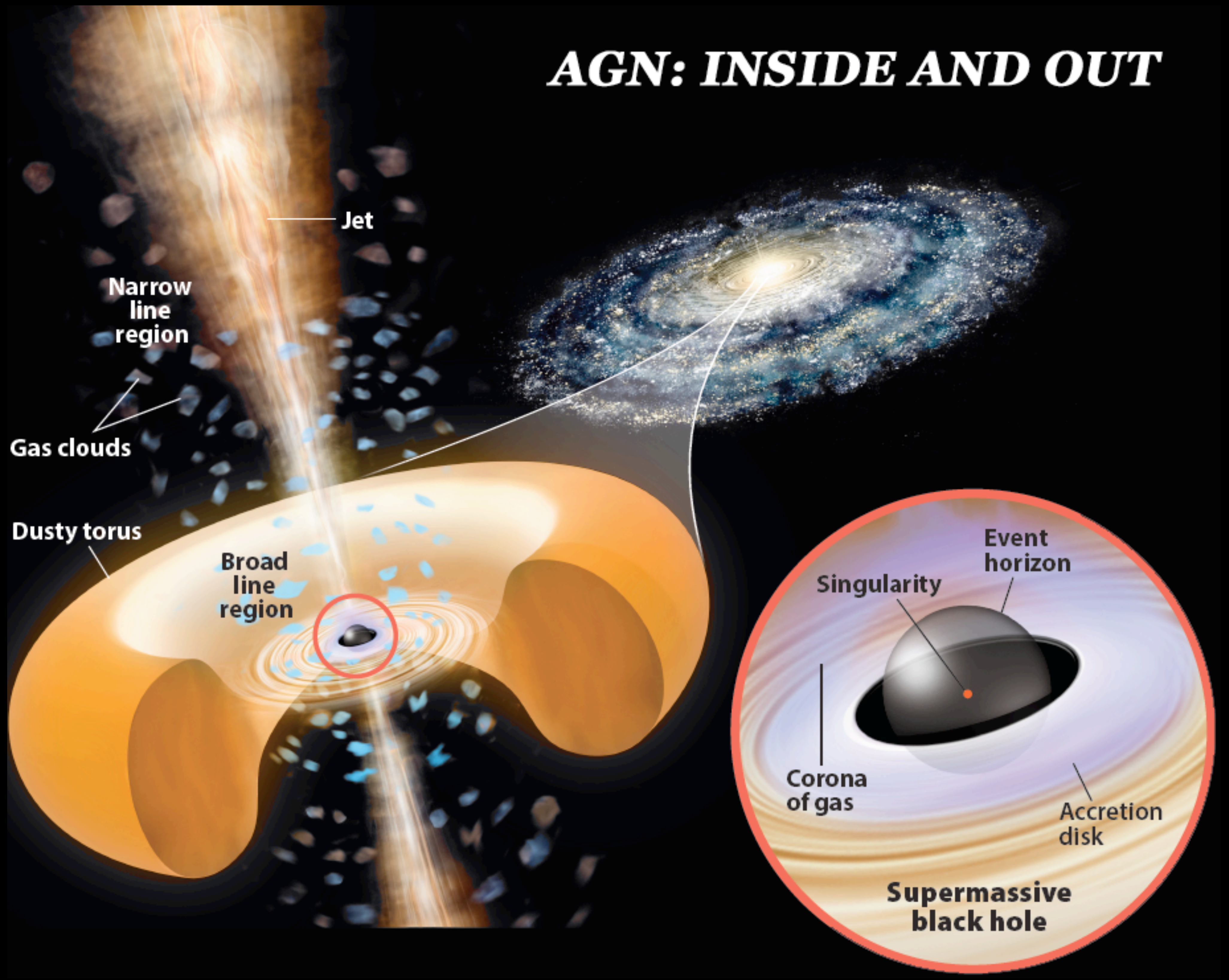


Neutrino Point Sources

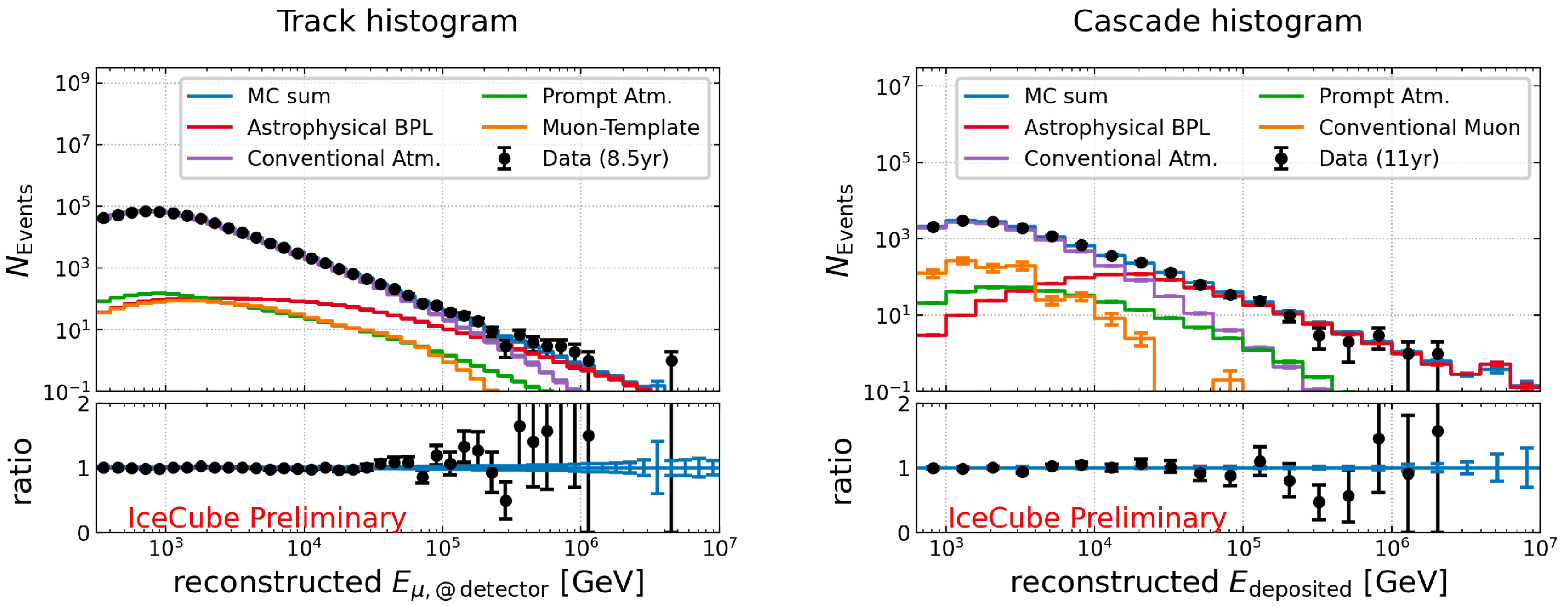
Blazar TXS 0506+065



Active Galactic Nucleus of M77



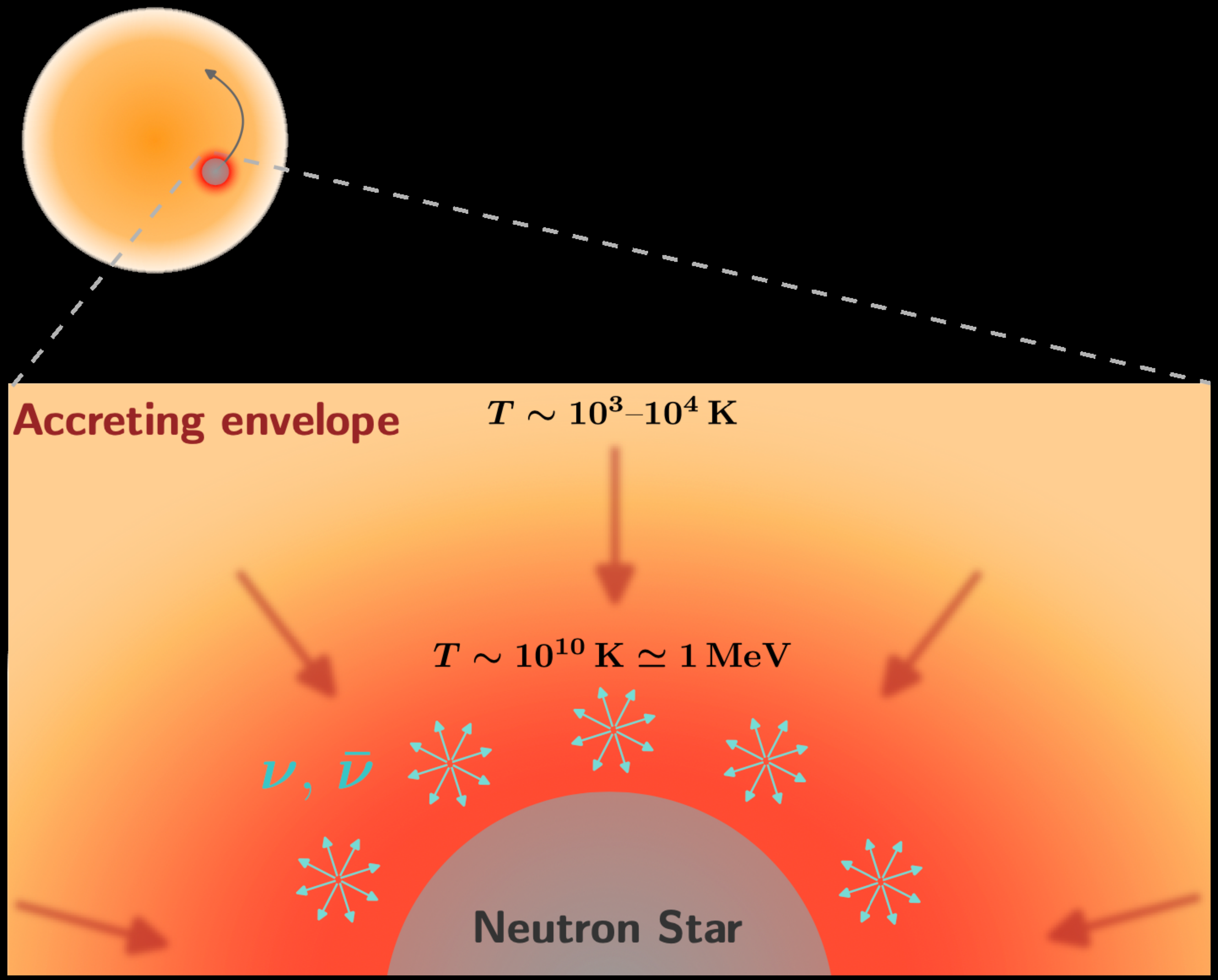
Diffuse Astrophysical Neutrinos



Naab Ganster Zhang (on behalf of IceCube), 2023

Neutron Stars

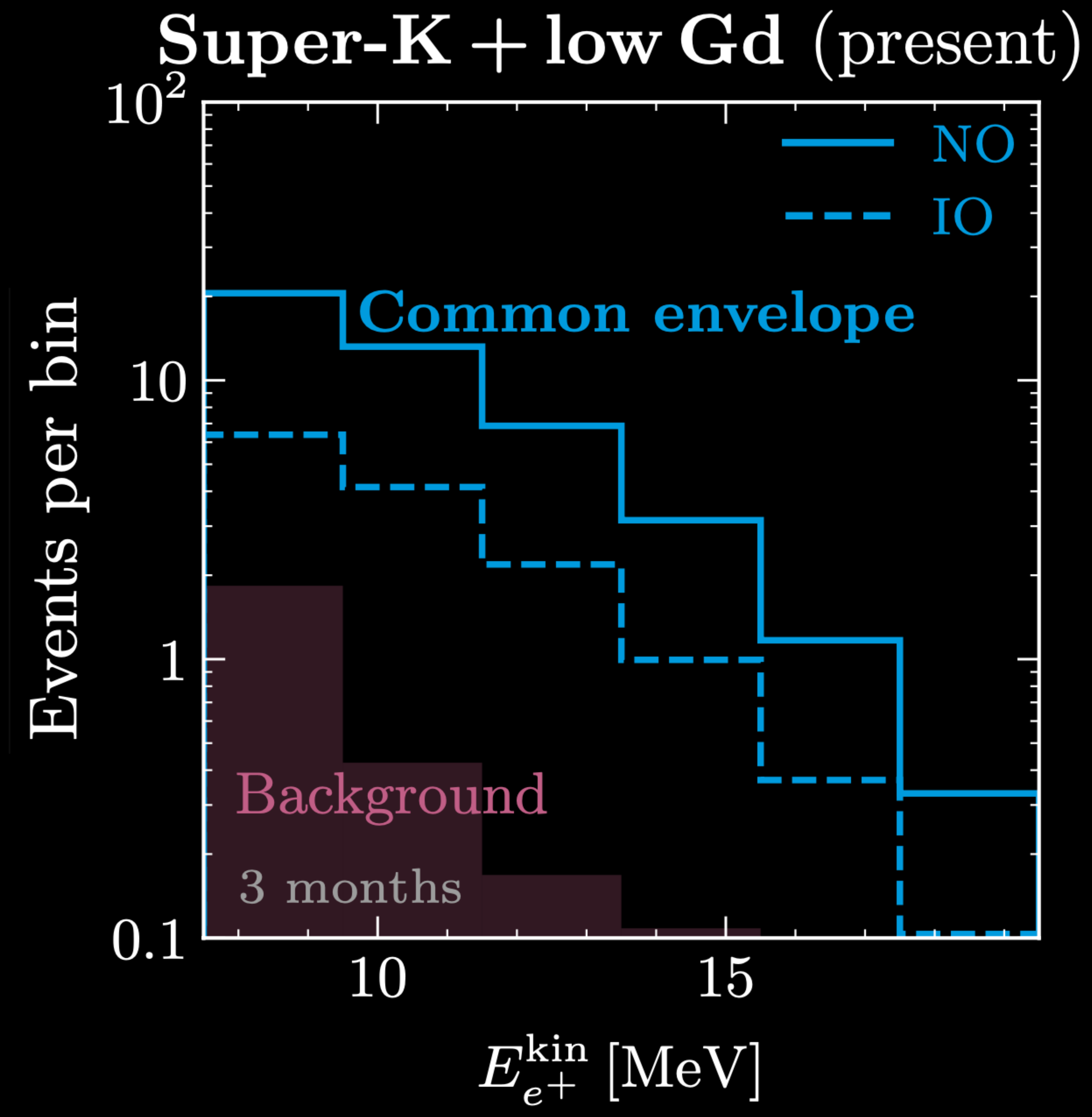
Common-Envelope Evolution



- neutron star enters companion star
- gigantic accretion rates
  (up to 0.1 $M_\odot$/yr for several months)
- only cooling channel is via neutrinos
  ➠ new type of neutrino source
- in addition: de-protonization
- rate < core collapse SN rate

Beacom Esteban JK *in preparation*

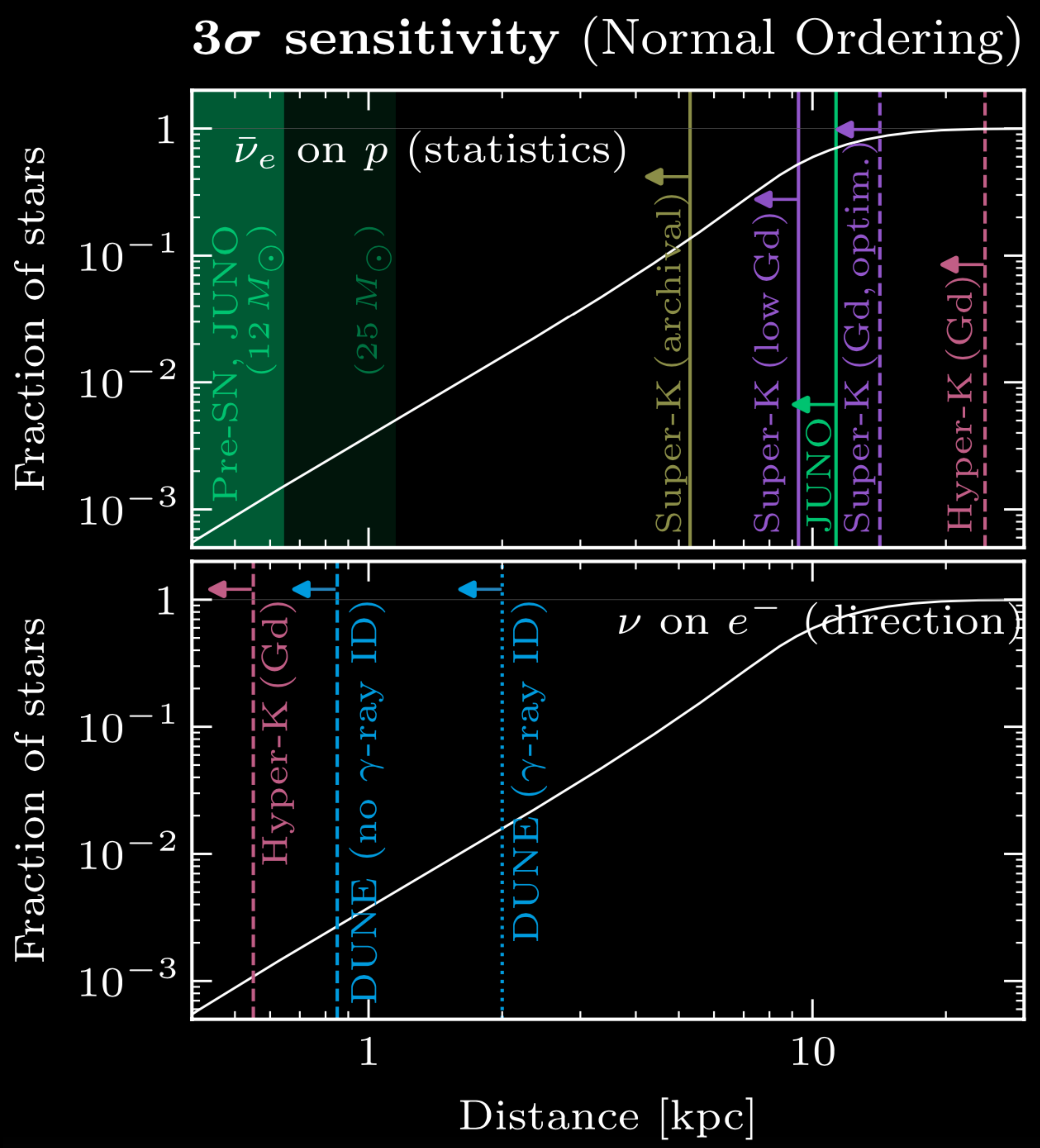
Common-Envelope Evolution



- neutron star enters companion star
- gigantic accretion rates
  (up to 0.1 M☉/yr for several months)
- only cooling channel is via neutrinos
  ➠ new type of neutrino source
- in addition: de-protonization
- rate < core collapse SN rate

Beacom Esteban JK *in preparation*

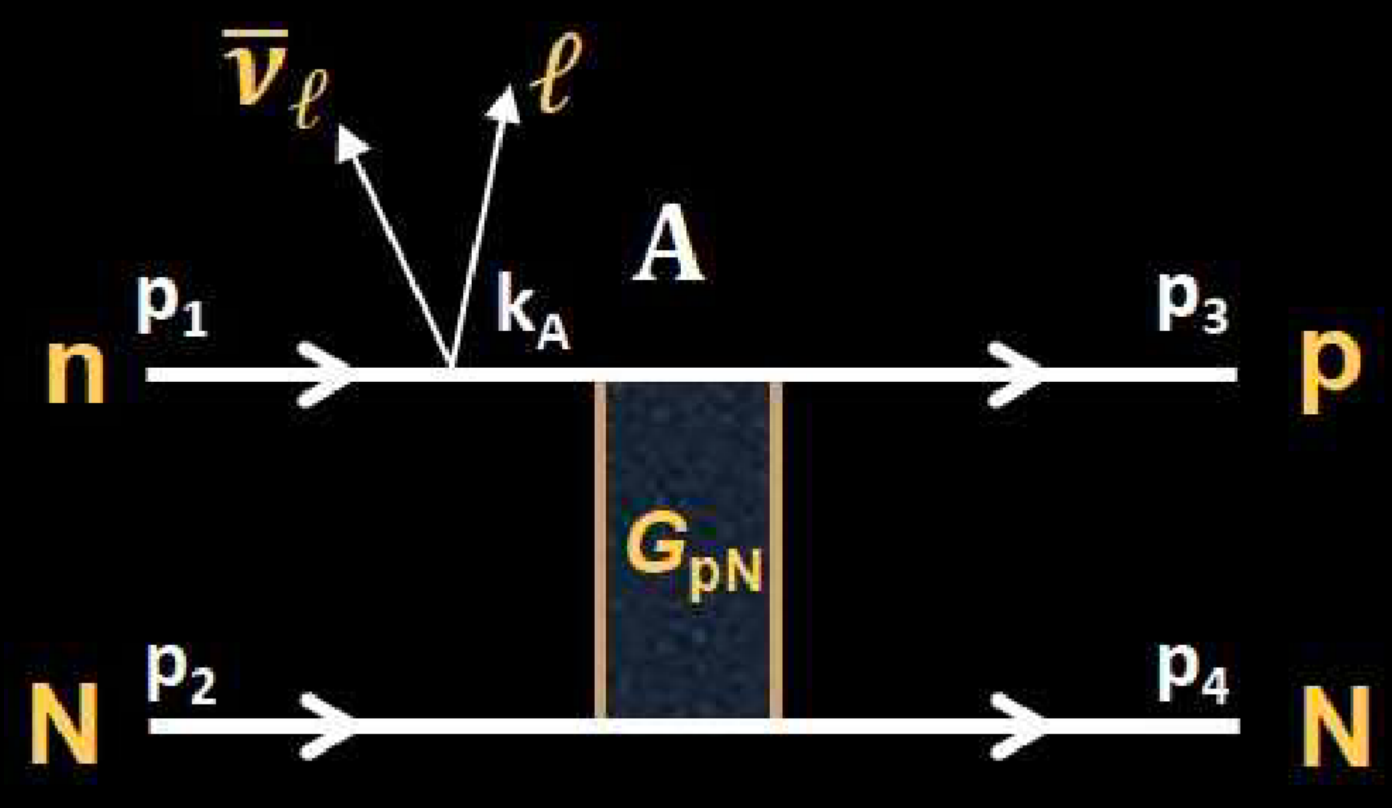
Common-Envelope Evolution



- neutron star enters companion star
- gigantic accretion rates
  (up to 0.1 $M_\odot$/yr for several months)
- only cooling channel is via neutrinos
  ➠ new type of neutrino source
- in addition: de-protonization
- rate < core collapse SN rate

Beacom Esteban JK *in preparation*

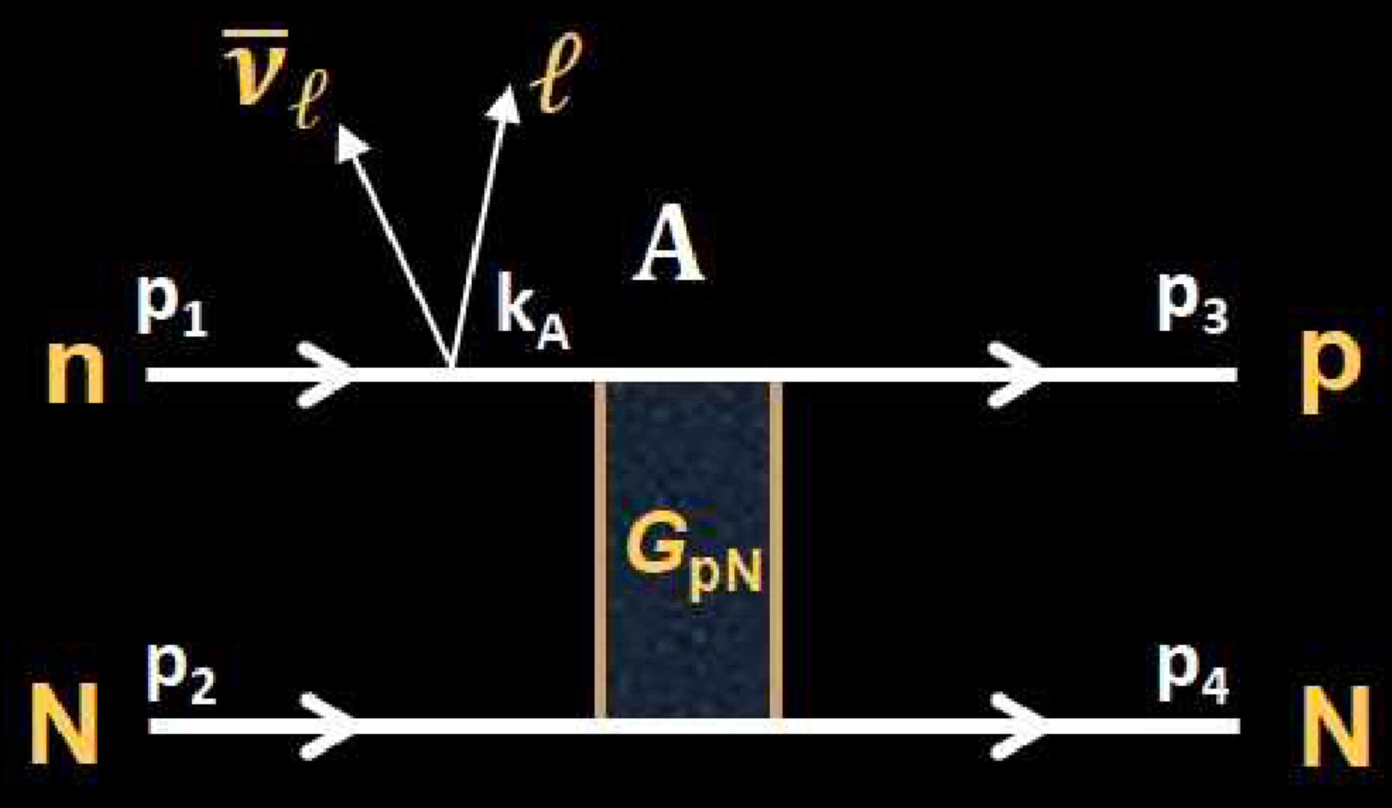
Neutrinos from Neutron Stars



thermal flux

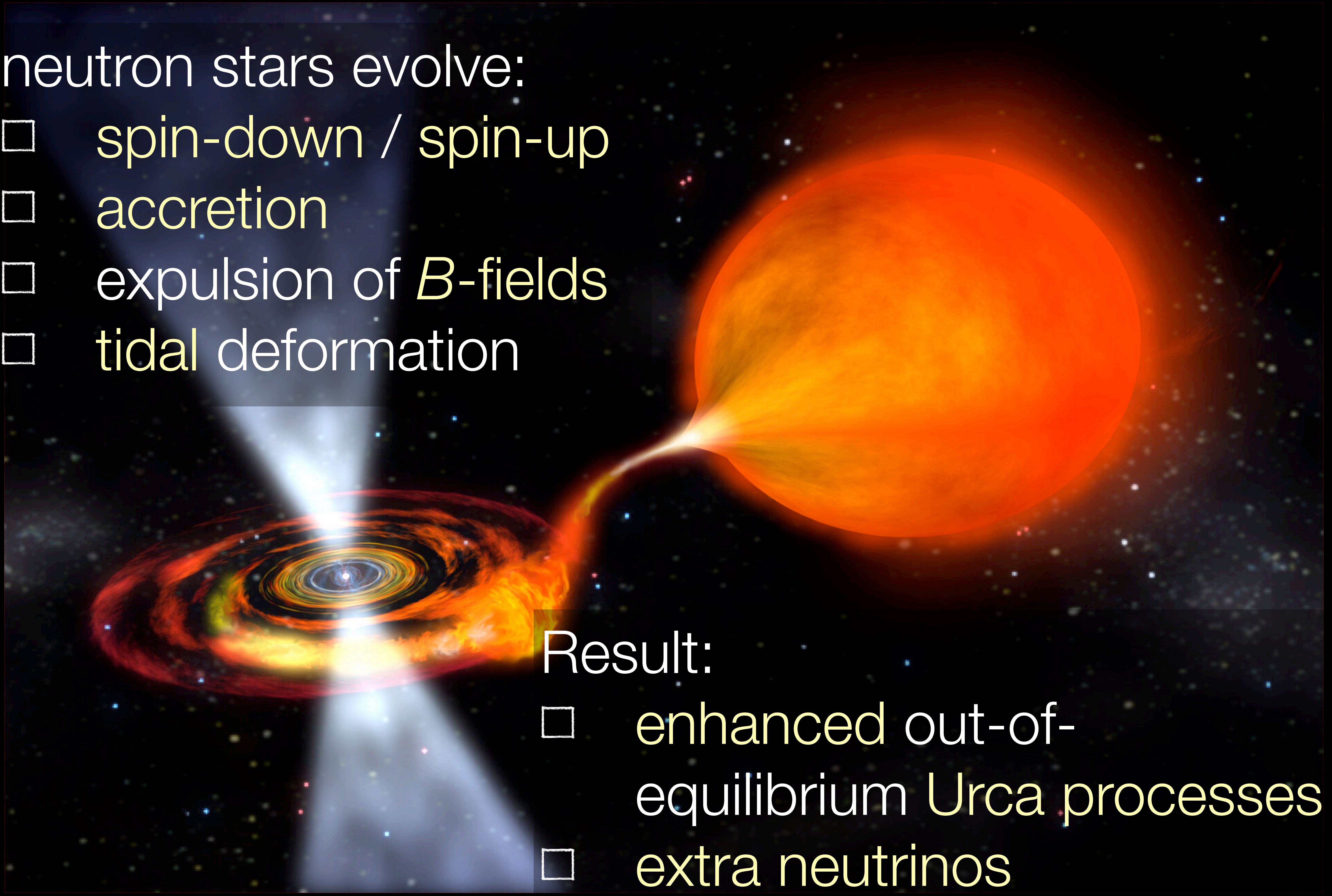
- from “Urca” processes
- low energy
- undetectable after ~10 sec

Neutrinos from Neutron Stars



thermal flux

- from "Urca" processes
- low energy
- undetectable after ~10 sec



neutron stars evolve:

- spin-down / spin-up
- accretion
- expulsion of *B*-fields
- tidal deformation

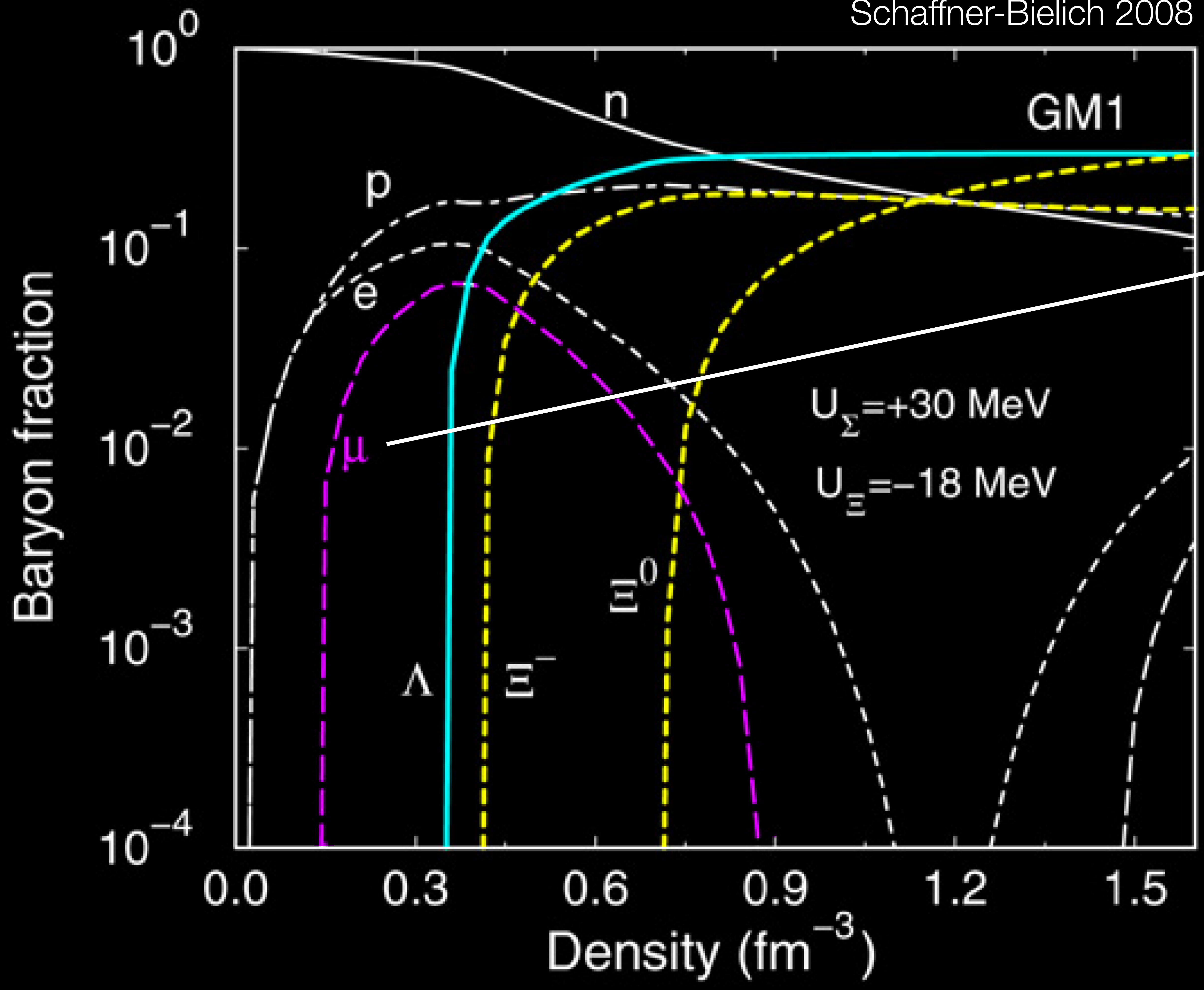
Result:

- enhanced out-of-equilibrium Urca processes
- extra neutrinos

JK Opferkuch *in preparation*

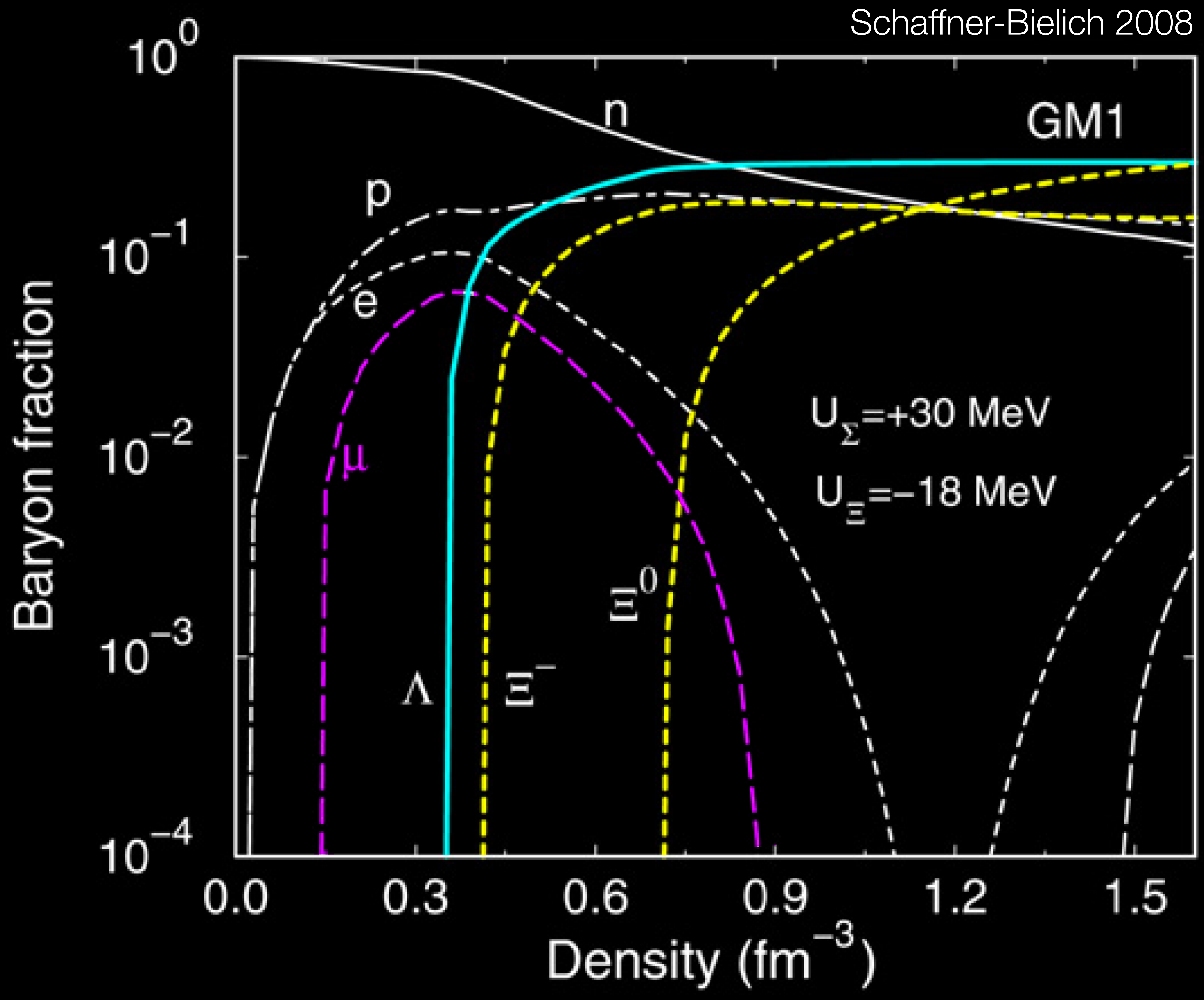
Muons in Neutron Stars

Schaffner-Bielich 2008



neutron stars harbor abundant quantities of muons

Muons in Neutron Stars



- in the core: μ decay Pauli-blocked
- drop in core density may reduce equilibrium μ abundance
- at $t \gtrsim 10^4$ yrs, Urca interactions too slow to maintain equilibrium
- muons diffuse outward and decay ➠ neutrinos!
- observable signal requires $\mathcal{O}(0.001)$ change in μ abundance

major caveat

- equilibrium μ abundance typically *increases* over time

The Early Universe

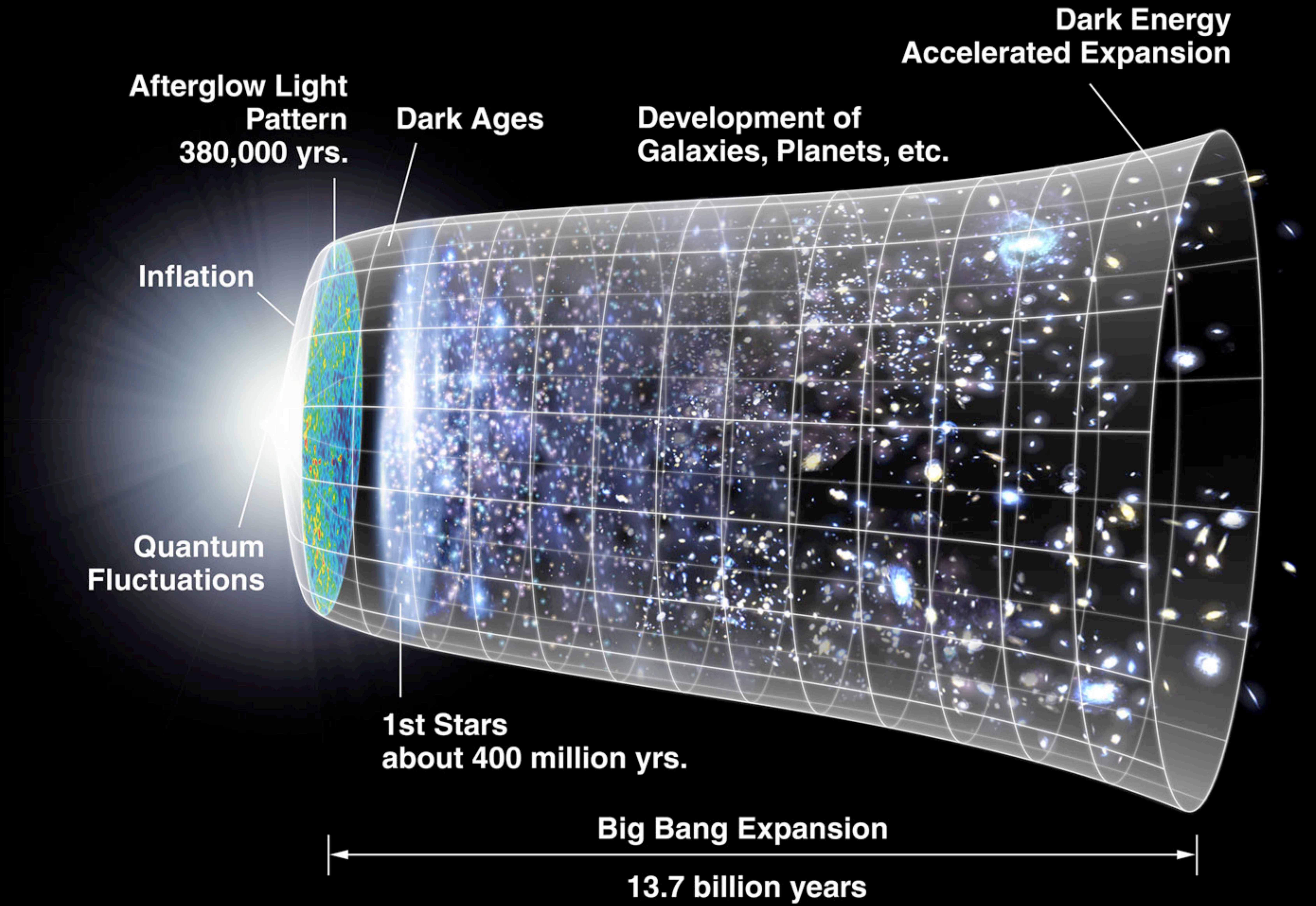
CERN

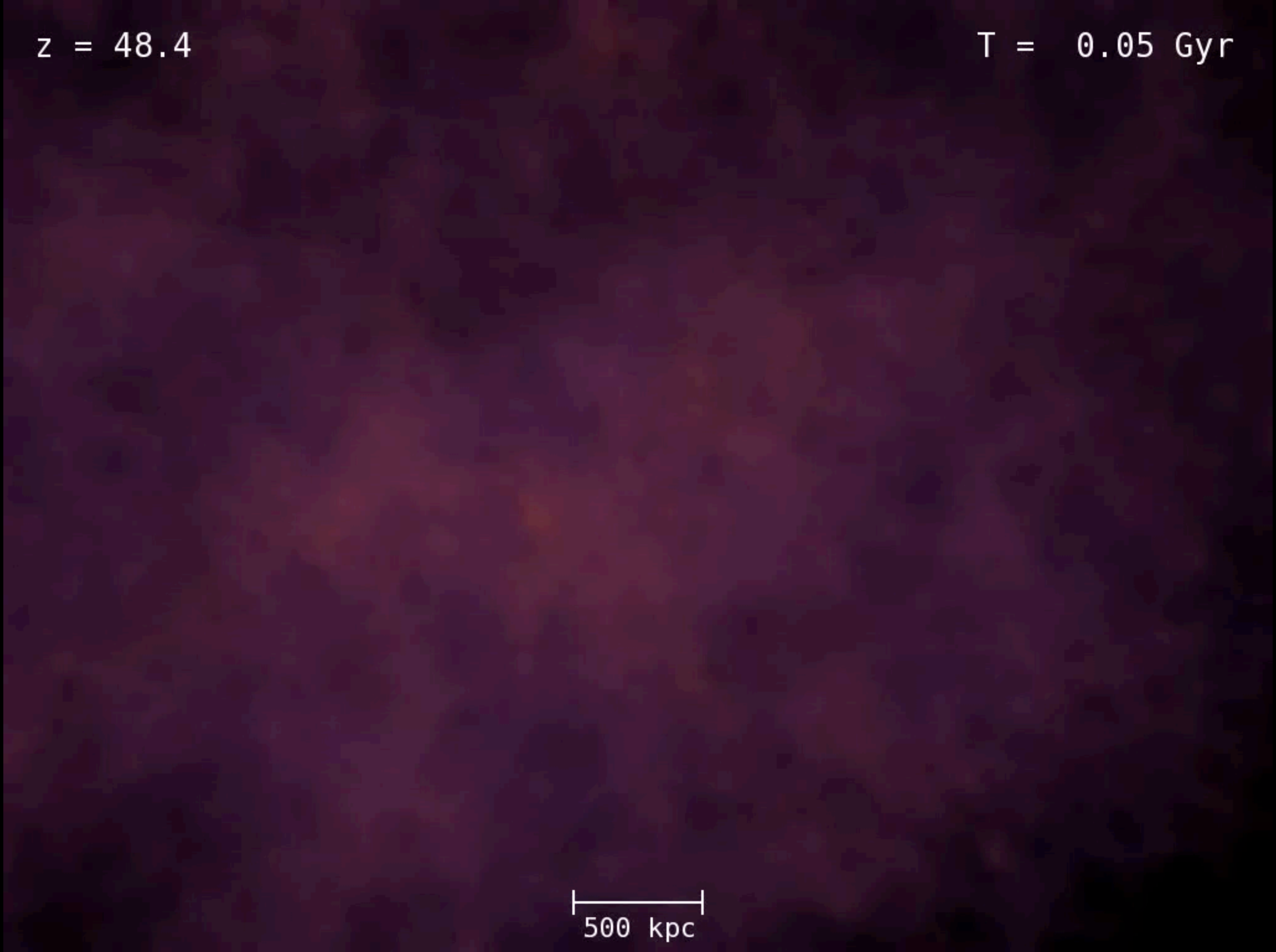
Neutrino PLATFORM

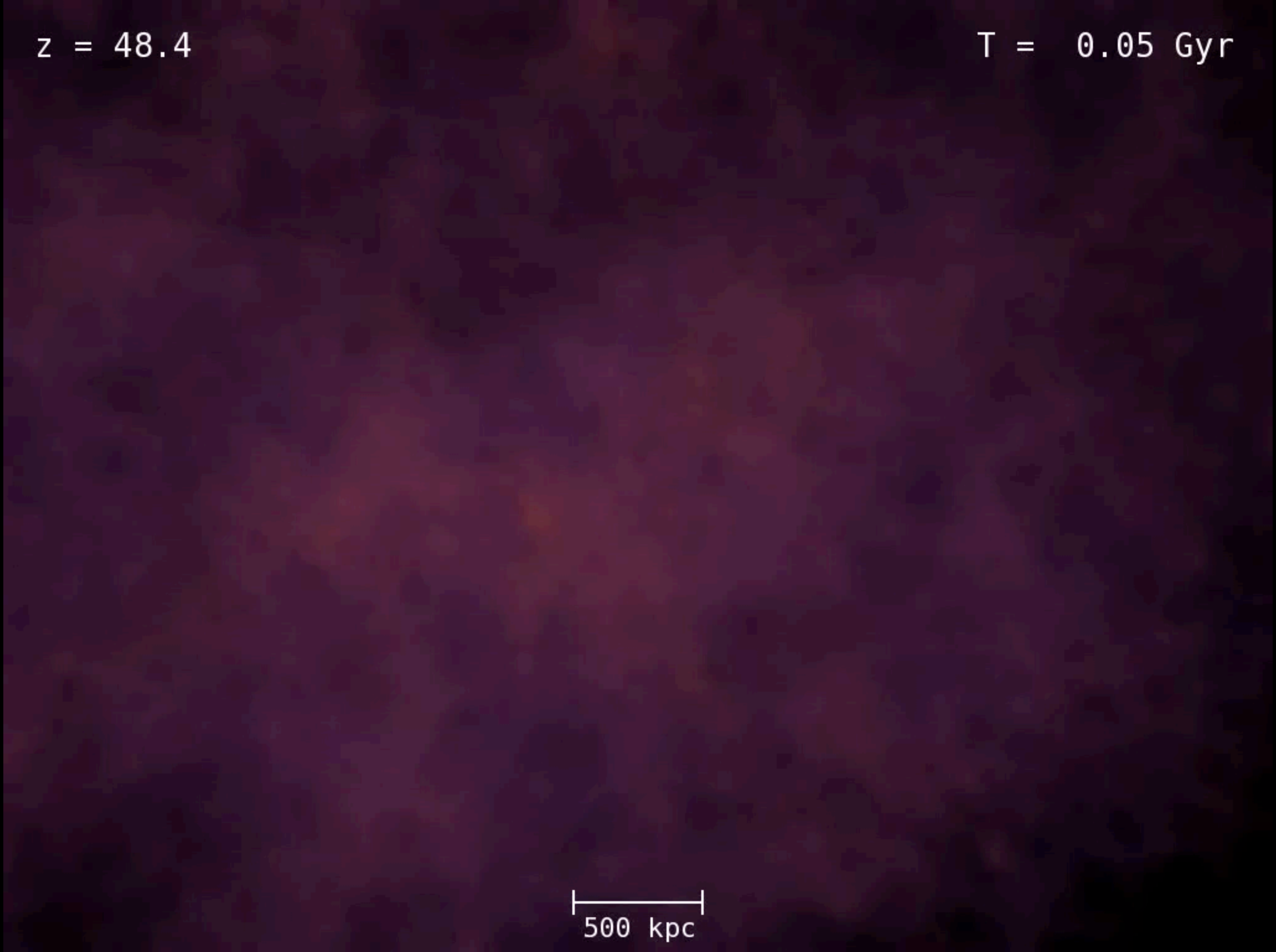
QUANTUM TECHNOLOGY INITIATIVE

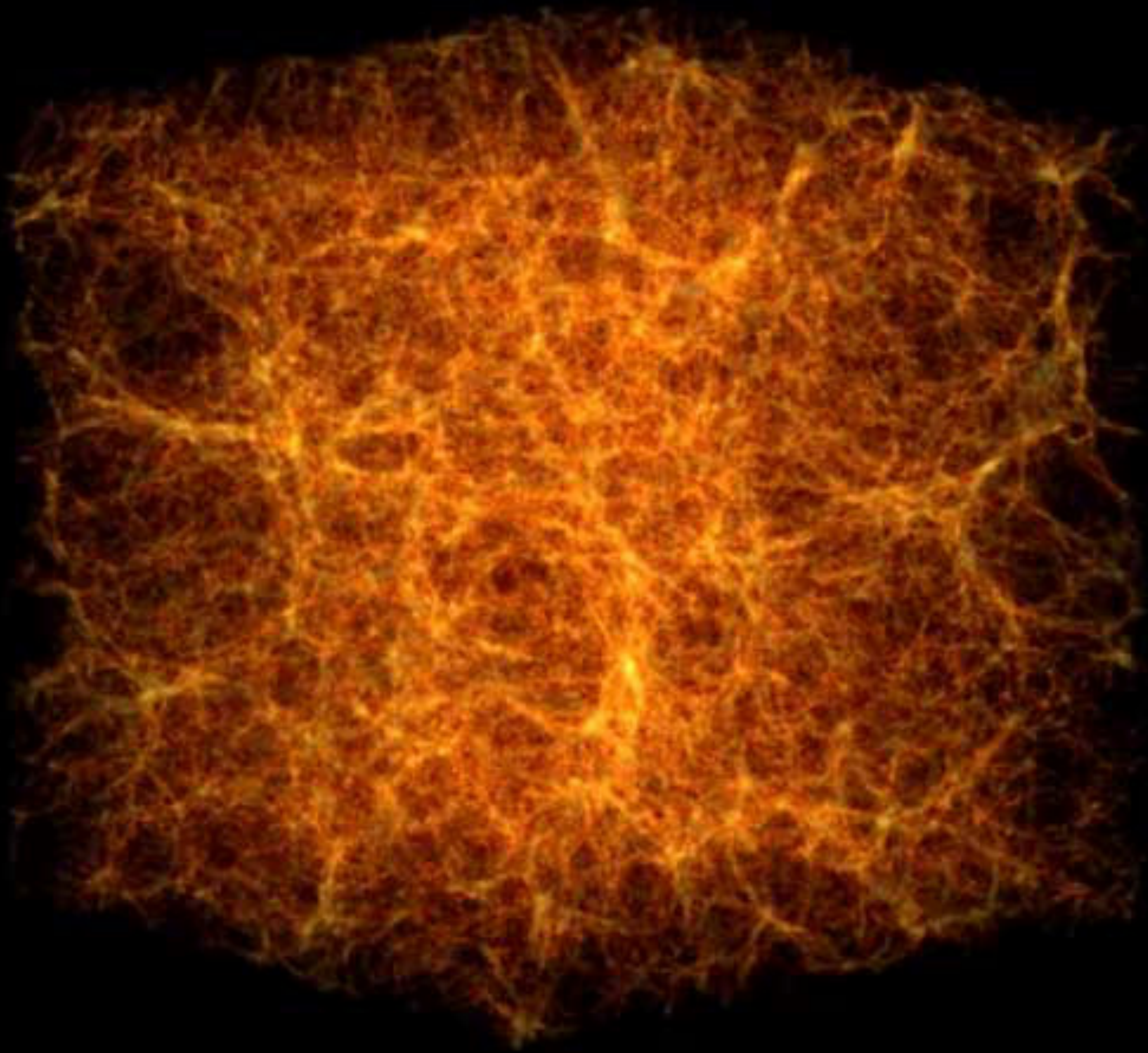
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Neutrinos in Cosmology

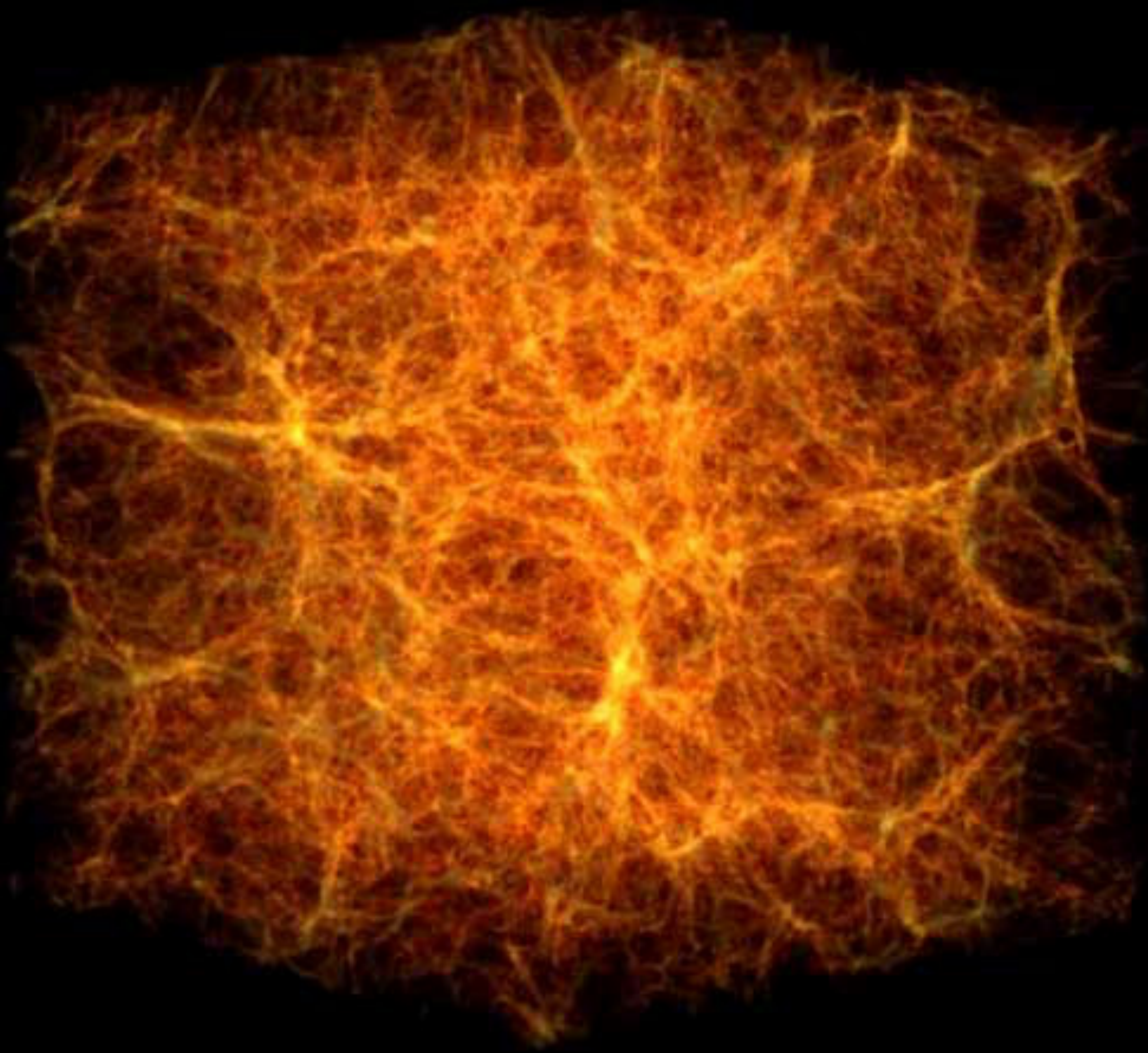



z = 48.4
T = 0.05 Gyr
500 kpc


z = 48.4
T = 0.05 Gyr
500 kpc

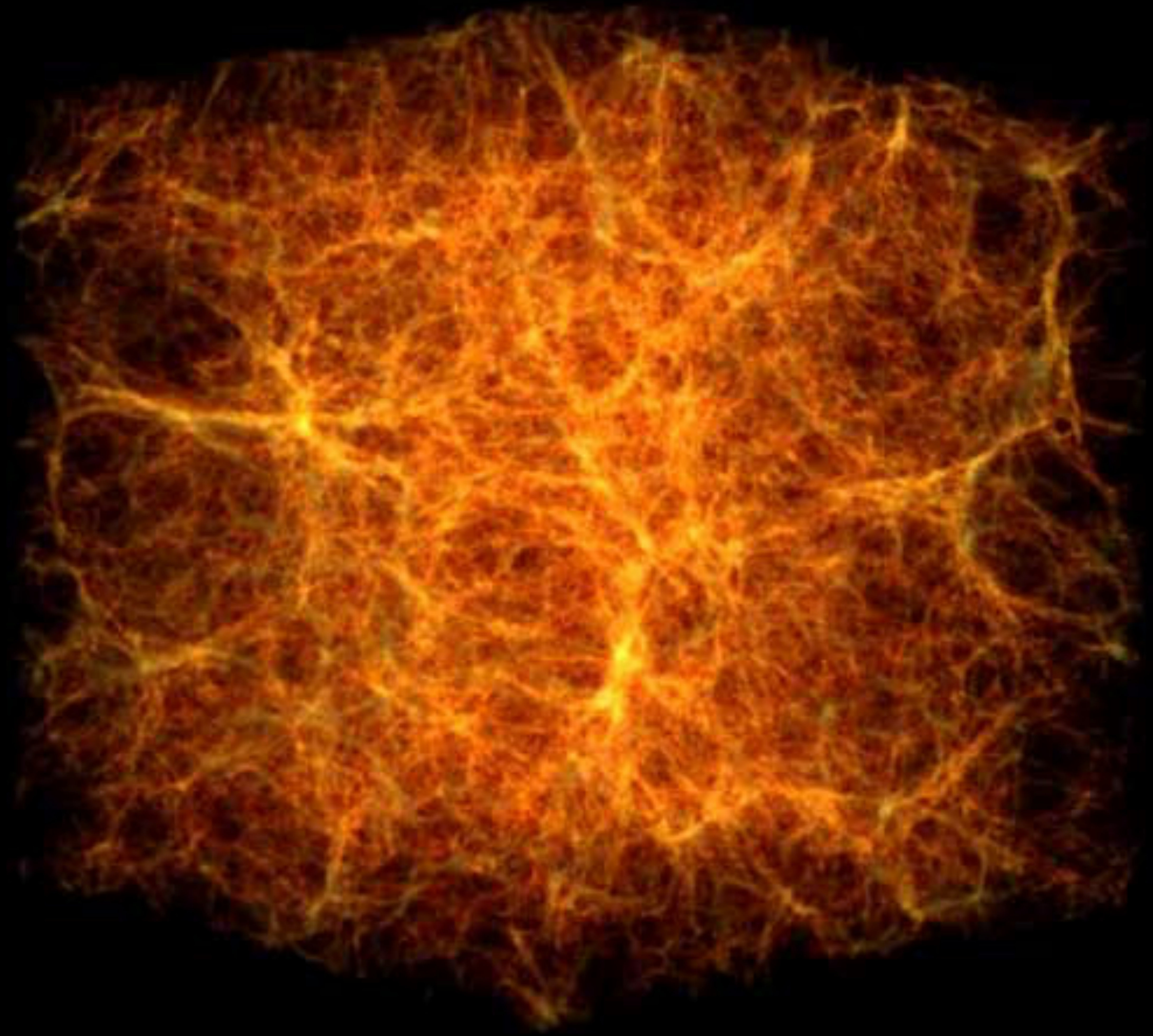


zero neutrino mass

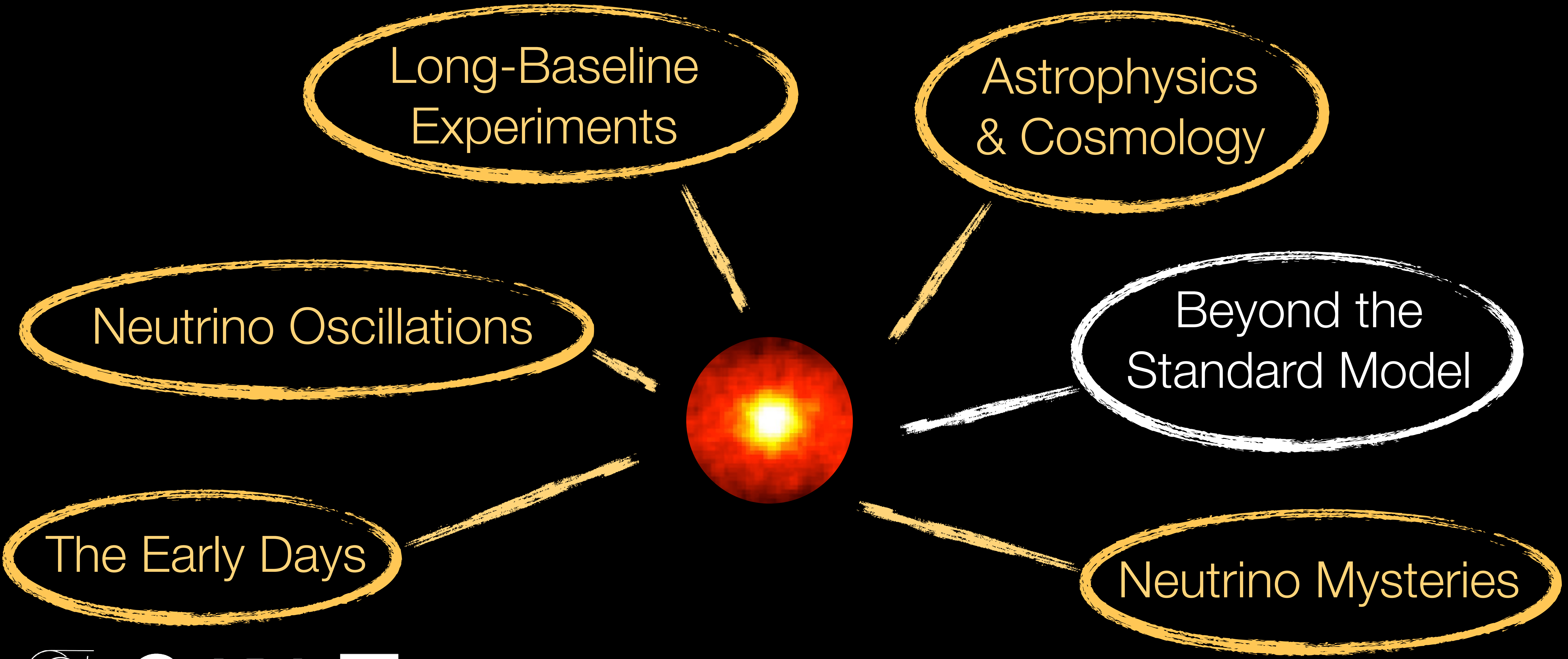


non-zero neutrino mass

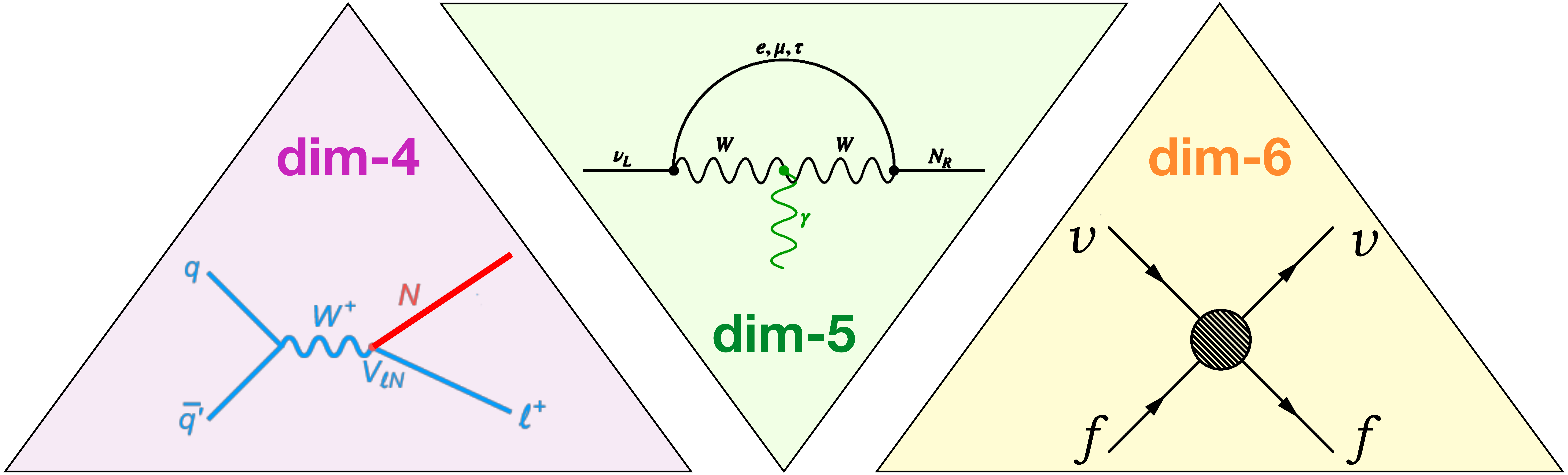
- Neutrinos are abundantly produced during the Big Bang
  - today: T ~ 1.95 K, n ~ 336 / cm^3
  - CMB: T ~ 2.73 K, n ~ 411 / cm^3
- direct detection impossible so far due to the low energy
- indirect evidence from
  - formation of large-scale structure
  - expansion rate of the Universe
- structure formation is sensitive to neutrino masses
  - expect first measurement of the absolute neutrino mass scale in ~ the next decade



Outline

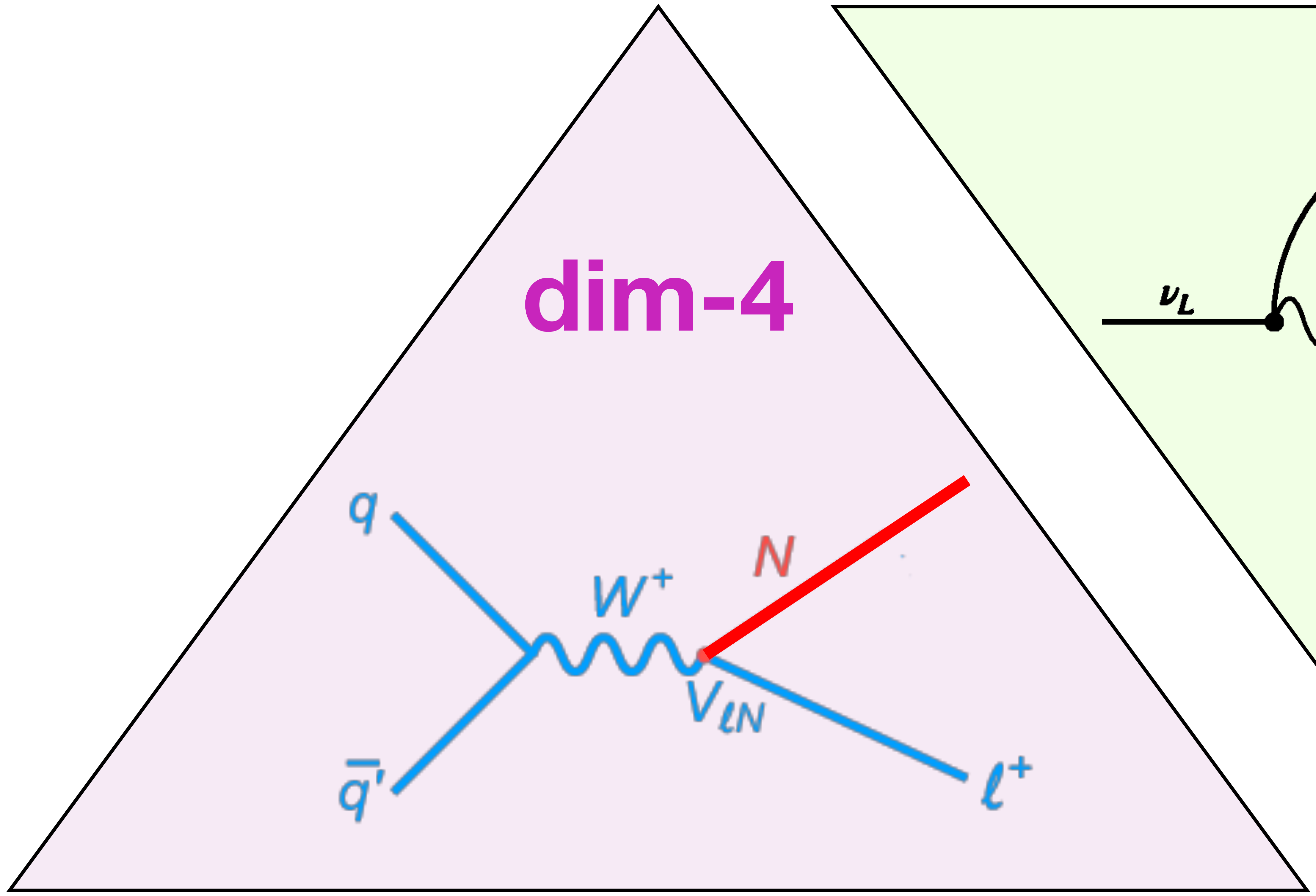

Long-Baseline Experiments
Astrophysics & Cosmology
Neutrino Oscillations
Beyond the Standard Model
The Early Days
Neutrino Mysteries

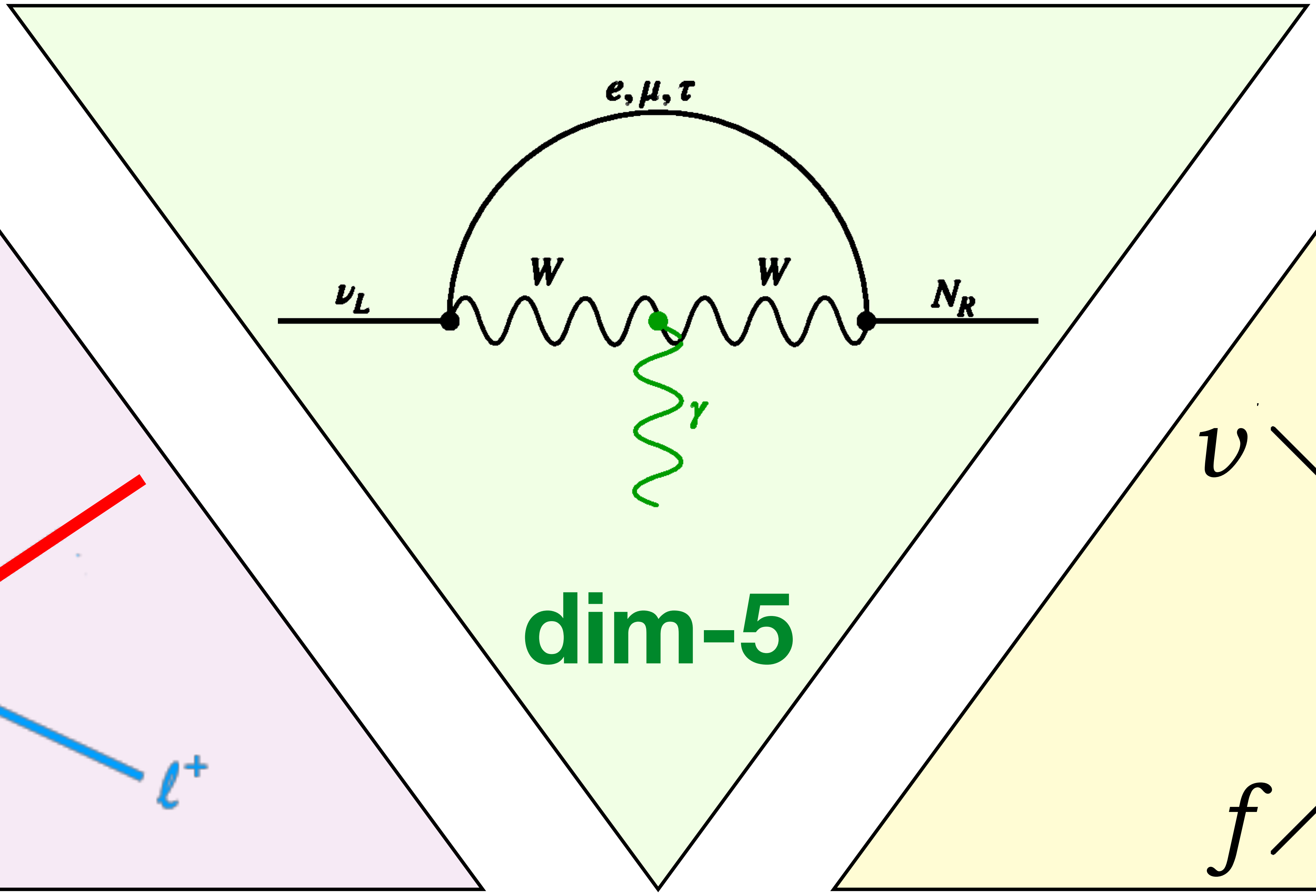
Neutrino Physics Beyond the Standard Model

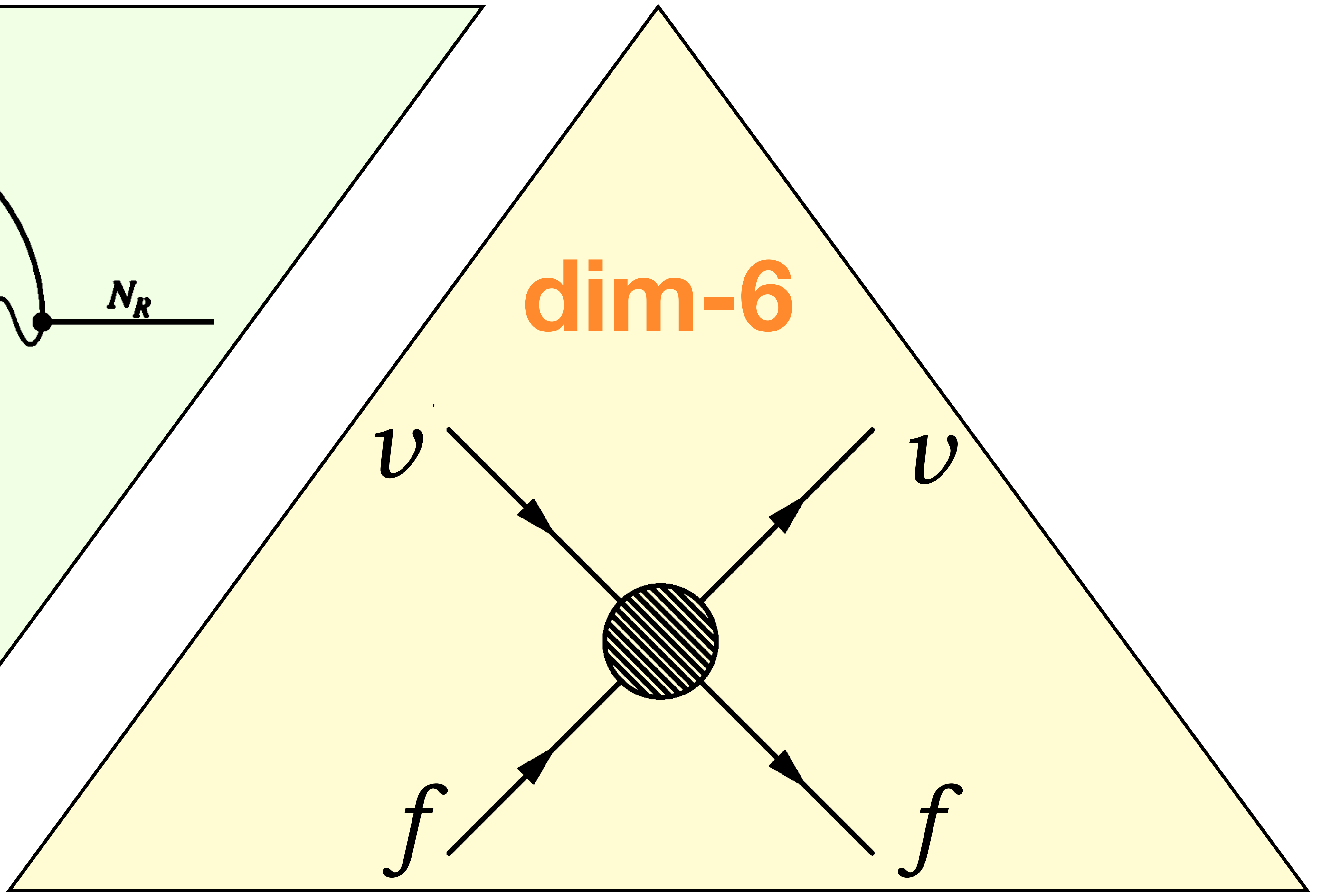


Neutrino Physics Beyond the Standard Model

e.g. neutrino magnetic moments



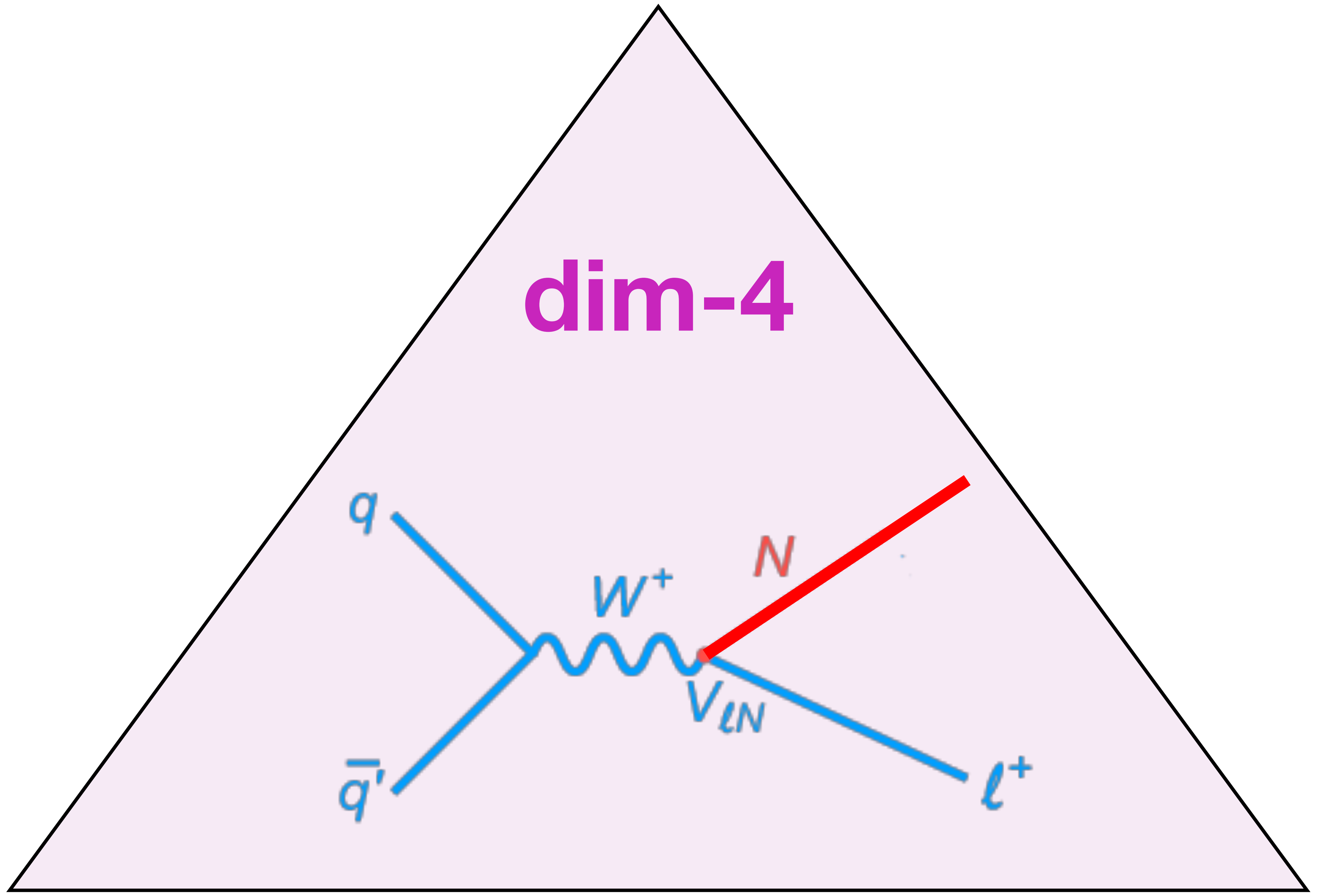




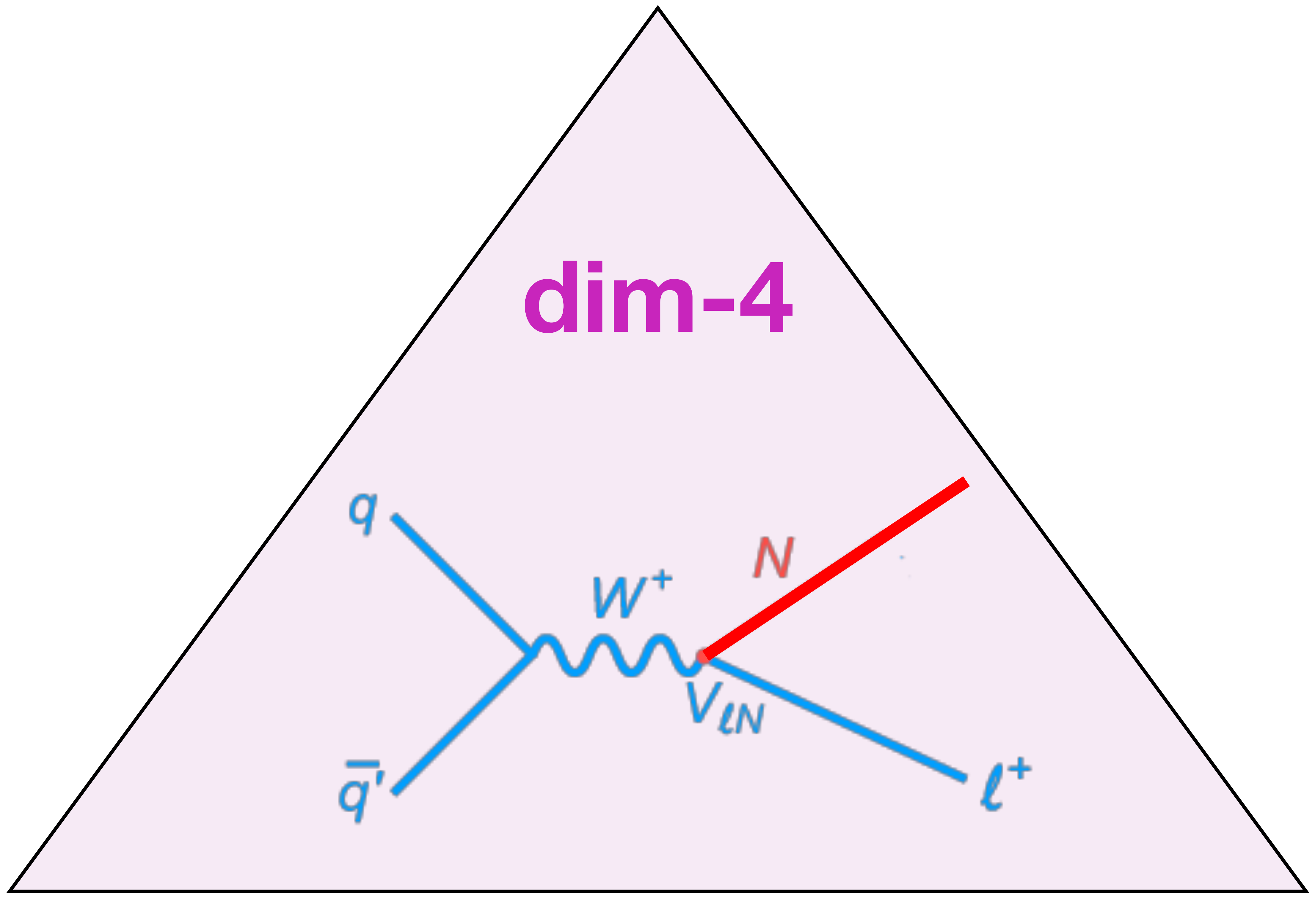
e.g. sterile neutrinos

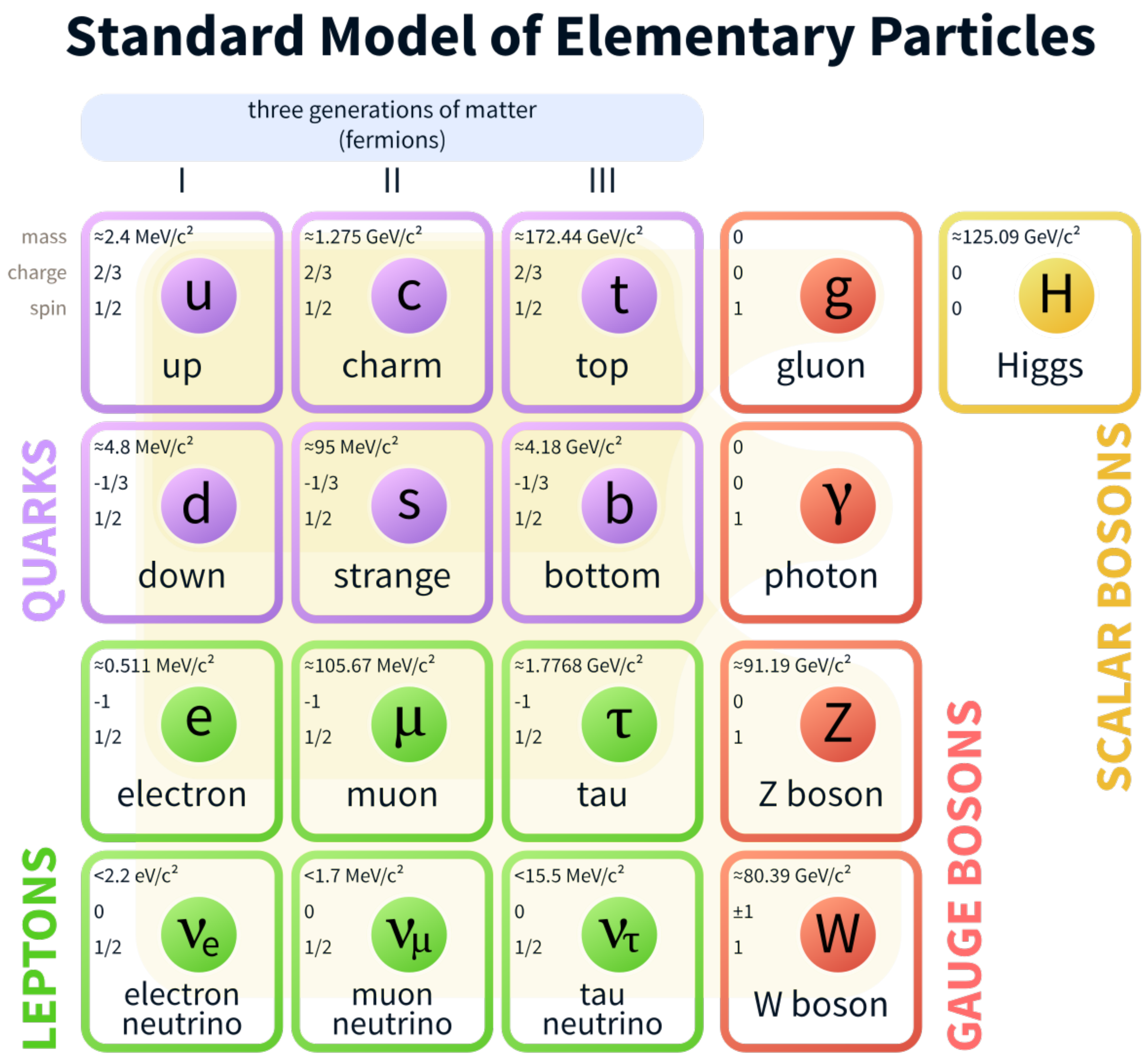
e.g. non-standard interactions

Sterile Neutrinos = new, uncharged fermions

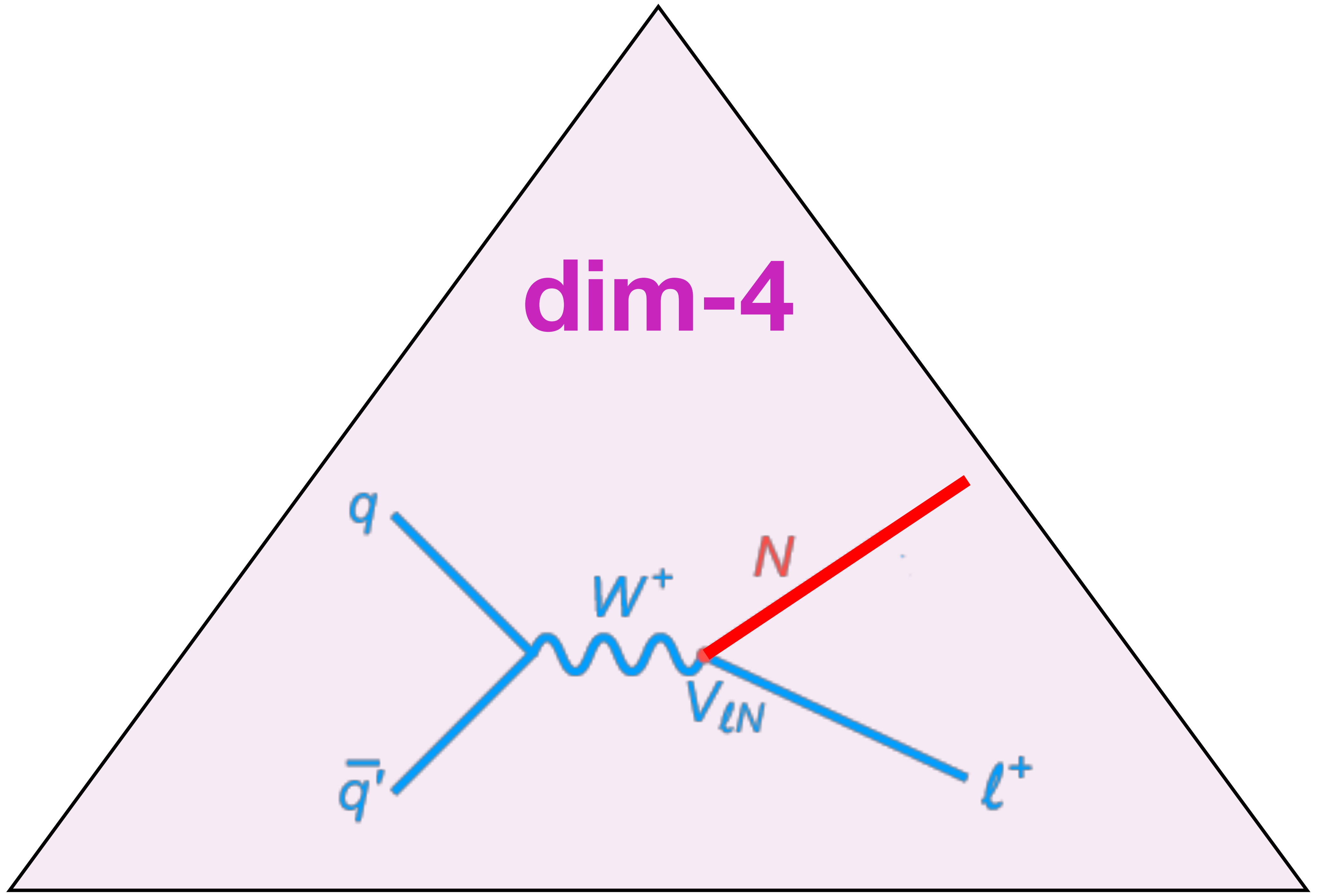


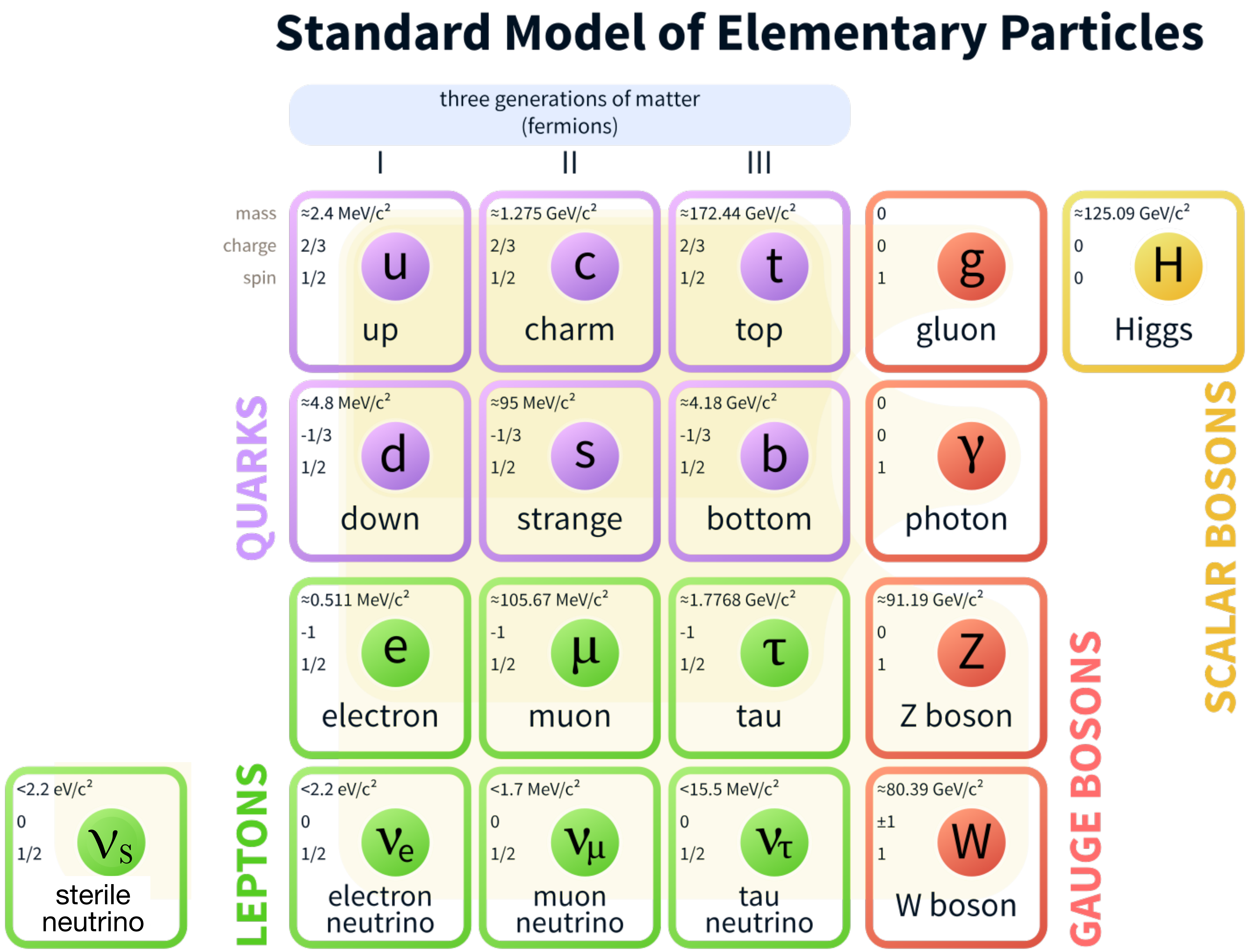
Sterile Neutrinos = new, uncharged fermions



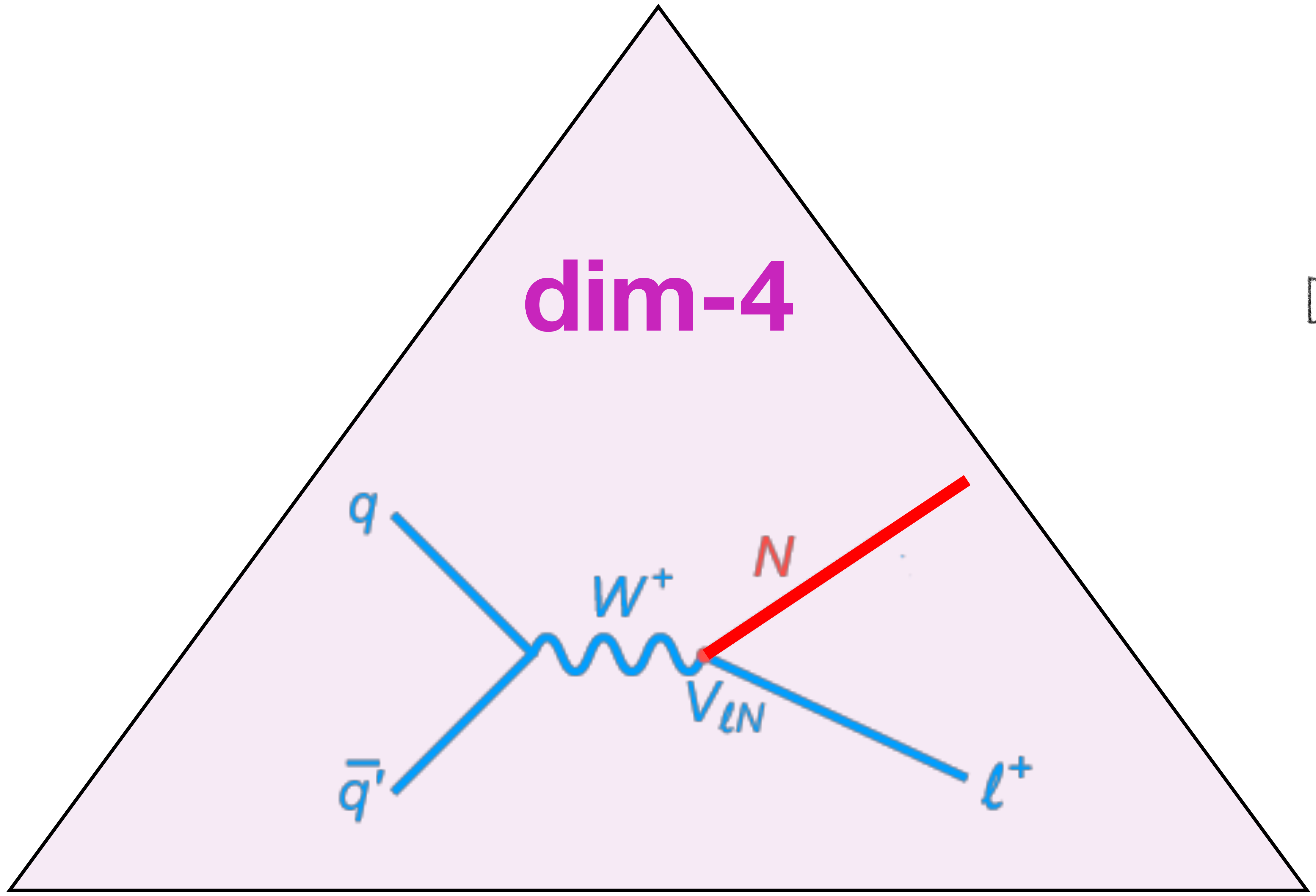


Sterile Neutrinos = new, uncharged fermions



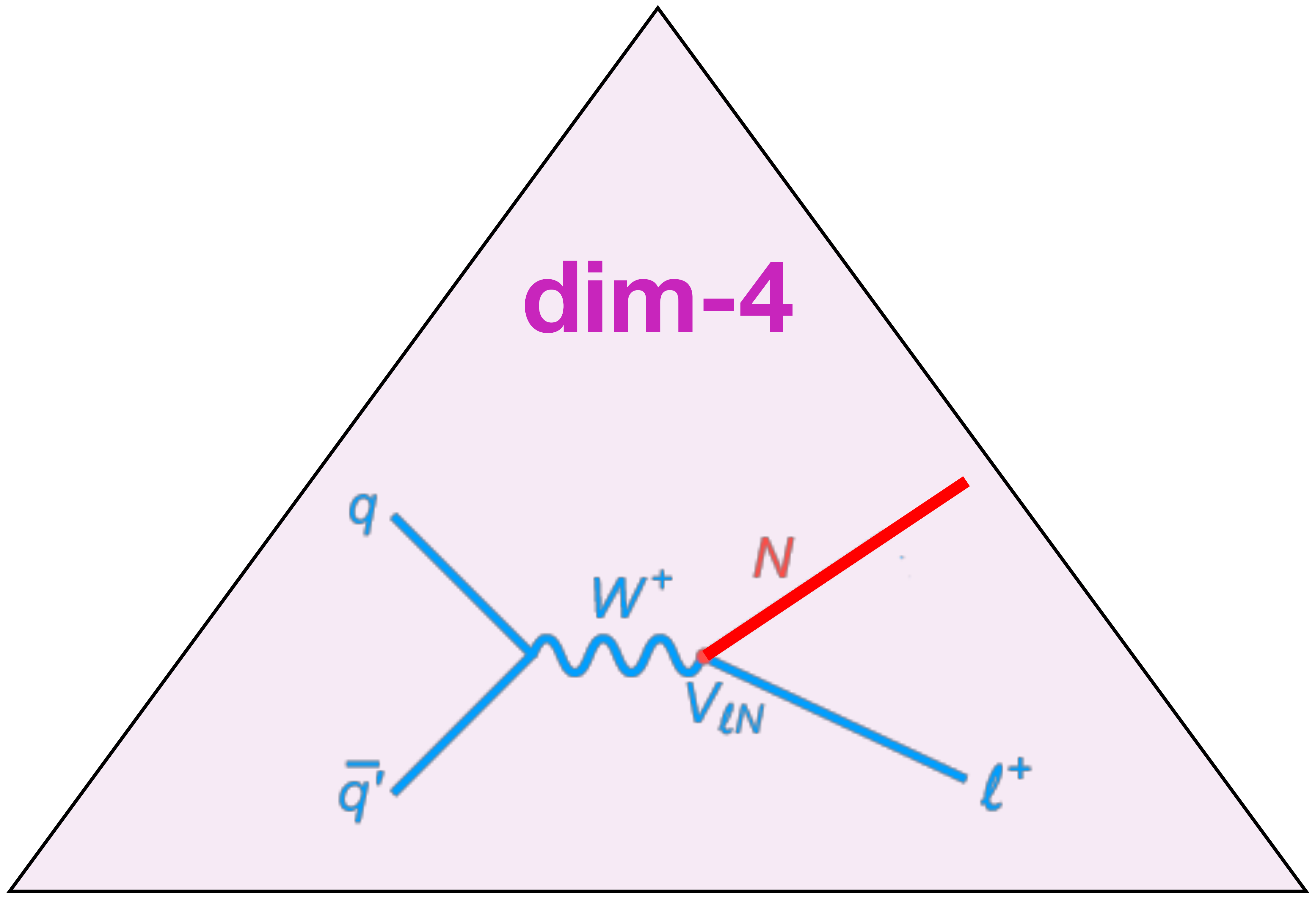


Sterile Neutrinos = new, uncharged fermions



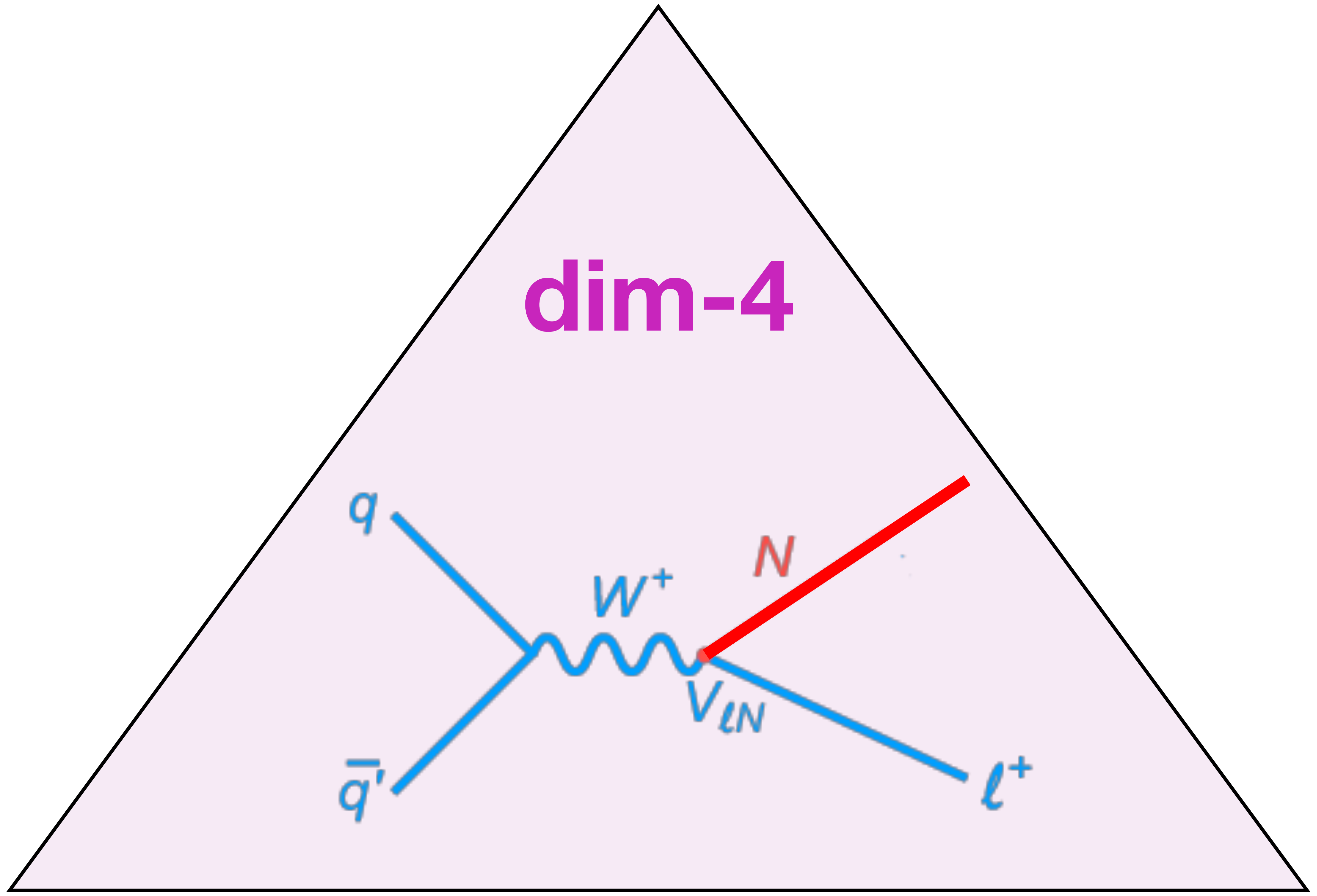
- Very generic extension of SM
  - leftovers of extended gauge multiplets in Grand Unified Theories?
- Useful phenomenological tool
  - neutrino masses (seesaw mechanism, $m \sim$ TeV…M_{Pl})
  - cosmic baryon asymmetry (thermal leptogenesis at $m \gg 100$ GeV, ARS leptogenesis at $m < 100$ GeV)
  - dark matter ($m \sim$ keV)
  - mediator to a dark sector (any mass)

Sterile Neutrinos = new, uncharged fermions



$$y_{\alpha\beta}\bar{L}_\alpha\tilde{H}N_\beta$$

Sterile Neutrinos = new, uncharged fermions



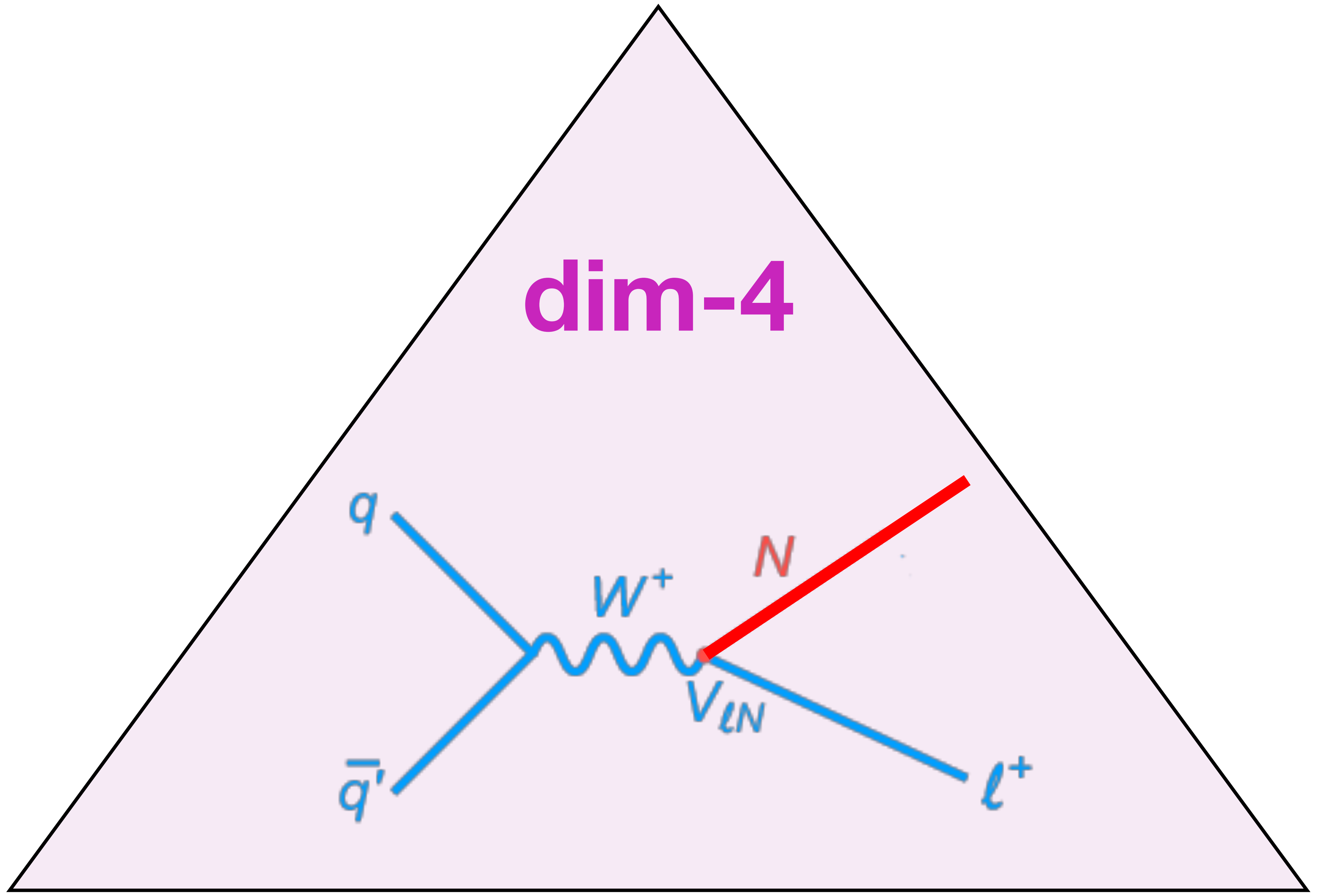
SM lepton doublet

SM Higgs doublet

$$y_{\alpha\beta} \bar{L}_\alpha \tilde{H} N_\beta$$

SM singlet fermion
(heavy neutral lepton (HNL)
= sterile ν = right-handed ν)

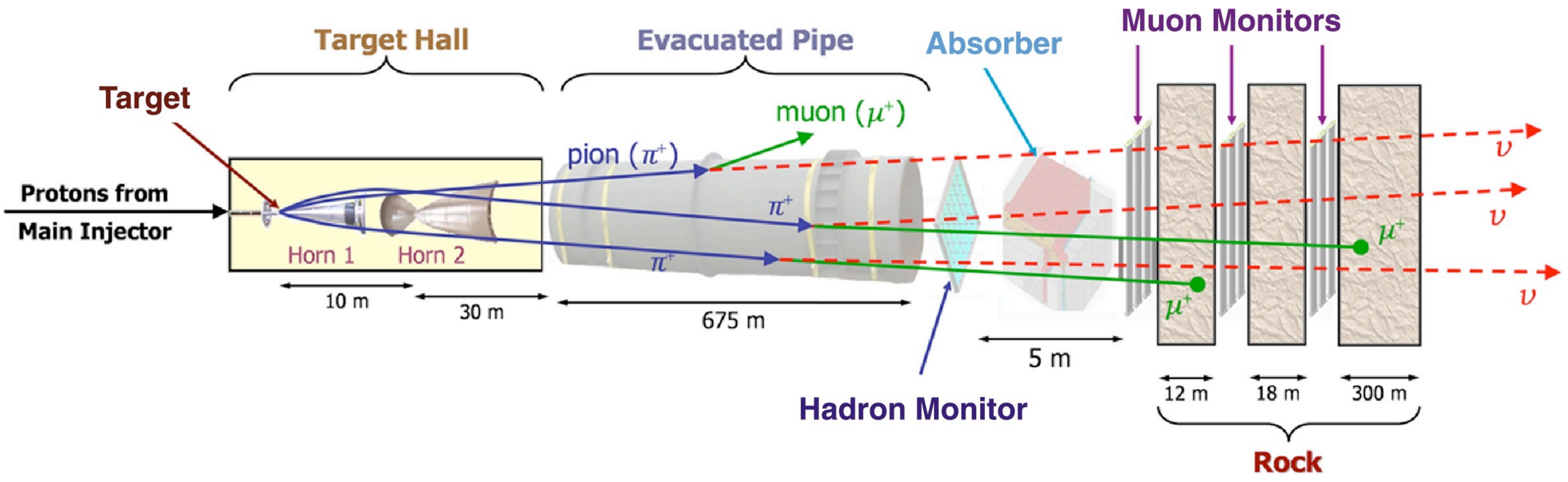
Sterile Neutrinos = new, uncharged fermions



$$y_{\alpha\beta} \bar{L}_\alpha \tilde{H} N_\beta$$

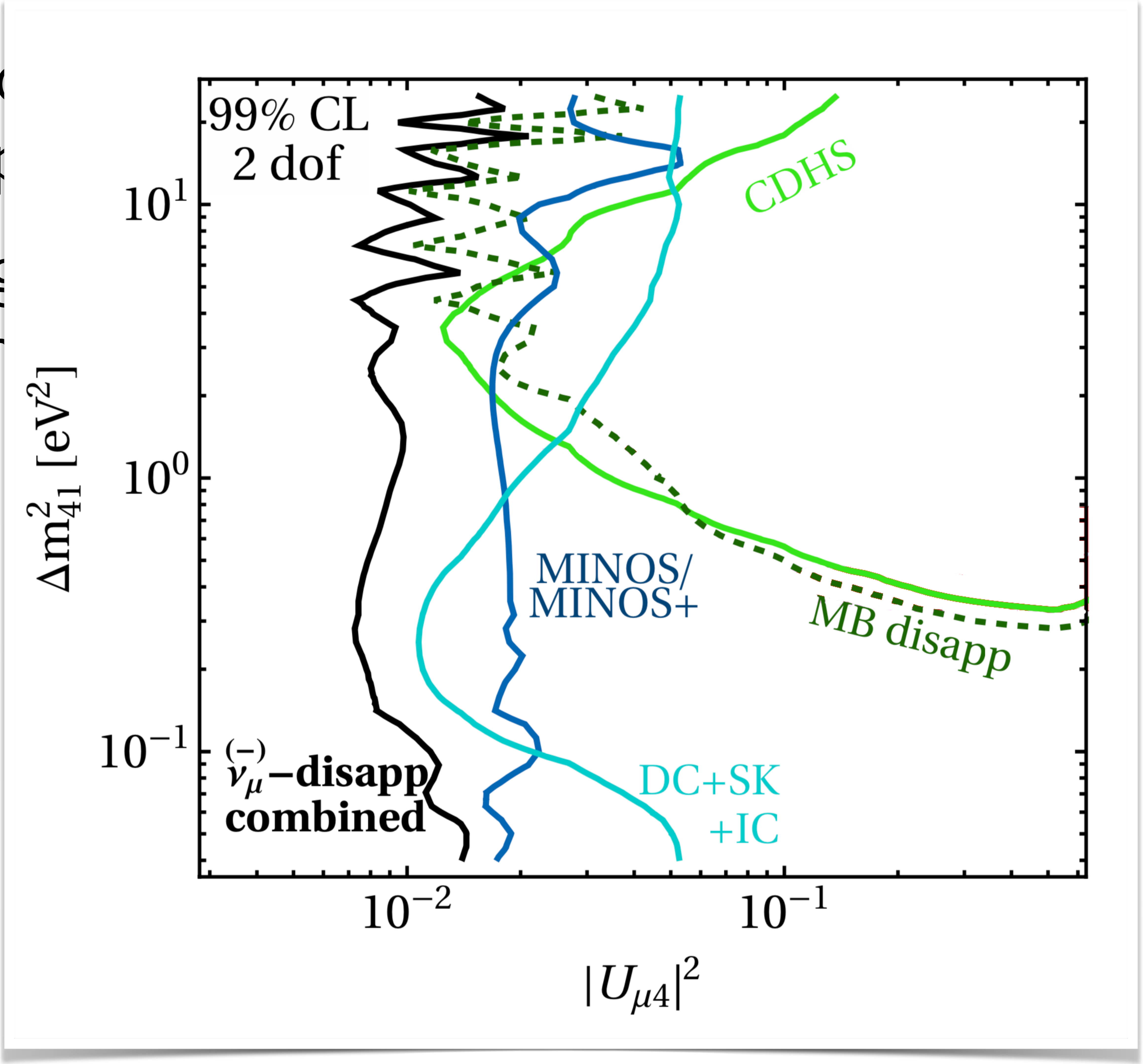
Sterile Neutrino Oscillations

- Use intense flux of ν_μ from pion decay in accelerator experiment or in the upper atmosphere
- Look for "missing" ν_μ at distances too short for standard oscillations



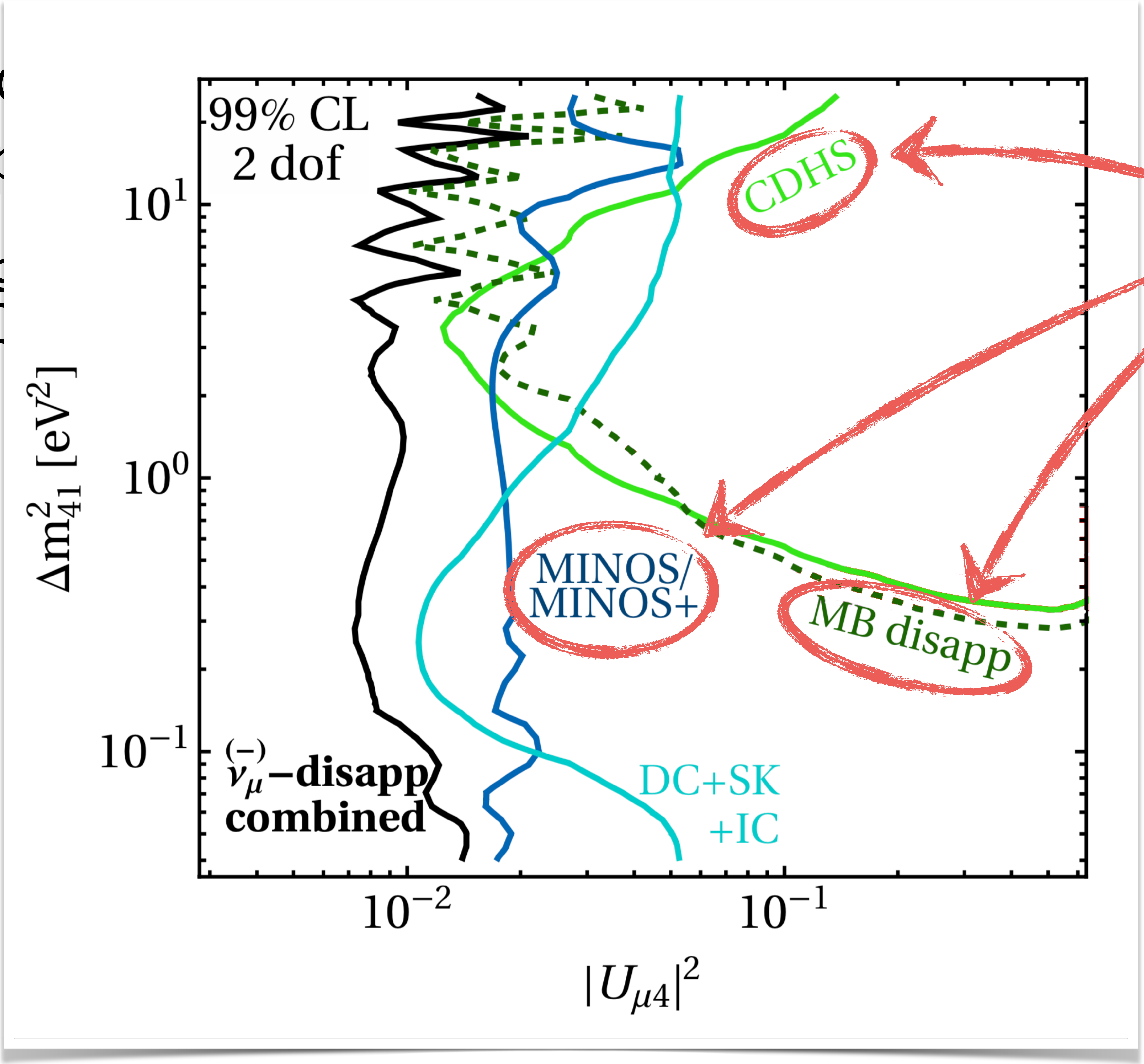
Sterile Neutrino Oscillations

- Use intense flux (
  in accelerator exp
- Look for “missing
  too short for stan



Sterile Neutrino Oscillations

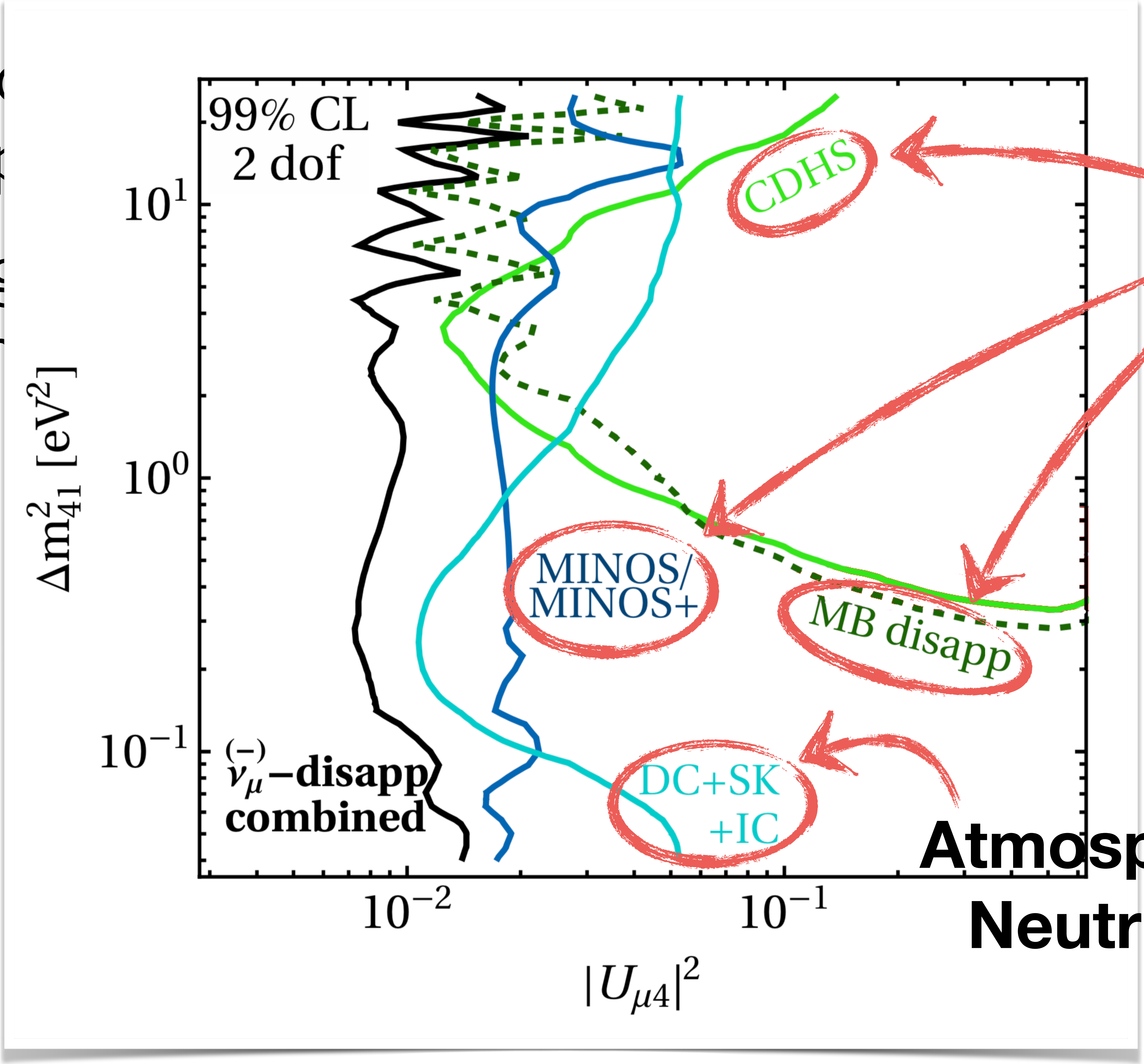
- Use intense flux ⟨cut off⟩ in accelerator exp⟨cut off⟩
- Look for "missing⟨cut off⟩ too short for star⟨cut off⟩



Accelerator Experiments

Sterile Neutrino Oscillations

- Use intense flux (
  in accelerator exp
- Look for “missing
  too short for star

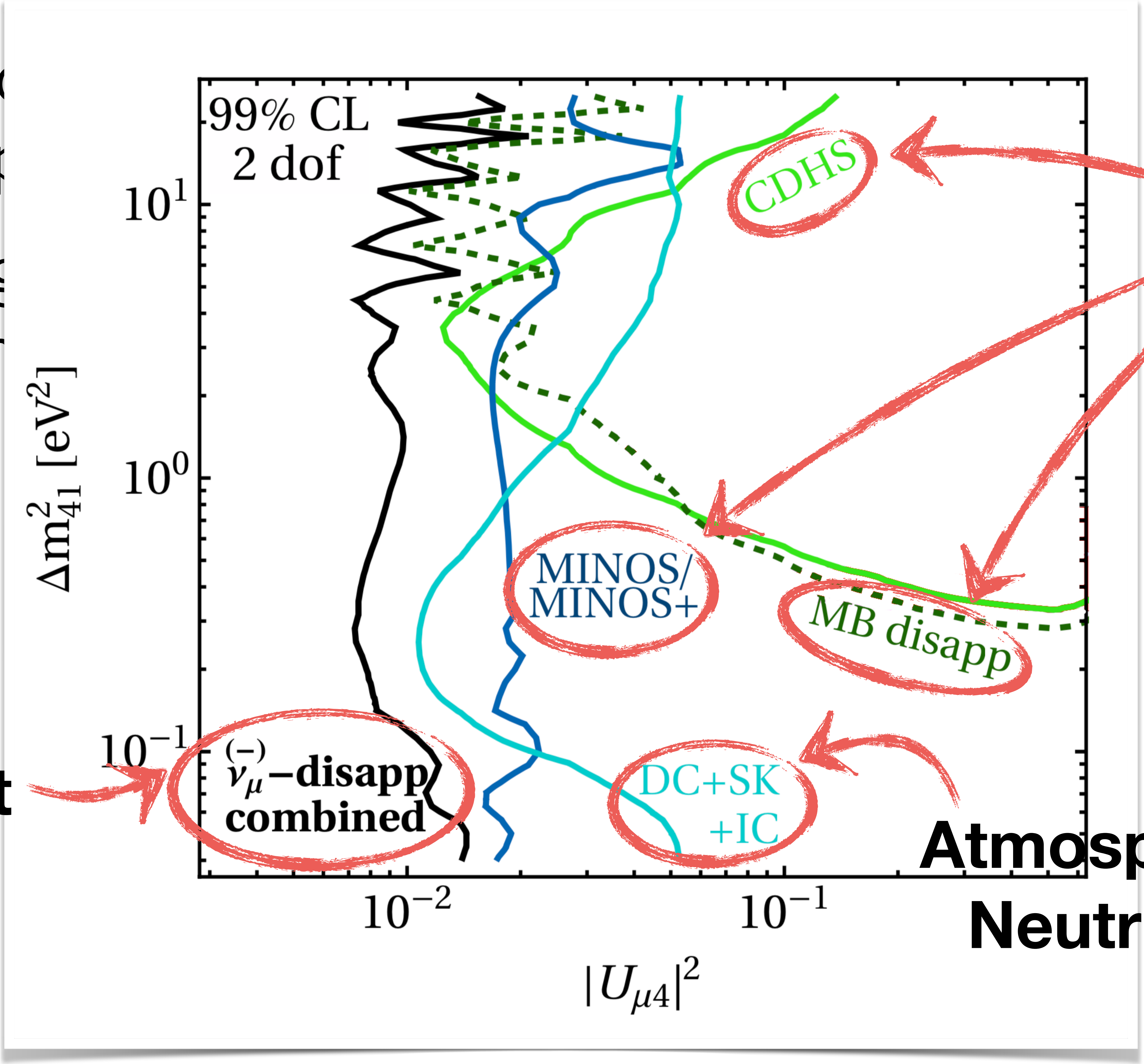


Accelerator Experiments

Atmospheric Neutrinos

Sterile Neutrino Oscillations

- Use intense flux o
  in accelerator exp
- Look for "missing
  too short for stan



Accelerator Experiments

Combined Fit

Atmospheric Neutrinos

Sterile Neutrinos and Cosmology

An extra light neutrino species with sizeable mixing is in severe tension with cosmology.

Standard picture: ν_s production via oscillation at $T \gtrsim$ MeV

$N_{eff} \lesssim 3.38$ ⚡

$\Sigma m_\nu \lesssim 0.23$ eV ⚡

… but there may be ways out in non-minimal models

Sterile Neutrinos and Cosmology

An extra light neutrino species with sizeable mixing is in severe tension with cosmology.

Standard picture: ν_s production via oscillation at $T \gtrsim$ MeV

$N_{eff} \lesssim 3.38$ ⚡

$\Sigma m_\nu \lesssim 0.23$ eV ⚡

measure for the
energy density in relativistic particles
extra neutrino species would imply $N_{eff} \sim 4$

… but there may be ways out in non-minimal models

Sterile Neutrinos and Cosmology

An extra light neutrino species with sizeable mixing is in severe tension with cosmology.

Standard picture: ν_s production via oscillation at $T \gtrsim$ MeV

$N_{eff} \lesssim 3.38$ ⚡

measure for the **energy density in relativistic particles** extra neutrino species would imply $N_{eff} \sim 4$

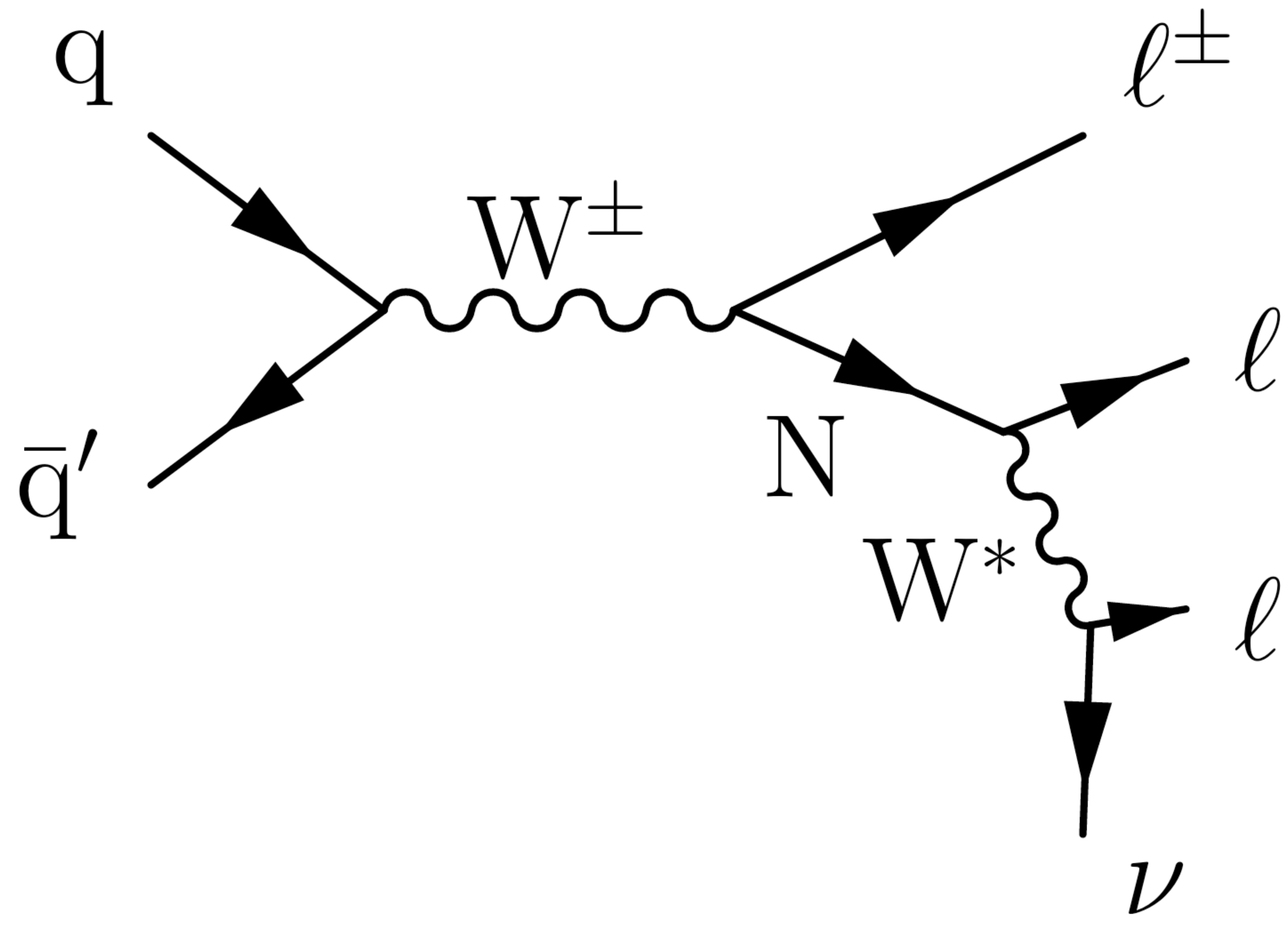
$\Sigma m_\nu \lesssim 0.23$ eV ⚡

sum of neutrino masses affects structure formation sterile neutrino compatible with anomalies would imply $\Sigma m_\nu \sim 1$ eV

… but there may be ways out in non-minimal models

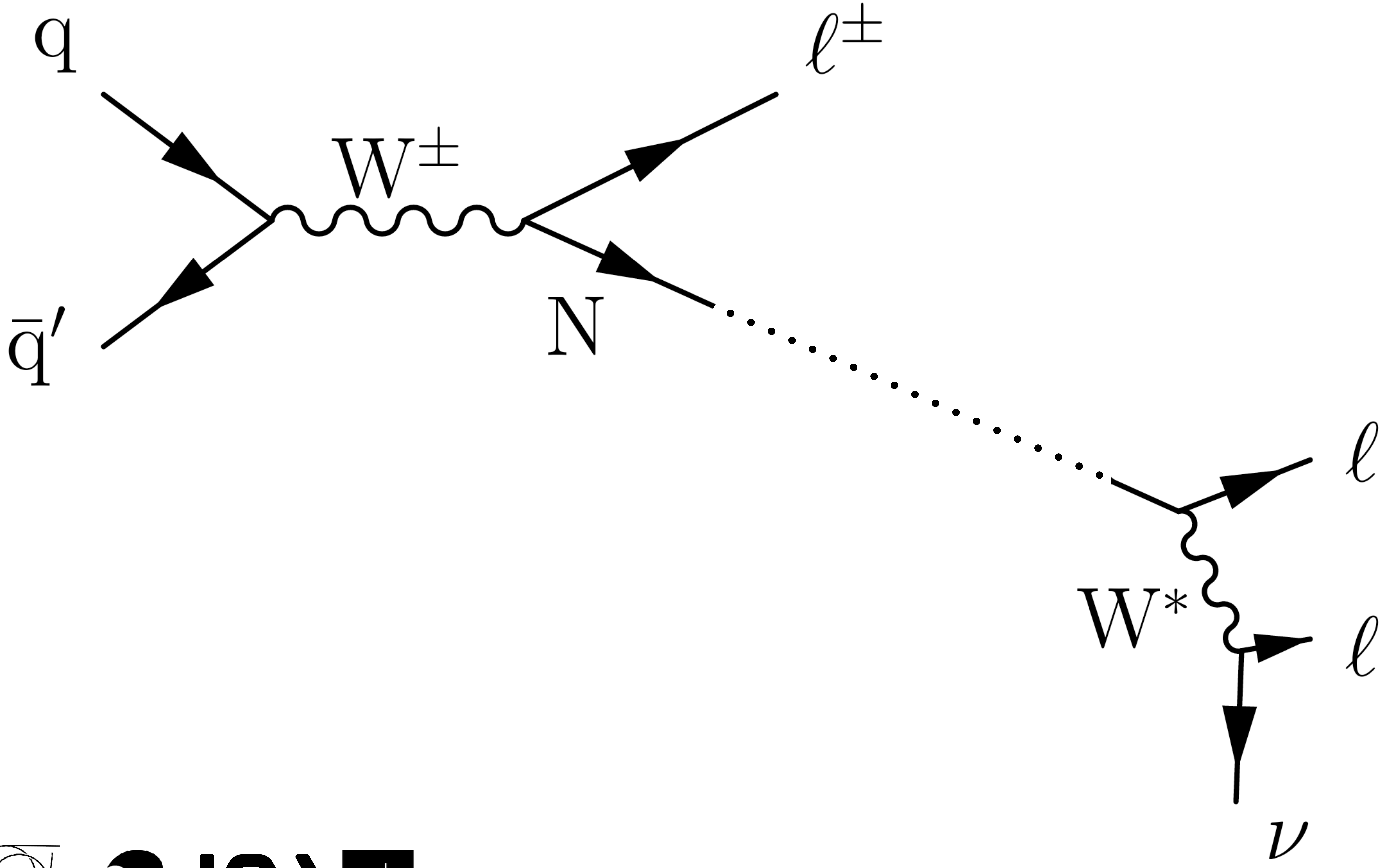
Heavier Sterile Neutrinos – "Heavy Neutral Leptons"

$$y_{\alpha\beta} \bar{L}_\alpha \tilde{H} N_\beta$$

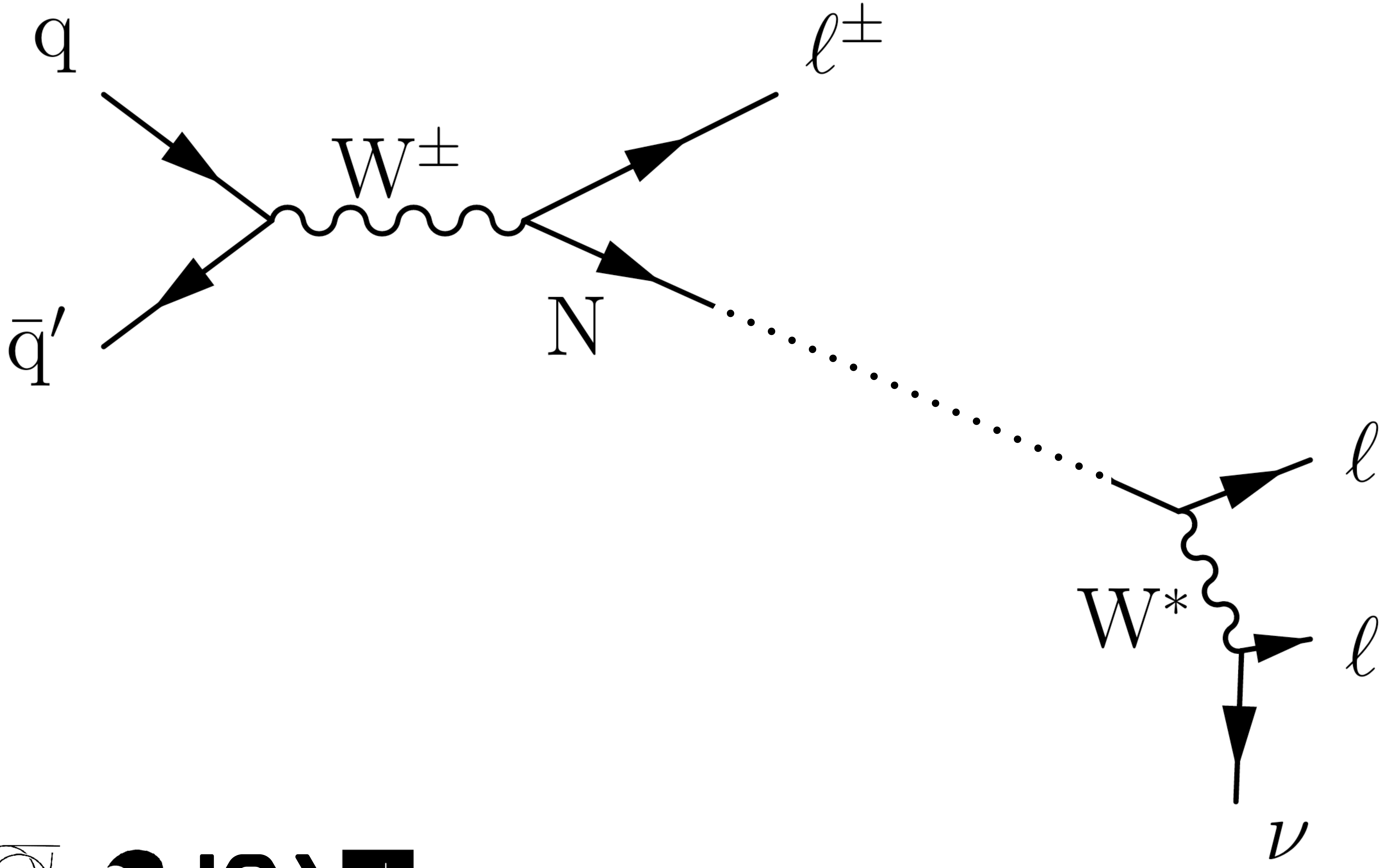


- leads to mixing between *ν* and *N*
  - ➠ any process that makes *ν* in the SM can also make *N* (suppressed by a mixing angle)
  - ➠ meson decays

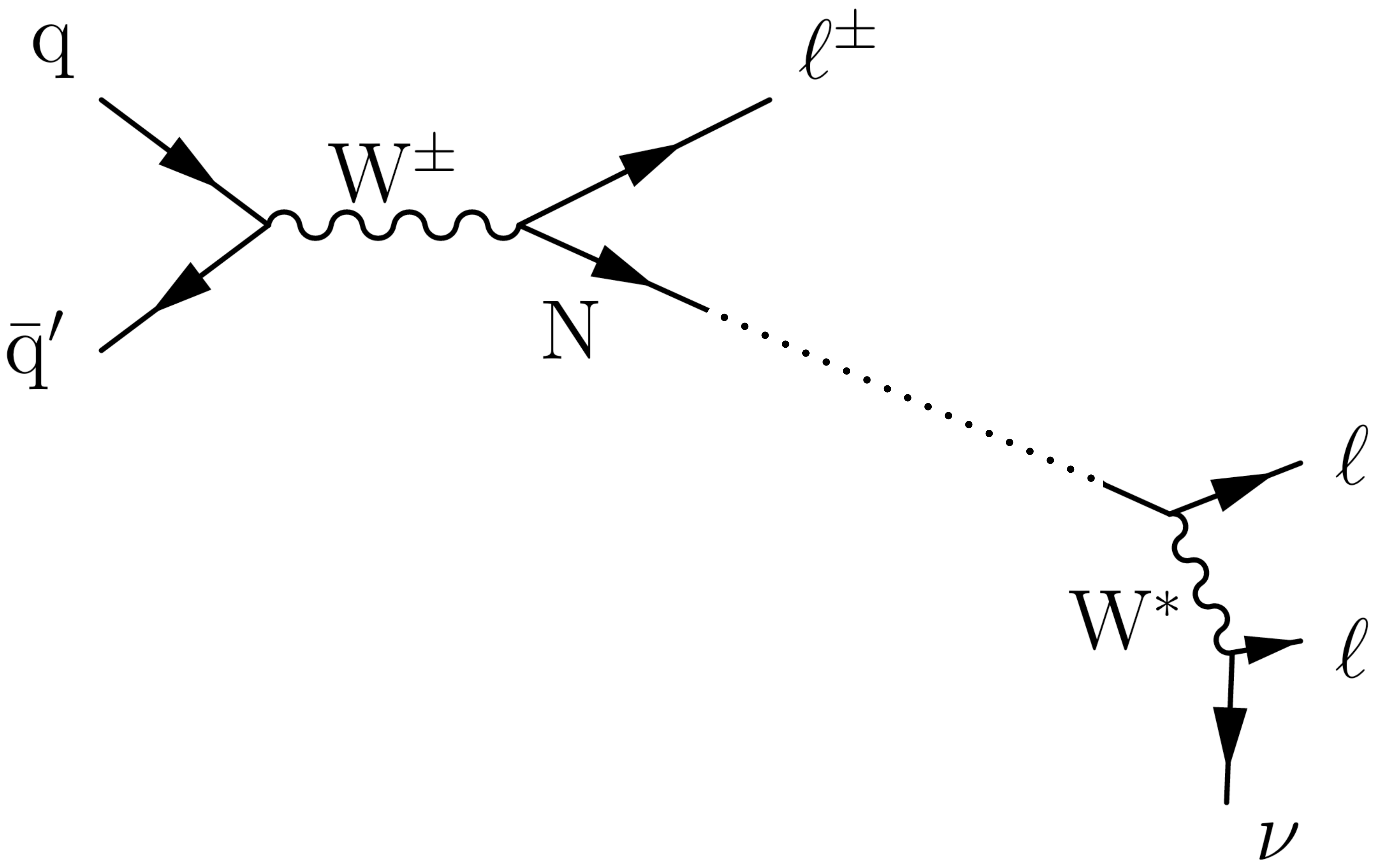
Heavier Sterile Neutrinos – “Heavy Neutral Leptons”

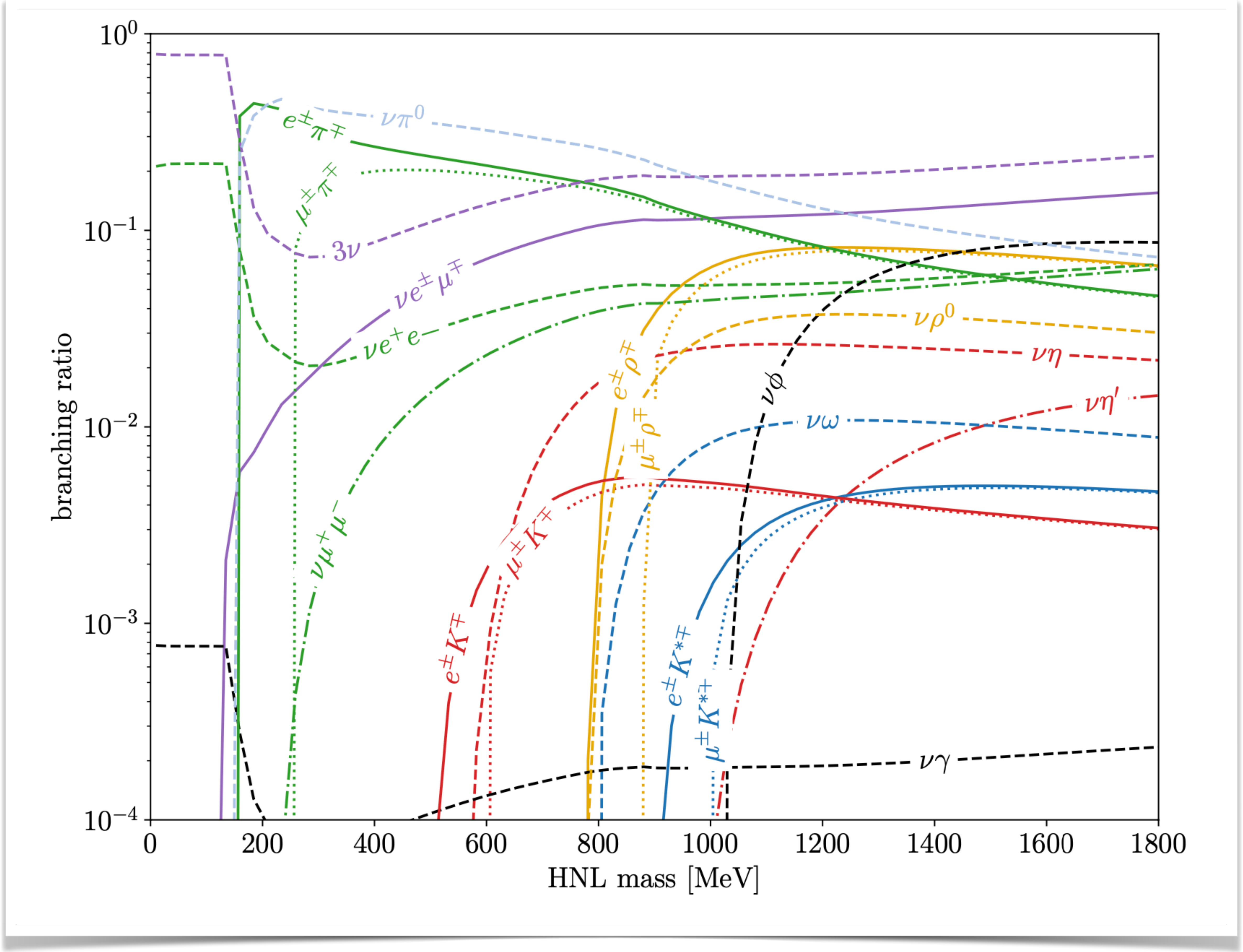


Heavier Sterile Neutrinos – “Heavy Neutral Leptons”



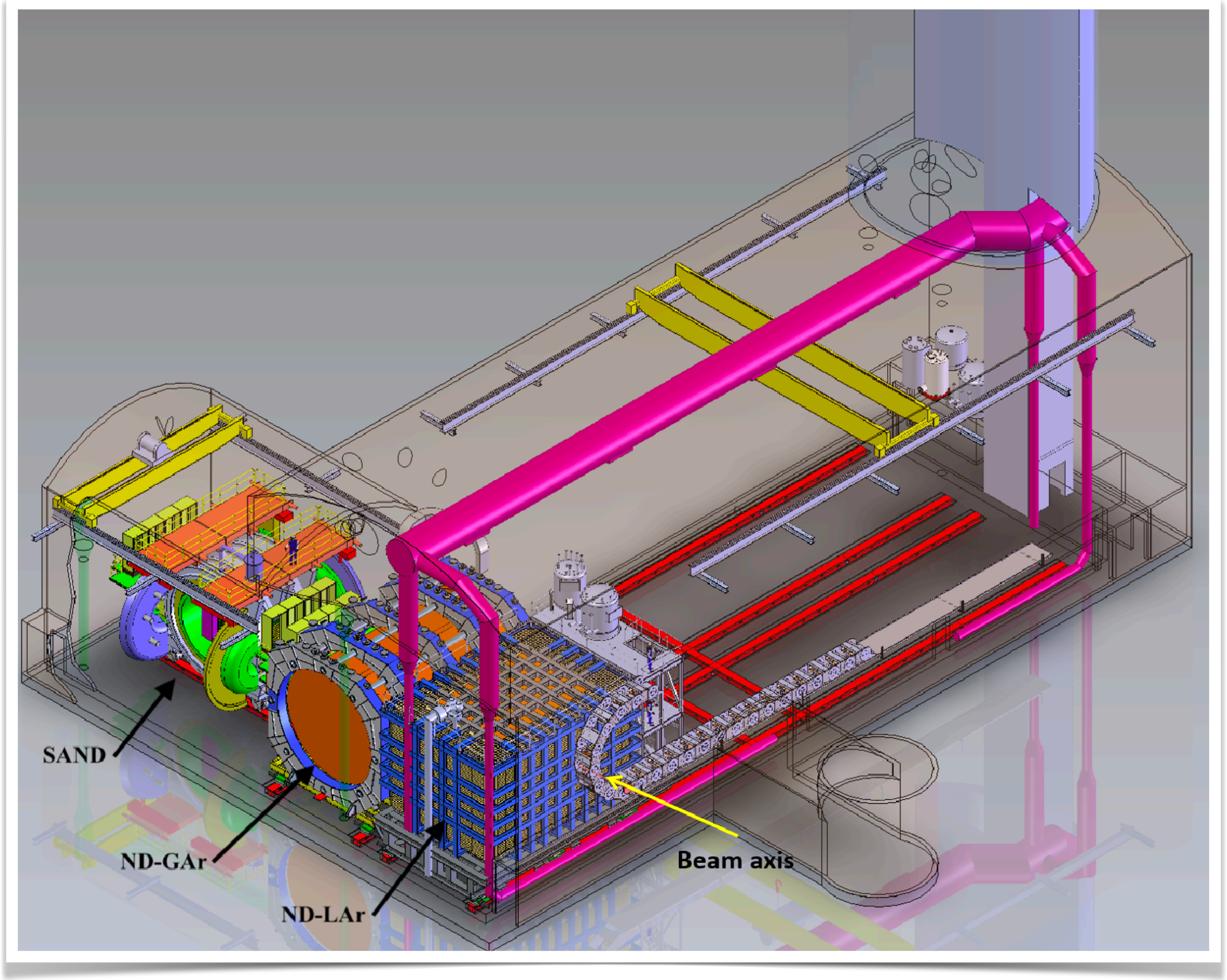
Heavier Sterile Neutrinos – “Heavy Neutral Leptons”



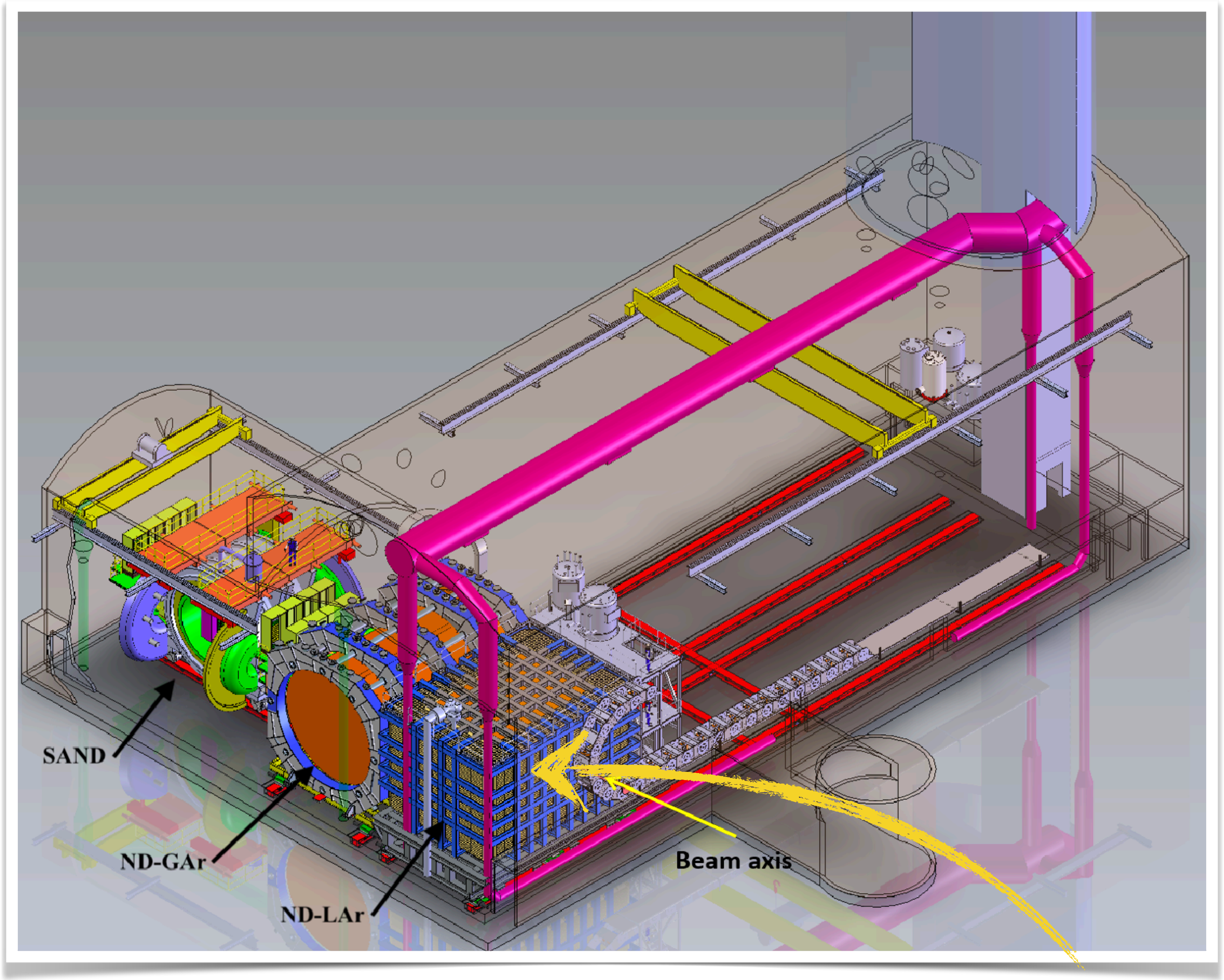


The DUNE Beam

The DUNE Near Detectors

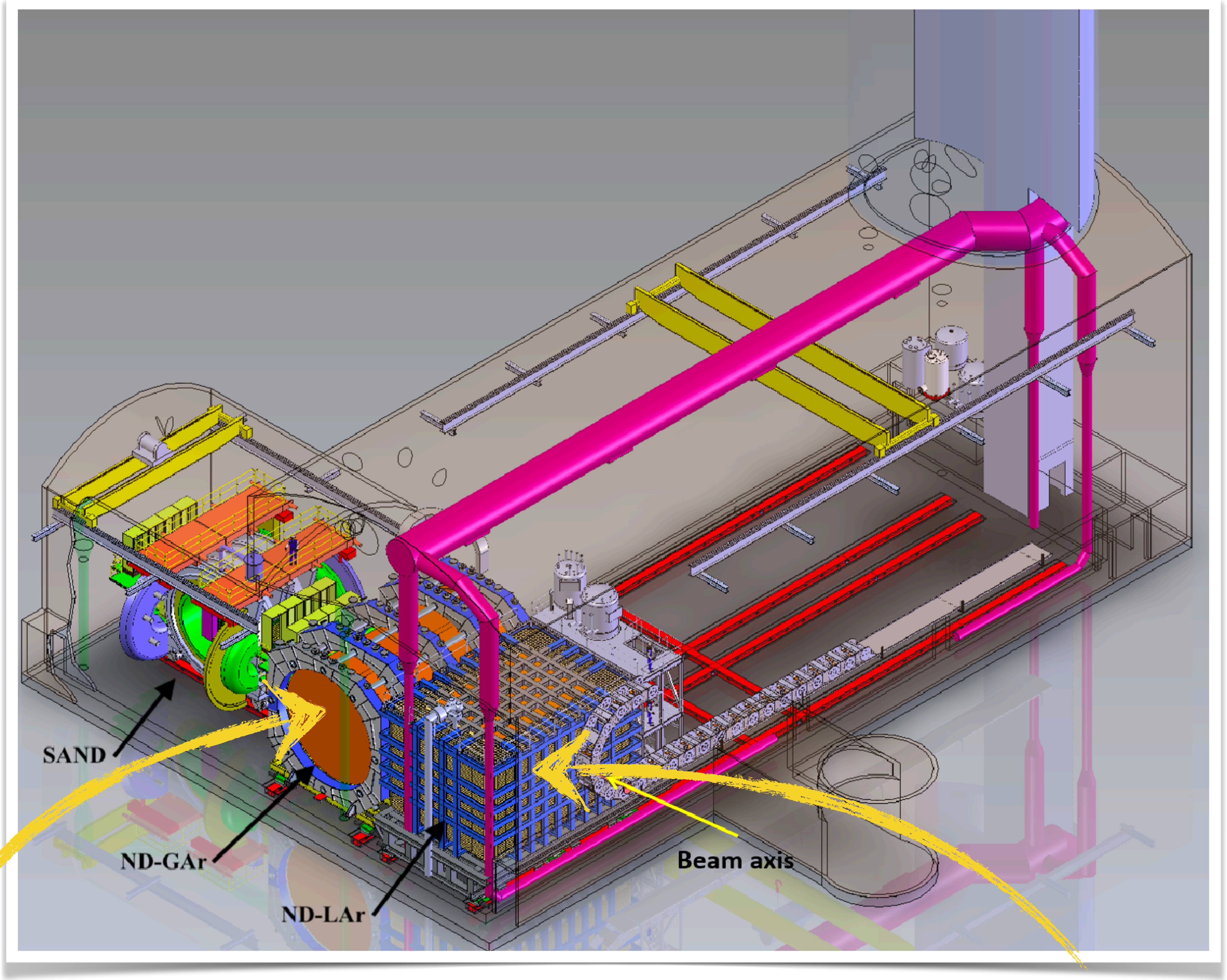


The DUNE Near Detectors



Liquid Argon TPC ("ND-LAr")

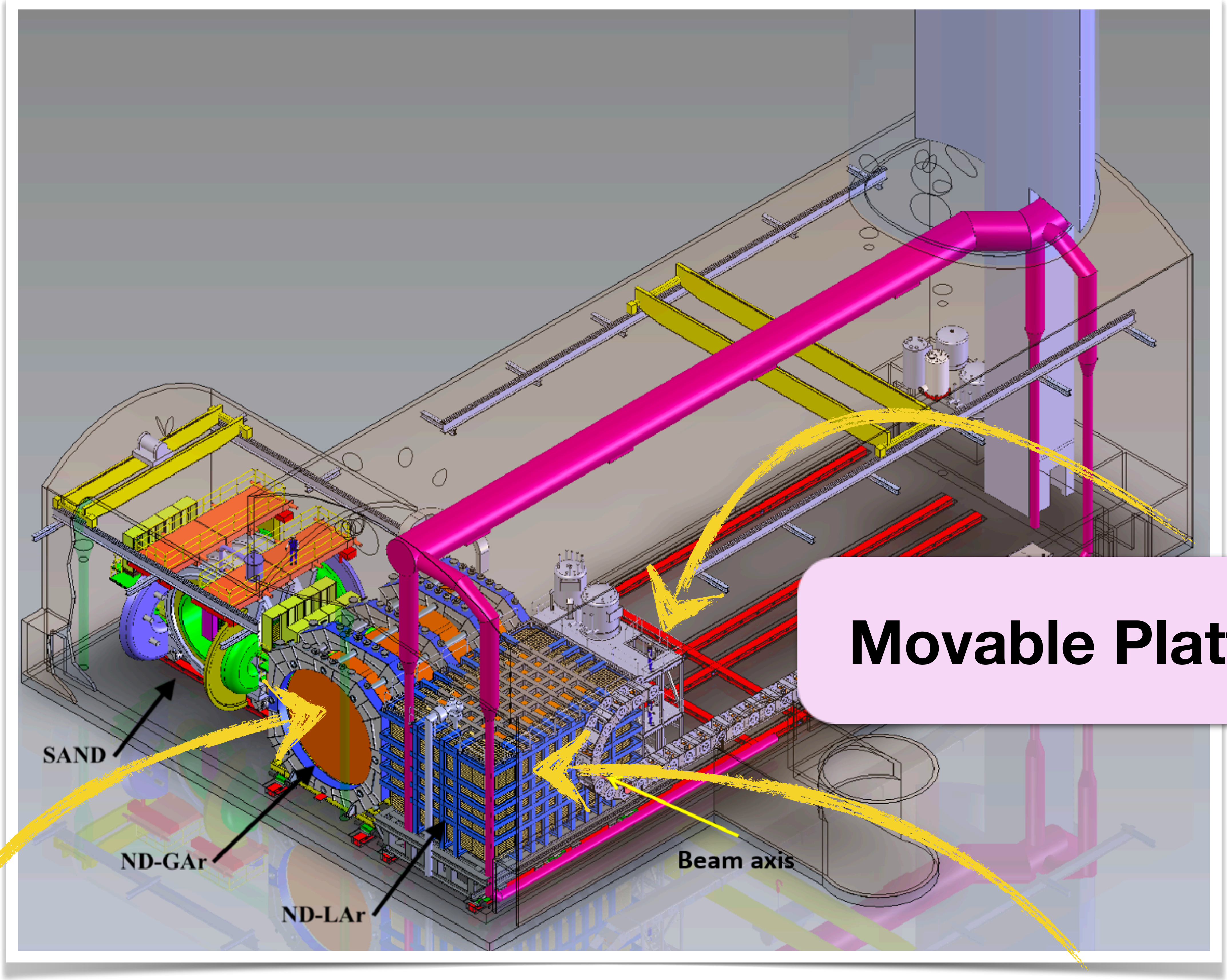
The DUNE Near Detectors



HP Gas TPC + ECal ("ND-GAr")

Liquid Argon TPC ("ND-LAr")

The DUNE Near Detectors

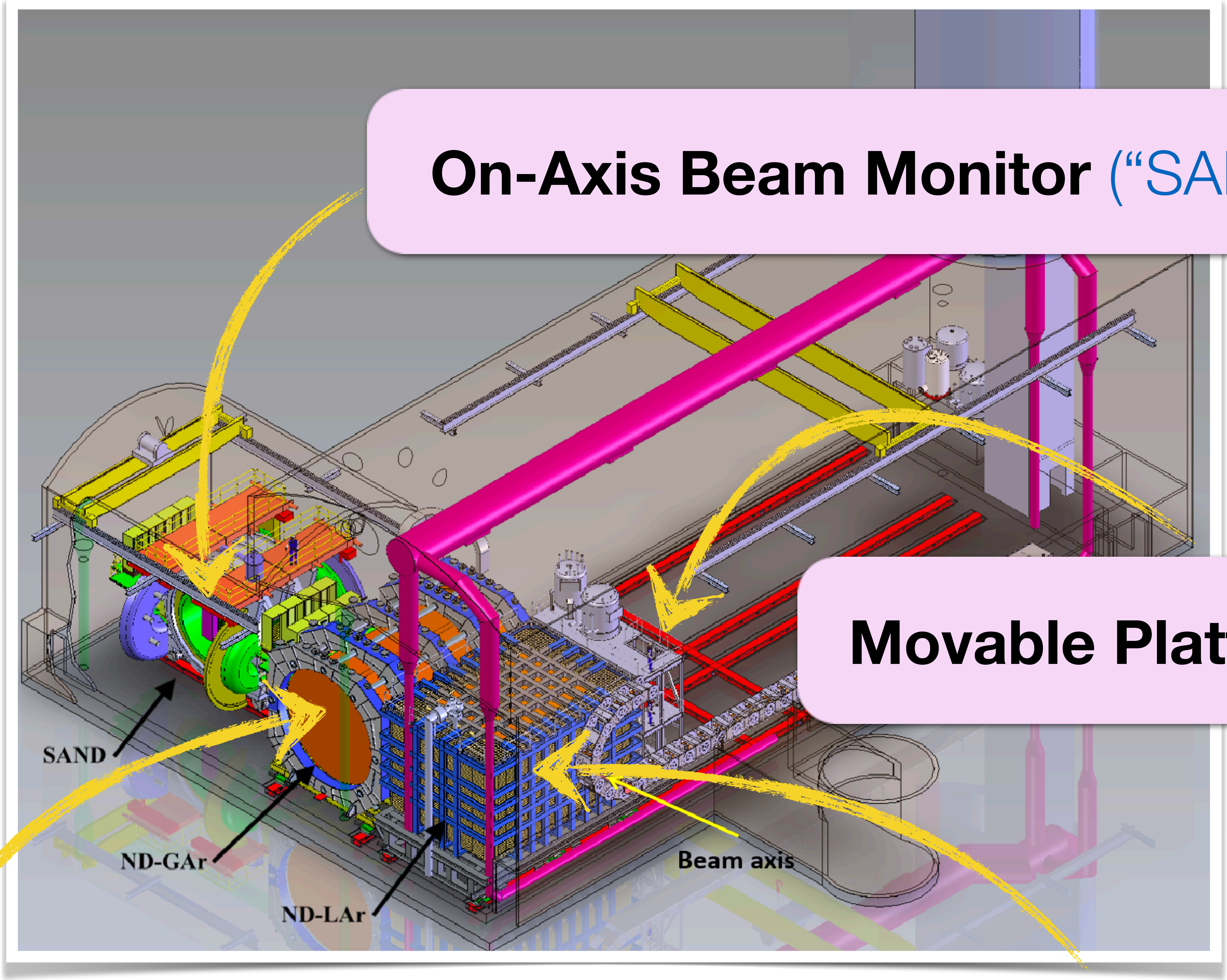


Movable Platform ("PRISM")

HP Gas TPC + ECal ("ND-GAr")

Liquid Argon TPC ("ND-LAr")

The DUNE Near Detectors



On-Axis Beam Monitor ("SAND")

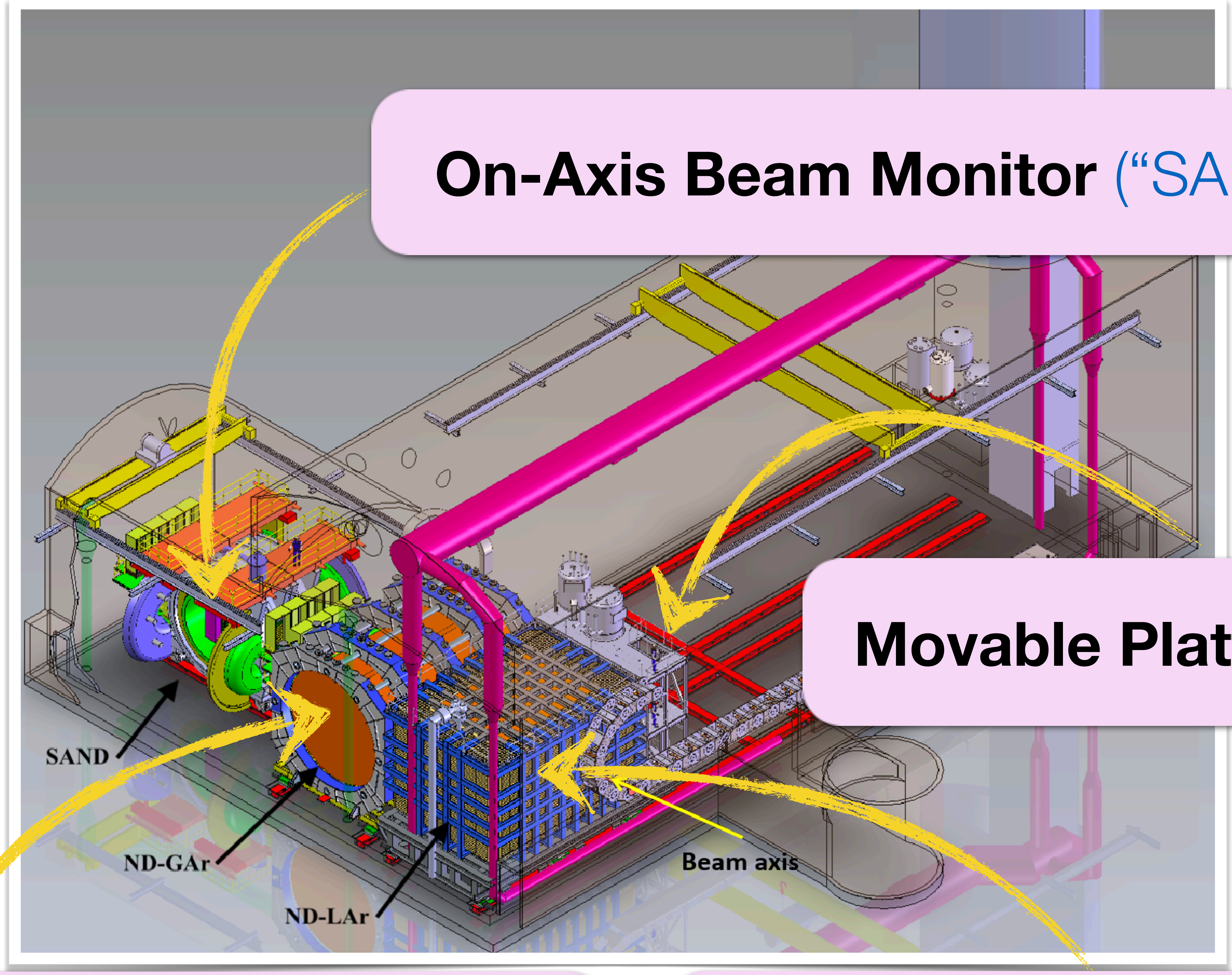
Movable Platform ("PRISM")

HP Gas TPC + ECal ("ND-GAr")

Liquid Argon TPC ("ND-LAr")

The DUNE Near Detectors

On-Axis Beam Monitor (“SAND”)

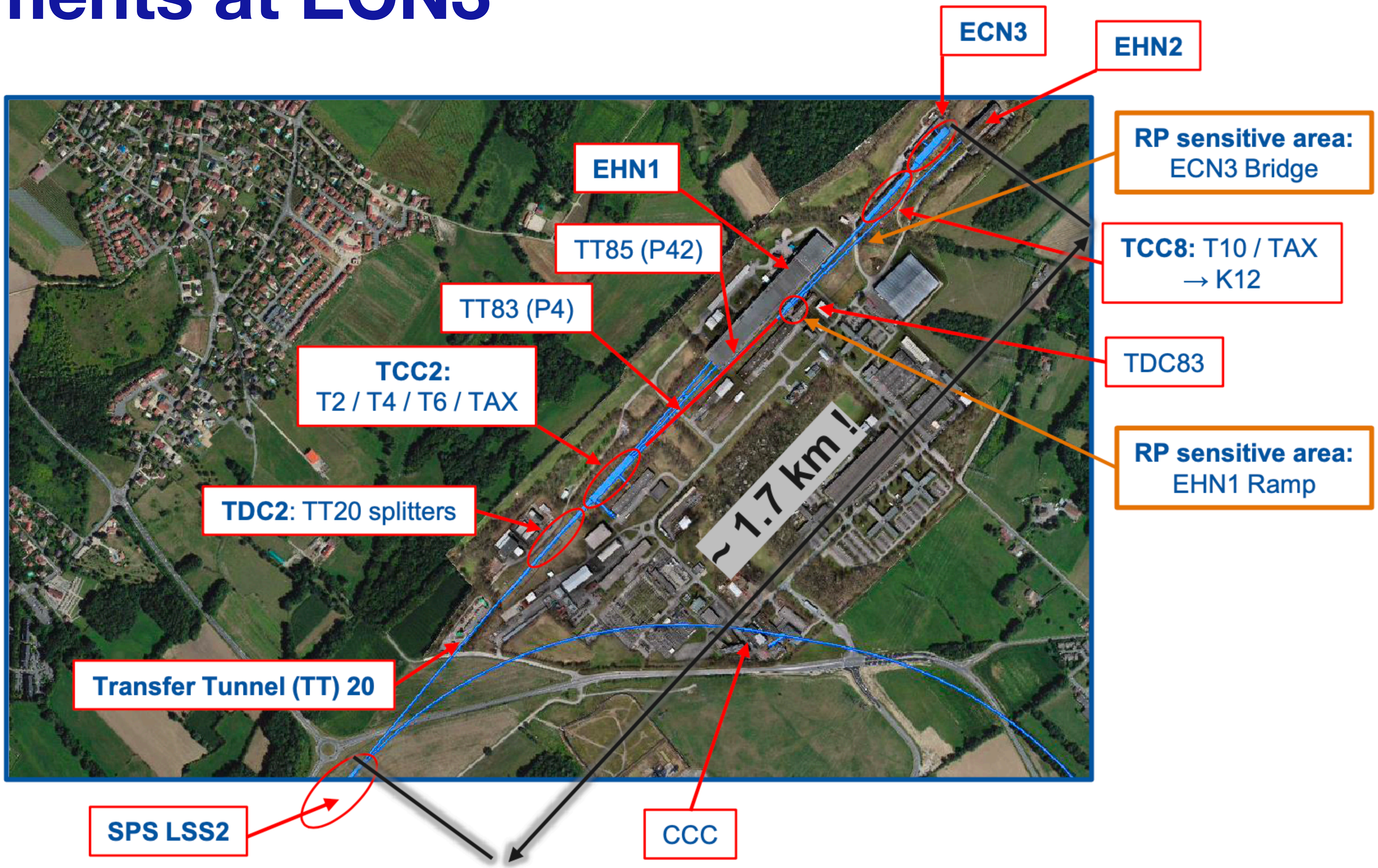


Movable Platform (“PRISM”)

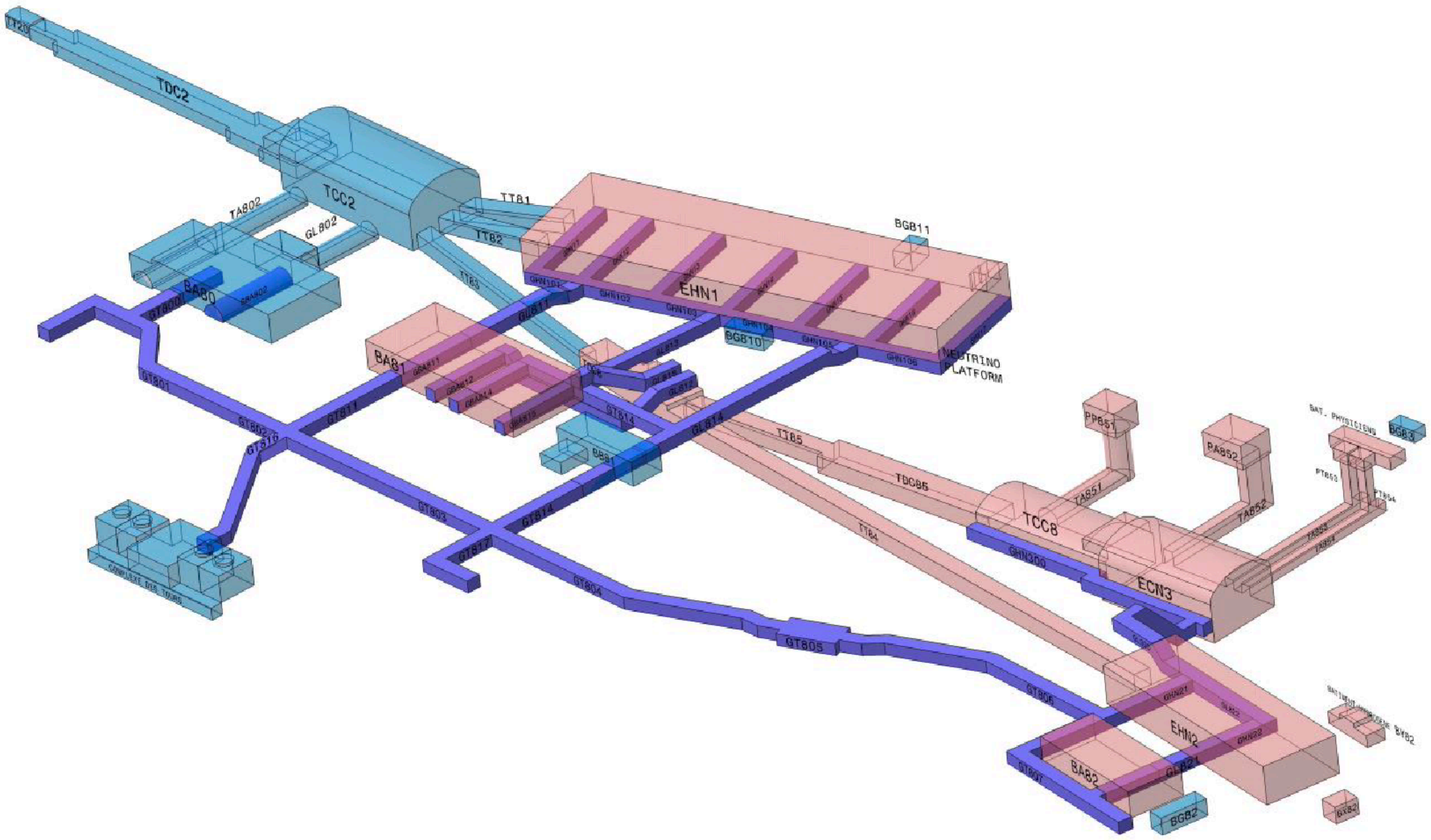
HP Gas TPC + ECal (“SEASIDE”)
(**S**ystem of **E**vaporated **A**rgon for **S**ystematics, **I**nteractions, and **D**etailed **E**vent Topologies)

Liquid Argon TPC (“LAGOON”)
(**L**iquid **A**rgon **G**adget for **O**n-axis and **O**ff-axis **N**eutrinos

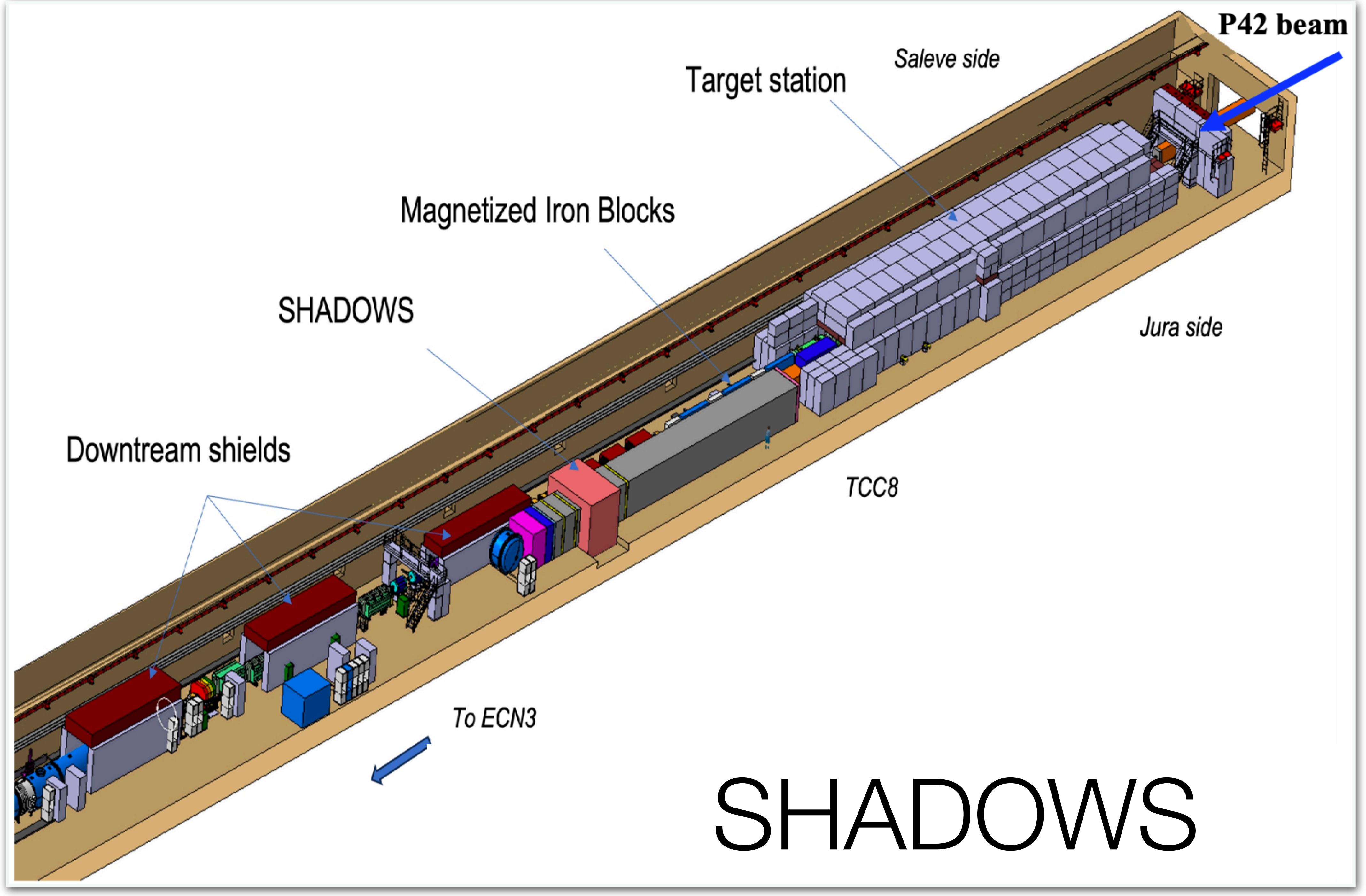
New Experiments at ECN3

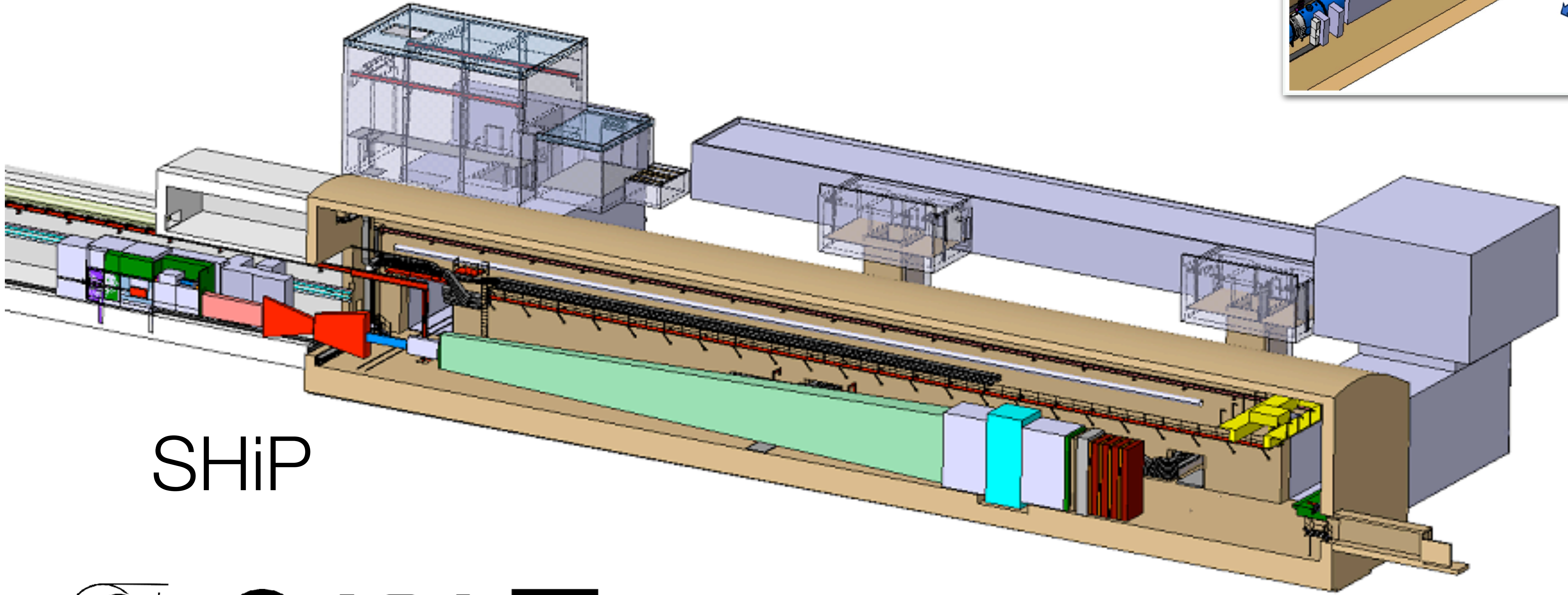


New Experiments at ECN3



A New Experiment at ECN3

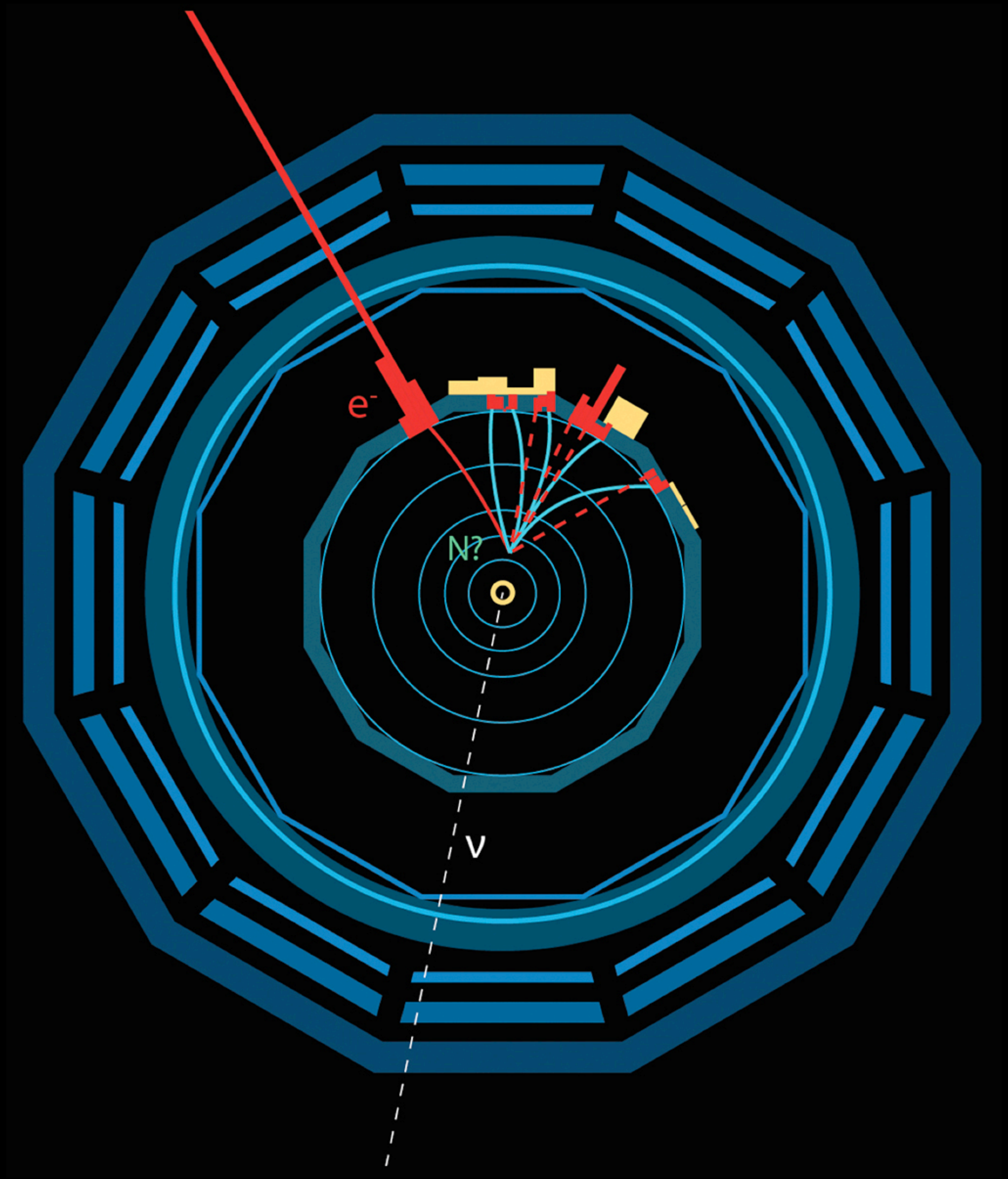




SHiP

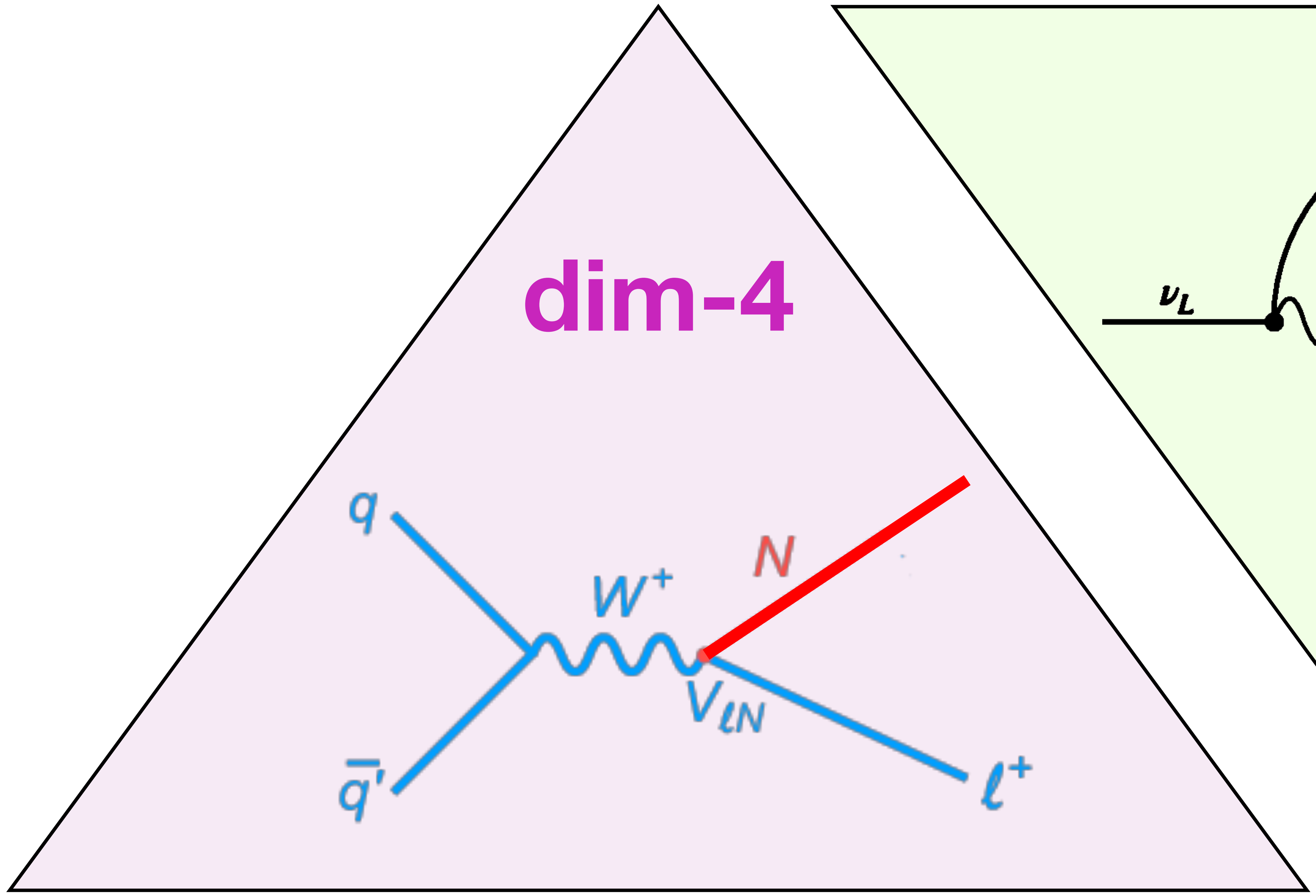
Heavy Neutral Leptons at Colliders

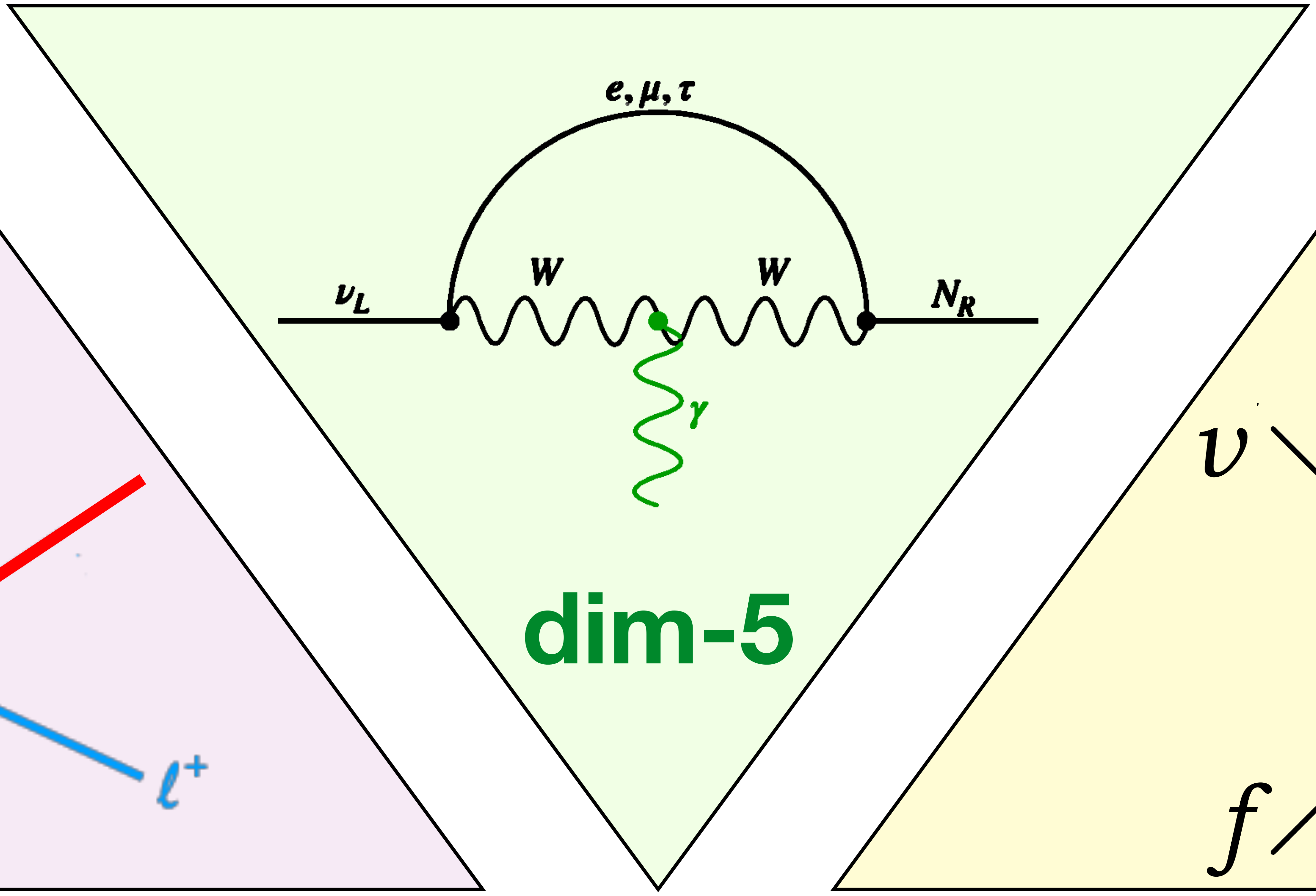
*remember: sterile neutrino = heavy neutral lepton = right-handed neutrino

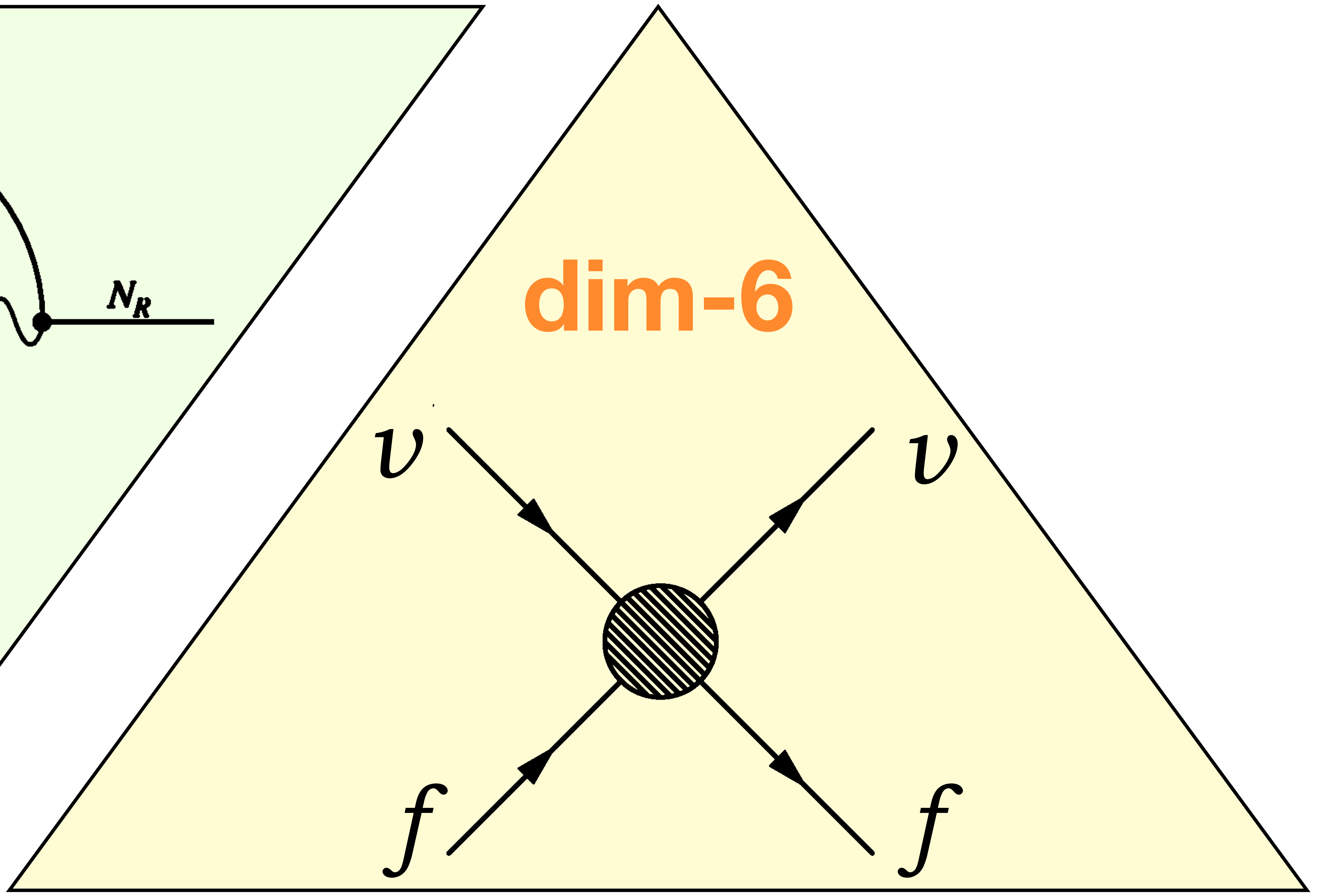


Neutrino Physics Beyond the Standard Model

e.g. neutrino magnetic moments



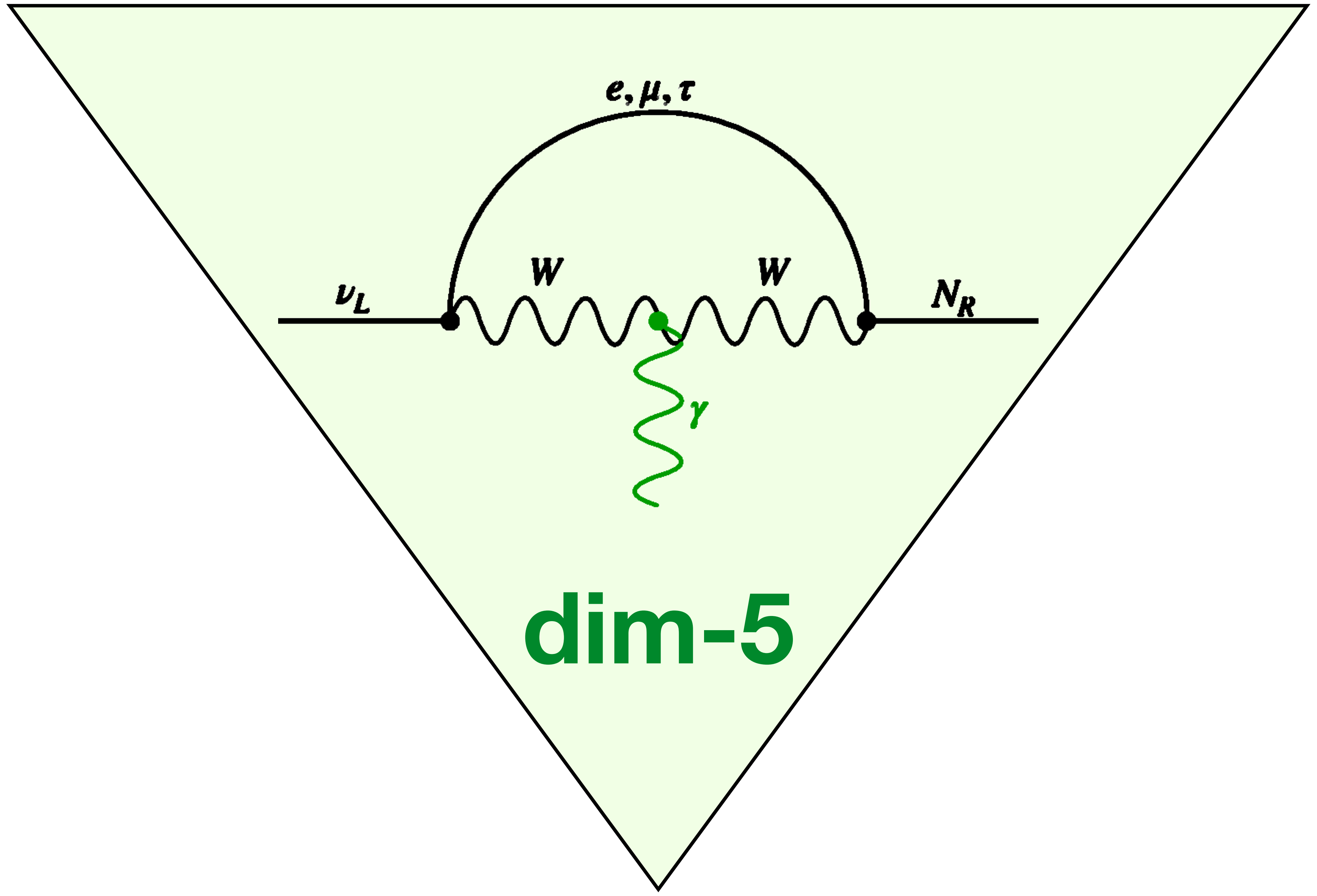




e.g. sterile neutrinos

e.g. non-standard interactions

Neutrino Magnetic Moments



Neutrino Magnetic Moments

Petcov 1977
Fujikawa Shrock 1980

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

Neutrino Magnetic Moments

- Magnetic m

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

Neutrino Magnetic Moments

- Magnetic m

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

Couples LH and RH neutrinos

electromagnetic field strength tensor

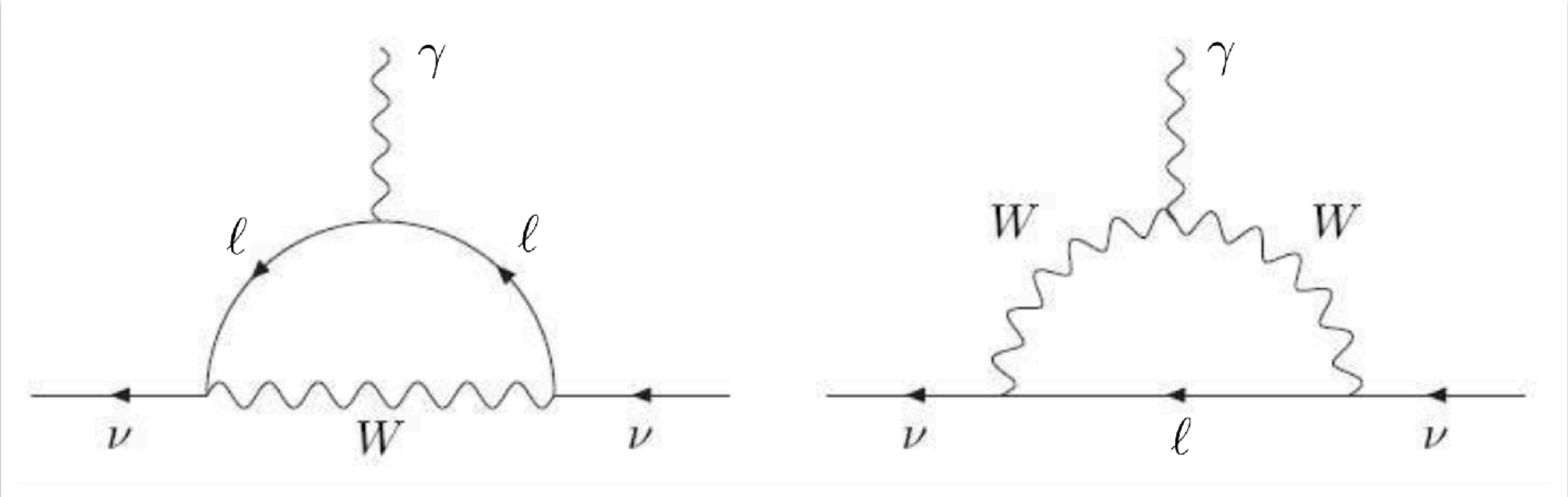
Petcov 1977
Fujikawa Shrock 1980

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



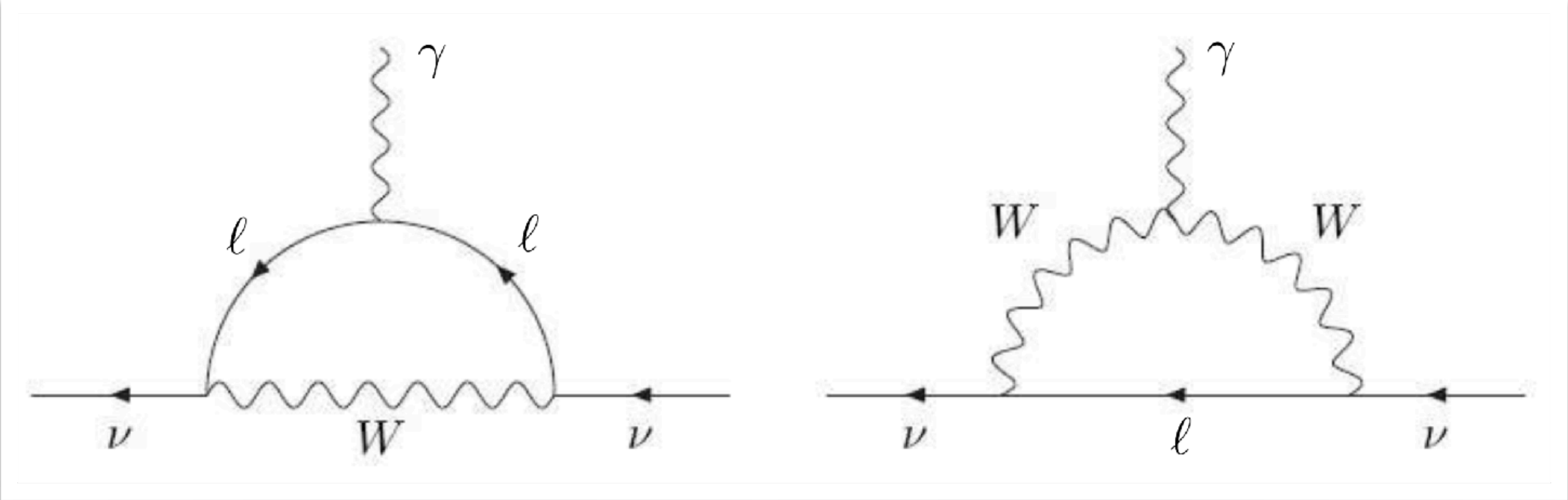
Petcov 1977
Fujikawa Shrock 1980

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

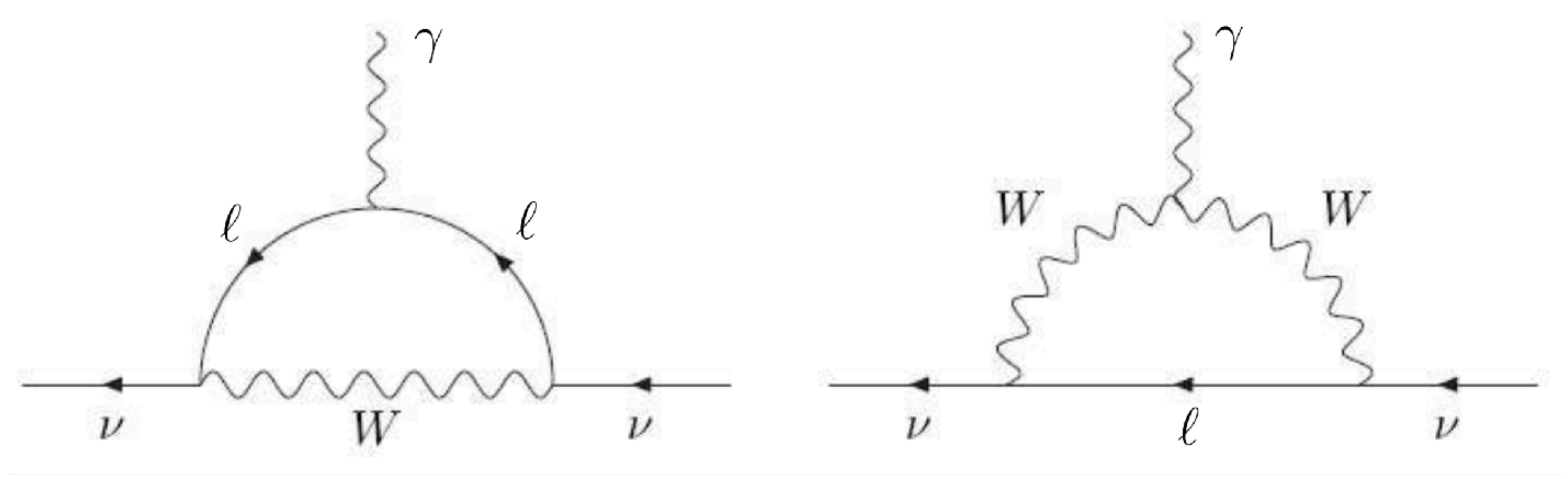
Petcov 1977
Fujikawa Shrock 1980

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

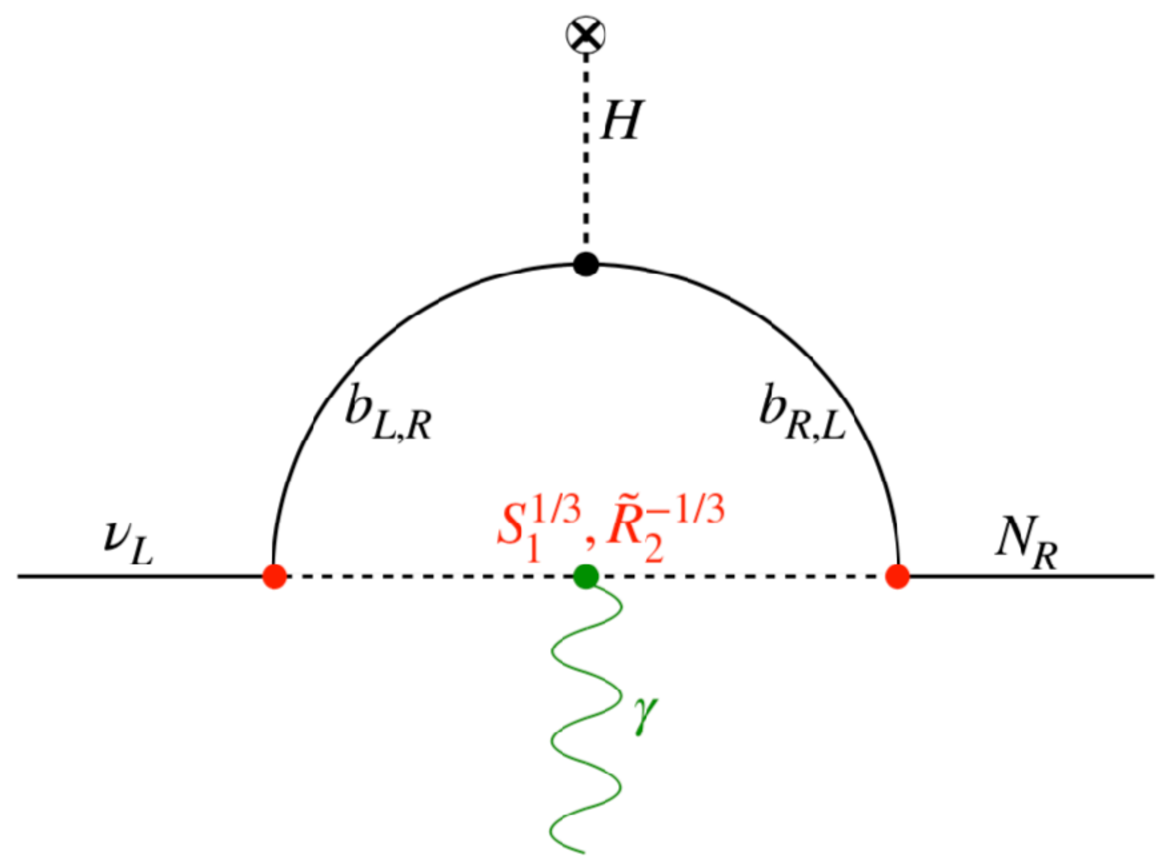


- Numerically tiny: $10^{-19}\ \mu_B$

Petcov 1977
Fujikawa Shrock 1980

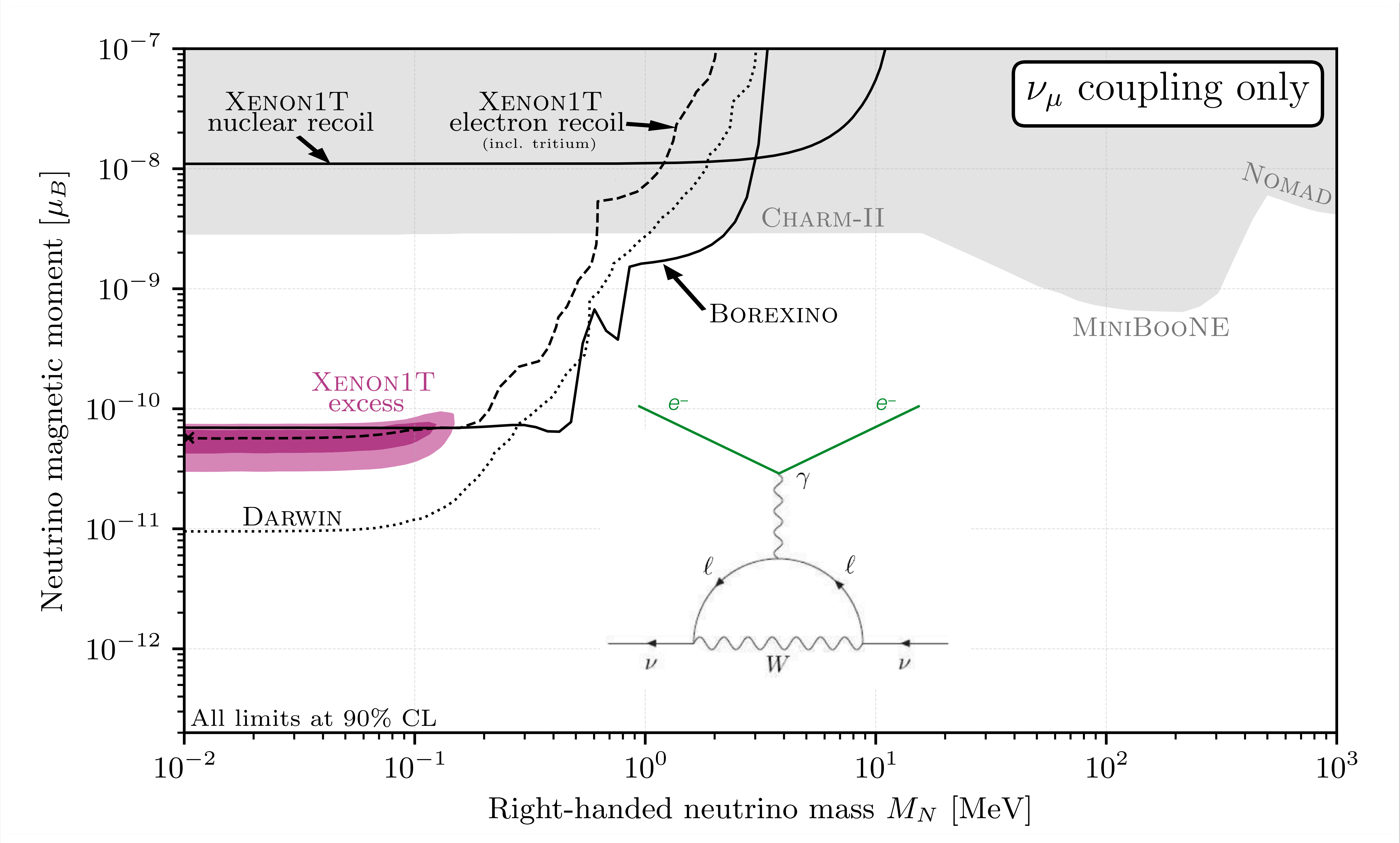
- Can be significantly enhanced in extensions of the SM

leptoquark model, inspired by B physics anomalies



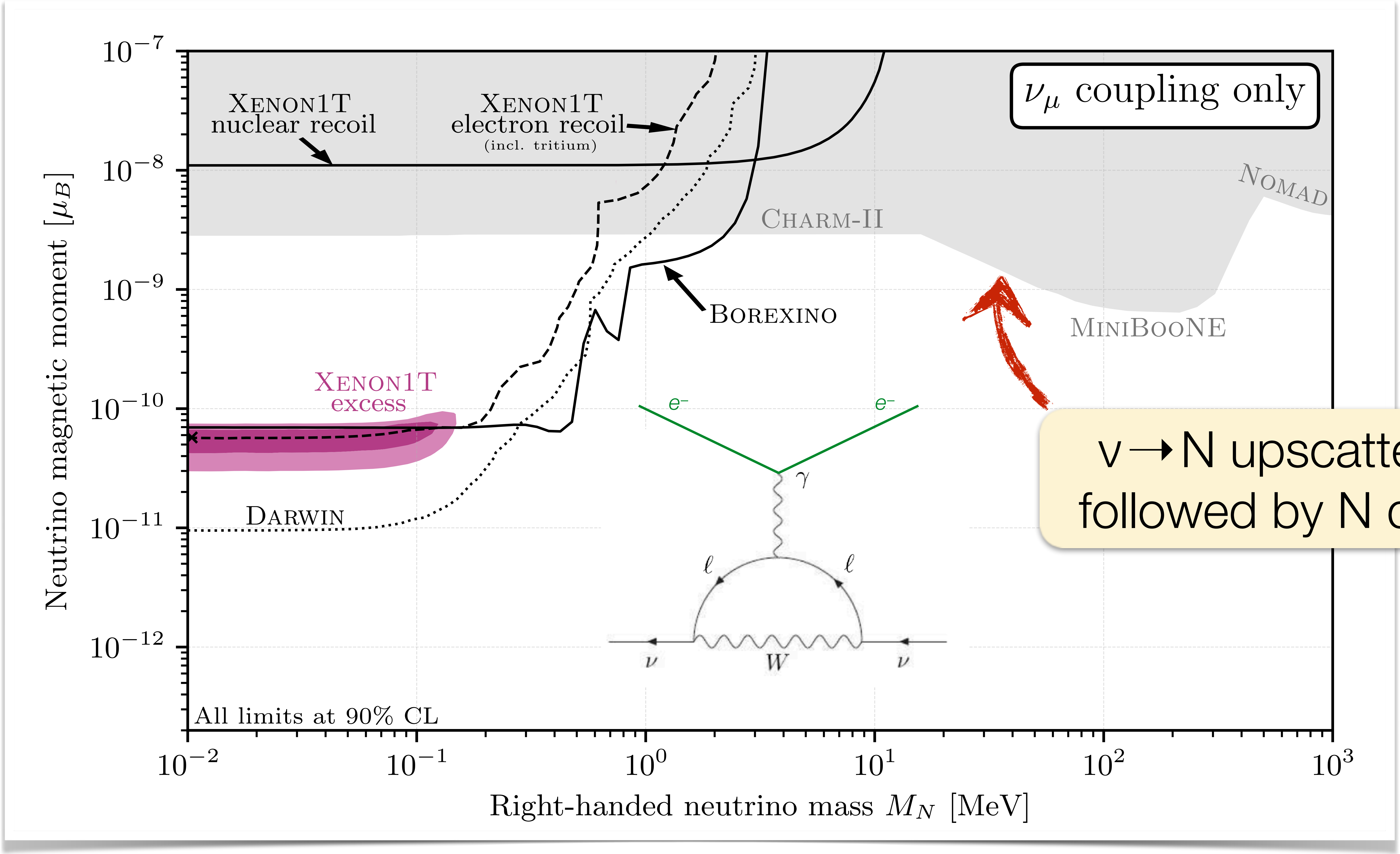
Brdar Greljo JK Opferkuch
2007.15563

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

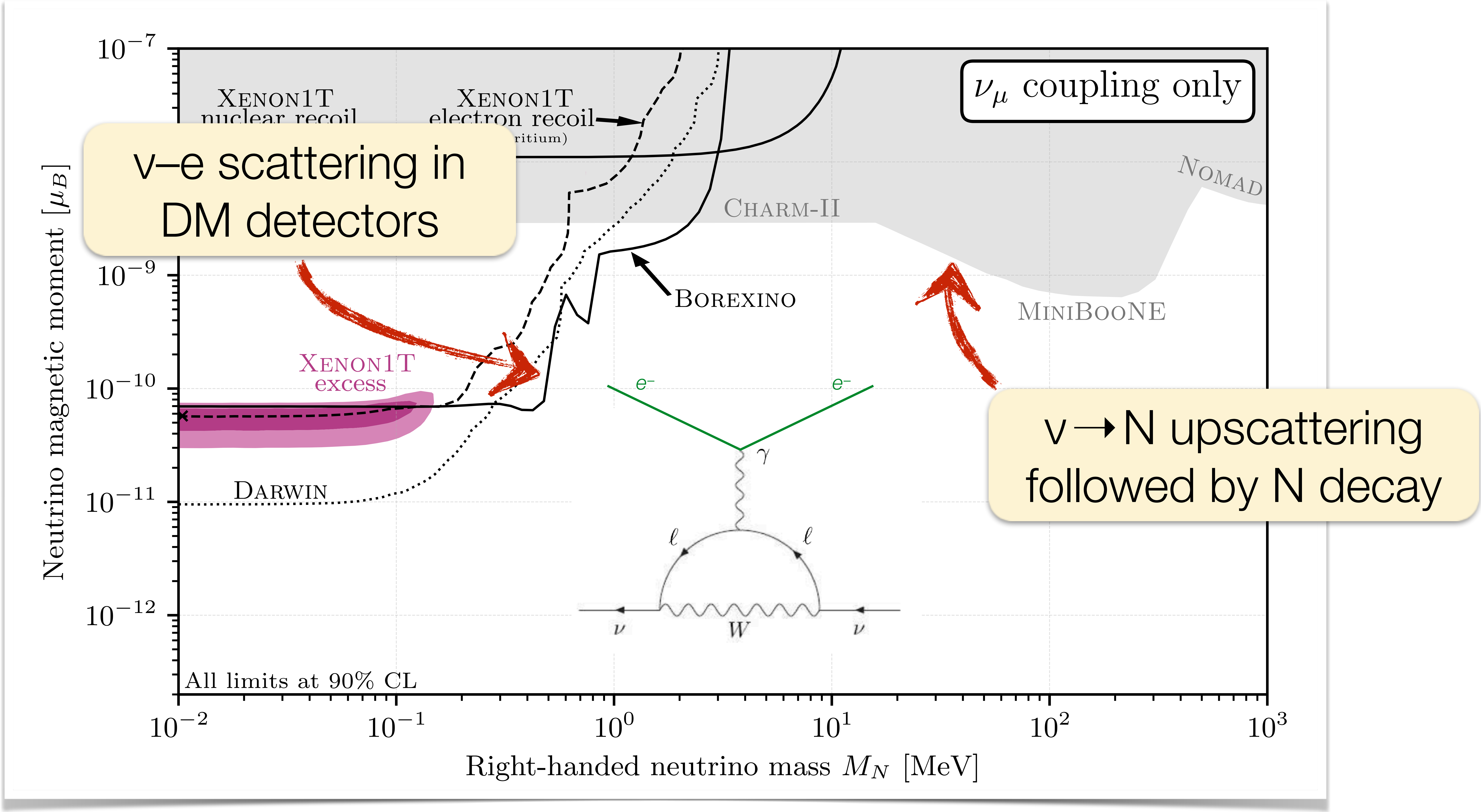
Neutrino Magnetic Moments: Constraints



ν → N upscattering followed by N decay

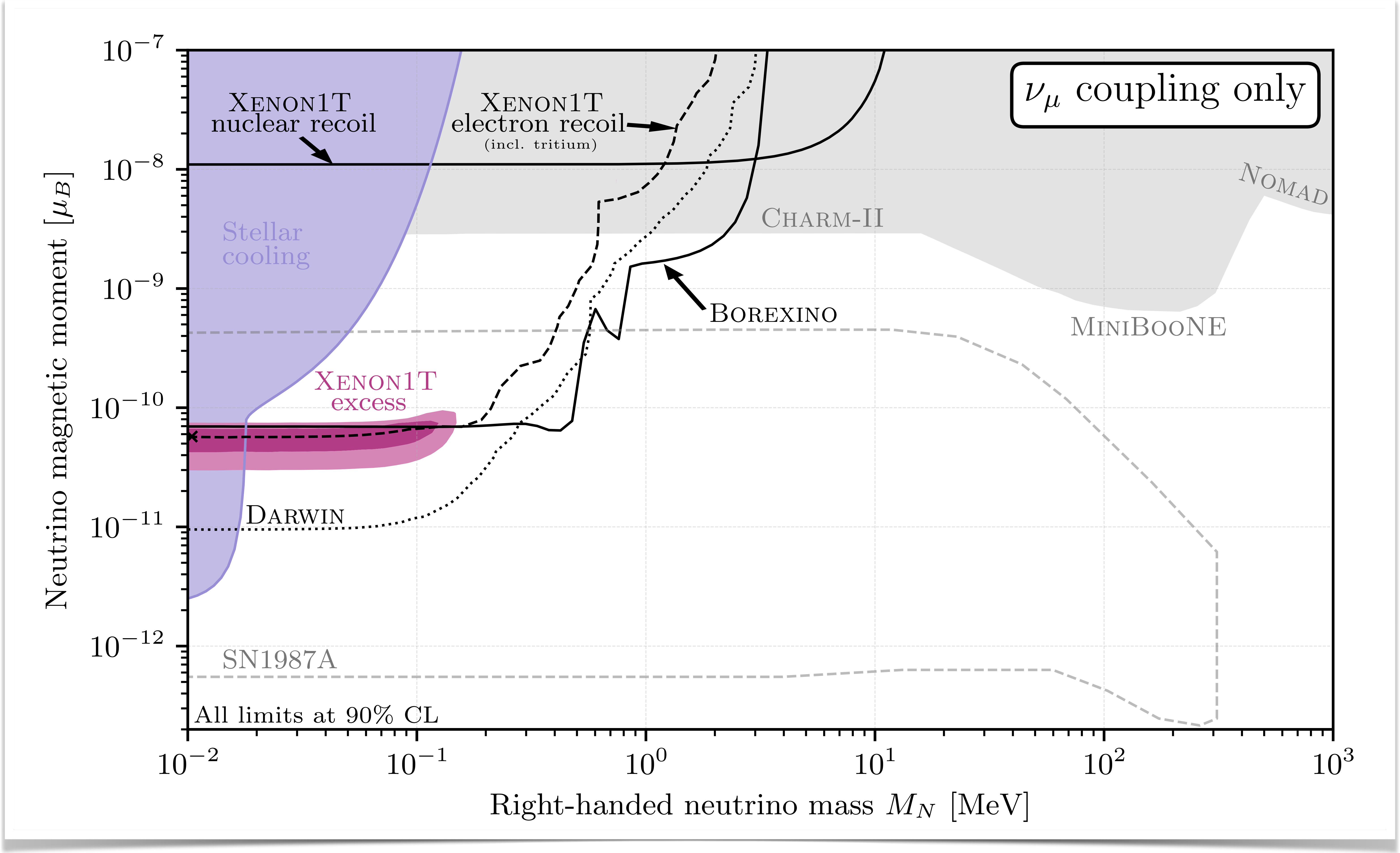
Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

Neutrino Magnetic Moments: Constraints



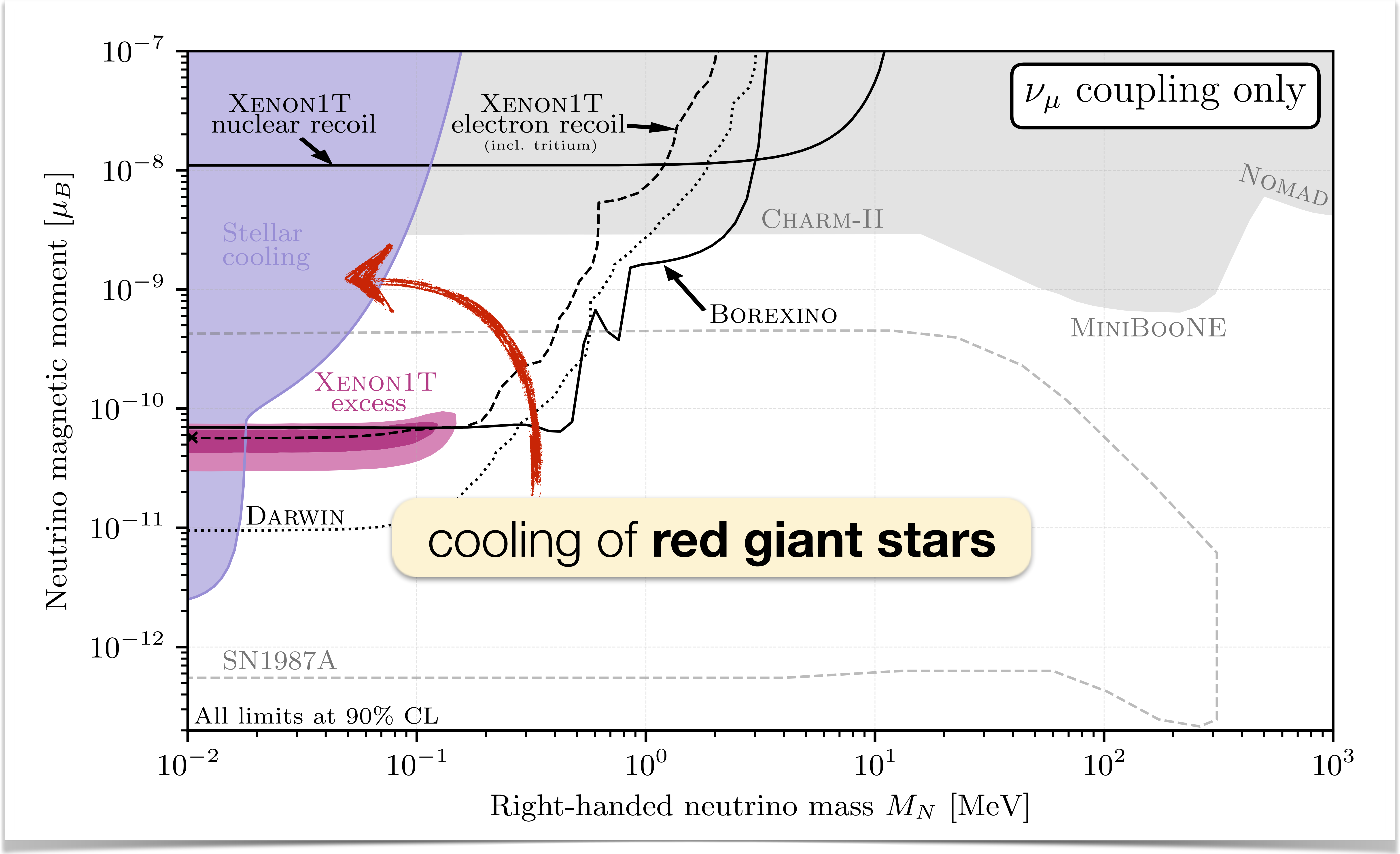
Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

Neutrino Magnetic Moments: Constraints



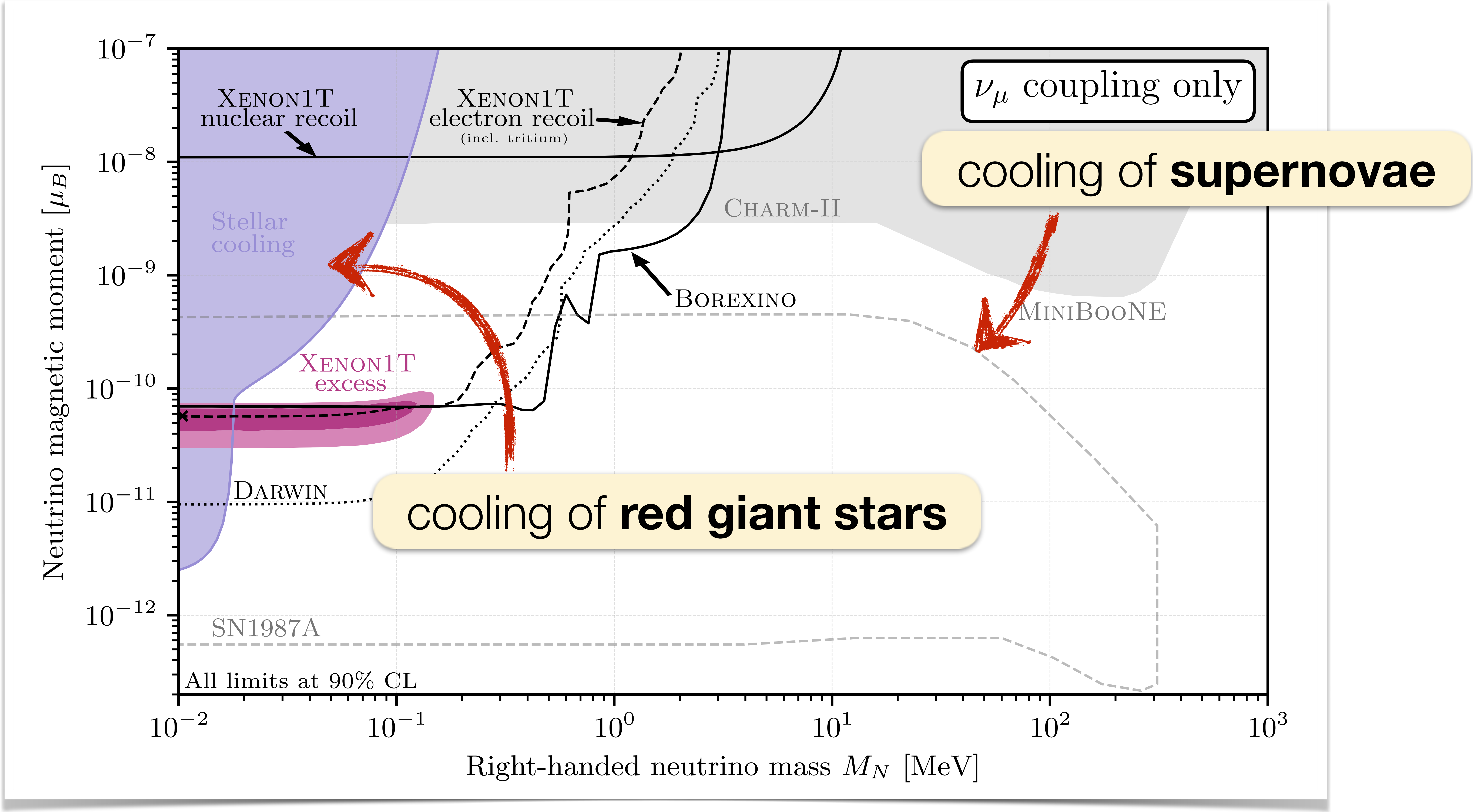
Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

Neutrino Magnetic Moments: Constraints



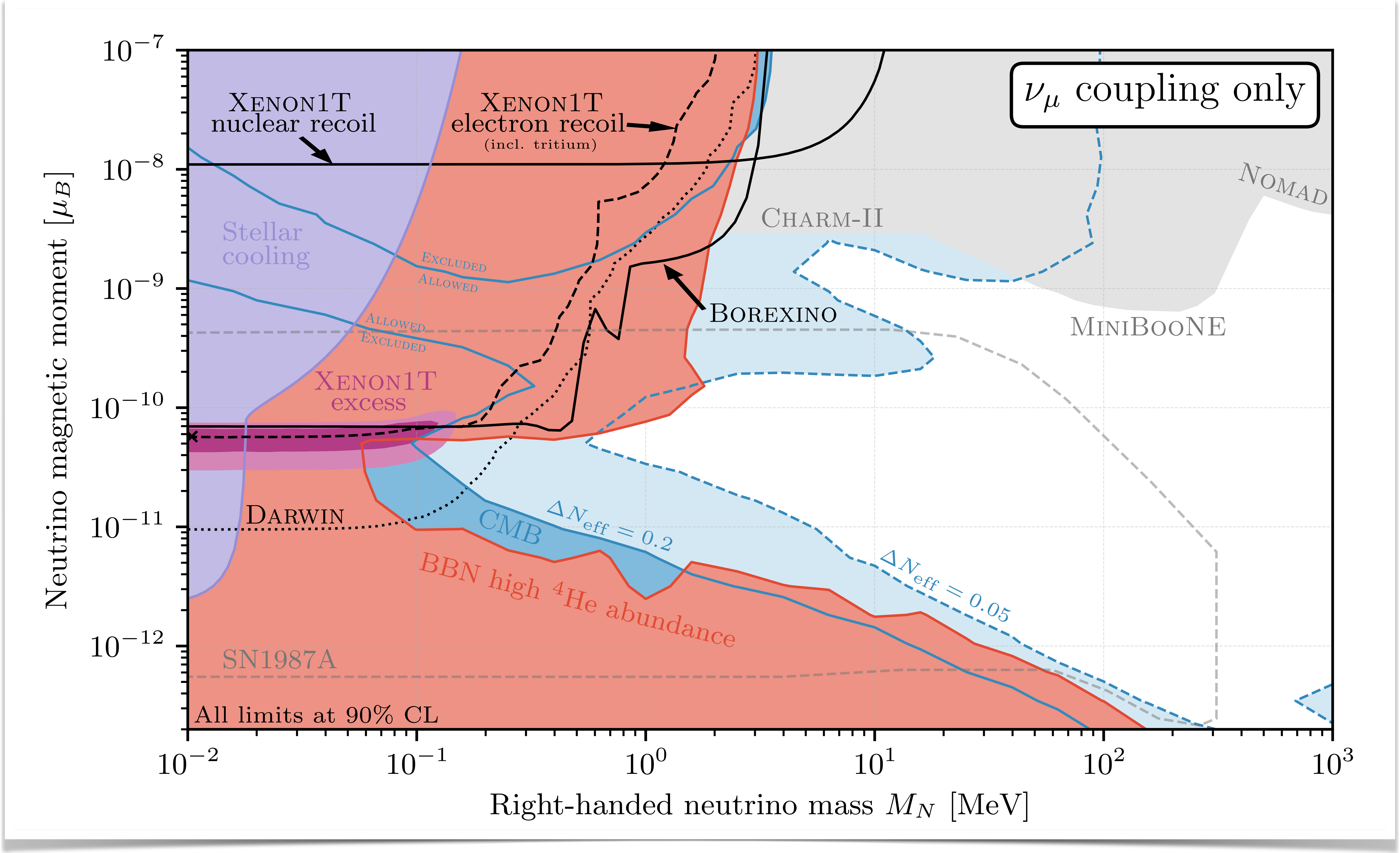
Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

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

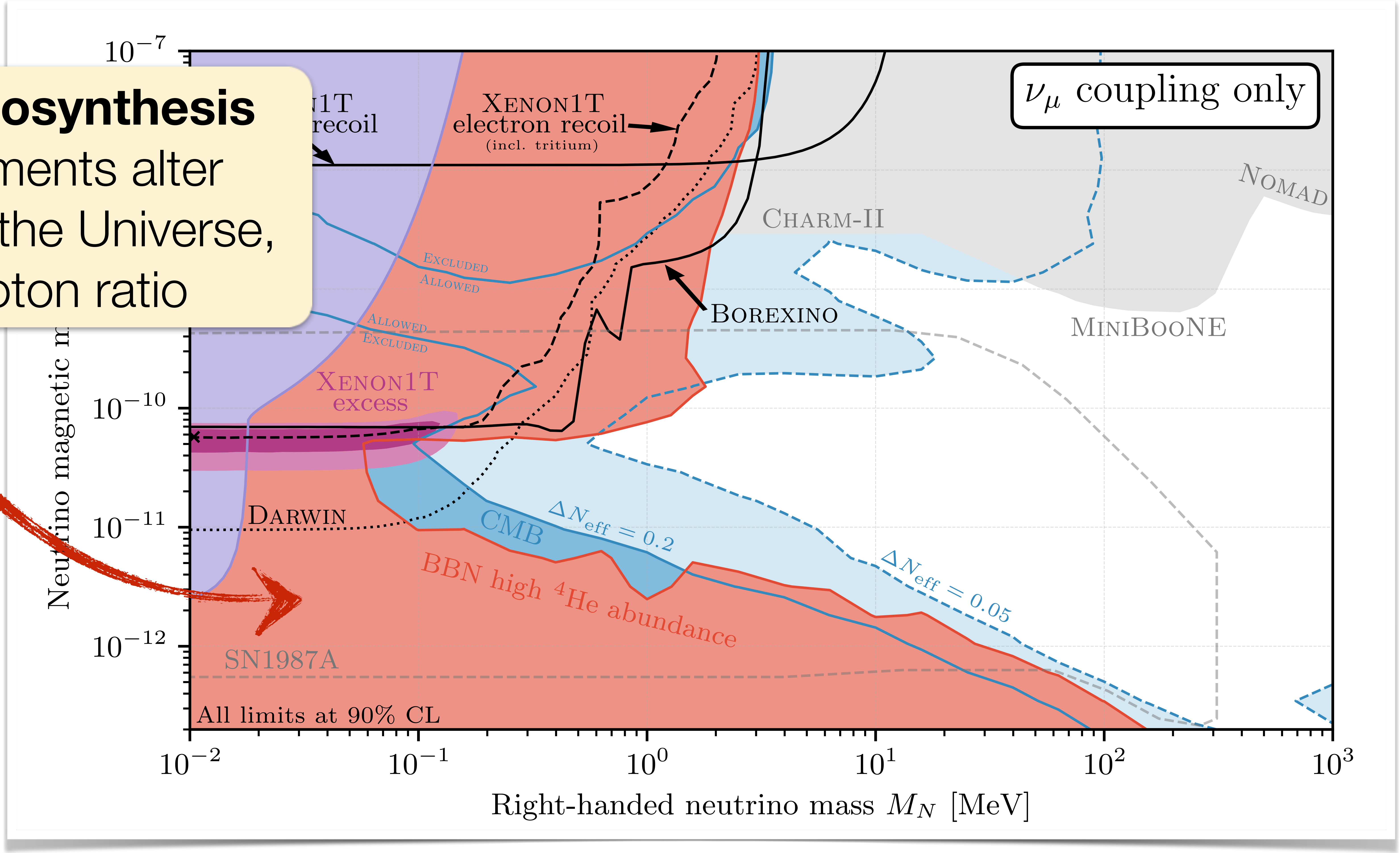
Neutrino Magnetic Moments: Constraints



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

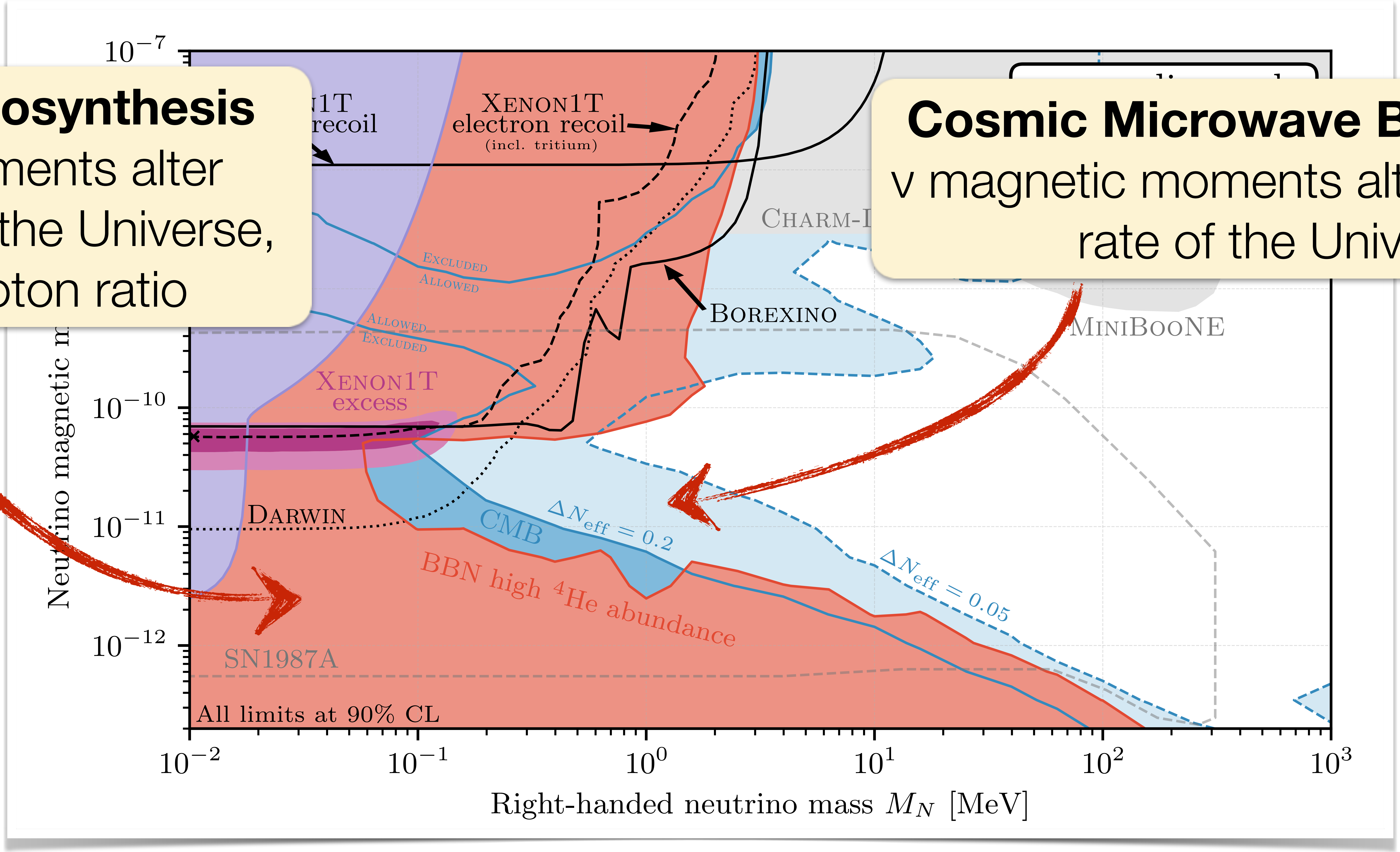


Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

Neutrino Magnetic Moments: Constraints

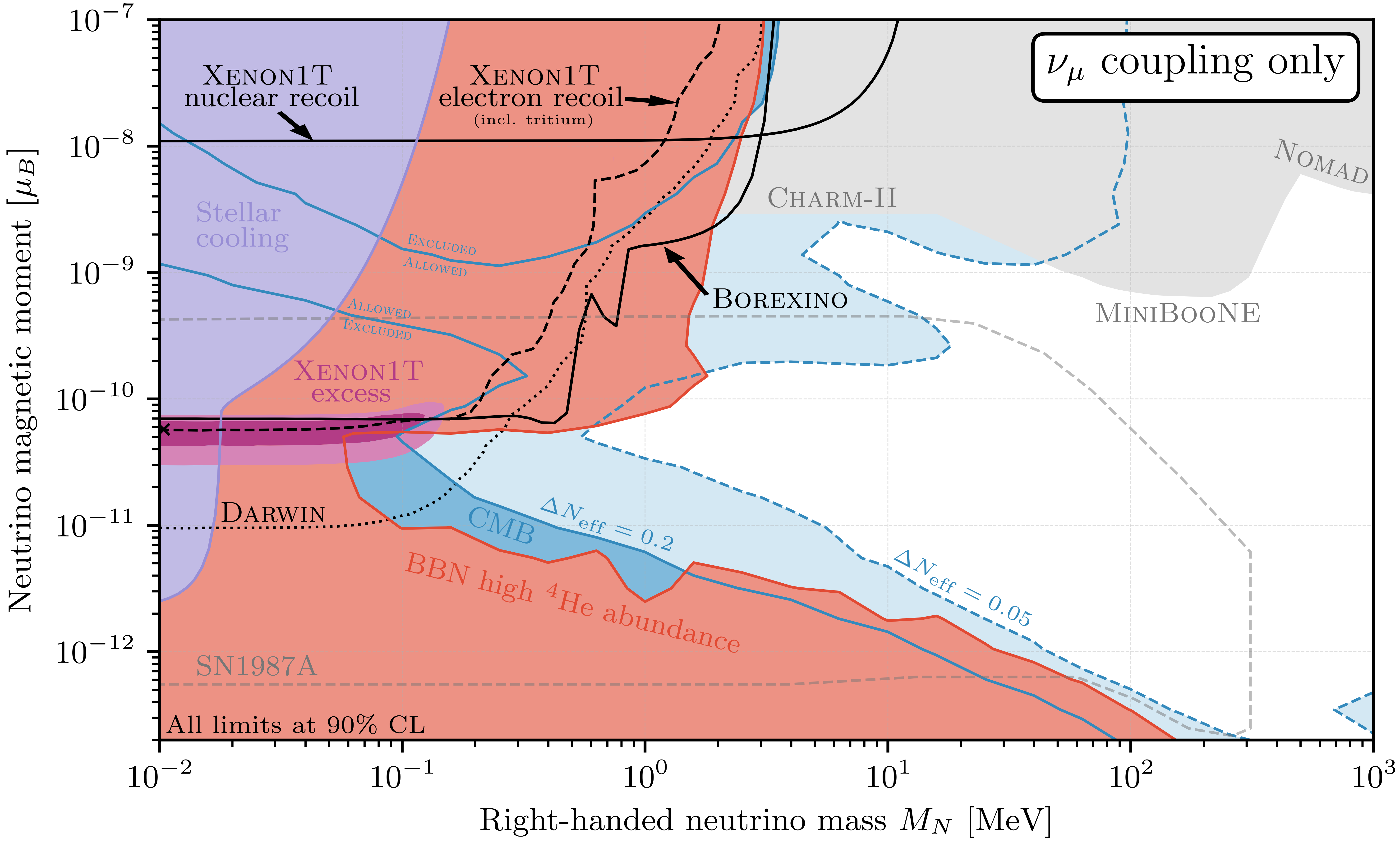
Big Bang Nucleosynthesis
ν magnetic moments alter expansion rate of the Universe, baryon-to-photon ratio

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



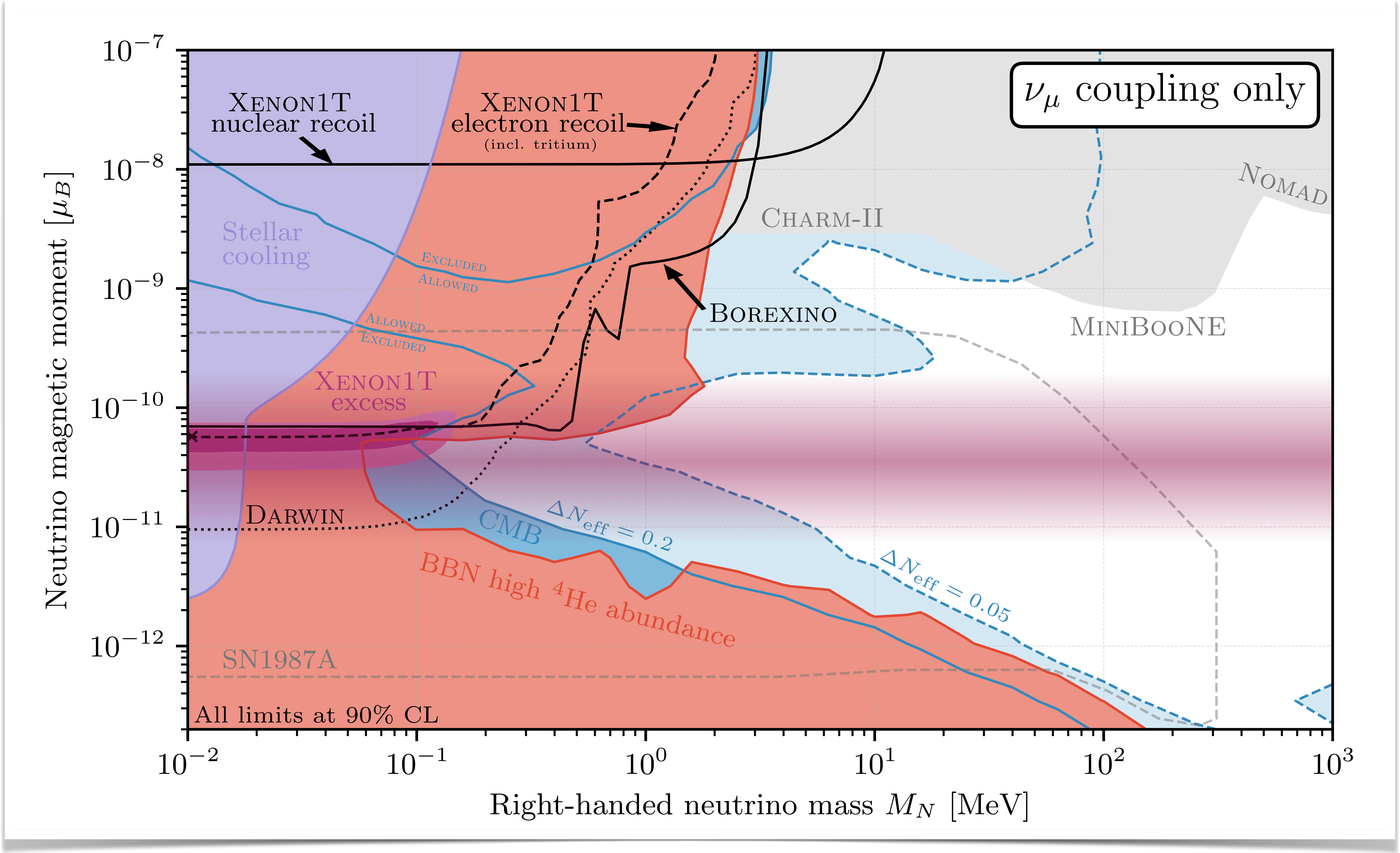
Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

Neutrino Magnetic Moments: Constraints



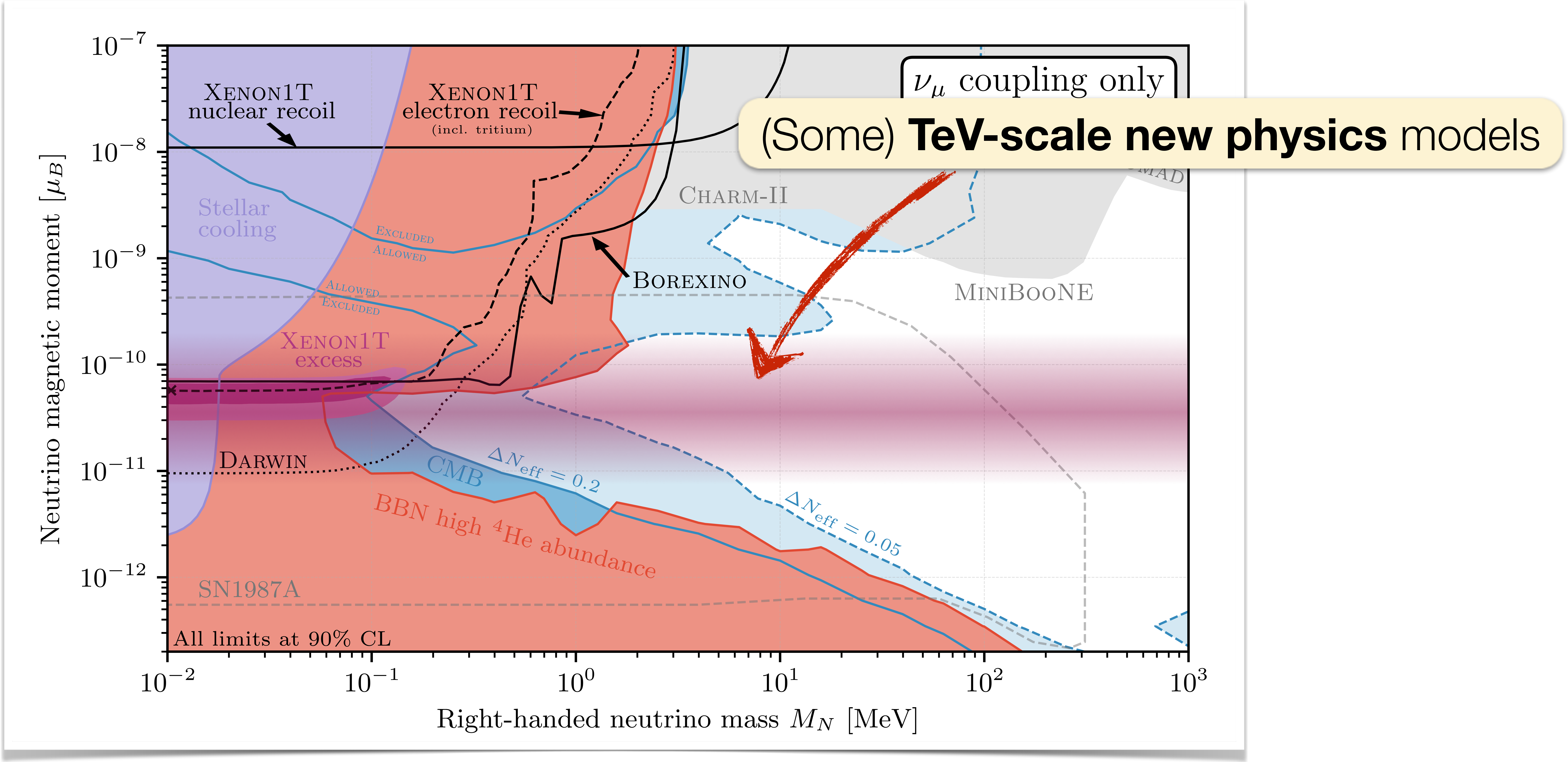
Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

Neutrino Magnetic Moments: Constraints



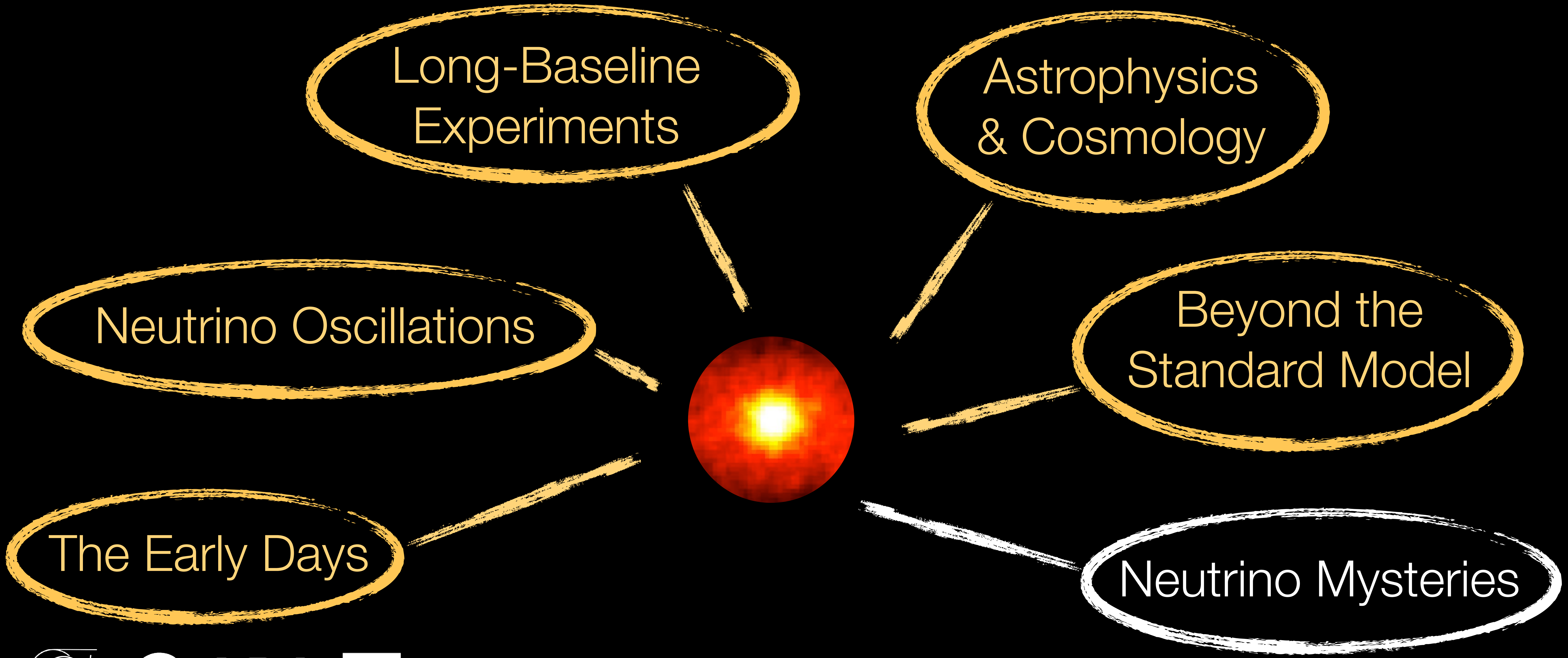
Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

Neutrino Magnetic Moments: Constraints



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

LSND

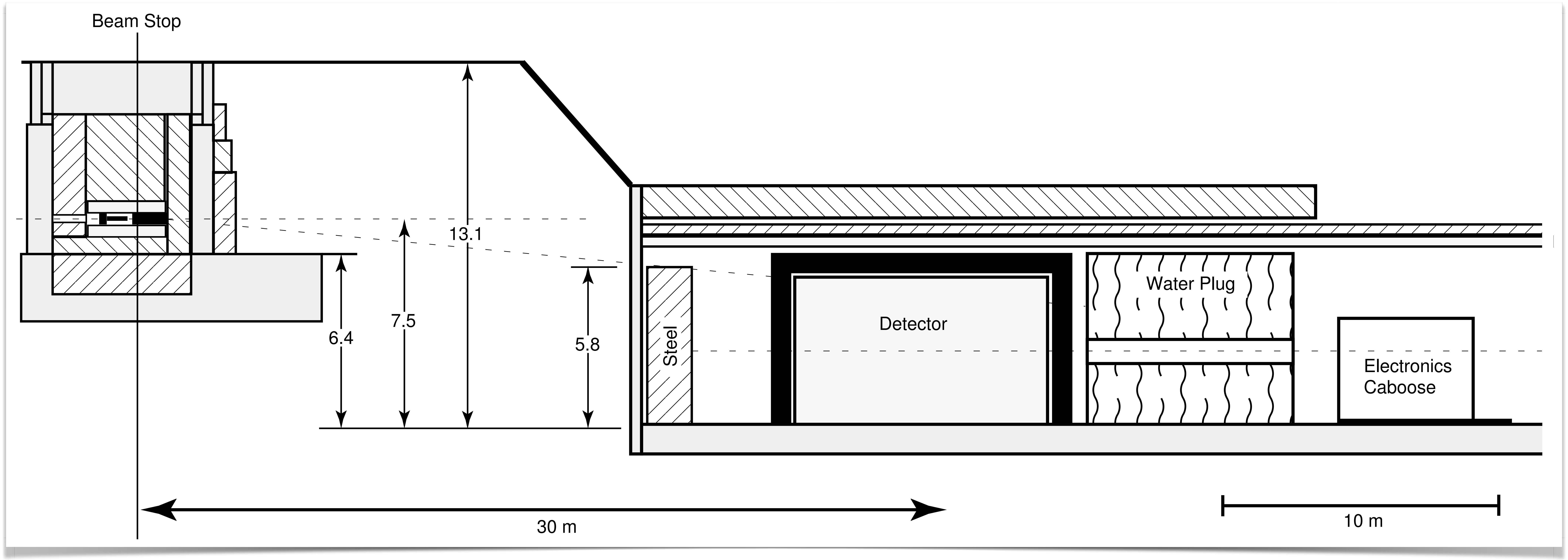
CERN

Neutrino PLATFORM

QUANTUM TECHNOLOGY INITIATIVE

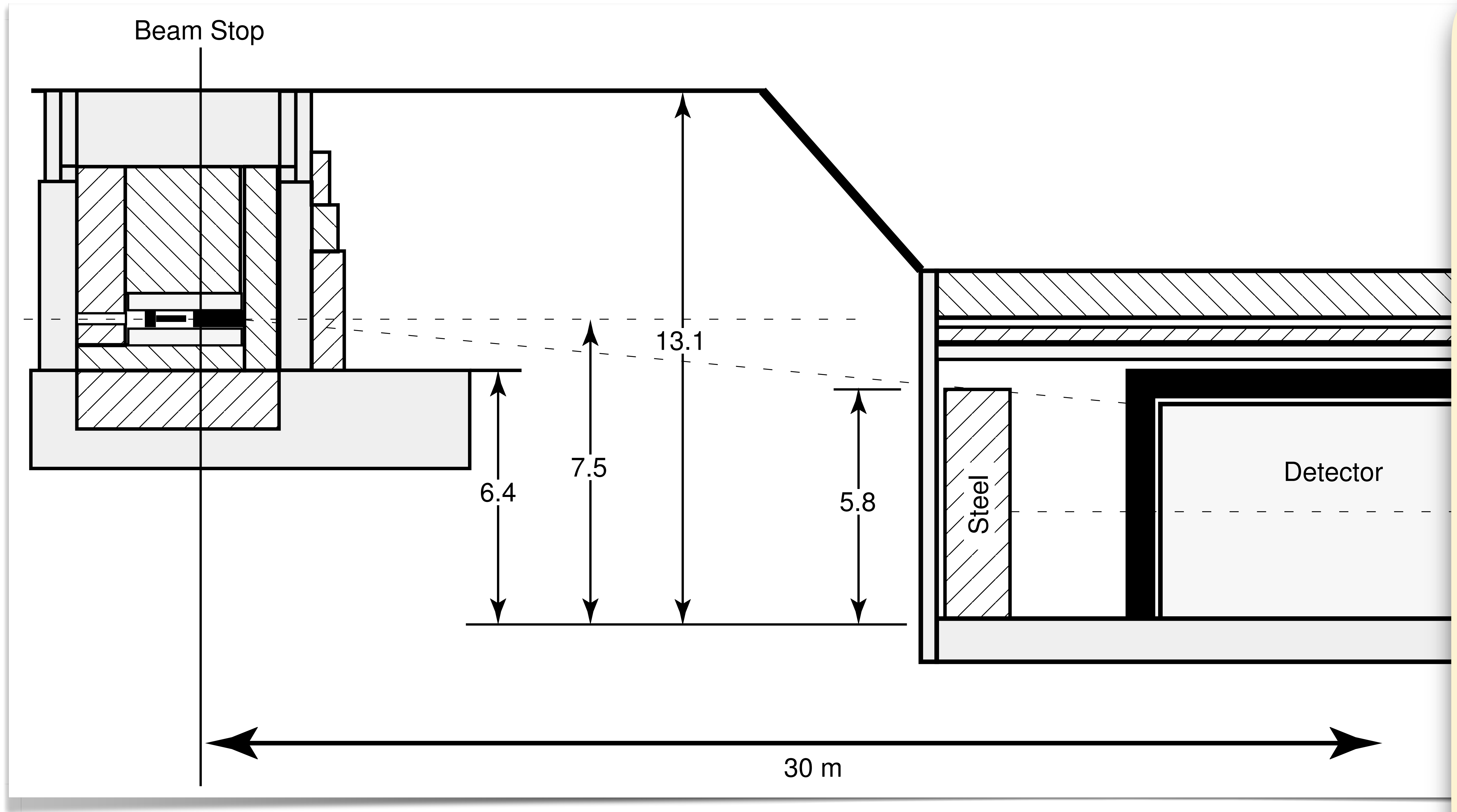
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

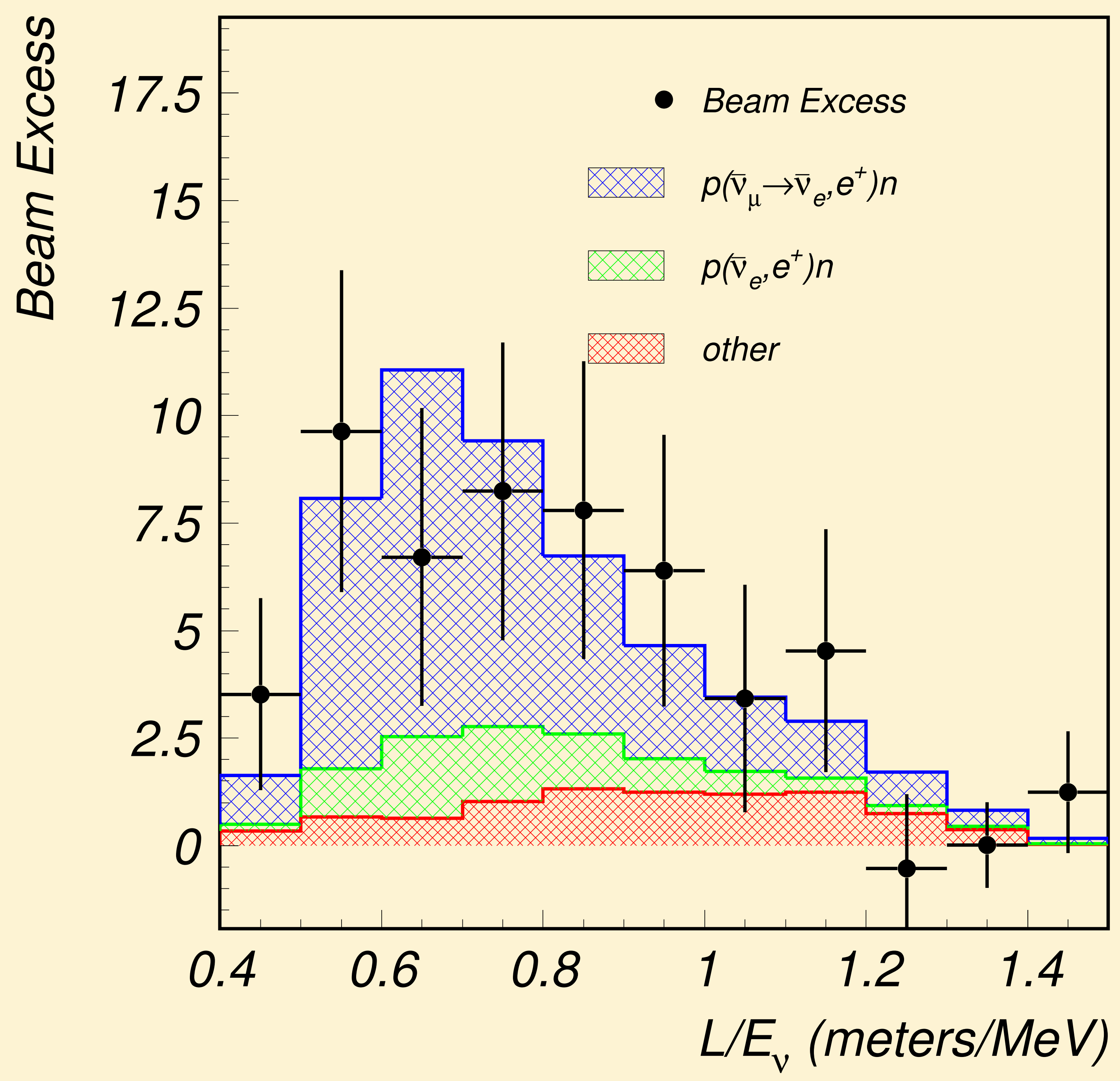
LSND – Liquid Scintillator Neutrino Detector (~1998)



- $\bar{\nu}_e$ appearance search in $\bar{\nu}_\mu$ beam
- source–detector distance ~ 30 m (too short for standard oscillations)
- $\nu_\mu \to \nu_e$ oscillations mediated by sterile neutrino?

LSND – Liquid Scintillator Neutrino Detector (~1998)



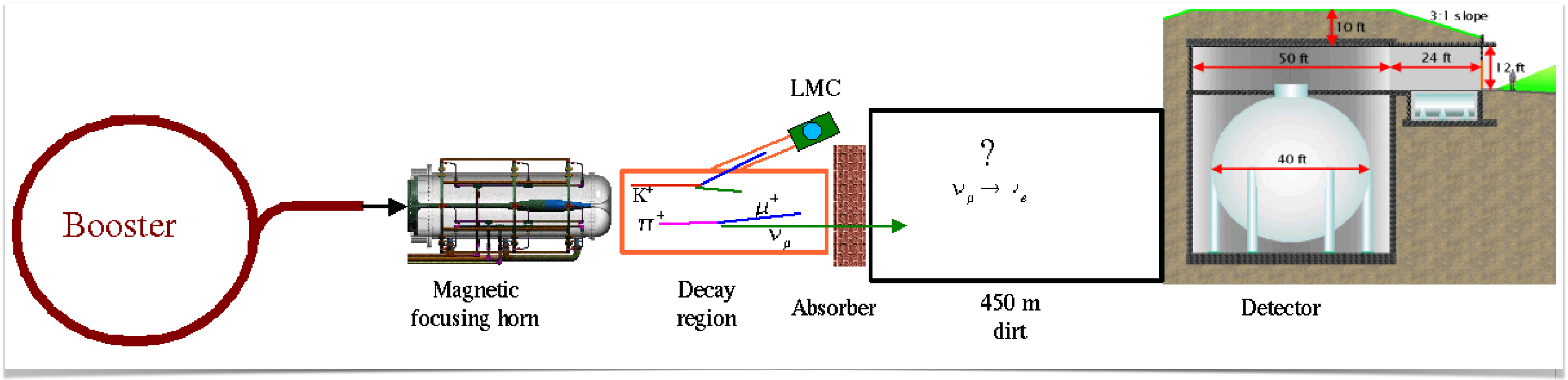


LSND Collaboration, hep-ex/0104049

- $\bar{\nu}_e$ appearance search in $\bar{\nu}_\mu$ beam
- source–detector distance ~ 30 m (too short for standard oscillations)
- $\nu_\mu \to \nu_e$ oscillations mediated by sterile neutrino?

MiniBooNE

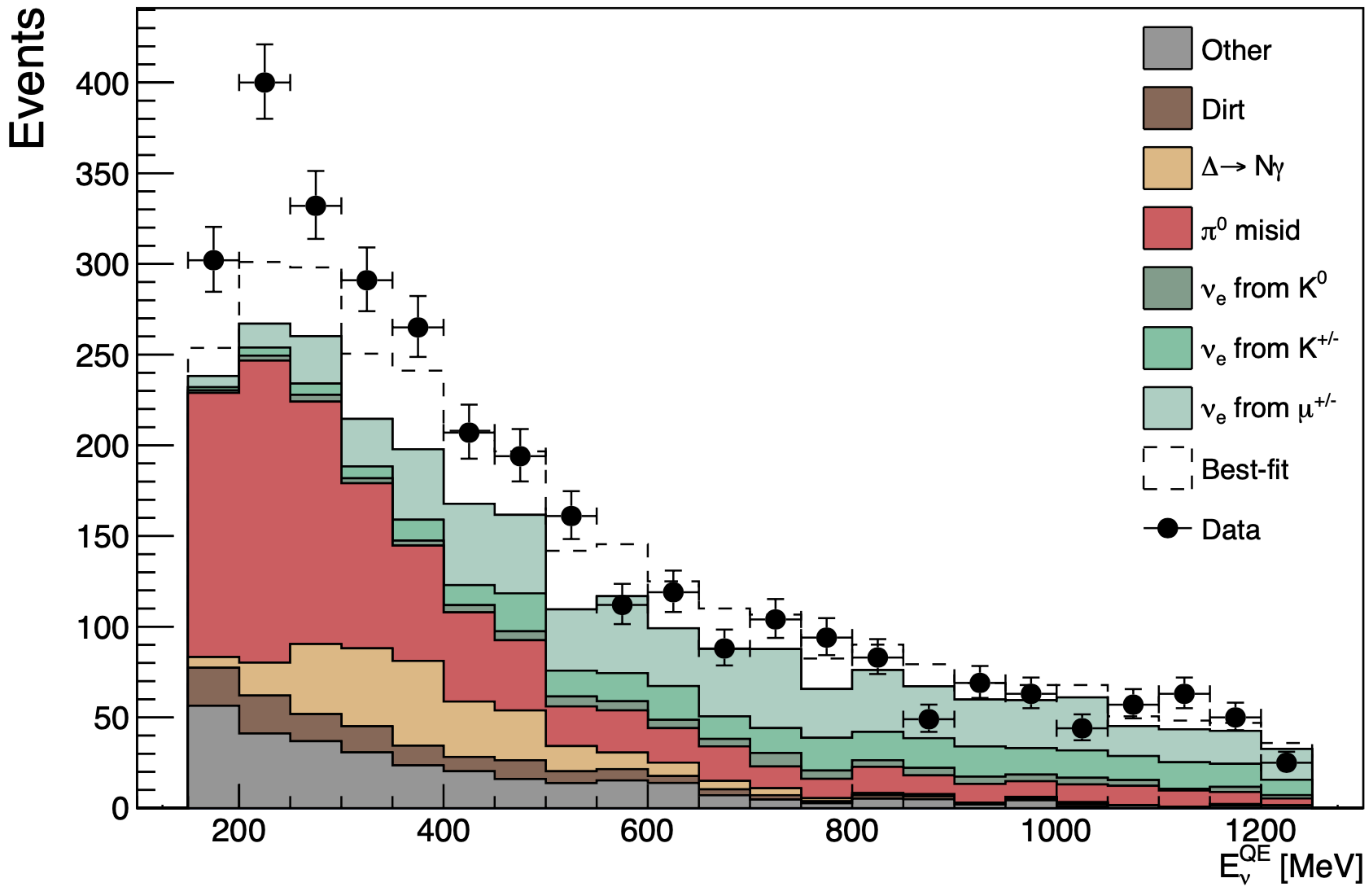
MiniBooNE



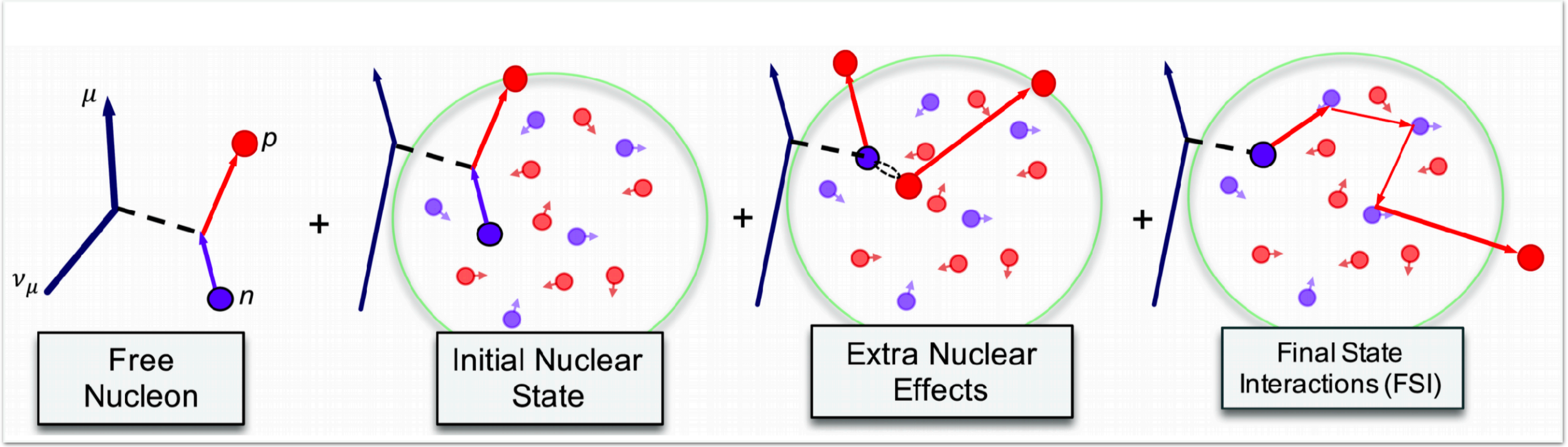
Booster
Magnetic focusing horn
LMC
K^+
π^+
μ^+
ν_μ
Decay region
Absorber
?
$\nu_\mu \to \nu_e$
450 m dirt
3:1 slope
10 ft
50 ft
24 ft
12 ft
40 ft
Detector

MiniBooNE

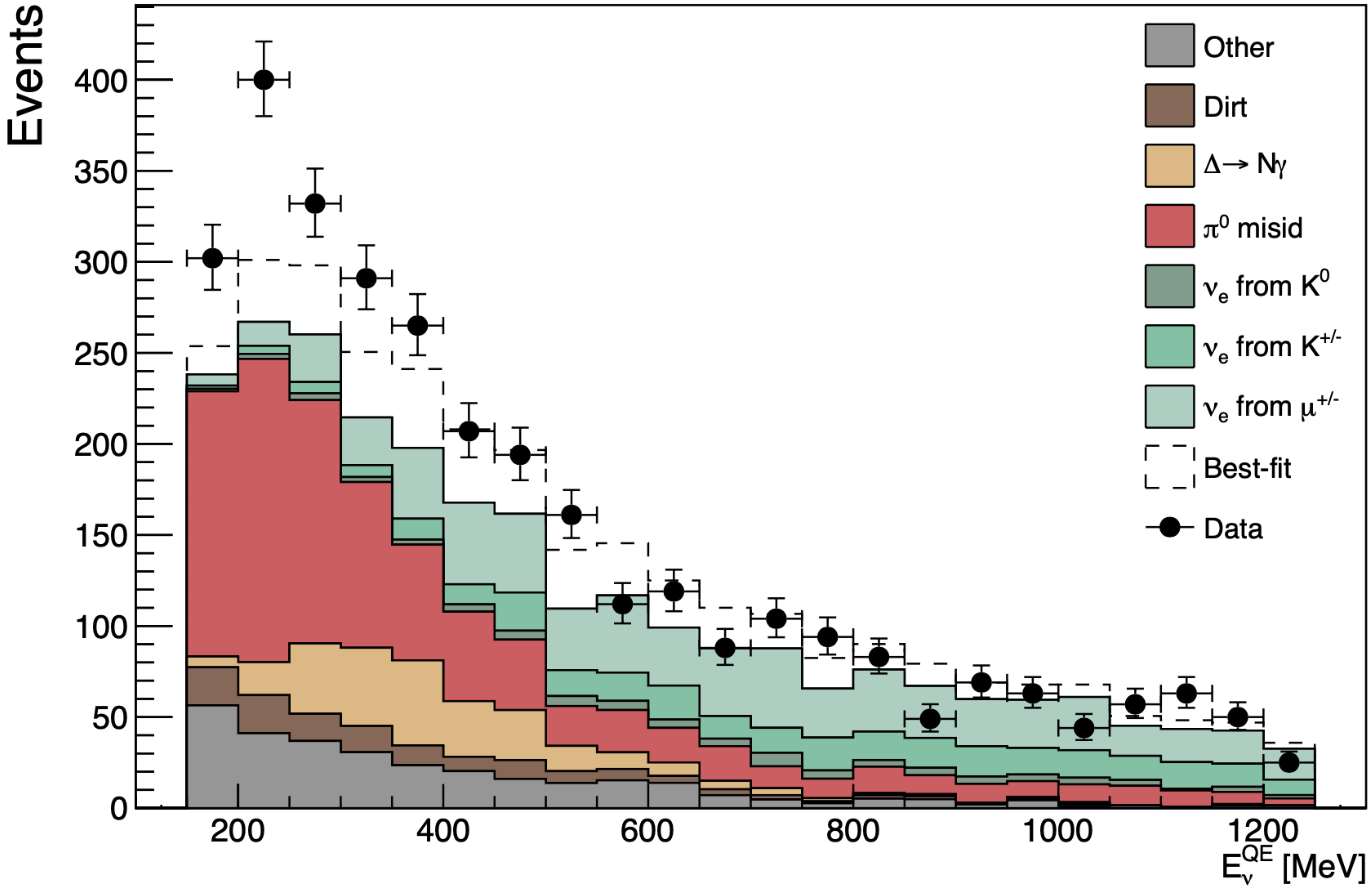
- ν_e excess in ν_μ beam (4.8σ significance)
- source–detector distance ~ 1 km (too short for standard oscillations)



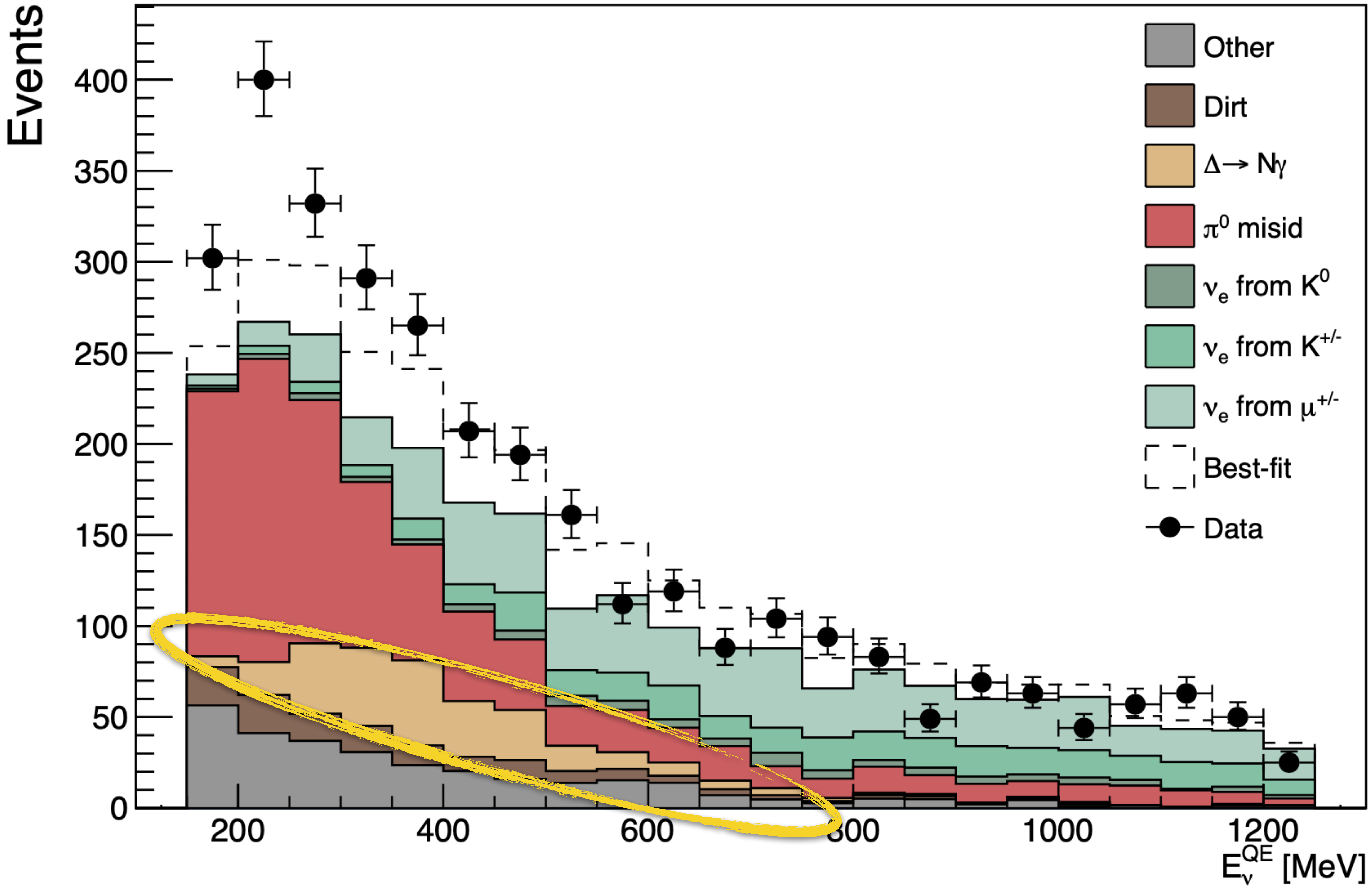
Neutrino Interactions are complicated



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

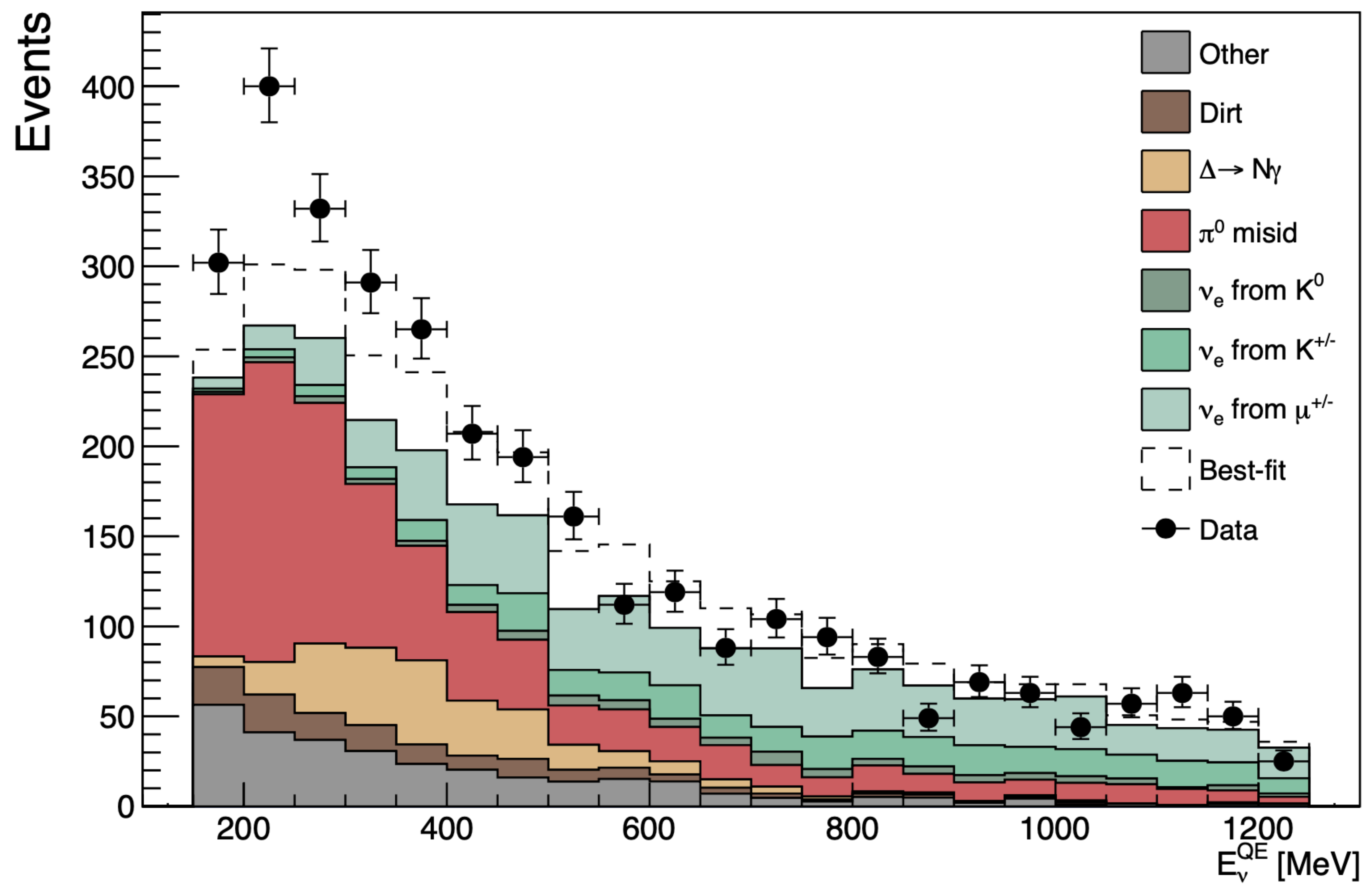


Example: $\Delta \to N + \gamma$



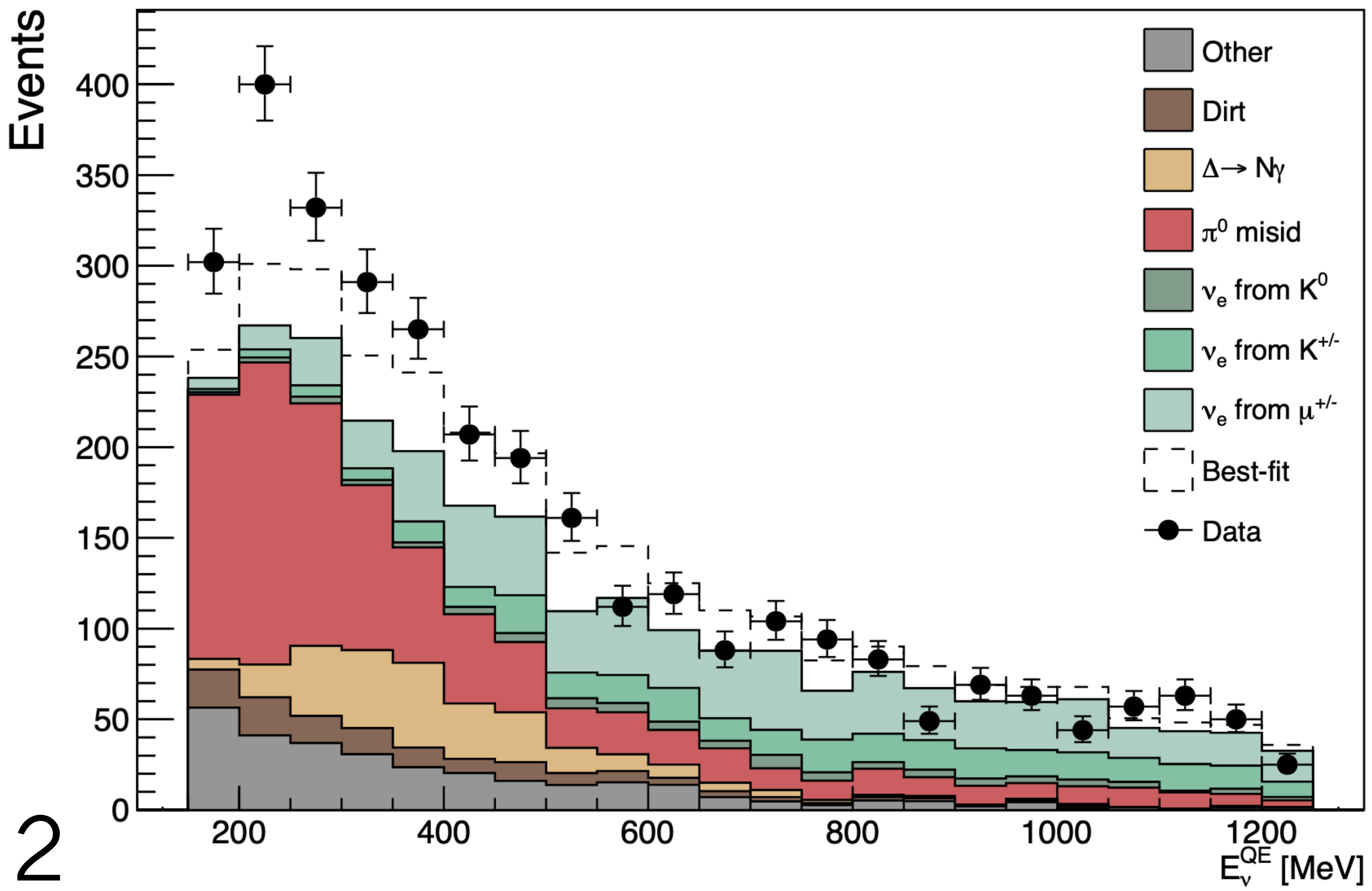
Example: $\Delta \to N + \gamma$

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



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

- Δ production rate can be estimated from $\Delta \to \pi + N$
- Pions may be absorbed on their way out of the nucleus
- may excite another Δ resonance
  ➠ $\Delta \to N + \gamma$ 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

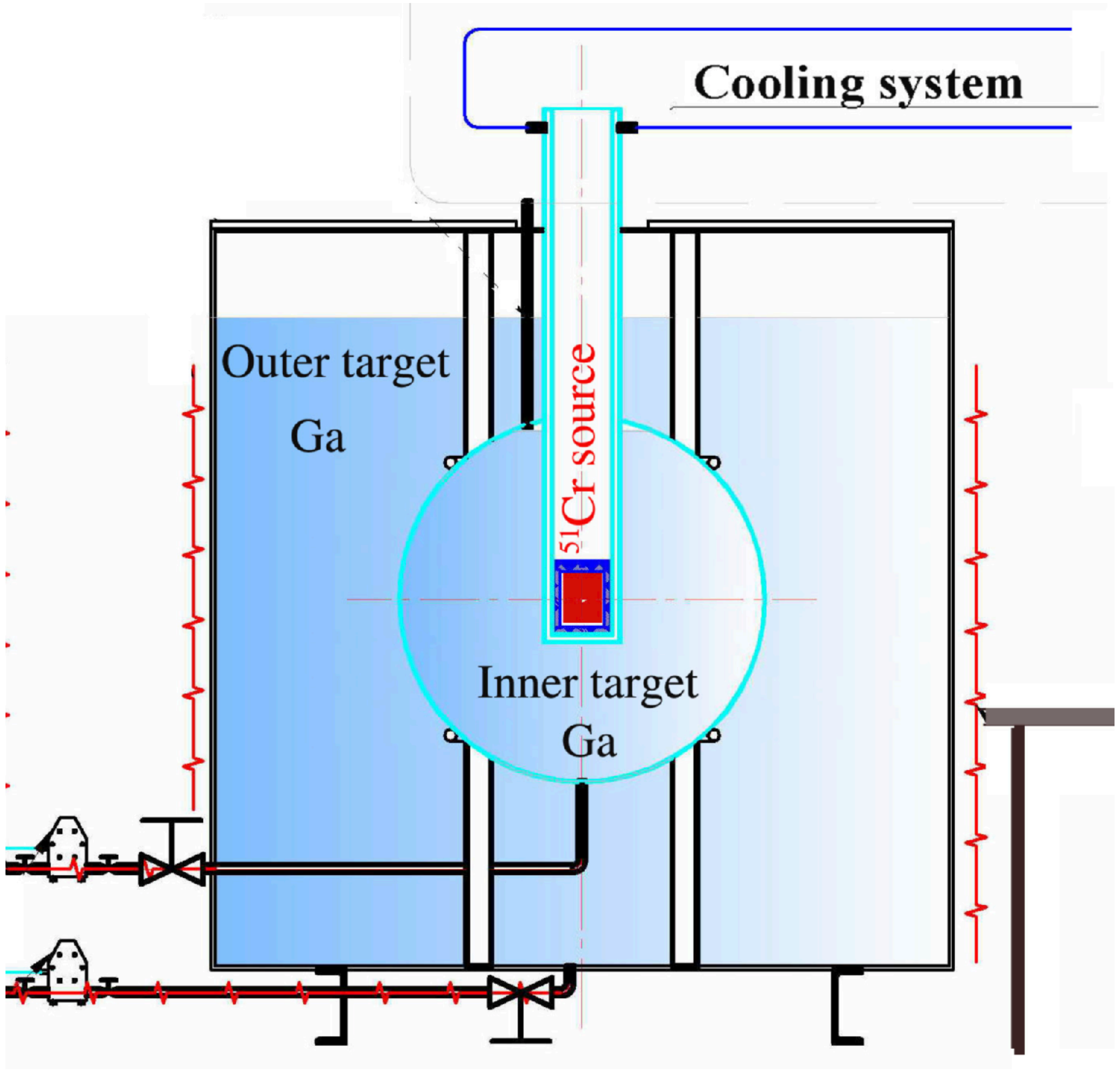
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

The Gallium Anomaly

- Experiments with intense radioactive sources
- Neutrino detection via

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

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

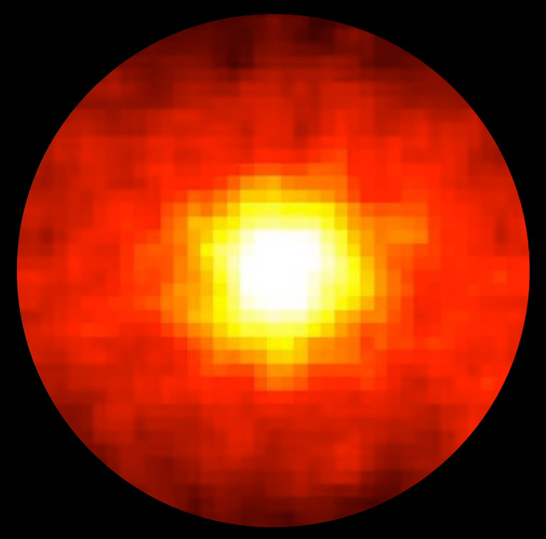


Giunti Laveder 1006.3244
BEST arXiv:2109.11482
Barinov Gorbunov arXiv:2109.14654

Summary

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