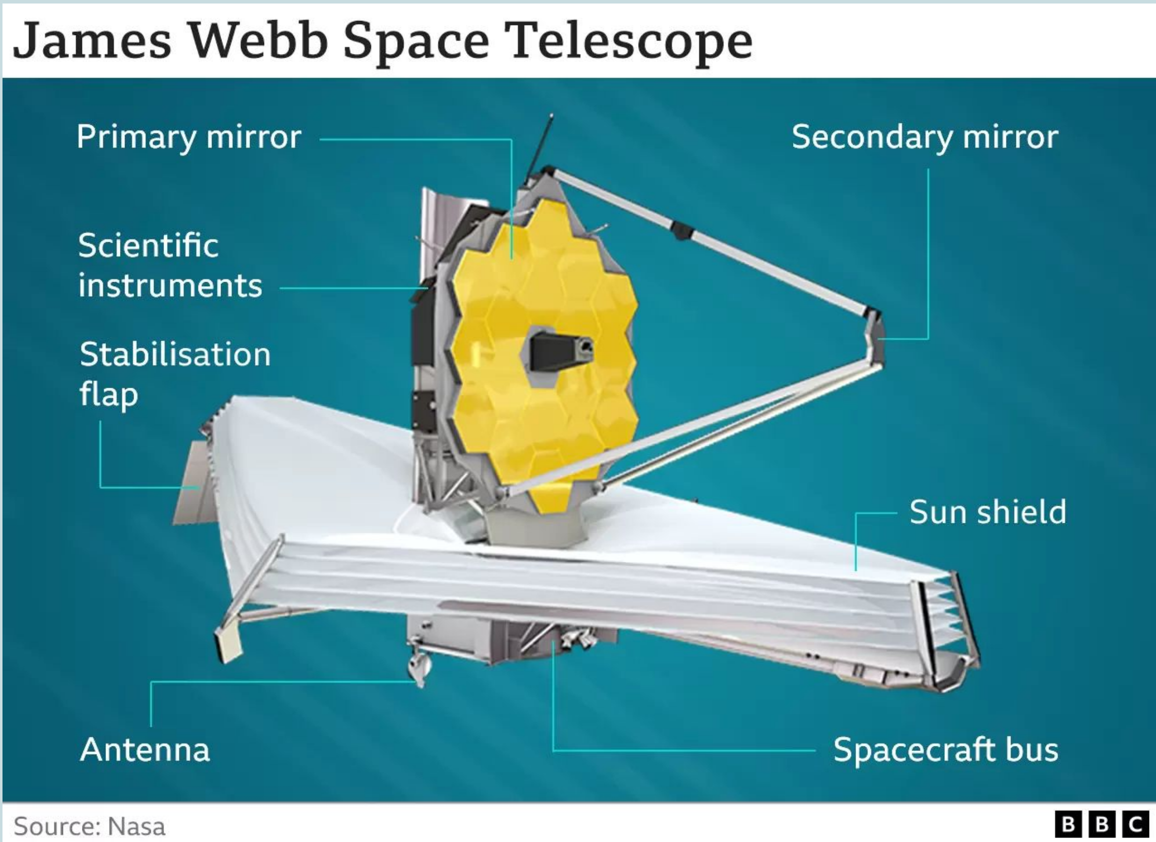
How to unravel the youngest Universe: Introduction to the PTOLEMY project

Chris Tully (Princeton University)

4 December 2024
Genoa, Italy

Research supported by John Templeton Foundation

ERA OF AMAZING NEW TELESCOPES



https://www.space.com
/james-webb-space-tel
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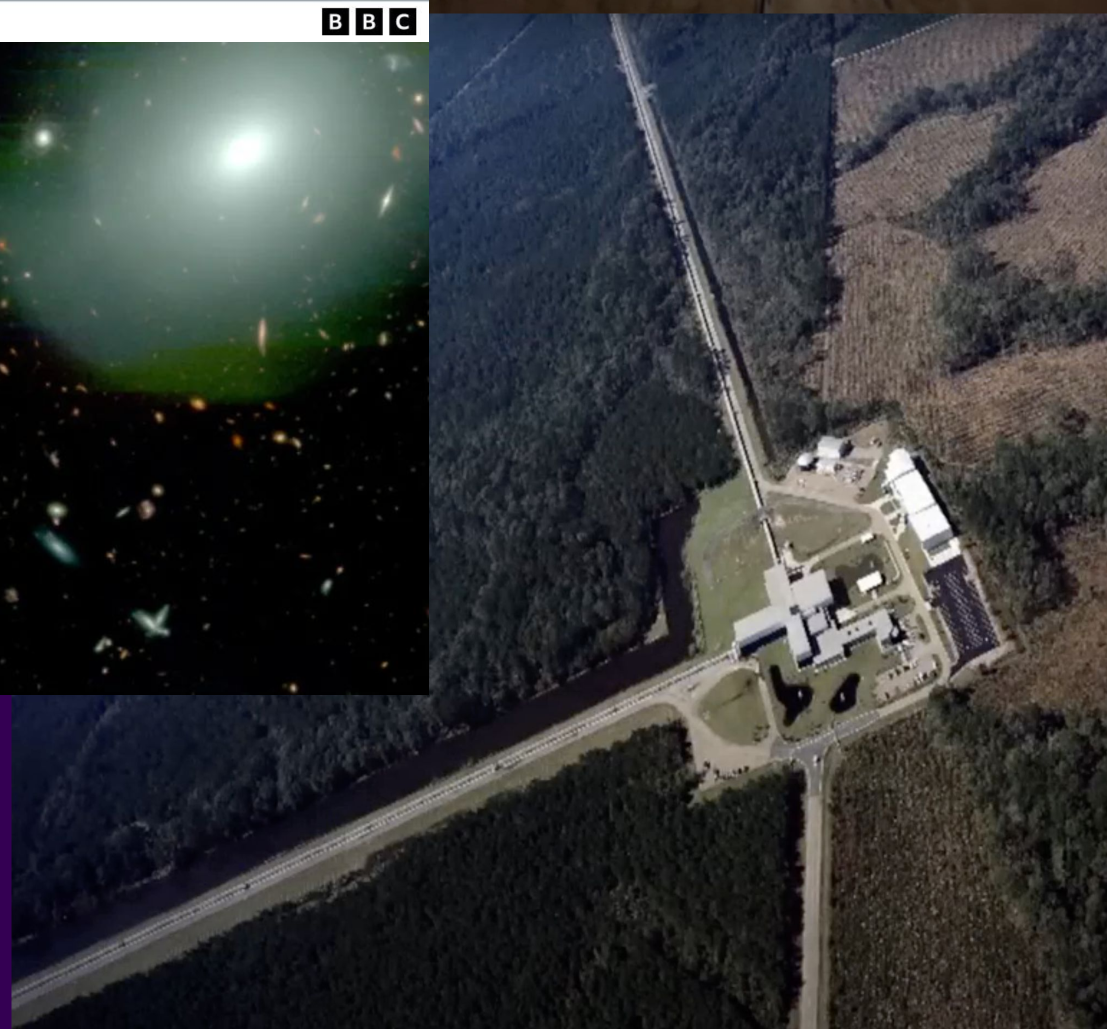
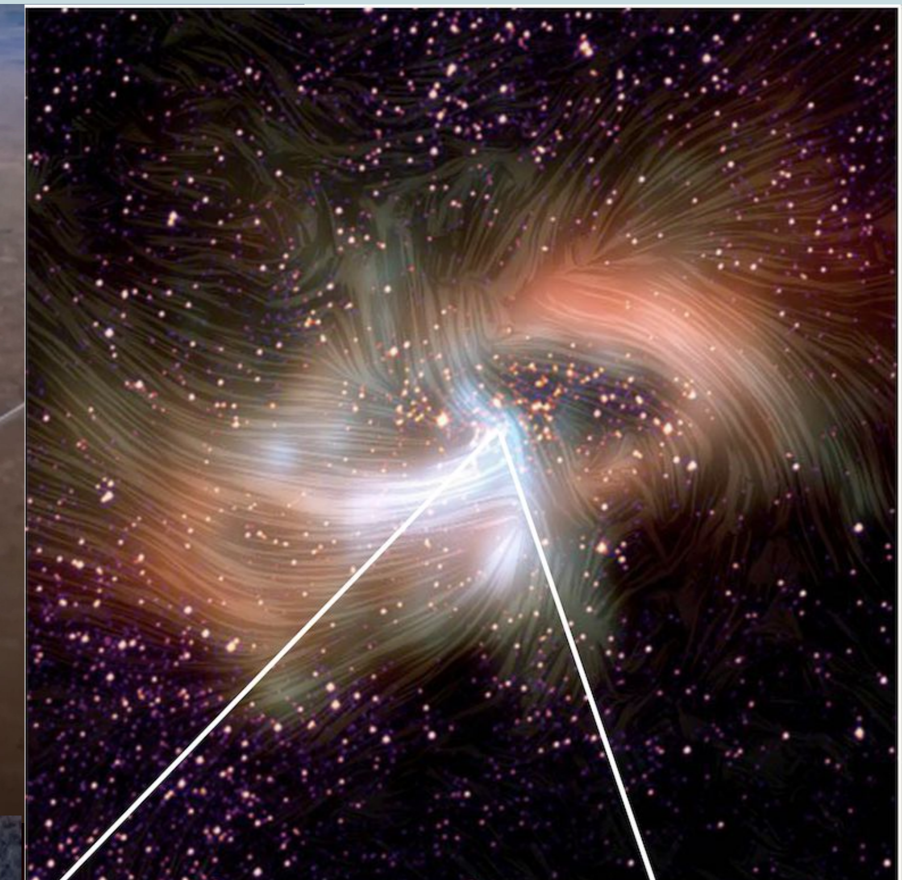
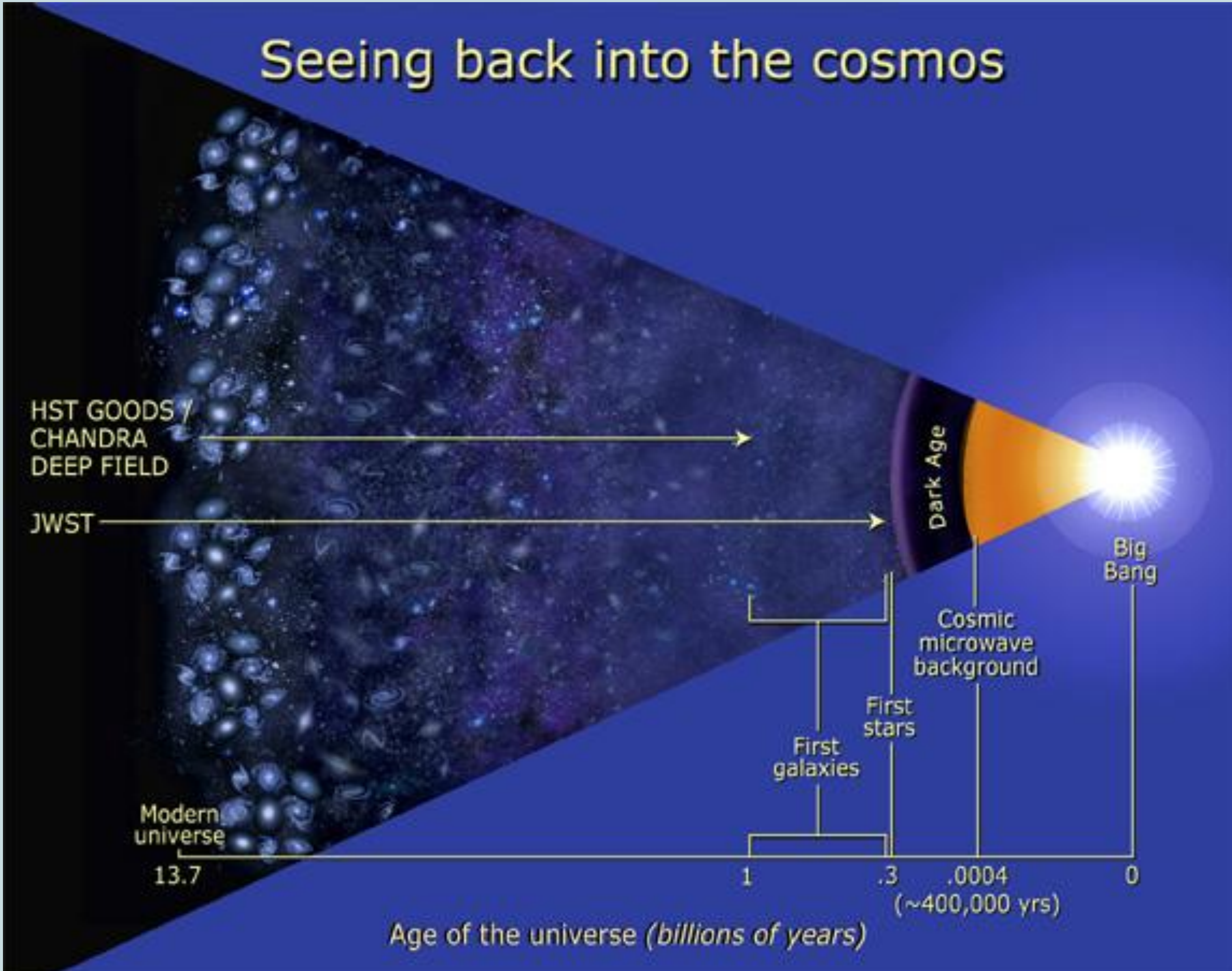
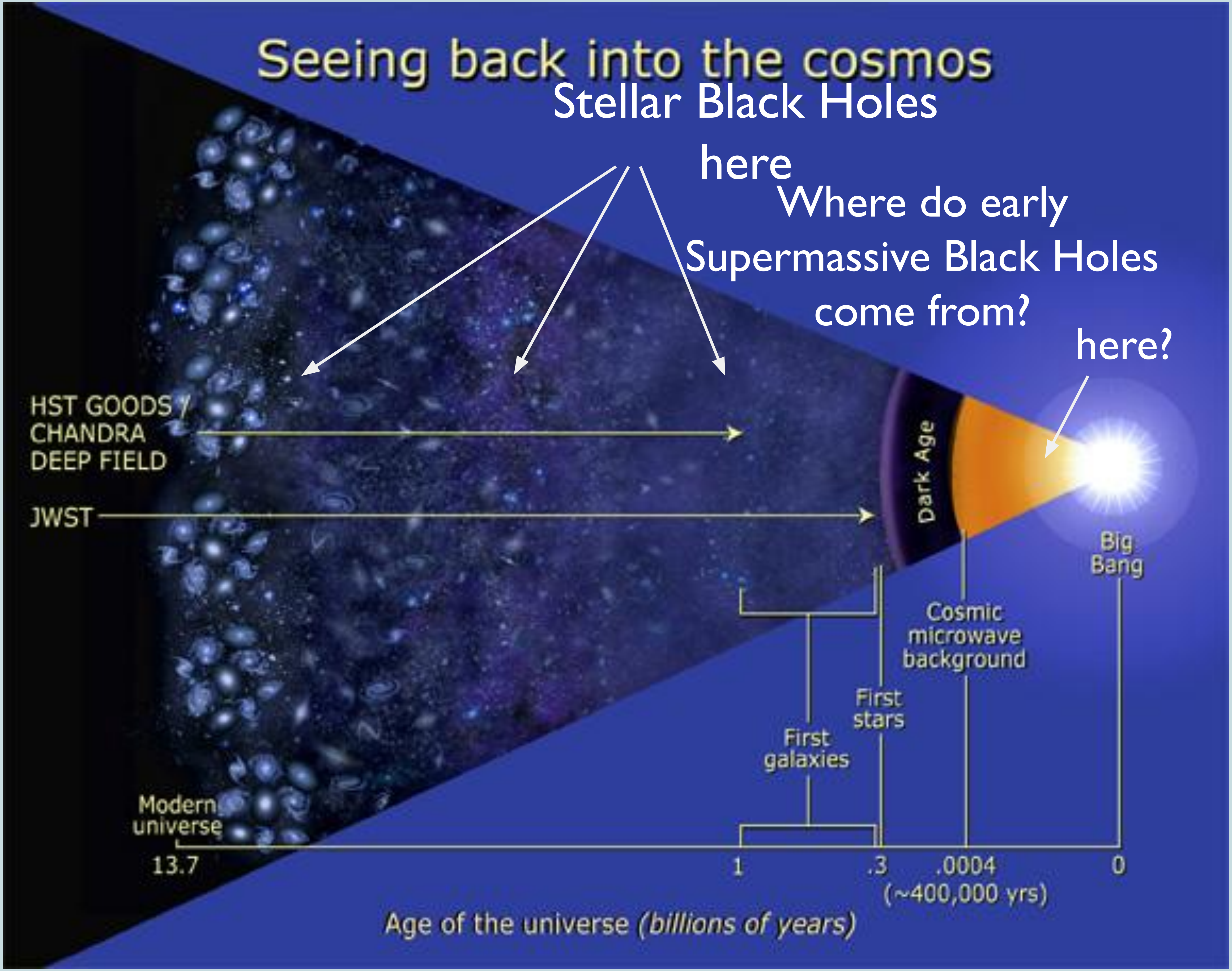




Event Horizon Telescope
Supermassive Black Hole
at Center of Milky Way Galaxy


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 /
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(~400,000 yrs)
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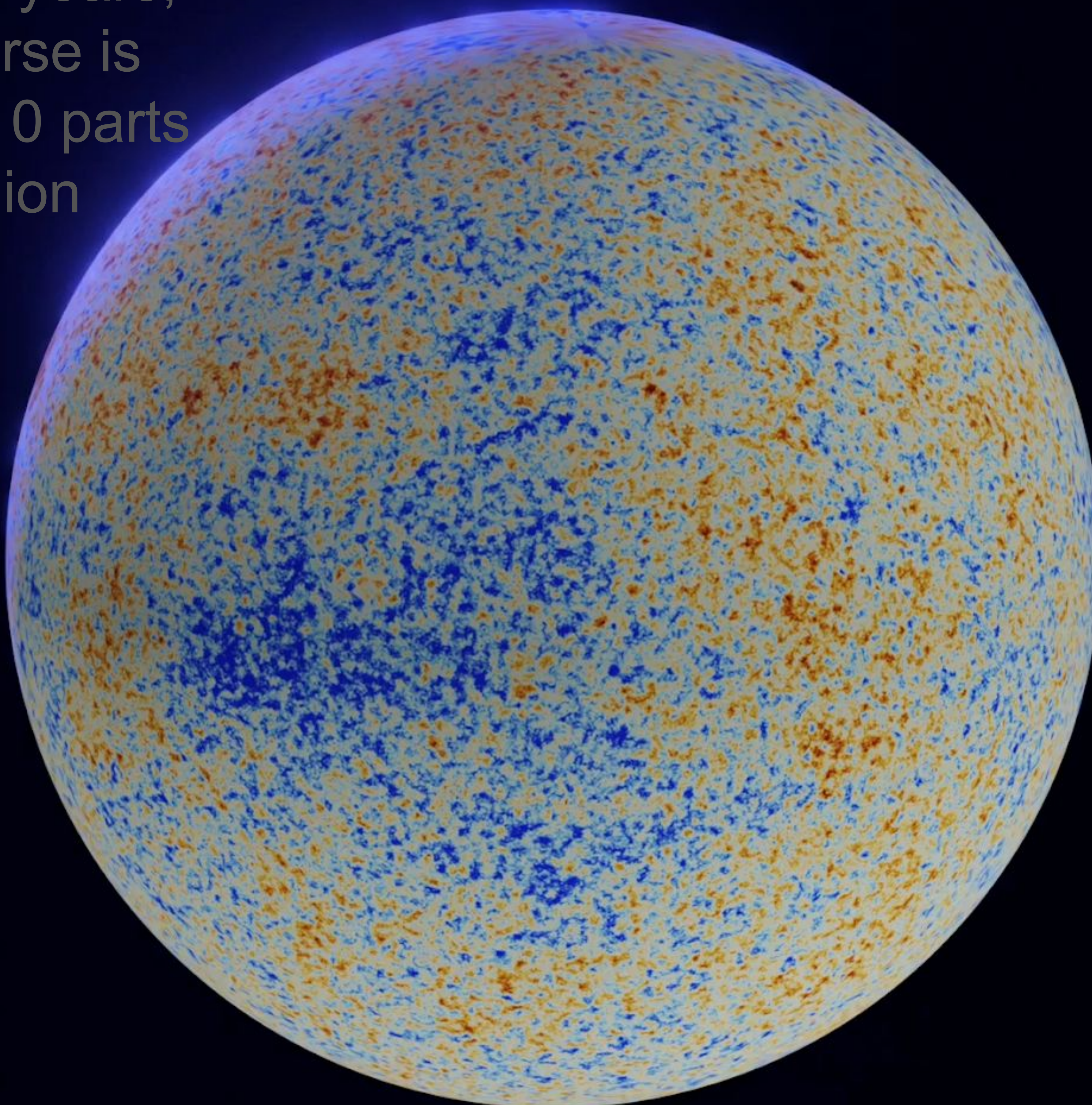
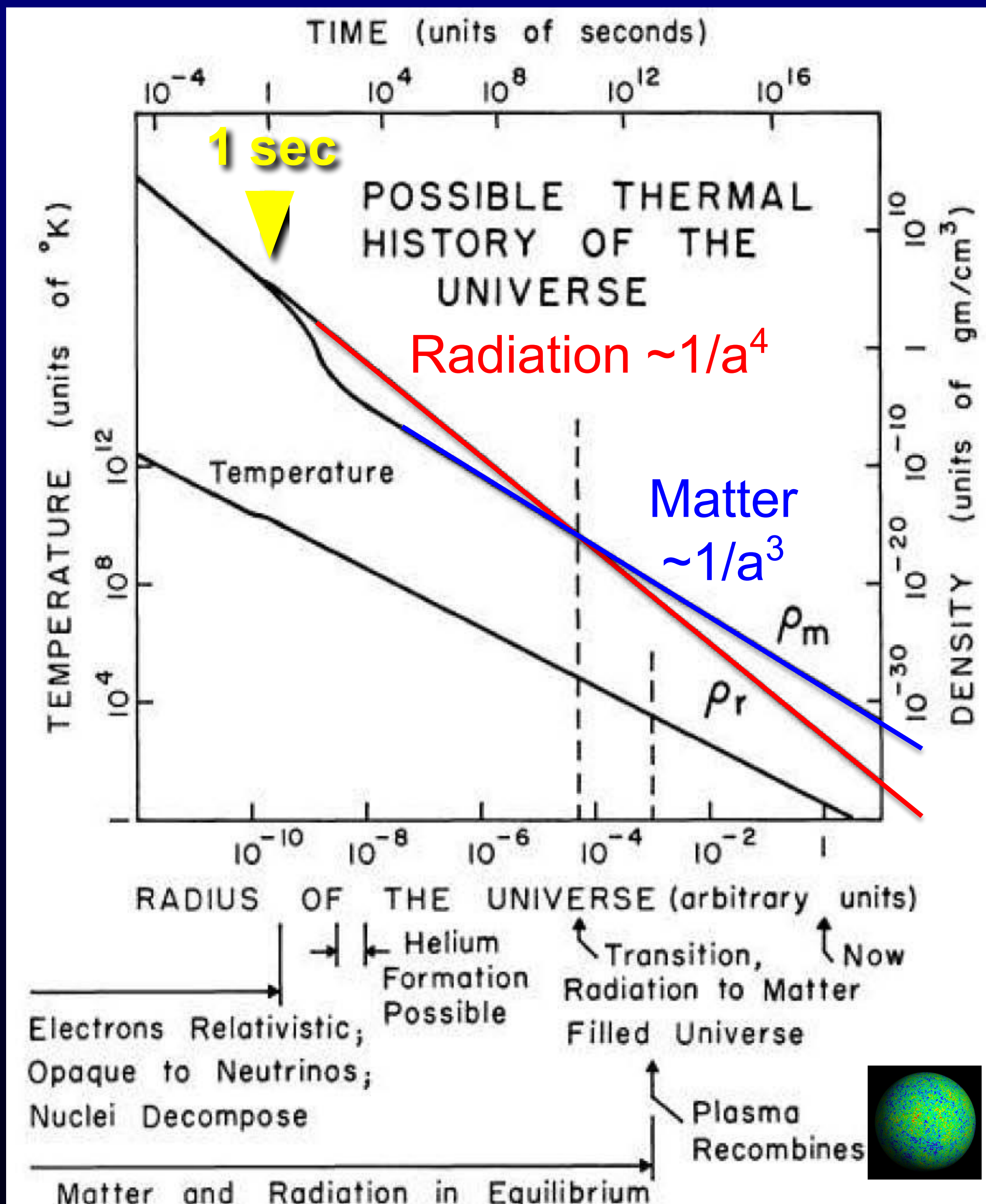
Age of the universe (billions of years)

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



Cosmic Neutrino Background



Number density:

$n_\nu = 112/cm^3$

Temperature:

$T_\nu \sim 1.95K$

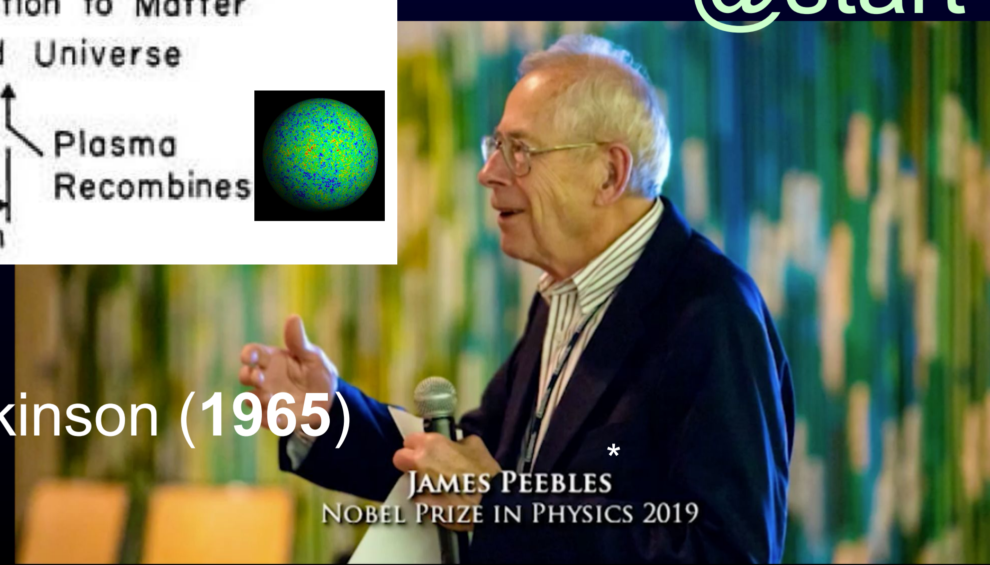
Time of decoupling:

$t_\nu \sim 1$ second

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

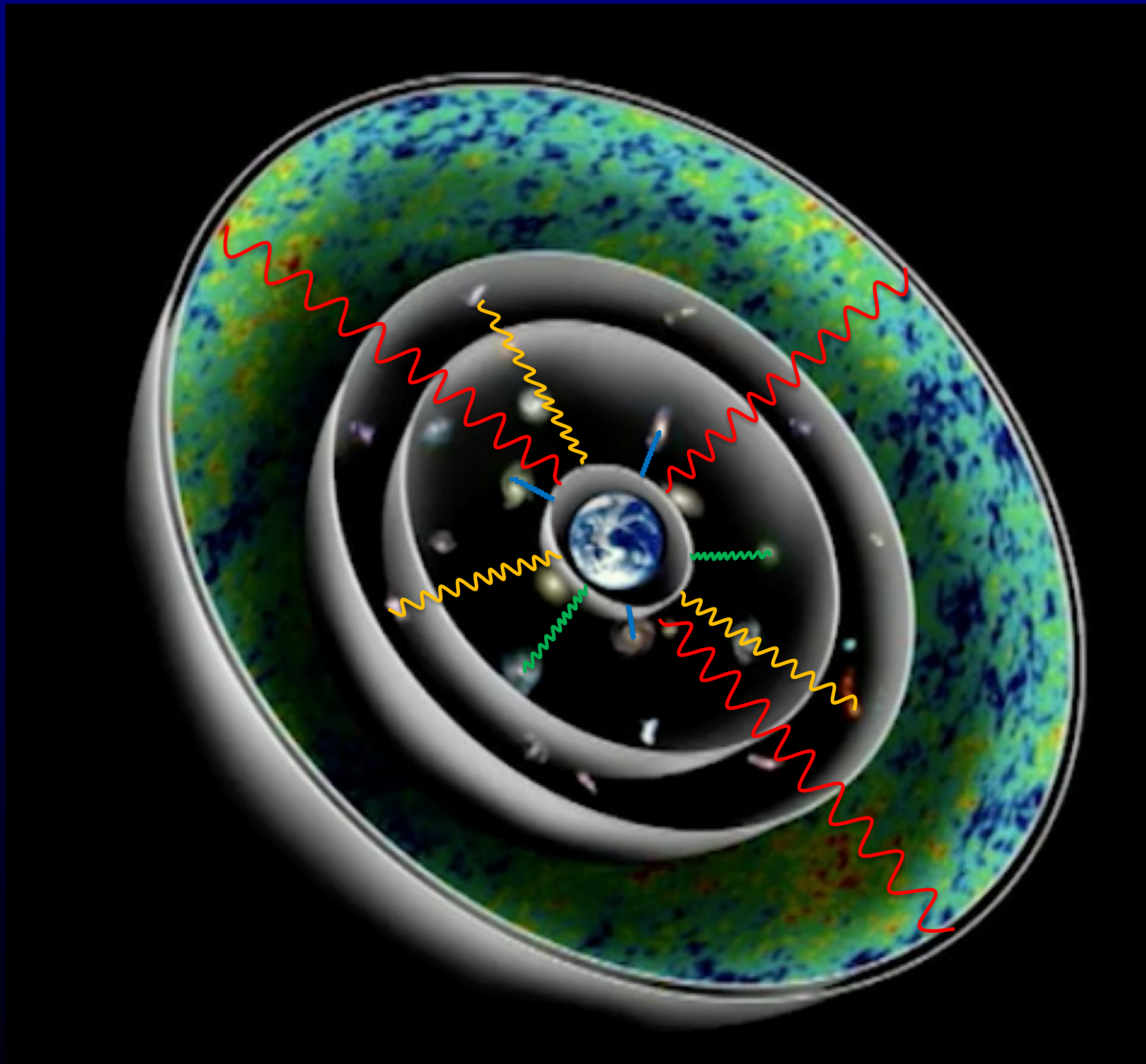
neutron/proton ratio @start of nucleosynthesis

 ^{4}He ^{2}H (^{3}He)



Dicke, Peebles*, Roll, Wilkinson (1965)

Looking Back in Time with Photons



Emission Time

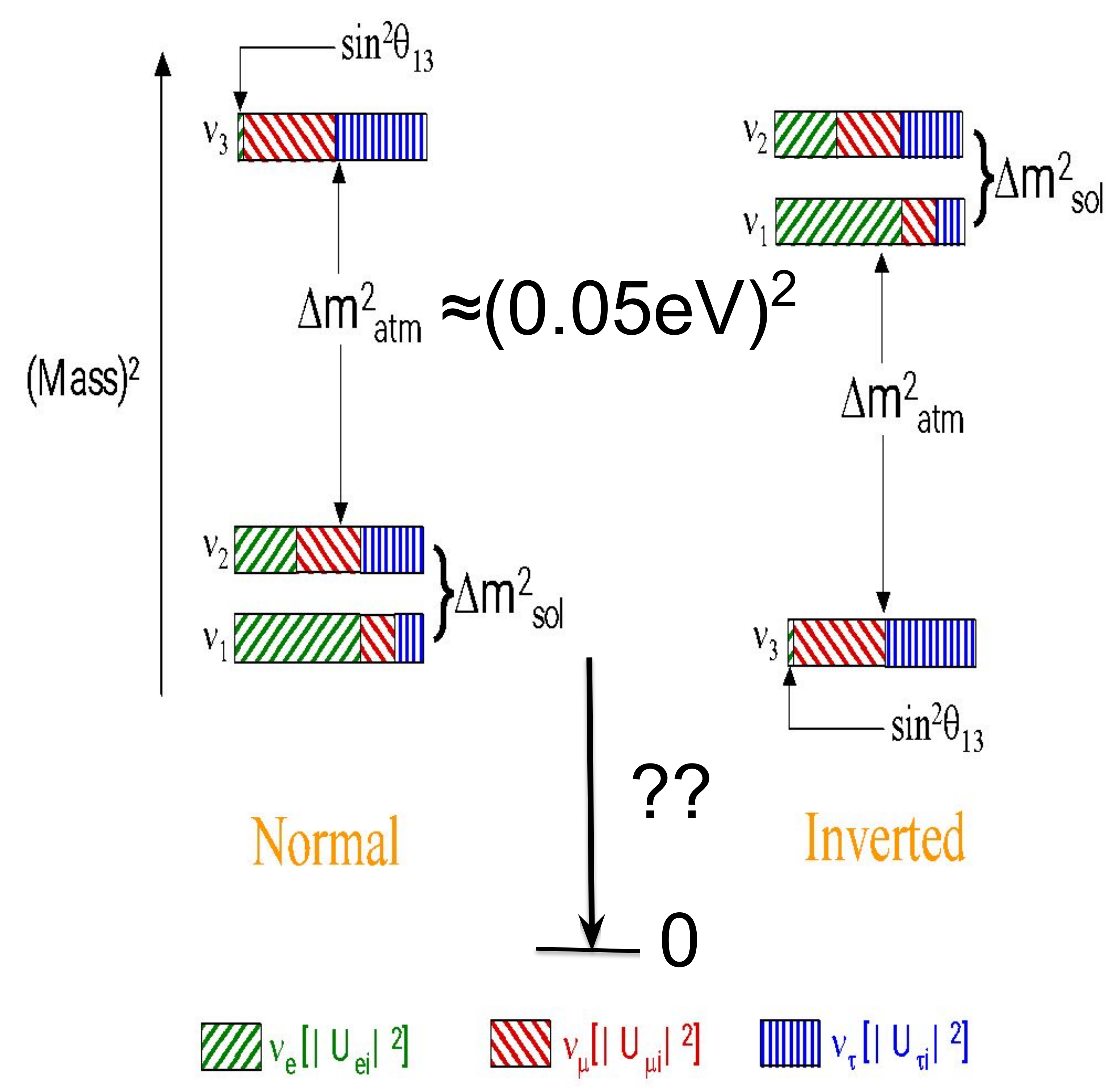
-13.8×10^9 years

-4×10^9 years

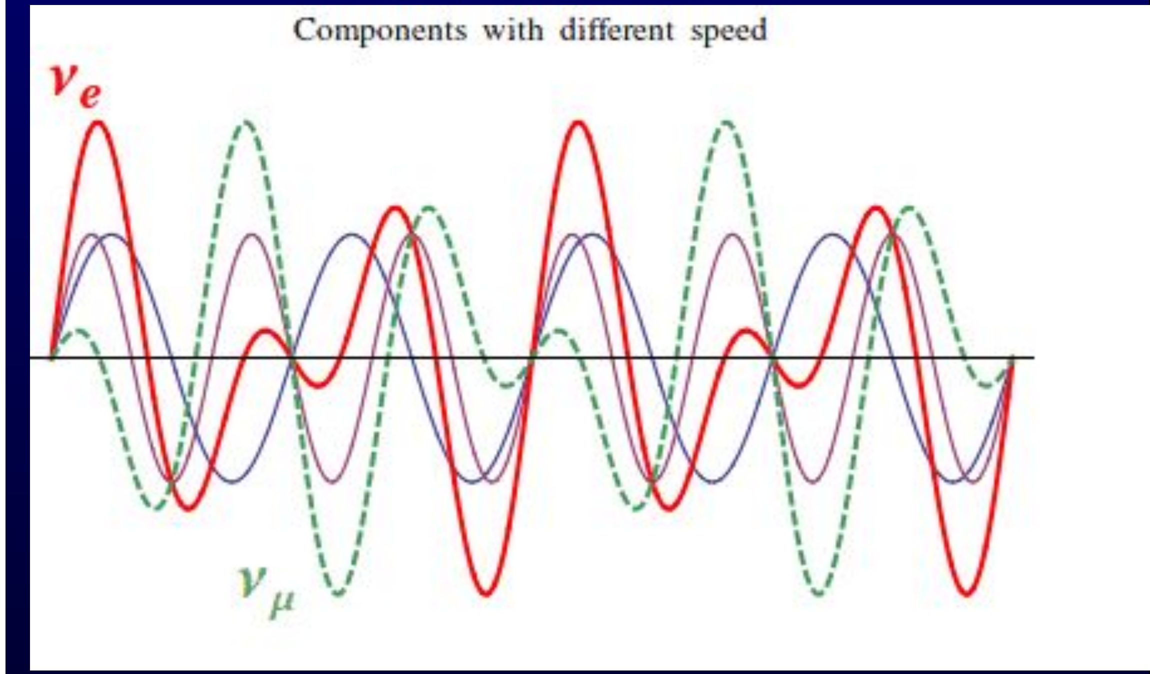
-200×10^6 years

-2×10^6 years

Neutrino Masses from Oscillations



Theory developed by Bruno Pontecorvo



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

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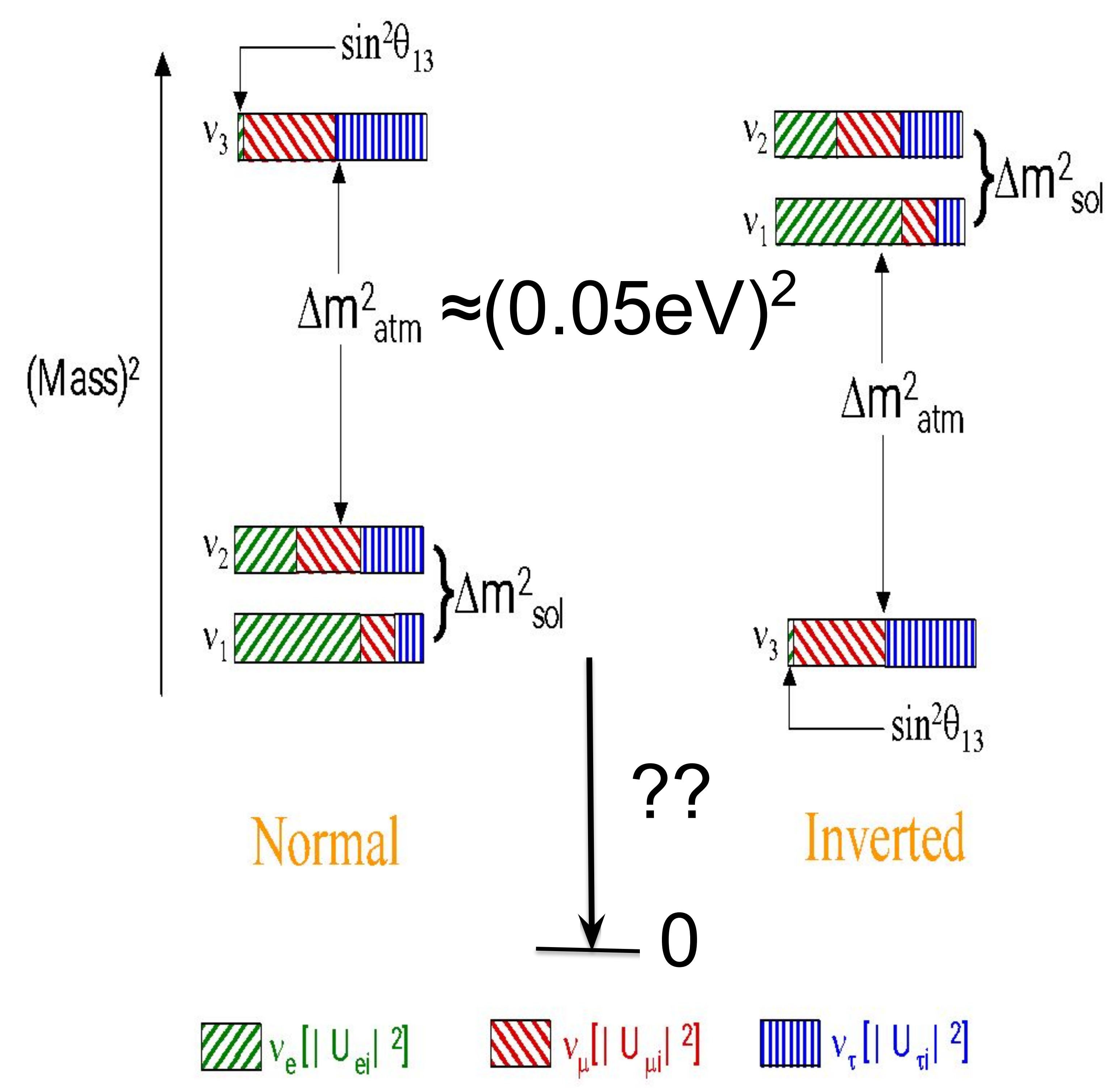

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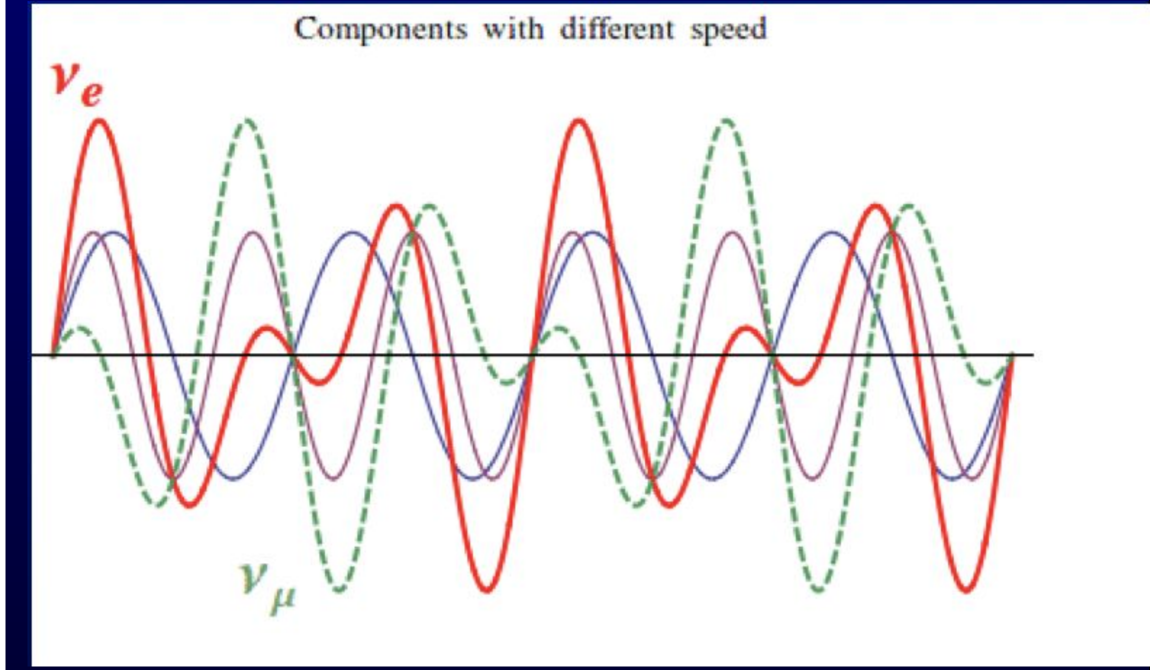

3 mass eigenstates
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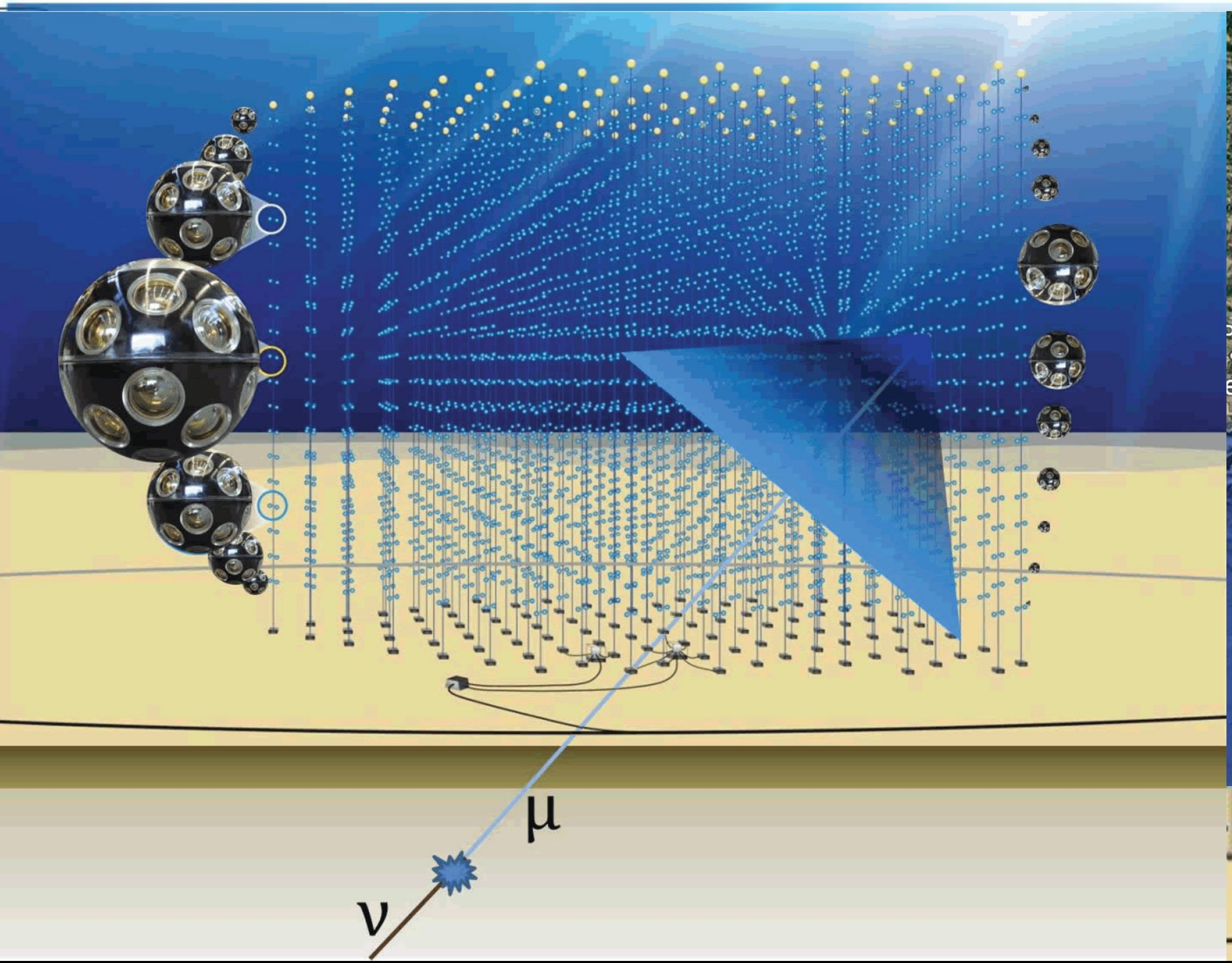
Neutrino Mass Oscillation Observatory

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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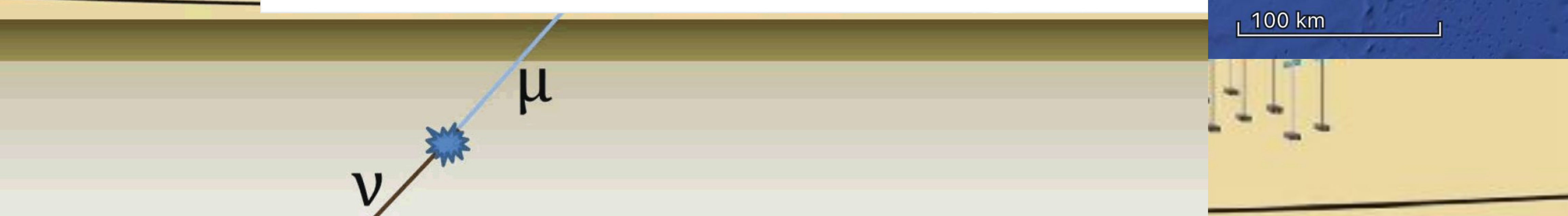
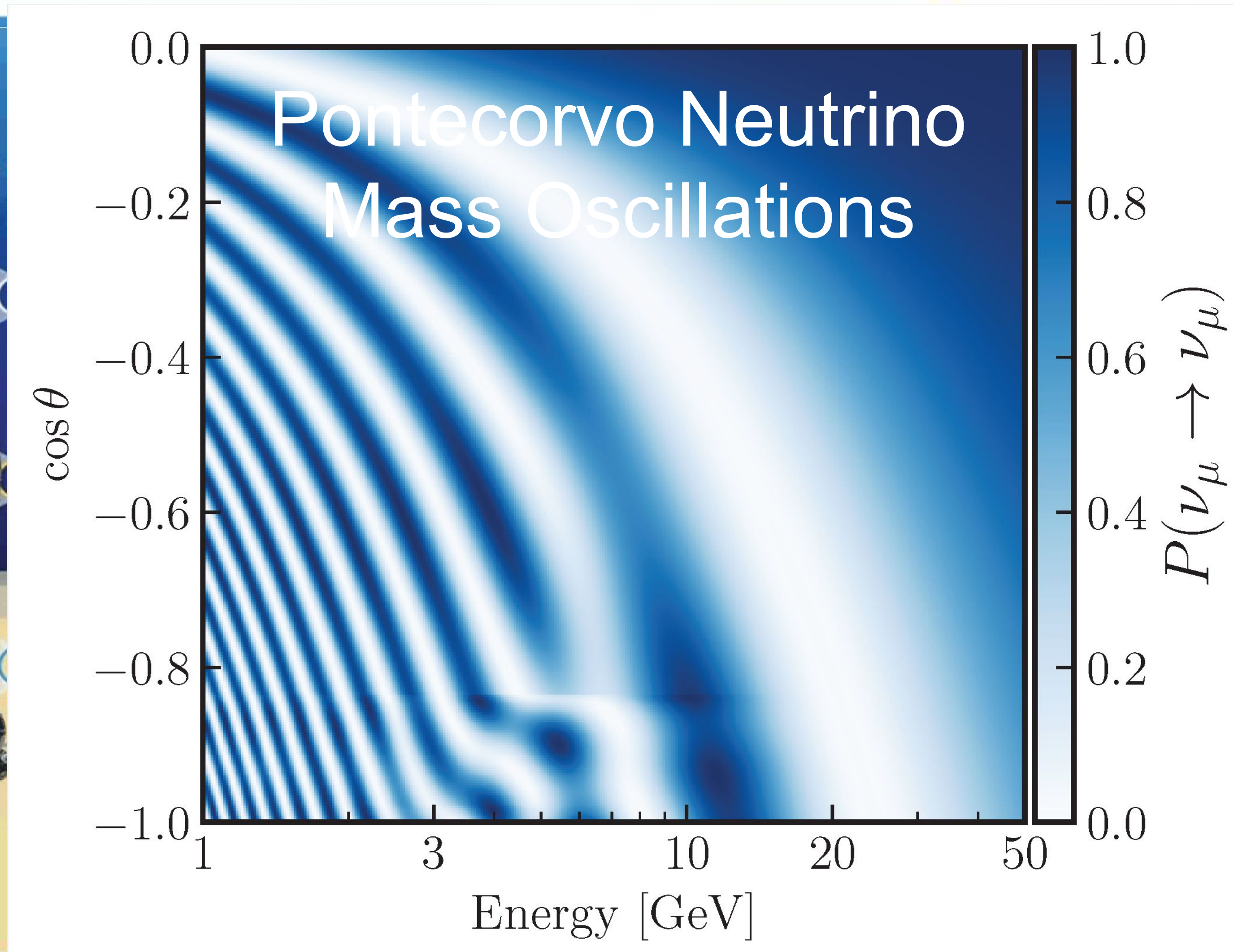
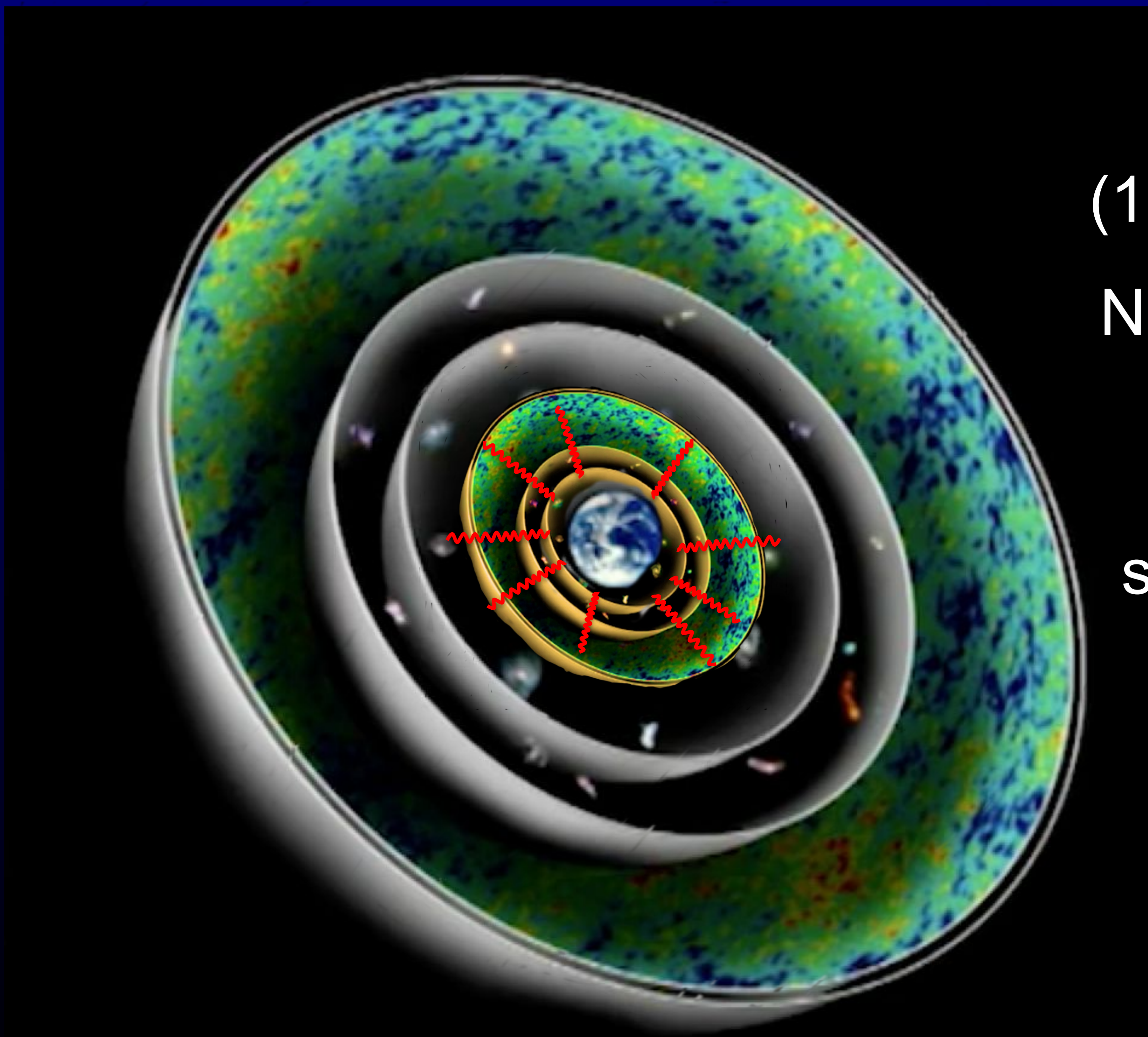




Massive Neutrino Timeline



Emission Time

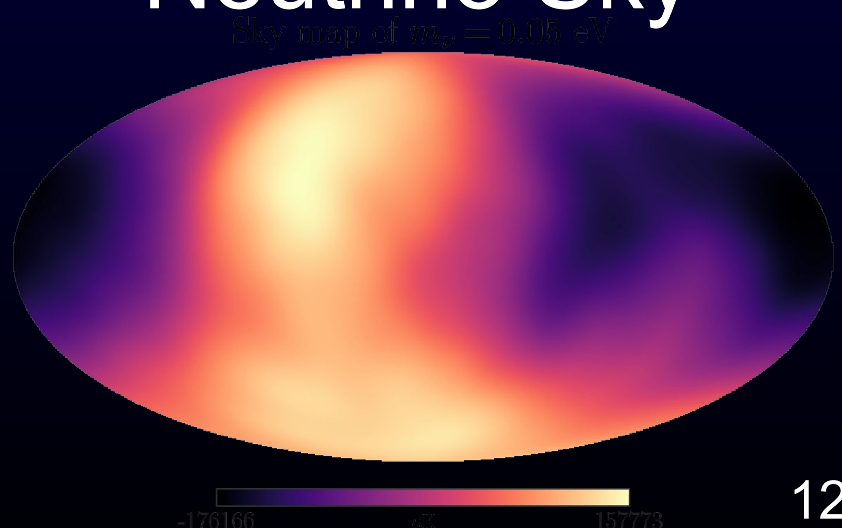
-13.8x10^9 years

(1 second after Big Bang)

No comparable flux from other sources

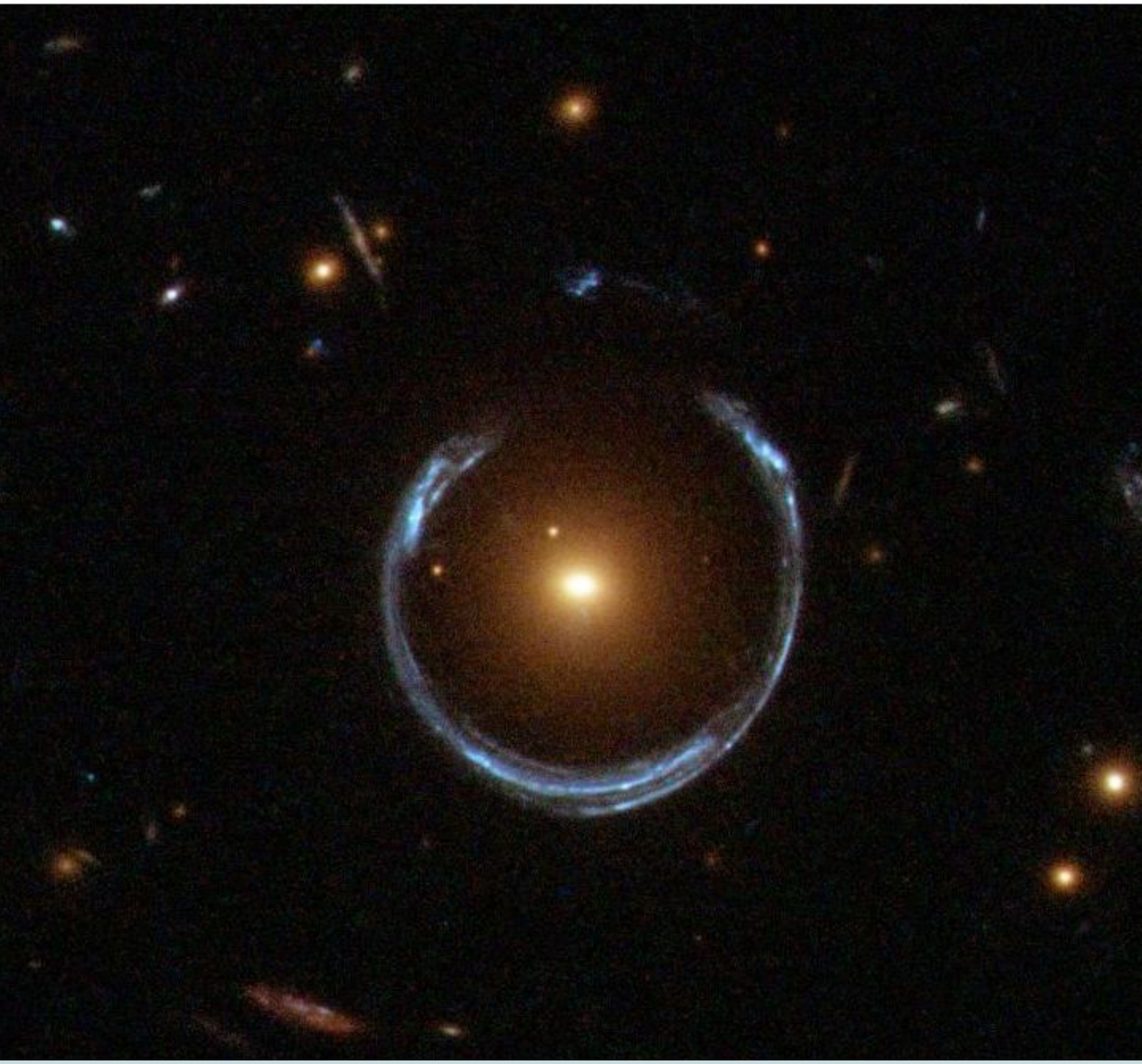
Starting radius more spread out due to mass

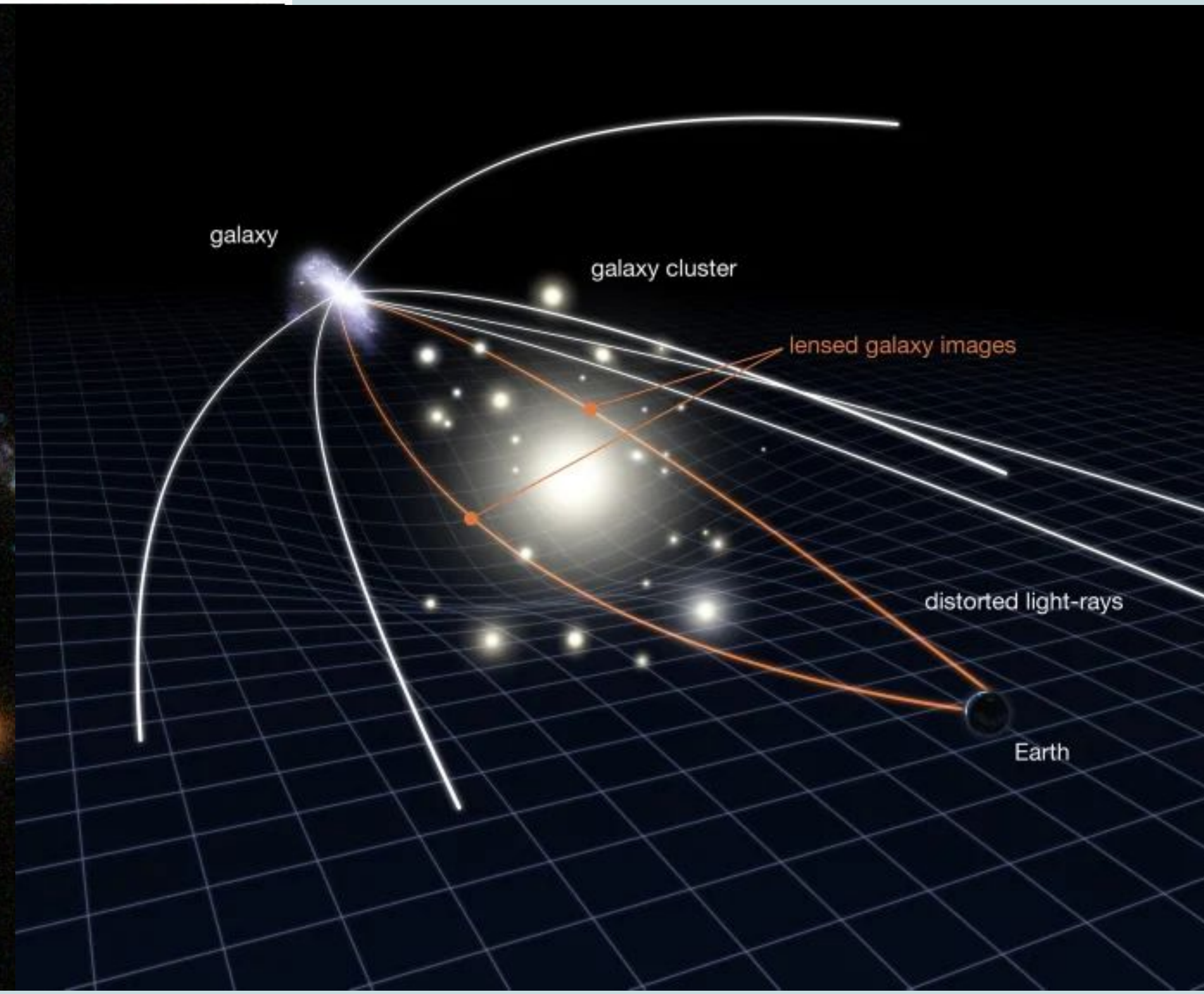
Neutrino Sky



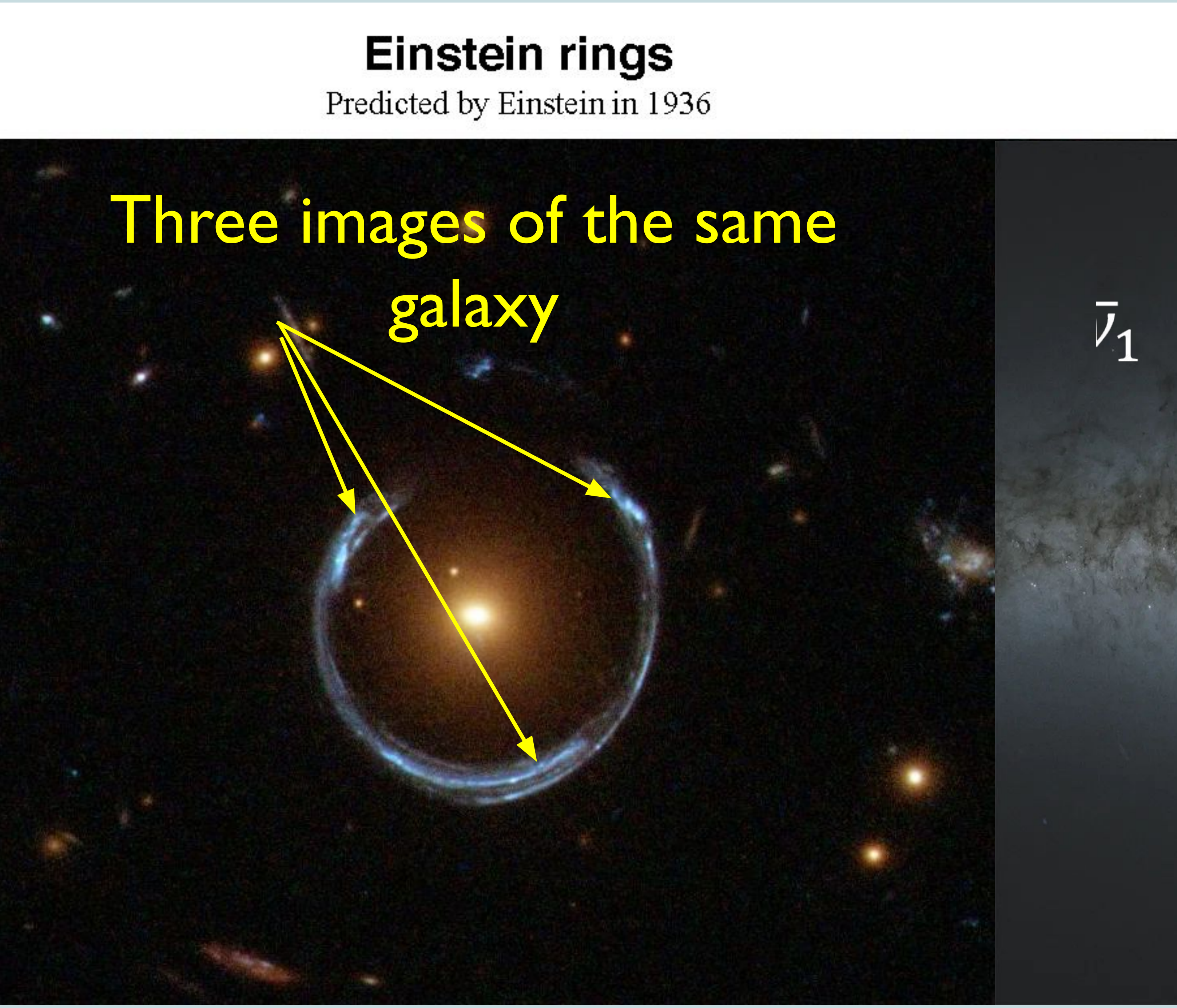
Einstein rings

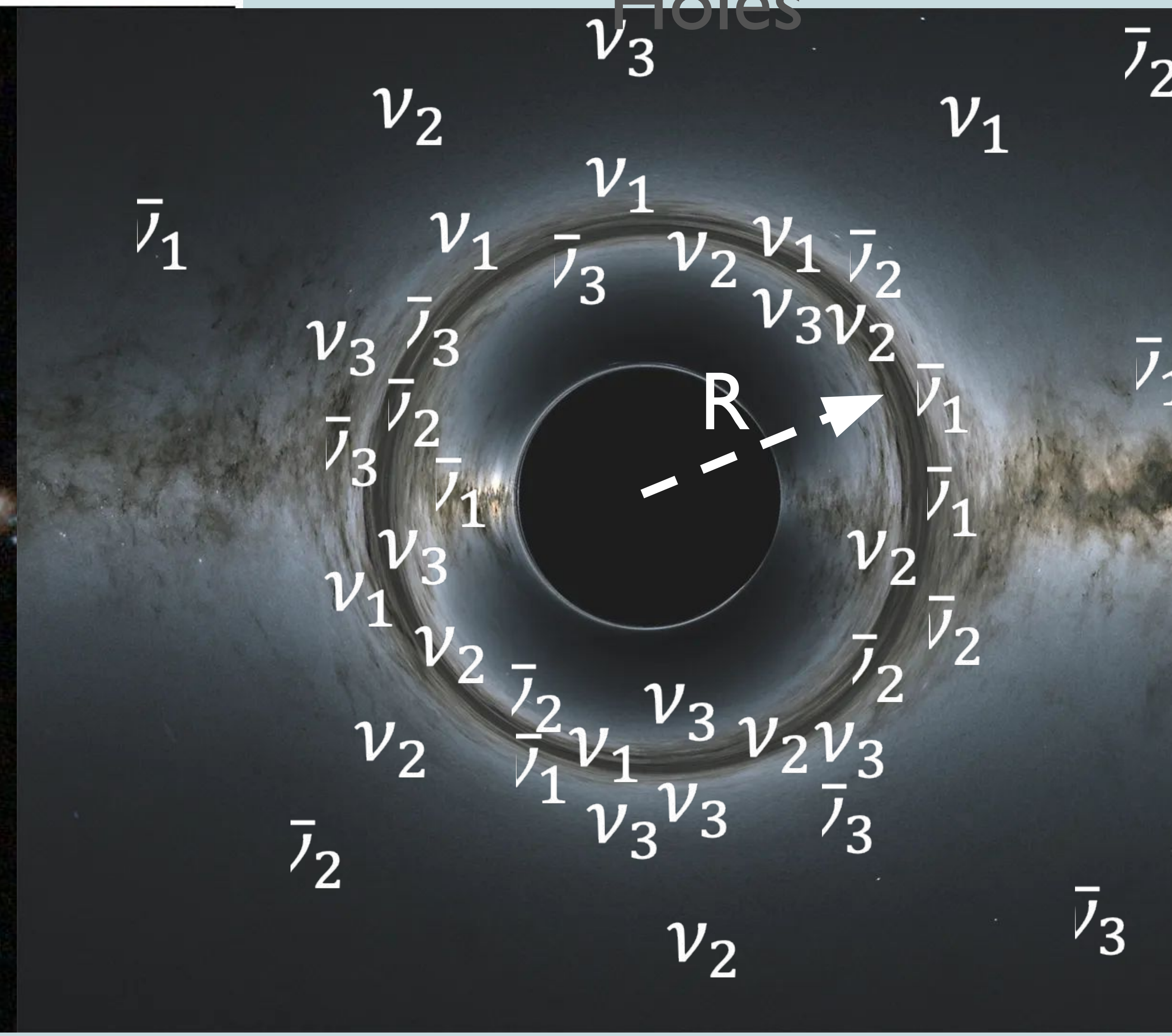
Predicted by Einstein in 1936





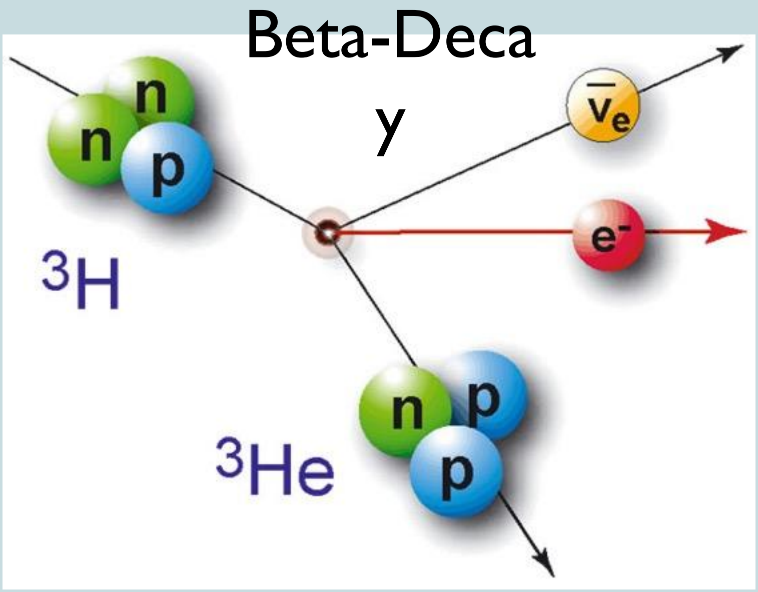
Neutrino Rings? from Primordial Black Holes

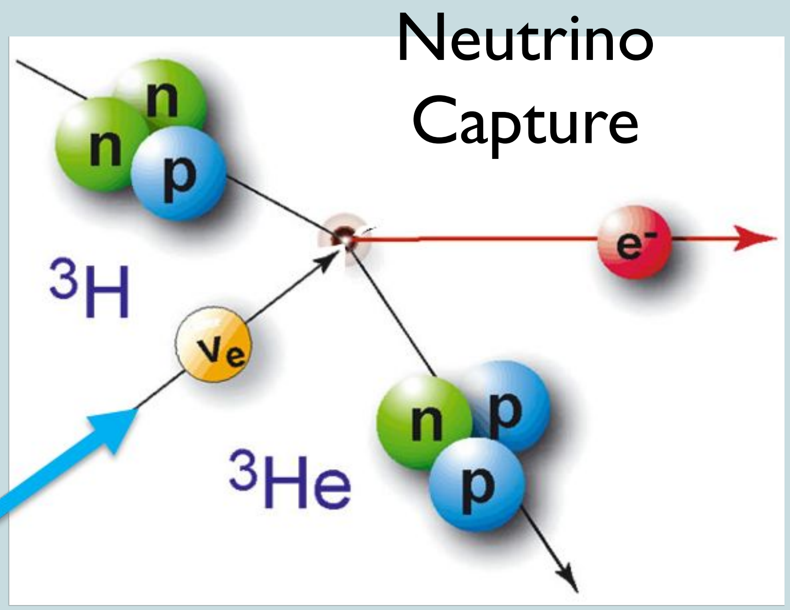


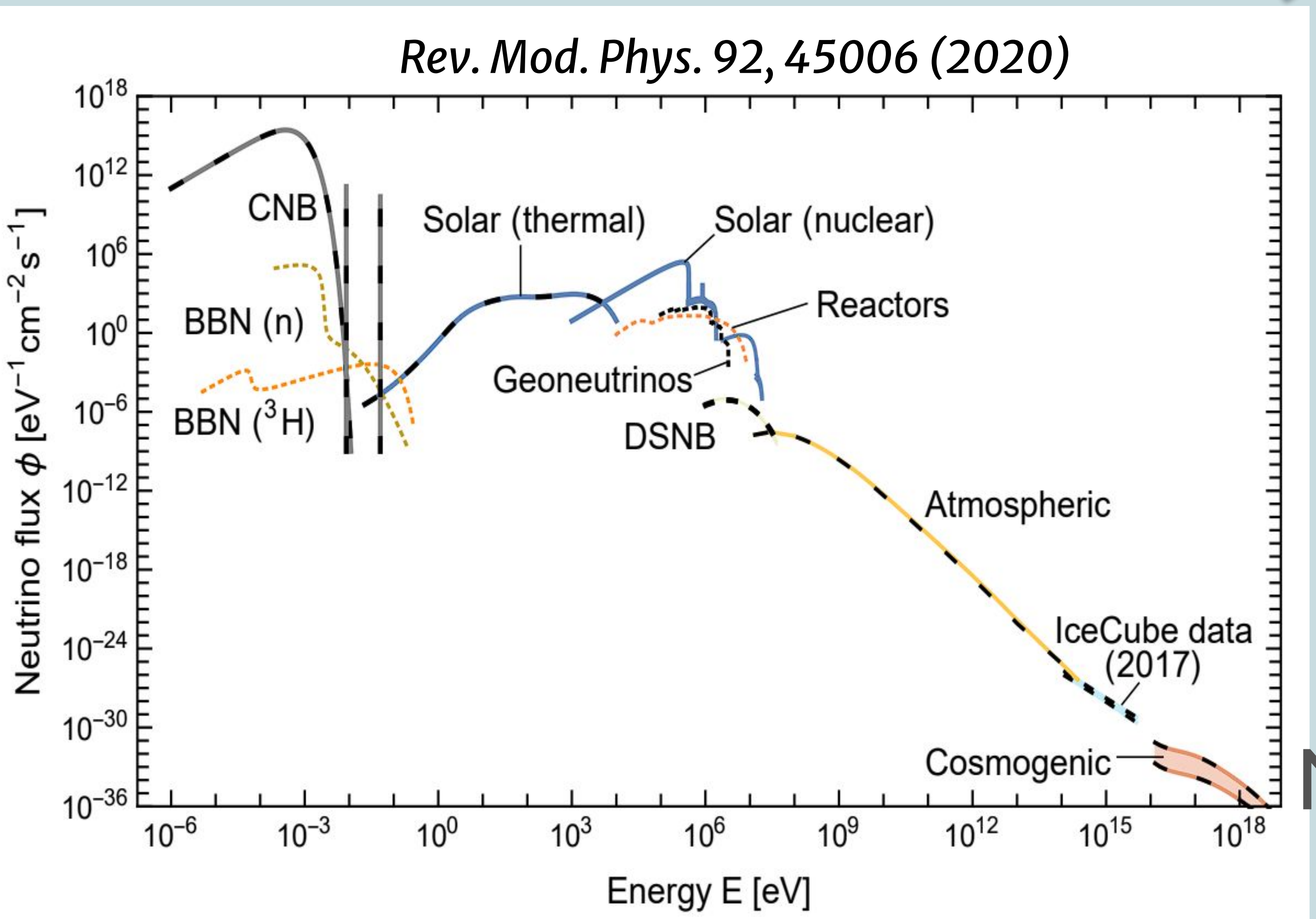


PTOLEMY - RELIC NEUTRINO DETECTION

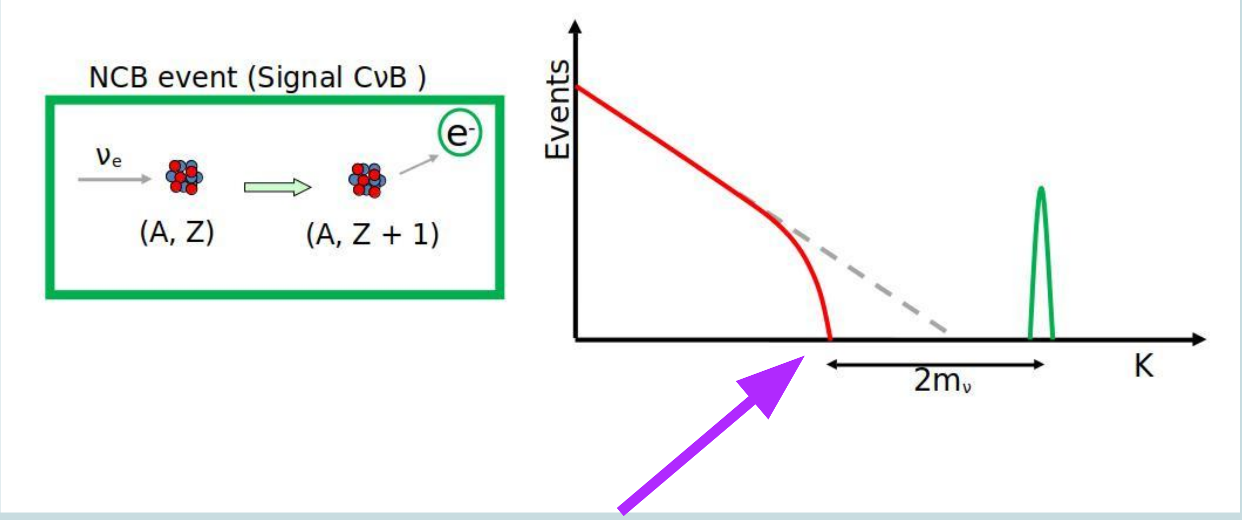
PonTecorvo Observatory for Light Early-universe Massive-neutrino Yield







Signature of CνB



Neutrino Mass Effect on Endpoint Predicted by Enrico Fermi

IDEA OF ENRICO FERMI

90 year anniversary!

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

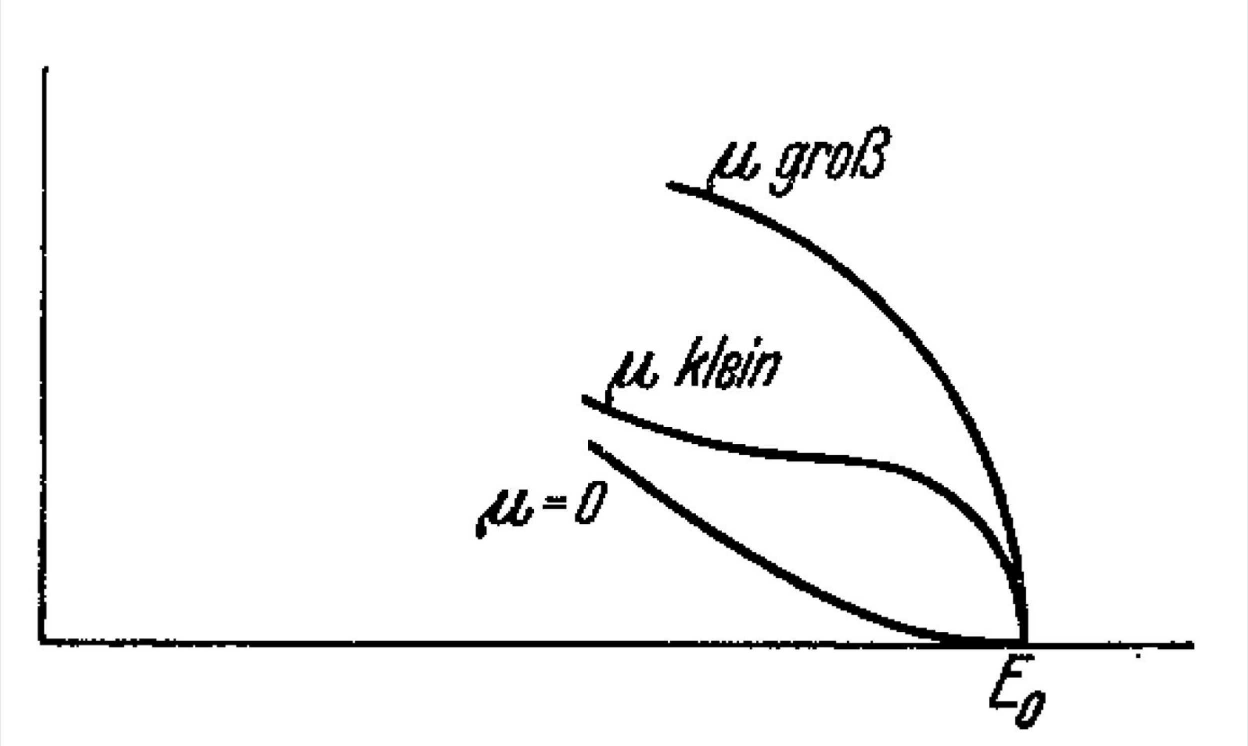
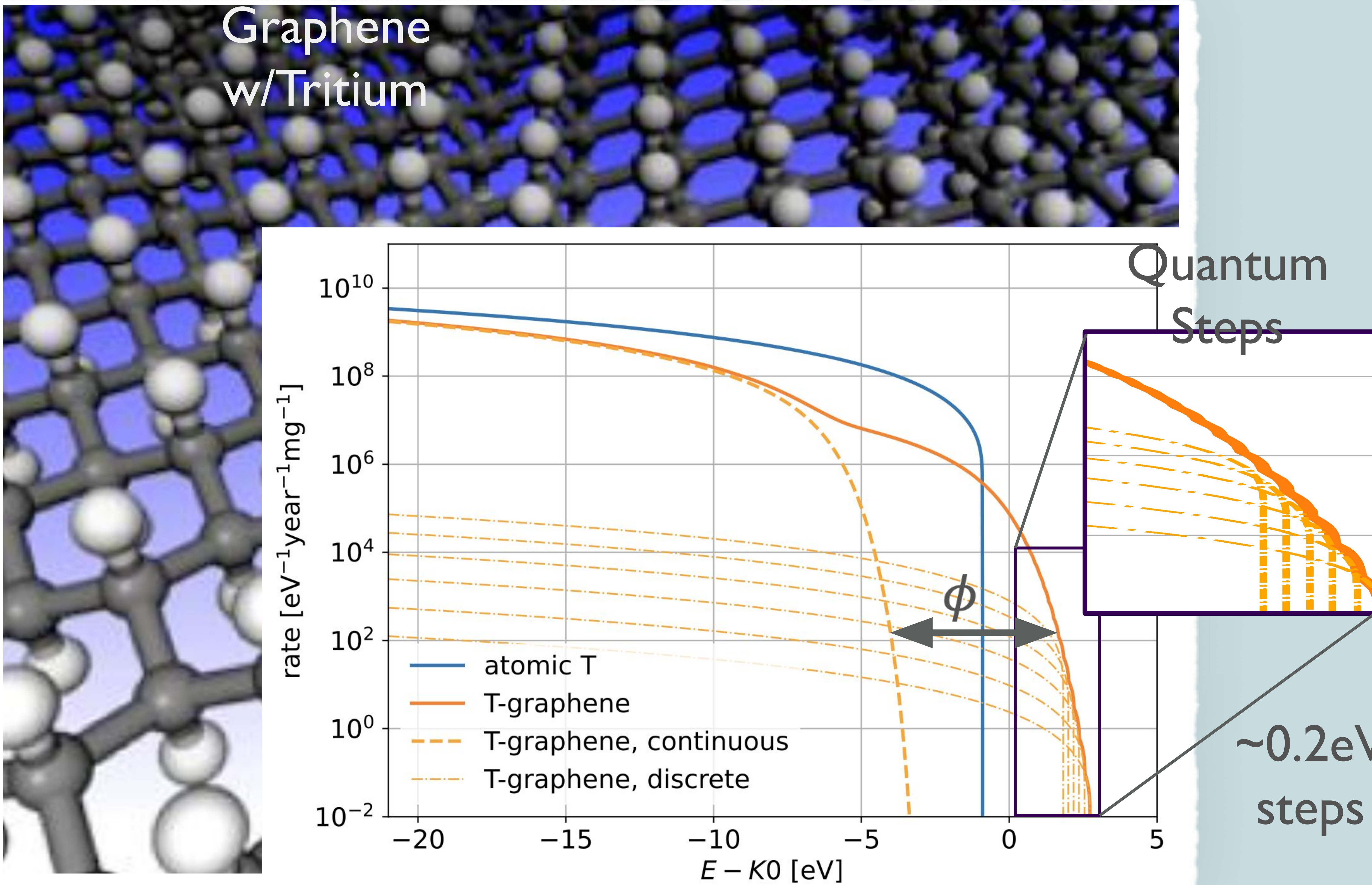


Fig. 1.

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



Quantum Steps

~0.2eV steps

Other graphene structures also under study

$\phi \equiv$ "Atomic" work function

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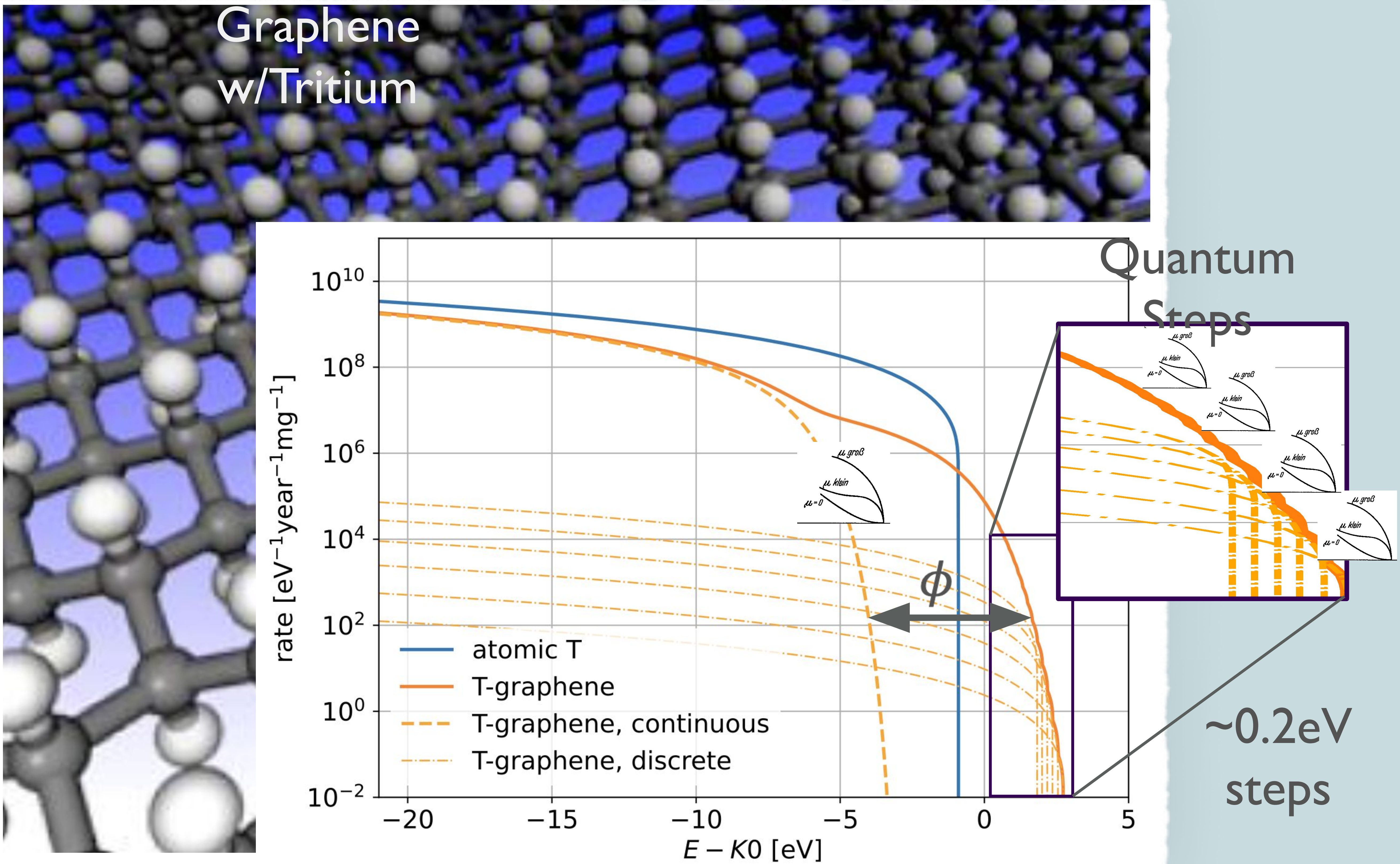

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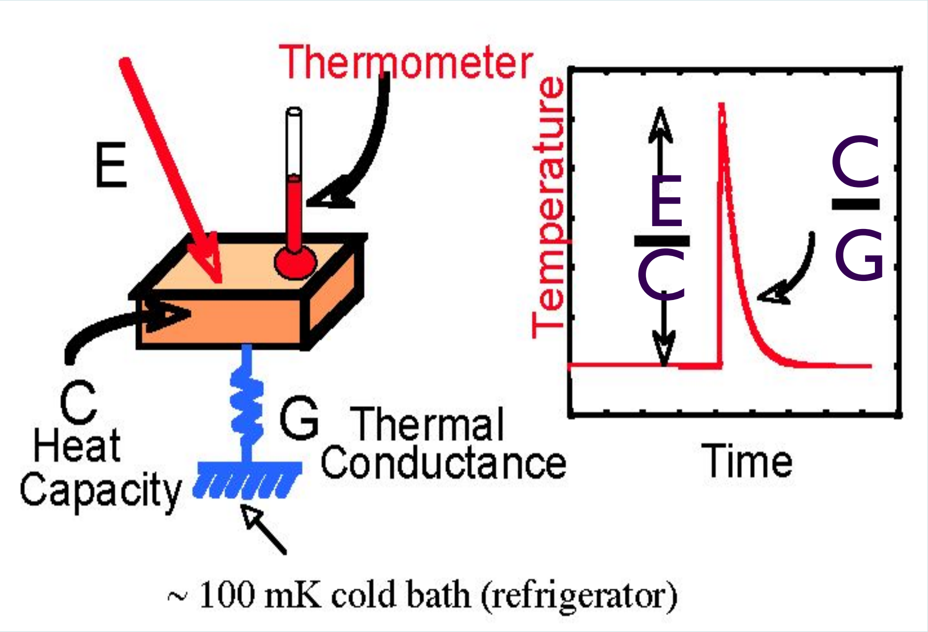
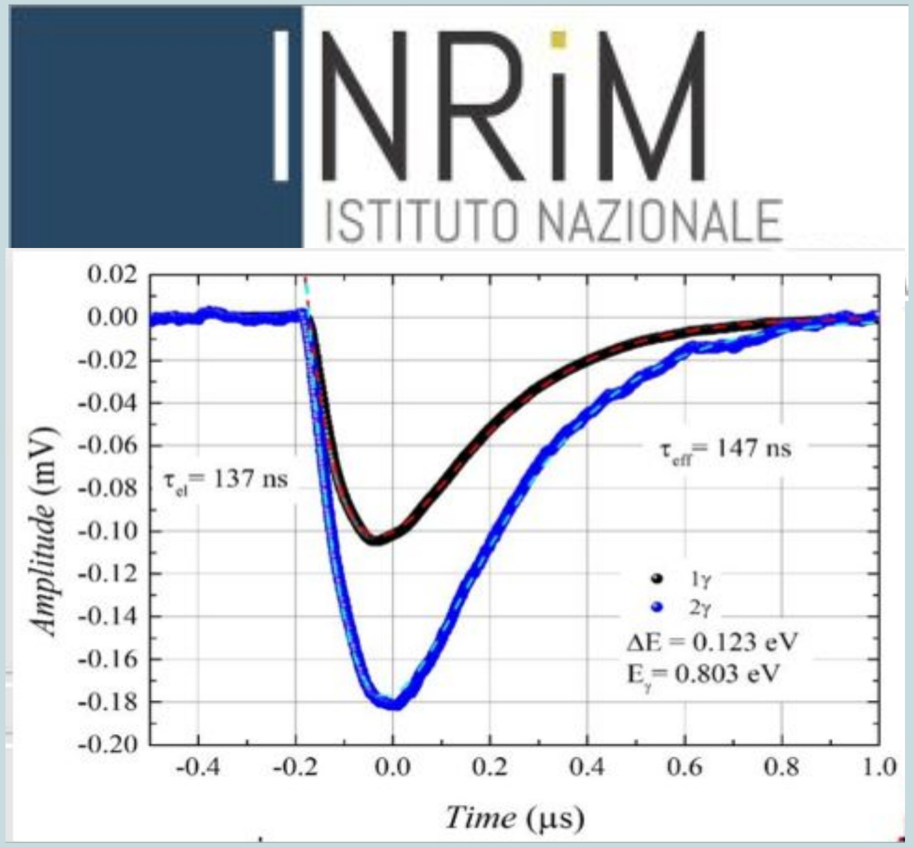
MICRO-CALORIMETER



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

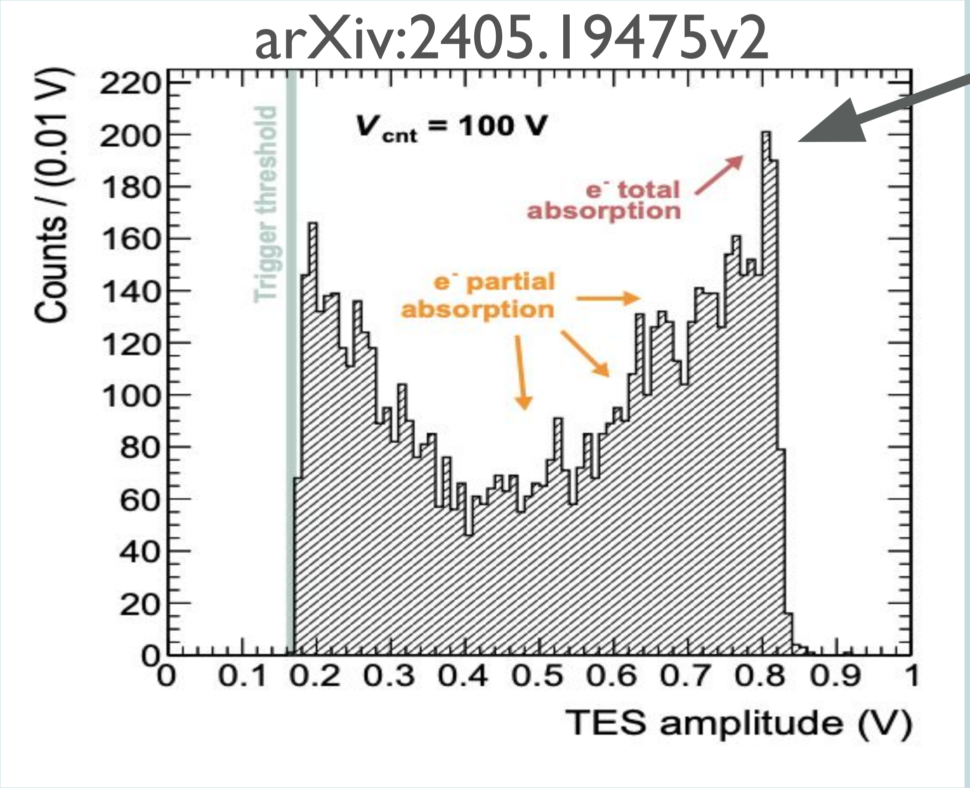
translates to $\Delta E \propto E^{\alpha}$ $(\alpha \leq 1/3)$

ΔE_{FWHM} = 0.022 eV @ 0.8 eV



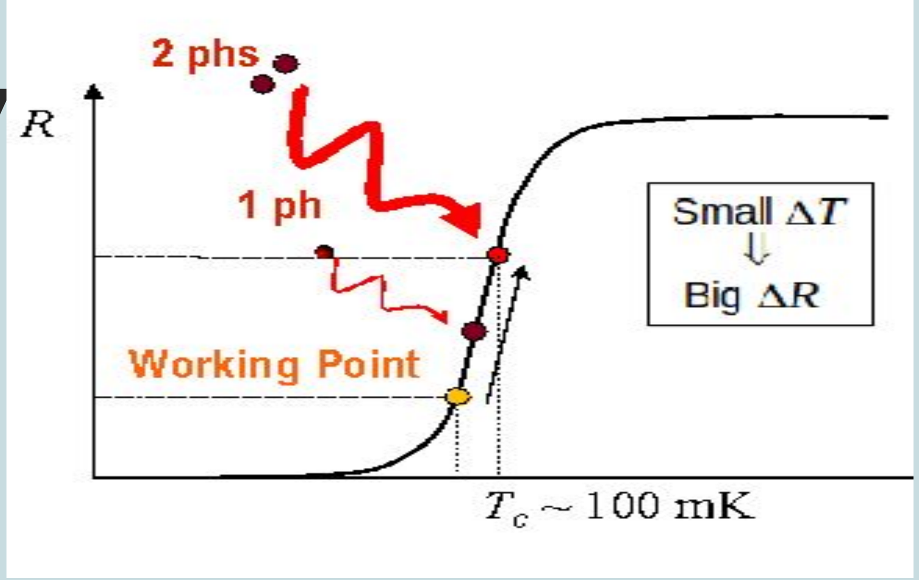
Based on the expertise of the INRiM an important results have been achieved on electron measurement with TES.

Key elements of the measurements: performing TES and new e-source based on nanostructures



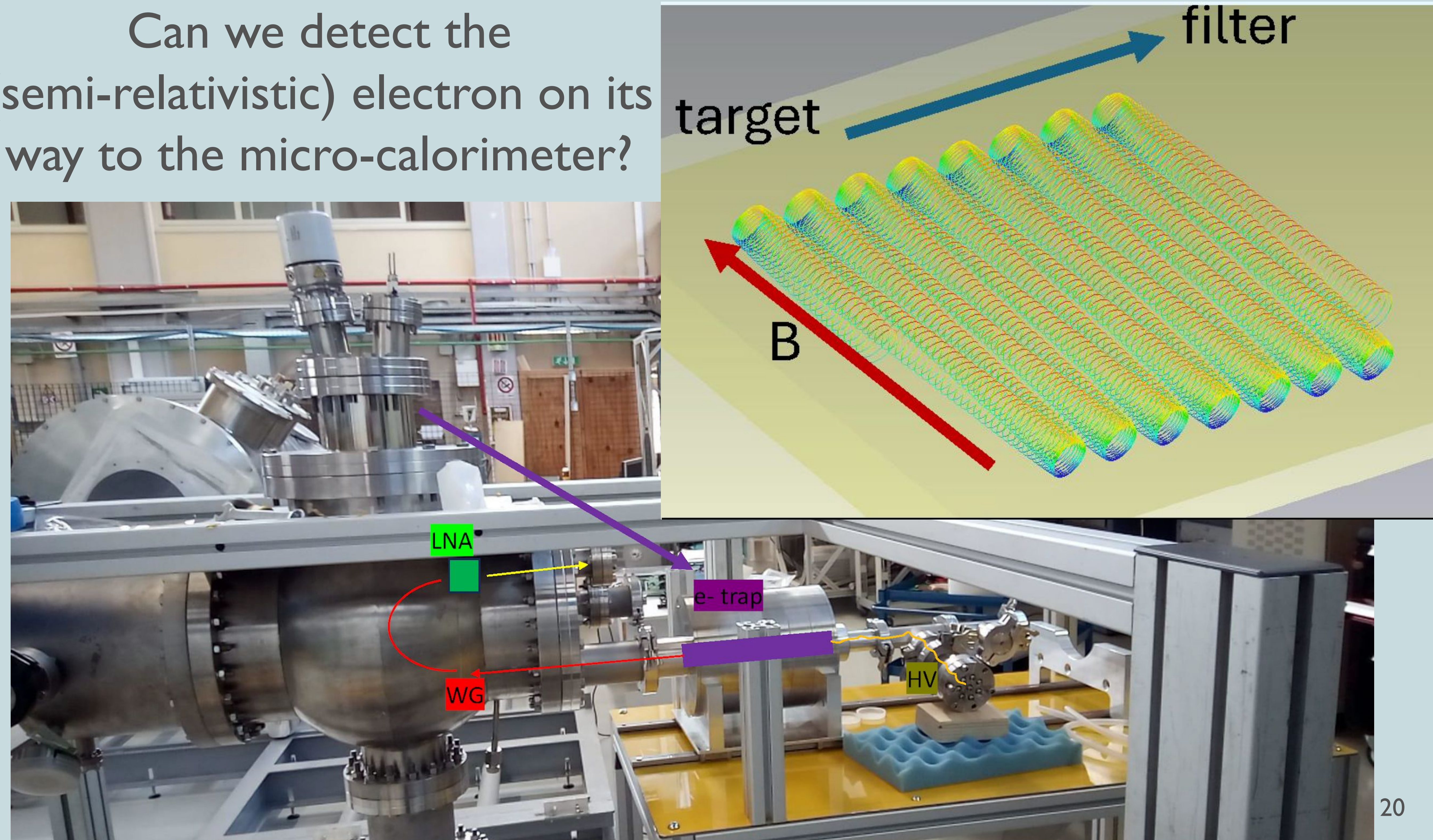
First measurement of electrons at 100 V with resolution of ~1-1.5 eV

Best in the World!

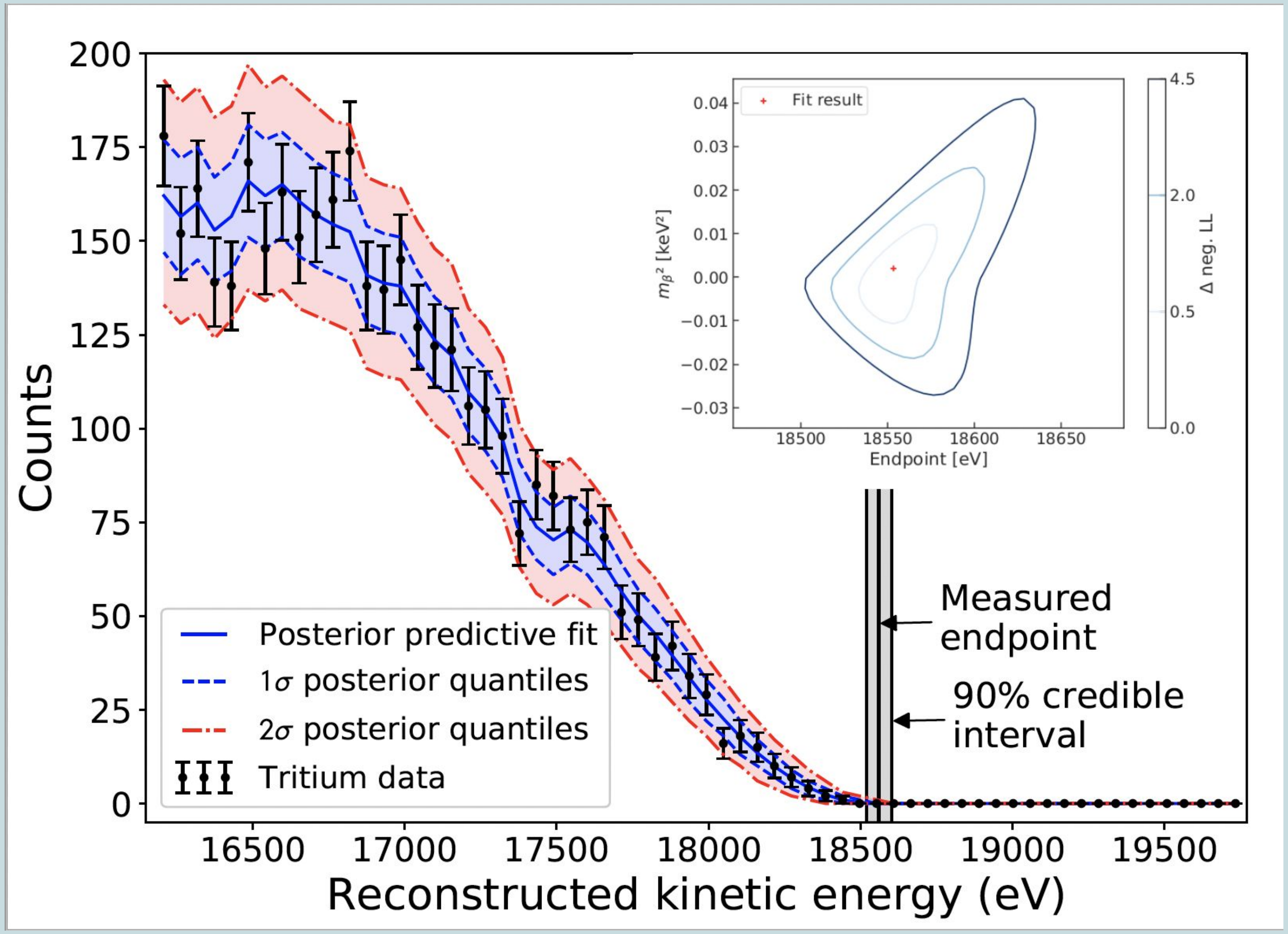


RF MEASUREMENTS
NON-DESTRUCTIVE ELECTRON TAG

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

$< 3\times10^{-10}$ /eV/s (90% CL)

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

ACHIEVED!! RF MEASUREMENTS

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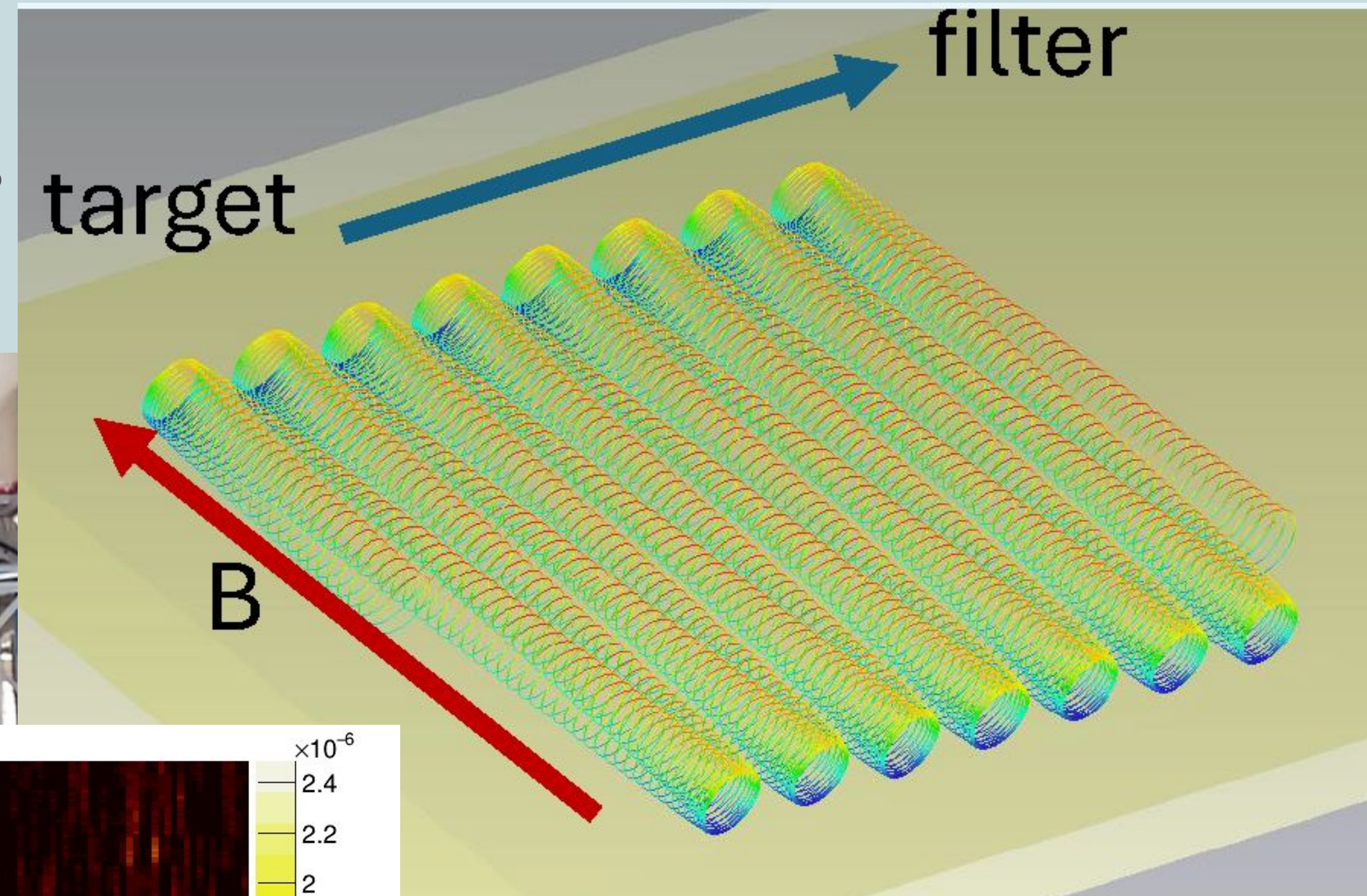
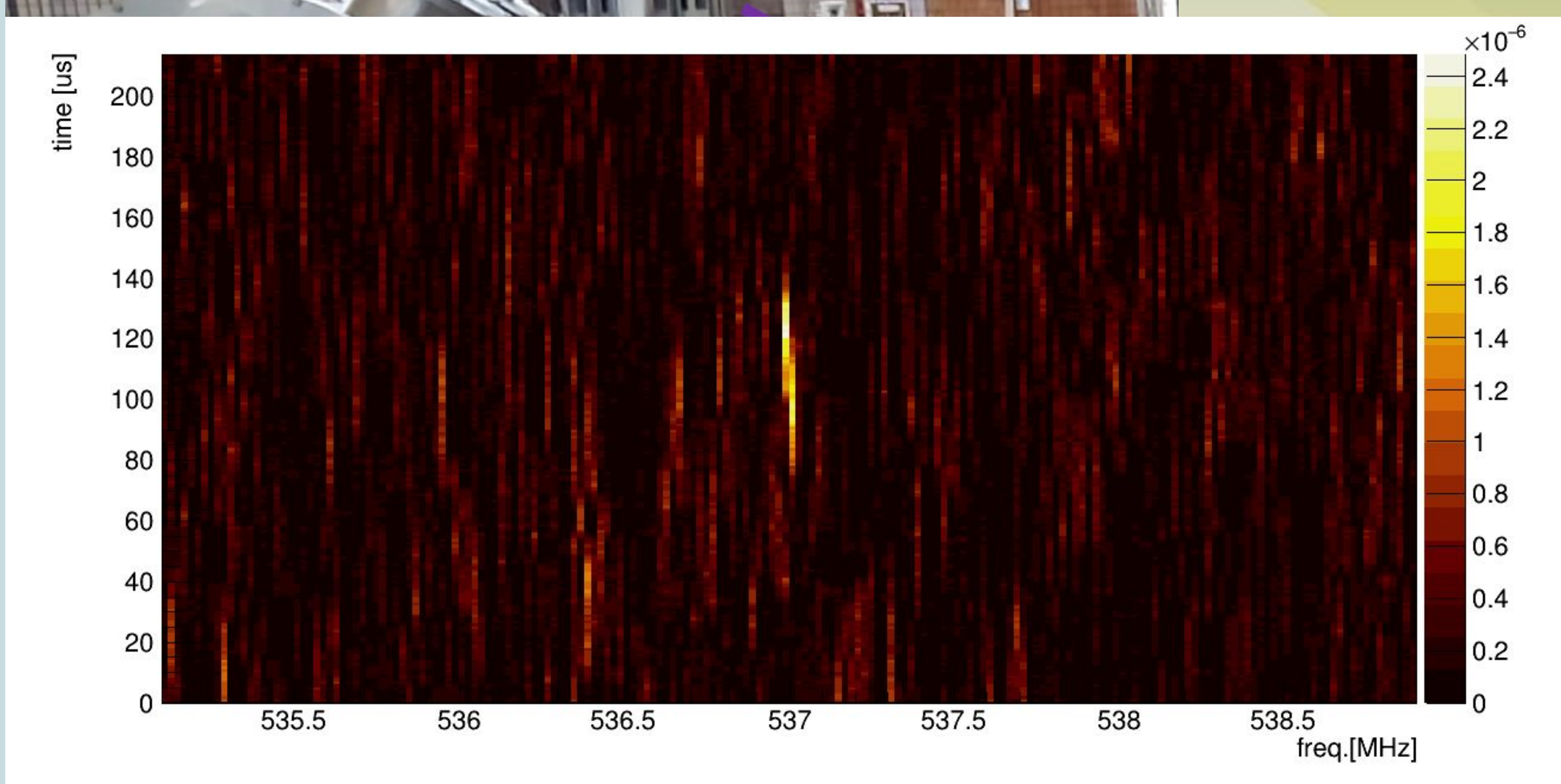
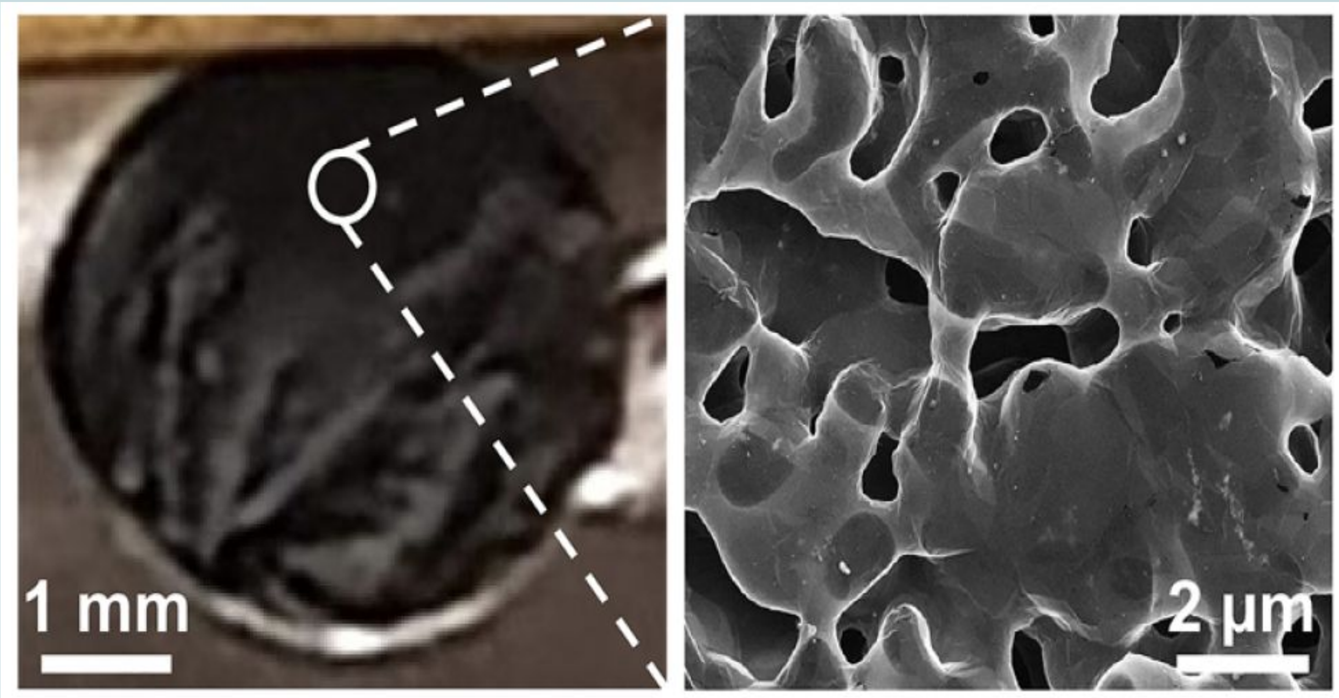
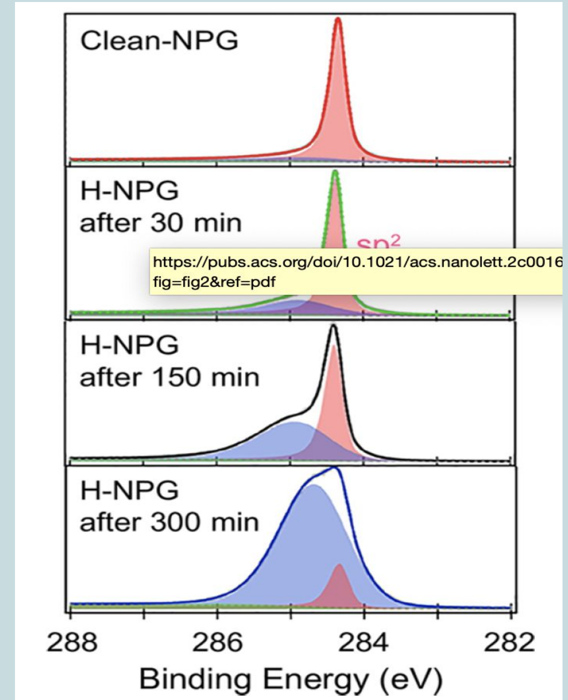




TARGET FABRICATION

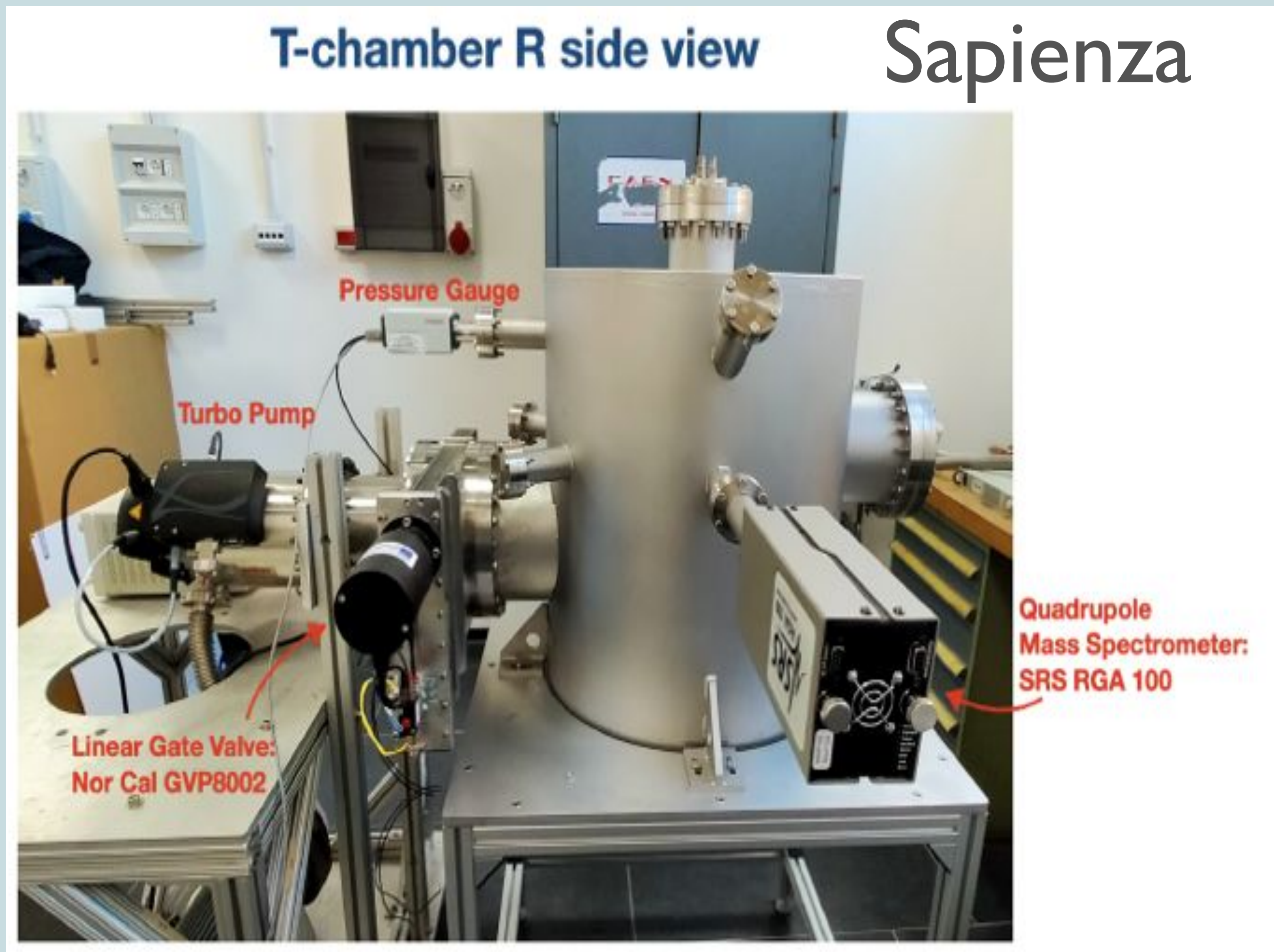




Best in the World!

Hydrogenation of nano-porous graphene (left and center) showing over 90% coverage per carbon atom through the increase of sp^3 bonding (blue on right)
[*DOI: 10.1021/acs.nanolett.2c00162*](https://doi.org/10.1021/acs.nanolett.2c00162)

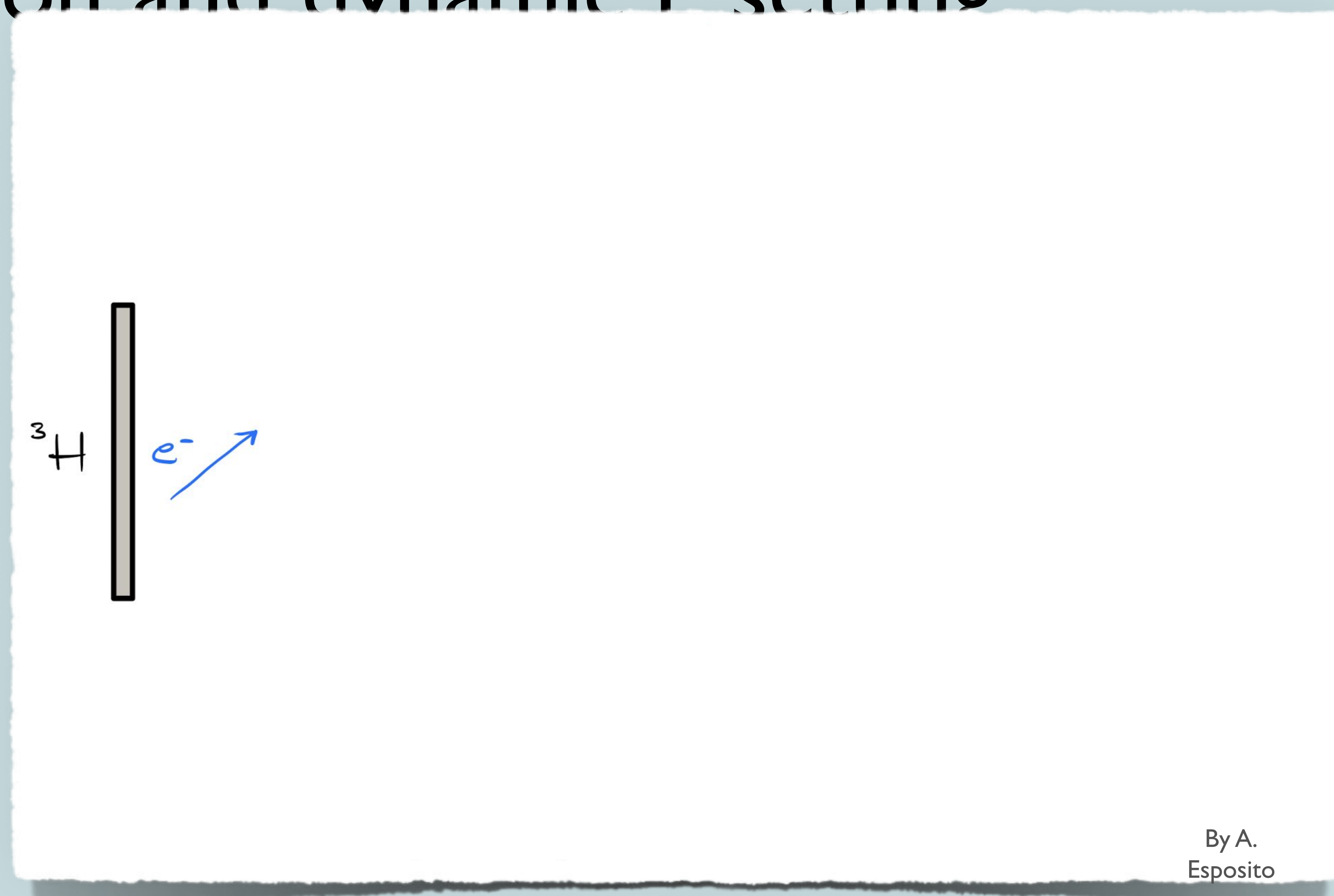
Sapienza



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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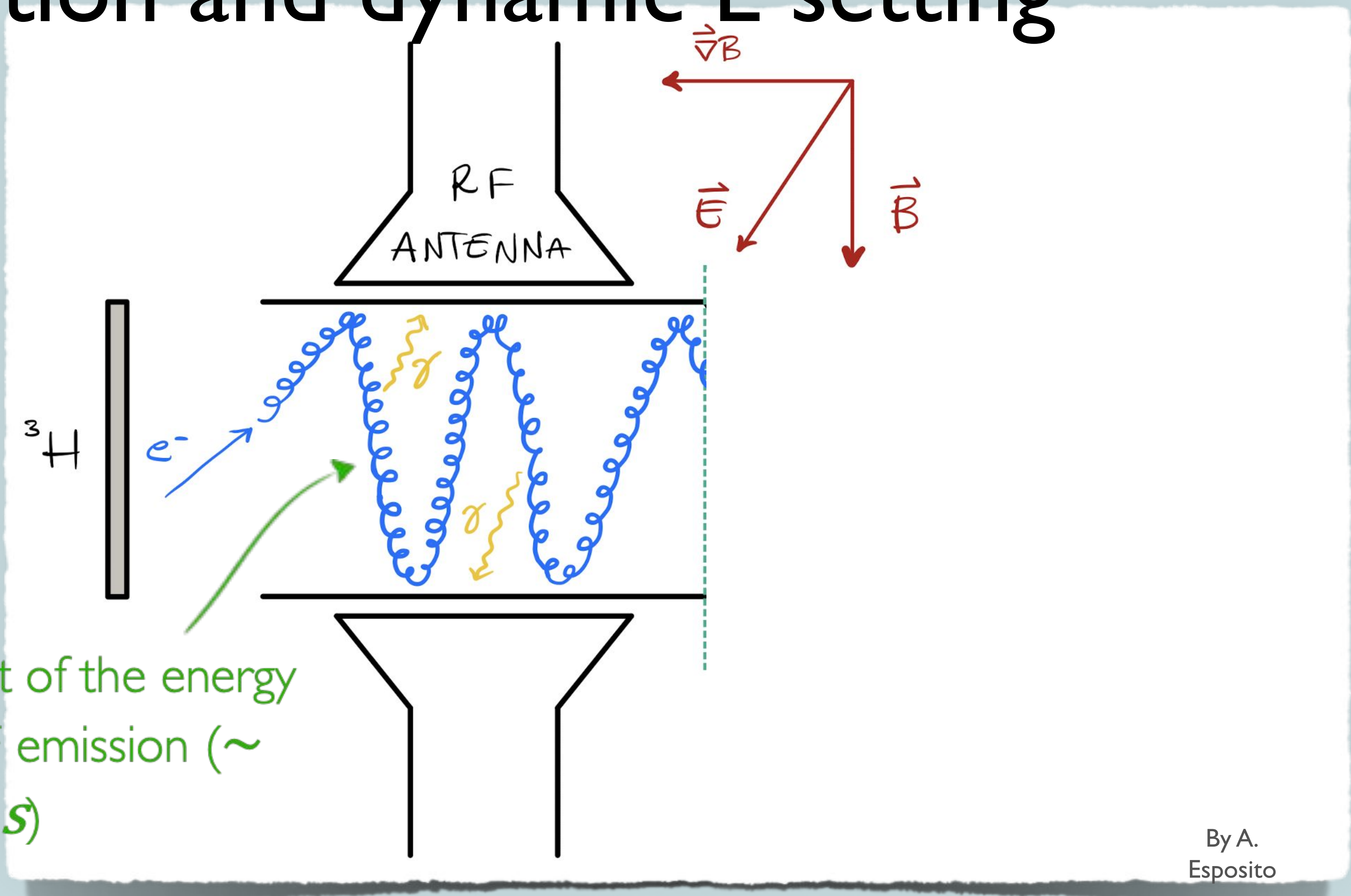

first measurement of the energy via cyclotron RF emission (~ $10\mu s$)

By A. Esposito

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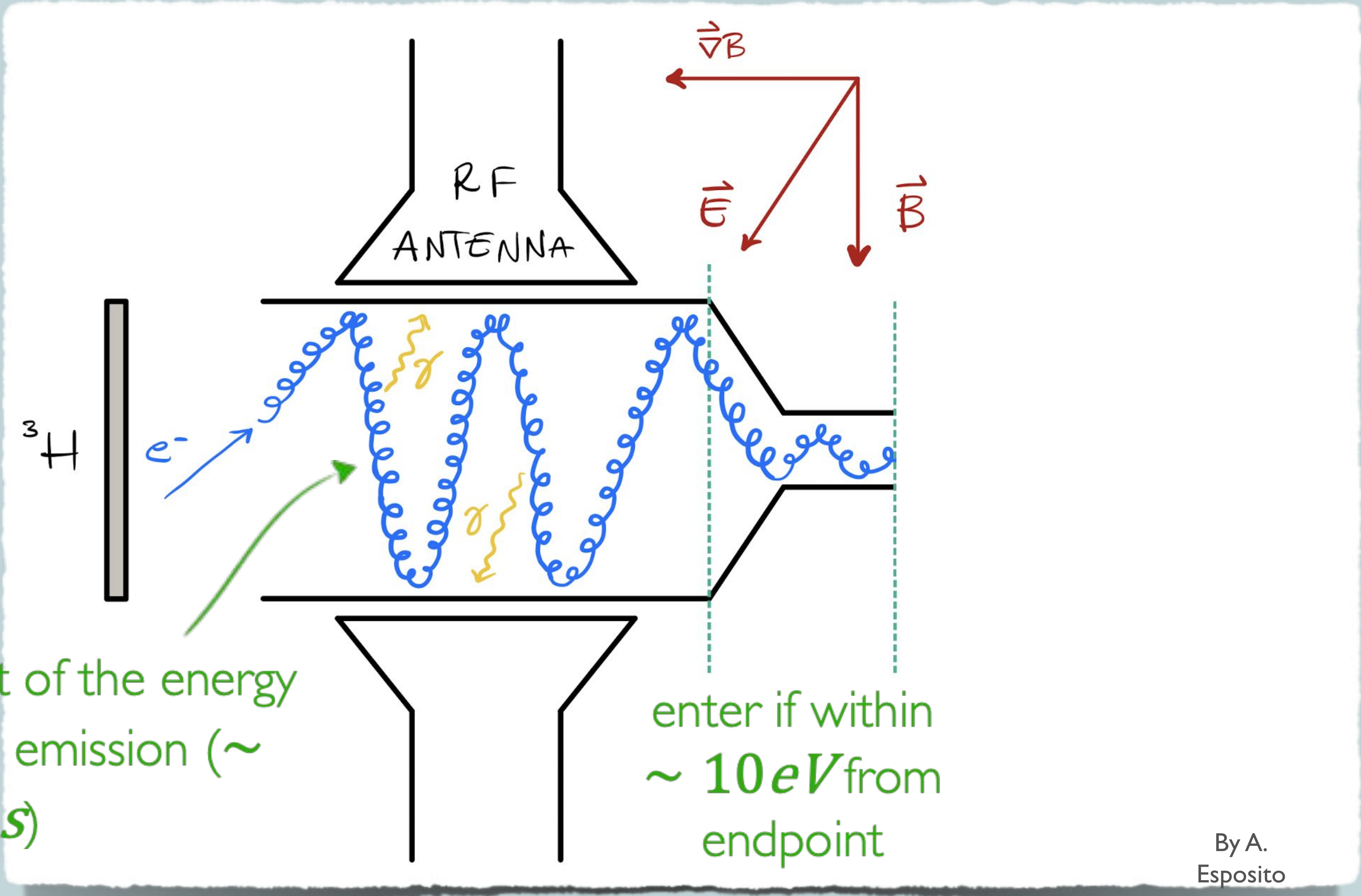

first measurement of the energy via cyclotron RF emission ($\sim 10\mu s$)

enter if within $\sim 10 eV$ from endpoint

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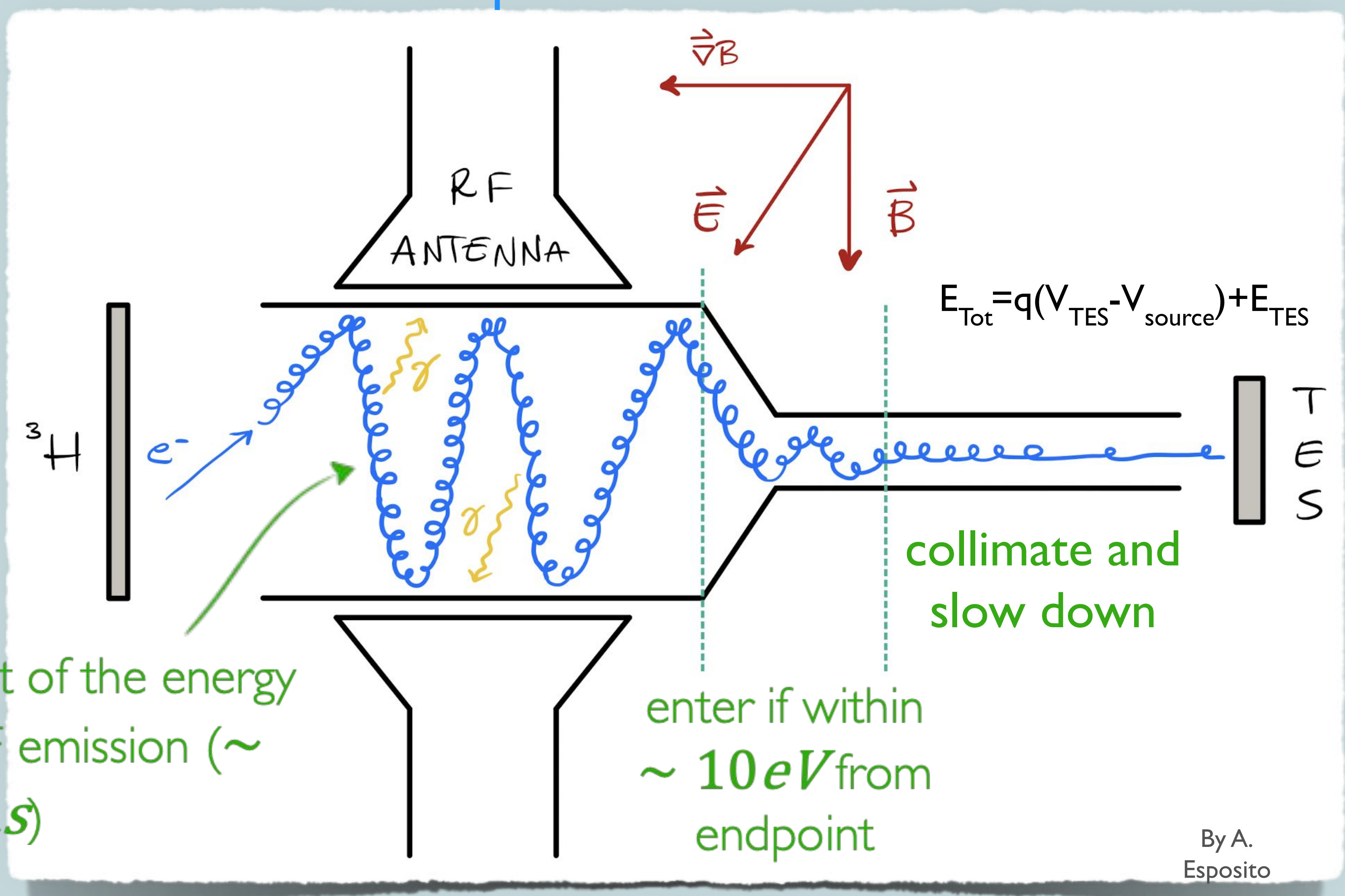
ΔV known to 1 ppm precision



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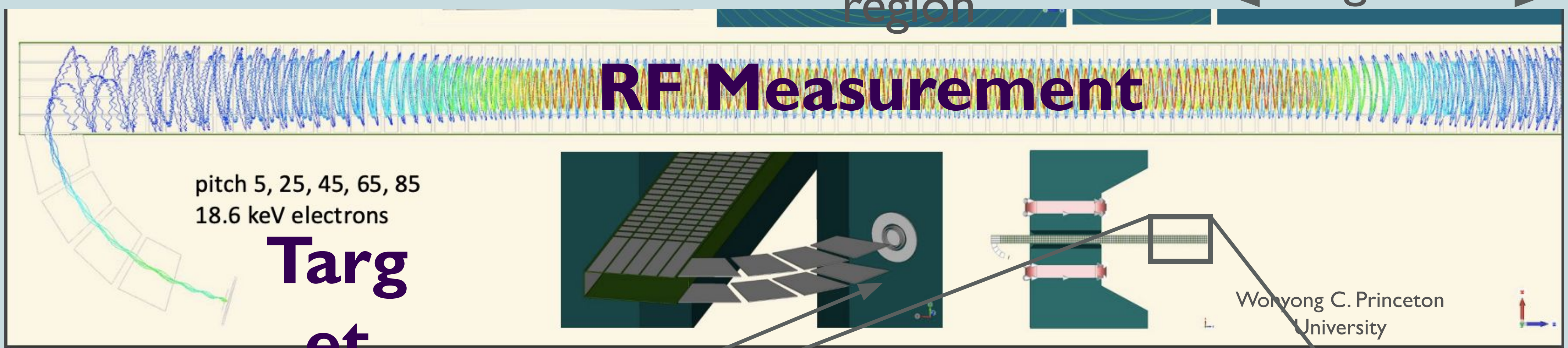
Detailed simulation of the PTOLEMY filter

Magnet 1 T field

RF region

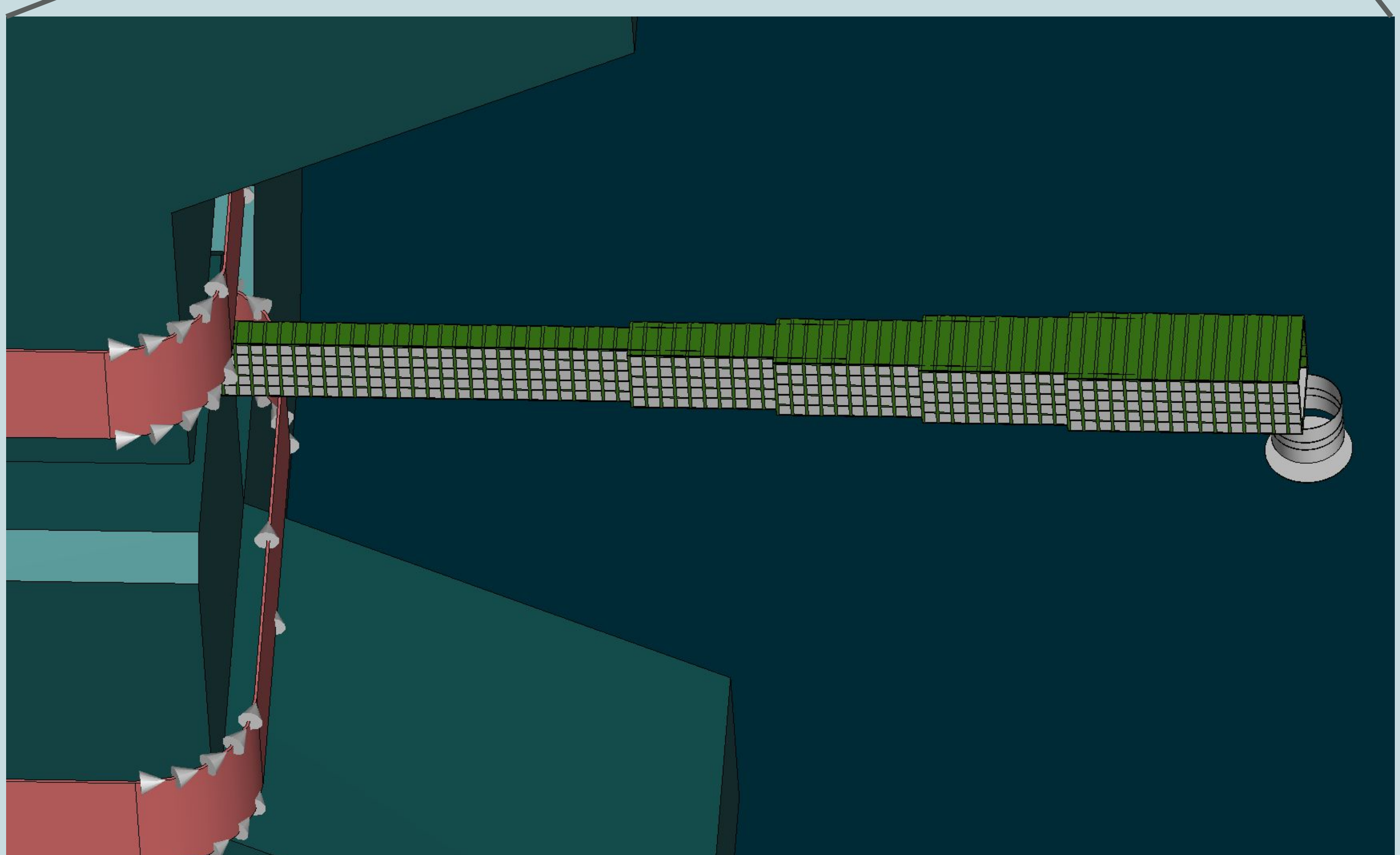
Filter region



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)

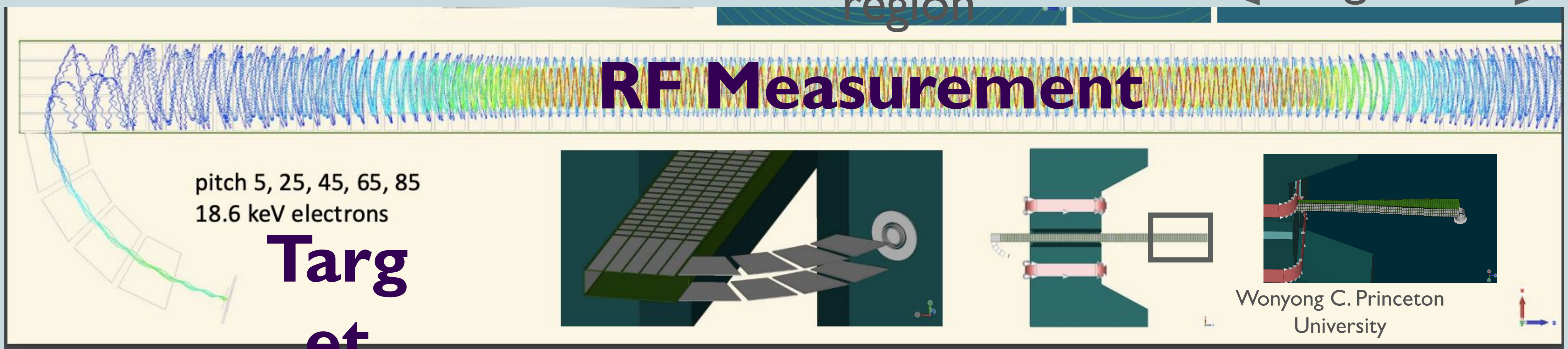
Microcalorimeter

End-to-End Drift Collimation and Transmission Results

Magnet 1 T field

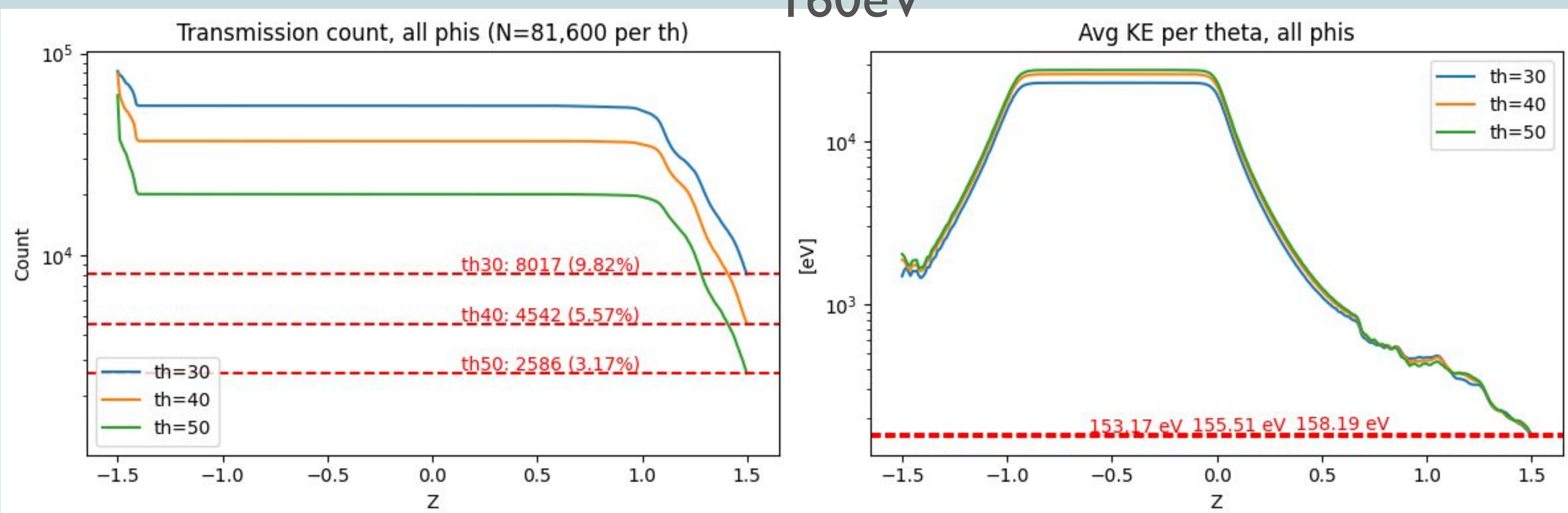
RF region

Filter region



Micro-Cal

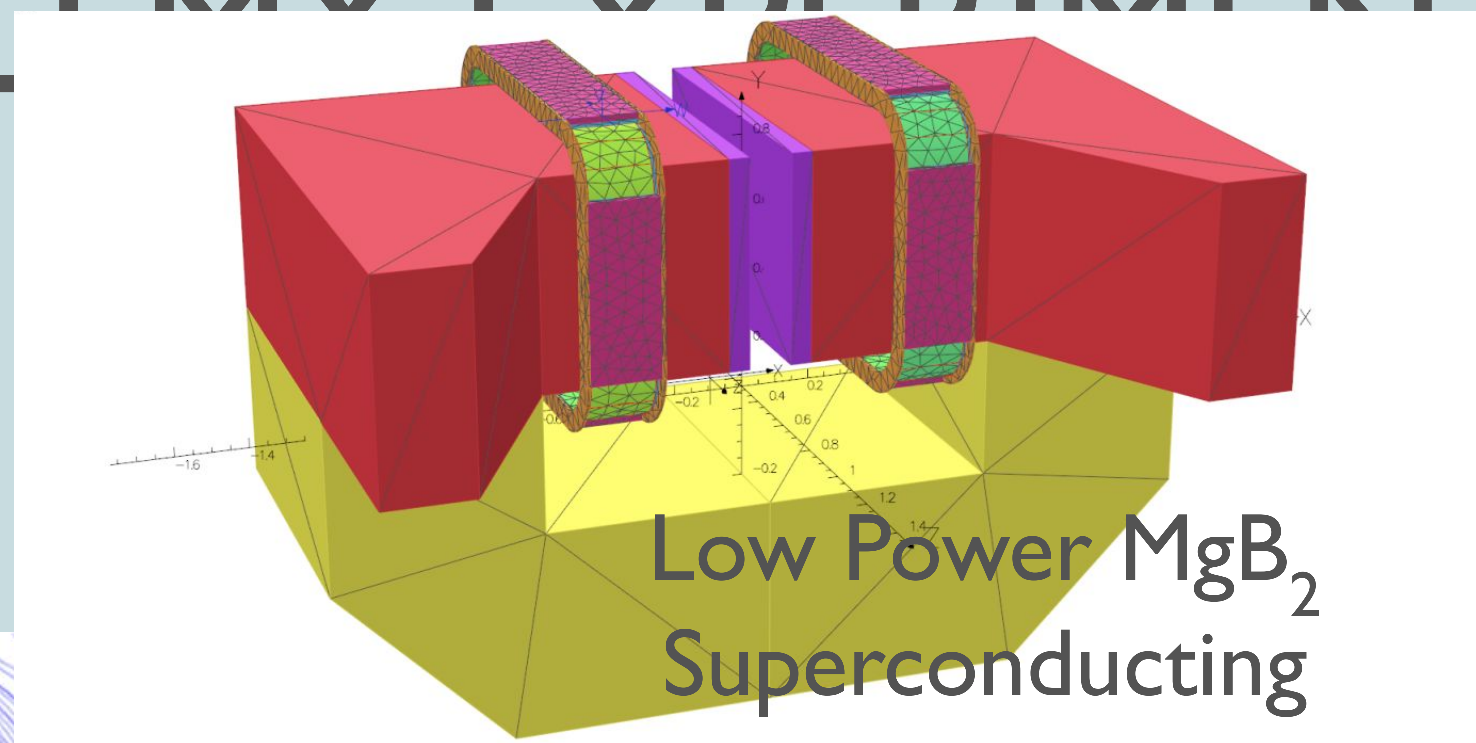
10% Static Transport Achieved!!! Down to 160eV



INSTALLED AT THE LNGS KEY ELEMENT TO REALIZE THE PTOLEMY EXPERIMENT

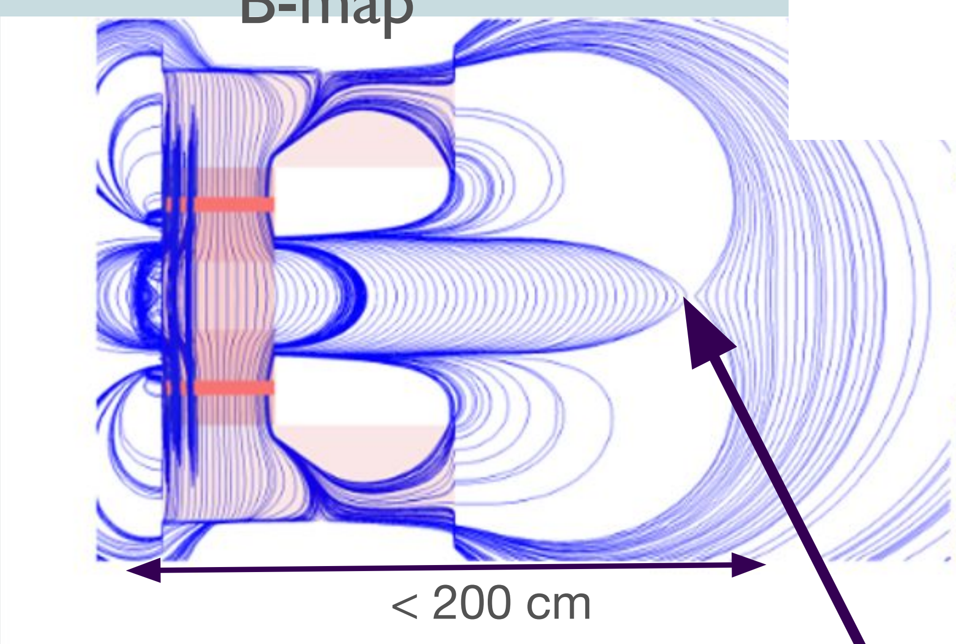
Construction ASG/Suprasys consortium of a 6G dipole with special attention to the fringe field

Tour on Friday!!



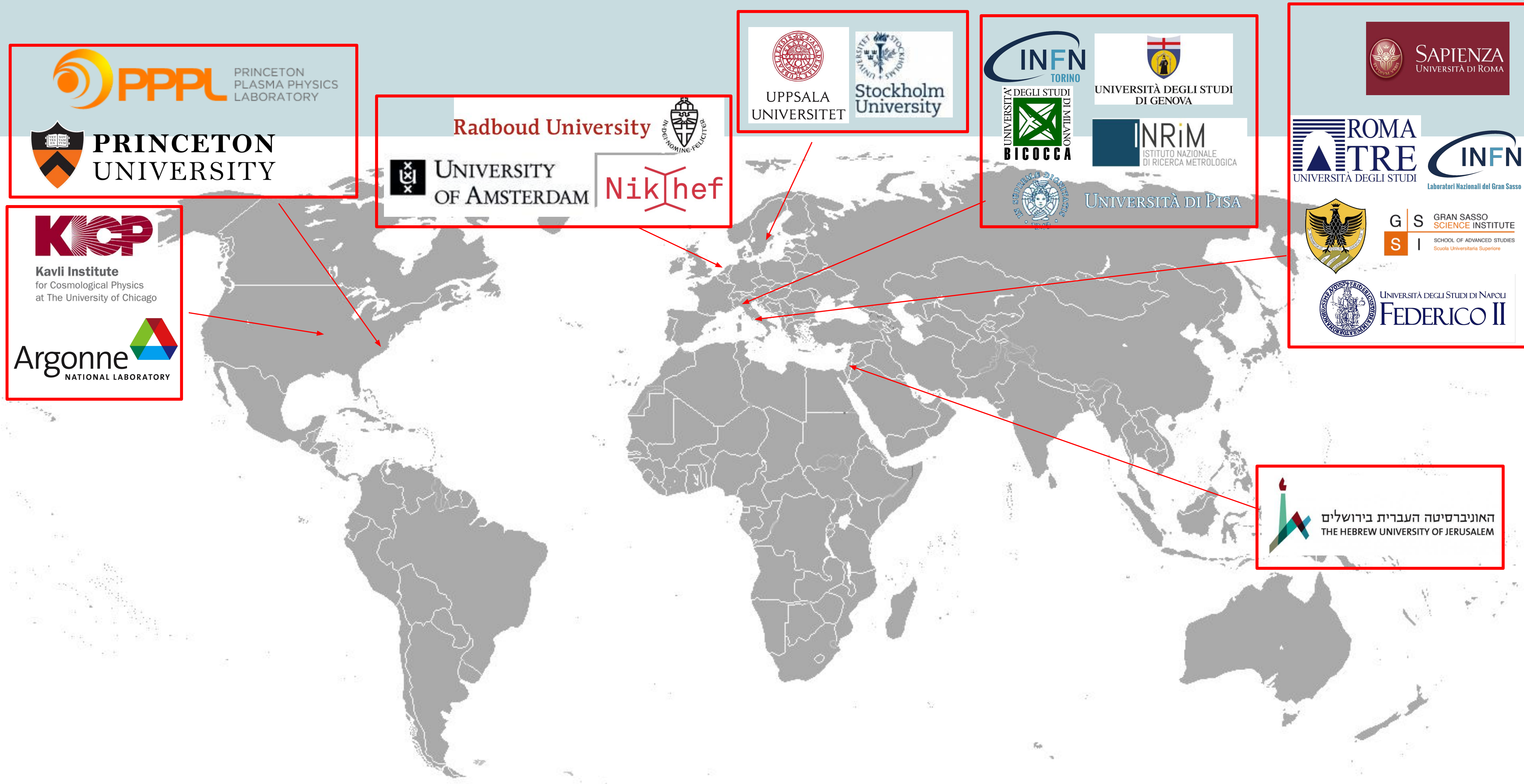
Low Power MgB_2 Superconducting Conduction-cooled Coils

Simulated B-map



Zero B field saddle point key feature of the field map

The PTOLEMY Collaboration



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 next year
- Prototype baseline option is: T embedded on graphene; New concept EM filter; electron energy resolution measured in several steps (MCP/SDD). Ultimately operating TES with sub-eV energy resolution.