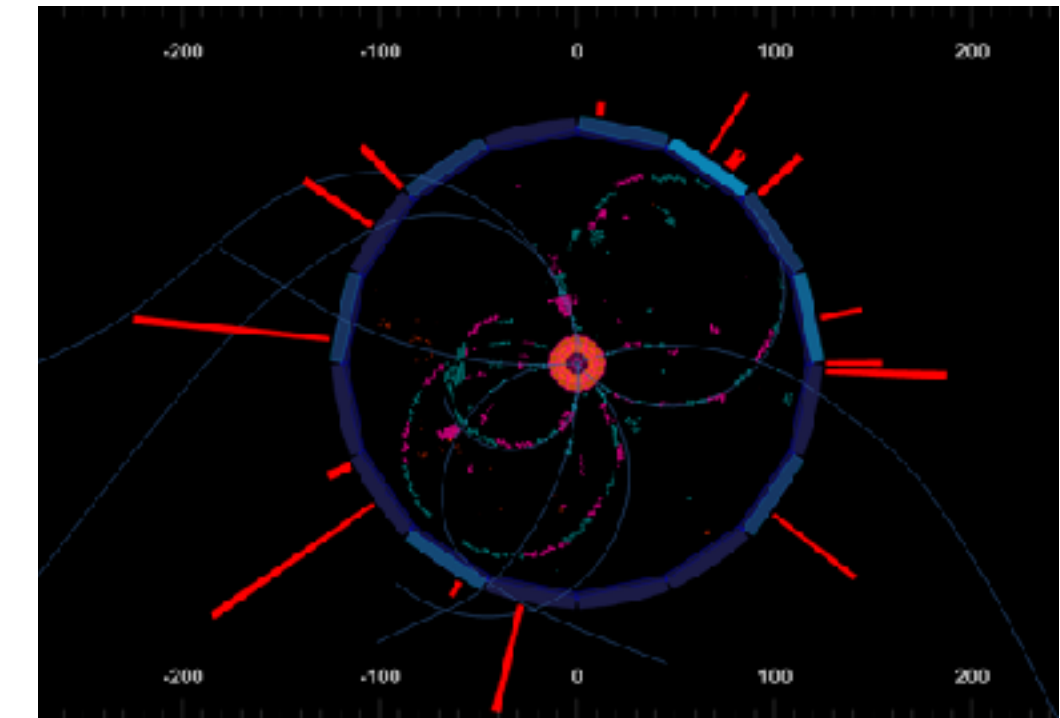


NEW PHYSICS SEARCHES WITH HIGH INTENSITY BEAMS

RYAN PLESTID





PART 1

A (DARK) MOTIVATION



PART 2

THE INTENSITY FRONTIER



PART 3

SOME RECENT WORK



PART 1

A (DARK) MOTIVATION



PART 2

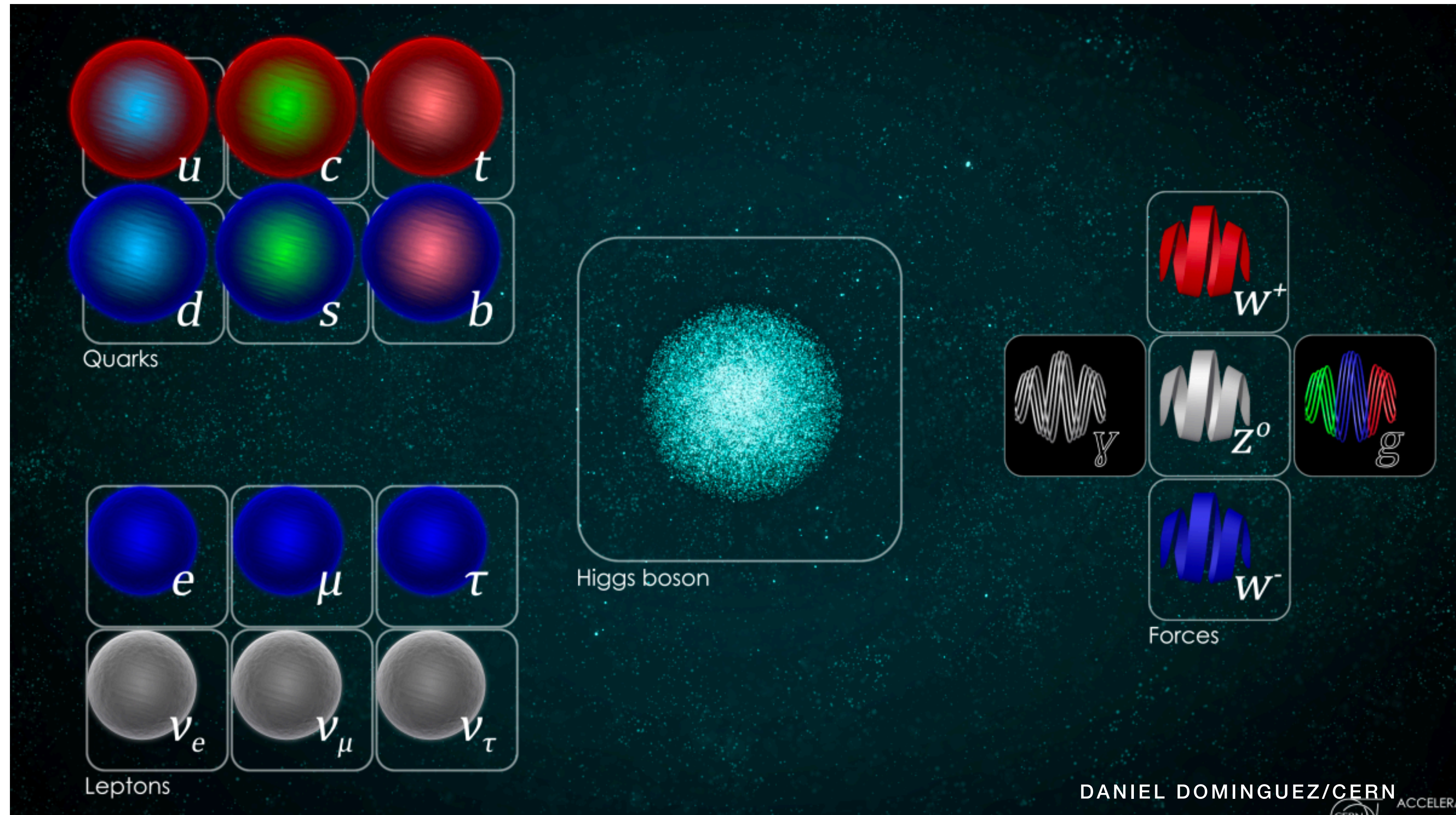
THE INTENSITY FRONTIER



PART 3

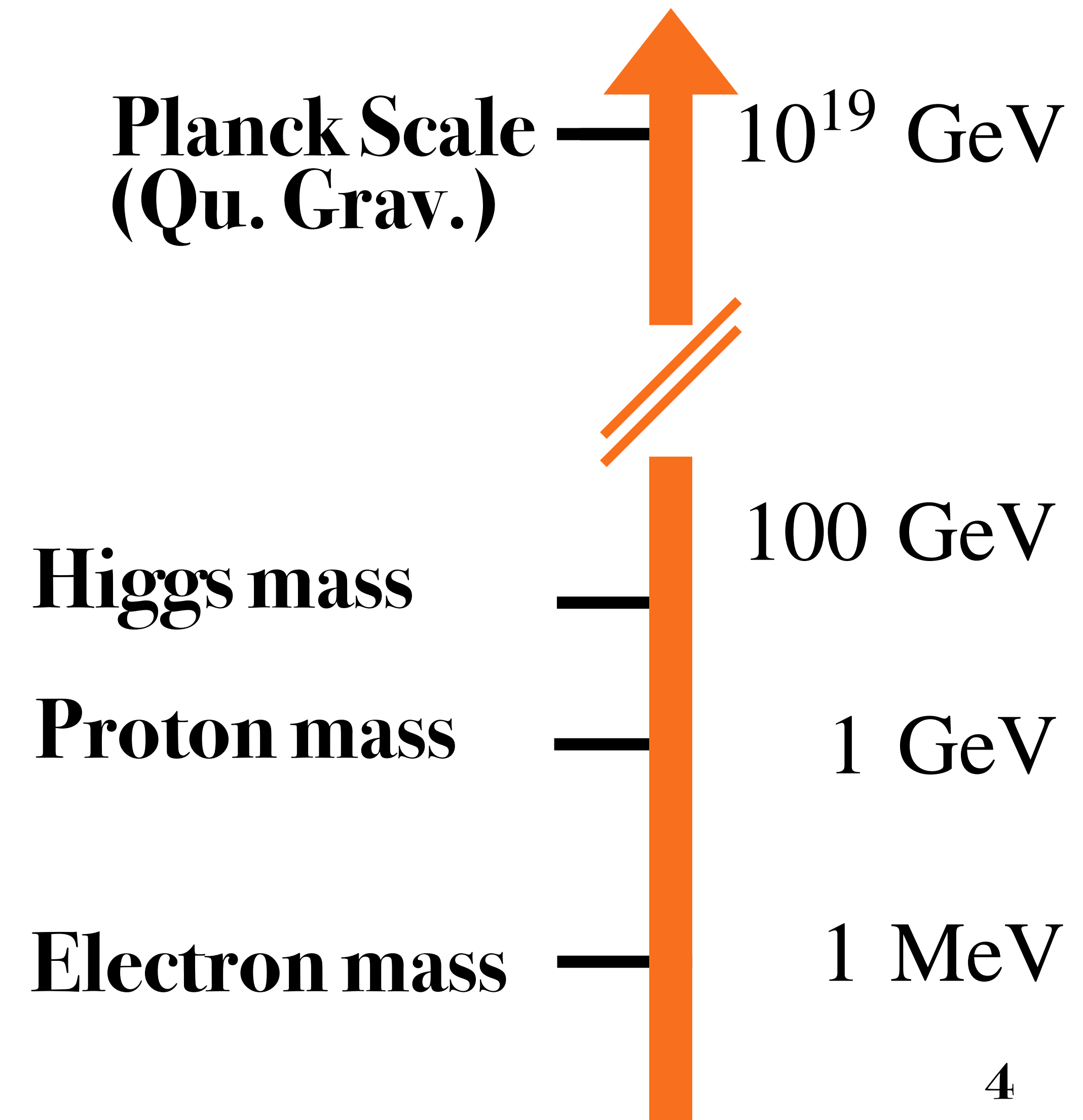
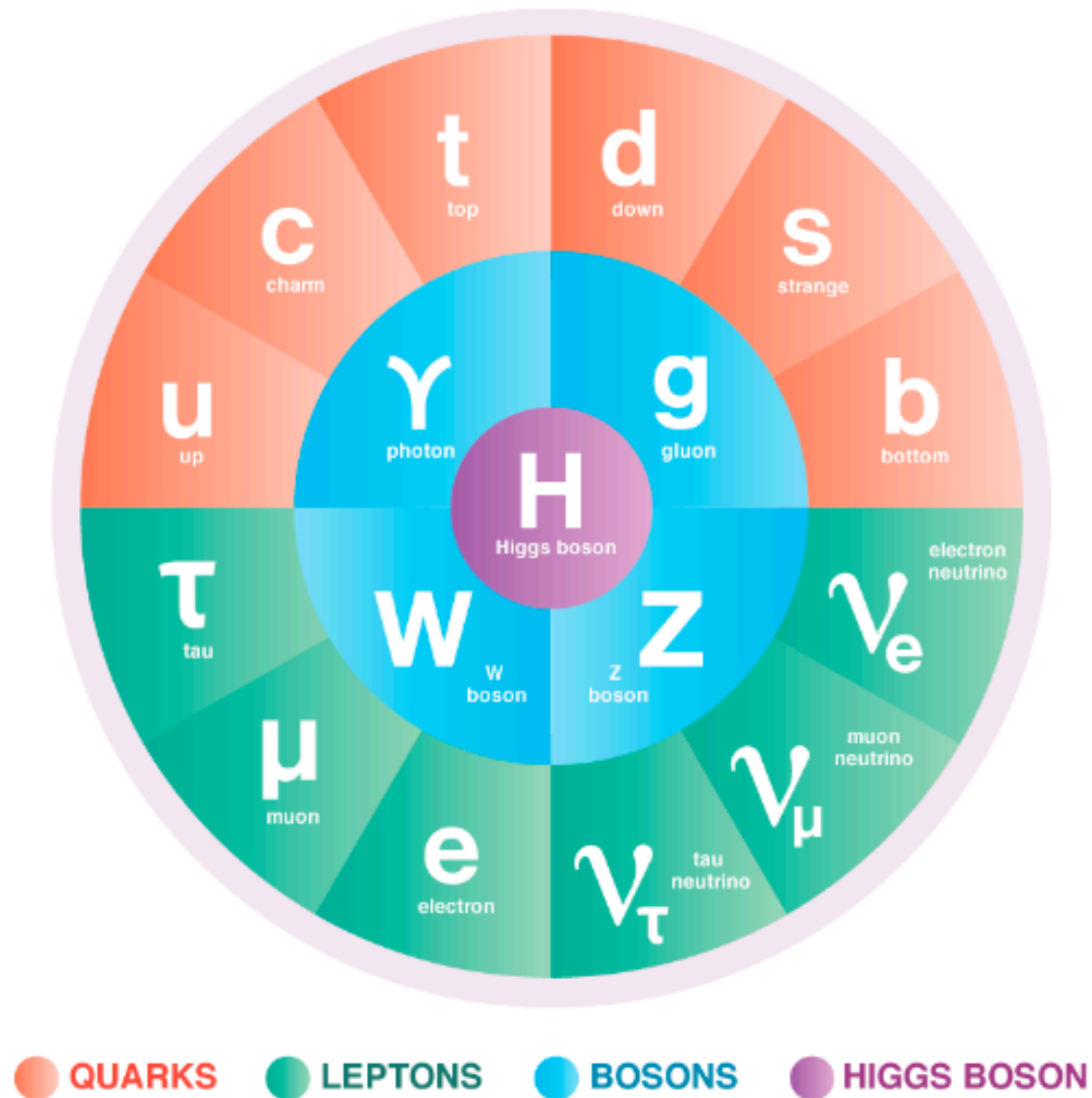
SOME RECENT WORK

WHAT WE KNOW ABOUT NATURE



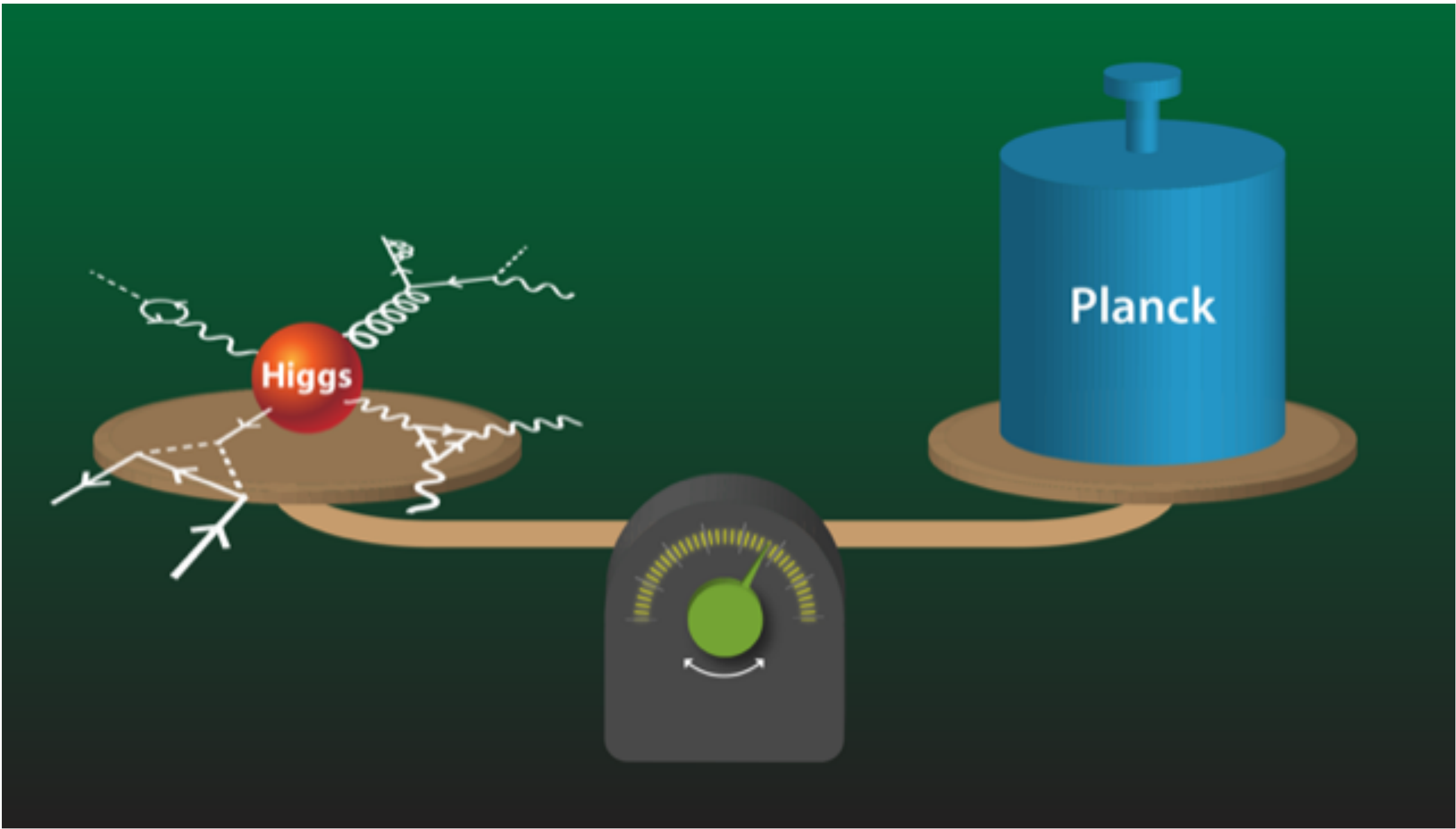
THREE COPIES (FLAVORS)

WHAT WE KNOW ABOUT NATURE



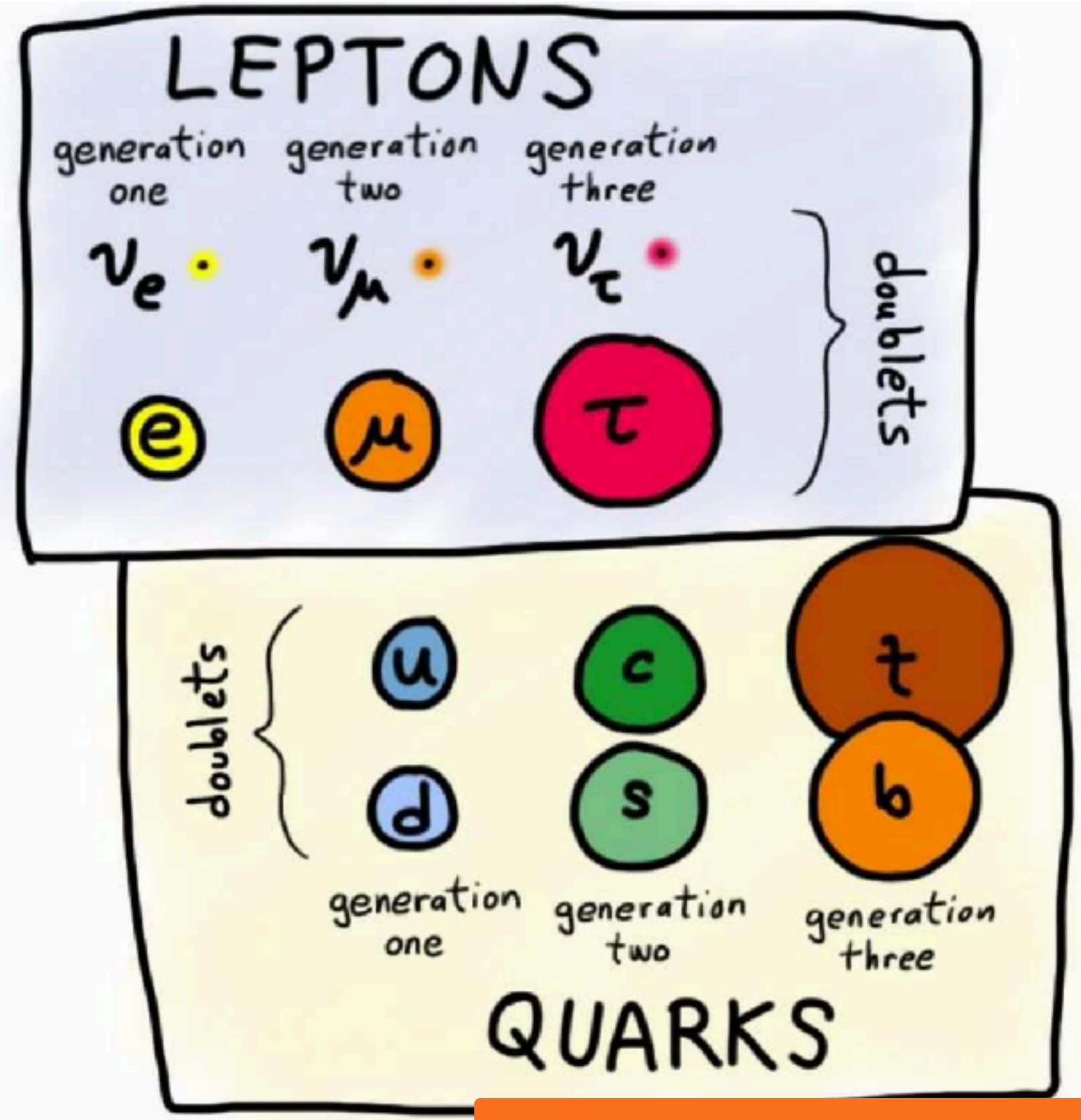
WHAT WE KNOW BUT FIND PUZZLING

Why is the Higgs light



APS/ALAN STONEBREAKER

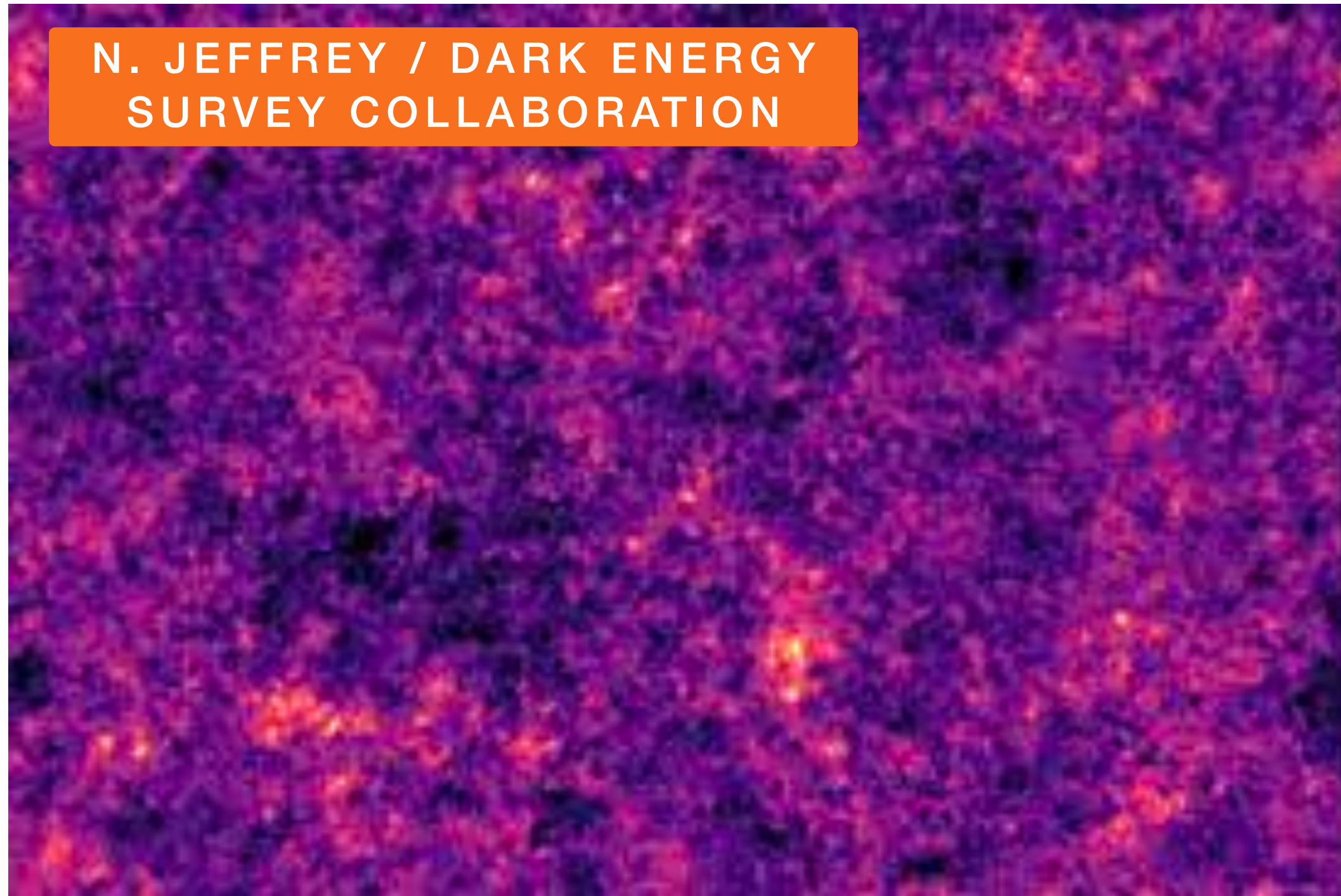
Why are there 3 flavors with identical quantum numbers?



CERN/JIM PIVARSKI

WHAT WE KNOW WE DON'T KNOW.

N. JEFFREY / DARK ENERGY
SURVEY COLLABORATION



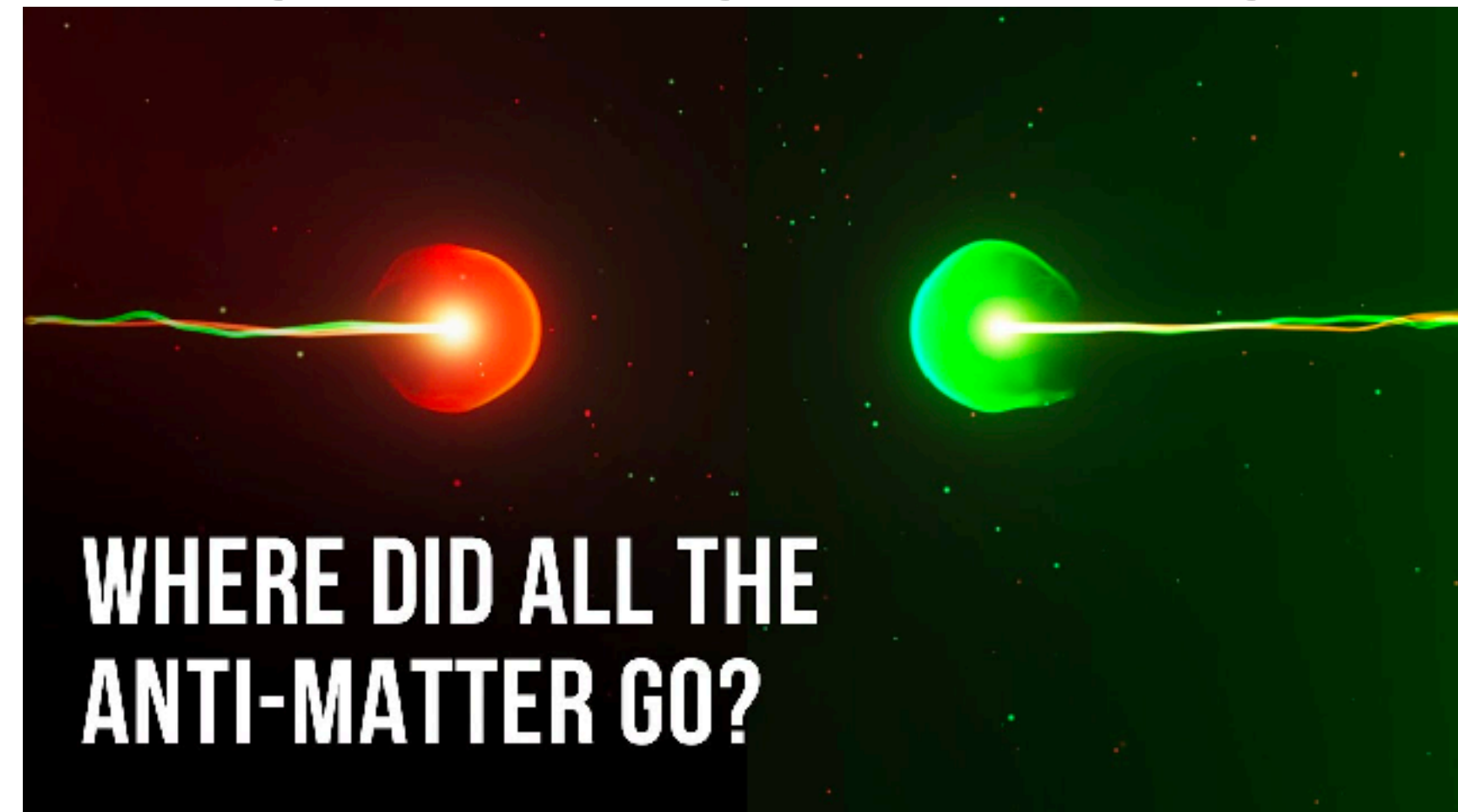
Dark matter

Neutrino mass origin

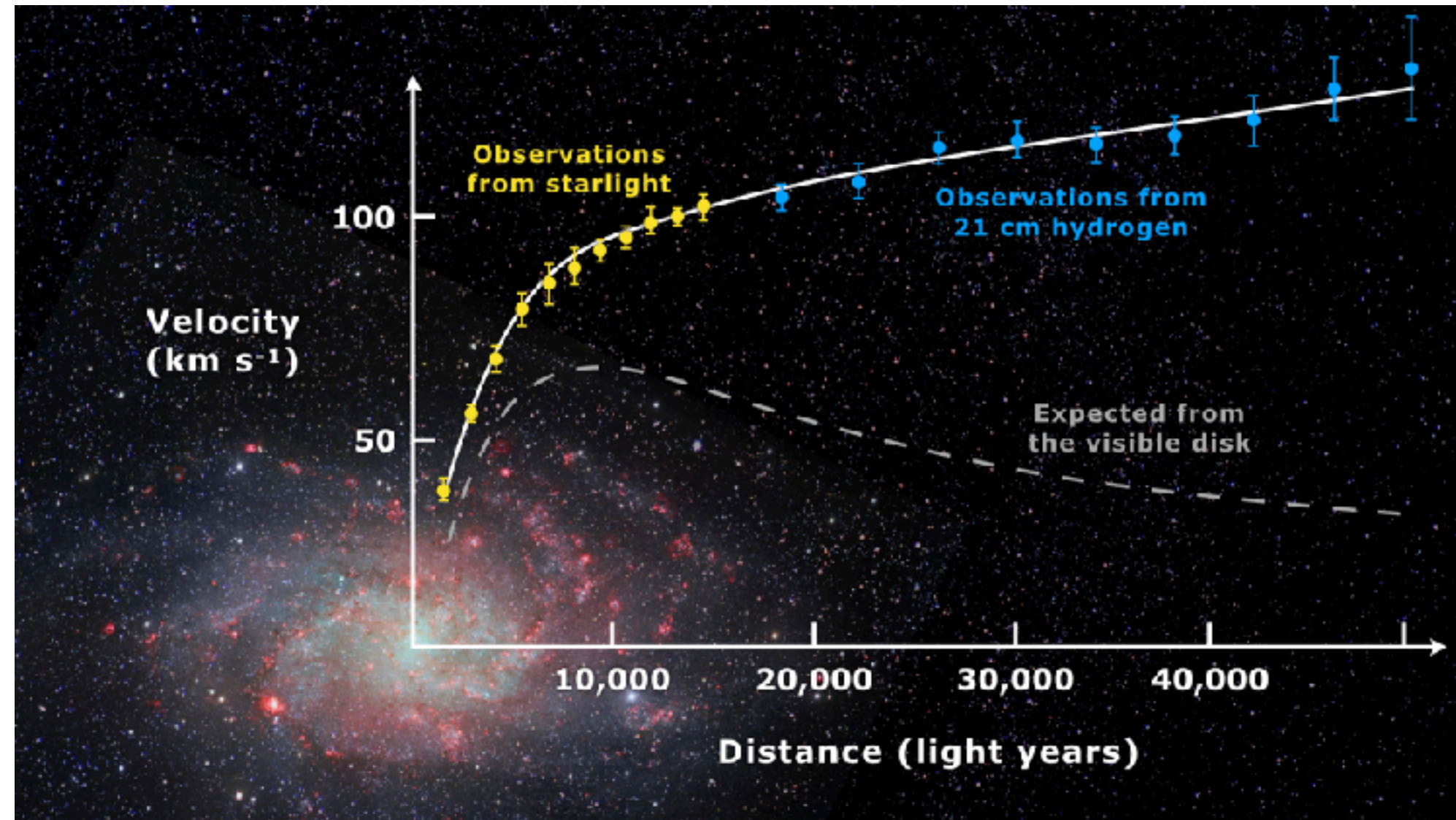
KATRIN EXPERIMENT



Baryon asymmetry

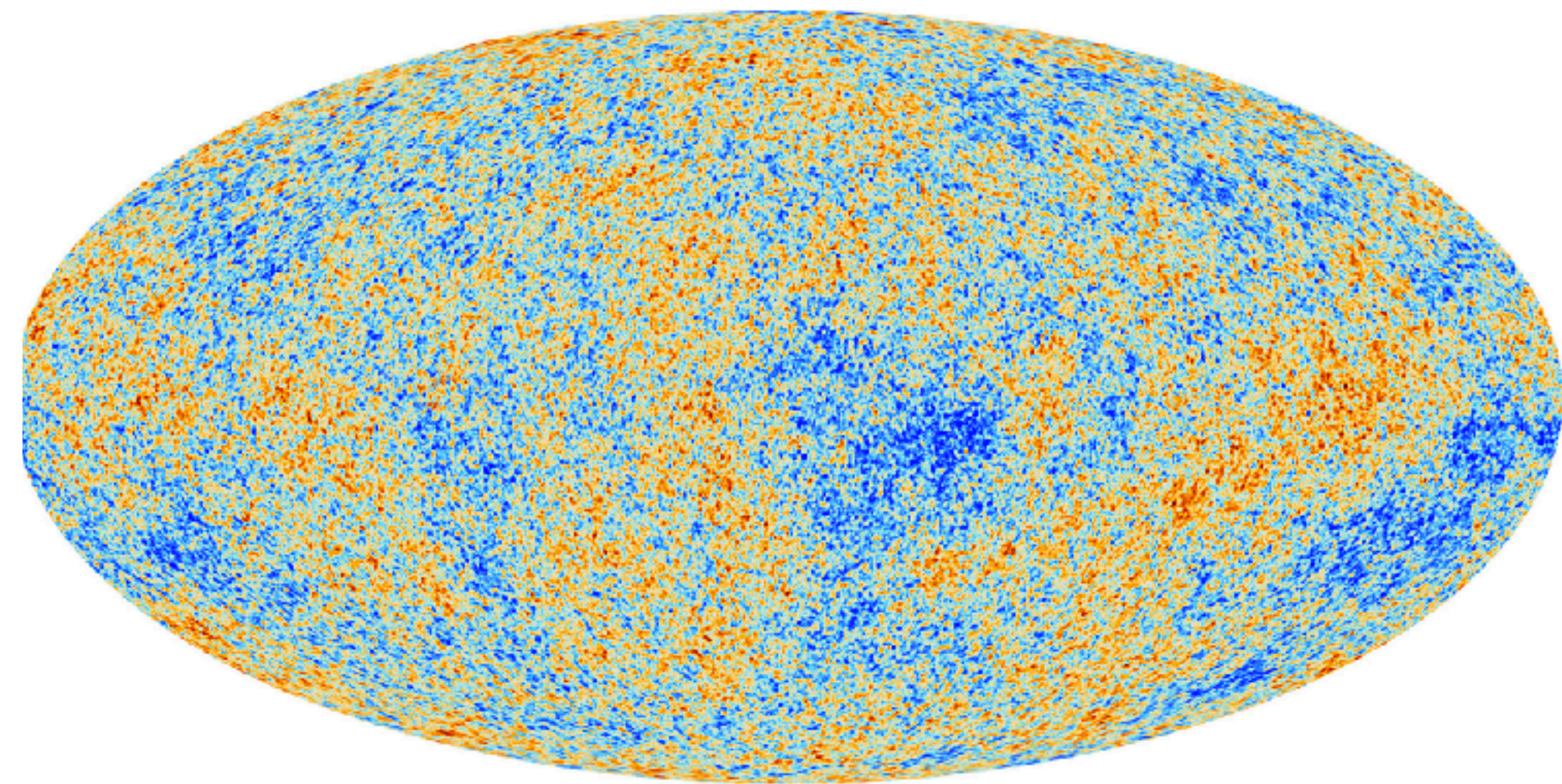


Dark Matter



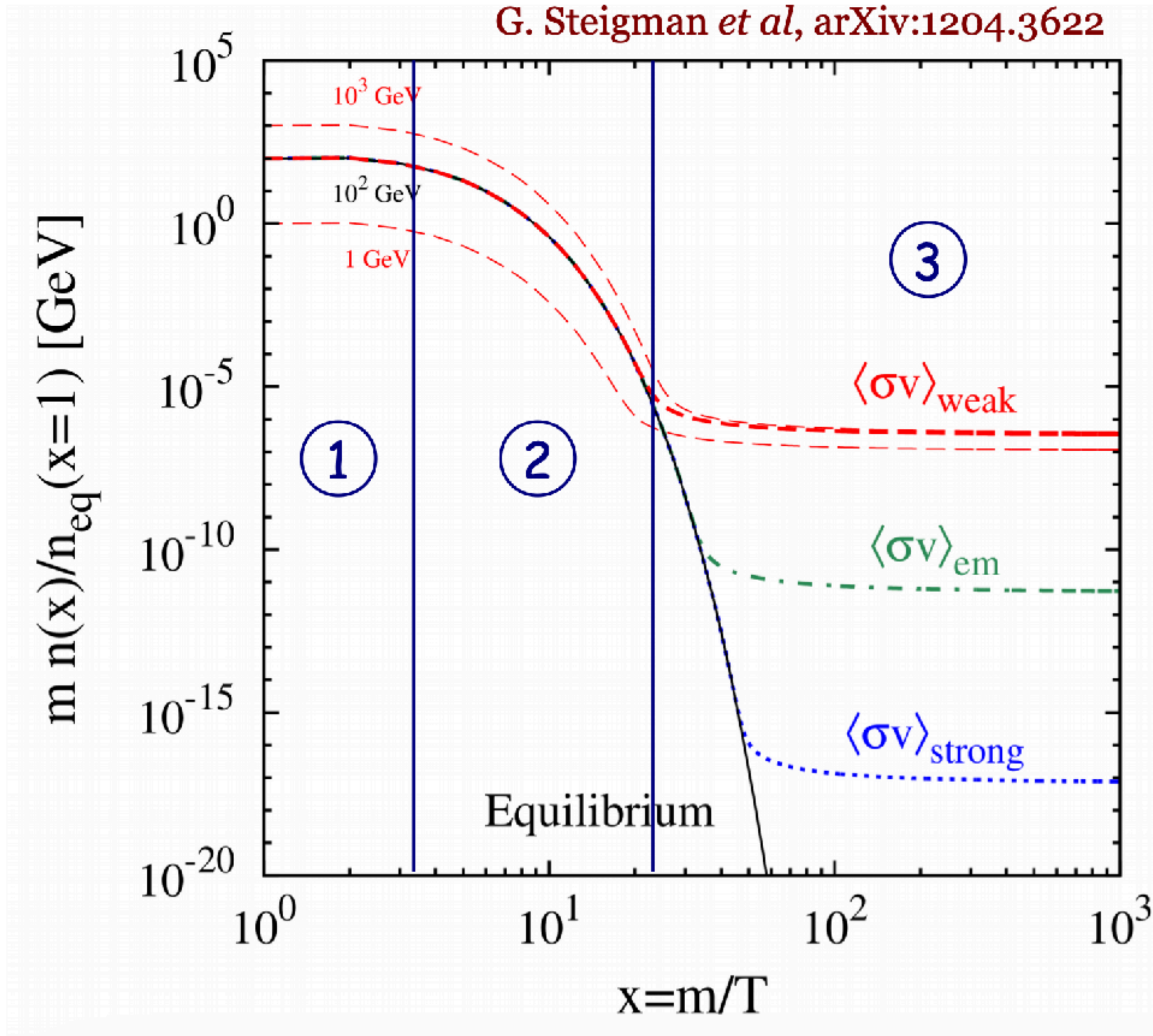
MARIO DELEO/ WIKIPEDIA

- Gravitating mass but unknown particle.
- Evidence from astrophysics and cosmology.
- Many open questions!



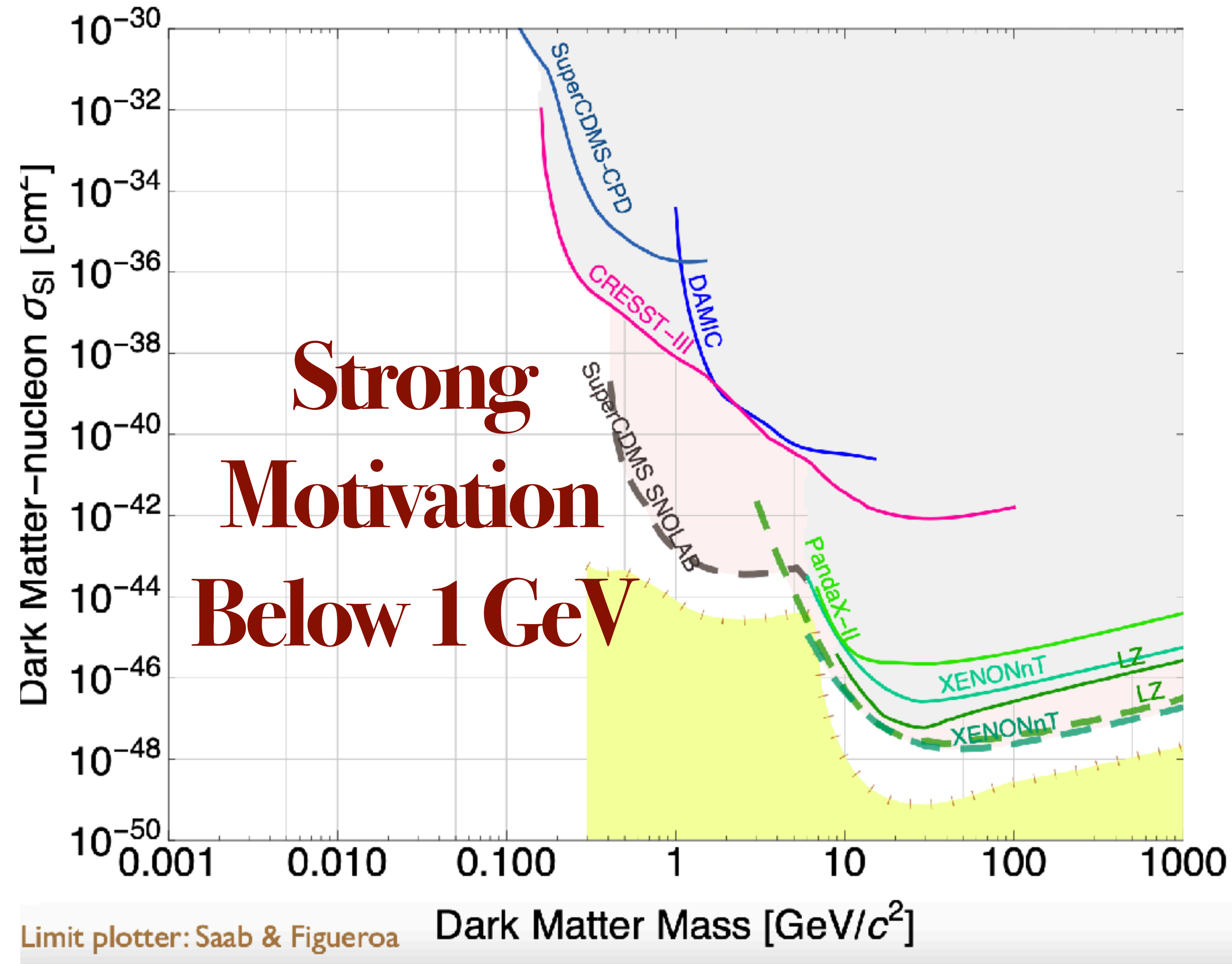
ESA/PLANCK COLLABORATION

A Thermal Paradigm

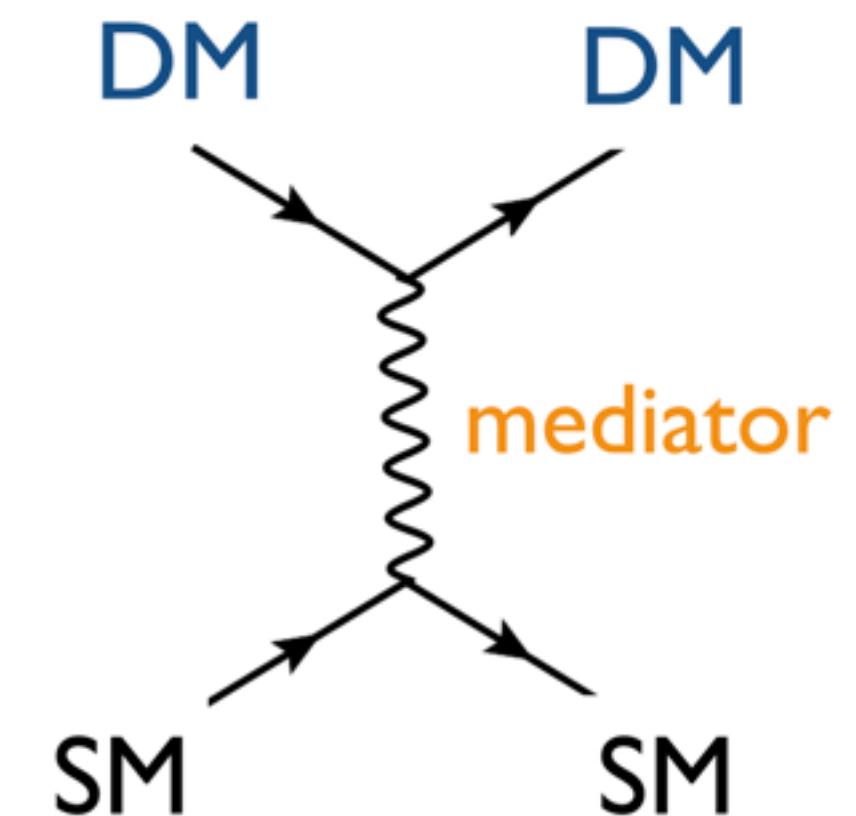


- Thermally produced dark matter.
- A compelling mechanism.
- Below 1 GeV requires a mediator.
- Options include dark photon.

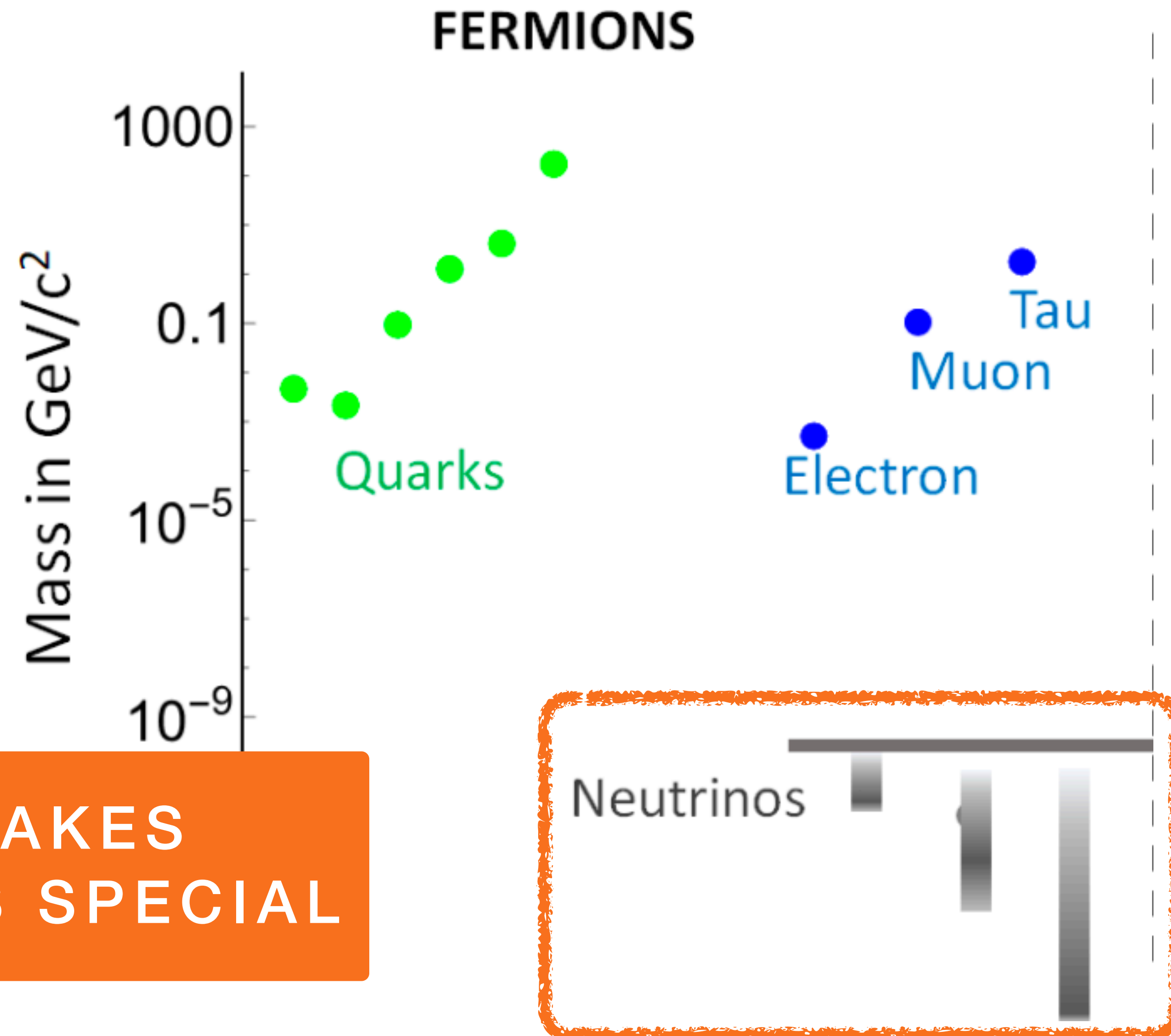
A Thermal Paradigm



- Thermally produced dark matter.
- A compelling mechanism.
- Below 1 GeV *requires a mediator*.



FERMION MASSES IN NATURE



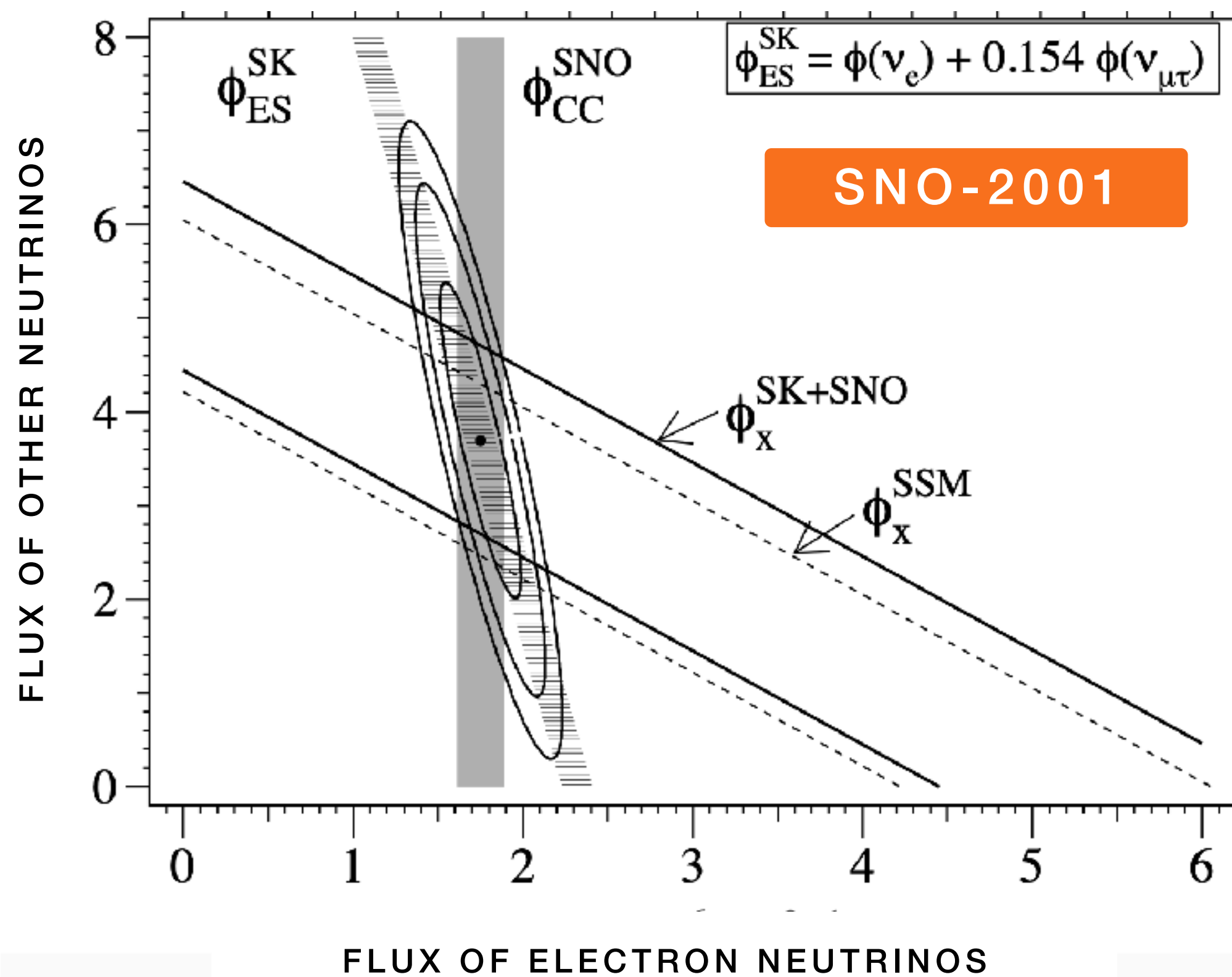
THIS MAKES
NEUTRINOS SPECIAL



Neutrino Masses & Oscillations

- Speed of light $\rightarrow$ clocks don't tick.
- Neutrinos change flavor $\rightarrow$ massive.

NEUTRINOS CHANGE FLAVOR
THEREFORE
NEUTRINOS HAVE MASS



FIRST LABORATORY EVIDENCE OF PHYSICS BEYOND THE STANDARD MODEL

- If SM were to hold up to the Planck scale then we predict

$$m_\nu^2 \lesssim 10^{-8} \text{ eV}^2$$

- But SNO & Super-K measured.

$$m_1^2 - m_2^2 \sim 10^{-5} \text{ eV}^2$$

$$m_1^2 - m_3^2 \sim 10^{-3} \text{ eV}^2$$

NEUTRINOS ARE "HEAVY"

THEREFORE

THE SCALE OF NEW PHYSICS IS "LOW"

(BELOW PLANCK SCALE)

- If SM were to hold up to the Planck scale then we predict

$$m_\nu^2 \lesssim 10^{-8} \text{ eV}^2$$

- But SNO & Super-K measured.

$$m_1^2 - m_2^2 \sim 10^{-5} \text{ eV}^2$$

$$m_1^2 - m_3^2 \sim 10^{-3} \text{ eV}^2$$

THEORIES OF NEUTRINO MASS

- The SM does not have right-handed neutrinos.

$\Rightarrow$ no* neutrino mass

$$m_\nu \neq 0$$

Dirac
neutrinos

- A right-handed "partner" exists.

Majorana
neutrinos

- Neutrinos are their own anti-particle.

SO(10)
GUT

Inverse
See-Saw

Type-I, II, III
See-Saw

Majorons

Zee-Babu

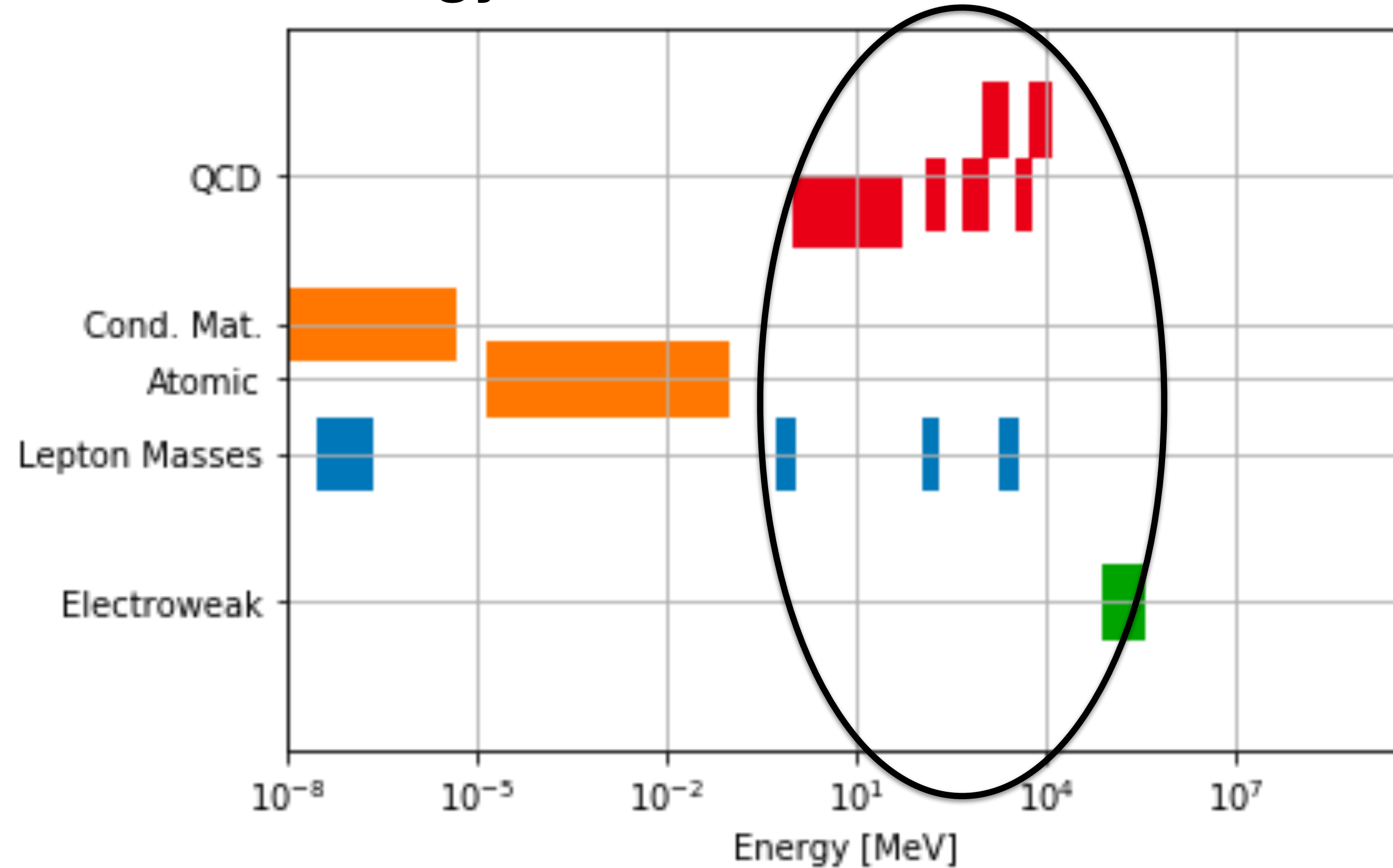
- **Unambiguous evidence of new physics.**

- **All have** new particles.

- Can search for visible decays.

WHERE SHOULD WE LOOK?

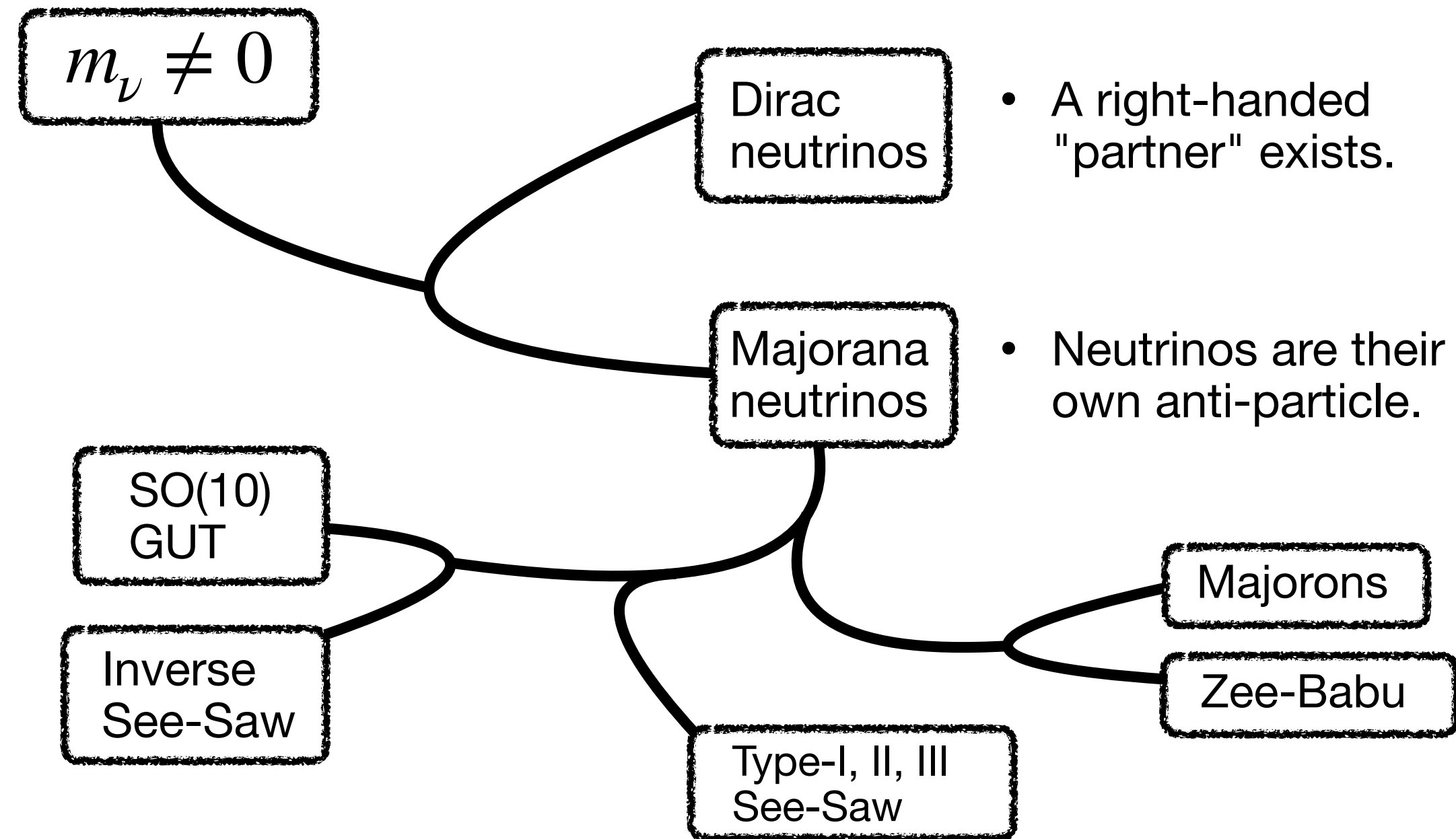
Energy Scales in the Standard Model



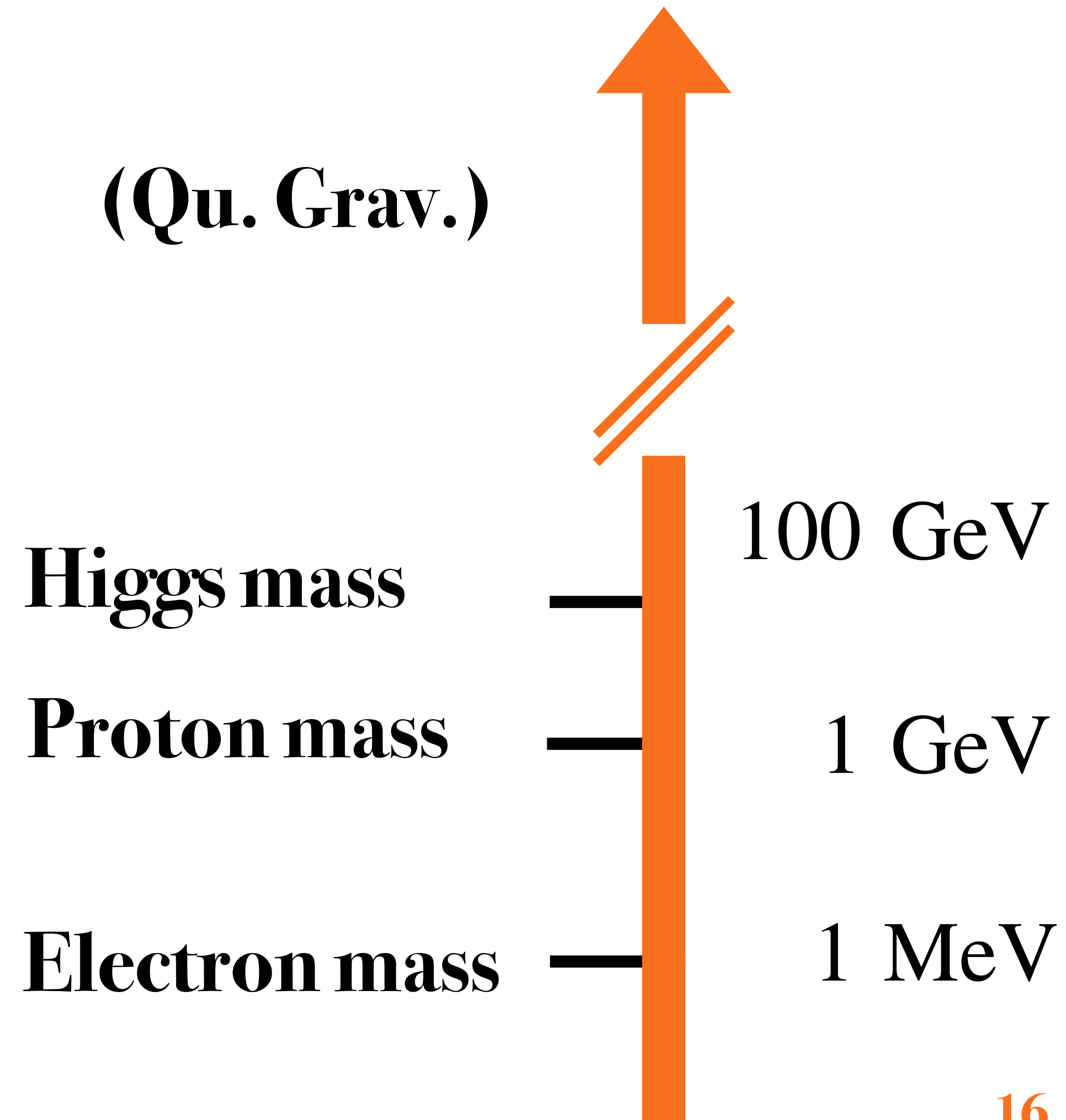
MANY TOOLS AT
"MEDIUM" ENERGY

ALLOWS FOR VERY
HIGH LUMINOSITY

A UV-AGNOSTIC STRATEGY



- Many possible UV completions.
- Focus: low-energy observables.
- Includes ***on-shell*** production!



NATURE'S RULE BOOK



NATURE'S RULE BOOK



Assume

- Quantum mechanics.
- Special relativity.
- Acausal observations are independent.

NATURE'S RULE BOOK



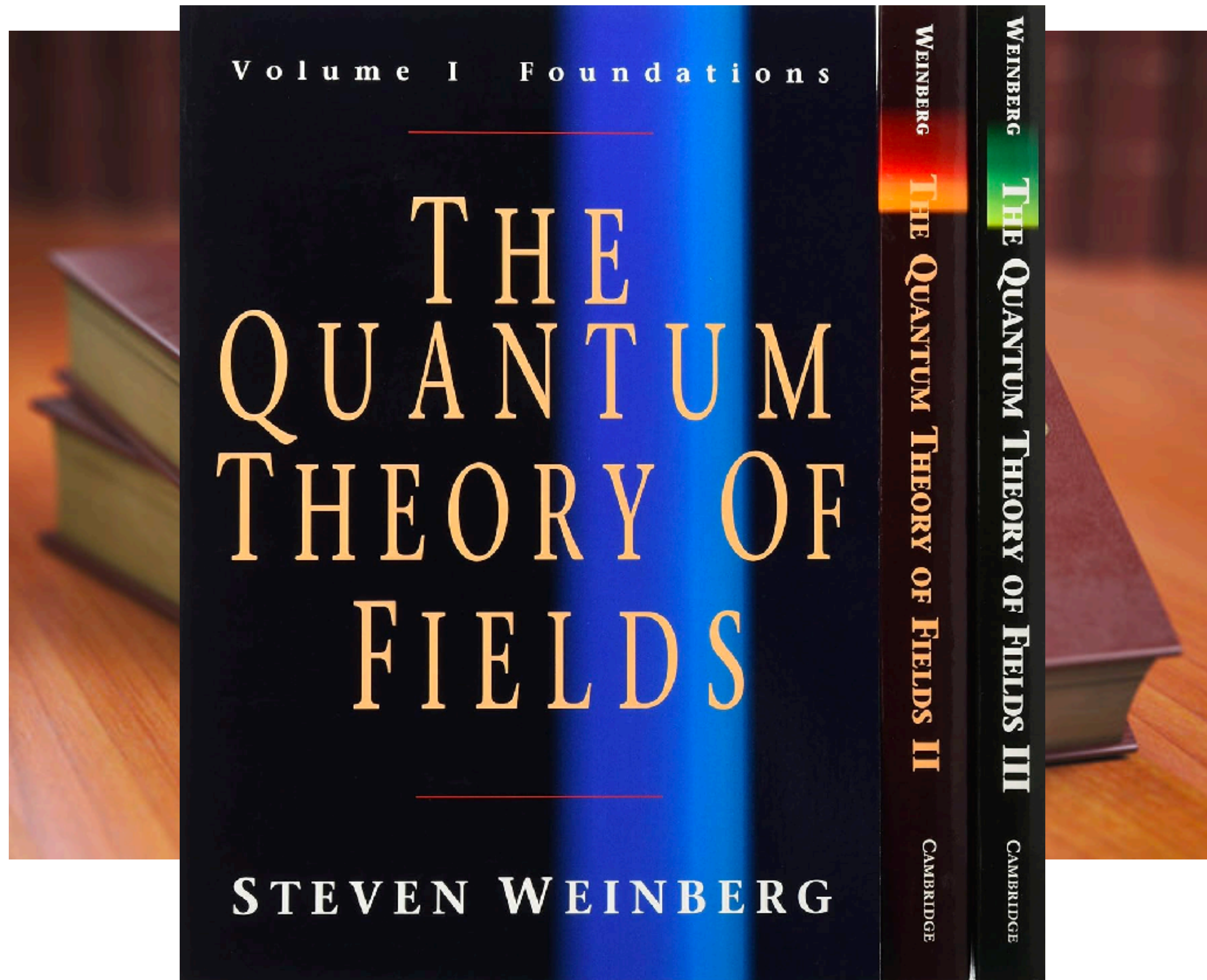
Assume

- Quantum mechanics.
- Special relativity.
- Acausal observations are independent.

Unique Solution

- Local quantum field theory.
- Restrictive ruleset.

NATURE'S RULE BOOK



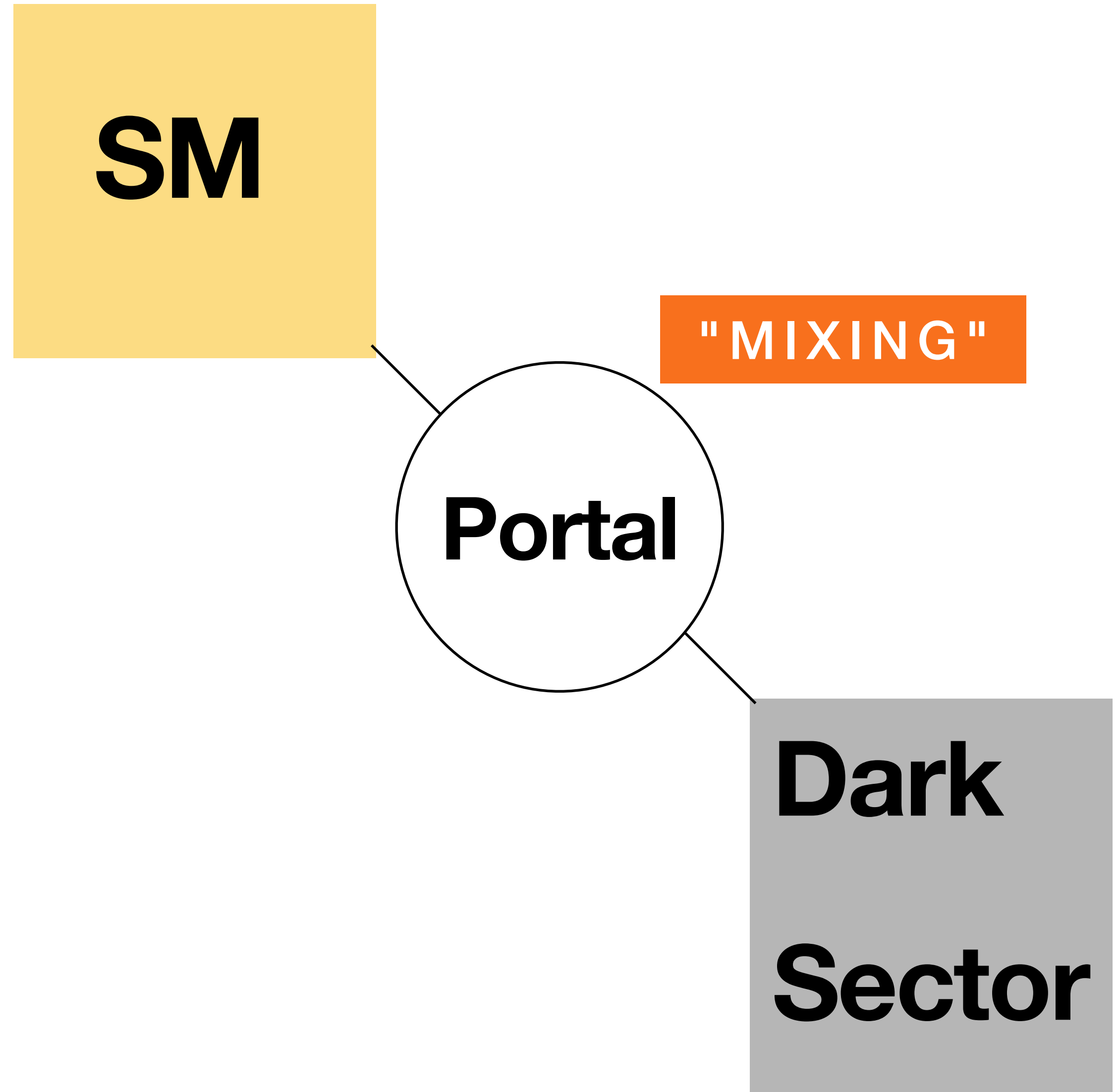
Assume

- Quantum mechanics.
- Special relativity.
- Acausal observations are independent.

Unique Solution

- Local quantum field theory.
- Restrictive ruleset.

- If light new physics exists it can't feel known forces.
- Possibly complex dark sector (e.g. SM-like).
- Few interactions available.
- Focus on "portals".



NEUTRINO PORTAL

- Neutrinos (weak).

AXION PORTAL

- Pions, kaons. (strong).

VECTOR PORTAL

- Electrons/Photons (electric & magnetic).

SM

HIGGS PORTAL

$$H^\dagger H |S|^2$$

NEUTRINO PORTAL

LHN

Portal

$$(\partial_\mu a) J^\mu$$

AXION PORTAL

$$F'_{\mu\nu} B^{\mu\nu}$$

VECTOR PORTAL

**Dark
Sector**

- Anomaly free $U(1)$.

$$\begin{matrix} B-L \\ L_i-L_j \end{matrix} \quad V \rightarrow e^+e^-$$

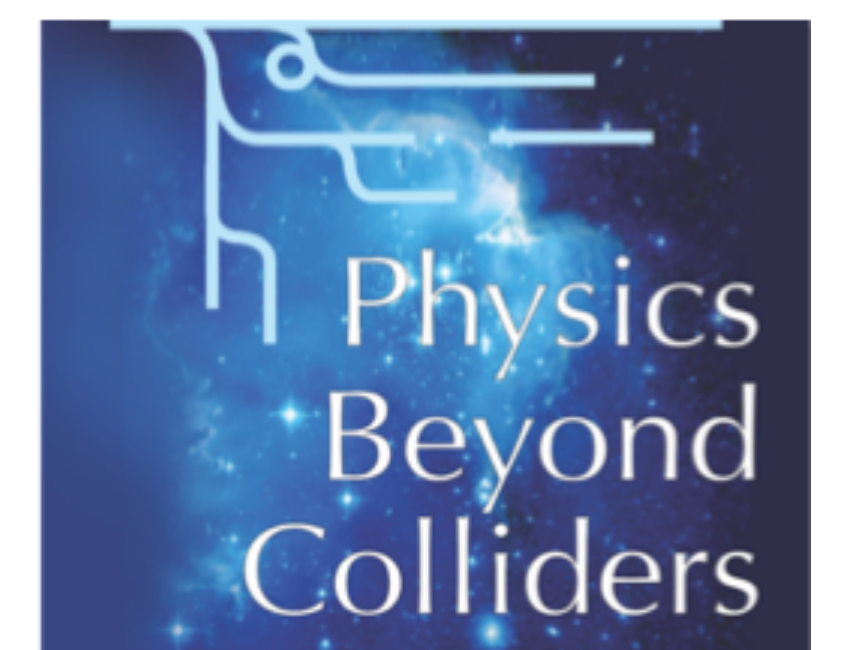
- pNGB == ALP

$$\frac{1}{f_a} \partial_\mu a J^\mu \quad a \rightarrow \gamma\gamma$$

- Heavy Majorana neutrino.

$$LHN \quad N \rightarrow e^+e^-\nu$$

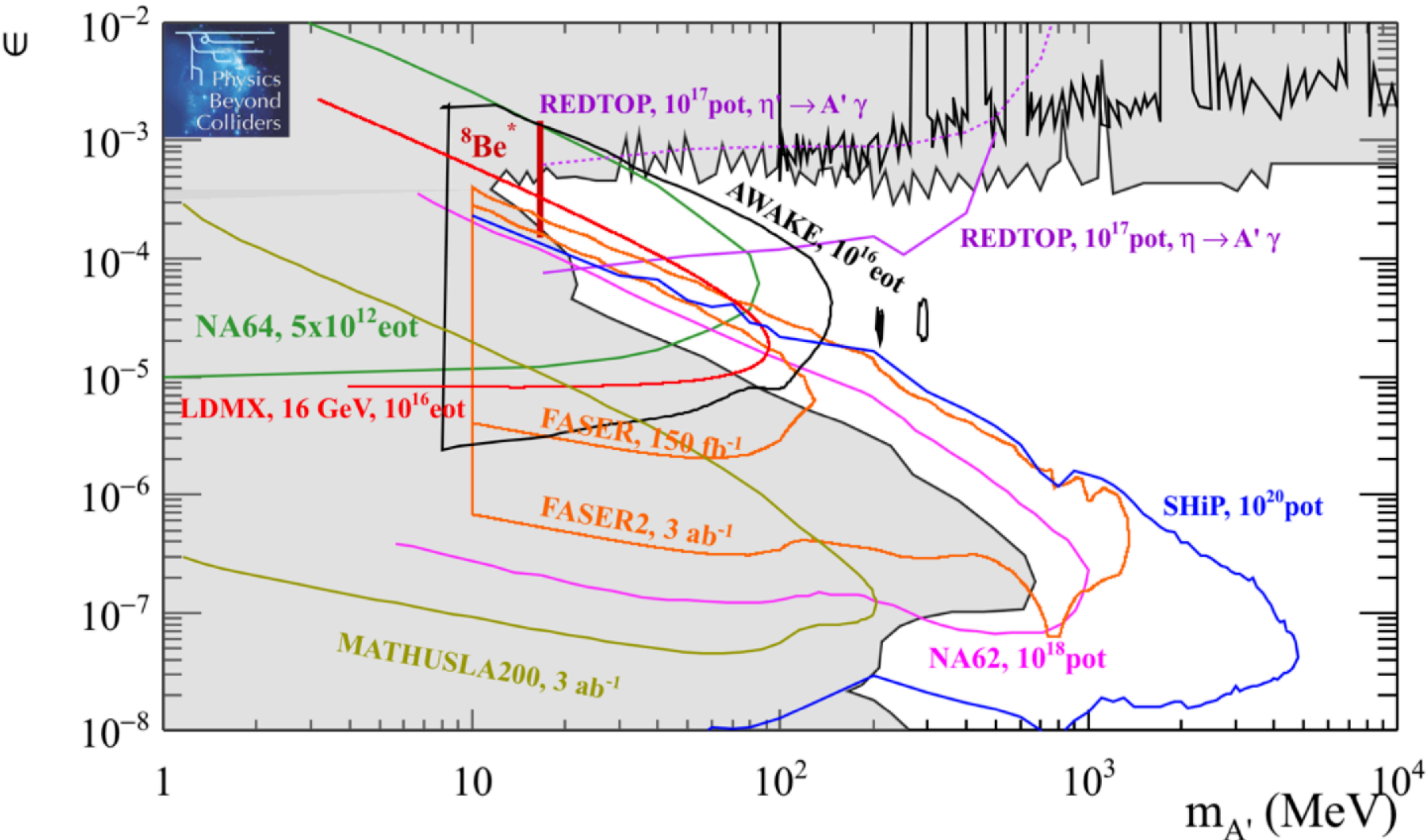
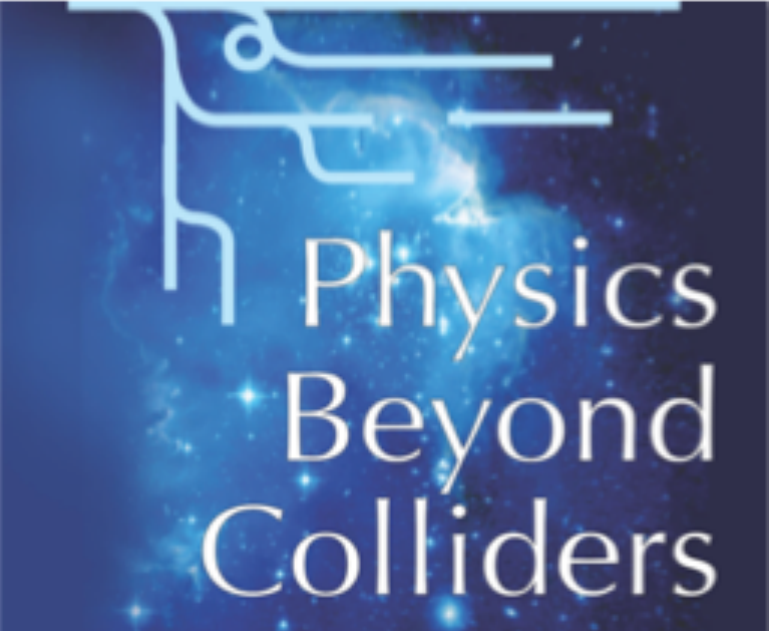
BENCHMARK MODELS



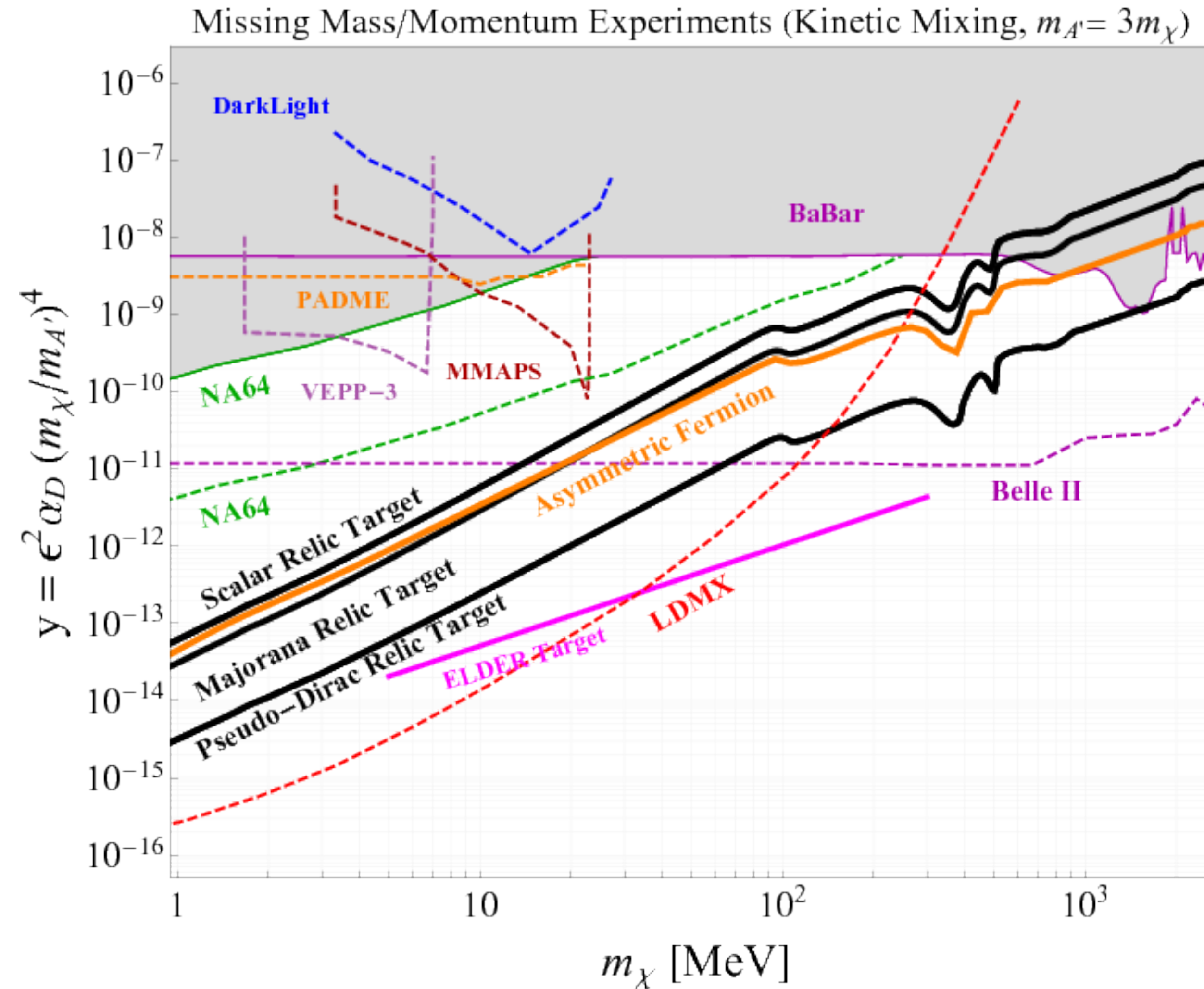
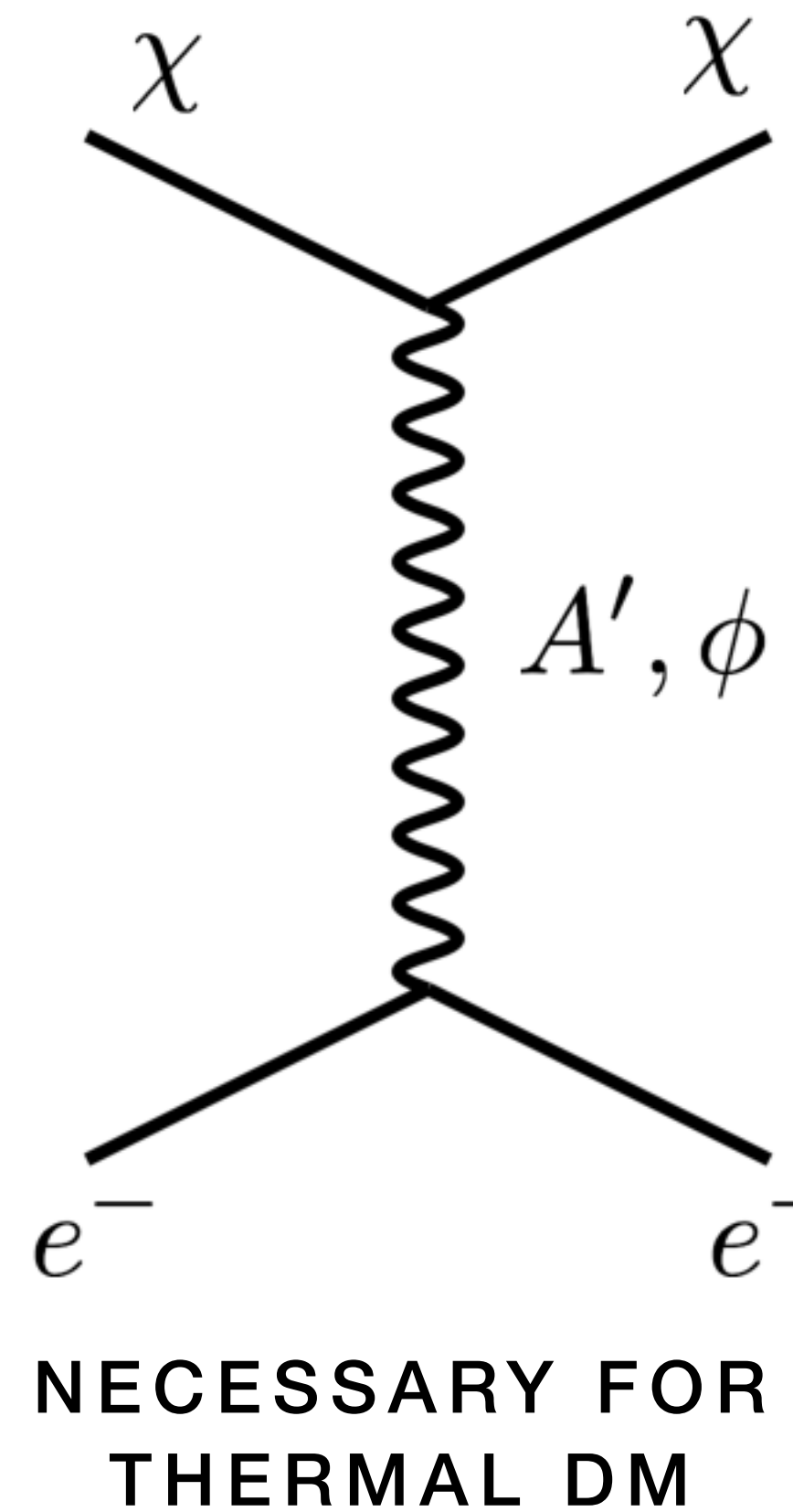
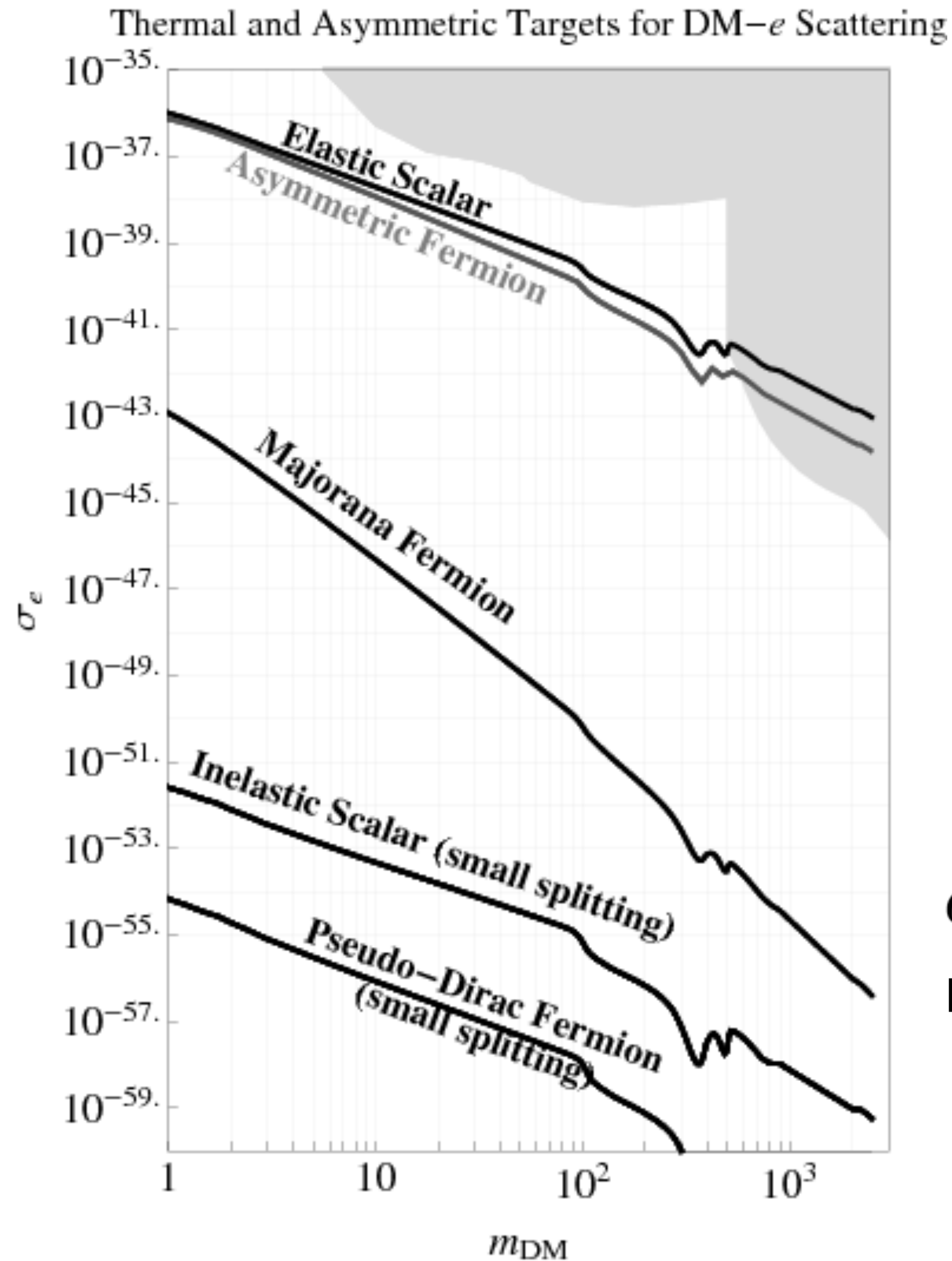
9	Physics reach of PBC projects in the MeV-GeV mass range	73
9.1	Vector Portal	78
9.1.1	Minimal Dark Photon model (BC1)	78
9.1.2	Dark Photon decaying to invisible final states (BC2)	83
9.1.3	Milli-charged particles (BC3)	90
9.2	Scalar Portal	93
9.2.1	Dark scalar mixing with the Higgs (BC4 and BC5)	93
9.3	Neutrino Portal	97
9.3.1	Neutrino portal with electron-flavor dominance (BC6)	98
9.3.2	Neutrino portal with muon-flavor dominance (BC7)	101
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9.4	Axion Portal	106
9.4.1	Axion portal with photon-coupling (BC9)	106
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9.4.3	Axion portal with gluon-coupling (BC11)	113
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10.1	Measurement of EDMs as probe of NP in the multi TeV scale	115
10.2	Experiments sensitive to Flavour Violation	116
10.3	B physics anomalies and $BR(K \rightarrow \pi \nu \bar{\nu})$	120

- Representative.
- Non-exhaustive.
- Overlapping coverage.
- Simplified models.

BENCHMARK: DARK PHOTON



DARK MATTER TARGETS

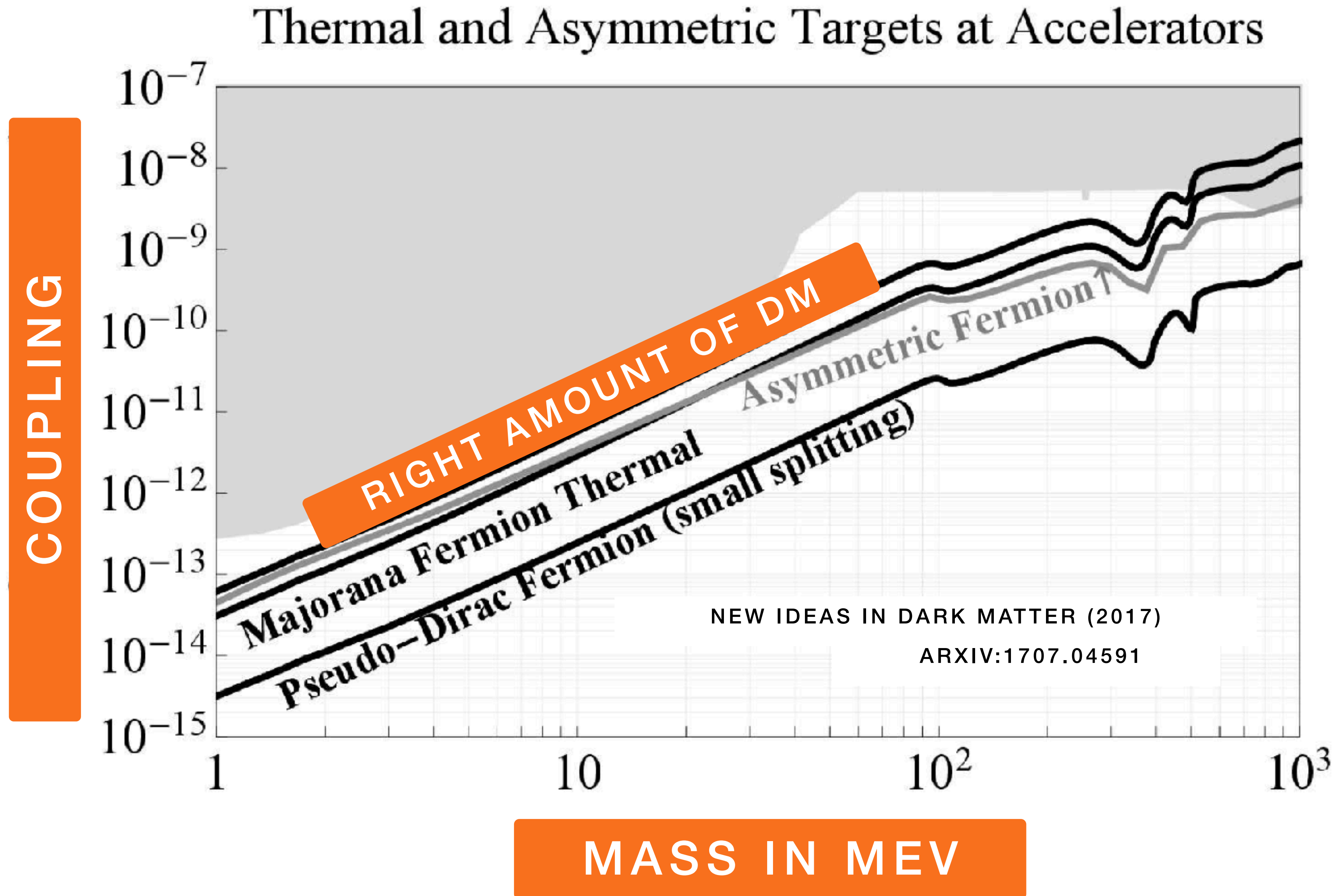


NR KINEMATICS

REL. KINEMATICS

DARK MATTER TARGETS AT ACCELERATORS

- Relic abundance is predictive.
- Well defined targets.
- Can search for dark matter "in the lab".





PART 1

A (DARK) MOTIVATION



PART 2

THE INTENSITY FRONTIER



PART 3

SOME RECENT WORK



PART 1

A (DARK) MOTIVATION



PART 2

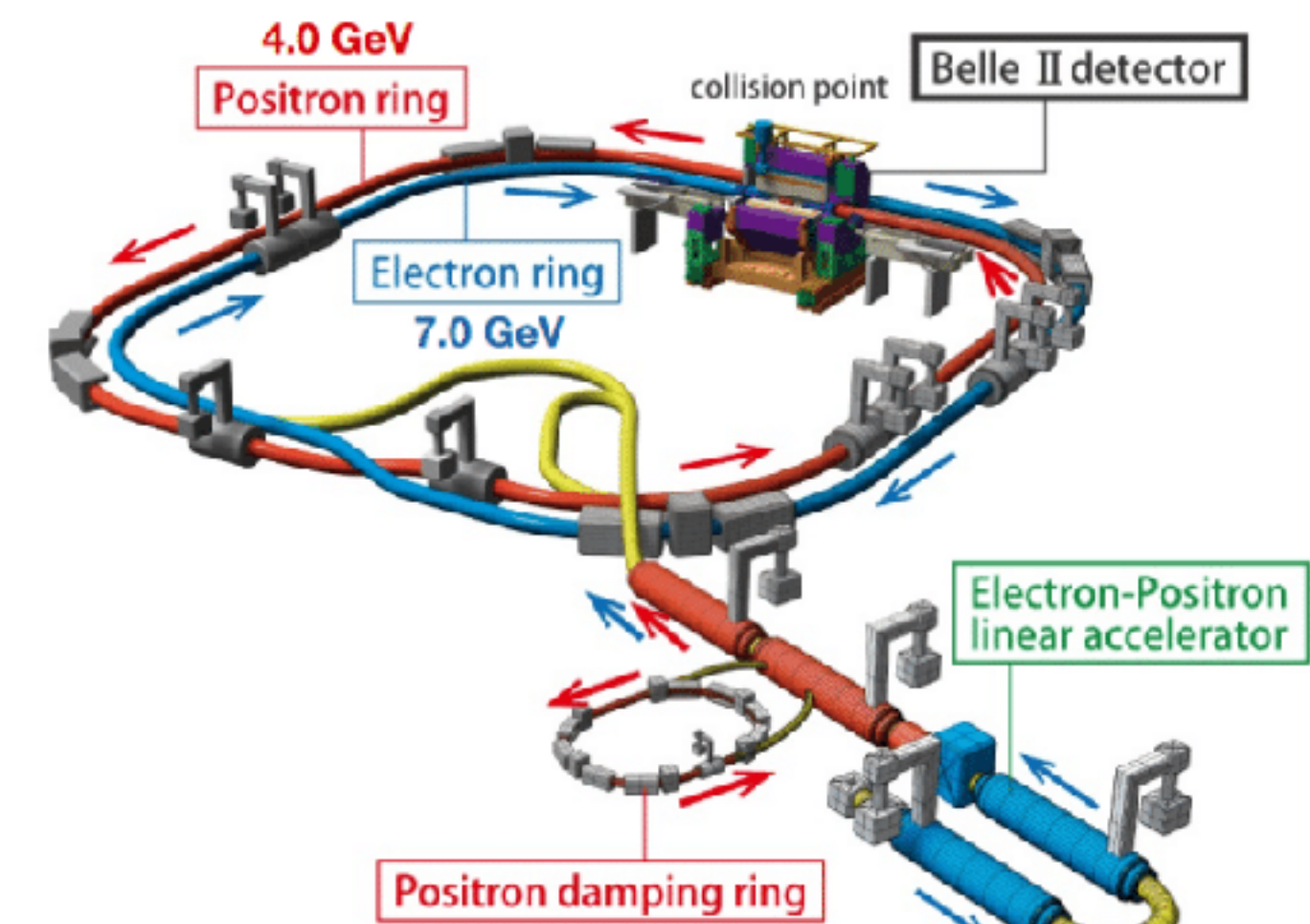
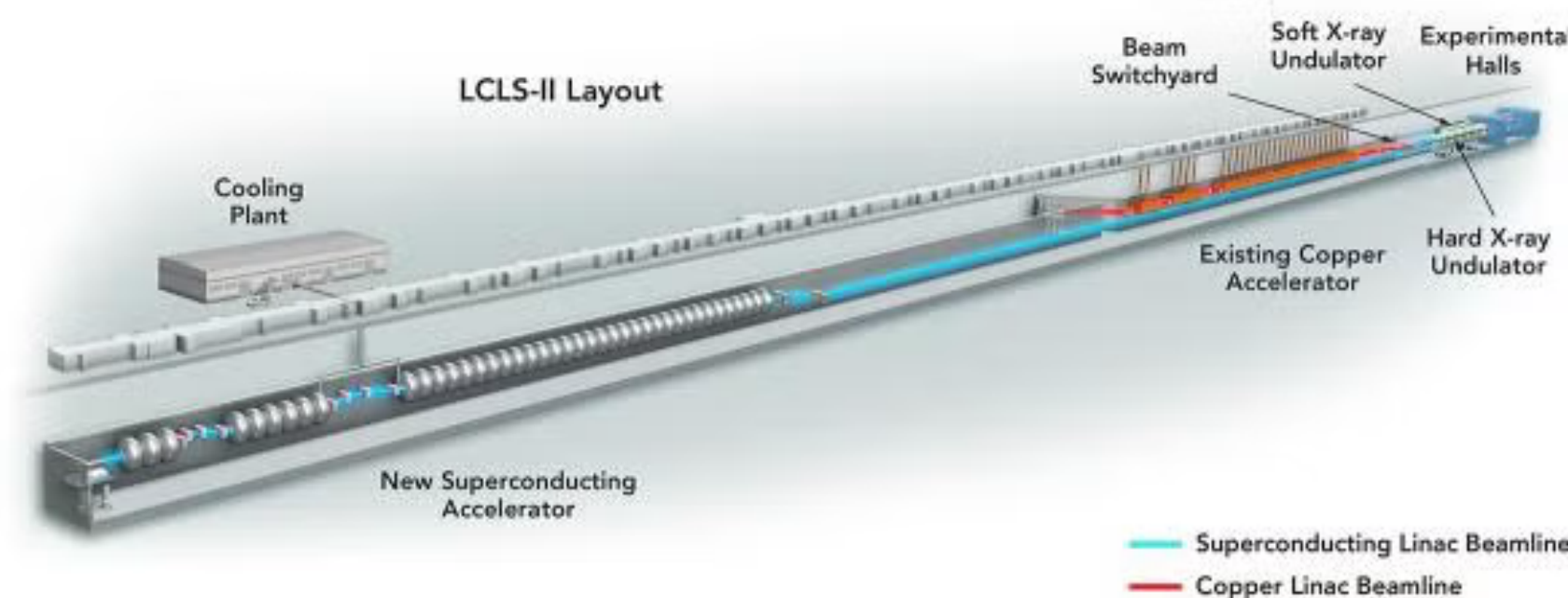
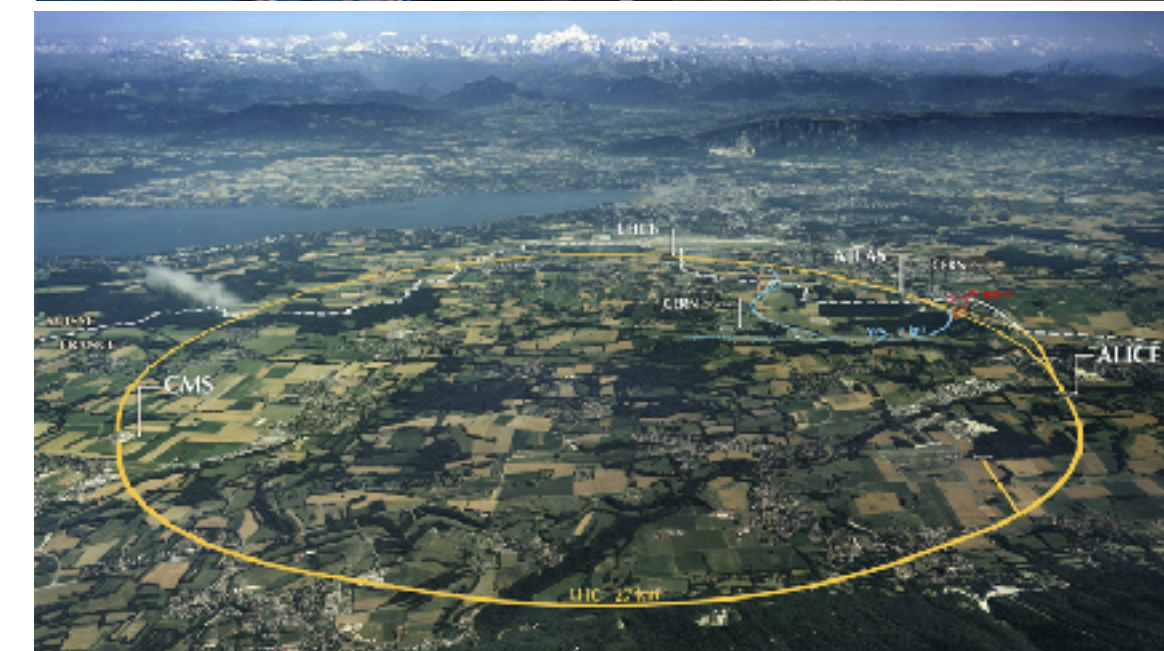
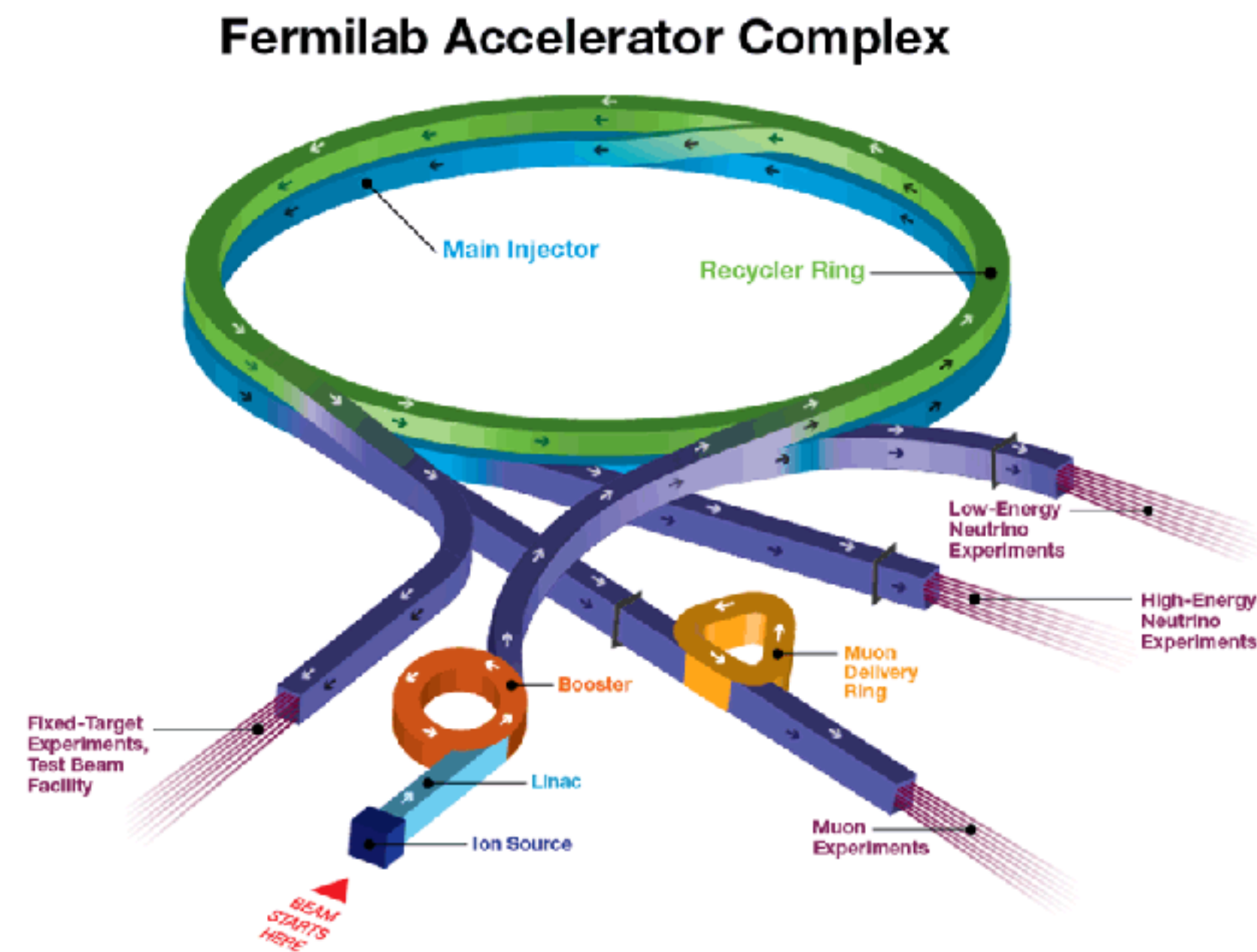
THE INTENSITY FRONTIER



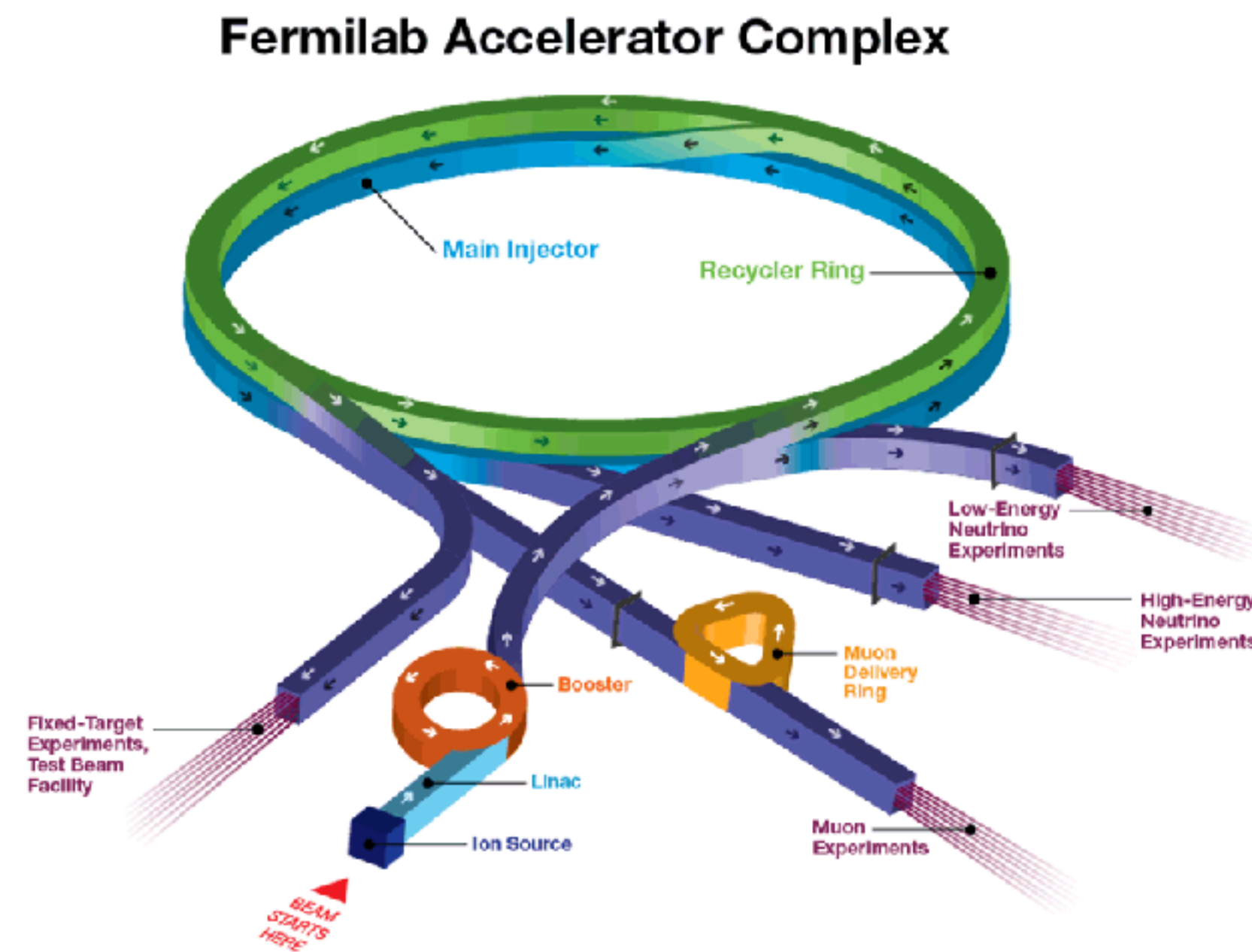
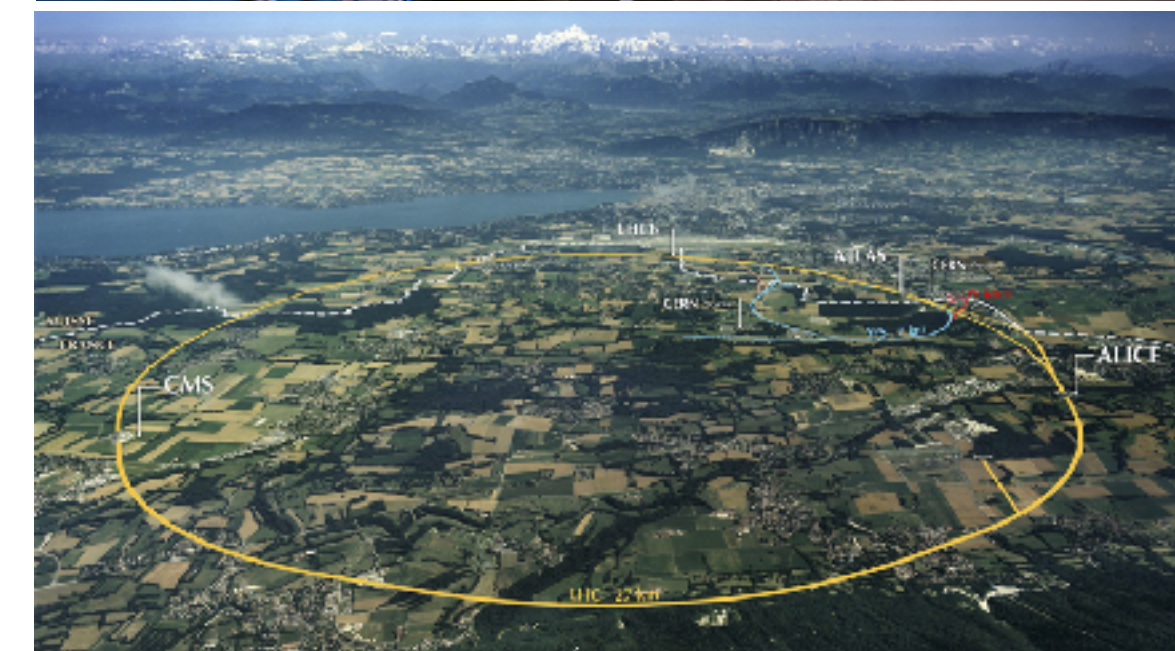
PART 3

SOME RECENT WORK

HIGH INTENSITY BEAMS



HIGH INTENSITY BEAMS

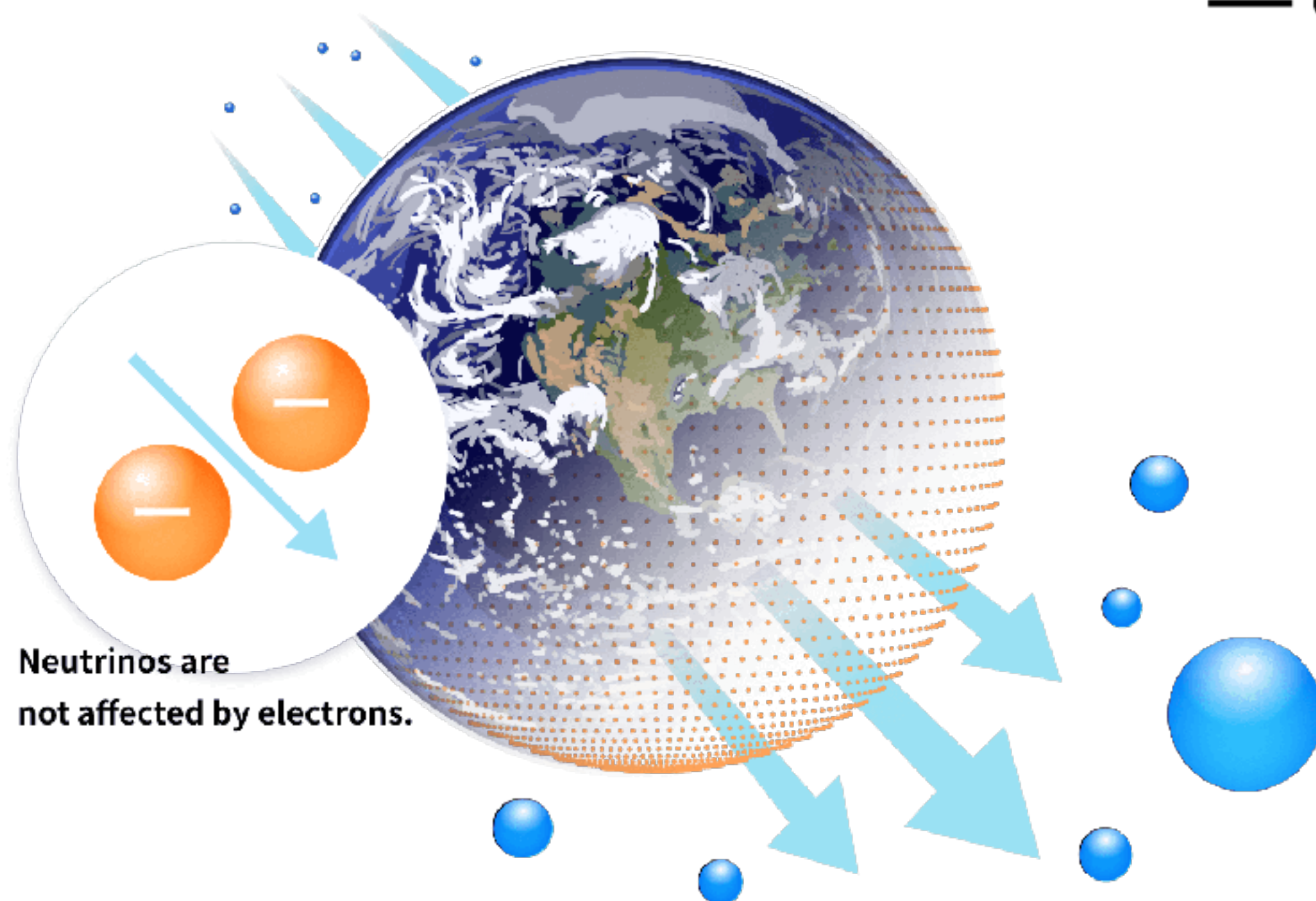
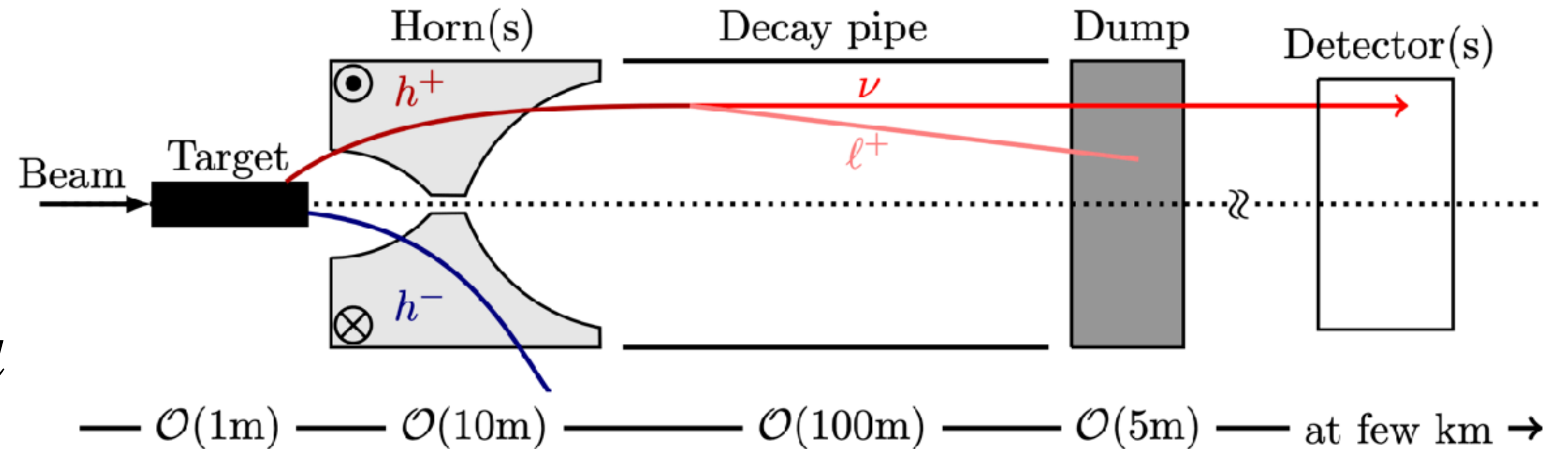


- Use high energy beams to make dark particles.
- Detect the dark particles that are produced.

EXAMPLE: NEUTRINO BEAMS

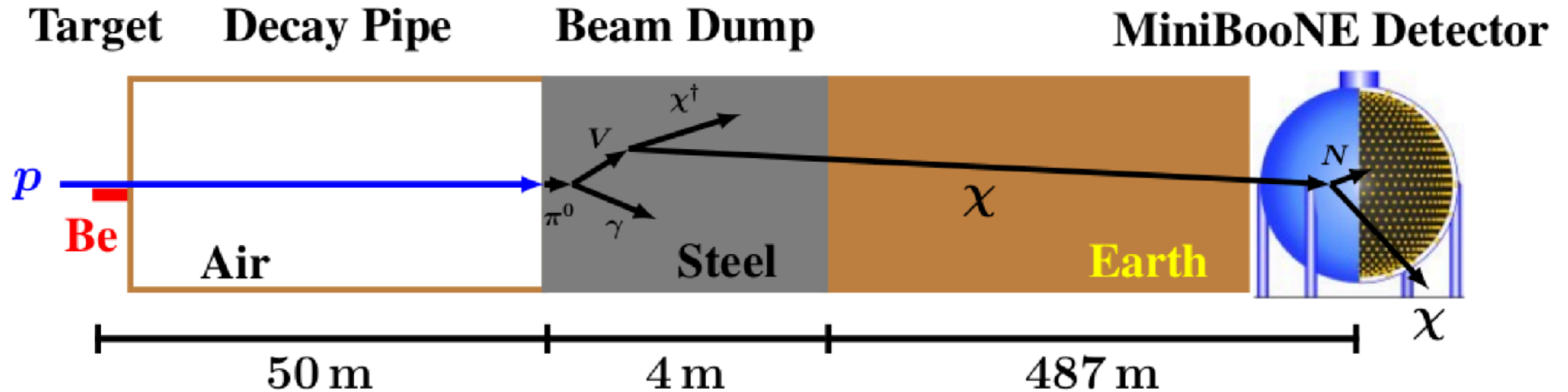
$$pA \rightarrow \pi X$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$



- Neutrino beams.
- High intensity proton source.
- Smashed into thick target.
- Produced in meson decays.

REUSING NEUTRINO BEAMS FOR BSM



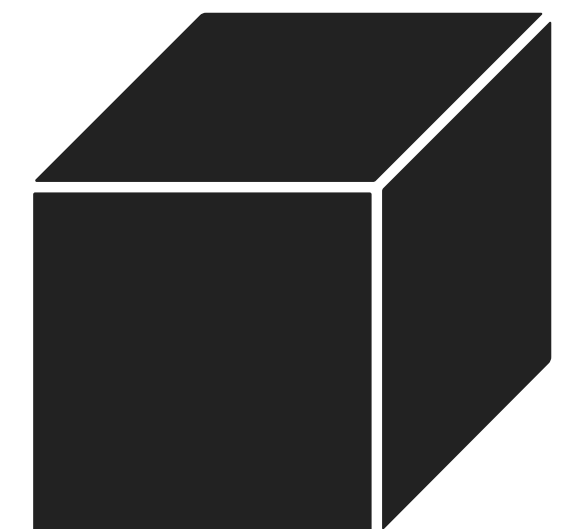
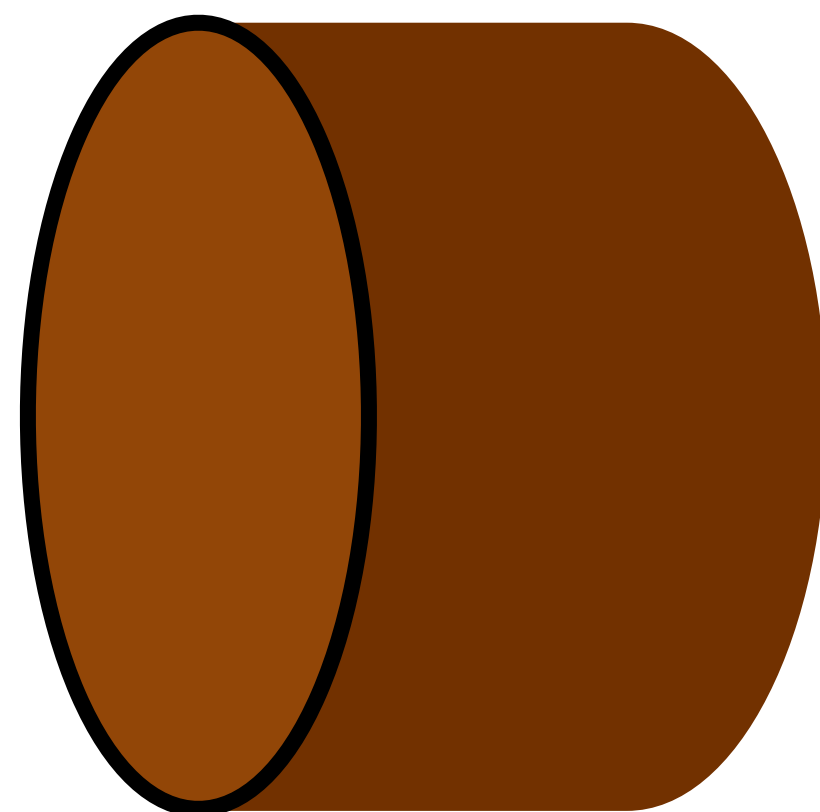
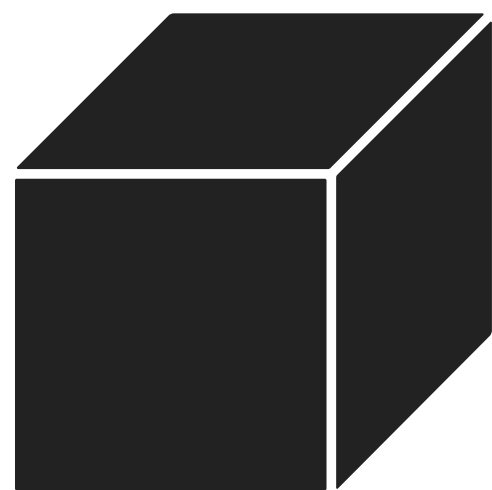
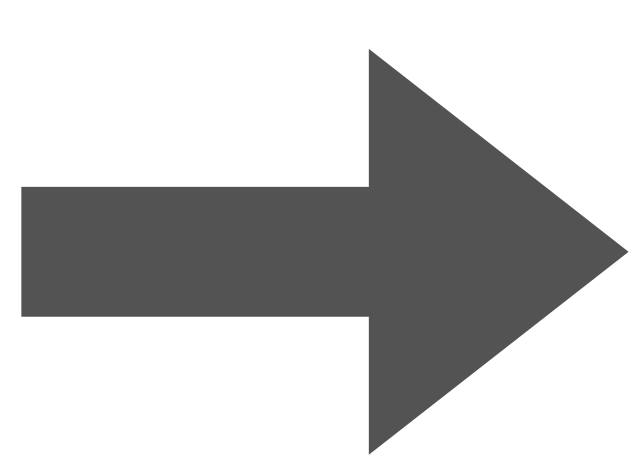
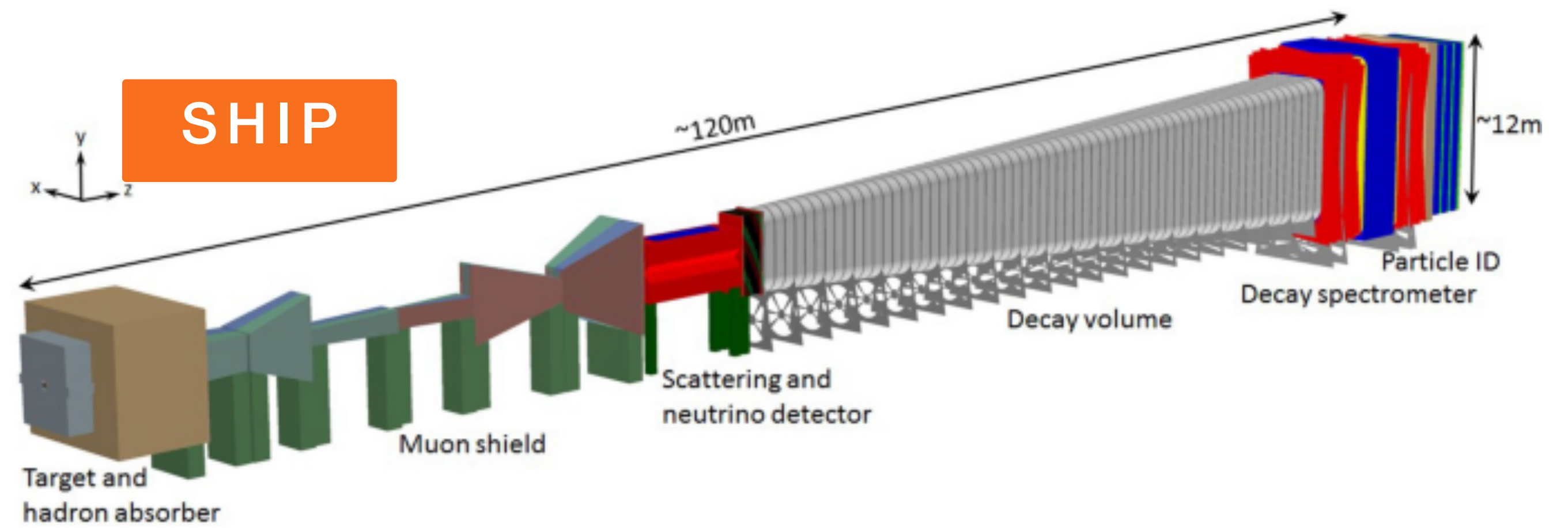
- Turn off horns: suppress background rate
- Collide with "dump" instead of target.
- Very successful run at MiniBooNE.



CONCEPTUAL OVERVIEW OF BEAM DUMPS



BEAM DUMPS!



Beam

target

dirt

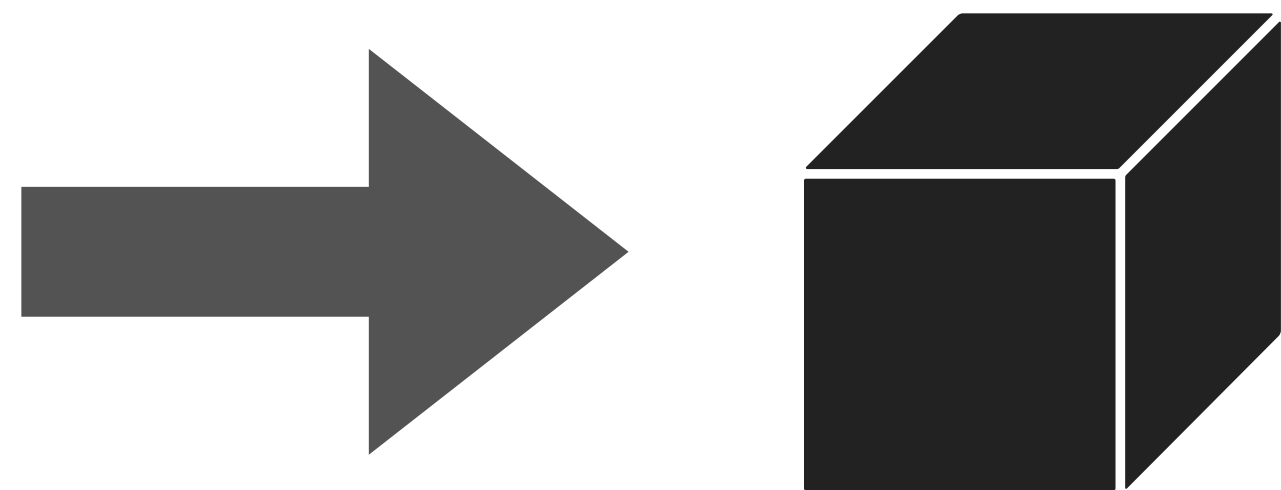
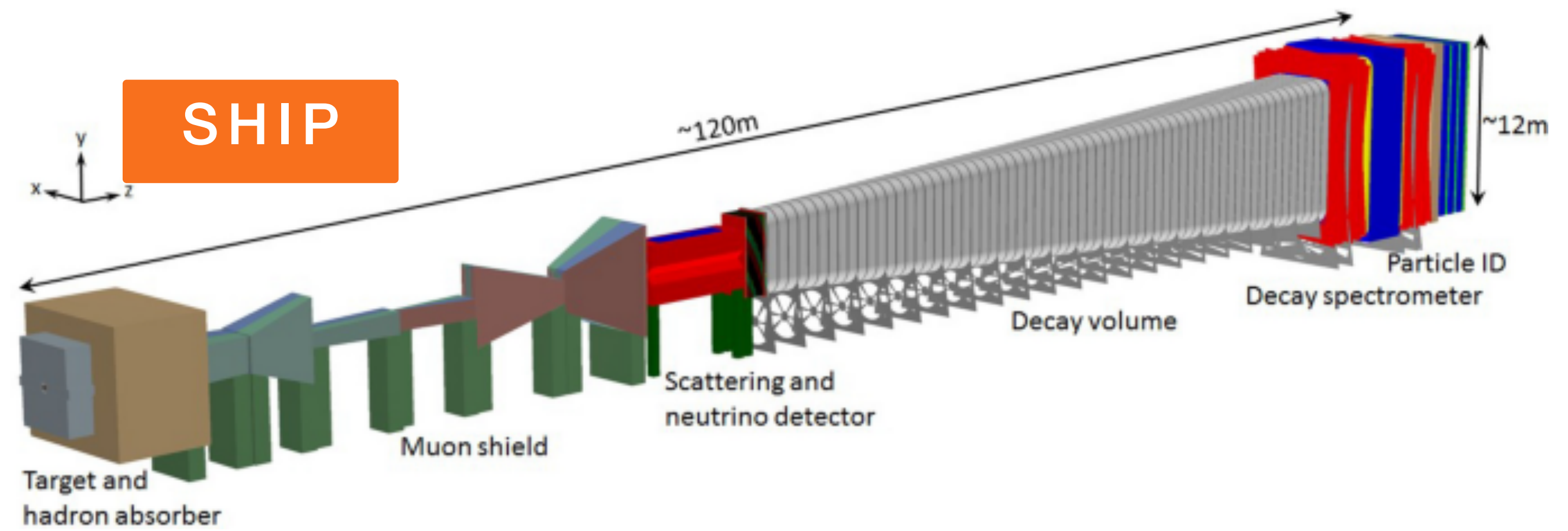
pipe (optional)

detector₃₀

CONCEPTUAL OVERVIEW OF BEAM DUMPS



DARK VECTORS



Beam target

$$\pi^0 \rightarrow \gamma V$$

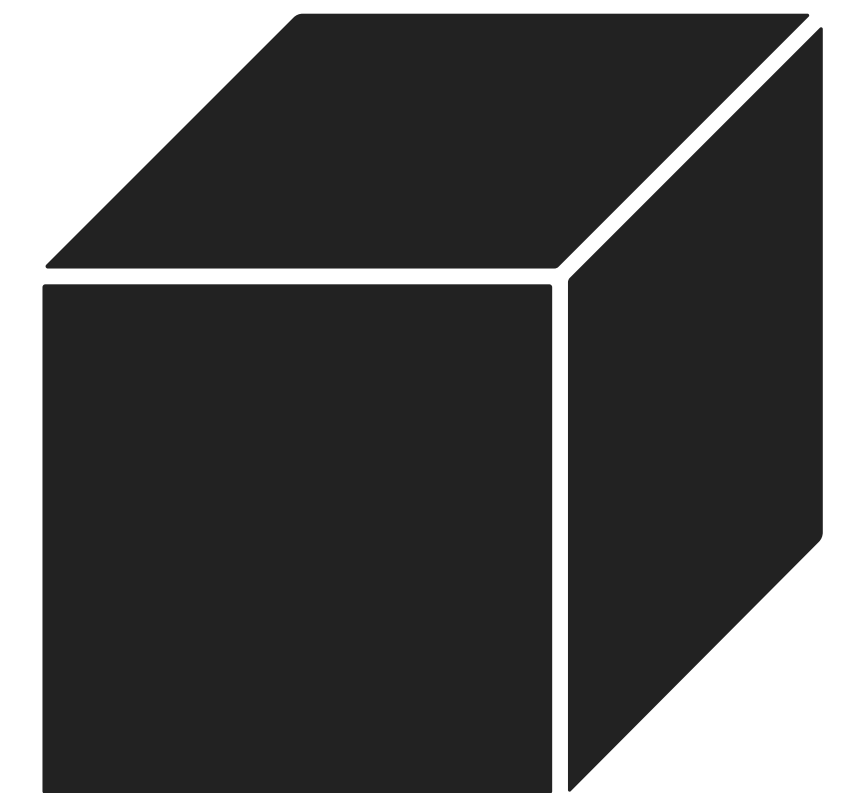
$$pA \rightarrow VX$$

$$pA \rightarrow VX$$

$$V \rightarrow e^+ e^-$$

$$Vn \rightarrow p\pi^-$$

$$Ve \rightarrow Ve$$

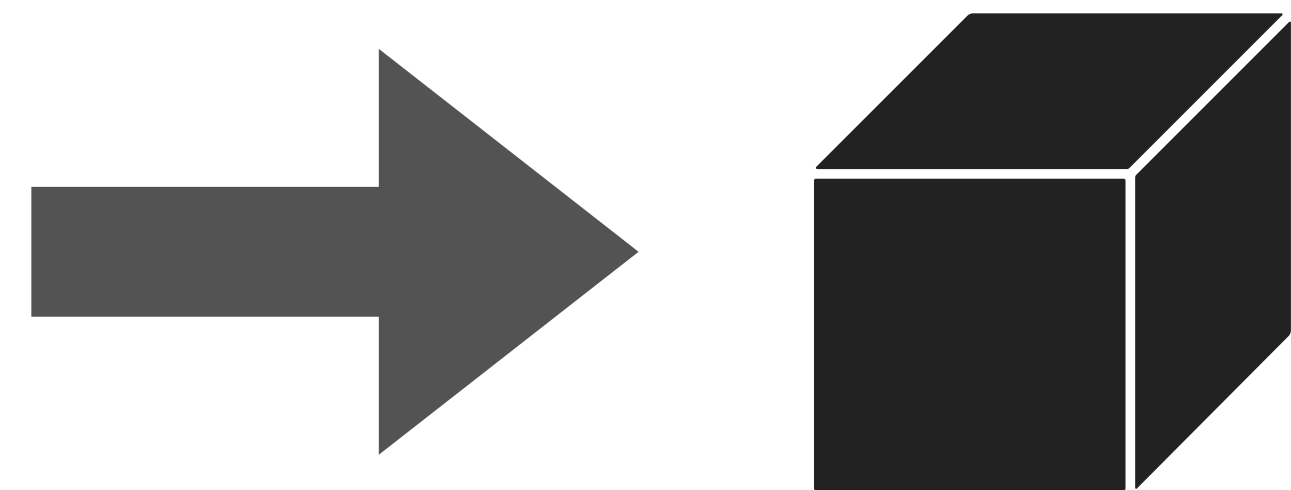
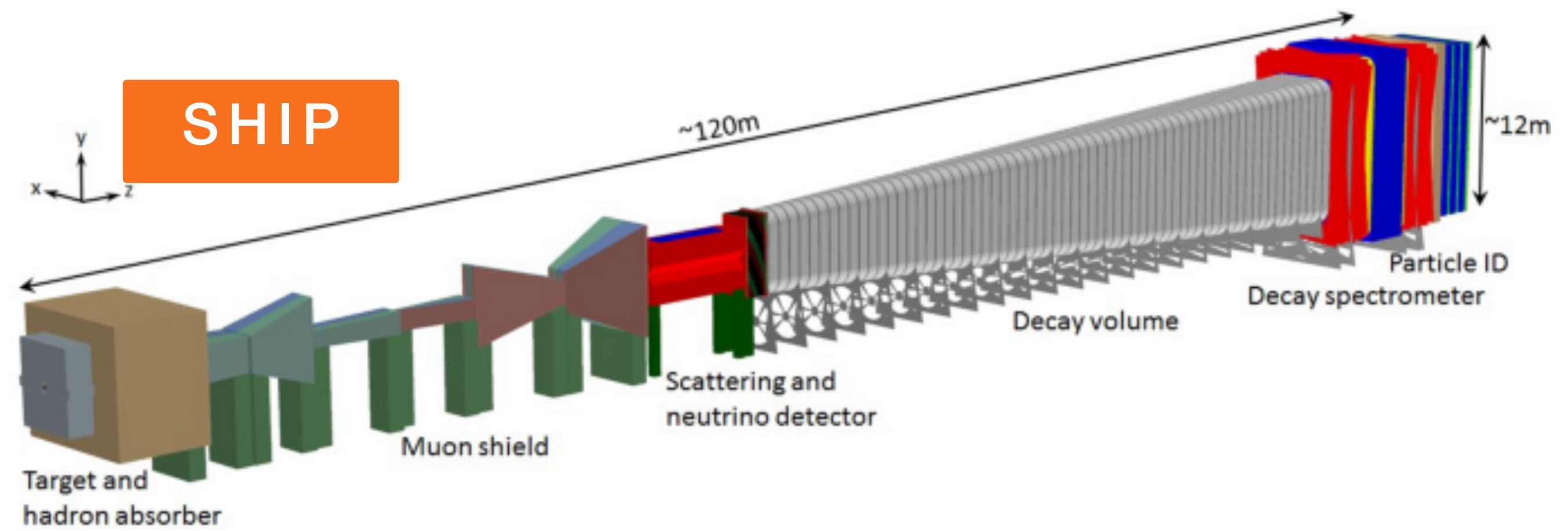


detector₃₁

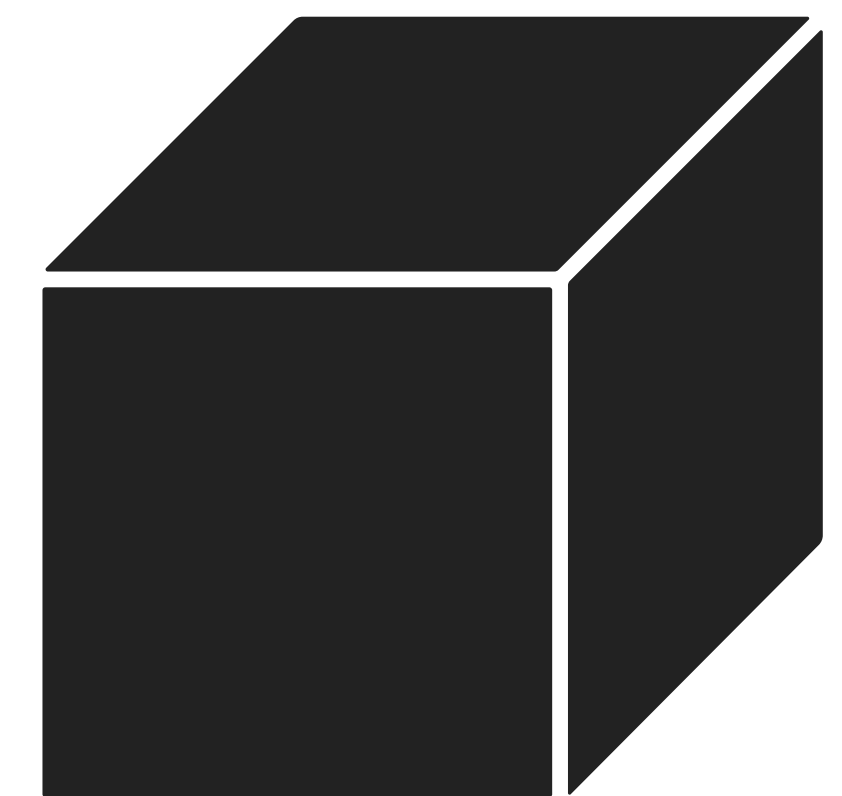
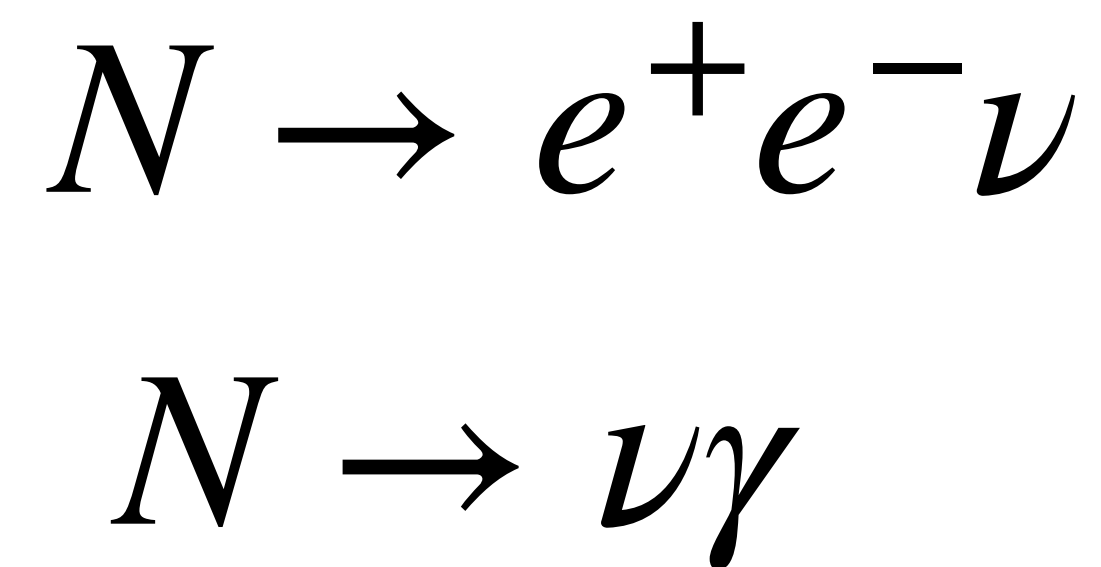
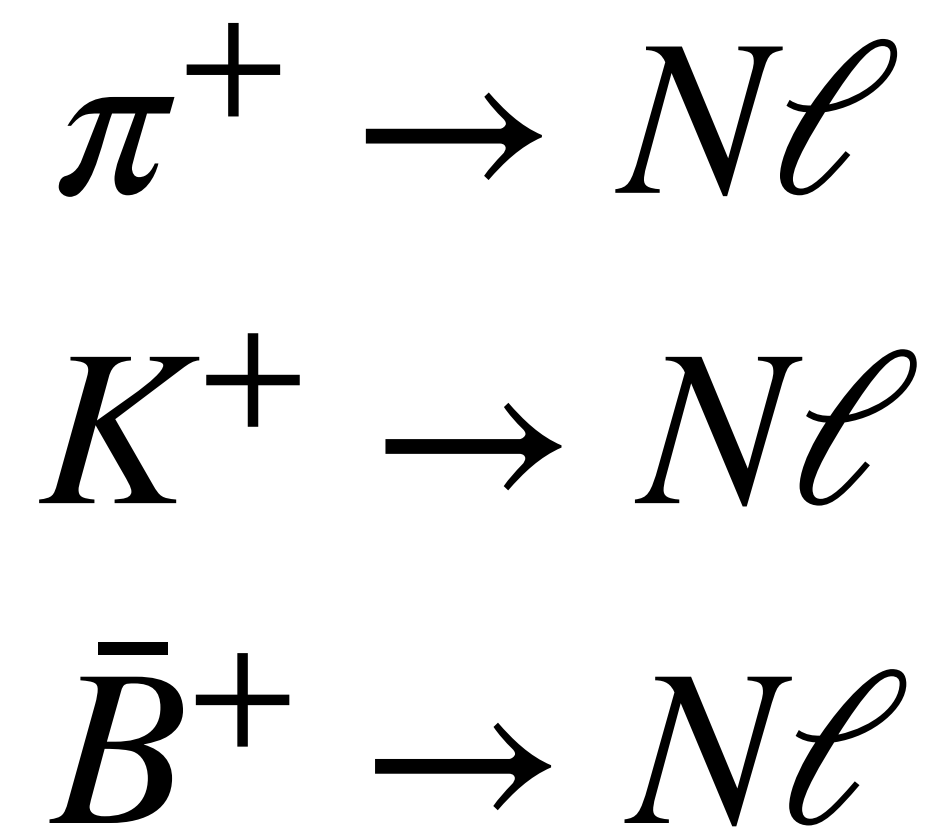
CONCEPTUAL OVERVIEW OF BEAM DUMPS



RIGHT-HANDED NEUTRINOS

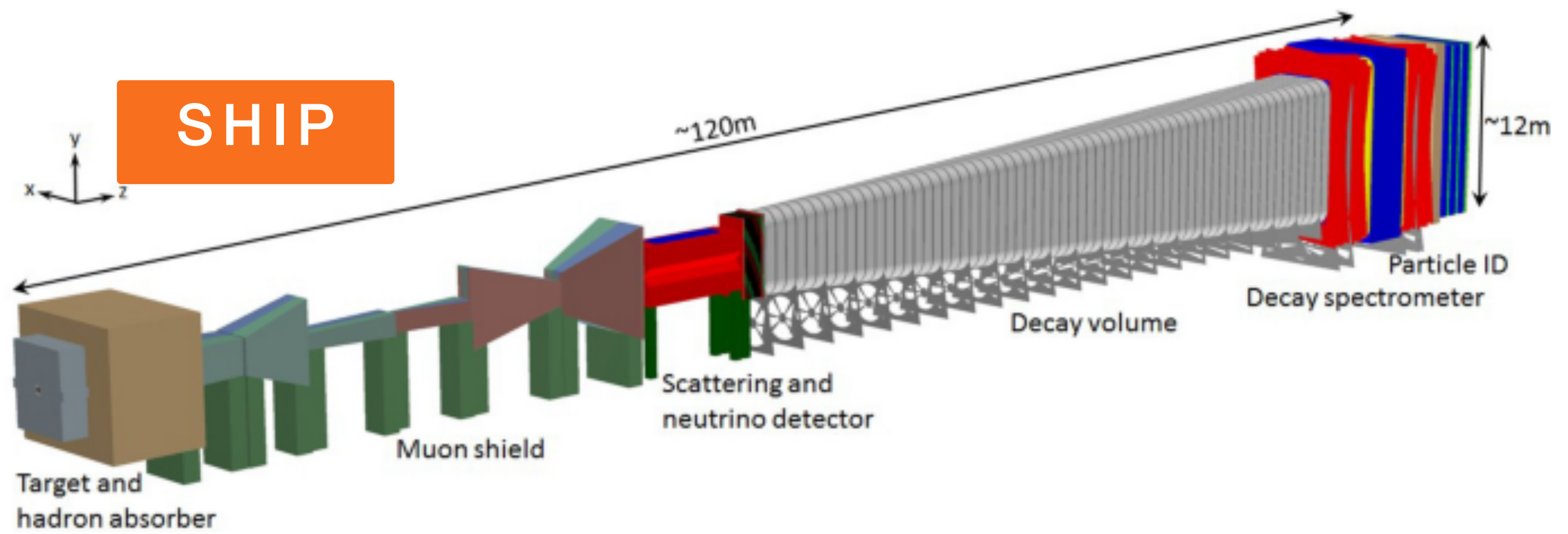


Beam target

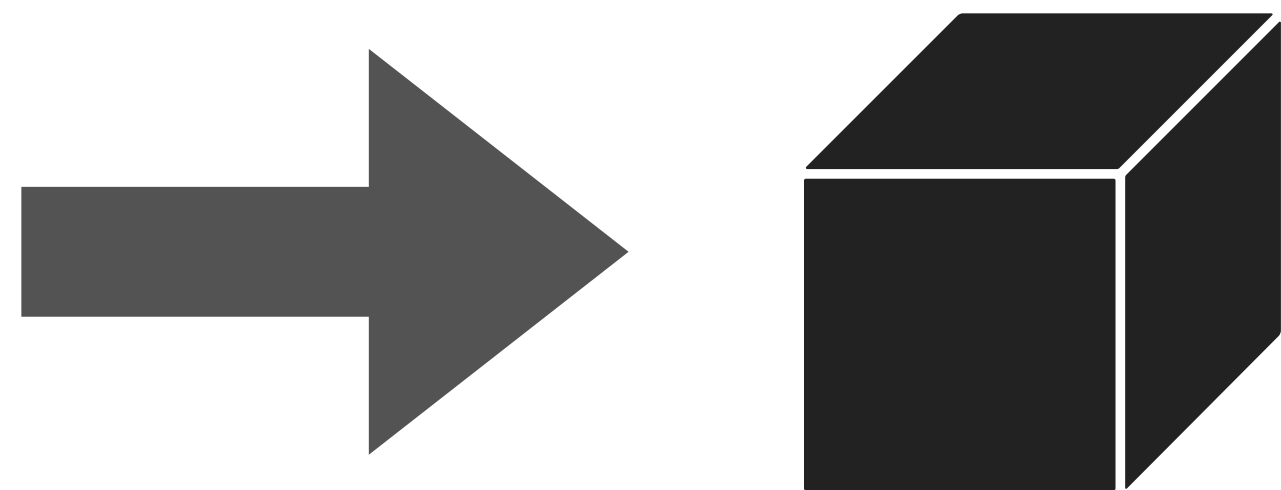


detector₃₂

CONCEPTUAL OVERVIEW OF BEAM DUMPS



AXION LIKE PARTICLES



Beam target

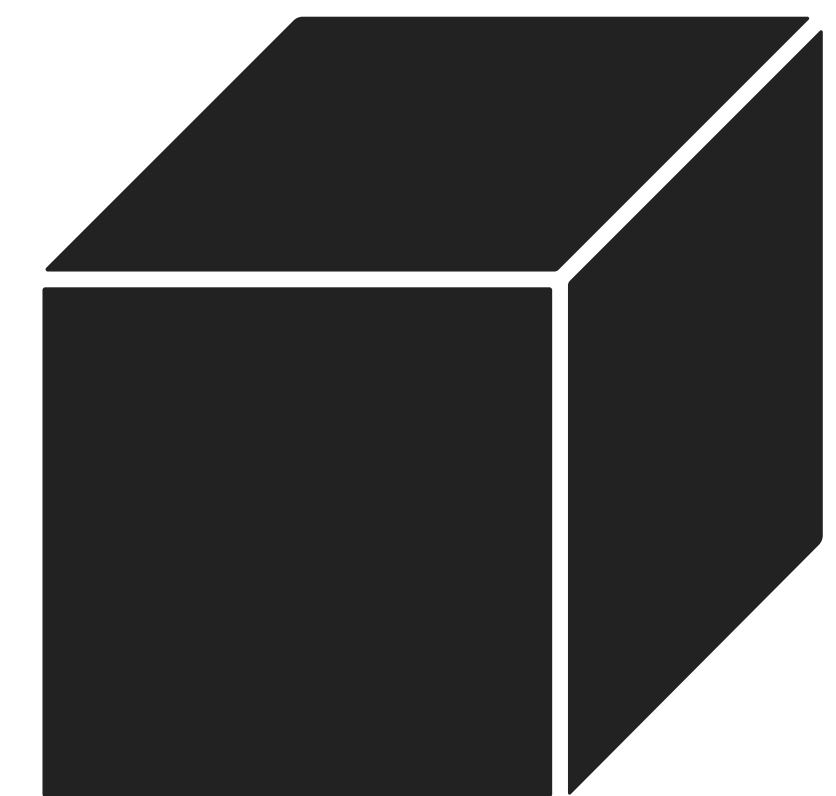
$$K \rightarrow \pi a$$

$$\gamma\gamma^* \rightarrow a$$

$$eA \rightarrow eAa$$

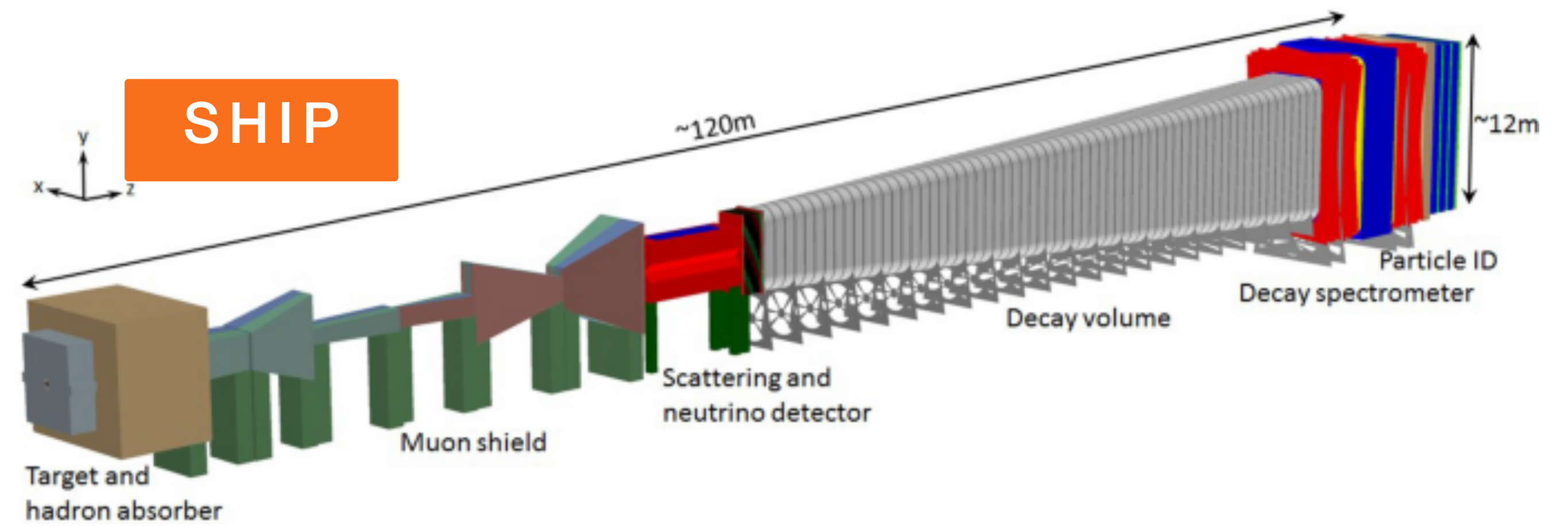
$$a \rightarrow \gamma\gamma$$

$$a \rightarrow e^+e^-$$

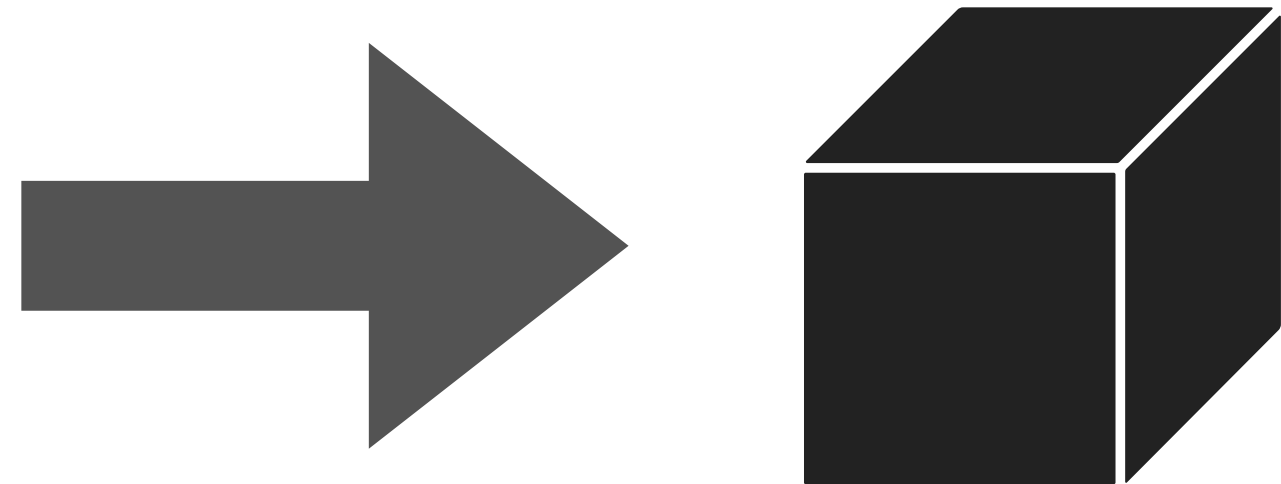


detector₃₃

CONCEPTUAL OVERVIEW OF BEAM DUMPS

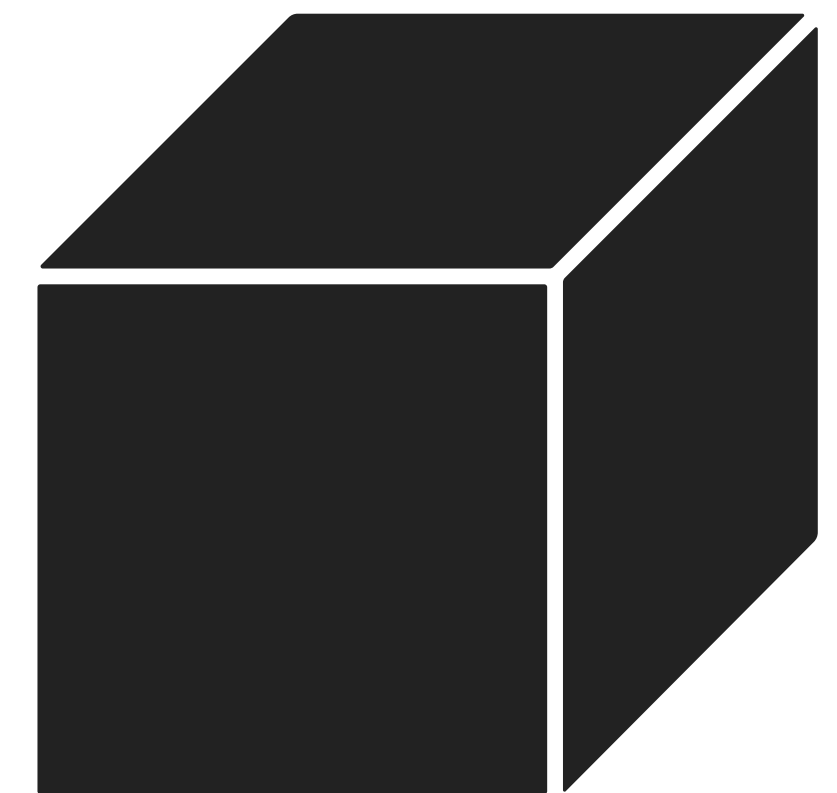


PRODUCTION



Beam target

DETECTION



detector₃₄

Cosmic rays



HARNIK, RP, POSPELOV,
RAMANI (2020)

- Scattering with dark matter.

RP, TAKHISTOV, TSAI, BRINGMANN,
KUSENKO, POSPELOV (2020)

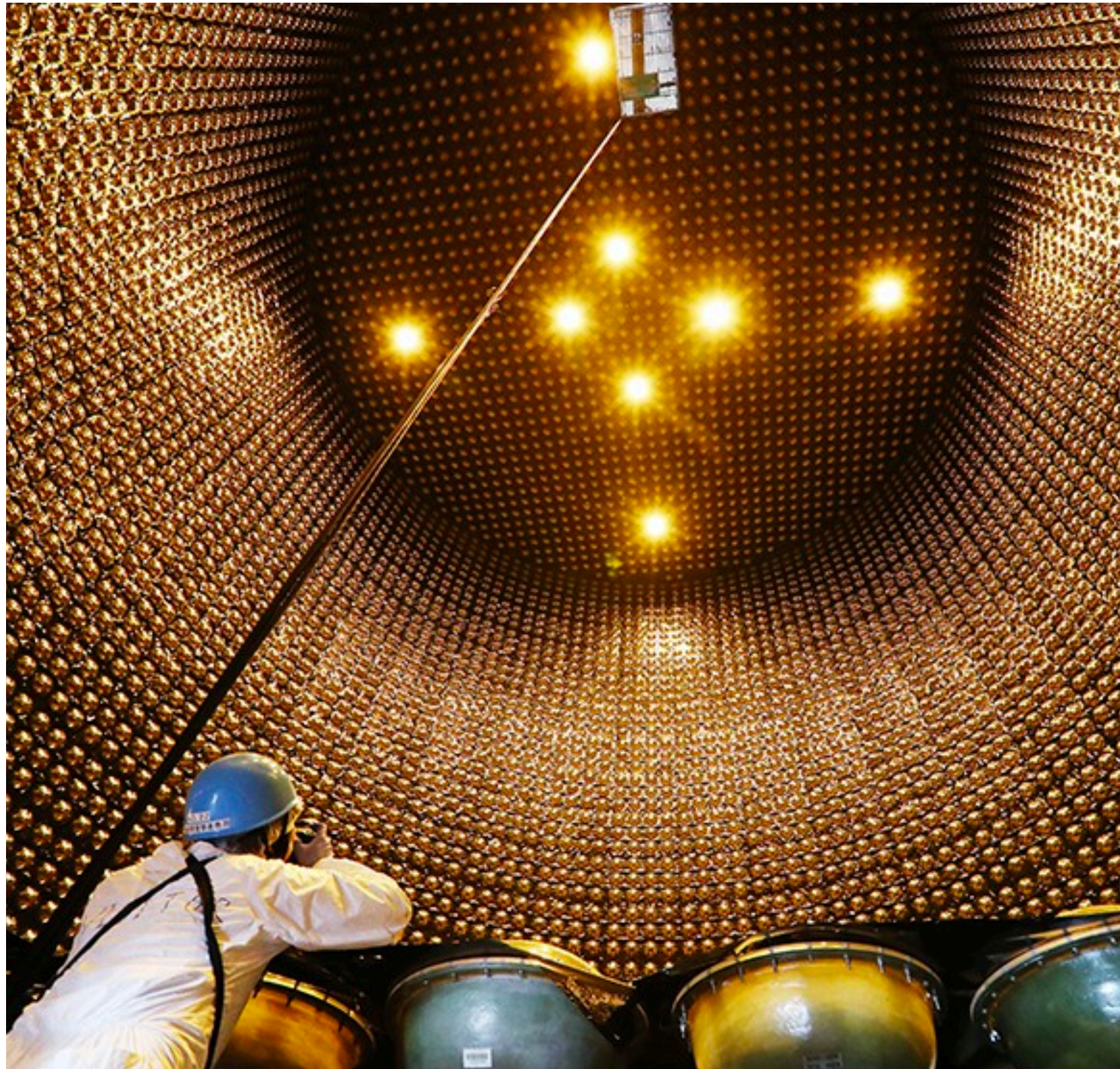
- Make dark particles in atmosphere.
- Novel search strategies.

MULTIPLE ADVANTAGES

Long length scales



SUPER-KAMIOKANDE



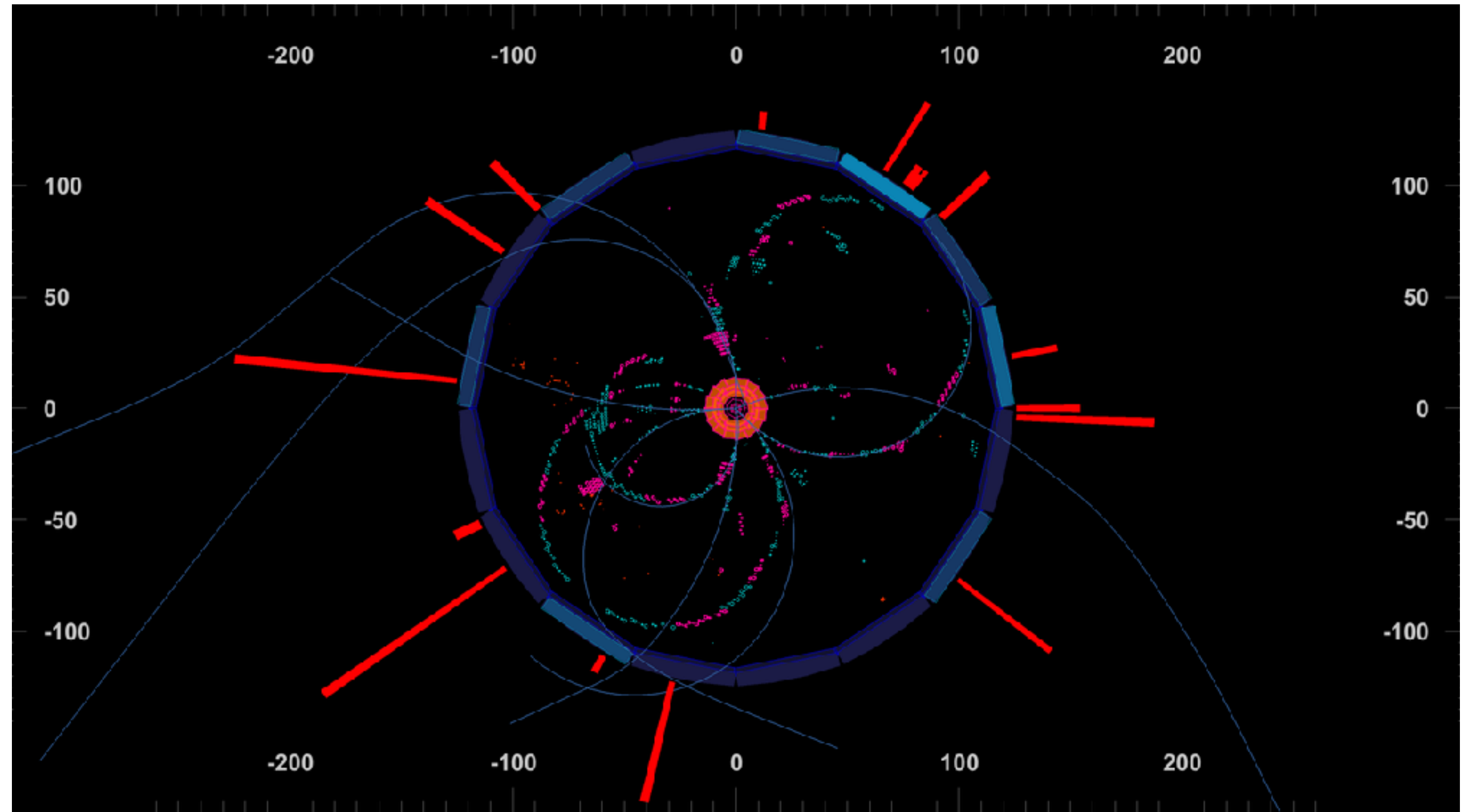
Big volumes



Long exposures

PROMPT SEARCHES

- Beam dumps fail if particle decays quickly.
- Can build detector closer to interaction.
- Smaller luminosity and so bigger couplings.



$$e^+e^- \rightarrow a \rightarrow \gamma\gamma$$

BUMP HUNT IN $(q_1 + q_2)^2$

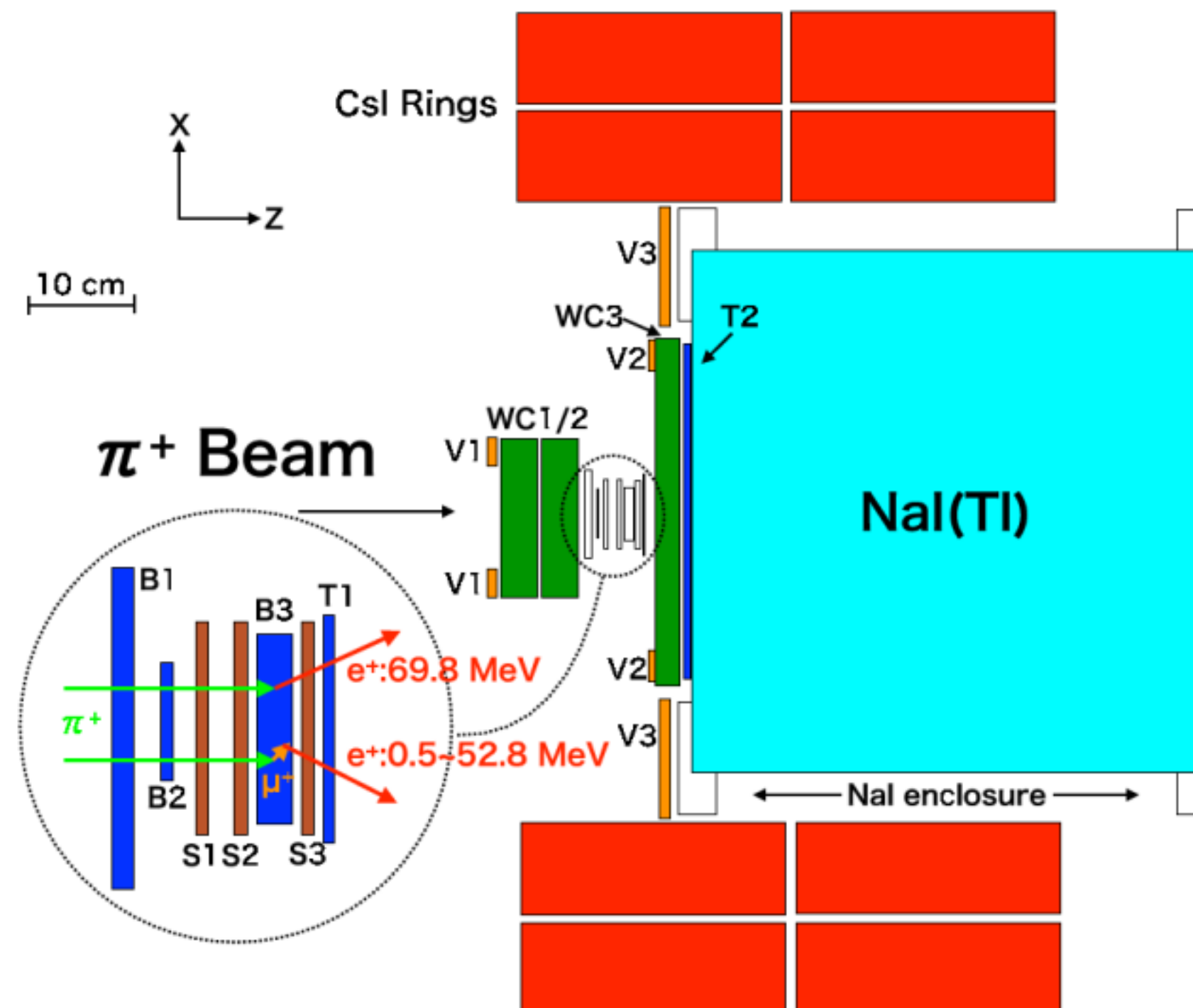
RARE EVENTS

- Huge statistical sample of SM particles.
- Look for controlled rare decay modes.
- Can also look for exotic neutrino scattering.

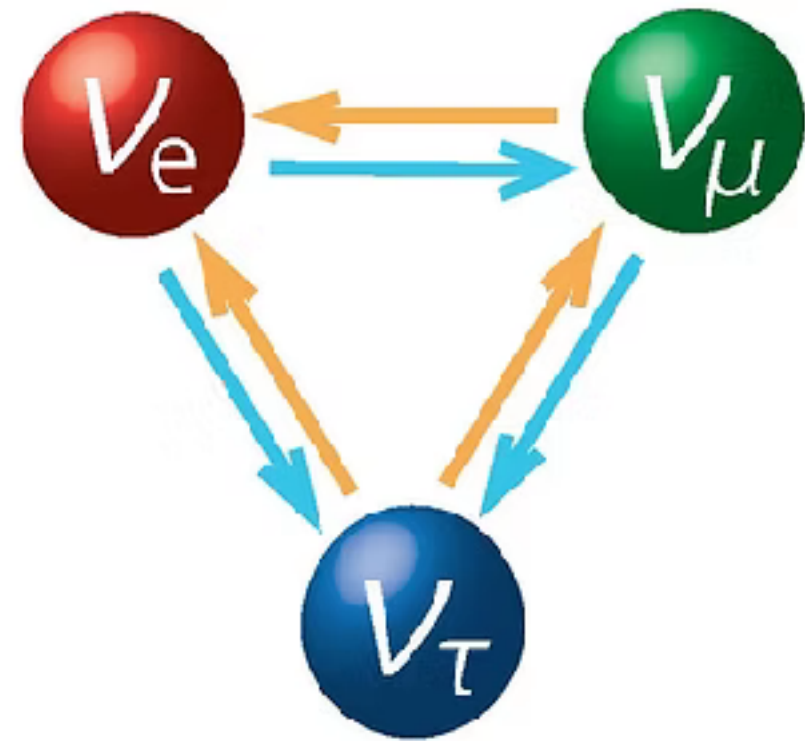
$$\mu^+ \rightarrow e^+ e^+ e^-$$

$$K^+ \rightarrow \pi^+ a$$

$$\pi^+ \rightarrow e^+ N$$



SPECIAL FEATURE: CLFV



- Lepton flavor is not conserved.

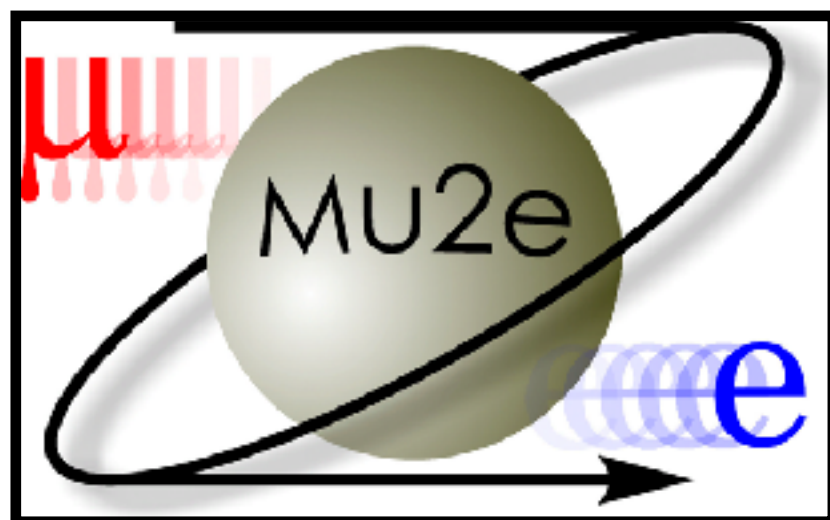
SEARCH FOR THESE PROCESSES

$$\mu \rightarrow e\gamma \quad \mu \rightarrow eee \quad \mu p \rightarrow ep$$

ANY SIGNAL IS PROOF OF NEW PHYSICS

SPECIAL FEATURE: CLFV

- There will be an **enormous** jump in sensitivity.



History of $\mu \rightarrow e\gamma$, $\mu N \rightarrow eN$, and $\mu \rightarrow 3e$

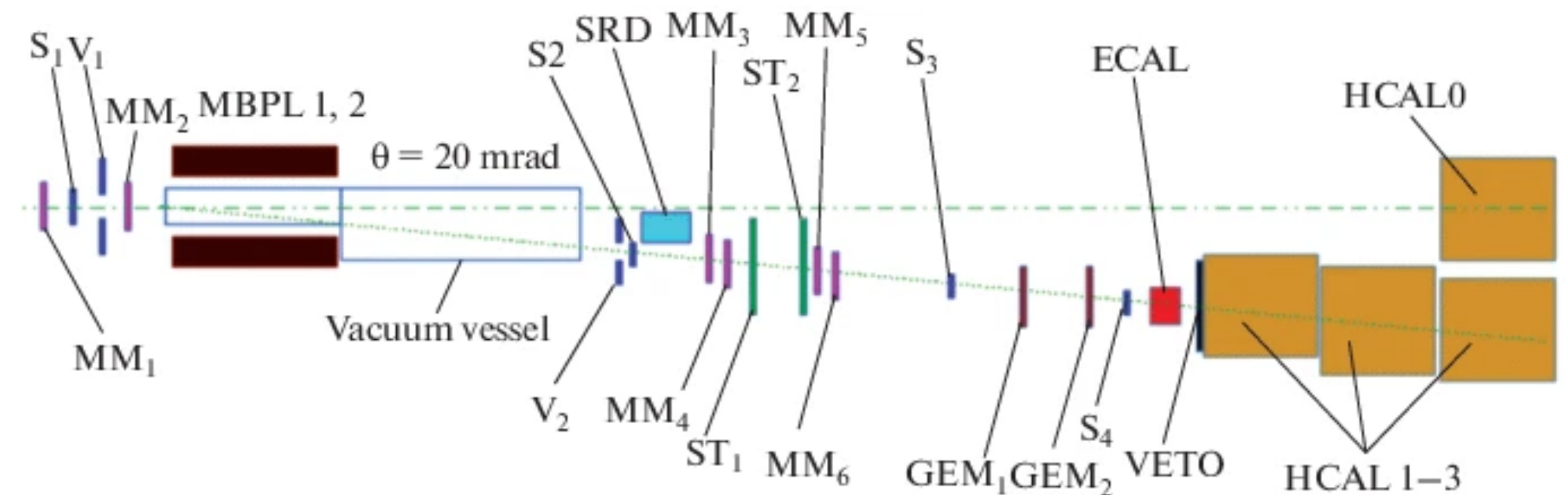


MISSING ENERGY/MOMENTUM

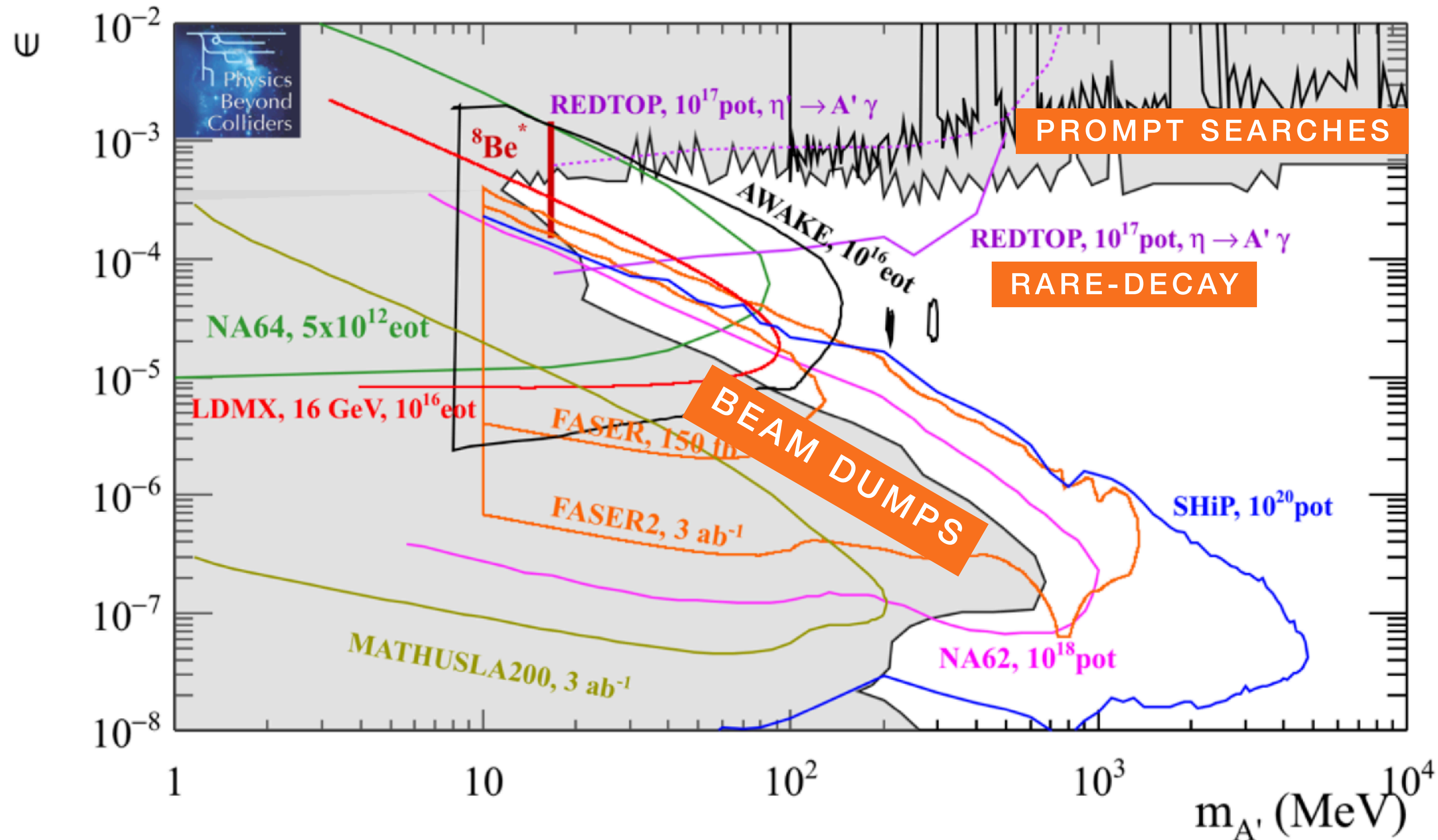
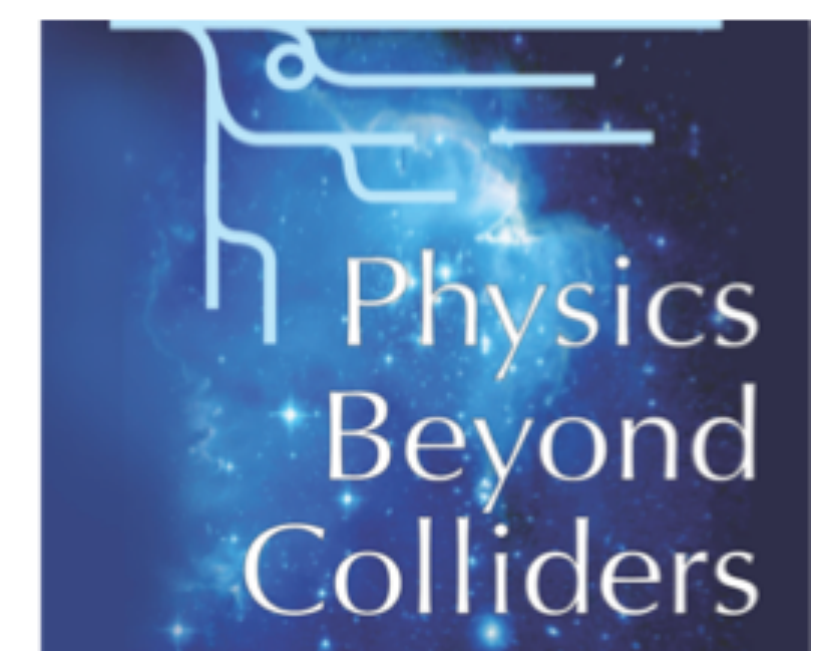
- Search for anomalous missing energy.
- Requires excellent background rejection.
- Examples: NA64, LDMX, FASER ν .

$$eA \rightarrow eA + \cancel{E}$$

$$eA \rightarrow eA + \cancel{p}_T$$



BENCHMARK: DARK PHOTON





PART 1

A (DARK) MOTIVATION



PART 2

THE INTENSITY FRONTIER



PART 3

SOME RECENT WORK



PART 1

A (DARK) MOTIVATION



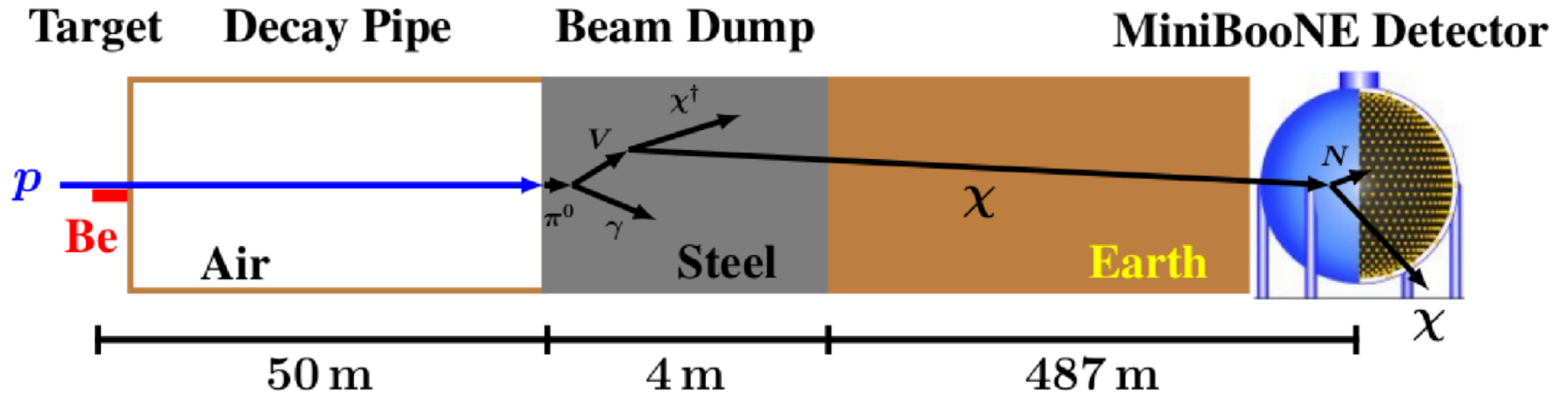
PART 2

THE INTENSITY FRONTIER



PART 3

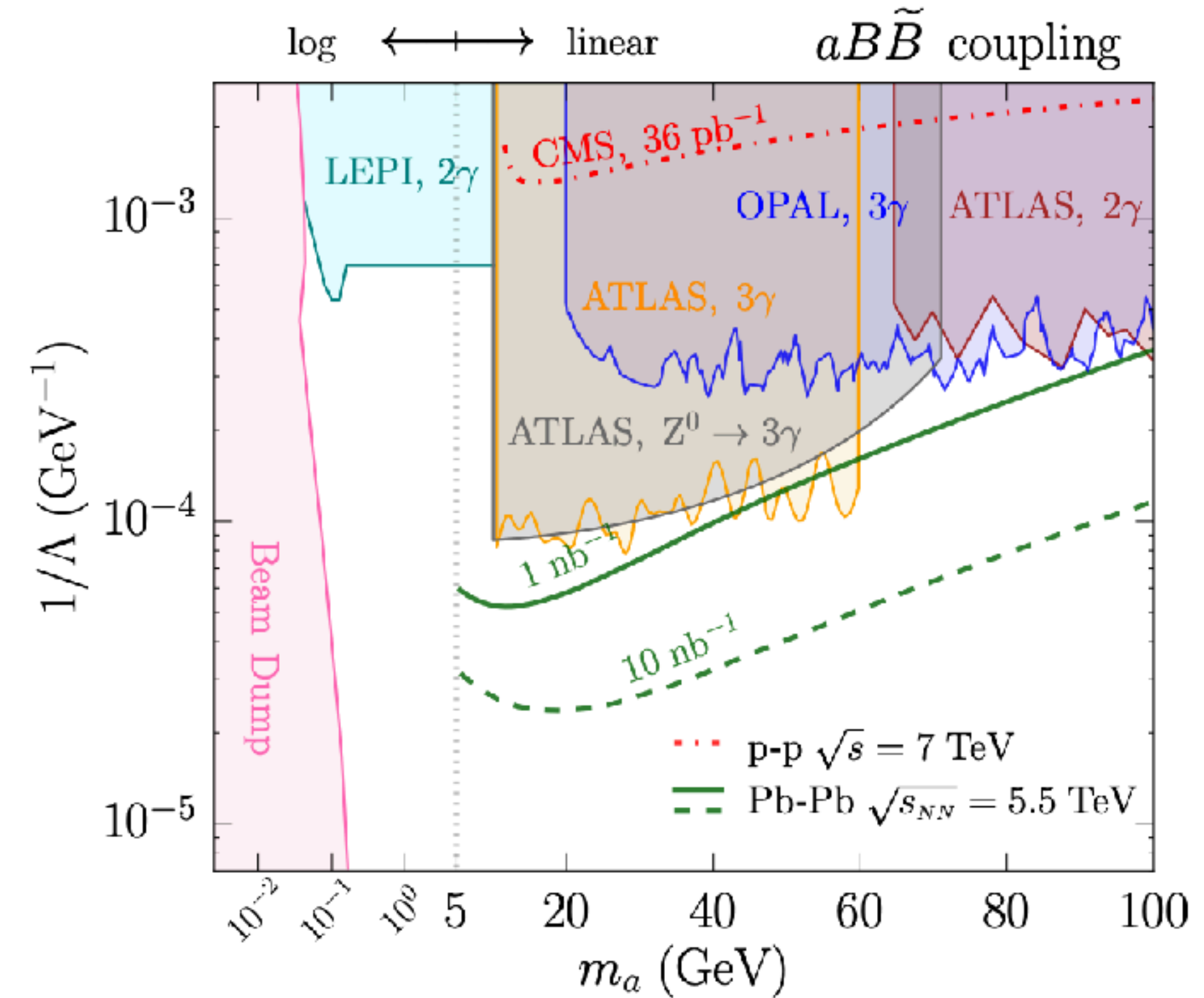
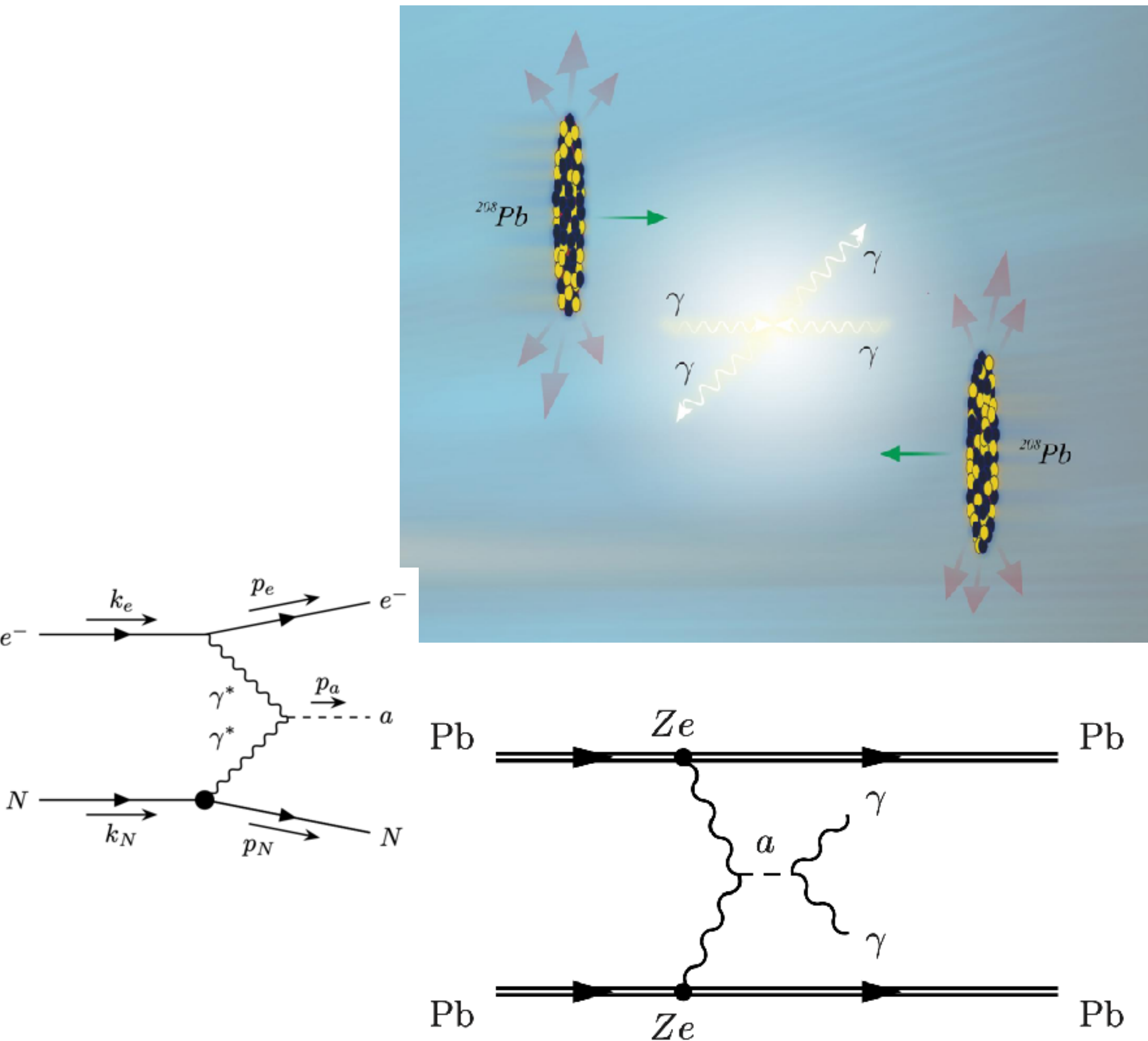
SOME RECENT WORK



Old Idea In New Places

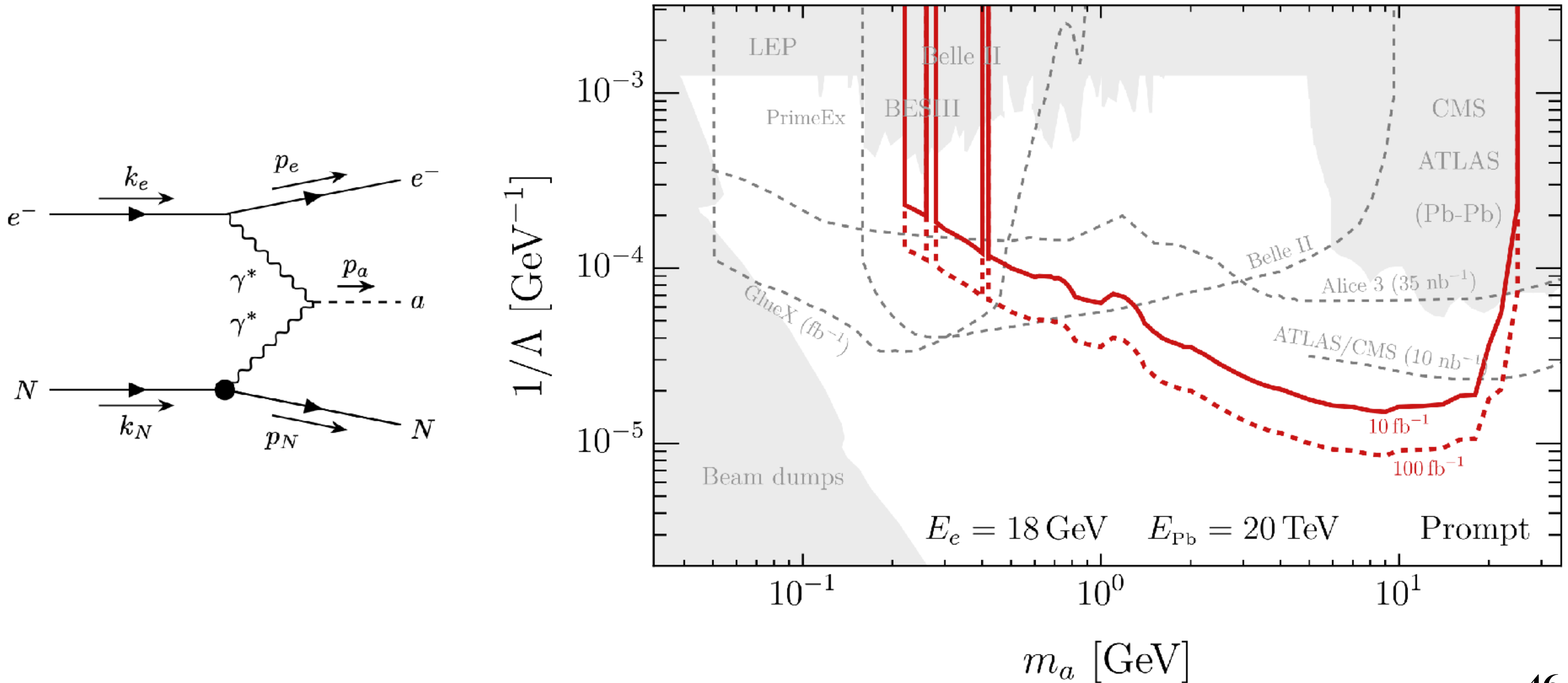
Ultra-Peripheral Collisions

KNAPEN, LIN, LOU, MELIA PRL (2016)



- Compromise between energy and intensity.

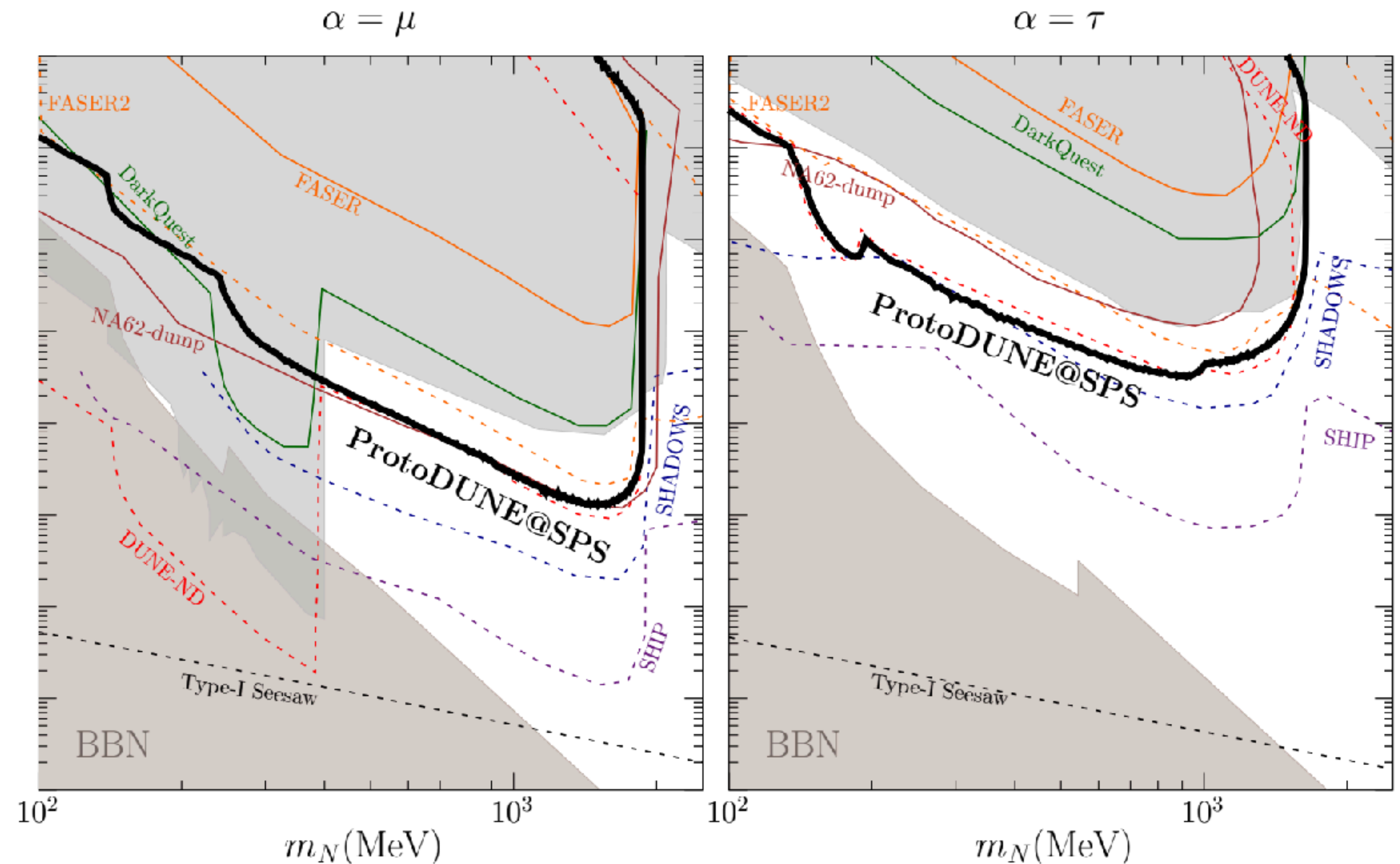
Same Idea: But Electron-Ion Collider



Using A Test Facility

PILAR COLOMA, JACOBO LOPEZ-PAVON, LAURA MOLINA-BUENO, AND SALVADOR URREA (2023)

PROTO DUNE === DEMONSTRATOR



MITP
SCIENTIFIC
PROGRAM

Open Questions and Future
Directions in Flavour Physics
November 4 – 15, 2024



<https://indico.mitp.uni-mainz.de/event/372>

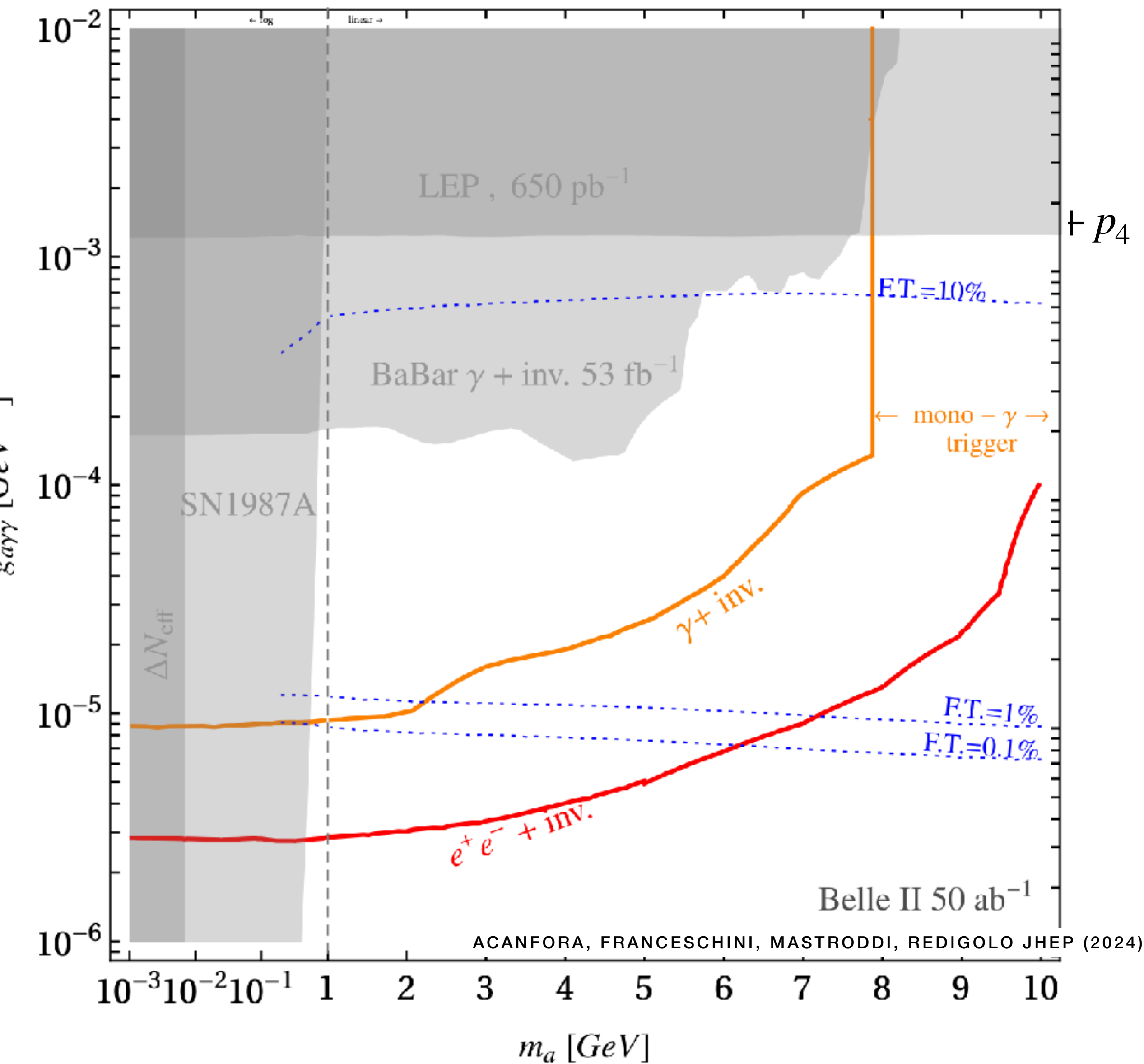
mitp
Mainz Institute for
Theoretical Physics

© Illustration: Claudia Cornelia

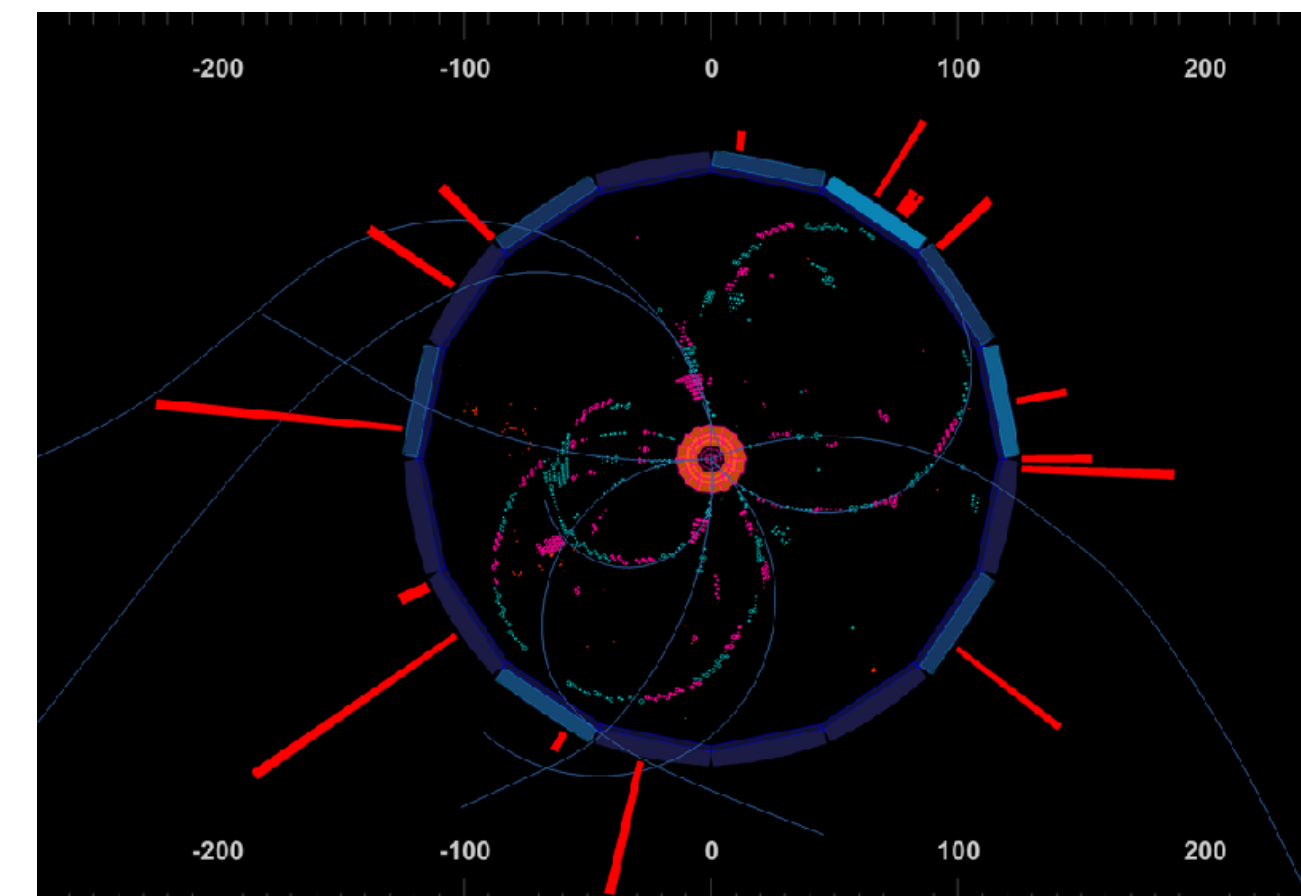
New Ideas In Old Places

Axions At B-Factories

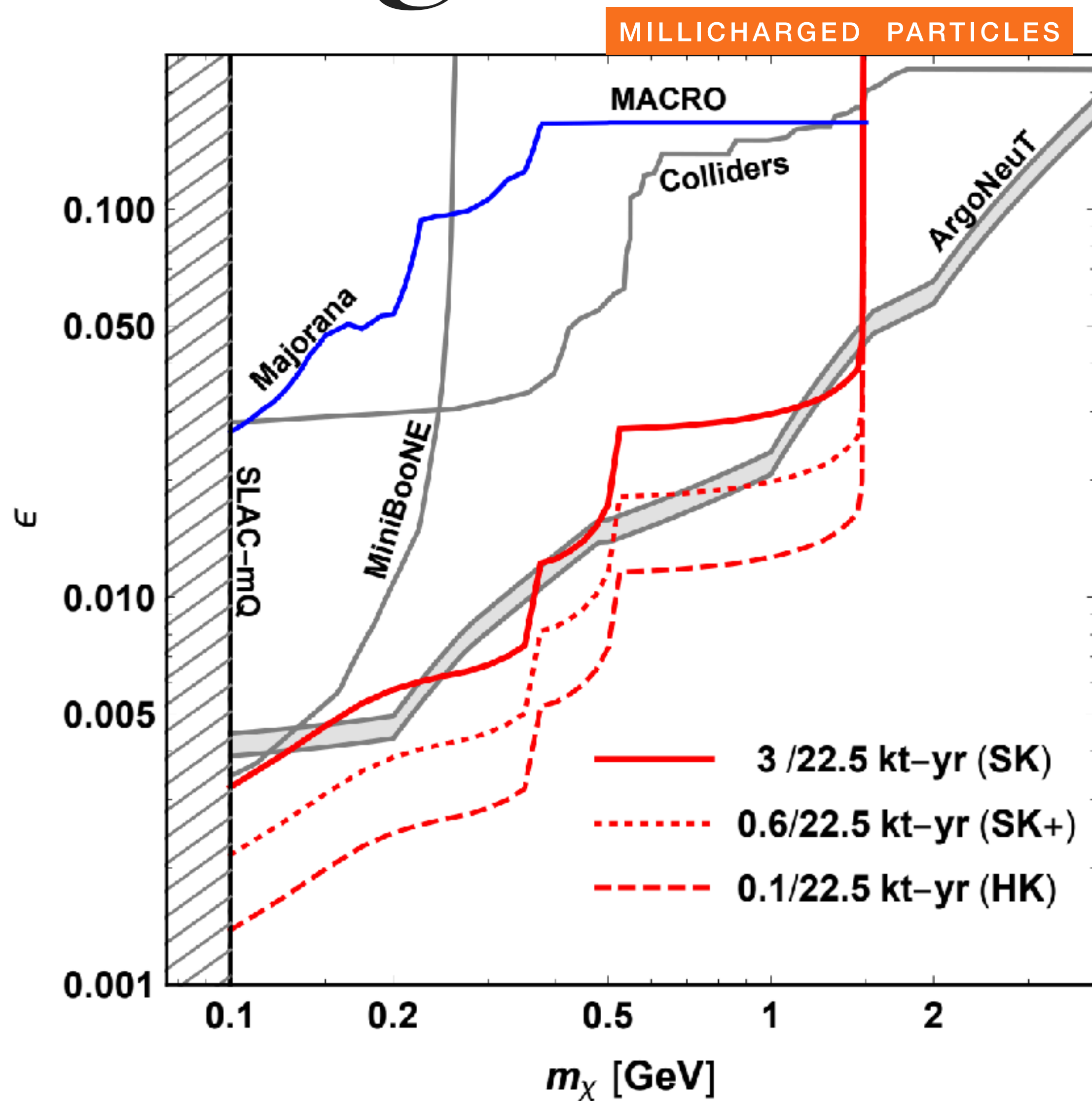
Missing momentum



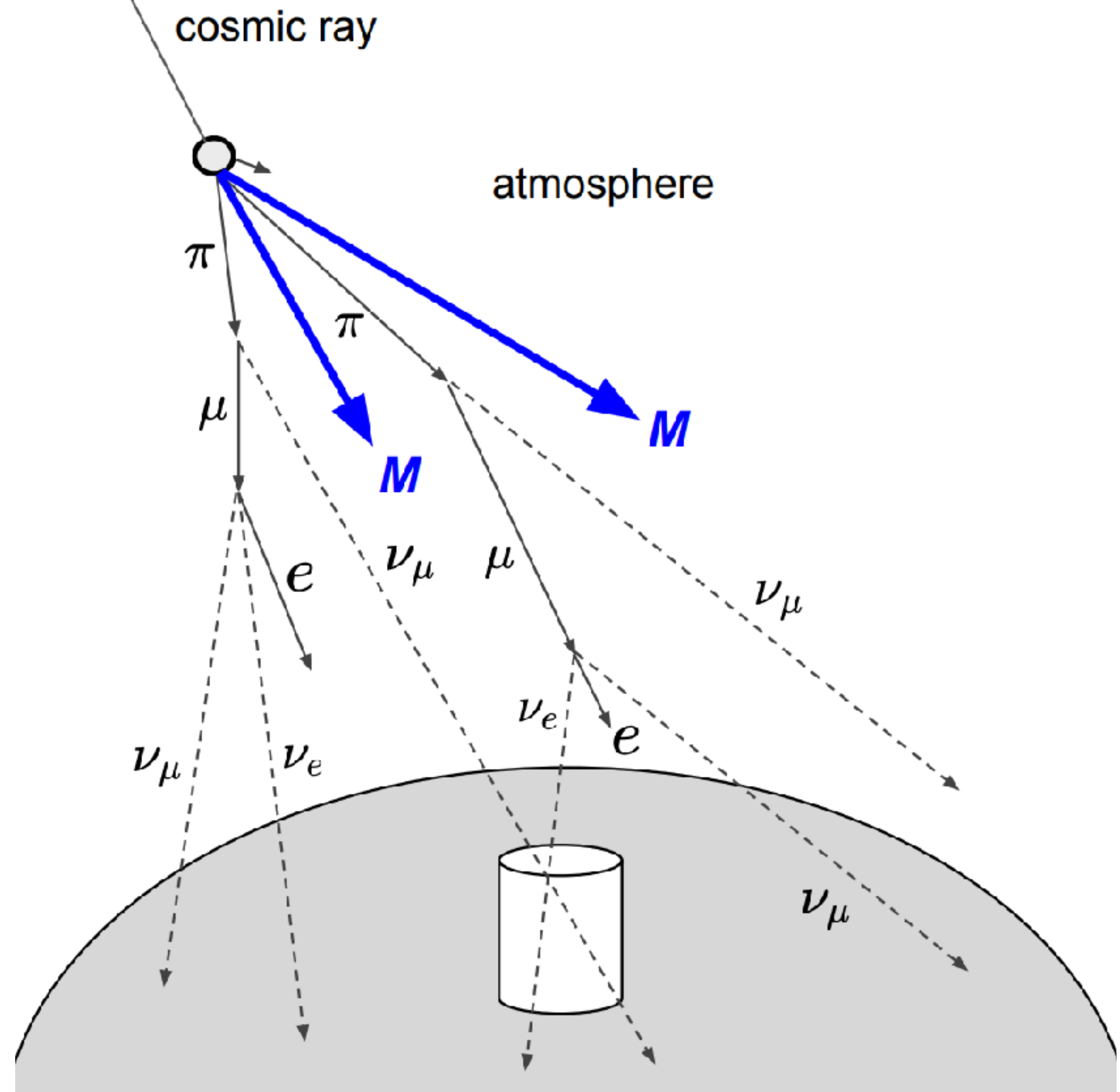
- New ideas for signals in **very well established** settings



Using Cosmic Rays



PLESTID, TAKHISTOV, TSAI,, BRINGMANN, KUSENKO, POSPELOV (2020)



Connections To Flavour

$$y_{ff'} \sim \left(\frac{\langle \Phi \rangle}{\Lambda} \right)^{[f]+[f']}$$

$$\frac{\alpha_s}{8\pi} \frac{a}{f_a} G \tilde{G} + \frac{E}{N} \frac{\alpha}{8\pi} \frac{a}{f_a} F \tilde{F}$$

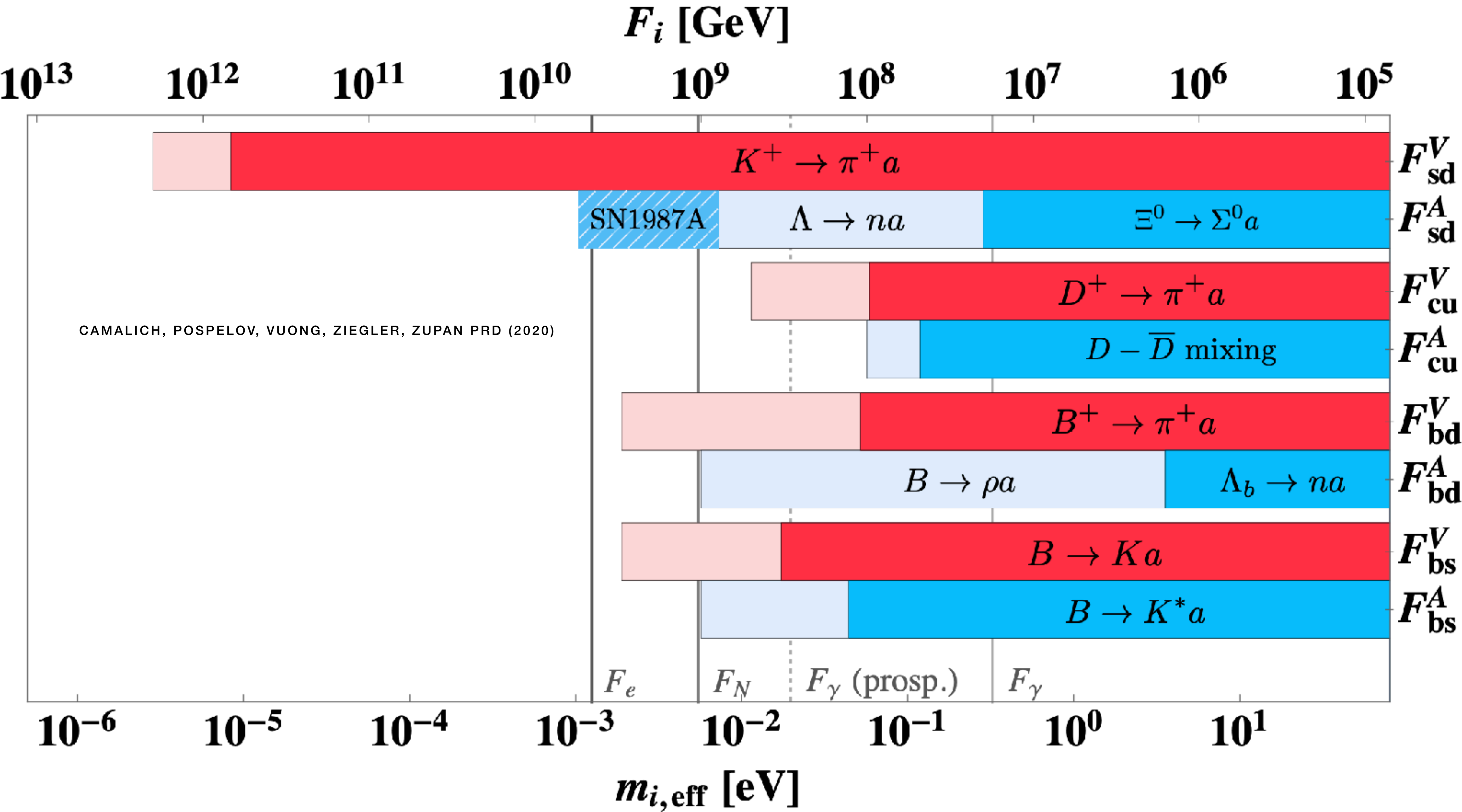
ANOMALY COEFFICIENTS

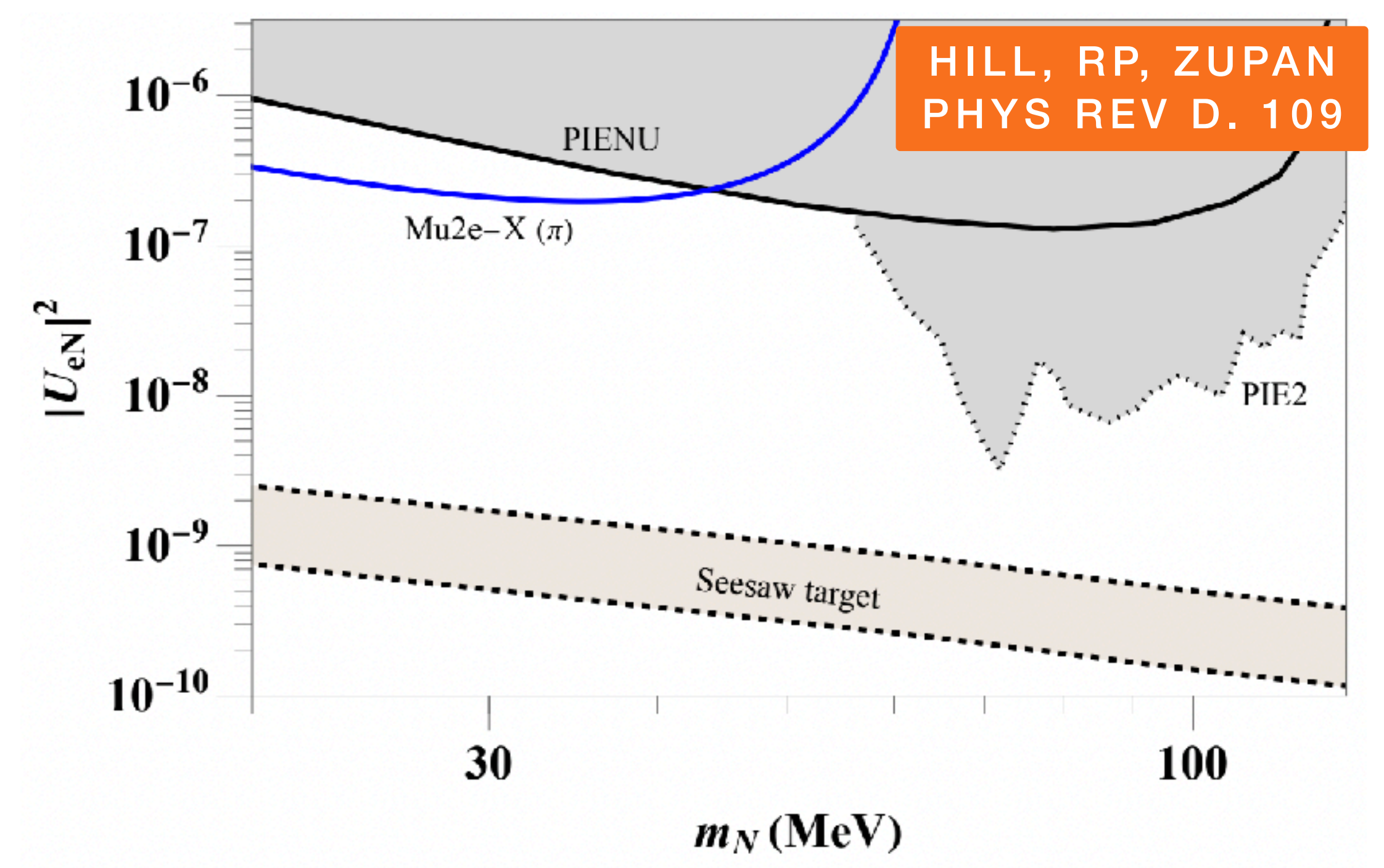
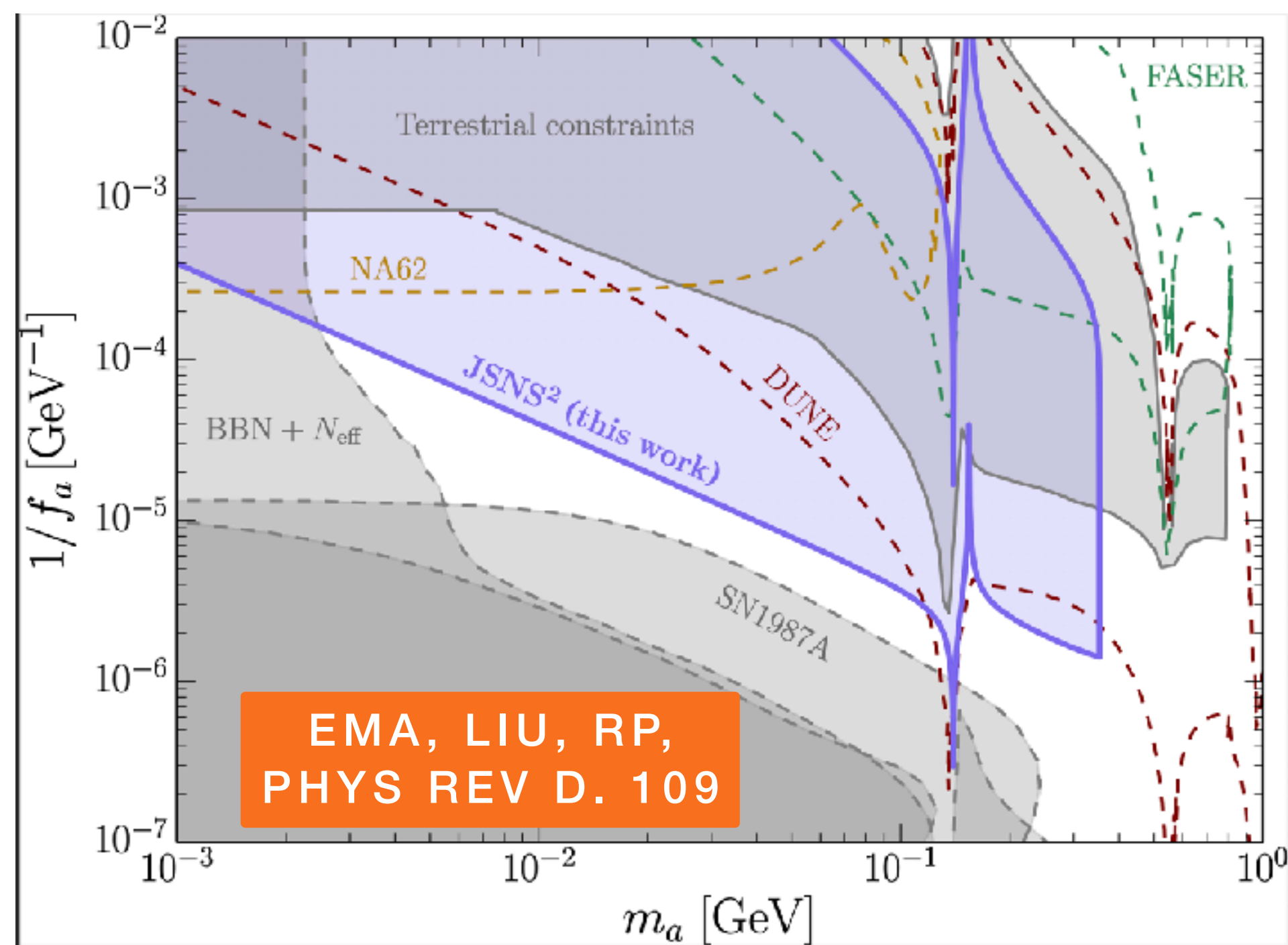
- Choose Froggatt-Nielsen charges to explain flavor.
- Froggatt-Nielsen charges fix the anomaly coefficients.

- Natural choices give a "canonical" QCD-axion!

$$\frac{E}{N} = \frac{8}{3} - 2 \frac{\log \frac{\det m_d}{\det m_e} - \log \alpha_{de}}{\log \frac{\det m_u \det m_d}{v^6} - \log \alpha_{ud}}$$

Connections To Flavour



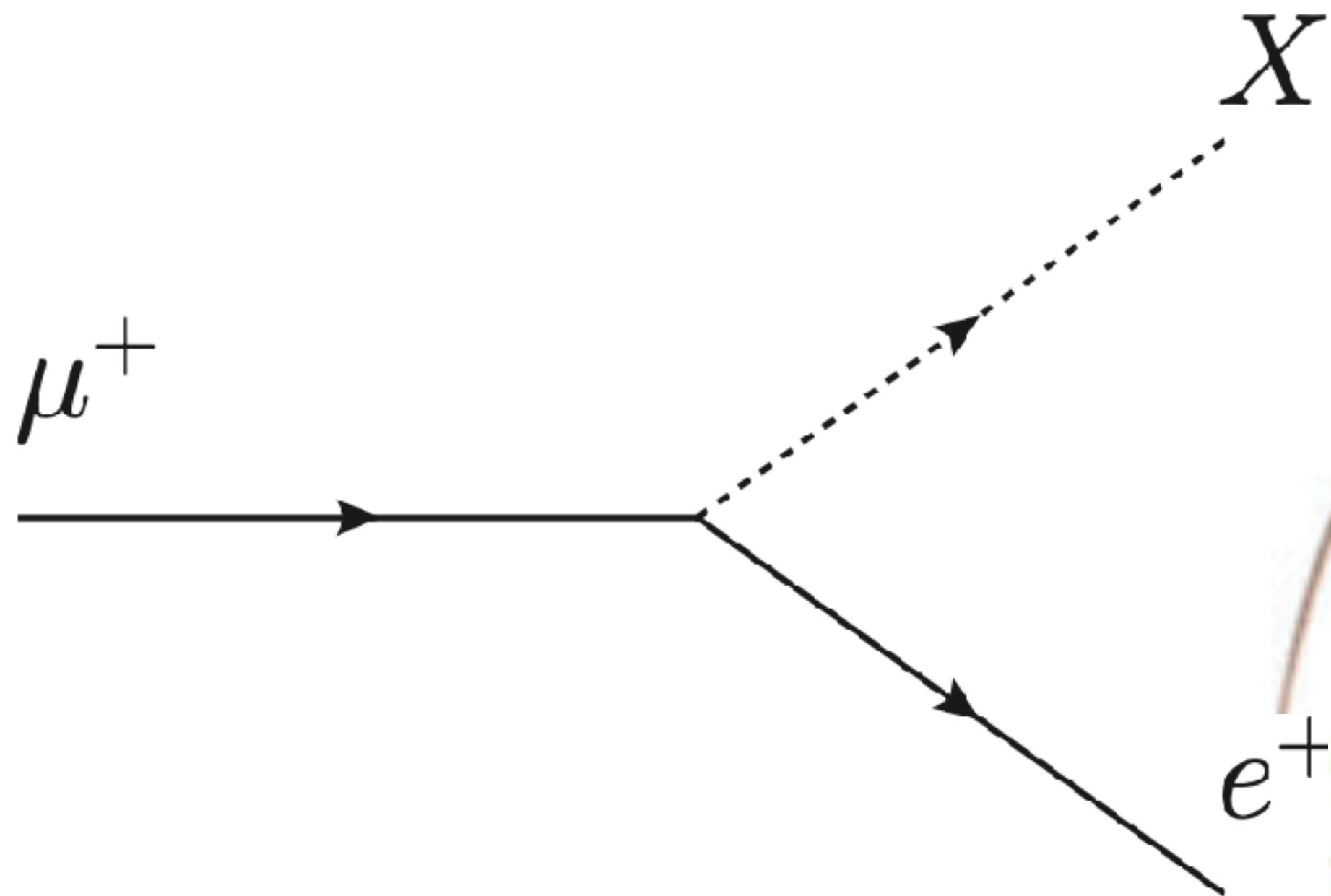


High Statistics Decays At Rest

Bump Hunts At Low Energies

LIGHT NEW PHYSICS

RARE BUT KINEMATICALLY DISTINCTIVE



TWO BODY DECAYS AT REST

$$\mu \rightarrow eX$$

$$\pi \rightarrow eX$$

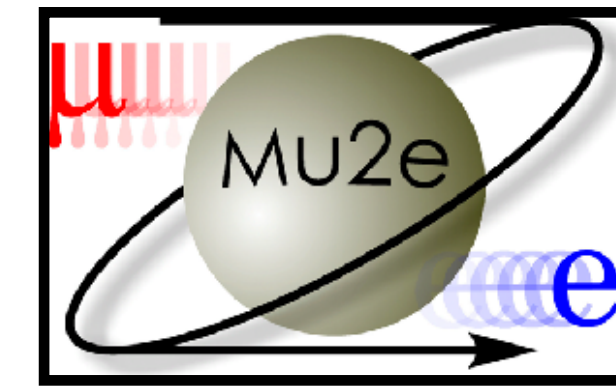
$$K \rightarrow \pi X$$

PARTICLE-X HAS FIXED
ENERGY

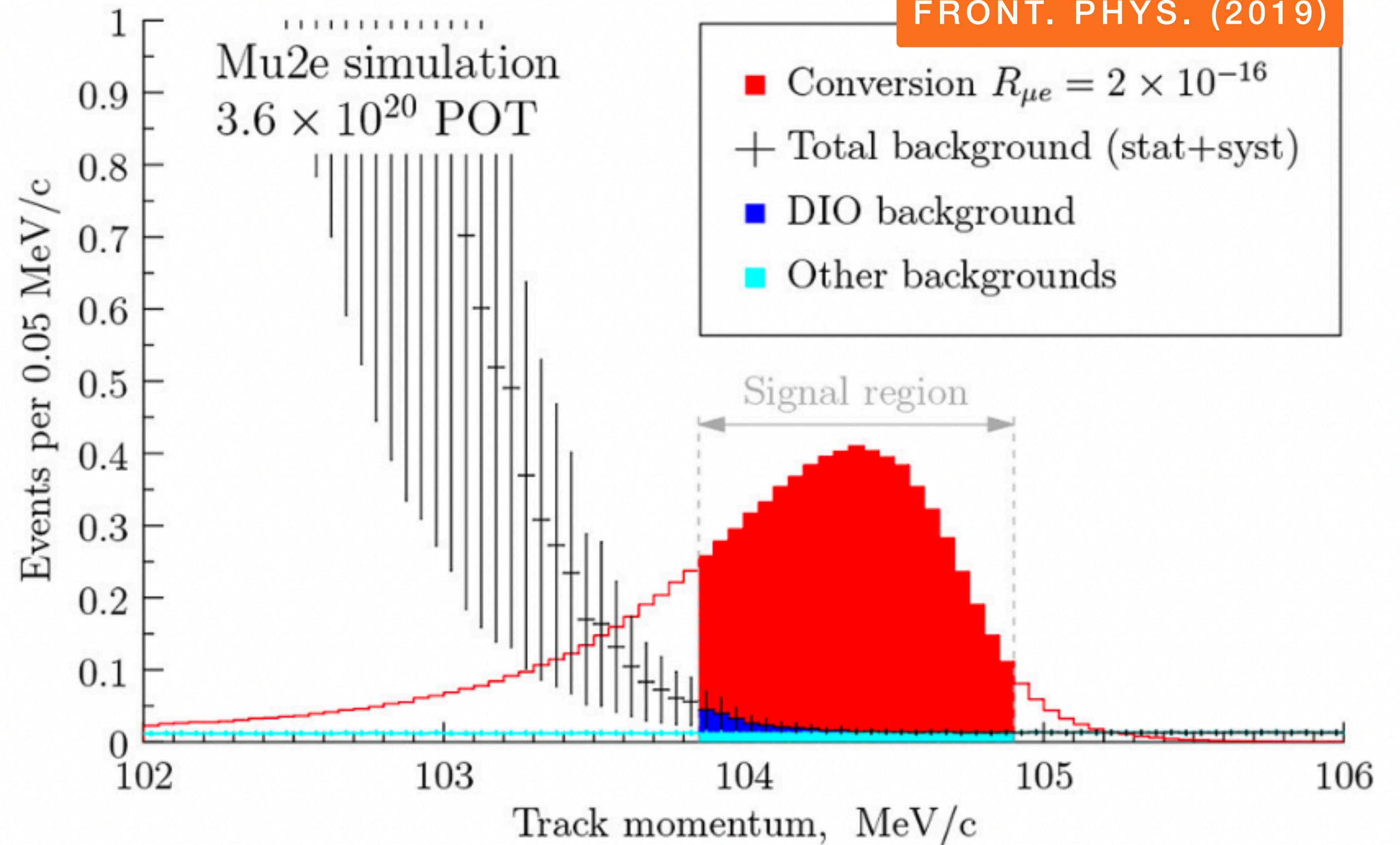
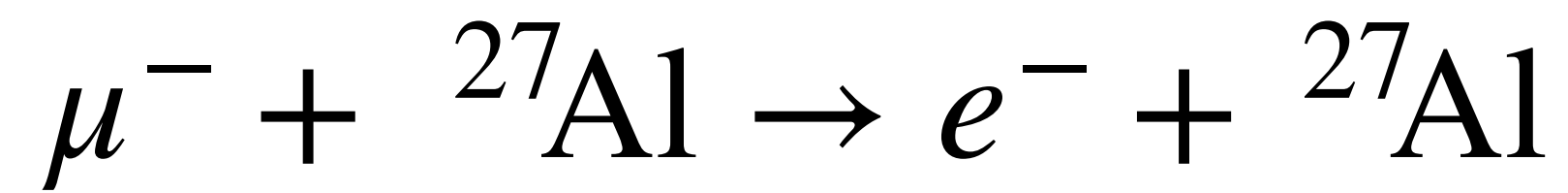
- Strategy 1: Measure energy of electron very precisely.
- Strategy 2: Look for decay of X

$$X \rightarrow \gamma\gamma$$

EXAMPLE: MU2E AT FERMILAB

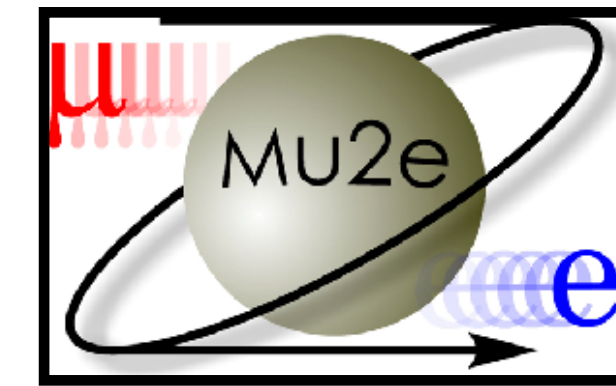


SIGNAL

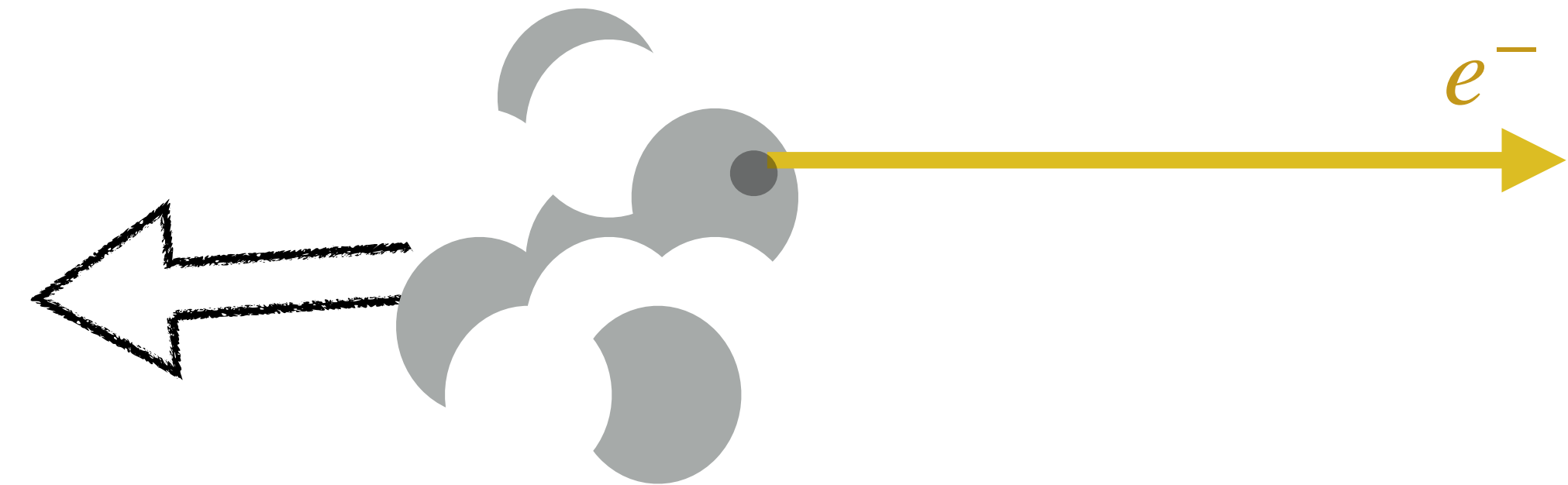
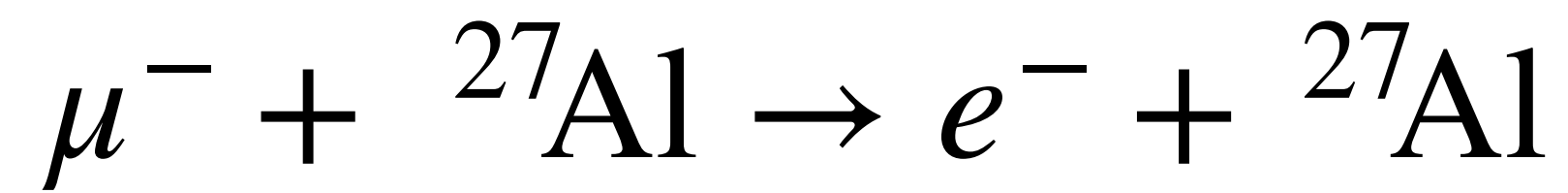


SEARCH FOR BUMP AT ENDPOINT

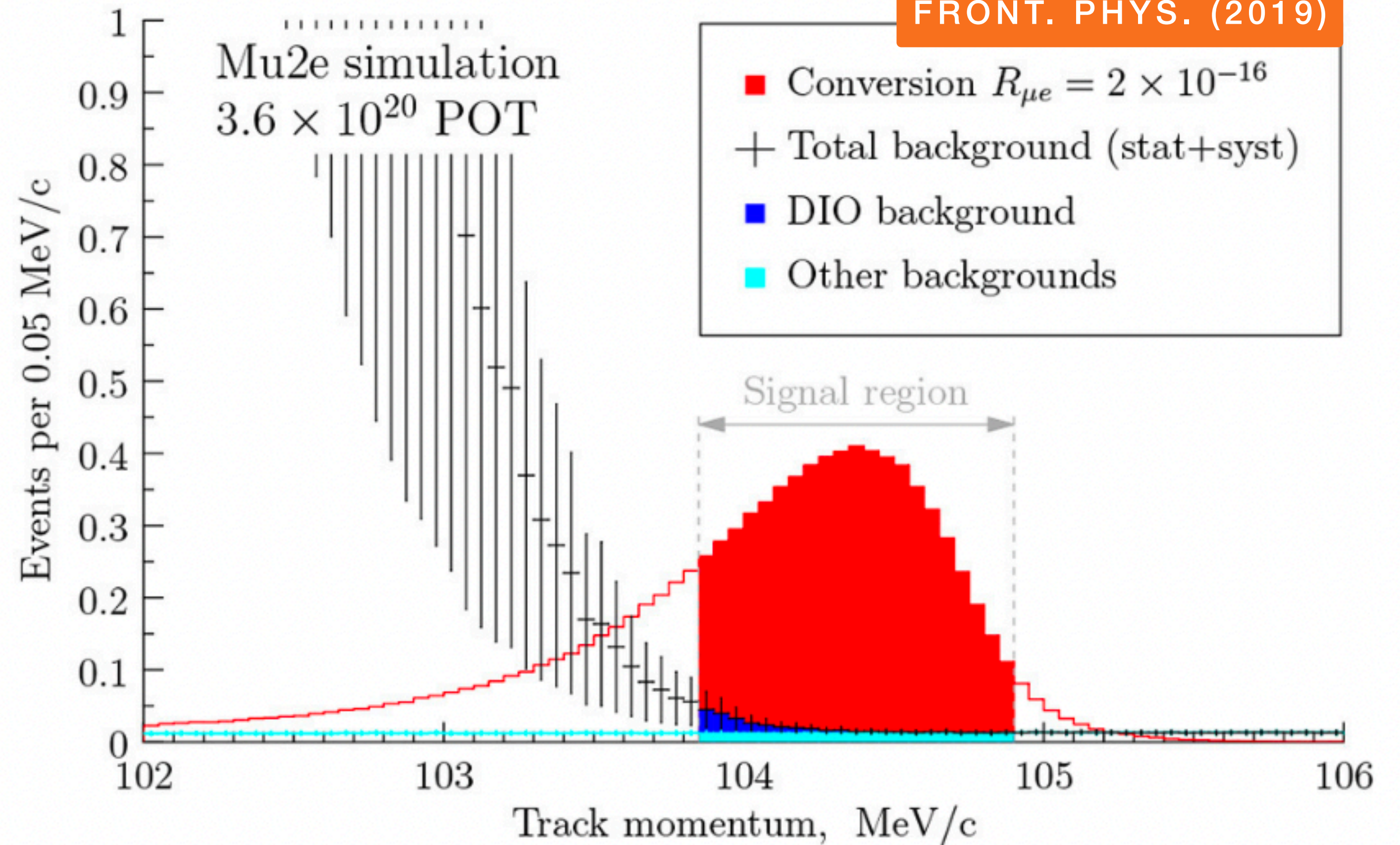
EXAMPLE: MU2E AT FERMILAB



SIGNAL



HIGH ENERGY e^-



SEARCH FOR BUMP AT ENDPOINT

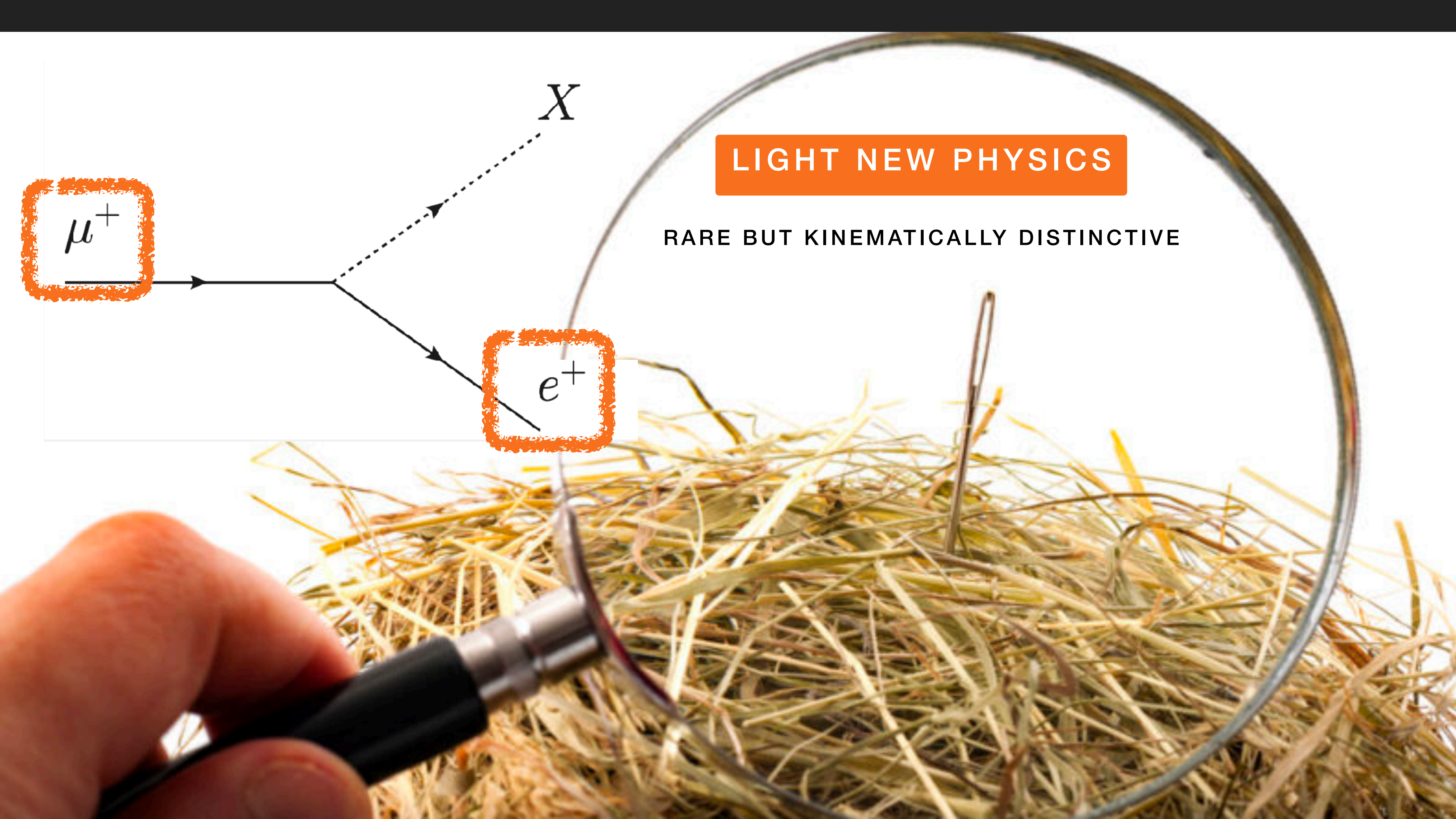
μ^+

X

LIGHT NEW PHYSICS

RARE BUT KINEMATICALLY DISTINCTIVE

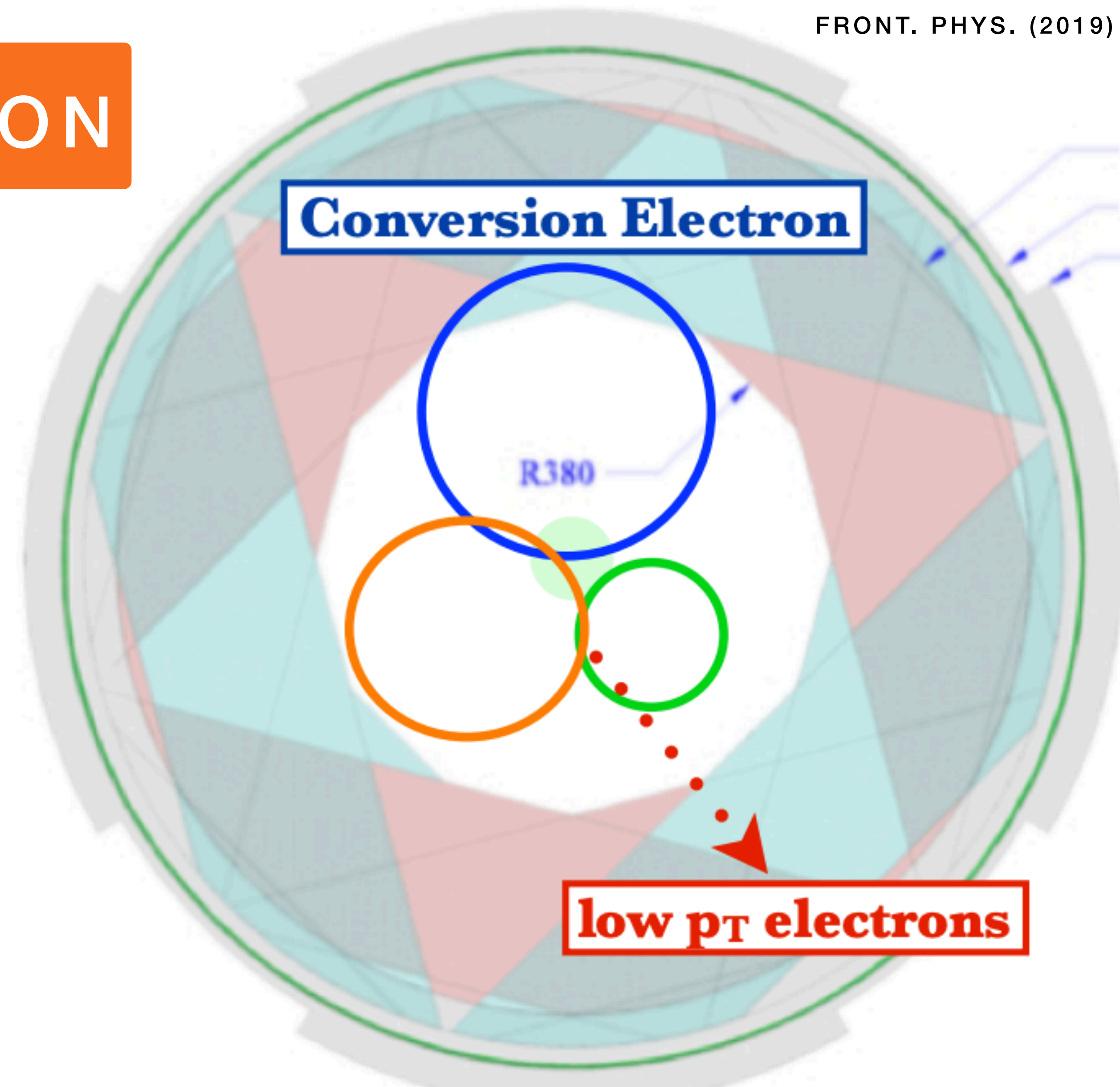
e^+



PLANNED μ^+ CALIBRATION

- Detector lets low energy positrons through.
- Lower magnetic-field enables low-energy positron detection.

$$\mu^+ \rightarrow e^+ X$$

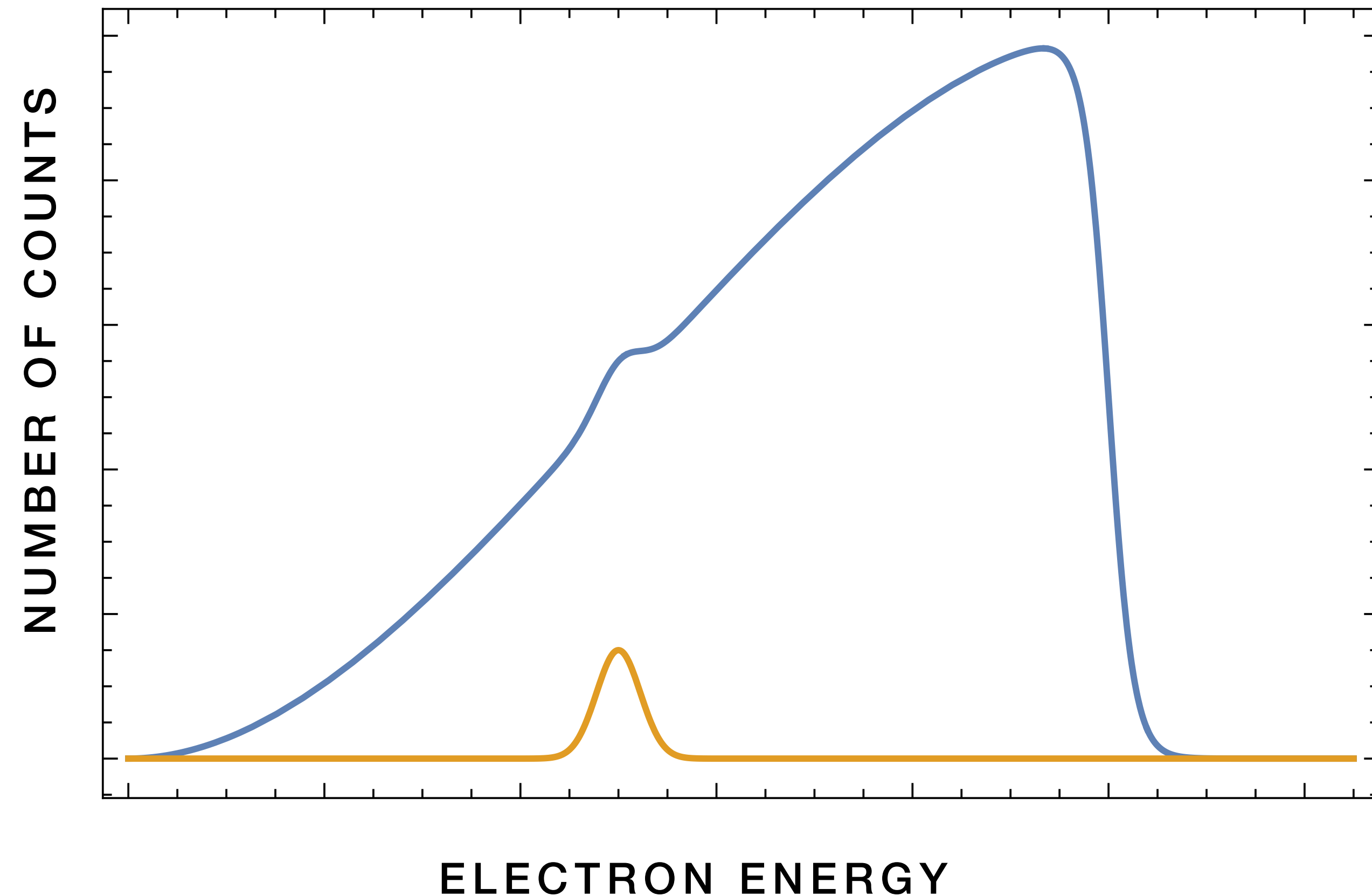


SEARCH FOR BUMP

- Data driven background.
- Search is statistics driven.

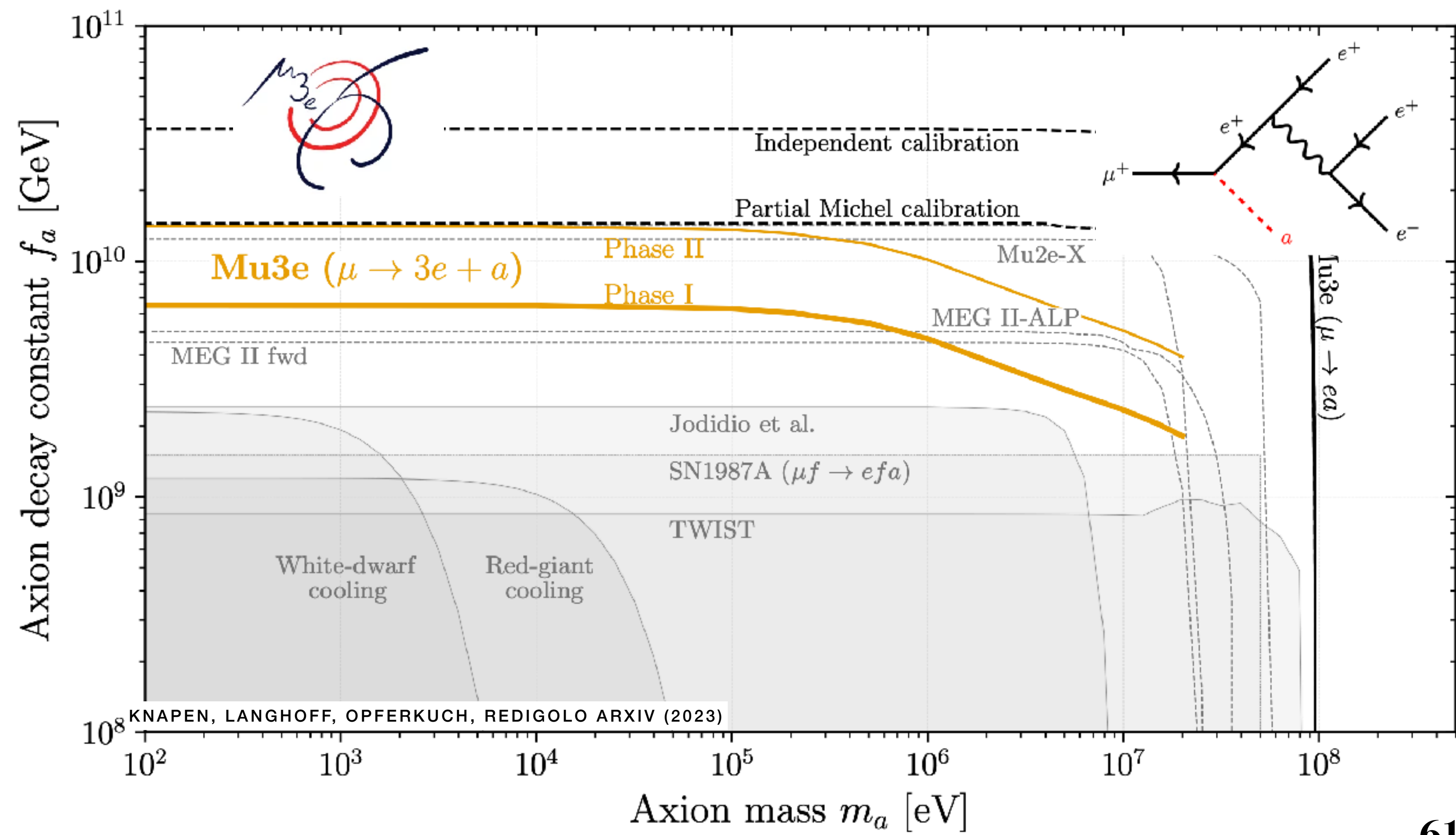
$$S/\sqrt{B}$$

S = signal B = background



PROBLEM: LOW MASS → BUMP IS ON EDGE

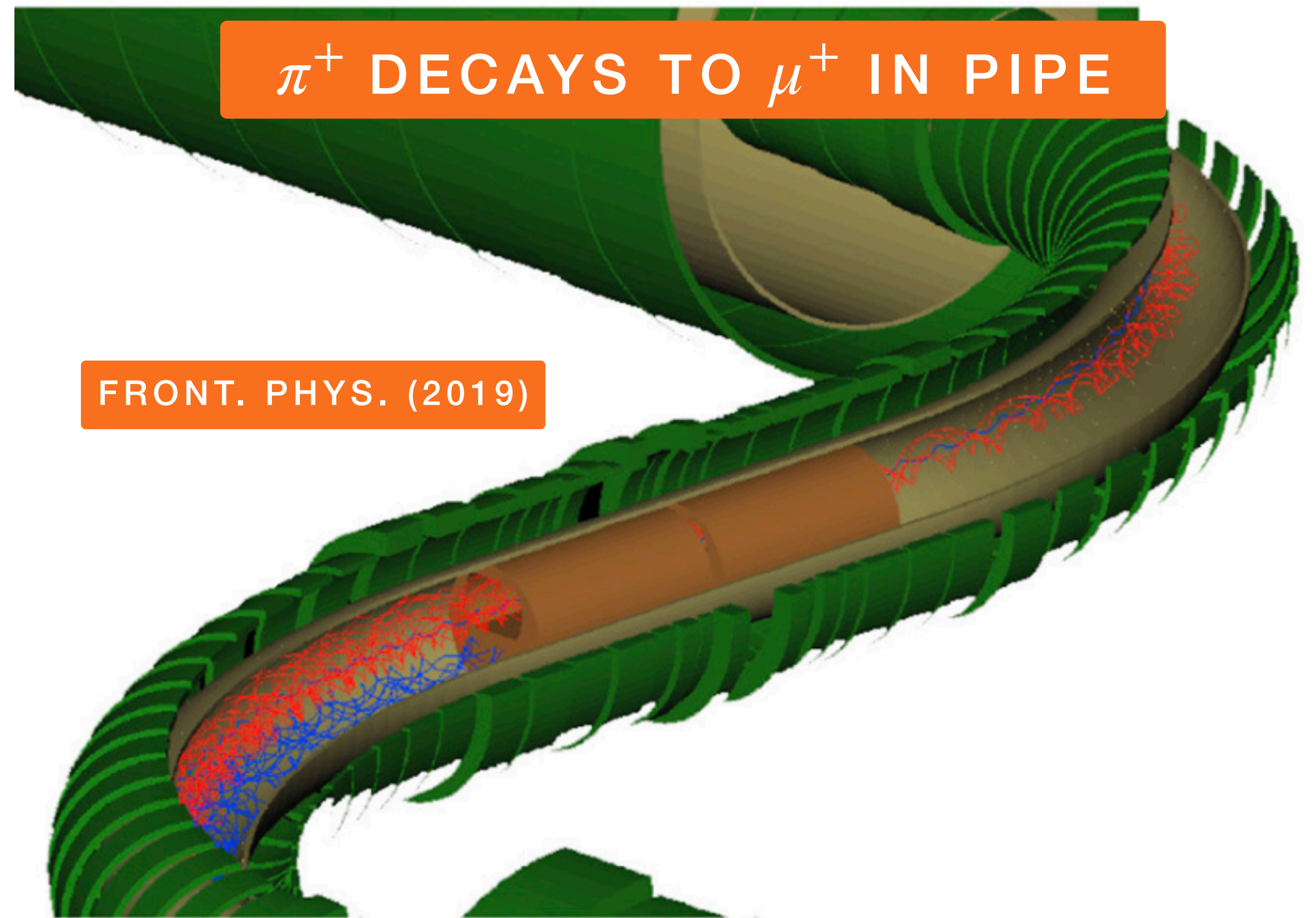
- Change the signal!
- Use Mu3e.
- Suppresses QED backgrounds.
- Take advantage of excellent vertex resolution.

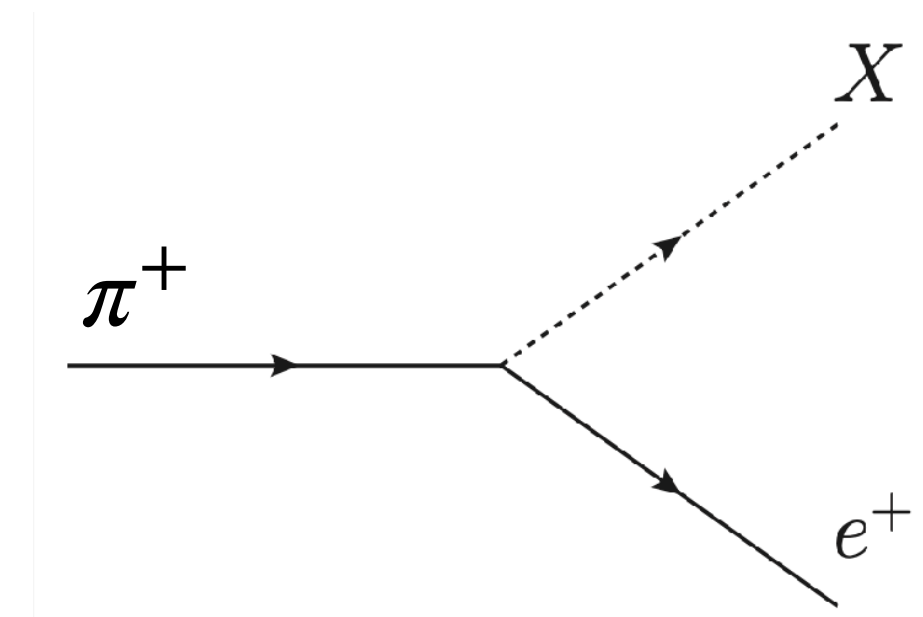
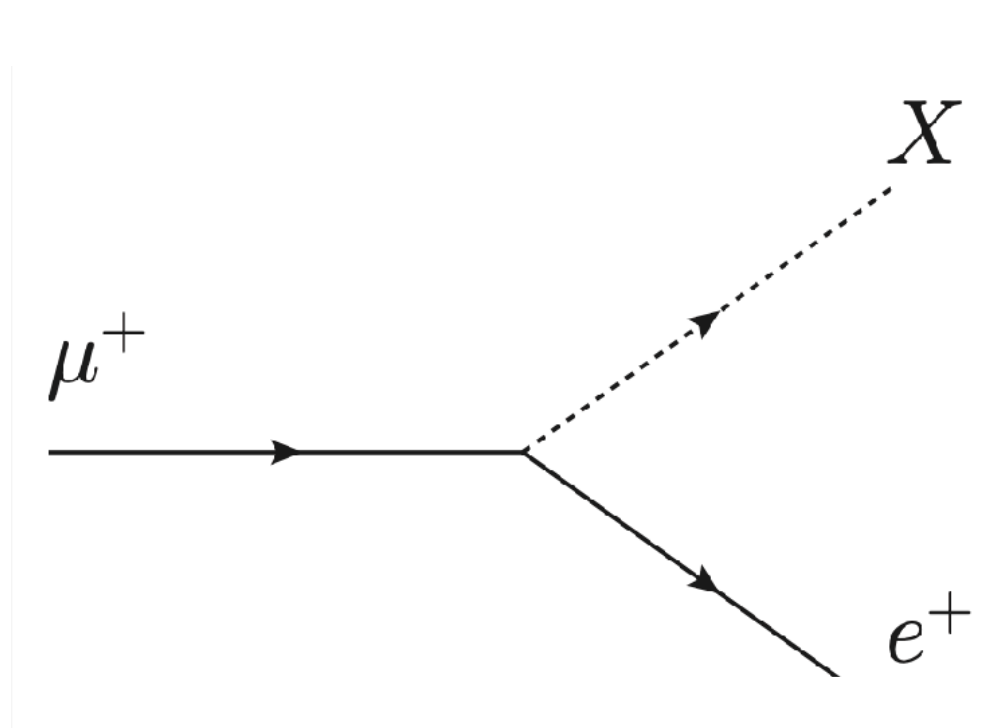


POTENTIAL π^+ CALLIBRATION

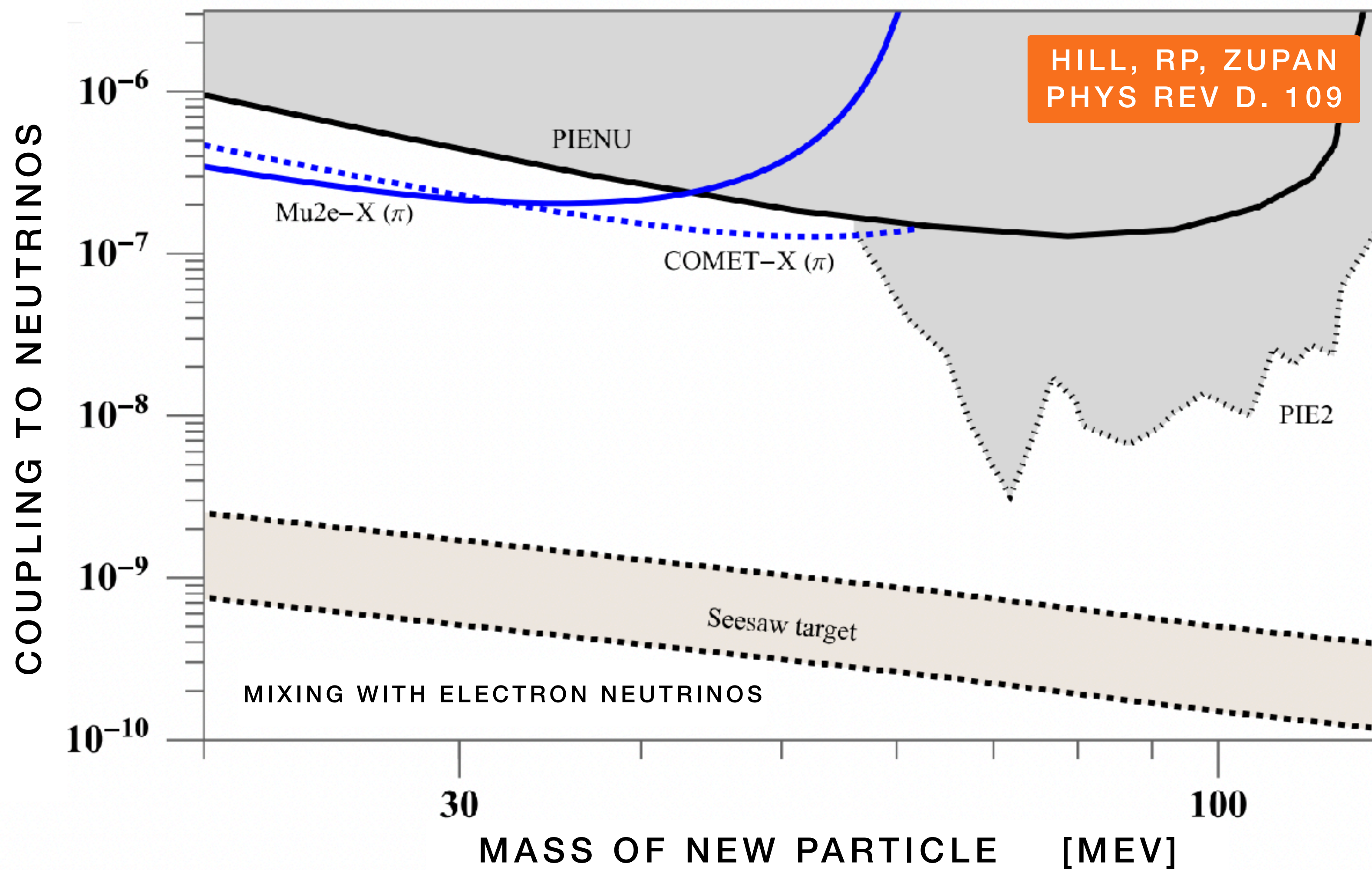
- The μ^+ comes from π^+ .
- There are still $\sim 10^{10}$ π^+
- Can do a search for

$$\pi^+ \rightarrow e^+ X$$



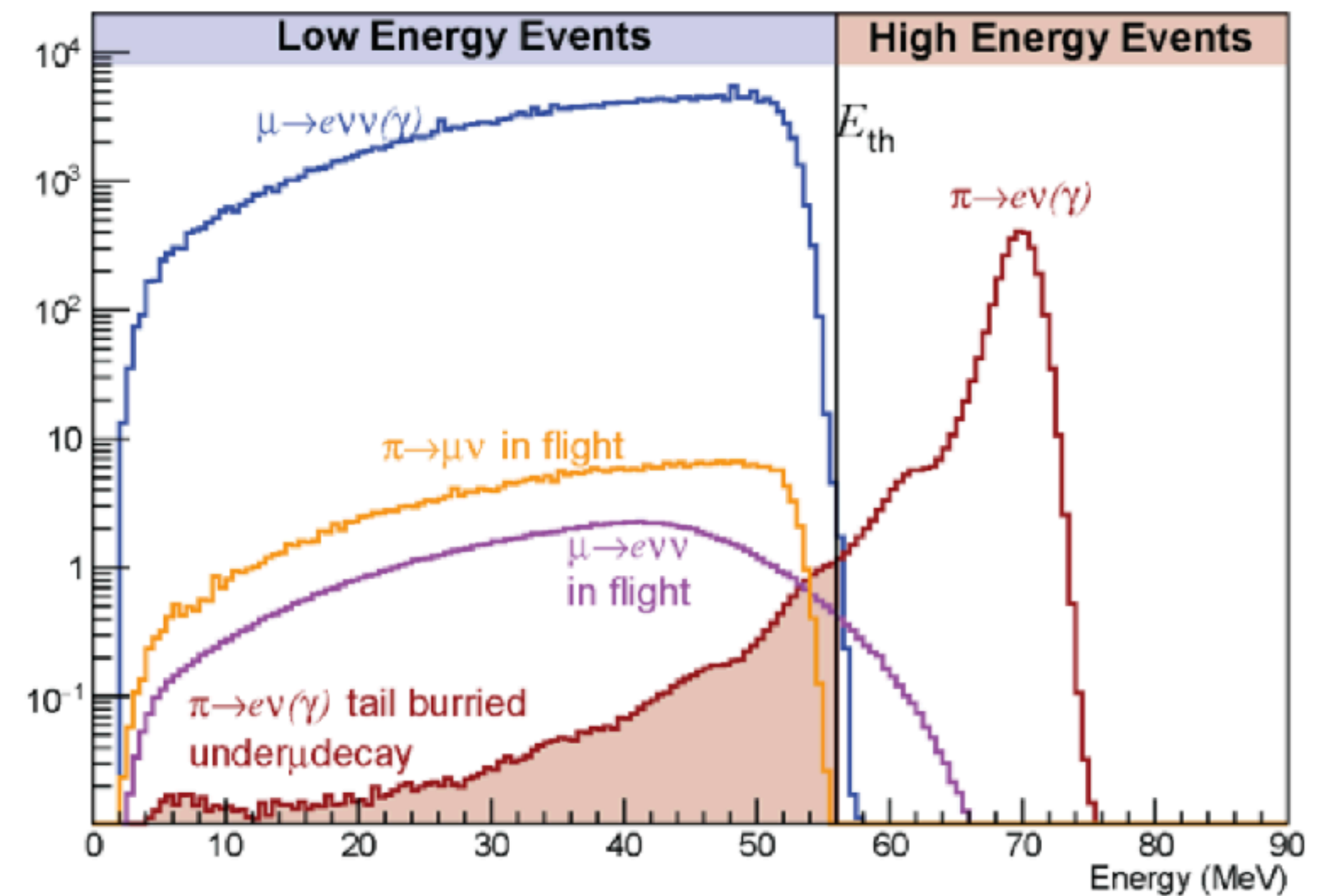
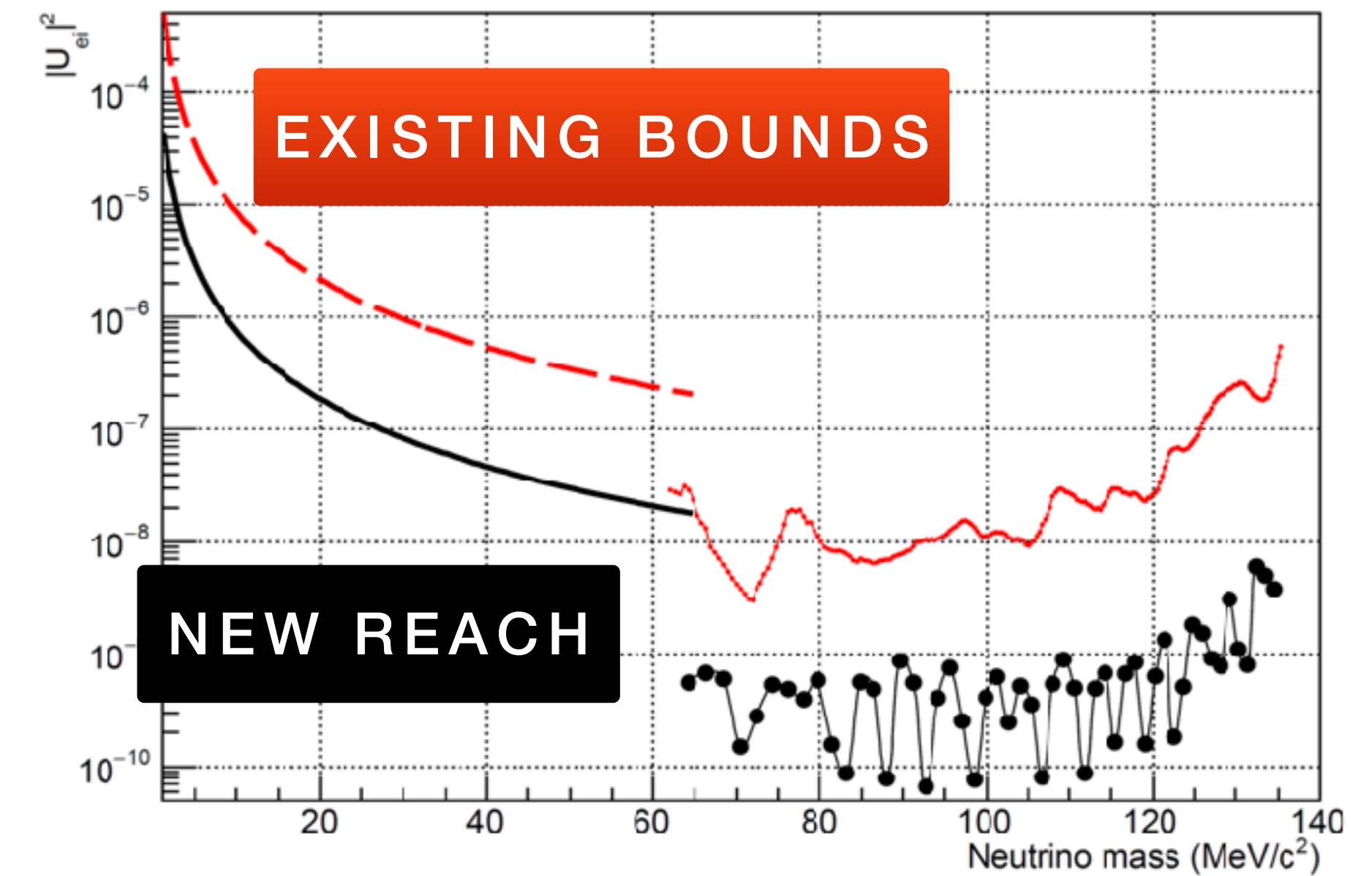
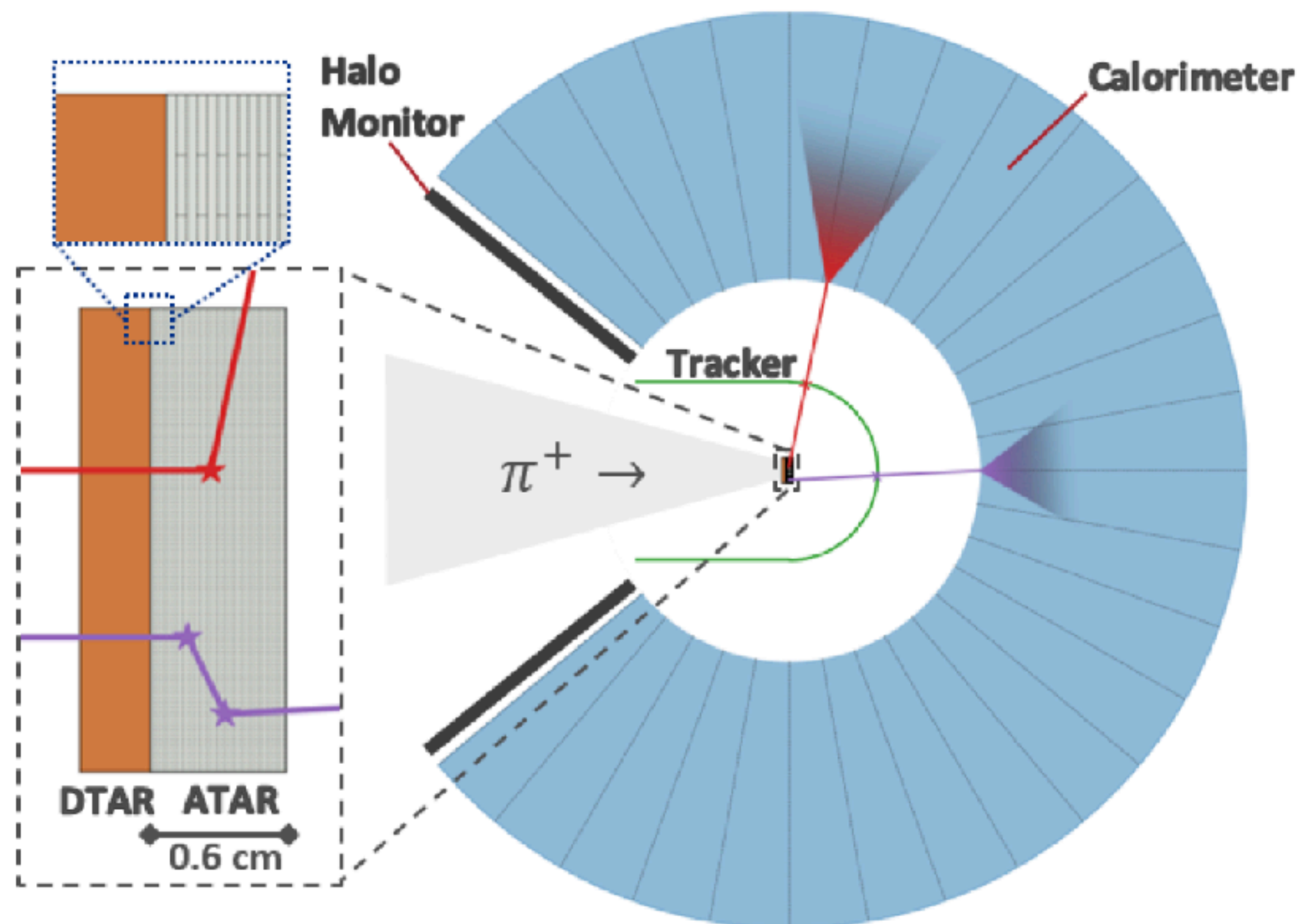


WORLD LEADING REACH



OTHER FUTURE FACILITIES

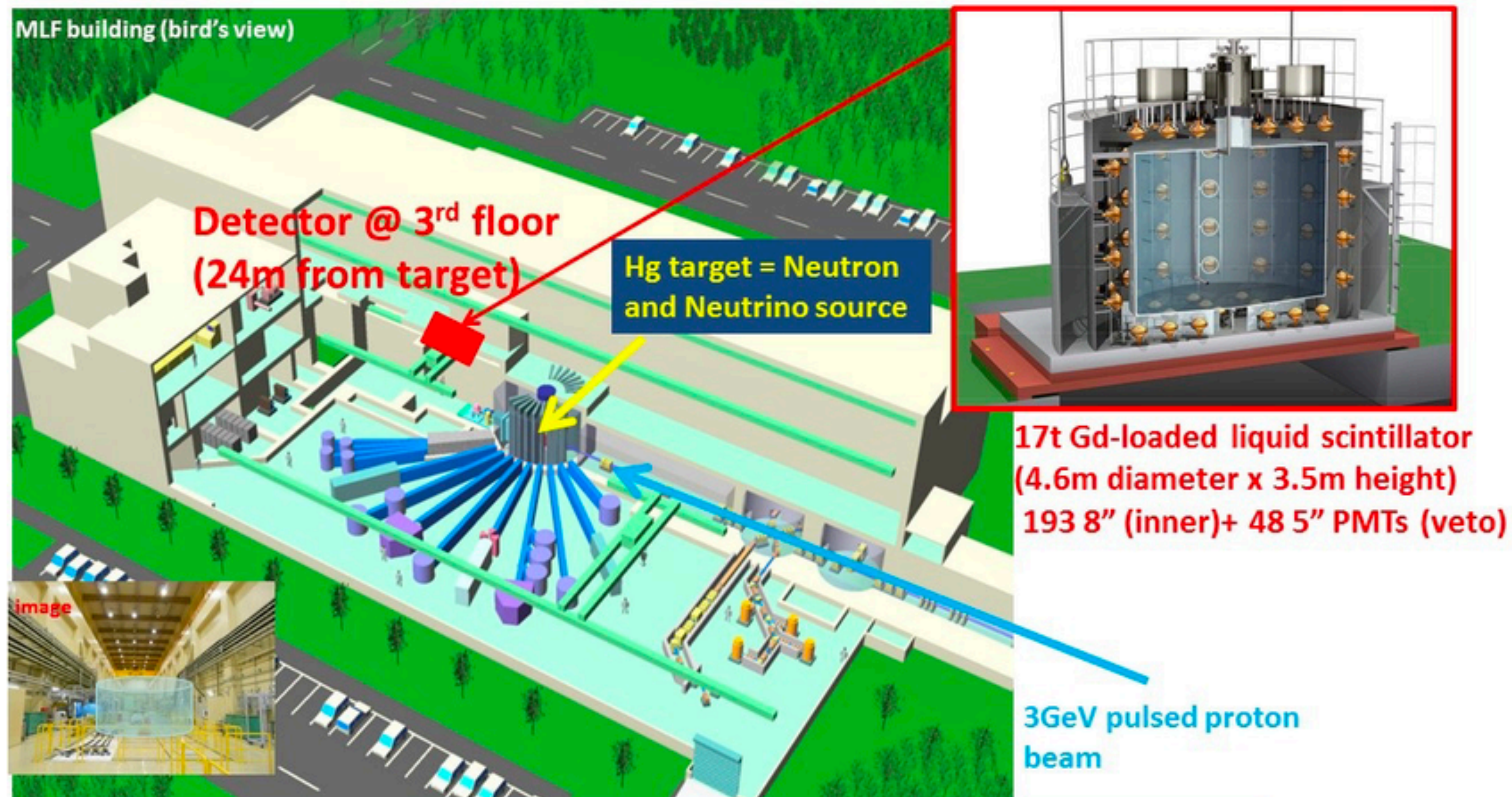
PIONEER



JSNS² @ J-PARC

J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source
(JSNS², J-PARC E56)

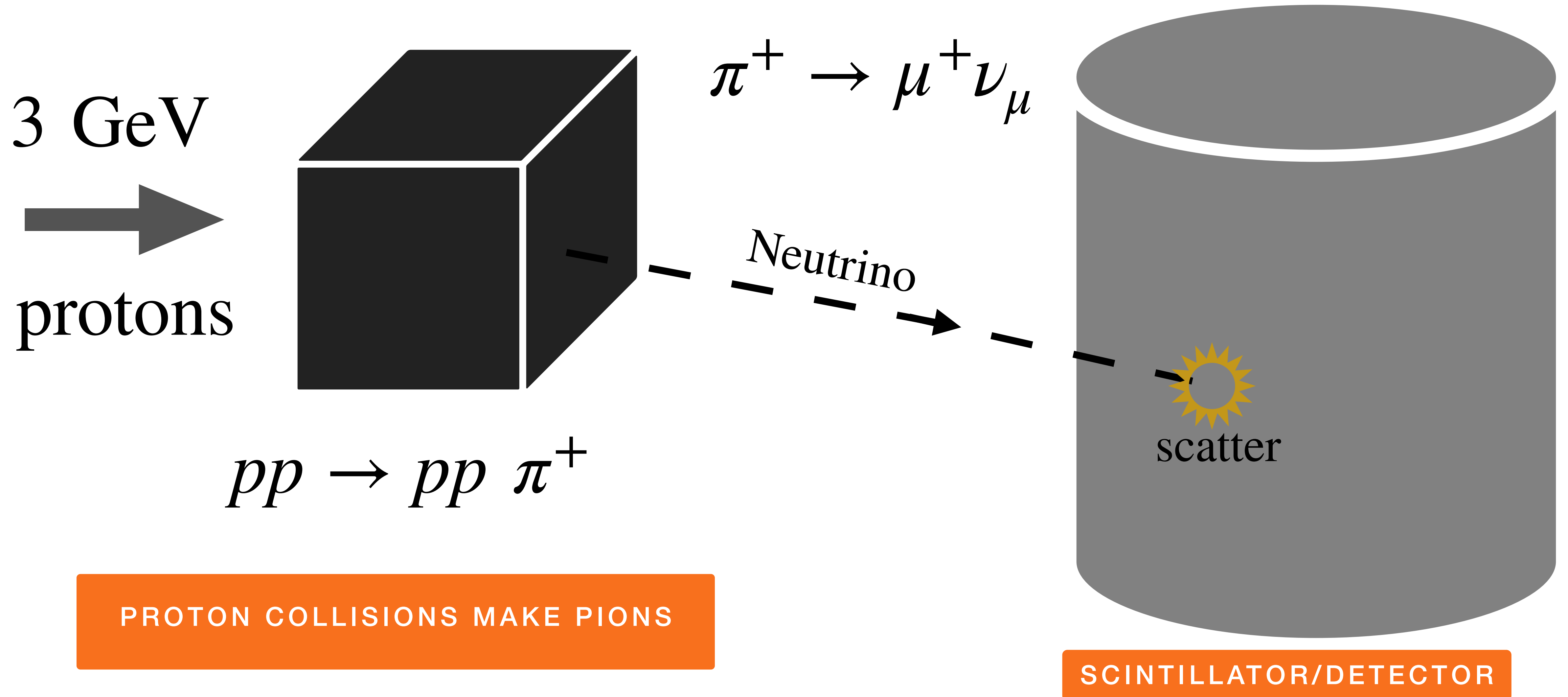
J-PARC MLF: World best environment



PROPOSED TO TEST
LSND ANOMALY

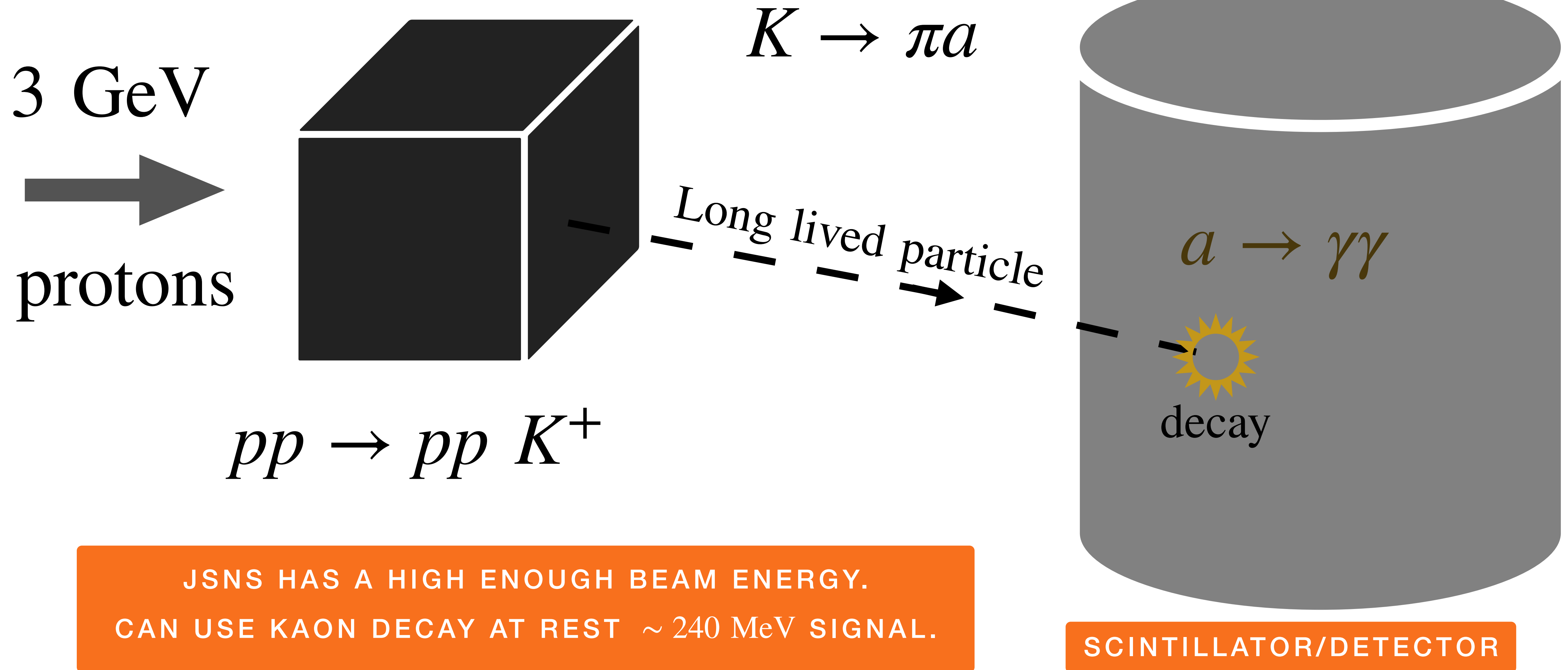
TAKING DATA NOW

JSNS² : A NEUTRINO EXPERIMENT



JSNS² : KAON DECAYS

AXION
PORTAL

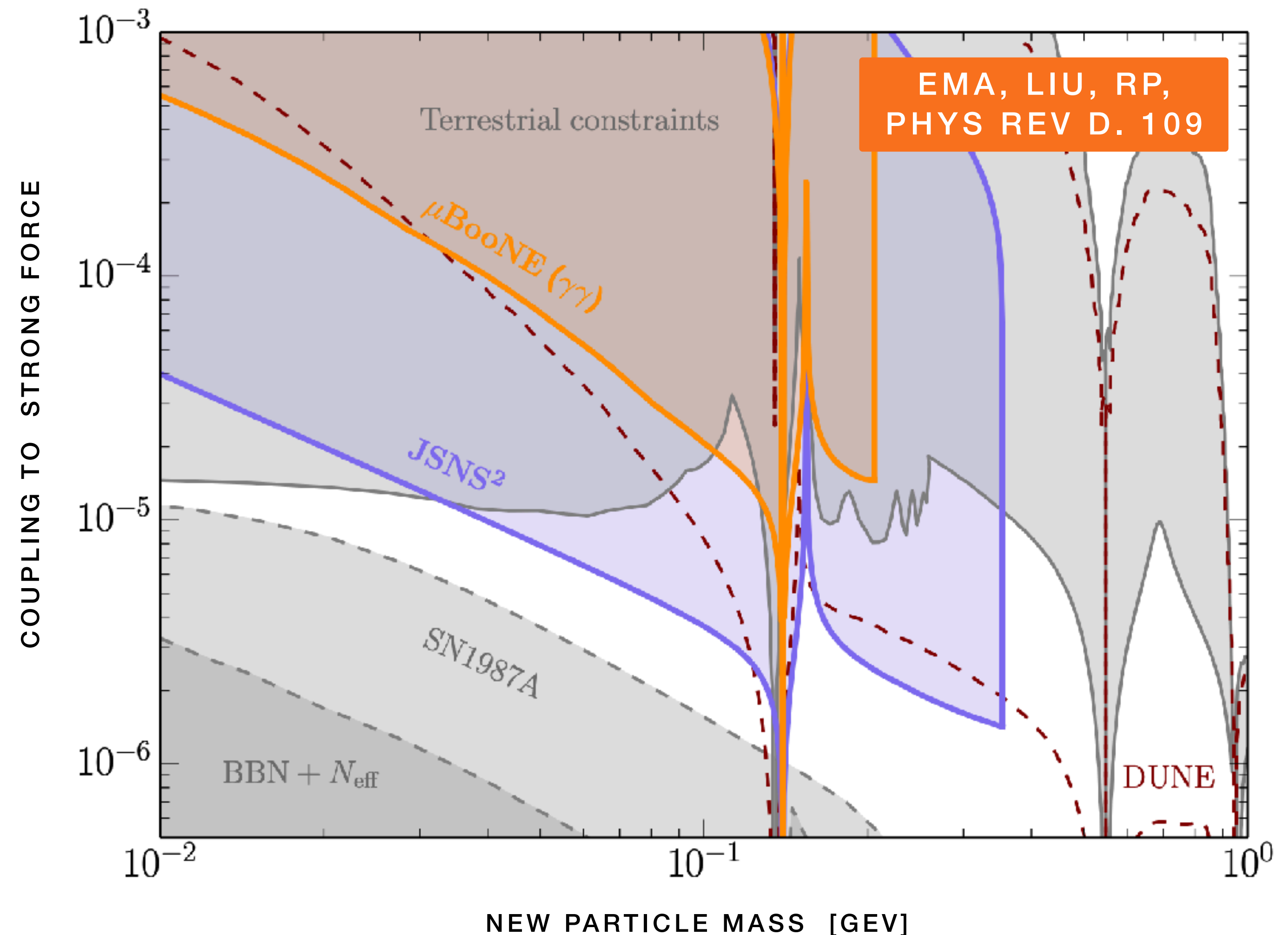


JSNS HAS A HIGH ENOUGH BEAM ENERGY.
CAN USE KAON DECAY AT REST ~ 240 MeV SIGNAL.

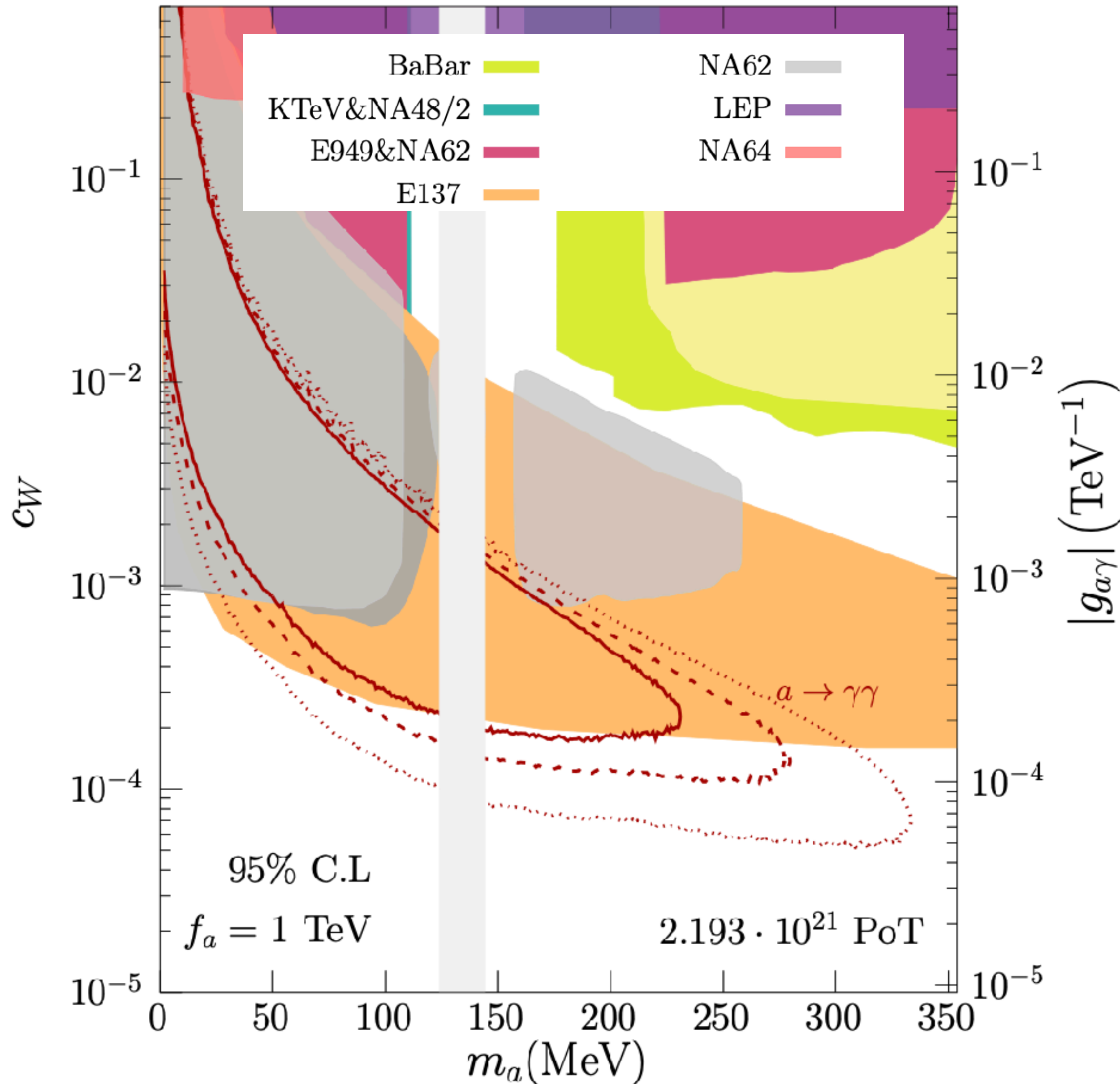
SENSITIVITY : GLUON-DOMINANCE

AXION
PORTAL

- Axion that couples to gluons (strong force).
- KDAR projections for JSNS-2 are world leading.
- New use for high energy data region.



RELATED IDEAS EXPLORED IN PAST



New bounds on axion-like particles from MicroBooNE

Pilar Coloma,^a Pilar Hernández^b and Salvador Urrea^b

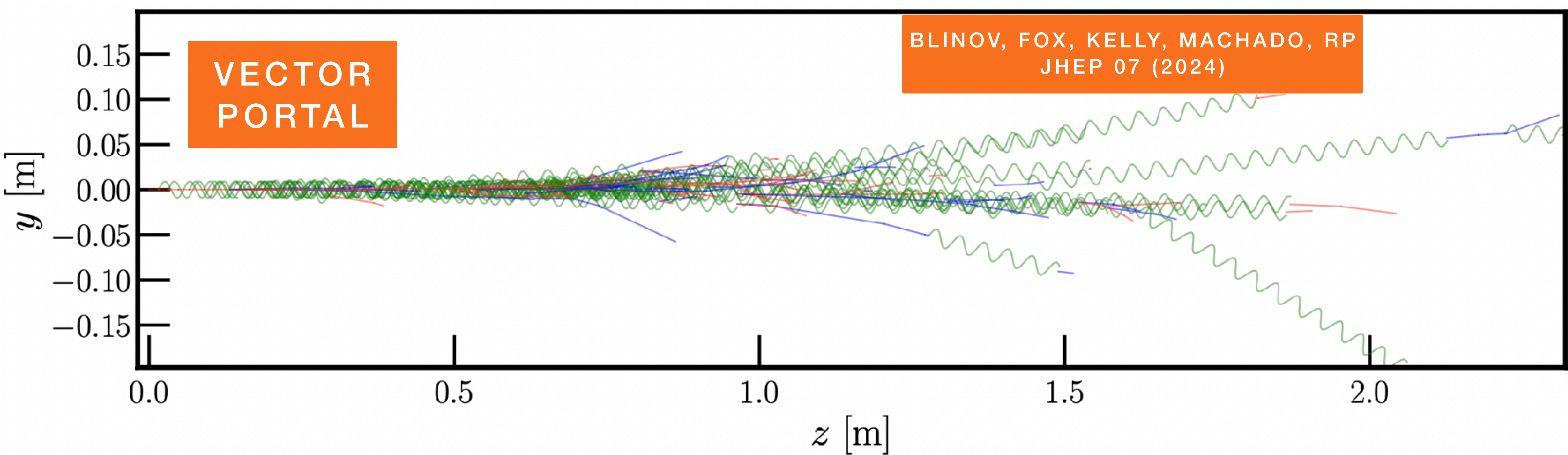
^a*Instituto de Física Teórica UAM-CSIC, Universidad Autónoma de Madrid, Calle de Nicolás Cabrera 13-15, Cantoblanco, E-28049 Madrid, Spain*

^b*Instituto de Física Corpuscular, Universidad de Valencia & CSIC, Edificio Institutos de Investigación, Calle Catedrático José Beltrán 2, 46980 Paterna, Spain*
E-mail: pilar.coloma@ift.csic.es, m.pilar.hernandez@uv.es, salvador.urrea@ific.uv.es

- Previously considered at MicroBooNE.
- See also:

Probing the Higgs portal at the Fermilab short-baseline neutrino experiments

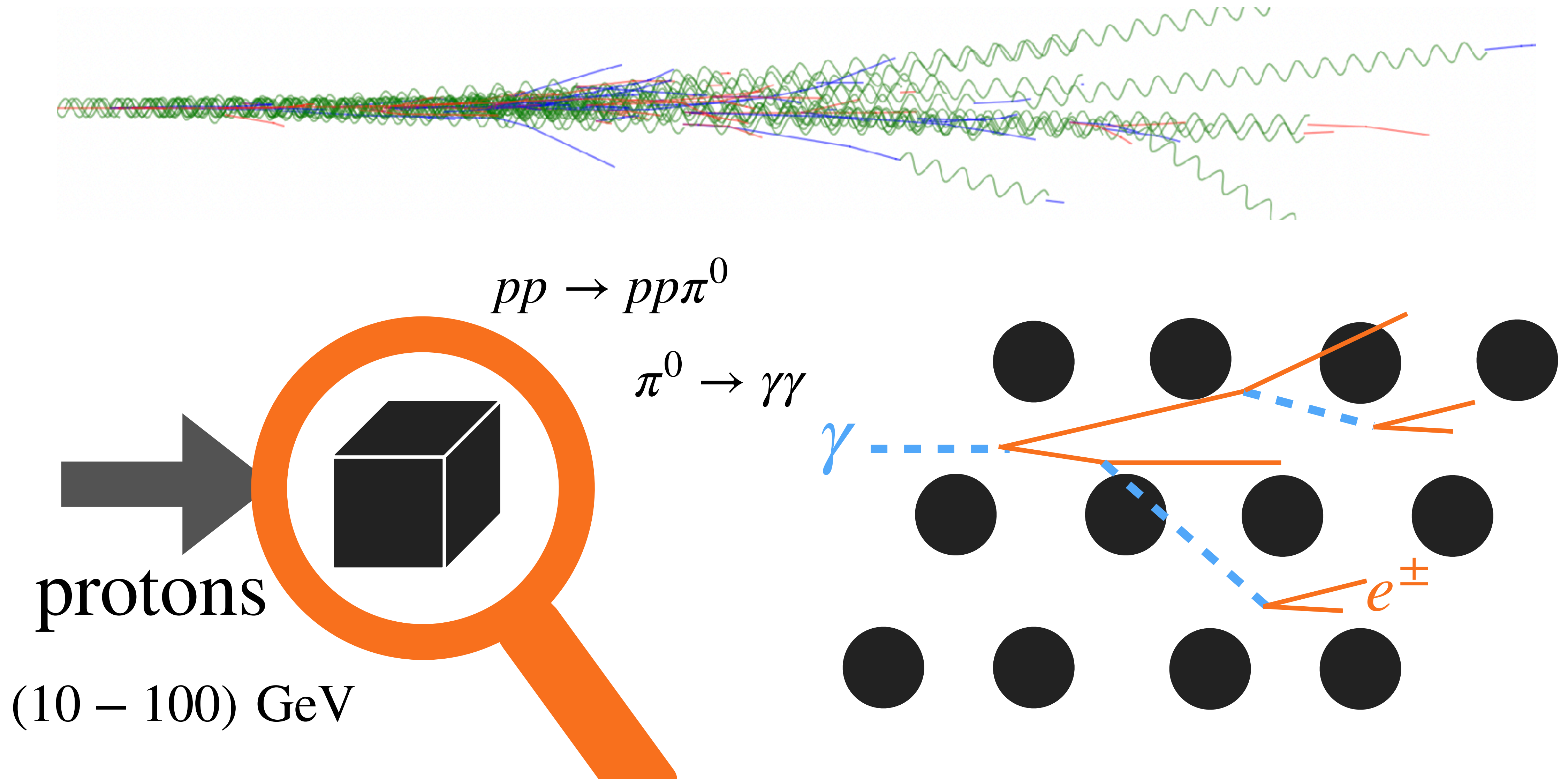
Brian Batell,^{1,*} Joshua Berger,^{1,†} and Ahmed Ismail^{1,2,‡}



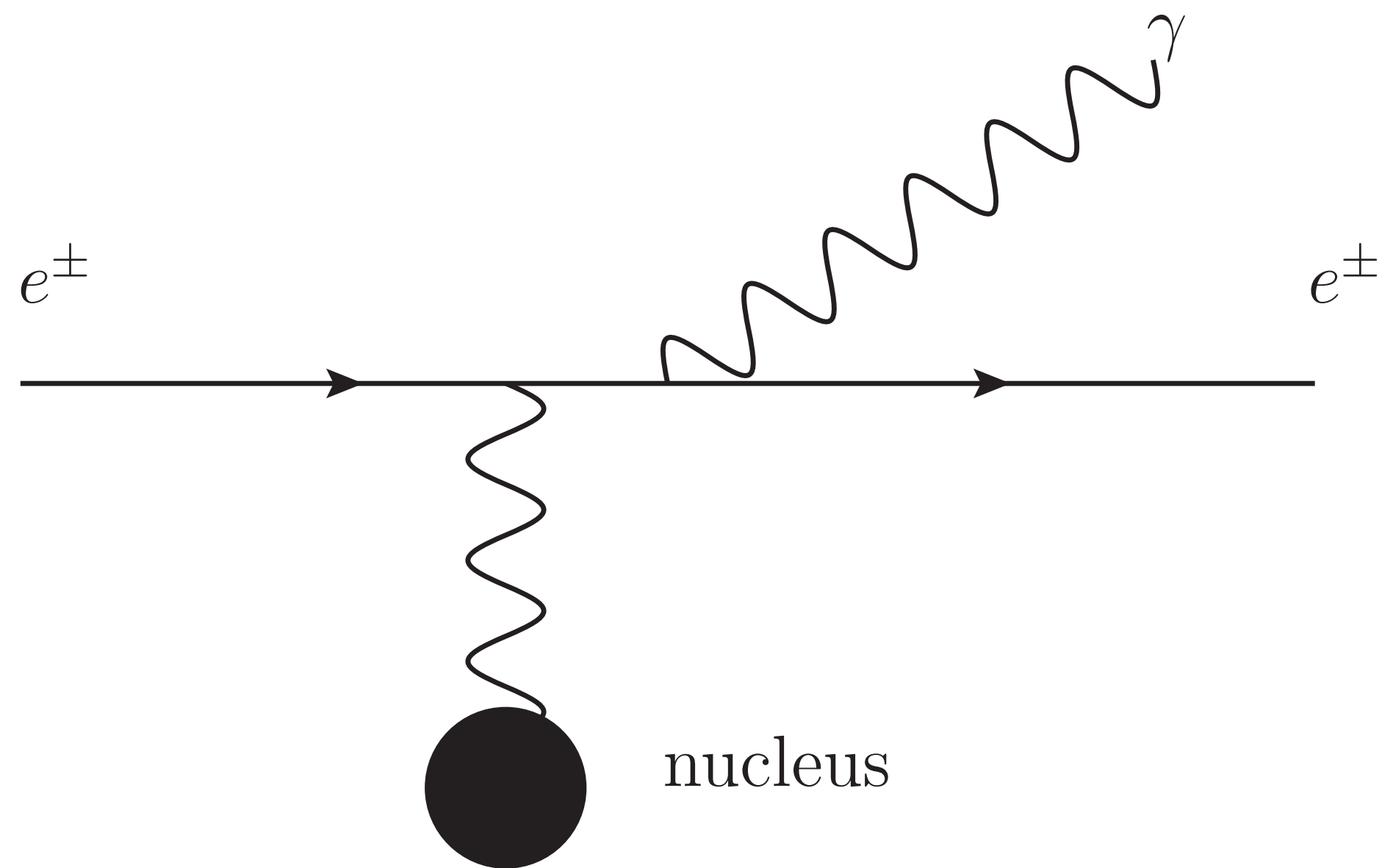
Cascade Production In Beam Dumps

Getting More Juice Out Of The Orange

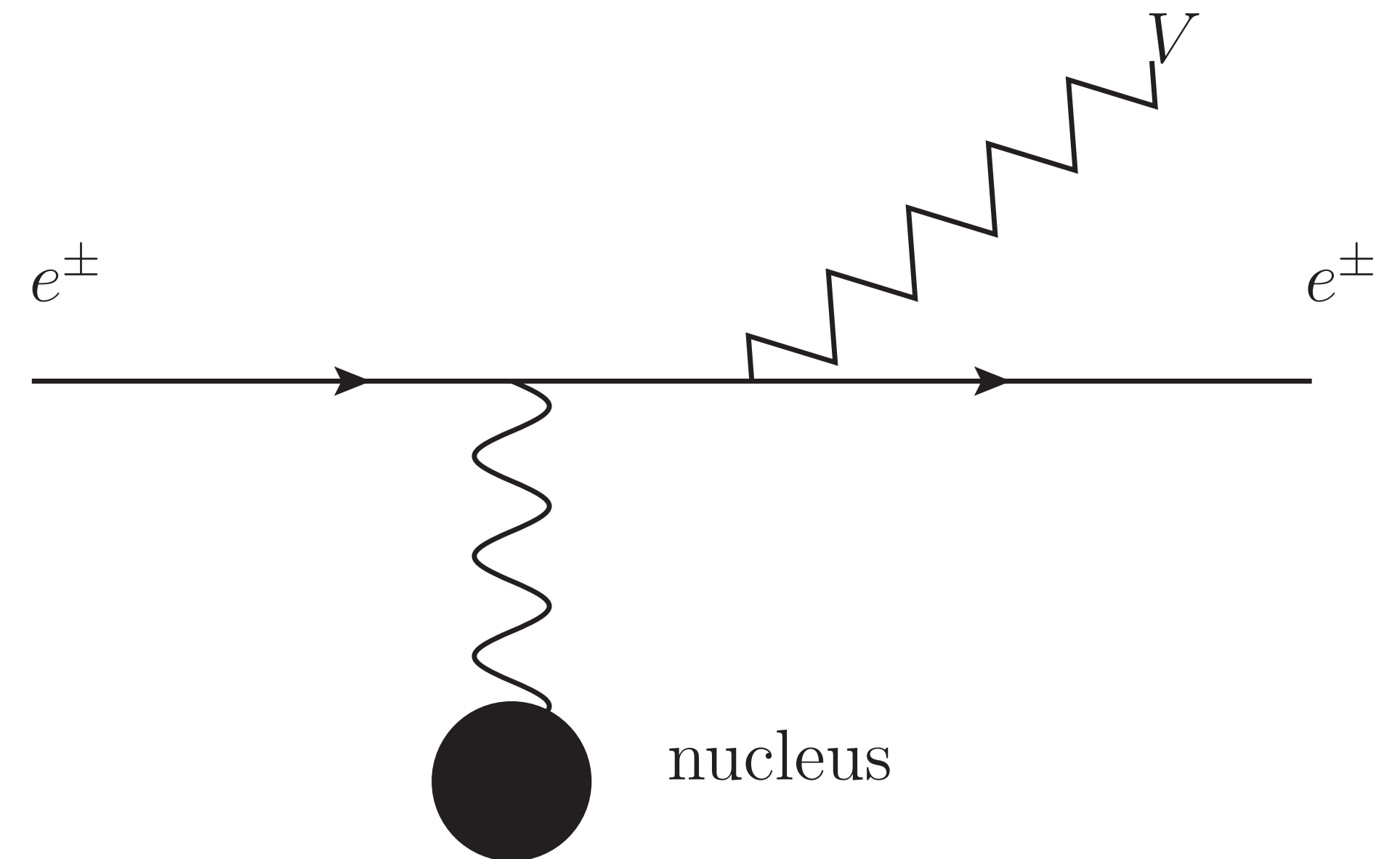
Secondary Production



SM Event $\rightarrow$ BSM Event

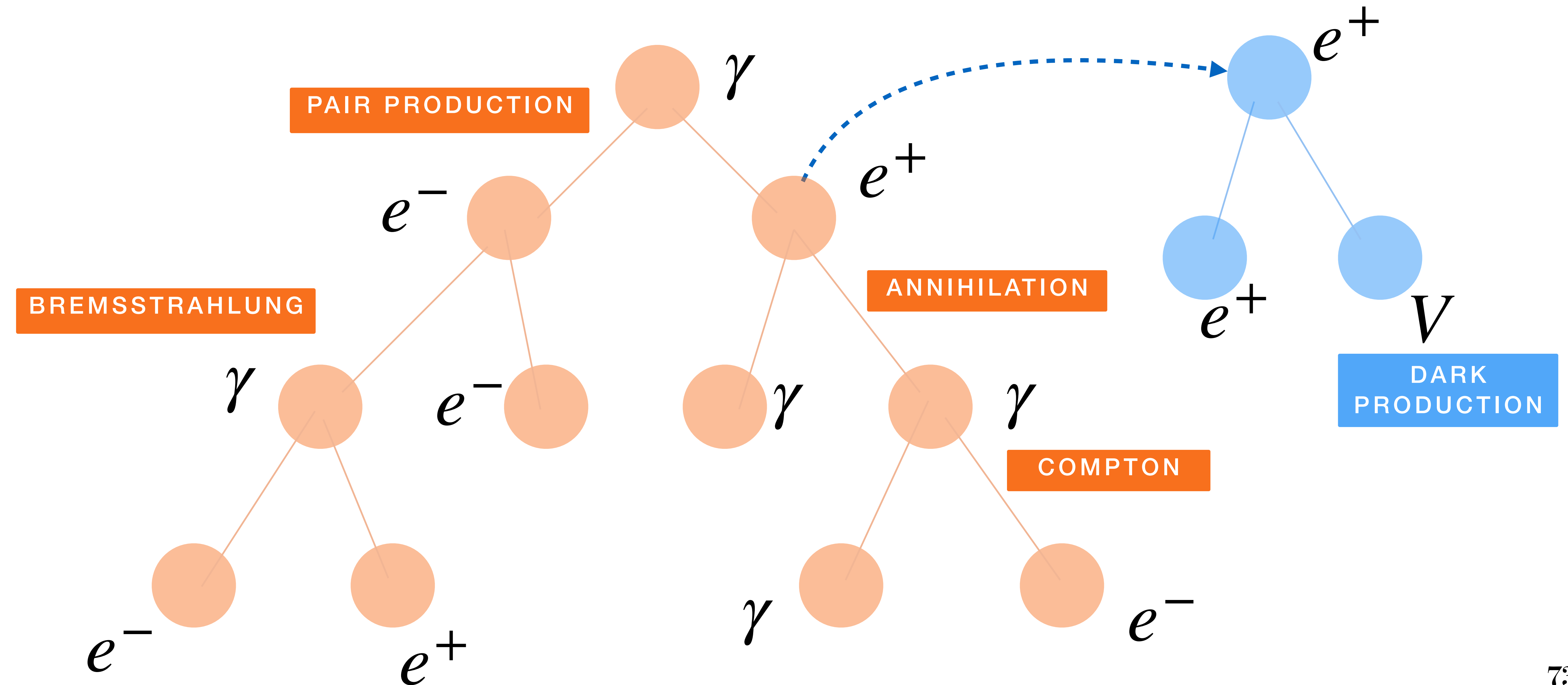


- Consider an event in a MC event record.



- How do we use this to generate BSM events?

SM Event Record $\rightarrow$ BSM Event Record



Implemented In PETITE

📖 README

BLINOV, FOX, KELLY, MACHADO, RP
JHEP 07 (2024)

PETITE

PETITE: Package for Electromagnetic Transitions In Thick-target Environments Monte Carlo generator for production of dark sector objects in thick-target experiments PETITE generates electromagnetic showers for incoming electron, positron or photon propagating through a dense medium, and includes the possibility of dark sector particle production.

Installation

To install, from the top directory run

```
pip install .
```

Dependencies

PETITE, its tutorials and tools require the following packages: numpy 1.24, vegas ($\geq 5.4.2$), cProfile, pickle, matplotlib, scipy, datetime, tqdm, copy, sys, random and functools. Using `pip install .` should install all requirements, but if needed, you can manually install these packages with

```
pip install <package_name>==<version_required>
```



[HTTPS://GITHUB.COM/KJKELLYPHYS/PETITE](https://github.com/kjkellyphys/petite)

Quick Intro To SHiP

PROTON BEAM

400 GeV

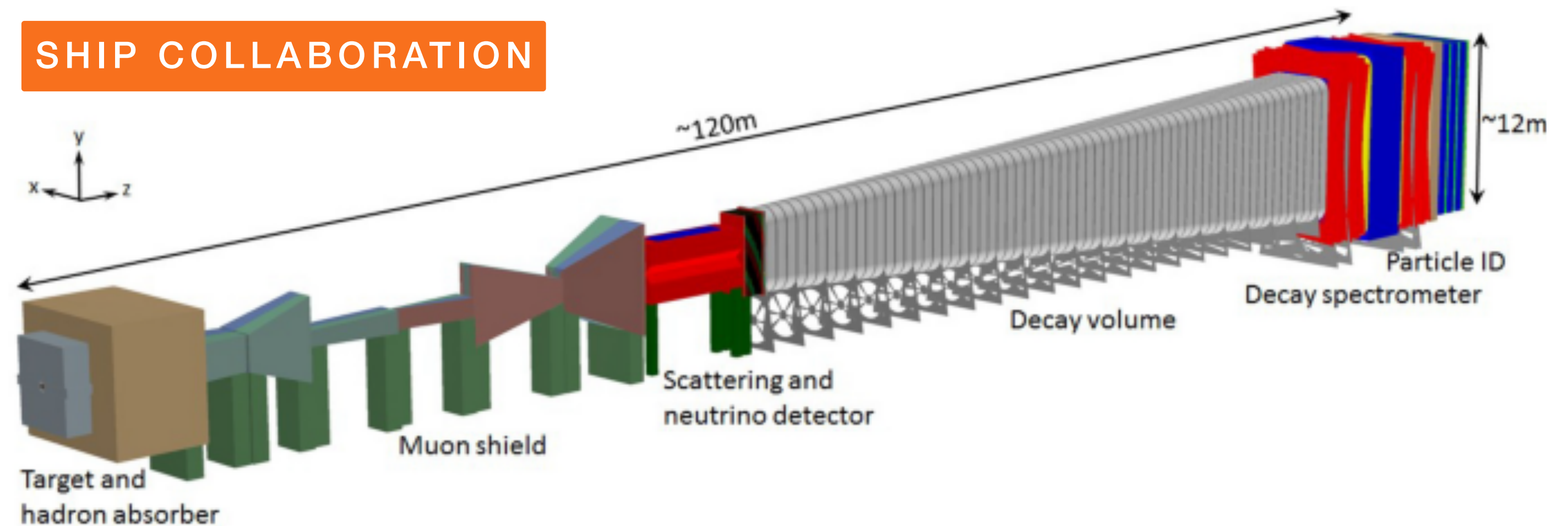
PROTONS ON TARGET

6×10^{20}

DECAY PIPE

$\sim 30 - 80$ m

SHIP COLLABORATION



- To be located at CERN.
- Excellent sensitivity to long-lived particles.
- Frontier experiment in this field.

Vector That Talks Mostly With Electrons

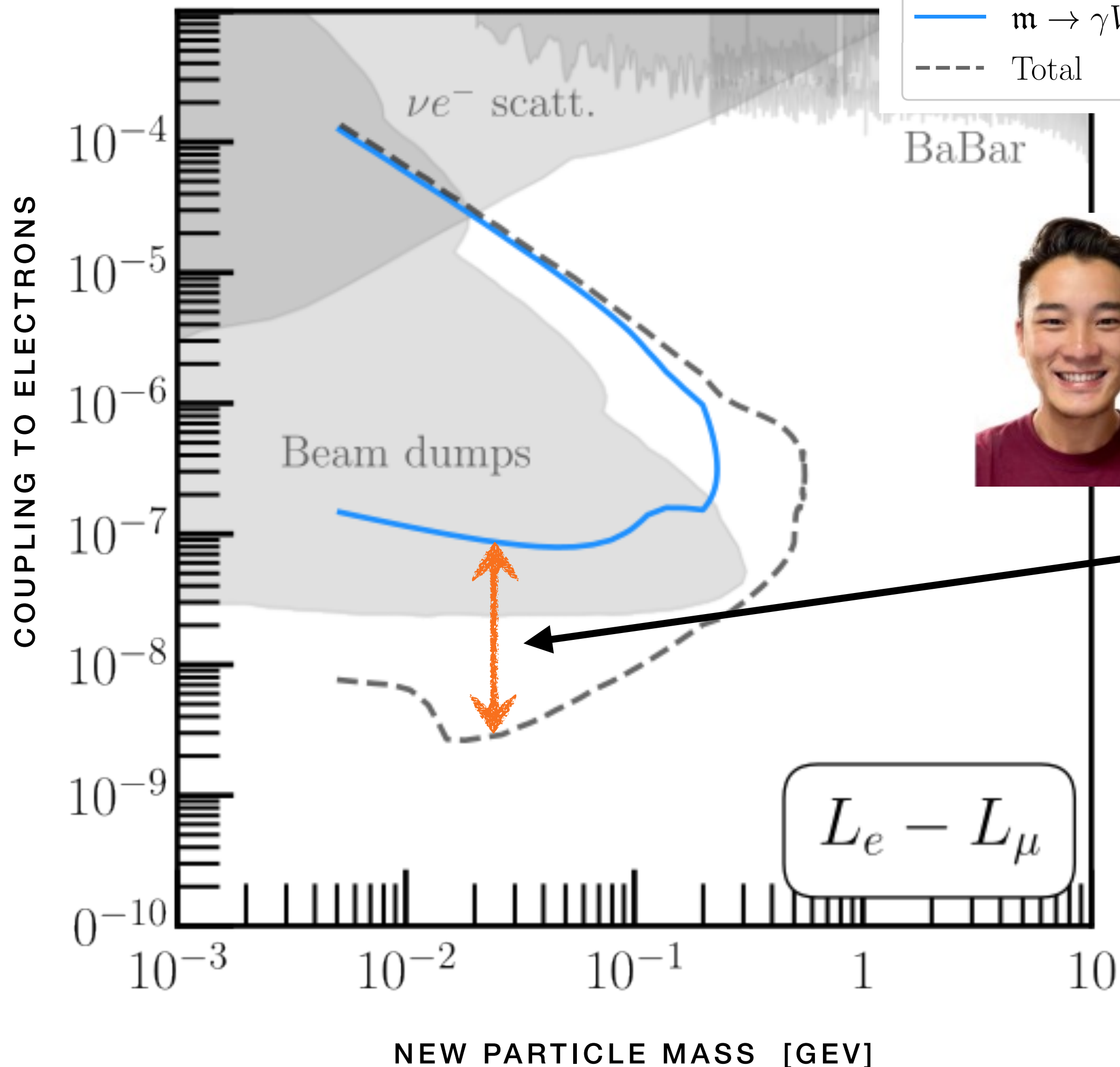
ZHOU, RP, KELLY, BLINOV, FOX
ARXIV:2412.01880

10 EVENT CONTOURS

SHiP, 6×10^{20} POT

— $m \rightarrow \gamma V$

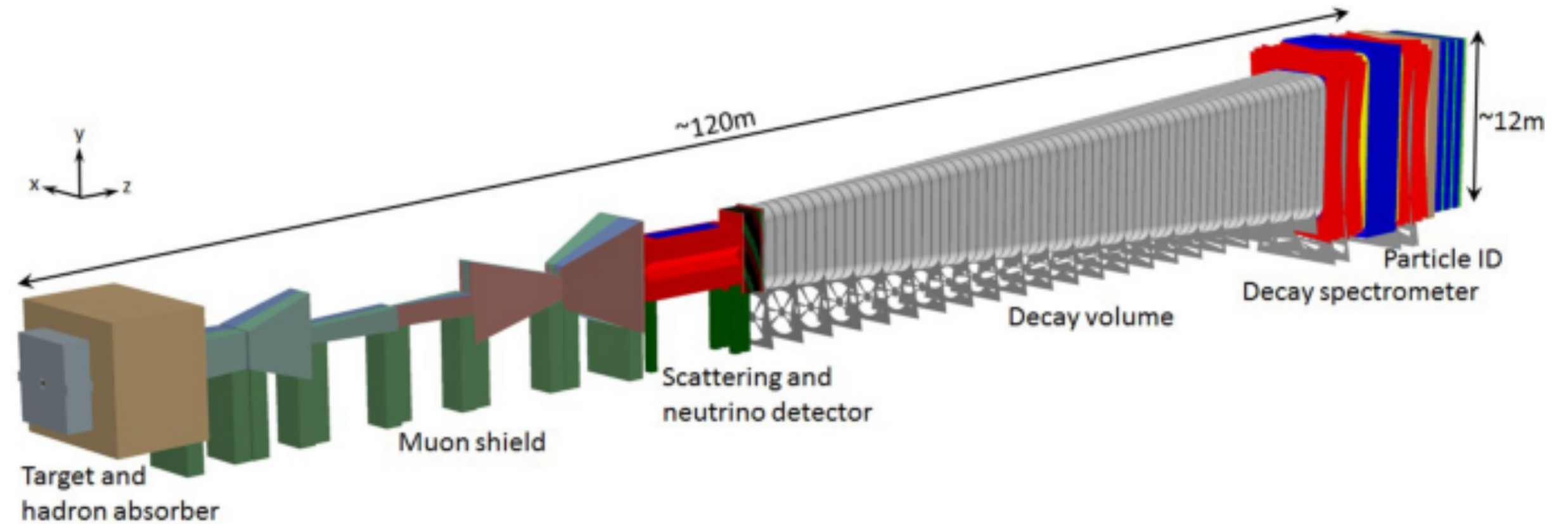
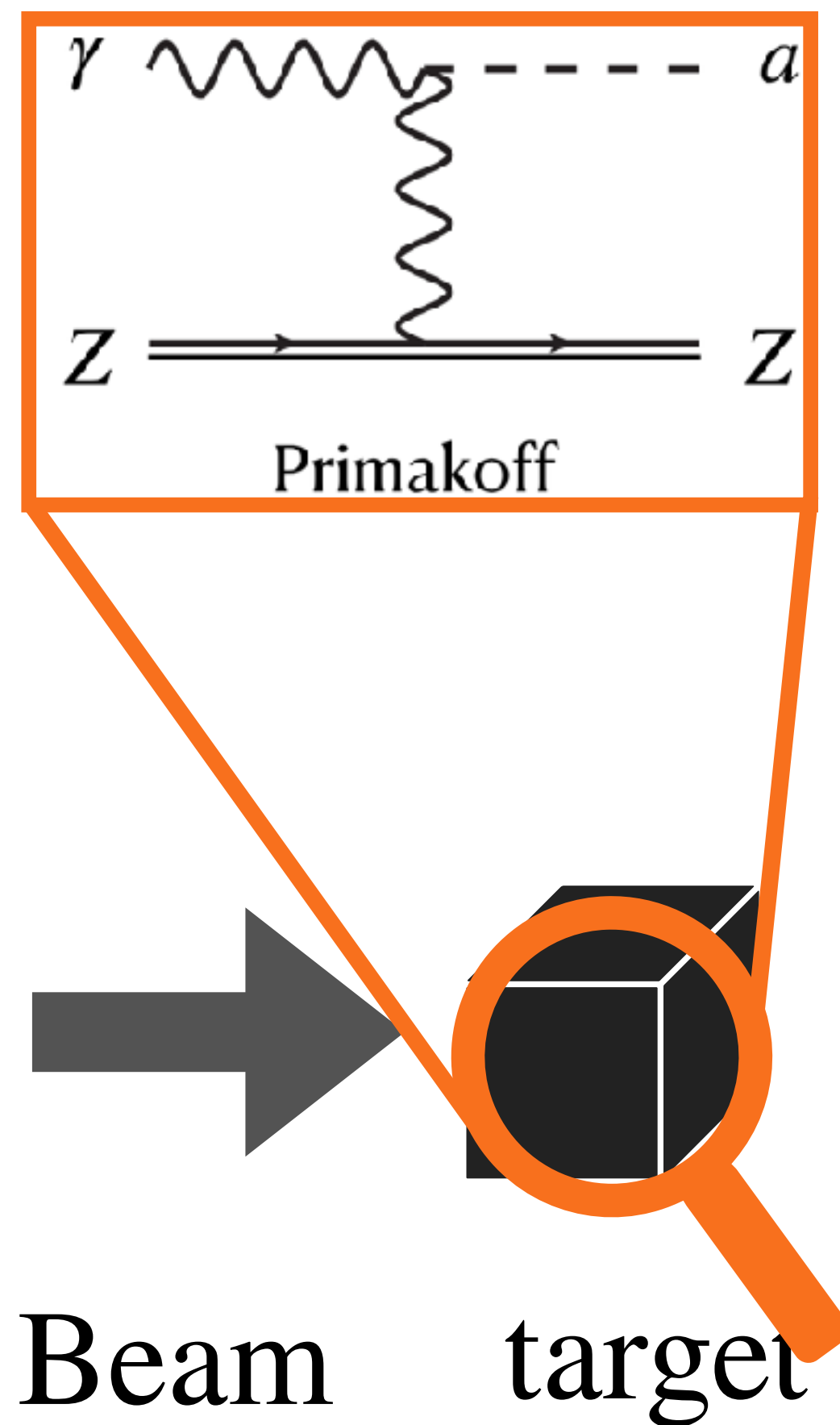
--- Total



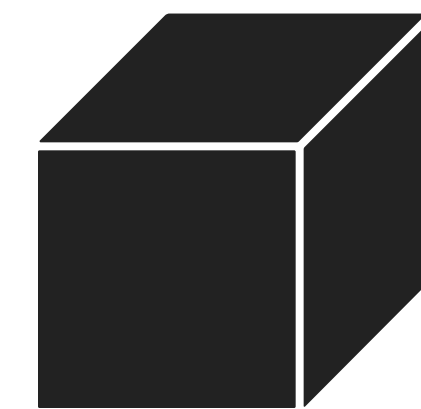
Huge Shift In Flux

- There are more chances to produce a dark photon.
- Later in the cascade have lower energy $\Rightarrow$ short-lived.
- Coupling to mesons is weaker than electrons.

Application To Axion-Like Particles



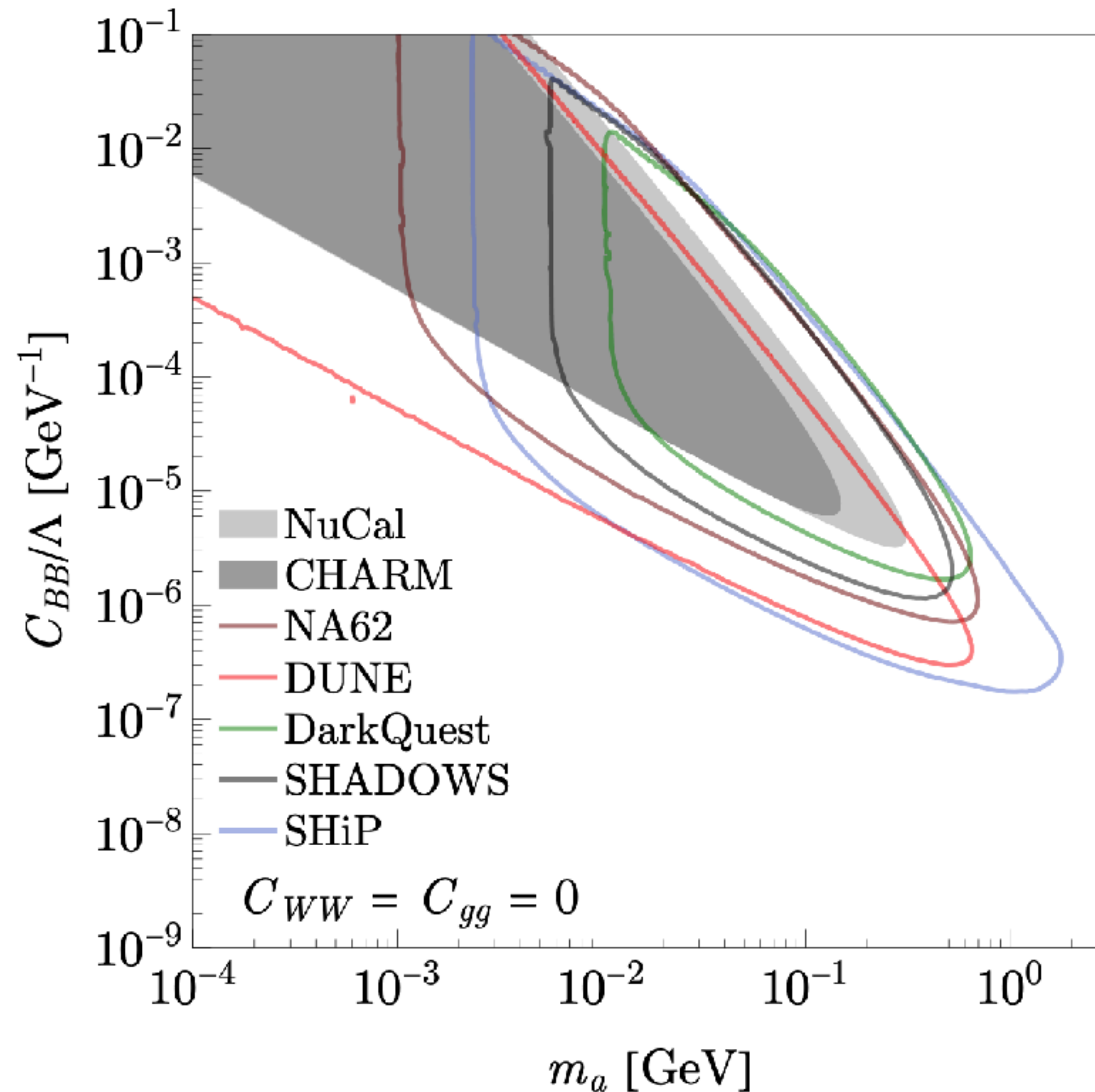
pipe



detector

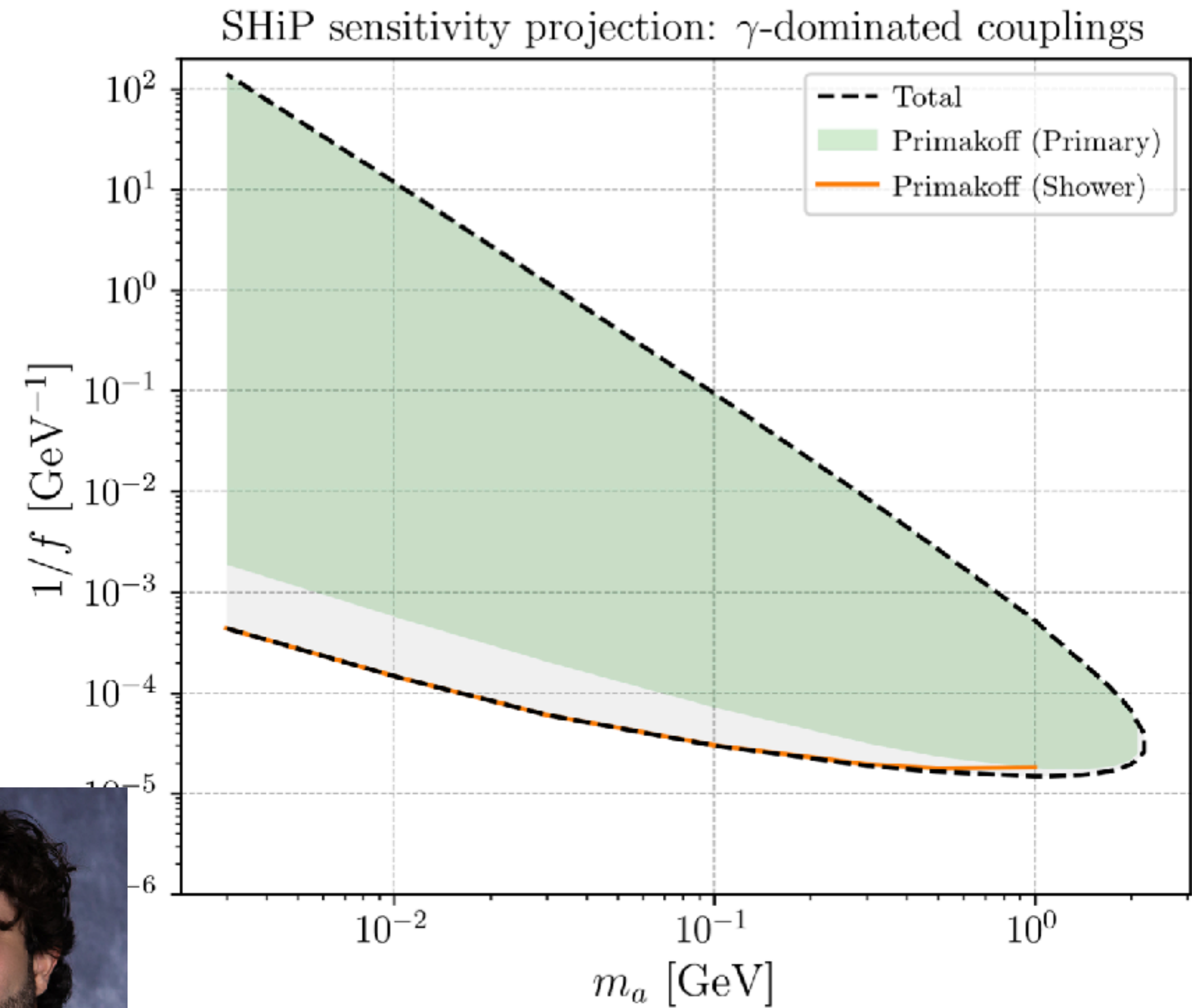
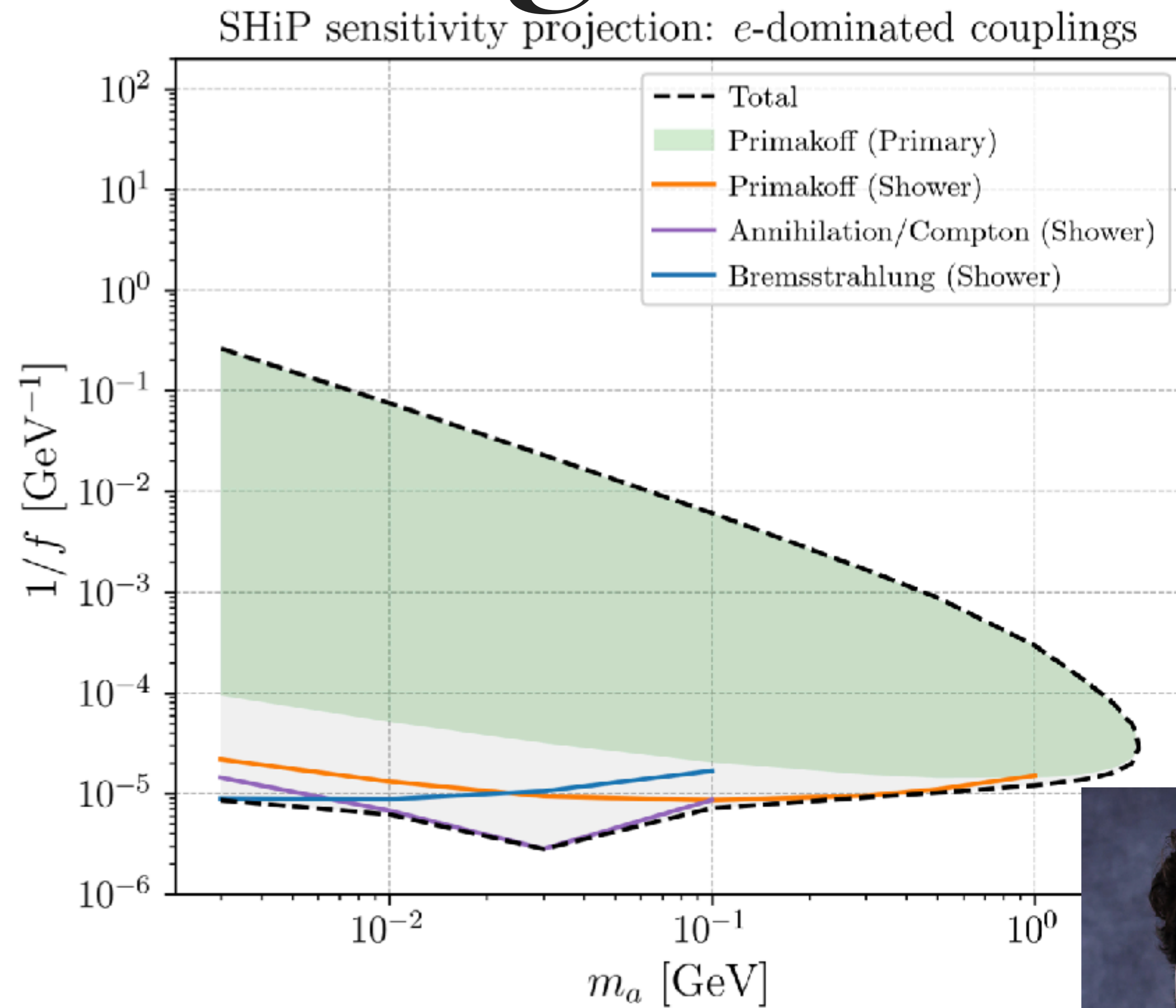
Past Work On ALPs Coupled To $\gamma\gamma$

JERHOT, DOBRICH, ERTAS, KAHLHOFER, SPADARO JHEP (2022)



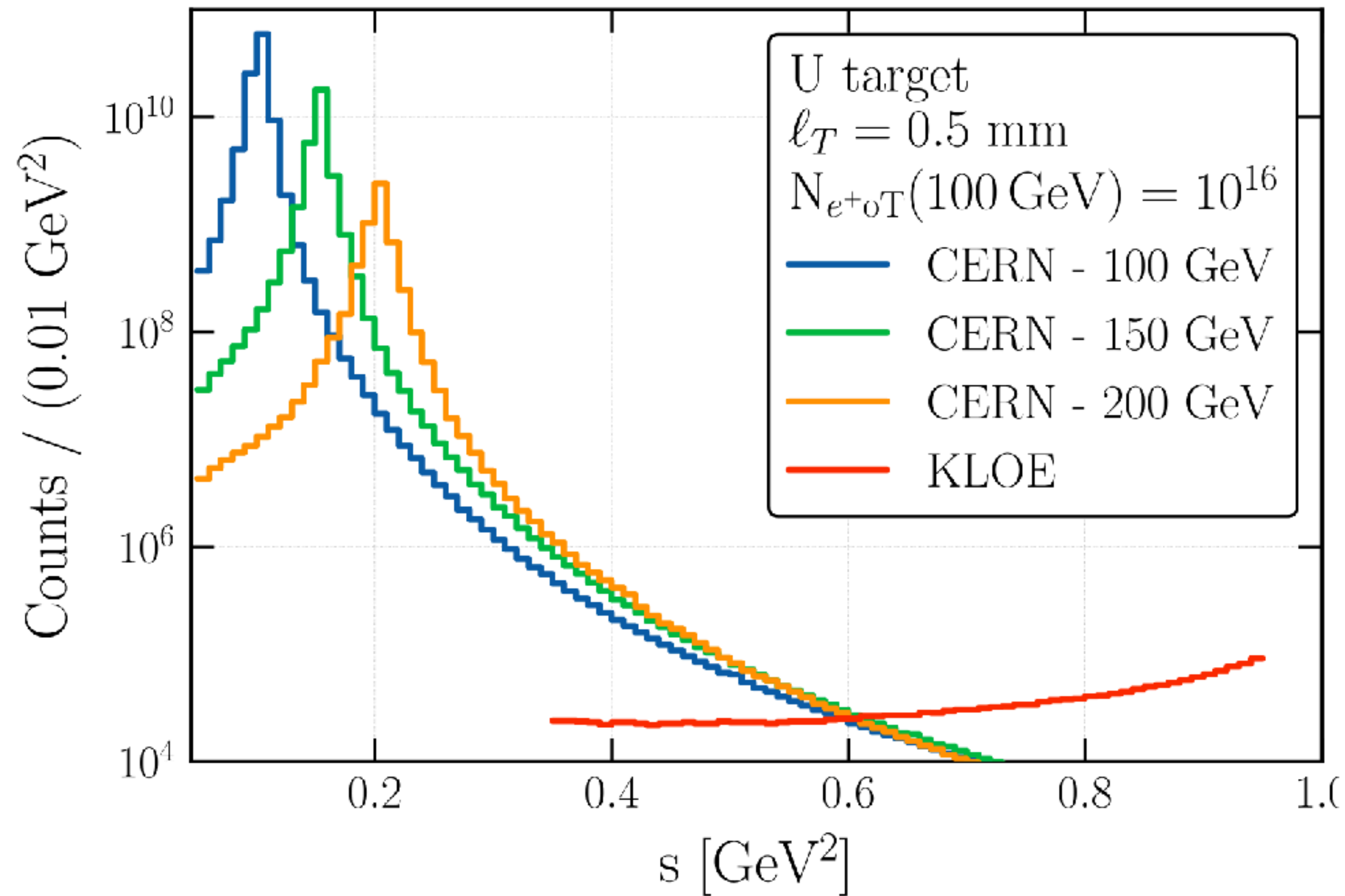
- Only includes primary photons.
- Secondary production in the dump can be substantial.

Including An EM Cascade



WITH S. PATRONE & N. BLINOV | 2509.14310

Related Work: Atomic Binding Effects

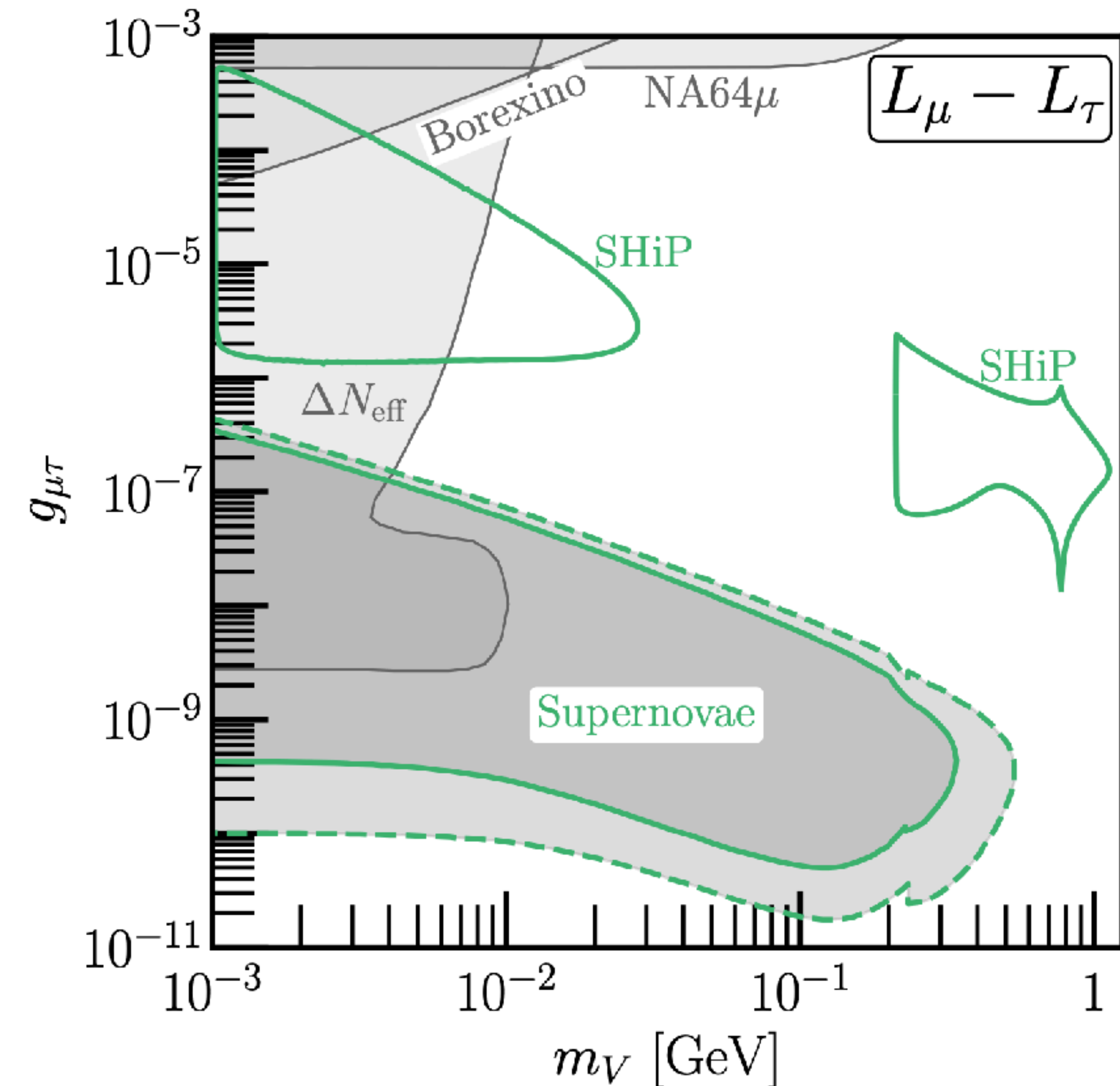


$$e^+e^- \rightarrow X(n\gamma)$$

- Positron annihilation on atomic electrons.
- Velocity distribution of electrons sculpts cross-section.
- Can **enhance reach** by increasing eff. c.o.m. energy

Atoms as Electron Accelerators for Measuring the Cross Section of $e^+e^- \rightarrow \text{Hadrons}$

Re-Visiting Gauged $L_\mu - L_\tau$



- Revisited limits on a notoriously difficult model to test.
- New supernova analysis.
- Found reach had been previously overestimated.



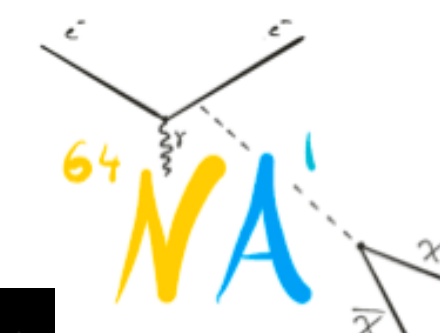
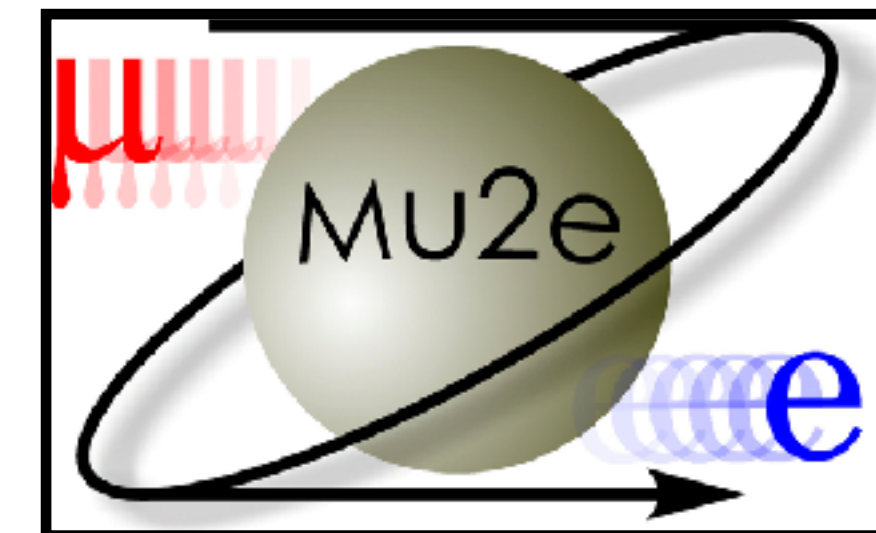
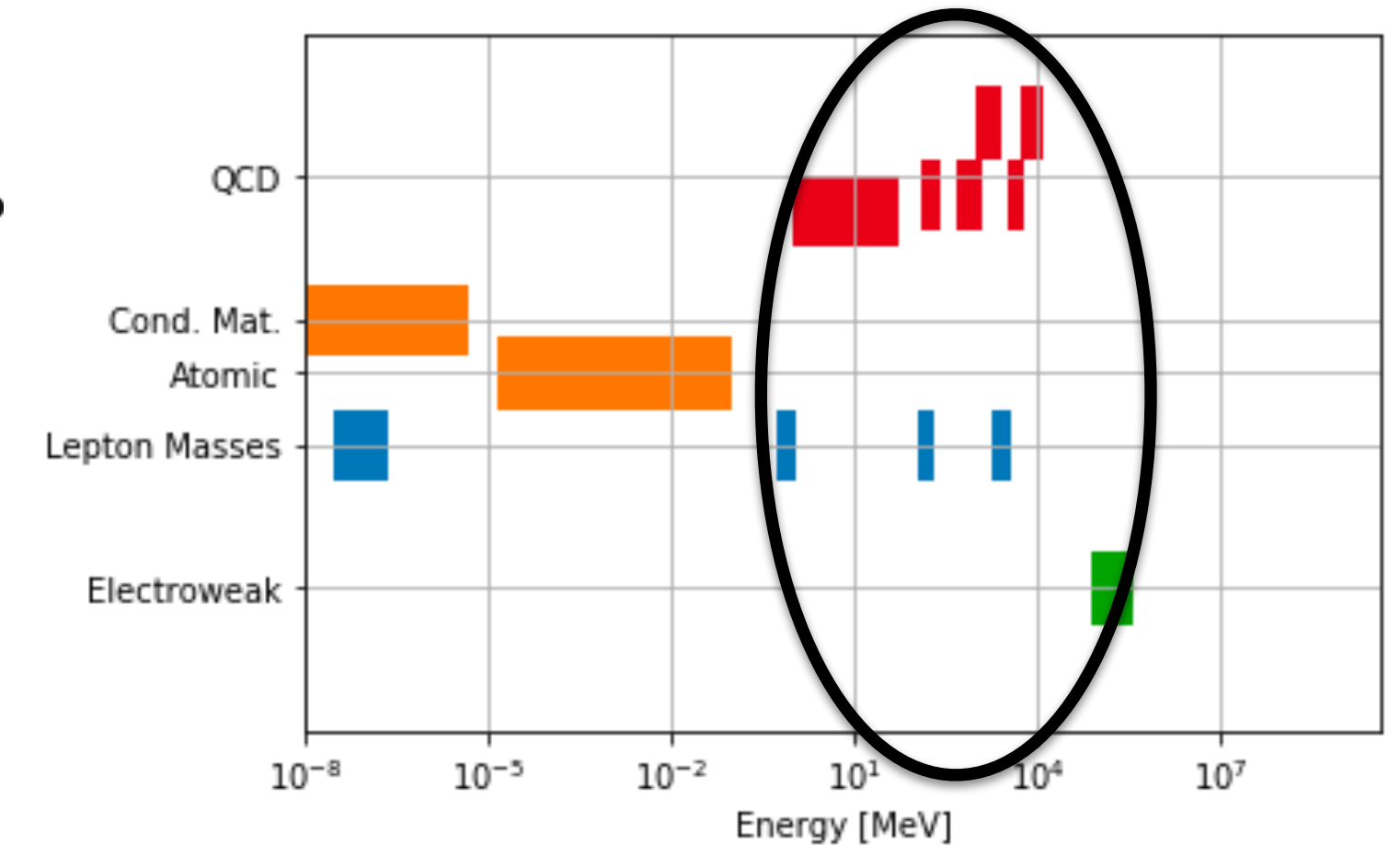
CHRISTMAS WORKSHOP



Summary & Conclusions

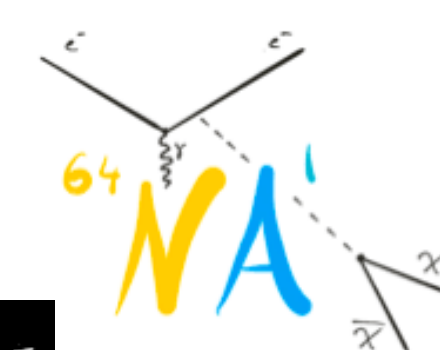
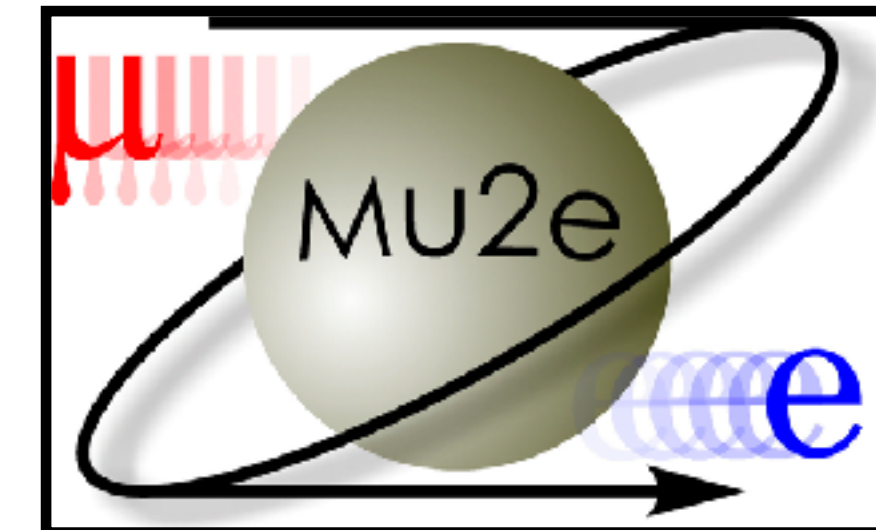
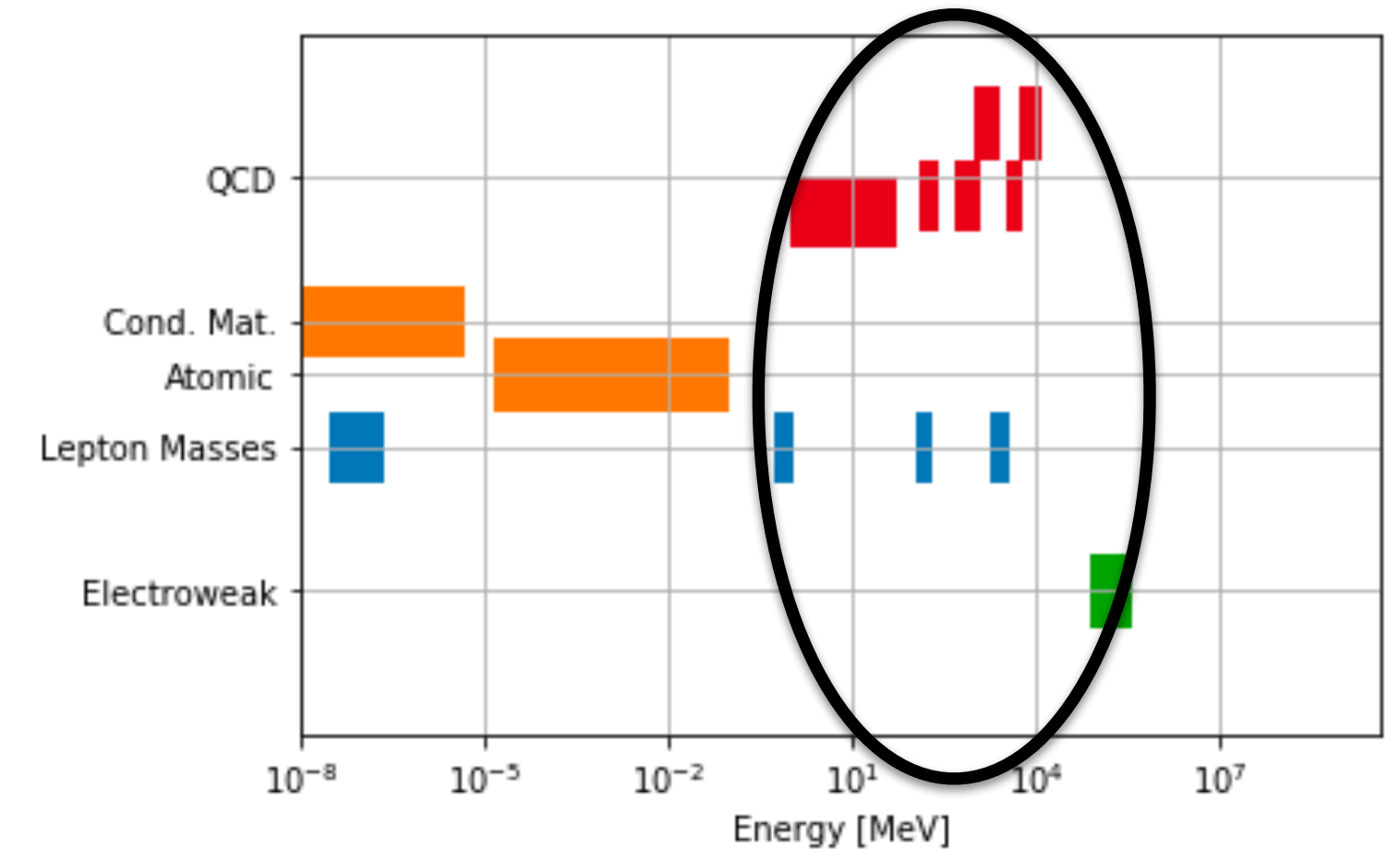
The Intensity Frontier Today

- All data is good data.
- Exciting portfolio of high intensity beams below the weak scale.
- A model-agnostic framework for:
 - i)* dark sectors, *ii)* precision, and
 - iii)* rare decays.
- Exciting complementarity with neutrino & flavour physics.



For The Students In The Crowd

1. Theory makes a real impact!
Can change interpretation by orders of magnitude.
2. Many energy and length scales:
A rich opportunity to learn about physics both old and new.
3. Every experimental talk ask:
what else can that thing do?



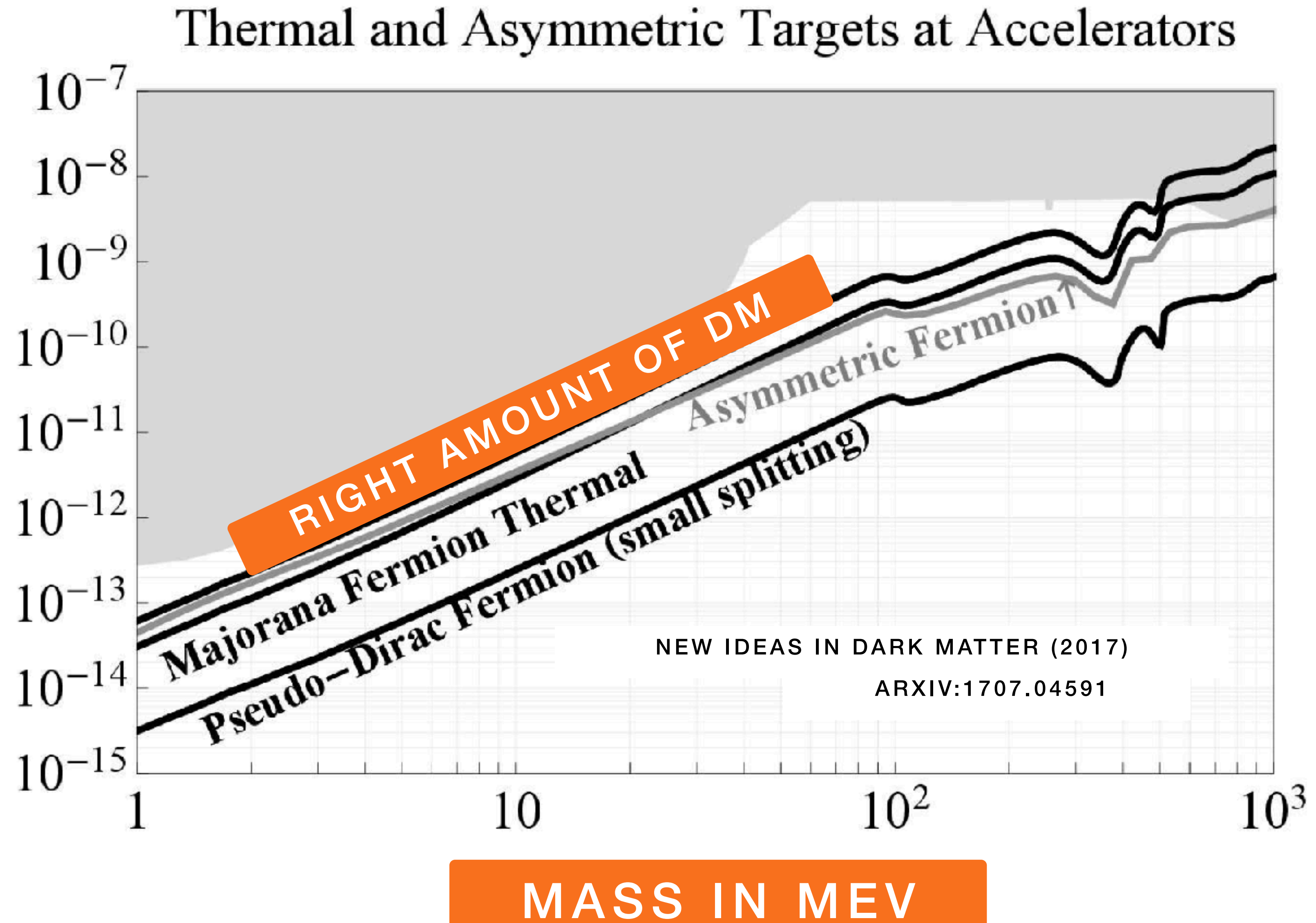


Backup Slides

DARK MATTER TARGETS AT ACCELERATORS

- Relic abundance is predictive.
- Well defined targets.
- Can search for dark matter "in the lab".

COUPLING



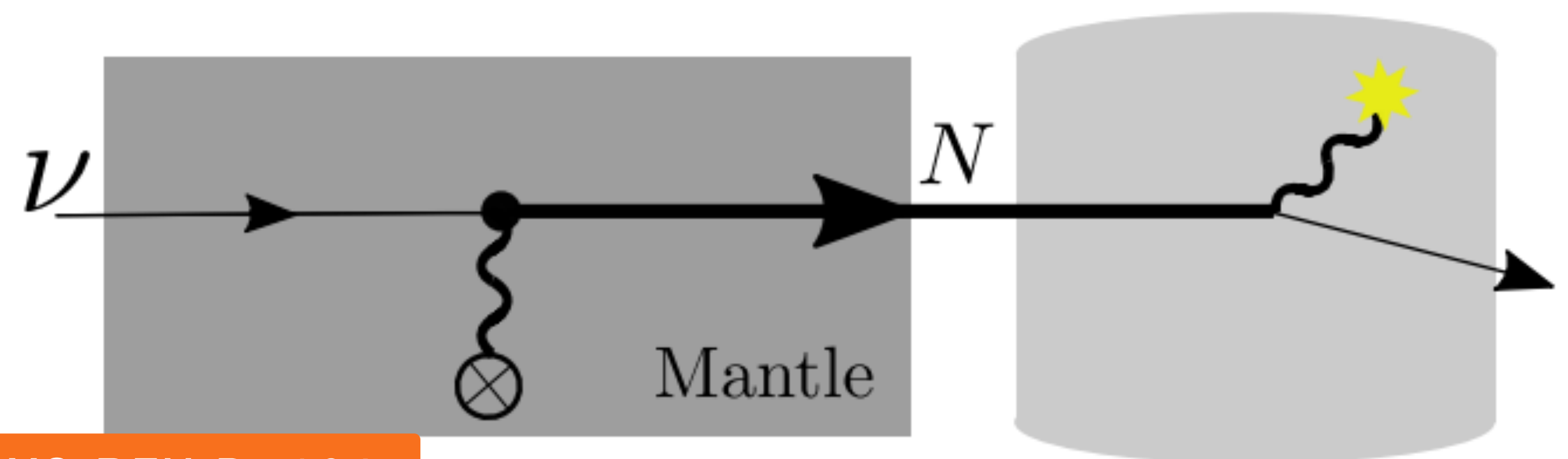
For the hierarchy $R_{\text{Earth}} \gg L_{\text{decay}} \gg L_{\text{detector}}$

- Column density scales with decay length.

Conclusion: You make more particles

- Long decay lengths make decays *inside* your detector less likely.

Conclusion: Fewer decays per particle.



For the hierarchy $R_{\text{Earth}} \gg L_{\text{decay}} \gg L_{\text{detector}}$

- Column density scales with decay length.

Conclusion: You make more particles

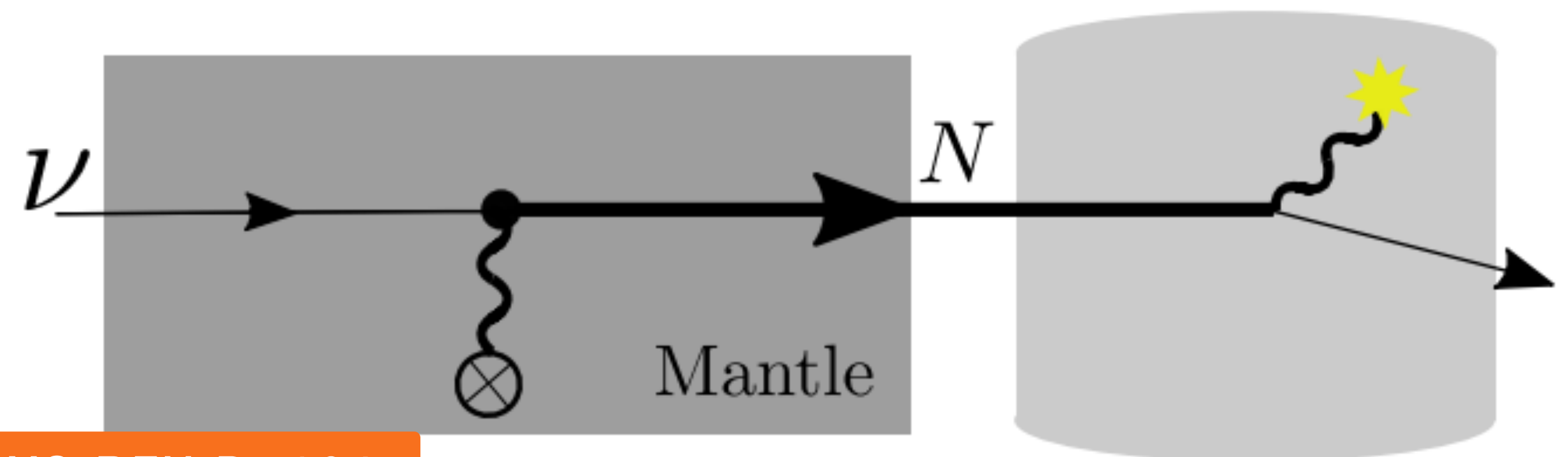
- Long decay length

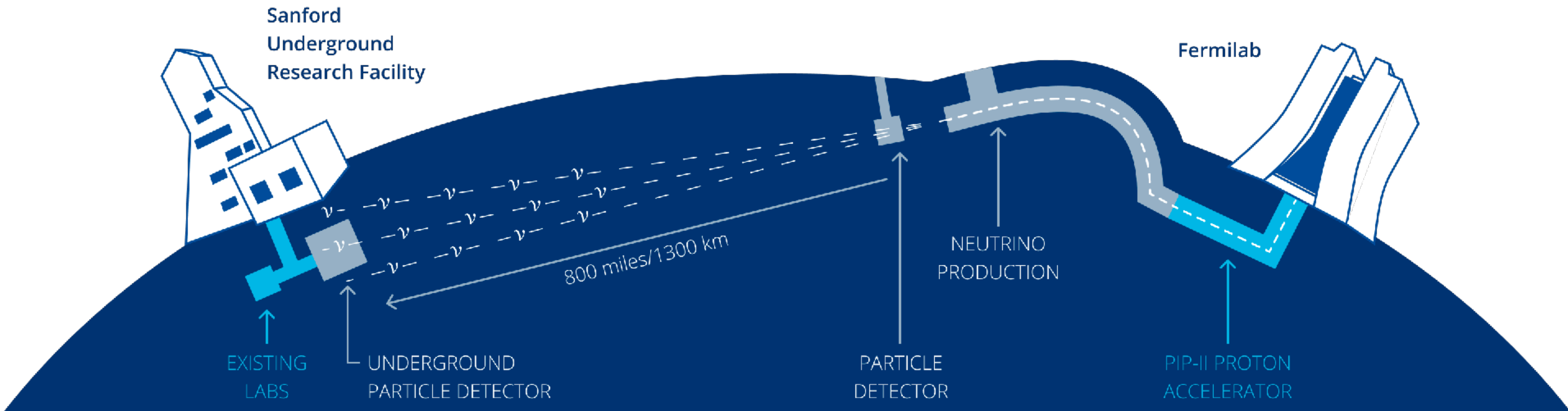
at detector less likely.

Conclusion:

more particle.

THESE PERFECTLY CANCEL!

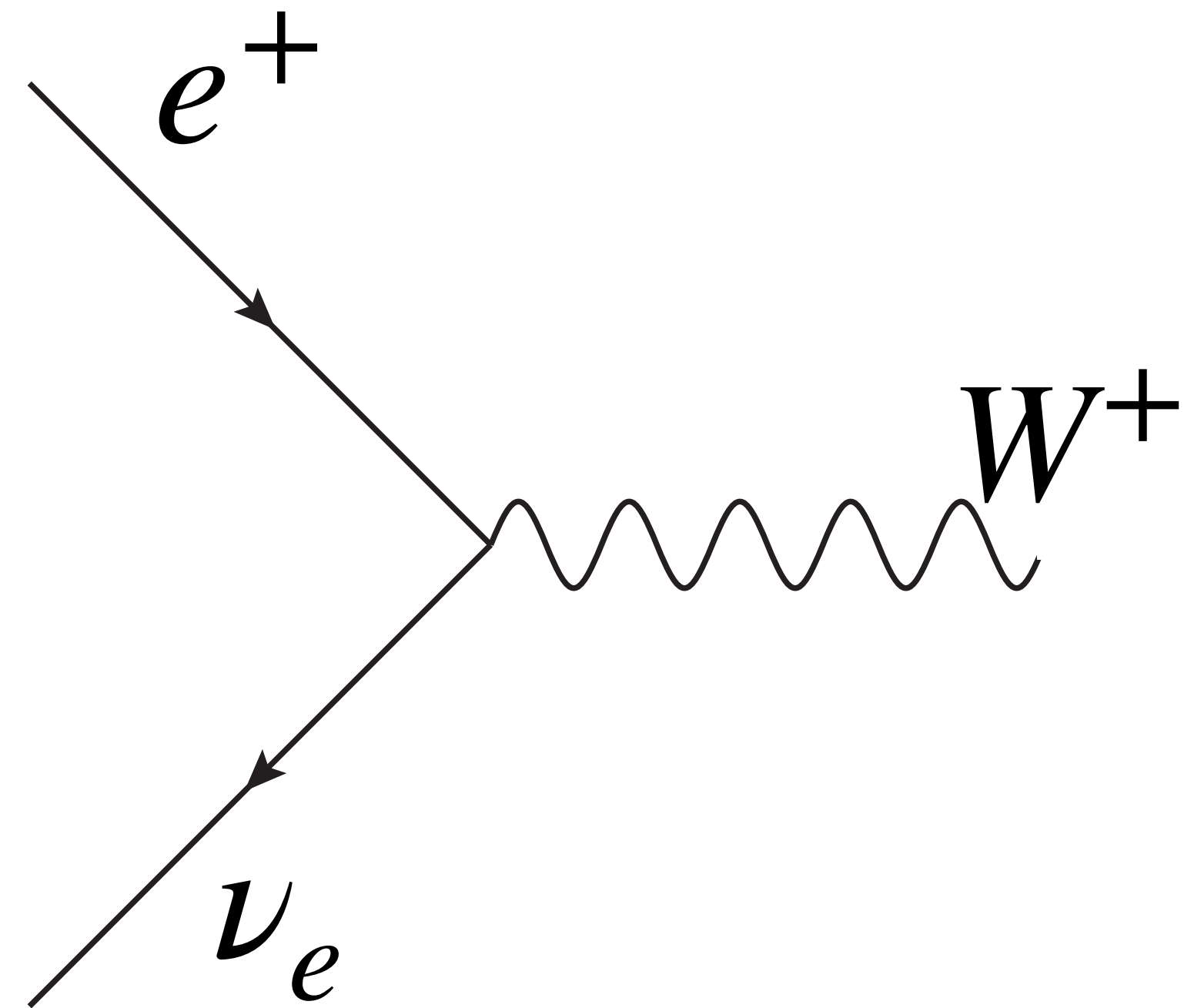




Oscillation Experiments

Ghost-Particles & Fundamental Physics

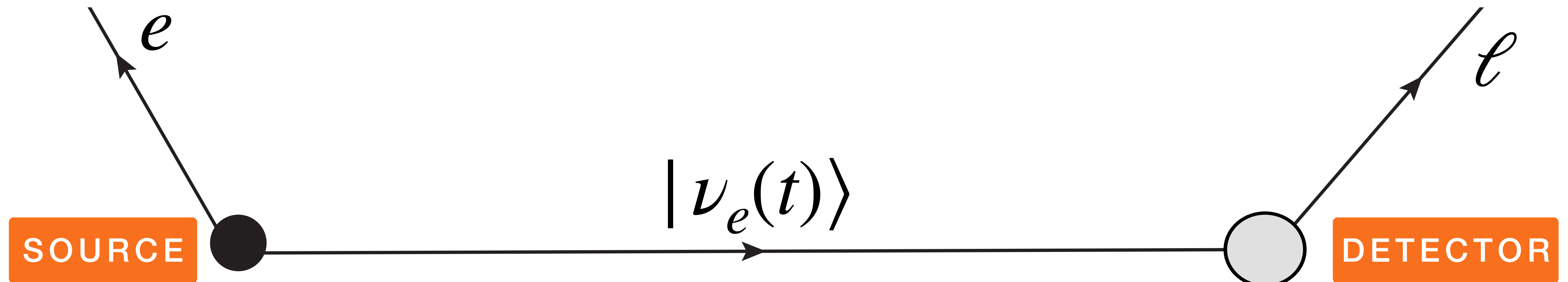
NEUTRINO OSCILLATIONS



P_{ee} = probability $\nu_e \rightarrow \nu_e$

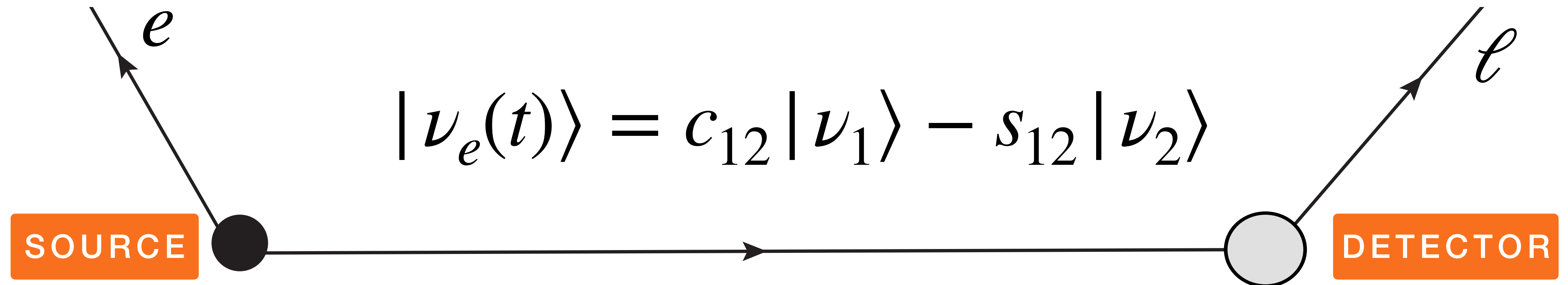
$P_{e\mu}$ = probability $\nu_e \rightarrow \nu_\mu$

$P_{\mu e}$ = probability $\nu_\mu \rightarrow \nu_e$



MASS VS FLAVOUR STATES

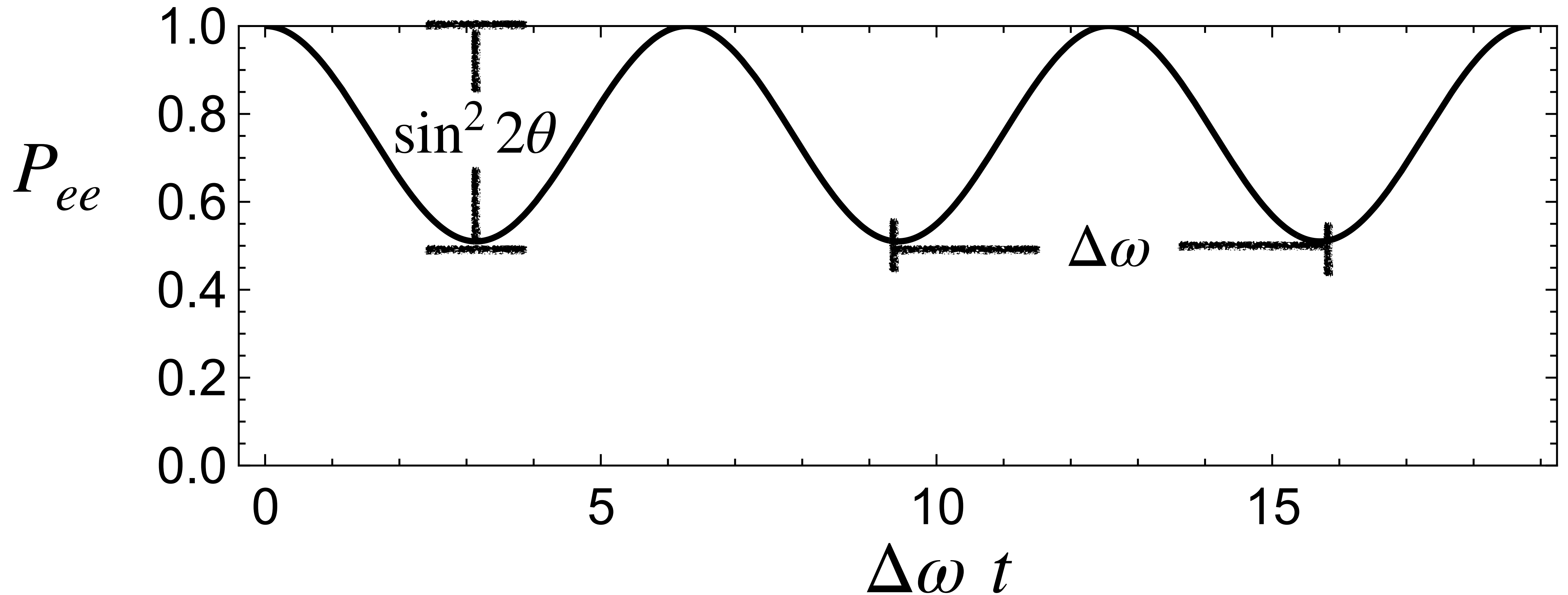
$$\text{FLAVOUR} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} \\ -\sin \theta_{12} & \cos \theta_{12} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \text{MASS}$$



$$|\nu_1(t)\rangle = e^{iE_1 t} |\nu_1\rangle \quad |\nu_2(t)\rangle = e^{iE_2 t} |\nu_2\rangle$$

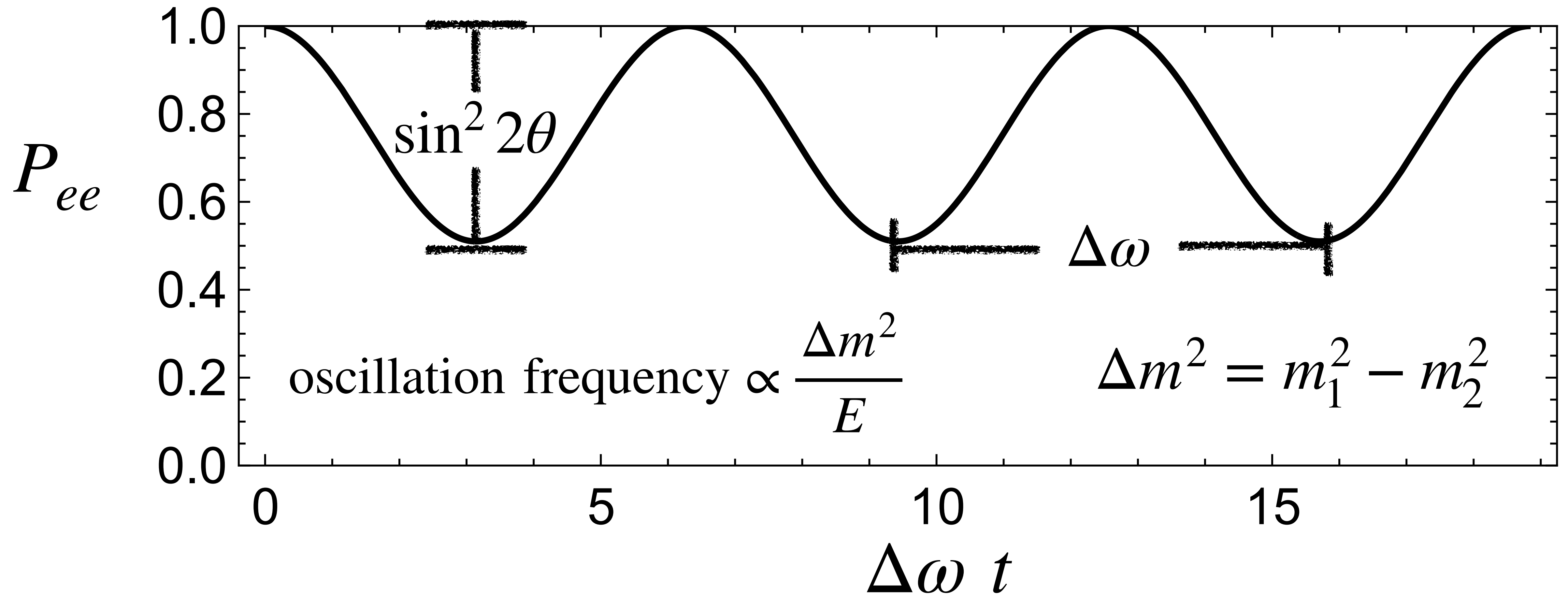
TWO FLAVOUR SCENARIO

$$P_{ee} = 1 - \frac{1}{2} \sin^2 2\theta + \frac{1}{2} \sin^2 2\theta \cos(\Delta\omega t)$$



TWO FLAVOUR SCENARIO

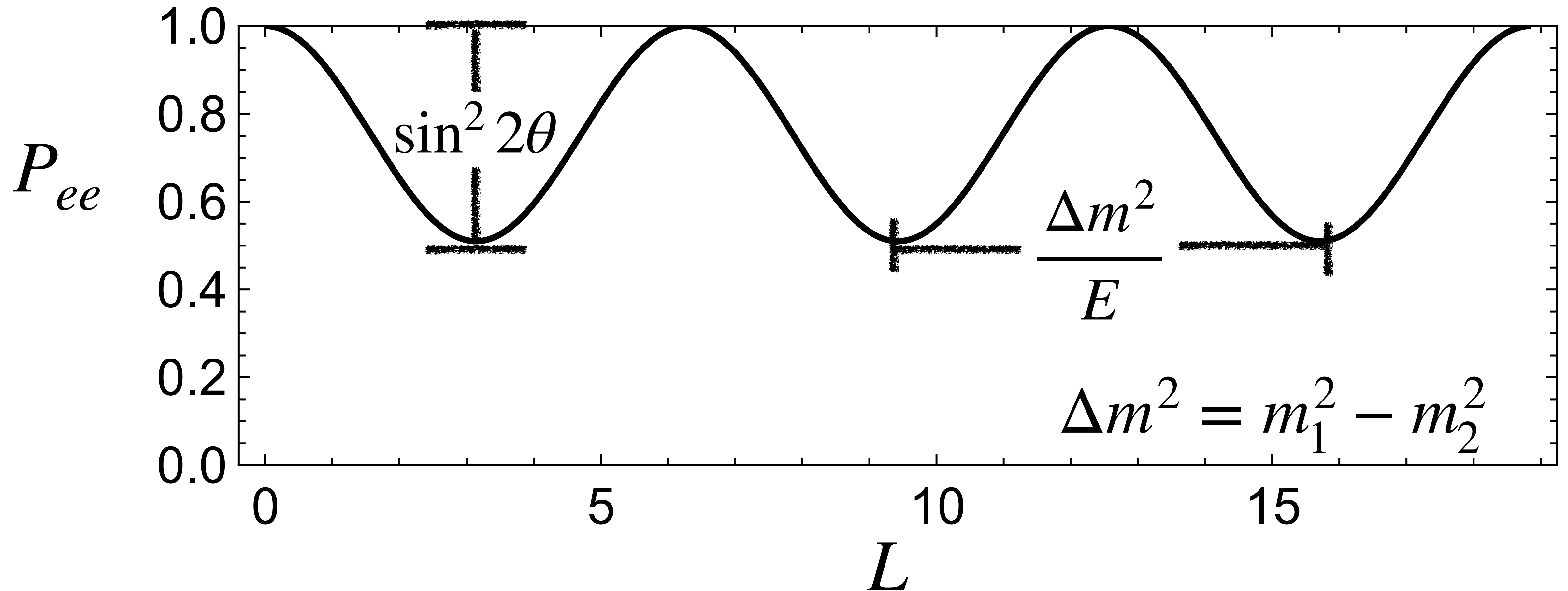
$$P_{ee} = 1 - \frac{1}{2} \sin^2 2\theta + \frac{1}{2} \sin^2 2\theta \cos(\Delta\omega t)$$



TWO FLAVOUR SCENARIO

$$\hbar = c = 1$$

$$P_{ee} = 1 - \frac{1}{2} \sin^2 2\theta + \frac{1}{2} \sin^2 2\theta \cos \left(\Delta m^2 \times \frac{L}{E} \right)$$

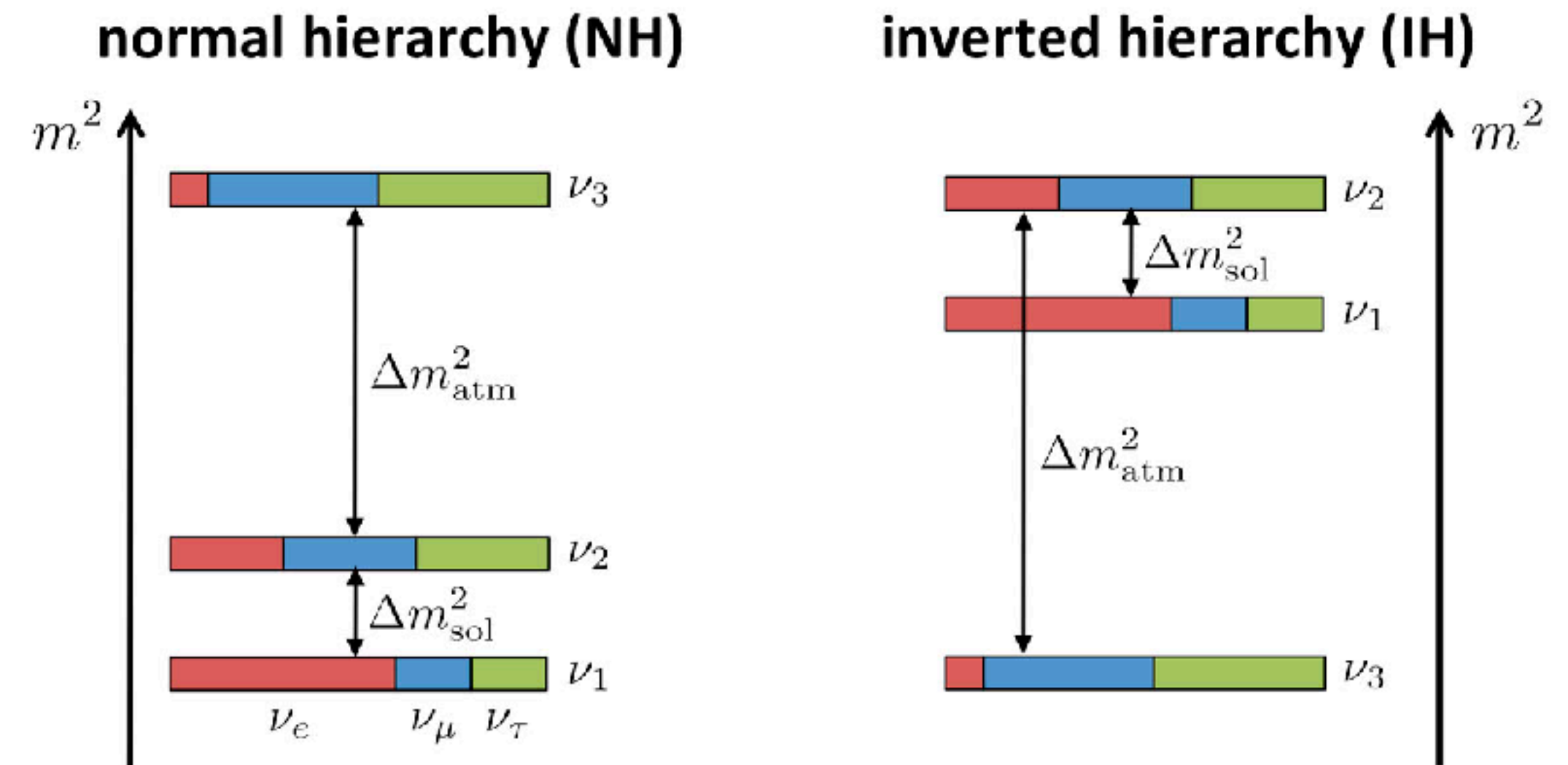


THREE FLAVOUR OSCILLATIONS

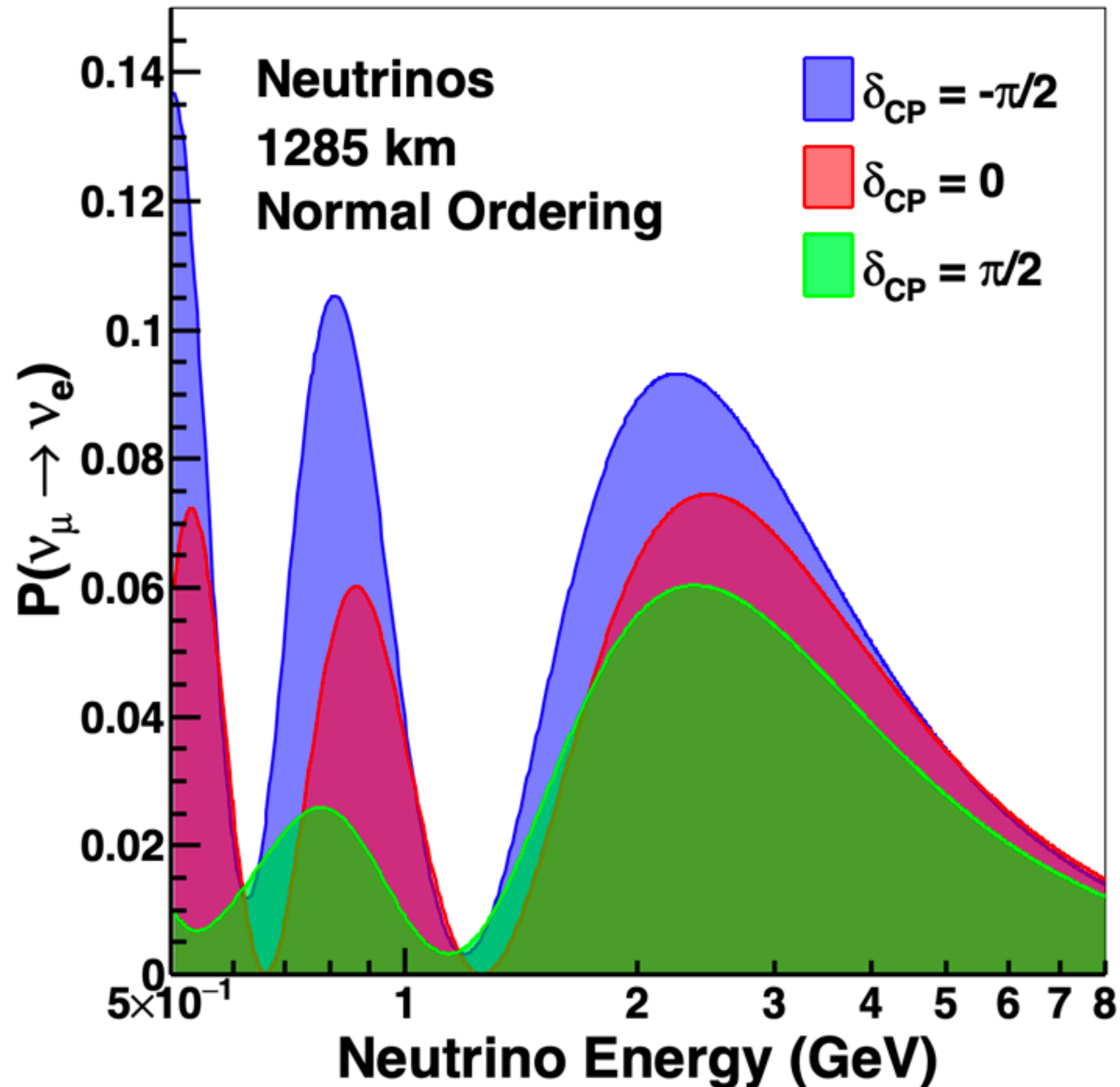
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$m_1^2 - m_2^2$$

$$m_2^2 - m_3^2 \approx m_1^2 - m_3^2$$

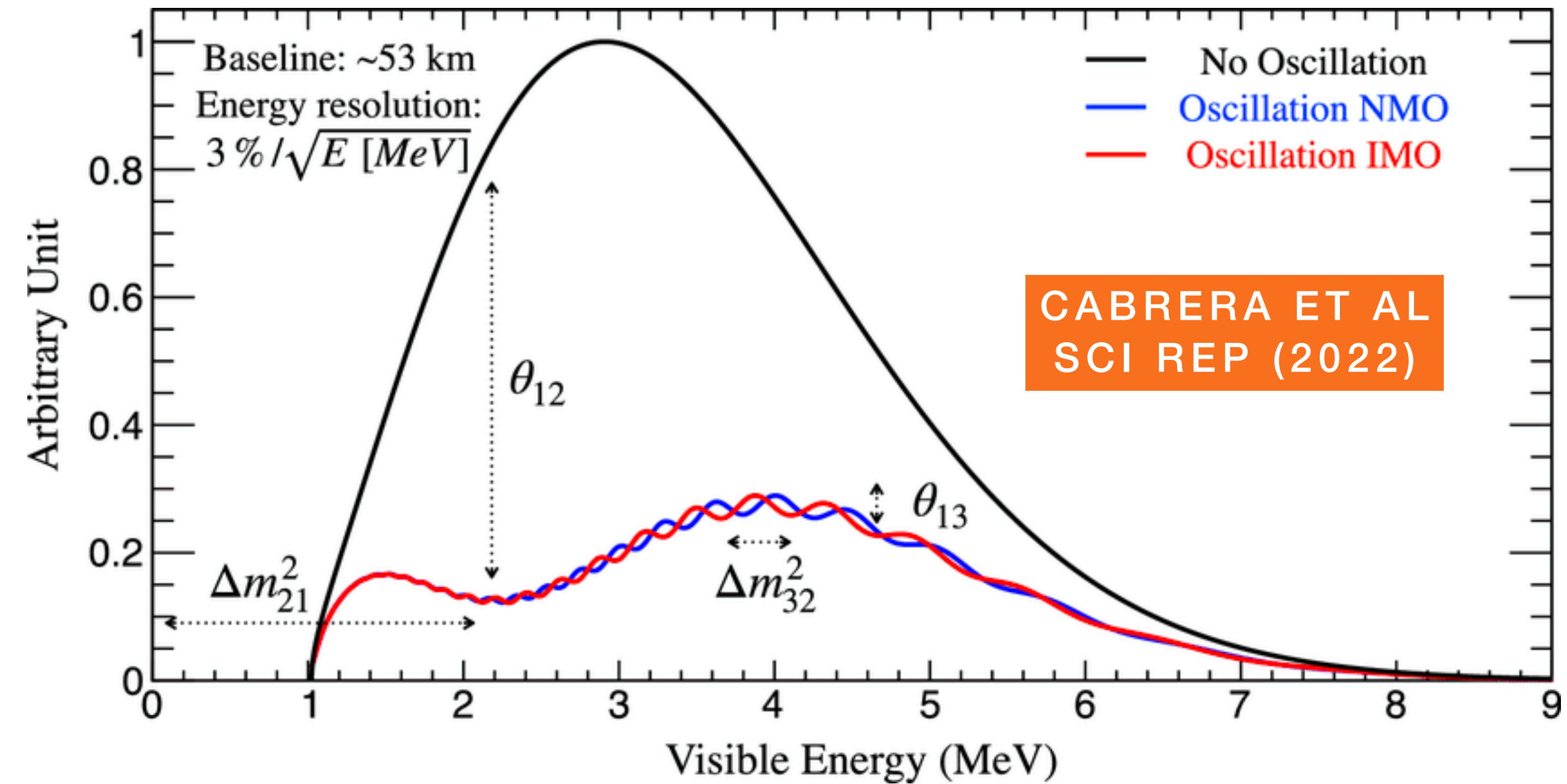


DUNE : MEASURE δ_{CP}

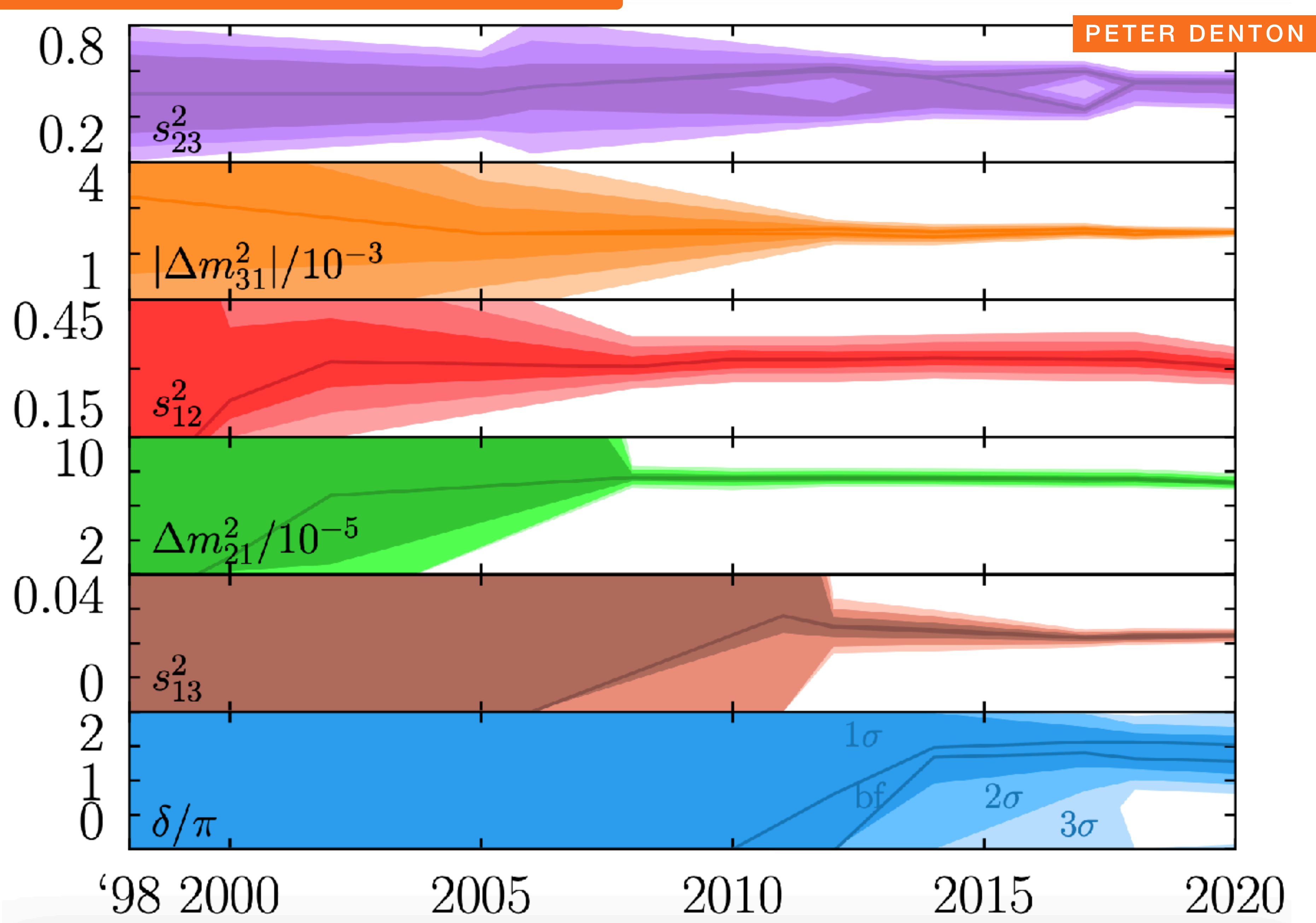


DUNE CDR

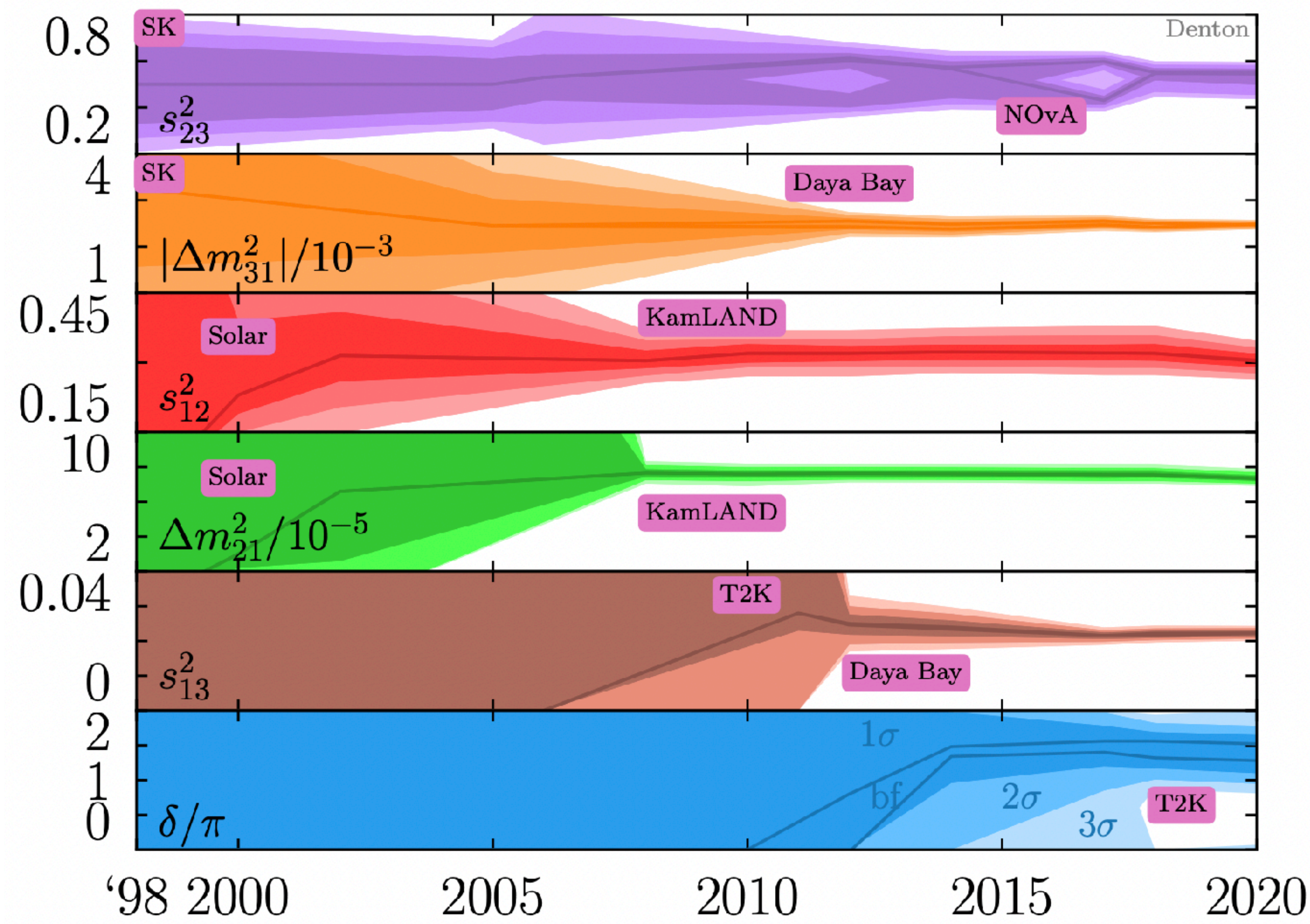
JUNO: MEASURE HIERARCHY

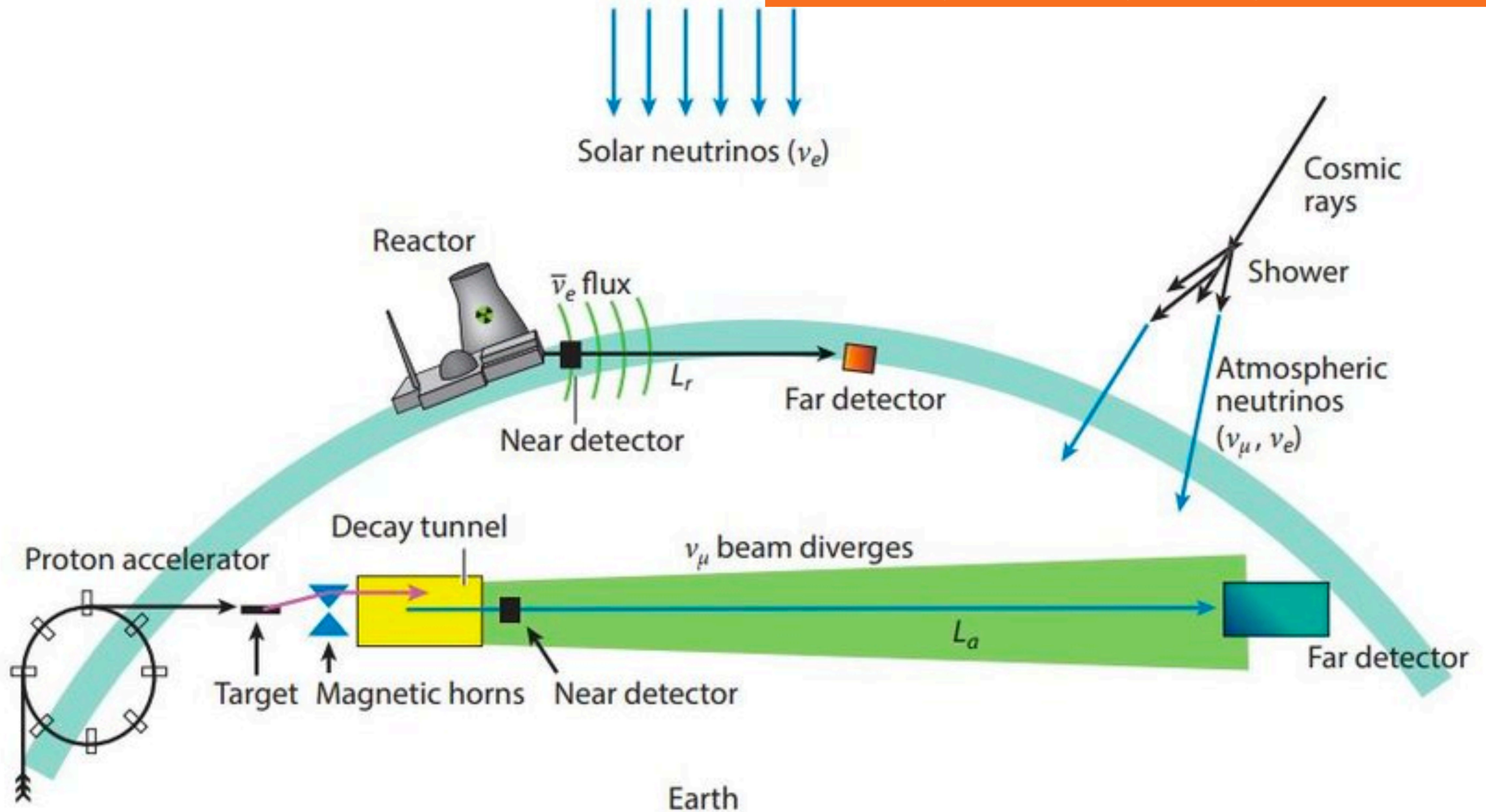


THREE FLAVOUR OSCILLATIONS



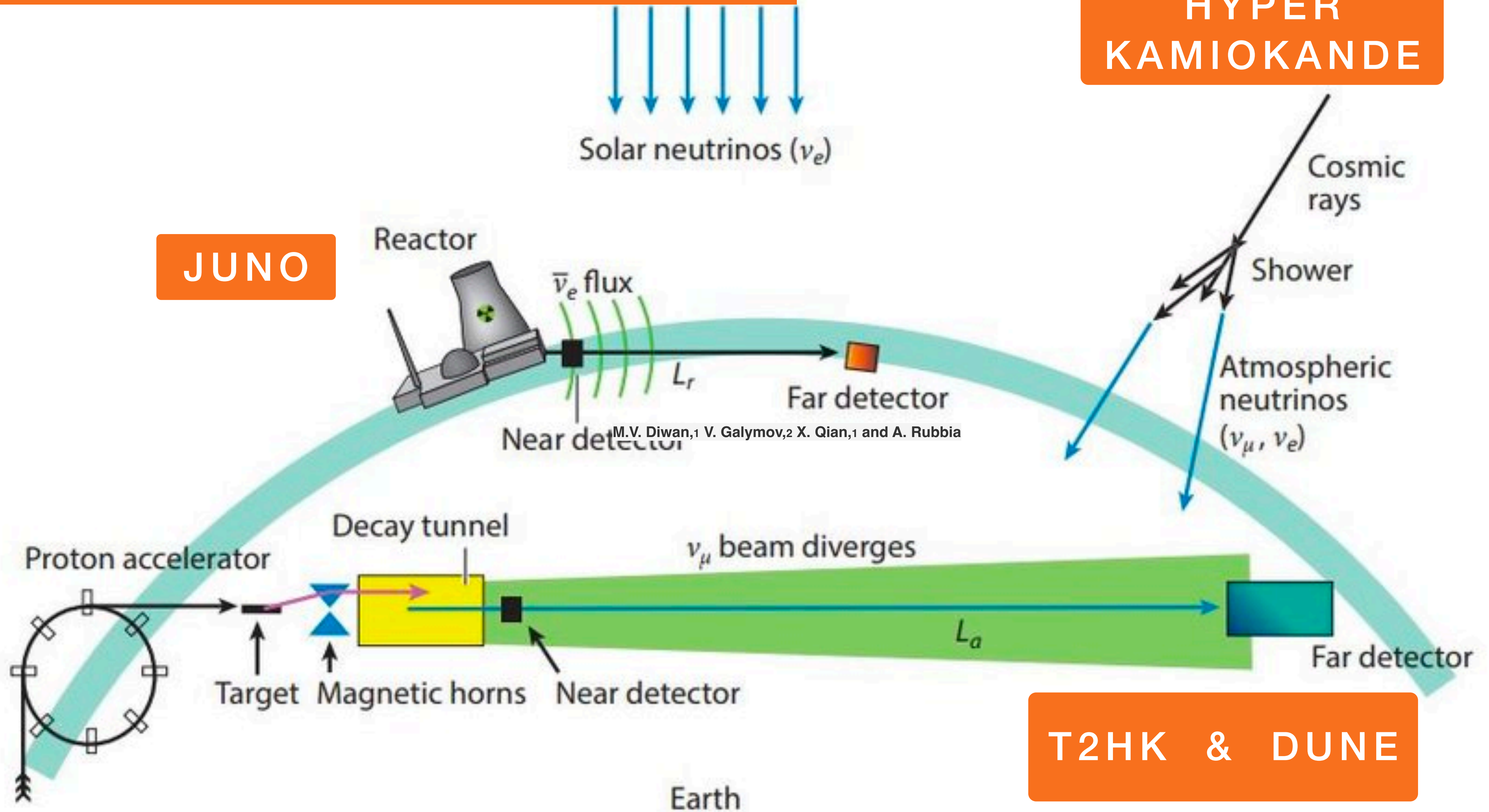
THREE FLAVOUR OSCILLATIONS





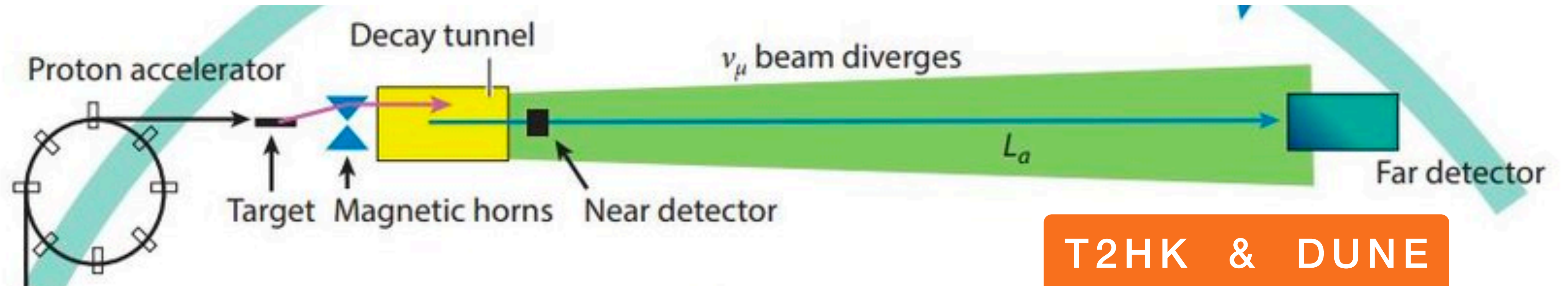
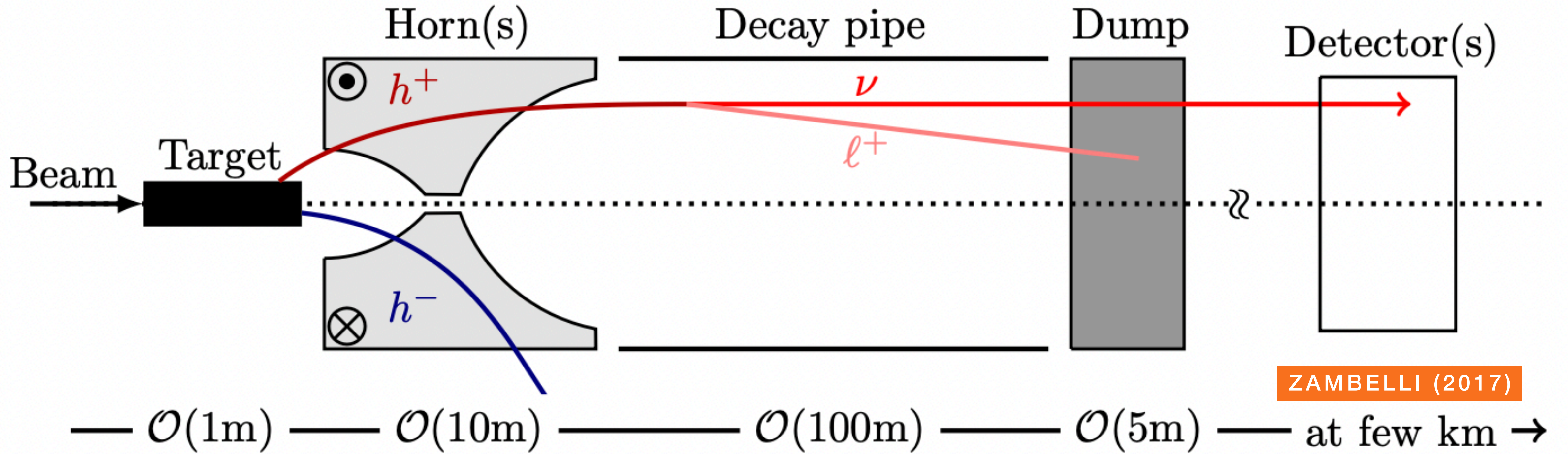
HYPER
KAMIOKANDE

JUNO



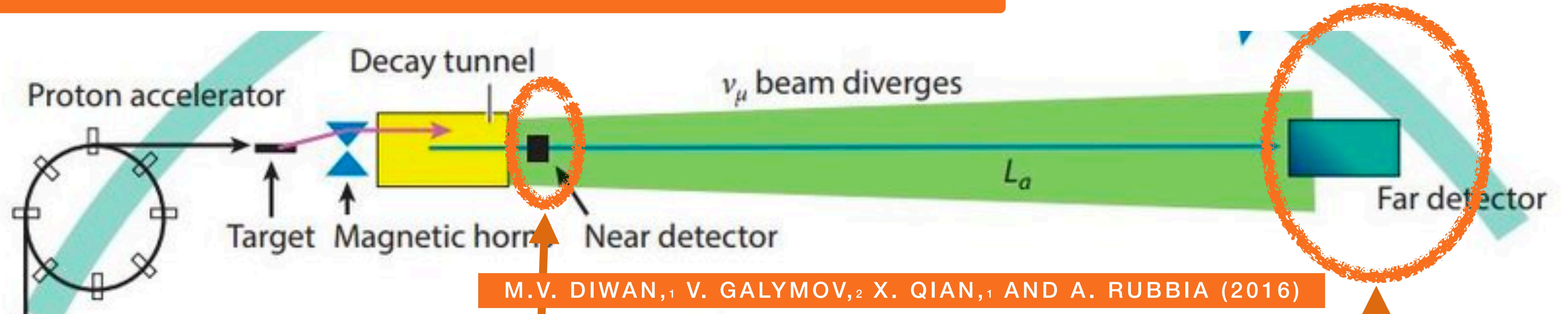
T2HK & DUNE

ACCELERATOR BASED NEUTRINOS



M.V. DIWAN,¹ V. GALYMOV,² X. QIAN,¹ AND A. RUBBIA (2016)

ACCELERATOR BASED NEUTRINOS



$$E_\nu \sim 1 \text{ GeV}$$

MEASURE NEUTRINOS HERE

ν_μ

Extract $P_{\mu \rightarrow e}(E_\nu)$

MEASURE NEUTRINOS HERE

ν_e ν_μ ν_τ

CROSS SECTION THEORY

EVENT RATE (s^{-1})

FLUX ($cm^{-2} s^{-1}$)

Theory Input

$$R \sim N_T \times \Phi \times \sigma$$

NUMBER OF
TARGETS

CROSS SECTION (cm^2)

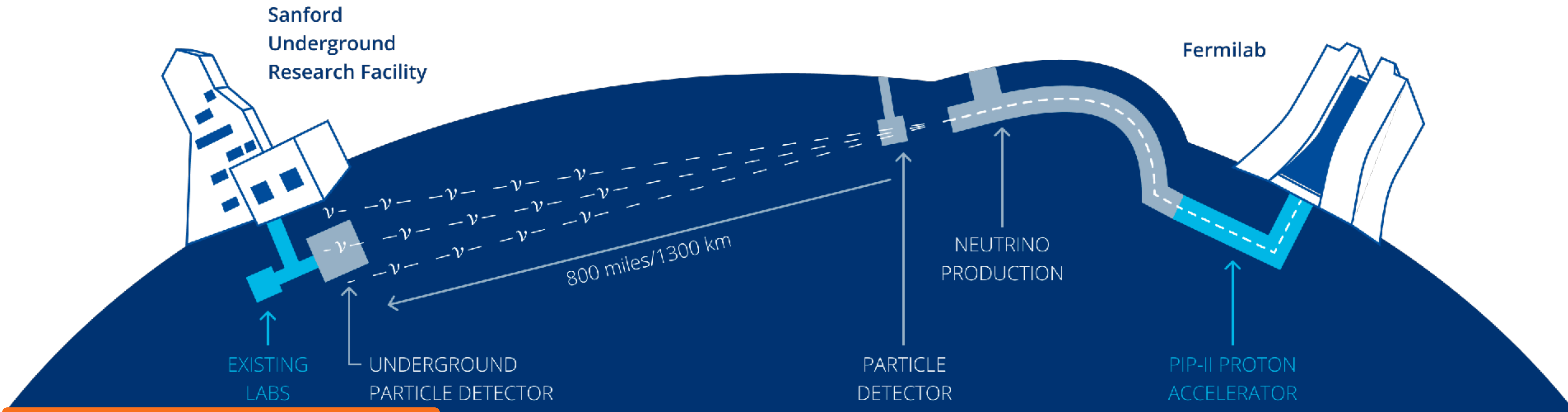
- Good theory for neutrino cross sections is a crucial input for future oscillation experiments.

- Next generation experiments require percent level precision.

$\sim 1\%$

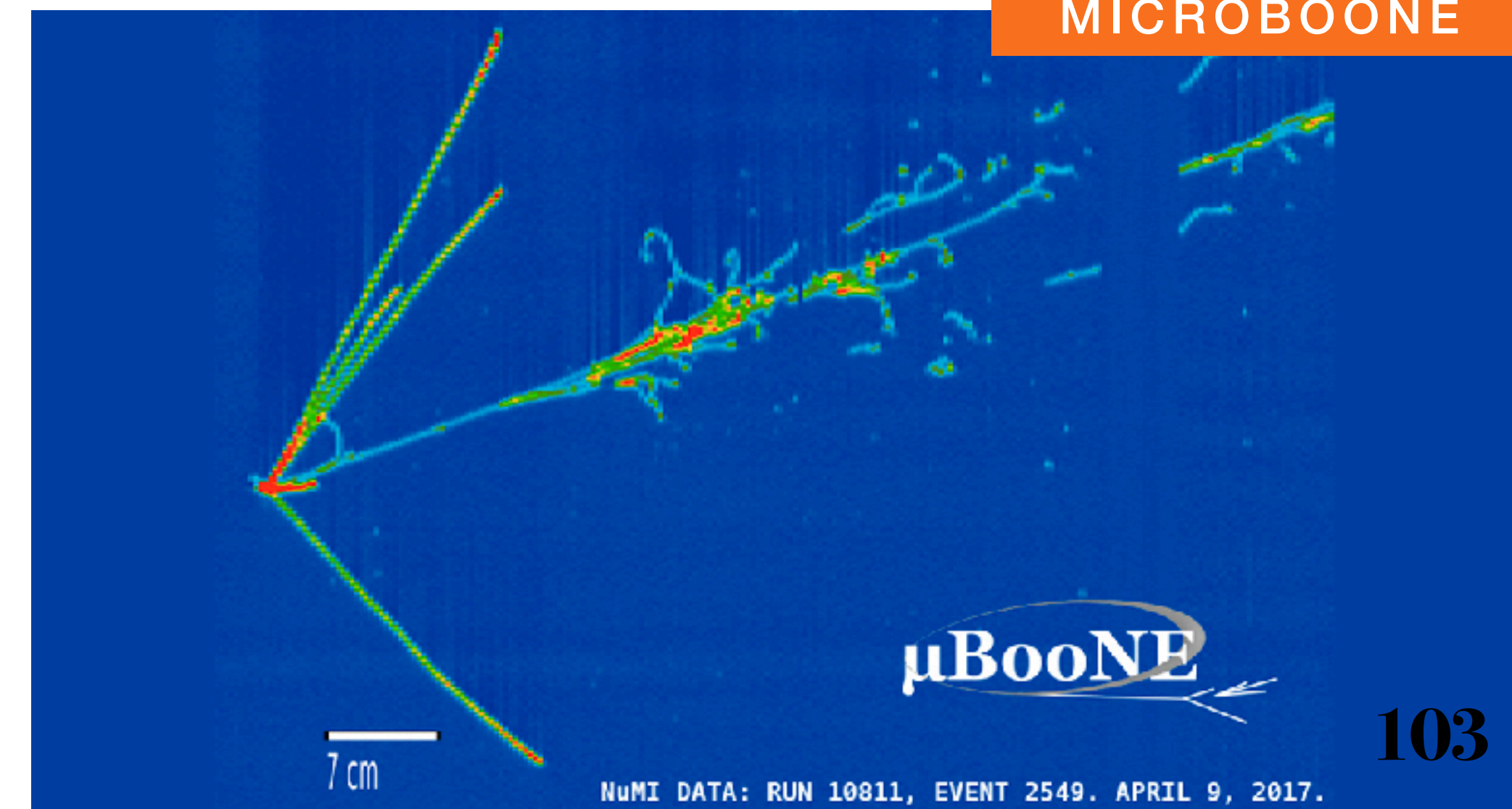
EXAMPLE: DUNE

DUNE COLLABORATION



STATISTICS RICH!

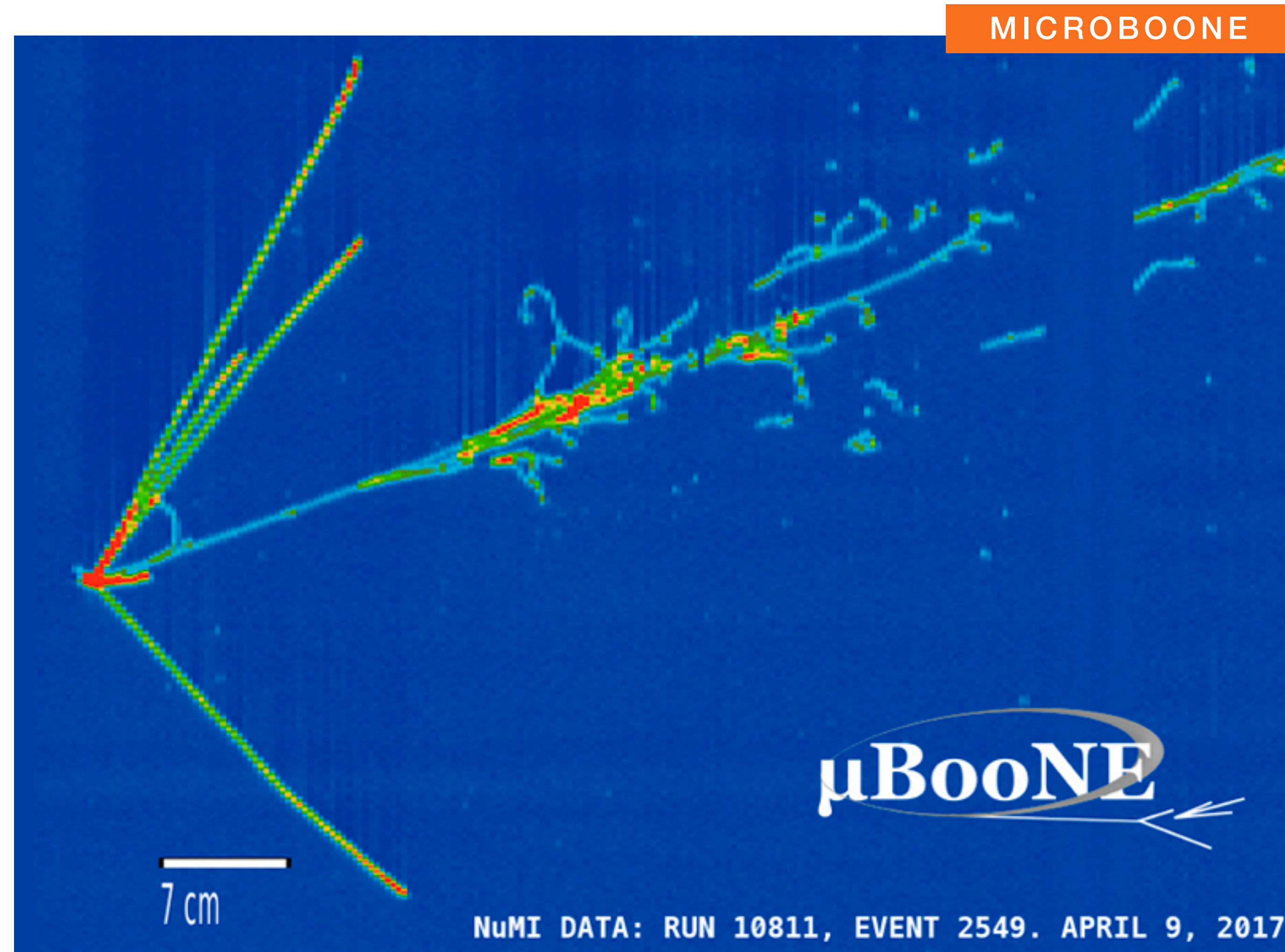
- State of the art liquid argon time projection chambers.
- Unprecedented power & statistics.
 $\sim 10^8$ events/yr @ Near Detector.



NEW TECHNOLOGY MEANS NEW SIGNALS

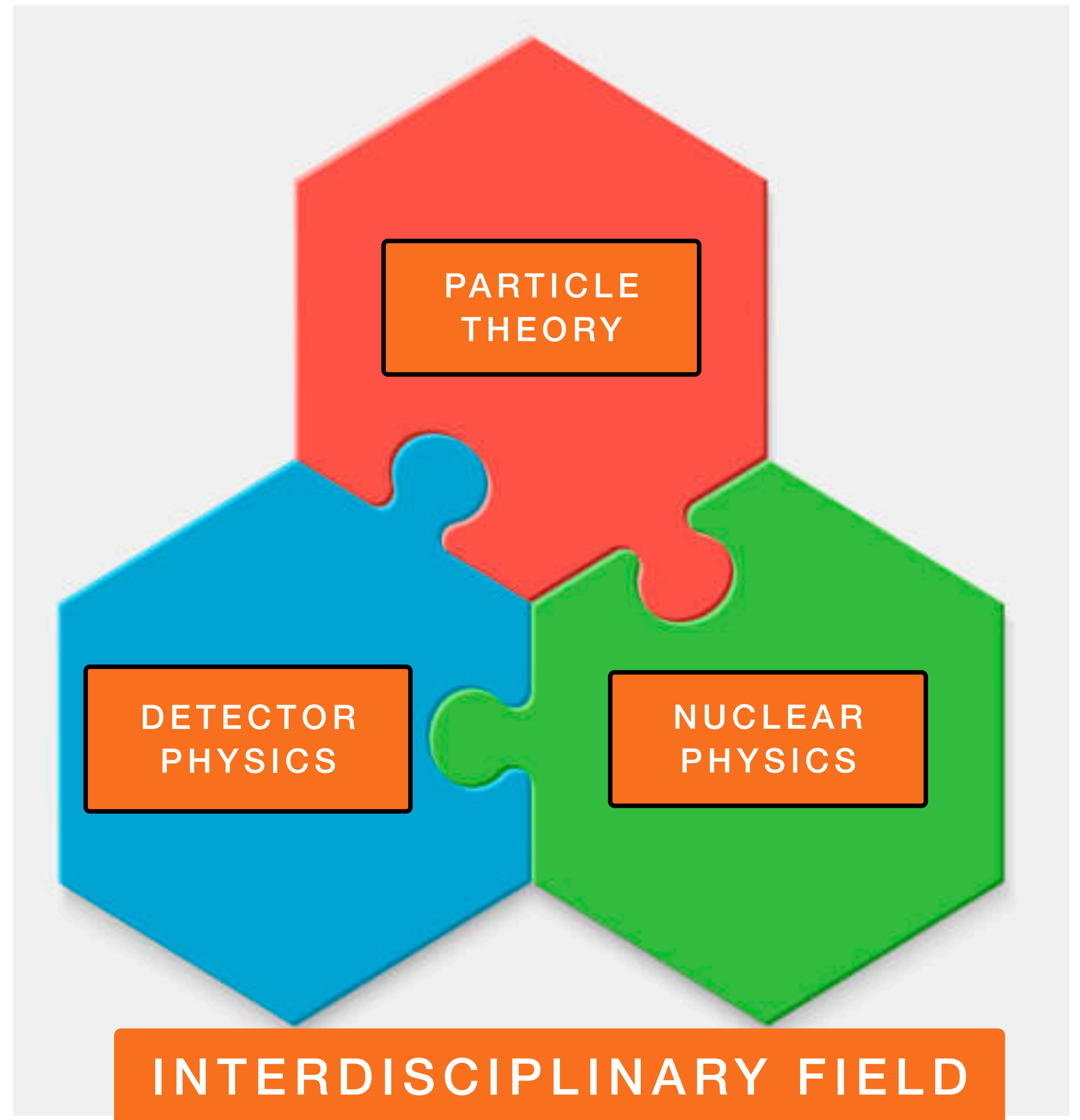
- Ability to measure exclusive final states (digital bubble chamber).
- Reaction cross sections are poorly understood for many exclusive channels.

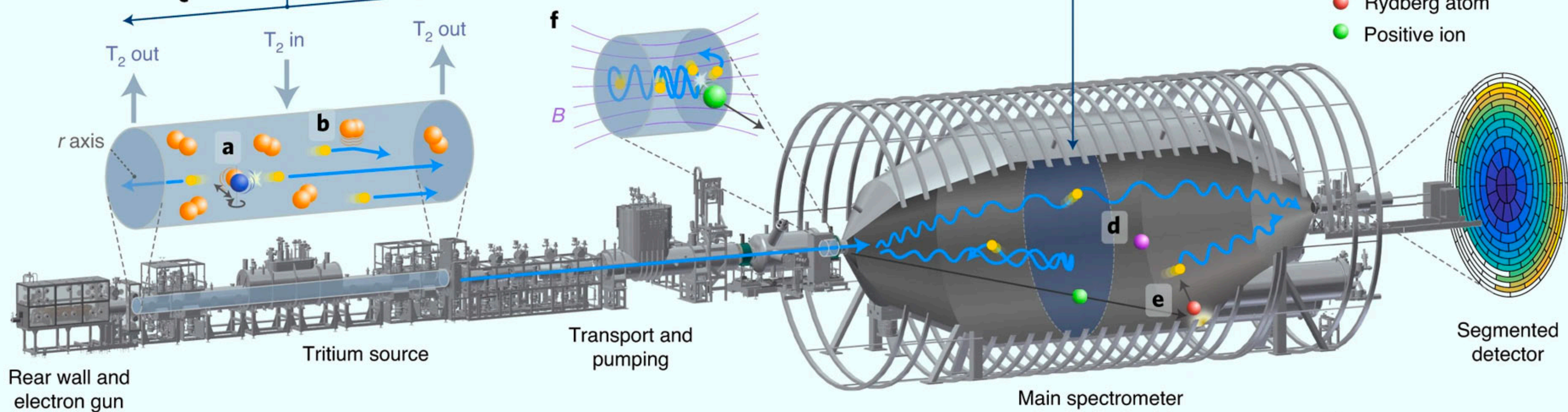
REQUIRES NEW AND
BETTER THEORY



EXPERIMENTS USE NUCLEI

- Need nuclear matrix elements. (**Nucl. Th.**)
- Need to understand quantum field theory foundation. (**Particle Th.**)
- Need to understand how the detector works!





Neutrino Mass Measurements

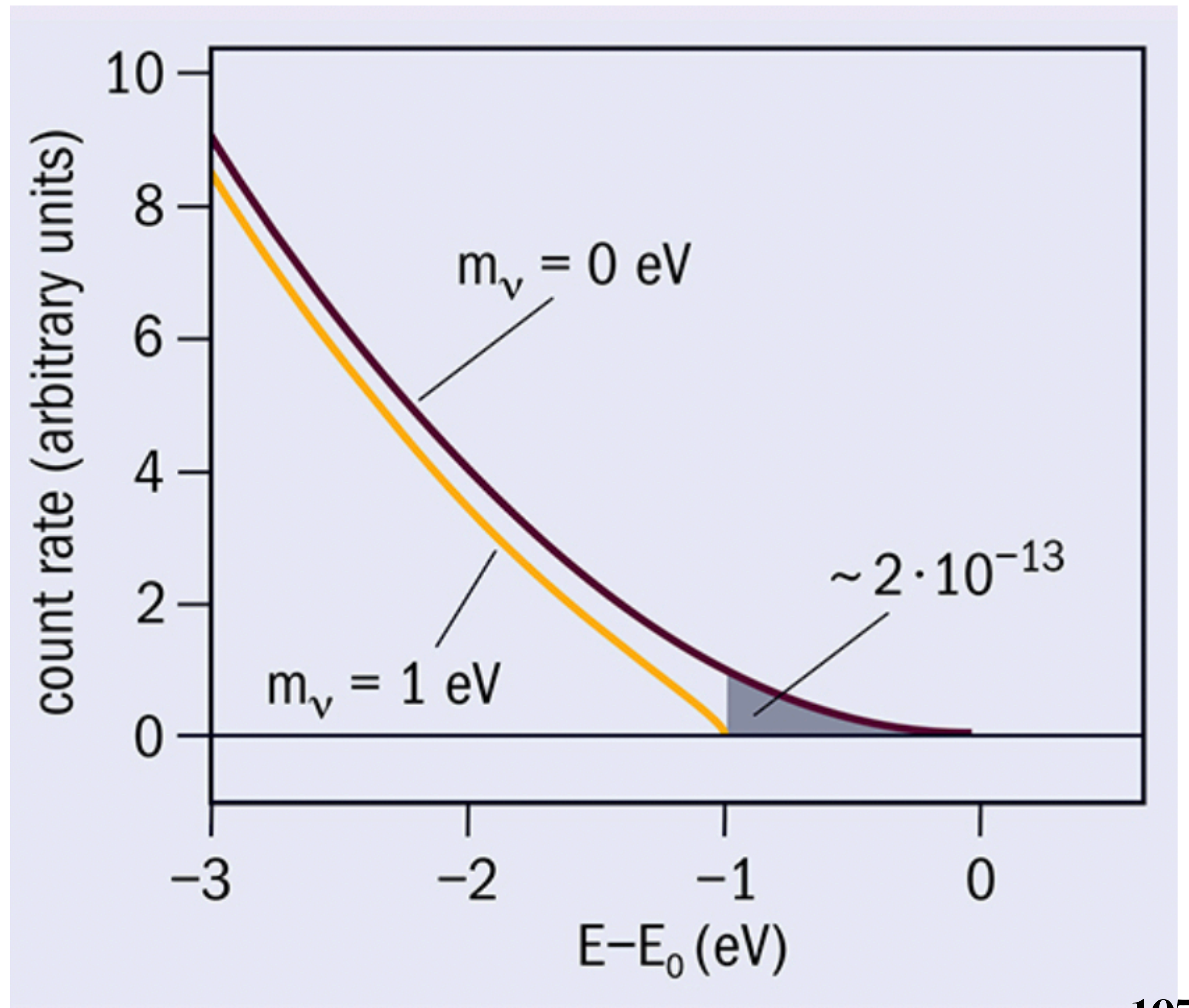
DIRECT MASS MEASUREMENTS (KATRIN)

- Study tritium beta decay.

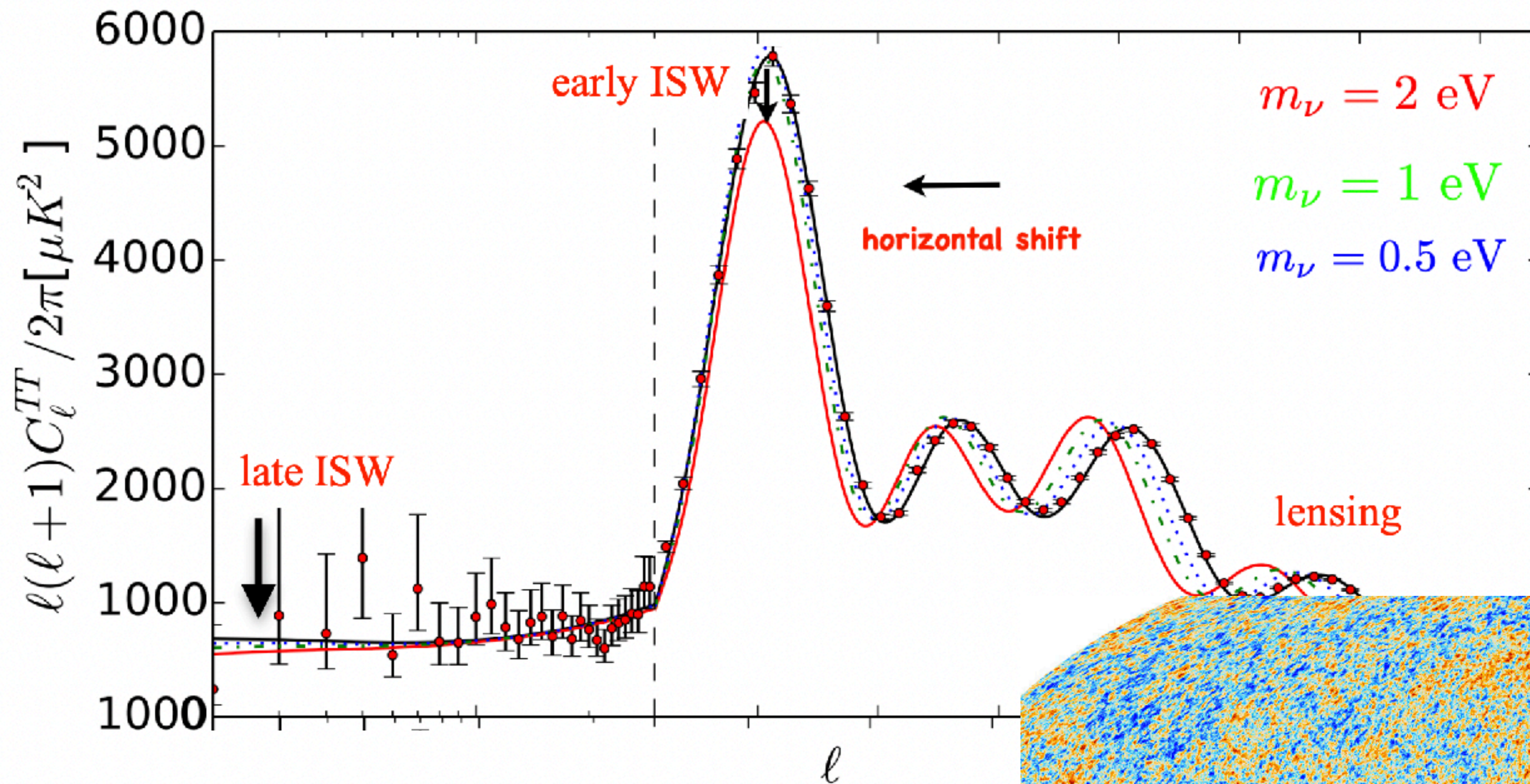


- End point energy shifts due to rest mass of neutrino.

$$m_{\nu} \leq 0.8 \text{ eV}$$

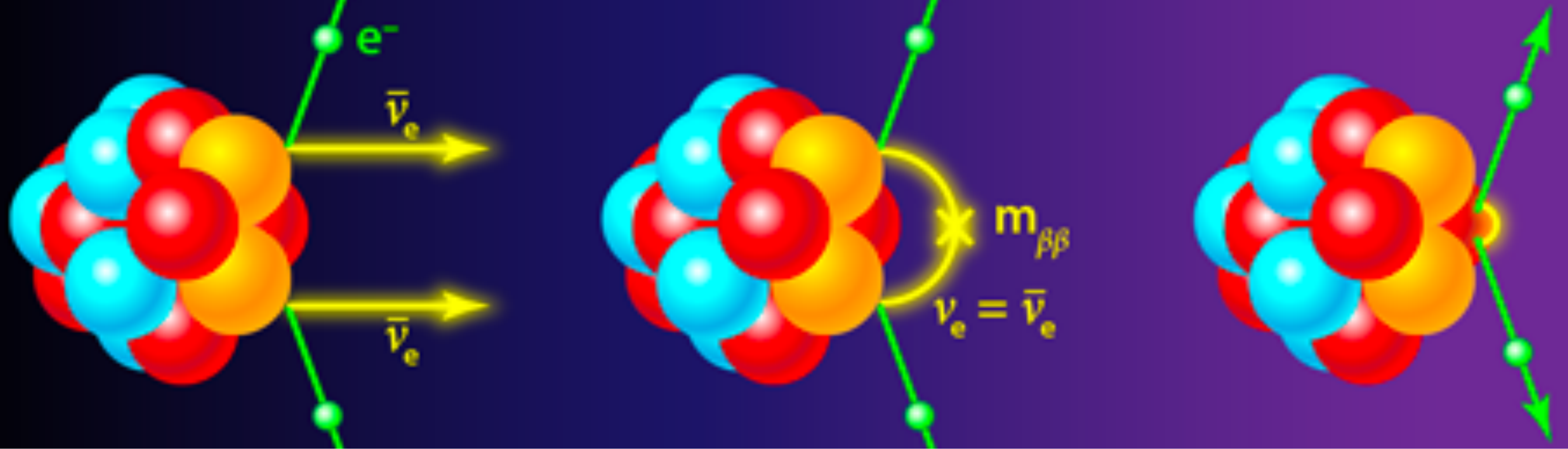


COSMOLOGICAL INFERENCE (PLANCK)



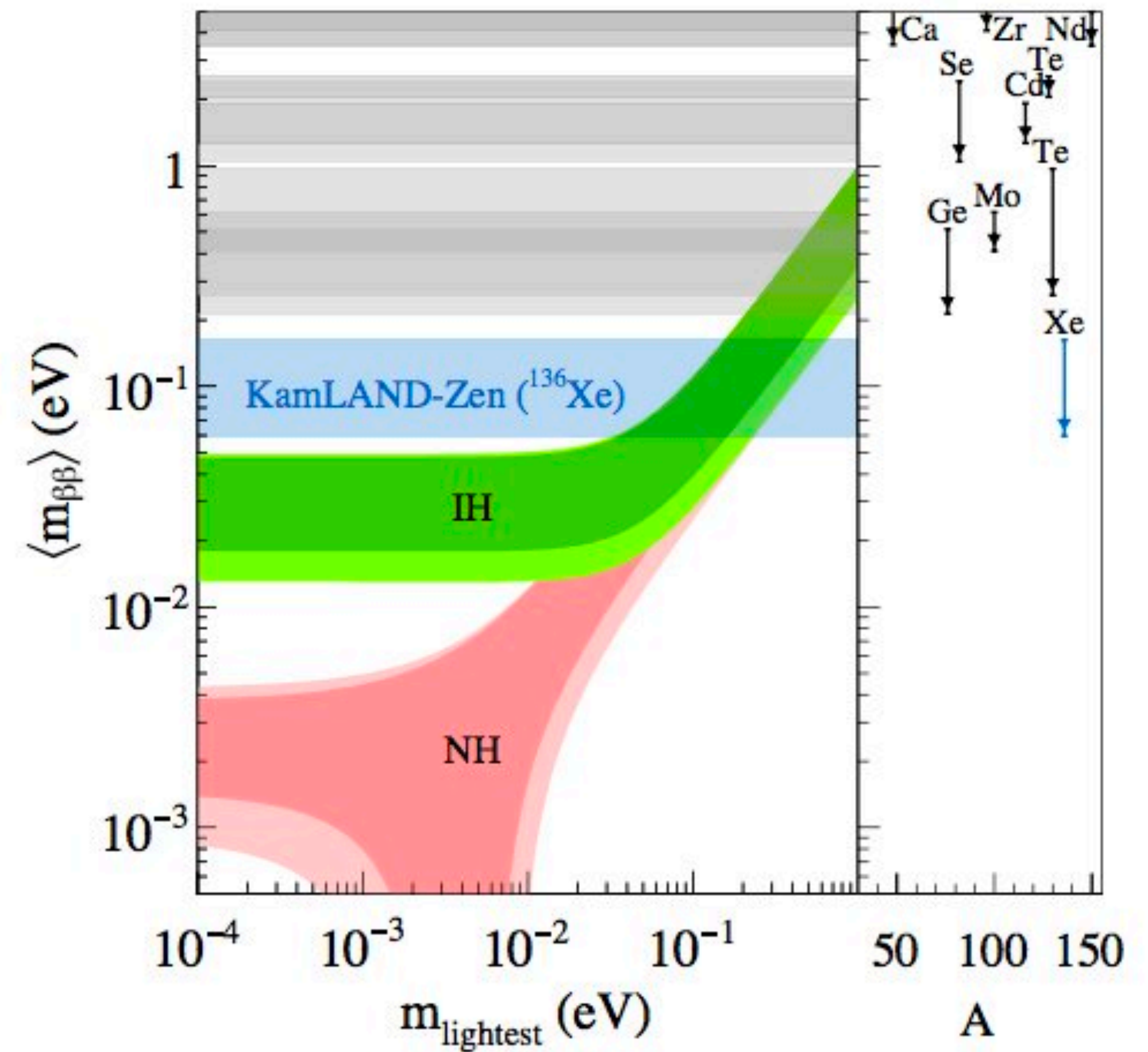
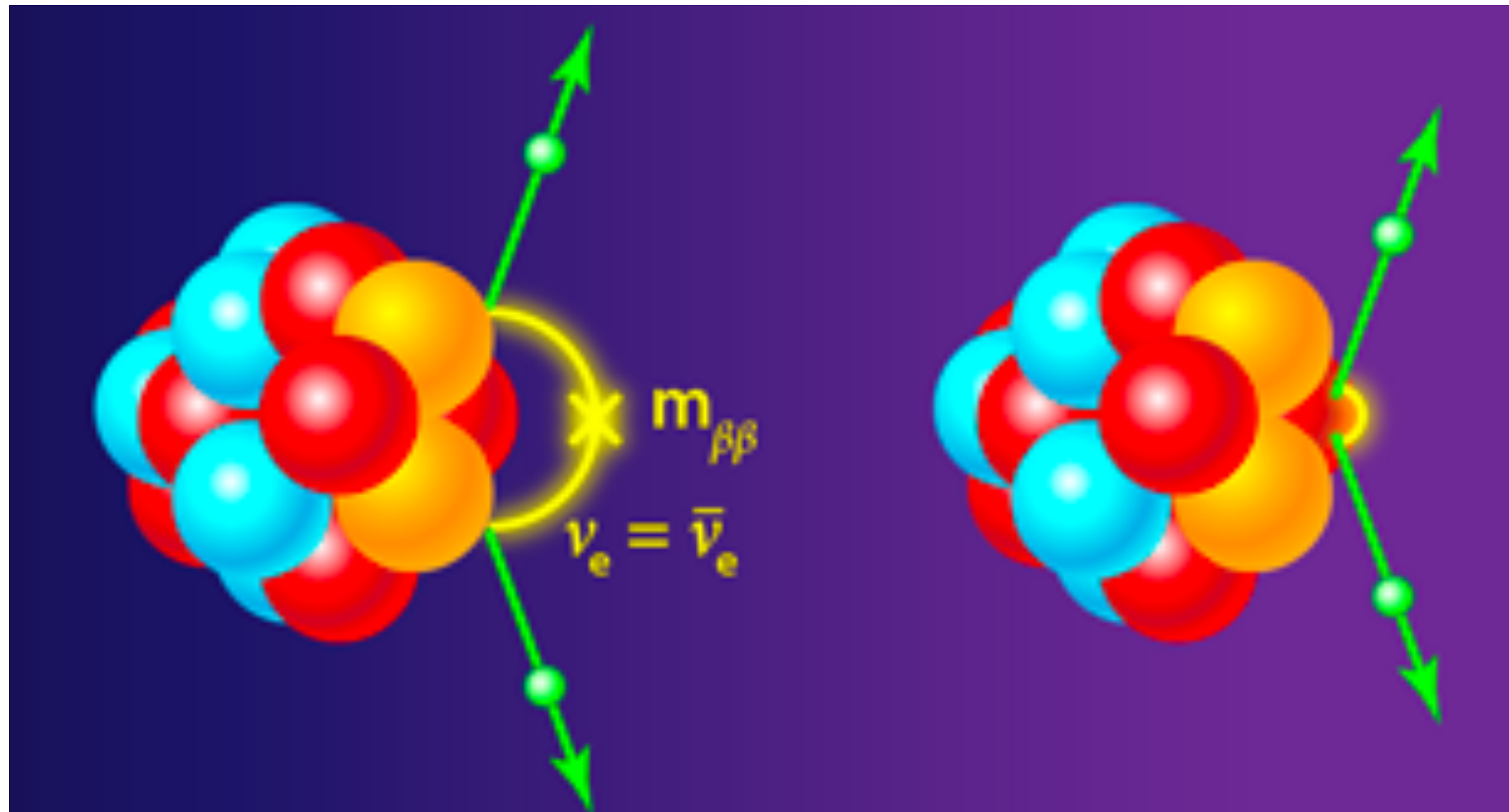
DECOMPOSE INTO
SPHERICAL HARMONICS

$$m_\nu \leq 0.12 \text{ eV}$$



Lepton Number Violation

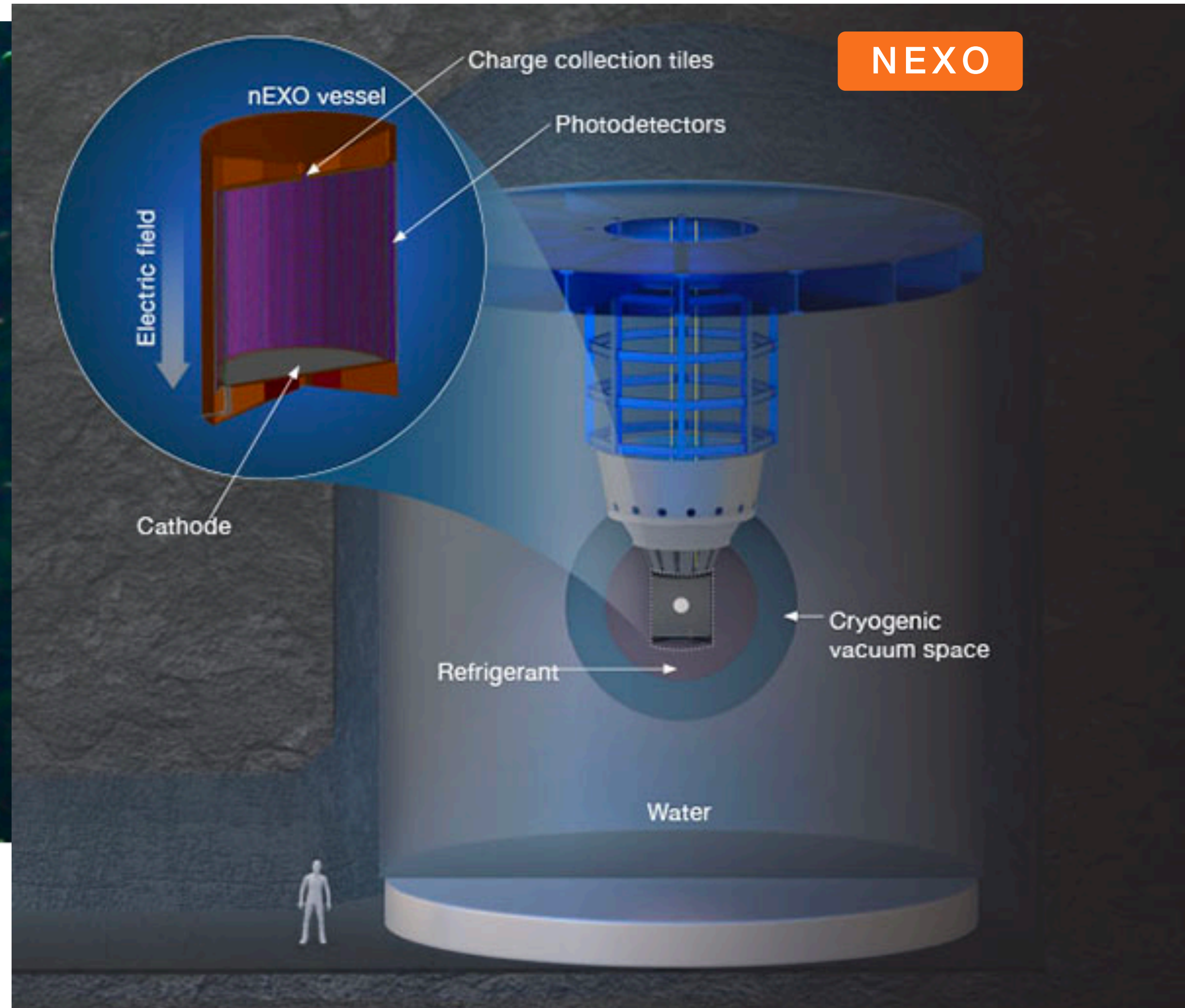
NEUTRINOLESS DOUBLE BETA DECAY



$$[A, Z] \rightarrow [A, Z - 2] + 2e^+$$

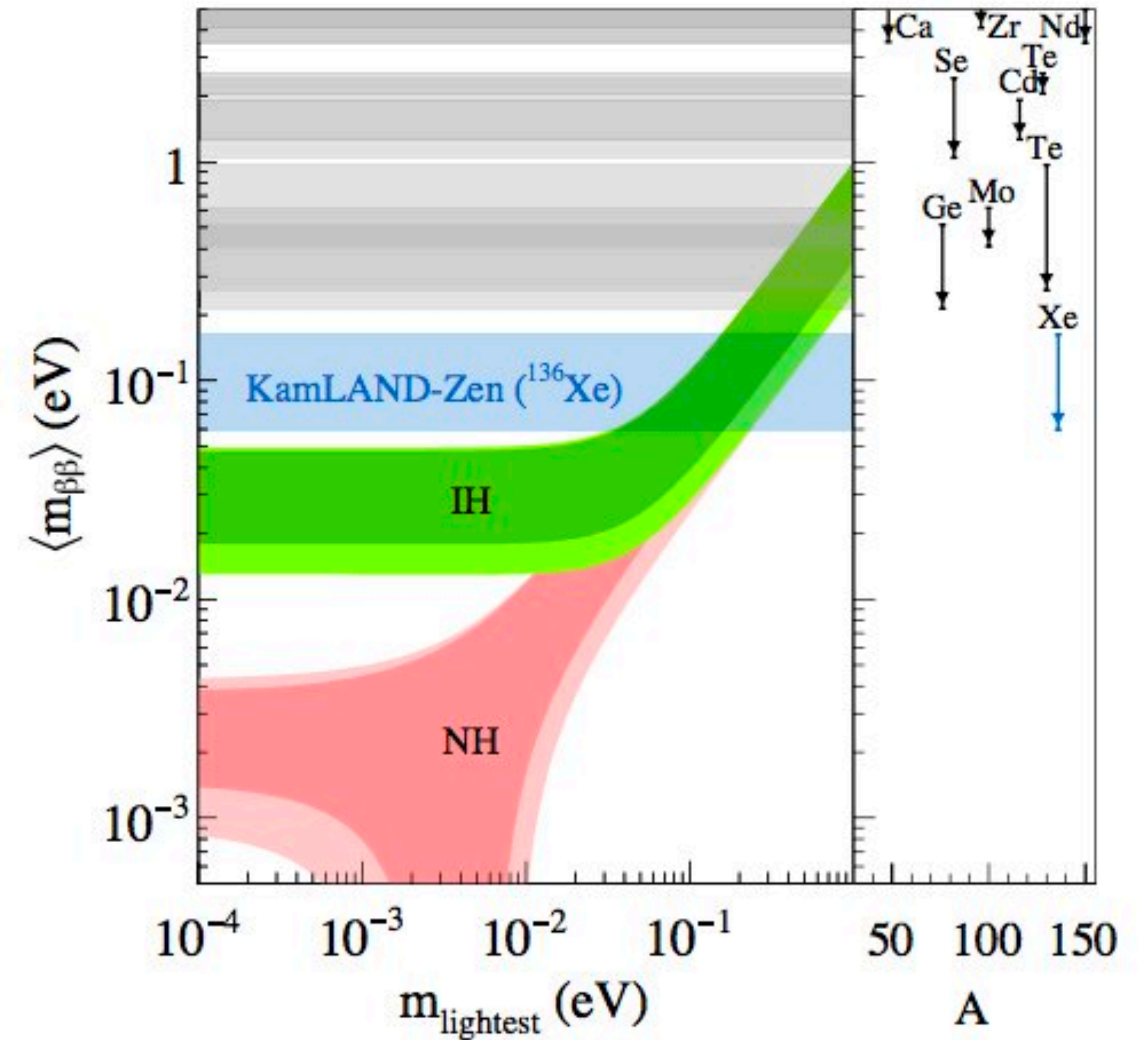
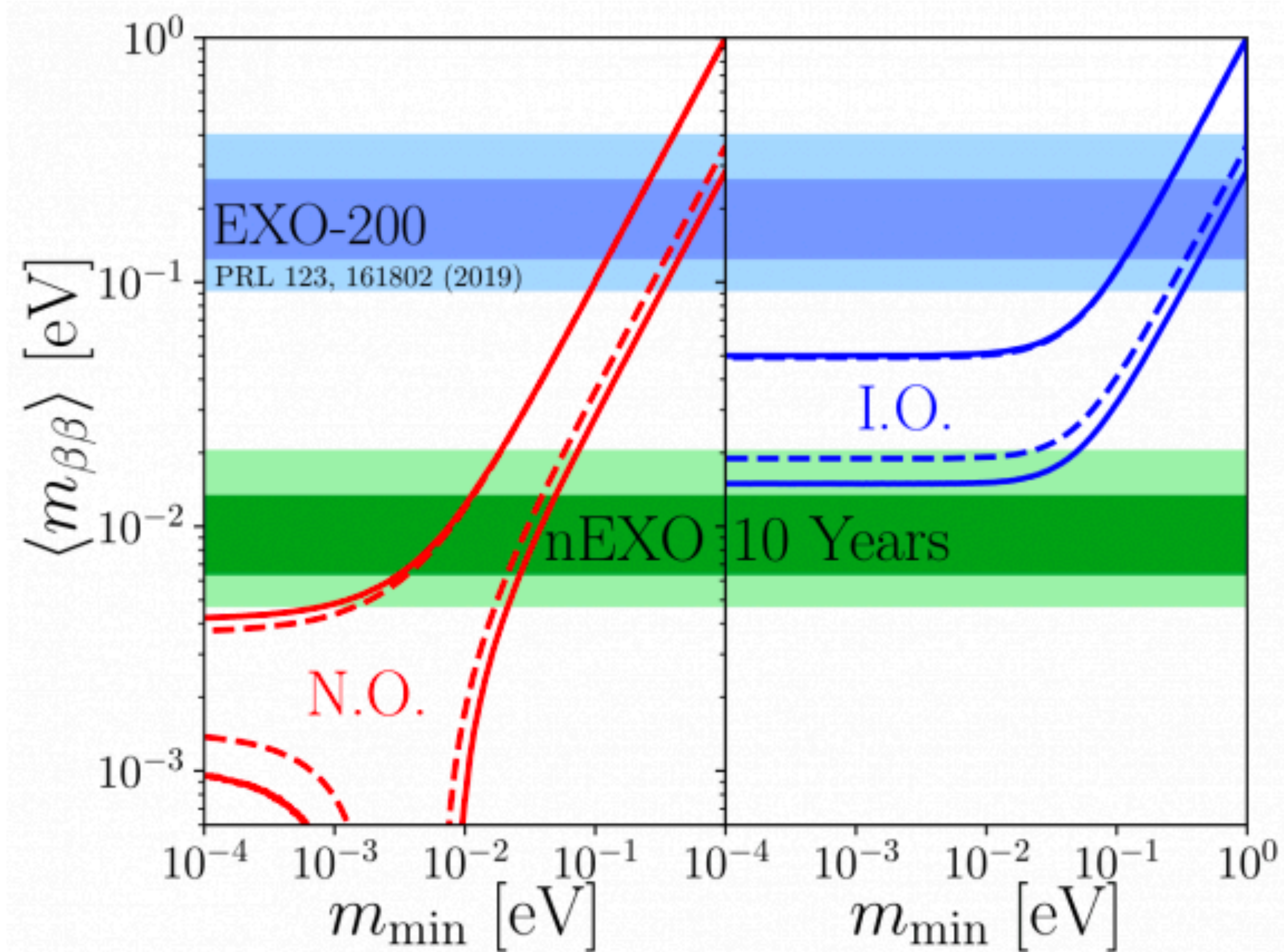
- Virtual neutrinos self-annihilate if they are Majorana.

TONNE-SCALE EXPERIMENTS



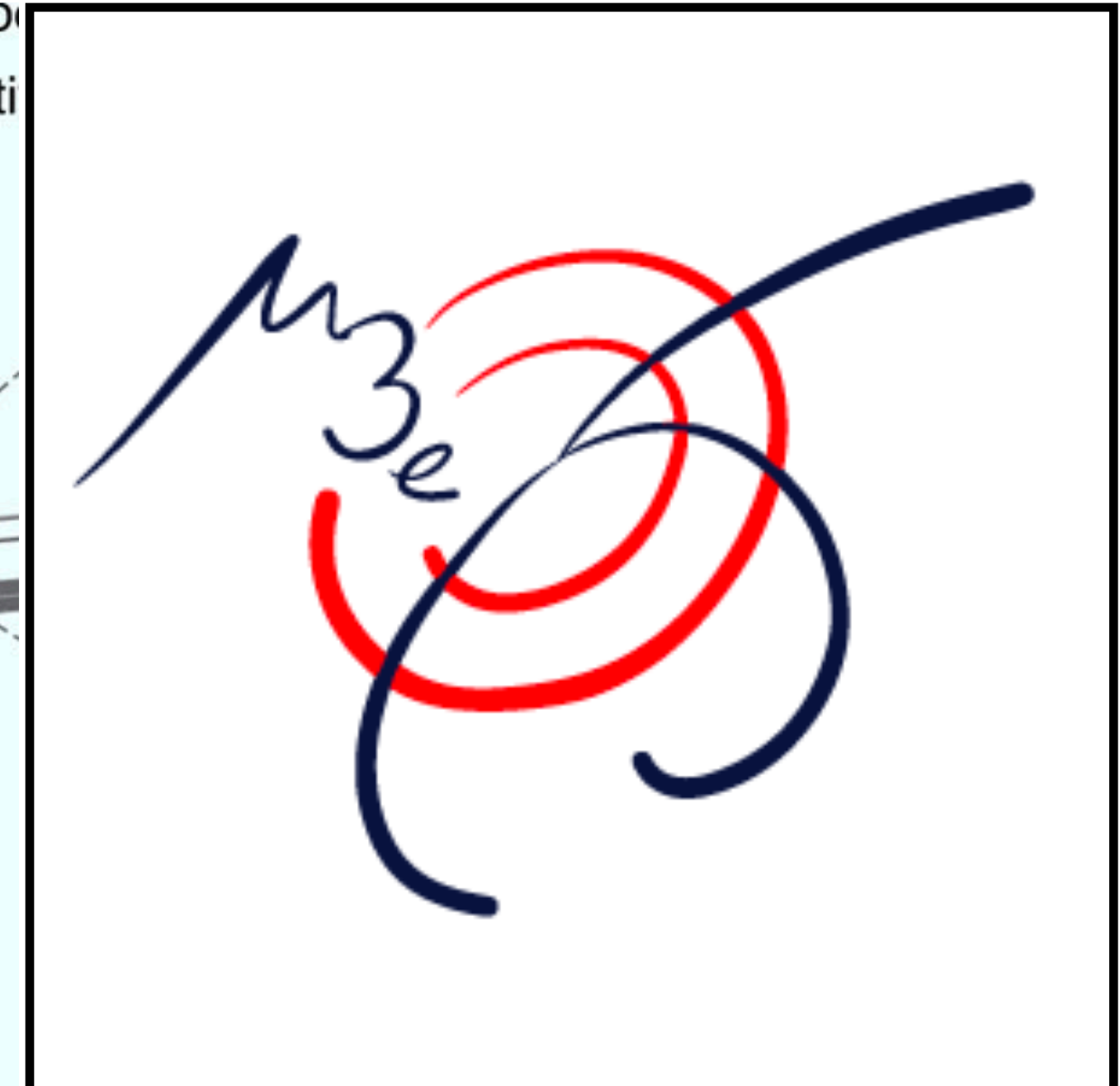
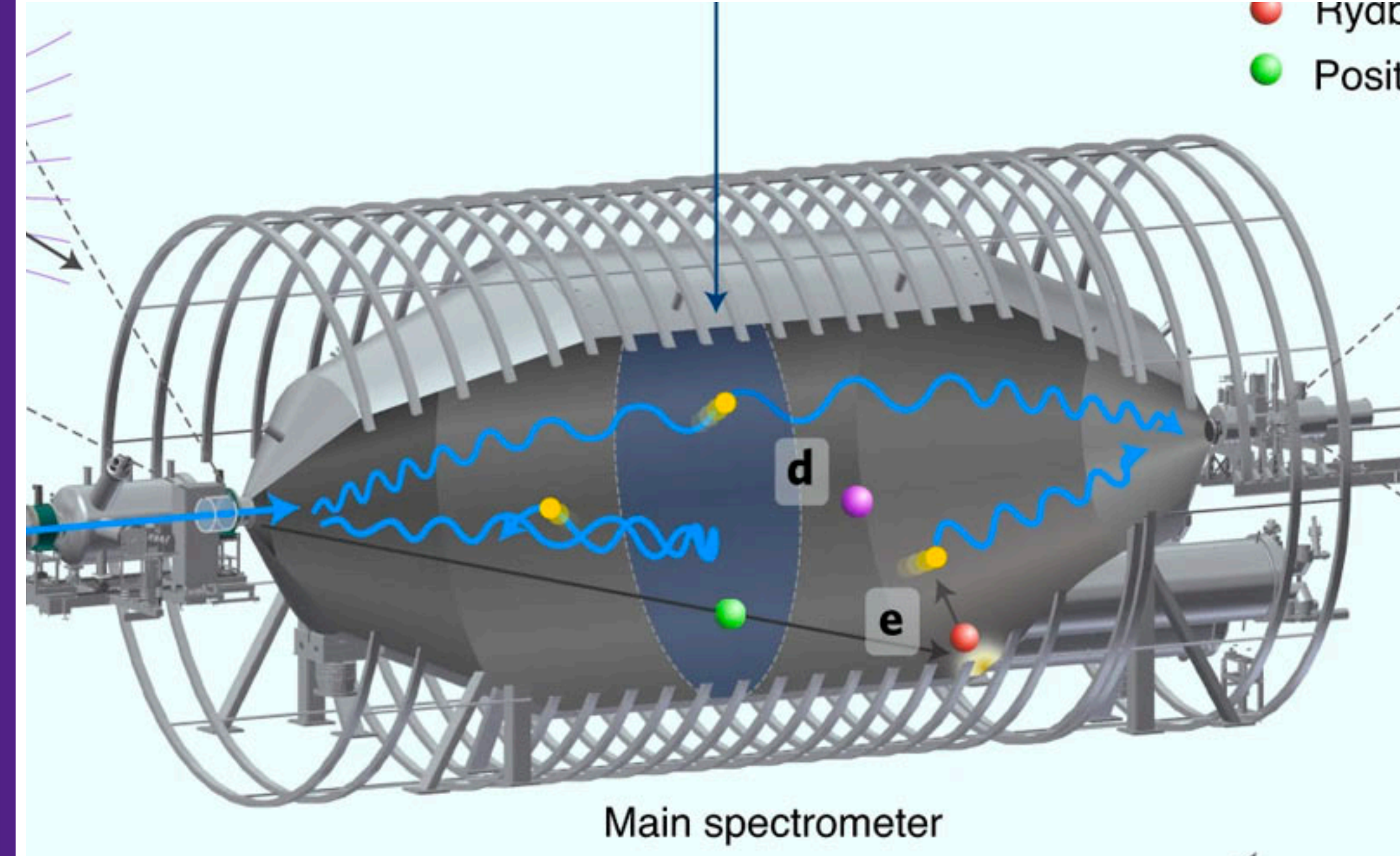
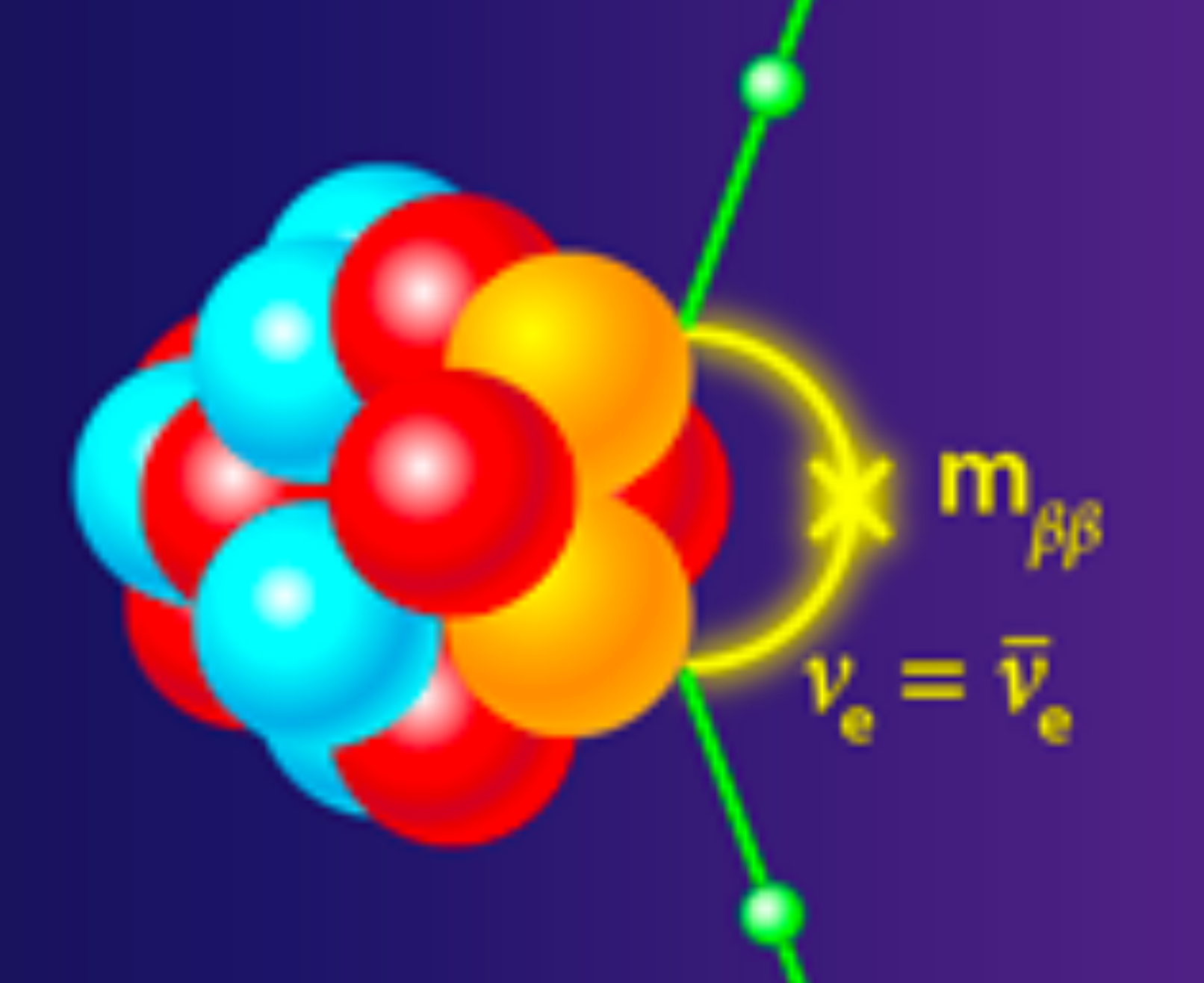
- Will cover inverted hierarchy prediction.

TONNE-SCALE EXPERIMENTS

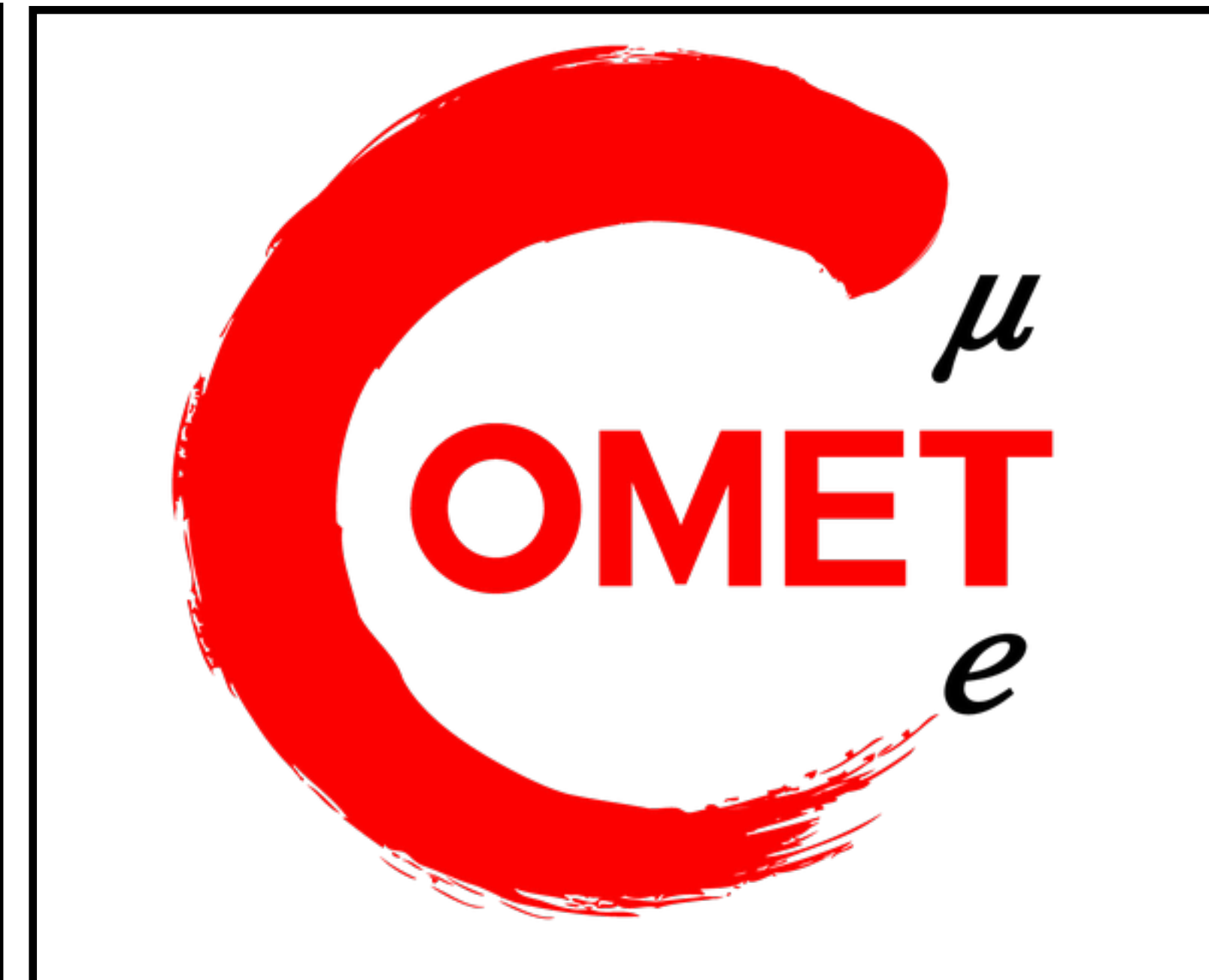
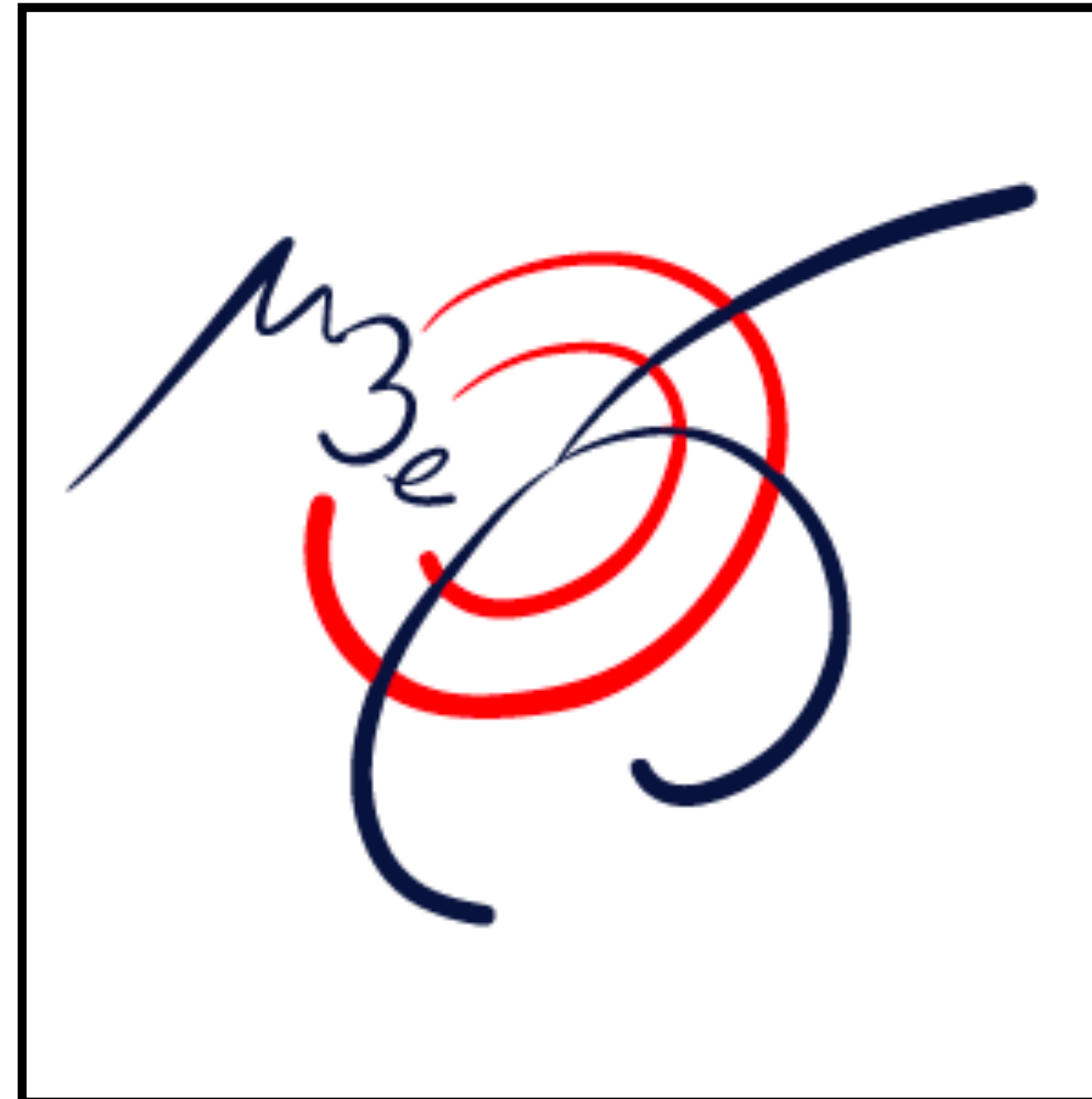
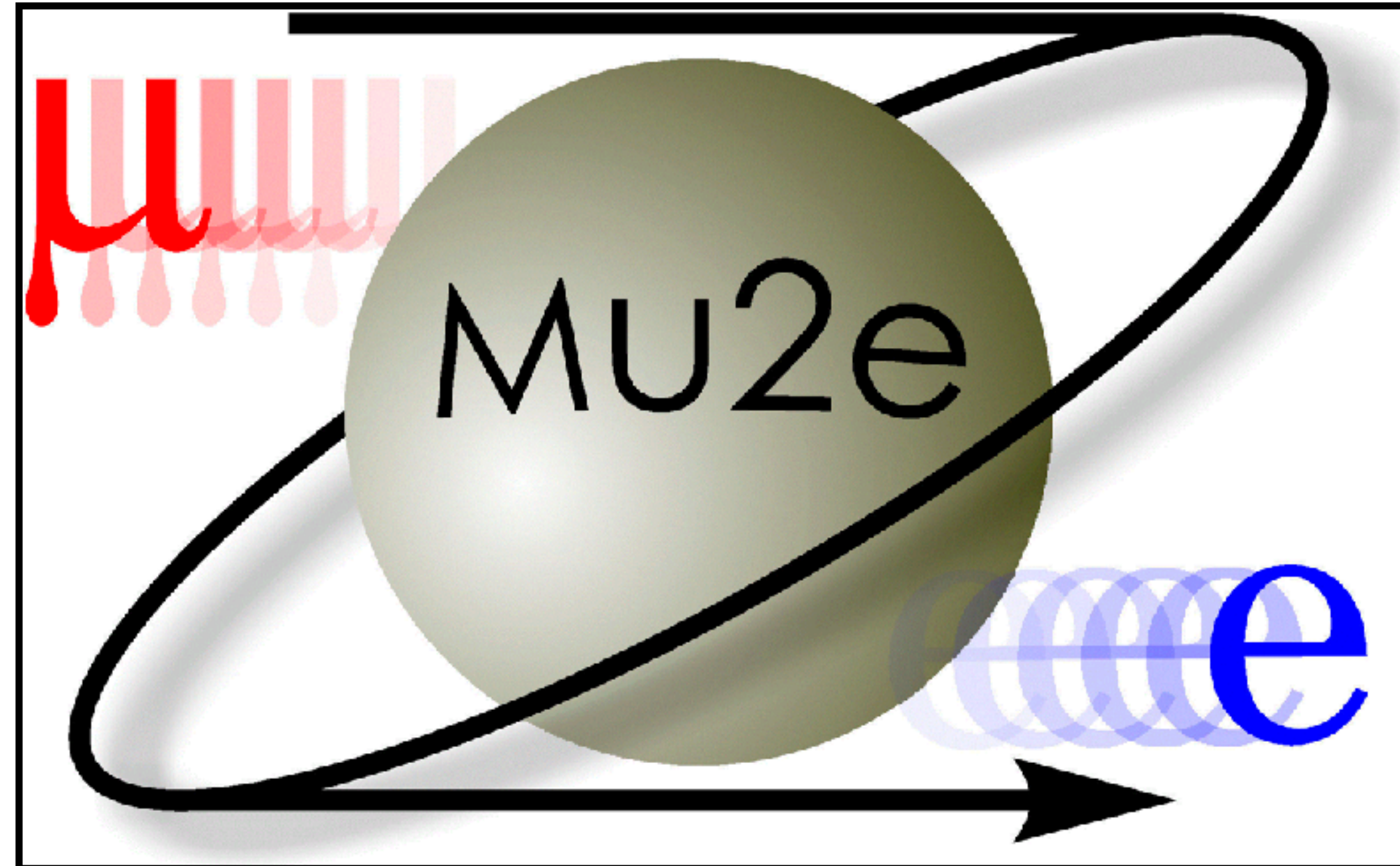


- Will cover inverted hierarchy prediction.

DIRECT PROBE OF NEUTRINO MASS



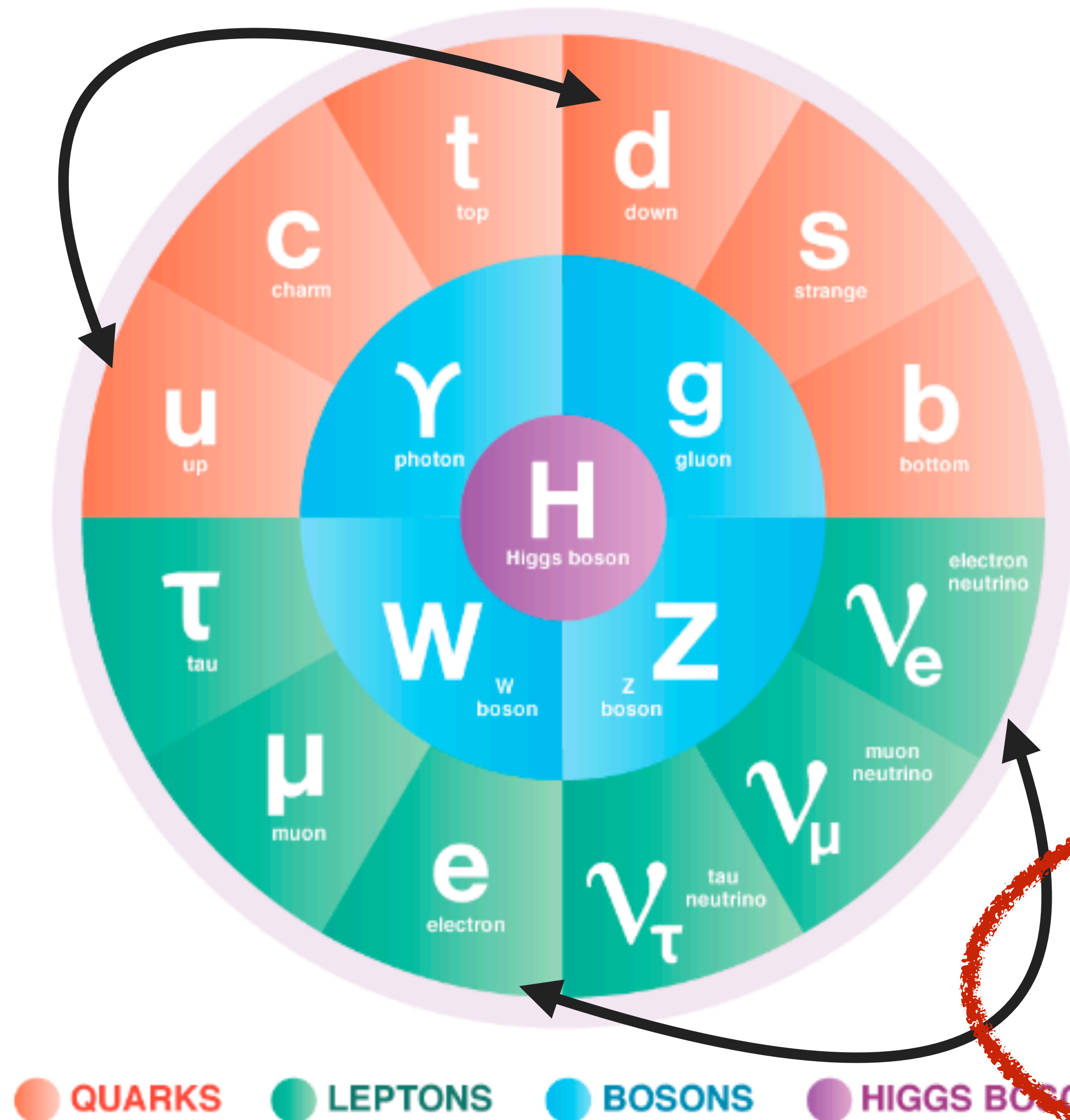
Symmetries & Neutrino Masses



(Charged) Lepton Flavour Violation

THE STANDARD MODEL

- Three types of vector (spin-1) bosons
- Mediate strong, weak, & electromagnetic forces.
- Quarks & Leptons



$$\begin{pmatrix} u \\ d \end{pmatrix}$$

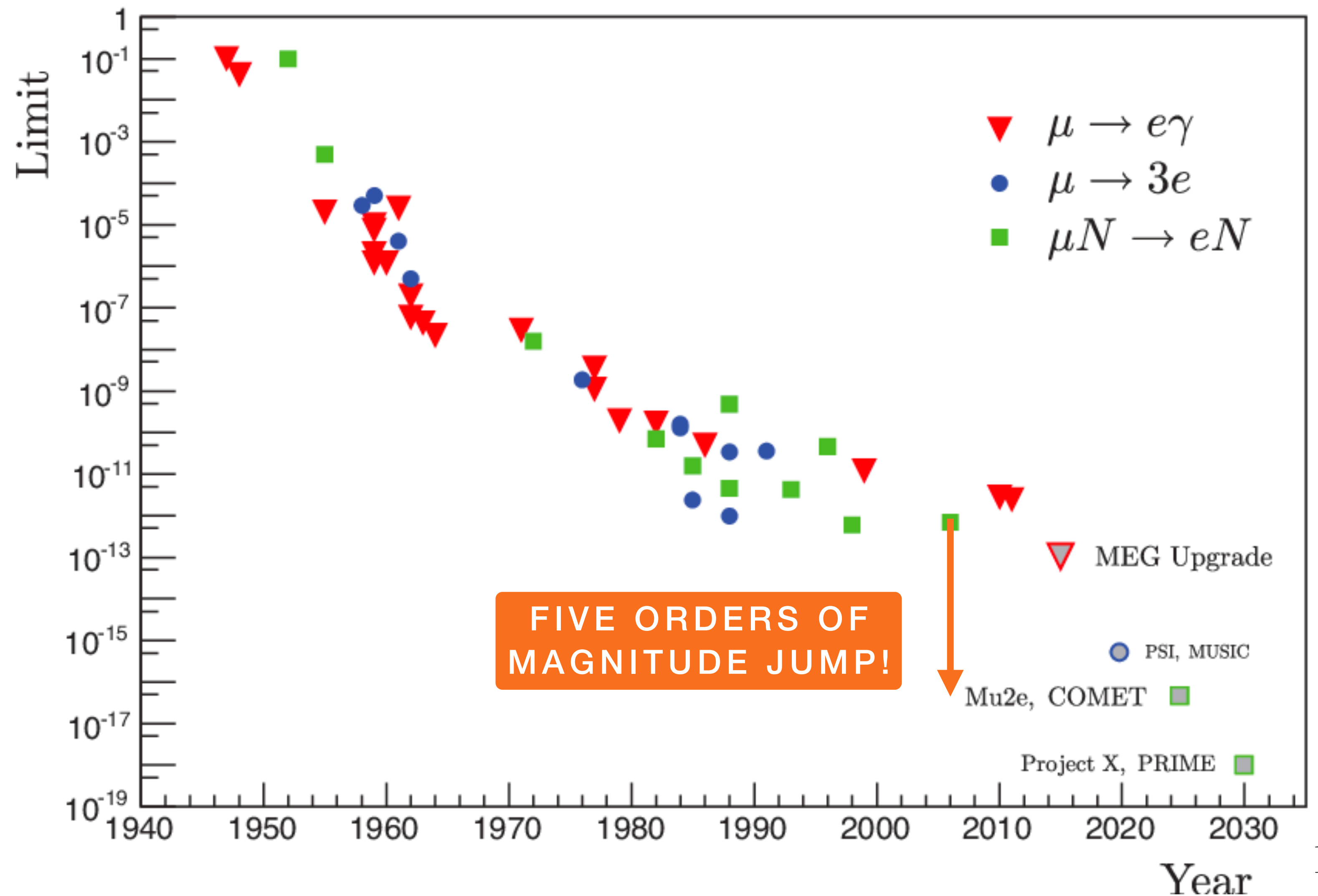
$$\begin{pmatrix} e \\ \nu_e \end{pmatrix}$$

DOUBLETS RELATED BY THE WEAK INTERACTION.

MUONS TURNING INTO ELECTRONS

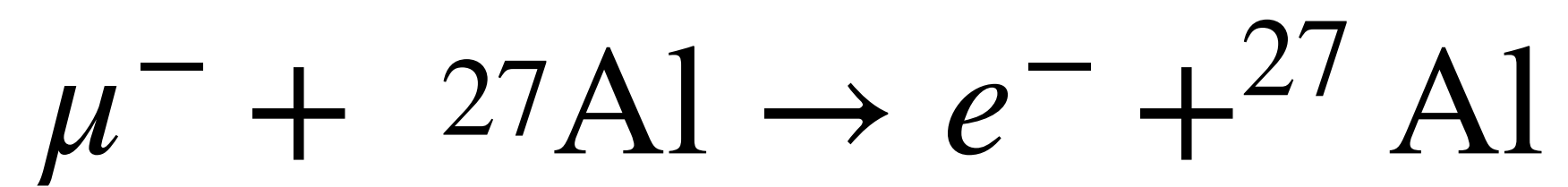
- New experiments will offer huge jumps in sensitivity.
- Additional probe of lepton flavor violation.

History of $\mu \rightarrow e\gamma$, $\mu N \rightarrow eN$, and $\mu \rightarrow 3e$

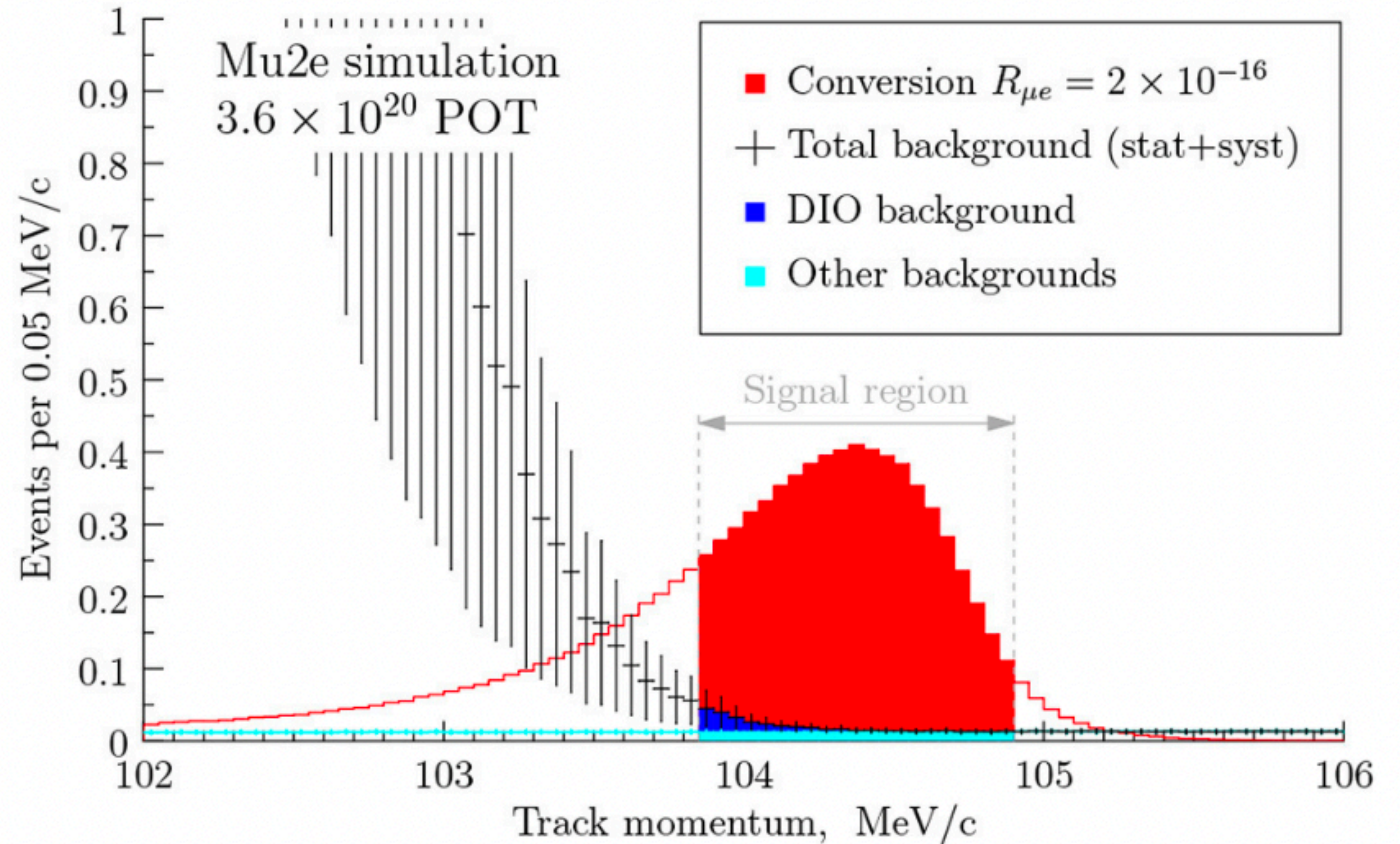
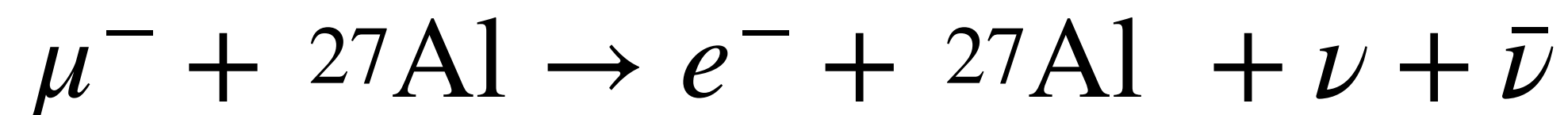


EXAMPLE: MU2E AT FERMILAB

SIGNAL



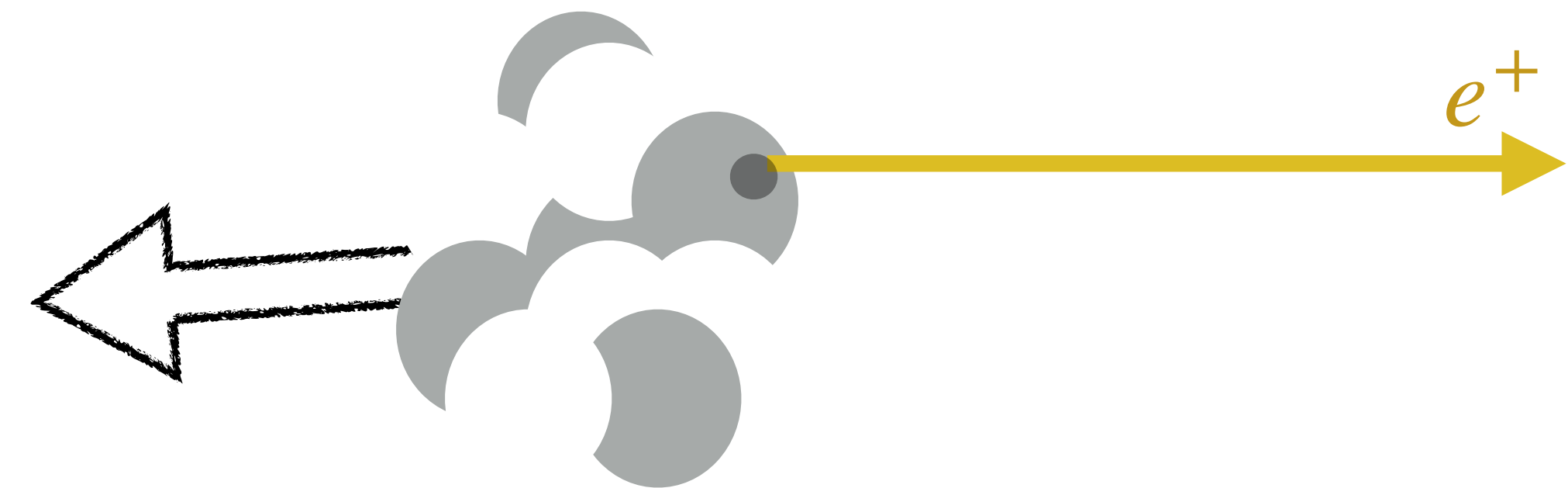
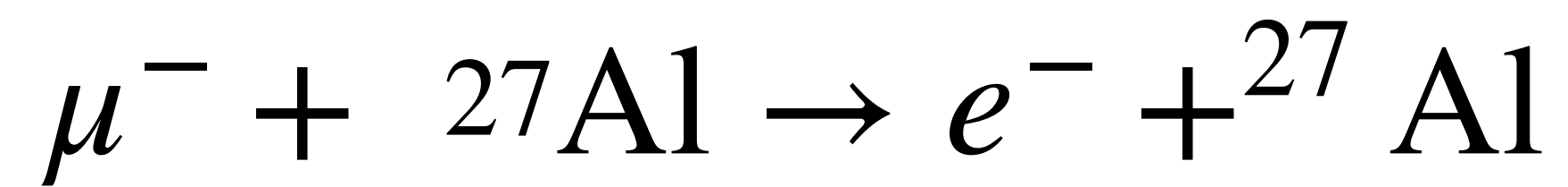
BACKGROUND



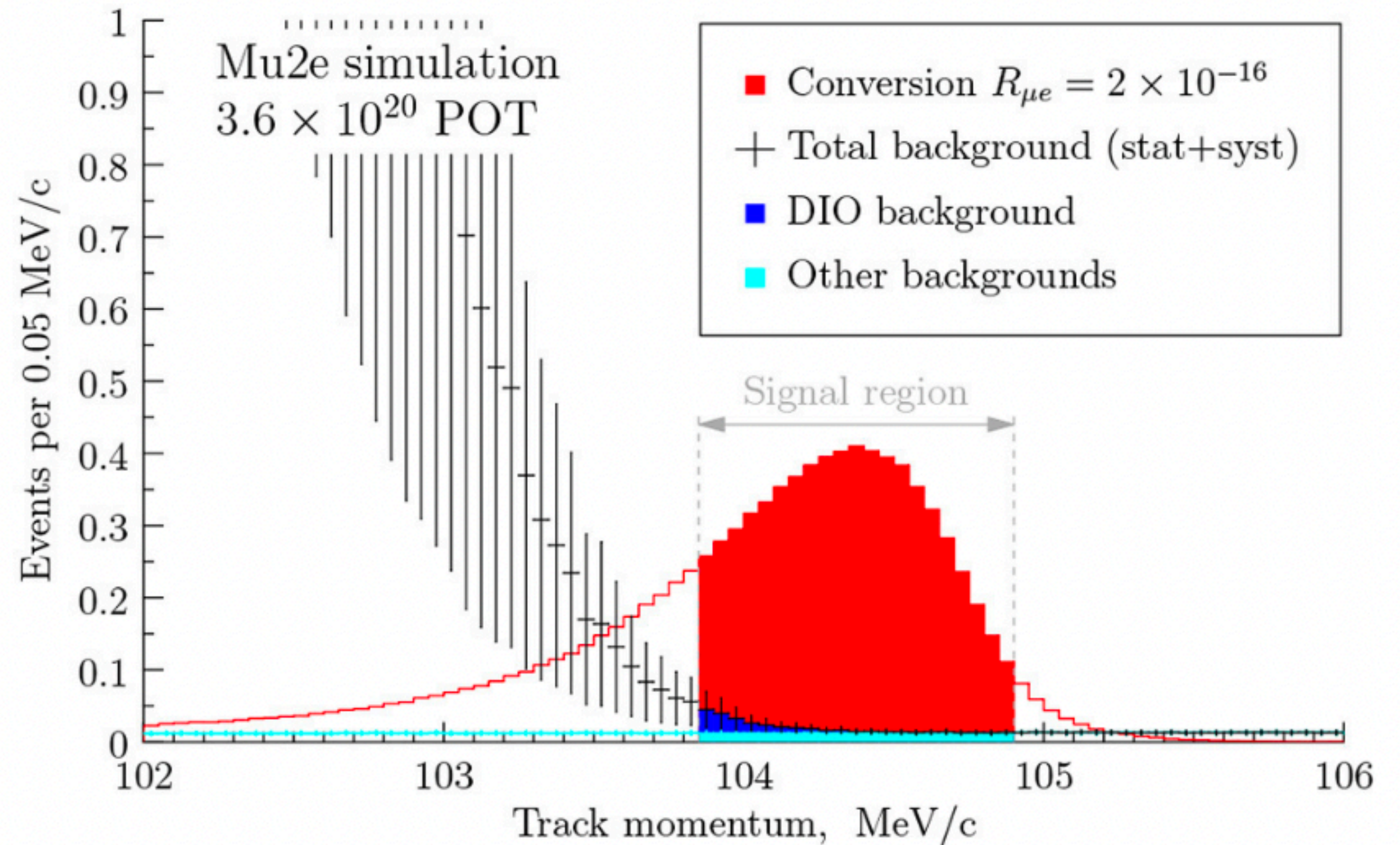
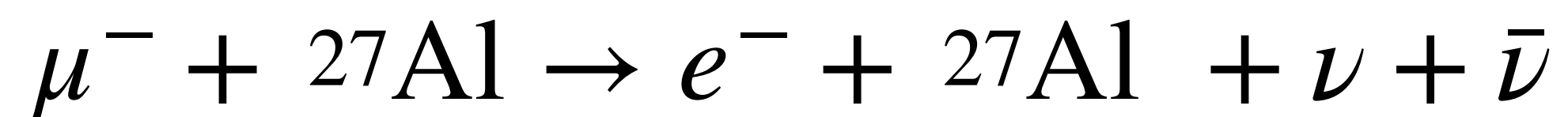
SEARCH FOR BUMP AT ENDPOINT

EXAMPLE: MU2E AT FERMILAB

SIGNAL



BACKGROUND



SEARCH FOR BUMP AT ENDPOINT