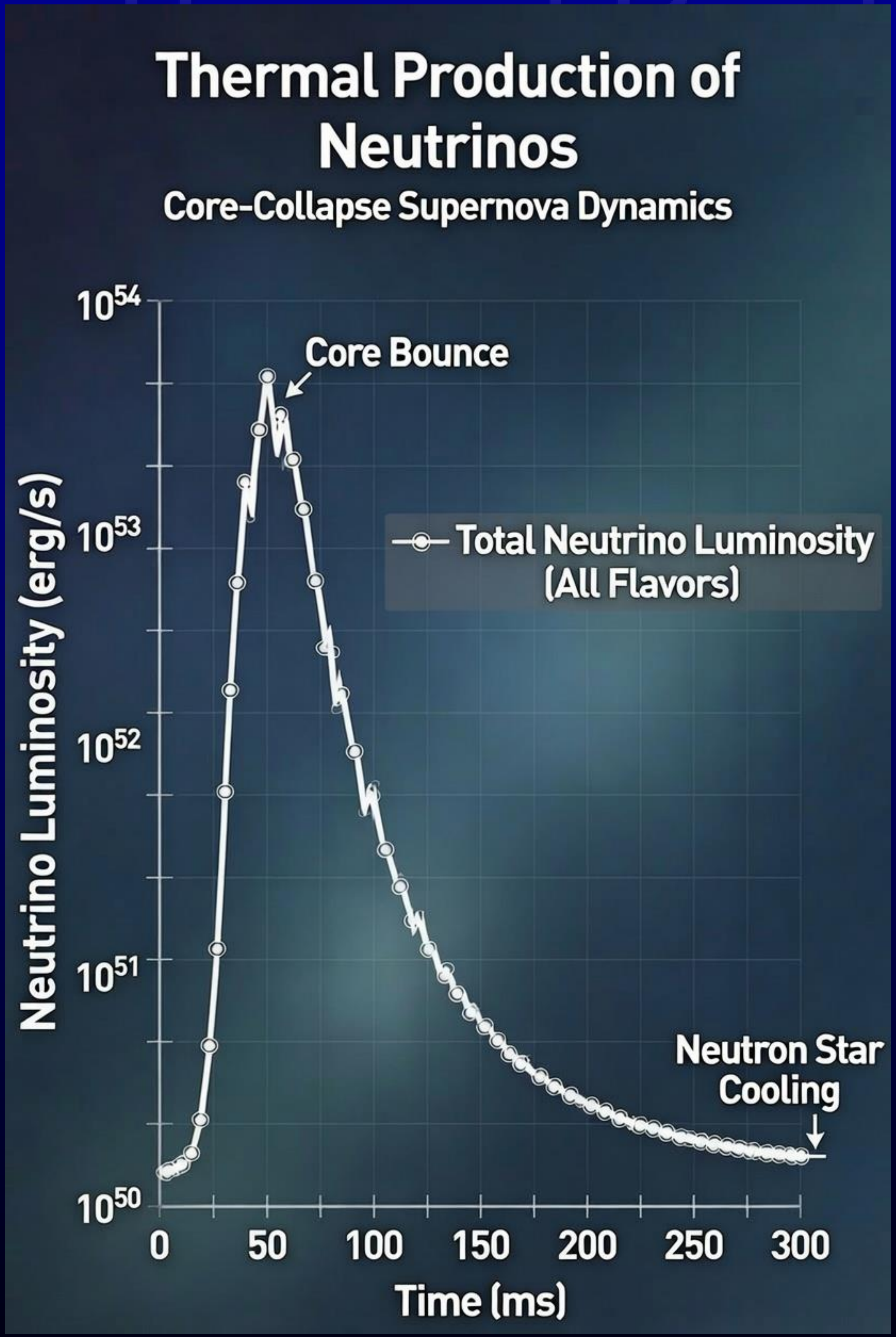
PTOLEMY

Paving the way for thermal relic neutrino detection and the neutrino mass measurement with PTOLEMY

Chris Tully (Princeton University)
On Behalf of the PTOLEMY Collaboration

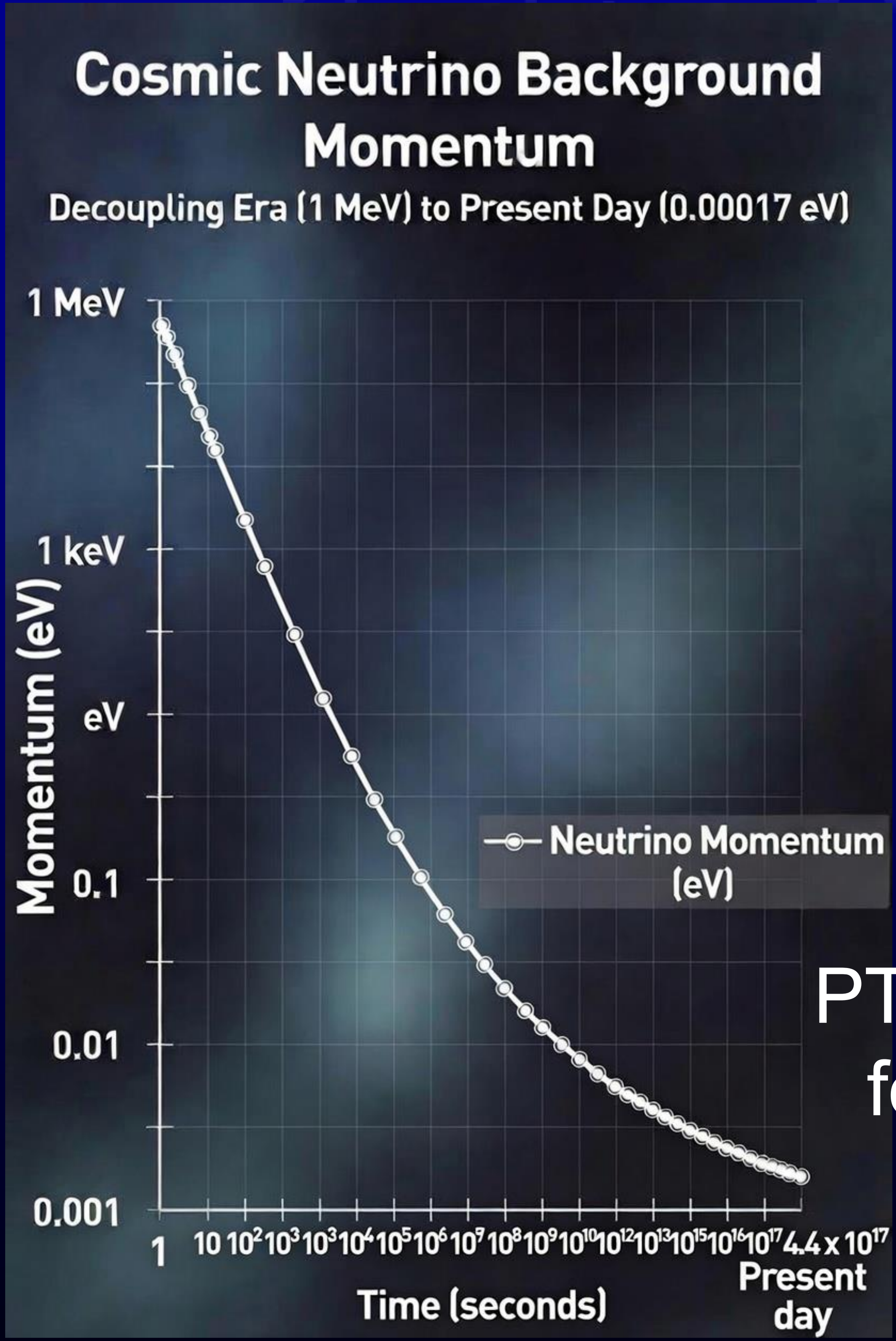
June 25, 2026
Neutrino 2026
Irvine, California, USA

Thermal Production of Neutrinos



- Two areas of study seek these neutrinos
  - Core-Collapse Supernova
  - Big Bang Neutrinos, aka “relic” neutrinos
- Both depend on absolute neutrino mass(es)
  - CCSN: Arrival time/reshaping of flavor composition
  - Relics: Separation power in neutrino capture experiments (PTOLEMY)

Neutrino Mass Observable

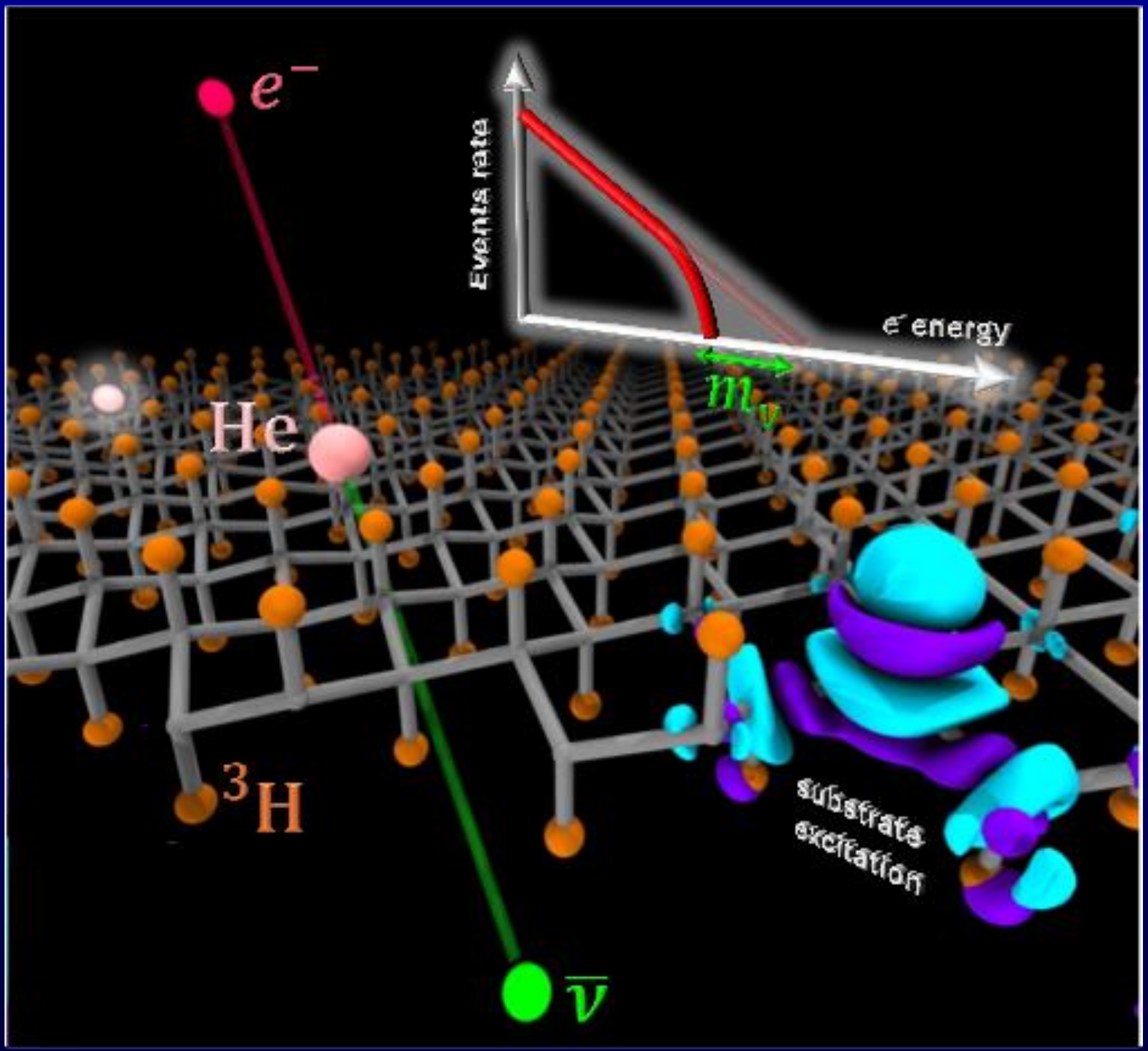


- Hubble expansion cooling of the relic neutrino thermal momentum leaves very little kinetic energy
  - Relative to masses of 0.01eV and higher
- As the absolute neutrino mass measurement pushes below 0.2eV
  - Atomic scales can dominate direct measurement techniques

PTOLEMY proposes a new "window" for neutrino mass(es) in the range 0.02-0.2eV

http://ptolemy.lngs.infn.it

Tritiated-Graphene



β-decay spectrum of tritiated graphene: Combining nuclear quantum mechanics with density functional theory

Andrea Casale, Angelo Esposito, Guido Menichetti, and Valentina Tozzini

Phys. Rev. C 113, 054607 (2026)

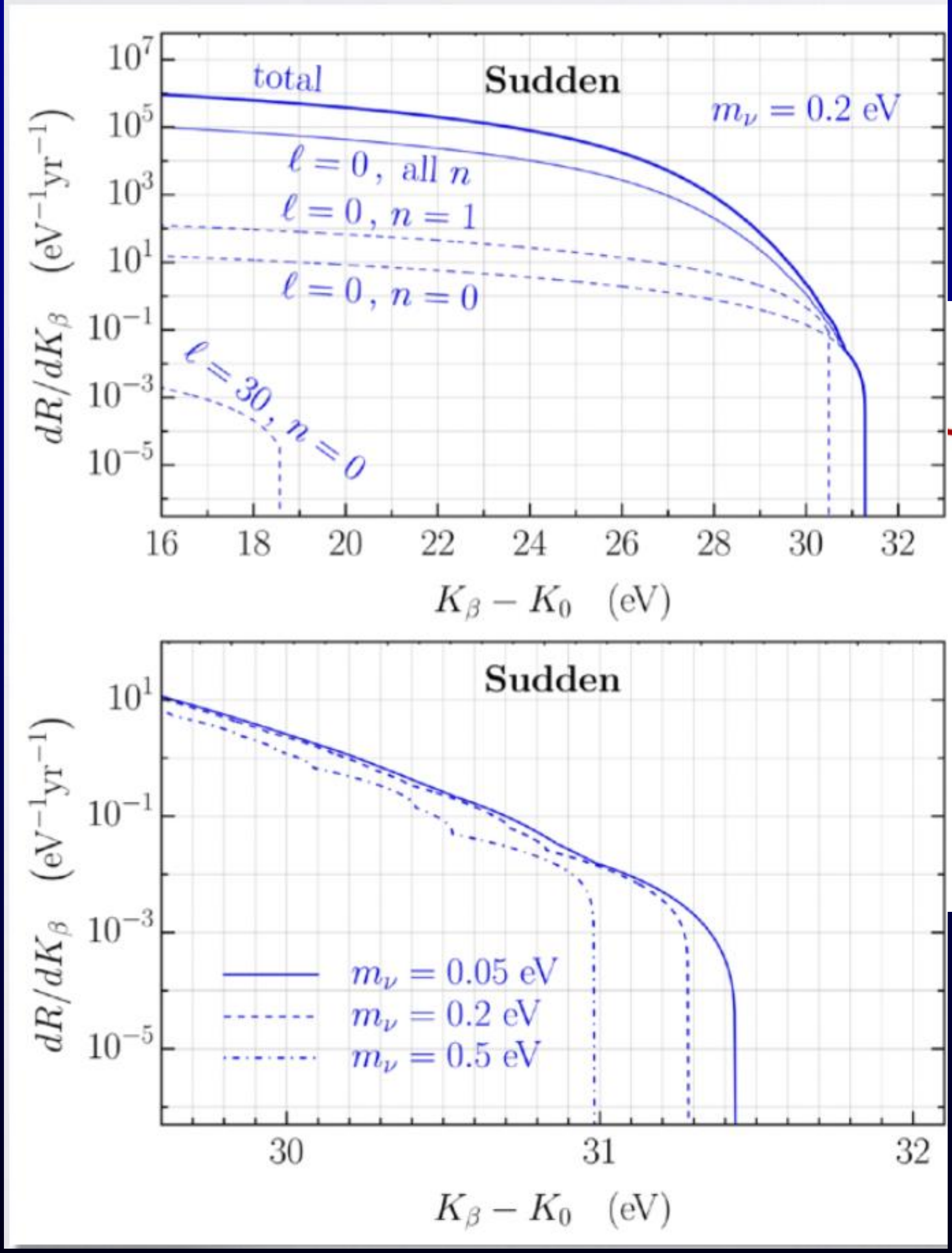
Published May 13, 2026

Quantum "window" of substrate excitations predicts a potential low state density region of 0.02-0.2eV

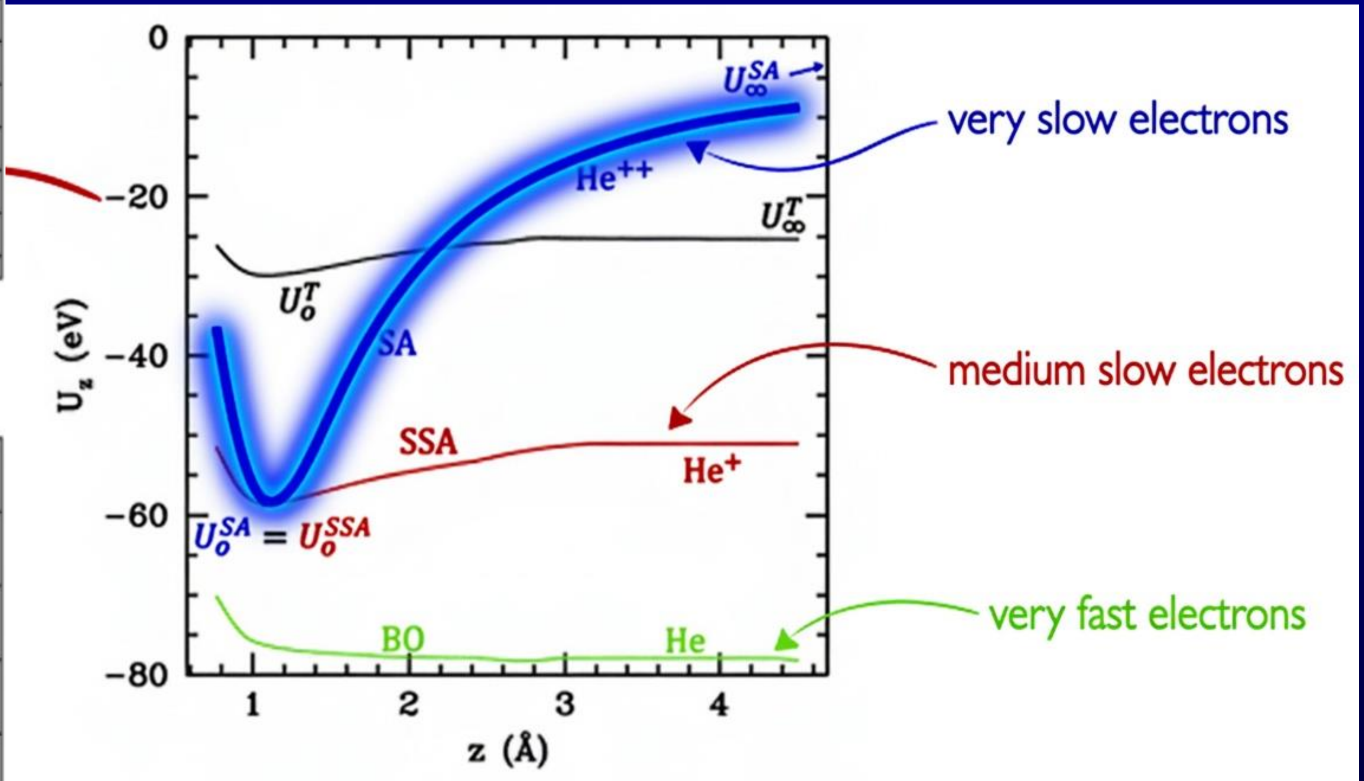
Compare with ro-vibrational T_2 that is fully opaque below ~0.3eV

APS Viewpoint on "A Solid-State Pathway to Neutrino Mass" (May, 2026) https://physics.aps.org/articles/v19/67

Mystery of Timescales



"Sudden" Approximation (SA)



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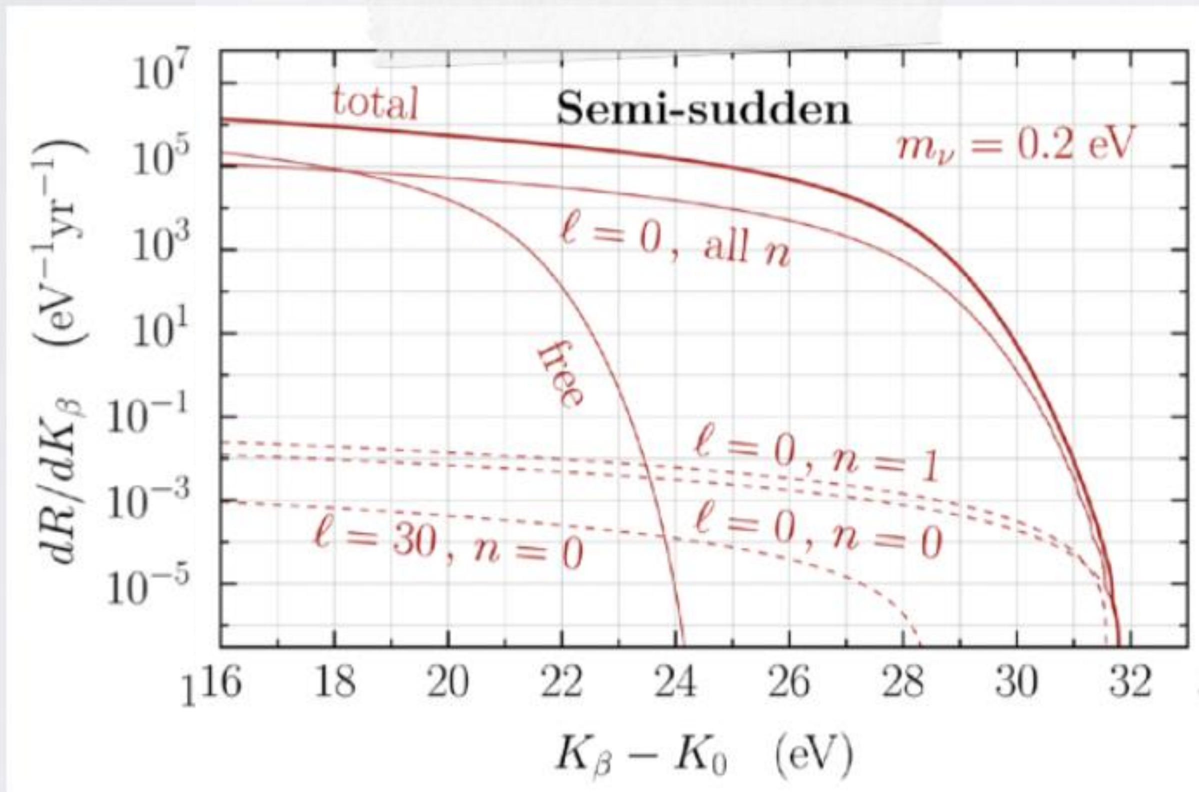
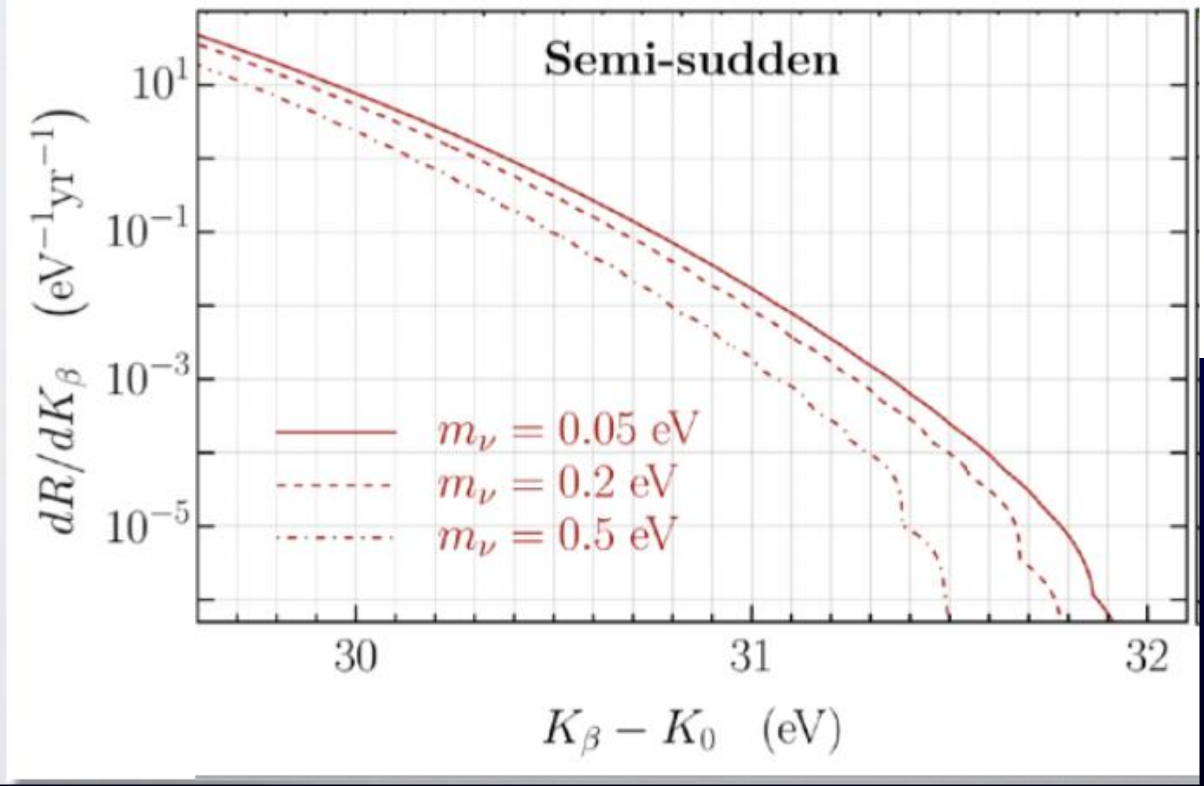
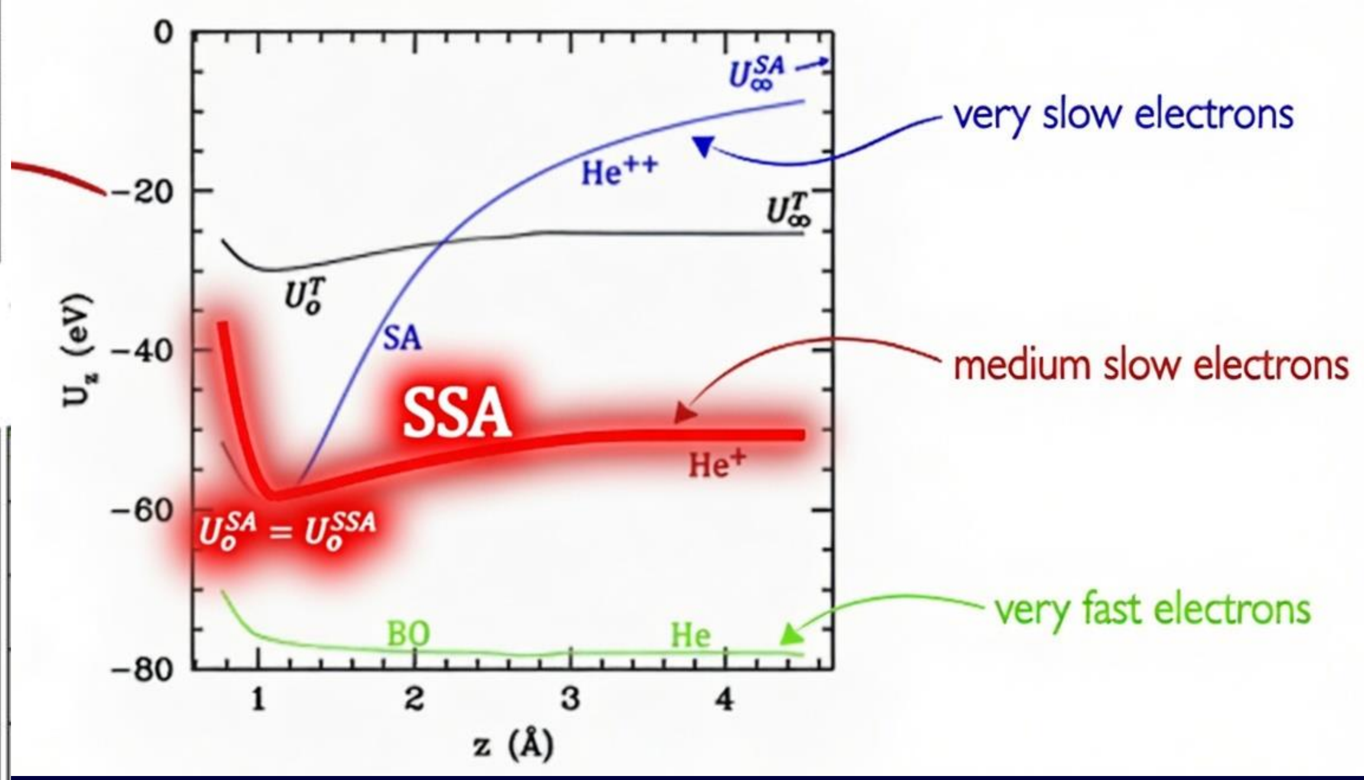
Mystery of Timescales





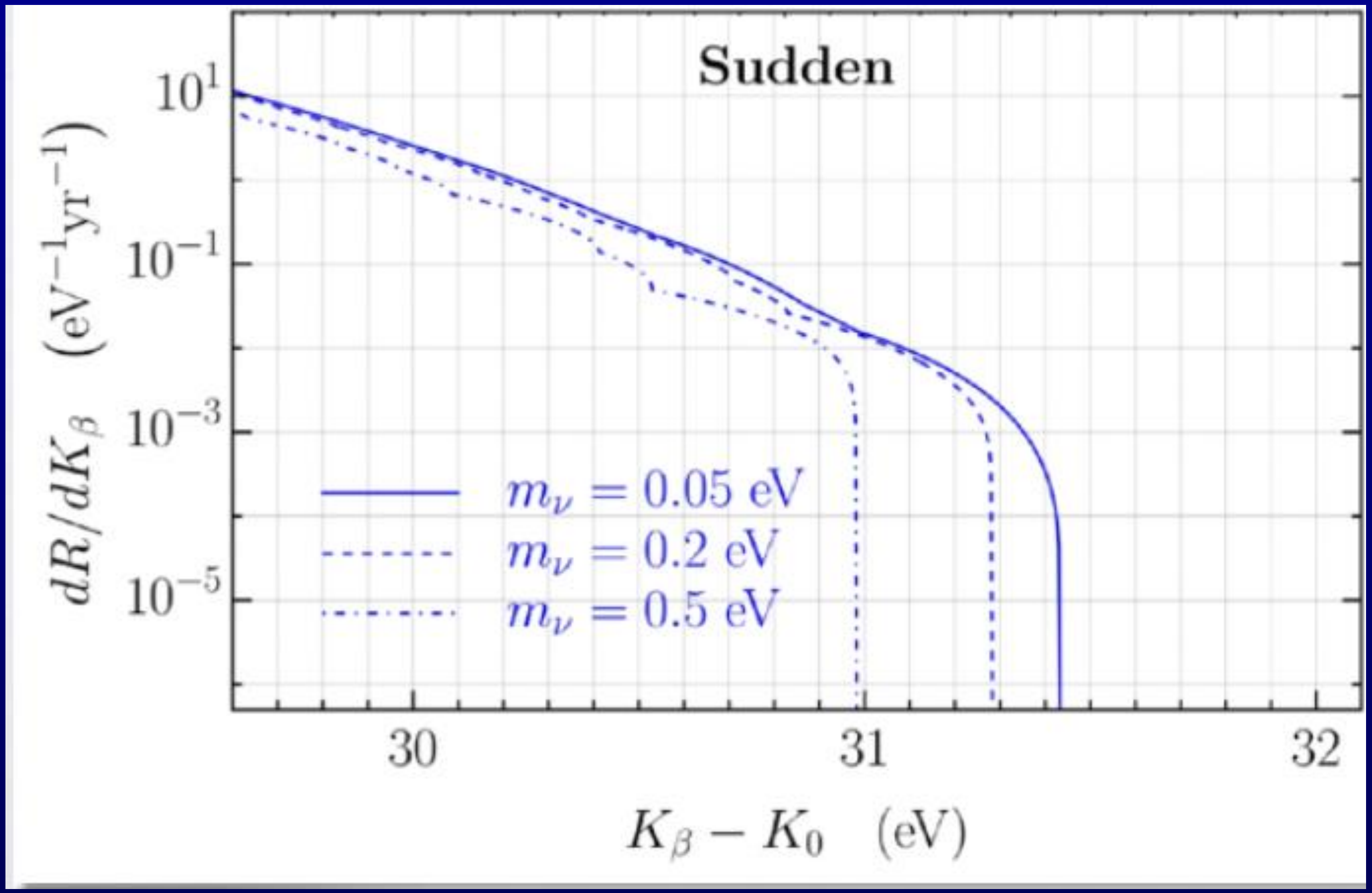
"Semi-Sudden" Approximation (SSA)



→ at least Graphene allows for quantum engineering of material properties

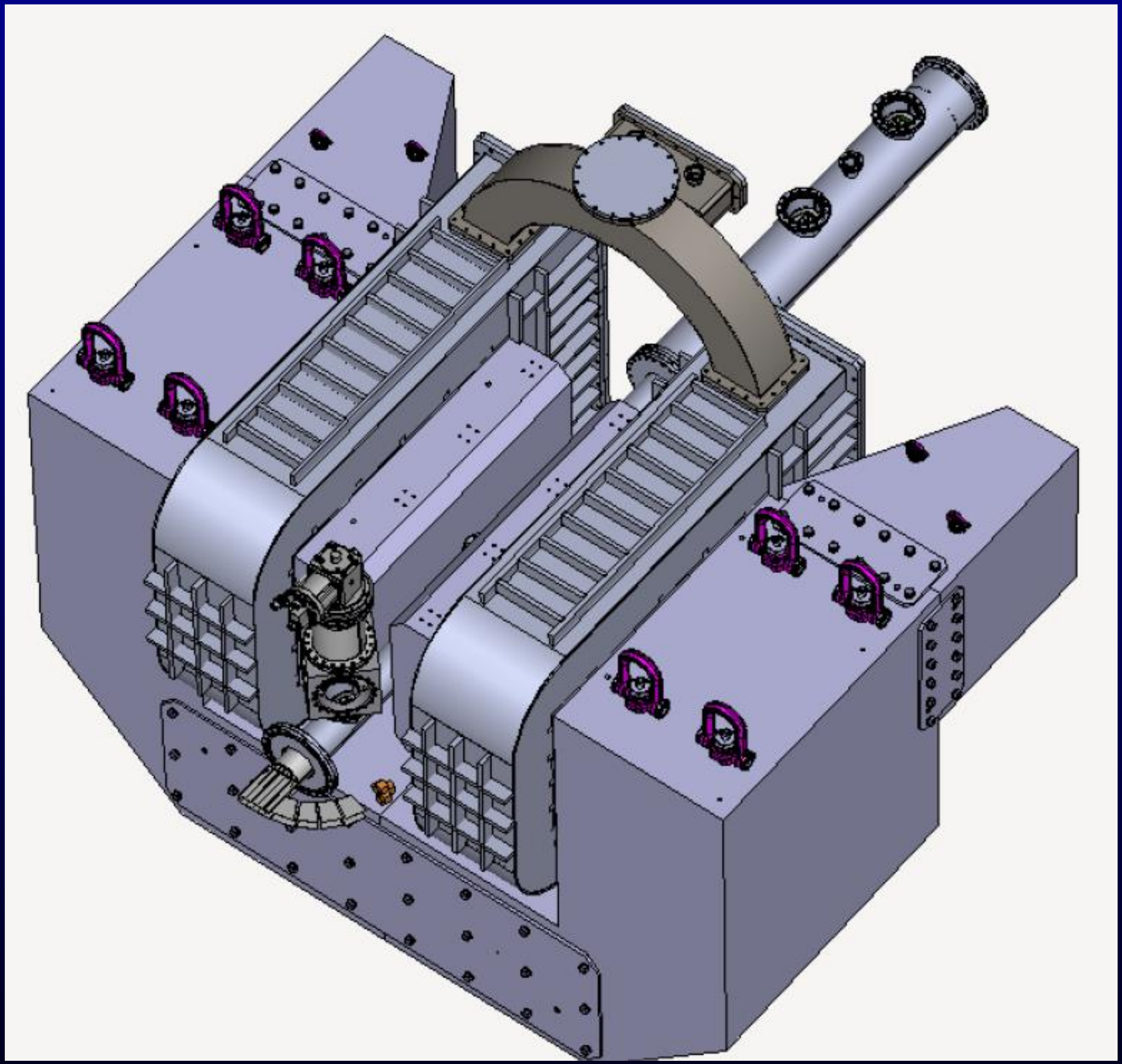
Phys. Rev. C 113, 054607 (2026)

PTOLEMY Approach

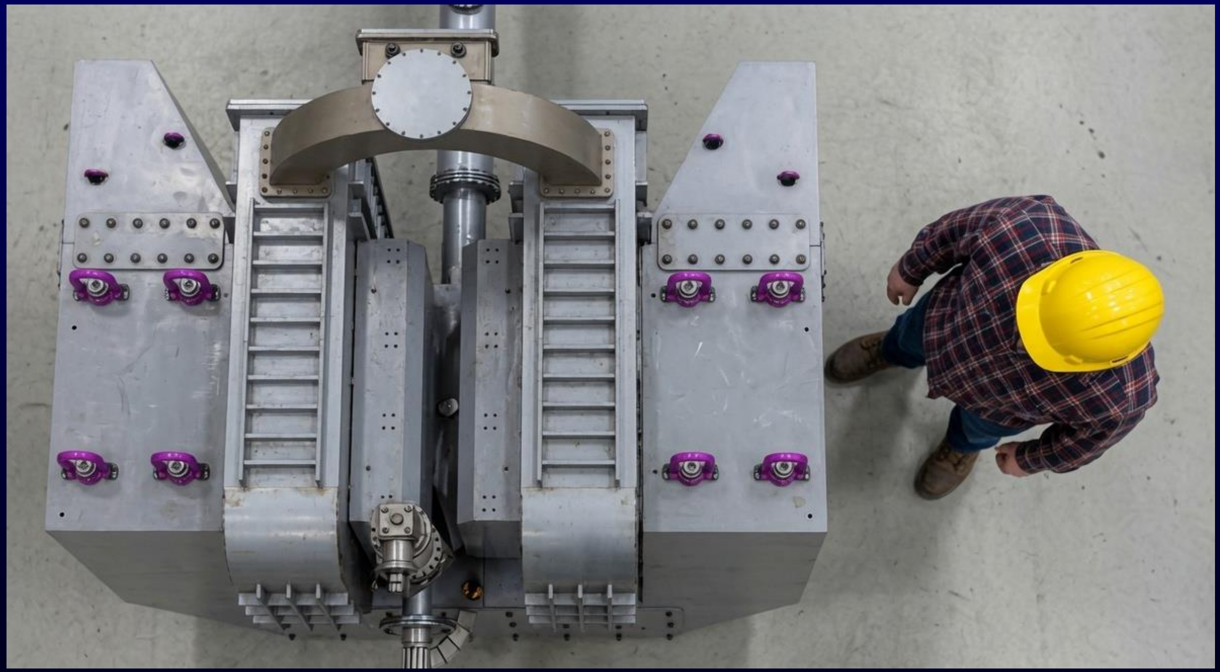


- Ultra-High Resolution
  - Push down to 10meV where optical transitions can be resolved
  - Achievable with an Electrostatic Hemispherical Spectrometer
- Effective Reduction in Tritium Mass Requirements
  - Neutrino Mass Observable appears on every excitation threshold, repeated through the endpoint spectrum
  - No longer required to go to absolute endpoint to have neutrino mass sensitivity (sensitivity paper in progress)

ASG Superconductors/Suprasys MgB_2 Magnet for LNGS

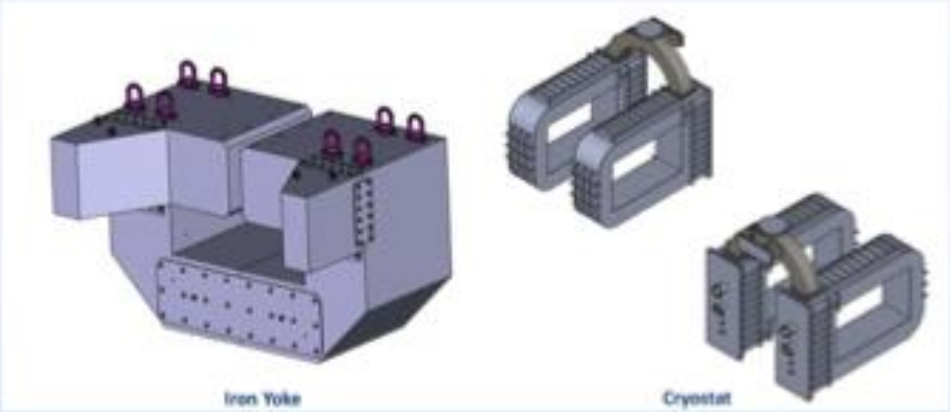


- PTOLEMY Magnet
  - New approach to electro-magnetic spectrometer
  - Electrons from tritium drift transverse to magnetic field



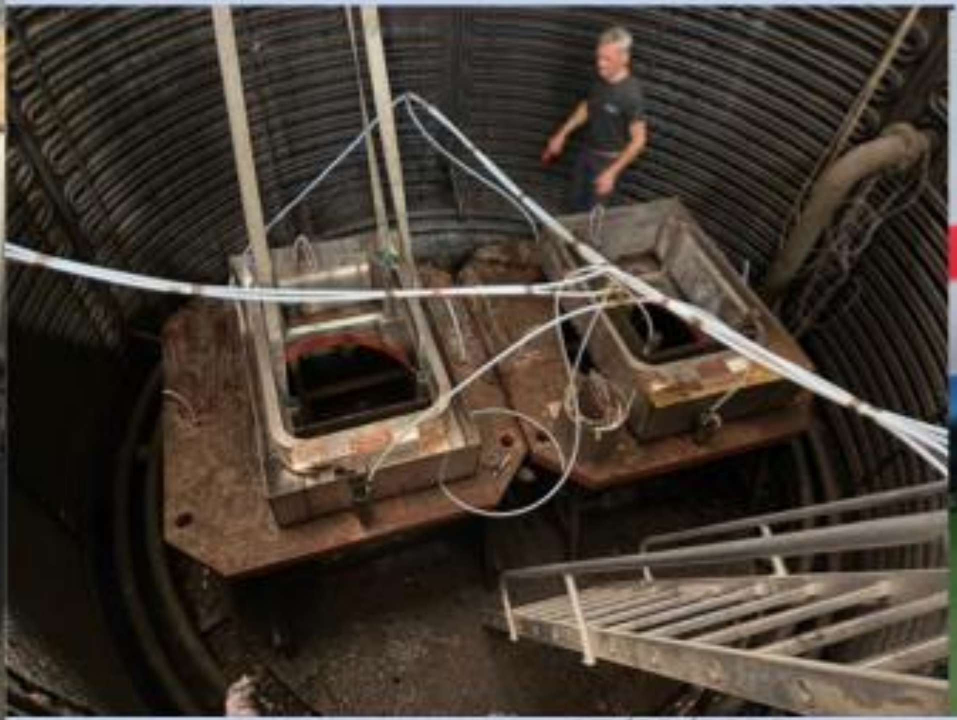
Rendered/Reference Size

Magnet under construction at ASG (Genova-IT)



Yoke construction

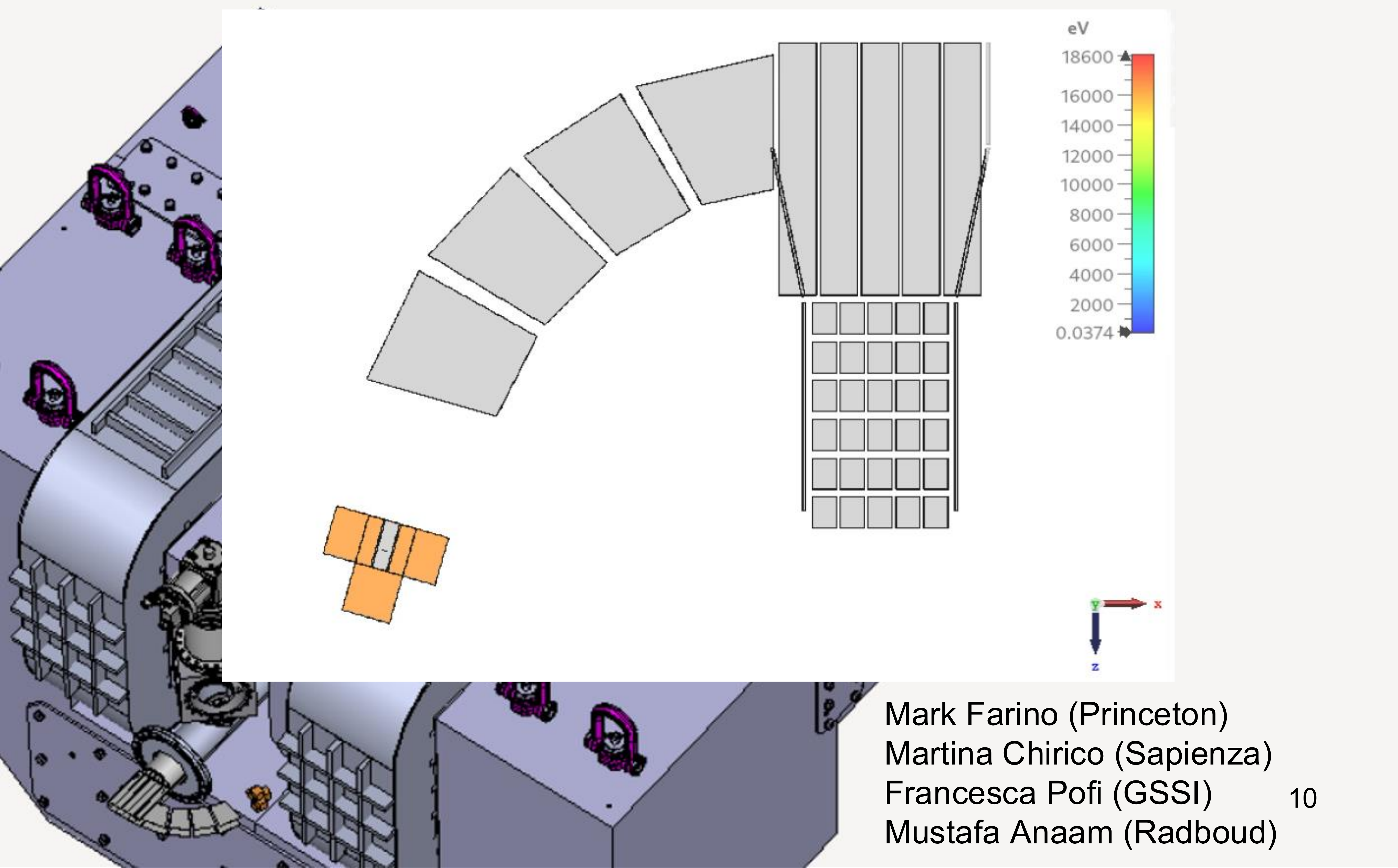
SC Coil impregnation



Coil cold test facility

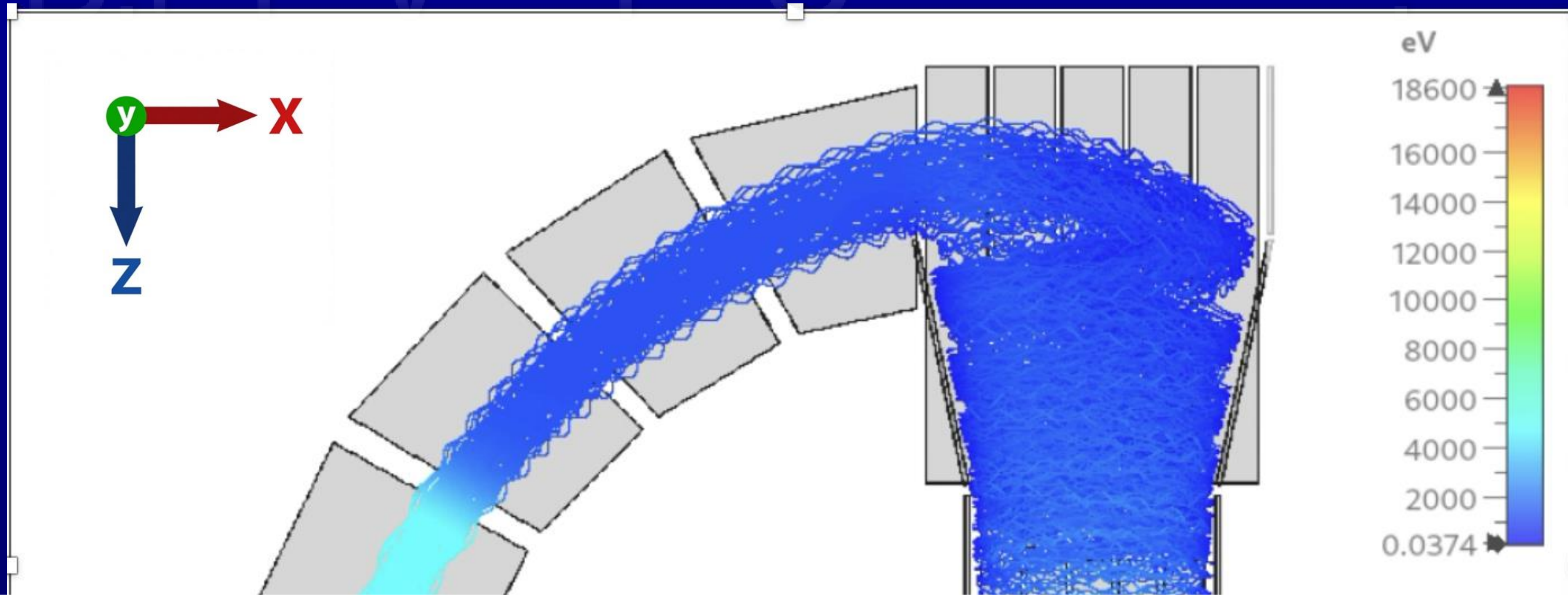
27/02/2026

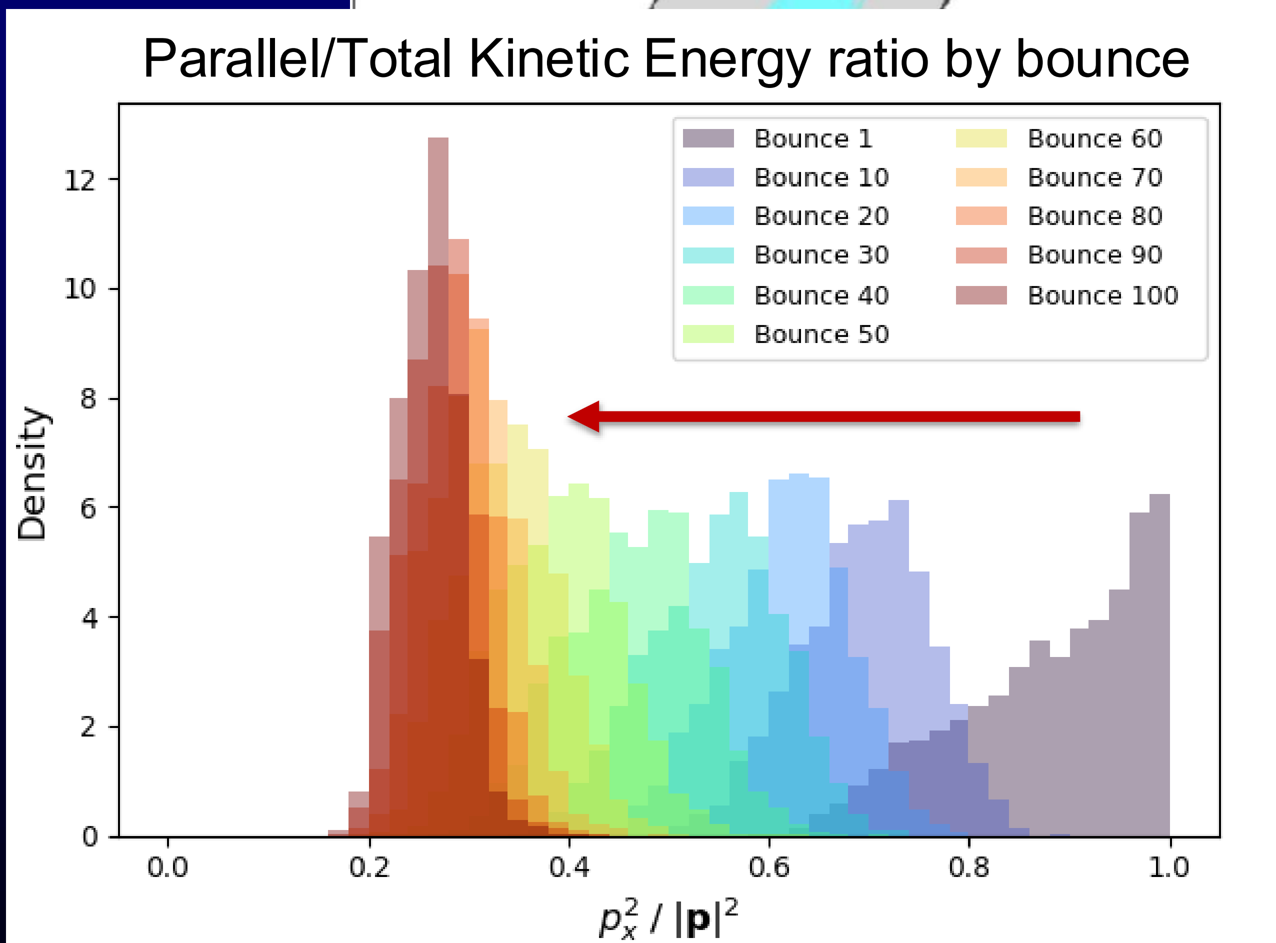
Tritium Endpoint Electron Injection

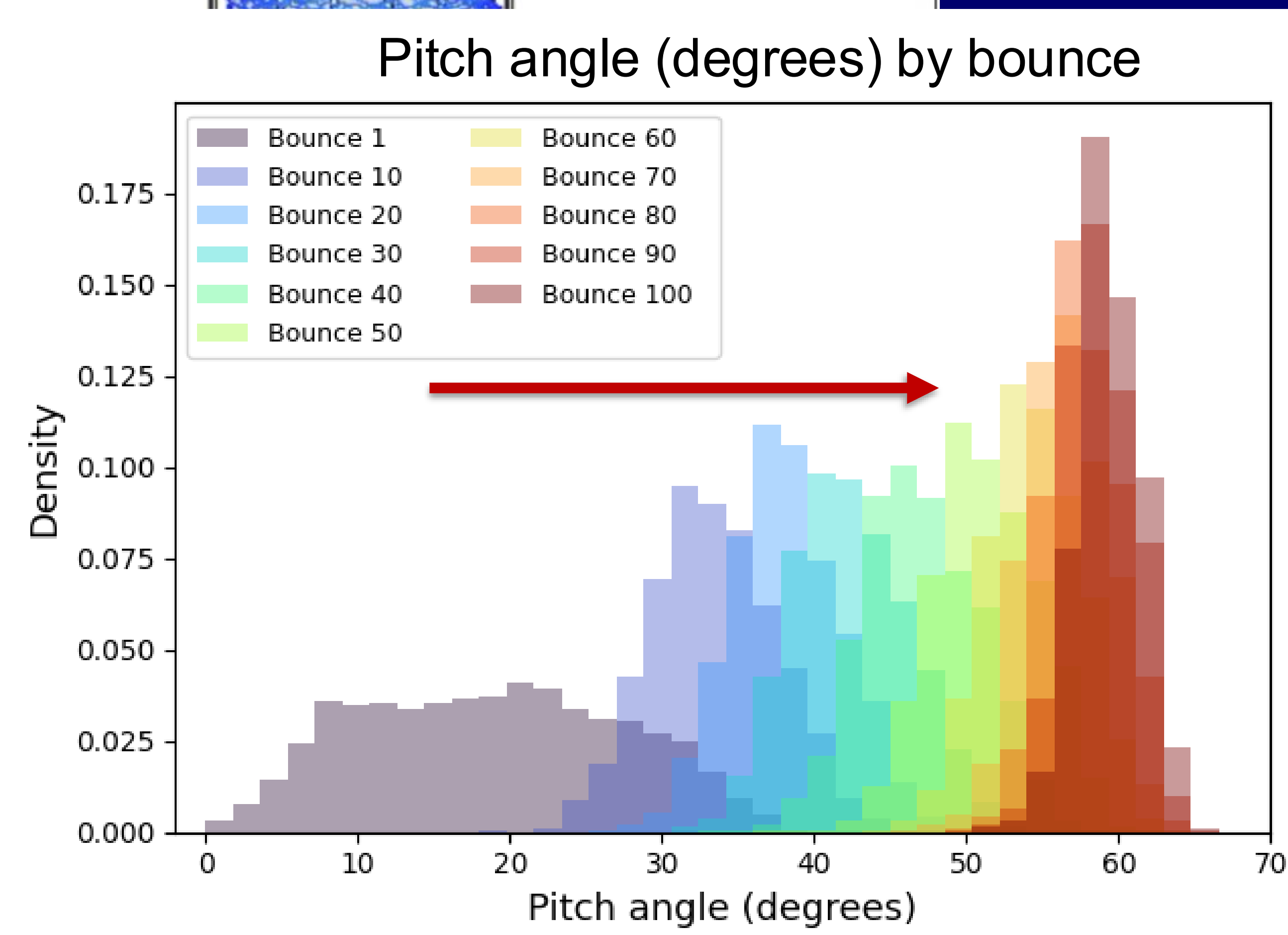


Mark Farino (Princeton)
Martina Chirico (Sapienza)
Francesca Pofi (GSSI)
Mustafa Anaam (Radboud)

Pitch Angle Compression



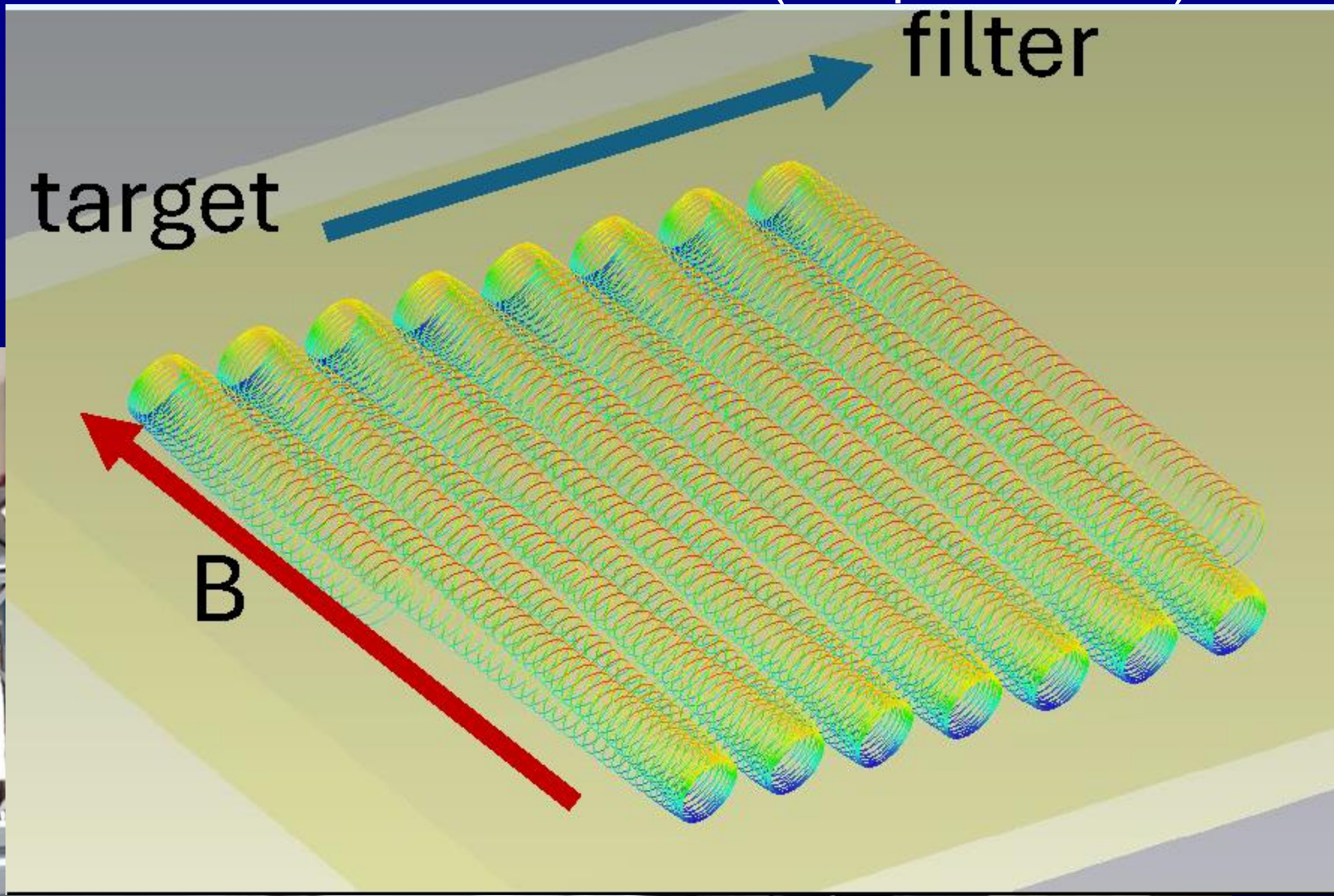


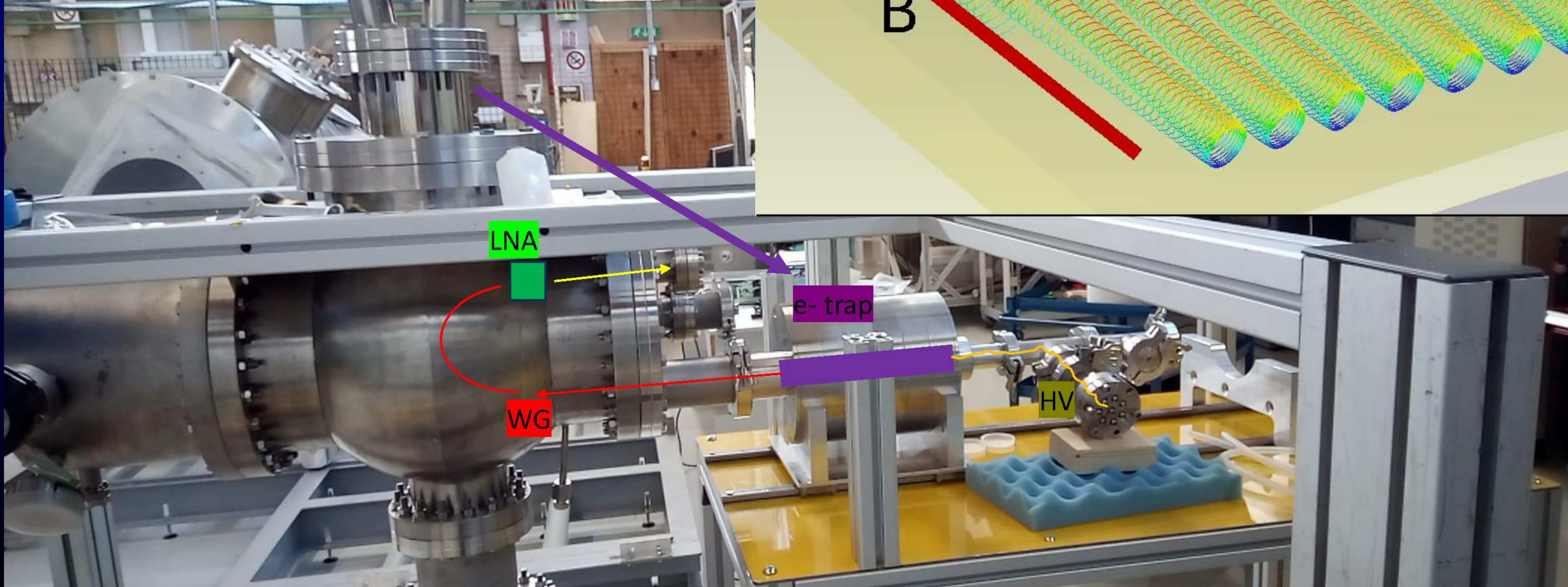


RF Measurements
Non-Destructive Electron Tag

Federico Virzi (L'Aquila/LNGS)

Tagging electrons in flight!
using Project 8 methods





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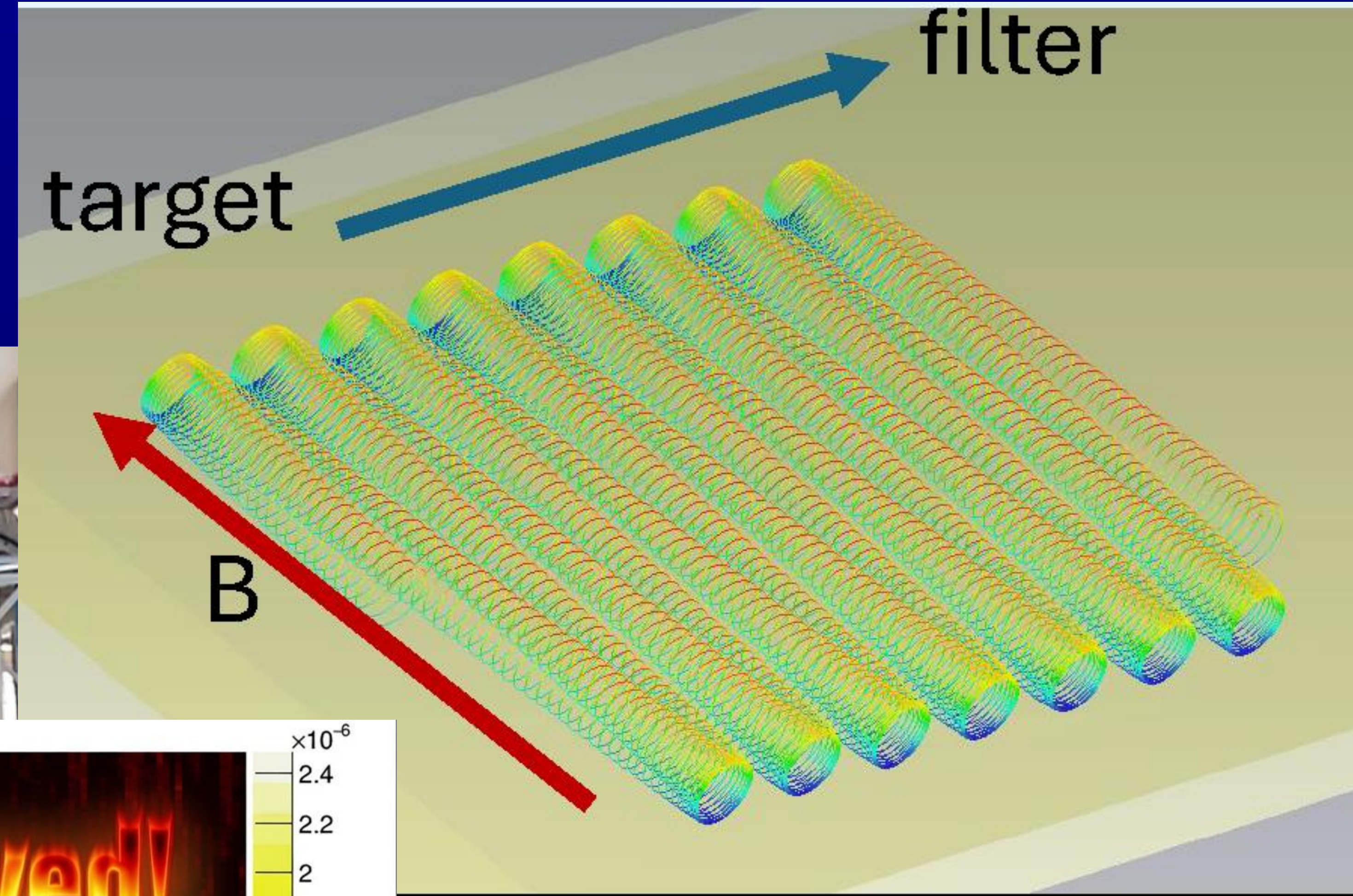
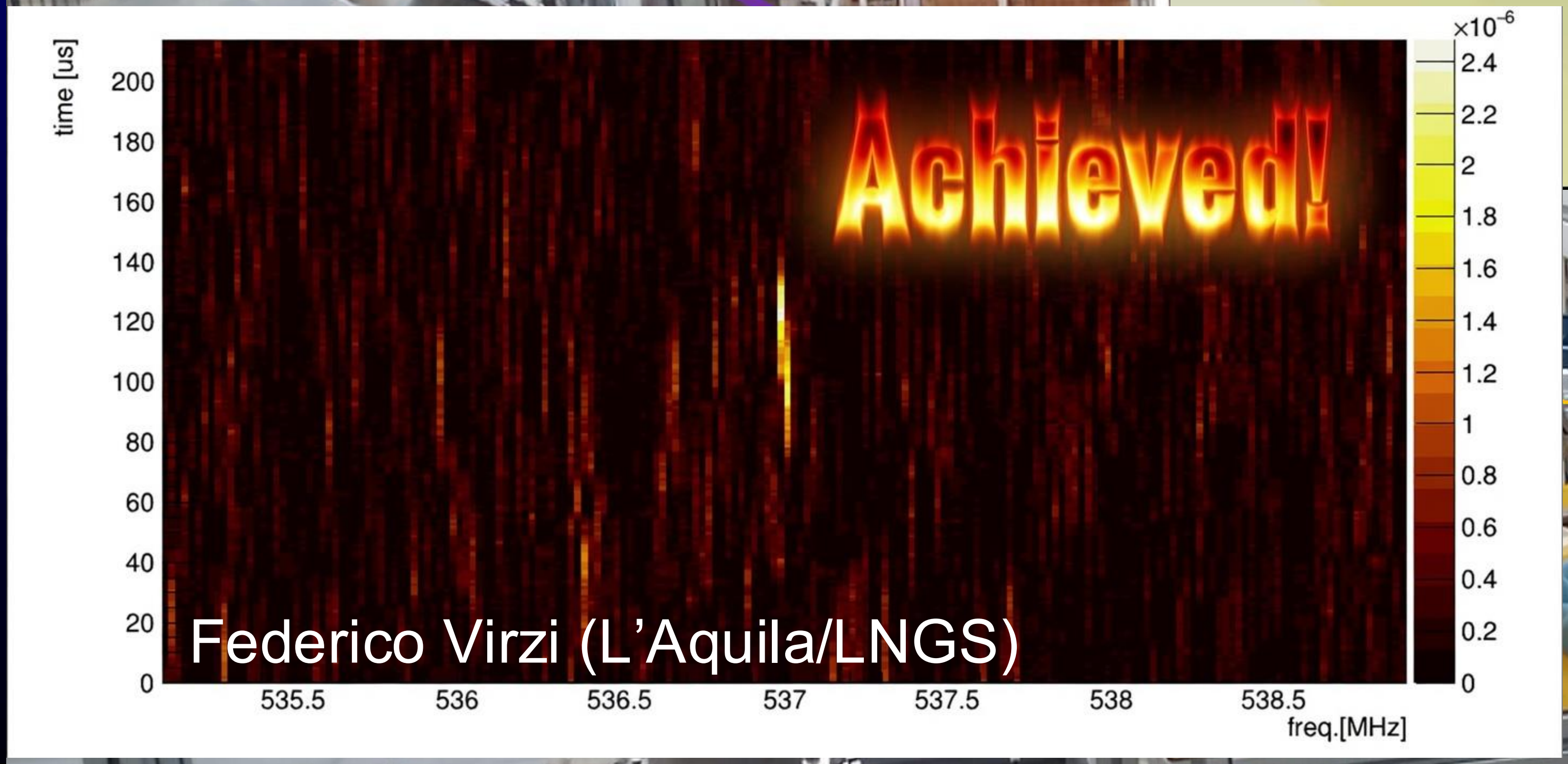
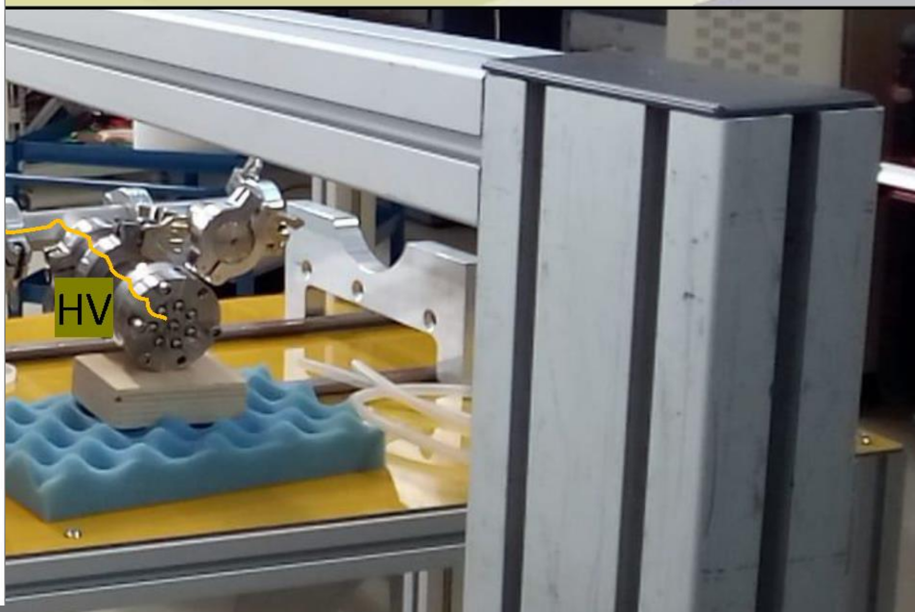




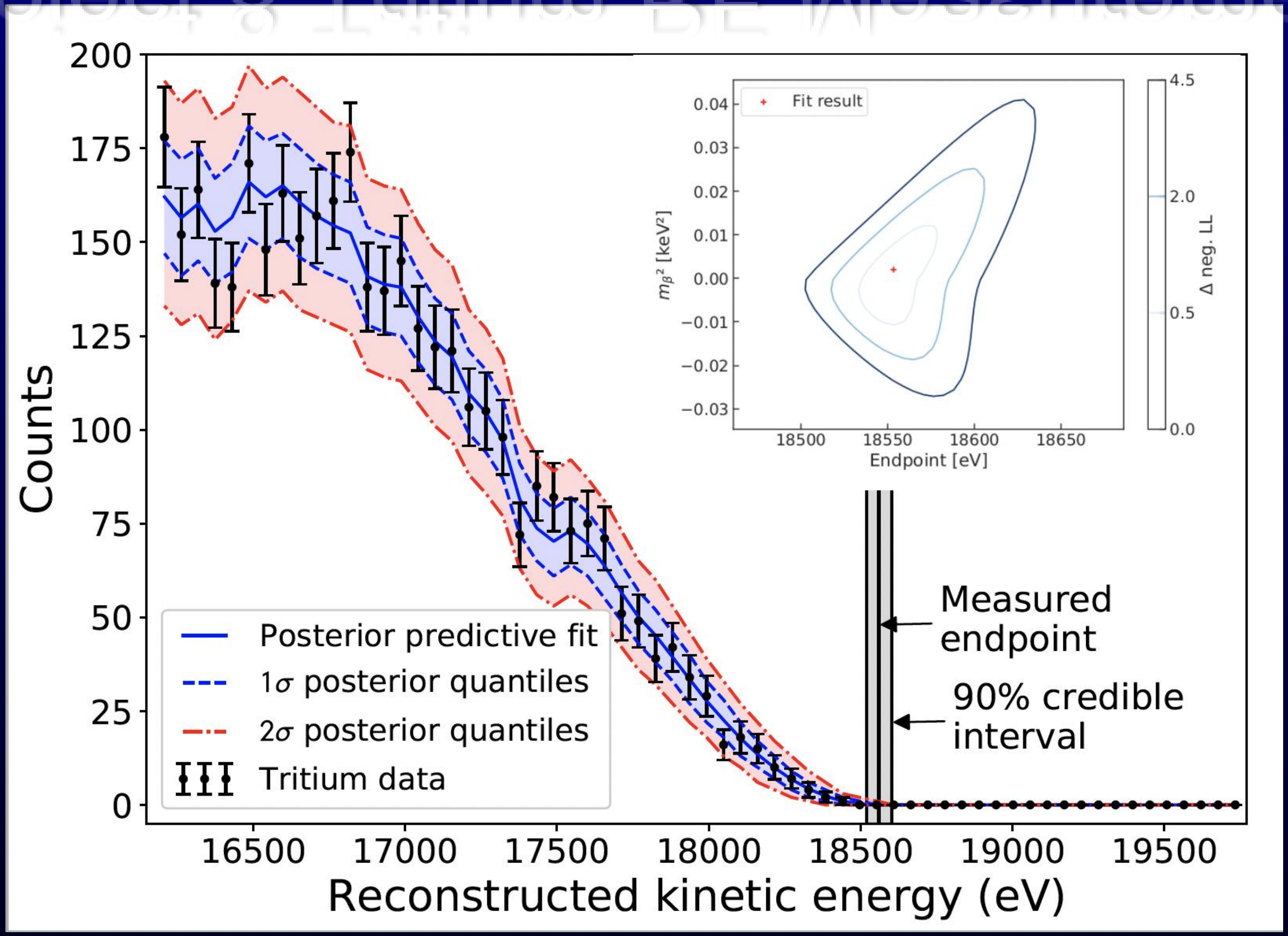


RF Measurement with 10eV Resolution on Total Energy

Highly suppresses backgrounds registered coincident on final measurement system

→ Except non-tritium electrons from source

Project 8 Tritium RF Measurement



https://arxiv.org/abs/2203.07349

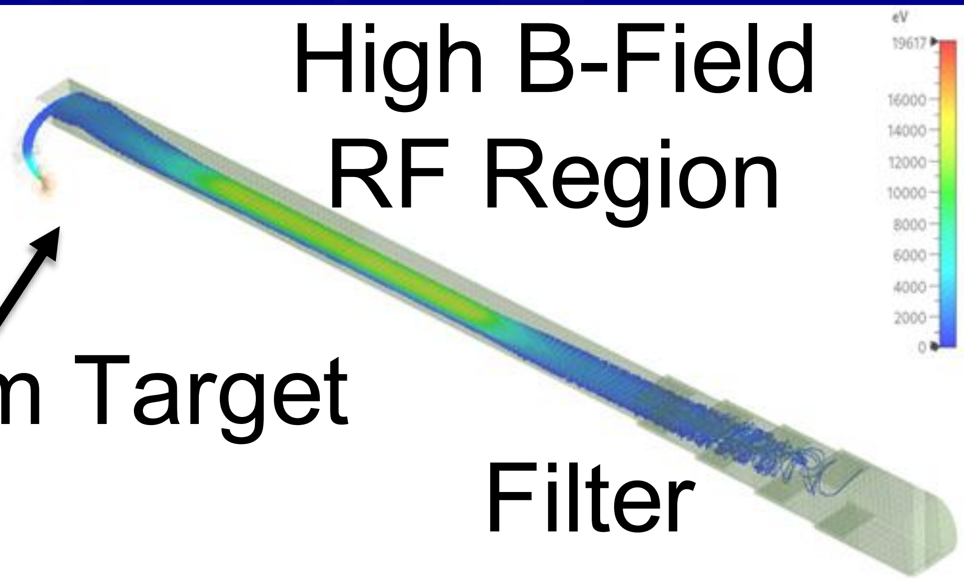
No events observed above endpoint,
Setting upper limit on background rate

< 3×10^{-10} /eV/s (90% CL)

→ Background Rate < 1 event per eV in 100 years!

Final Kinetic Energy Measurement

High B-Field RF Region



Injection from Target

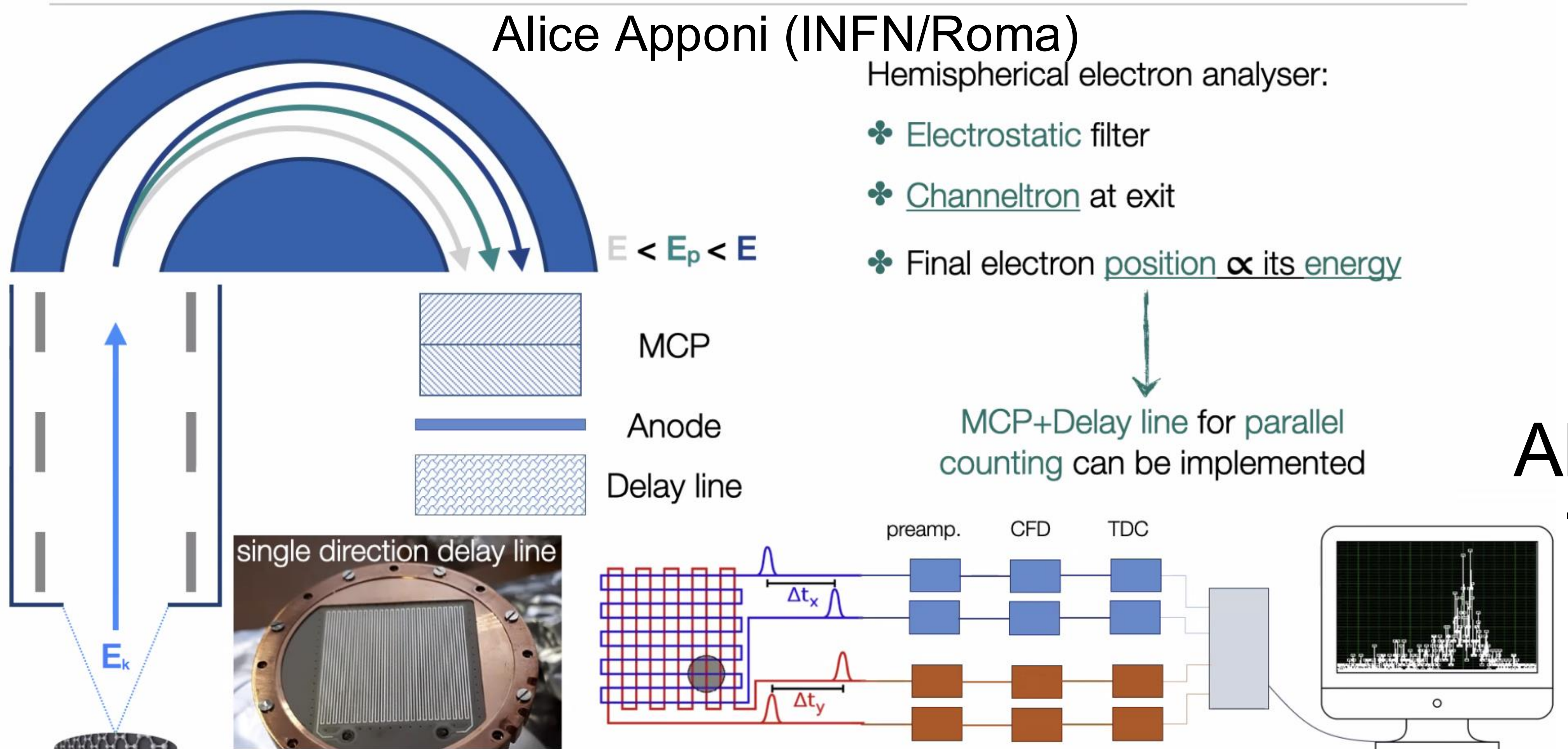
Filter

Goal for Electrostatic Hemispherical Analyzer: 10meV@10eV

Zero B-Field Kinetic Energy Measurement

Hemispherical Electron Analyser: an Electrostatic Filter for Electrons

Alice Apponi (INFN/Roma)

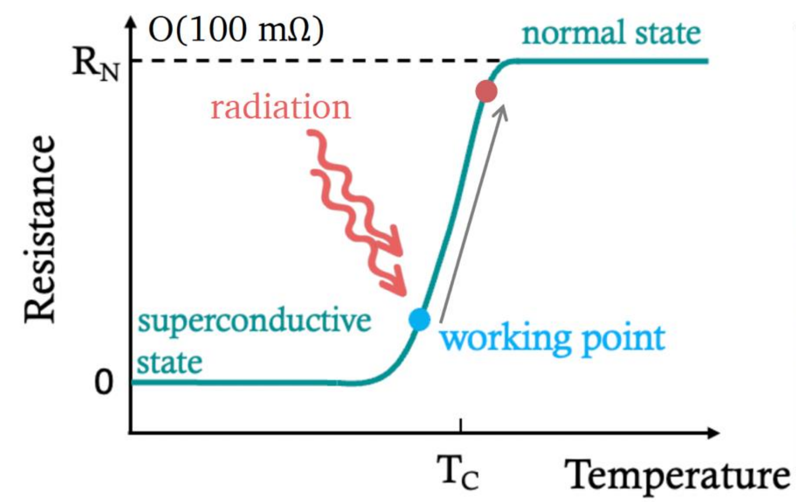


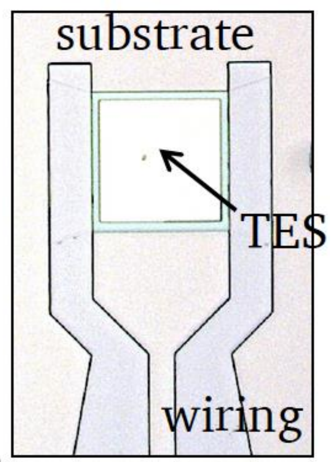
Also developing TES microcal (50meV)

Transition-Edge Sensor μCal

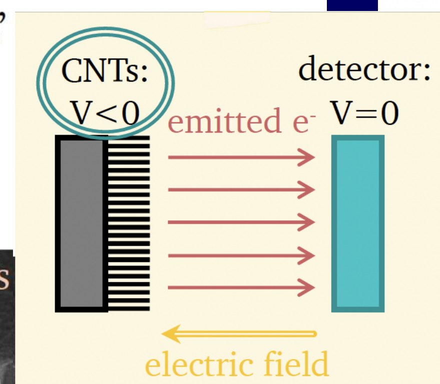
Carlo Pepe (Barcelona,IMB-CNM-CSIC)

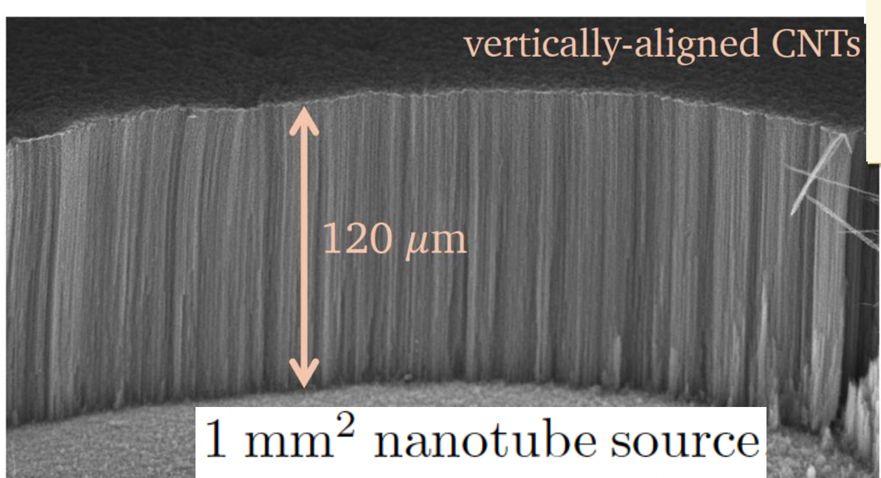
- TES: superconductive film operated at its superconductive transition
- Critical temperatures of ~ 100 mK ⇒ **cryogenic** detector
- **Sharp** superconductive transition: typical width of few mK





- Particle absorption ⇒ small ΔT ⇒ measurable ΔR
- Carbon **nanotubes** (**CNTs**): graphene 'straws'
  - diameter ~ 20 nm
  - length ~ 100 μm
- Tip factor γ ~ 10^3 - 10^4 enhances local $\vec{E}$



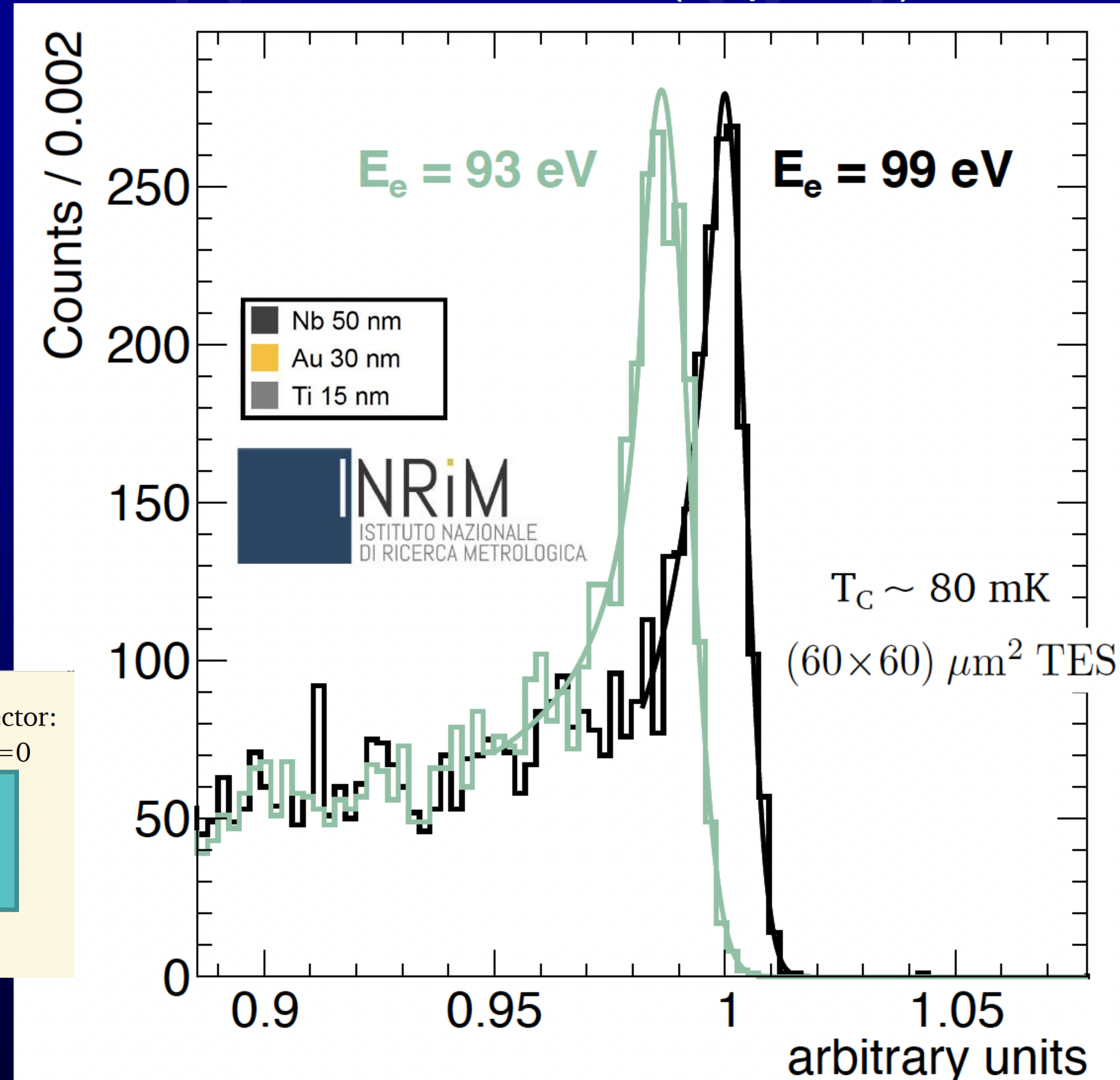


Francesco Pandolfi (INFN/Roma)
Alice Apponi (INFN/Roma)

original idea by Alice Apponi

TITAN LAB

Benedetta Corcione (Sapienza)



$$\langle \Delta E_{\mathrm{gaus}} \rangle = (0.479 \pm 0.041 \pm 0.055)\ \mathrm{eV}$$

Achieved: 0.5eV@100eV

Next Step: 0.05eV@10eV

Period of Rapid Progress

Publications (Newest First)

Towards Low-Energy Electron High-Resolution Spectroscopy with Transition-Edge Sensors
R. Amendola et al.
arXive:2602.21694 (25 Feb 2026)
Key result on TES energy resolution for low-energy electrons (~0.48 eV)
Benedetta Corcione (Sapienza)

Ultra-high precision high voltage system for PTOLEMY
R. Amendola et al.
JINST 21 (2026) P04009
Nicola Rossi (LNGS)

Stability of highly hydrogenated monolayer graphene in ultra-high vacuum and in air
Alice Apponi et al.
Appl. Surf. Sci. 723, 165658 (2026)
Long-term stability of hydrogenated graphene in UHV (relevant for tritium storage in PTOLEMY); rapid oxidation in air with recovery via atomic hydrogen exposure
Alice Apponi (INFN/Roma)

A demonstration of slowed electron E×B drift for PTOLEMY
M. Farino et al.
JINST 20 (2025) P08025
Mark Farino (Princeton), Andi Tan (Princeton)

β-decay spectrum of tritiated graphene: Combining nuclear quantum mechanics with density functional theory
A. Casale et al.
Phys. Rev. C 113, 054607 (2026)
(This is the paper featured in the May 2026 APS Physics Viewpoint)
Andrea Casale (Columbia), Angelo Esposito (Sapienza)
Guido Menichetti (Pisa), Valentina Tozzini (Pisa)

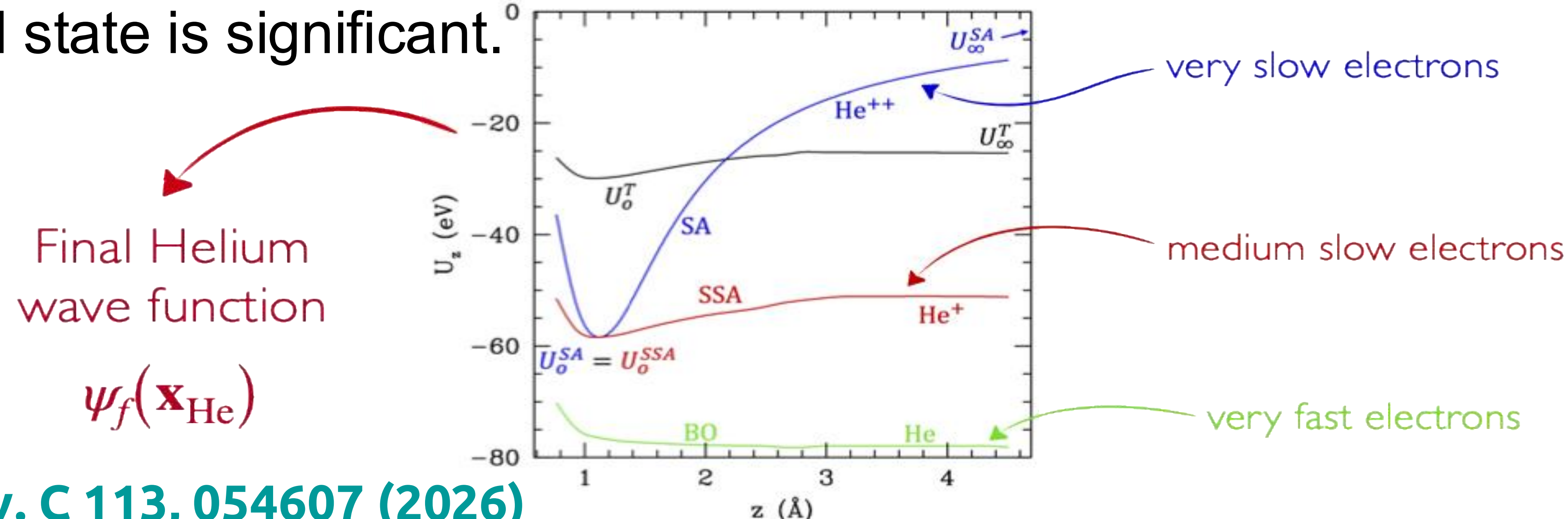
Quantized Nuclear Recoil in the Search for Sterile Neutrinos in Tritium Beta Decay with PTOLEMY
W. Chung et al.
Universe 11(9), 297 (2025)
Wonyong Chung (Princeton)

- Soon to come
  - Mass Sensitivity
  - Mini-Filter with Halbach Magnet

Future of Tritium for Relics

Depends on physics studies with tritiated graphene:

If the sudden approximation holds with a deep potential for the He daughter, there may be substrates where the transition into the ground state is significant.



Phys. Rev. C 113, 054607 (2026)

Alternatively, if the binding of atomic T is weak, estimated to be 0.1meV on the surface of liquid Helium, then a shallow potential may be more favorable.

coherent neutrino scattering

S. A. Lyon, Kyle Castoria, Ethan Kleinbaum, Zhihao Qin, Arun Persaud, Thomas Schenkel, and Kathryn M. Zurek. Single phonon detection for dark matter via quantum evaporation and sensing of ^{3}He. Phys. Rev. D, 109:023010, 2024.

Heavy Targets for Neutrino Capture

Idea first promoted here:

(**Cheipesh Yevheniia**, Cheianov V and Boyarsky A 2021 Phys. Rev. D 104 116004)

"Goodness^{-1}" Dimensionless Parameter $$\gamma = \left[\frac{Q^2 m_{\mathrm{el}}}{m_{\mathrm{nucl}}^3 c^4} \right]^{1/4}$$

Case for ^{241}Pu (N. De Groot, J. Phys. G: Nucl. Part. Phys. 50 (2023) 055106)

Isotope	Q (keV)	$t_{1/2}$ (yr)	$(\sigma v)_\nu (10^{-46} \mathrm{cm}^2)$	$\gamma/\gamma_{^3H}$
^{3}H	18.6	12.3	39.2	1.0
^{63}Ni	66.9	100	0.069	0.19
^{151}Sm	76.6	90	0.048	0.10
^{171}Tm	96.5	1.92	1.2	0.11
^{241}Pu	20.8	14.4	15.1	0.039

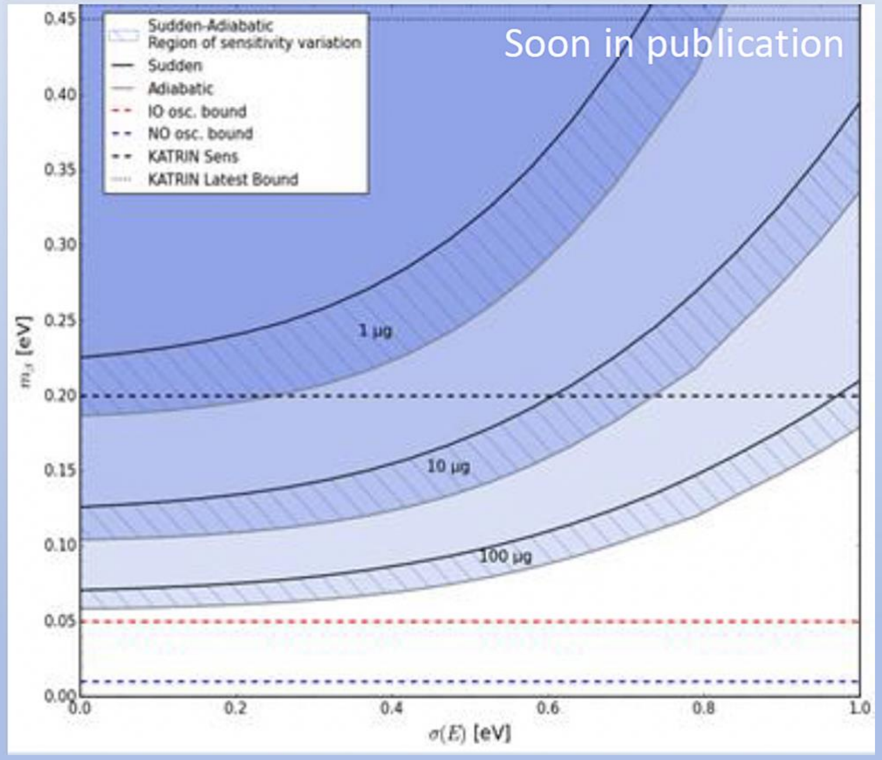
← Excellent

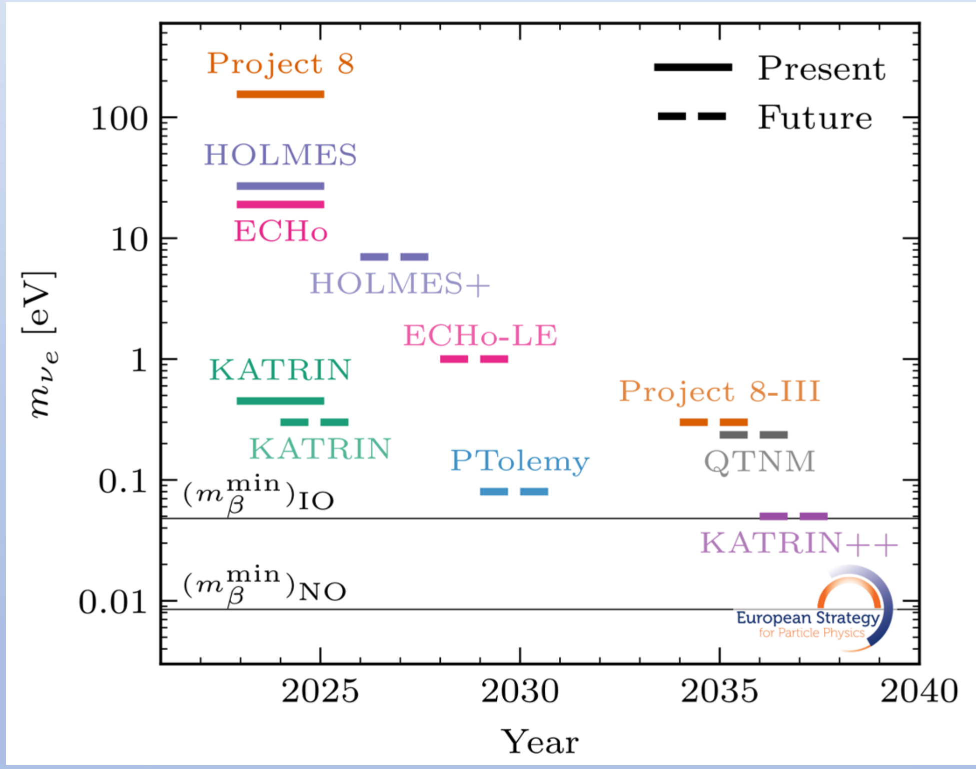
^{241}Pu produced in large quantities for fission reactor fuel

Continuous flow chemical separation methods to remove daughter isotopes (^{241}Am, ^{237}U /PUREX + γ/α veto)

Outlook: Mass Sensitivity

- Phase0(-2027): Demonstrate we master the technology, evaluate the transfer efficiency function from target region to the final measuring point (calorimeter)
- Phase1(2028-2030): demonstration of the ultimate energy resolution (50 meV) and realize the physics measurement on neutrino mass with 1 or few microgram of T

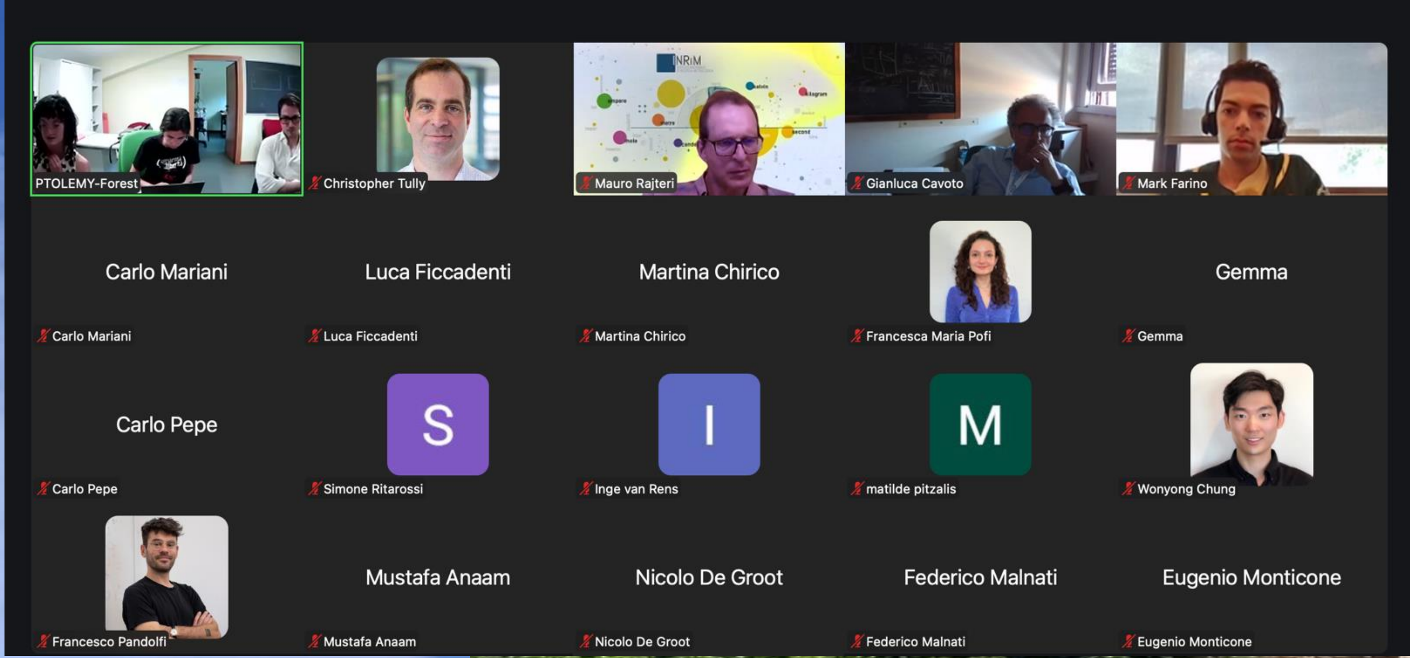




- Phase2(2030-): Work on PTOLEMY module with large T mass instrumentation in view of relic neutrino detection

https://arxiv.org/pdf/2511.03883

Work In Progress



Next month
@INRiM

Backup

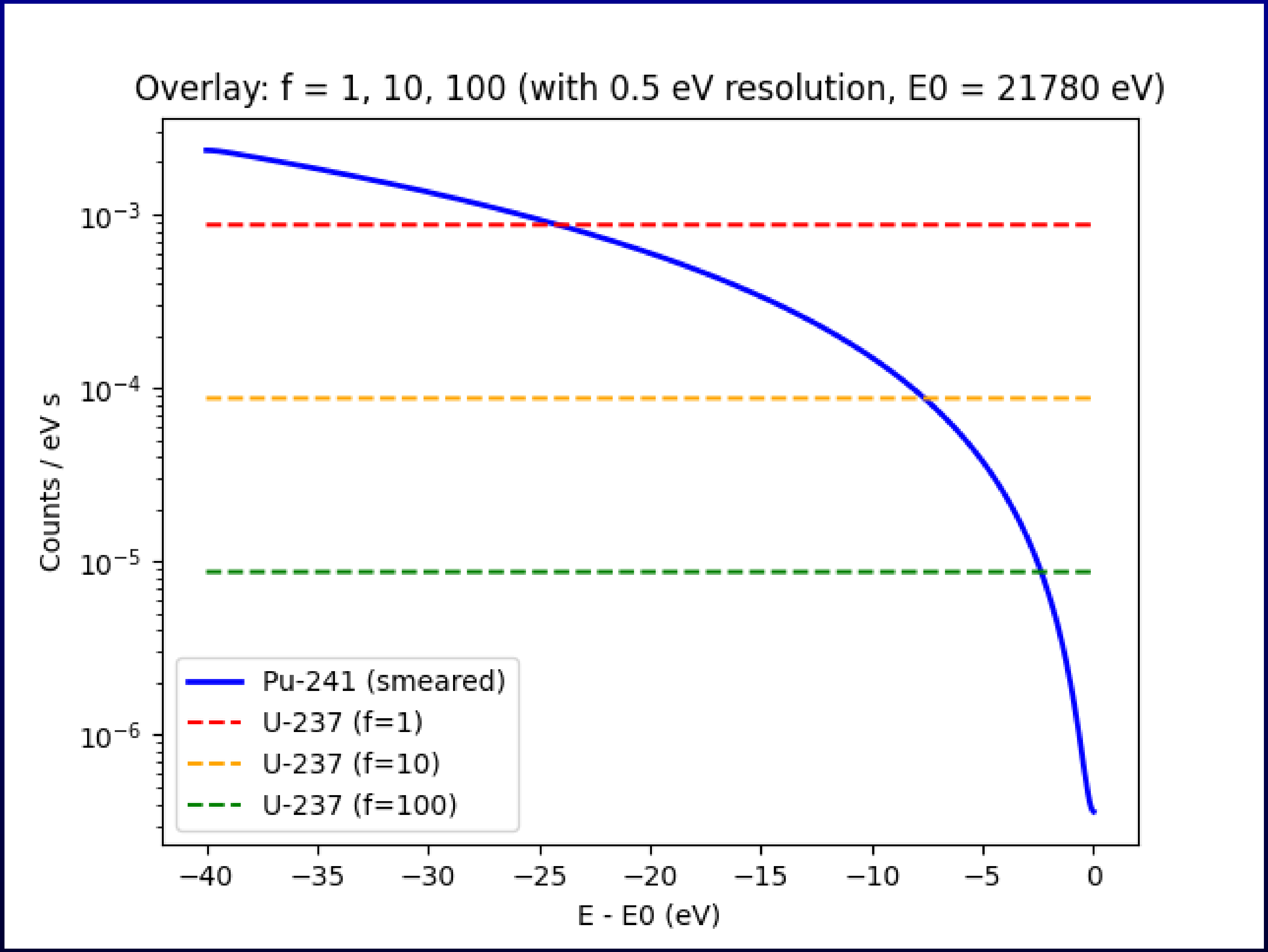
CONCLUSION

- PTOLEMY's goal is to eventually detect the cosmic neutrino background
- The detector prototype will be ready at LNGS by the end of this year
- Ultimate goals of the Demonstrator: instrumented mass ~ tens of μg, energy resolution ~ 50 meV
- "Intermediate" physics program of Demonstrator: neutrino mass measurements (or limits) striving to go beyond what has been achieved by all previous experiments.

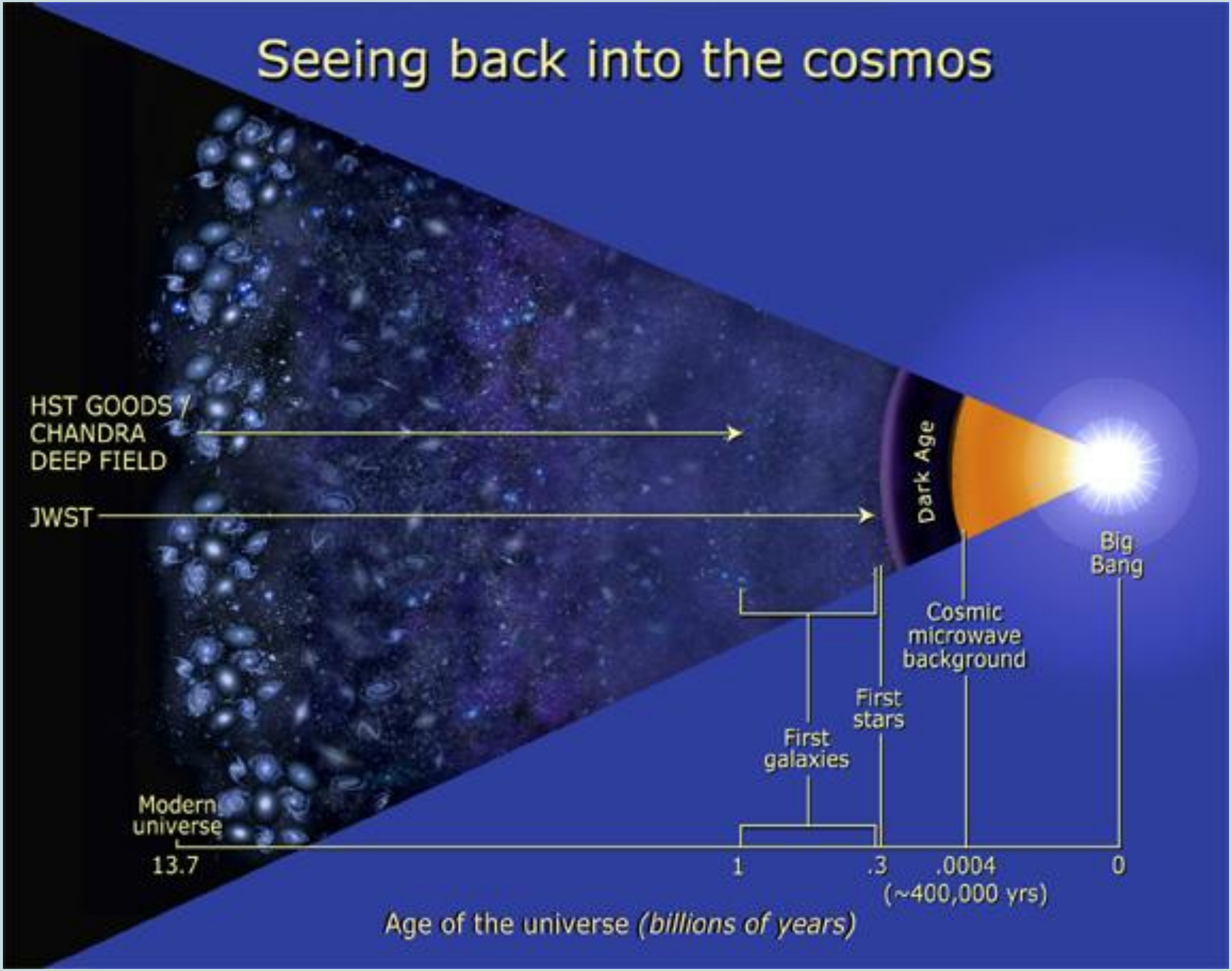
The PTOLEMY Collaboration

R. Ammendola,[1] A. Apponi,[2] G. Benato,[3,4] M.G. Betti,[5,6] R. Biondi,[3,4] P. Bos,[7,8] M. Cadeddu,[9] A. Casale,[10] O. Castellano,[2,11] G. Cavoto,[5,6] L. Cecchini,[5] E. Celasco,[12,13] M. Chirico,[5,6] W. Chung,[14] A.G. Cocco,[3] A.P. Colijn,[7,8] B. Corcione,[5,6,*] N. D'Ambrosio,[3] M. D'Incecco,[3] G. De Bellis,[5,15] M. De Deo,[3] N. de Groot,[16] A. Esposito,[5,6] M. Farino,[14] S. Farinon,[12] A.D. Ferella,[3,17] L. Ferro,[9,18] L. Ficcadenti,[5] G. Galbato Muscio,[5,19] S. Gariazzo,[20,21,22] H. Garrone,[20,23,24] F. Gatti,[12,13] F. Malnati,[20,23,25] G. Mangano,[26,27] L.E. Marcucci,[28,29] C. Mariani,[5,6] J. Mead,[7,8] G. Menichetti,[29] M. Messina,[3] E. Monticone,[20,23] M. Naafs,[7] S. Nagorny,[3,4] V. Narcisi,[9,18] F. Pandolfi,[5] R. Pavarani,[9,18] C. Pepe,[30] C. Pérez de los Heros,[31] O. Pisanti,[26,27] F.M. Pofi,[3,4] A.D. Polosa,[5,6] I. Rago,[5] M. Rajteri,[20,23] S. Ritarossi,[2,11] N. Rossi,[3] A. Ruocco,[2,11] G. Salina,[1] A. Santucci,[9,18] M. Sestu,[9,18] A. Tan,[14] V. Tozzini,[28,32] C.G. Tully,[14] I. van Rens,[16] F. Virzi,[3,17] G. Visser,[7] and M. Viviani[29]

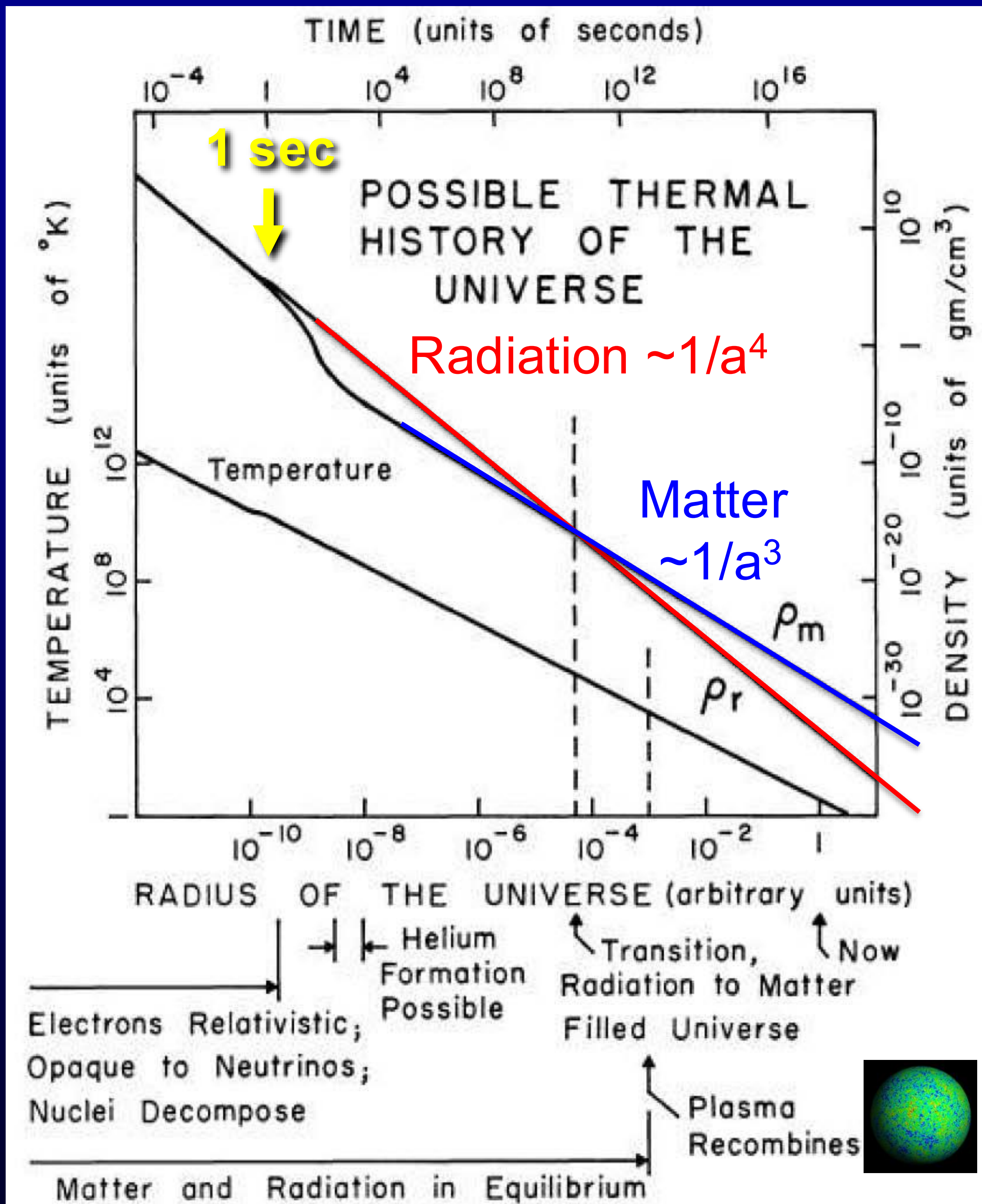
Active Purification of ^{241}Pu



”It may not be that hopeless.” [N. de Groot, 2026]


Seeing back into the cosmos
HST GOODS / CHANDRA DEEP FIELD
JWST
Dark Age
Big Bang
Cosmic microwave background
First stars
First galaxies
Modern universe
13.7
1
.3
.0004
(~400,000 yrs)
0
Age of the universe (billions of years)

Cosmic Neutrino Background



Number density:

$n_\nu = 112/cm^3$

Temperature:

$T_\nu \sim 1.95K$

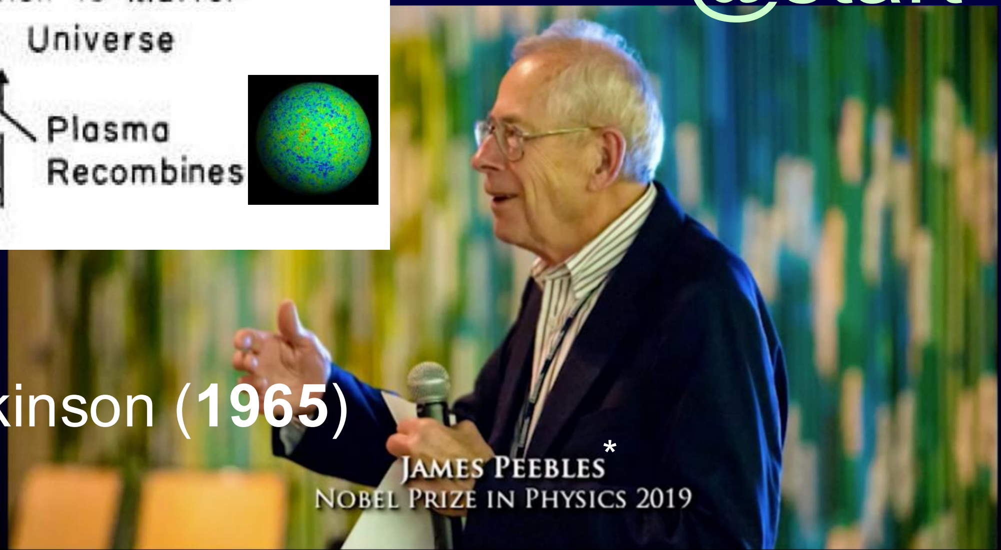
Time of decoupling:

$t_\nu \sim 1$ second

~50% of the Total Energy Density of the Universe @ 1 sec

neutron/proton ratio @start of nucleosynthesis

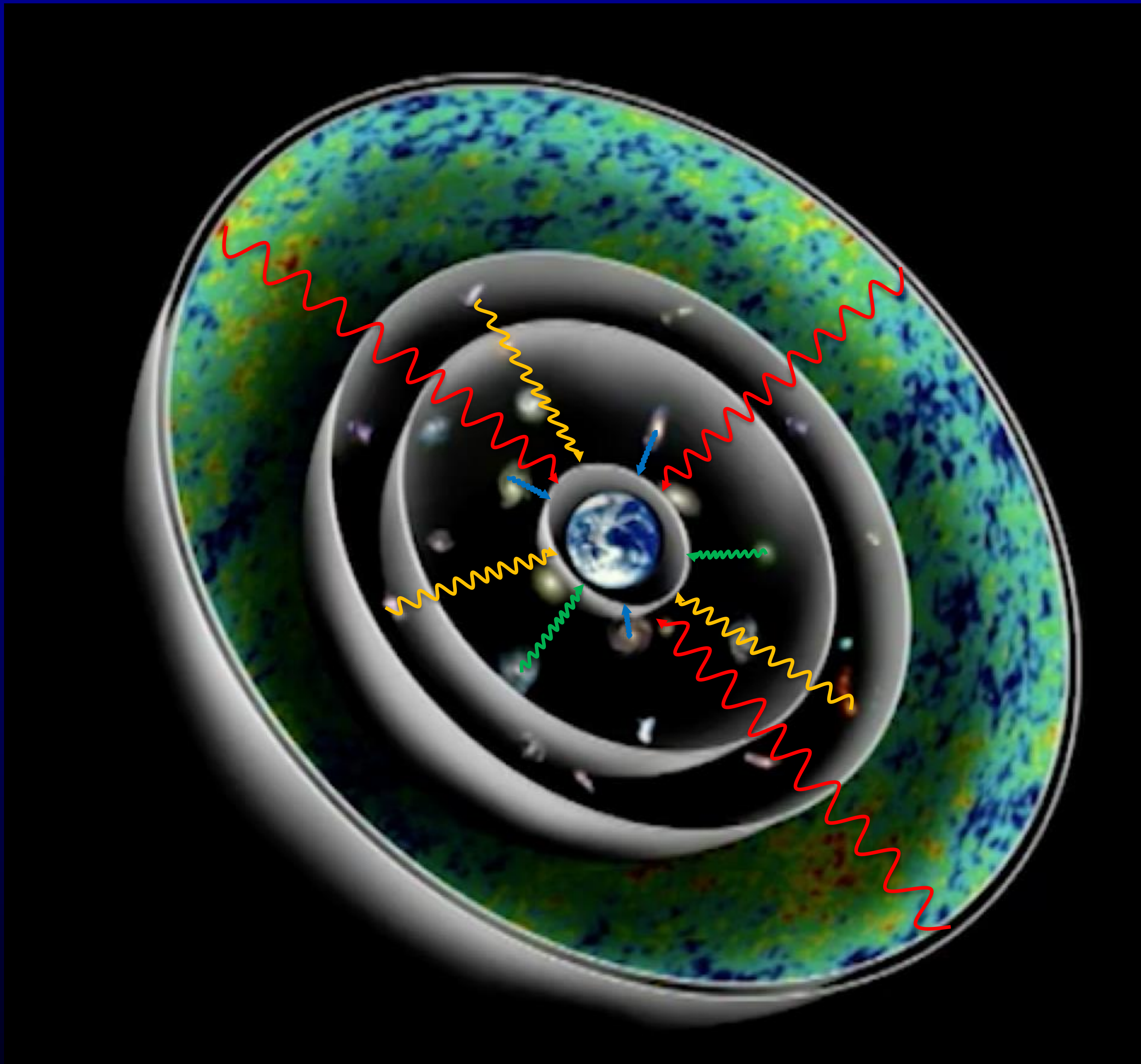
→ ^4He
^2H
(^3He)
^7Li



Dicke, Peebles*, Roll, Wilkinson (**1965**)

Cosmology's Century (2020)

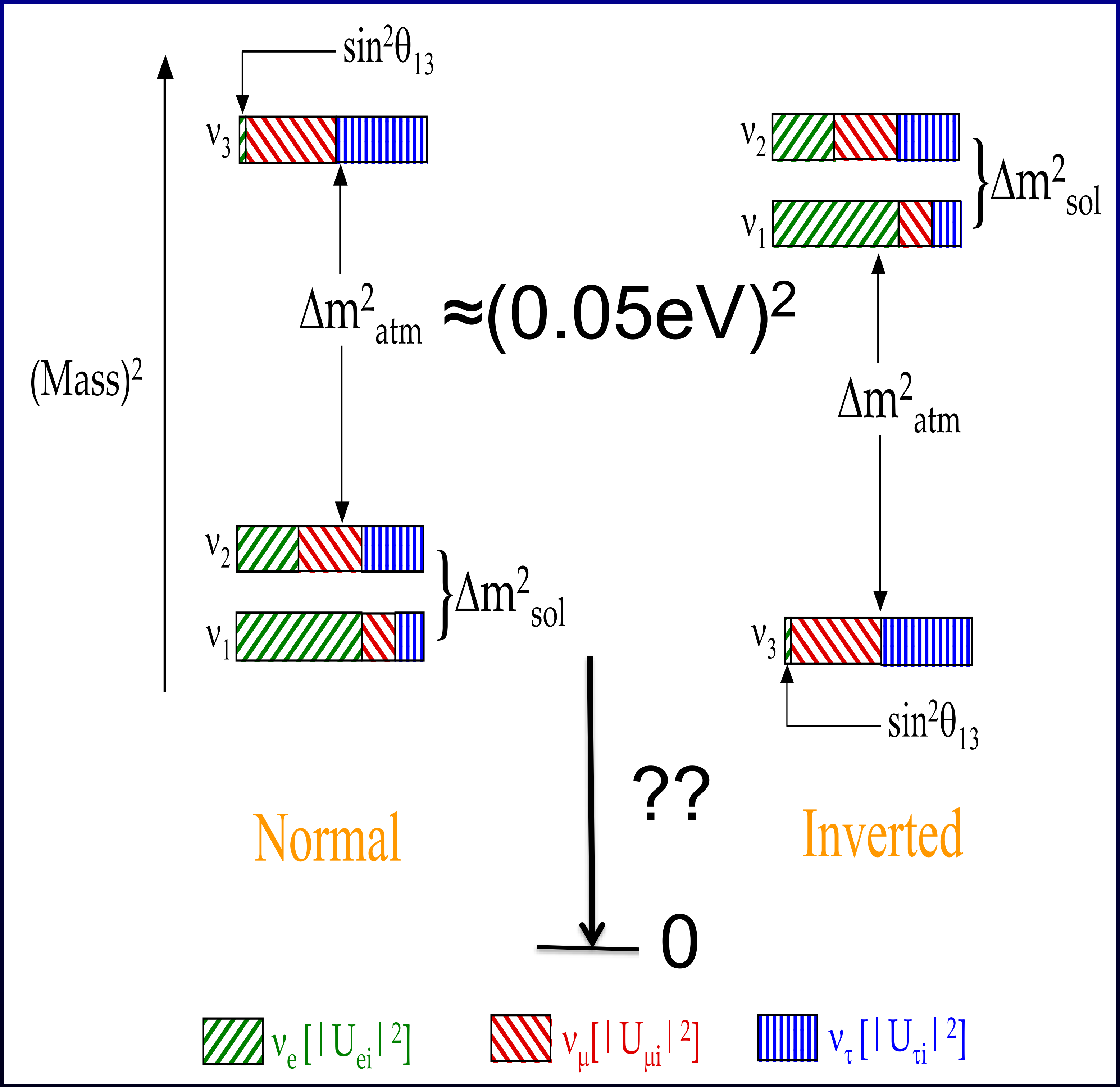
Looking Back in Time with Photons



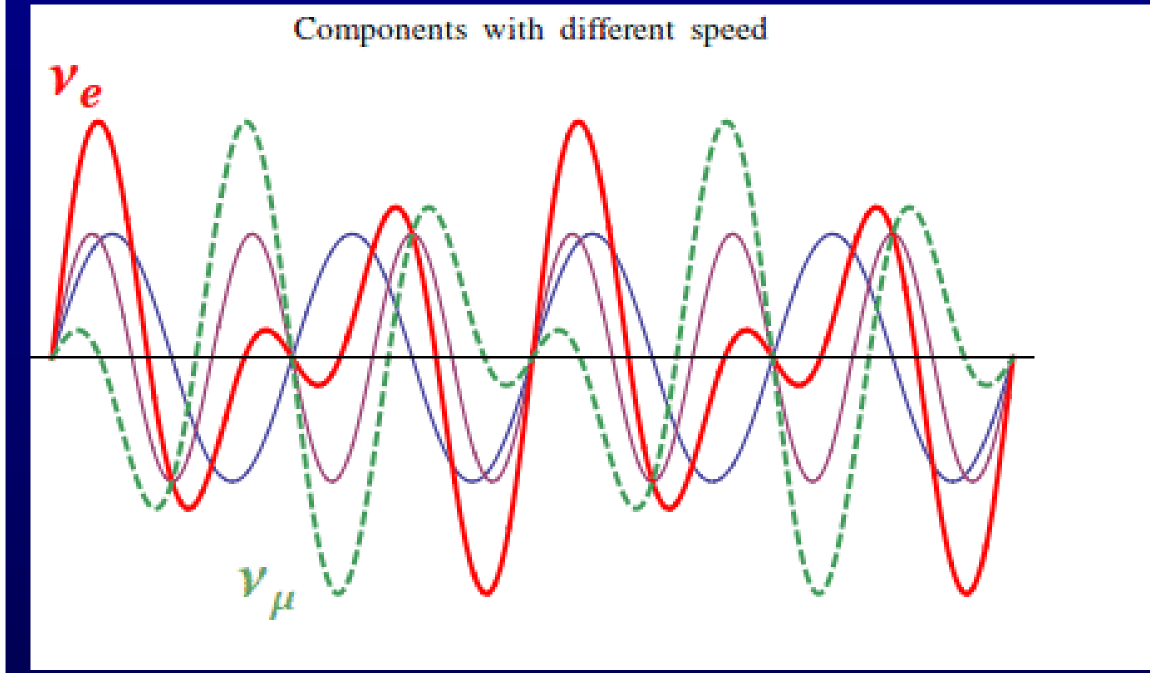
Emission Time

- -13.8×10^{9} years
- -4×10^{9} years
- -200×10^{6} years
- -2×10^{6} years

Neutrino Masses from Oscillations

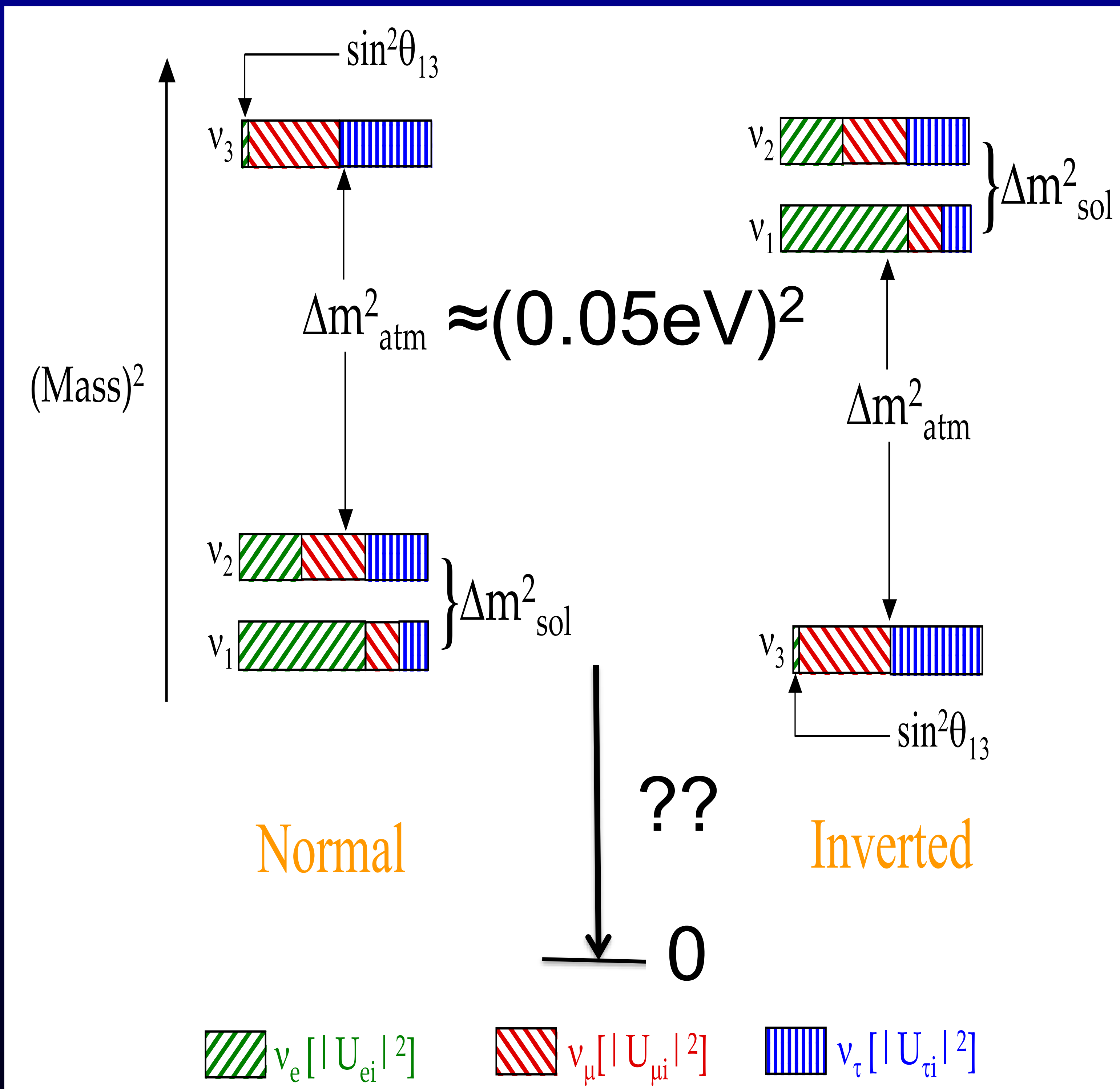


Theory developed by
Bruno Pontecorvo

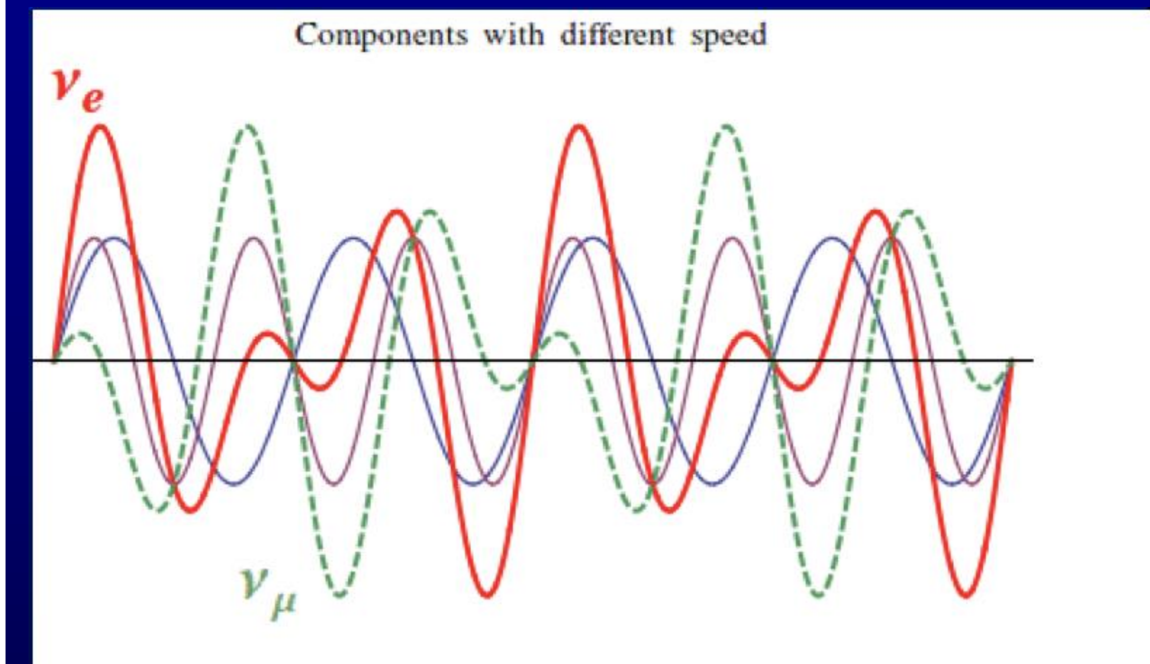


3 mass eigenstates
X
3 flavors
(electron, muon, tau)

Neutrino Masses from Oscillations

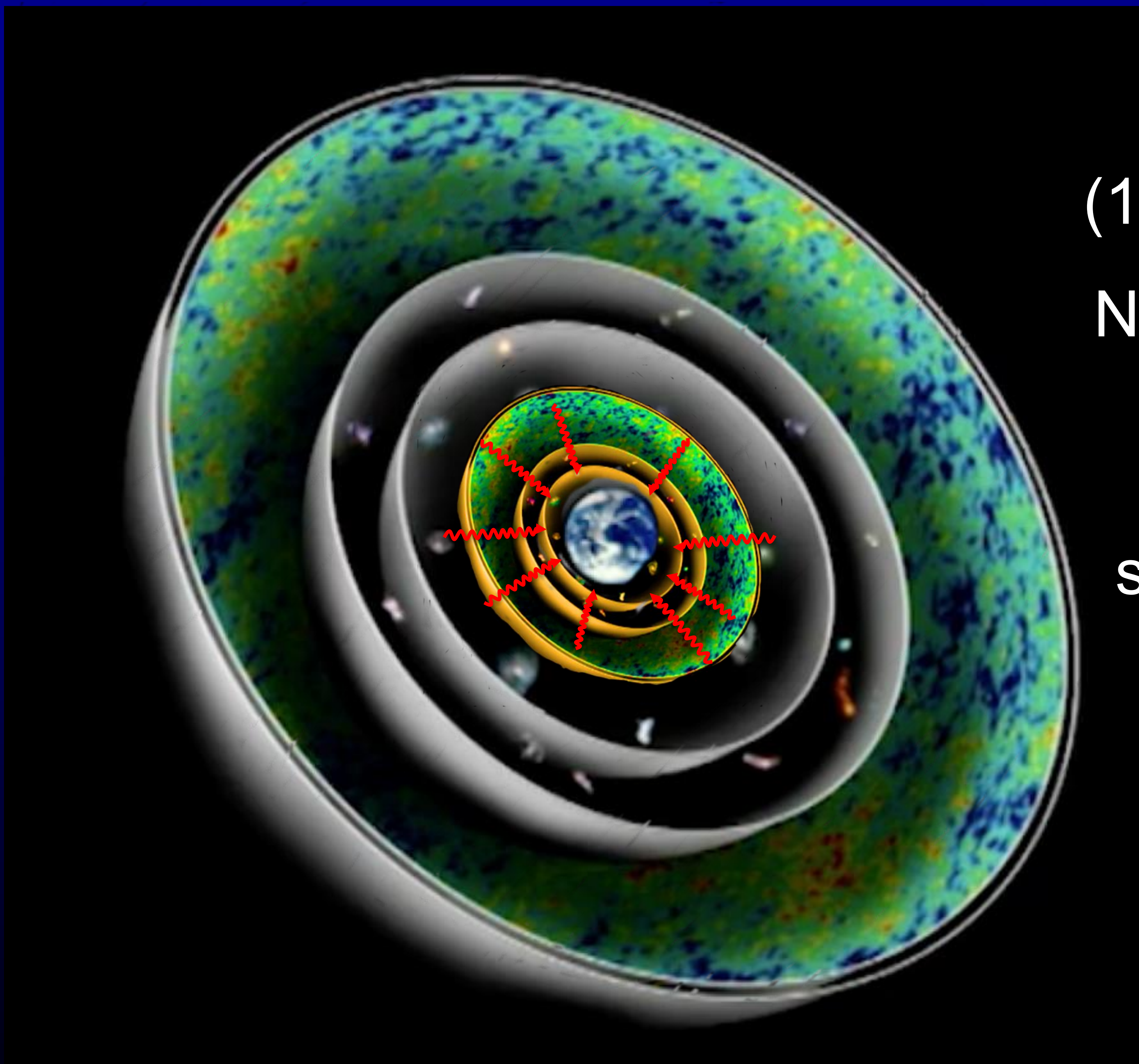


Theory developed by Bruno Pontecorvo



3 mass eigenstates
X
3 flavors
(electron, muon, tau)

Massive Neutrino Timeline



<u>Emission Time</u>

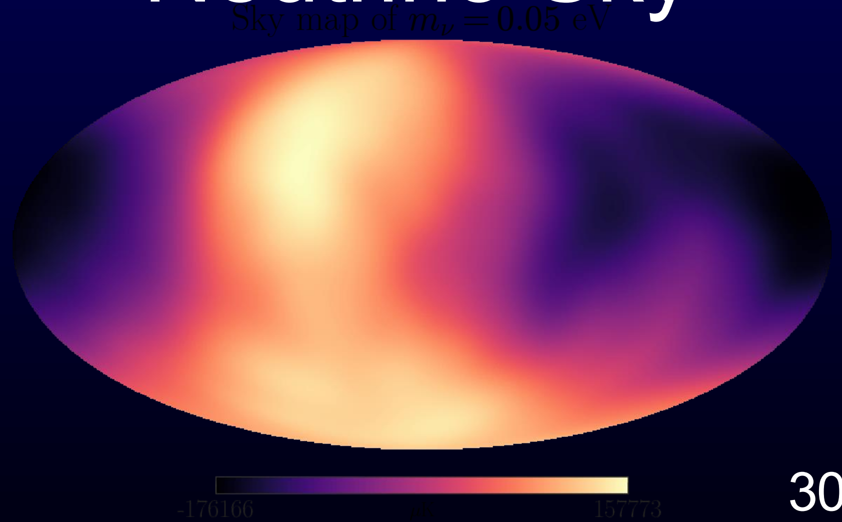
-13.8x10^9 years

(1 second after Big Bang)

No comparable flux from other sources

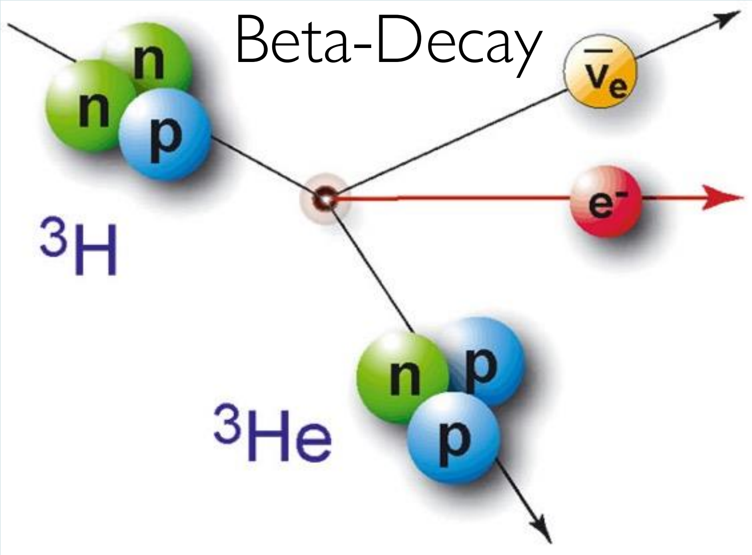
Starting radius more spread out due to mass

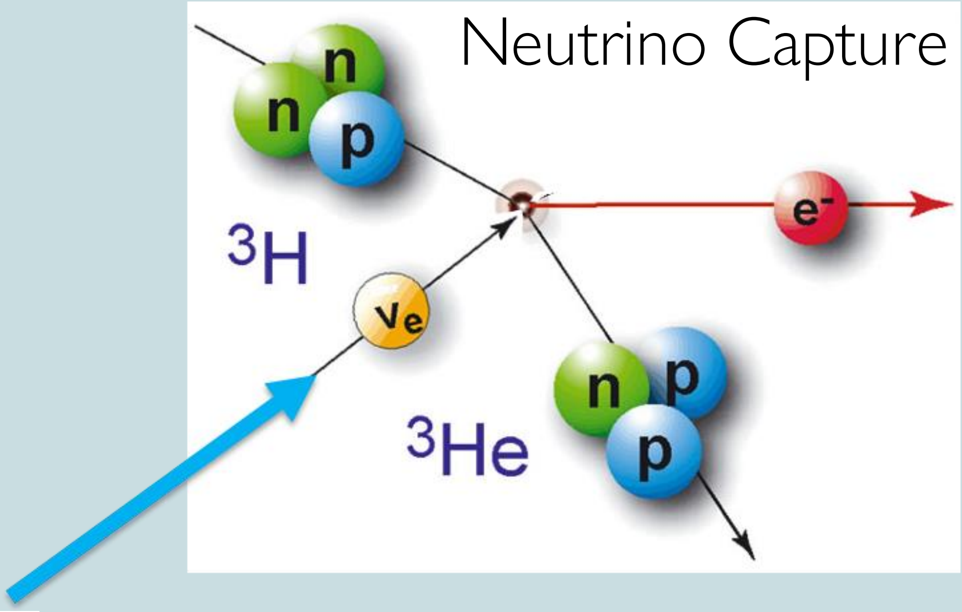
Neutrino Sky

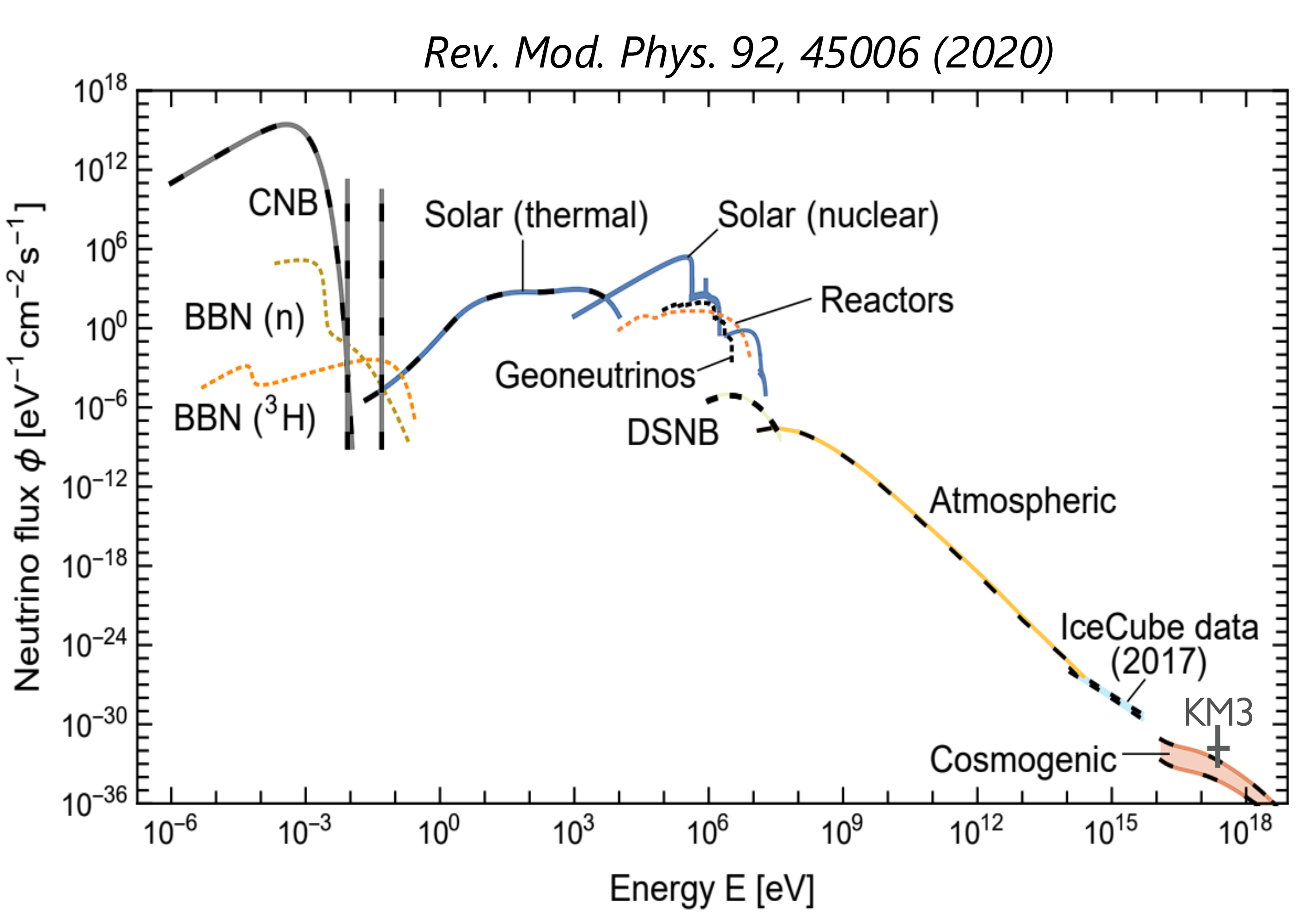


PTOLEMY - RELIC NEUTRINO DETECTION

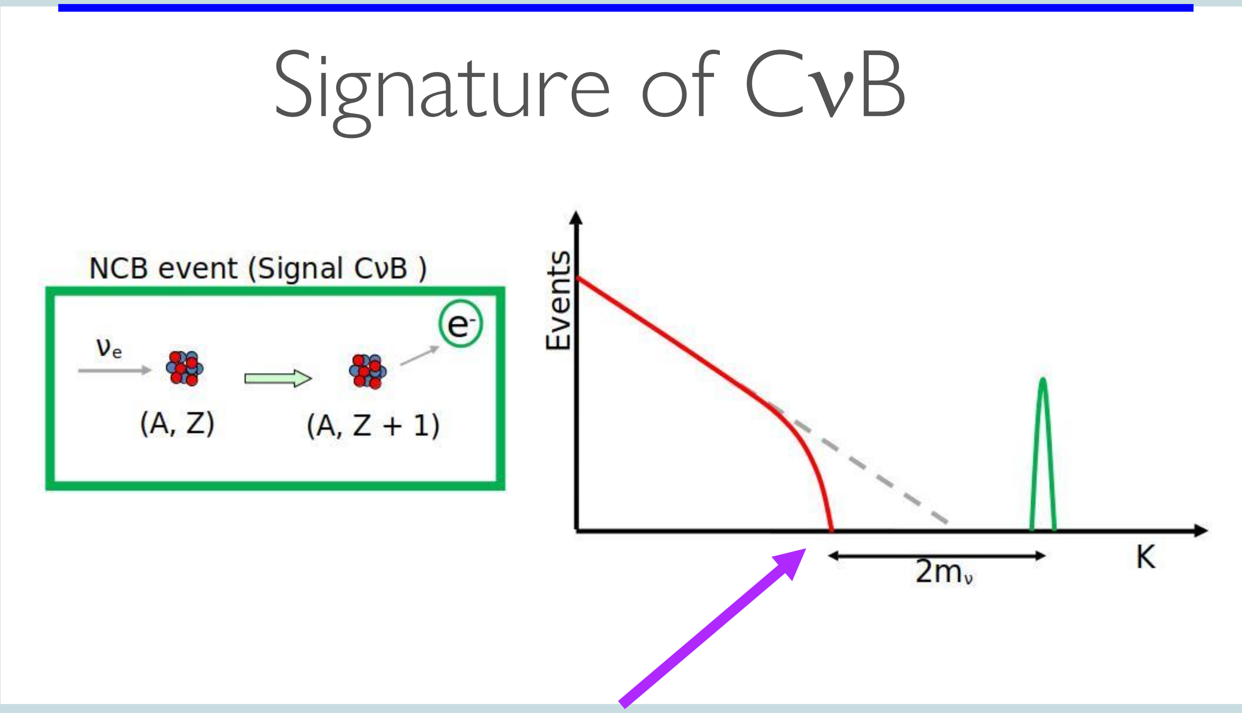
PonTecorvo Observatory for Light Early-universe Massive-neutrino Yield







[DOI: 10.1088/1475-7516/2007/06/015](https://doi.org/10.1088/1475-7516/2007/06/015)



Neutrino Mass Effect on Endpoint Predicted by Enrico Fermi

IDEA OF ENRICO FERMI

91 year anniversary!

Fermi, E. Versuch einer Theorie der β-Strahlen. I. *Z. Physik* **88**, 161–177 (**1934**).
https://doi.org/10.1007/BF01351864

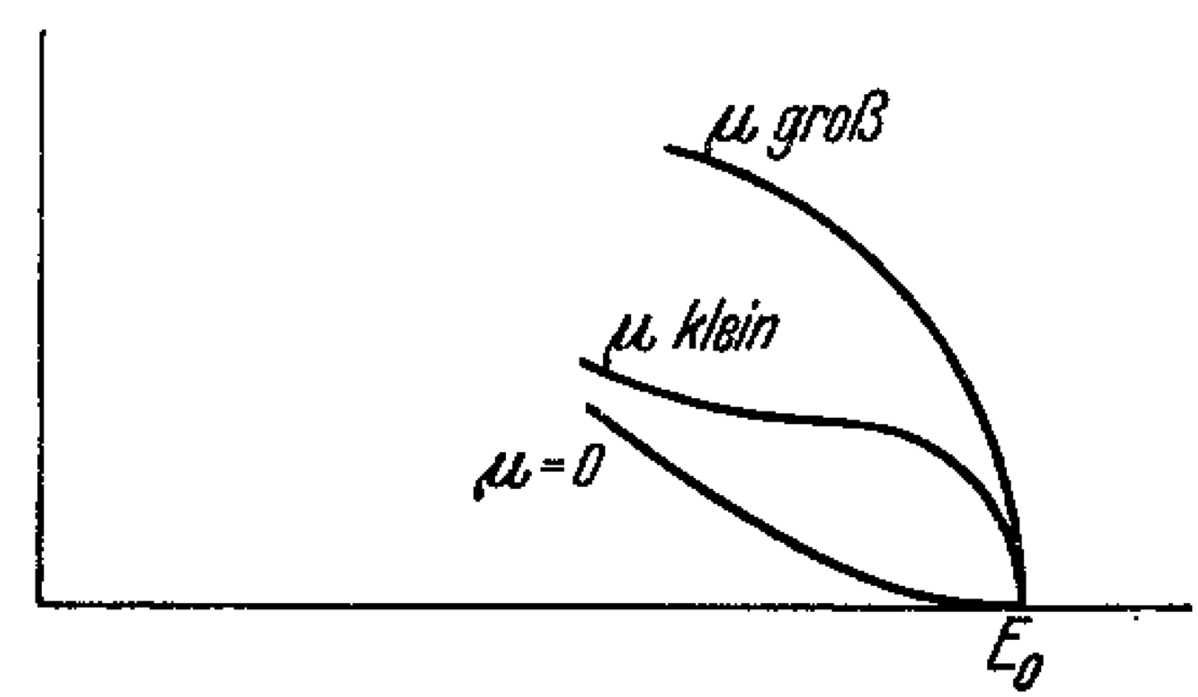
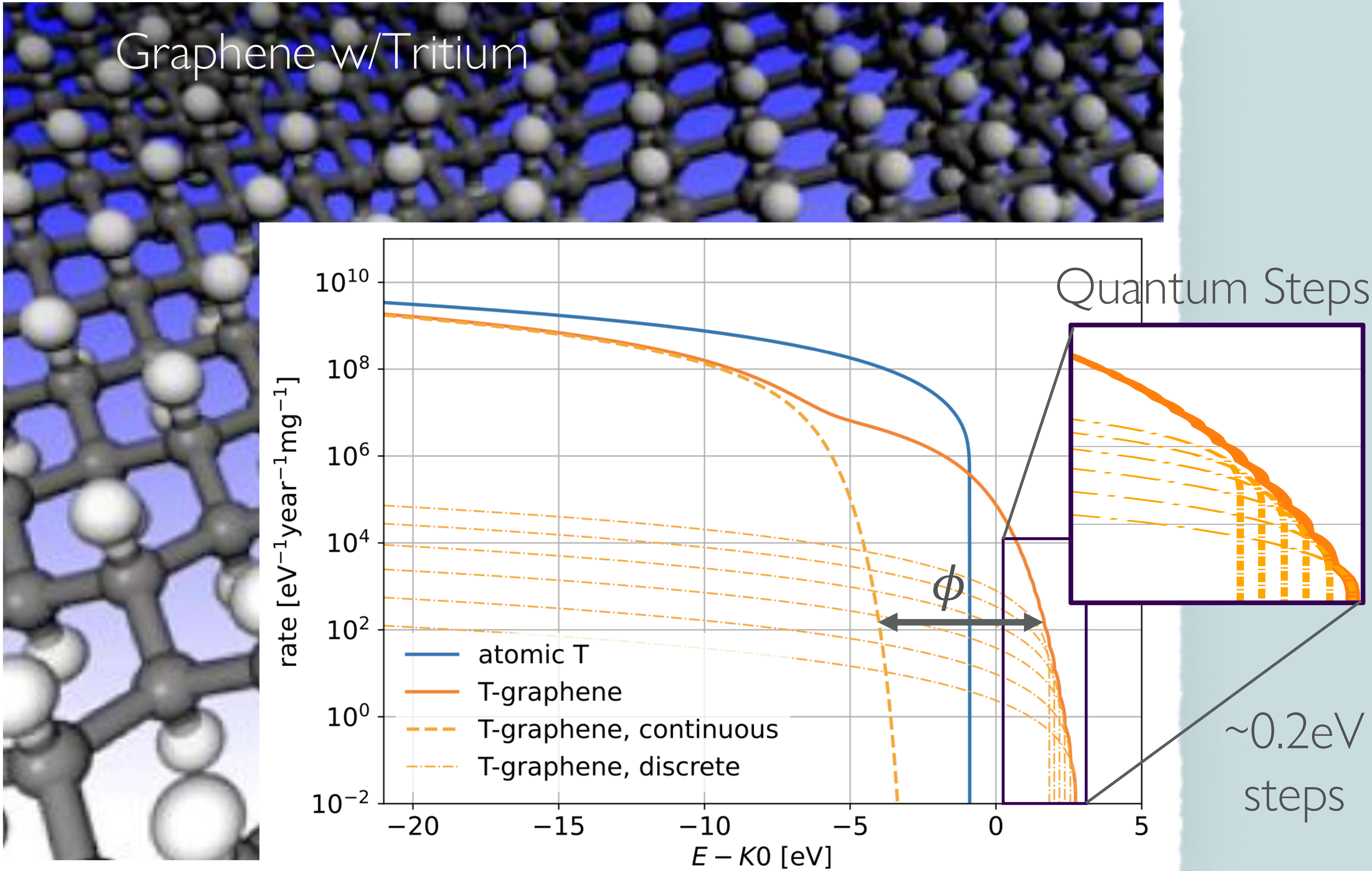


Fig. 1.

The neutrino masses are so tiny, their effects are smaller than atomic transitions in normal materials.
(There is a reason that there are no units on this plot.)

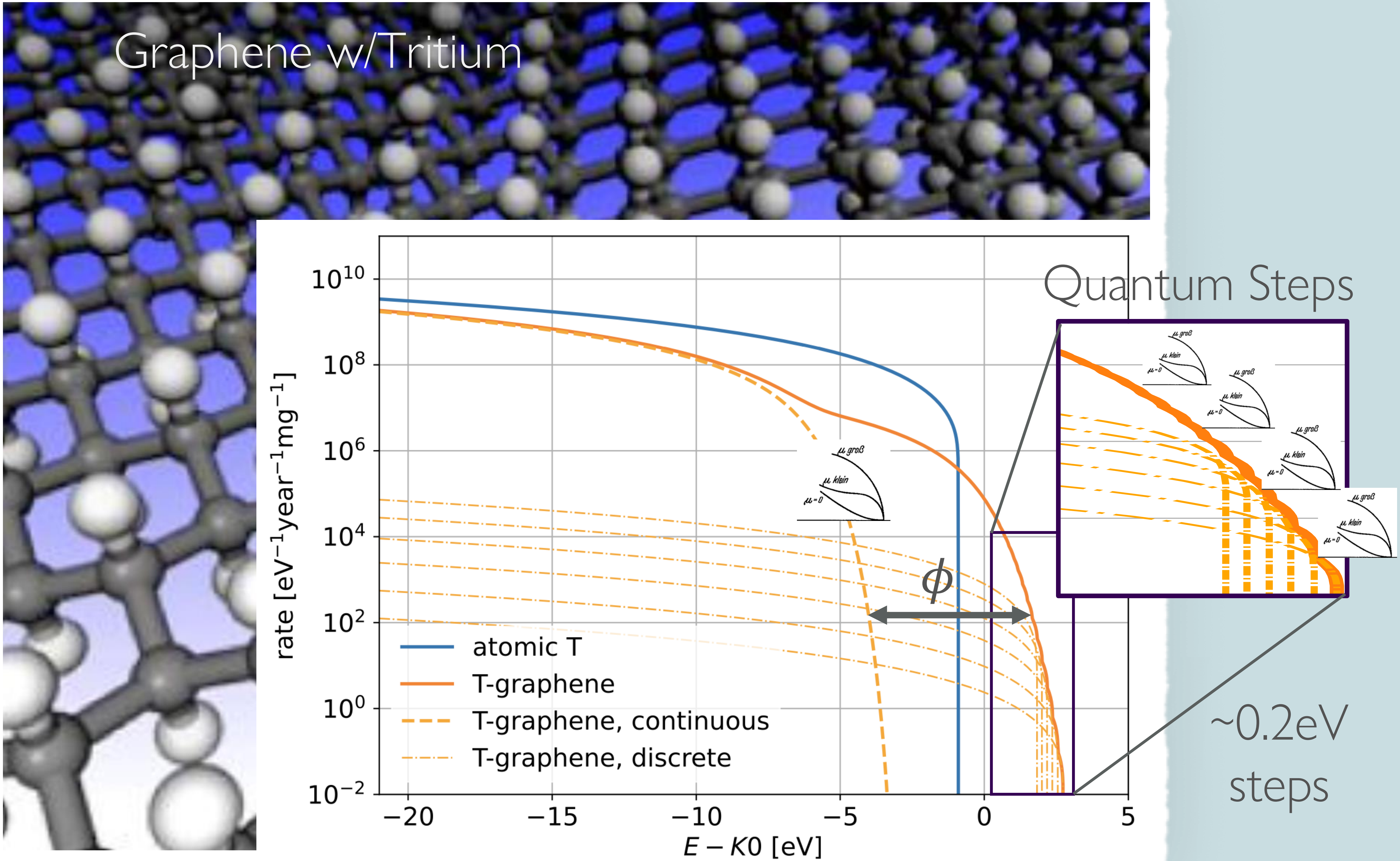
PTOLEMY: 2D MATERIAL - GRAPHENE



Other graphene structures also under study

$\phi \equiv$ "Atomic" work function

PTOLEMY: 2D MATERIAL - GRAPHENE

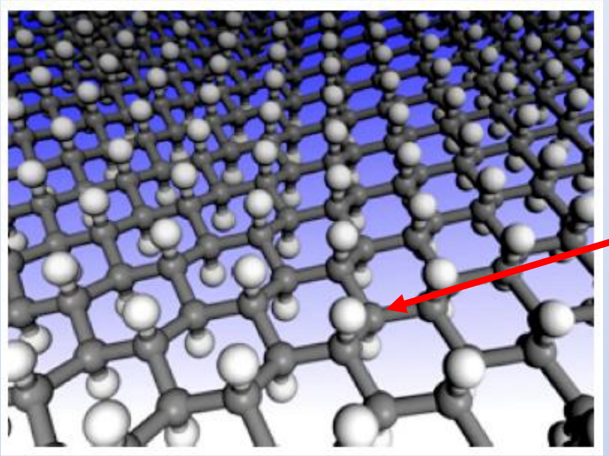


Other graphene structures also under study

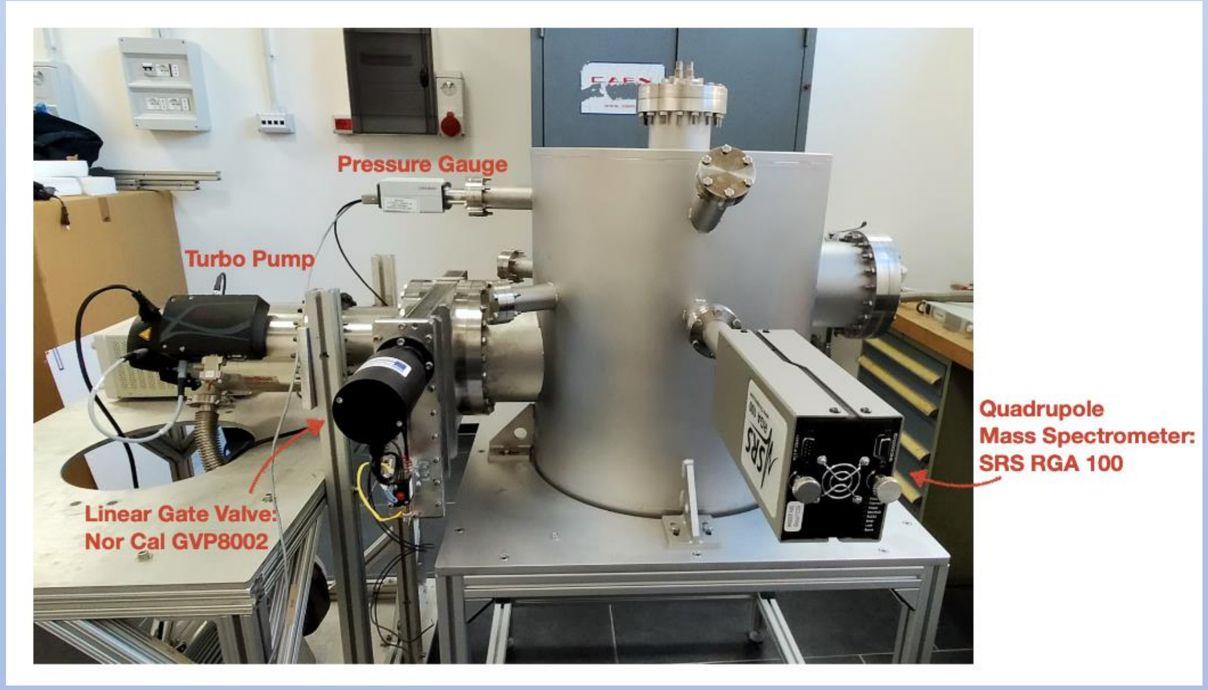
$\phi \equiv$ "Atomic" work function

Fabrication of a Tritiated-Graphene Target/Source
Hydrogen and Deuterium loading on graphene at Roma1 and Roma3

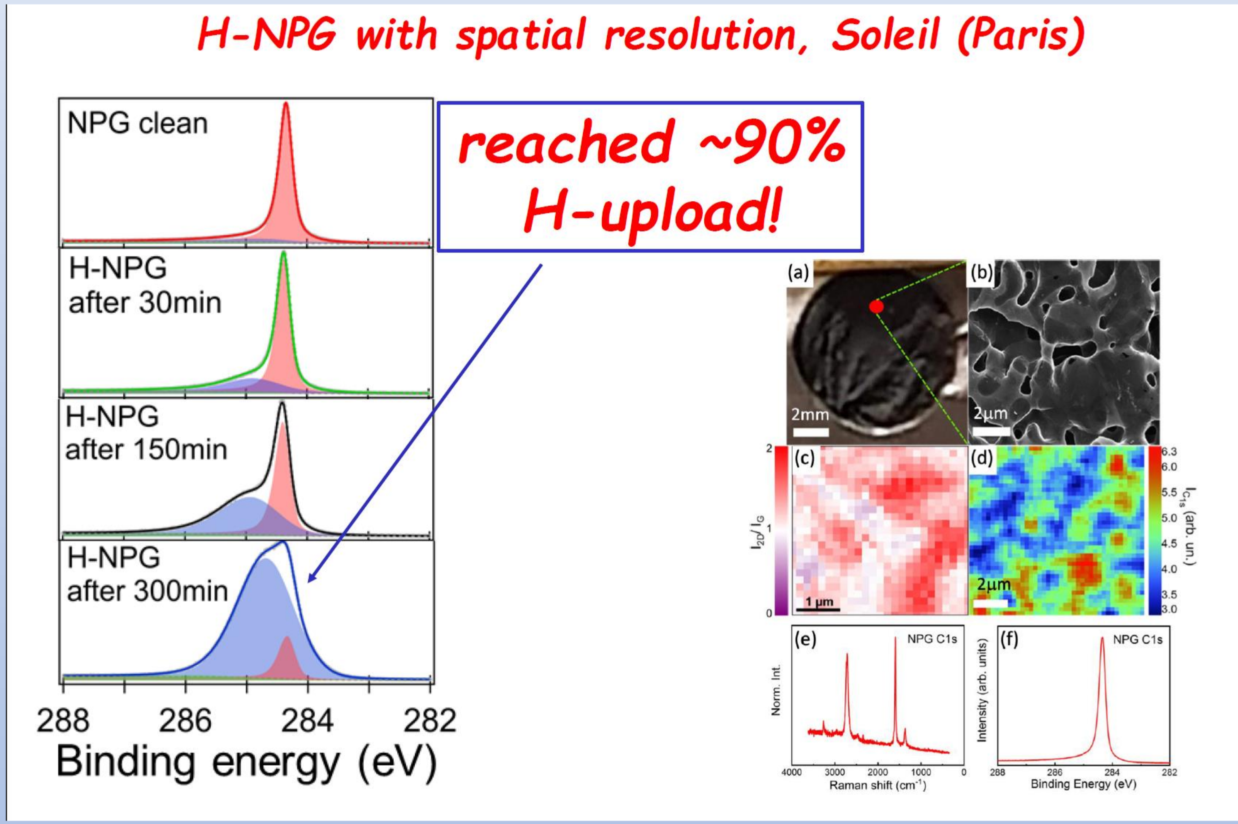
atomic H as a tool to '*pinch*' the sp^2 bonds towards a sp^3 configuration
while maintaining the planar nature of graphene



T-chamber in Rome side view:



H on Nanoporous Graphene (NPG):



Betti et all, Nano Lett. **22**, 2971 (2022)

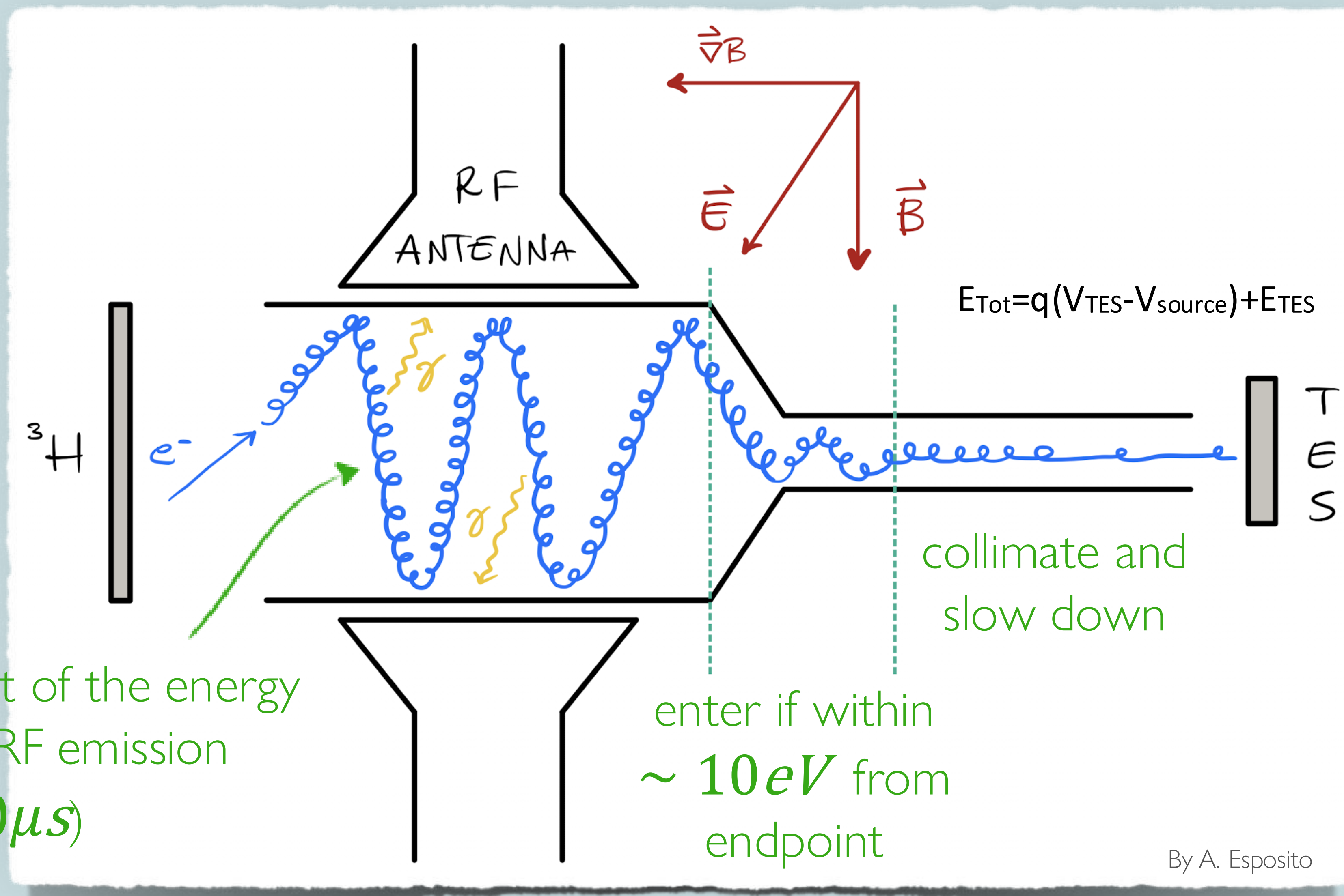
UKAEA's Active Gas Handling System
(tritium for JET, EU Tokamak) for
feasibility study & design requirement of a
new T loading chamber

PTOLEMY: THE IDEA

JINST 17 (2022) 05, P05021

- A new electromagnetic filter idea based on RF detection and dynamic E setting

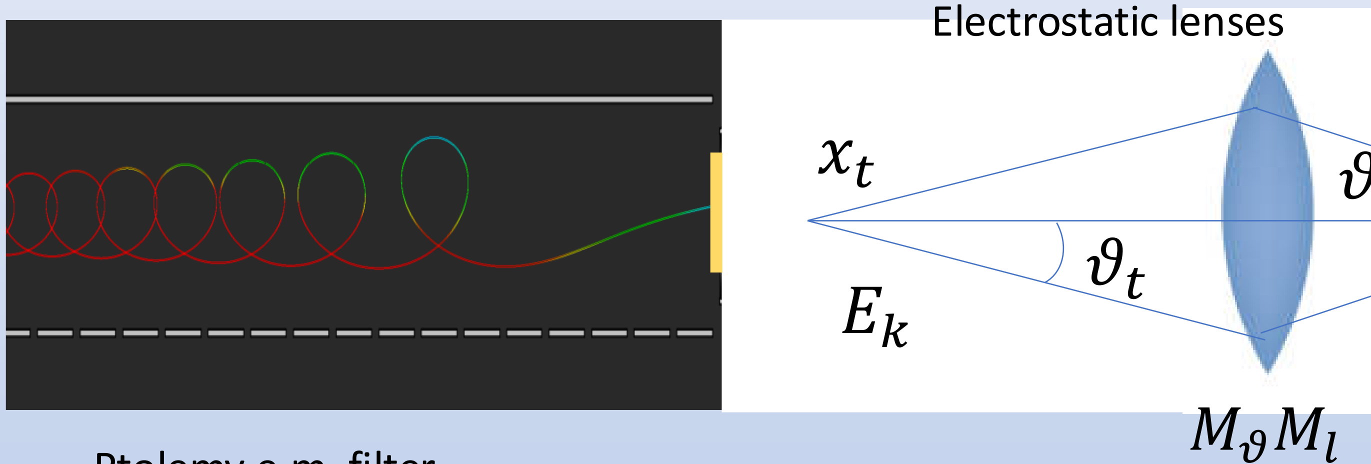
ΔV known to 1 ppm precision



first measurement of the energy via cyclotron RF emission ($\sim 10\mu s$)

Precision energy measurement from Condensed Matter/ARPES

Electostatic analyser

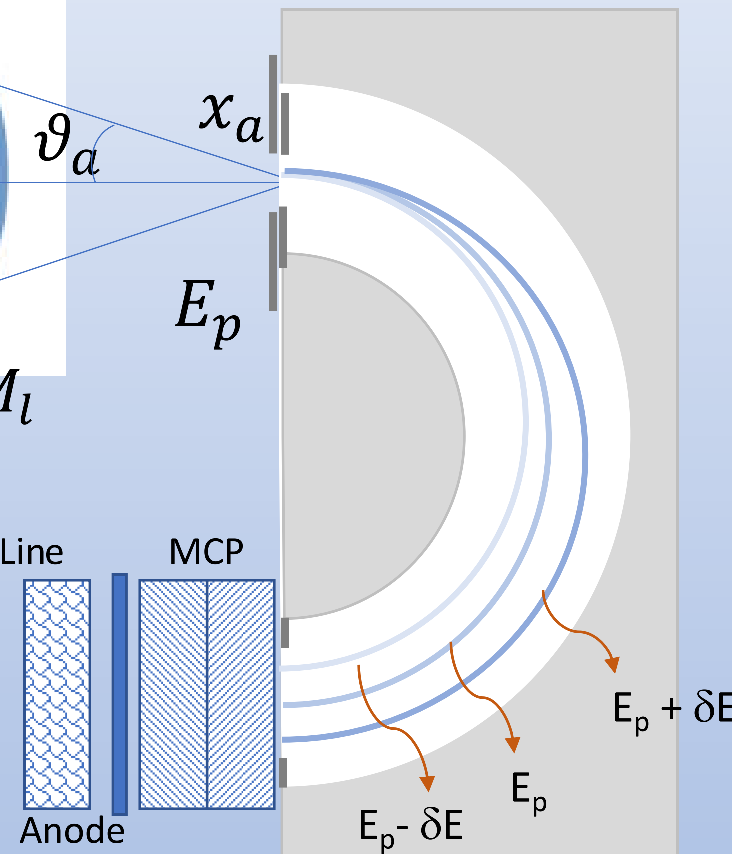


Ptolemy e.m. filter

Electron optic basic equation

Helmholtz – Lagrange law

$$x_t \vartheta_t \sqrt{E_k} = x_a \vartheta_a \sqrt{E_p}$$



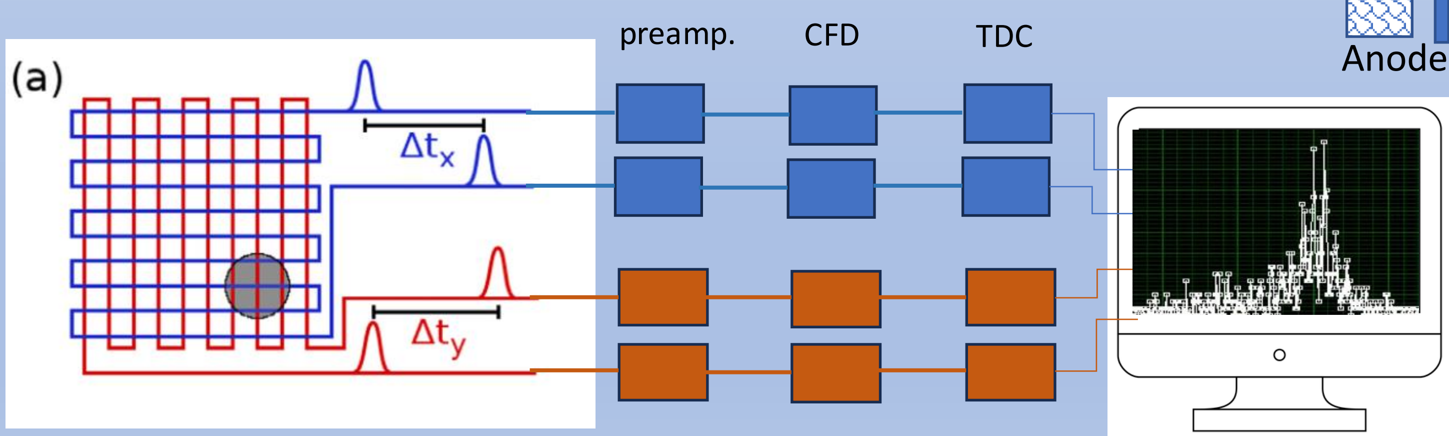
Two concentric hemispheres for the energy selection

Energy resolution (bandpass energy):

$$\frac{\Delta E}{E_p} = \frac{x}{2R_0} + \frac{\vartheta^2}{4}$$

ΔE: energy resolution
E_p : pass energy
x: slit width
R_0: mean radius
θ: accepted angle

Position sensitive detector (MCP+delay line) allows parallel acquisition



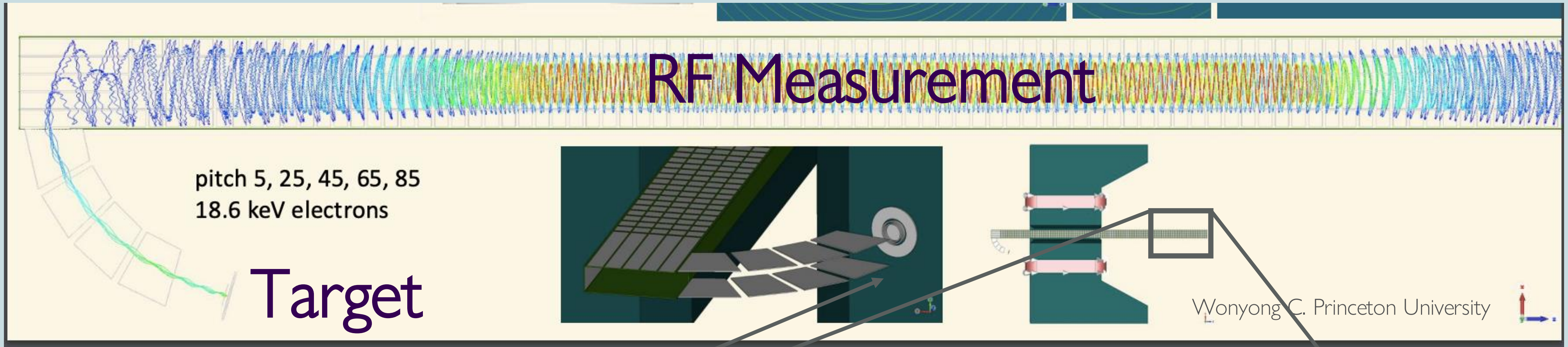
Specs Phoibos 225

~few meV energy resolution

Detailed simulation of the PTOLEMY filter

Magnet 1 T field
RF region

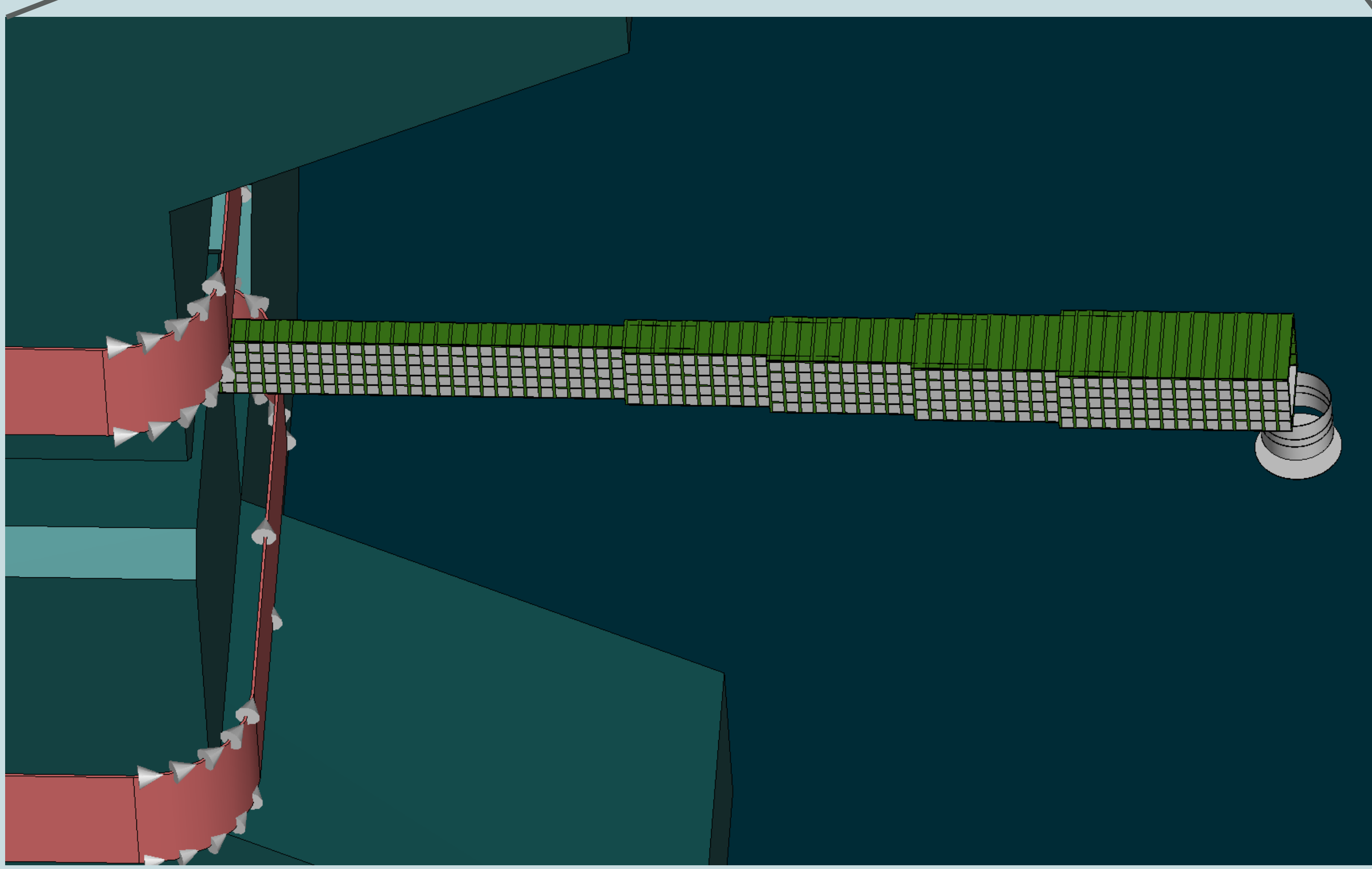
Filter region



Micro-Cal

Geometry relying on modularity approach to increase instrumented target mass

Micro-calorimeter region with focusing system to match beam and calorimeter array



Zero B Field FOCUSING
with Einzel lens (90 degress

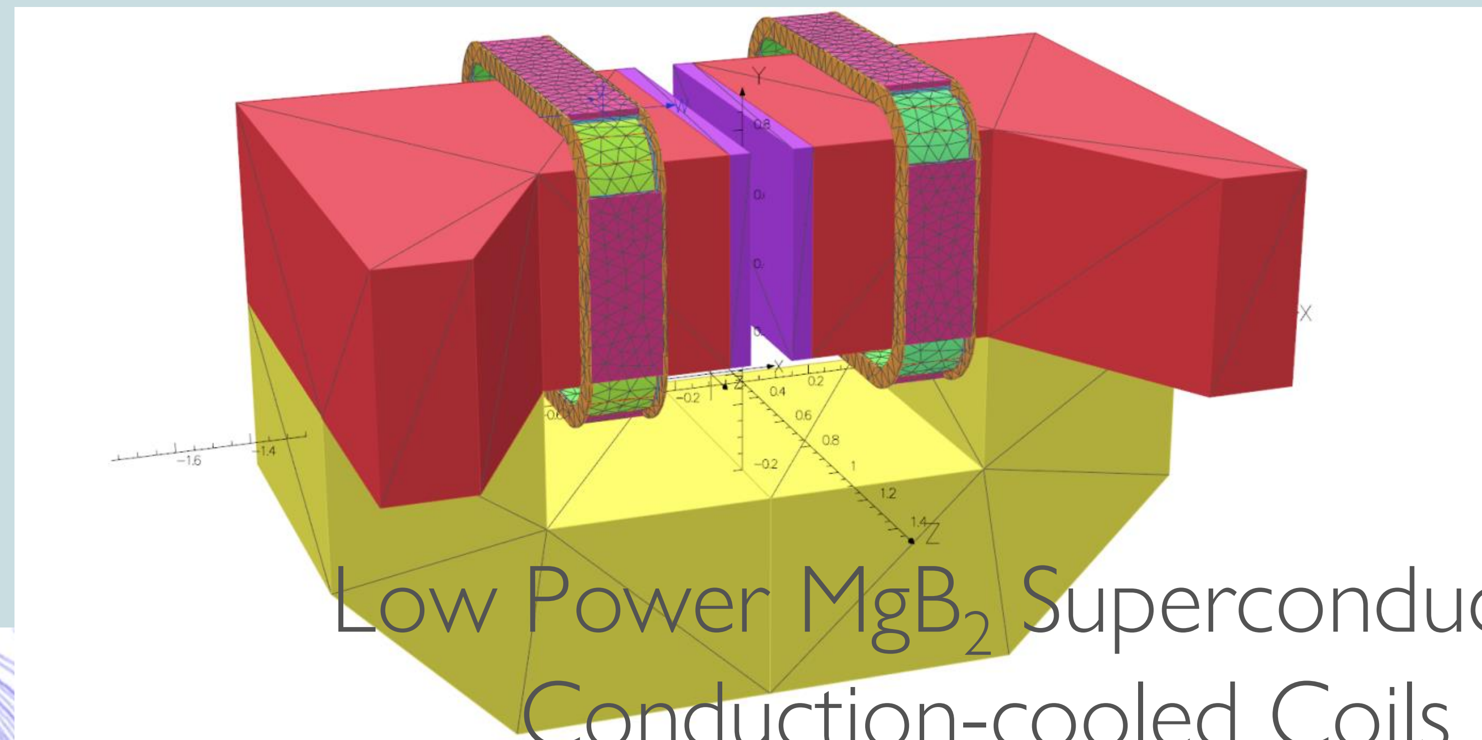
Microcalorimeter

DEMONSTRATOR MAGNET

BEING BUILT AND WILL BE INSTALLED AT THE LNGS
KEY ELEMENT TO REALIZE THE PTOLEMY EXPERIMENT

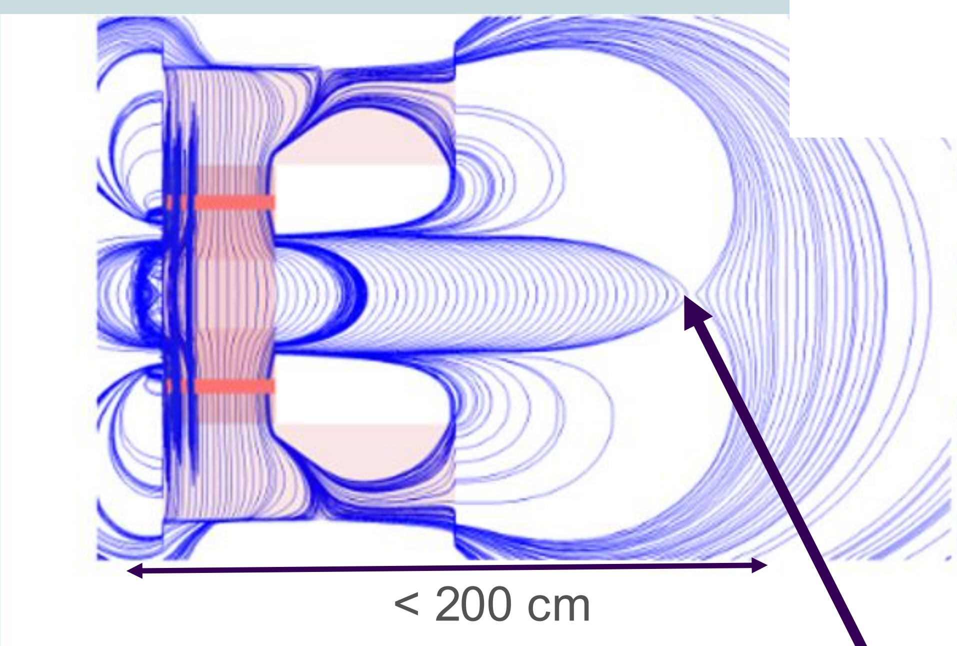
Construction ASG/Suprasys consortium of a SC dipole with special attention to the fringe field

Under construction in Genova → Shipment to CERN → LNGS



Low Power MgB_2 Superconducting Conduction-cooled Coils

Simulated B-map



Zero B field saddle point key feature of the field map

The PTOLEMY Collaboration