PTOLEMY

How to unravel early moments of the Universe with neutrinos: Introduction to the PTOLEMY project

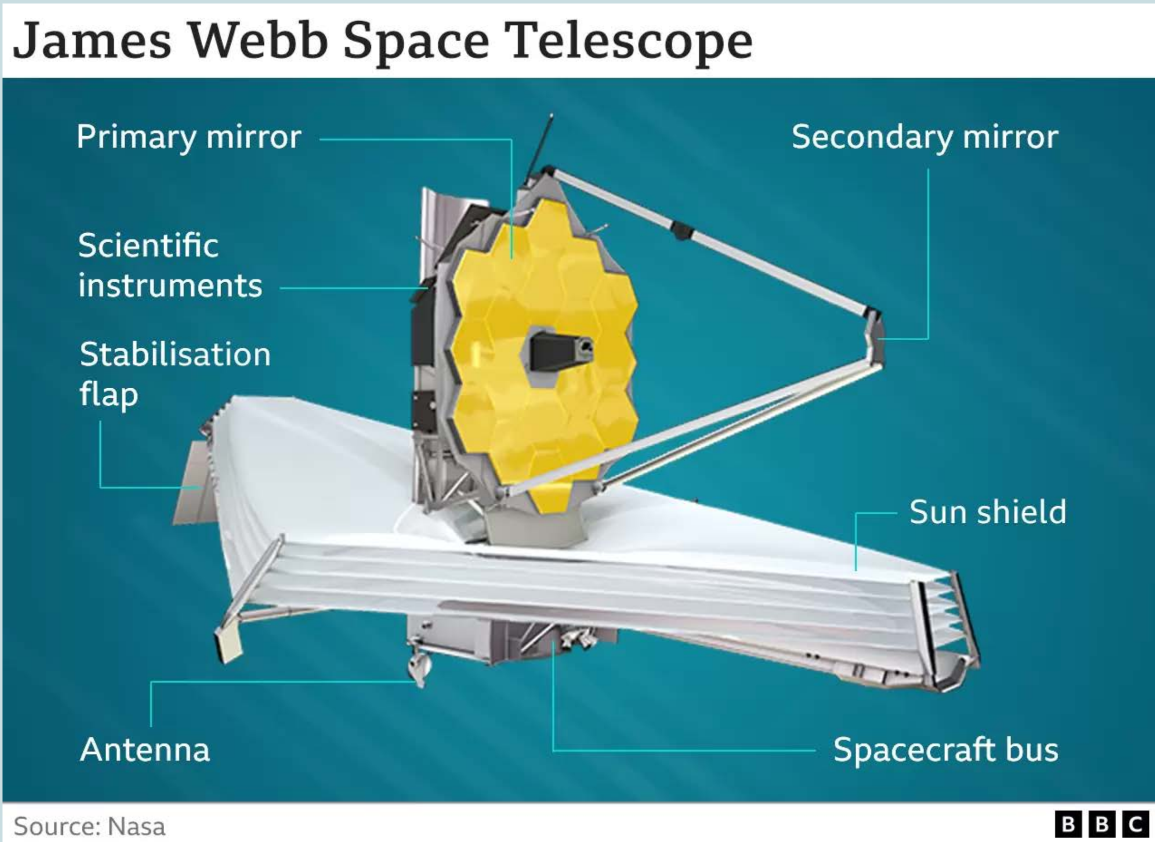
Chris Tully (Princeton University)

22 April 2025

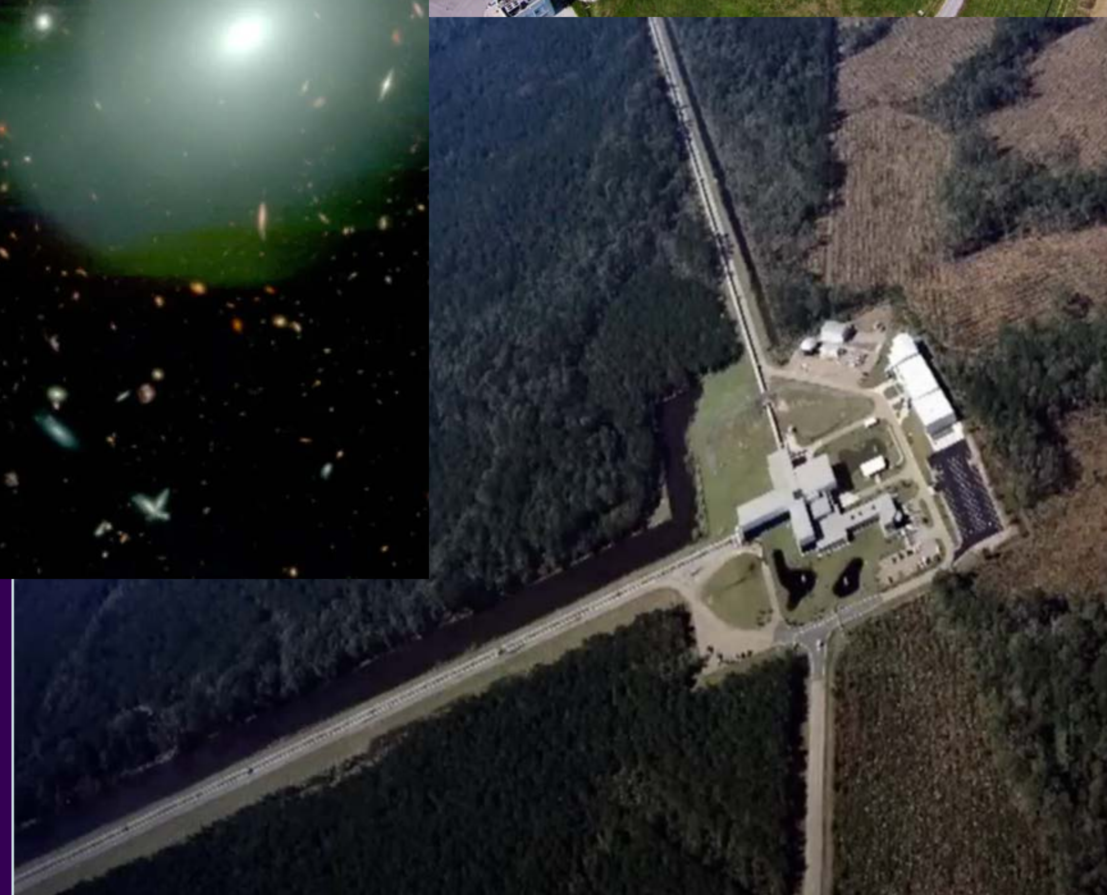
APC Astroparticule & Cosmologie, Université Paris Cité, Paris, France

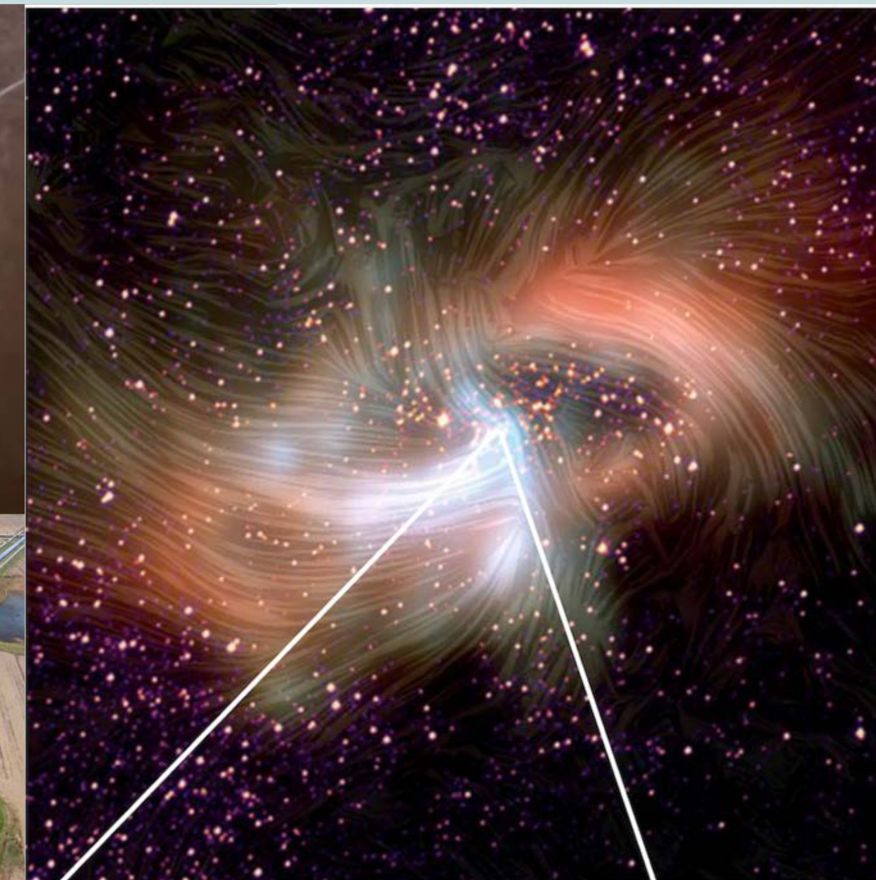
Research supported by John Templeton Foundation

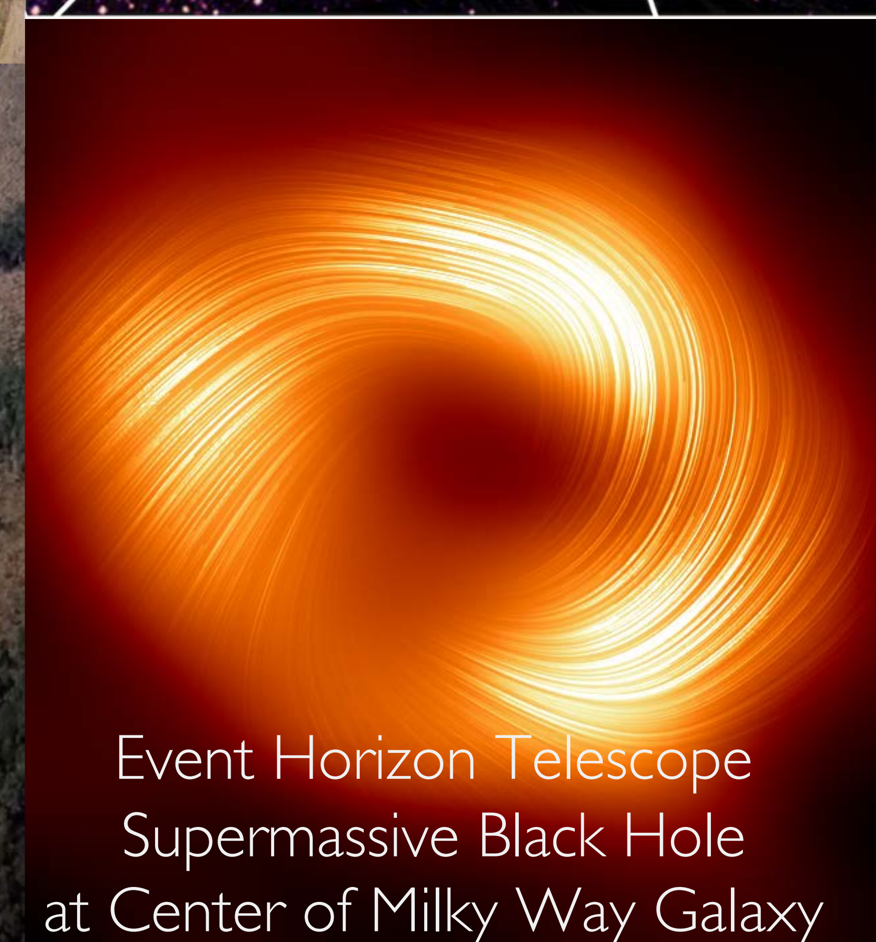
ERA OF AMAZING NEW TELESCOPES



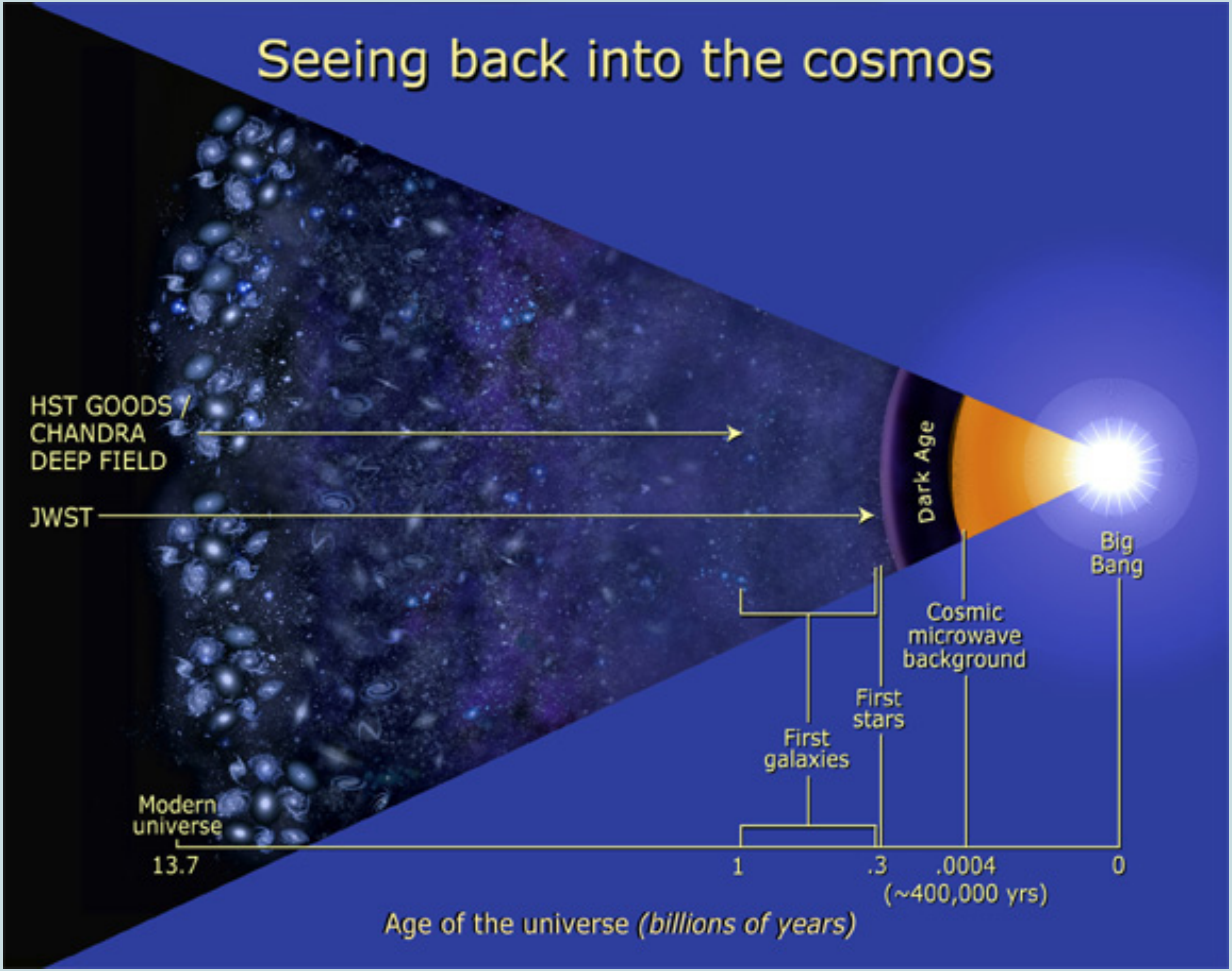
https://www.space.com/james-webb-space-telescope-ancient-black-hole-quasar



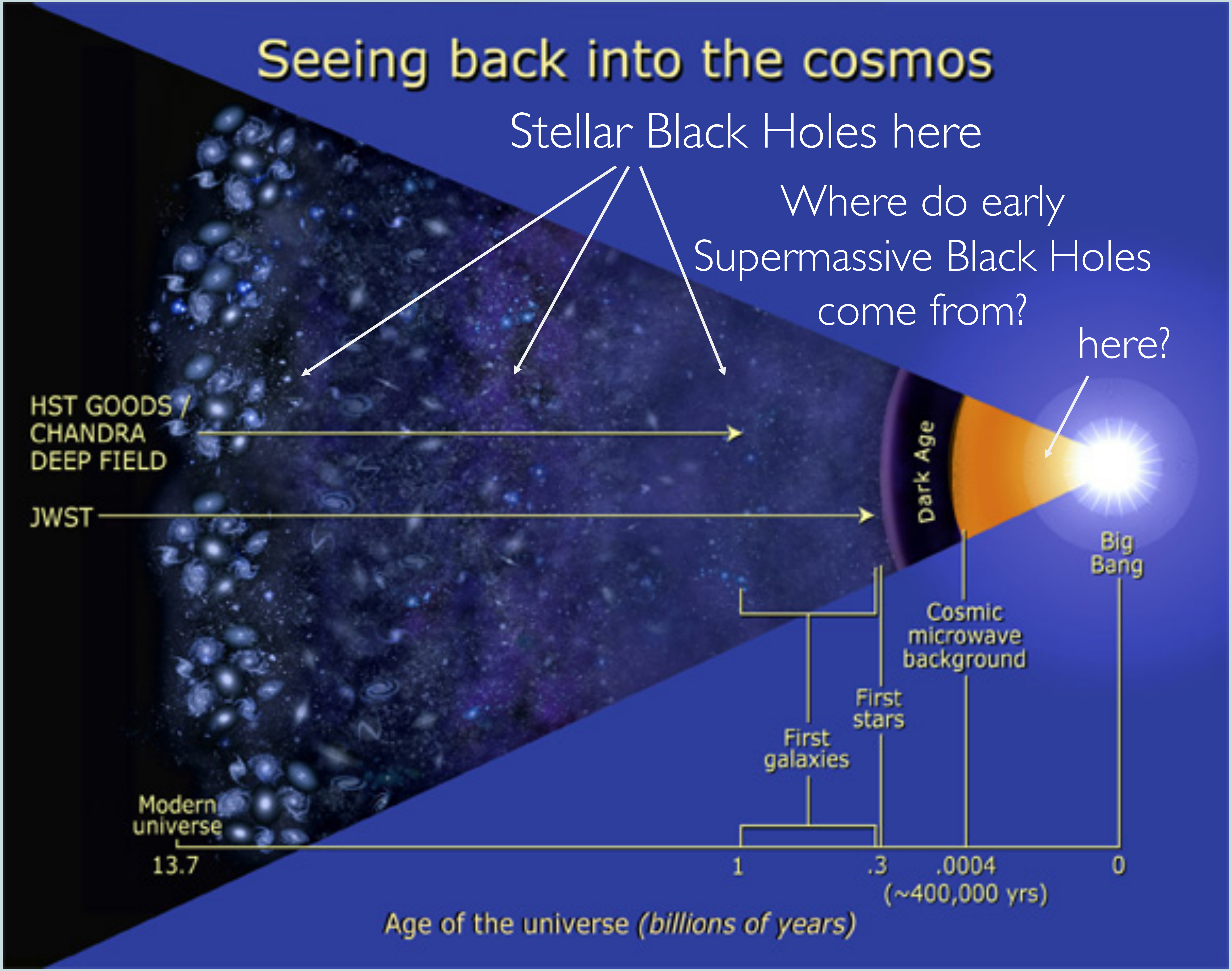




Event Horizon Telescope
Supermassive Black Hole
at Center of Milky Way Galaxy



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)*


Seeing back into the cosmos
Stellar Black Holes here
Where do early
Supermassive Black Holes
come from?
here?
HST GOODS /
CHANDRA
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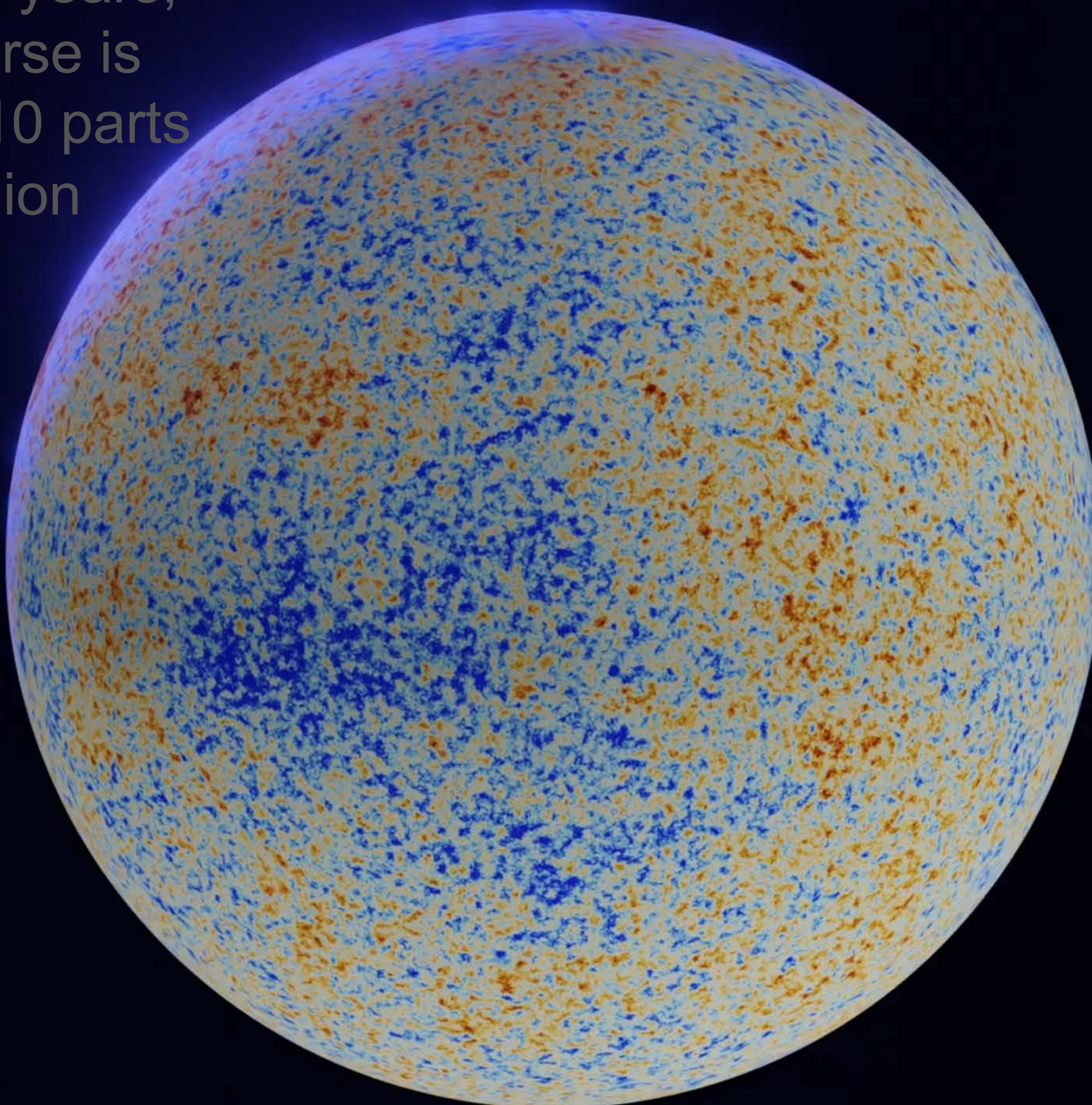
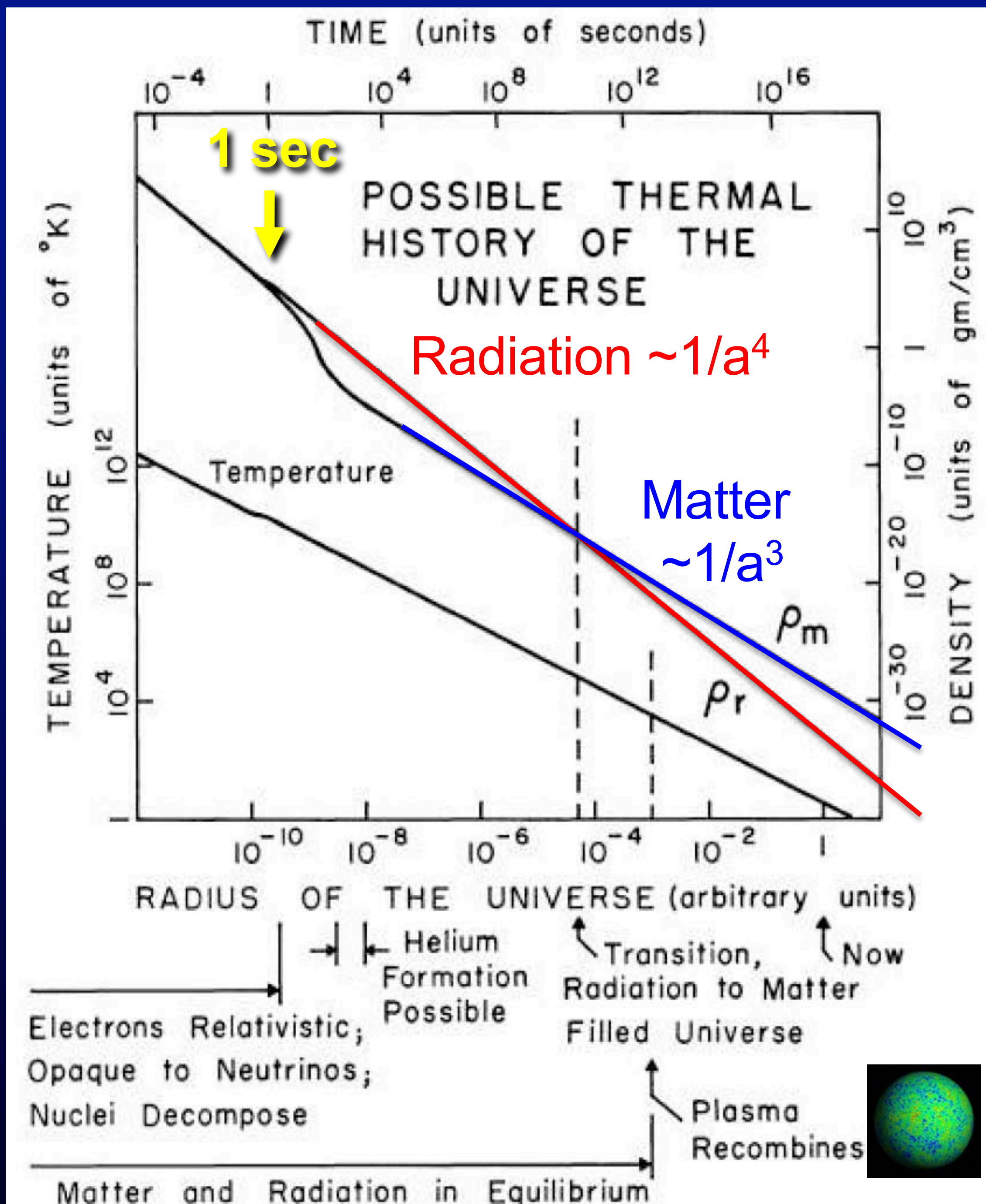
(~400,000 yrs)
0
Age of the universe (billions of years)

At 330,000 years, the Universe is smooth to 10 parts per million



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

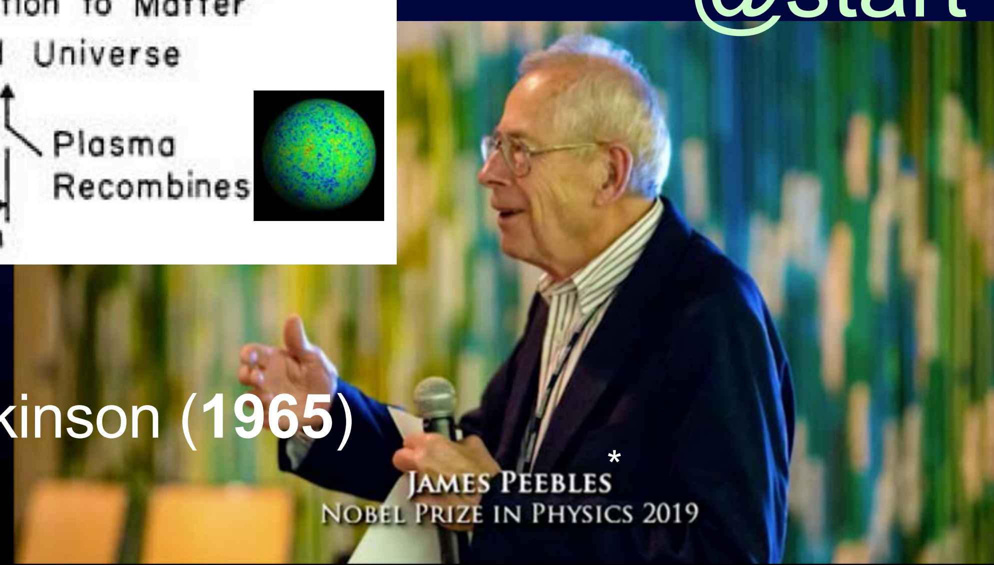
neutron/proton ratio @start of nucleosynthesis

→ ^4He

^2H

(^3He)

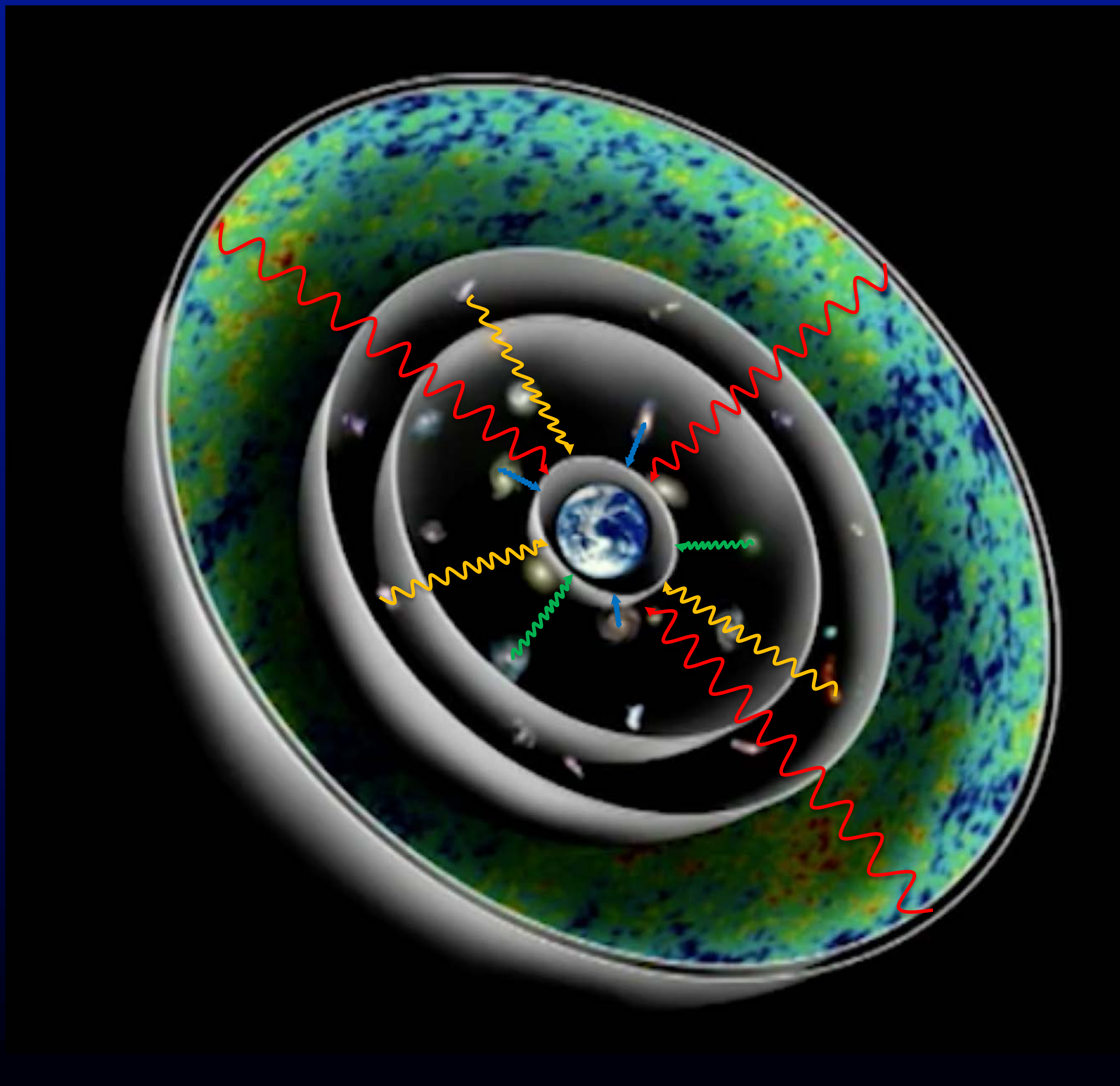
^7Li



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

Cosmology's Century (2020)

Looking Back in Time with Photons



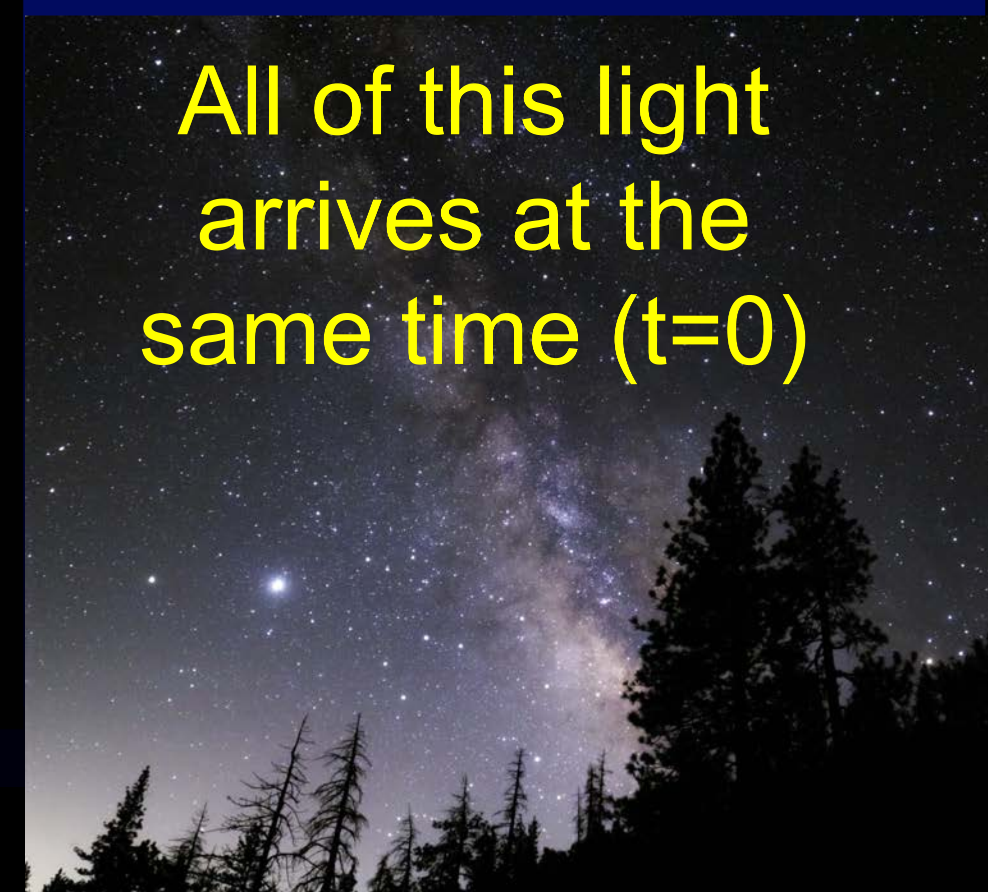
<u>Emission Time</u>

-13.8×10^{9} years

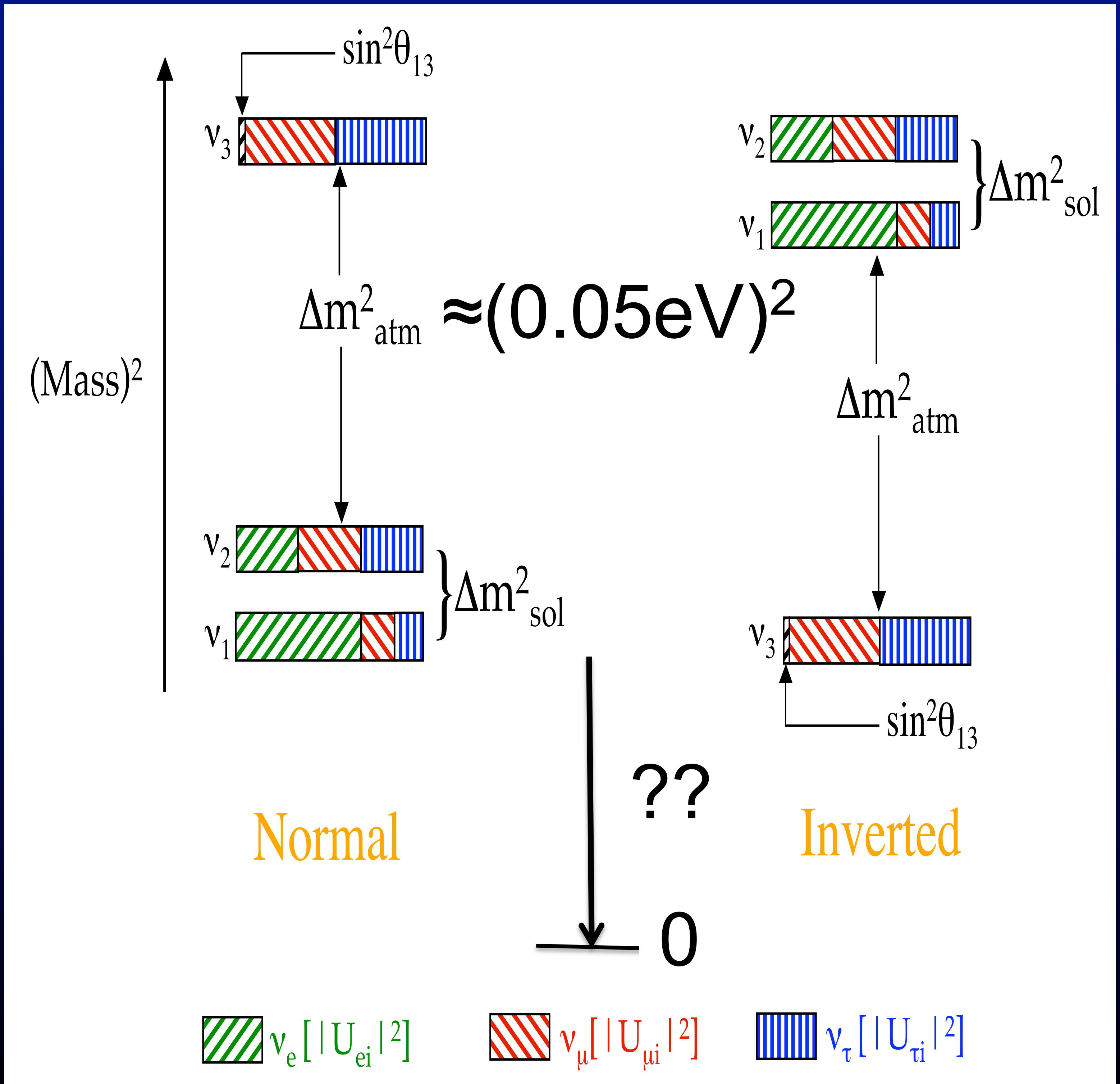
-4×10^{9} years

-200×10^{6} years

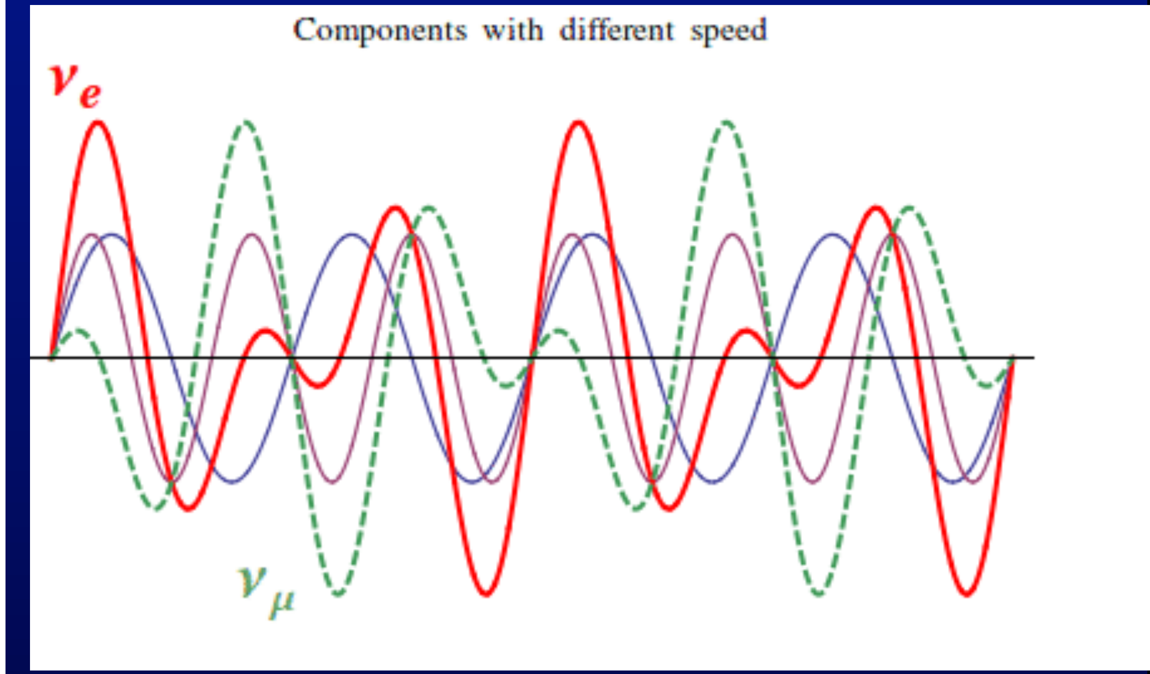
-2×10^{6} years



Neutrino Masses from Oscillations



Theory developed by Bruno Pontecorvo



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

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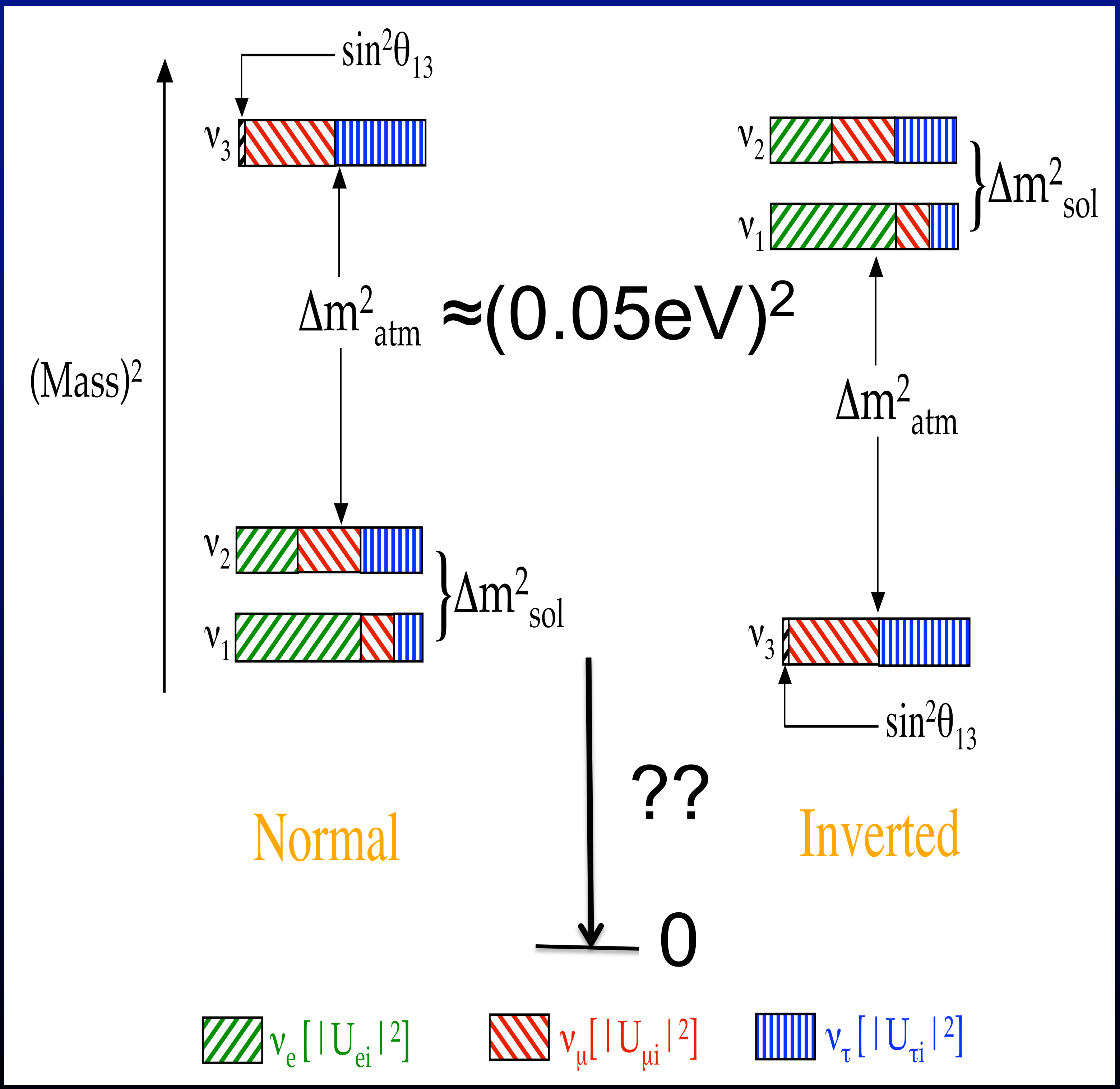

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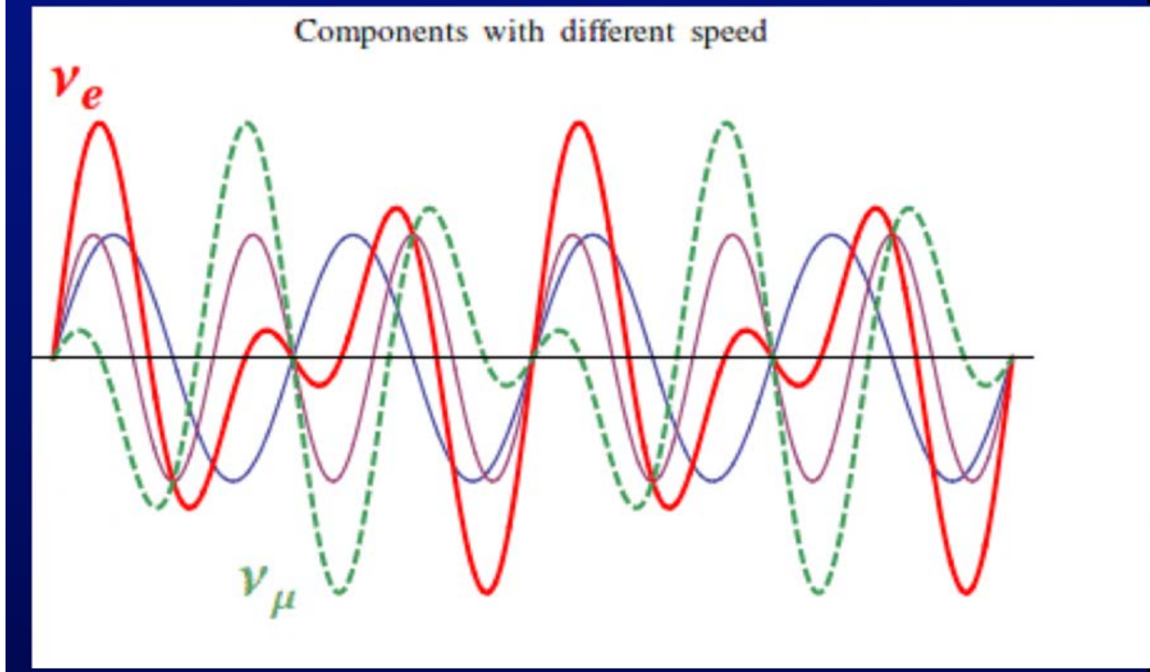


3 mass eigenstates

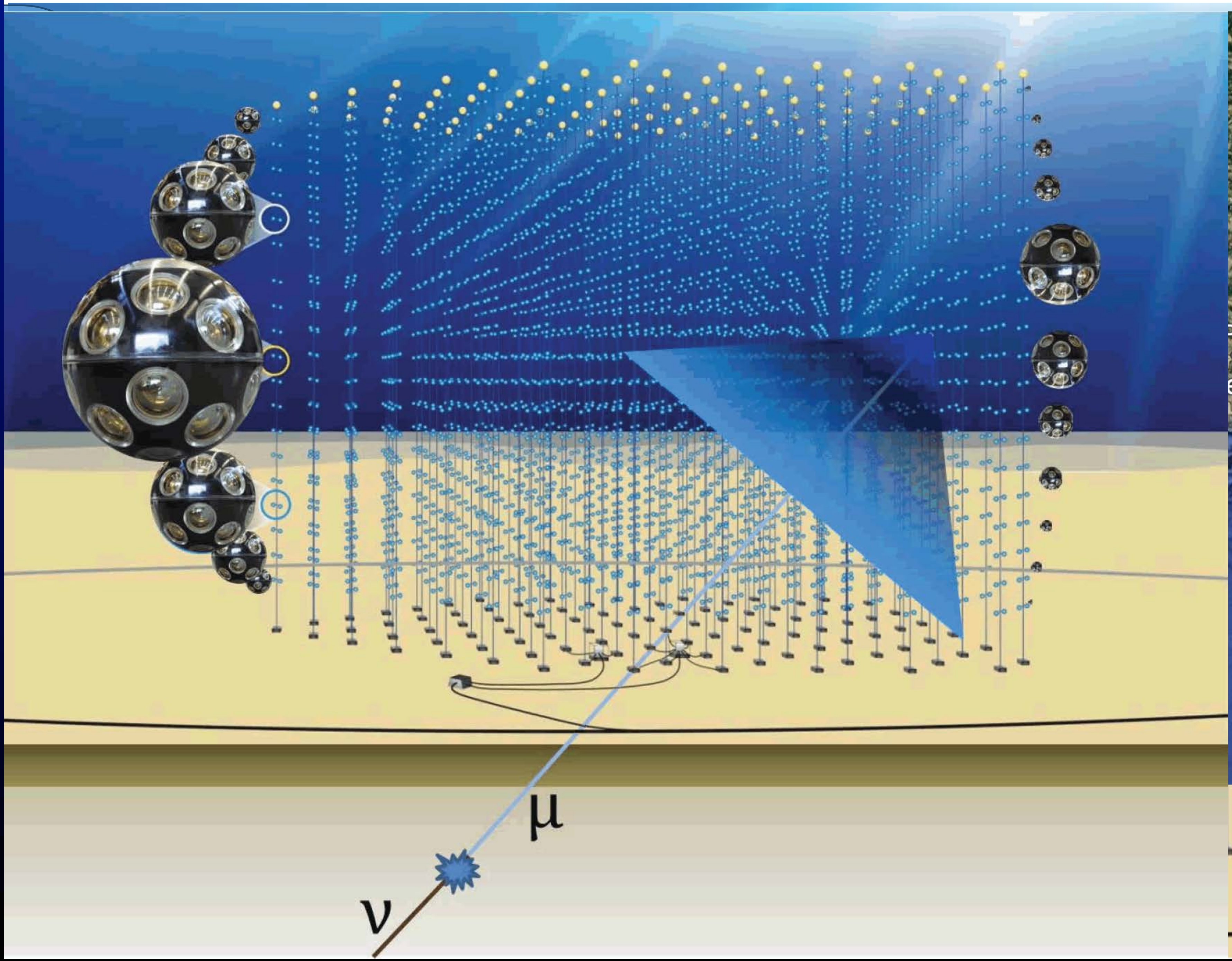
X

3 flavors

(electron, muon, tau)

Neutrino Mass Oscillation Observatory

KM3NeT/ORCA (**O**scillation **R**esearch with **C**osmics in the **A**byss)
determination of the neutrino mass hierarchy
(E_ν ~ MeV - GeV) low energy neutrinos
Depth – 2500 m – offshore Toulon (France)



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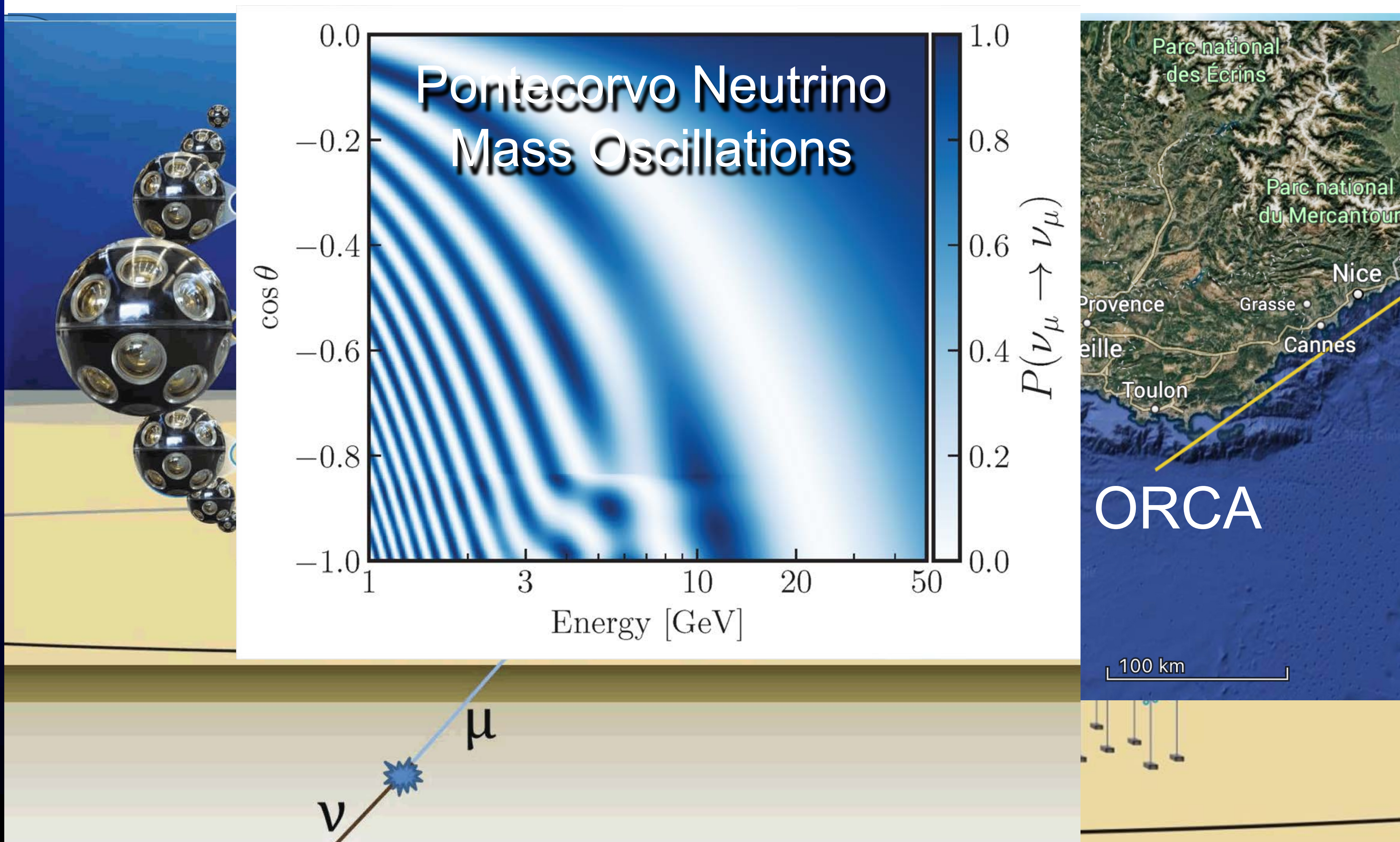
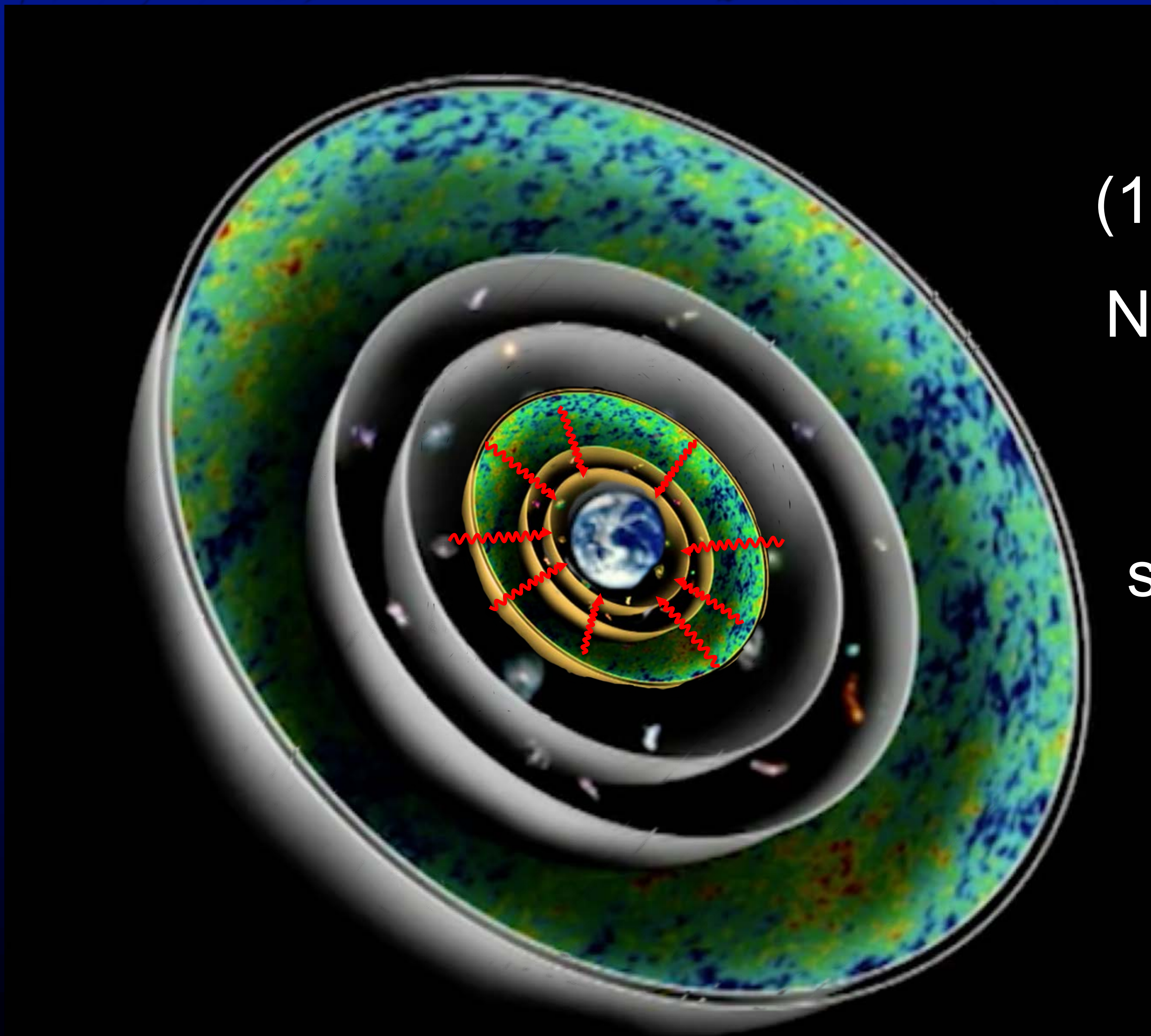


Massive Neutrino Timeline



Emission Time

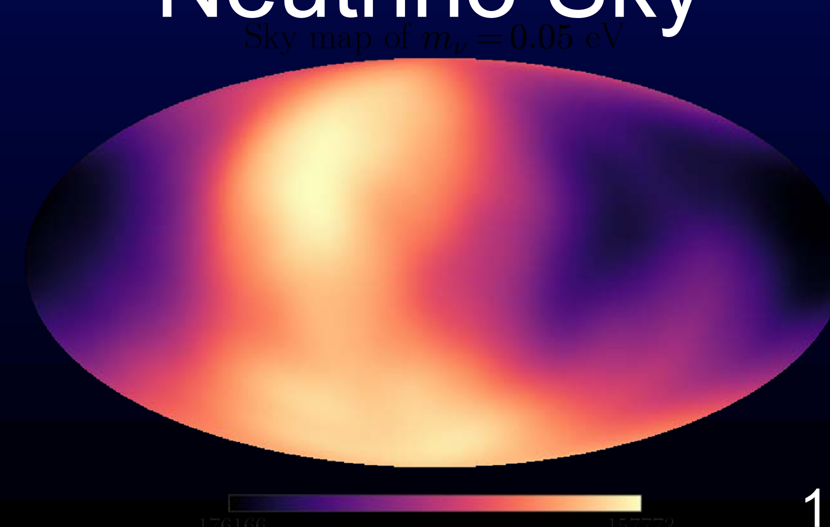
$-13.8\text{x}10^9$ years

(1 second after Big Bang)

No comparable flux from other sources

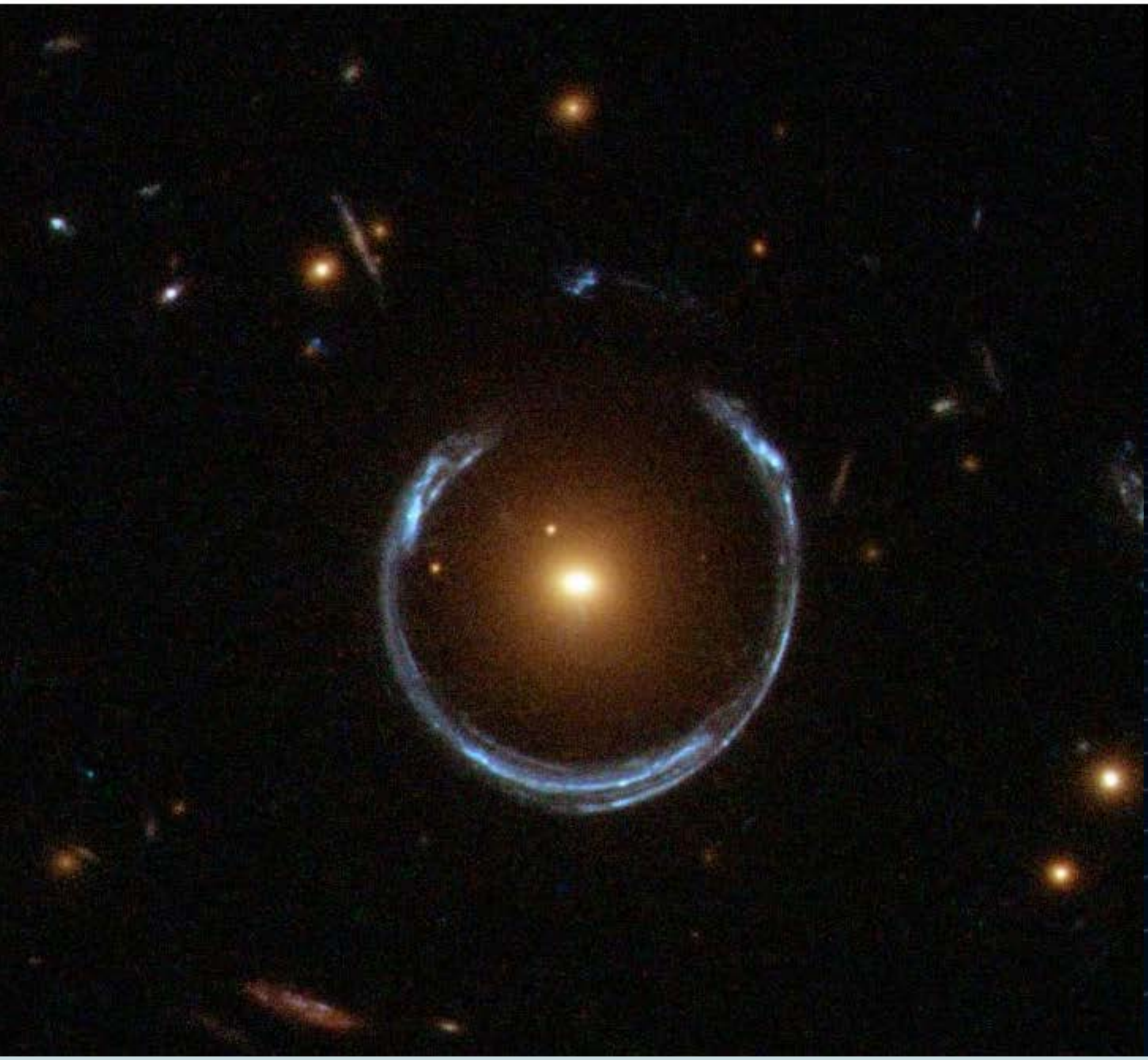
Starting radius more spread out due to mass

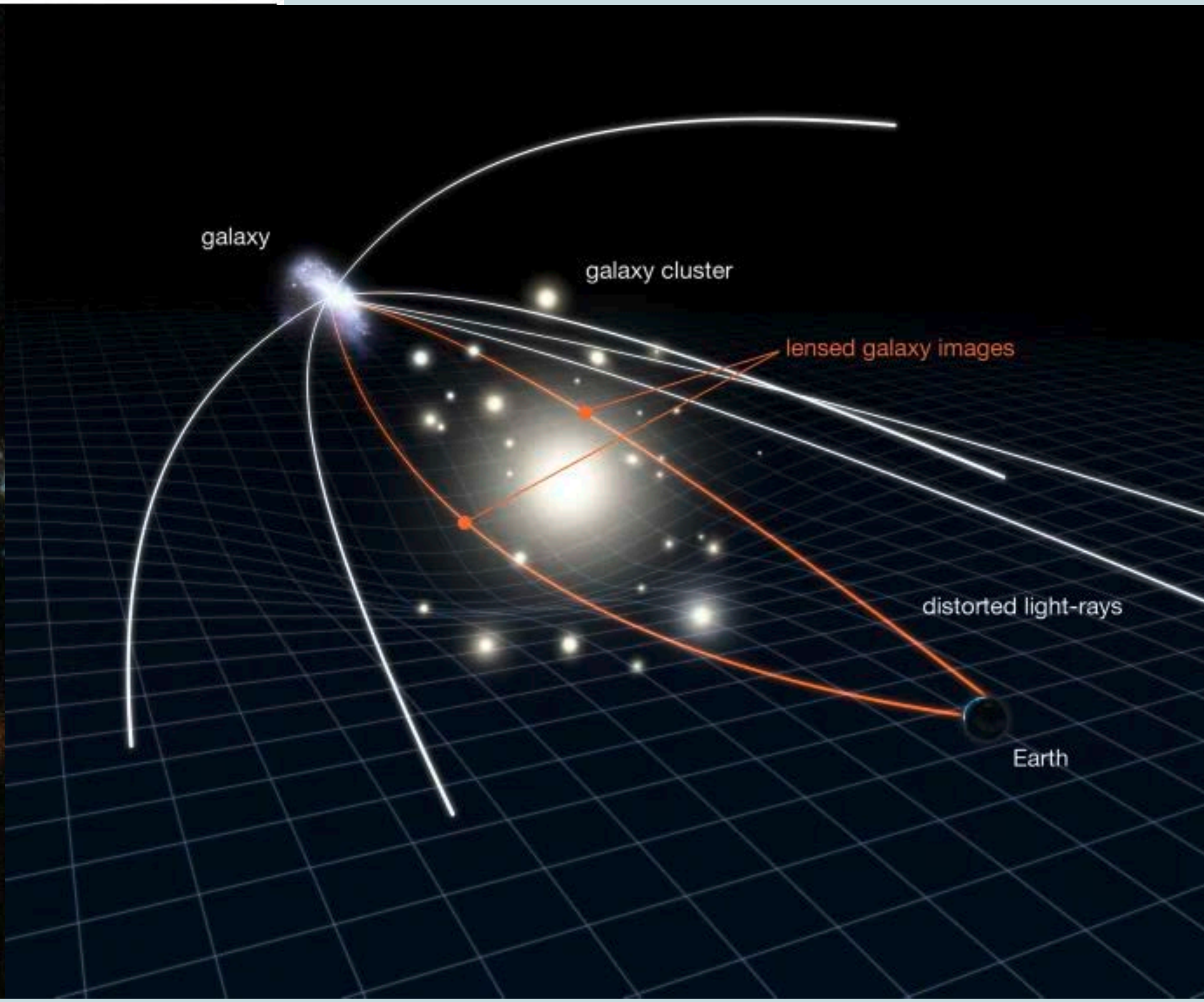
Neutrino Sky



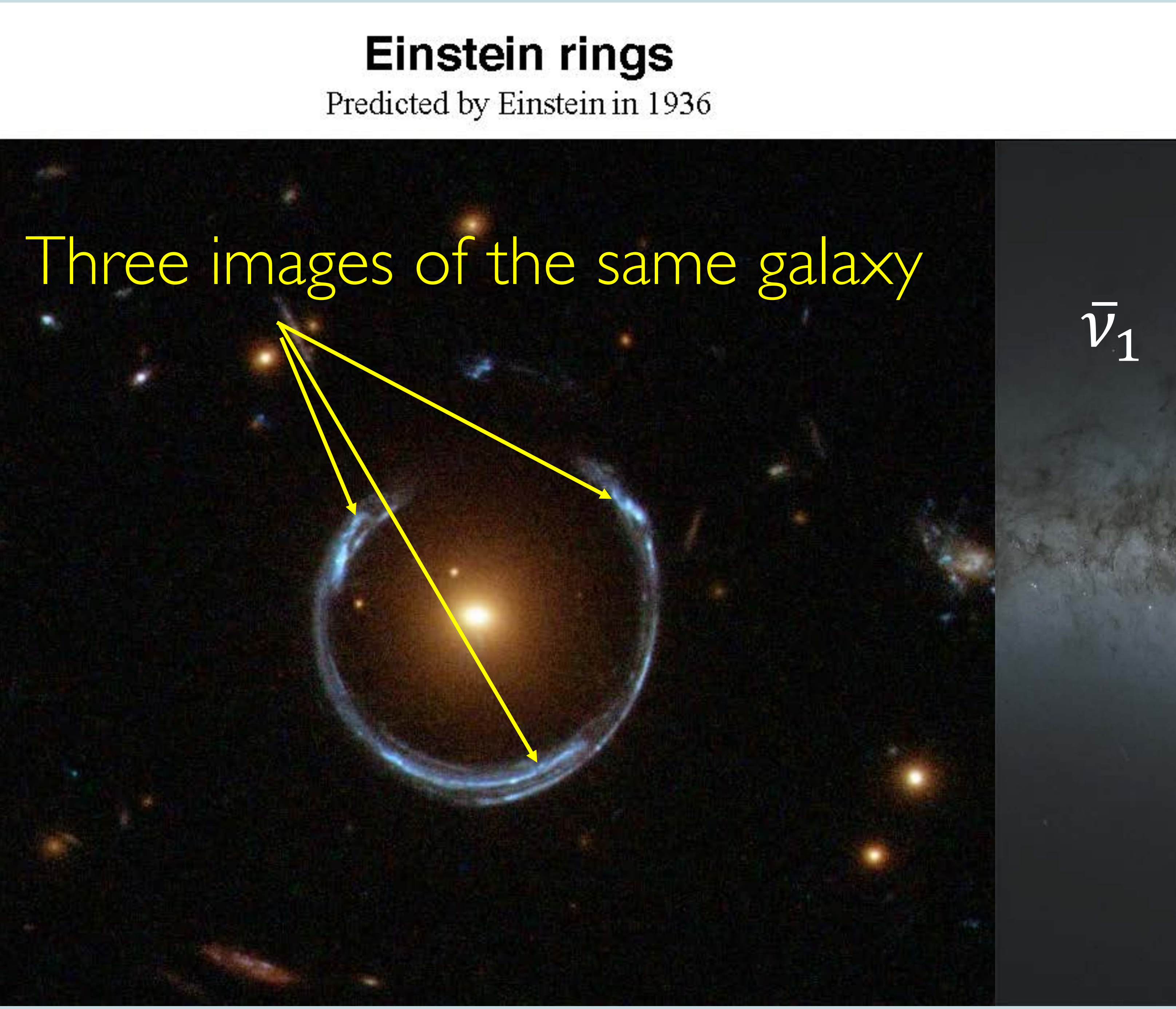
Einstein rings

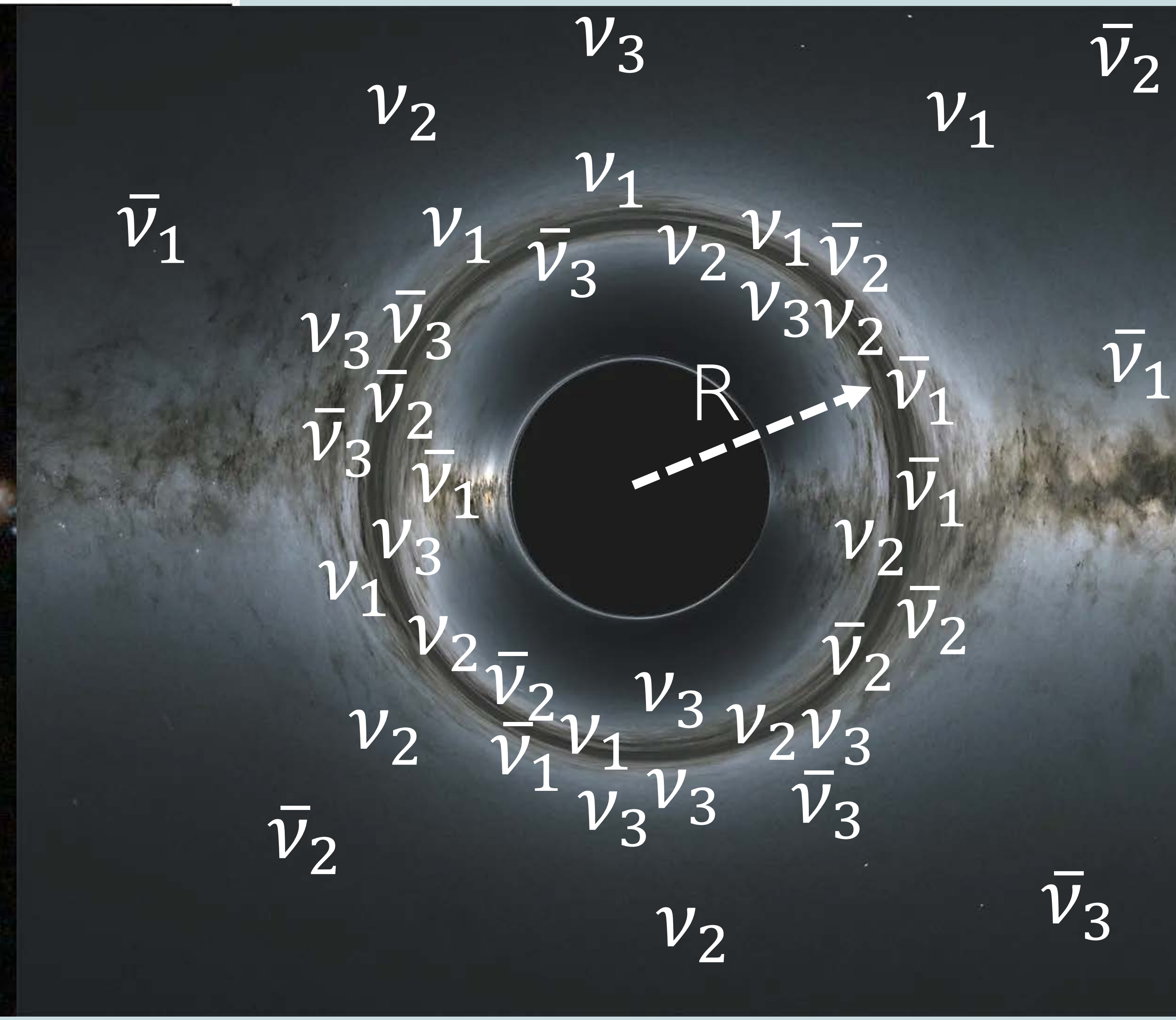
Predicted by Einstein in 1936





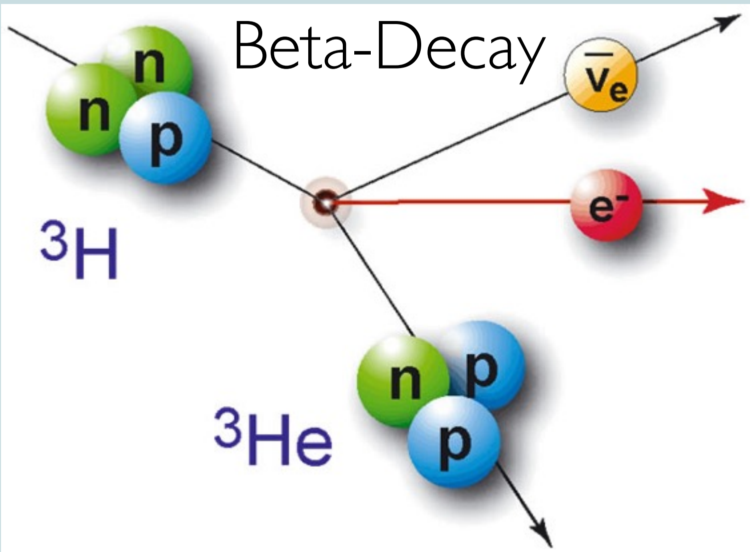
Neutrino Rings?
from Primordial Black Holes

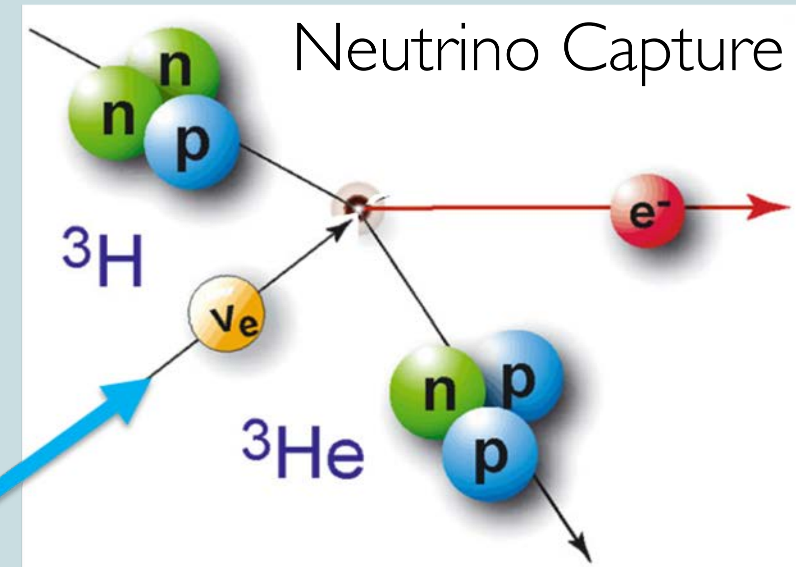




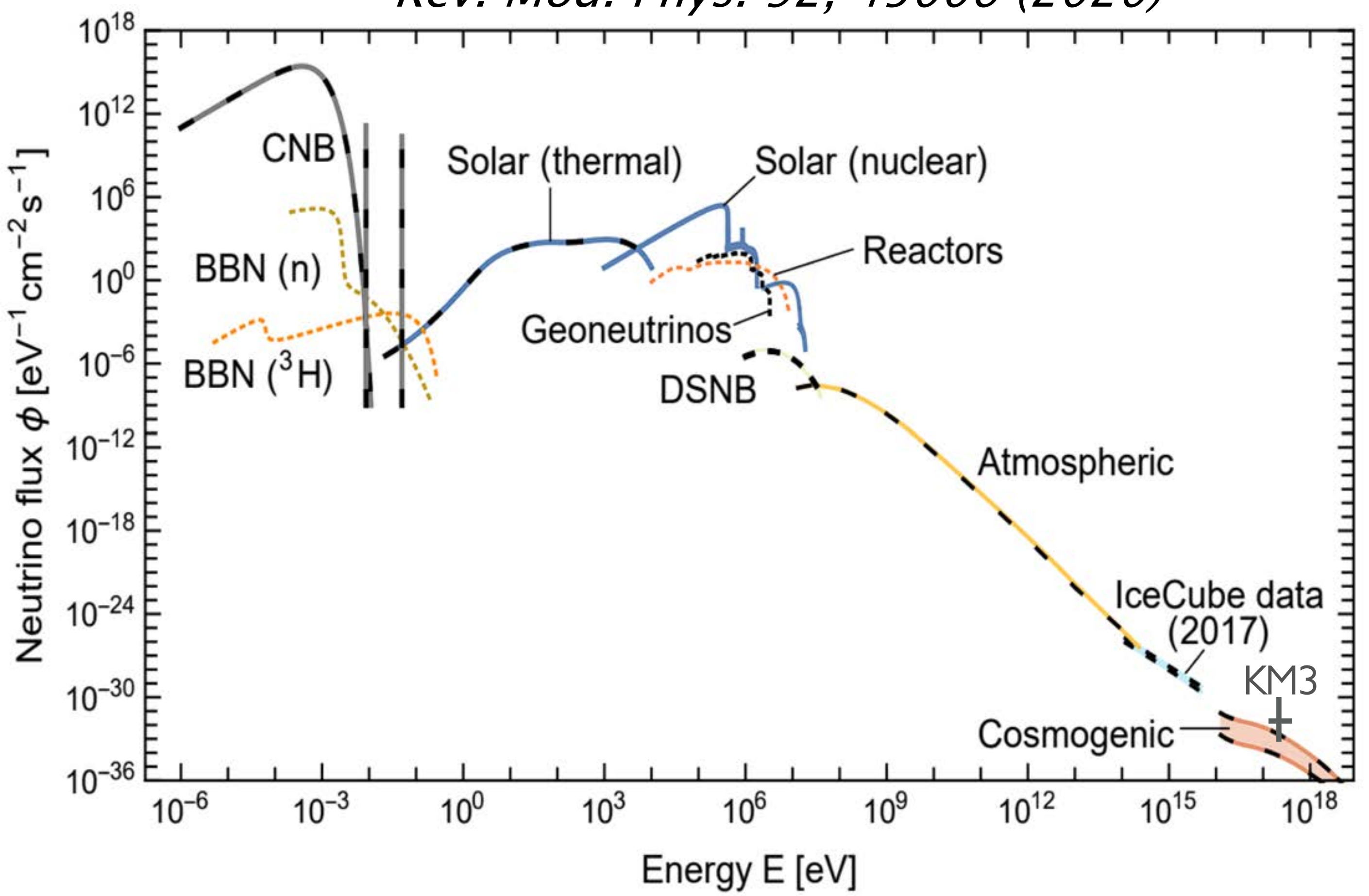
PTOLEMY - RELIC NEUTRINO DETECTION

PonTecorvo Observatory for Light Early-universe Massive-neutrino Yield



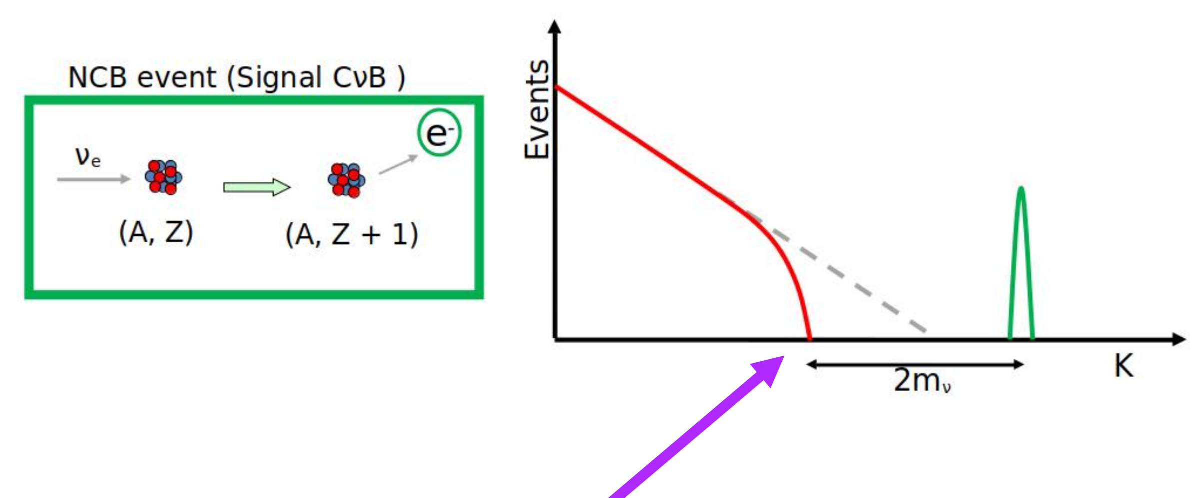


Rev. Mod. Phys. 92, 45006 (2020)



DOI: 10.1088/1475-7516/2007/06/015

Signature of CνB



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

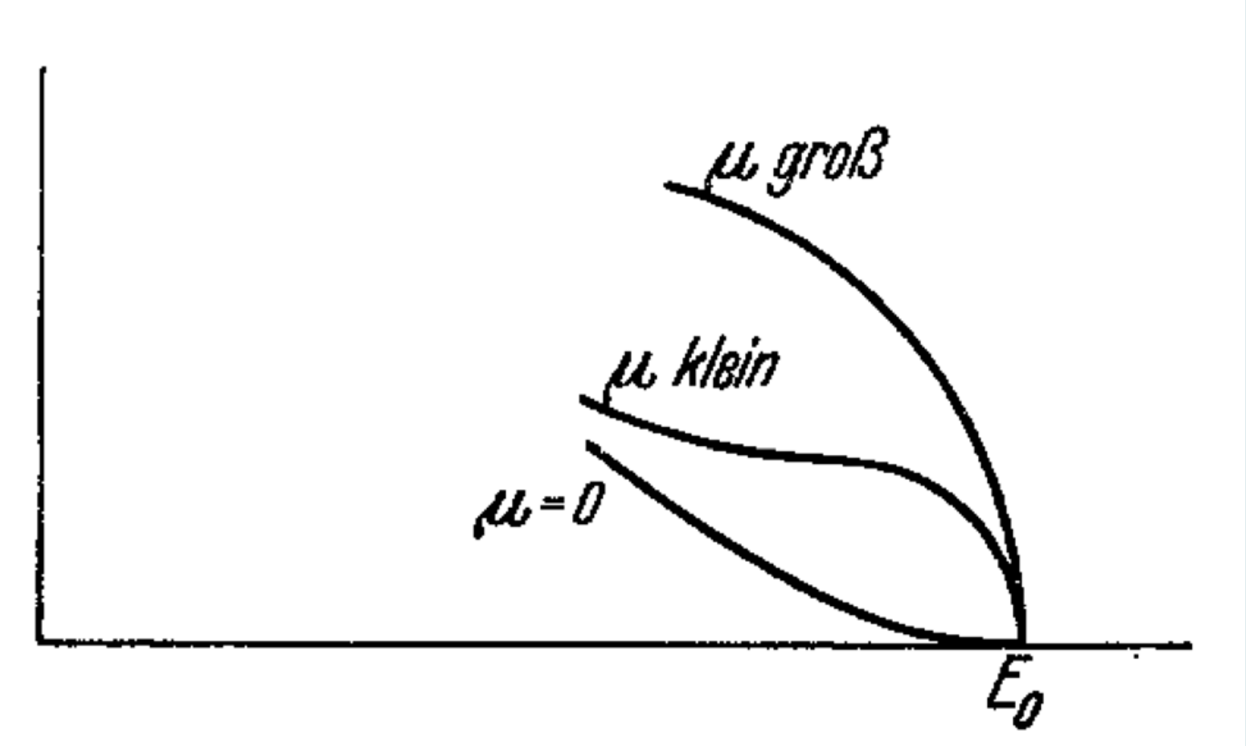
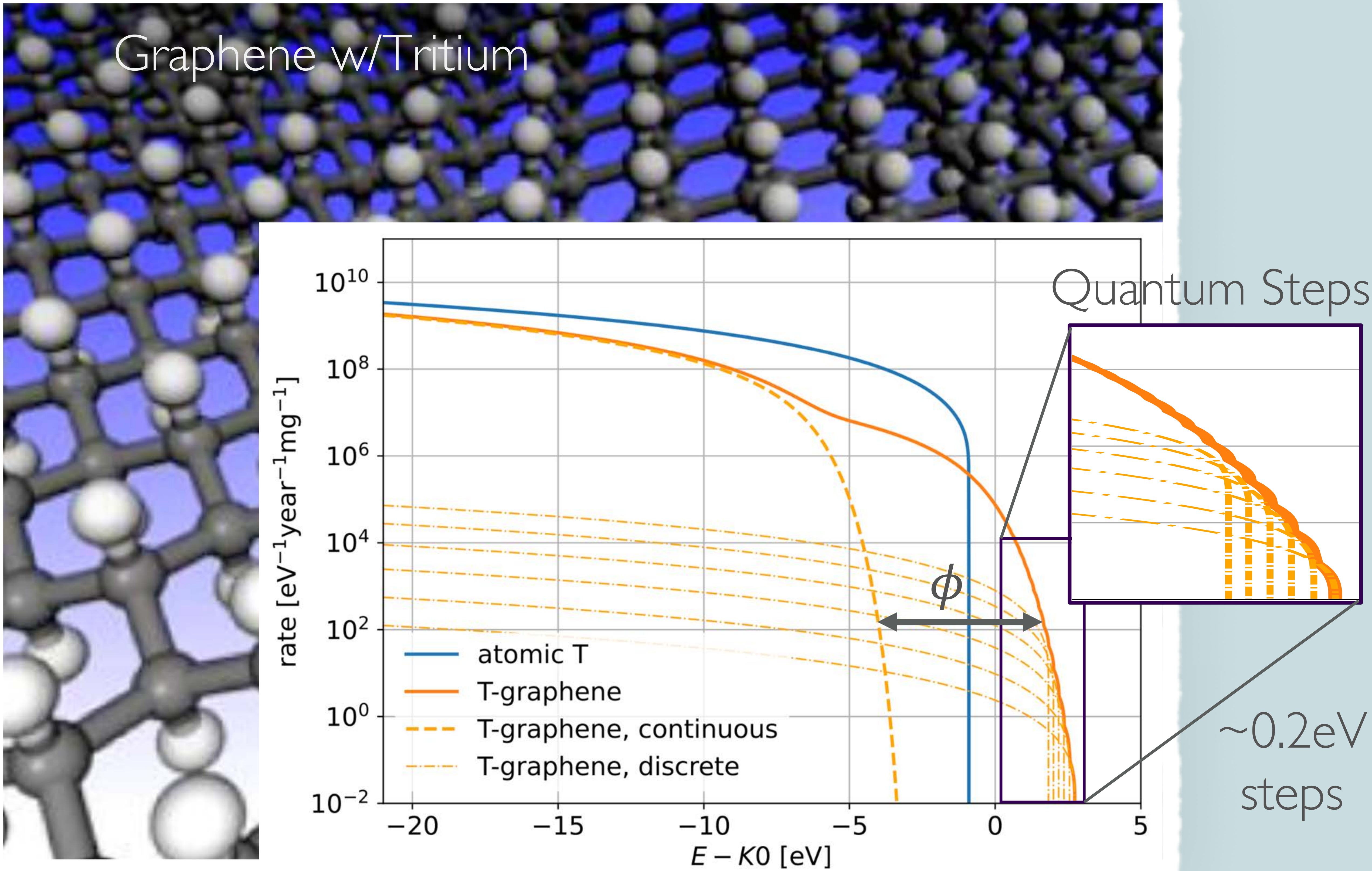


Fig. 1.

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

ϕ ≡ "Atomic" work function

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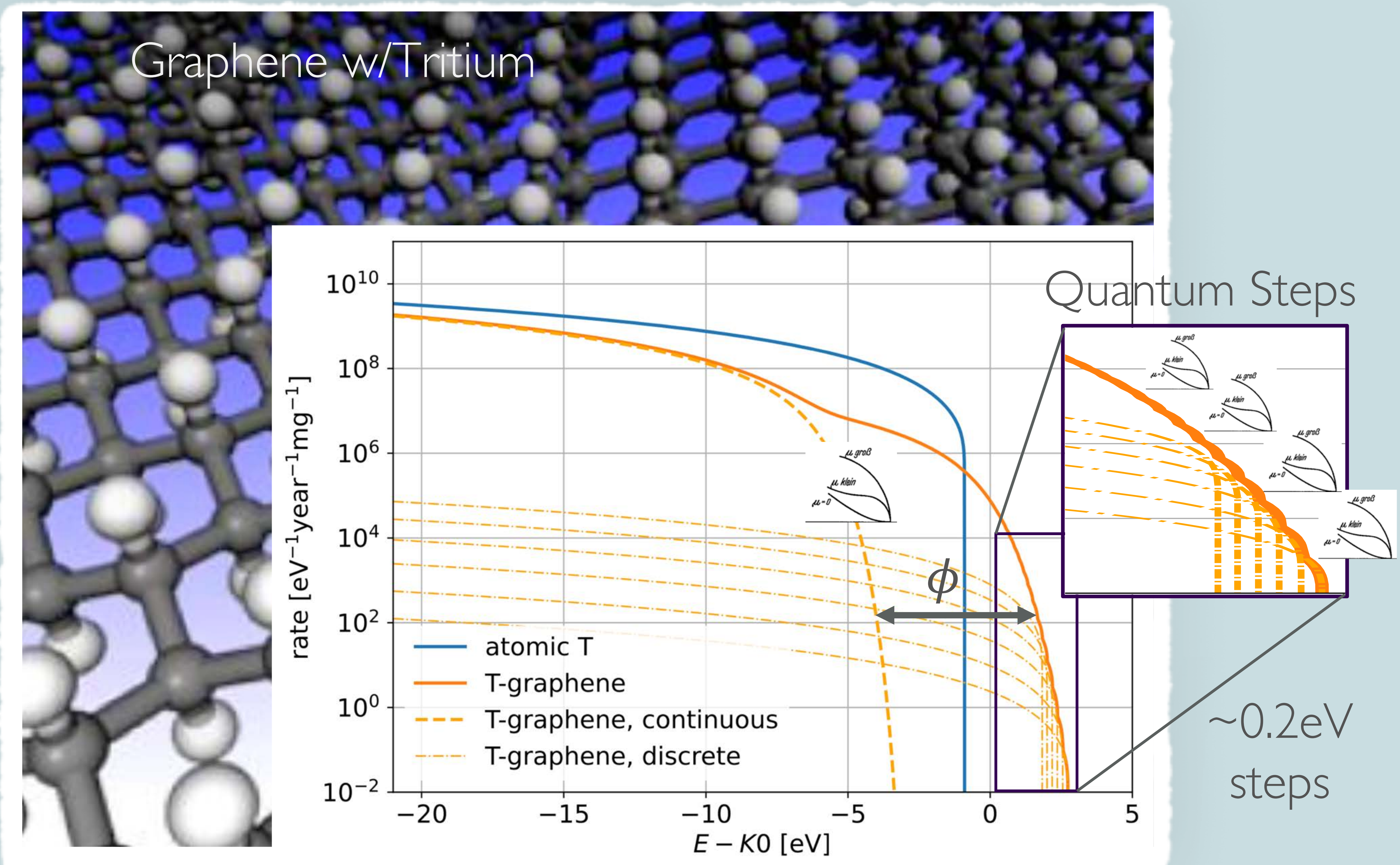

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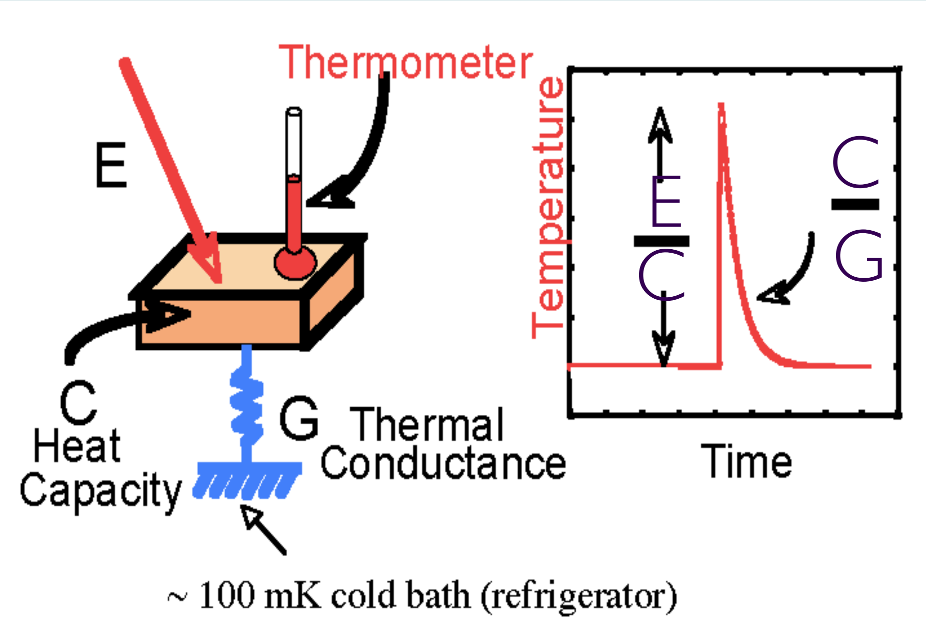
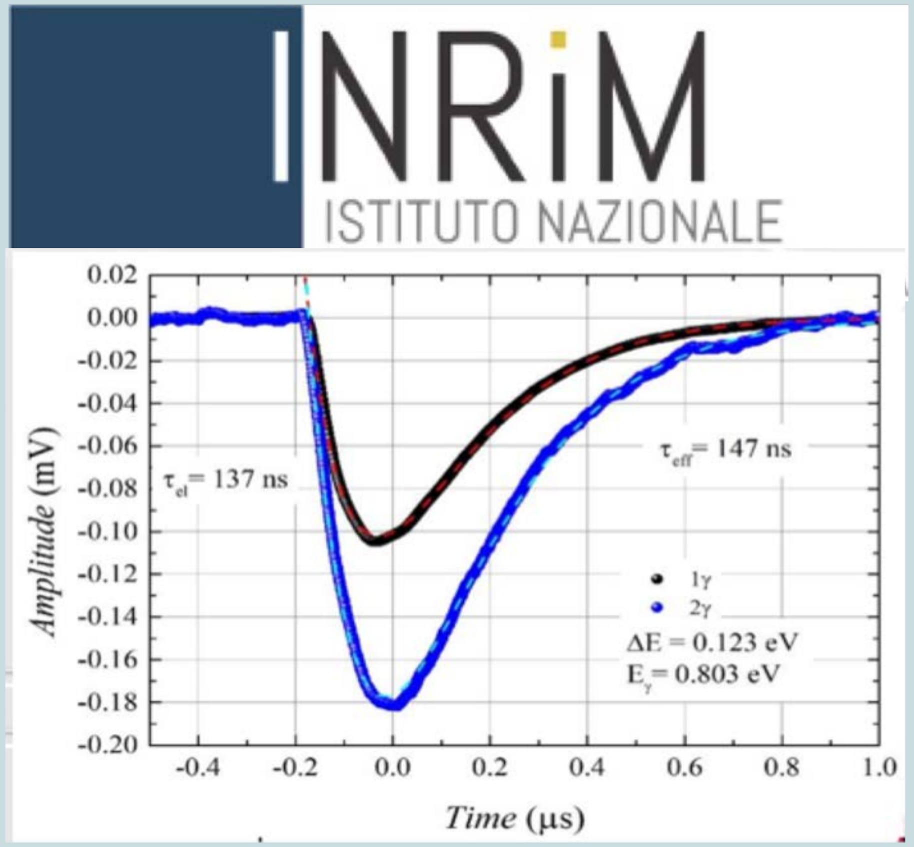
MICRO-CALORIMETER



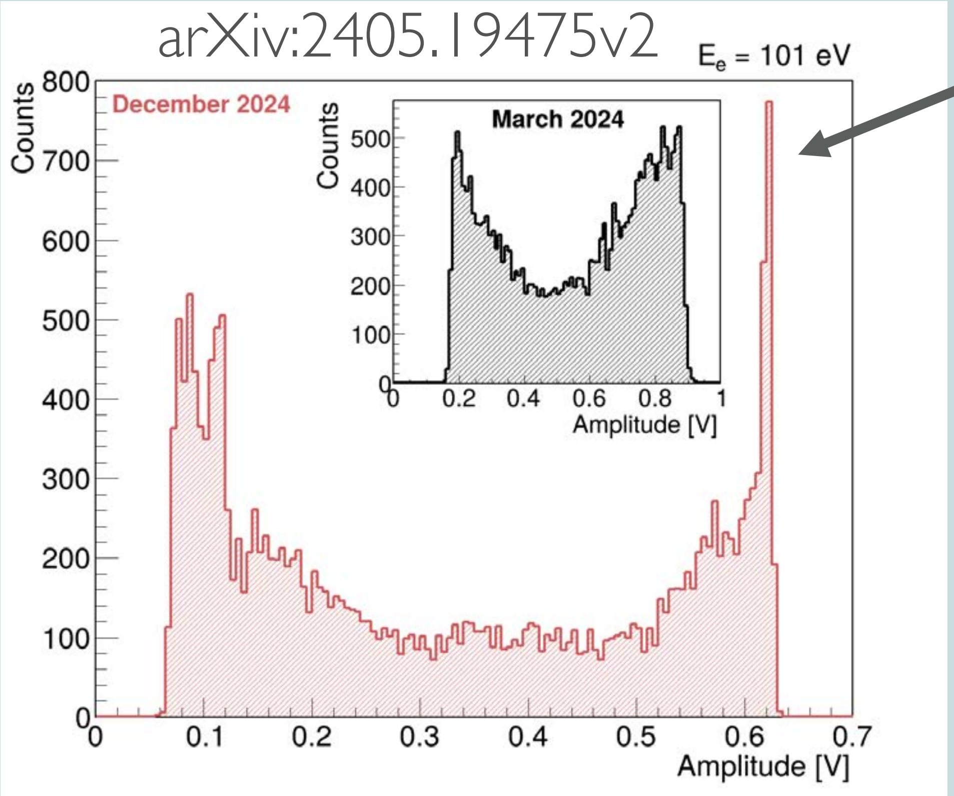
Design Goal (PTOLEMY): ΔE_{FWHM} = 0.05 eV @ 10 eV

translates to $\Delta E \propto E^{\alpha}$ $(\alpha \leq 1/3)$

ΔE_{FWHM} = 0.022 eV @ 0.8 eV

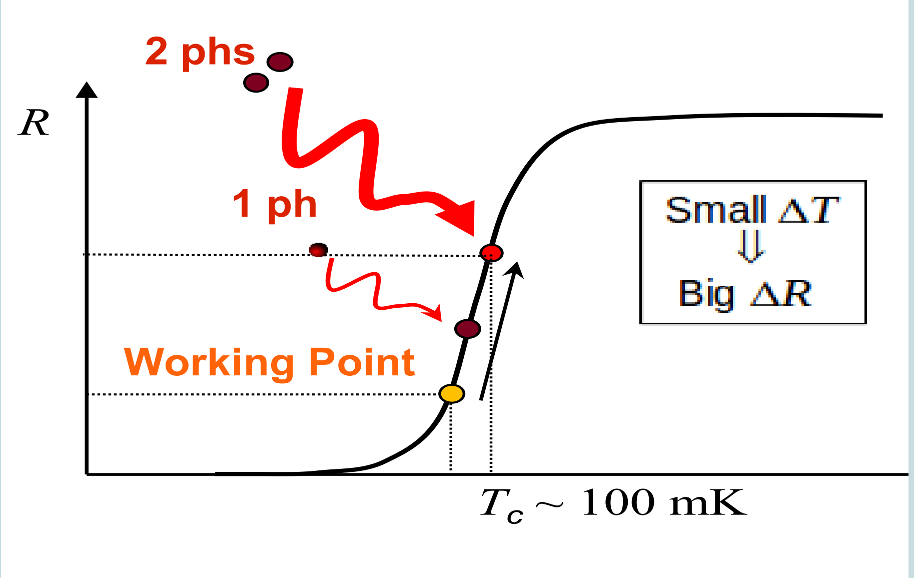


Based on the expertise of the INRiM important results have been achieved on electron measurement with TES.
Key elements of the measurements: performing TES and new e-source based on nanostructures



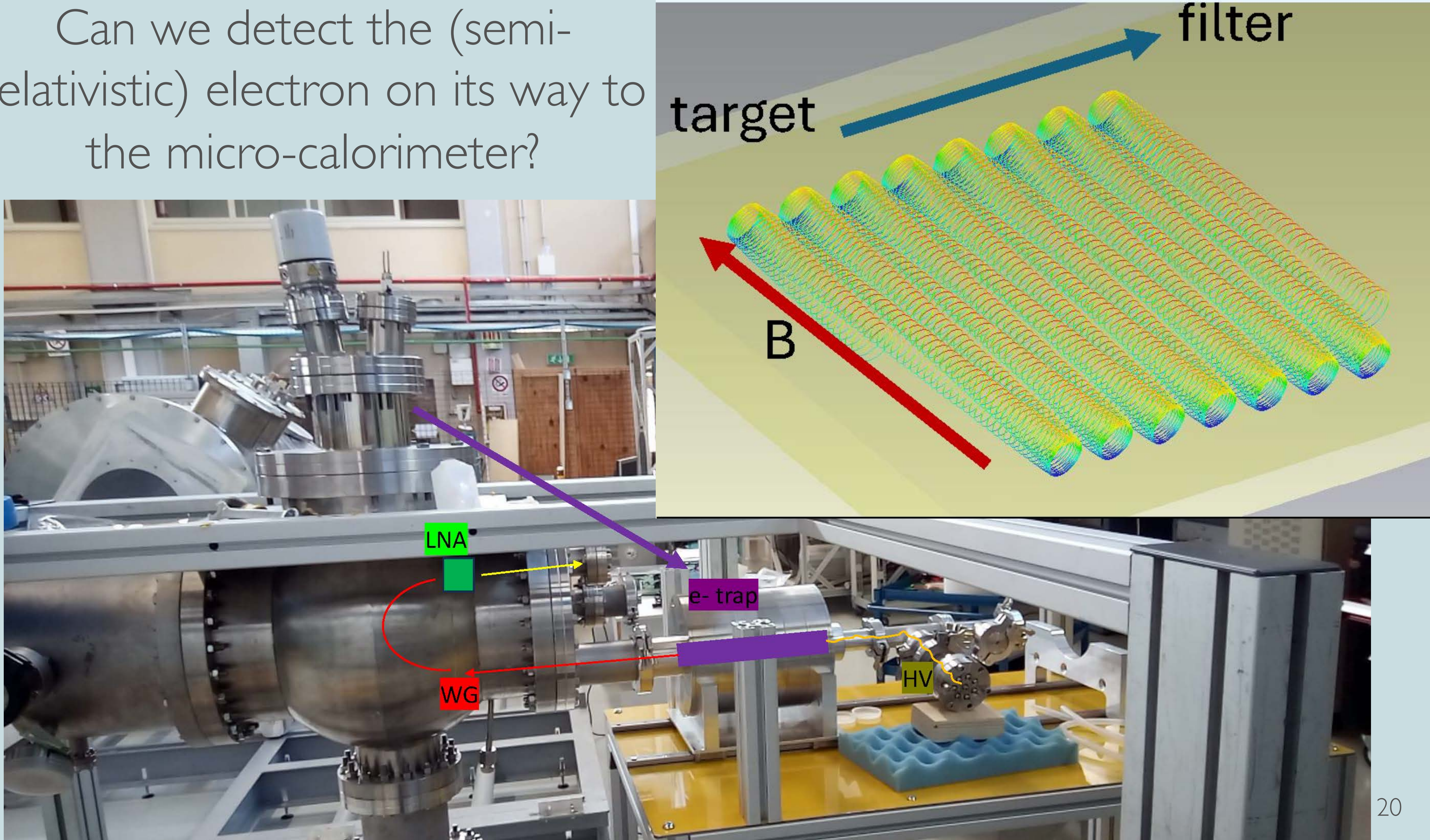
First measurement of electrons at 100 V with resolution of ~1-1.5 eV

Best in the World!

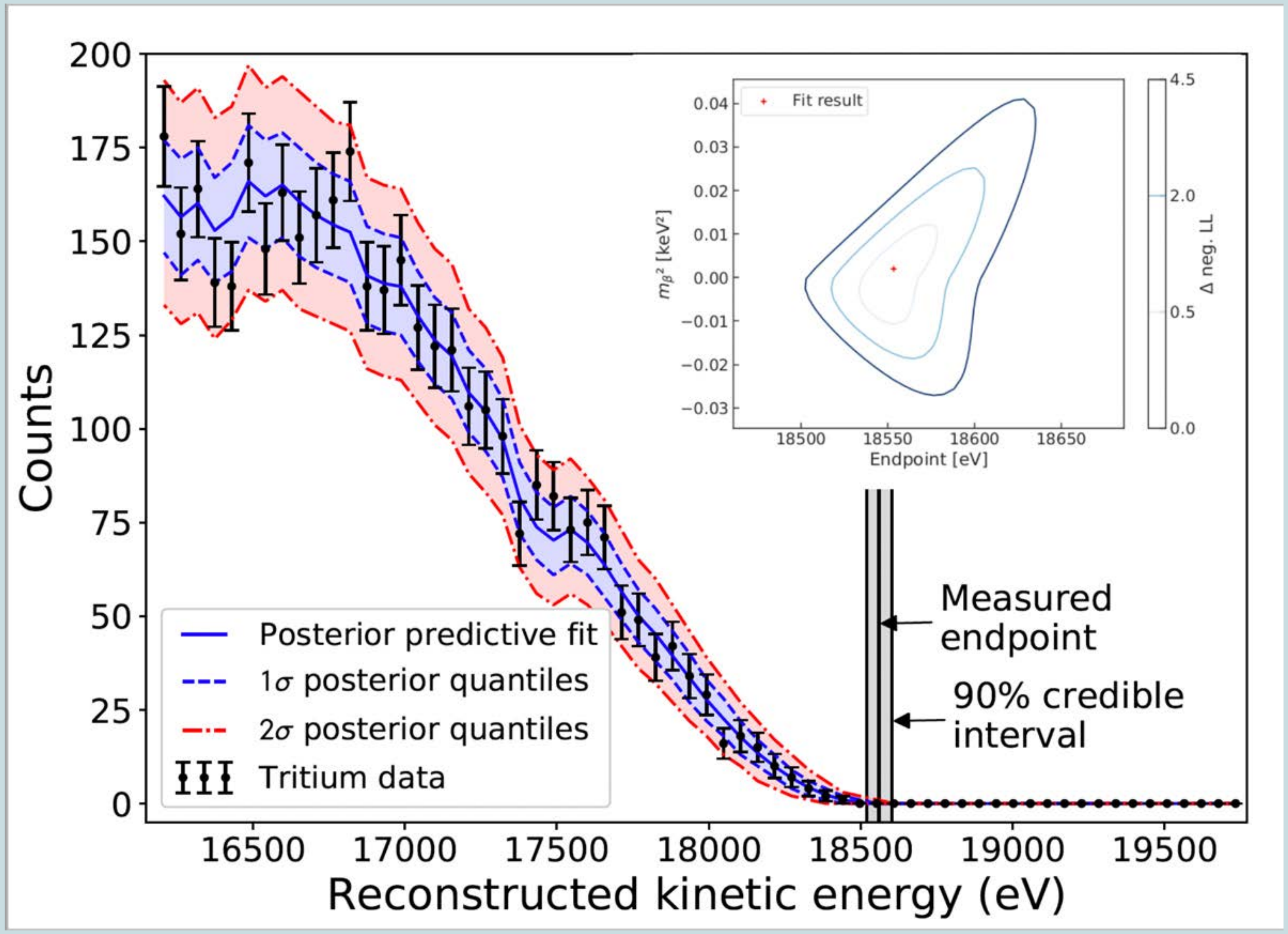


RF MEASUREMENTS
NON-DESTRUCTIVE ELECTRON TAG

Can we detect the (semi-relativistic) electron on its way to the micro-calorimeter?



RECENT PROJECT 8 TRITIUM RF MEASUREMENT



https://arxiv.org/abs/2203.07349

RF measurement background levels extremely low.

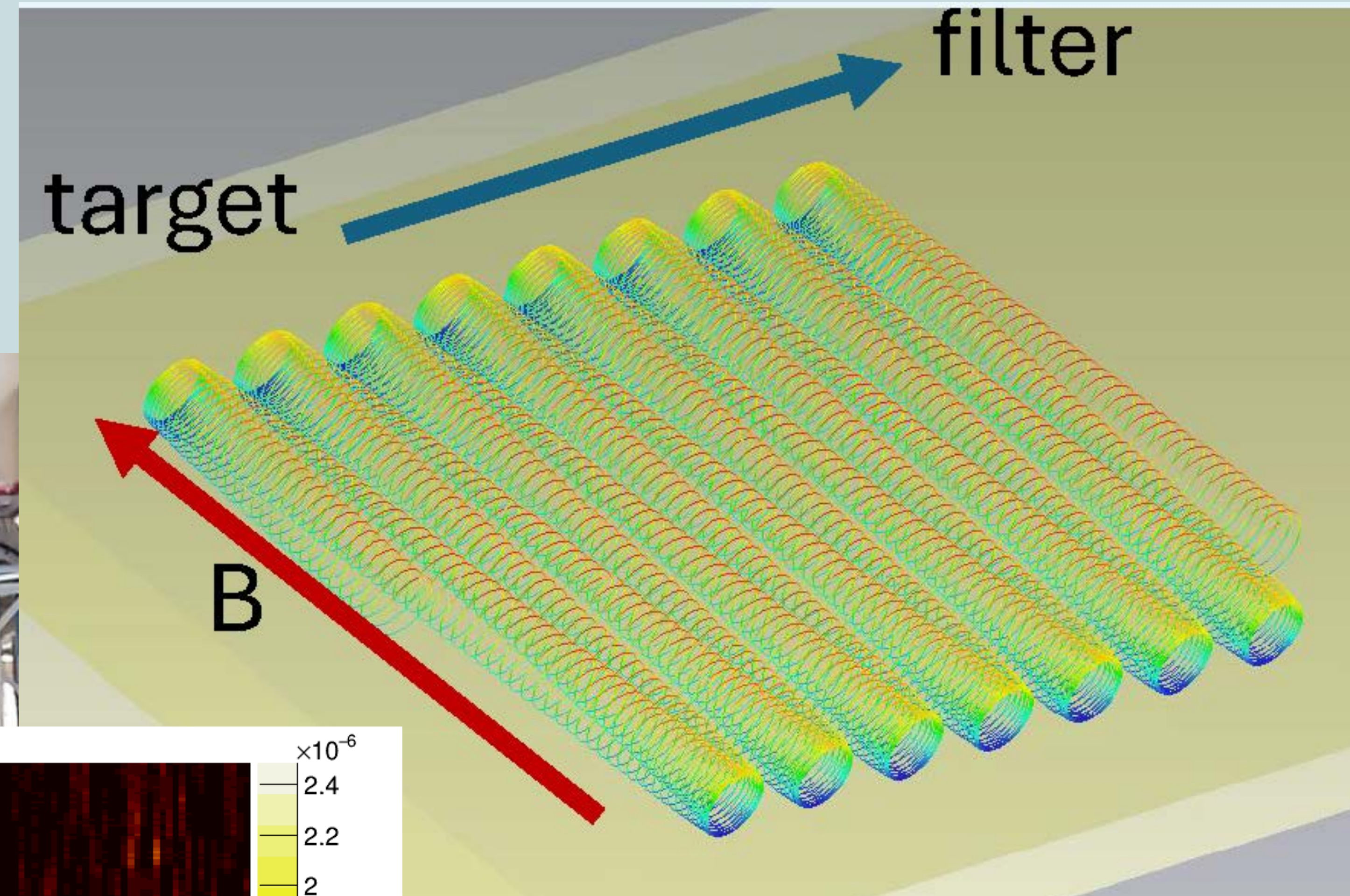
No events observed above endpoint,
Setting upper limit on background rate

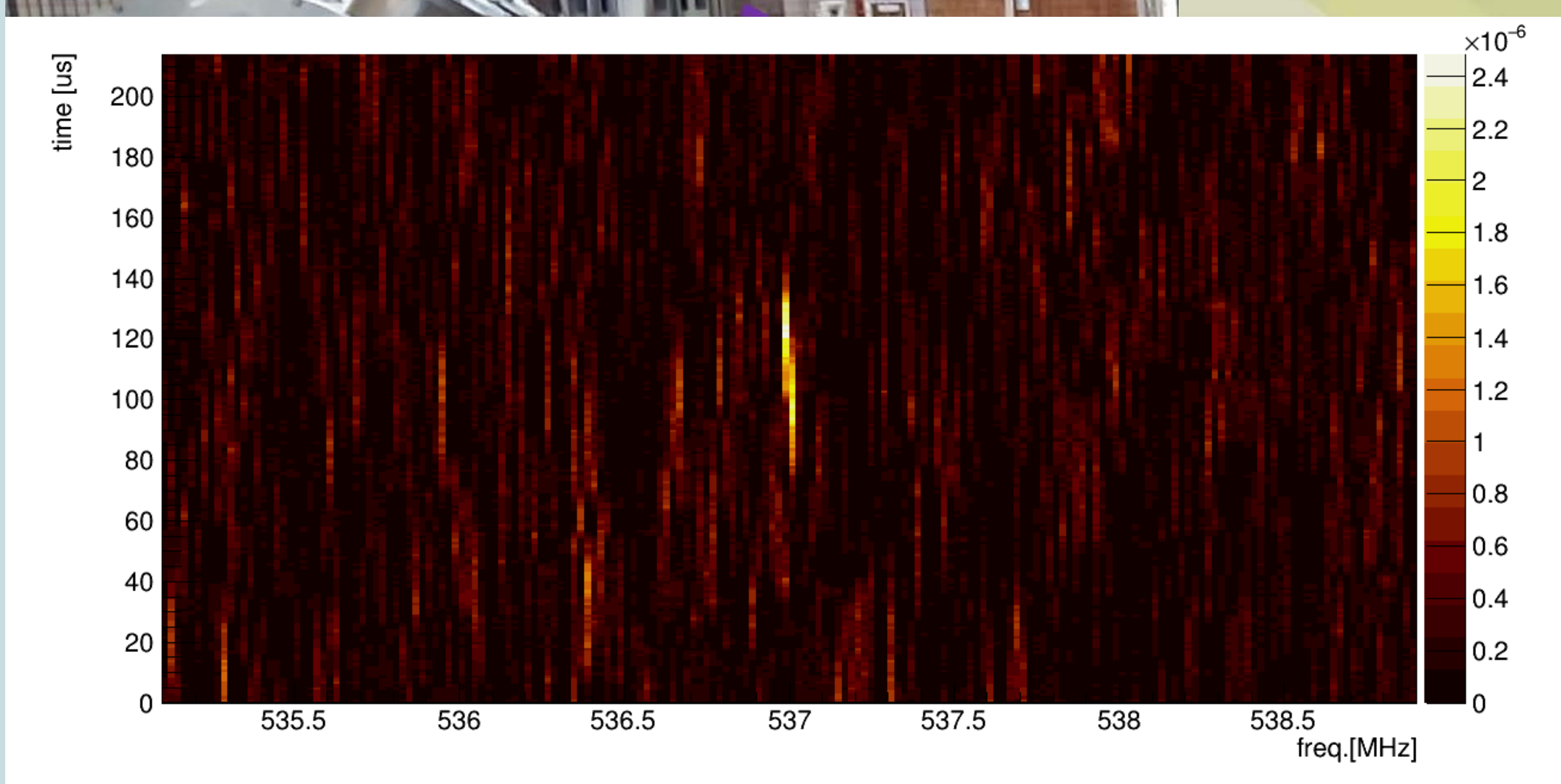
< 3×10^{-10} /eV/s (90% CL)

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

ACHIEVED!! RF MEASUREMENTS
NON-DESTRUCTIVE ELECTRON TAG

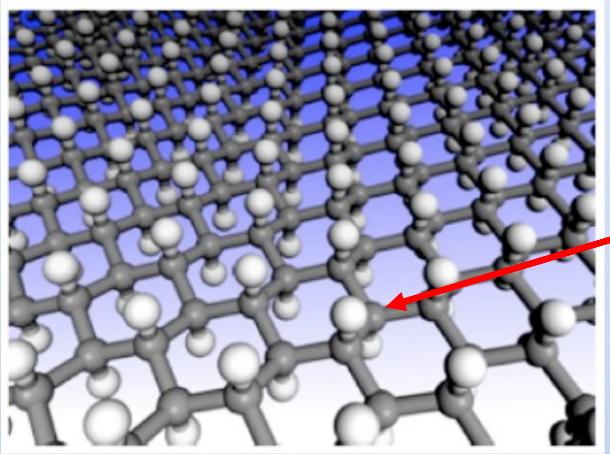
Can we detect the (semi-relativistic) electron on its way to the micro-calorimeter?





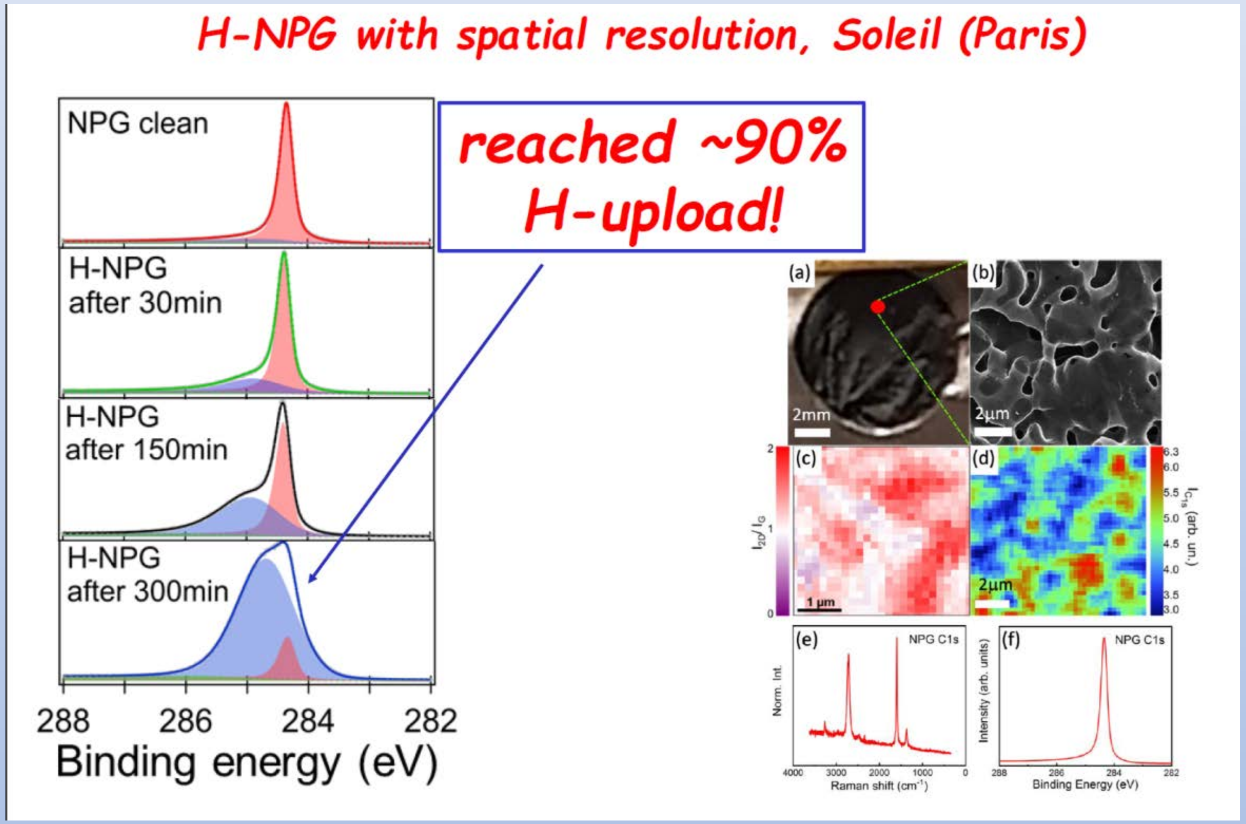
Fabrication of a Tritiated-Graphene Target/Source
Hydrogen and Deuterium loading on graphene at Roma1 and Roma3

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

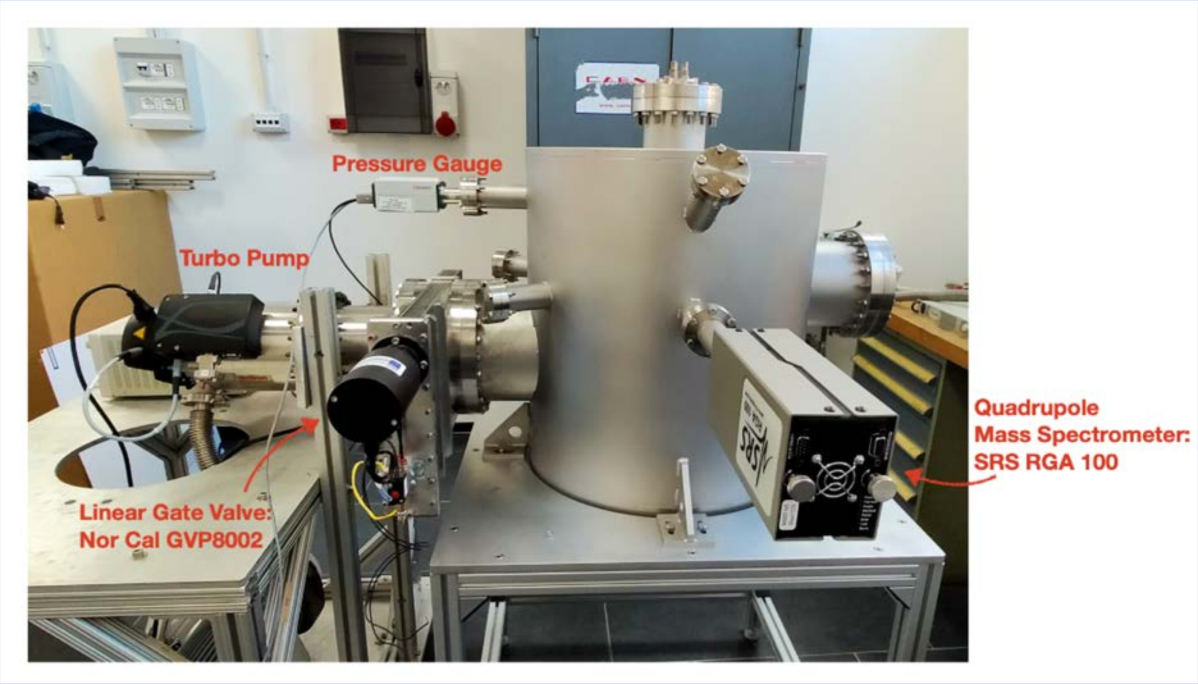


sp^3 C-H bond

H on Nanoporous Graphene (NPG):



T-chamber in Rome side view:



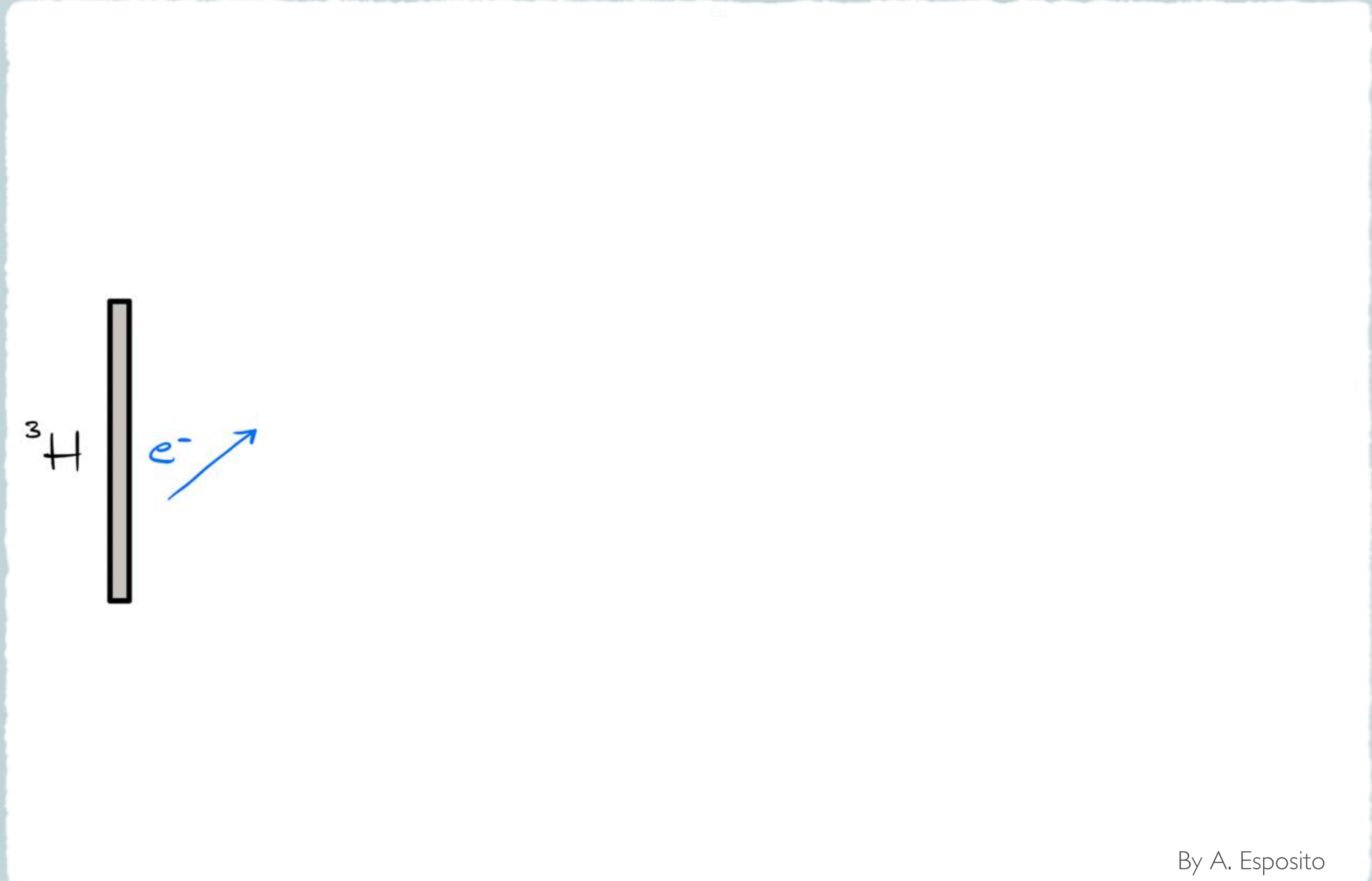
Betti et all, Nano Lett. **22**, 2971 (2022)

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



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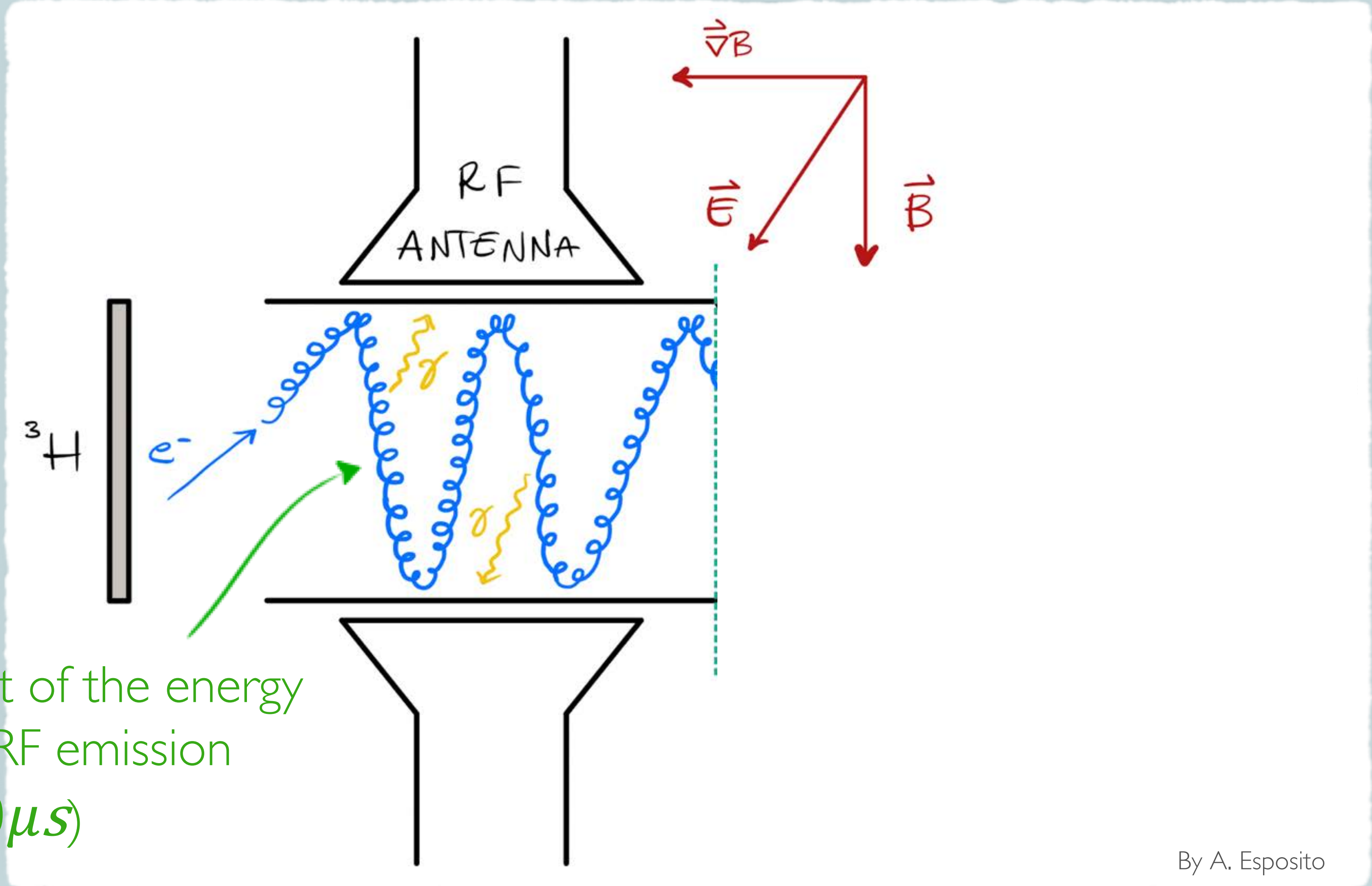

first measurement of the energy via cyclotron RF emission ($\sim 10\mu s$)

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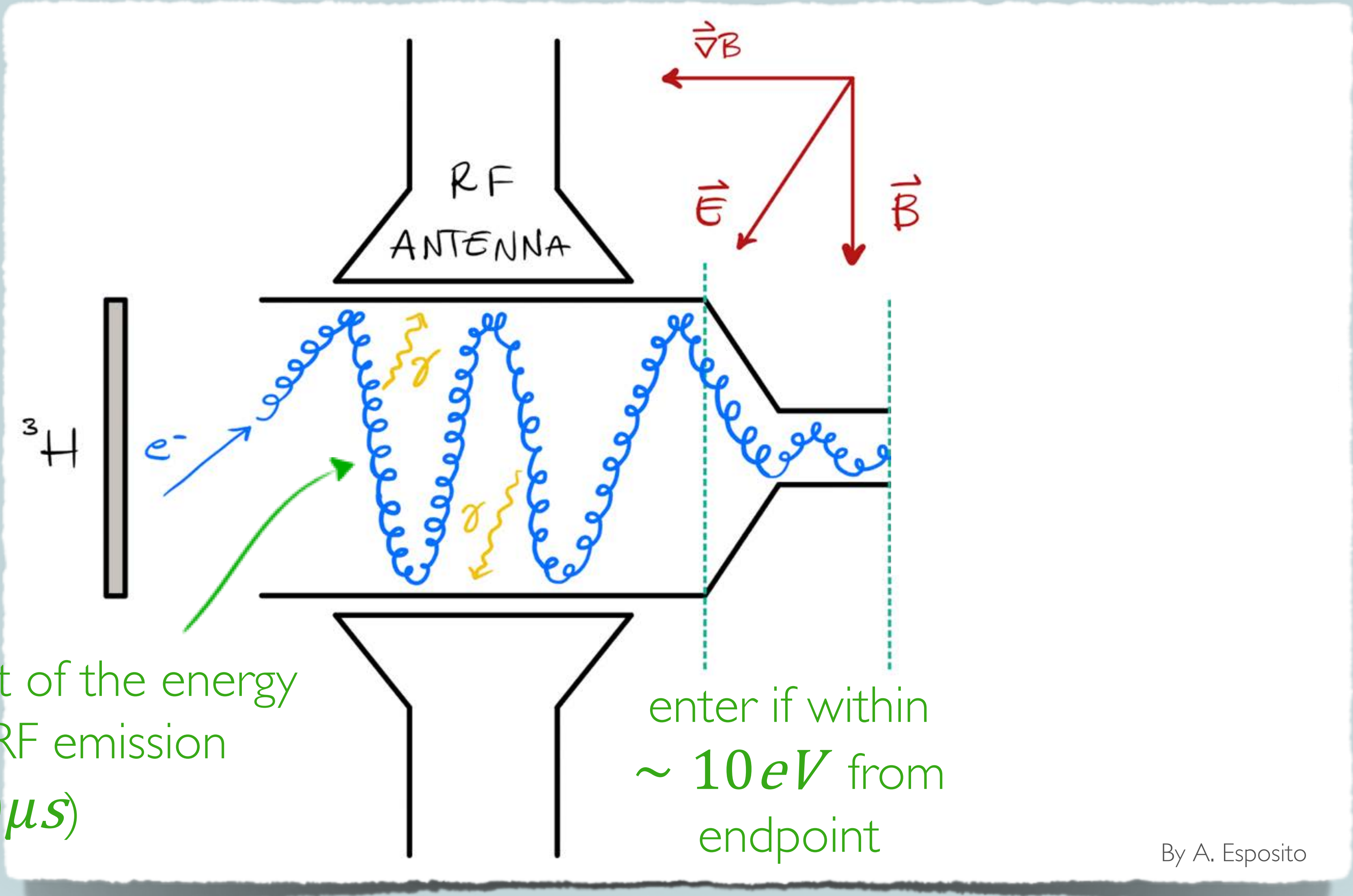


first measurement of the energy via cyclotron RF emission ($\sim 10\mu s$)

enter if within $\sim 10eV$ from endpoint

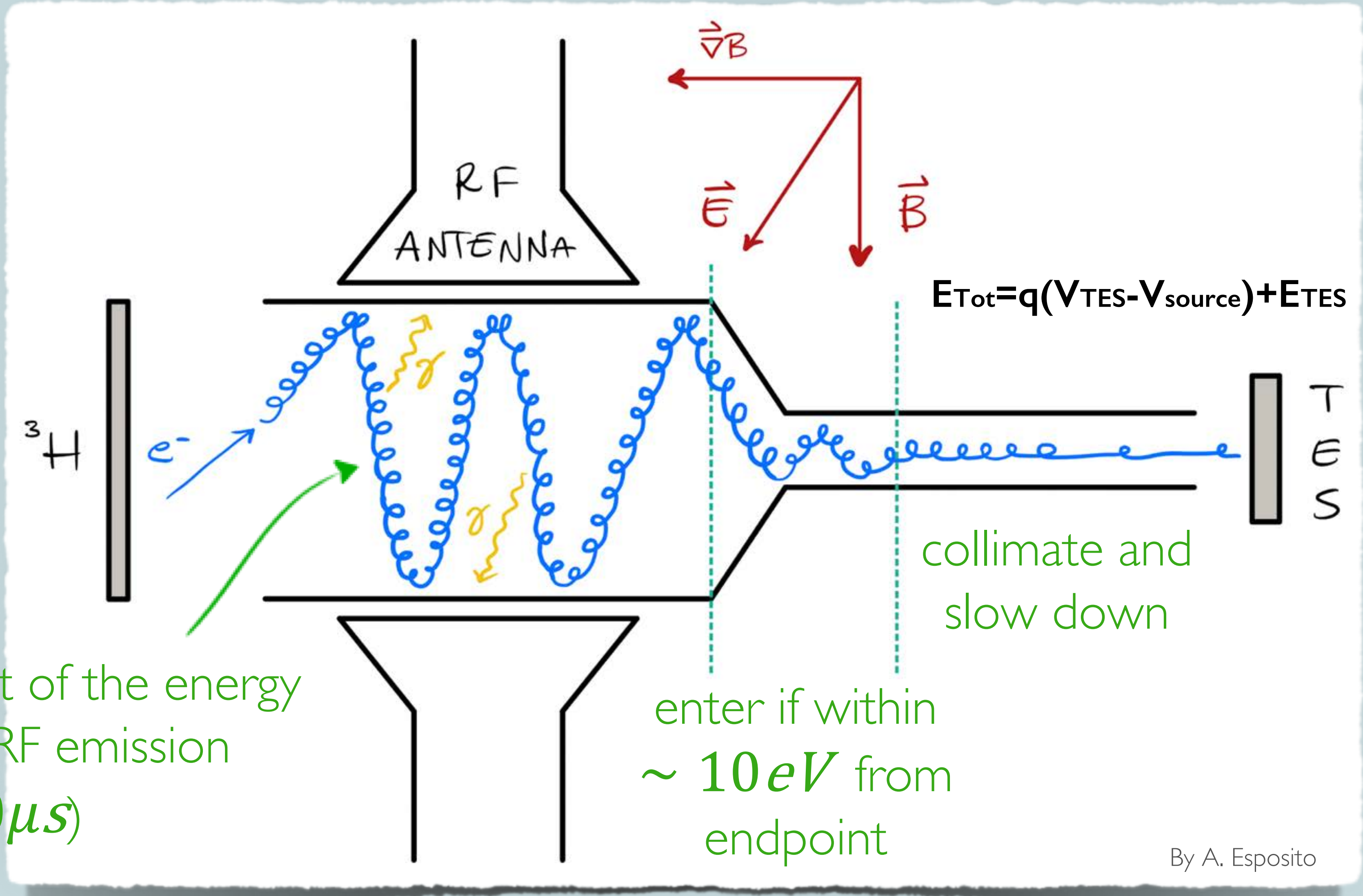
By A. Esposito

PTOLEMY: THE IDEA

JINST 17 (2022) 05, P05021

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

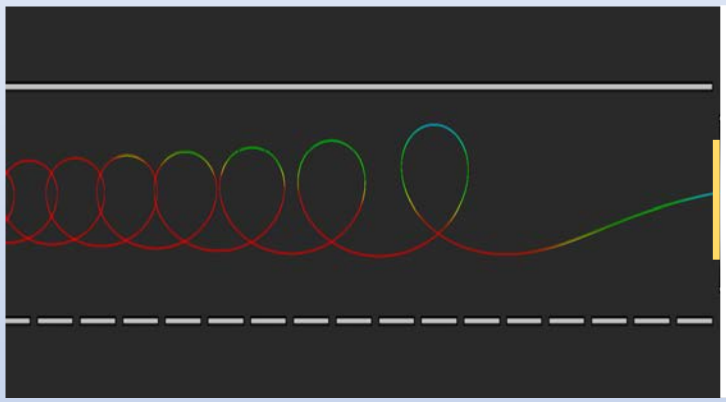
ΔV known to 1 ppm precision



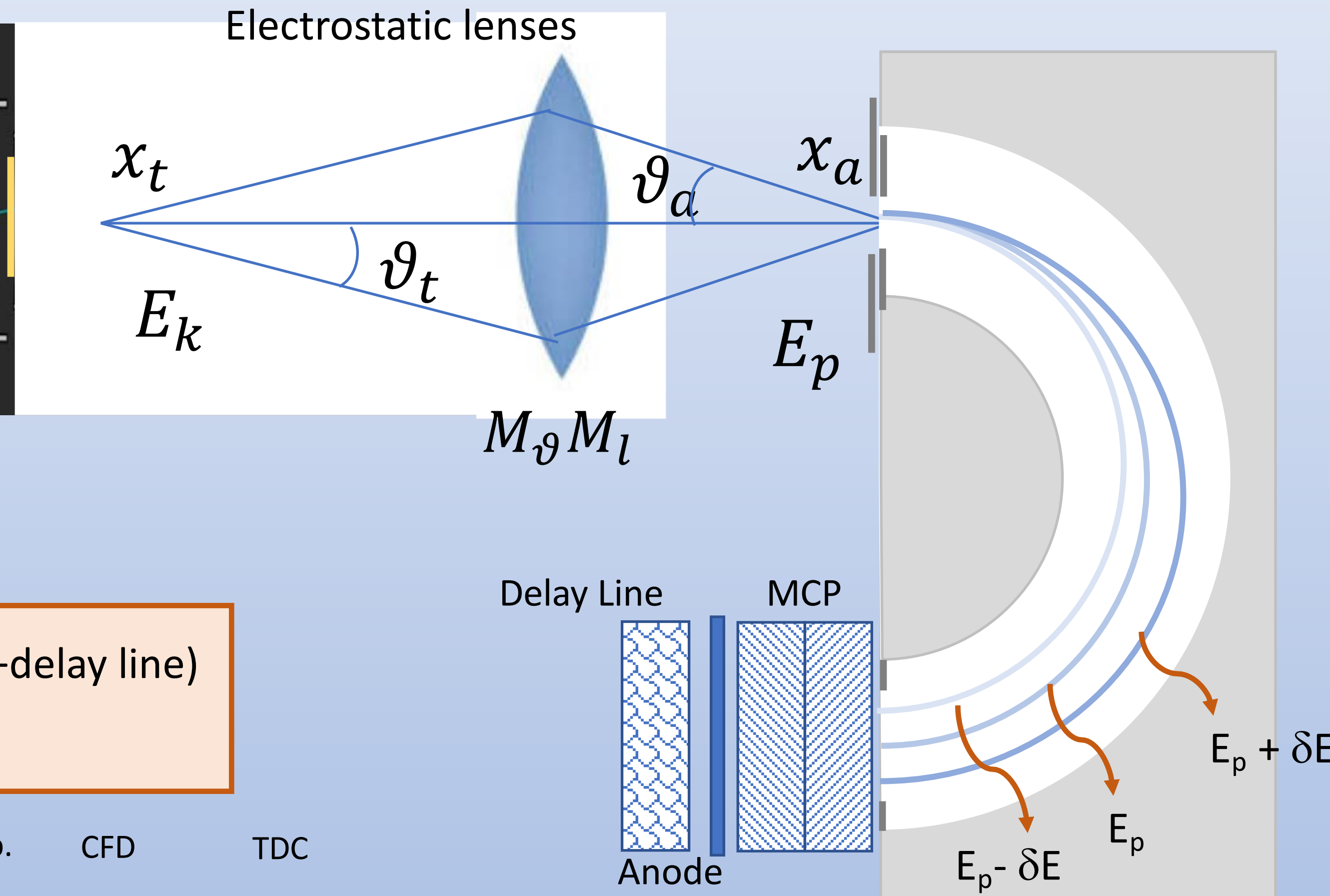
first measurement of the energy via cyclotron RF emission ($\sim 10\mu s$)

Precision energy measurement from Condensed Matter/ARPES

Electostatic analyser



Ptolemy e.m. filter



Electron optic basic equation

Helmholtz – Lagrange law

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

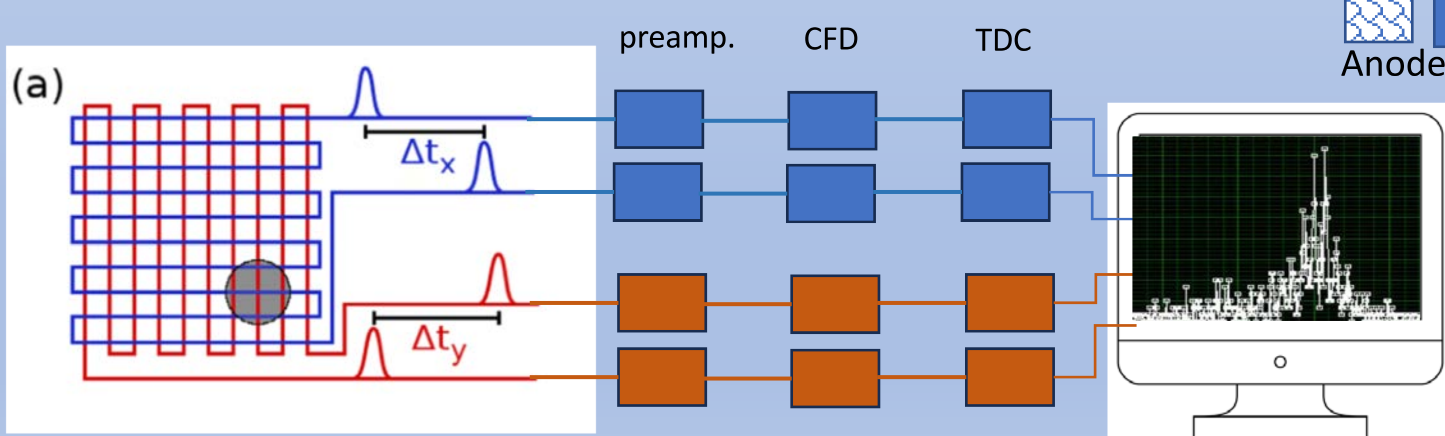
Two concentric hemispheres for the energy selection

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



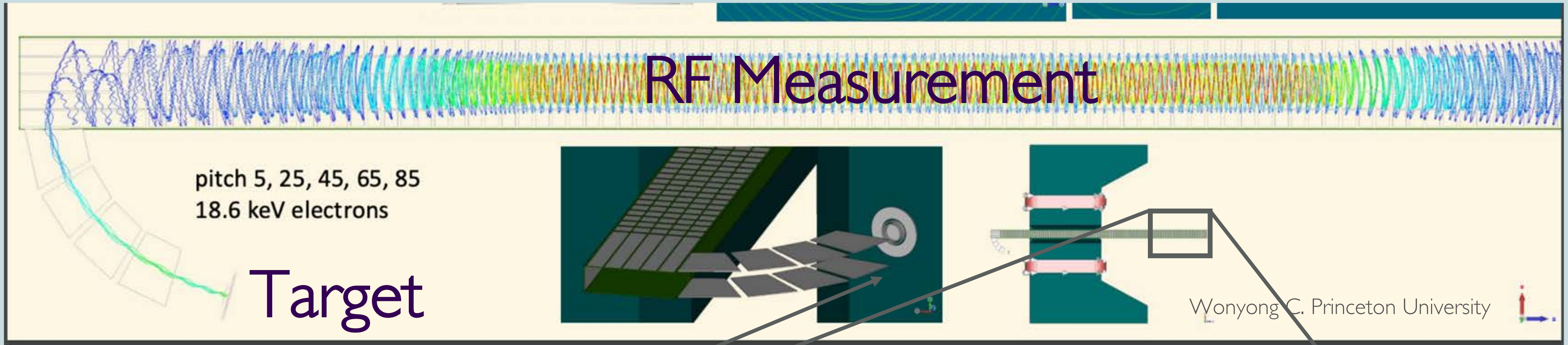
Specs Phoibos 225

~few meV energy resolution

Detailed simulation of the PTOLEMY filter

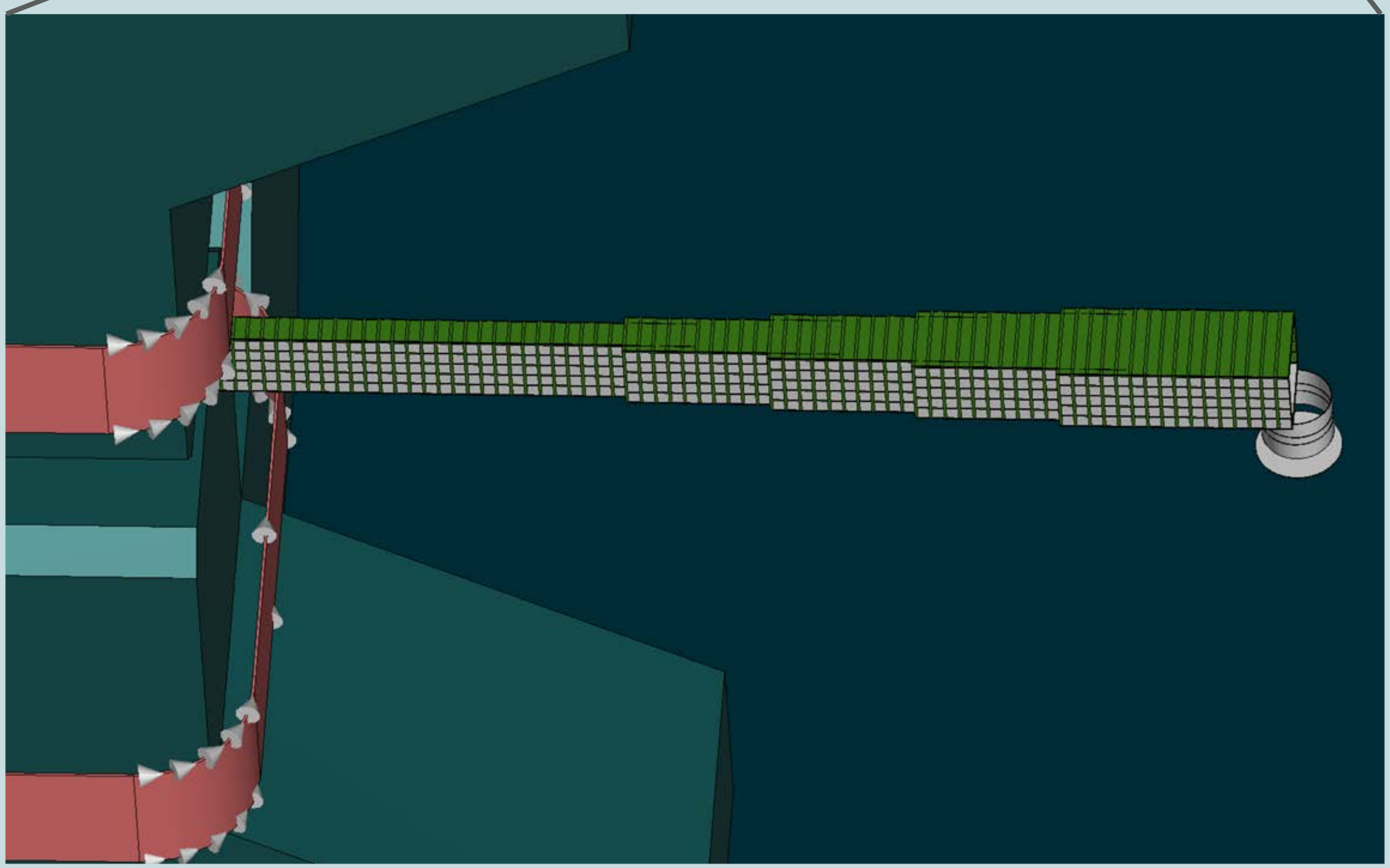
Magnet 1 T field
RF region

Filter region



Micro-Cal

Geometry relying on modularity approach to increase instrumented target mass

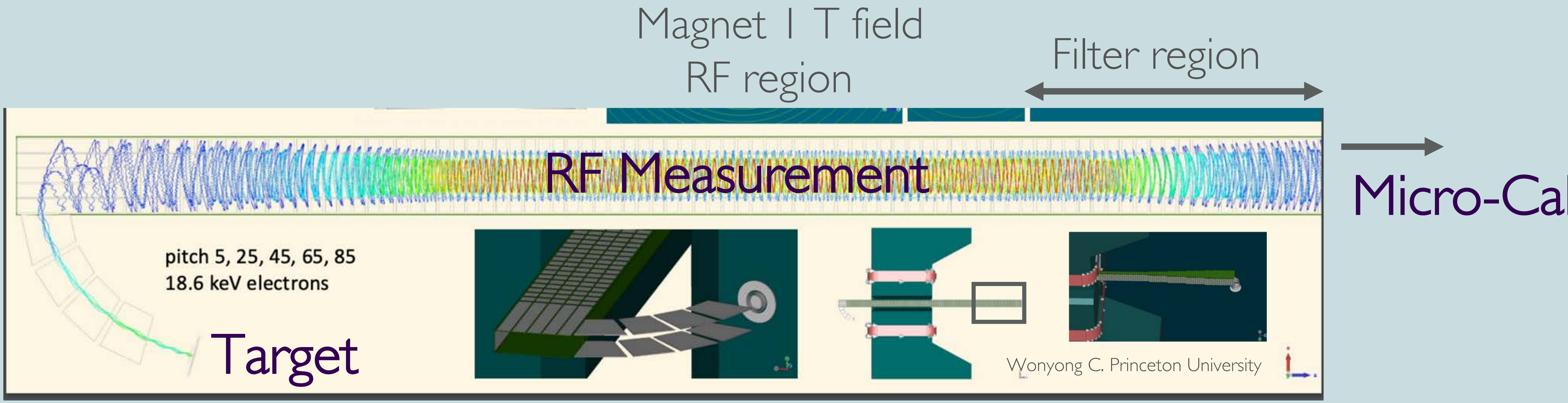


Micro-calorimeter region with focusing system to match beam and calorimeter array

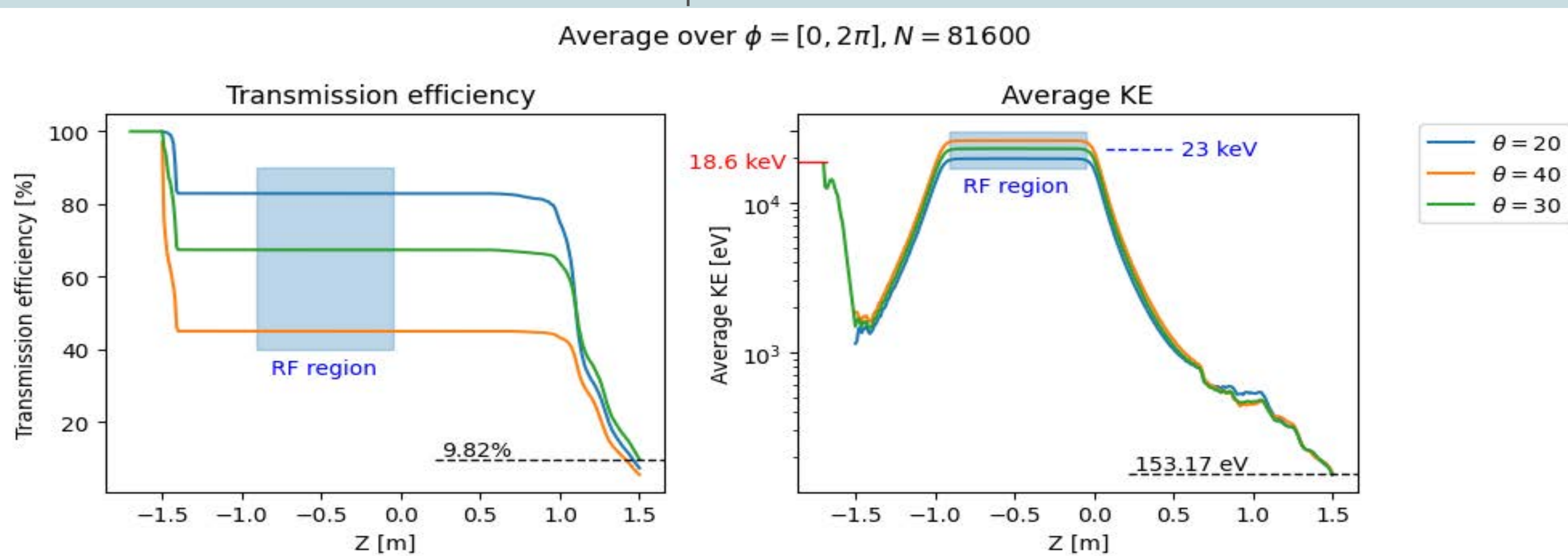
Zero B Field FOCUSING with Einzel lens (90 degress)

Microcalorimeter

End-to-End Drift Collimation and Transmission Results



10% Static Transport Achieved!!! Down to 160eV

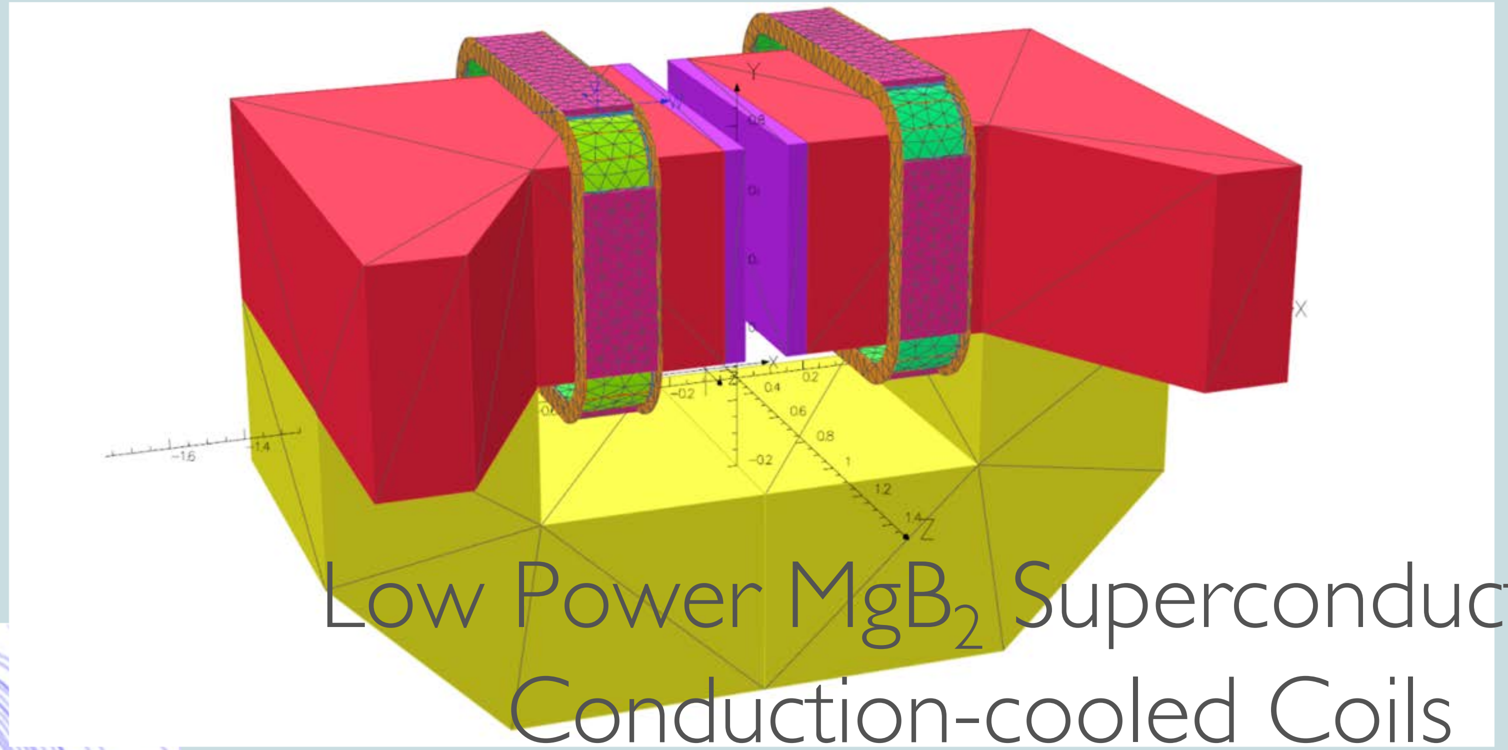


DEMONSTRATOR MAGNET

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

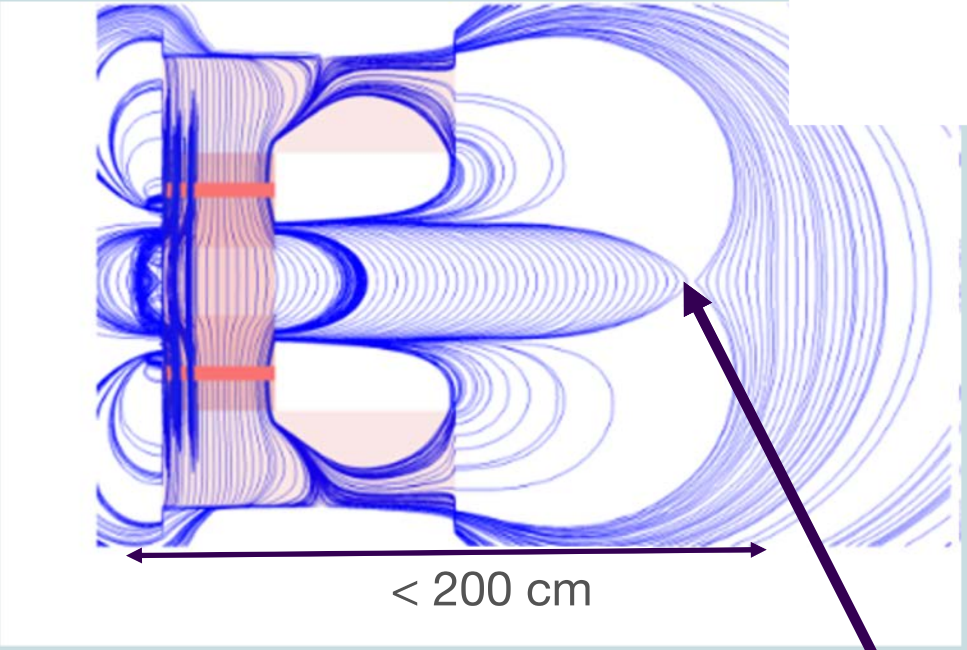
Construction ASG/Suprasys consortium of a SC dipole with special attention to the fringe field

Under construction in Genova → Shipment to CERN → LNGS



Low Power MgB_2 Superconducting Conduction-cooled Coils

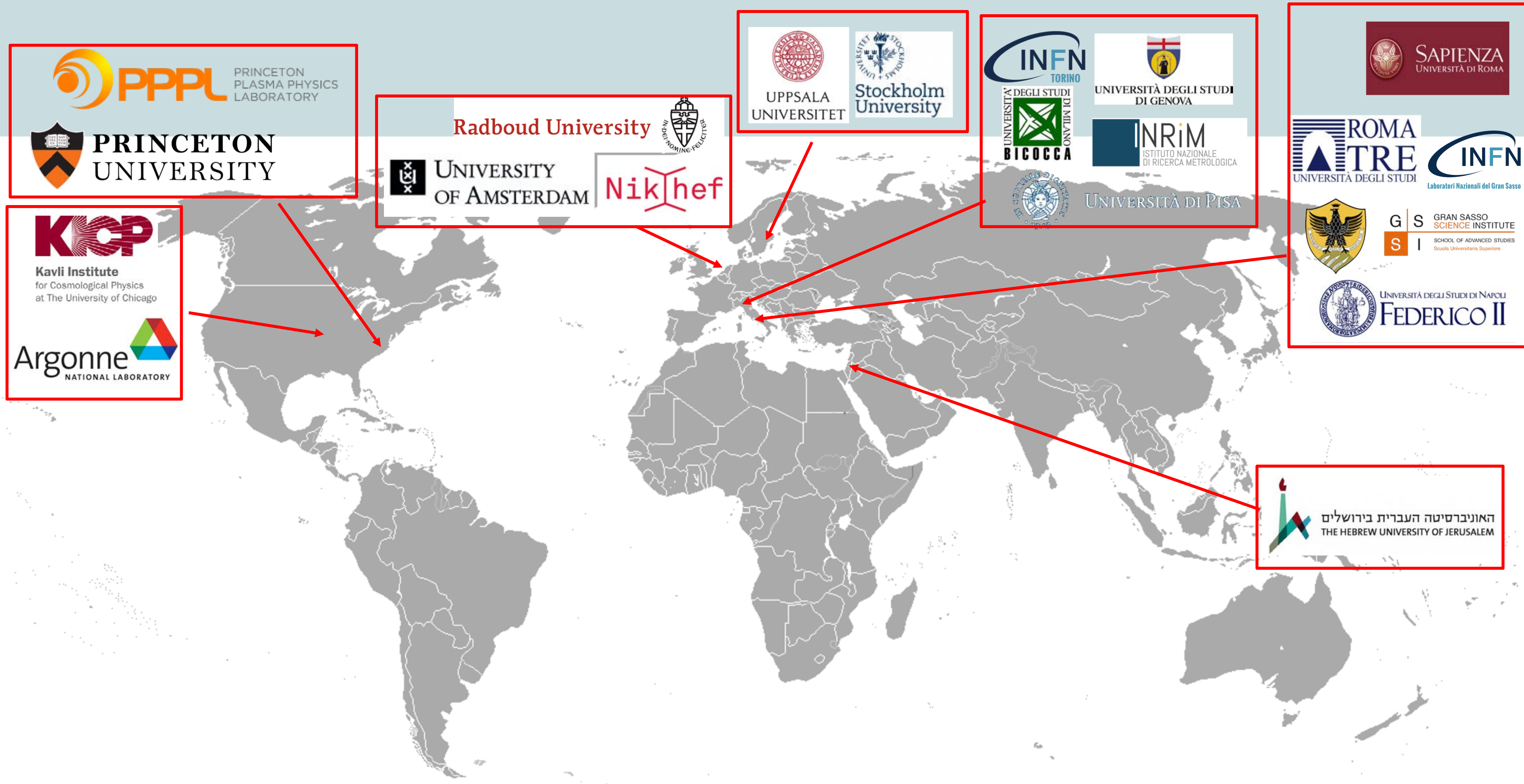
Simulated B-map



Vacuum System

Zero B field saddle point key feature of the field map

The PTOLEMY Collaboration



The PTOLEMY Collaboration

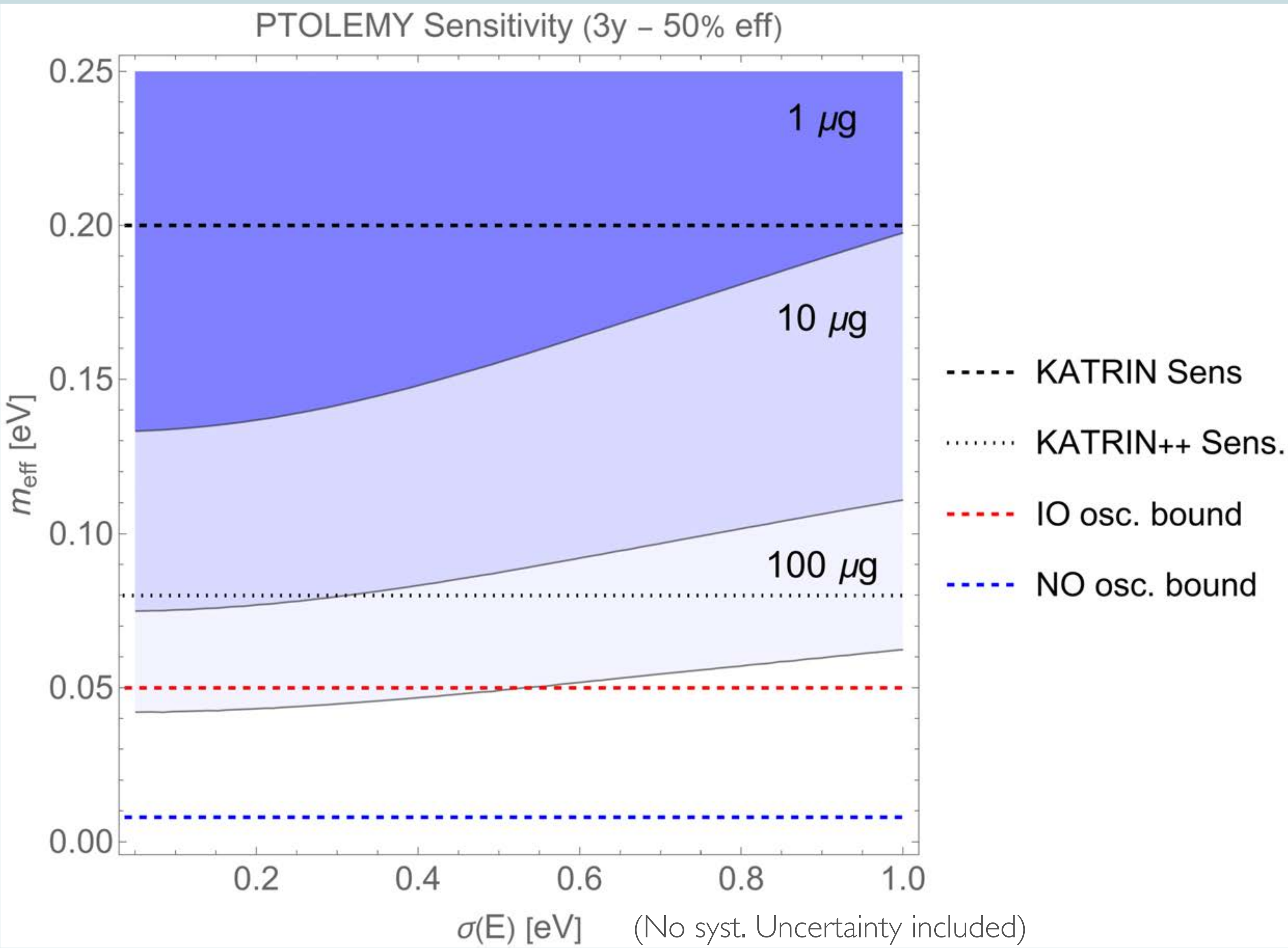
14 May 2024, Pollica, Italy

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
- Prototype baseline option is: T embedded on graphene; New concept EM filter; electron energy resolution measured in several steps (SDD/electrostatic spec/TES). Ultimately operating with sub-eV energy resolution.
- Ultimate goals of the Demonstrator: instrumented mass ~ hundreds of μg, energy resolution 50-100 meV, T storage solution will come from optimization of atomic T support structure. Time scale 5 years.
- "Intermediate" physics program of Demonstrator: neutrino mass measurements (or limits) beyond what has been achieved by all previous experiments.
- Submitted letter of intent to European Strategy for Particle Physics 2026 (#28)

BACKUP

SENSITIVITY AS A FUNCTION OF TRITIUM MASS



Remarks:

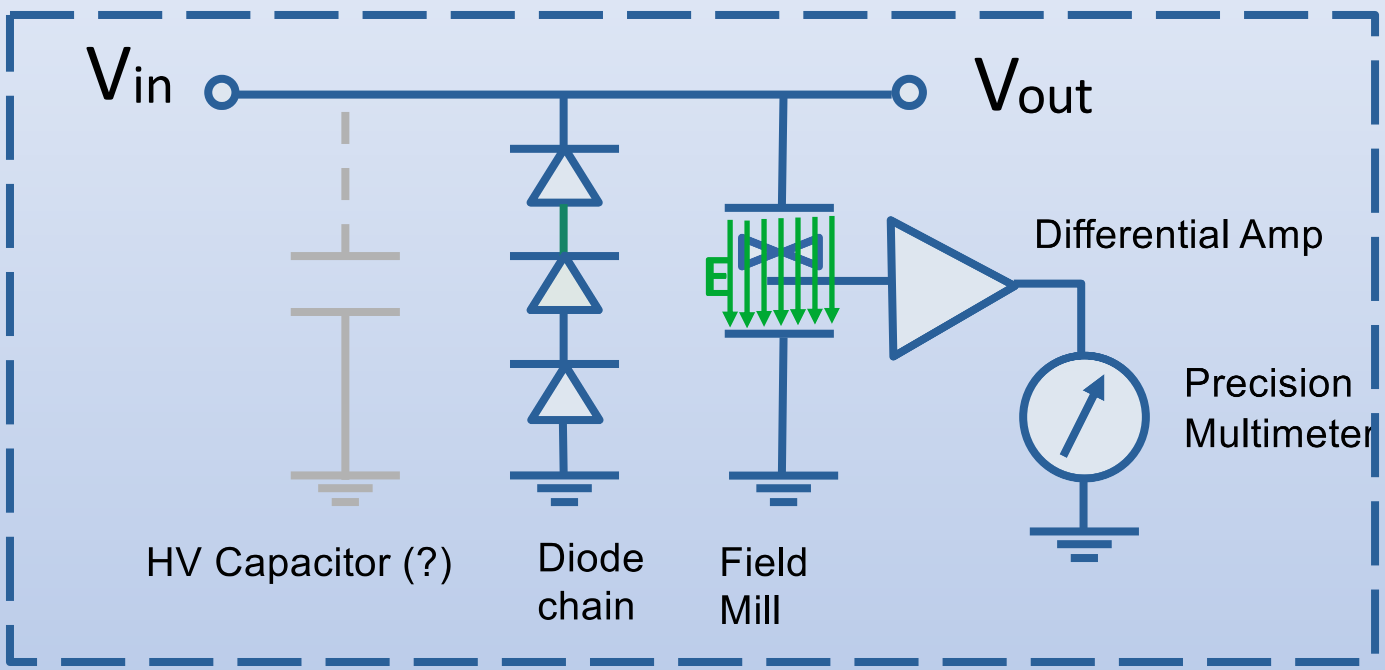
- the sensitivity is weakly dependent upon the energy resolution (500 meV is already a good starting point)

- 1 μg (7x7 cm^2) already provides competitive sensitivity

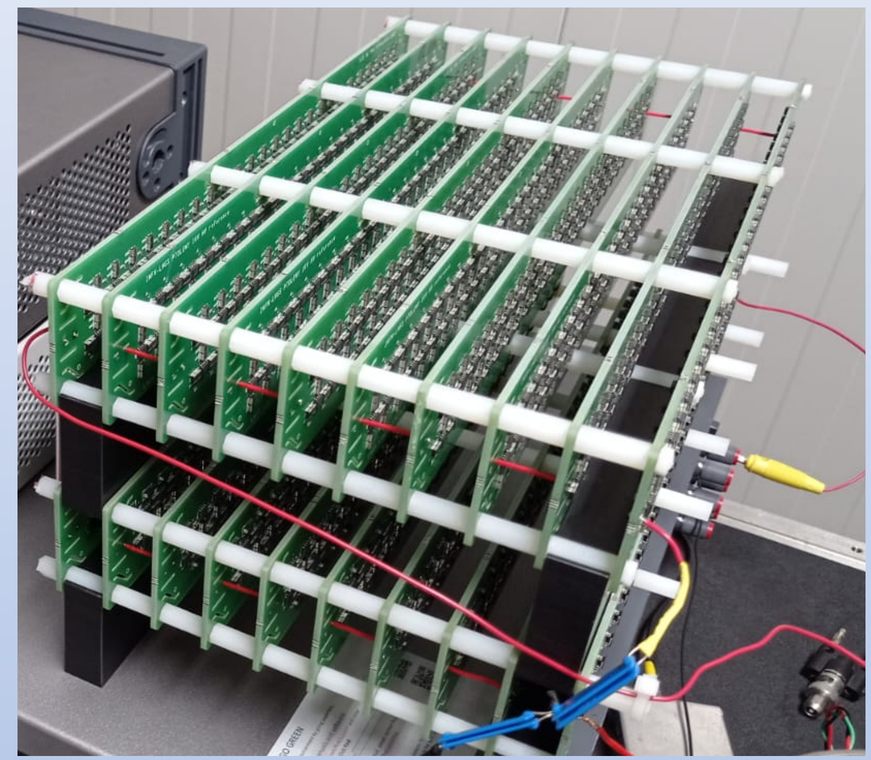
- 100 μg (0.5 m^2) can potentially probe the neutrino mass down to the IO scenario

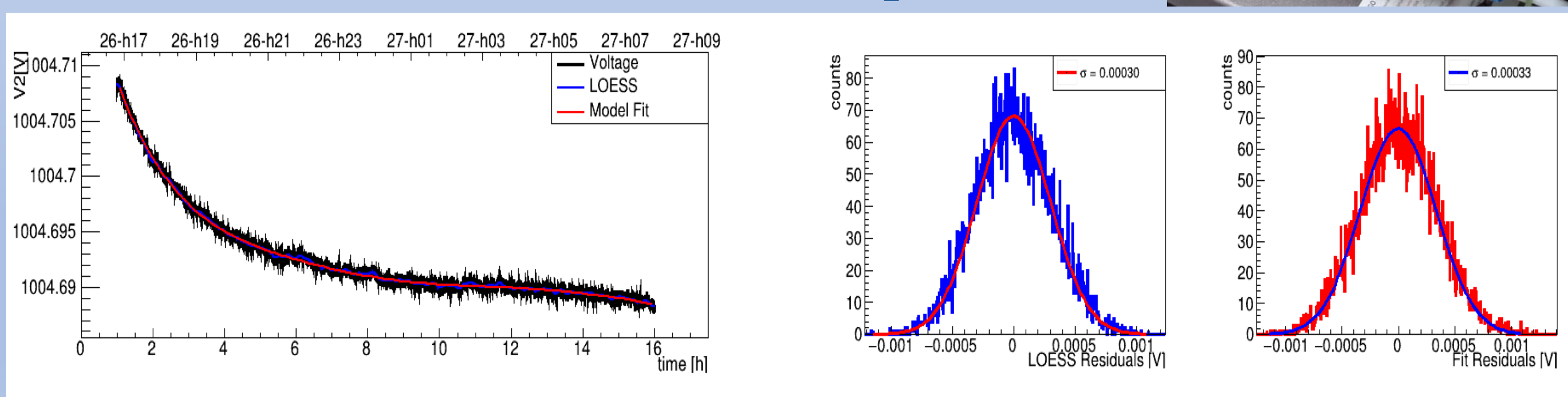
In preparation a theory paper on solid state effects on the electron spectrum & consequent theory systematics on m_ν **extraction**
(A. Casale, A. Esposito G. Menichetti, V. Tozzini)

HV High precision stability (LNGS)



Climatic chamber - N_2





Single board (1 kV)

$\sigma = 0.3$ mV