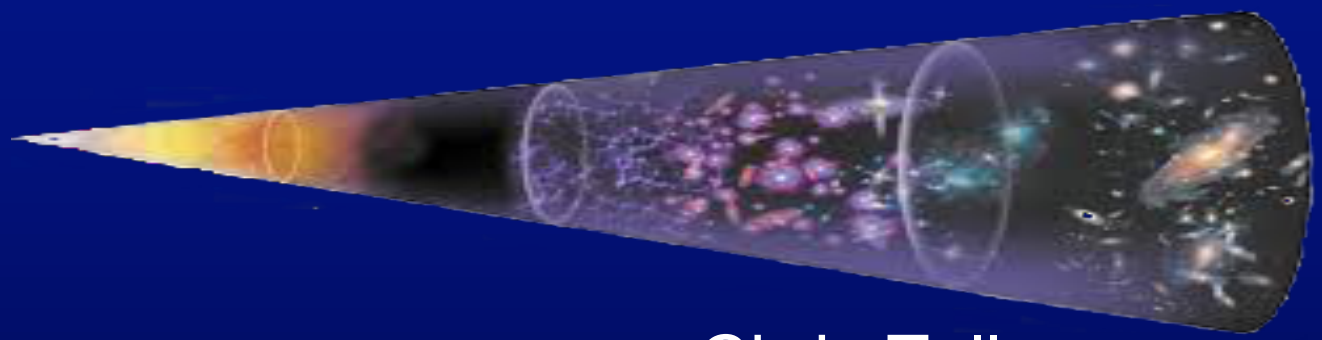
Detecting Cosmological Relic Neutrinos with PTOLEMY



Chris Tully

Princeton University

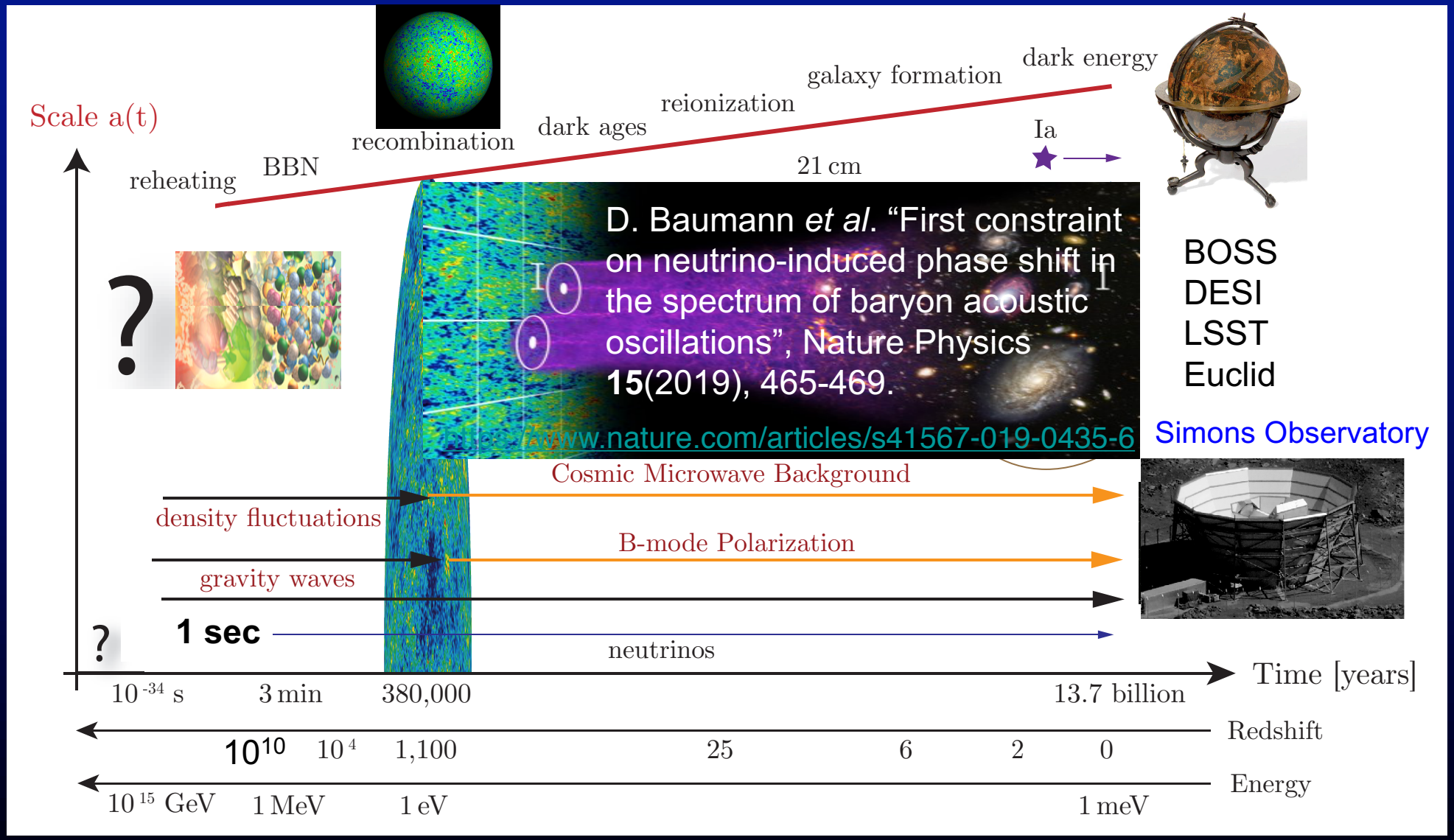
TOPICS IN COSMIC NEUTRINO PHYSICS

COSMIC PHYSICS CENTER, FERMILAB, 10 OCTOBER 2019

https://indico.fnal.gov/event/20434/

2015 Targeted Grant Award from the SIMONS FOUNDATION

Origin of Large Scale Structure



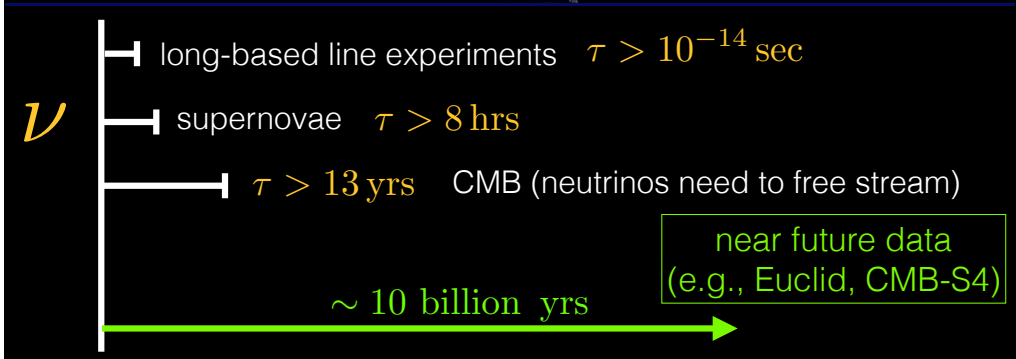
Baumann
(TASI 2012)

CNB Today

Large Scale Structure Signals of Neutrino Decay

Yuhsin Tsai
University of Maryland

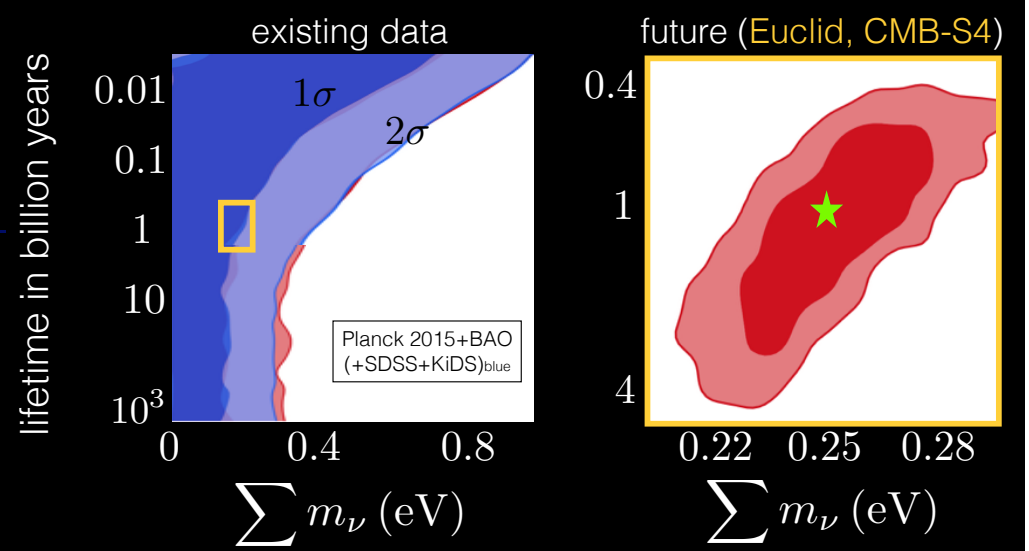
with Zackaria Chacko, Abhish Dev, Peizhi Du, Vivian Poulin
1909.05275, 19XX….



Chacko, Dev, Du, Poulin, **YT** (in preparation)
see also Serpico (2007)

Measure neutrino mass & lifetime

Chacko, Dev, Du, Poulin, **YT** (in preparation, preliminary)

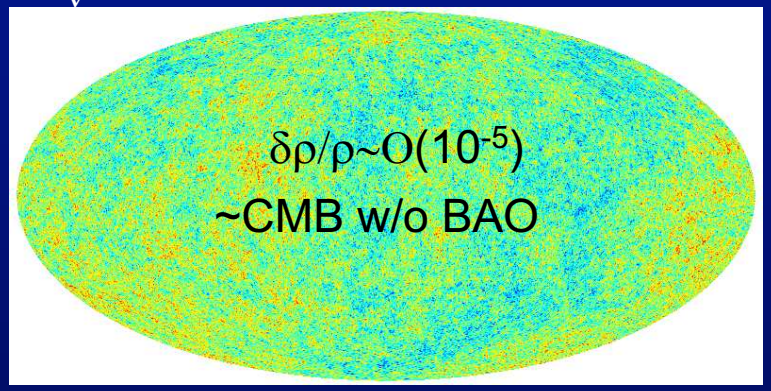


Something not expected??

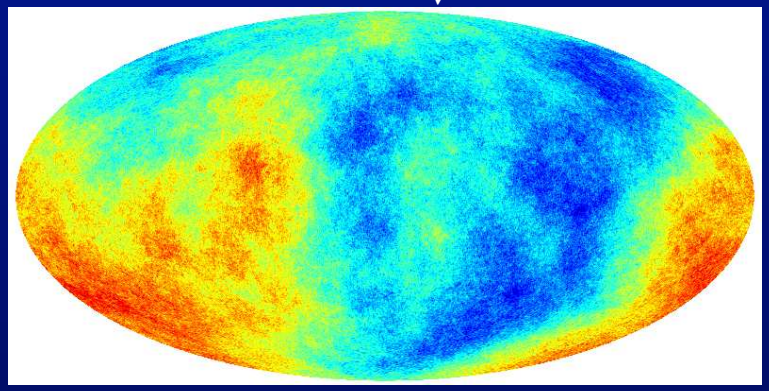
→ **CNB Direct Detection would need to resolve this**

Neutrino Sky

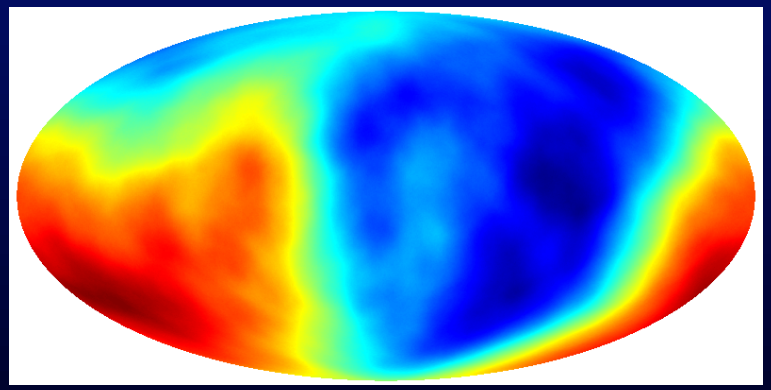
$m_\nu < 0.00001$ eV



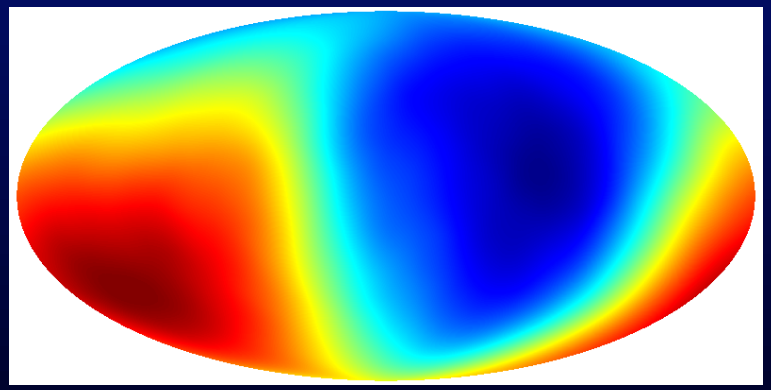
$m_\nu \sim 0.001$ eV



Hannestad, Brandbyge (2009)

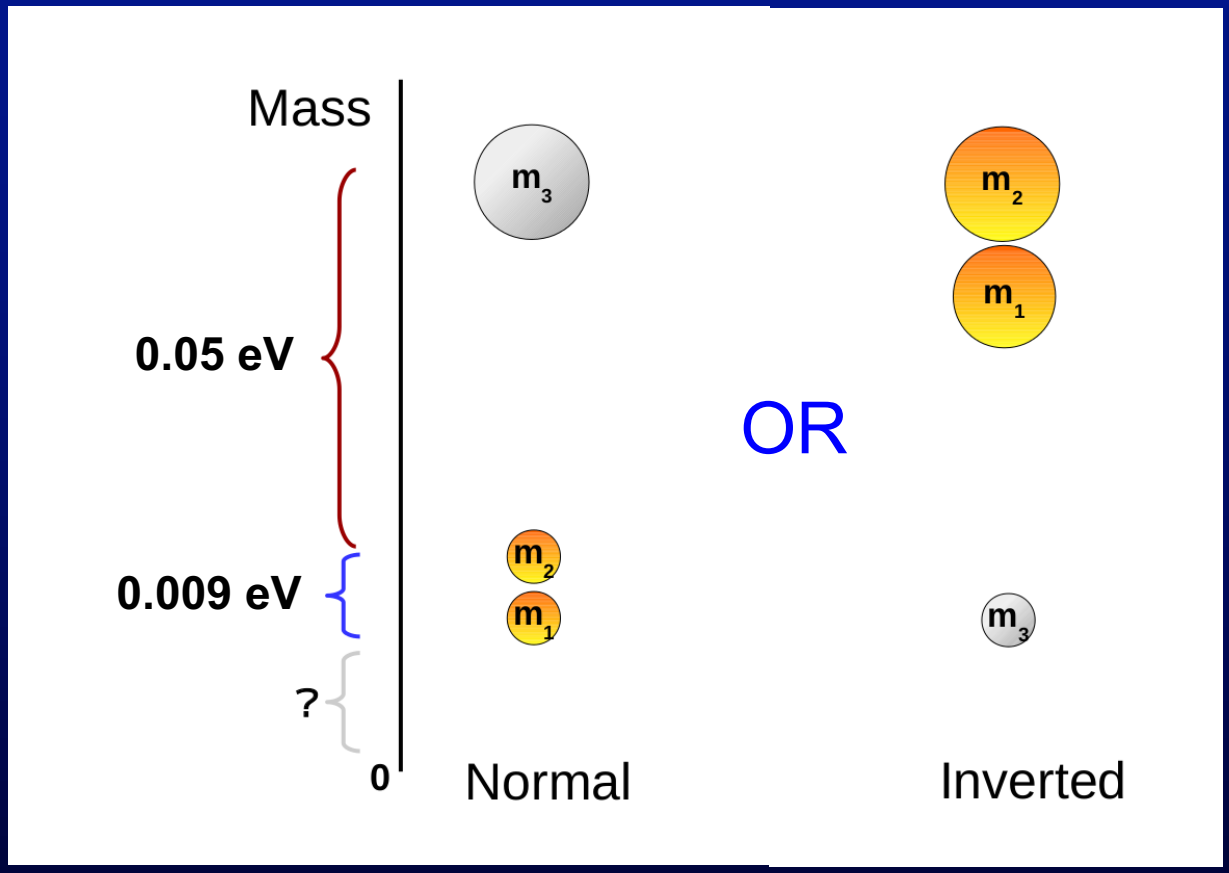


$m_\nu \sim 0.01$ eV

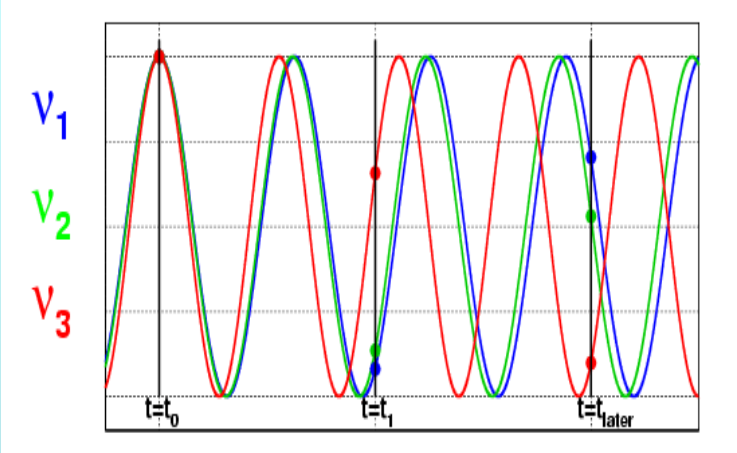


$m_\nu \sim 0.1$ eV

Neutrino Masses from Oscillations



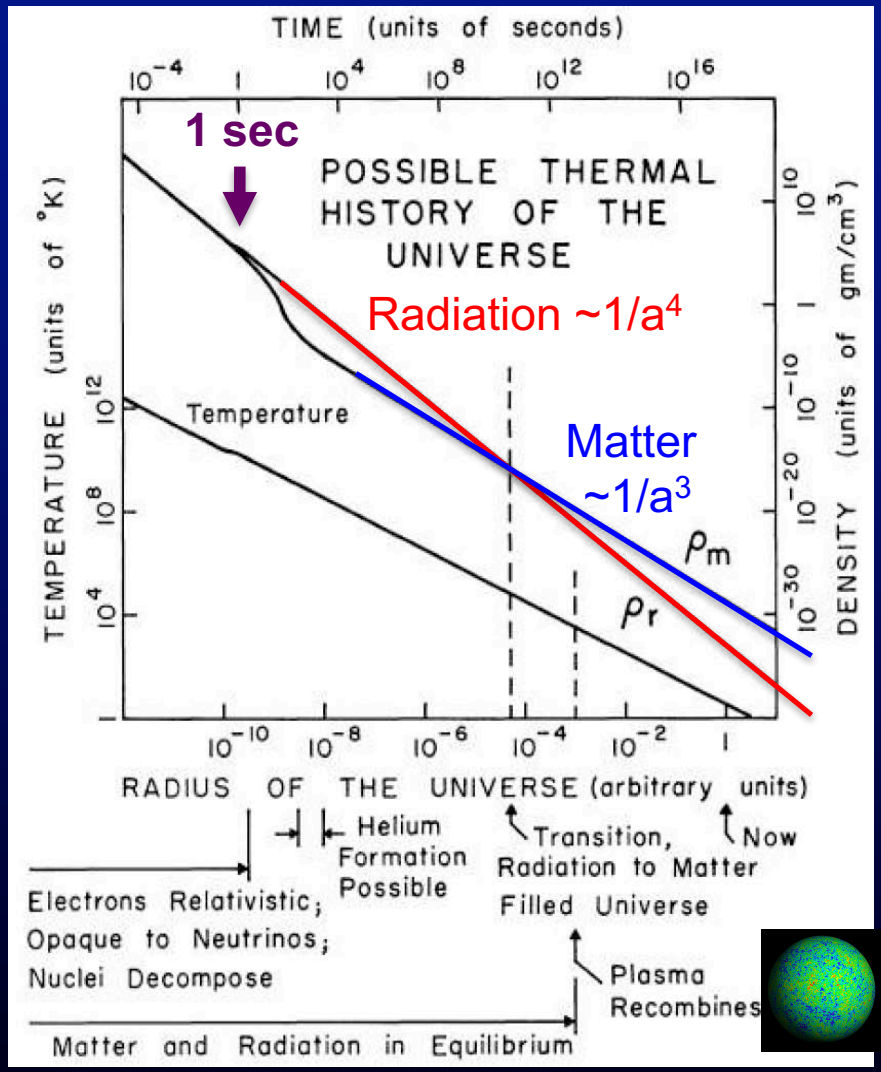
3 masses
X
3 flavors
(electron, muon, tau)



The absolute neutrino masses are not known.

It's not known at this time whether neutrinos masses are "Normal" or "Inverted".

Cosmic Neutrino Background



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

Number density:

$n_\nu = 112/cm^3$

Temperature:

$T_\nu \sim 1.95K$

Time of decoupling:

$t_\nu \sim 1$ second

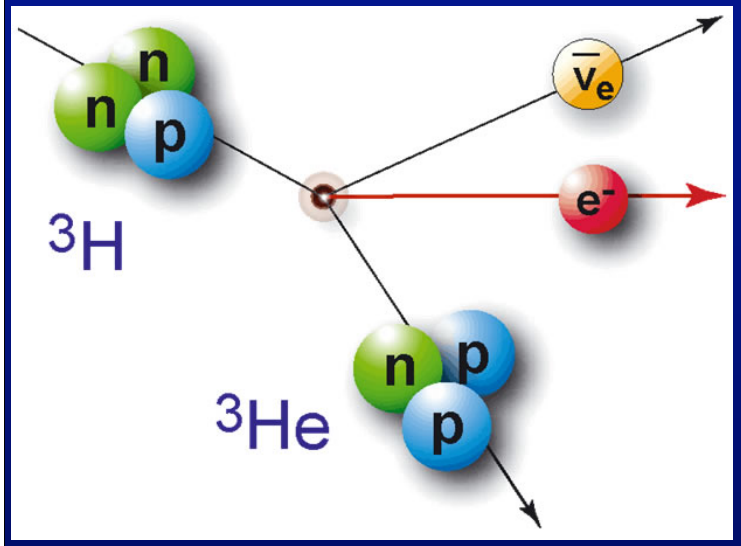
neutron/proton ratio @start of nucleosynthesis

Velocity distribution:

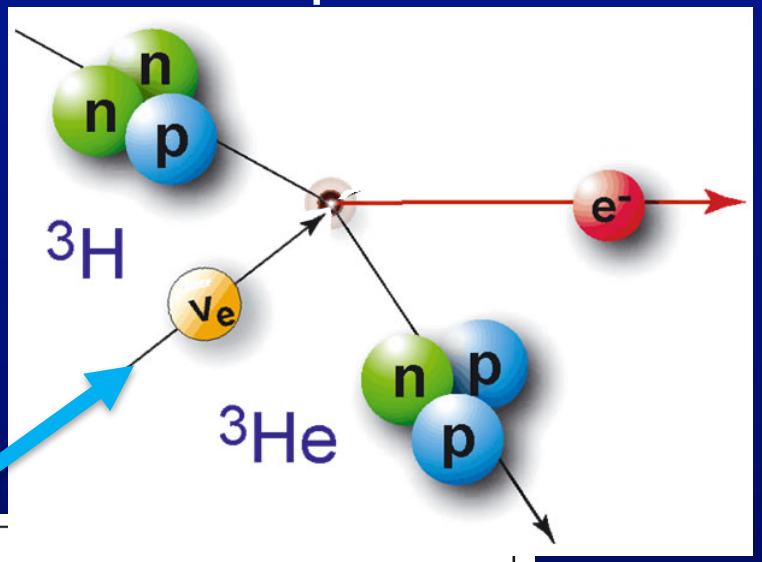
$\langle v_\nu \rangle \sim T_\nu / m_\nu$

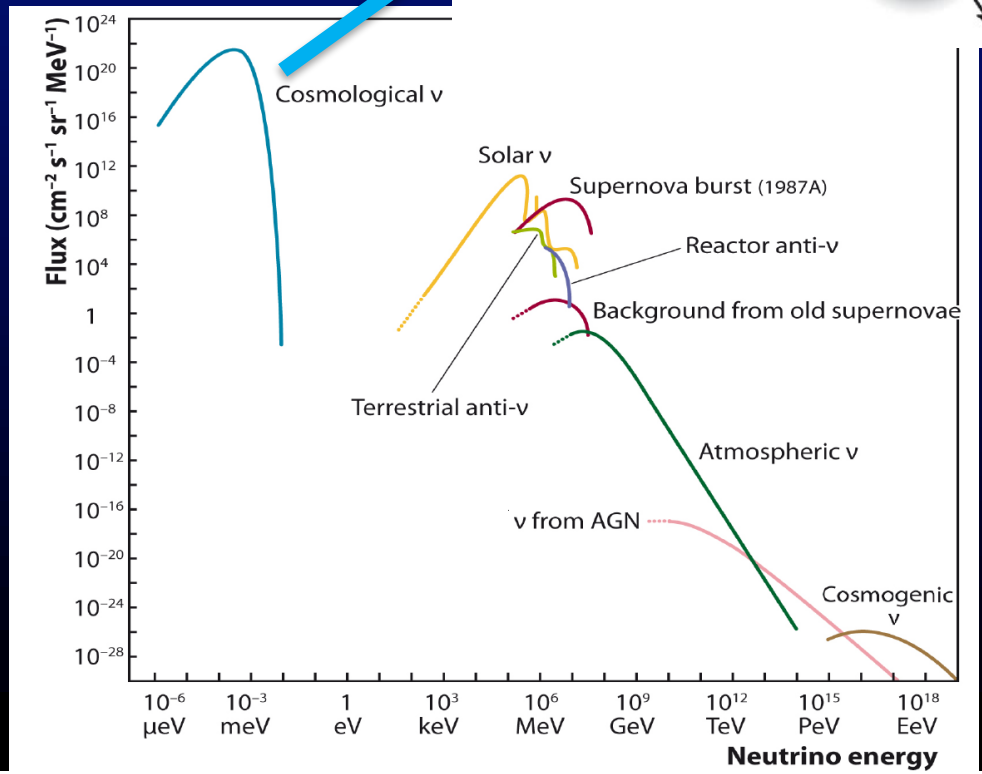
Non-linear distortions Villaescusa-Navarro et al (2013)

Neutrino capture on Tritium



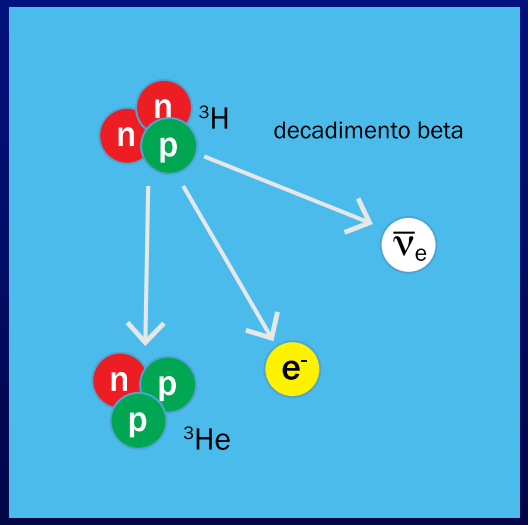
Tritium β-decay
(12.3 yr half-life)

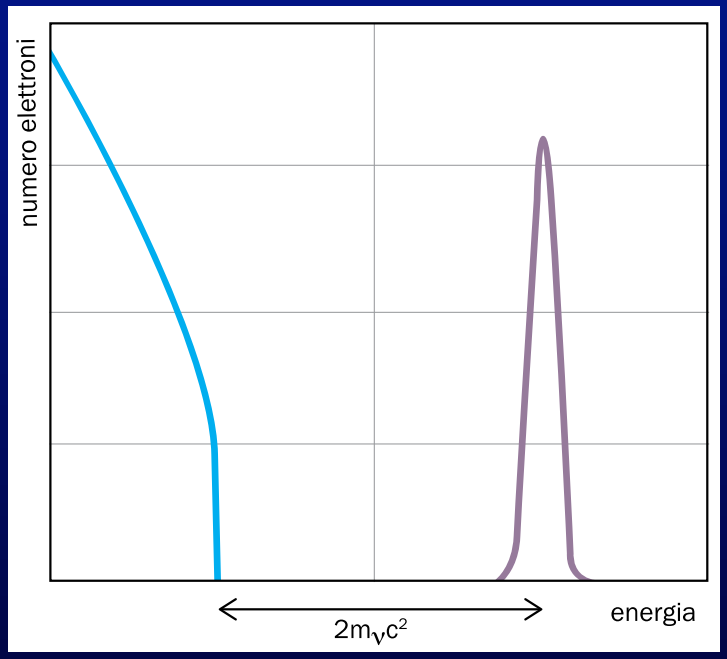


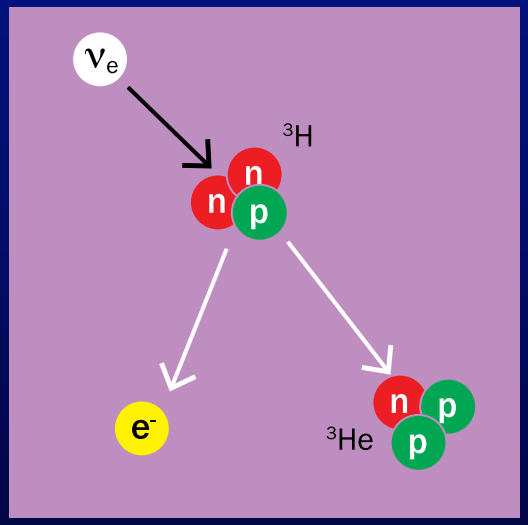


Detection Concept: Neutrino Capture

- Basic concepts[1] for relic neutrino detection were laid out in a paper by Steven Weinberg in **1962** [*Phys. Rev*. 128:3, 1457]







What do we know?

Electron flavor expected with

m > ~0.05eV

from neutrino oscillations

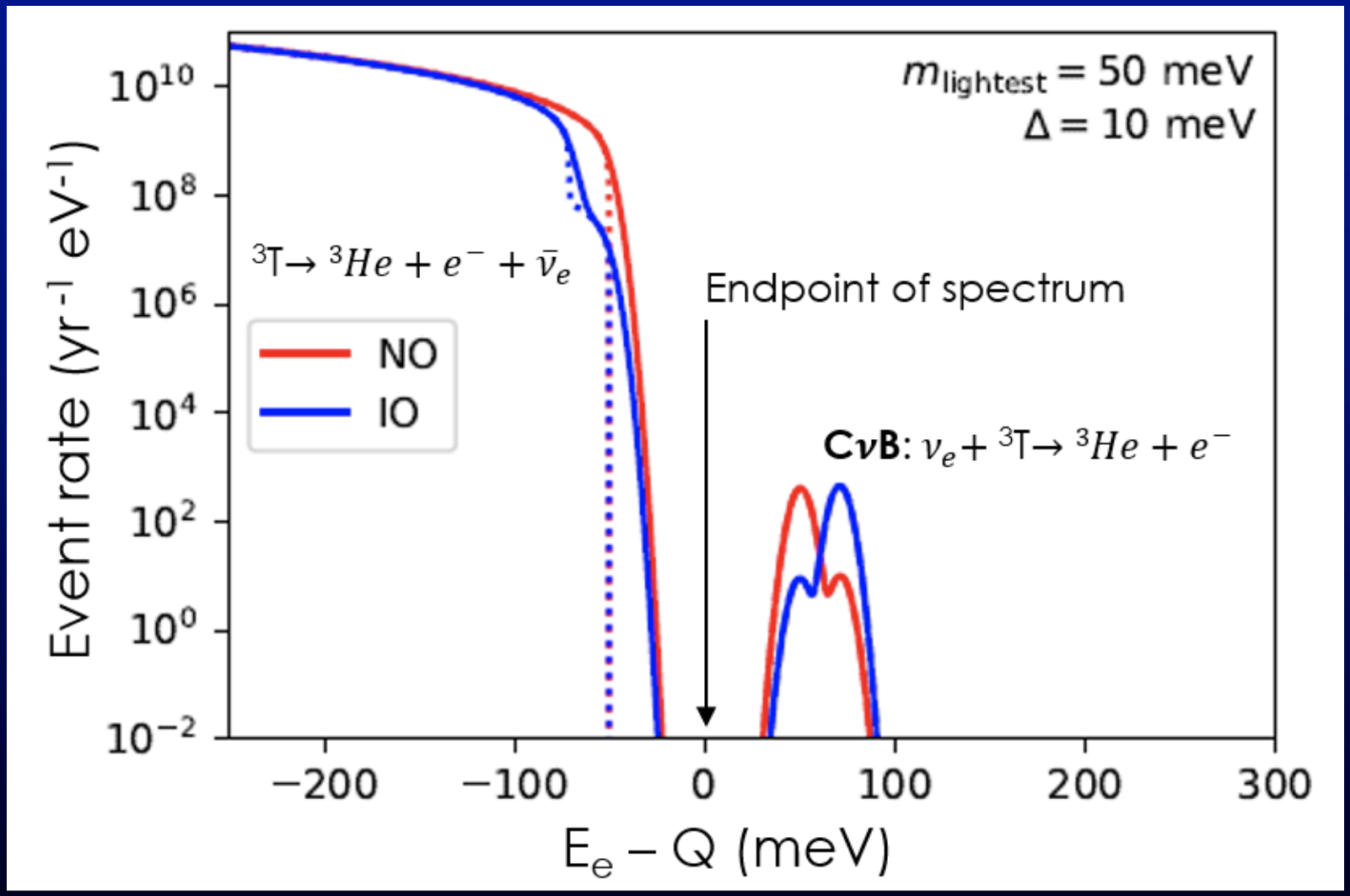
Gap (2m) constrained to

m < ~0.2eV

from Cosmology

[1]Finite neutrino mass, tritium and other isotopes studied for relic neutrino capture in this paper: JCAP **06** (2007) 015, DOI: 10.1088/1475-7516/2007/06/015 by Cocco, Mangano, Messina

Challenges: Resolution and Backgrounds



Neutrino physics with the PTOLEMY project,
M.G. Betti et al., JCAP **07** (2019) 047 DOI: 10.1088/1475-7516/2019/07/047
e-Print: arXiv:1902.05508

PTOLEMY Cosmic Neutrino Telescope

PonTecorvo Observatory for Light, Early-universe, Massive-neutrino Yield

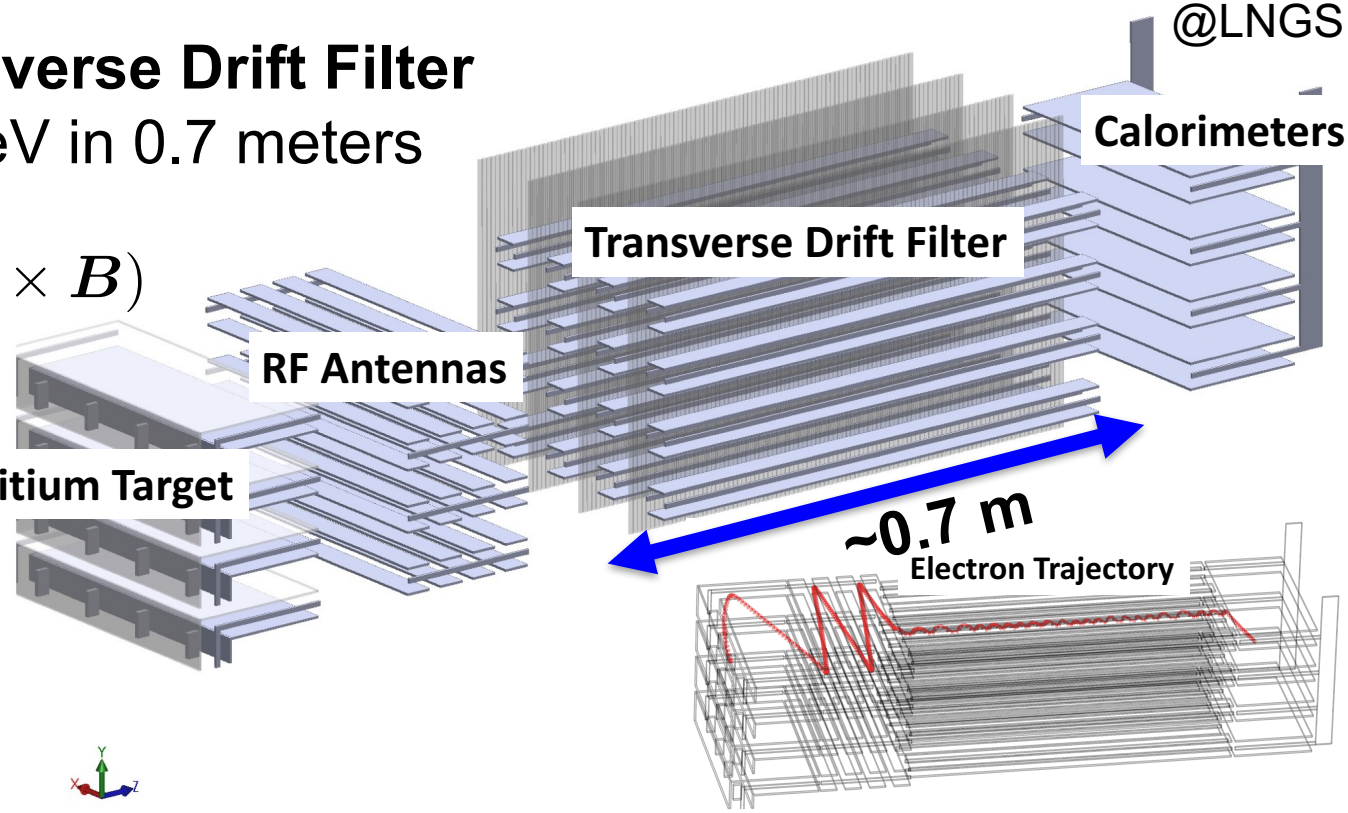
P T O L E M Y

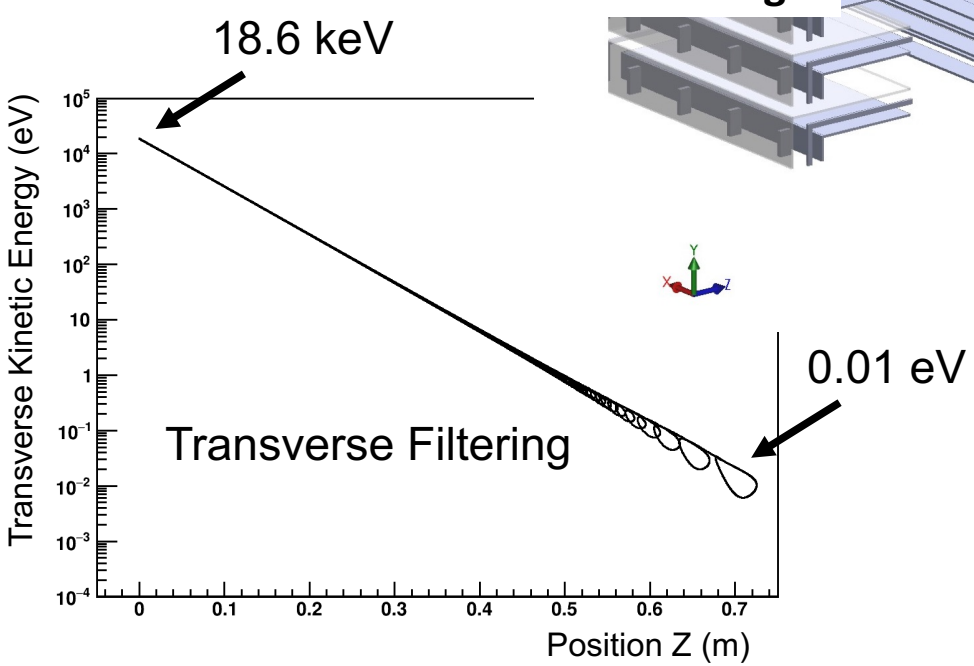
@LNGS

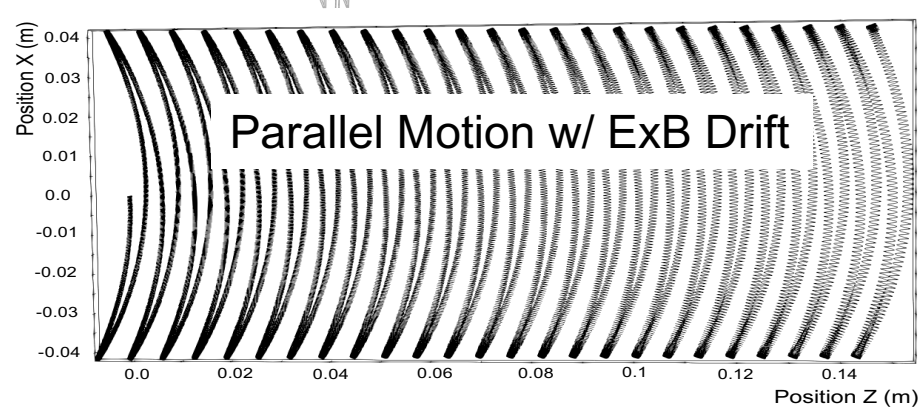
New Concept: **Transverse Drift Filter**

18.6 keV → 0.01 eV in 0.7 meters

$$\frac{dT_\perp}{dt} = \frac{\mu}{B^2}\boldsymbol{E}\cdot(\boldsymbol{\nabla}B\times\boldsymbol{B})$$

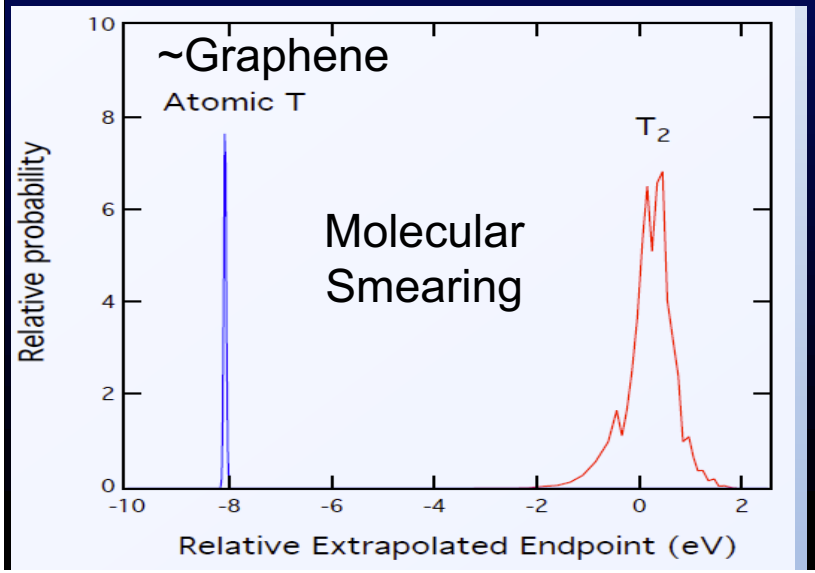


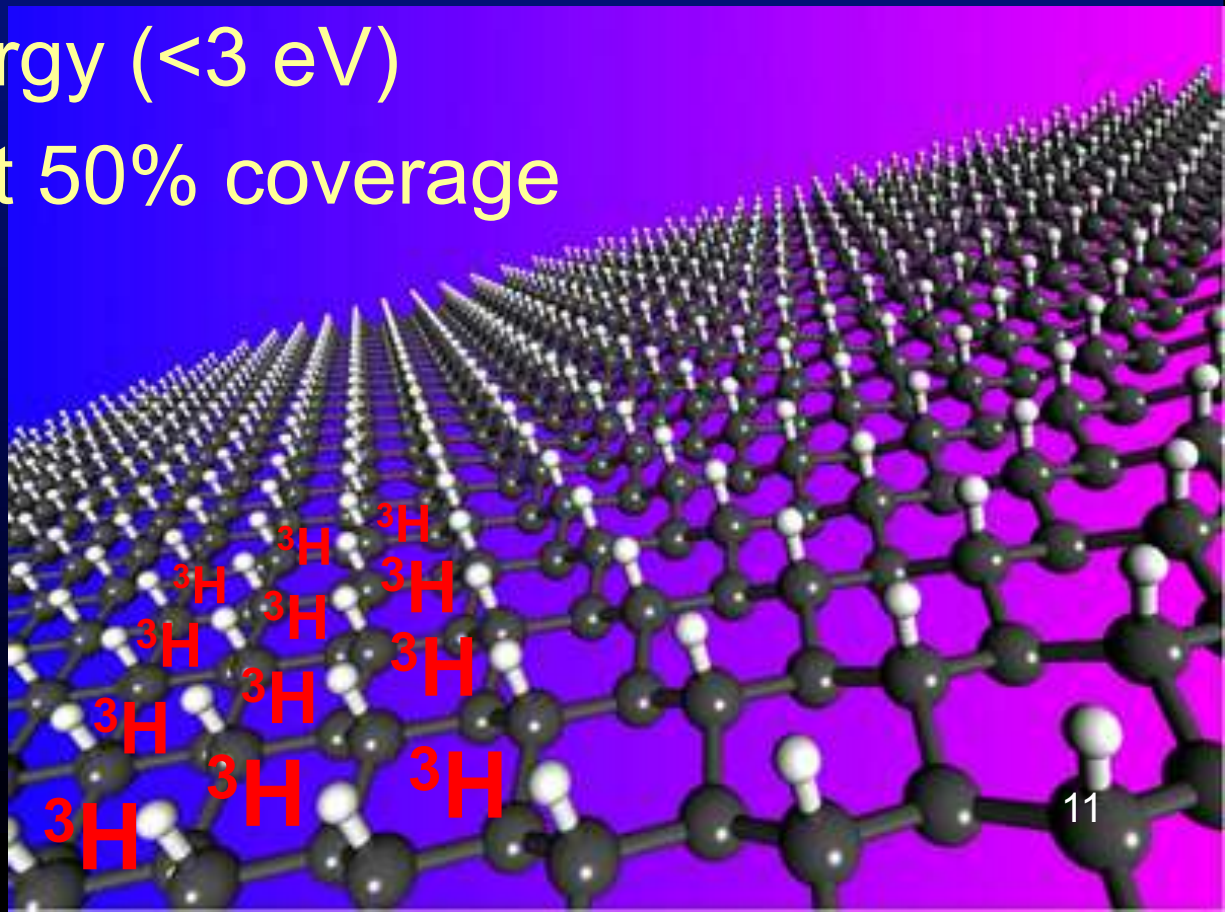




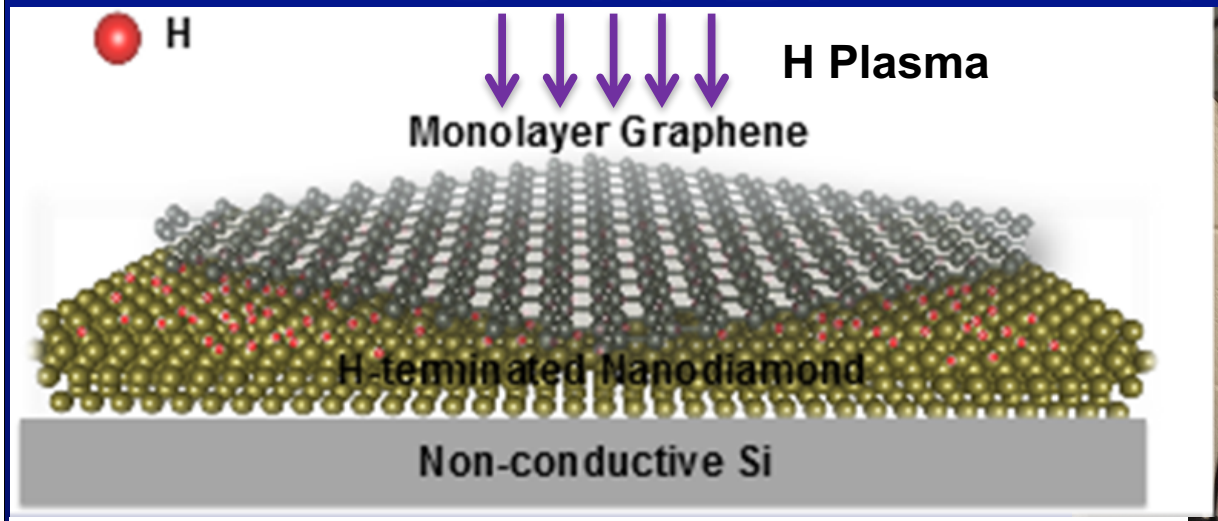
Cosmic Neutrino Telescope
Step 1: Quality of Lens Surface

- Choice: Graphene – atomic flatness
- Hosts "Lepton $\nu \rightarrow e^-$ shifting material" (tritium ^3H)
- Low binding energy (<3 eV)
- Ferromagnetic at 50% coverage

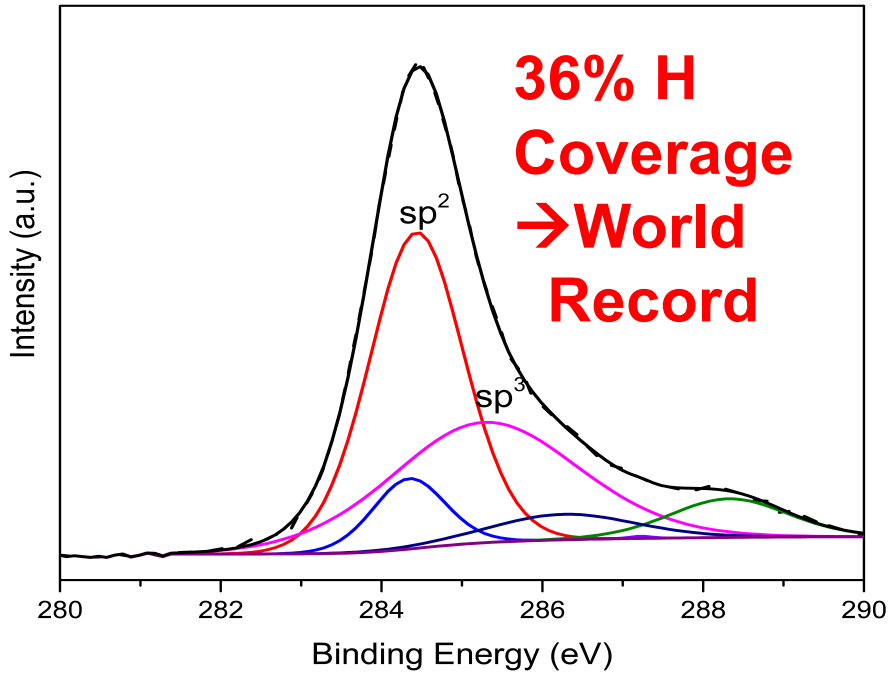


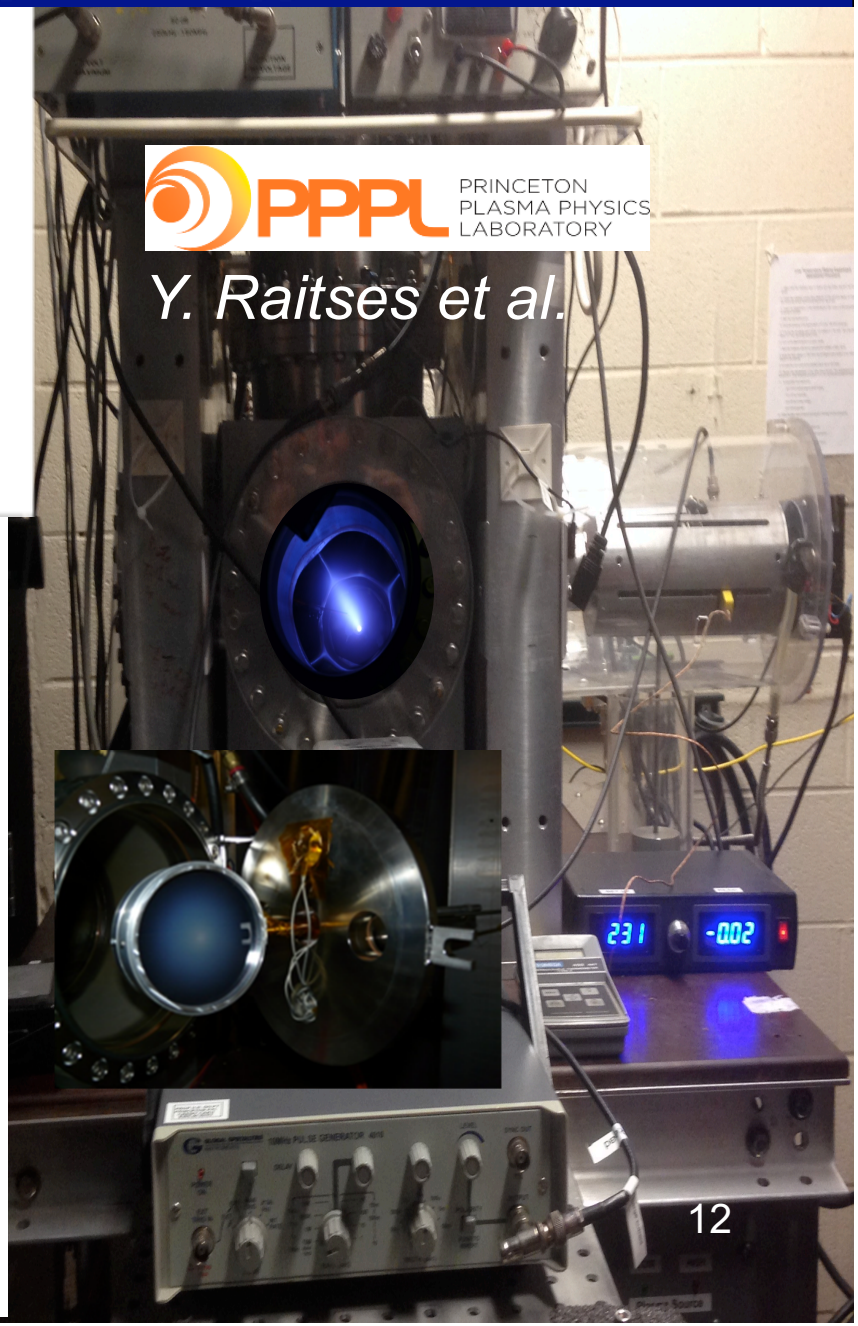


Cold Plasma Loading

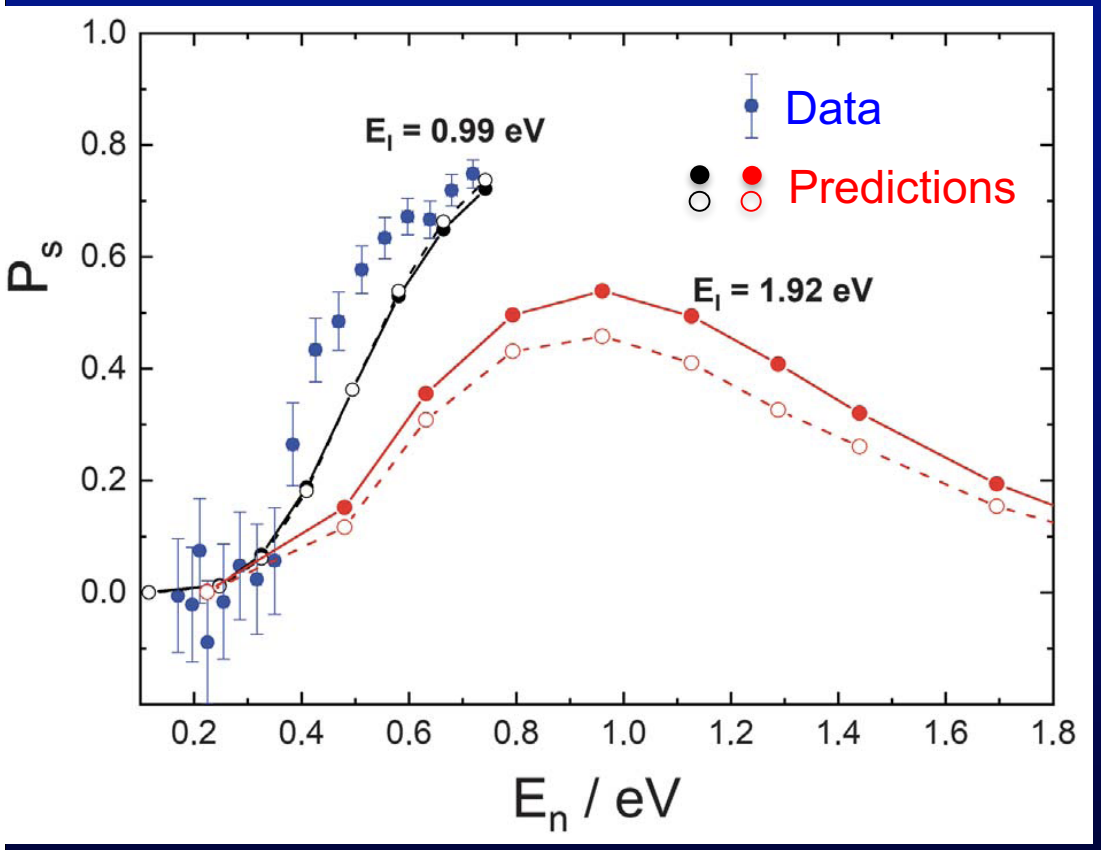


XPS Hydrogenation Results from Princeton

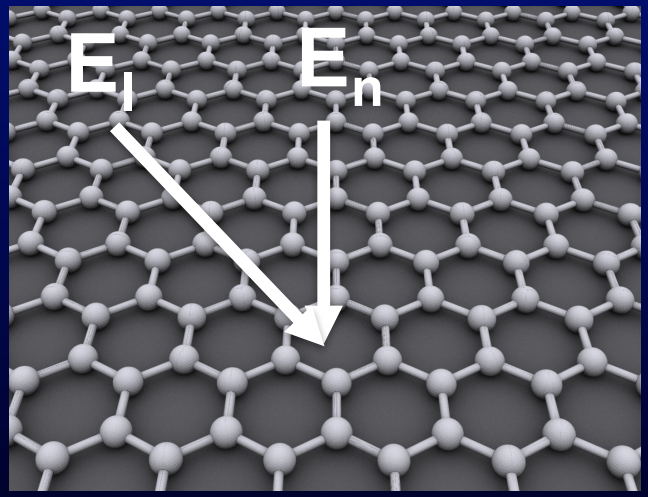




Sticking Probability of H on Graphene



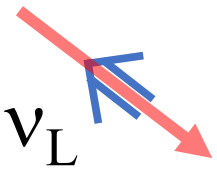
This technique repeated for ^{3}He and ^{3}H would provide data on final-state T-Graphene → ^{3}He-Graphene molecular smearing.

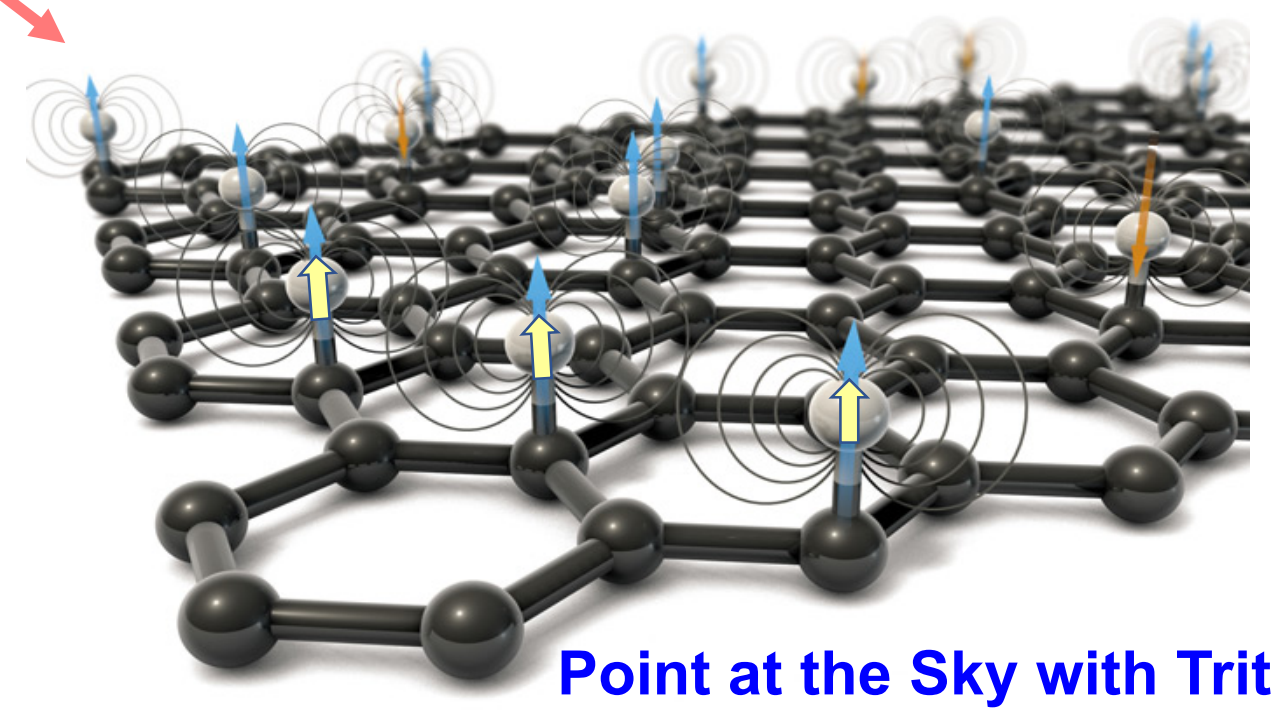


New ideas for magnetic transfer!

Imaging covalent bond formation by H atom scattering from graphene, Jiang et al., Science 364, 379–382 (2019) 26 April 2019.

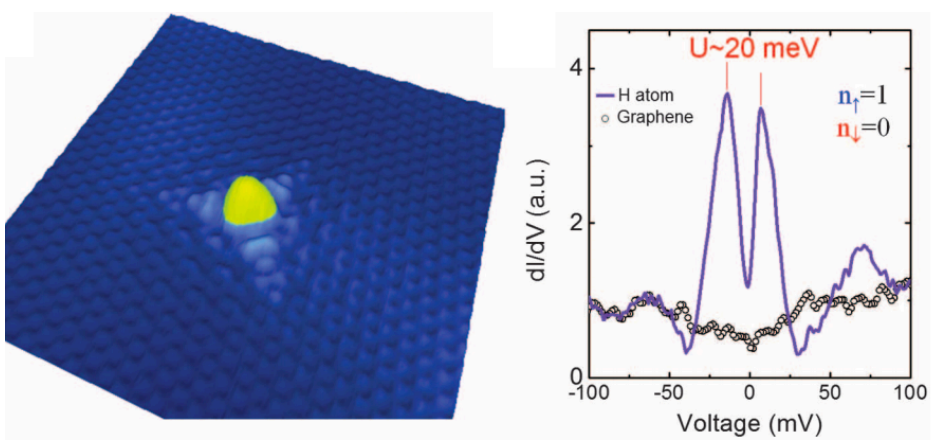
Polarized Tritium Target





Lisanti, Safdi, CGT, 2014.

Point at the Sky with Tritium Nuclear Spin ⇧

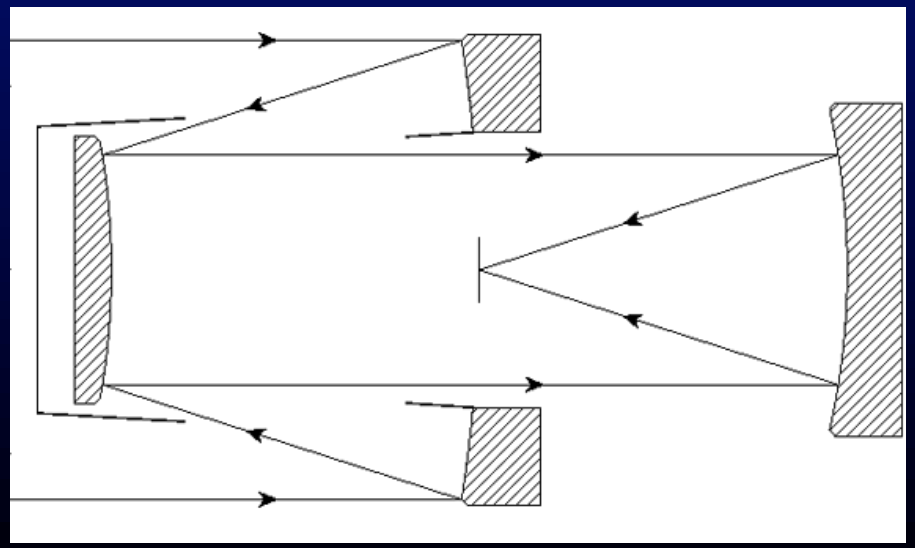


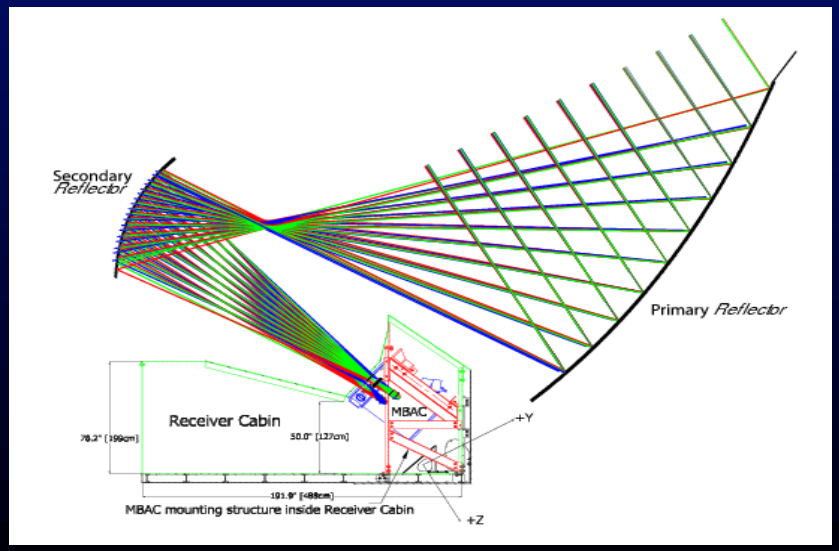
Hydrogen doping on graphene reveals magnetism

Gonzalez-Herrero, H. *et al.* Atomic-scale control of graphene magnetism by using hydrogen atoms. *Science (80).* **352,** 437–441 (2016).

Cosmic Neutrino Telescope
Step 2: Geometric Focus

- Choice: Reflector – Electrons guided by EM fields
- Reflection by voltage potential for electron pinned on magnetic field lines
- Angular deflection by ExB drift across B field lines





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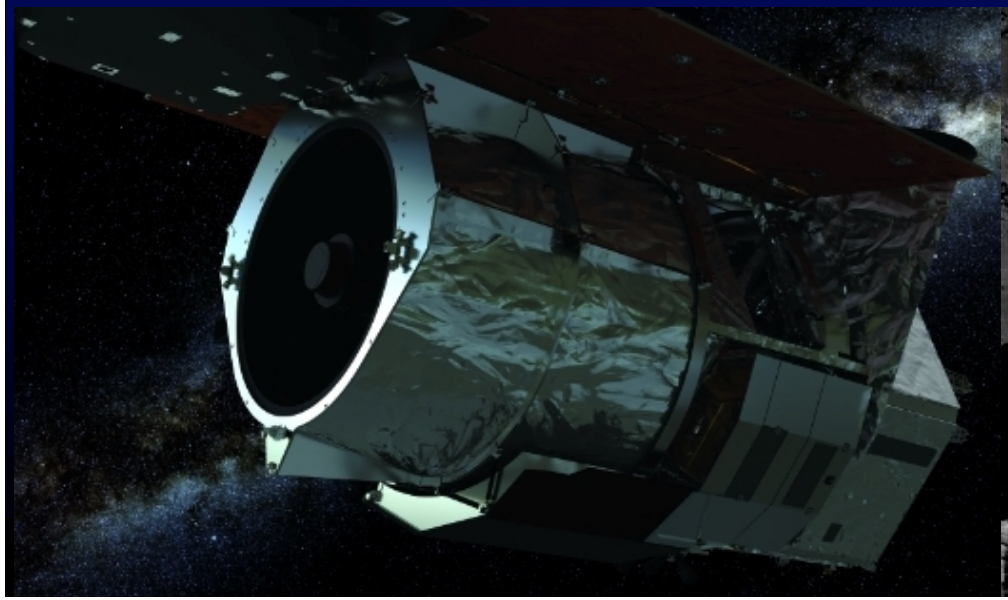
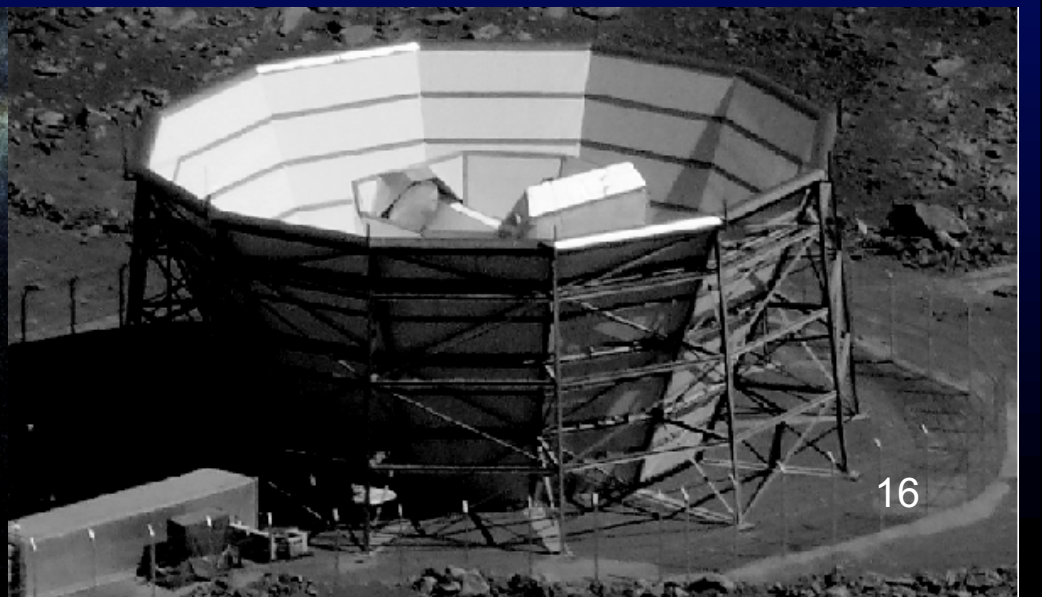
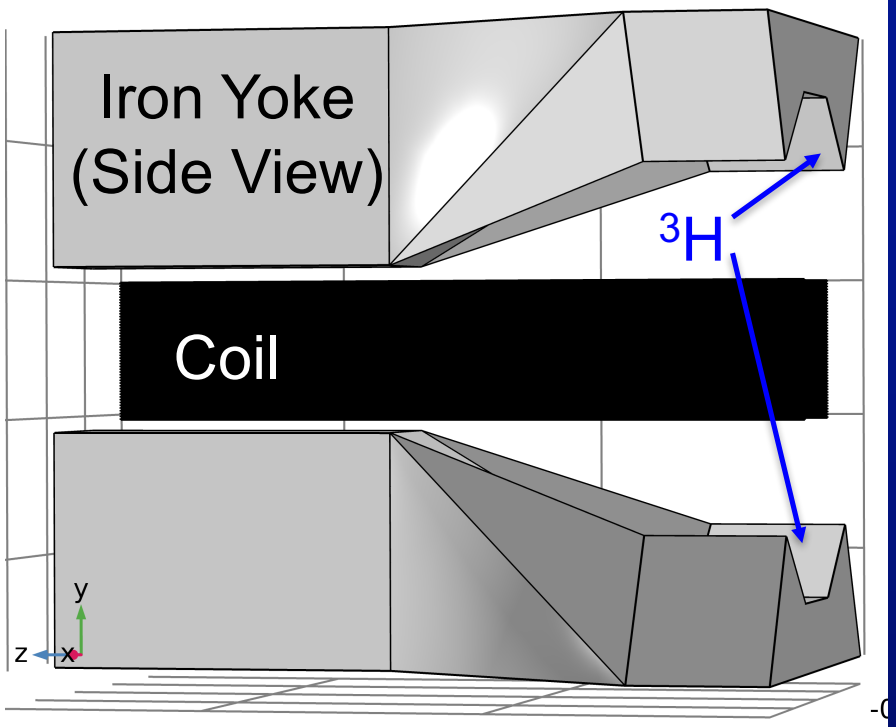
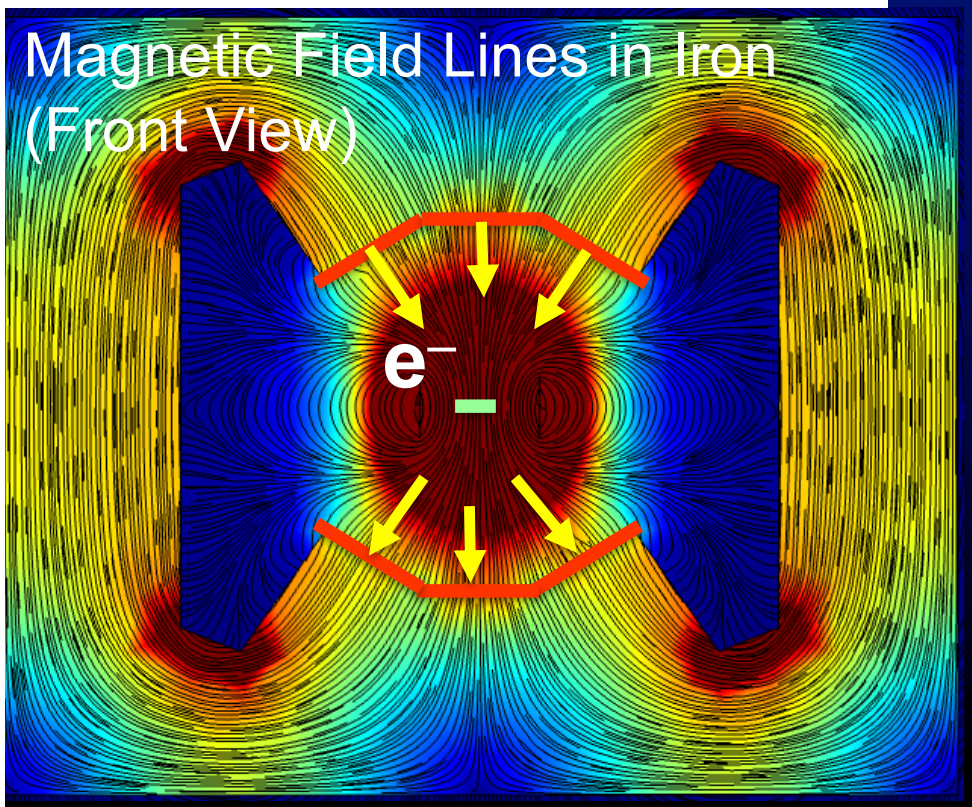




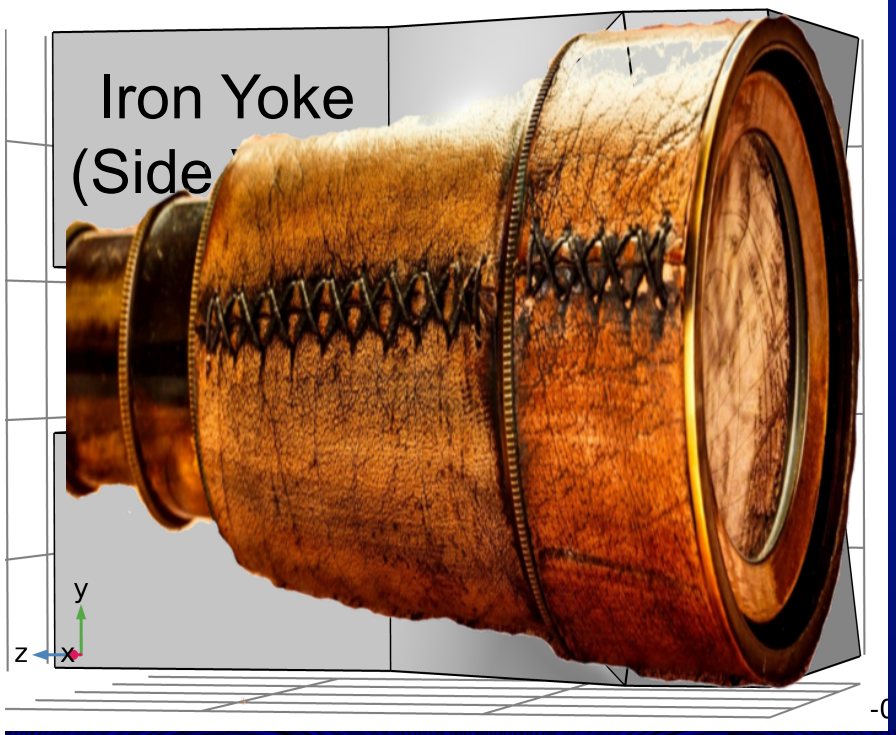
Target Geometry

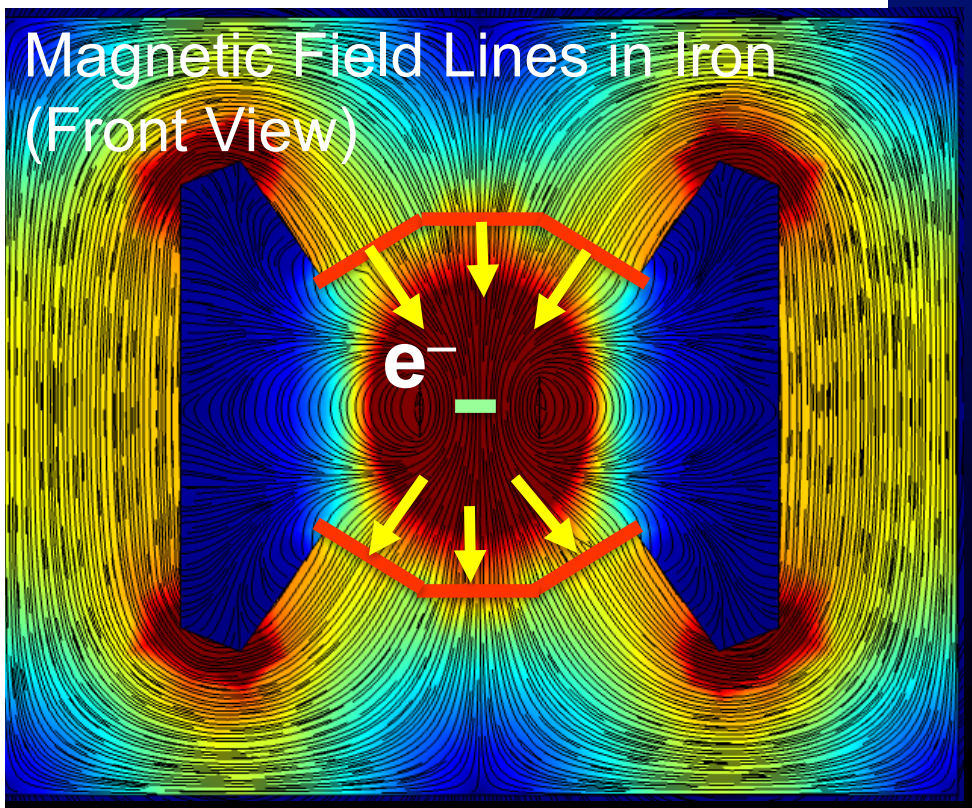




- Collect electrons over a large target area (end-on view in orange, normal to magnetic field yellow).
- Electrons are accelerated into a high magnetic flux region that is an order of magnitude smaller in cross section green.
- Through reflections and transverse drift (EM optics) **e⁻**'s enter the RF region (out of the screen).

Target Geometry





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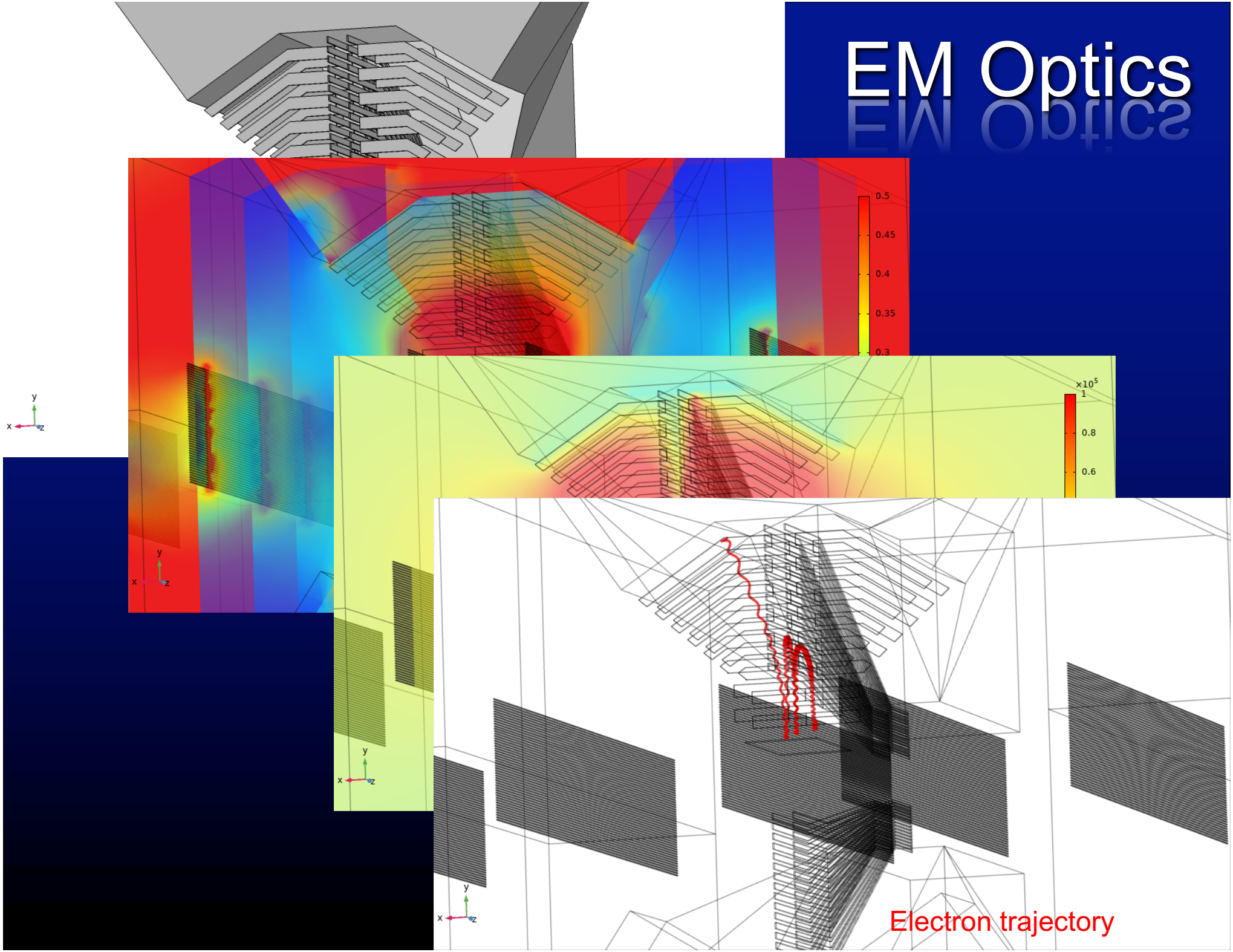
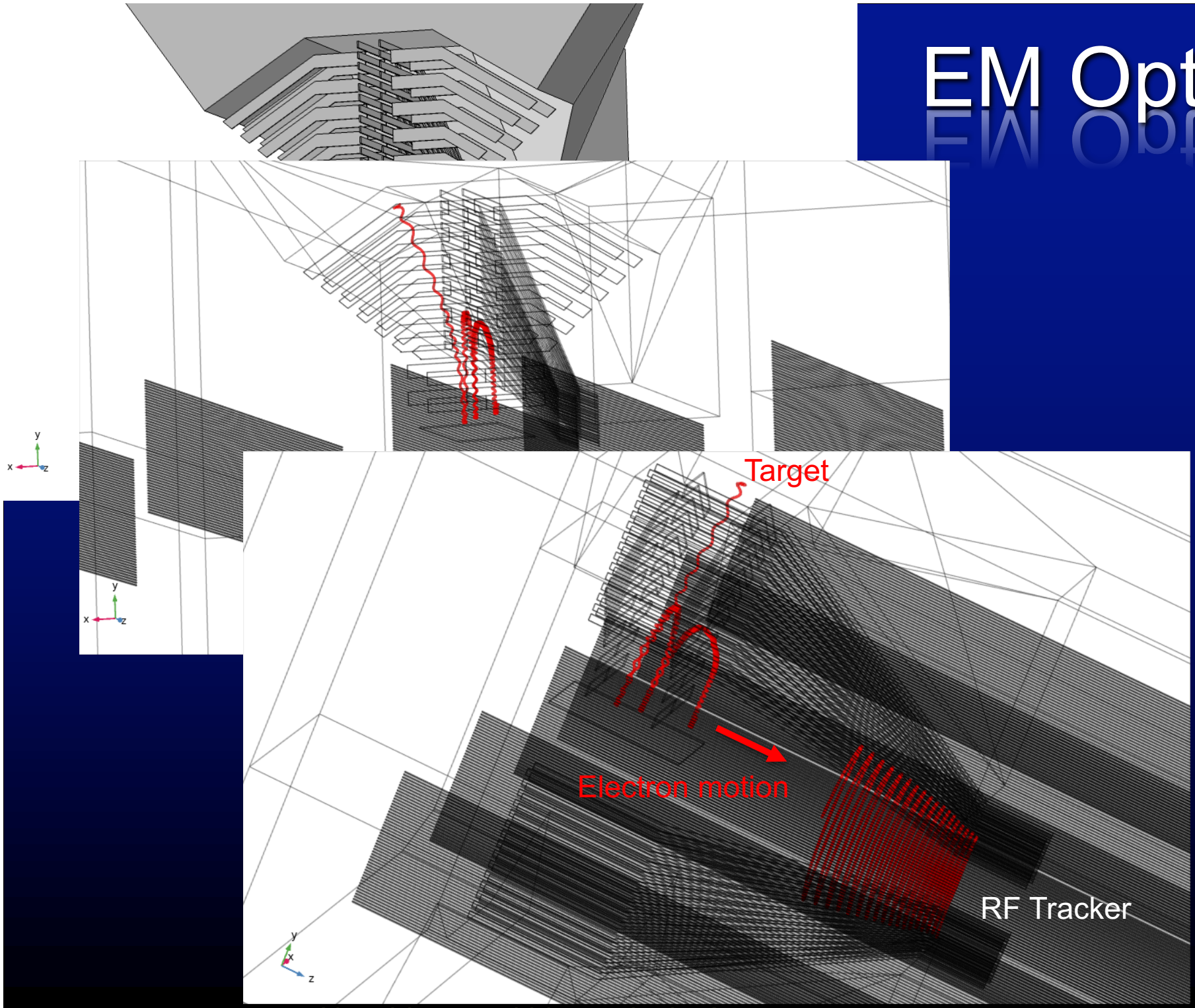
EM Optics



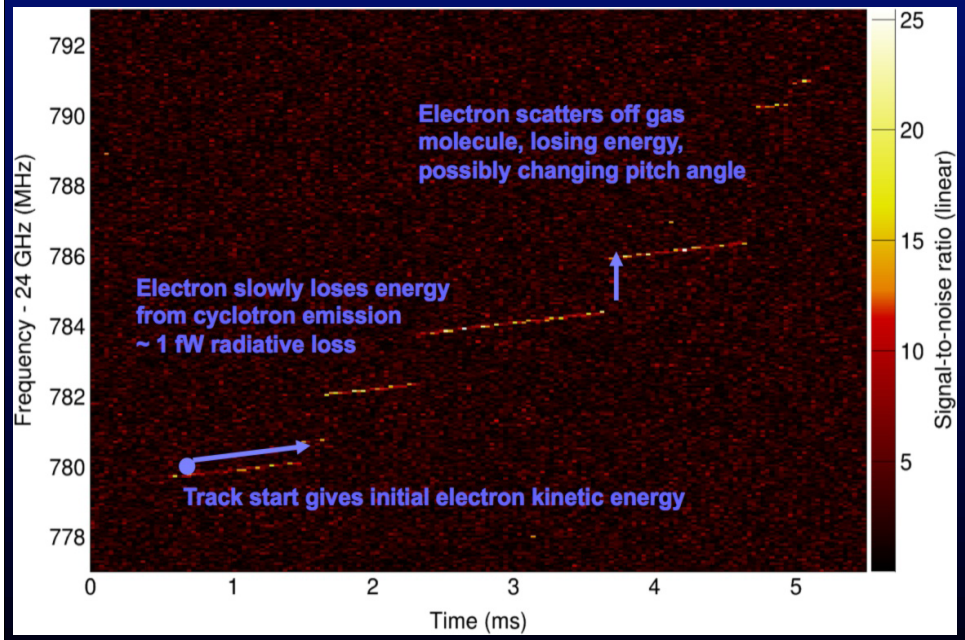
EM Optics

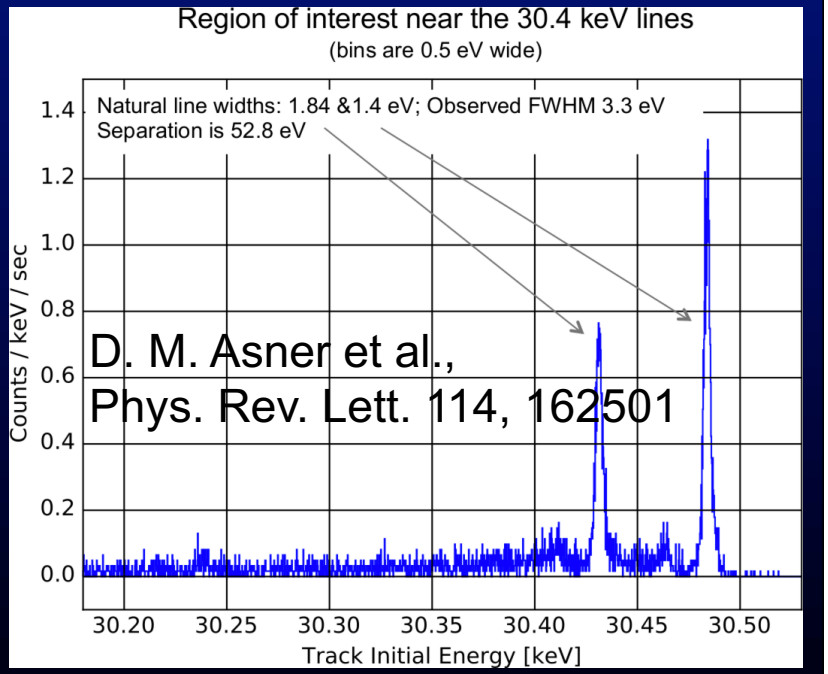


New ideas multi-layer design!

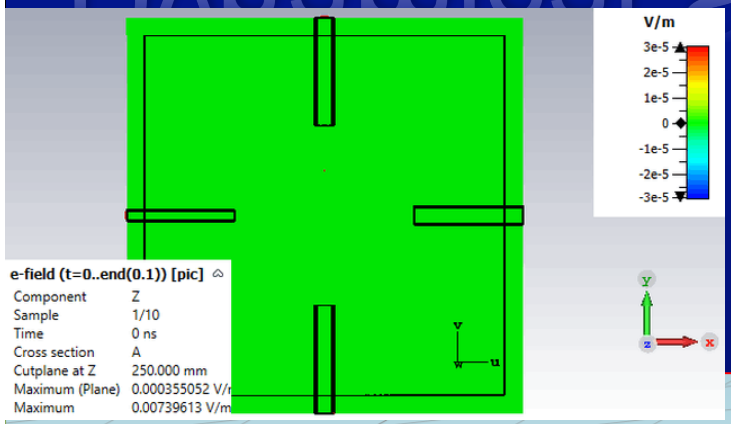
Cosmic Neutrino Telescope
Step 3: Dynamic Aperature

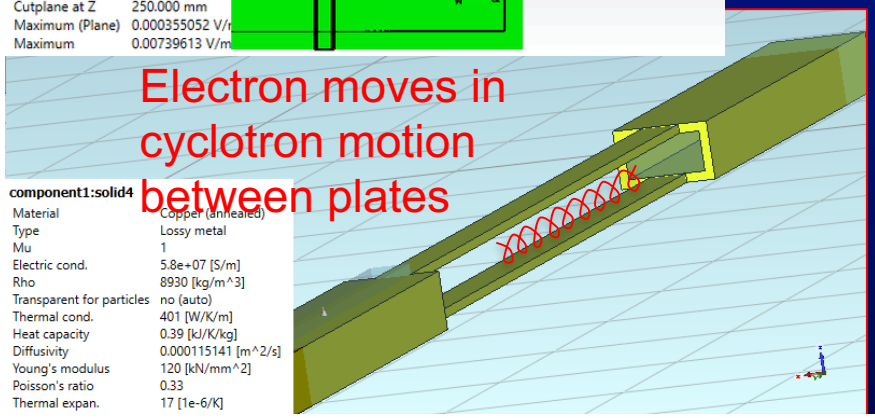
- Choice: RF tracking system – Project 8
- Estimates total momentum (ω_0/γ), $p_\perp$, $p_{||}$ to ~ 3eV





Dynamical Simulation of RF Signal





Electron moves in cyclotron motion between plates

Initial calculations using CST RF modeling tools:

→ Antenna configured to transition from Parallel Plate Waveguide to Rectangular Waveguide

→ Working on FPGA-accelerated parameter fitting

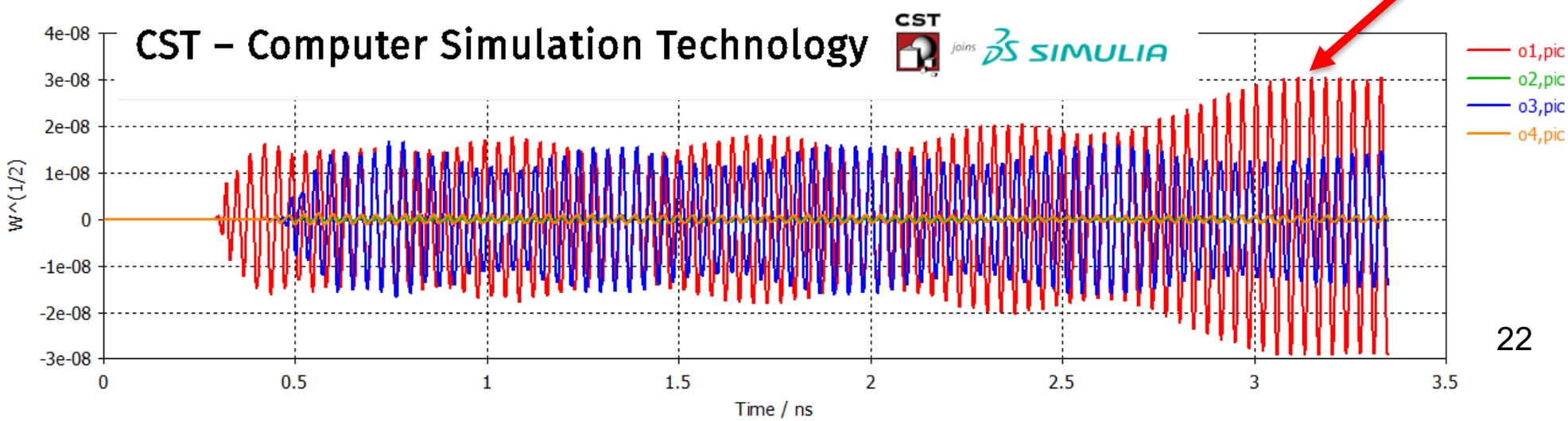
P_{signal}~0.1 fW

T_{LNA} ~6K

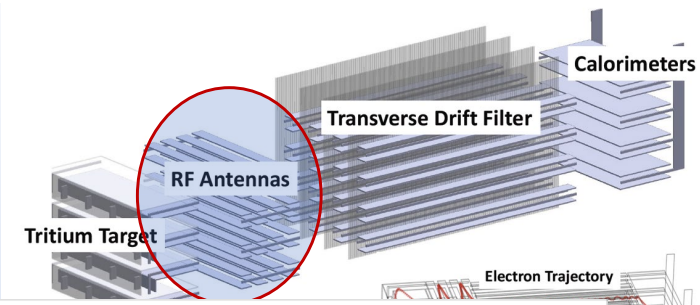
Dicke Radiometer eqn.

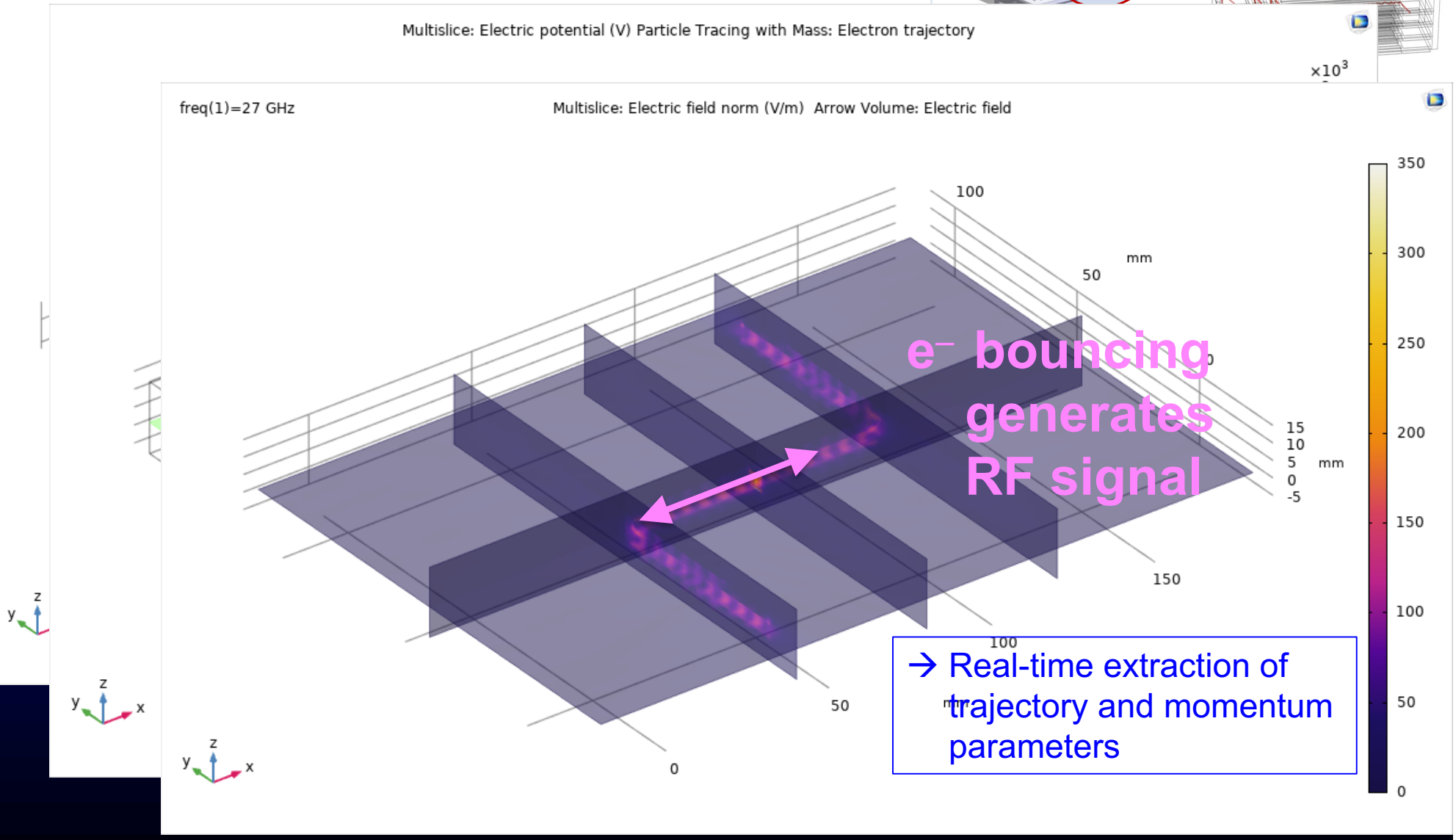
→ SNR~10 for 10^{-5}s

Normalization to Project 8 (https://arxiv.org/abs/1703.02037)



RF Tracking System



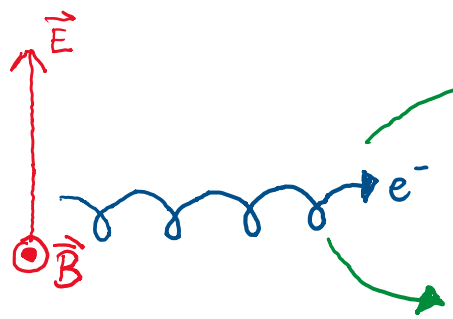


Cosmic Neutrino Telescope
Step 4: Fine Adjust

- Choice: Transverse Drift Filter – New Concept

Auke Pieter Colijn (PATRAS 2019)

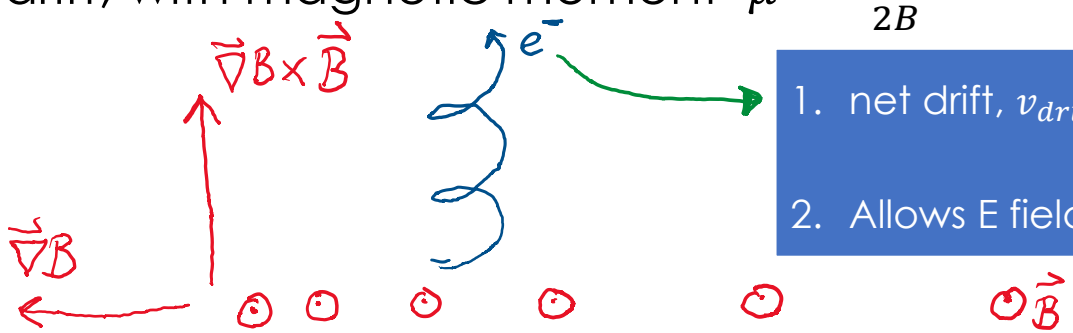
I: $\vec{E} \times \vec{B}$ drift



1. net drift, $v_{drift} = E/B$
2. no work, drift along equipotential planes

cyclotron motion – detectable RF

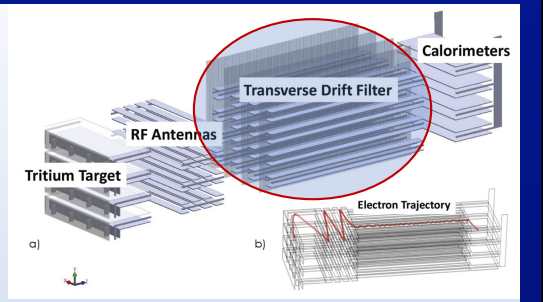
II: $\frac{\mu}{B^2}\vec{\nabla}B \times \vec{B}$ drift, with magnetic moment $\mu = \frac{m_e v_\perp^2}{2B}$

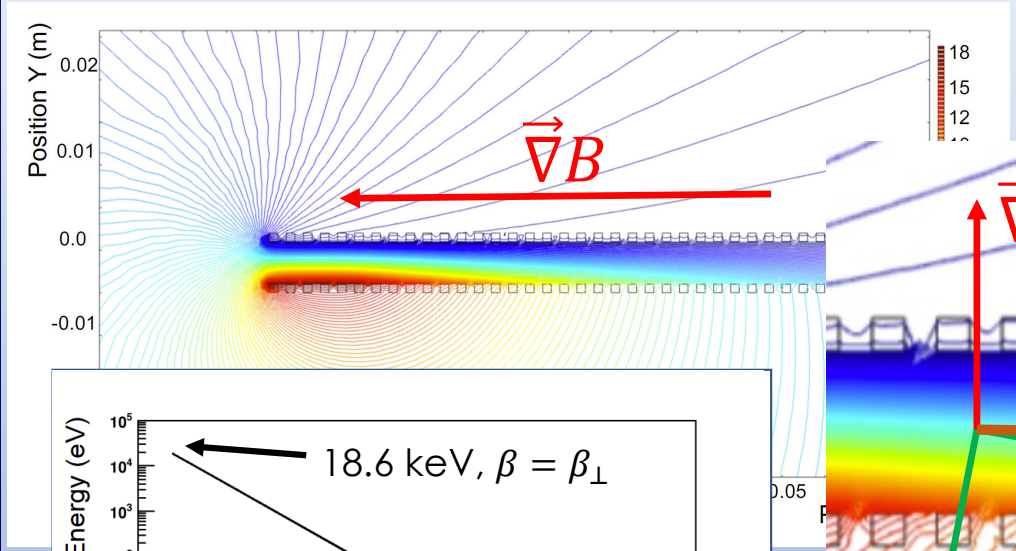


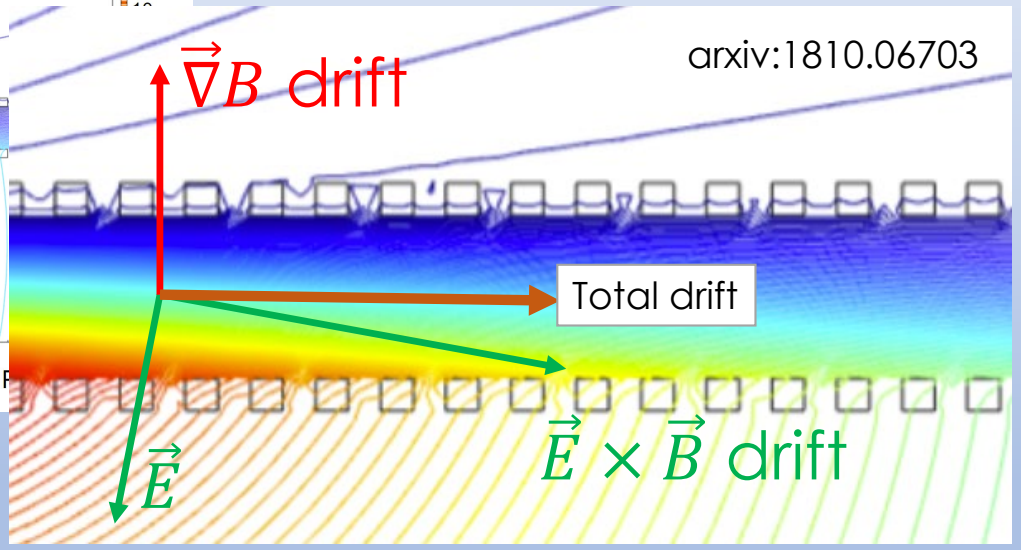
1. net drift, $v_{drift} = \mu \frac{|\vec{\nabla}B|}{B}$
2. Allows E field to work (!): $\frac{dT_\perp}{dt} = e\vec{E} \cdot \vec{v}_{drift}$

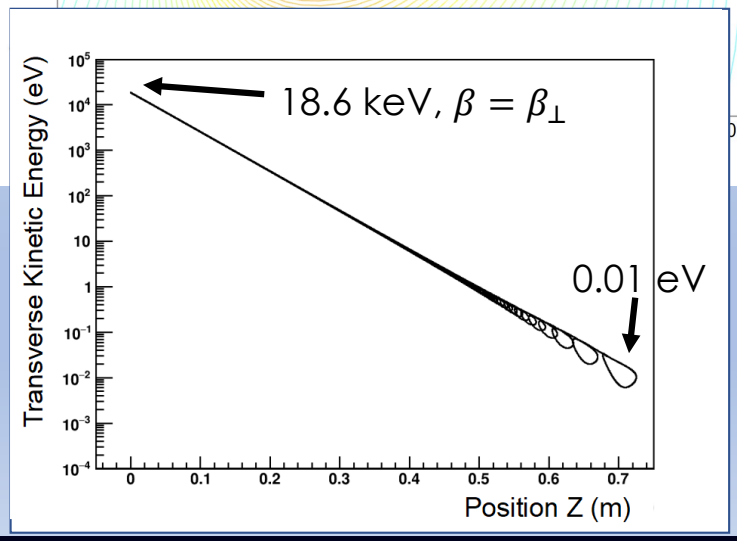
Transverse Filtering

PTOLEMY: Transverse drift filter









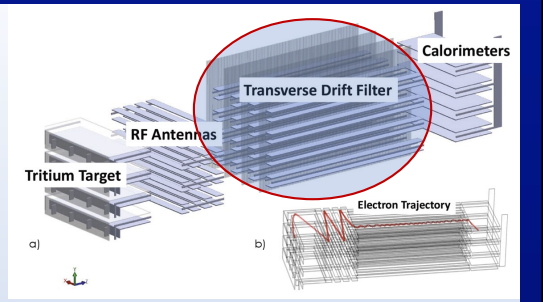
After filter, only component of β parallel to B is left.

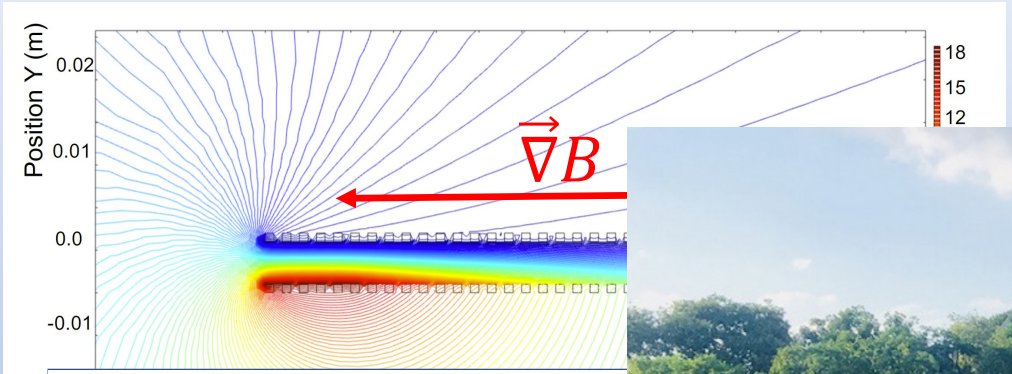
Can be reduced by retarding potential

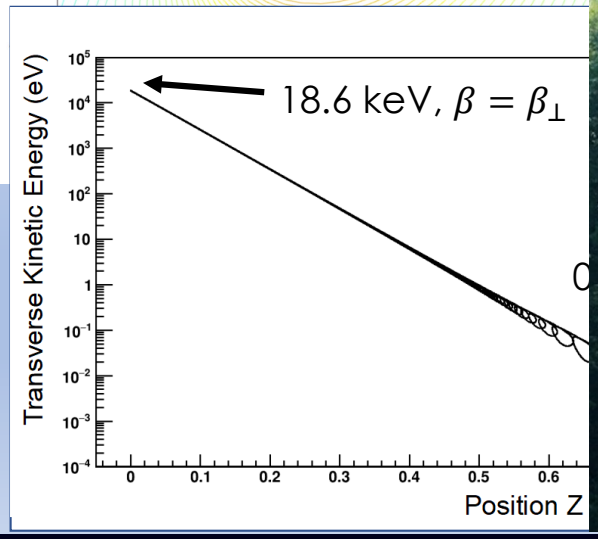
Important Properties for Calorimeter Stage:
Low magnet field, Small Area

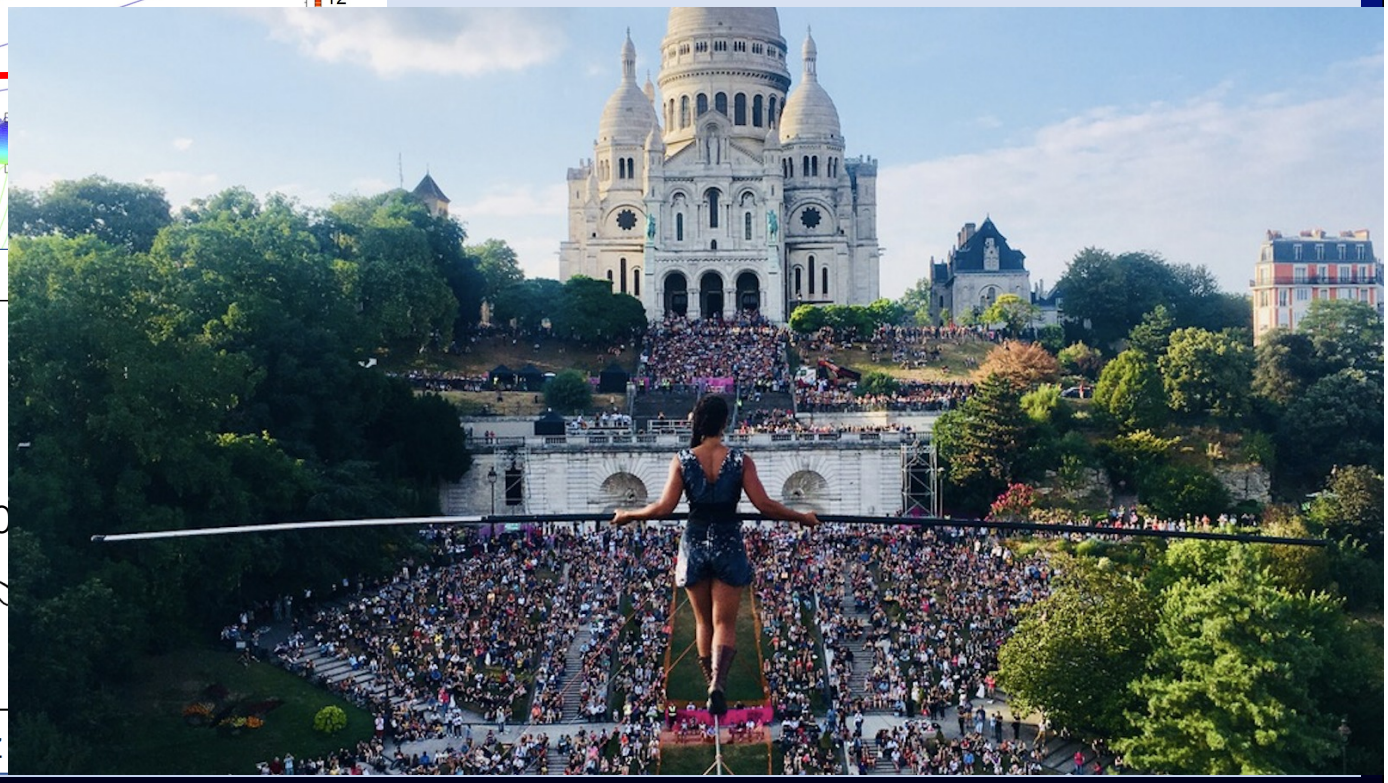
Transverse Filtering

PTOLEMY: Transverse drift filter





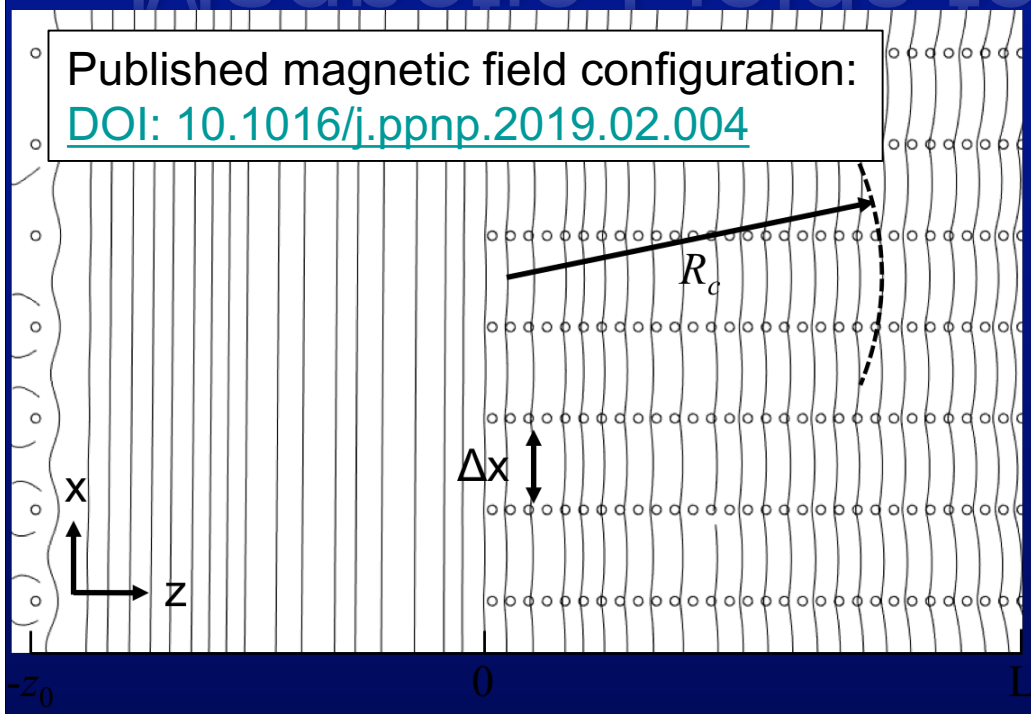


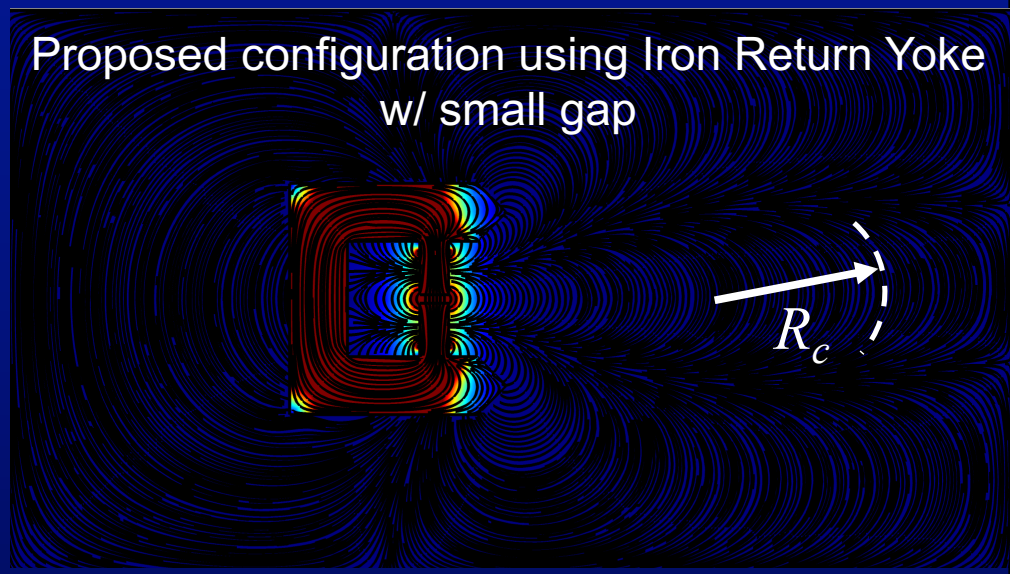


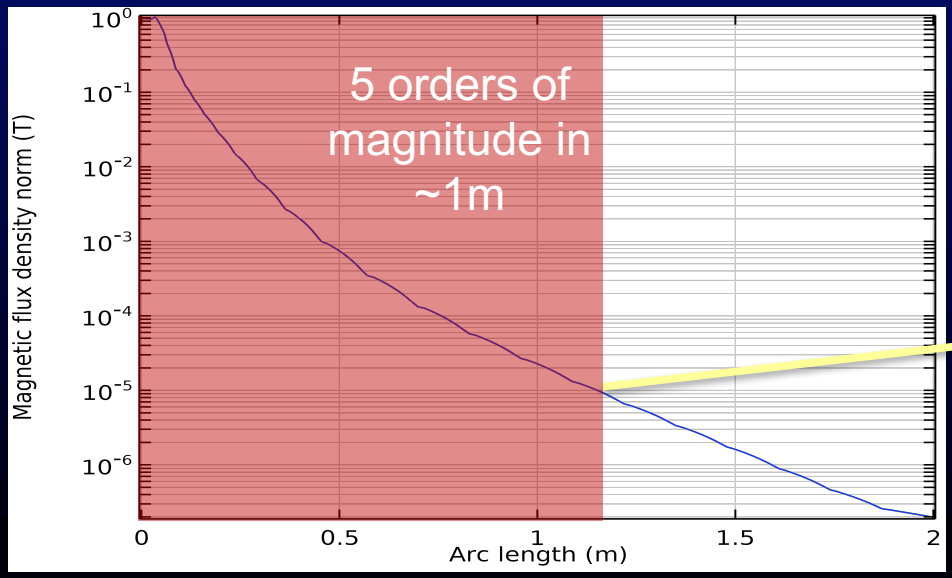
Important Properties for Calorimeter Stage:

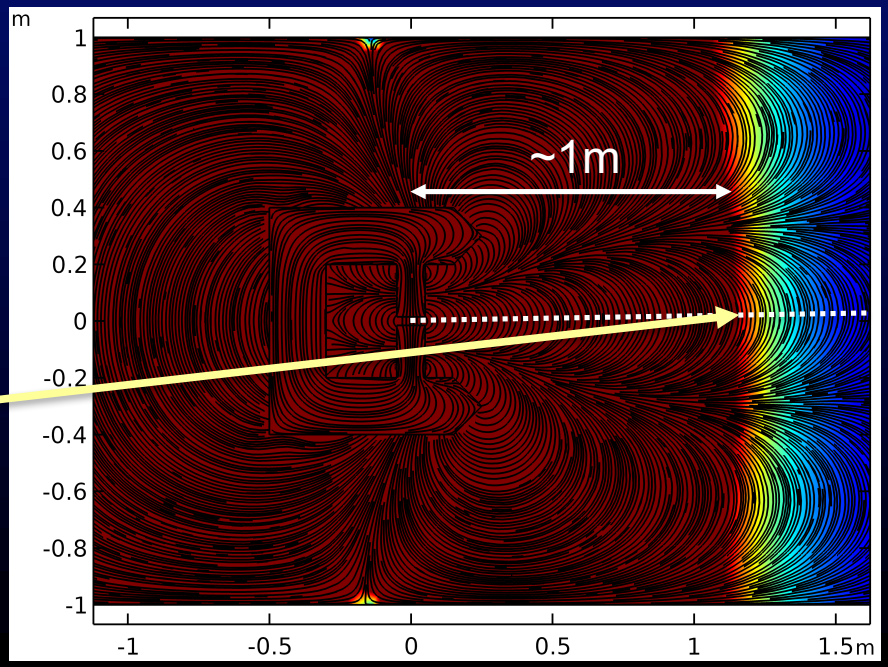
Low magnet field, Small Area

Magnetic Fields for Transverse Drift



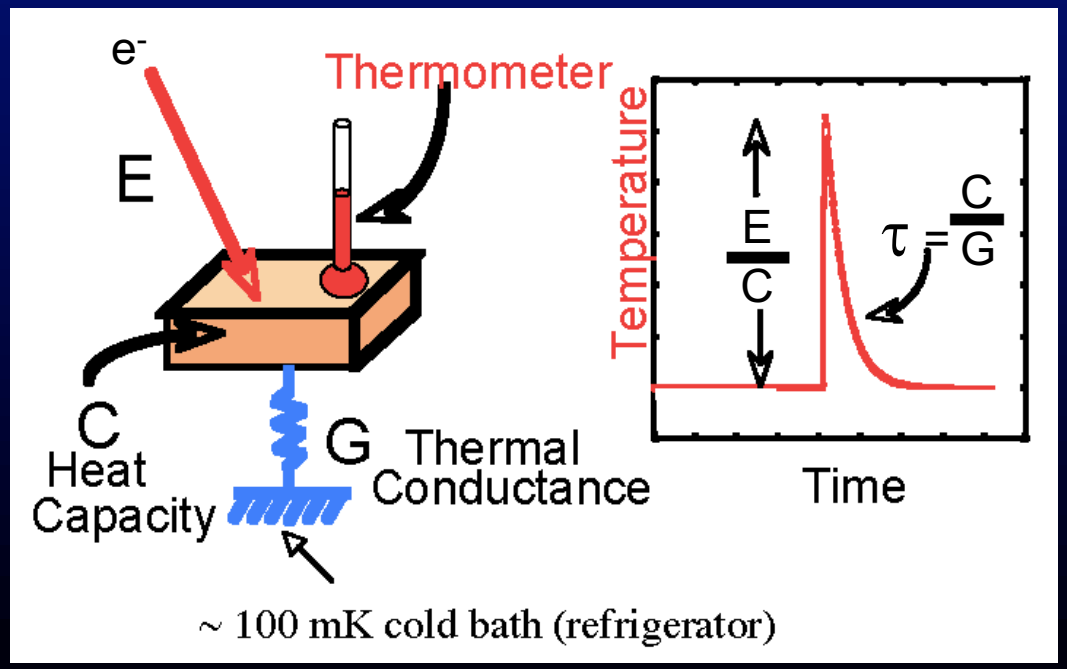






Cosmic Neutrino Telescope
Step 5: Eye Piece

- Choice: TES Microcalorimeter ~22meV resolution
- World-record resolution on IR photons
- ~10 nm of material to stop eV electrons



Thin sensors:
~1 eV electron can be stopped with very small C

Fast time response:
Time response (τ) also small (<μsec)

MicroCalorimeter R&D

$$E_e = e\left(V_{cal} - V_{target}\right) + E_{cal} + RF_{corr}$$

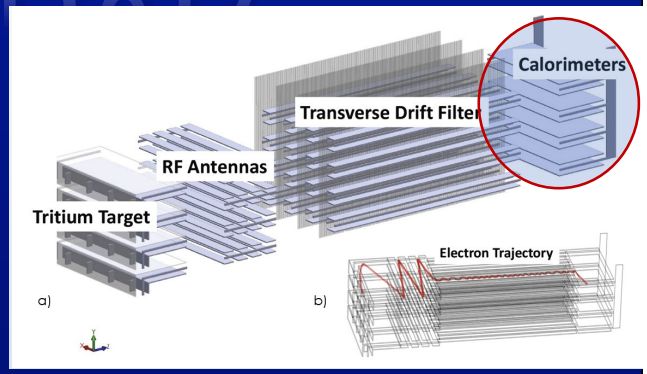
Now: 0.11 eV @ 0.8 eV and 106 mK and 10x10 μm^2
TiAuTi 90nm [Ti(45nm) Au(45nm)] (τ ~137 ns)

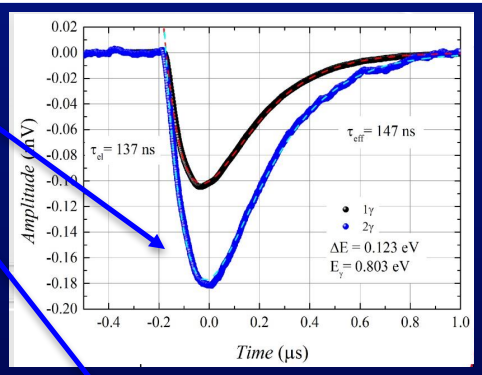
Design Goal (PTOLEMY): ΔE_{FWHM} = 0.05 eV @ 10 eV
translates to $\Delta E \propto E^{\alpha}$ $(\alpha \leq 1/3)$
ΔE_{FWHM} = 0.022 eV @ 0.8eV

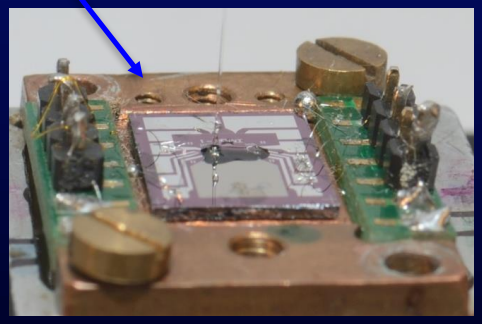
$$\Delta E_{FWHM} \approx 2.36 \sqrt{4 k_B T_c^2 \frac{C_e}{\propto} \sqrt{\frac{n}{2}}}$$

$\Delta E \propto T^{3/2}$ ⇨ T_c= 36 mK @10x10 μm^2 (t=90 nm)

⇨ T_c= 46 mK @10x10 μm^2 (t=45 nm)



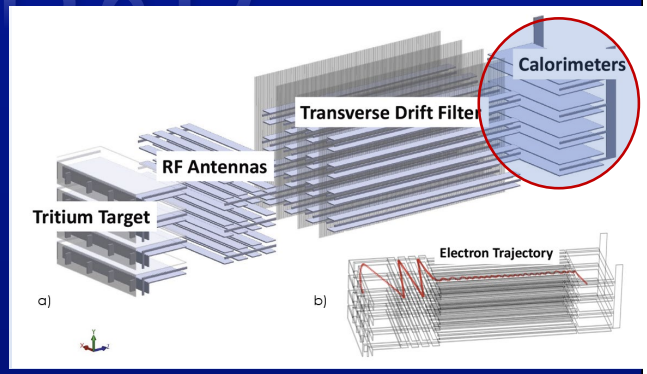


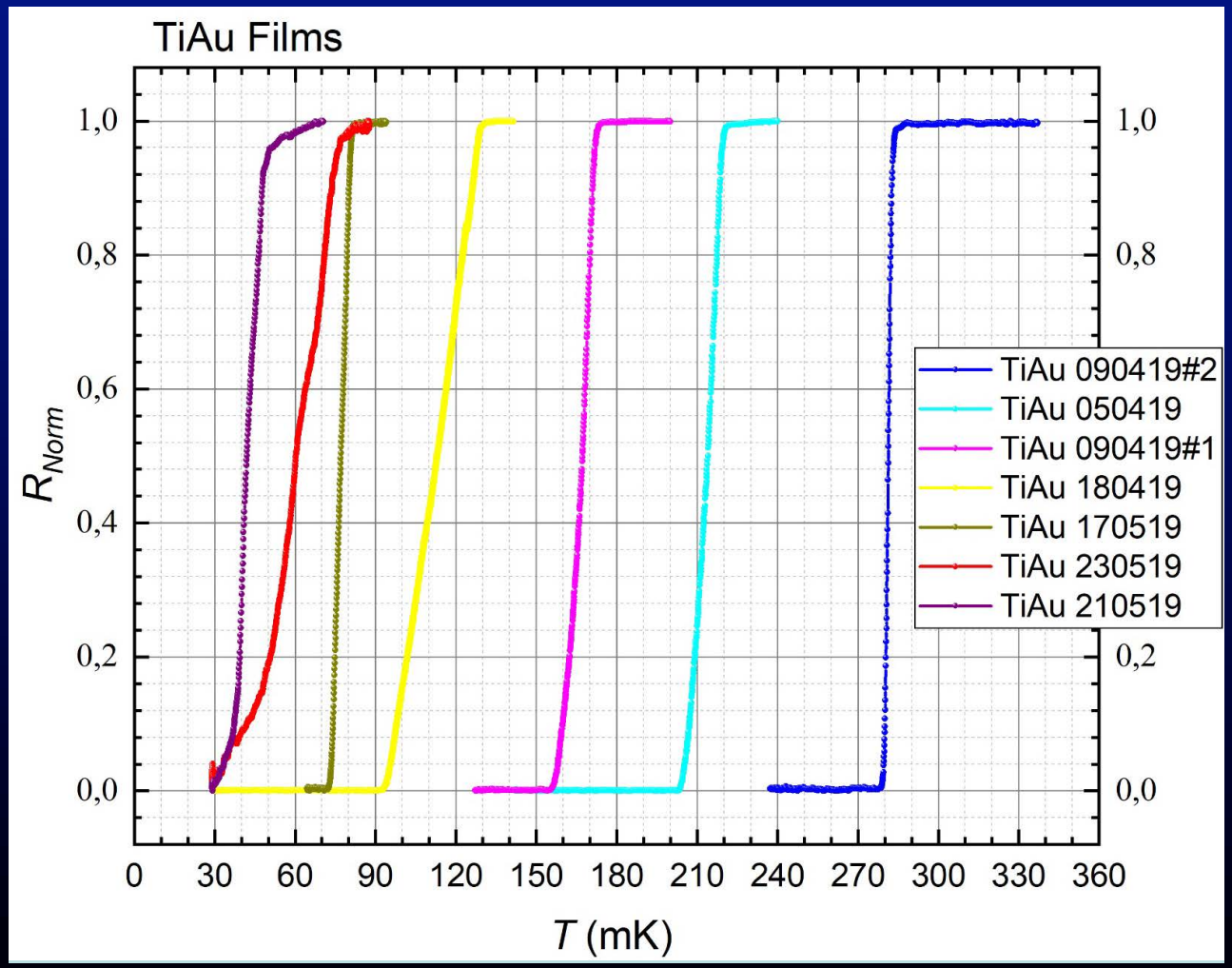


INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

MicroCalorimeter R&D

$$E_e = e\left(V_{cal} - V_{target}\right) + E_{cal} + RF_{corr}$$

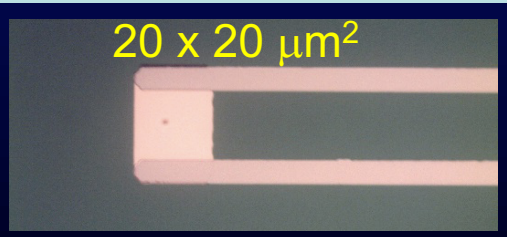




T_c=42 mK with:
Ti=11 nm and Au=27 nm

TiAu

Best solution in terms of heat capacity



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DI RICERCA METROLOGICA

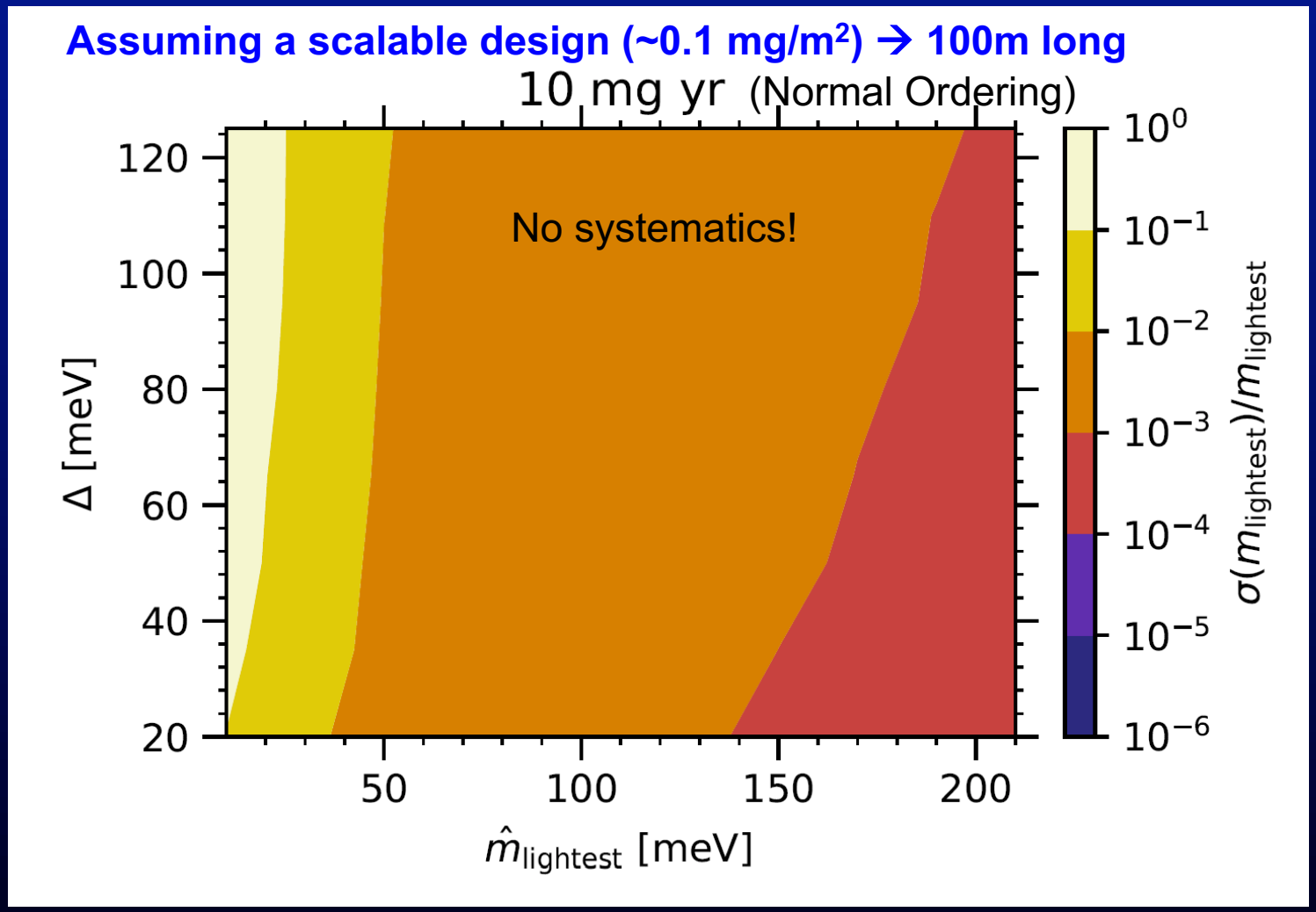
Recent Publications
[PTOLEMY COLLABORATION]

Experiment Design:
A design for an electromagnetic filter for precision energy measurements at the tritium endpoint, M.G. Betti et al., Prog.Part.Nucl.Phys. **106** (2019) 120-131, DOI: 10.1016/j.ppnp.2019.02.004, e-Print: arXiv:1810.06703

Physics Program (CNB, Mass, Sterile,..):
Neutrino physics with the PTOLEMY project, M.G. Betti et al., JCAP **07** (2019) 047,DOI: 10.1088/1475-7516/2019/07/047
e-Print: arXiv:1902.05508

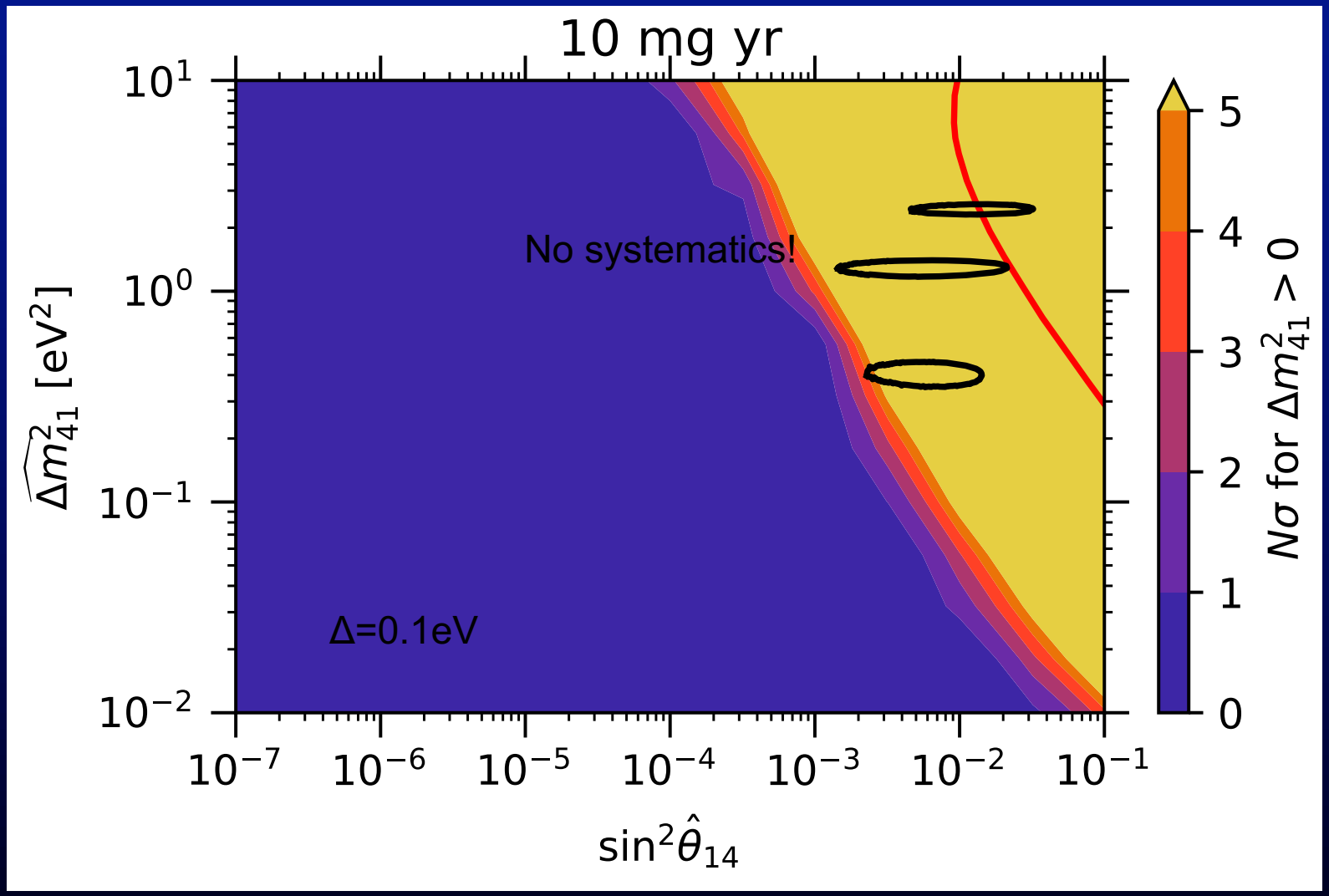
http://ptolemy.lngs.infn.it

Neutrino Mass Sensitivity



Neutrino physics with the PTOLEMY project,
M.G. Betti et al., JCAP **07** (2019) 047 DOI: 10.1088/1475-7516/2019/07/047
e-Print: arXiv:1902.05508

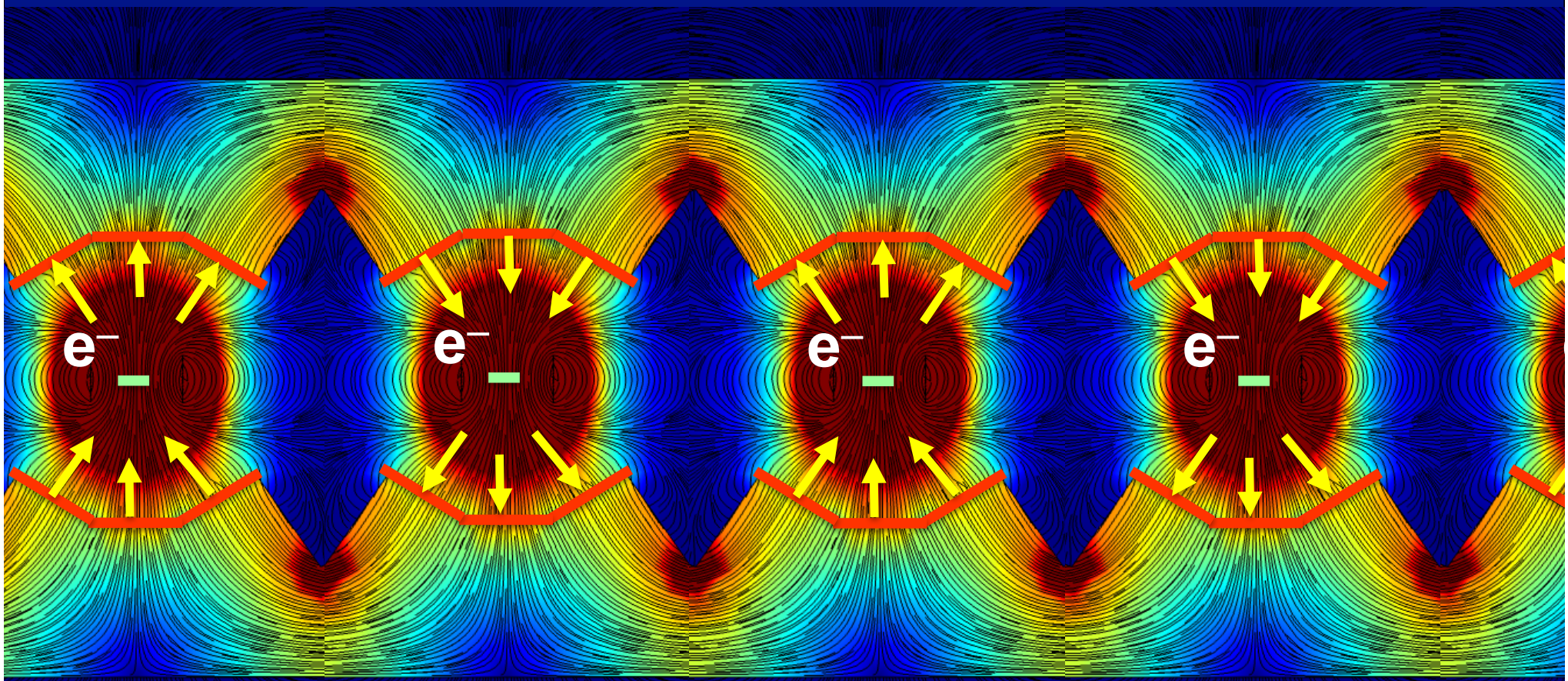
3+1 Sterile Sensitivity



Neutrino physics with the PTOLEMY project,
M.G. Betti et al., JCAP **07** (2019) 047 DOI: 10.1088/1475-7516/2019/07/047
e-Print: arXiv:1902.05508

Linearly Repeating Geometry

suitable for underground tunnel

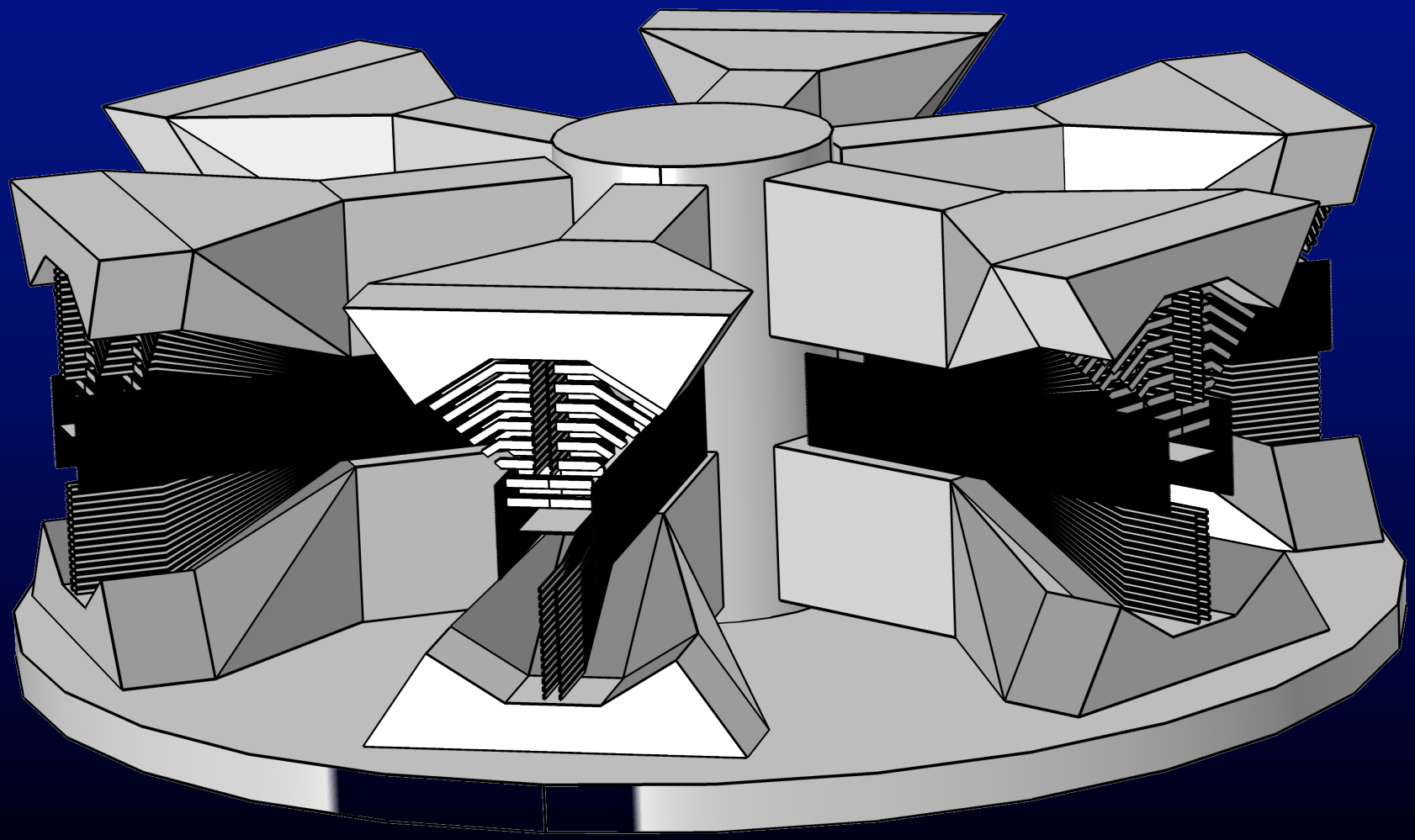


Repeated to reach 10mg → ~100 meters

OR…

Circular Geometry

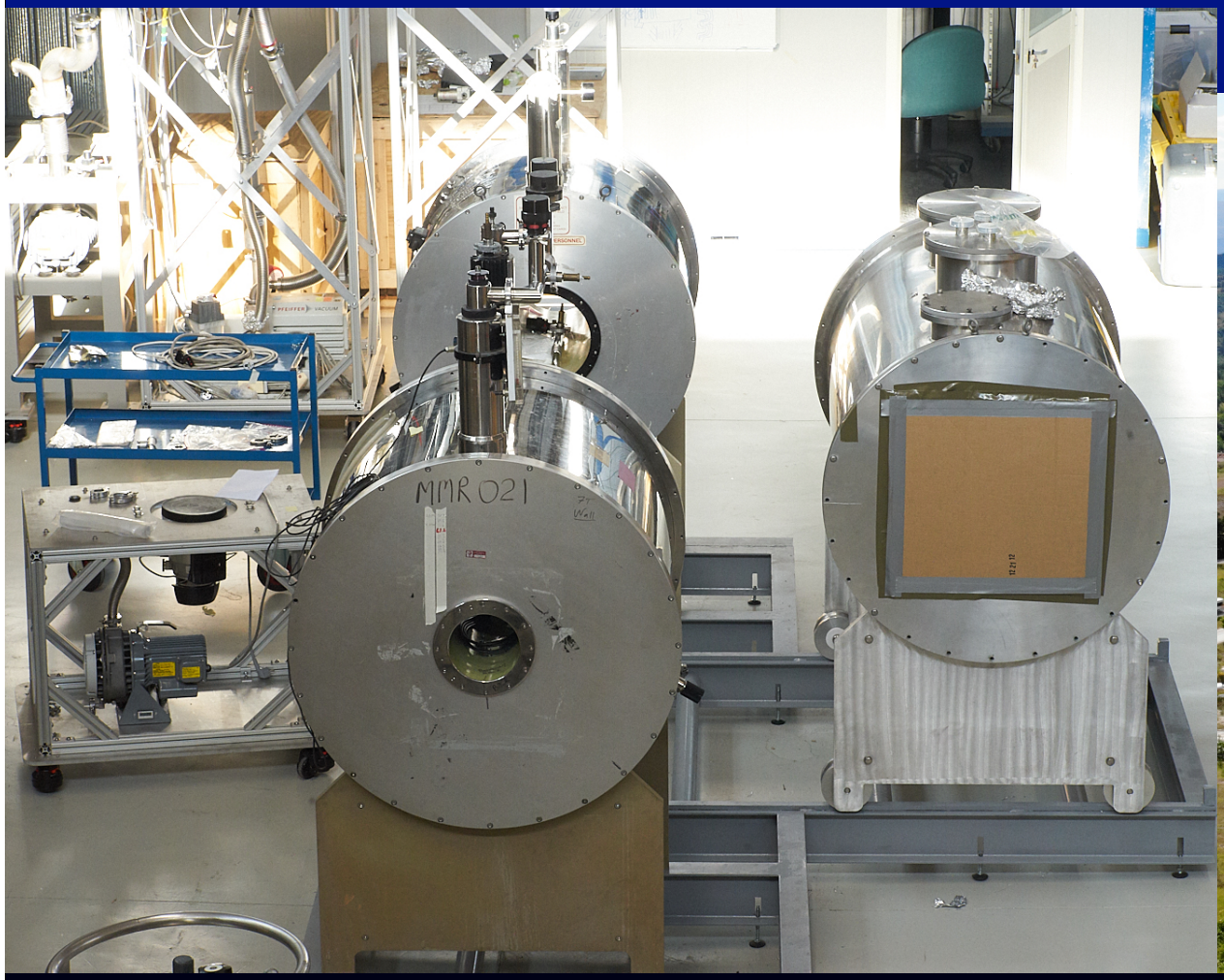
w/ microcalorimeter at center



PTOLEMY R&D at LNGS

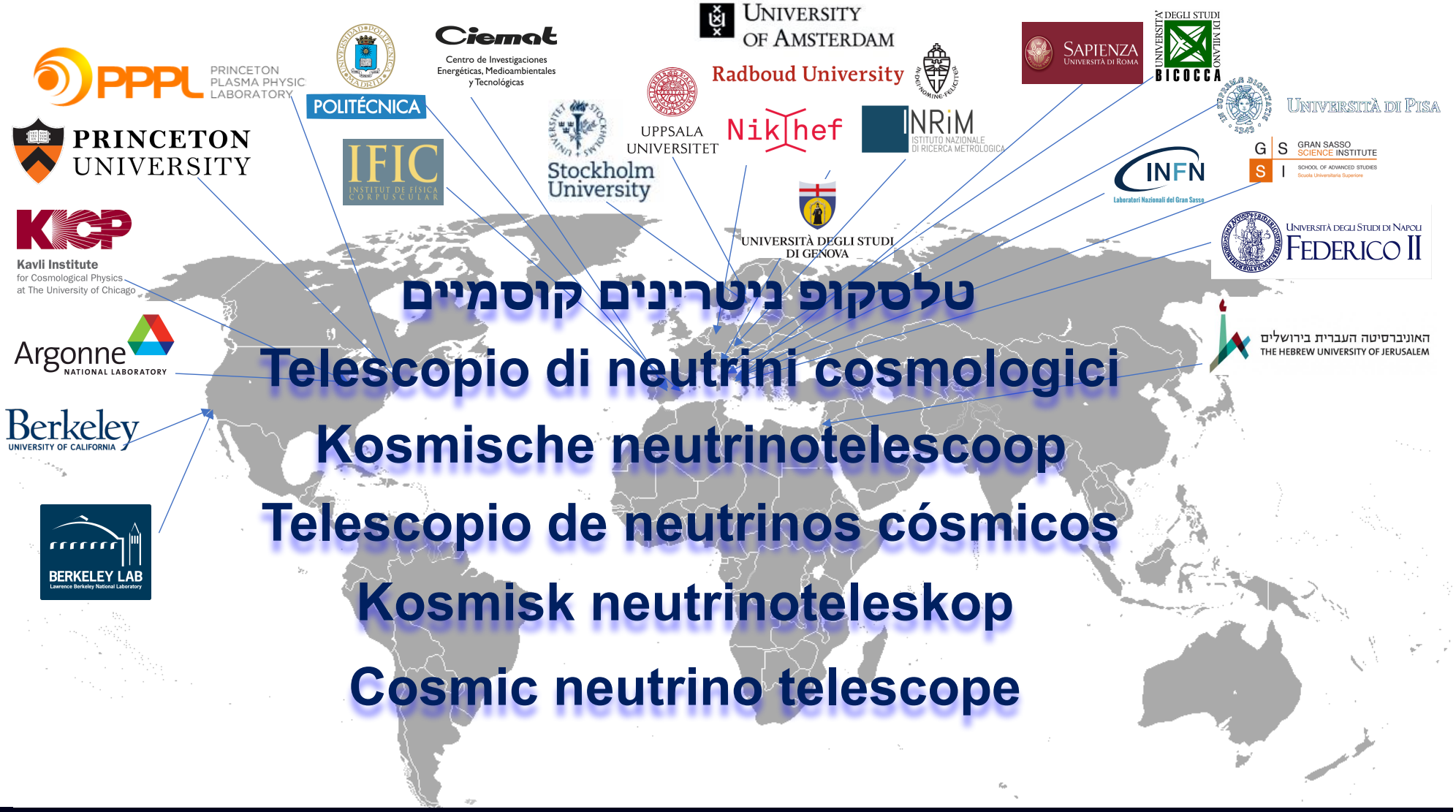
PonTecorvo Observatory for Light, Early-universe, Massive-neutrino Yield

Small but intense R&D effort hosted at the Gran Sasso National Laboratory in Italy



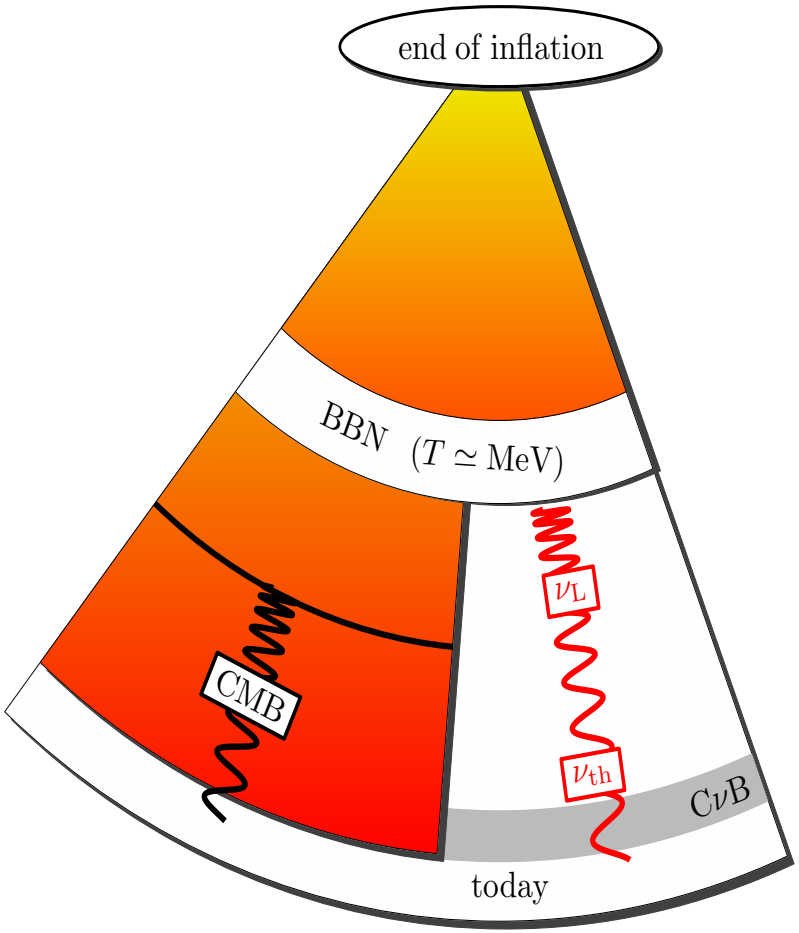
Exploring possible future sites that can host telescope operation with a 10mg tritium target

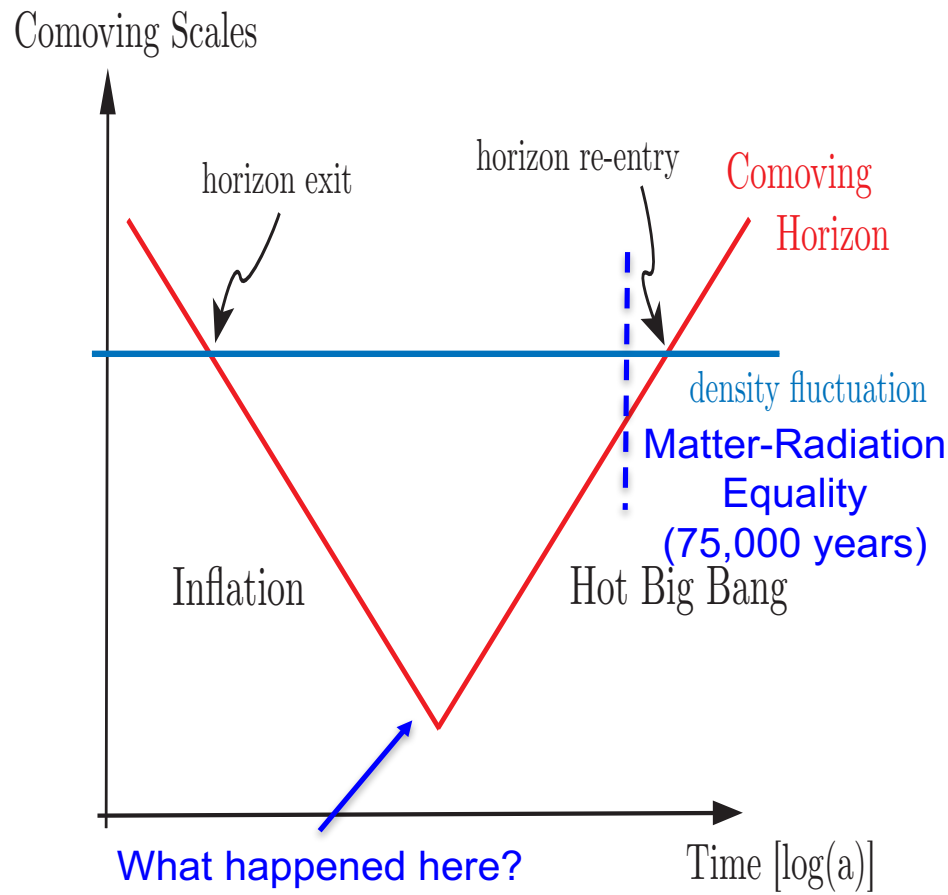
PTOLEMY World-Wide Collaboration



2015 Targeted Grant Award from the SIMONS FOUNDATION

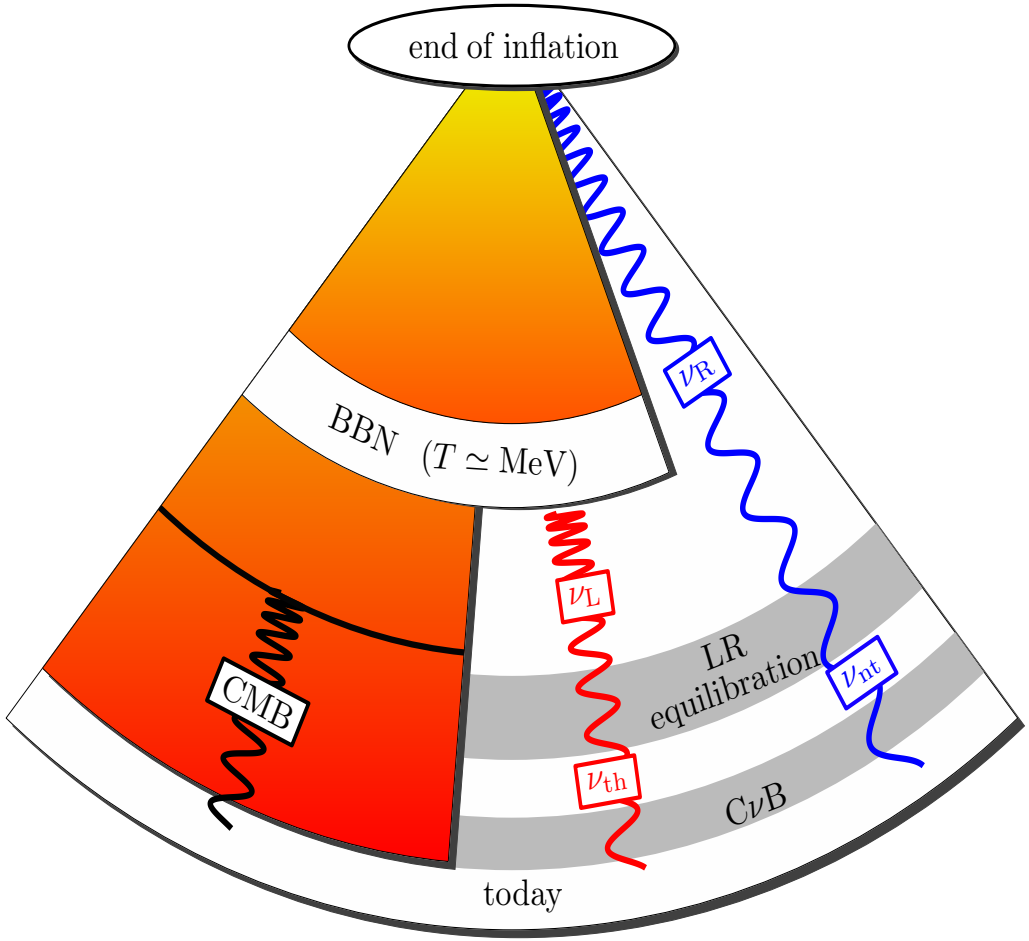
Inflation → Hot Big Bang

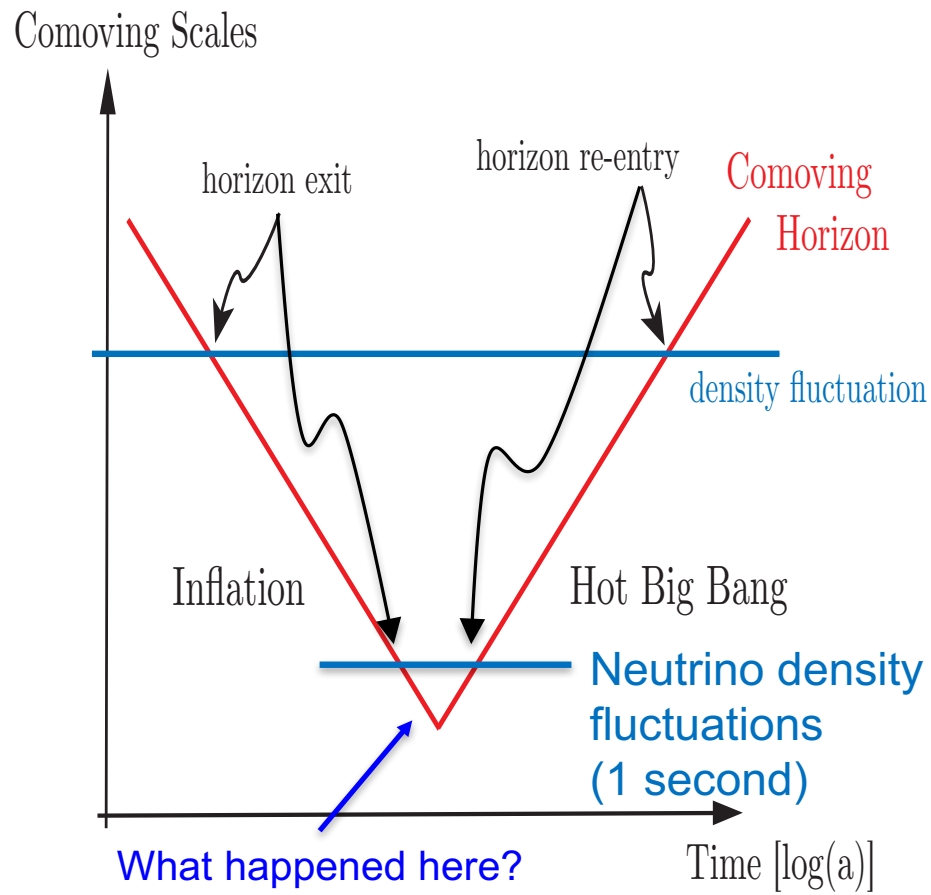




Baumann (TASI 2012)

Inflation → Hot Big Bang

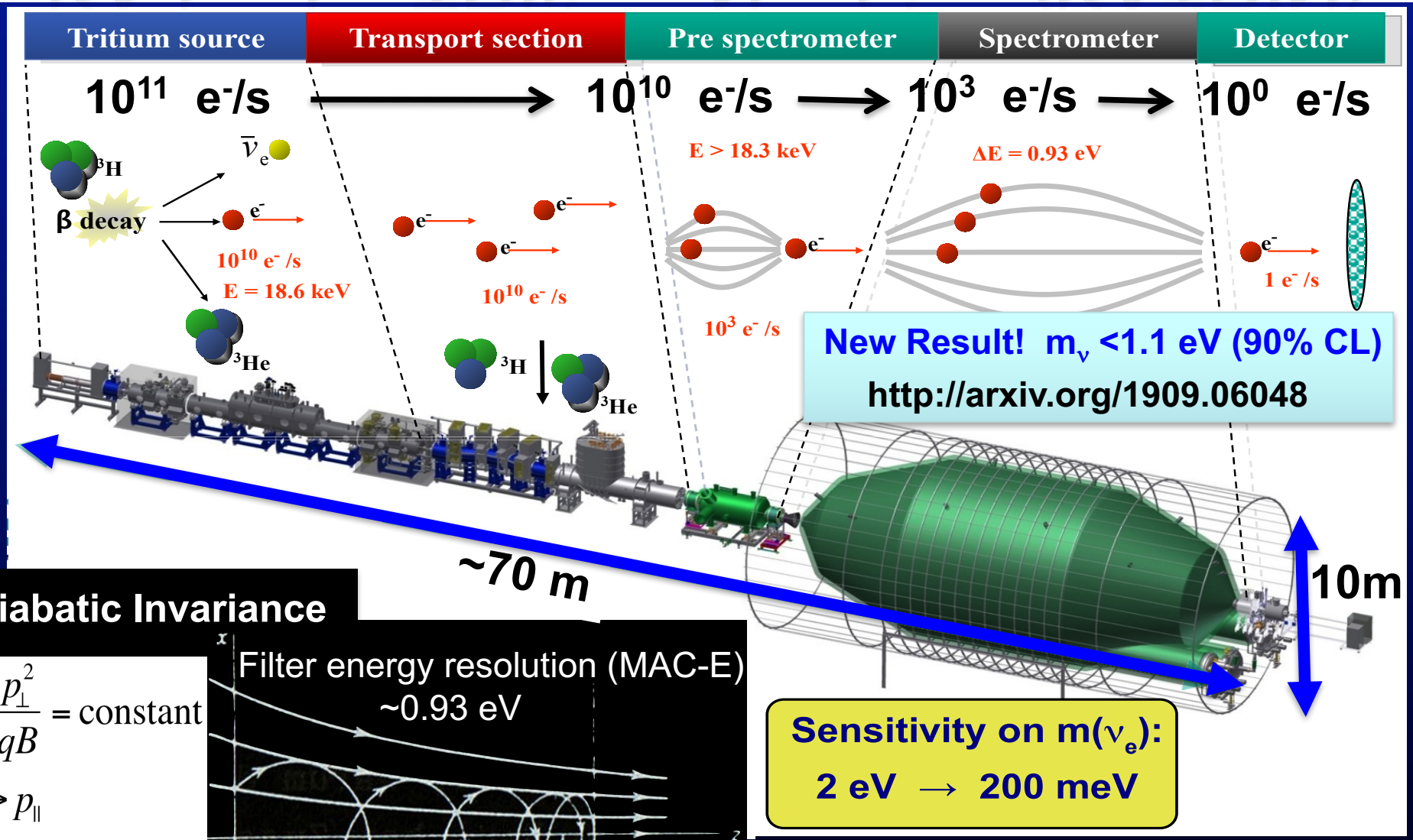




Ratz
(Erice 2017)

Additional Slides

KArlsruhe TRItium Neutrino (KATRIN)



New Result! m_ν <1.1 eV (90% CL)

http://arxiv.org/1909.06048

Sensitivity on $m(\nu_e)$:

2 eV → 200 meV

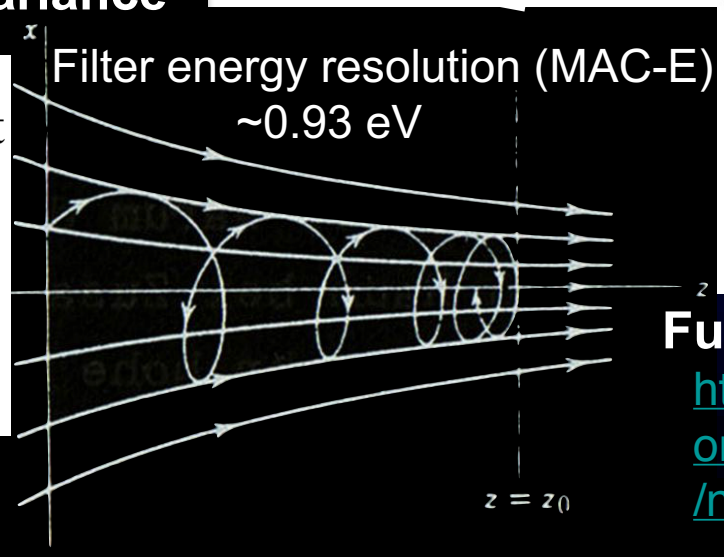
Adiabatic Invariance

$$\mu = \frac{p_\perp^2}{qB} = \text{constant}$$

$$p_\perp \rightarrow p_\parallel$$

Filter (E - Field)

$$p_\parallel \rightarrow p_\perp$$



Future of Neutrino Mass Measurements:

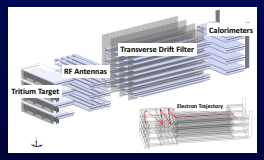
https://indico.cern.ch/event/740296/contributions/3160751/attachments/1738496/2812624/neutrino_town_meeting_weinheimer.pdf

Difference in Scales

KATRIN

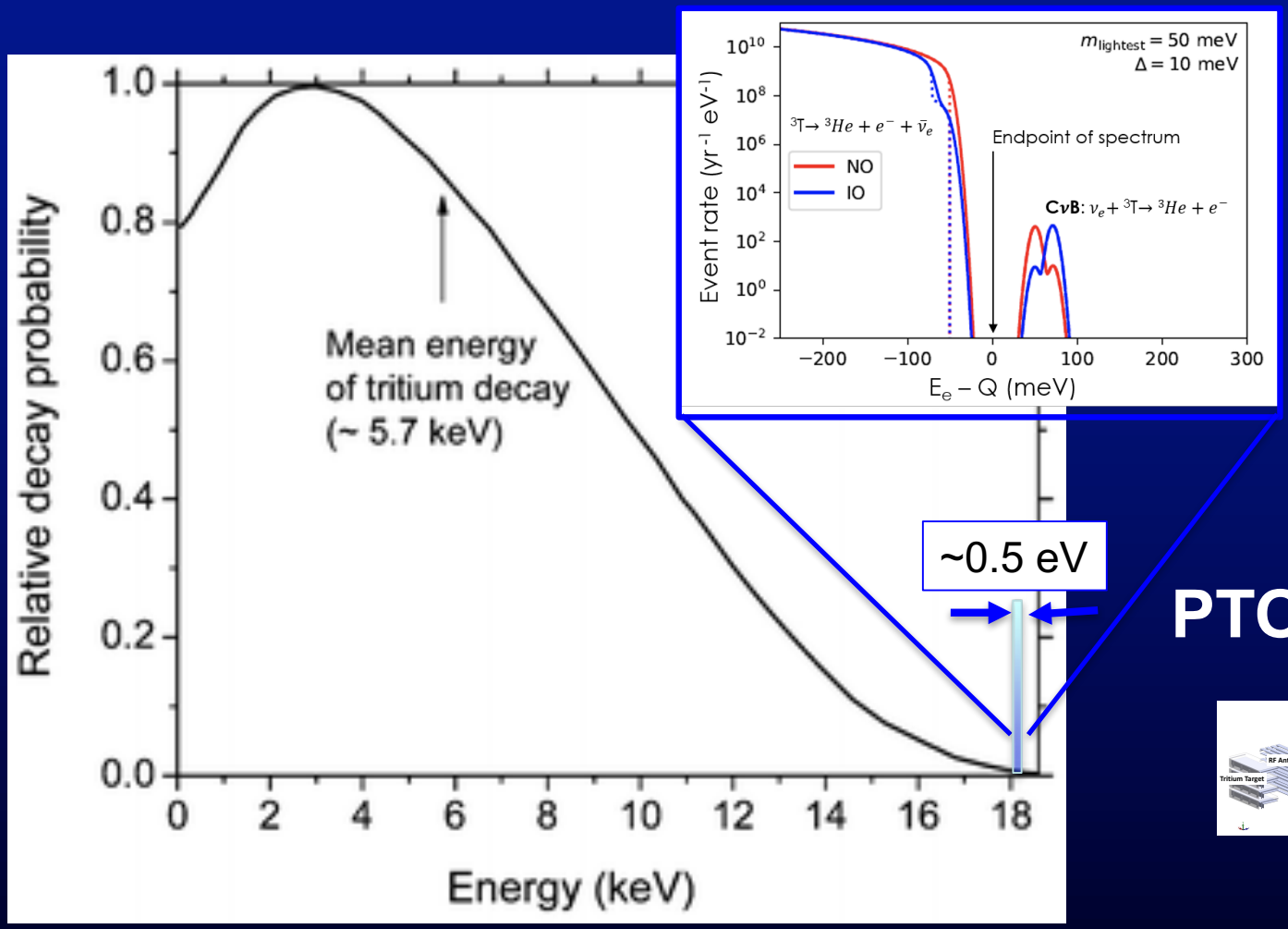
~1200m^3

PTOLEMY



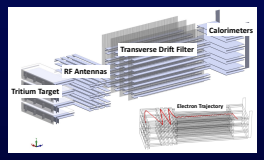
~1m^3

Difference in Scales



~0.5 eV

PTOLEMY



~1m^3

Stereo 27 GHz RF feeds

→ Digitally select endpoint electrons