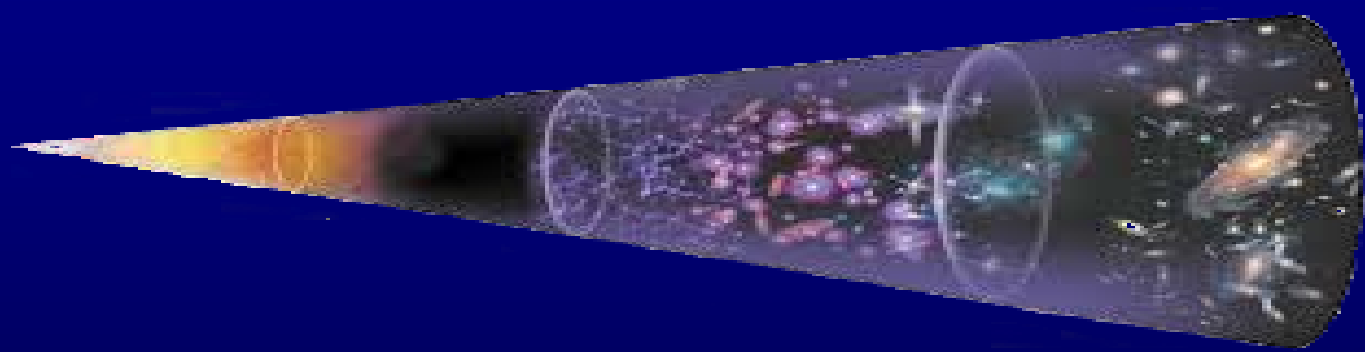
Towards the Construction of the First Cosmological Relic Neutrino Telescope with PTOLEMY



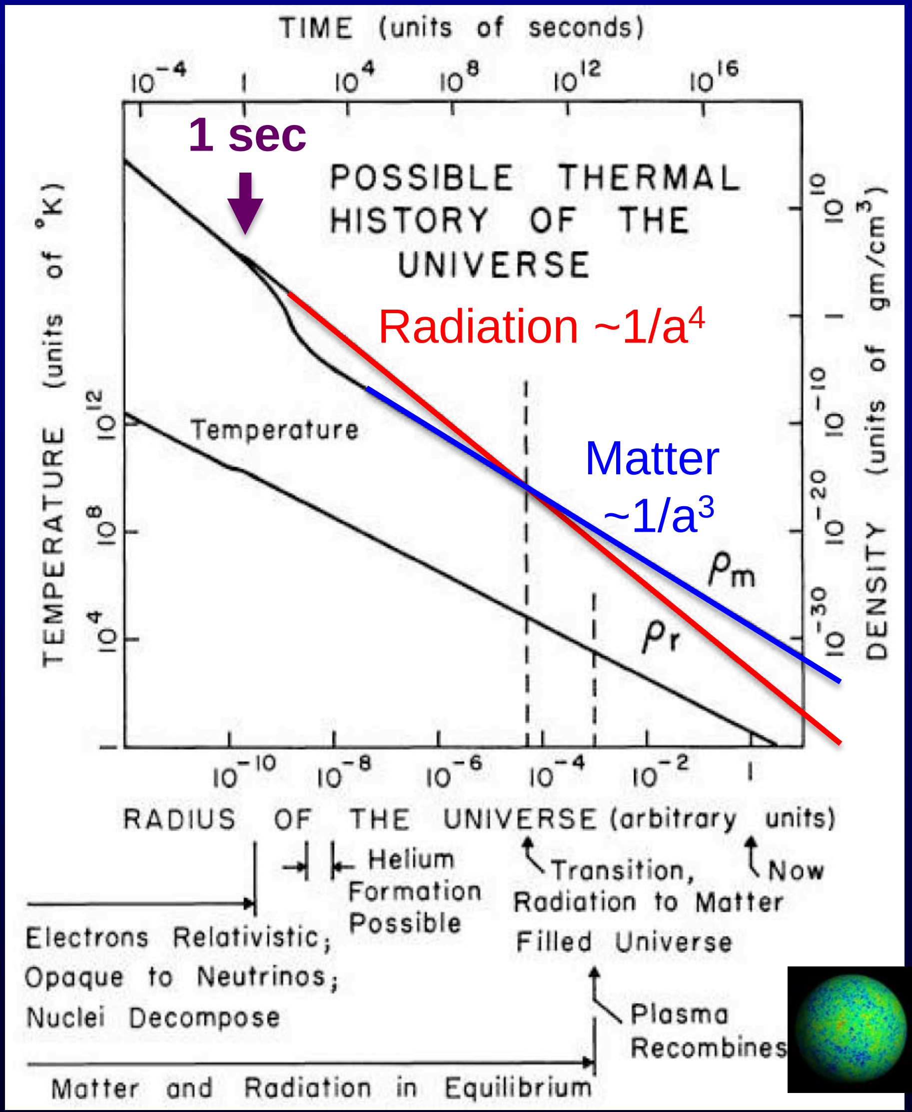
Chris Tully

Princeton University

INFN, NAPLES, 23 OCTOBER 2019

2015 Targeted Grant Award from the SIMONS FOUNDATION

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

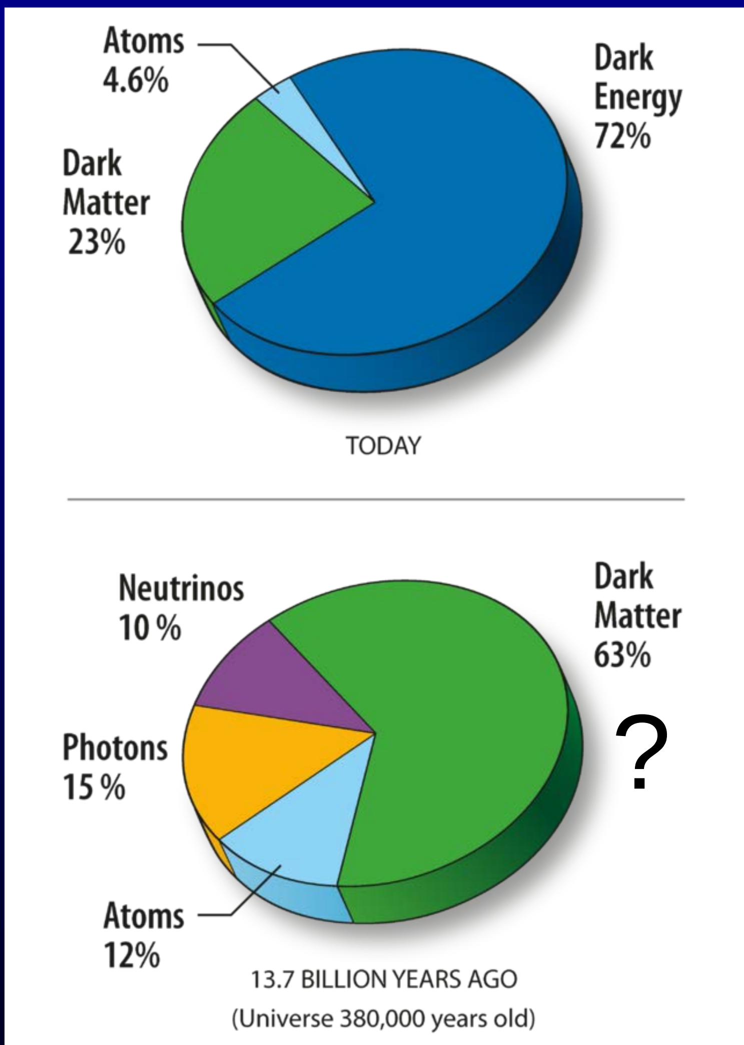
neutron/proton ratio @start of nucleosynthesis

Velocity distribution:

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

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

Early-Late Universe Evolution



Onset of a “constant” Dark Energy during the last doubling of the Universe is less certain

Tension between CMB determined Hubble Expansion (~x1100) and last ~15% are in 4-6σ disagreement and differ by ~9%

Massive neutrinos transition to non-relativistic during this time

CNB Today

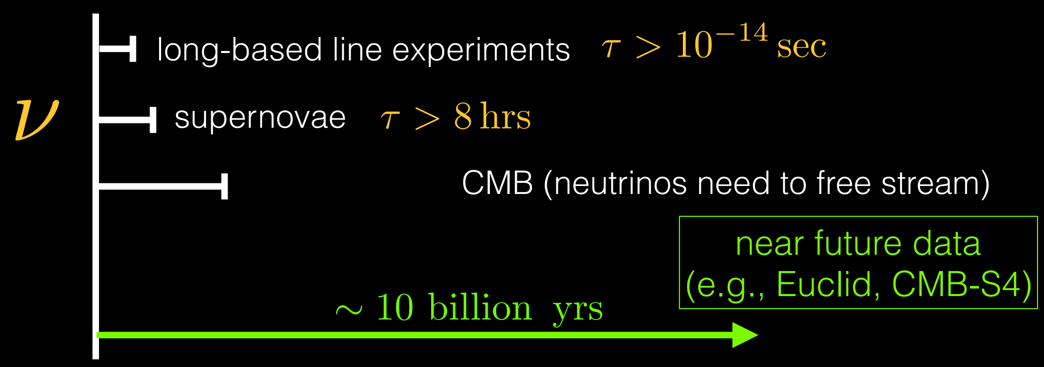
Large Scale Structure Signals of Neutrino Decay

Yuhsin Tsai

University of Maryland

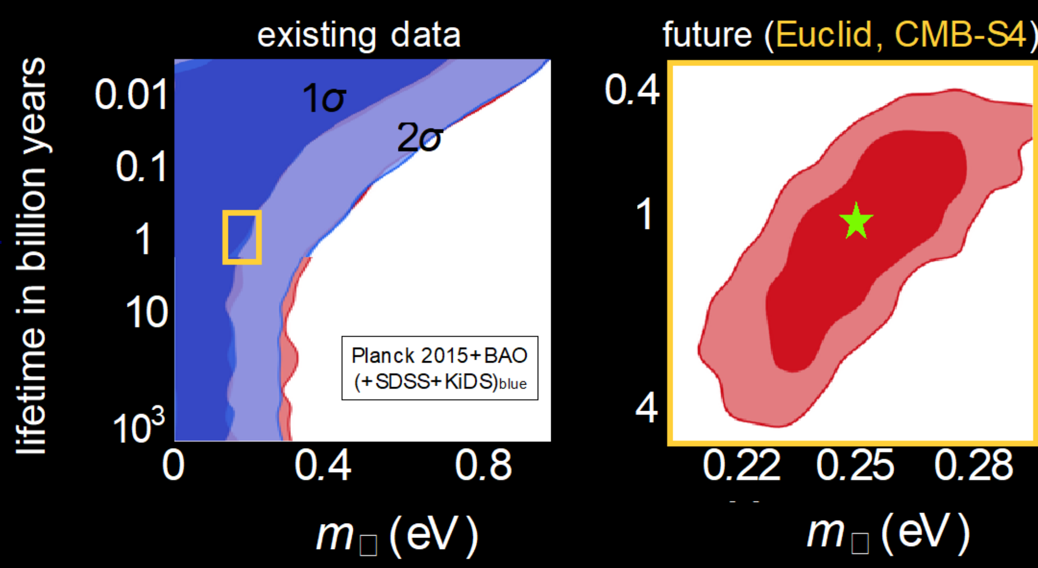
with Zackaria Chacko, Abhish Dev, Peizhi Du, Vivian Poulin

1909.05275, 19XX….



Measure neutrino mass & lifetime

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

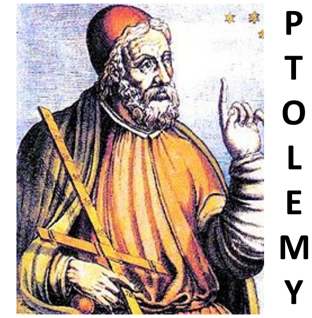


Something not expected??

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

PTOLEMY Cosmic Neutrino Telescope

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

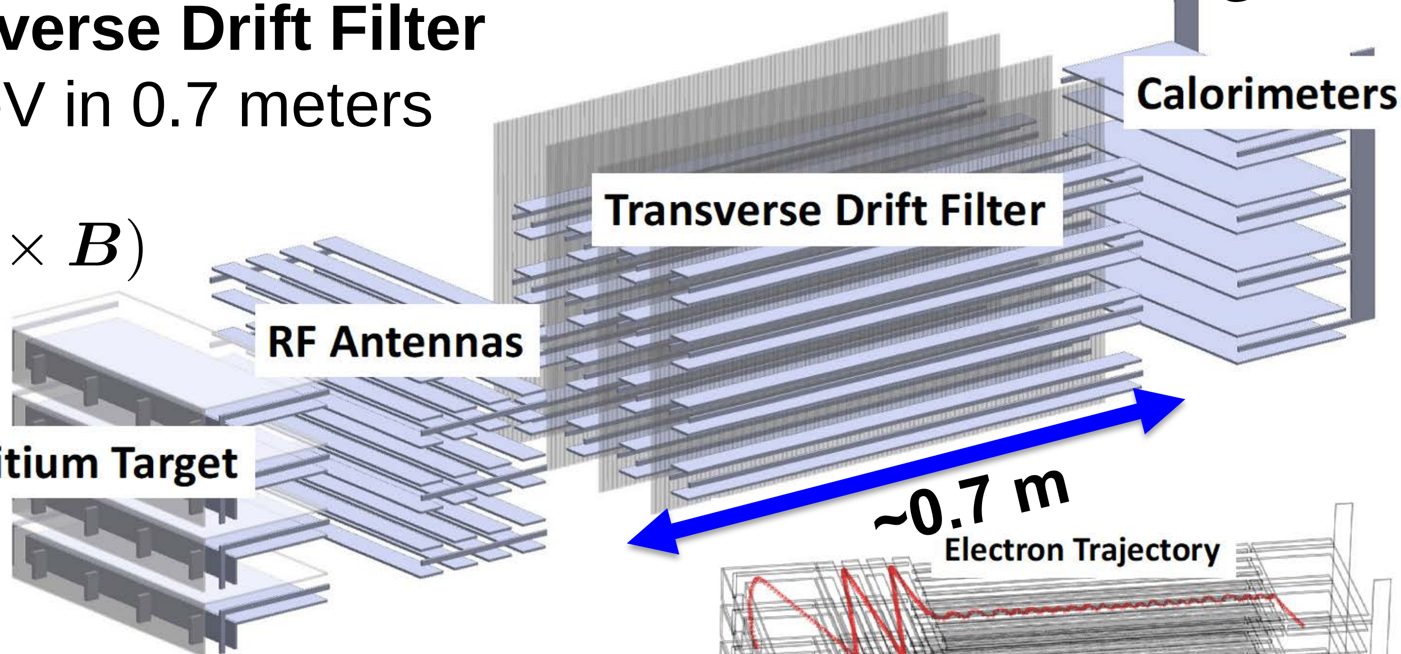


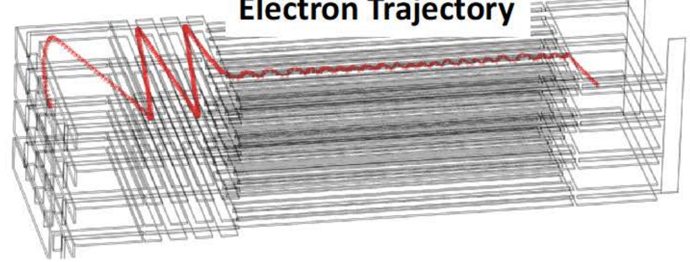
@LNGS

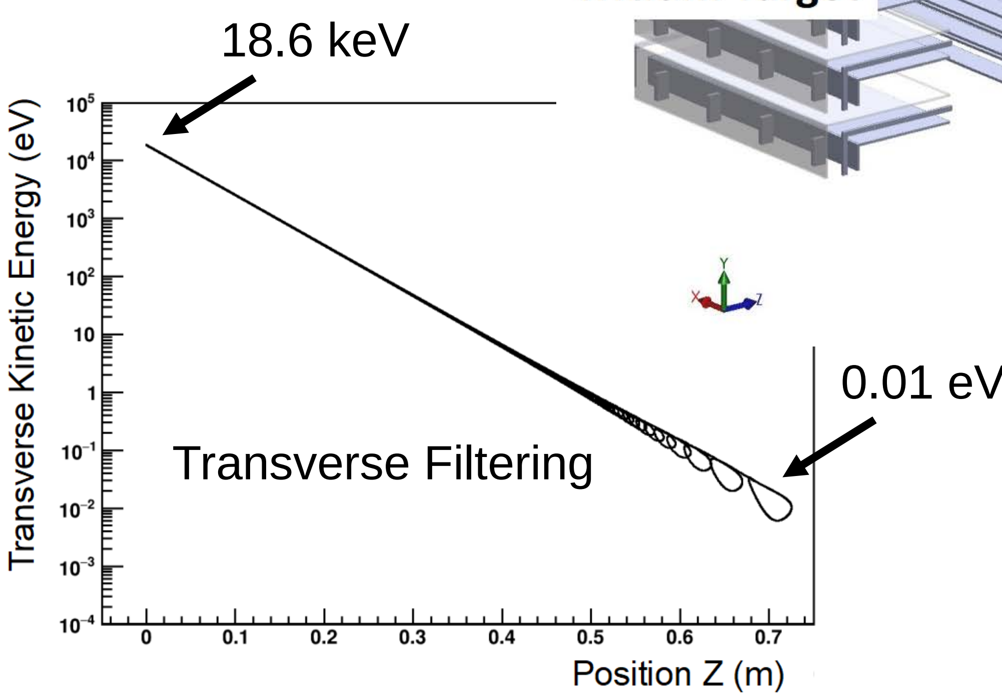
New Concept: **Transverse Drift Filter**

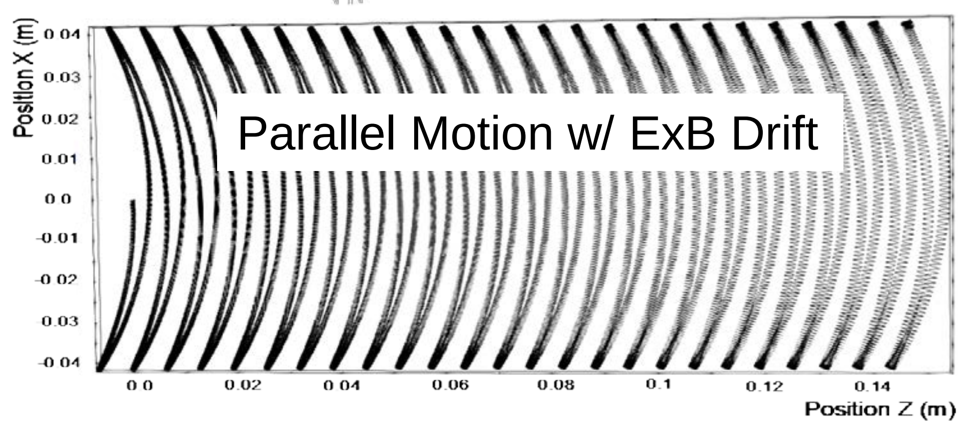
18.6 keV → 0.01 eV in 0.7 meters

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



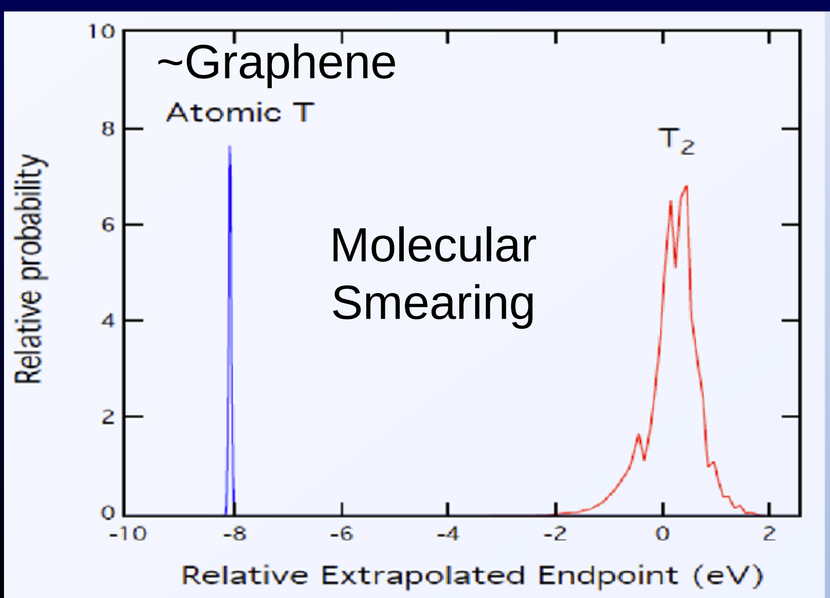


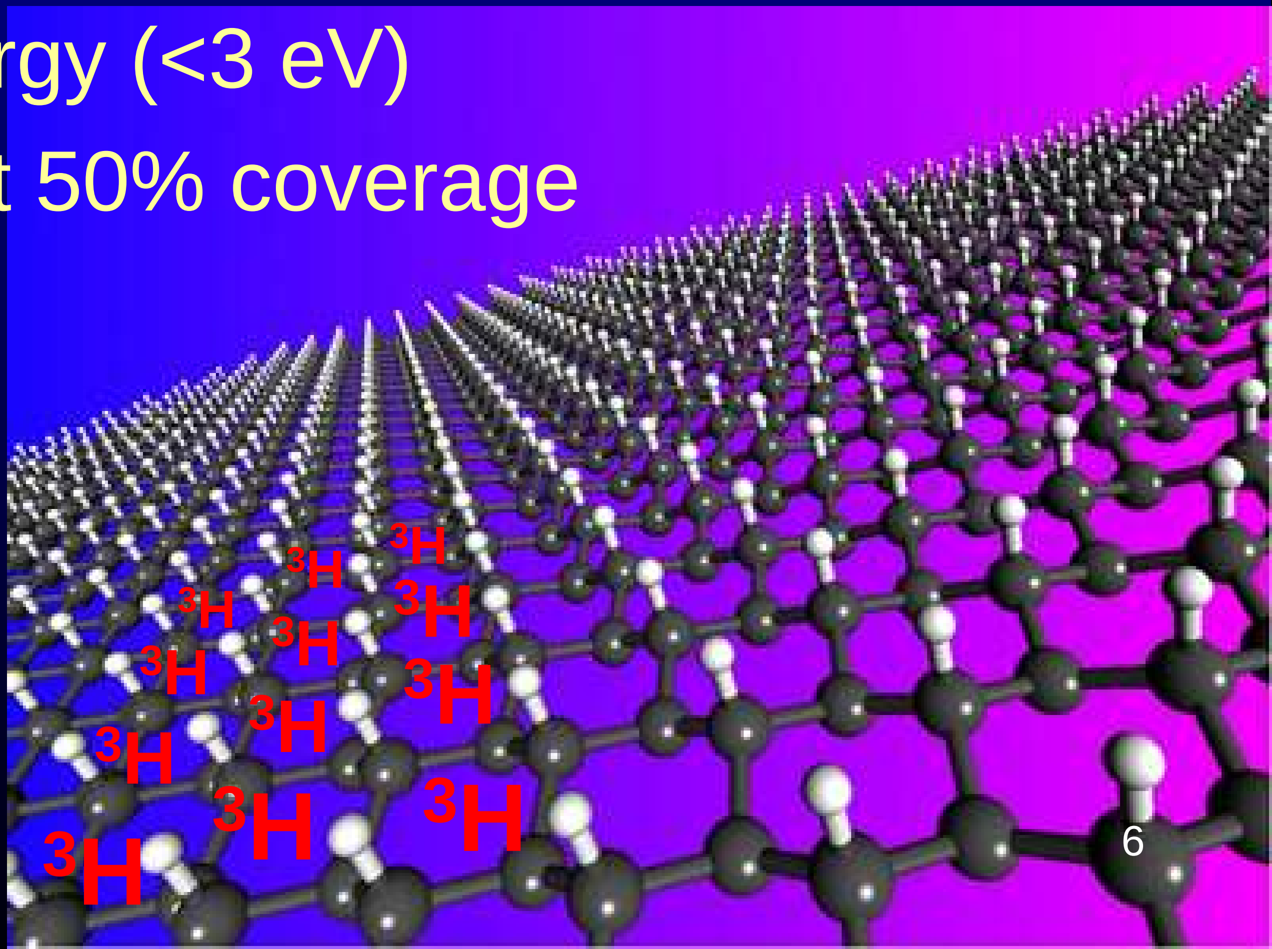




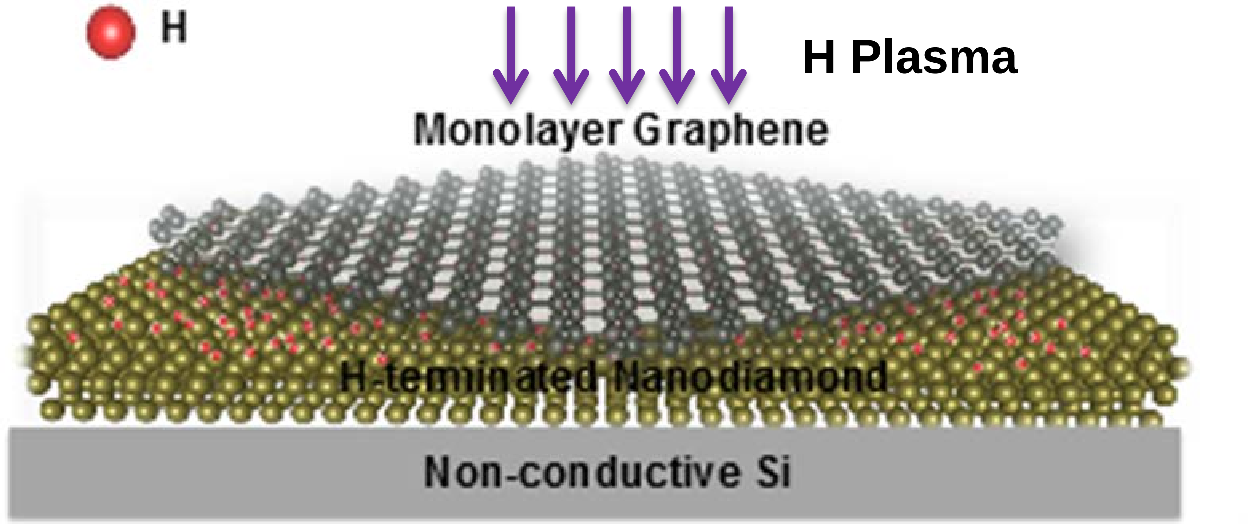
Cosmic Neutrino Telescope Step 1: Quality of Lens Surface

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

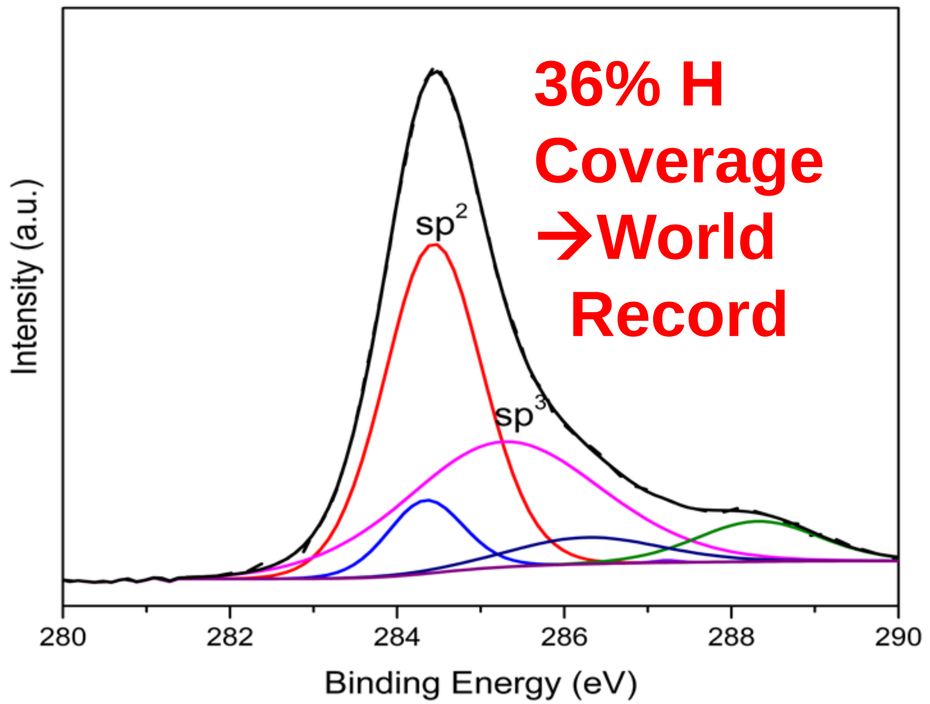


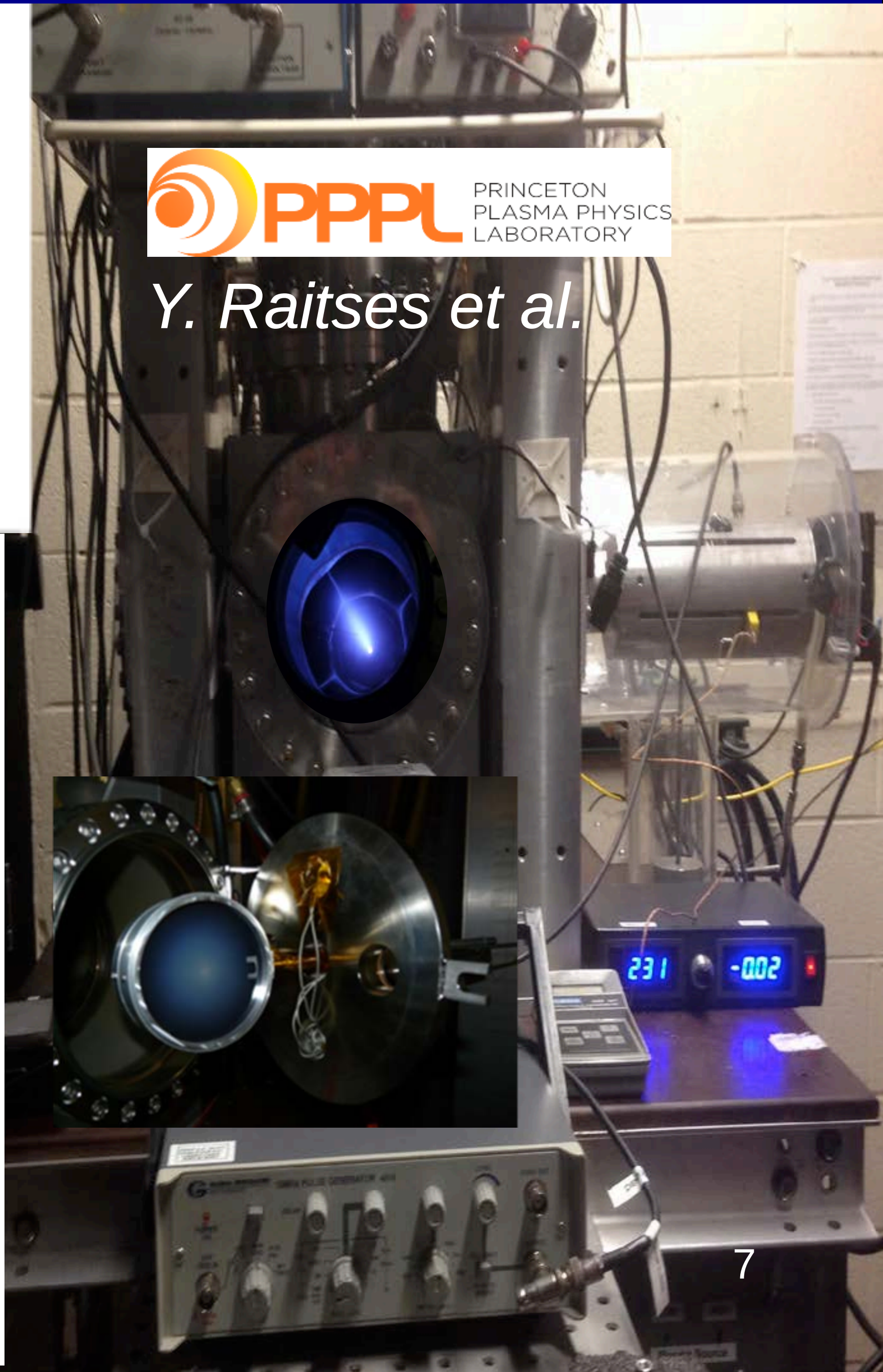


Cold Plasma Loading



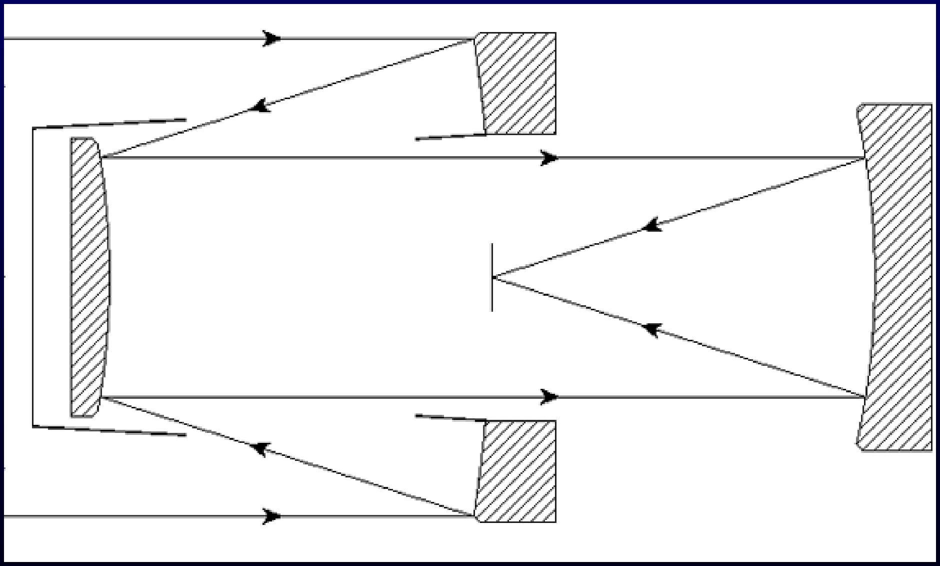
XPS Hydrogenation Results from Princeton

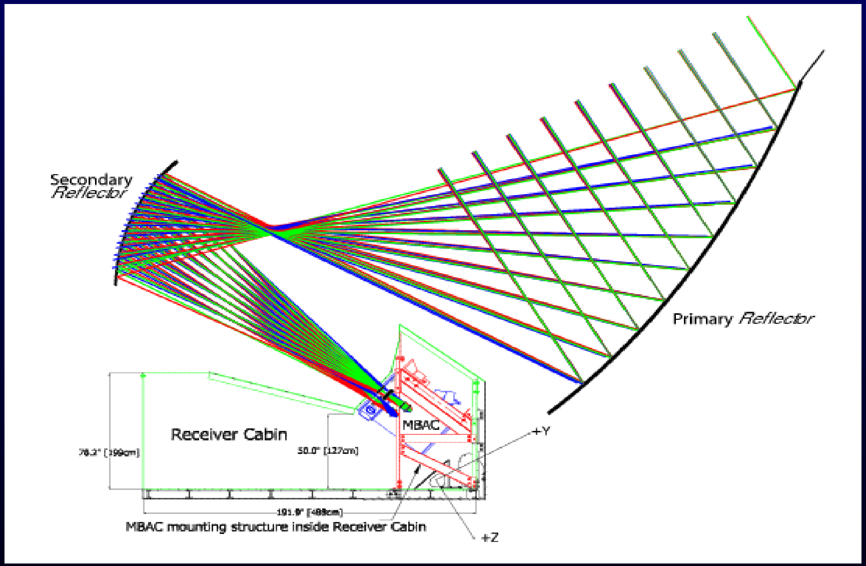




Cosmic Neutrino Telescope Step 2: Geometric Focus

- 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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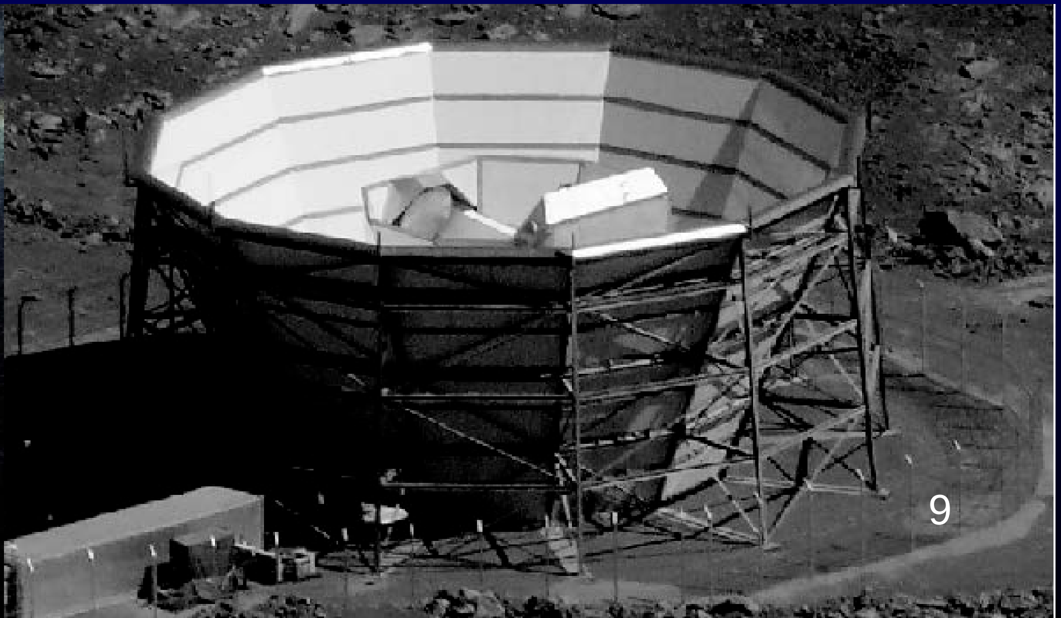
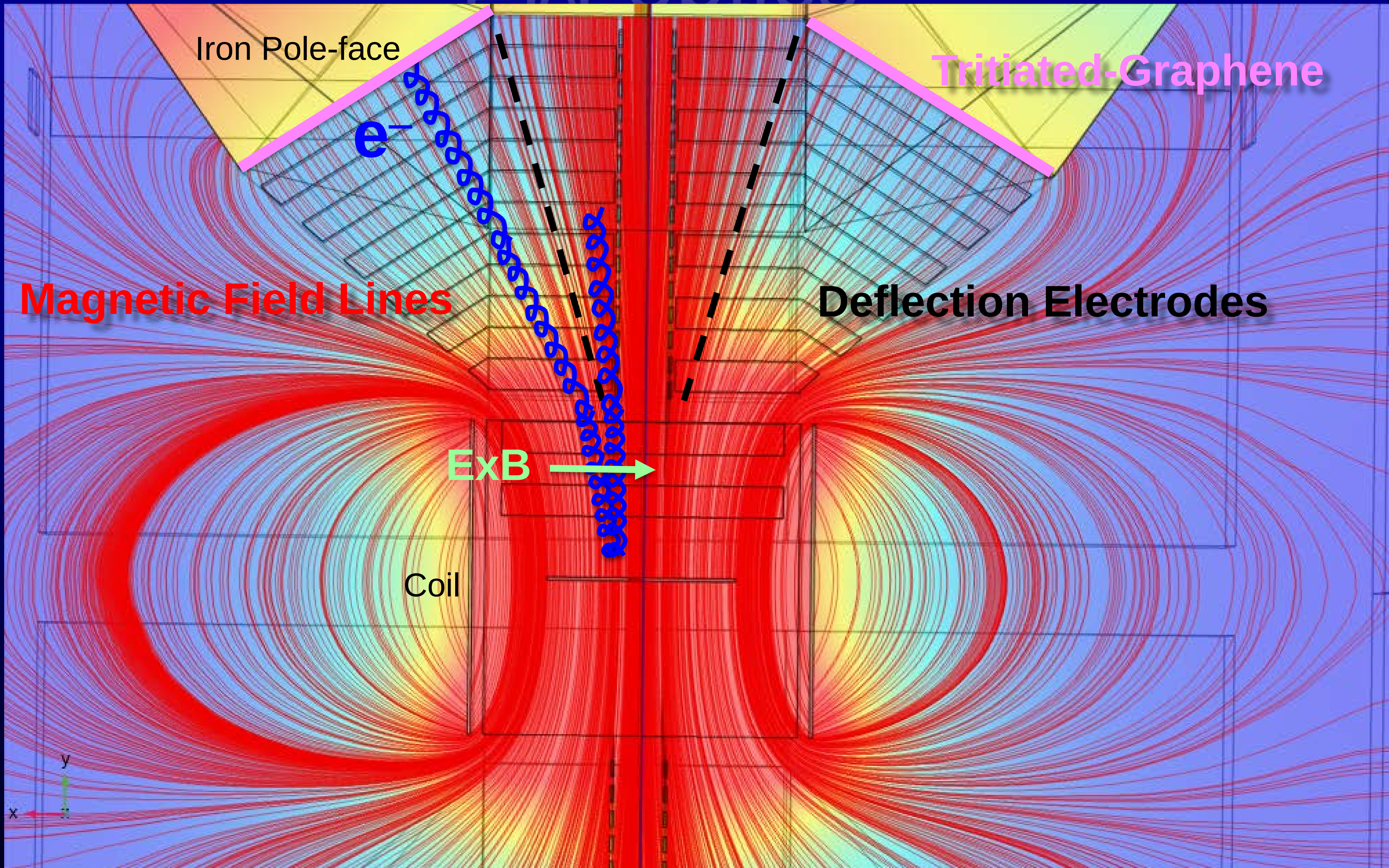
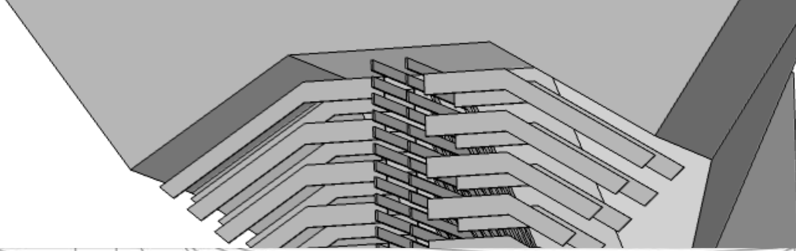


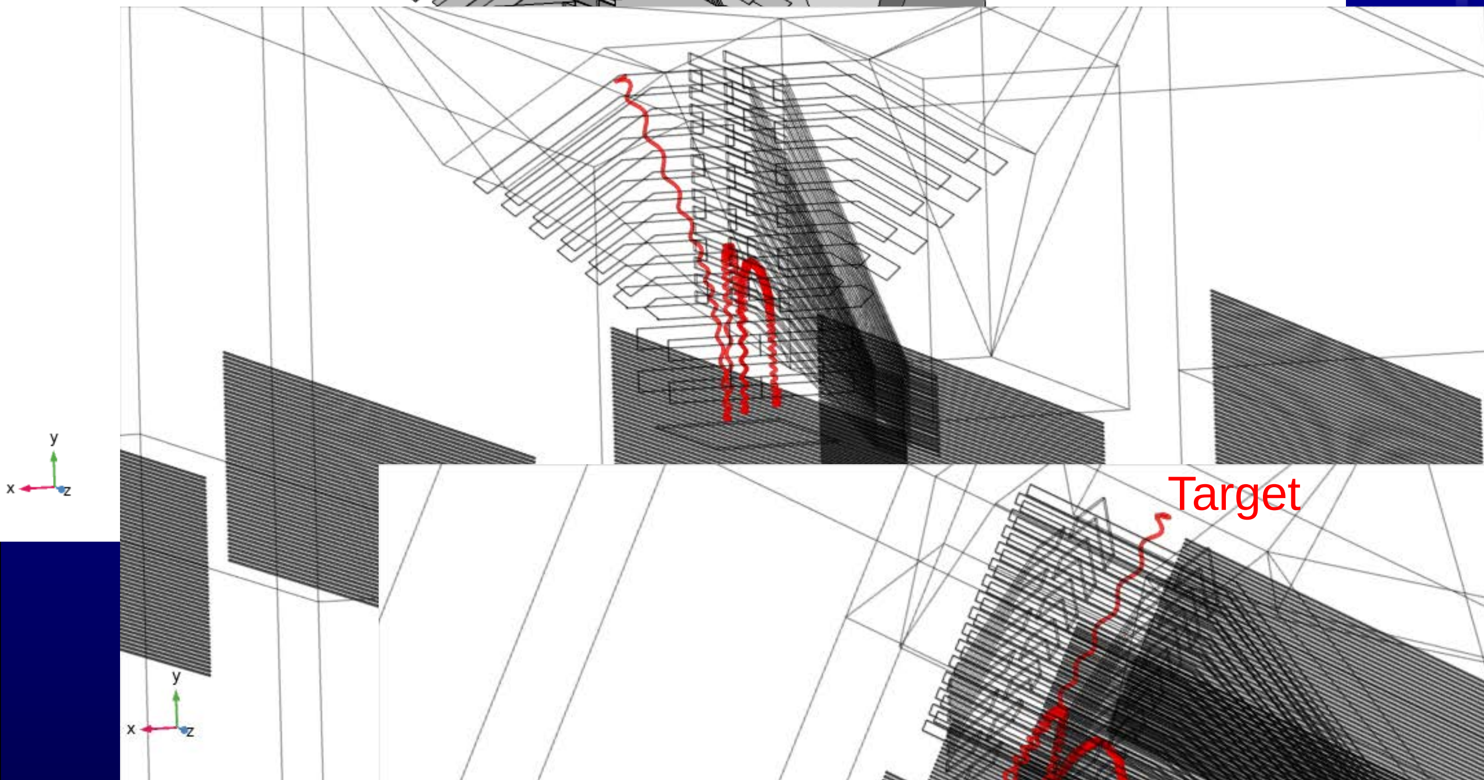
EM-optics

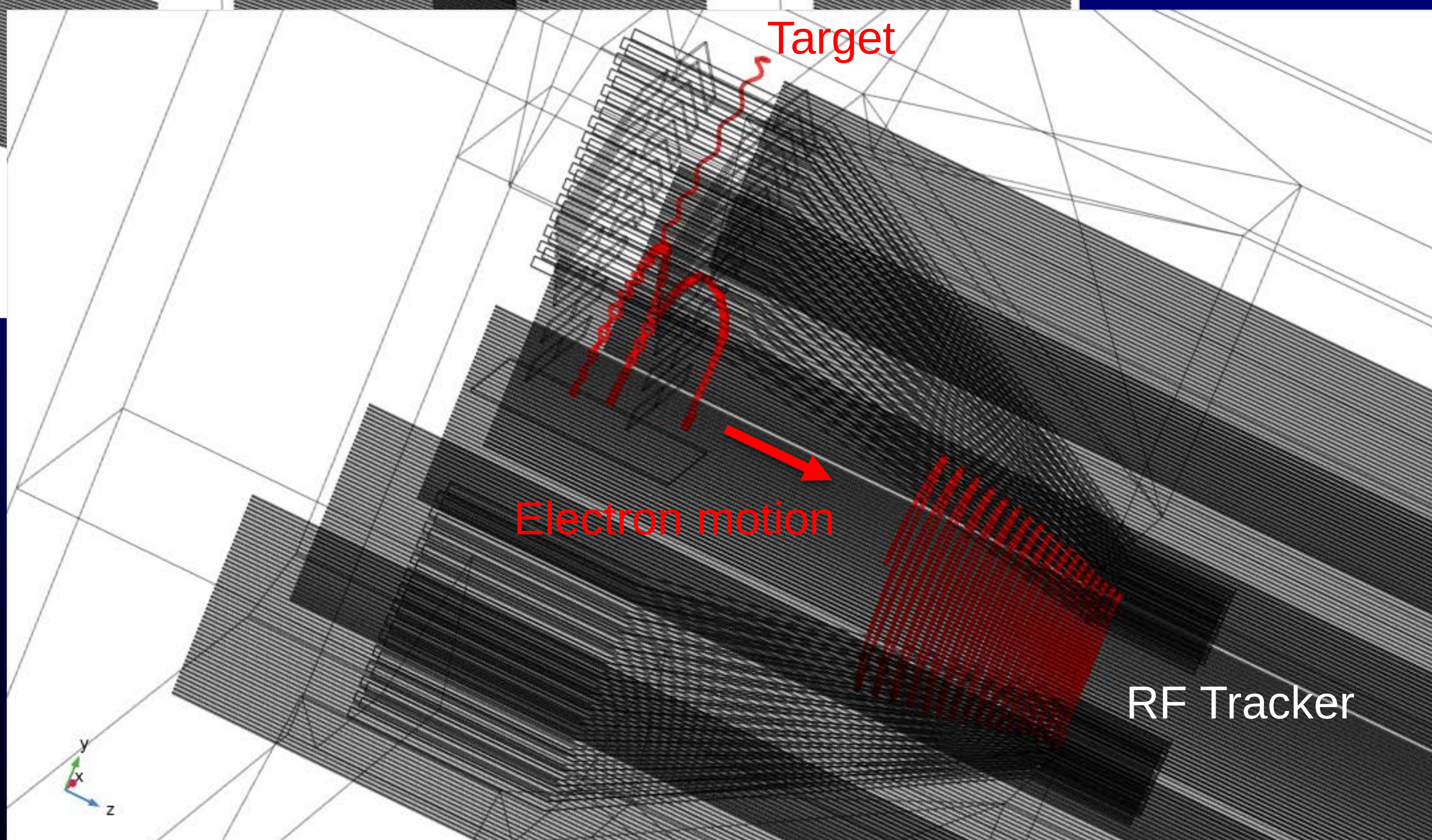


Iron Pole-face
Tritiated-Graphene
e⁻
Magnetic Field Lines
Deflection Electrodes
ExB
Coil
y
x

EM Optics



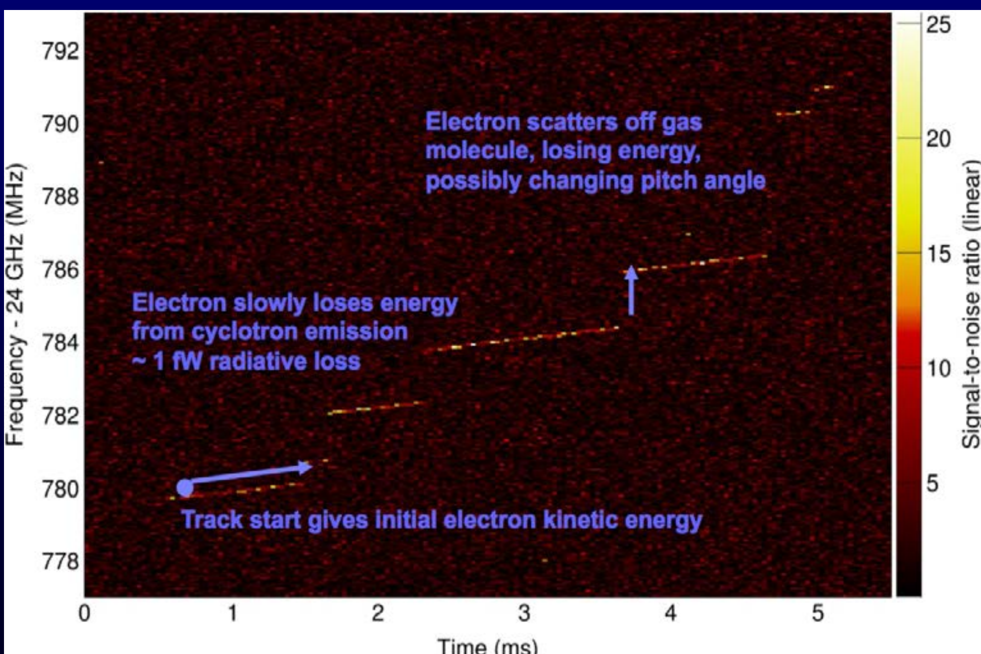


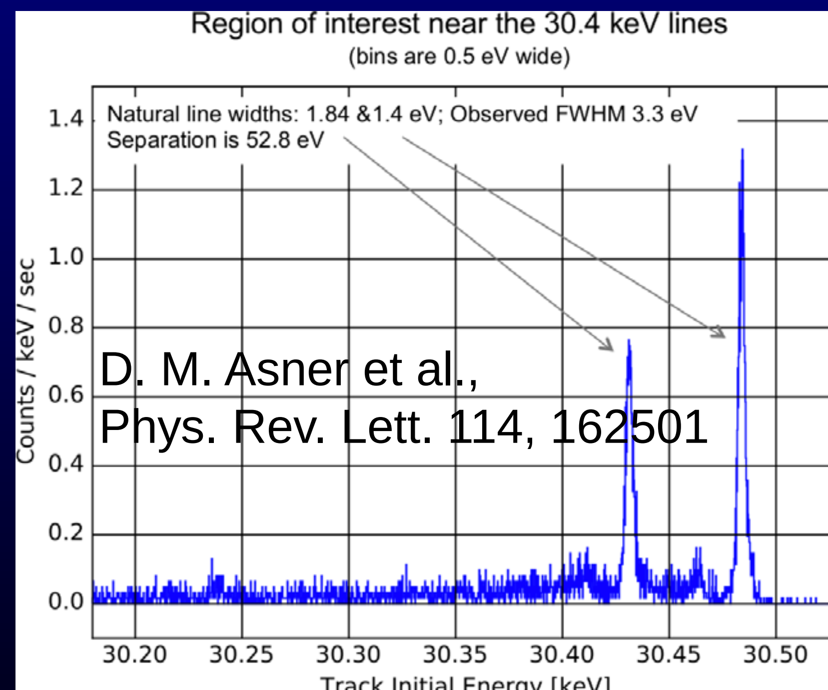


New ideas multi-layer design!

Cosmic Neutrino Telescope Step 3: Dynamic Aperature

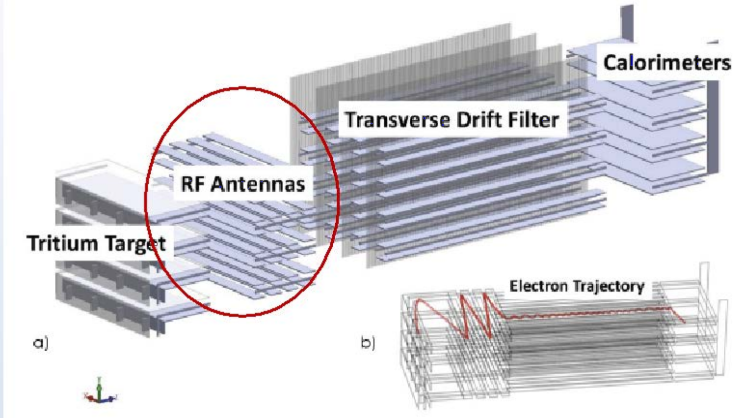
- Choice: RF tracking system – Project 8
- Estimates total momentum (ω_0/γ), $p_\perp$, $p_{||}$ to ~ 3eV

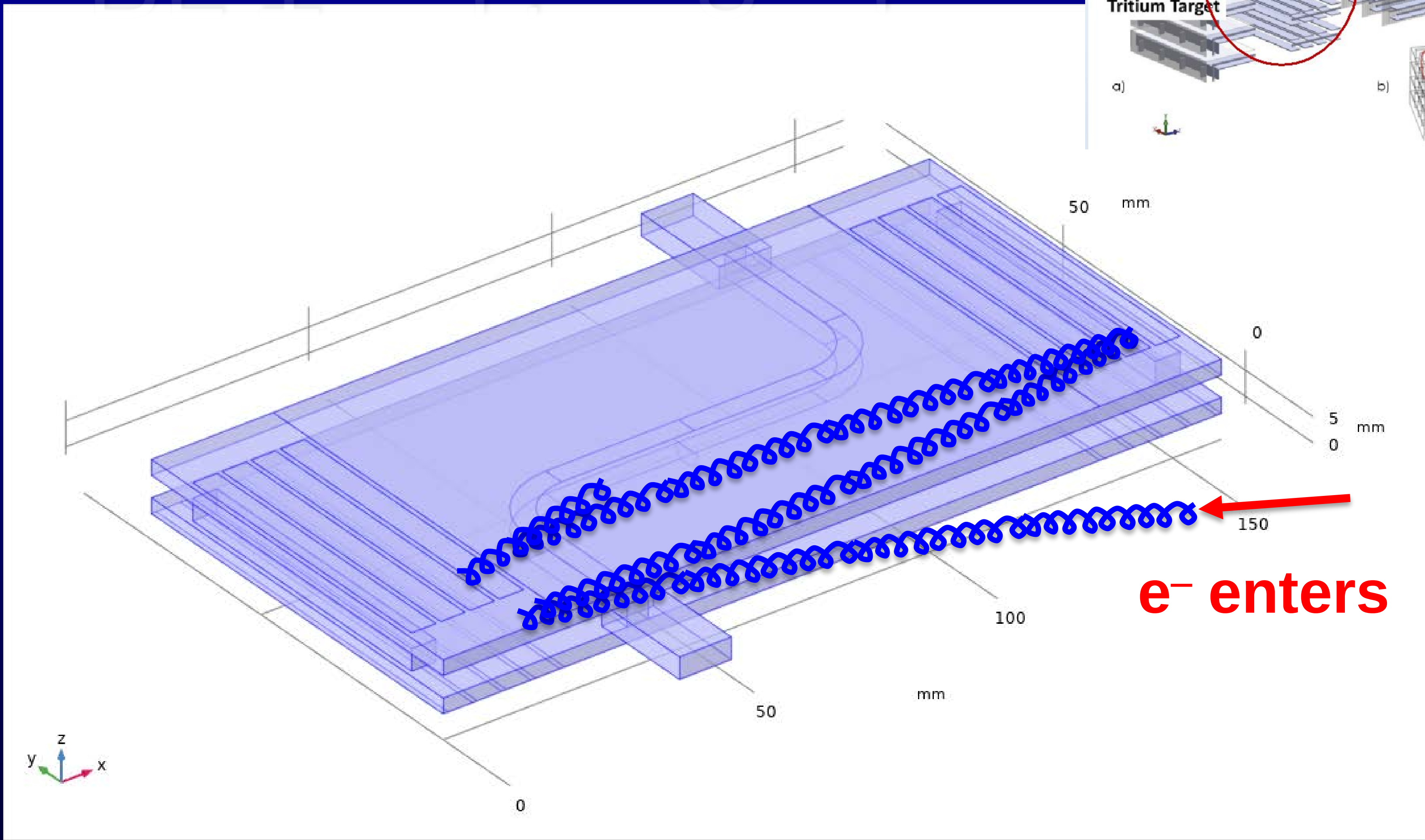




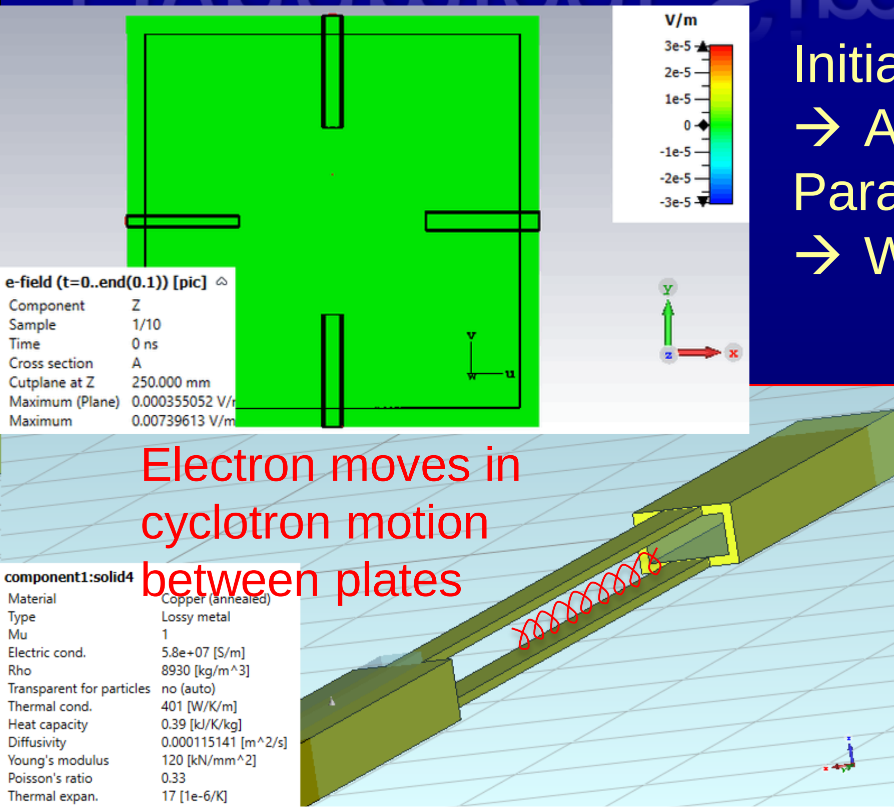
D. M. Asner et al.,
Phys. Rev. Lett. 114, 162501

RF Tracking System





Dynamical Simulation of RF Signal



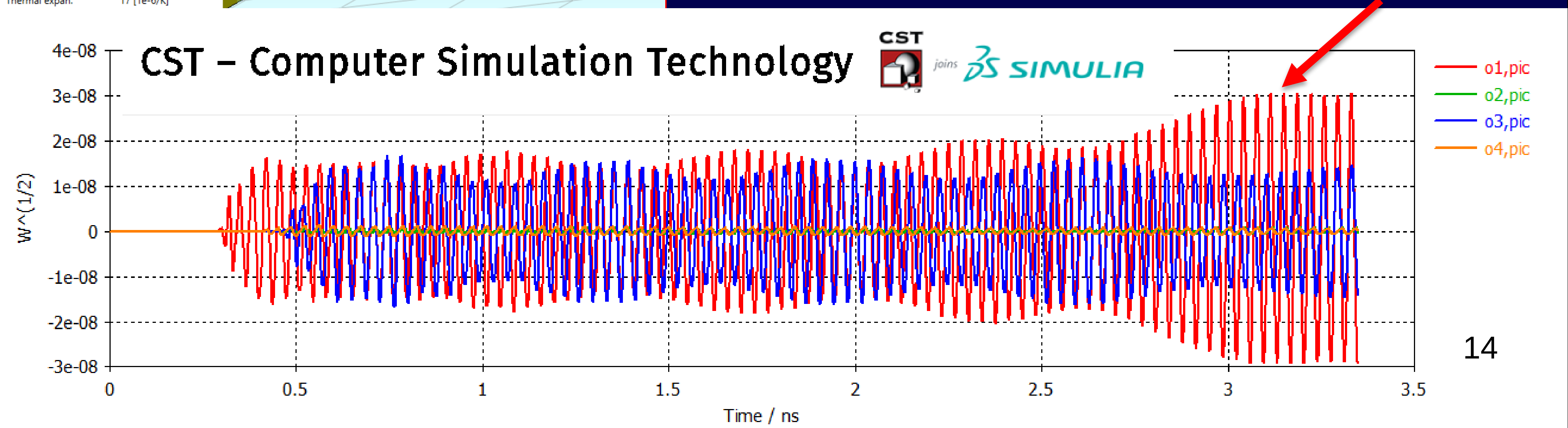
Initial calculations using CST RF modeling tools:
→ Antenna configured to transition from Parallel Plate Waveguide to Rectangular Waveguide
→ Working on FPGA-accelerated parameter fitting

P_{signal}~0.1 fW

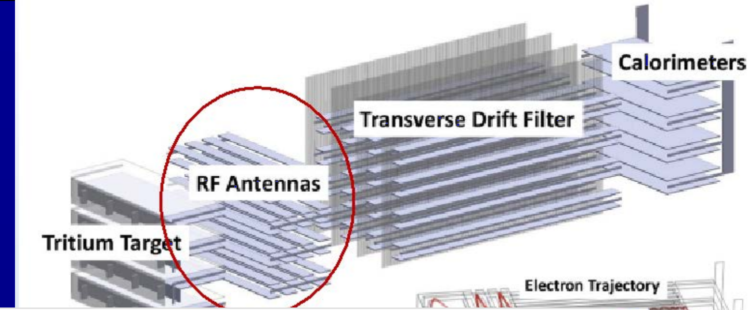
T_{LNA} ~6K

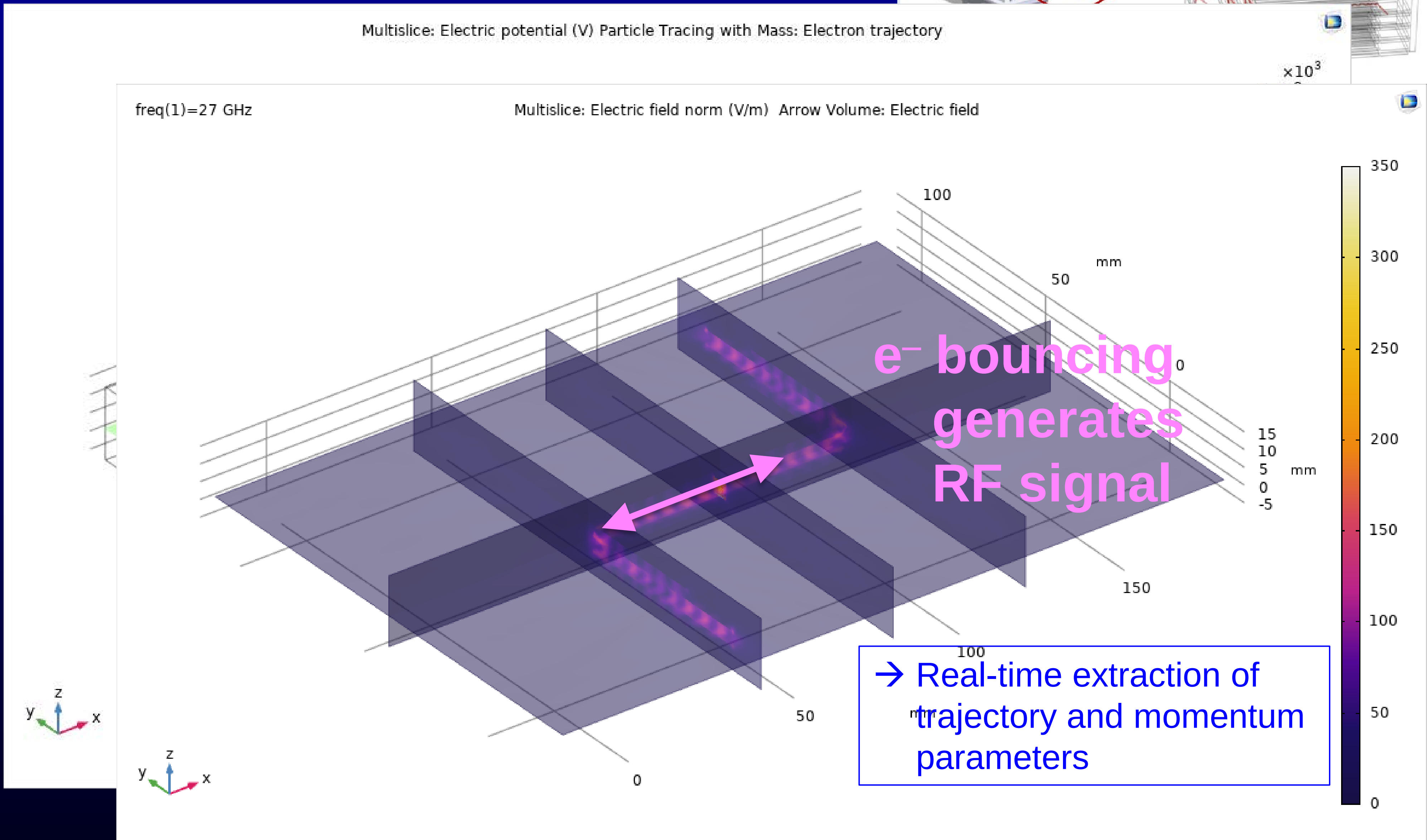
Dicke Radiometer eqn.
→ SNR~10 for 10^{-5}s

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



RF Tracking System



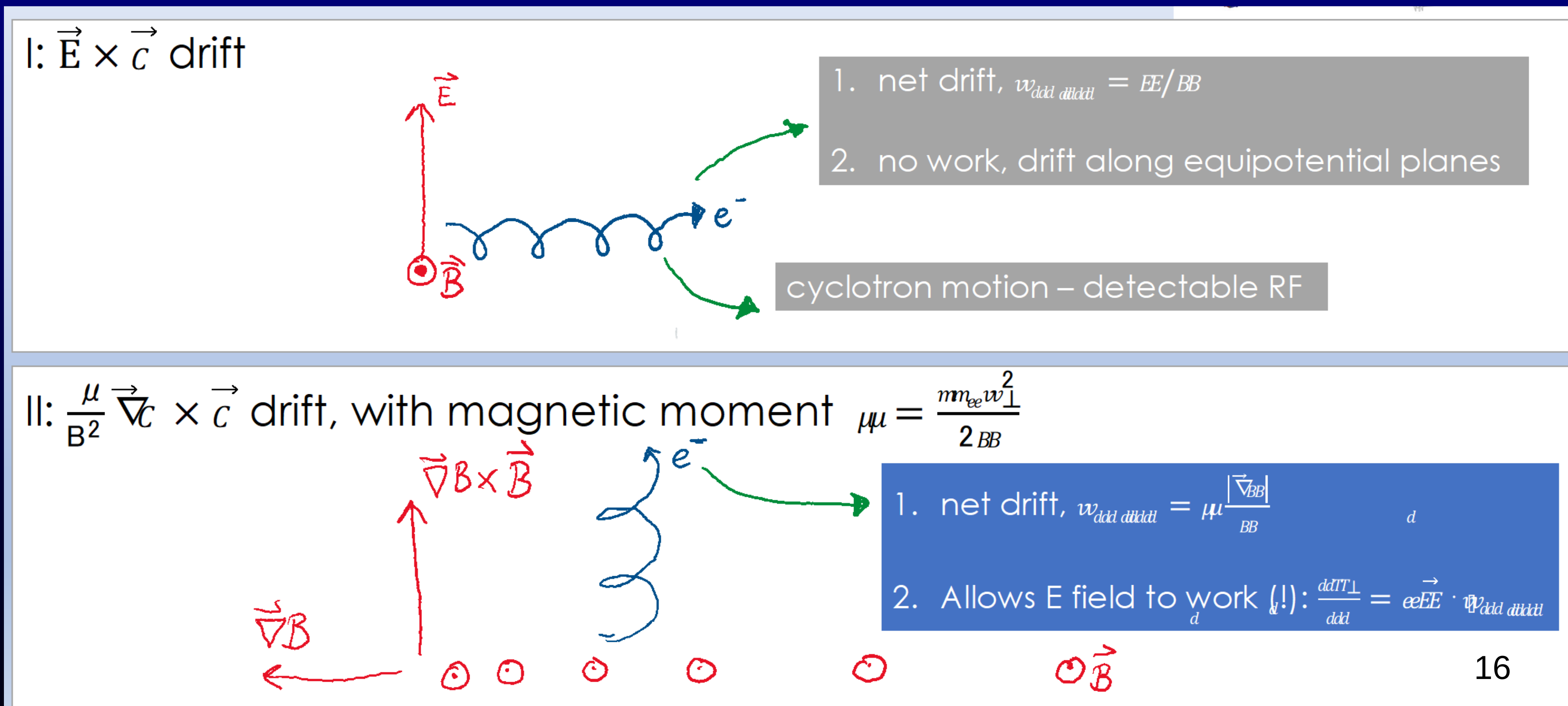


→ Real-time extraction of trajectory and momentum parameters

Cosmic Neutrino Telescope Step 4: Fine Adjust

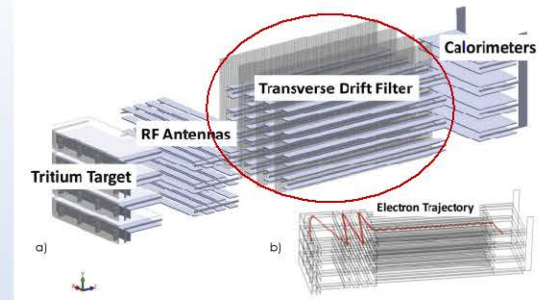
- Choice: Transverse Drift Filter – New Concept

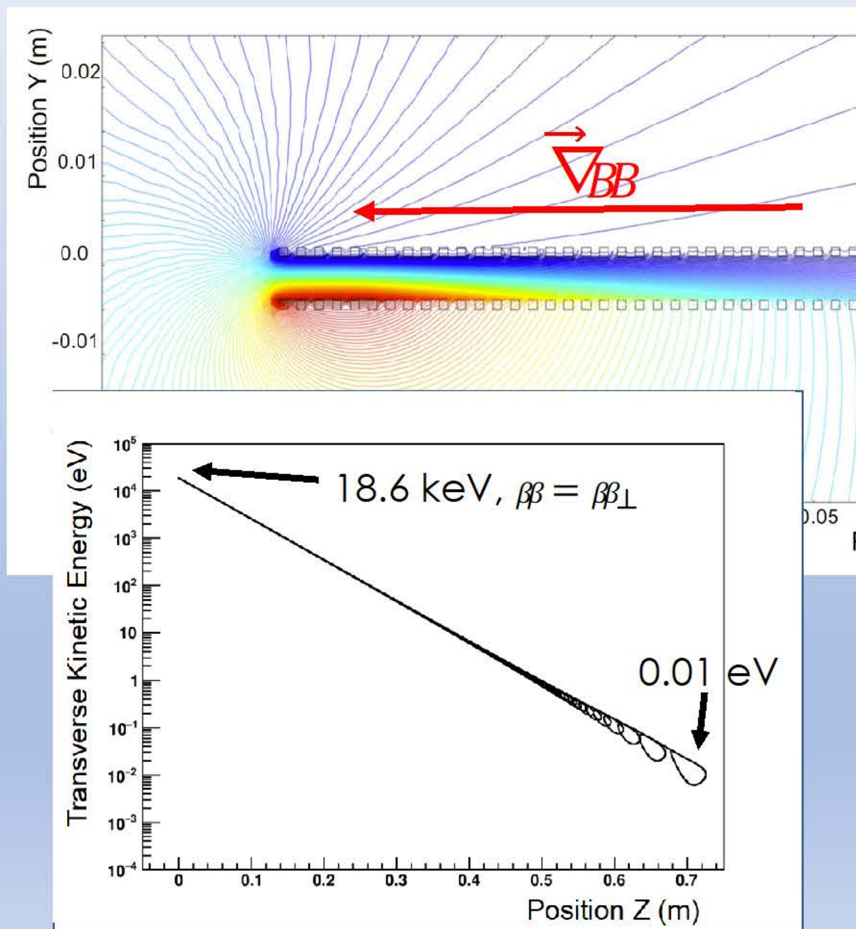
Auke Pieter Colijn (PATRAS 2019)

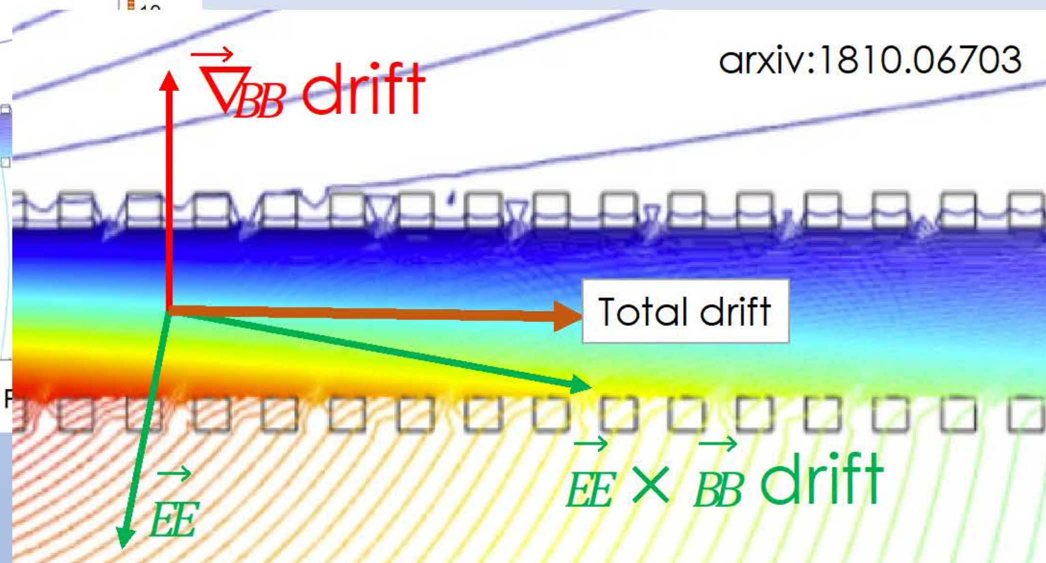


Transverse Filtering

PTOLEMY: Transverse drift filter







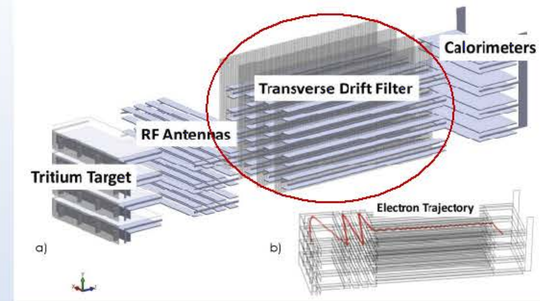
After filter, only component of β parallel to B is left.

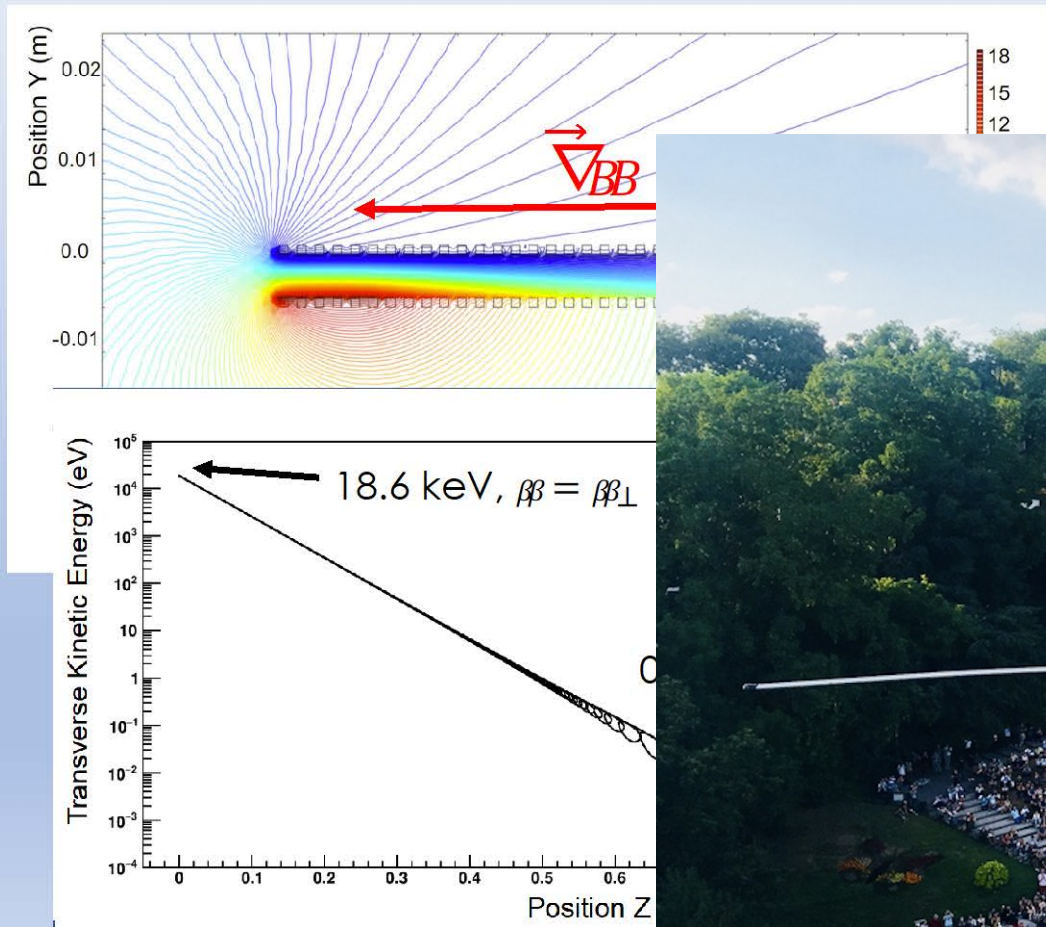
Can be reduced by retarding potential

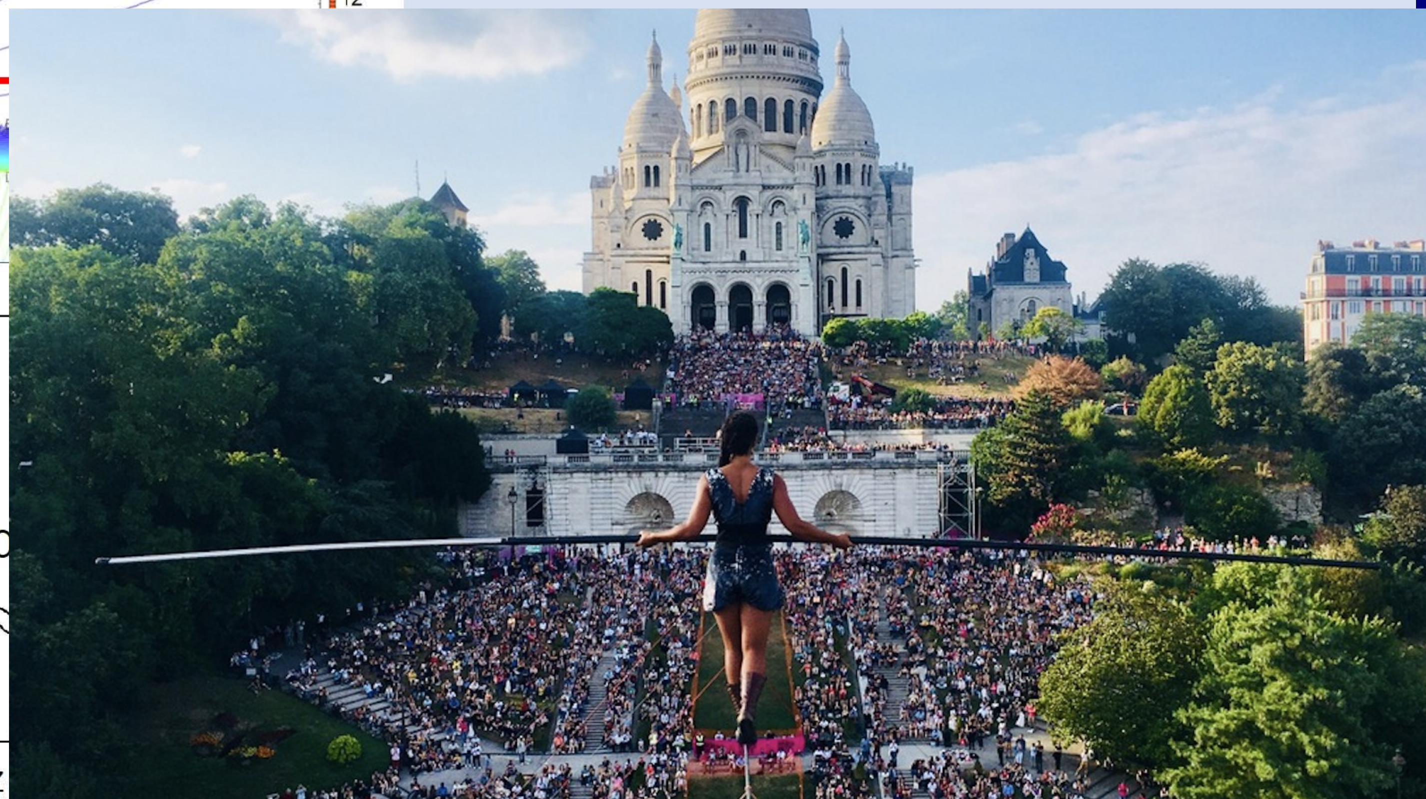
Important Properties for Calorimeter Stage:
Low magnet field, Small Area

Transverse Filtering

PTOLEMY: Transverse drift filter

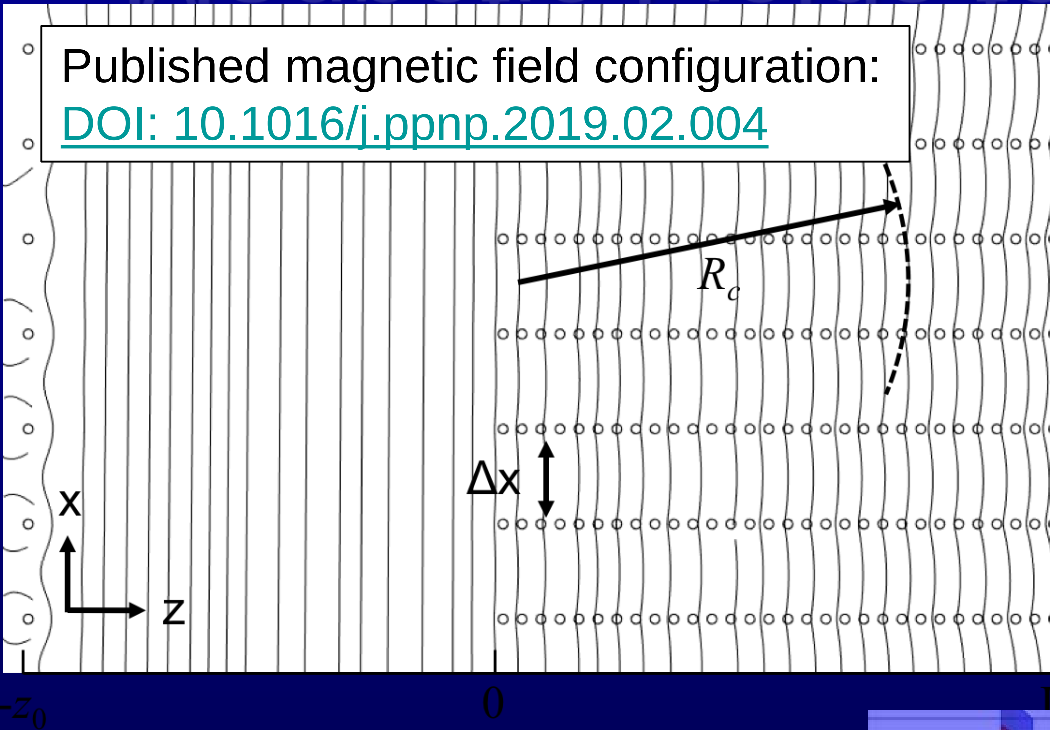


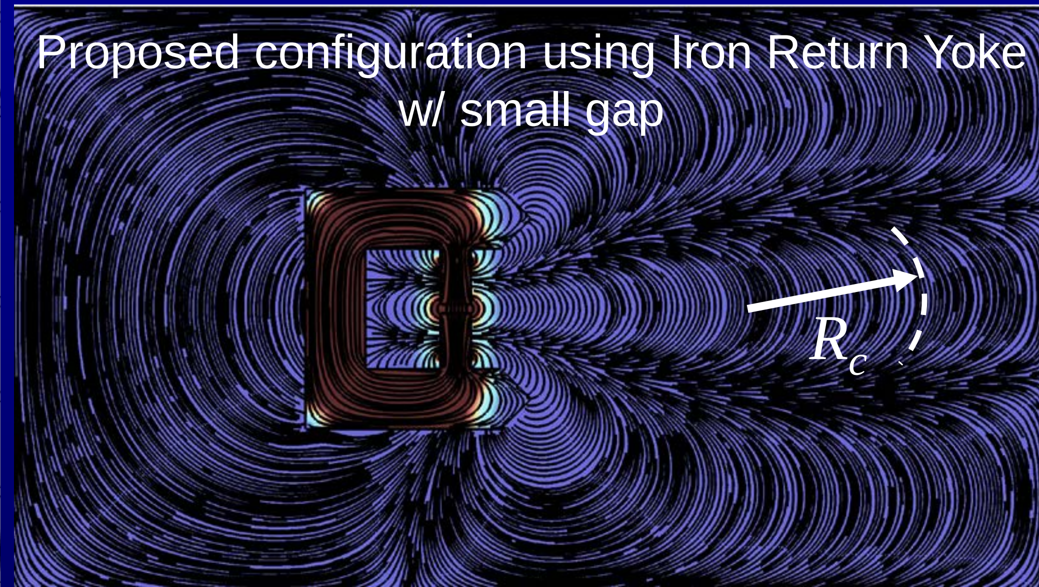


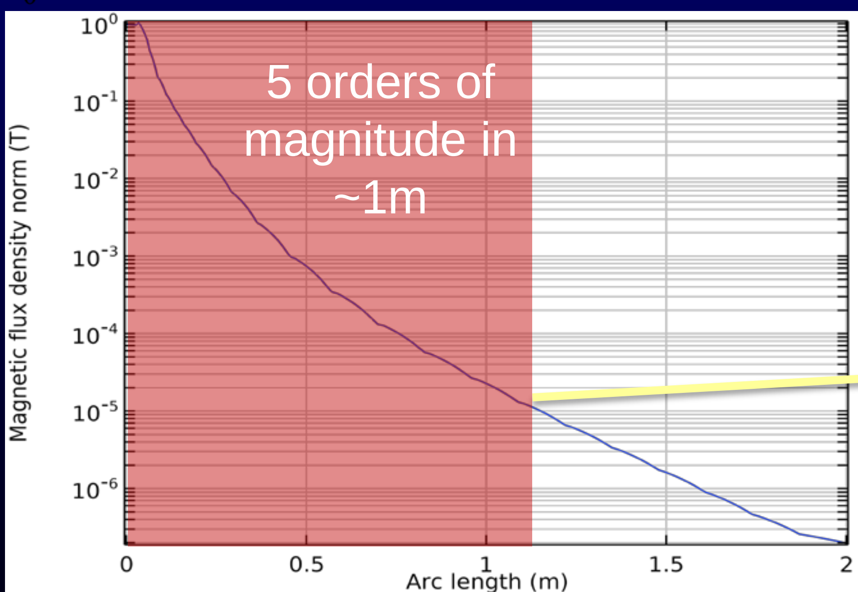


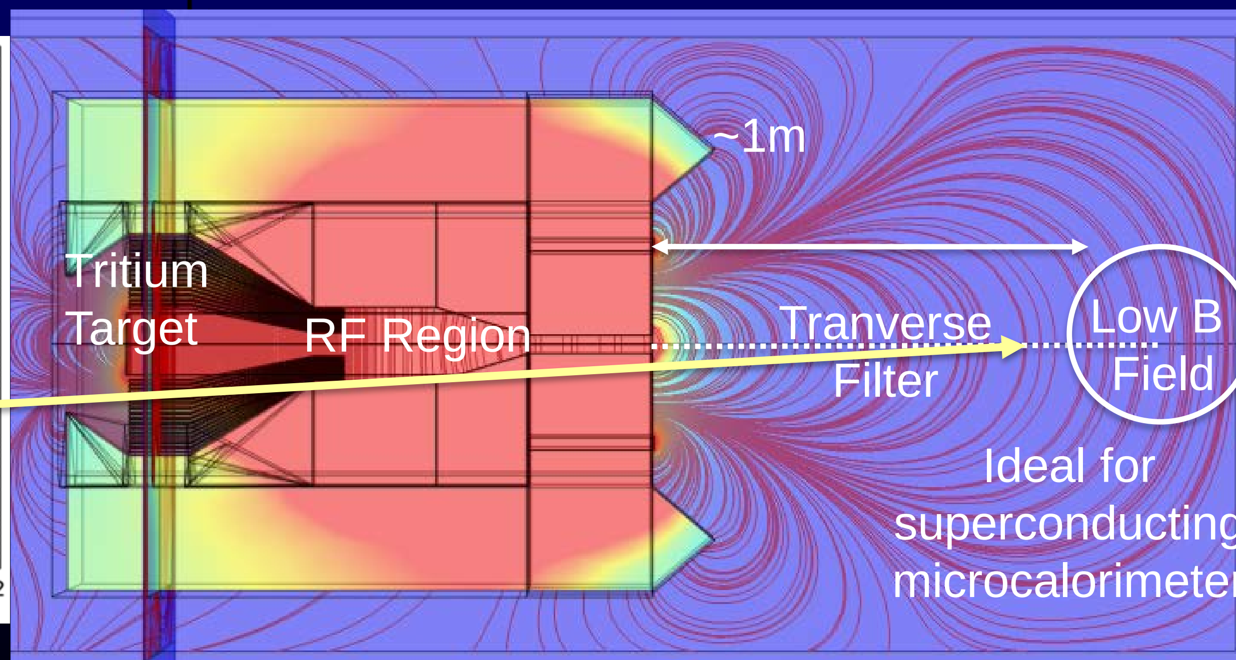
Important Properties for Calorimeter Stage:
Low magnet field, Small Area

Magnetic Fields for Transverse Drift



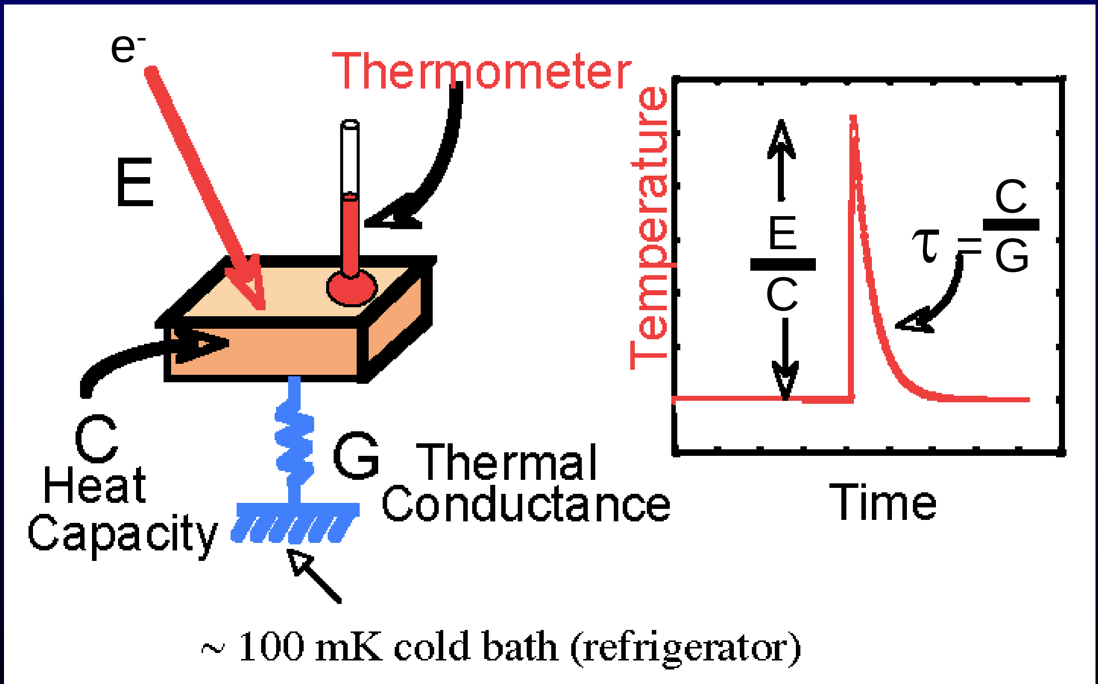






Cosmic Neutrino Telescope Step 5: Eye Piece

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

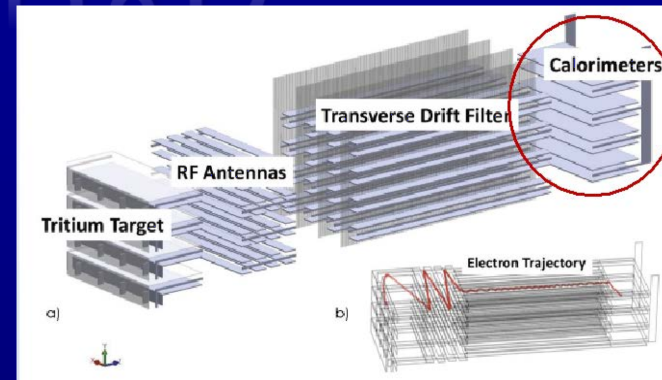


Thin sensors:
~1 eV electron can be stopped with very small C

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

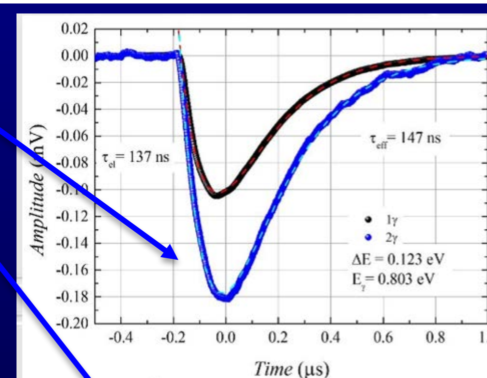
MicroCalorimeter R&D

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



Now: 0.11 eV @ 0.8 eV and 106 mK and 10x10 μm^2

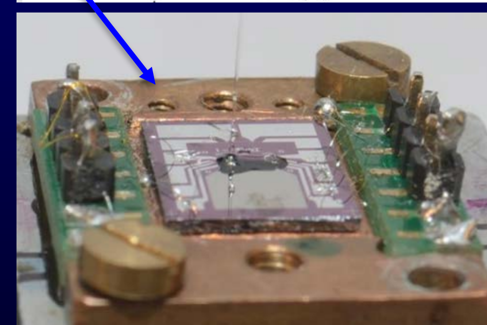
TiAuTi 90nm [Ti(45nm) Au(45nm)] (τ ~137 ns)



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

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

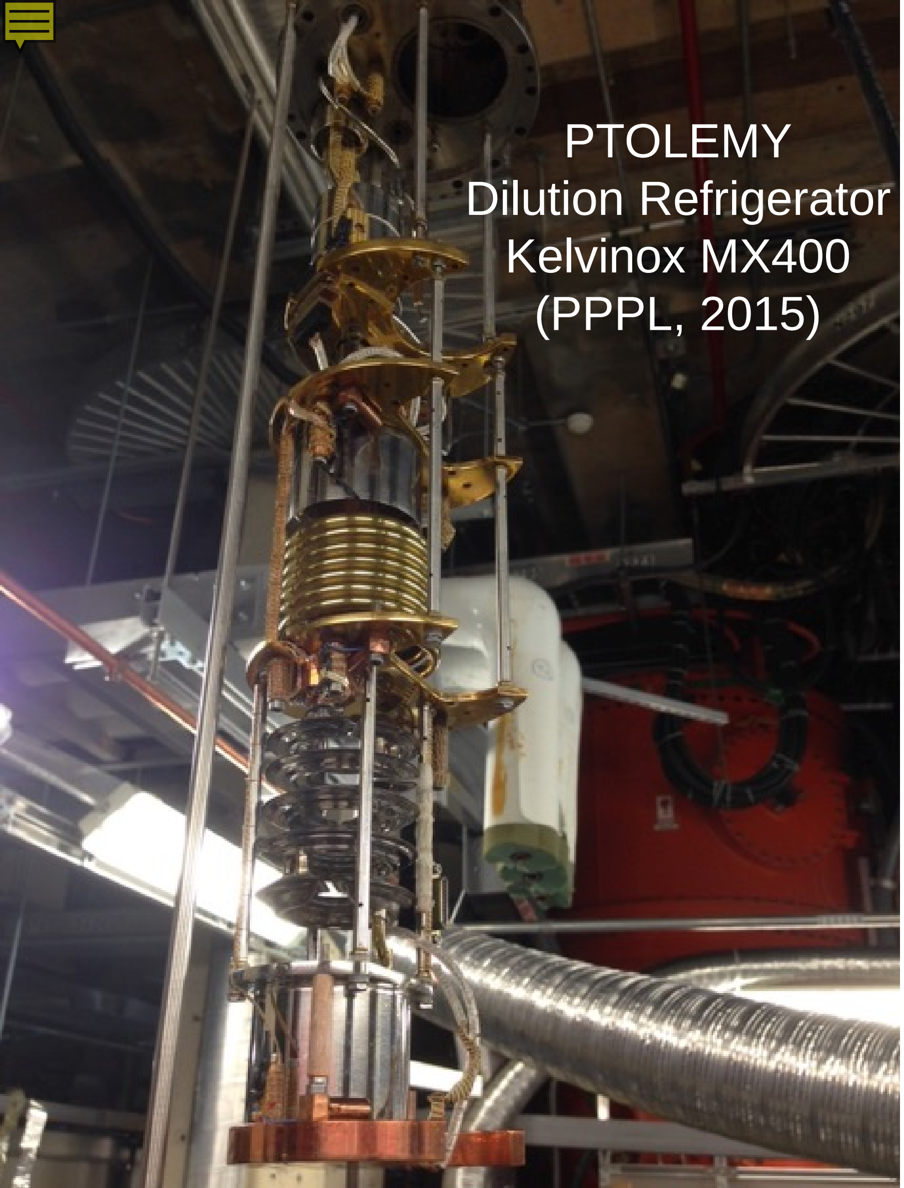
ΔE_{FWHM} = 0.022 eV @ 0.8eV

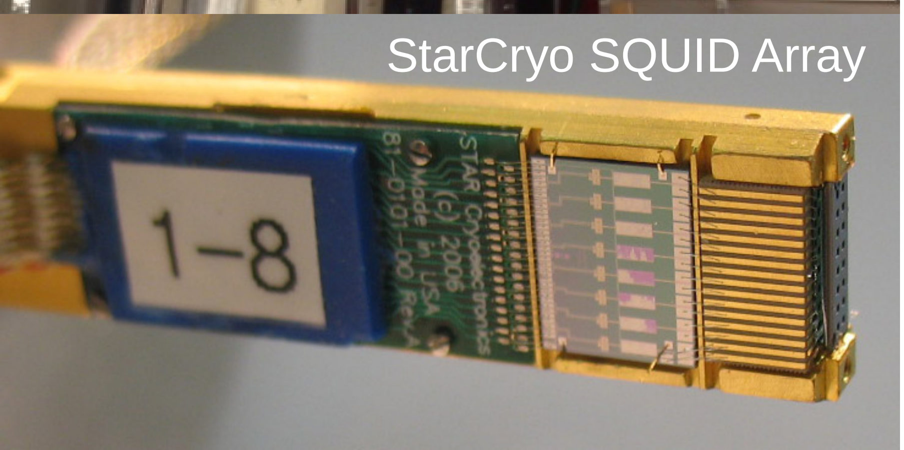


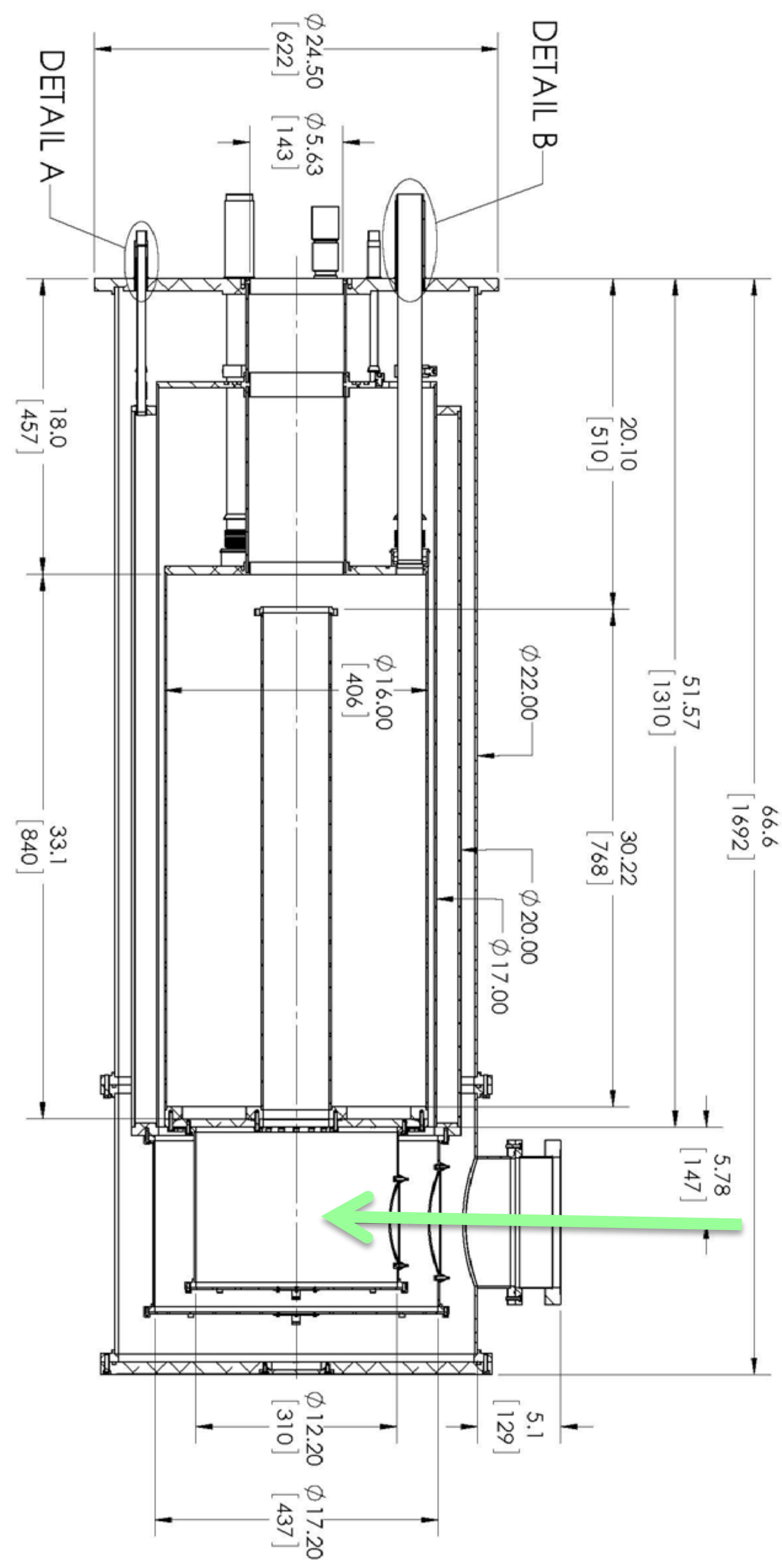
Now: 0.11 eV @ 0.8 eV and 106 mK and 10x10 μm^2

TiAuTi 90nm [Ti(45nm) Au(45nm)]

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA


PTOLEMY
Dilution Refrigerator
Kelvinox MX400
(PPPL, 2015)

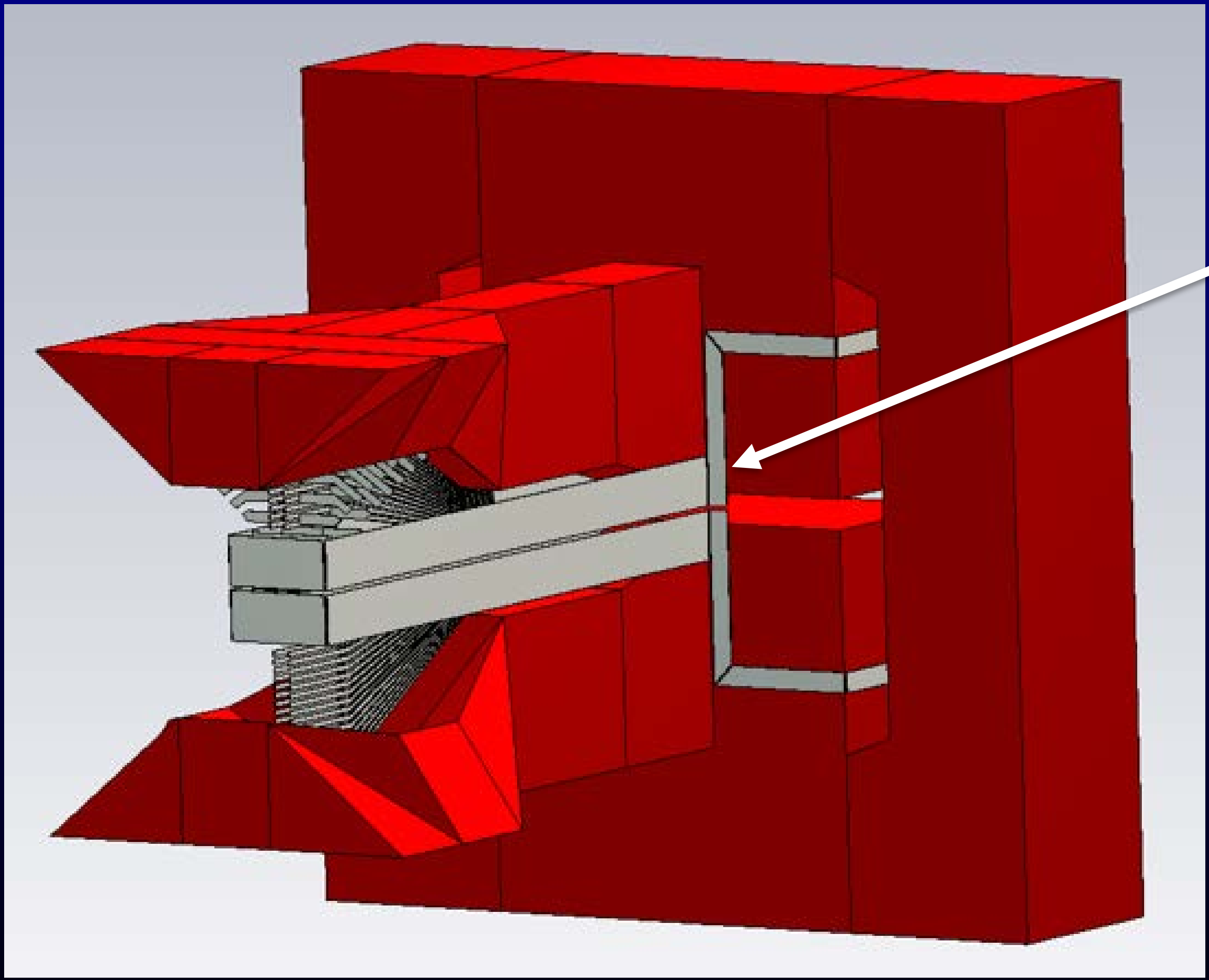

StarCryo SQUID Array
1–8


DETAIL A
DETAIL B


PTOLEMY
Custom Dewar
w/ Vacuum Path
to MAC-E filter
(on ship to LNGS)

Constructing the 1st CνB Telescope

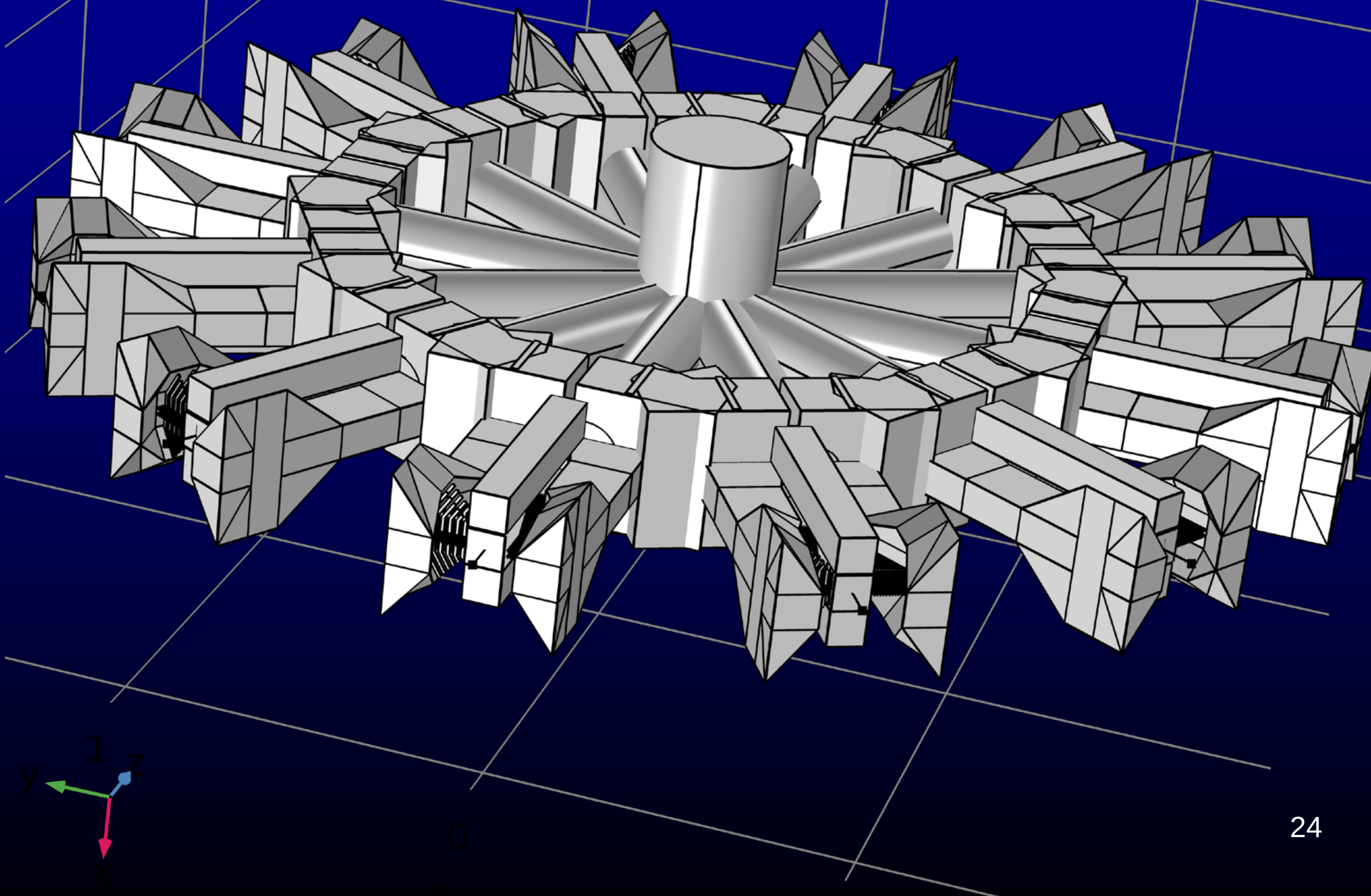
Full end-to-end EM transport with detailed RF signal simulation in CST software → Design to be ported to mechanical CAD



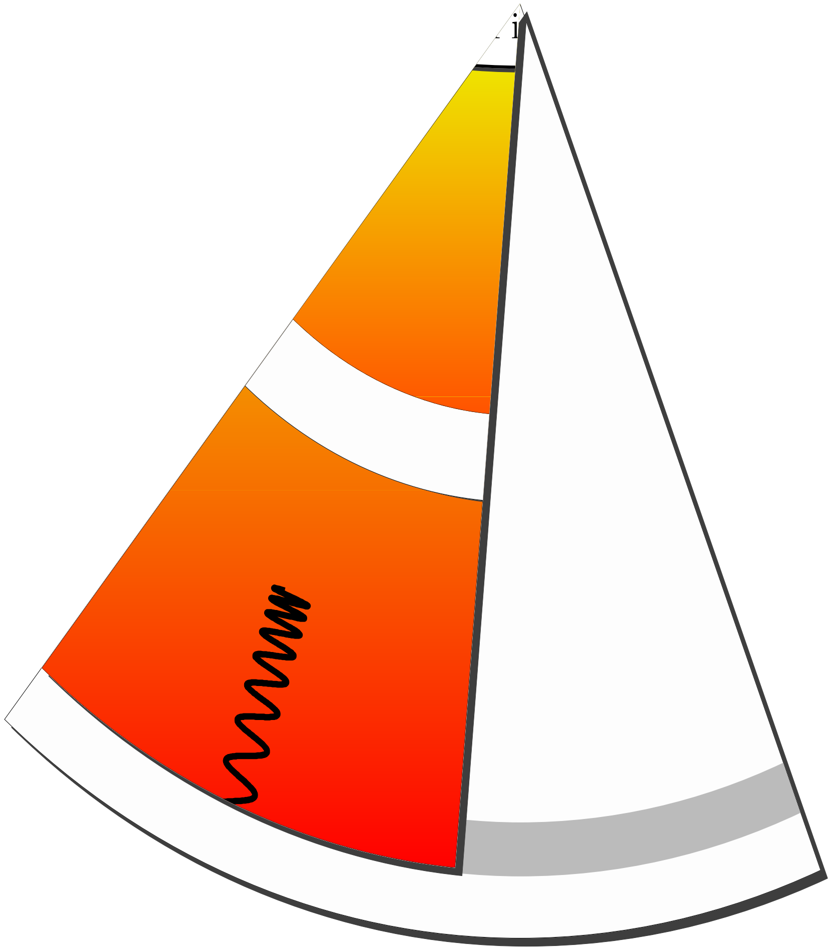
- Converting current sheets to realistic coils
- Tilting electrodes to be parallel to B field
- Computing fringe field and iron yoke shape

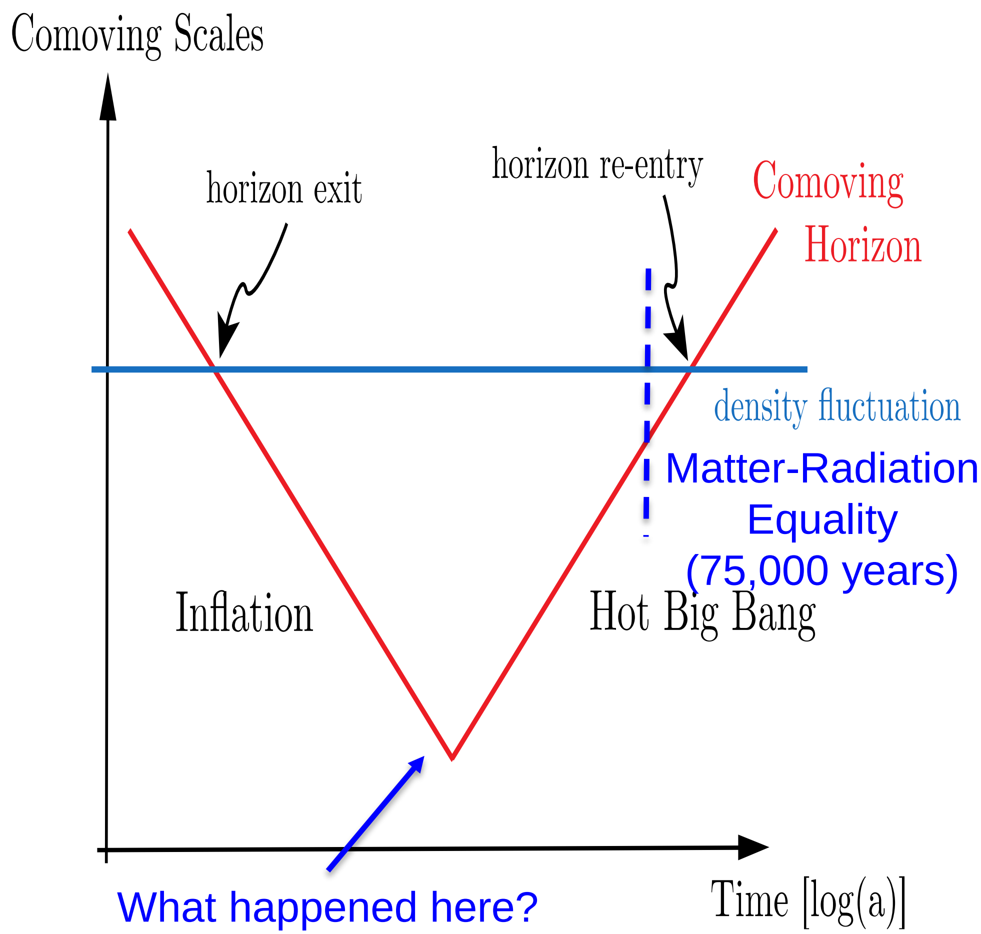
Circular Geometry

w/ microcalorimeter at center

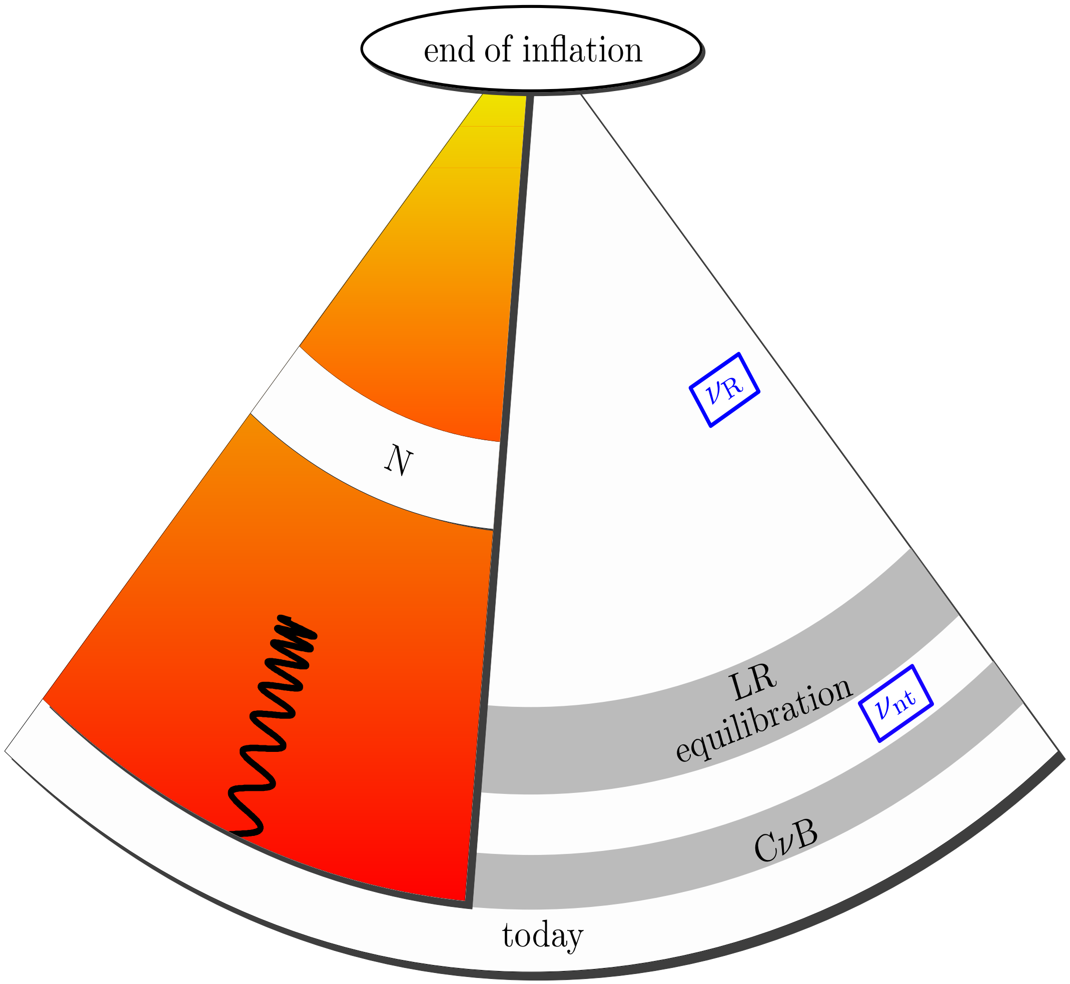


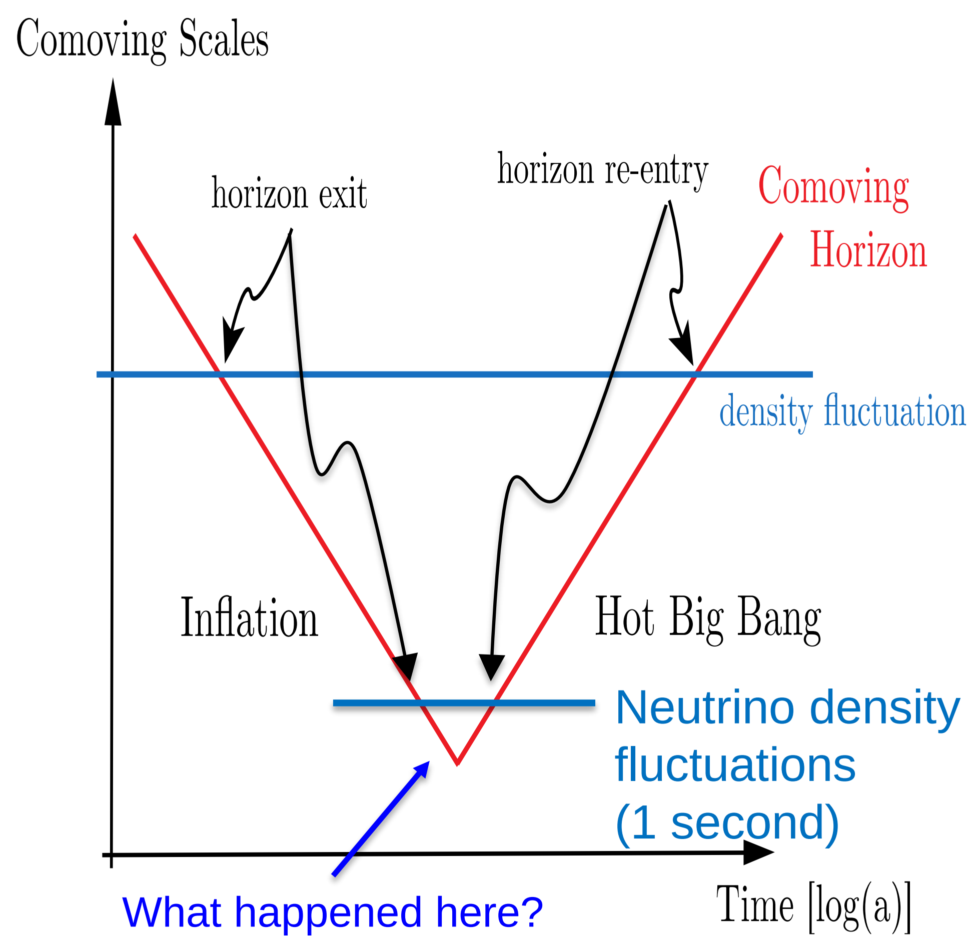
Inflation → Hot Big Bang





Inflation → Hot Big Bang





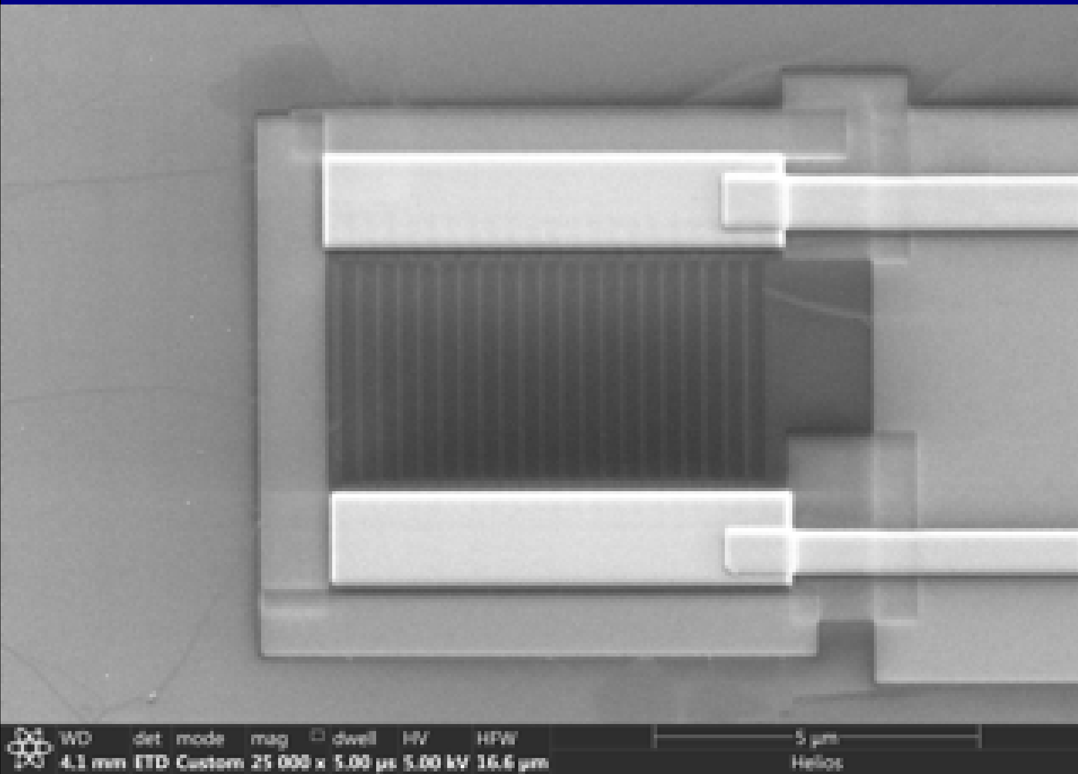
Ratz
(Erice 2017)

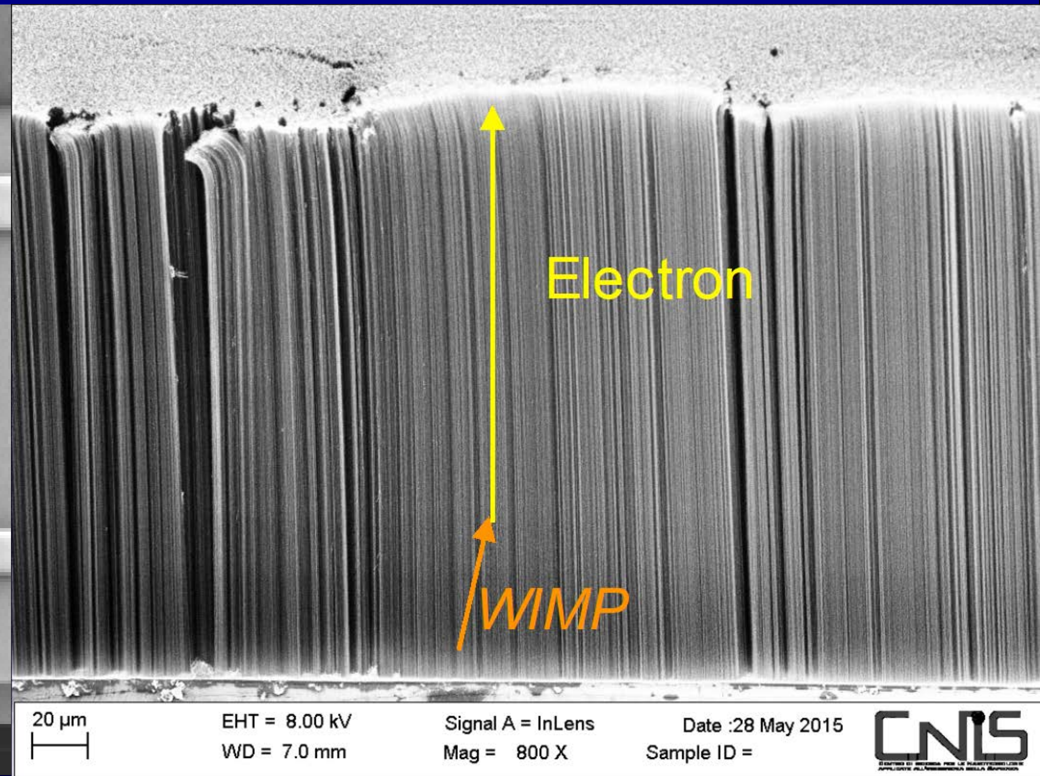
ADDITIONAL SLIDES

Graphene DM Targets: Two Concepts

PTOLEMY-G^3

PTOLEMY-CNT

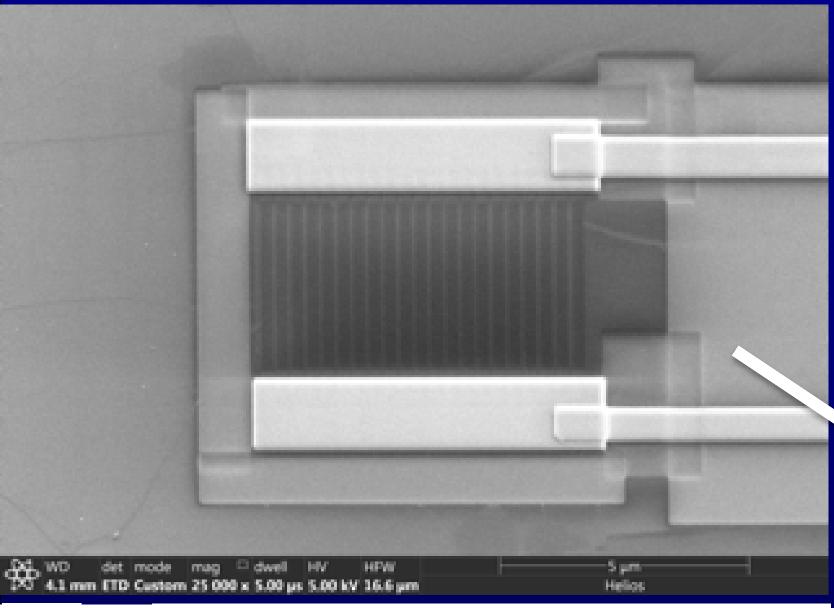




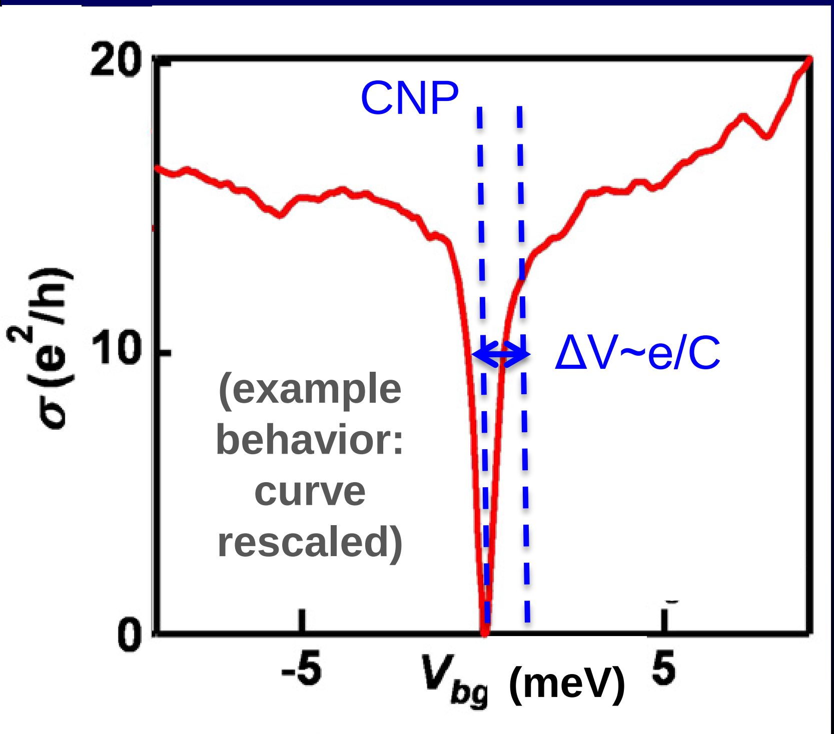
Self-instrumented with G-FETs

Anisotropy of aligned CNTs

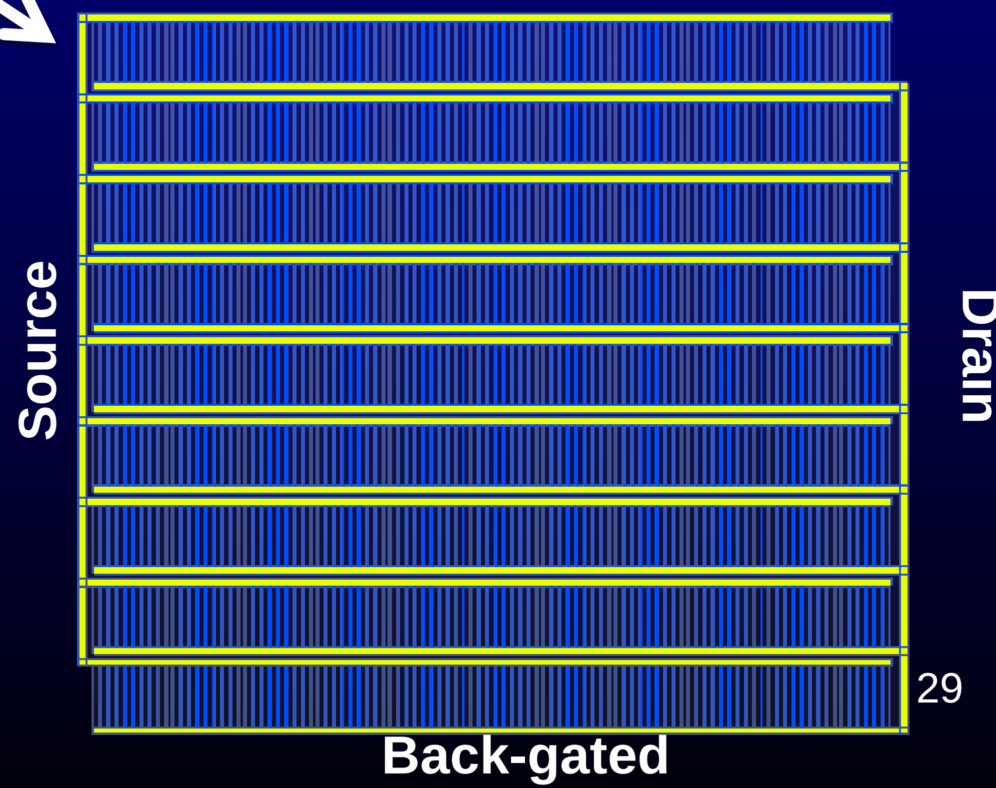
G-FET



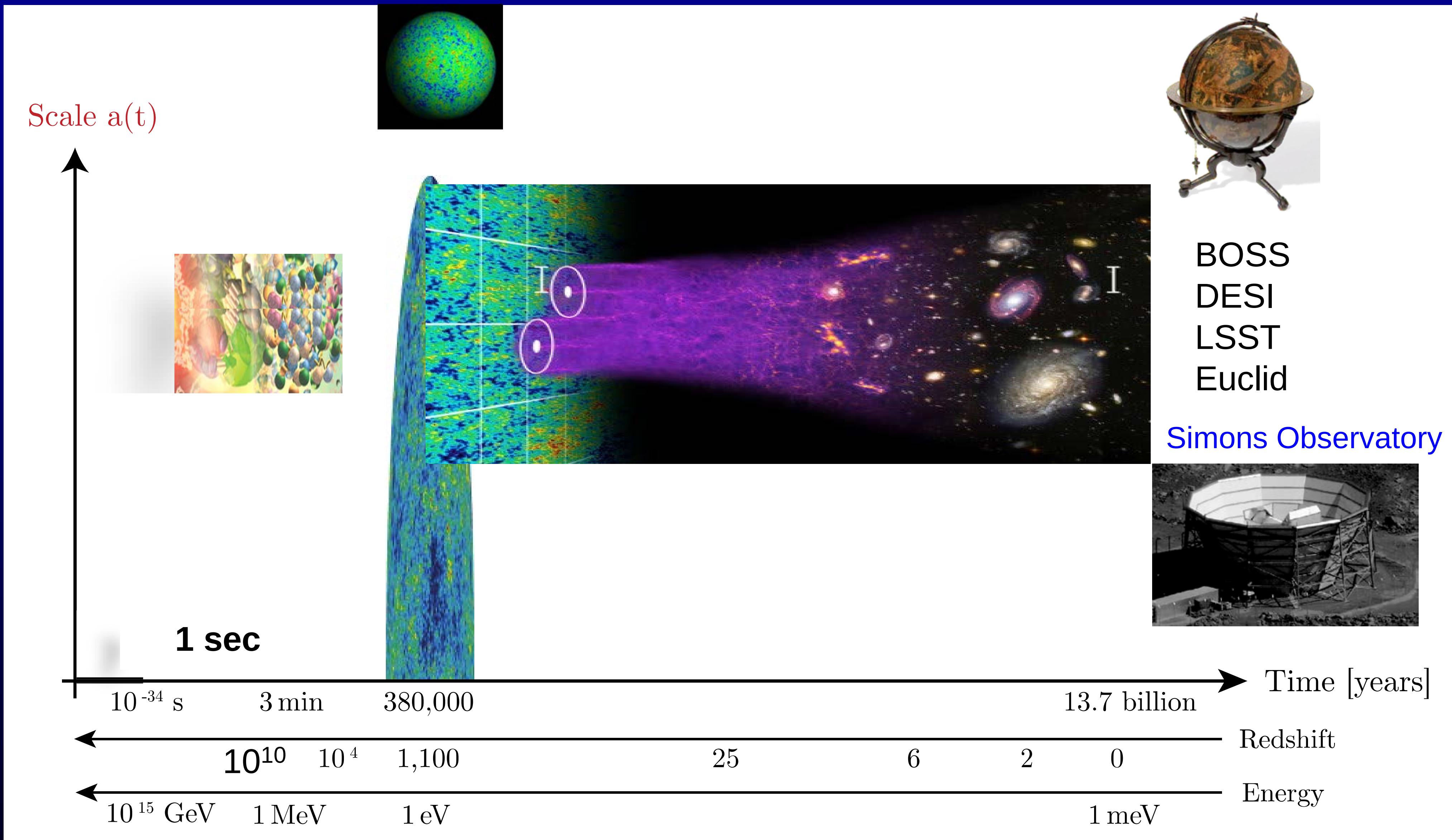
Principles of Operation:
- Tunable meV band gap set by nanoribbon width (E_{gap} ~ 0.8eV/width[nm])
- Large jump in conductivity (~10^{10} charge carriers) relative to charge neutrality point under the field-effect from a single electron scatter



Scalability to Interdigitated Capacitor

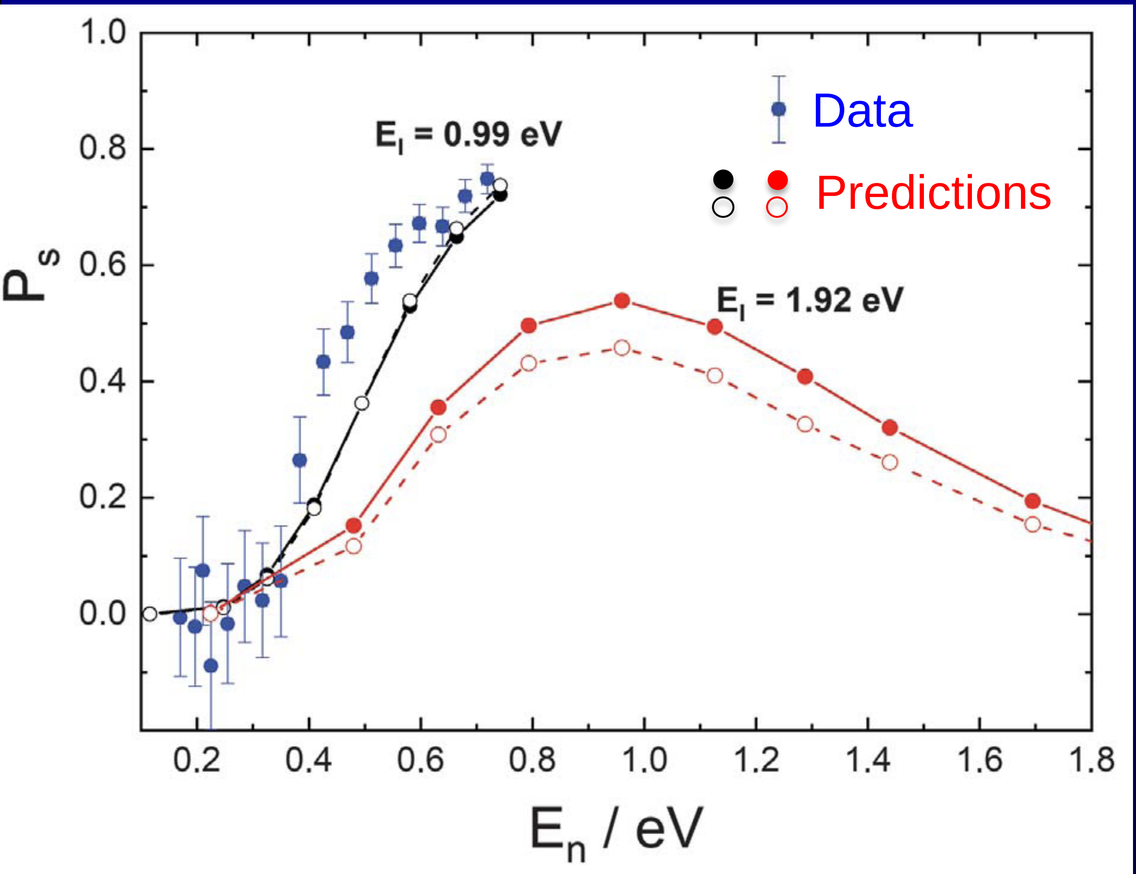


Origin of Large Scale Structure

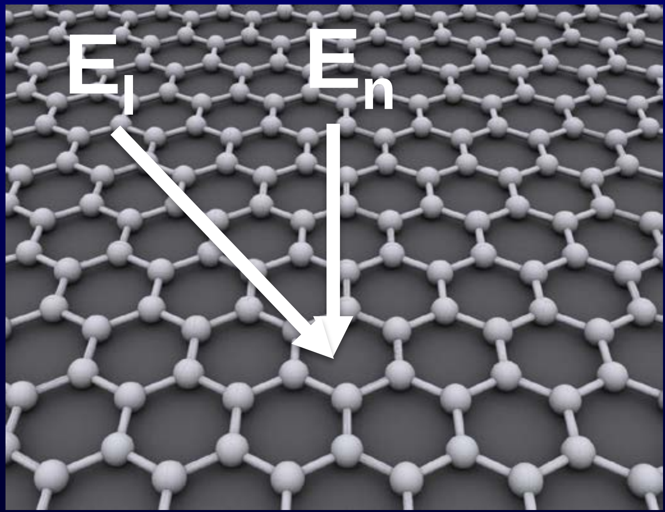


Baumann
(TASI 2012)

Sticking Probability of H on Graphene



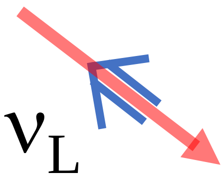
This technique repeated for ^{3}He and ^{3}H would provide data on final-state T-Graphene → ^{3}He-Graphene molecular smearing.

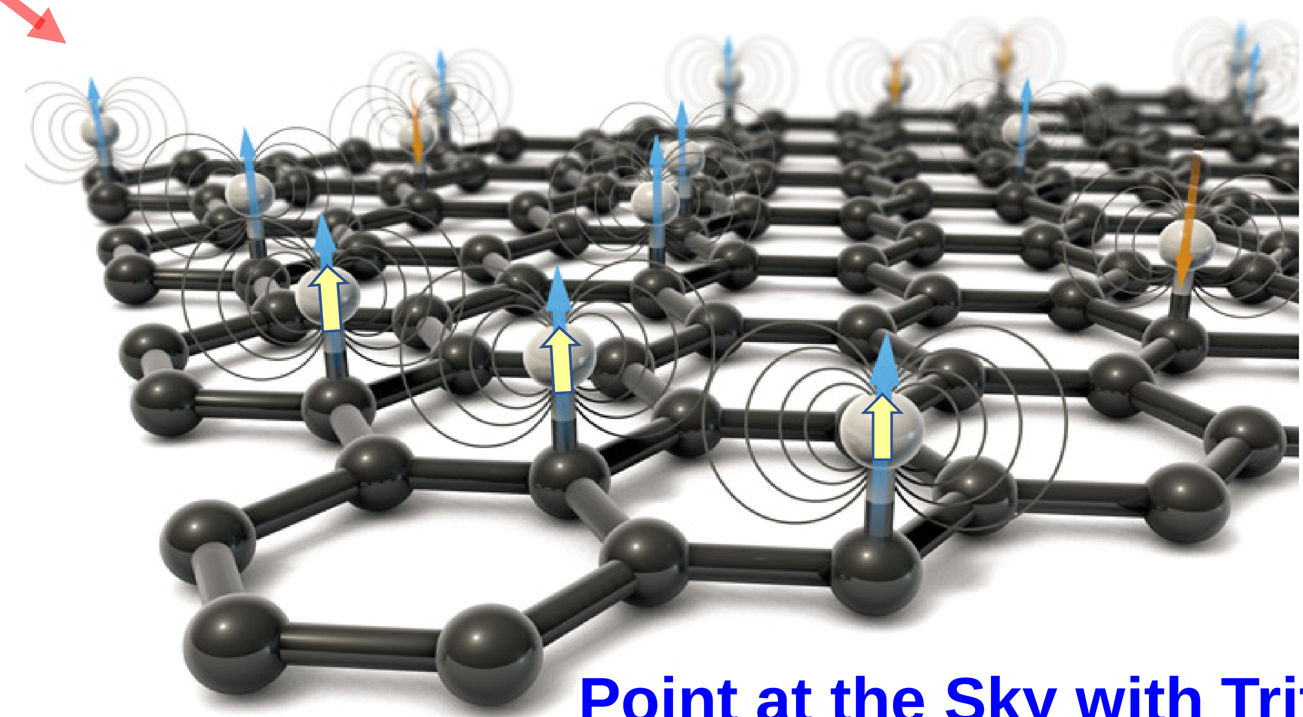


New ideas for magnetic transfer!

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

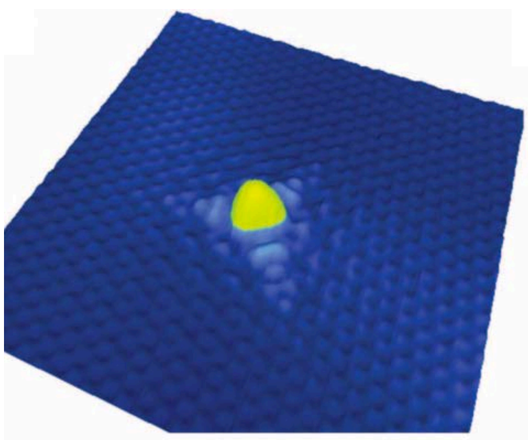
Polarized Tritium Target

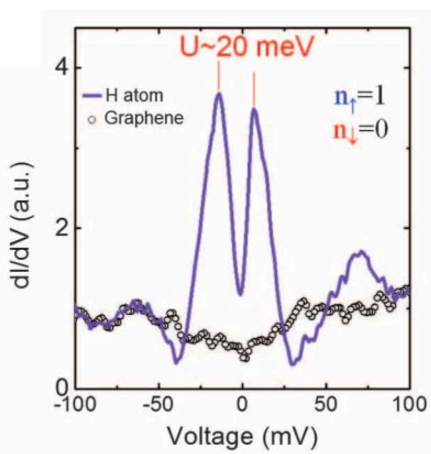




Lisanti, Safdi, CGT, 2014.

Point at the Sky with Tritium Nuclear Spin

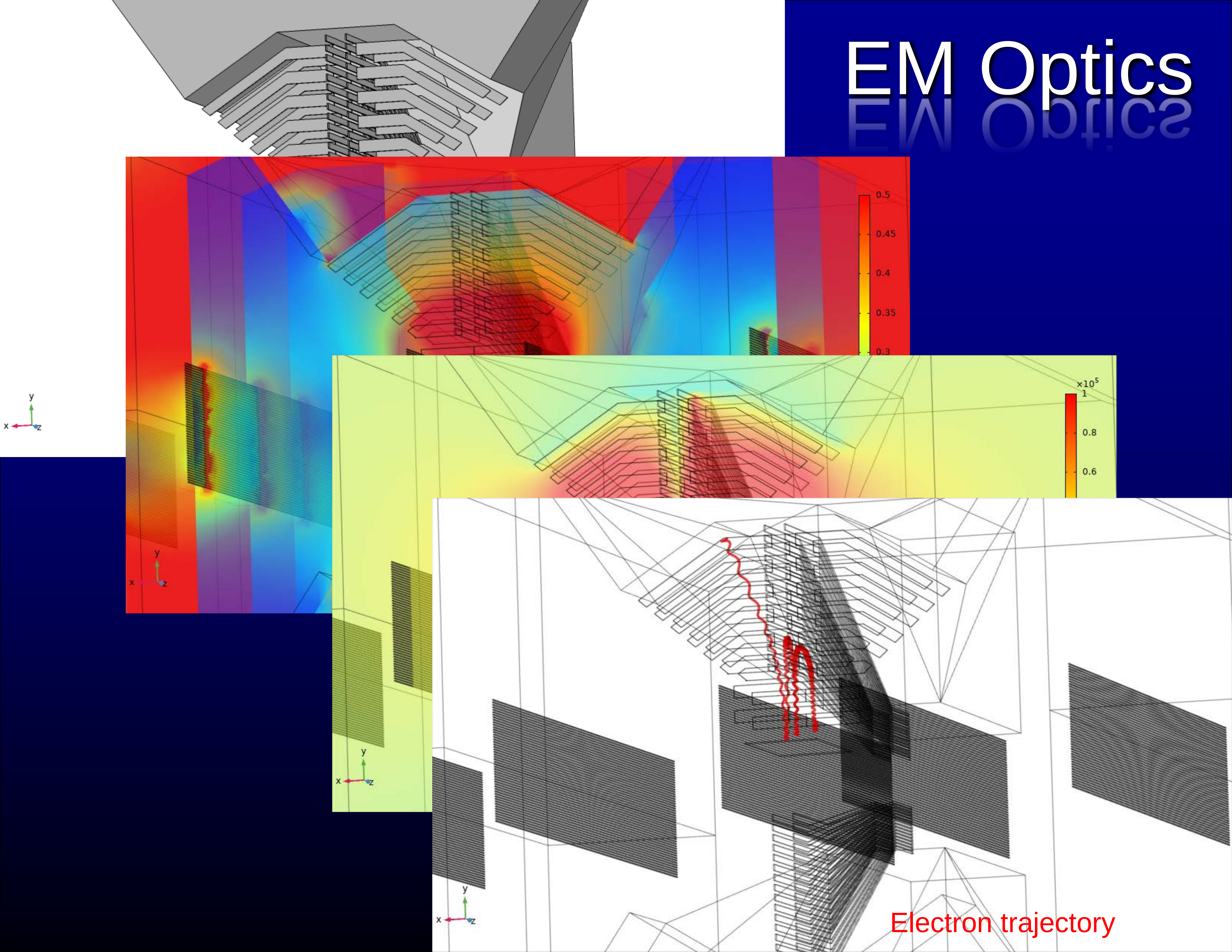




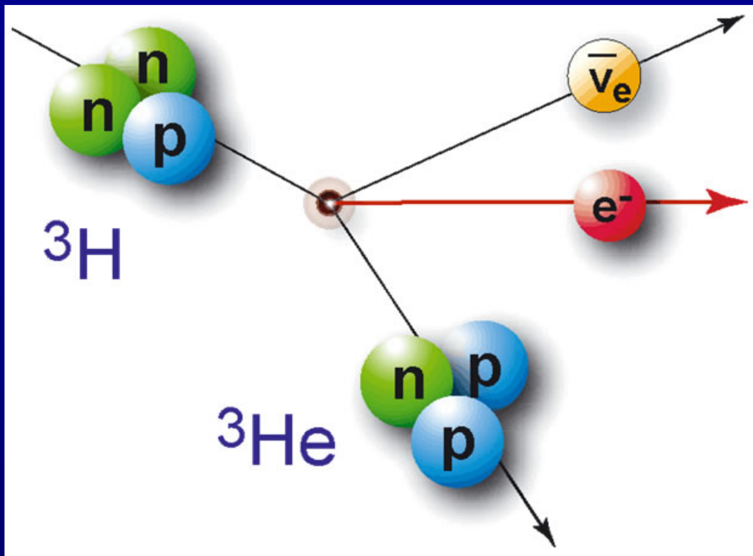
Hydrogen doping on graphene reveals magnetism

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

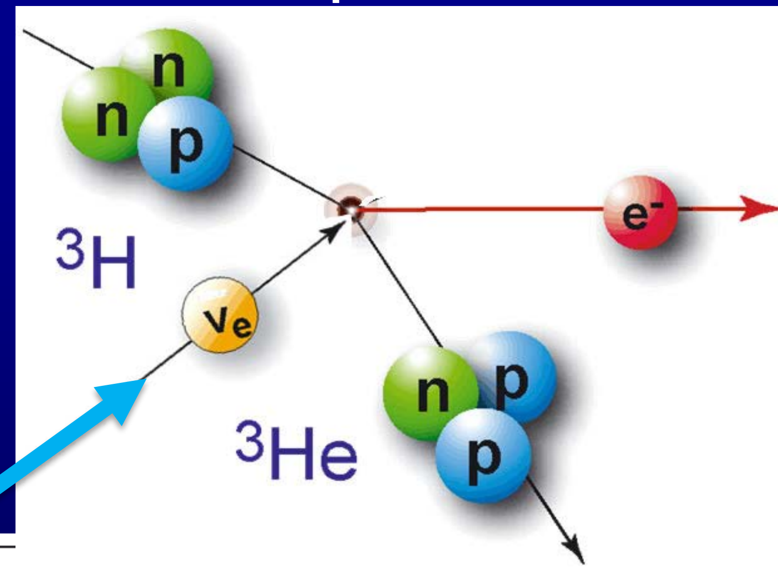
EM Optics

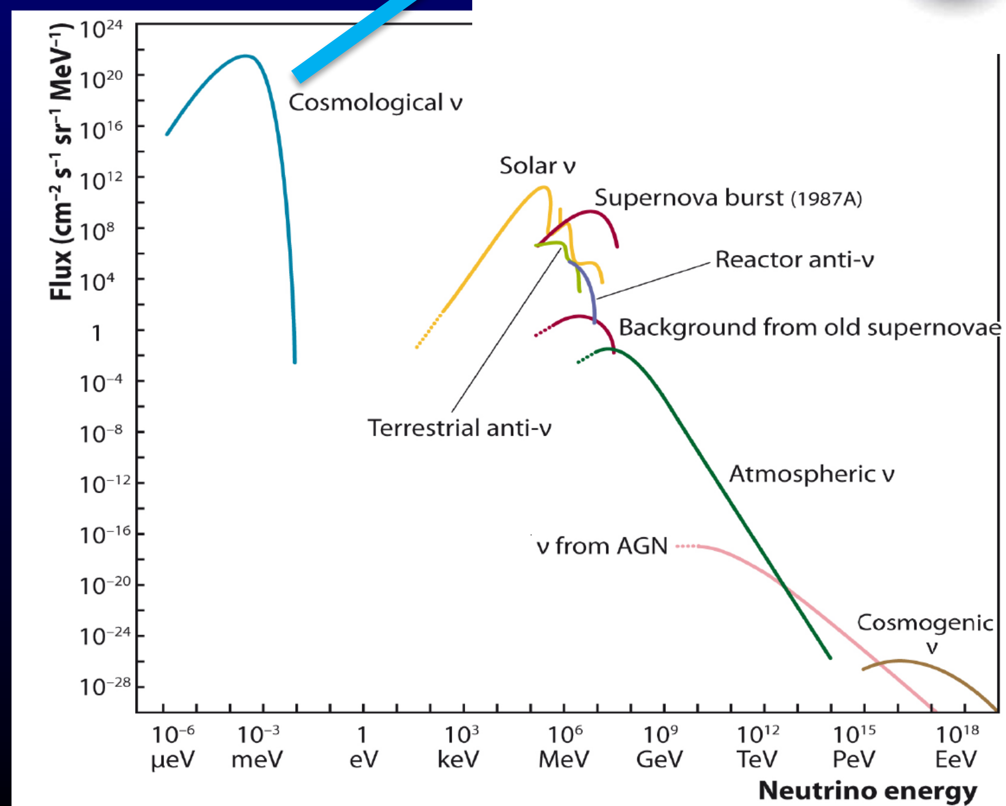


Neutrino capture on Tritium

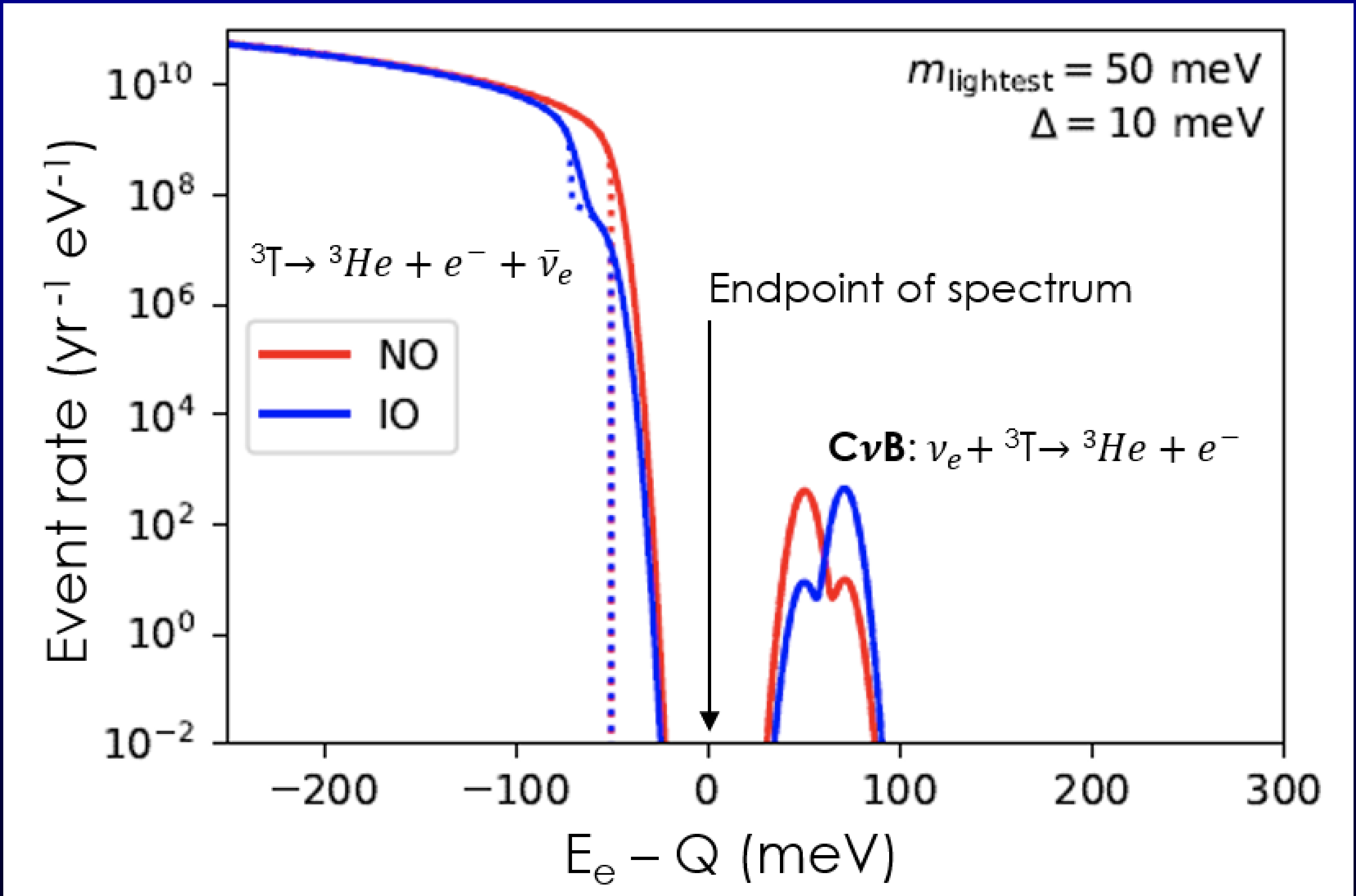


Tritium β-decay
(12.3 yr half-life)



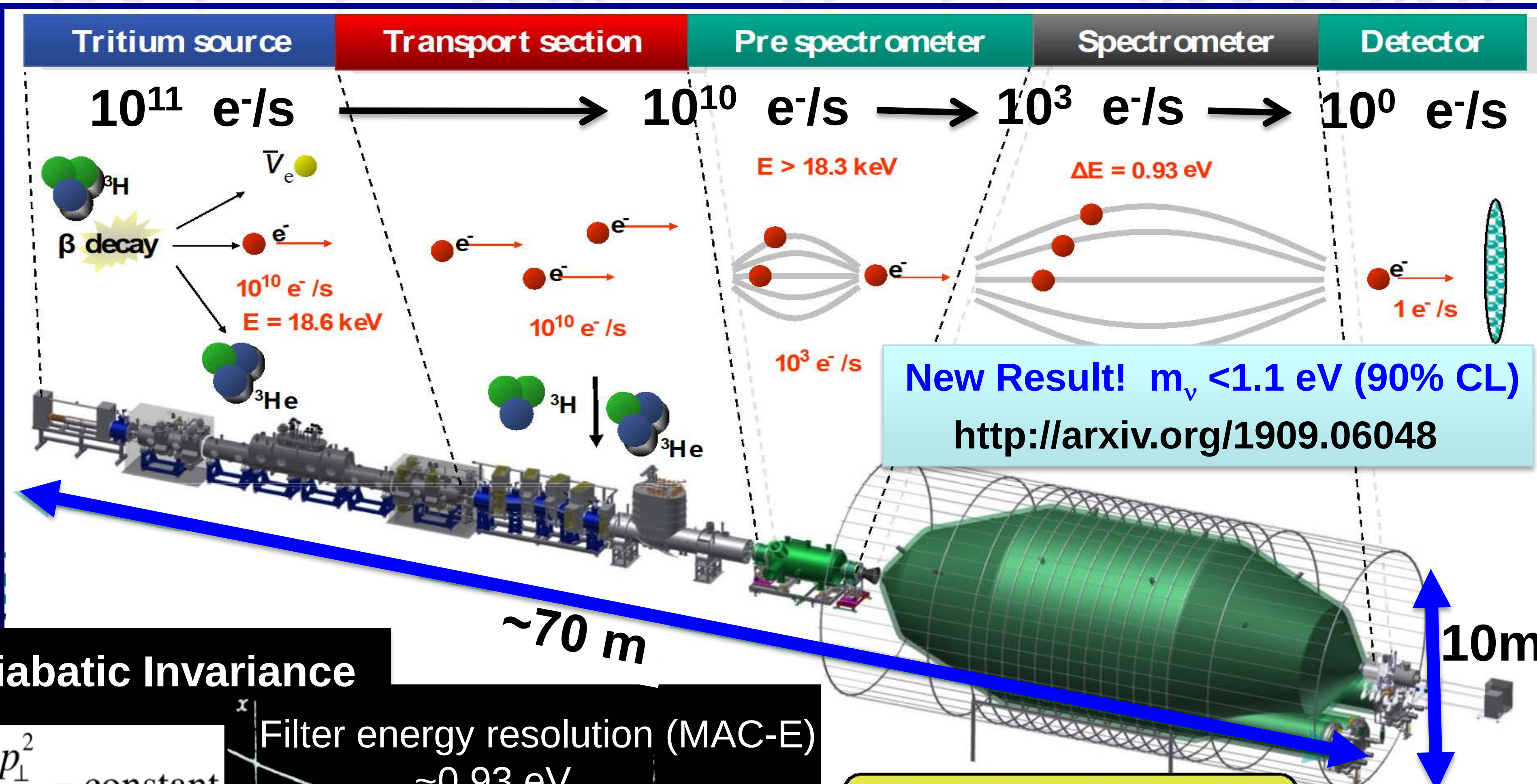


Challenges: Resolution and Backgrounds



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

KArlsruhe TRItium Neutrino (KATRIN)



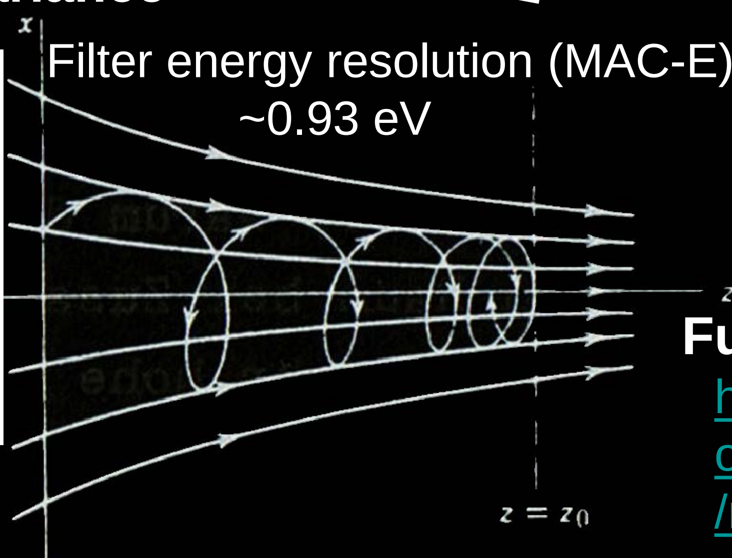
Adiabatic Invariance

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

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

Filter (E - Field)

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



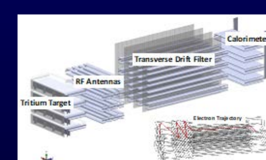
Future of Neutrino Mass Measurements:
https://indico.cern.ch/event/740296/contributions/3160751/attachments/1738496/2812624/neutrino_town_meeting_weinheimer.pdf

Difference in Scales

KATRIN

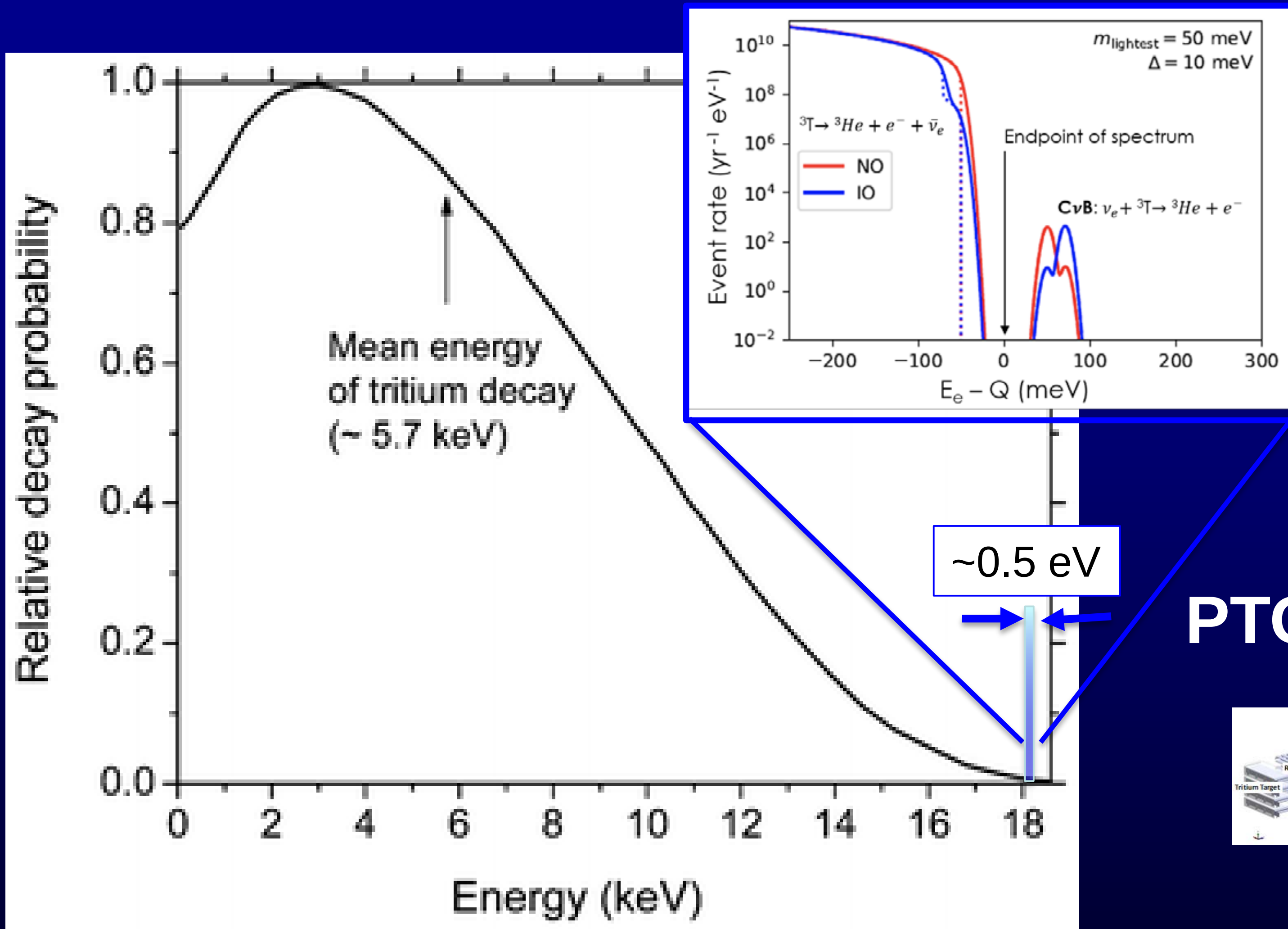
~1200m^3

PTOLEMY

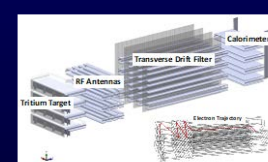


~1m^3

Difference in Scales



PTOLEMY



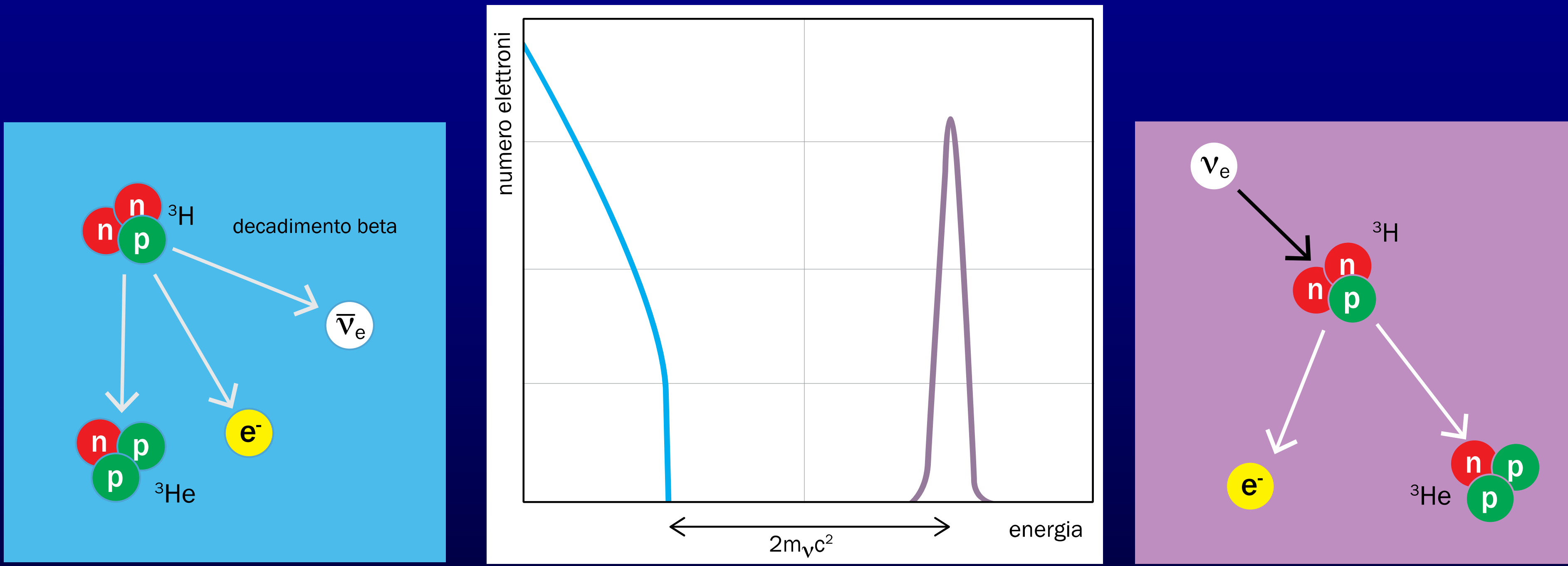
~1m^3

Stereo 27 GHz RF feeds

→ Digitally select endpoint electrons

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]



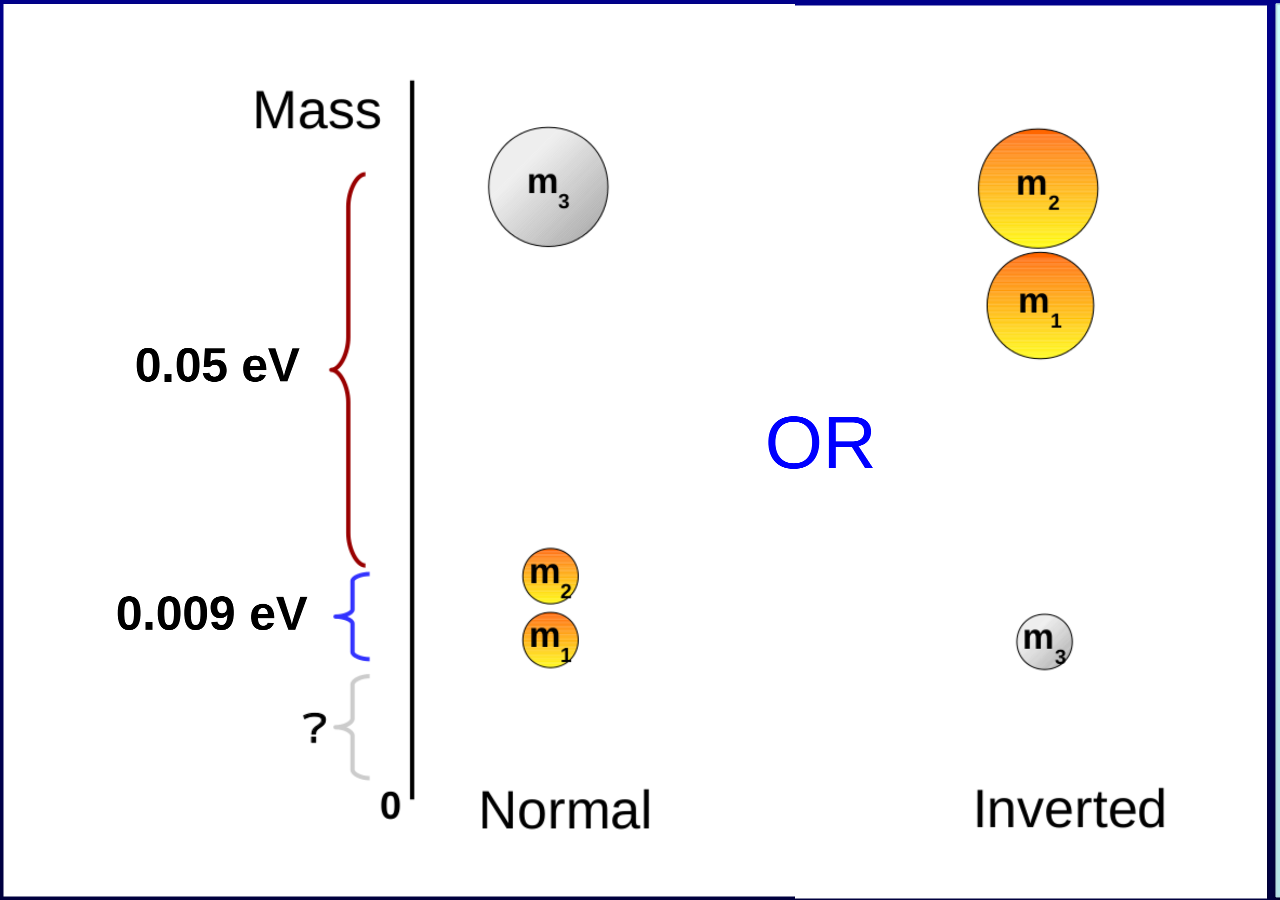
What do we know?

Electron flavor expected with
m > ~0.05eV
from neutrino oscillations

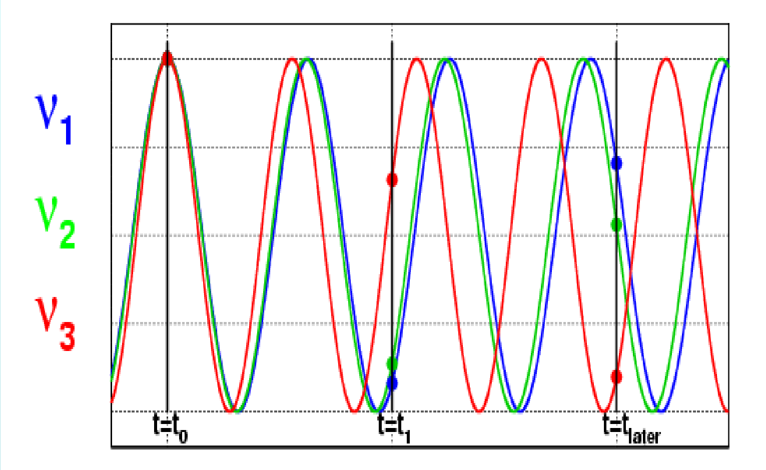
Gap (2m) constrained to
m < ~0.2eV
from Cosmology

[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

Neutrino Masses from Oscillations



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

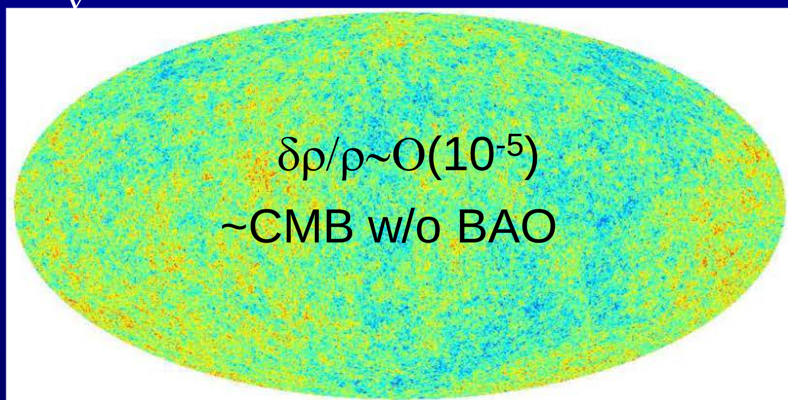


The absolute neutrino masses are not known.

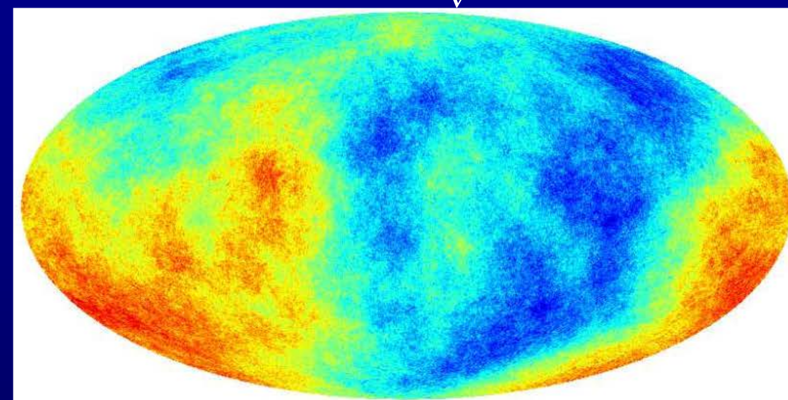
It's not known at this time whether neutrinos masses are "Normal" or "Inverted".

Neutrino Sky

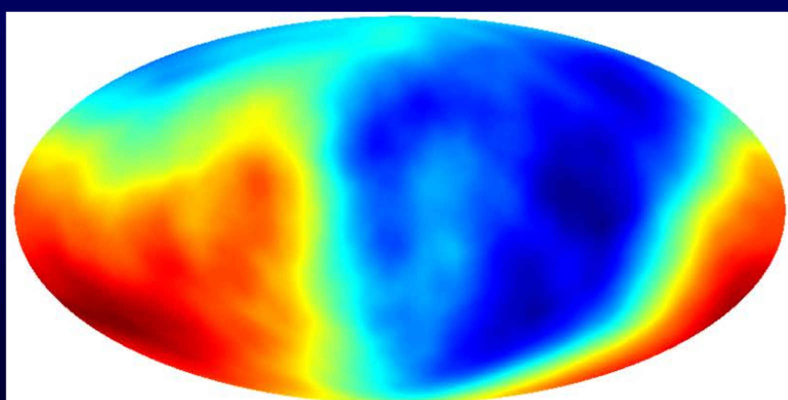
$m_\nu < 0.00001$ eV



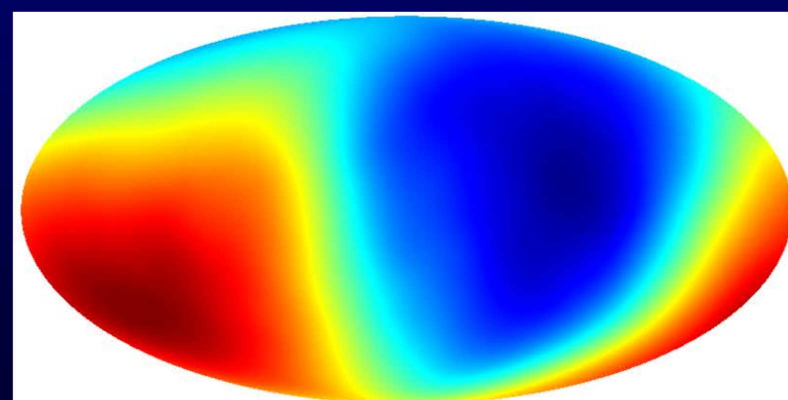
$m_\nu \sim 0.001$ eV



Hannestad, Brandbyge (2009)

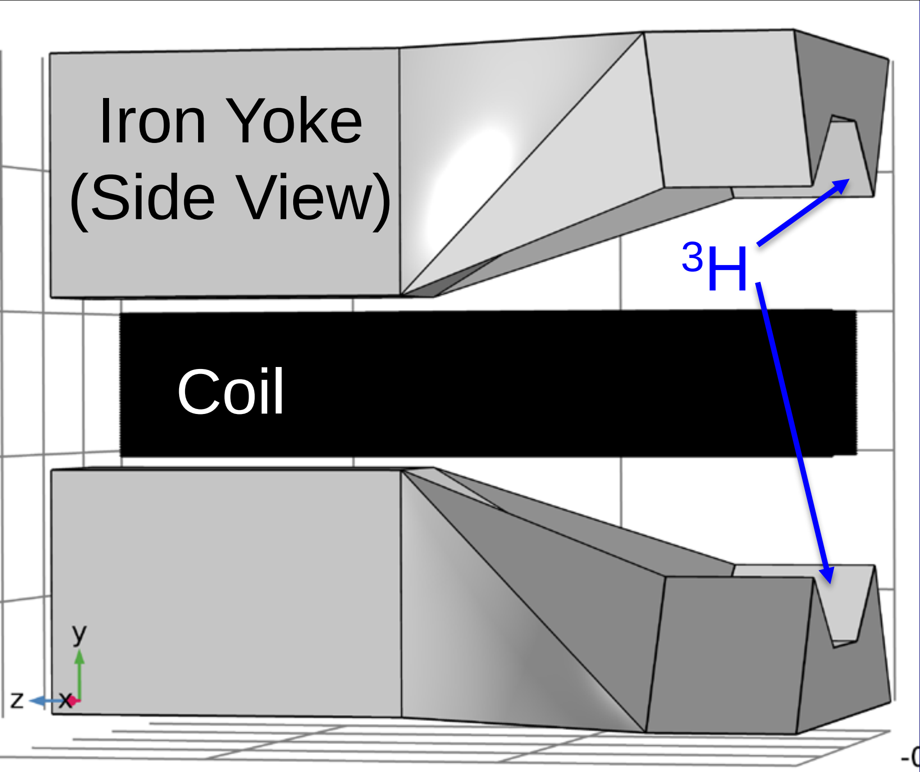


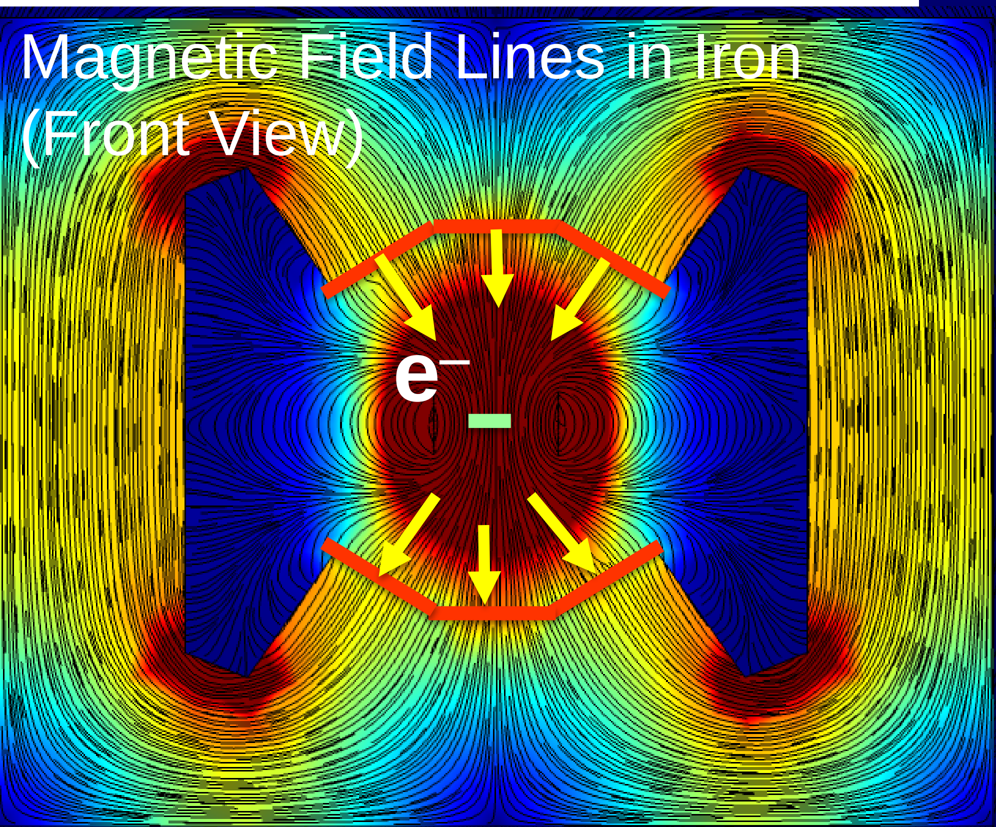
$m_\nu \sim 0.01$ eV



$m_\nu \sim 0.1$ eV

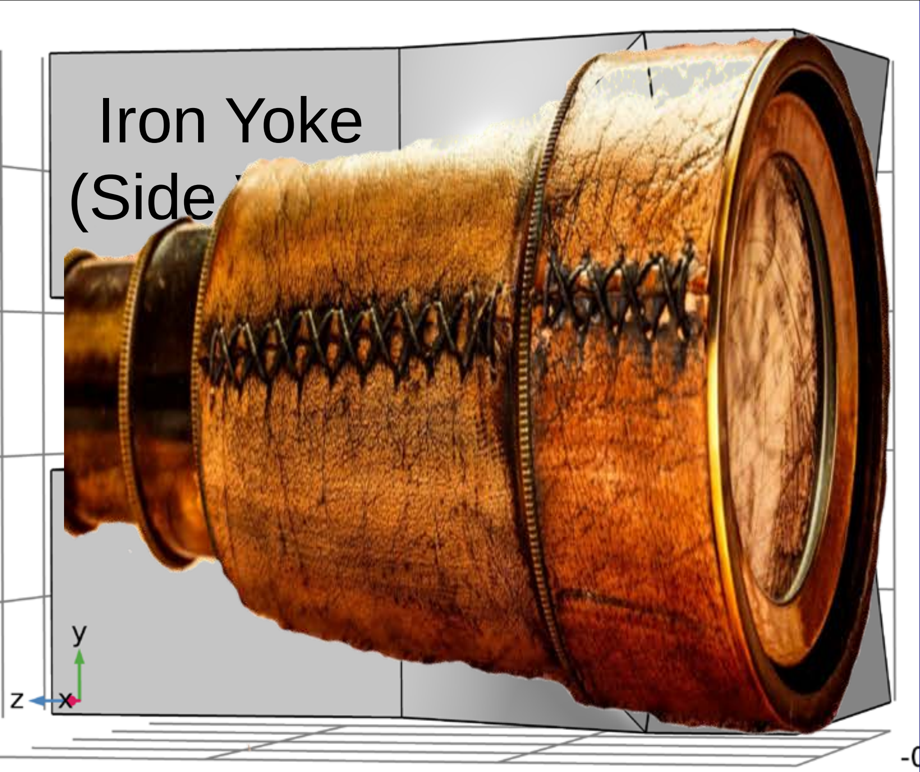
Target Geometry

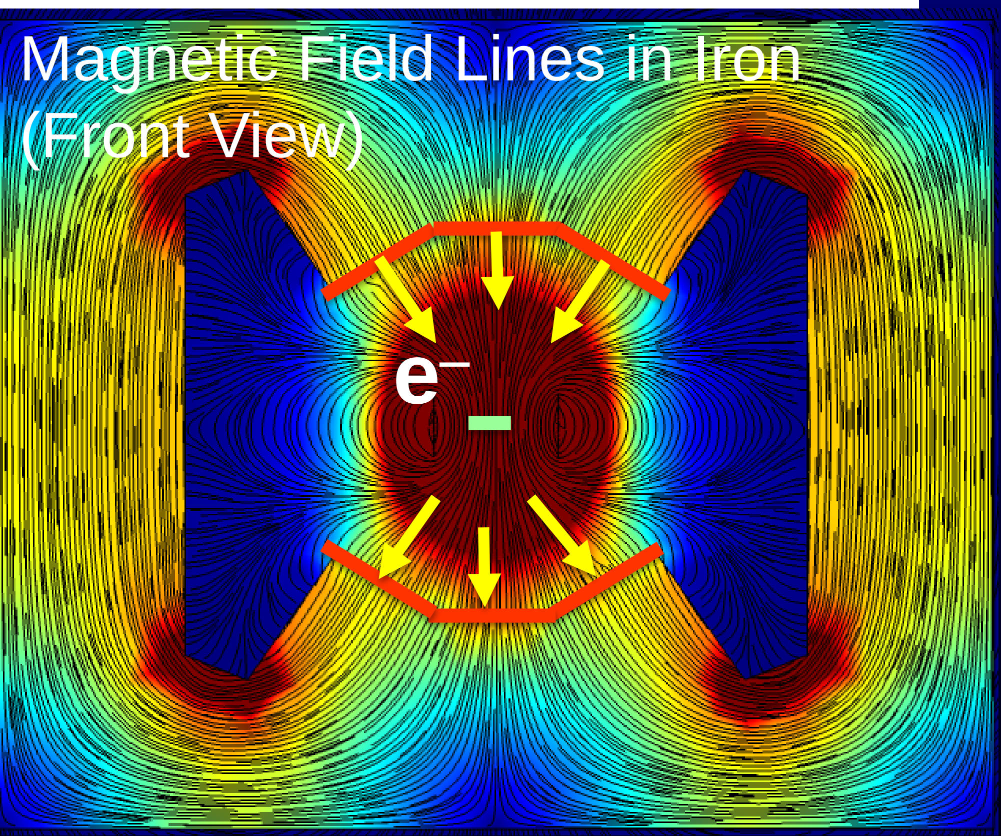




- Collect electrons over a large target area (end-on view in orange, normal to magnetic field yellow).
- Electrons are accelerated into a high magnetic flux region that is an order of magnitude smaller in cross section green.
- Through reflections and transverse drift (EM optics) **e**–'s enter the RF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

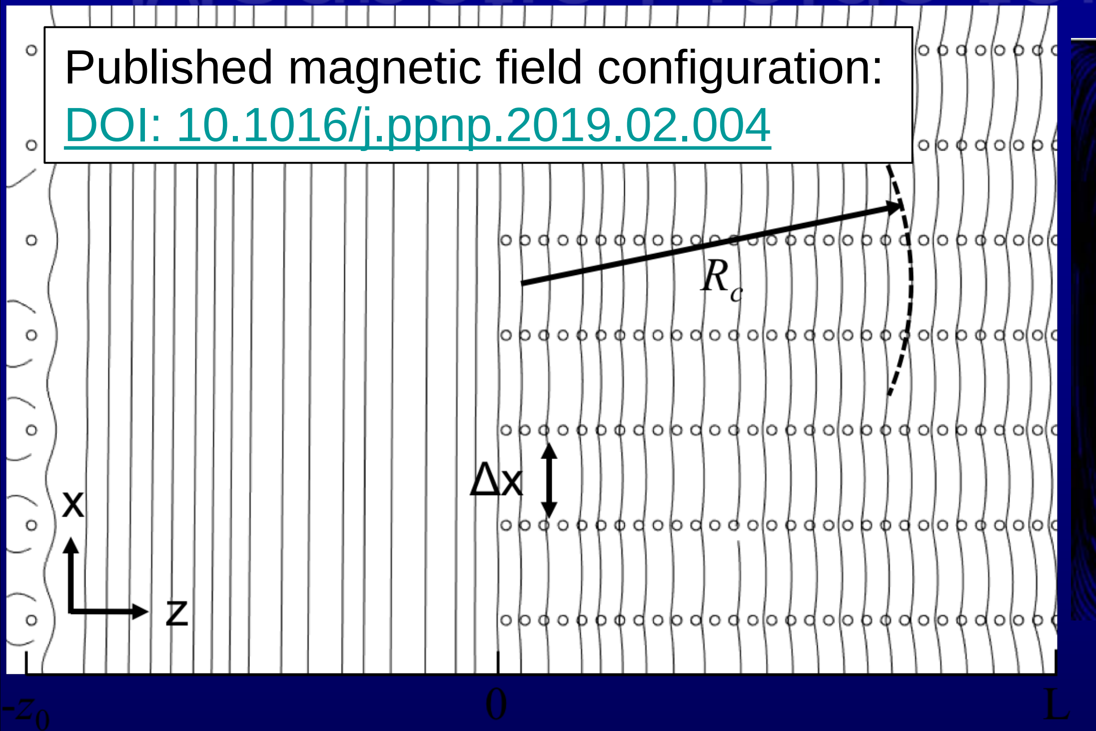
Target Geometry

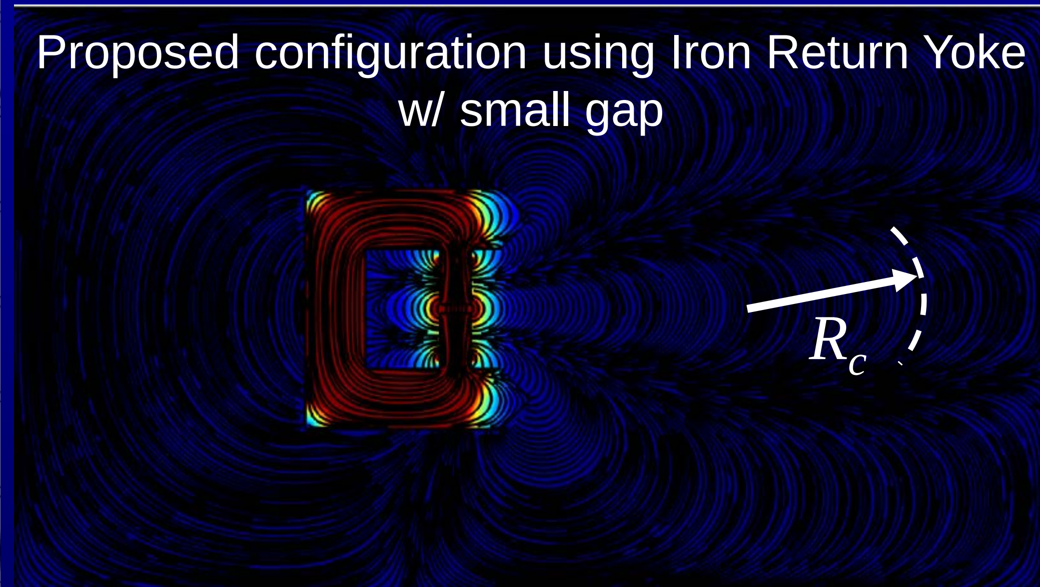


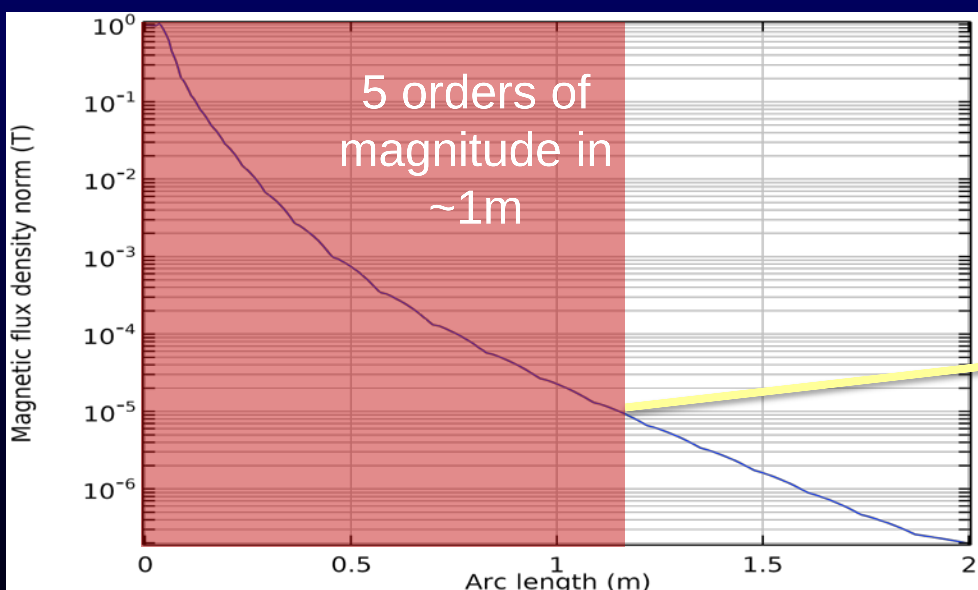


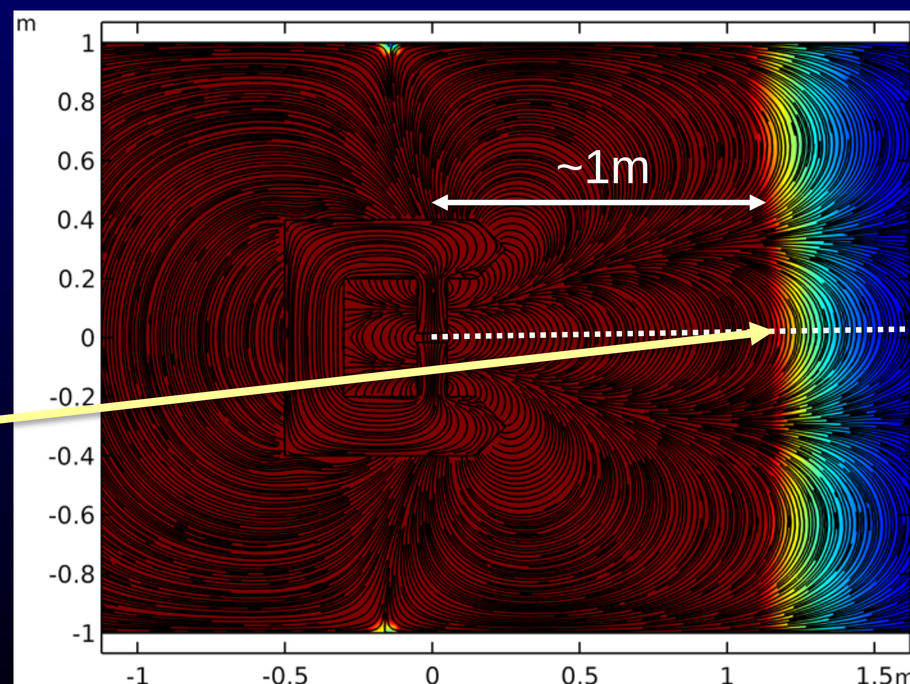
- Collect electrons over a large target area (end-on view in orange, normal to magnetic field yellow).
- Electrons are accelerated into a high magnetic flux region that is an order of magnitude smaller in cross section green.
- Through reflections and transverse drift (EM optics) **e⁻**'s enter the RF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

Magnetic Fields for Transverse Drift



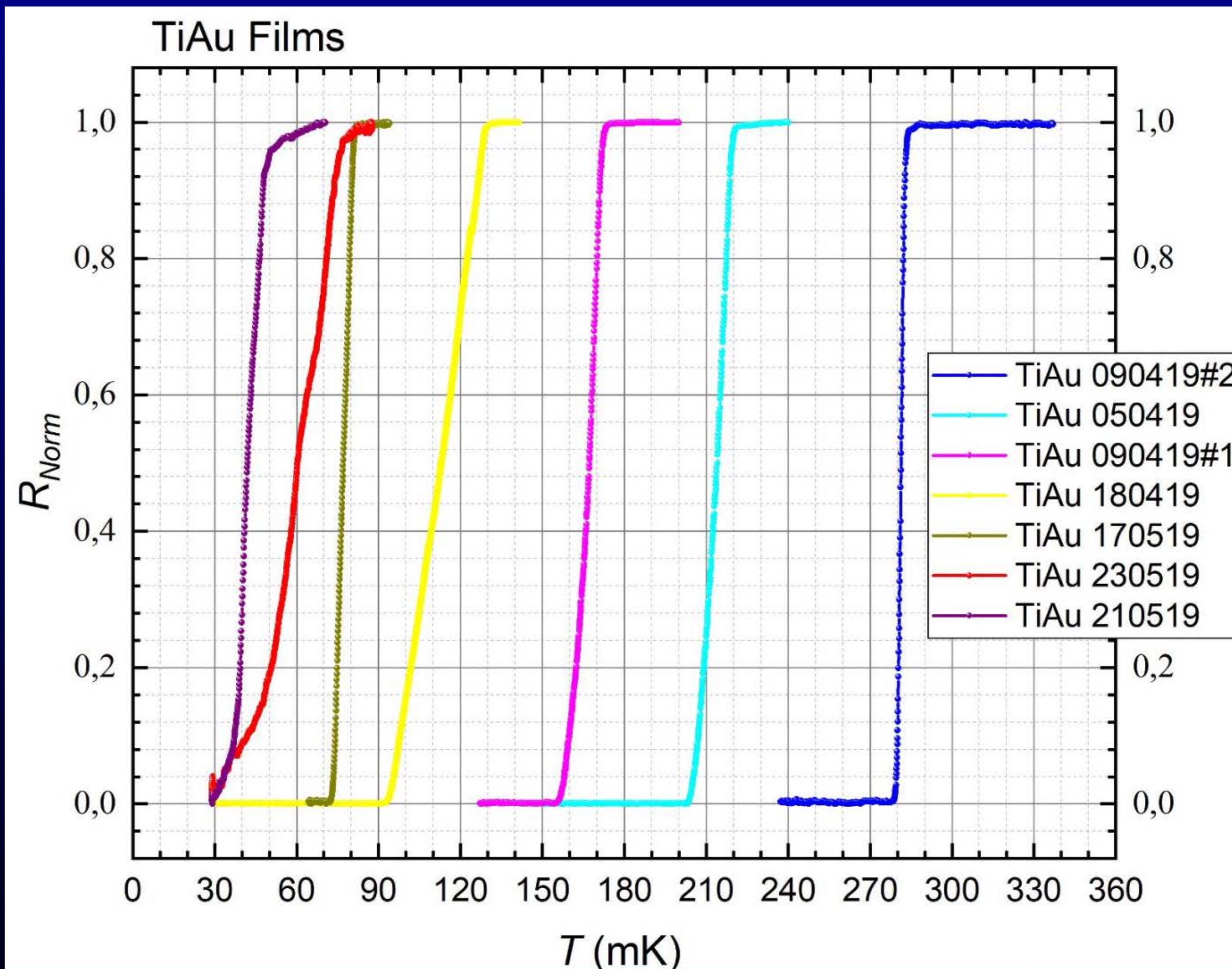


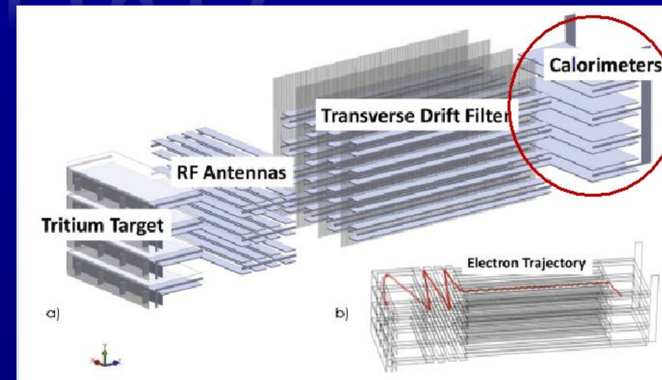




MicroCalorimeter R&D

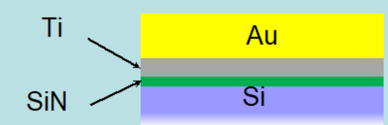
$$E_e = e\left(V_{cal} - V_{target}\right) + E_{cal} + RF_{corr}$$





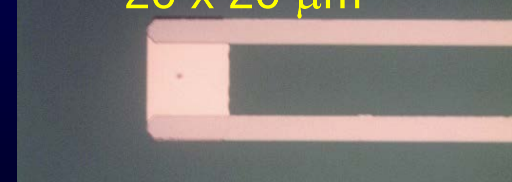
T_c=42 mK with:
Ti=11 nm and Au=27 nm

TiAu



Best solution in terms of heat capacity

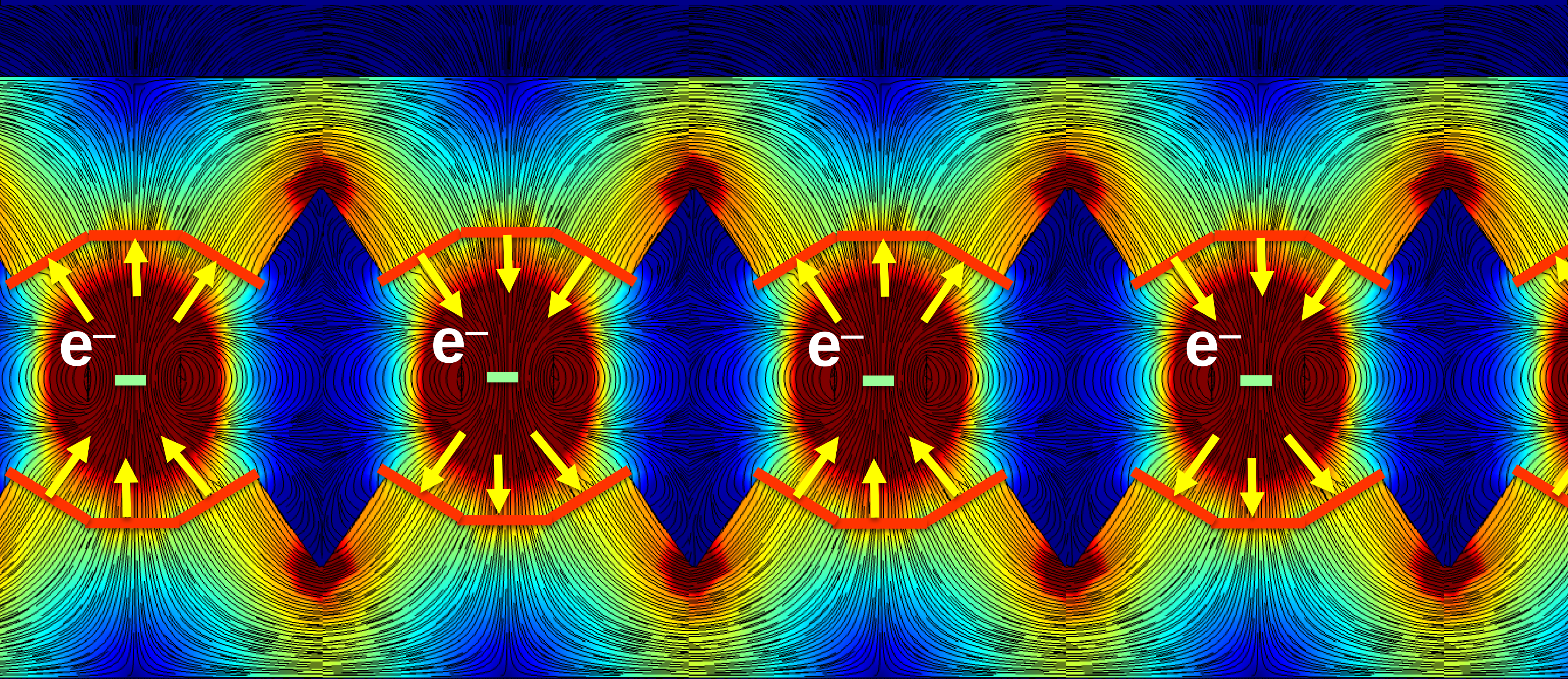
20 x 20 μm^2



INRiM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA

Linearly Repeating Geometry

suitable for underground tunnel



Repeated to reach 10mg → ~100 meters

OR…

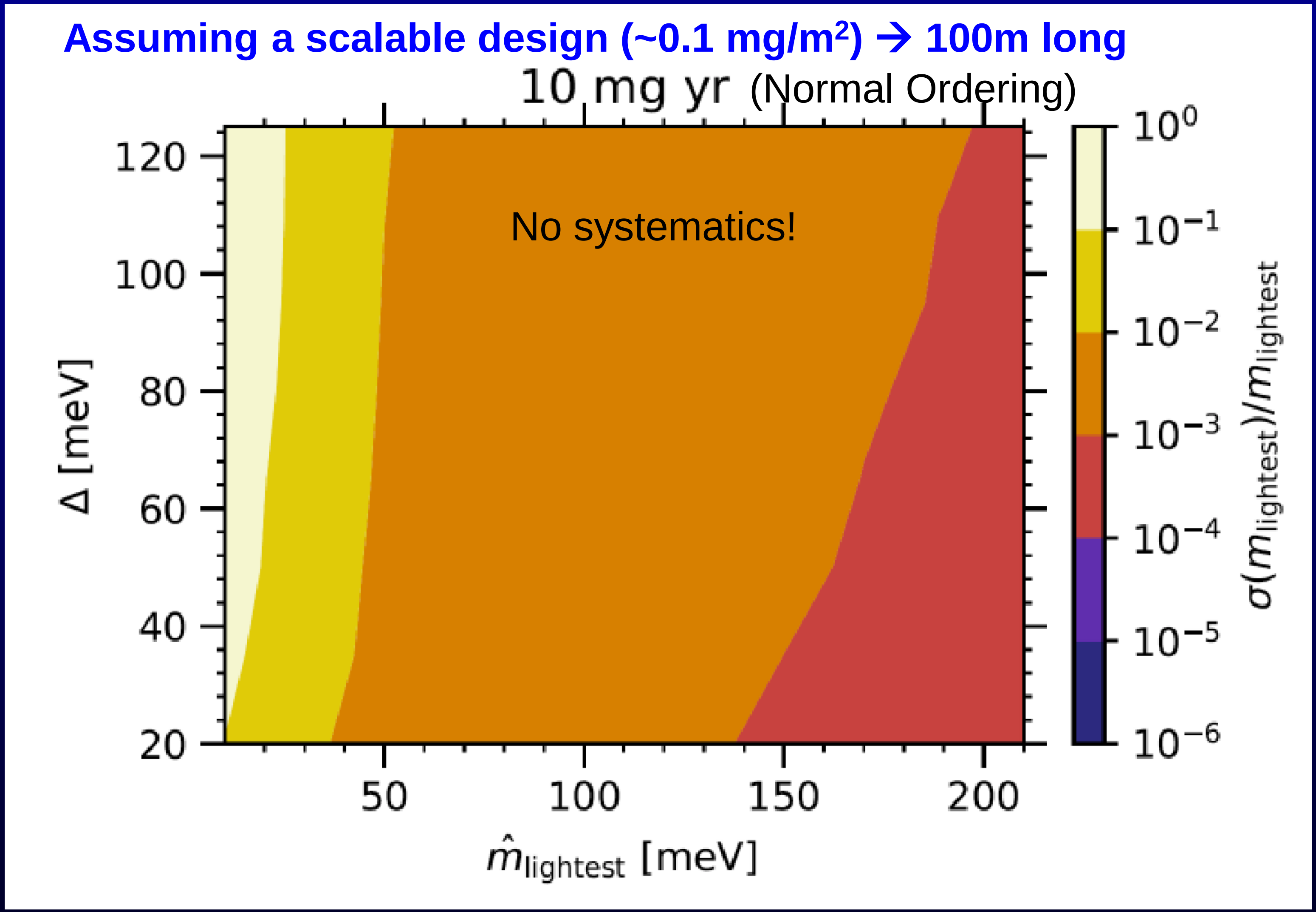
Recent Publications
[PTOLEMY COLLABORATION]

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

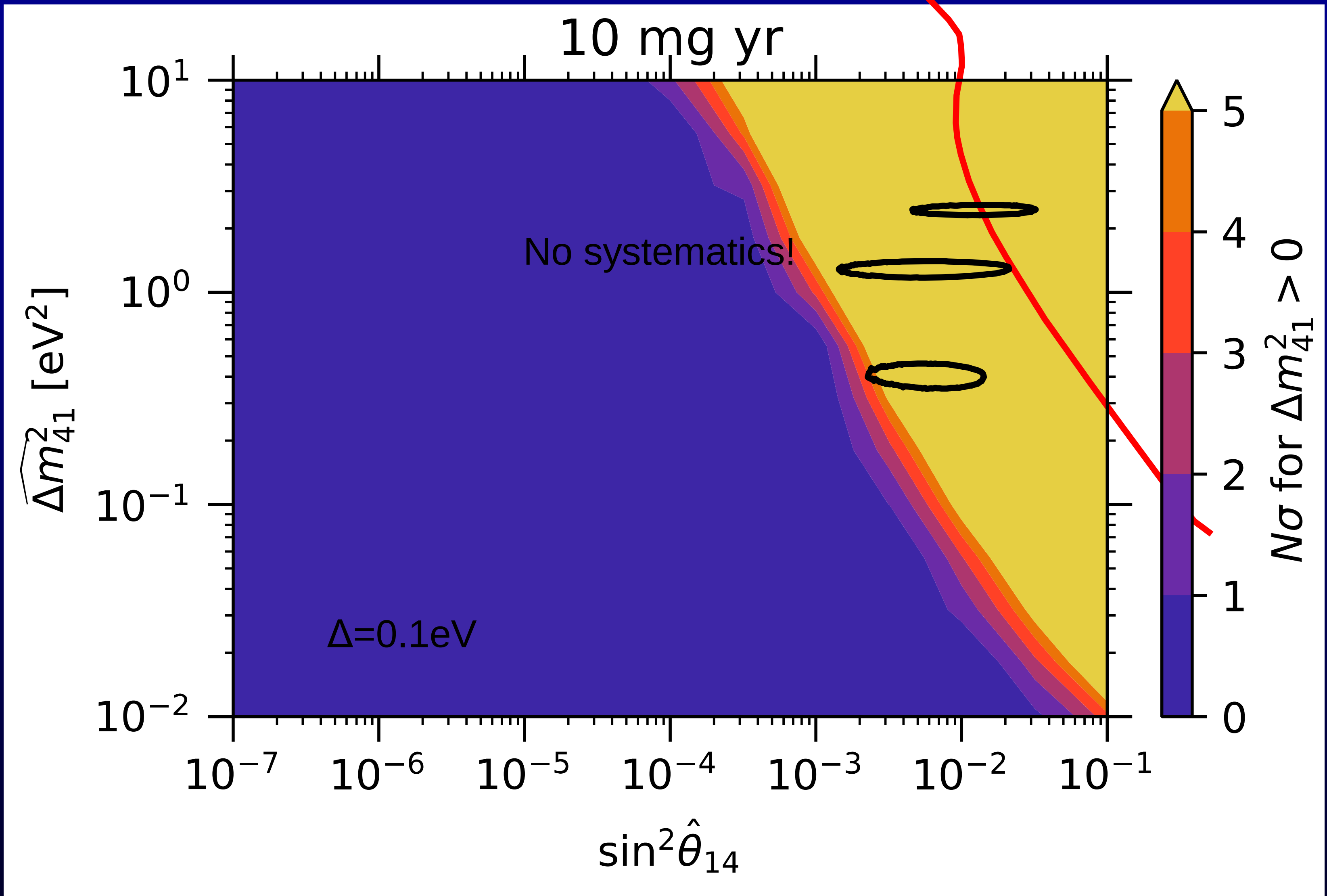
http://ptolemy.lngs.infn.it

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

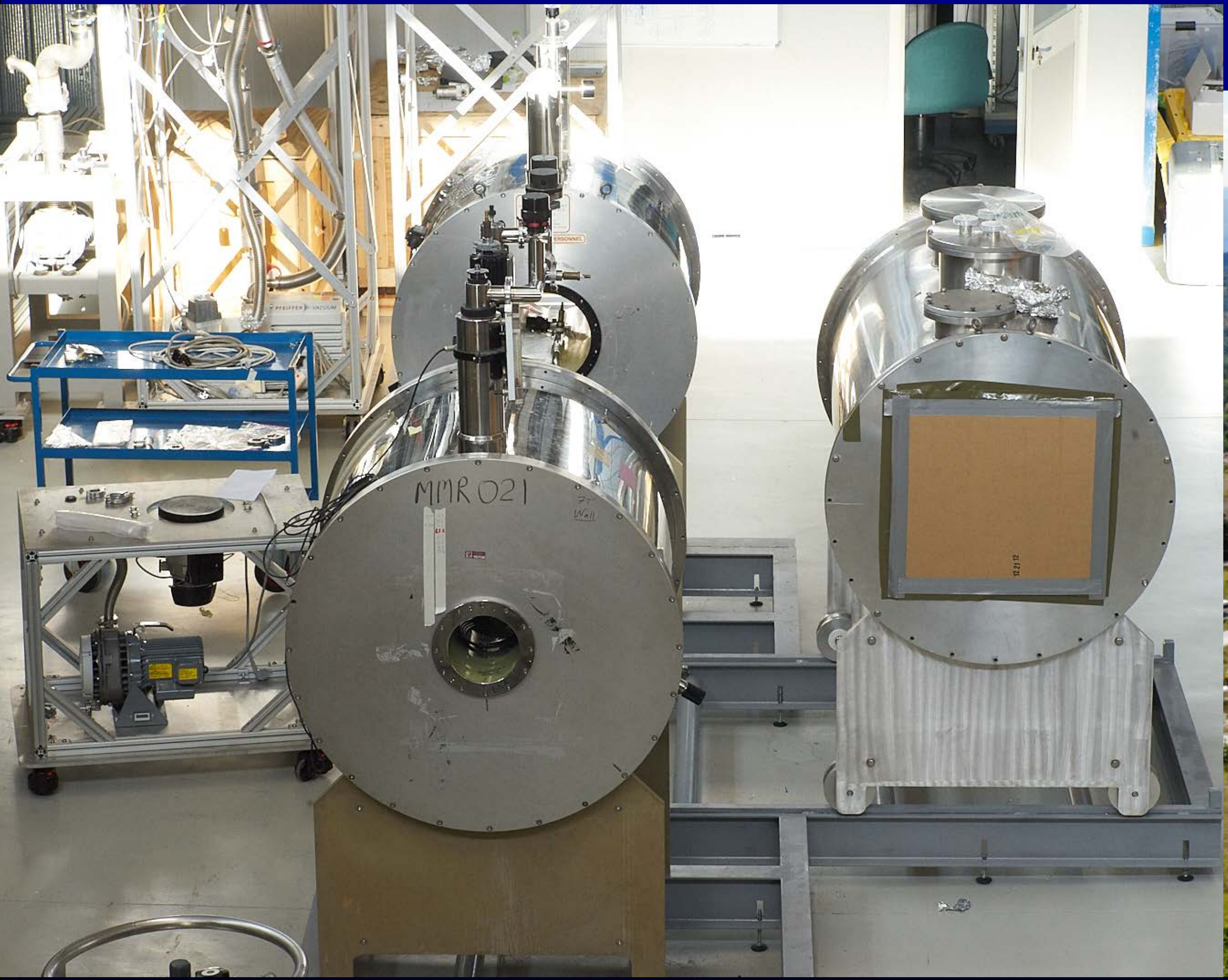


Neutrino physics with the PTOLEMY project,
M.G. Betti et al., JCAP **07** (2019) 047 DOI: 10.1088/1475-7516/2019/07/047
e-Print: arXiv:1902.05508

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

טלסקופ ניטרינים קוסמיים

Telescopio di neutrini cosmologici

Kosmische neutrinotelescoop

Telescopio de neutrinos cósmicos

Kosmisk neutrinoteleskop

Cosmic neutrino telescope

2015 Targeted Grant Award from the SIMONS FOUNDATION