Direct neutrino mass measurements

Cheryl Patrick, University College London
International Neutrino Summer School 2019, Fermilab

A nice, easy reminder of neutrino oscillations

A nice, easy reminder of neutrino oscillations

$$P(\nu_{l_\alpha} \rightarrow \nu_{l_\beta}, x) = \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta M^2(\mathrm{eV}^2) x(\mathrm{km})}{p_\nu(\mathrm{GeV})}\right)$$

(Two-flavour approximation)

A nice, easy reminder of neutrino oscillations

Distance travelled

$$P(\nu_{l_\alpha} \rightarrow \nu_{l_\beta}, x) = \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta M^2(\mathrm{eV}^2) x(\mathrm{km})}{p_\nu(\mathrm{GeV})} \right)$$

(Two-flavour approximation)

Oscillation probability

Momentum

A nice, easy reminder of neutrino oscillations

$$P(\nu_{l_\alpha} \to \nu_{l_\beta}, x) = \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta M^2 (\mathrm{eV}^2) x(\mathrm{km})}{p_\nu (\mathrm{GeV})} \right)$$

(Two-flavour approximation)

Mixing angle

Squared mass difference

… and a more complicated one

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$
$$+2\sum_{i>j} \mathrm{Im}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

… and a more complicated one

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PMNS mixing matrix, $U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{bmatrix}$$

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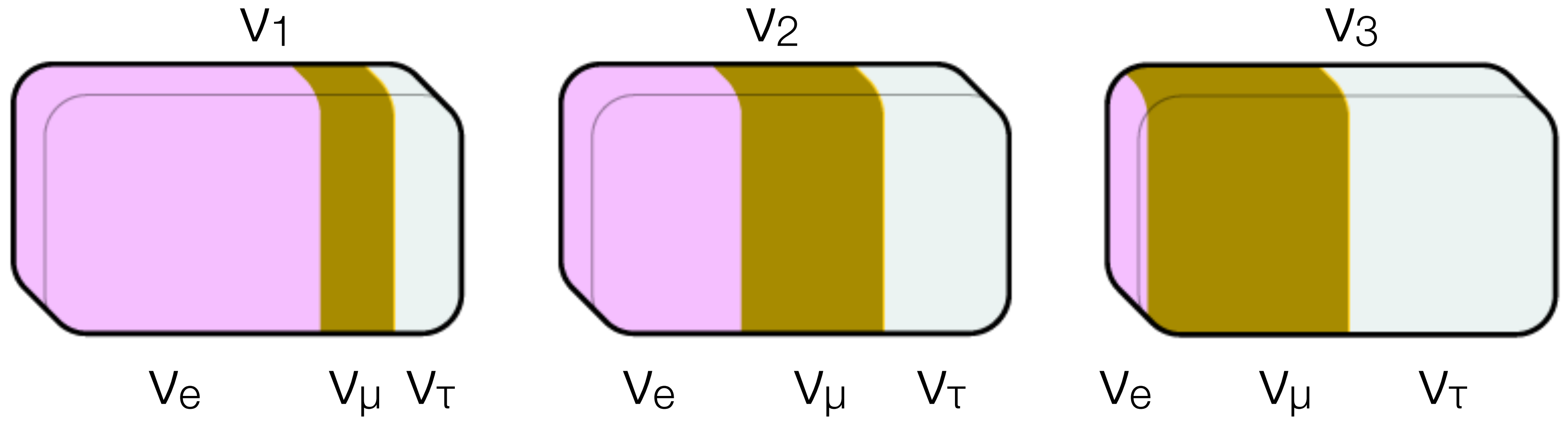

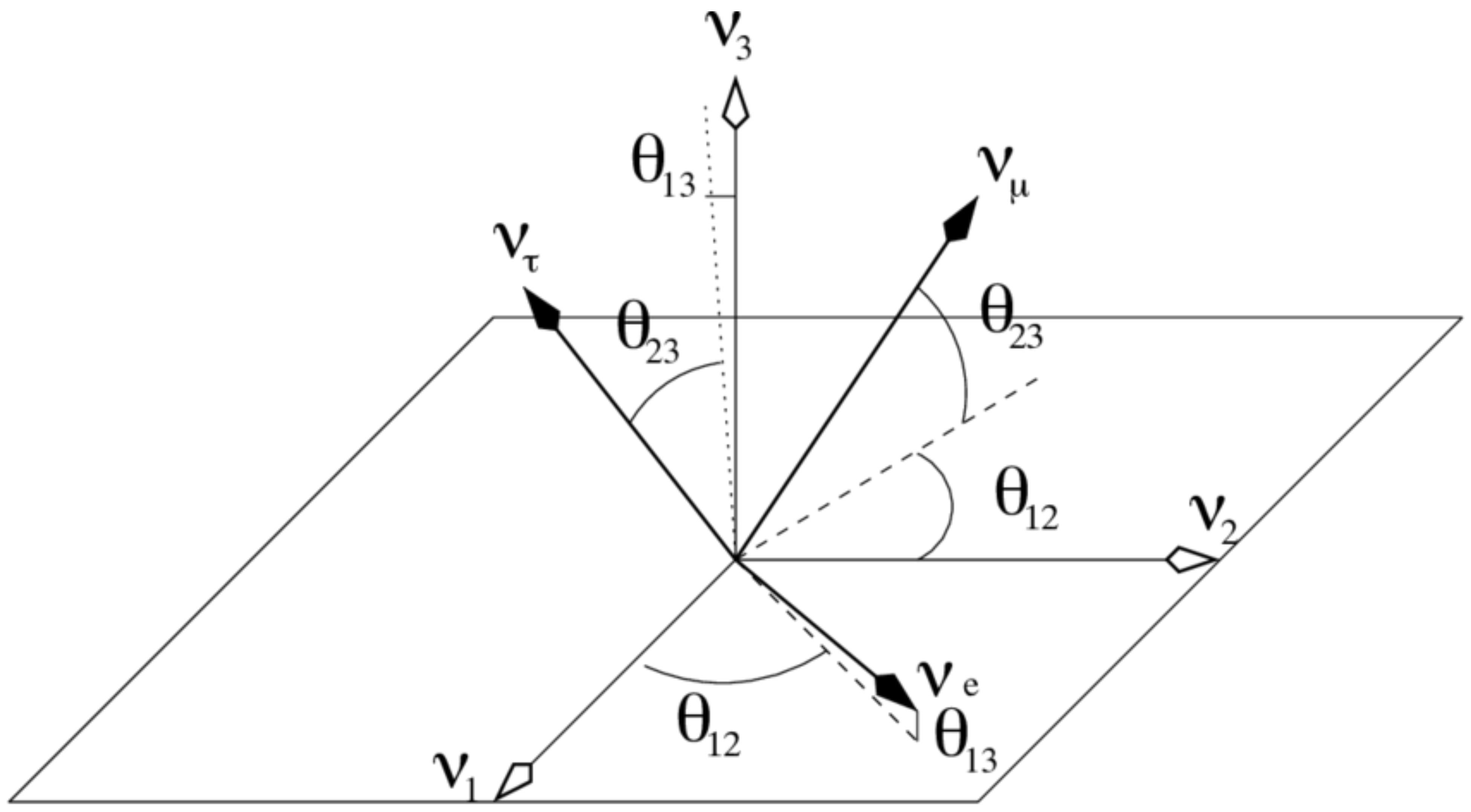

Sines and cosines of mixing angles

PMNS mixing matrix, $U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$

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CP-violating phase changes sign for antineutrinos

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Majorana phases - more on these later!

… and a more complicated one

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}\left(U_{\alpha i}^{*}U_{\beta i}U_{\alpha j}U_{\beta j}^{*}\right)\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$

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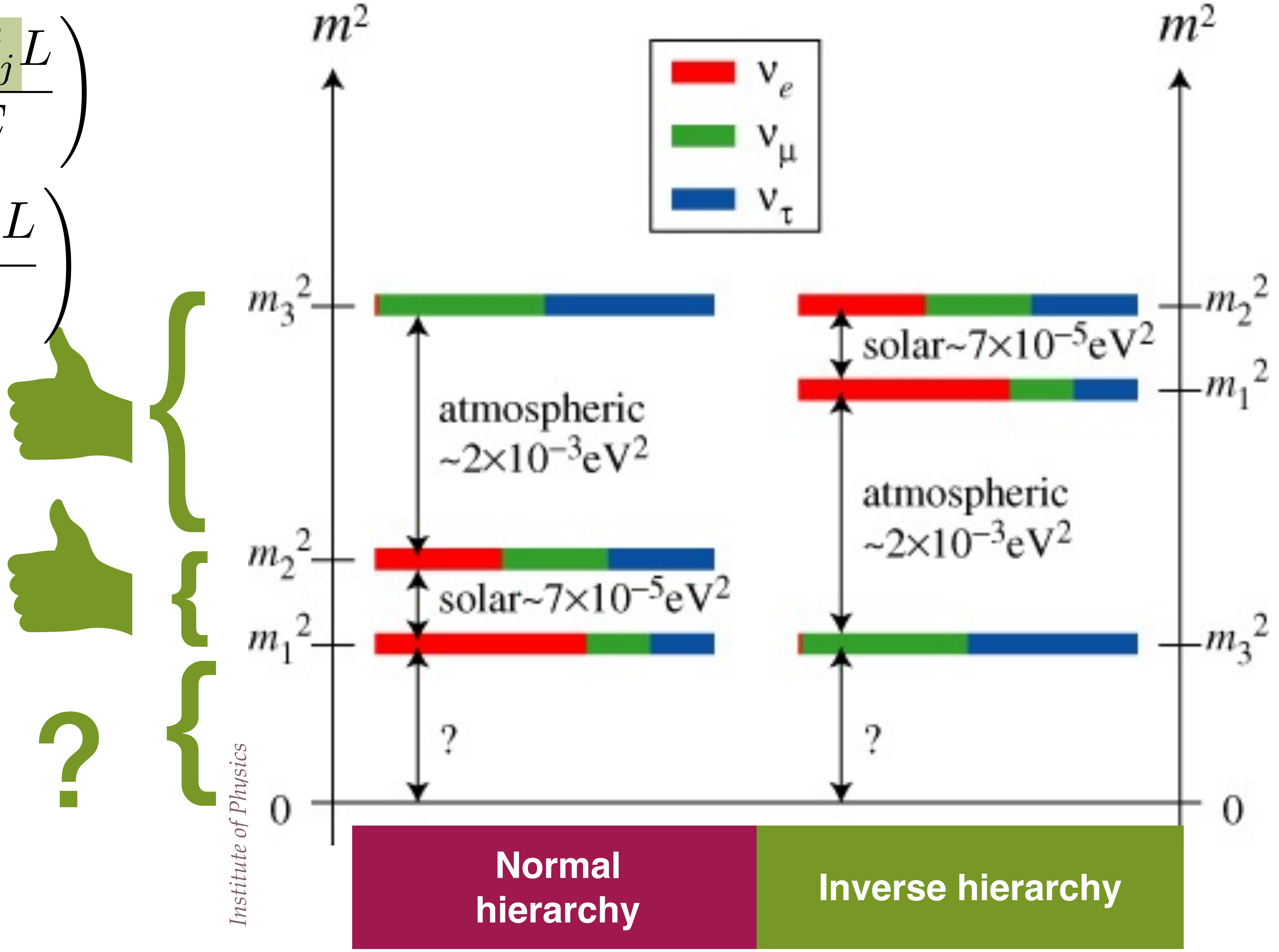


How to measure a neutrino's mass

Indirectly

cycling-challenge.com

Directly

Photo: Daniel Schwen

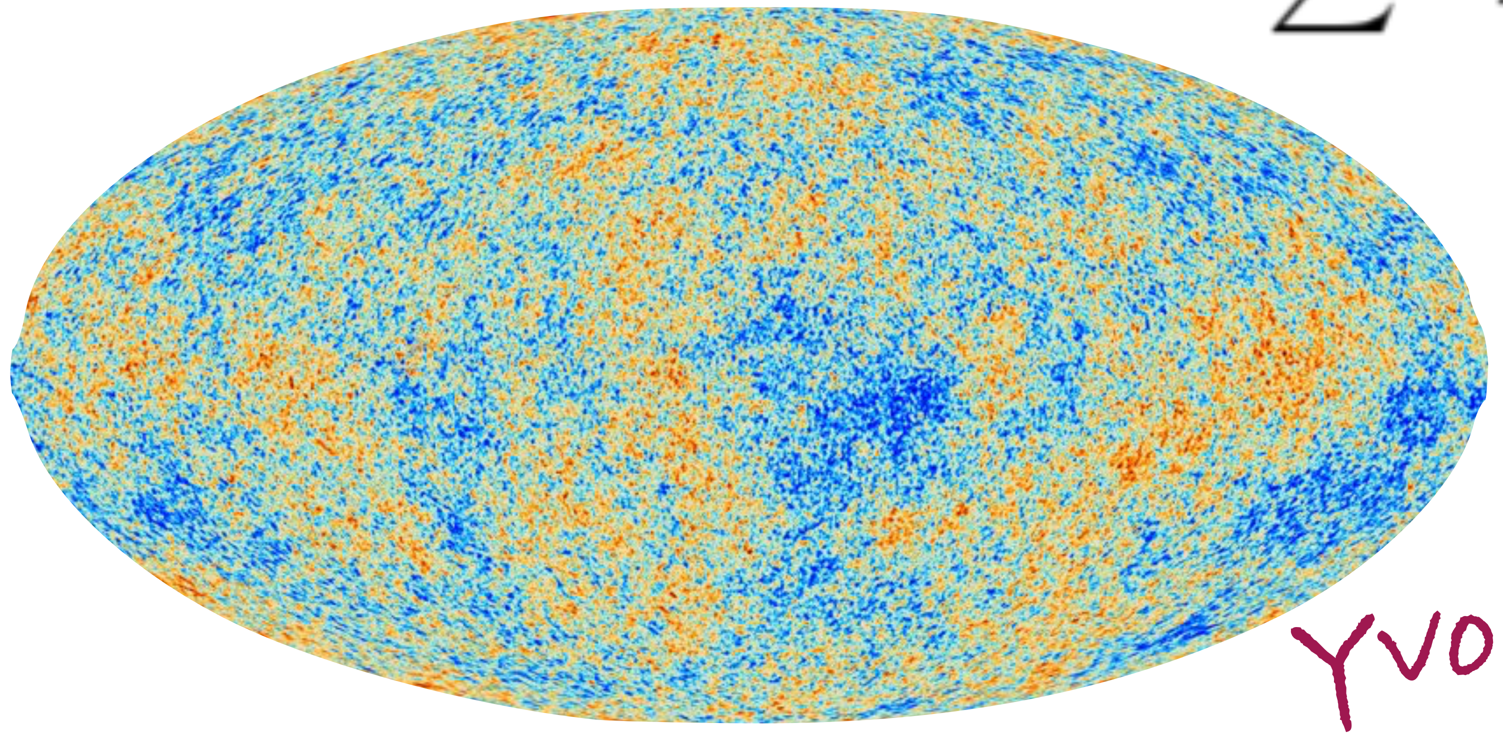
How to measure a neutrino's mass

Indirectly	Directly

Indirectly

Cosmology

$$\sum m_\nu$$



Friday, Aug 16th 2019

Yvonne Wong's talk

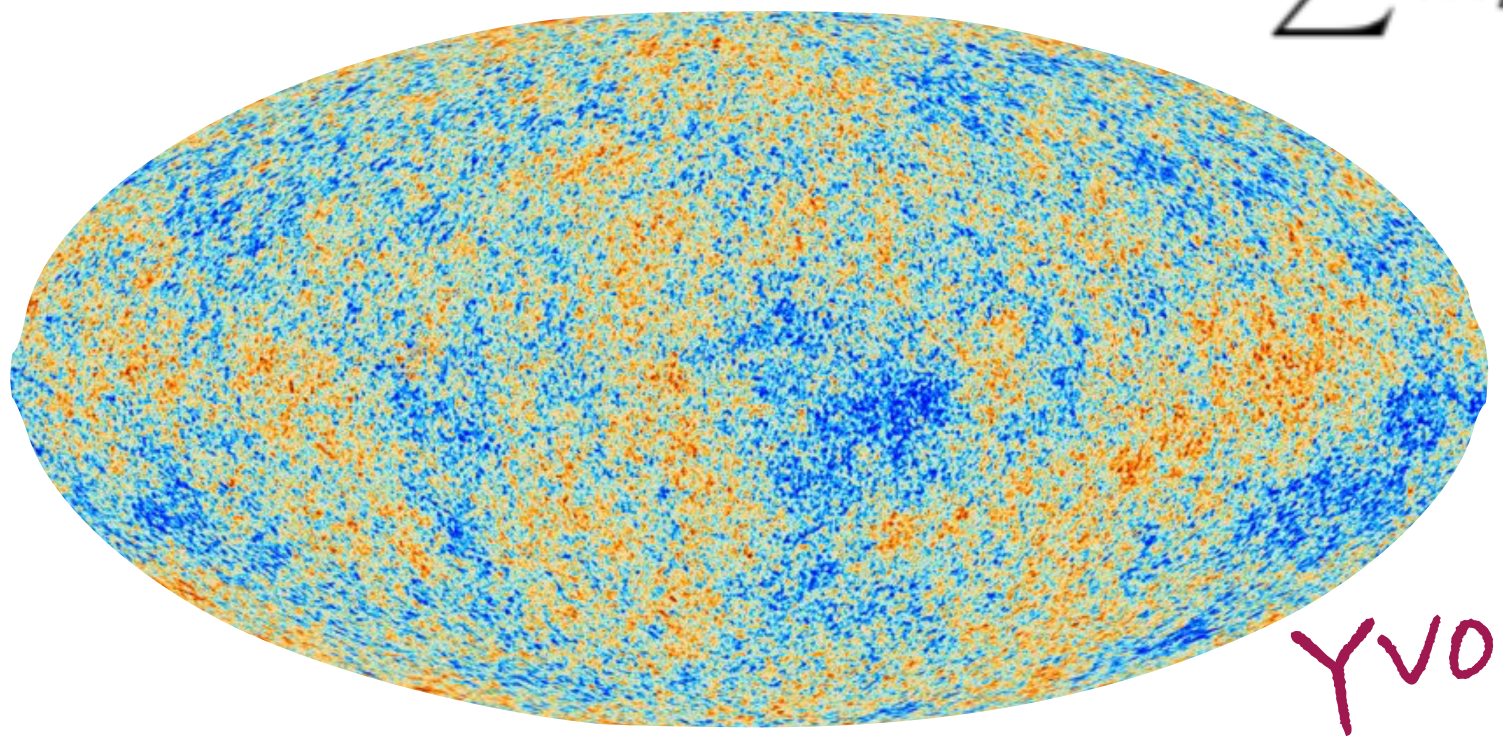
Directly

How to measure a neutrino's mass

Indirectly	Directly

Cosmology

$\sum m_\nu$



August 2019

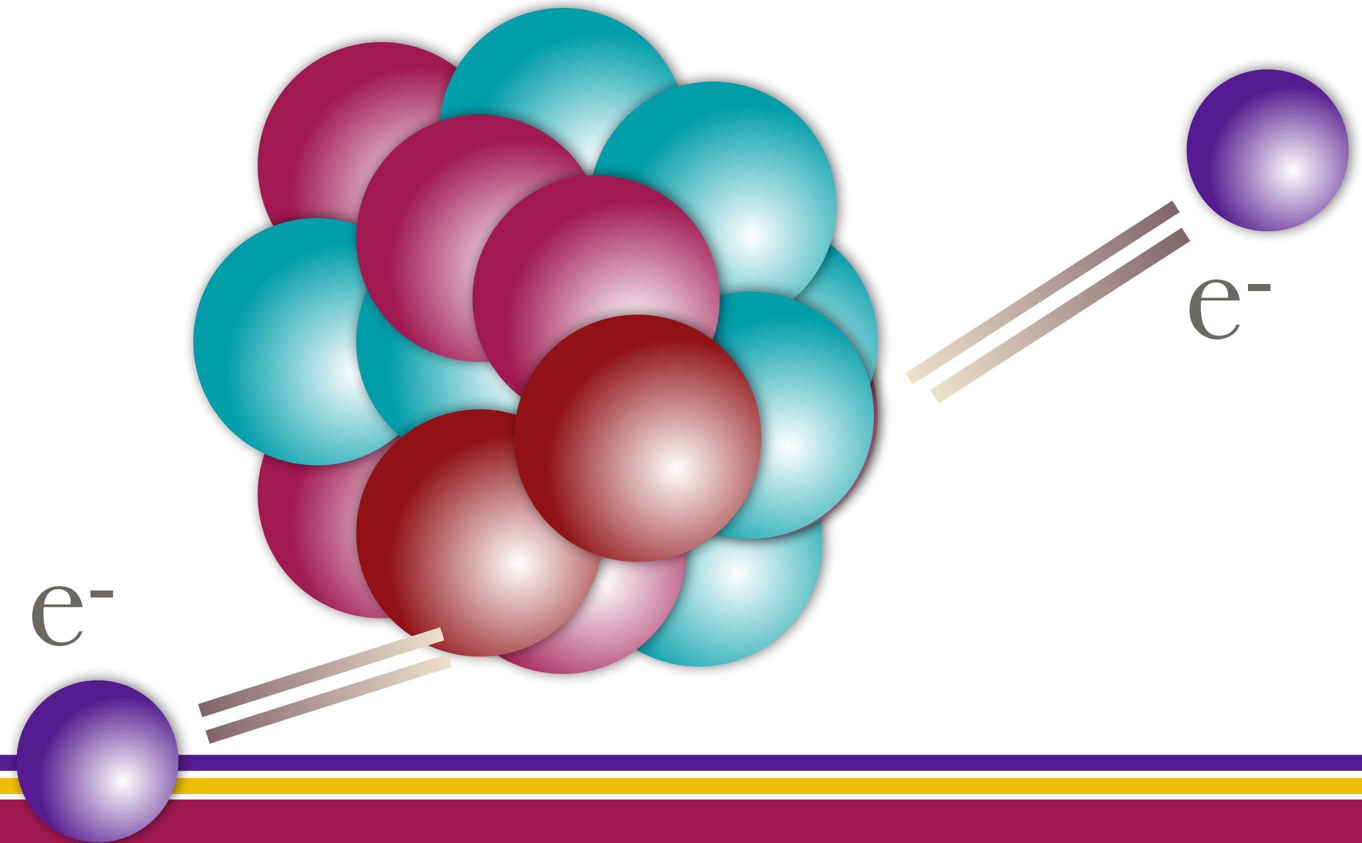
S	M	T	W	T	F	S
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	31

Friday, Aug 16th 2019

Yvonne Wong's talk

Neutrinoless double-beta decay

After the break!

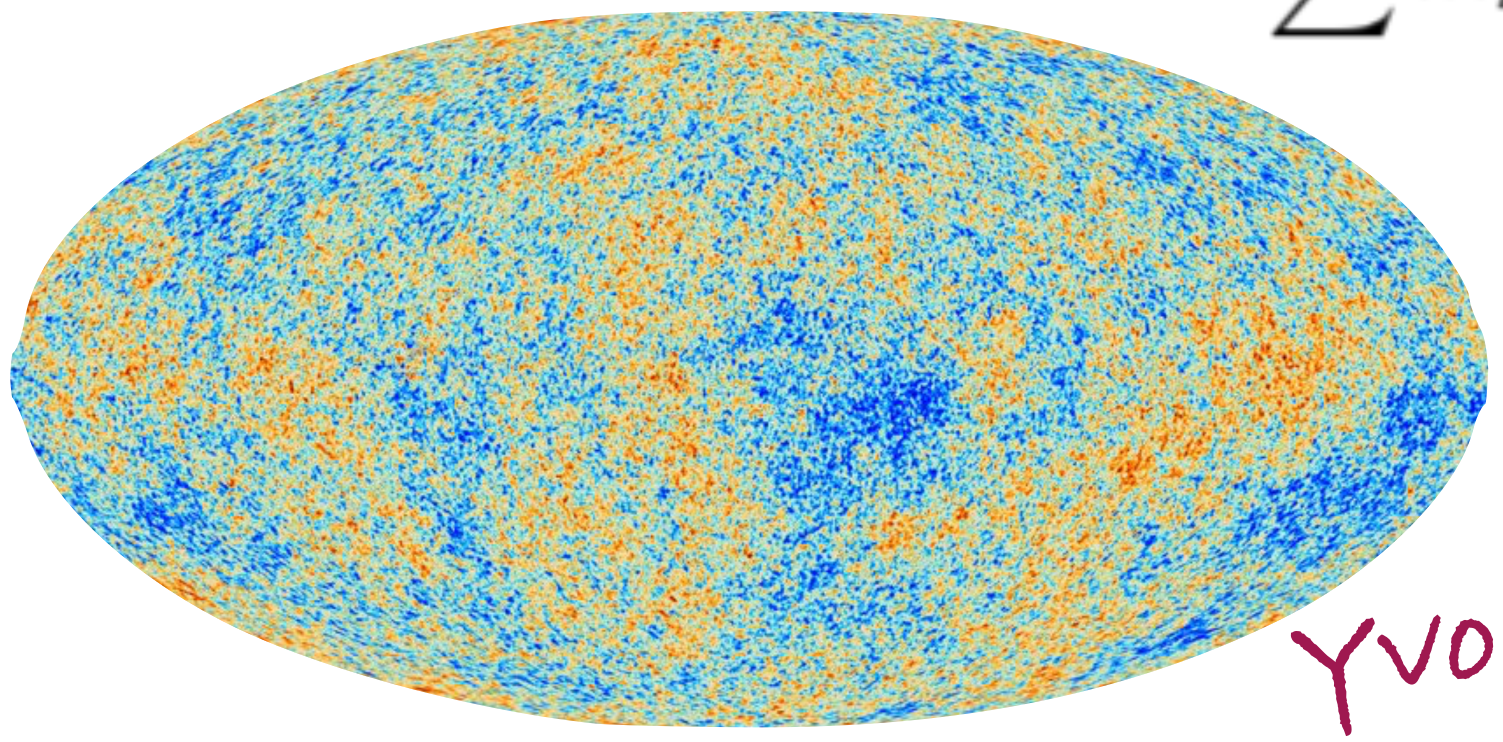


How to measure a neutrino's mass

Indirectly

Cosmology

$\sum m_\nu$



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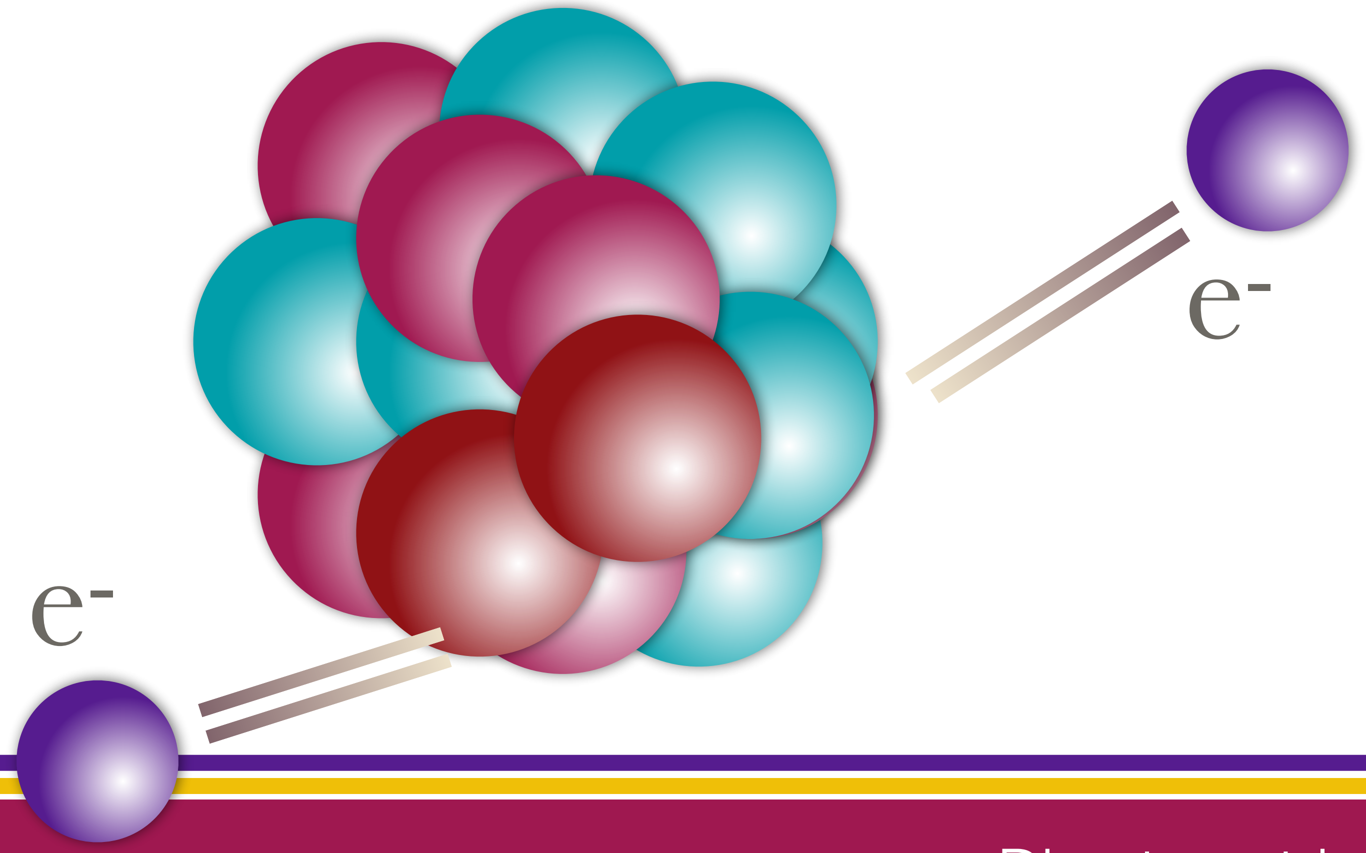


Directly

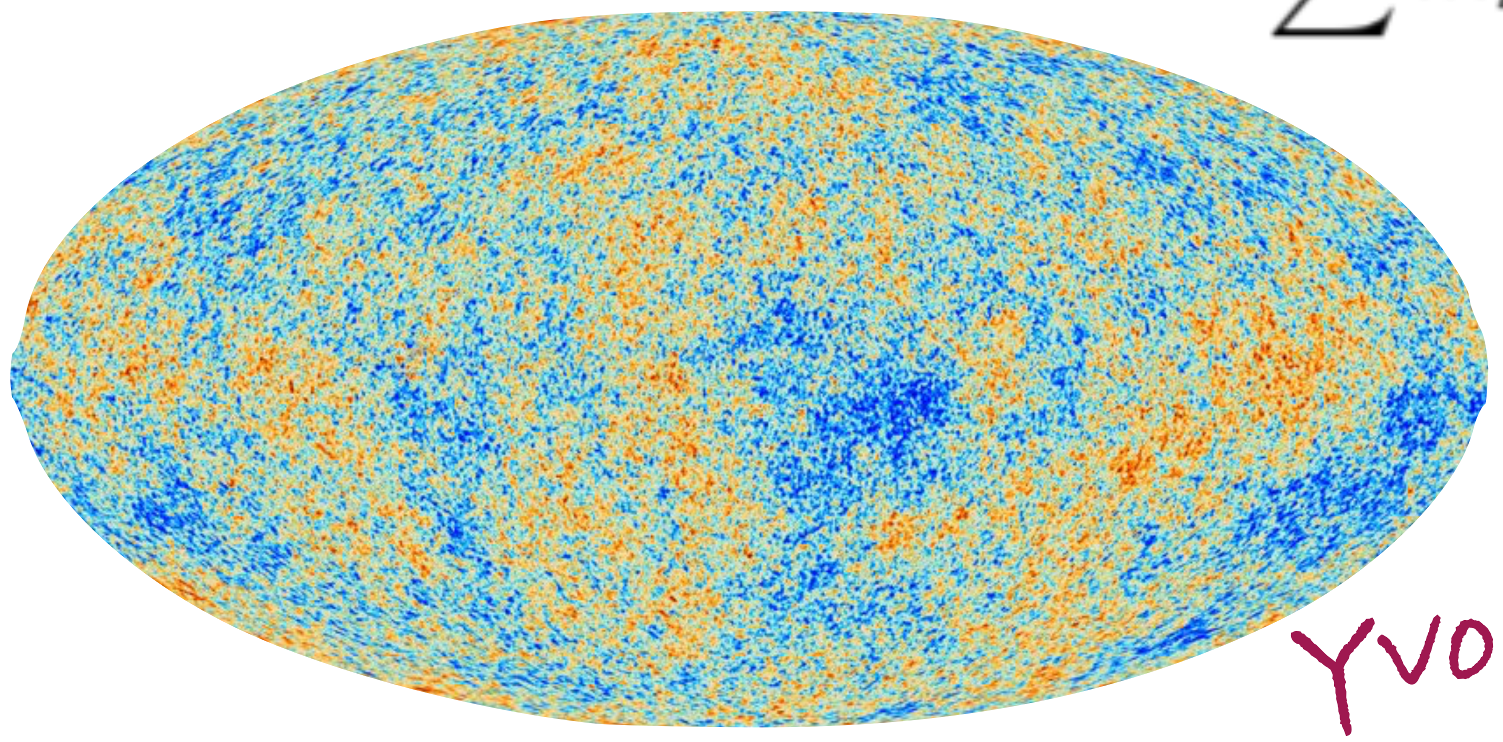
Supernova time-of-flight measurements

How to measure a neutrino's mass

UCL

Indirectly

Cosmology



$\sum m_\nu$

Friday, Aug 16th 2019

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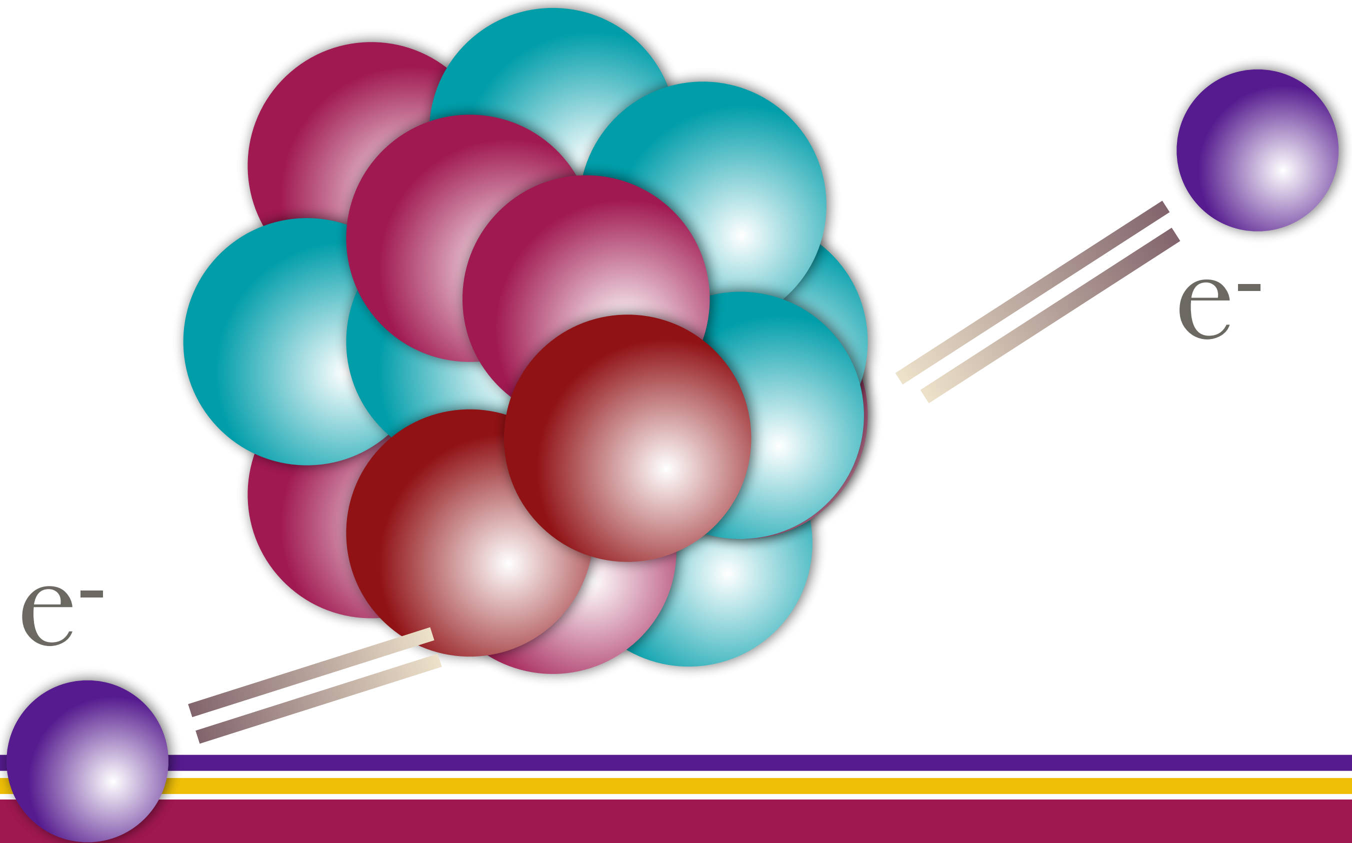
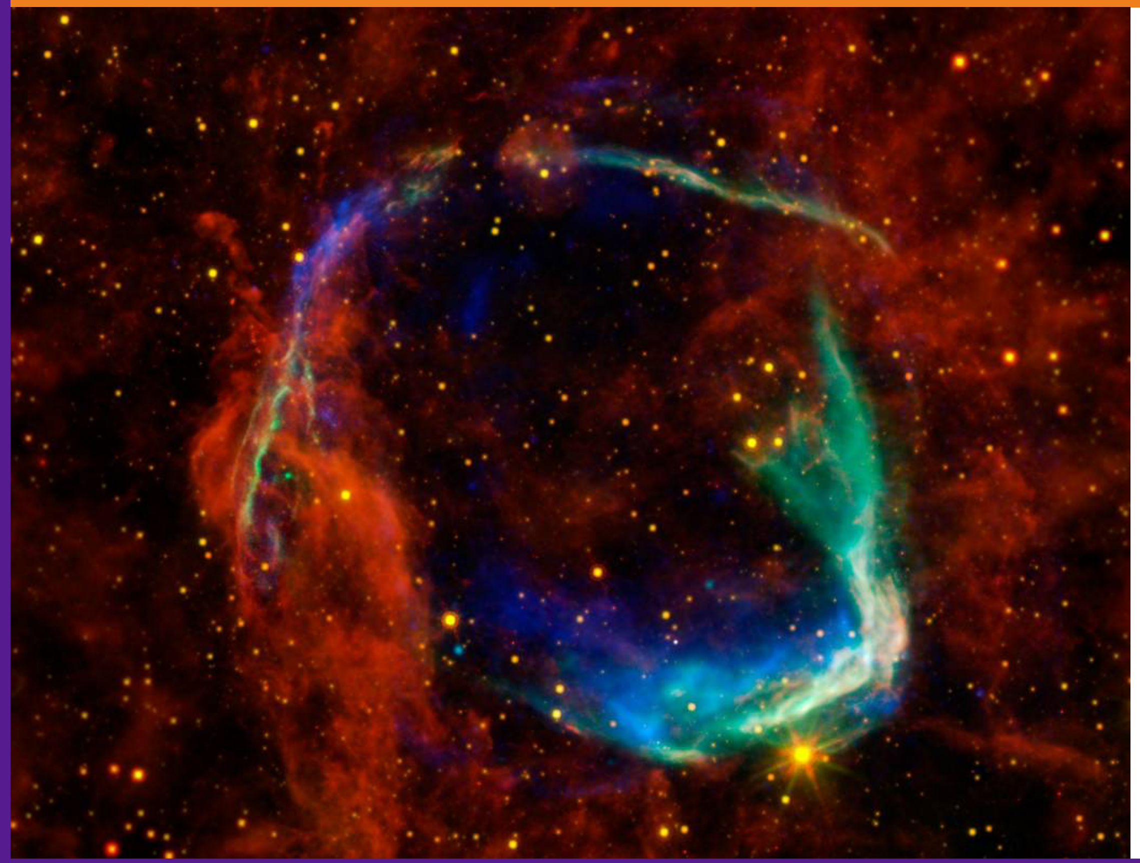


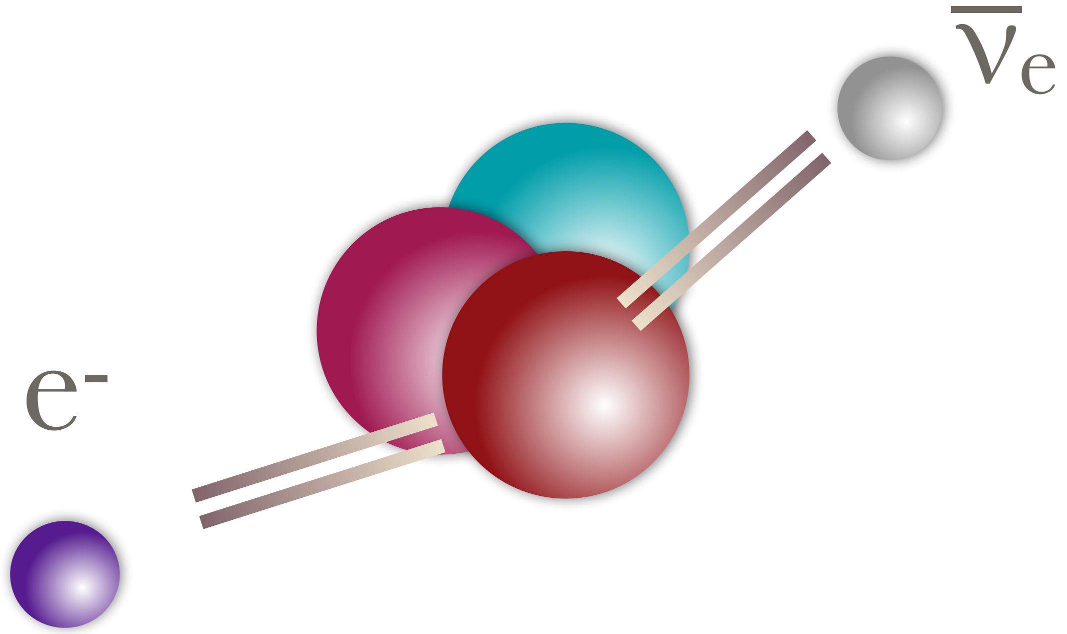
Directly



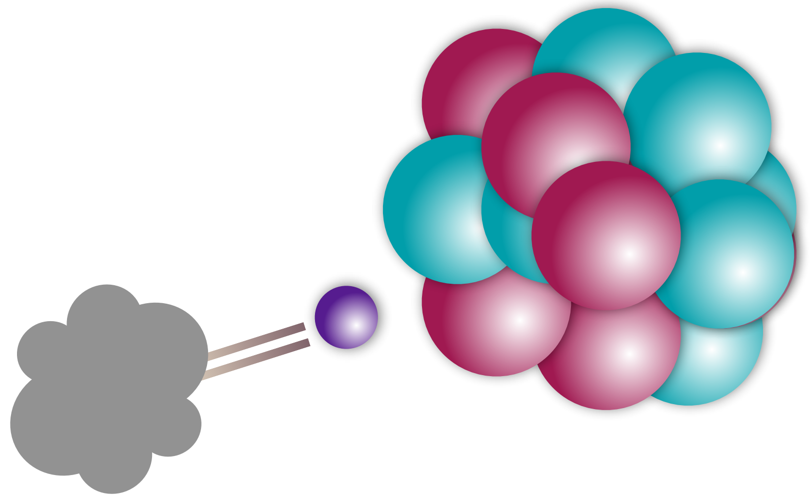
Supernova time-of-flight measurements

Weak interaction kinematics

β decay (tritium)



Electron capture



(^{163}Ho)

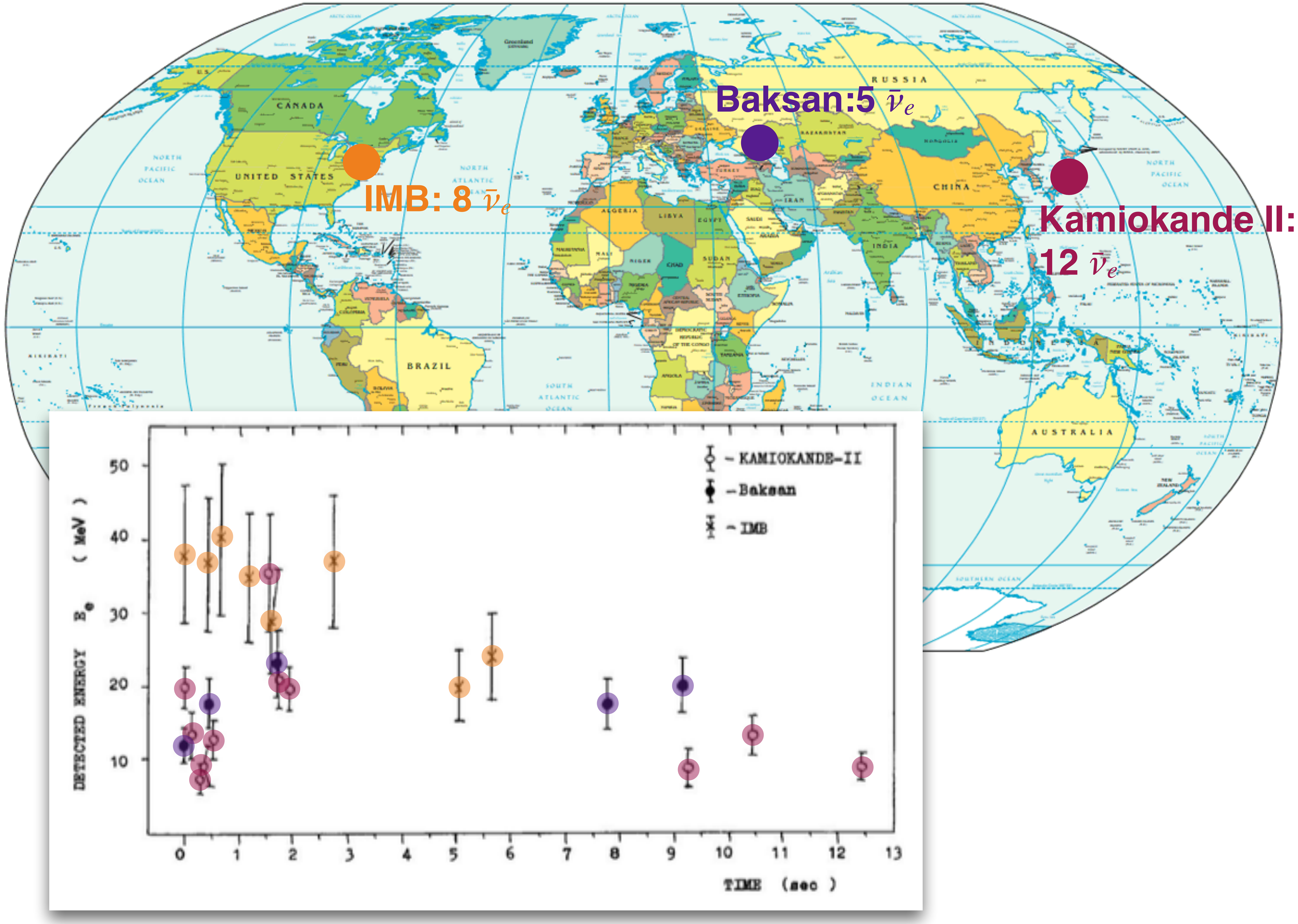
Supernova time-of-flight measurements

February 1987

Sun	Mon	Tue	Wed	Thu	Fri	Sat
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28

Spotted Supernova!

Supernova time-of-flight measurements



- **Neutrinos** emitted at **core collapse**; visible **light** only transmitted once shockwave reaches star's **surface**

Modelling supernova time-of-flight measurements

T Laredo et al,Phys.Rev. D65 (2002) 063002

Neutrino emission **Propagation to Earth** **Detection probability**

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Neutrino emission | **Propagation to Earth** | **Detection probability**

- Two sources:
  - **Cooling** of new neutron star in supernova core
  - Possible: hot, shocked **accreting** matter
- Paper compares 14 different emission models in Bayesian analysis

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$$\Phi(E, t^{\mathrm{det}}) = \frac{1}{4\pi D^2}\dot{N}(E, t^{\mathrm{em}})$$

Flux spectrum as function of detected time

Emitted neutrino time and energy spectrum

Modelling supernova time-of-flight measurements

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$$\Phi(E, t^{\rm det}) = \frac{1}{4\pi D^2}\dot{N}(E, t^{\rm em})$$

$$t^{\rm det} = t^{\rm em} + \boxed{\Delta t(m_\nu, E)} - \boxed{t^{\rm off}}$$

Propagation time depends on energy **and $\bar{\nu}_e$ mass**

Clocks on experiments aren't aligned exactly

Modelling supernova time-of-flight measurements

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Propagation to Earth

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$$\Delta t(m_\nu, E) = 2.57 \left(\frac{m_\nu}{\mathrm{eV}}\right)^2 \left(\frac{E}{\mathrm{MeV}}\right)^{-2} \frac{D}{50\ \mathrm{kpc}}\ \mathrm{s.}$$

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Detection probability

- Main mechanism:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- Event rate depends on interaction **cross section** & **positron detection** efficiency
- Depends on energy & detector design

Modelling supernova time-of-flight measurements

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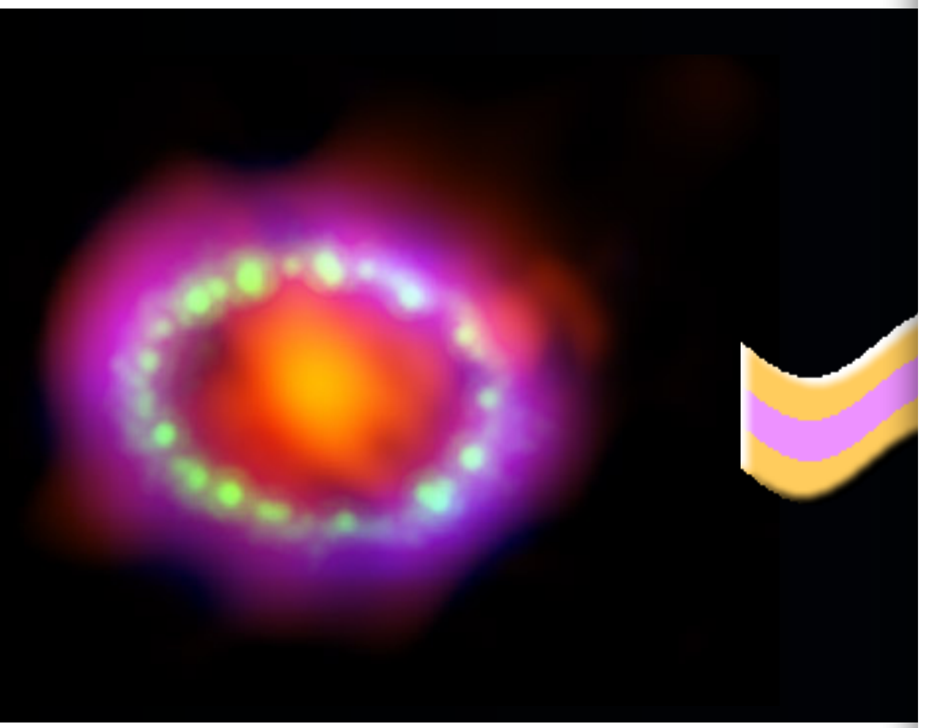
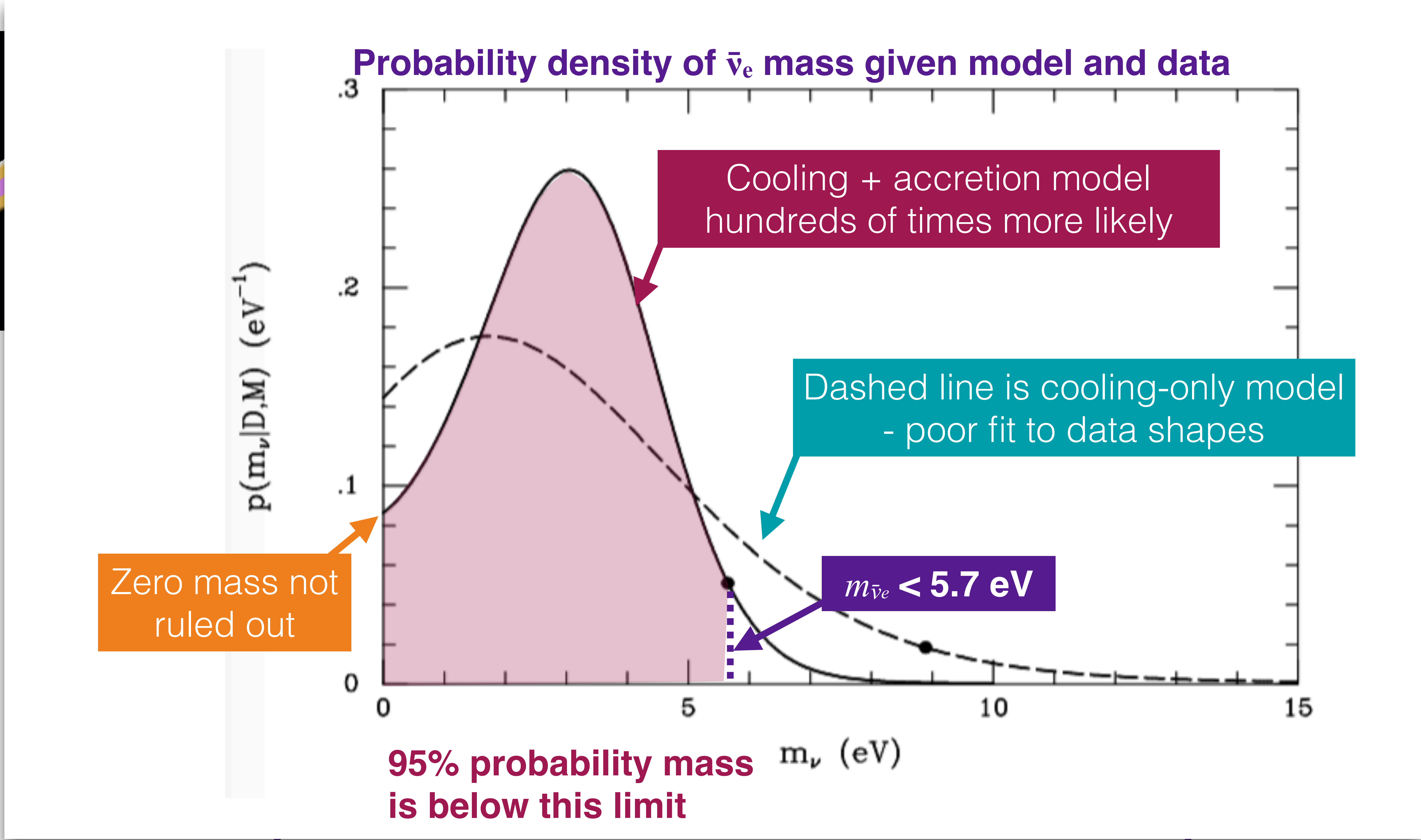
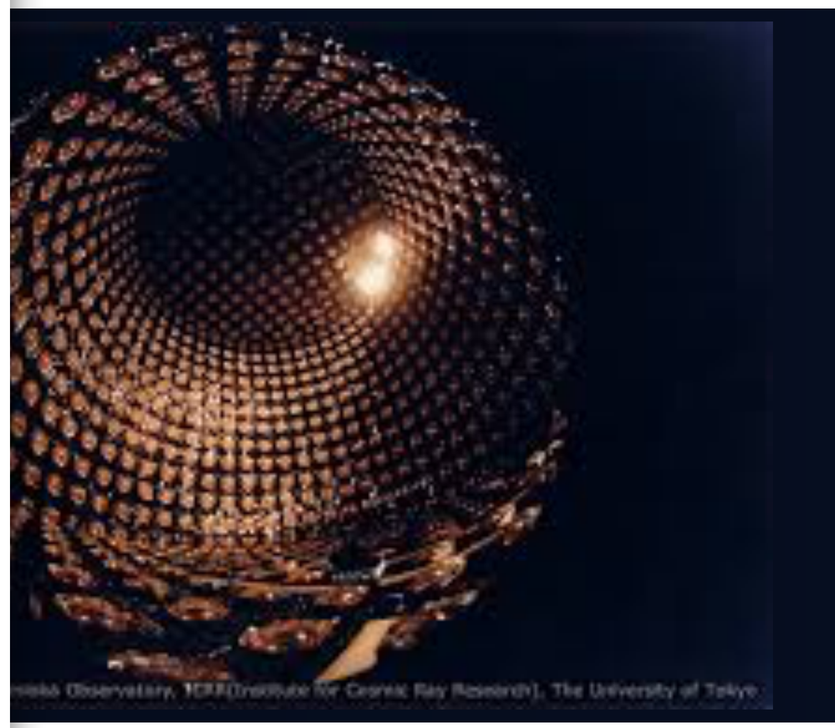
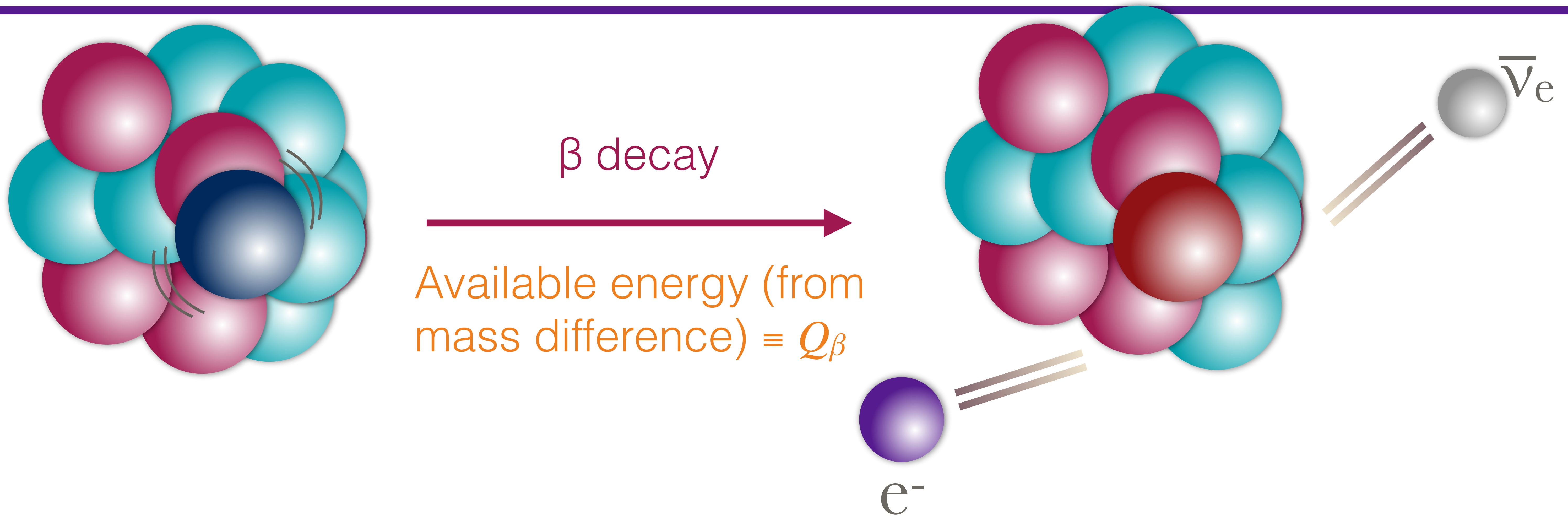
Neutrino emission | **Propagation to Earth** | **Detection probability**







Back to basics - looking at beta decay



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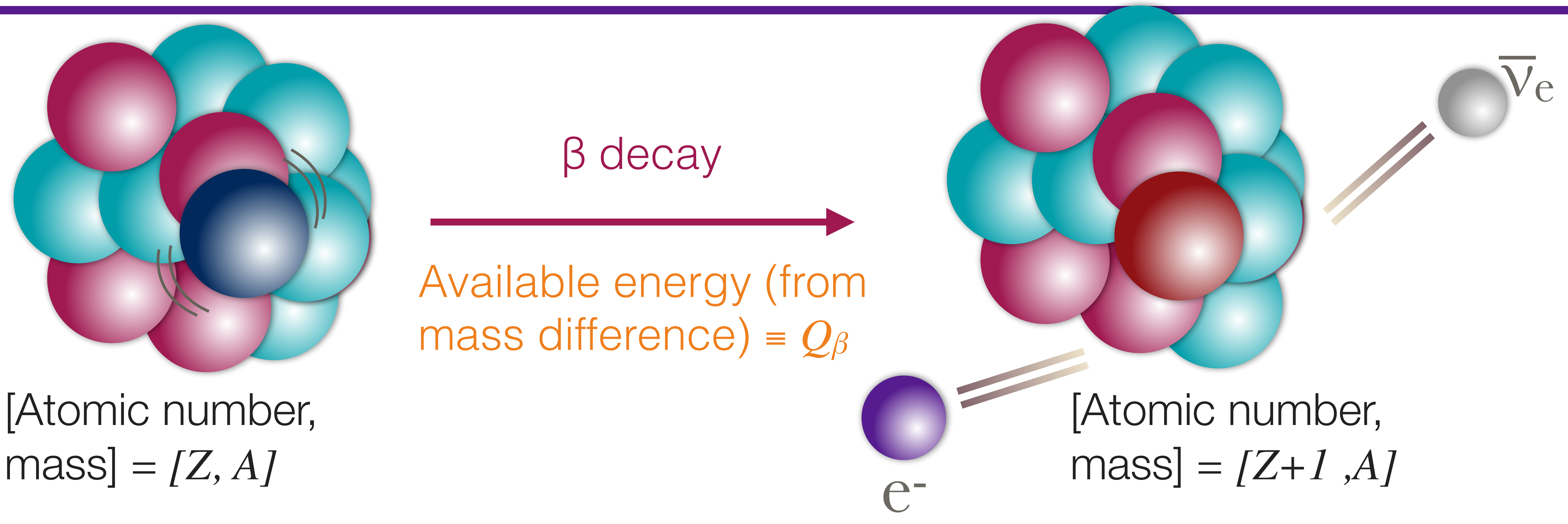
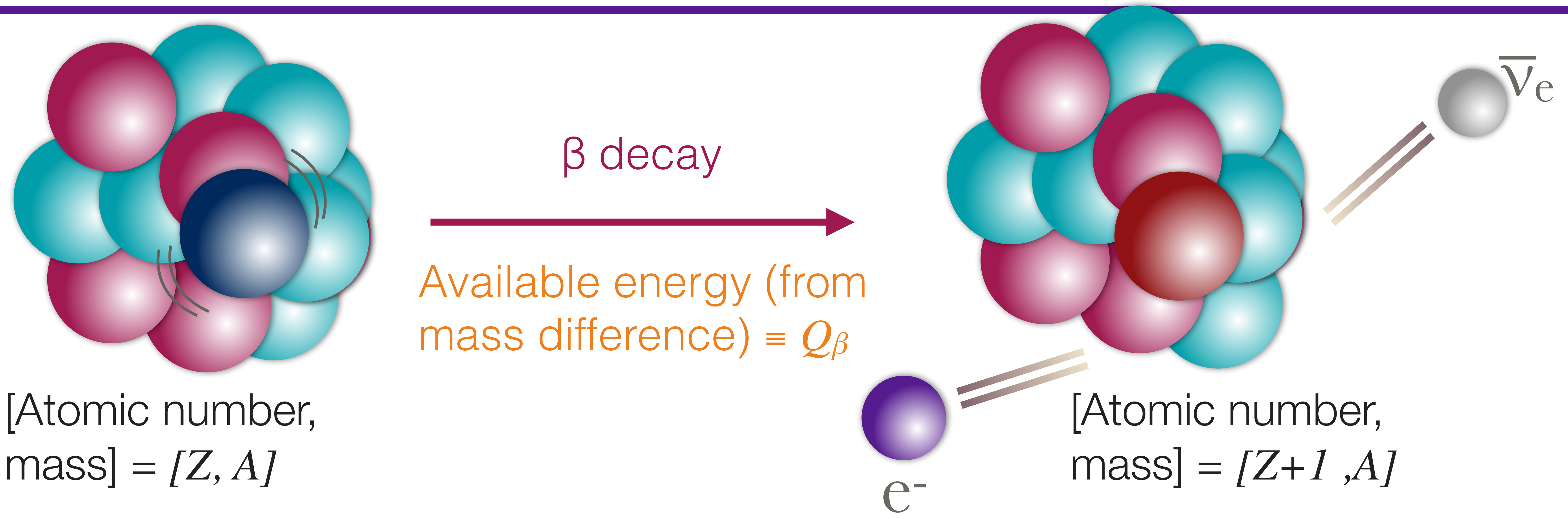


Mass of nucleus = mass of atom - mass of electrons

$$Q_\beta = (\ M\ [Z,A] - Z\, m_e\ ) - (\ M\ [Z+1,A] - (Z+1)\ m_e\ ] + m_e\ )$$

Daughter nucleus + β electron

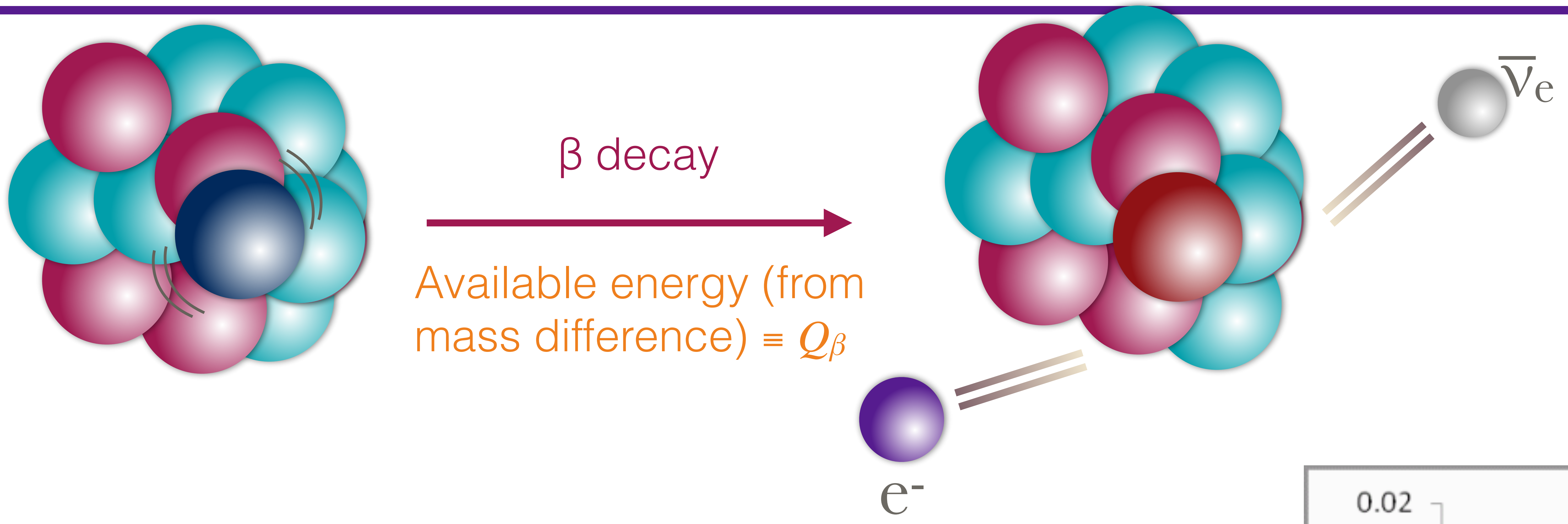
Back to basics - looking at beta decay



$$Q_\beta = (M [Z,A] - Z\, m_e) - (M [Z+1,A] - (Z+1)\, m_e] + m_e)$$

$$= (M [Z,A] - M [Z+1,A])$$

Back to basics - looking at beta decay



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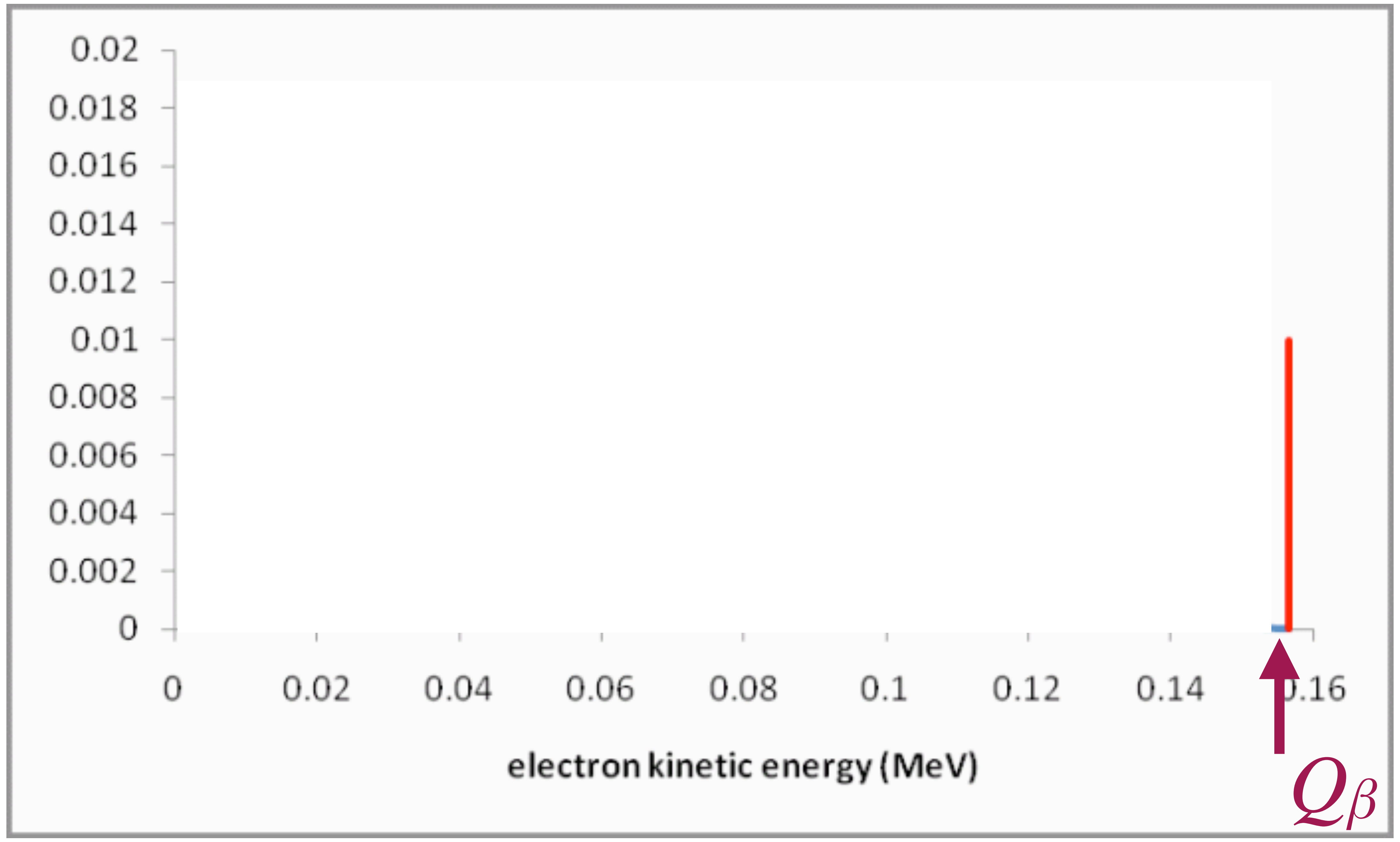
I have done a terrible thing, I have postulated a particle that cannot be detected.

Wolfgang Pauli, 1930



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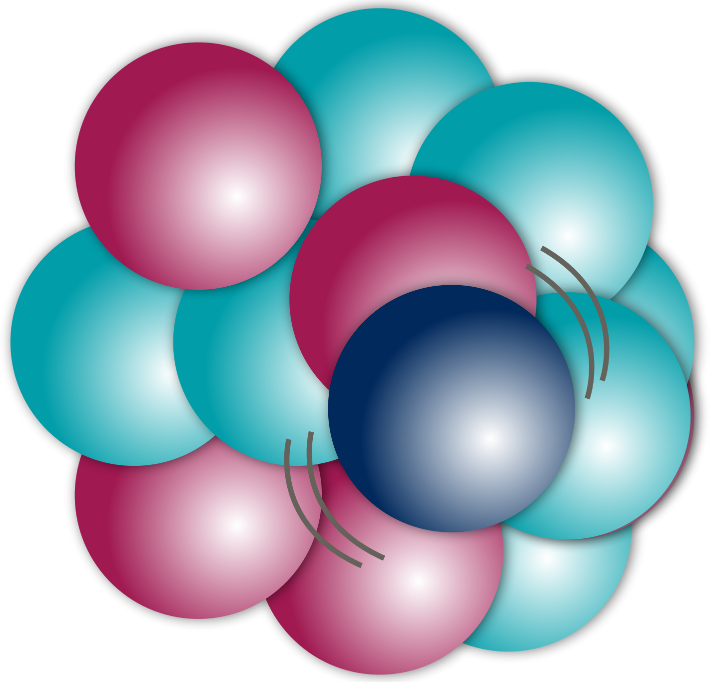
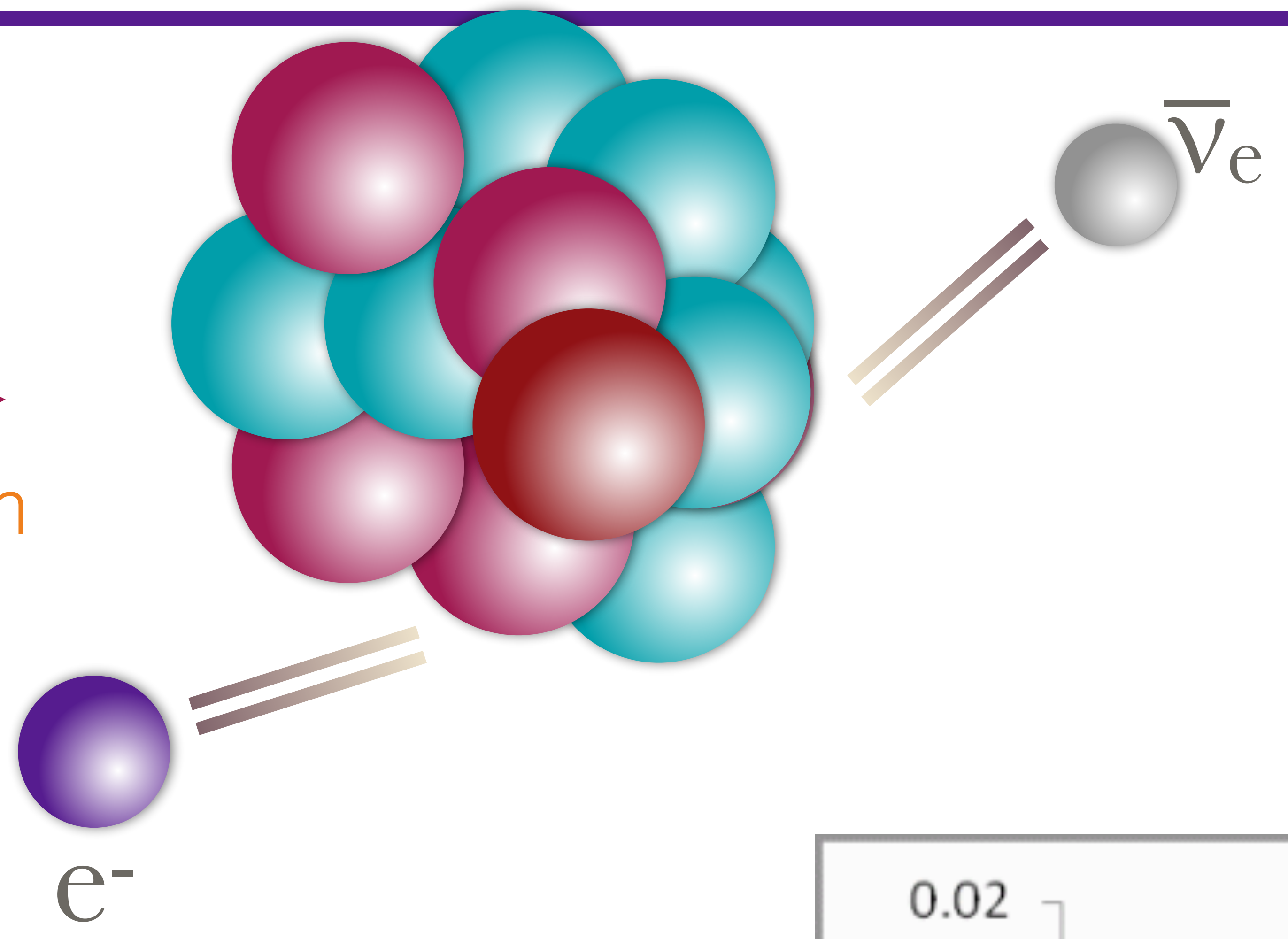


β decay

Available energy (from mass difference) ≡ Q_β



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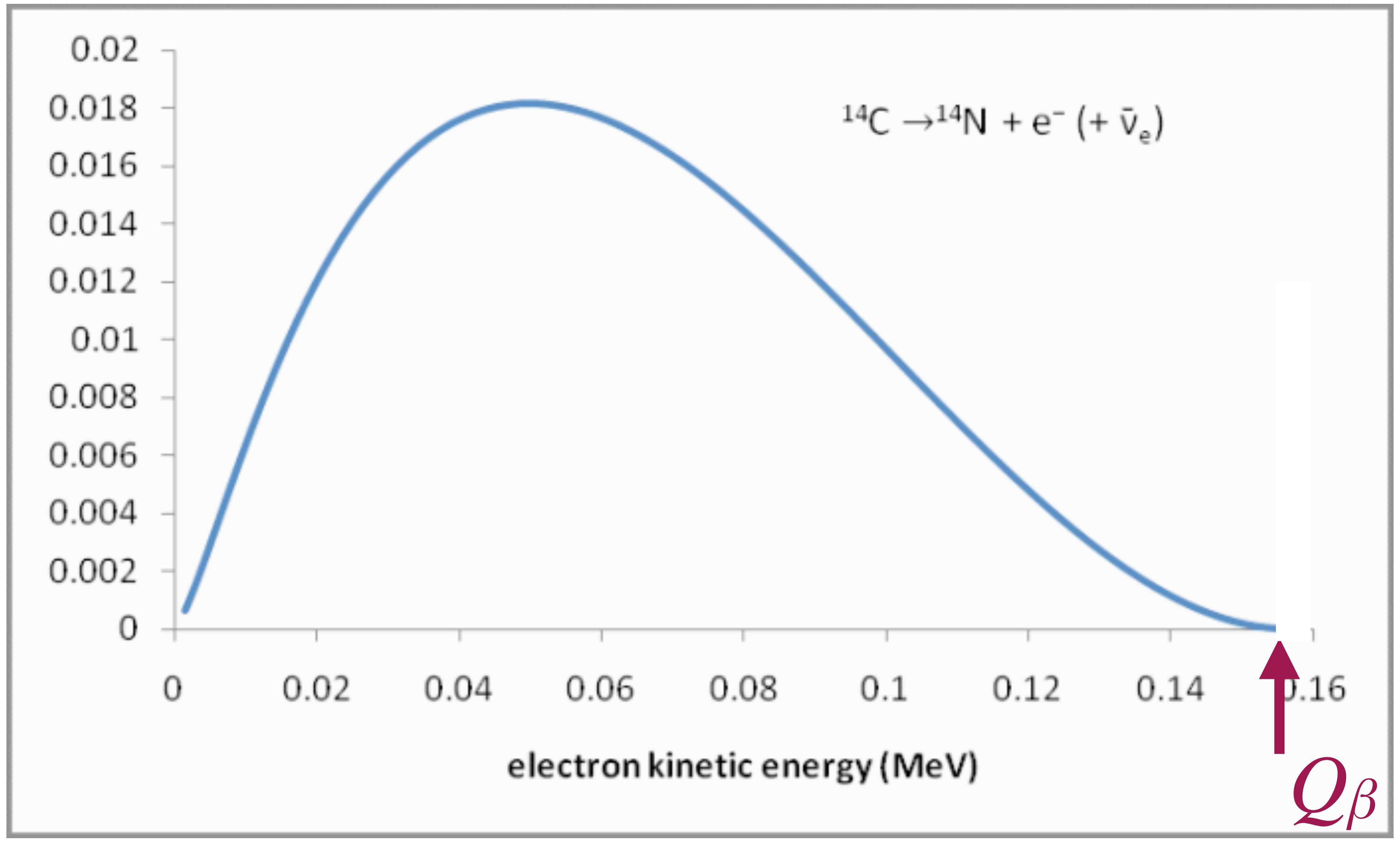
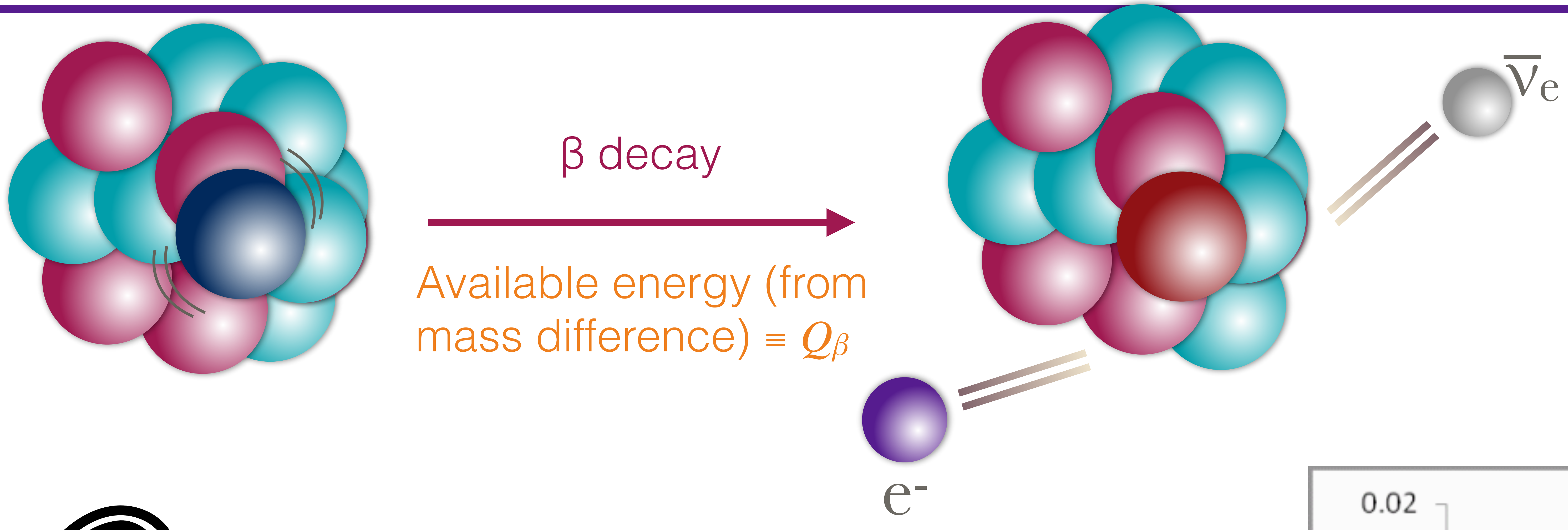


Back to basics - looking at beta decay



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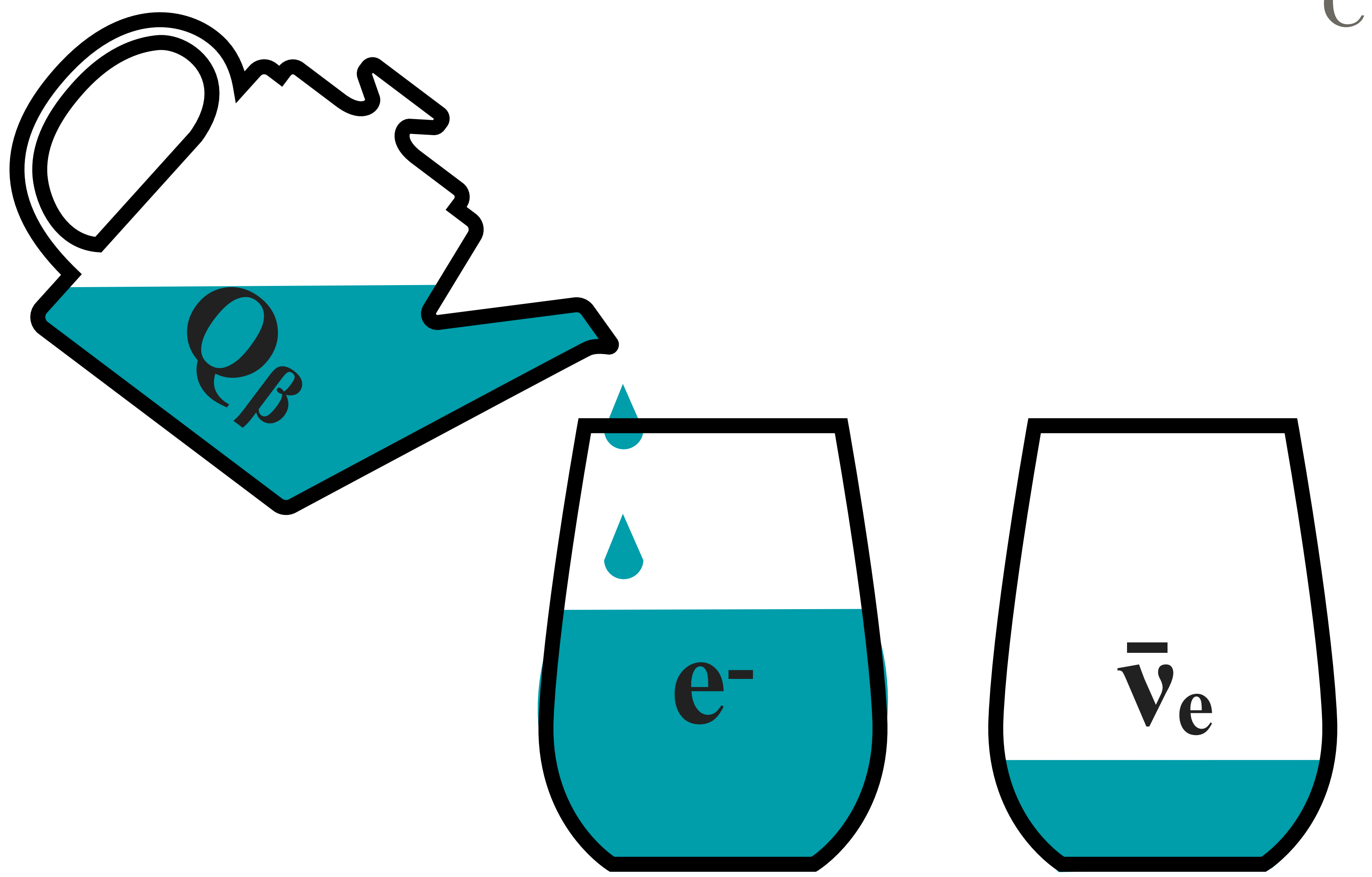

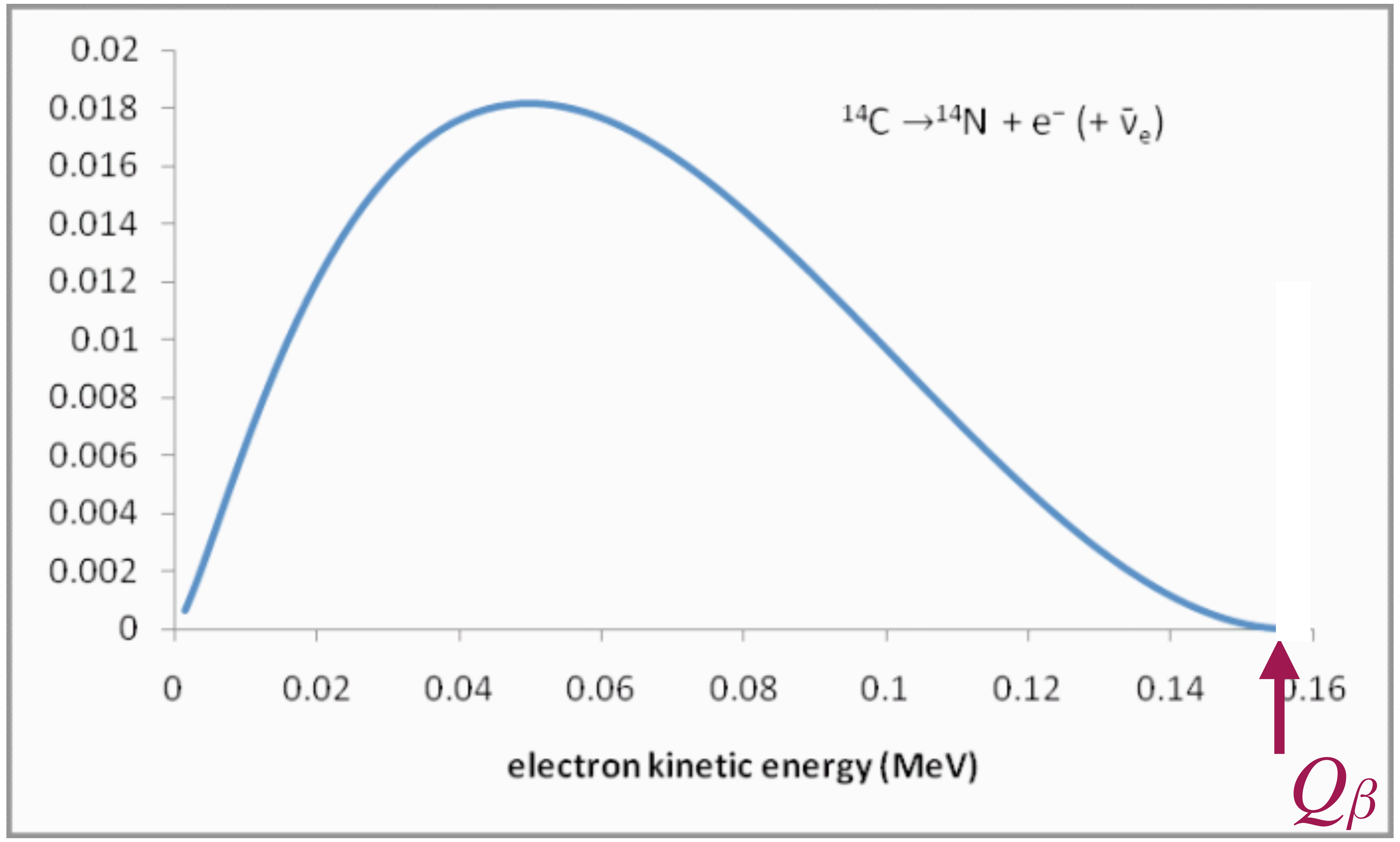

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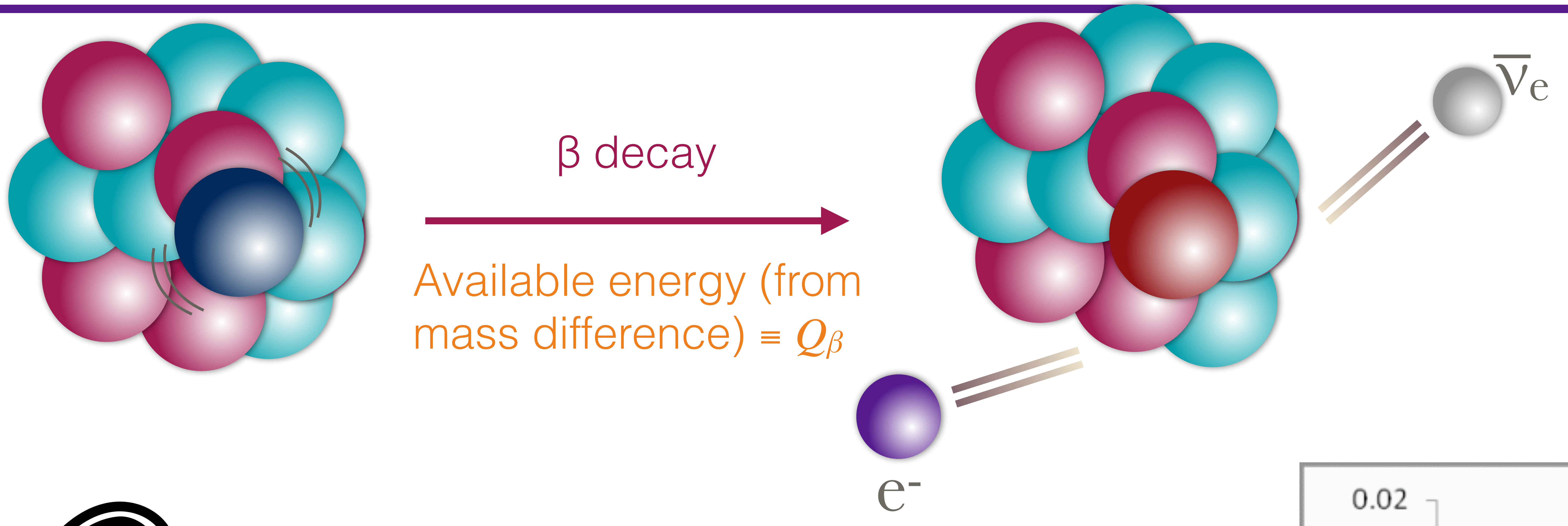

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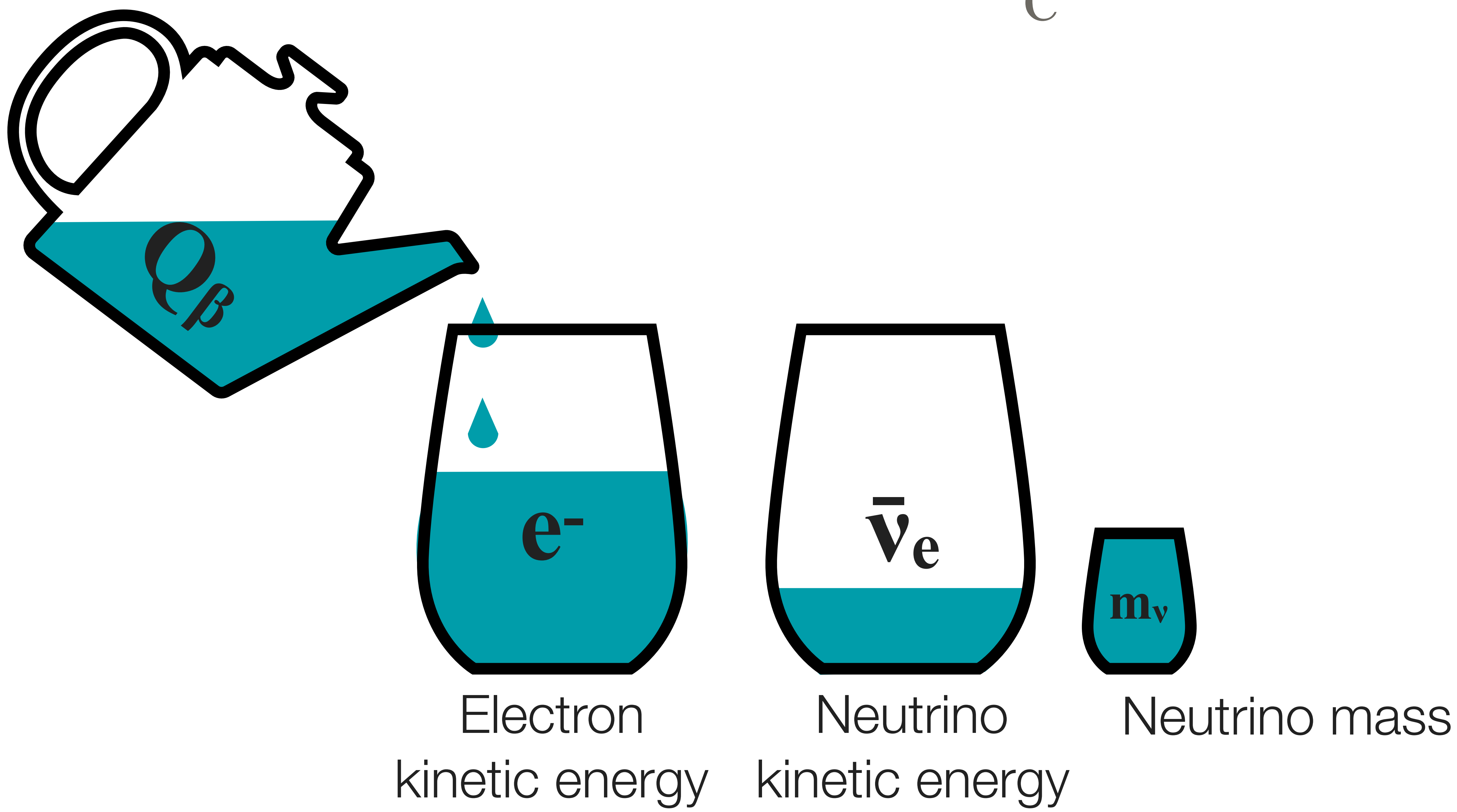

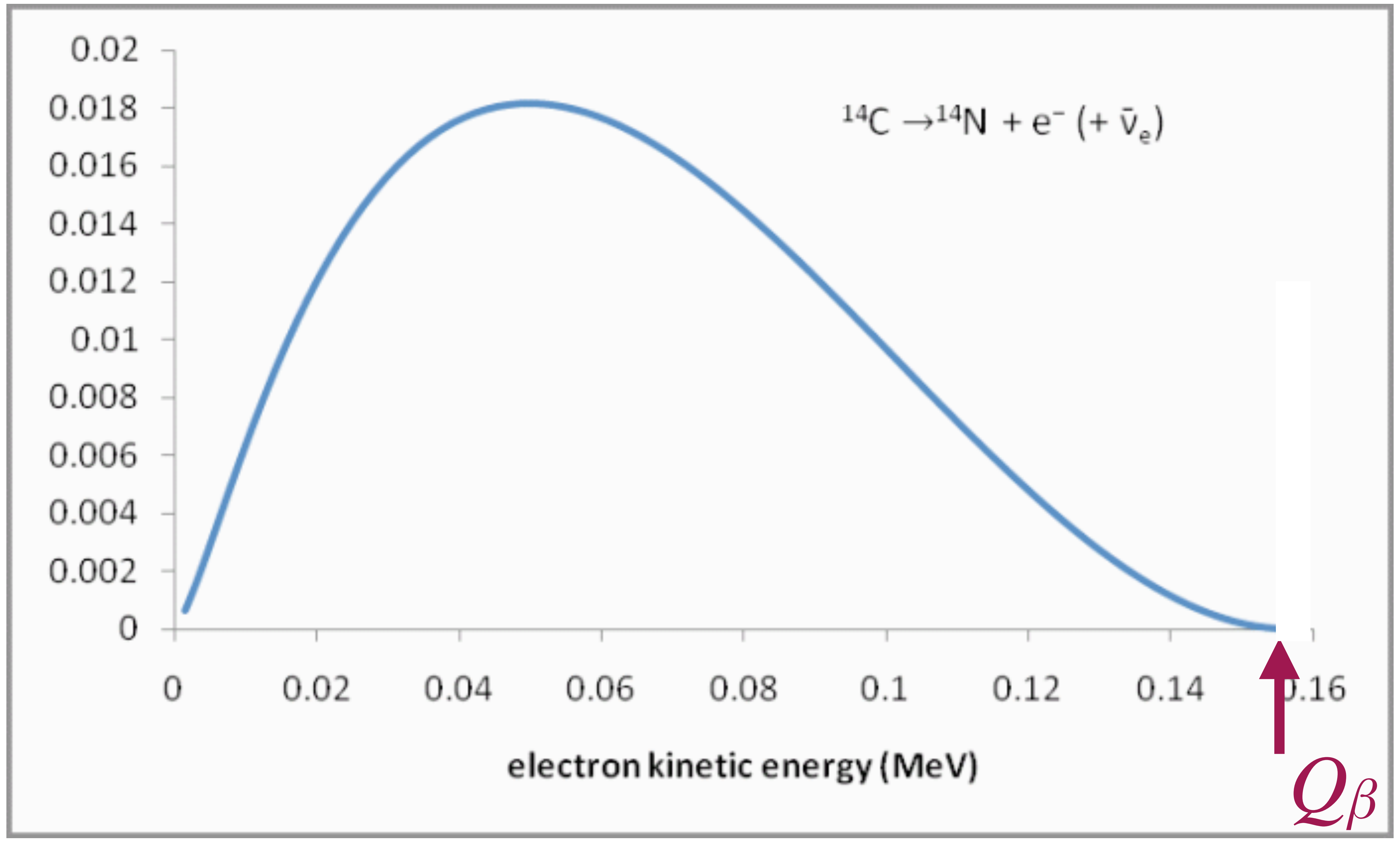

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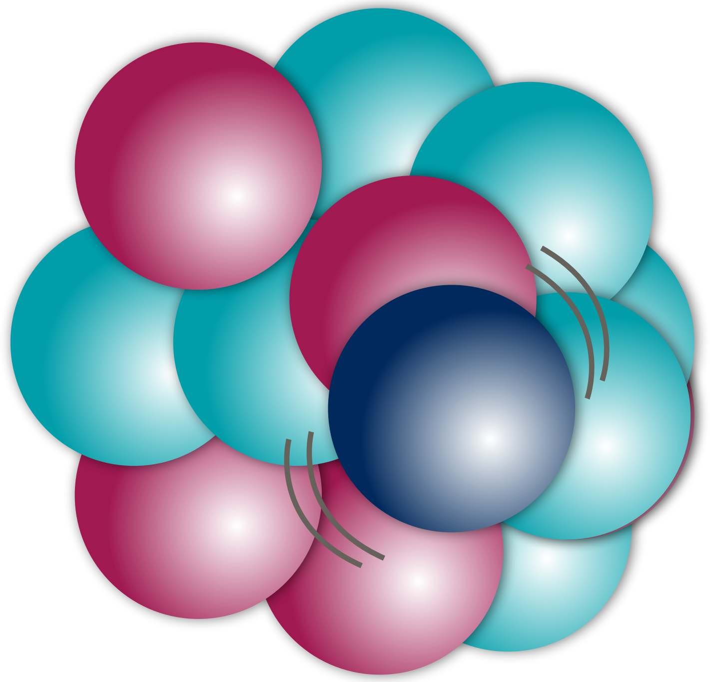

β de

Available er
mass differe

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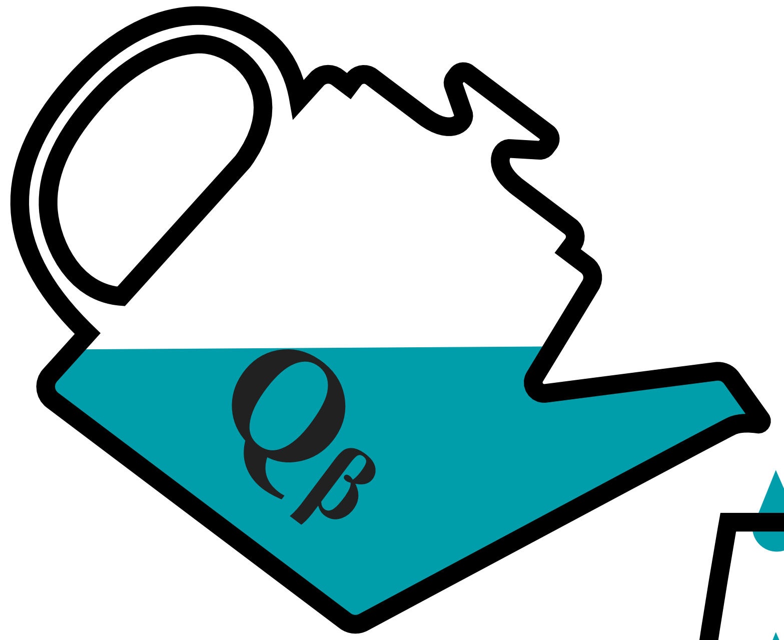
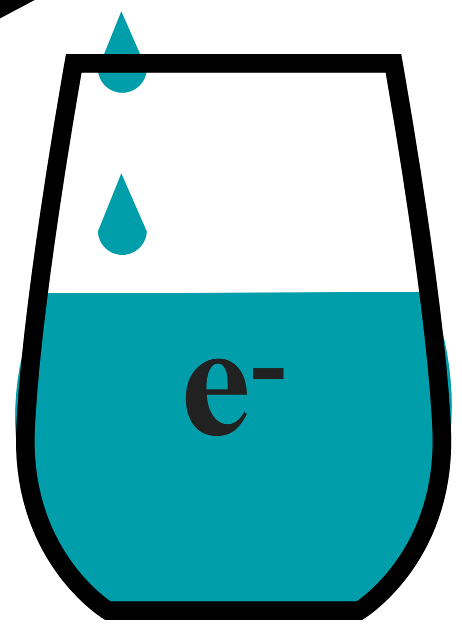
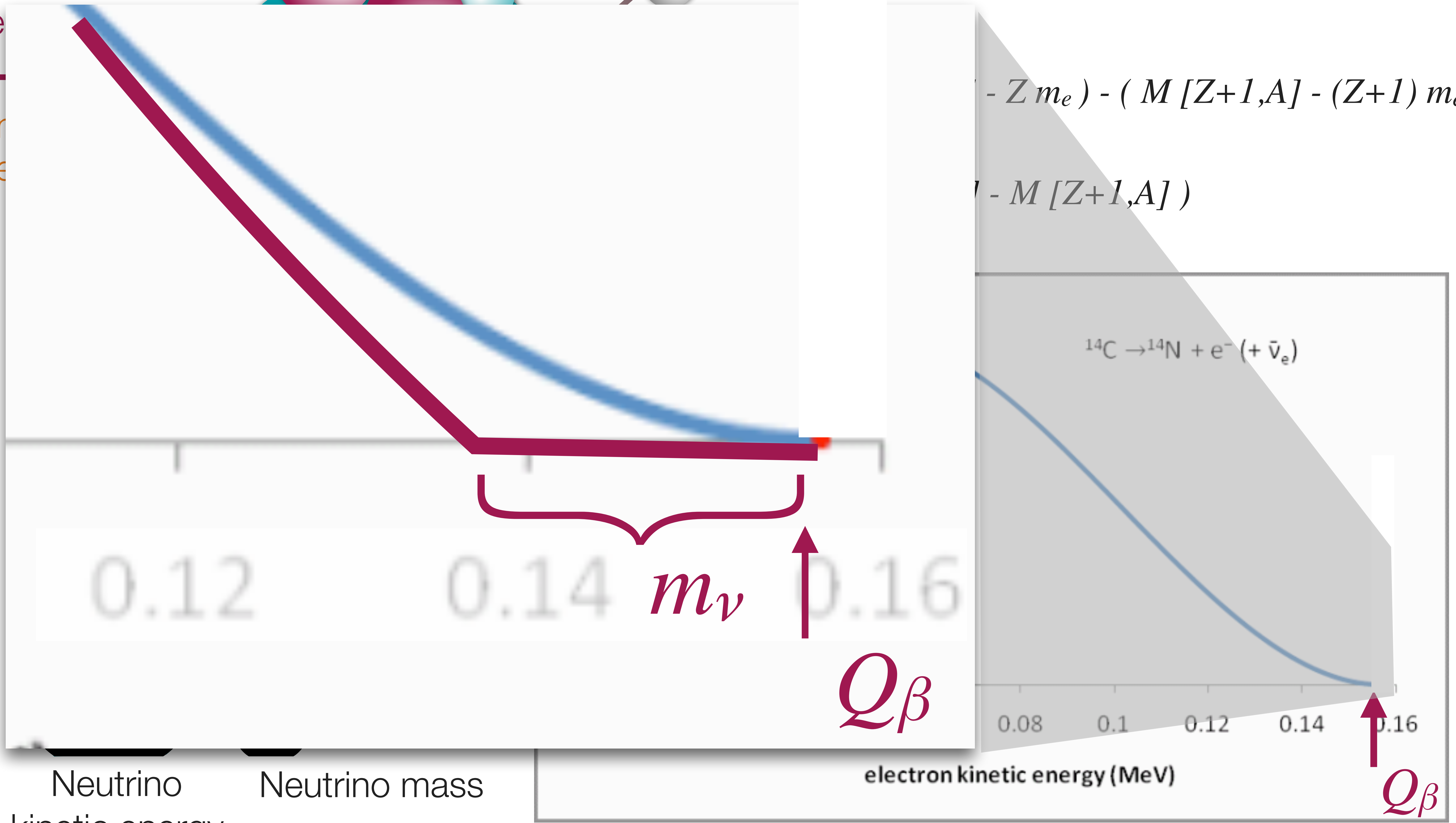
$- M\,[Z+1,A]\,)$







Electron kinetic energy

Neutrino kinetic energy

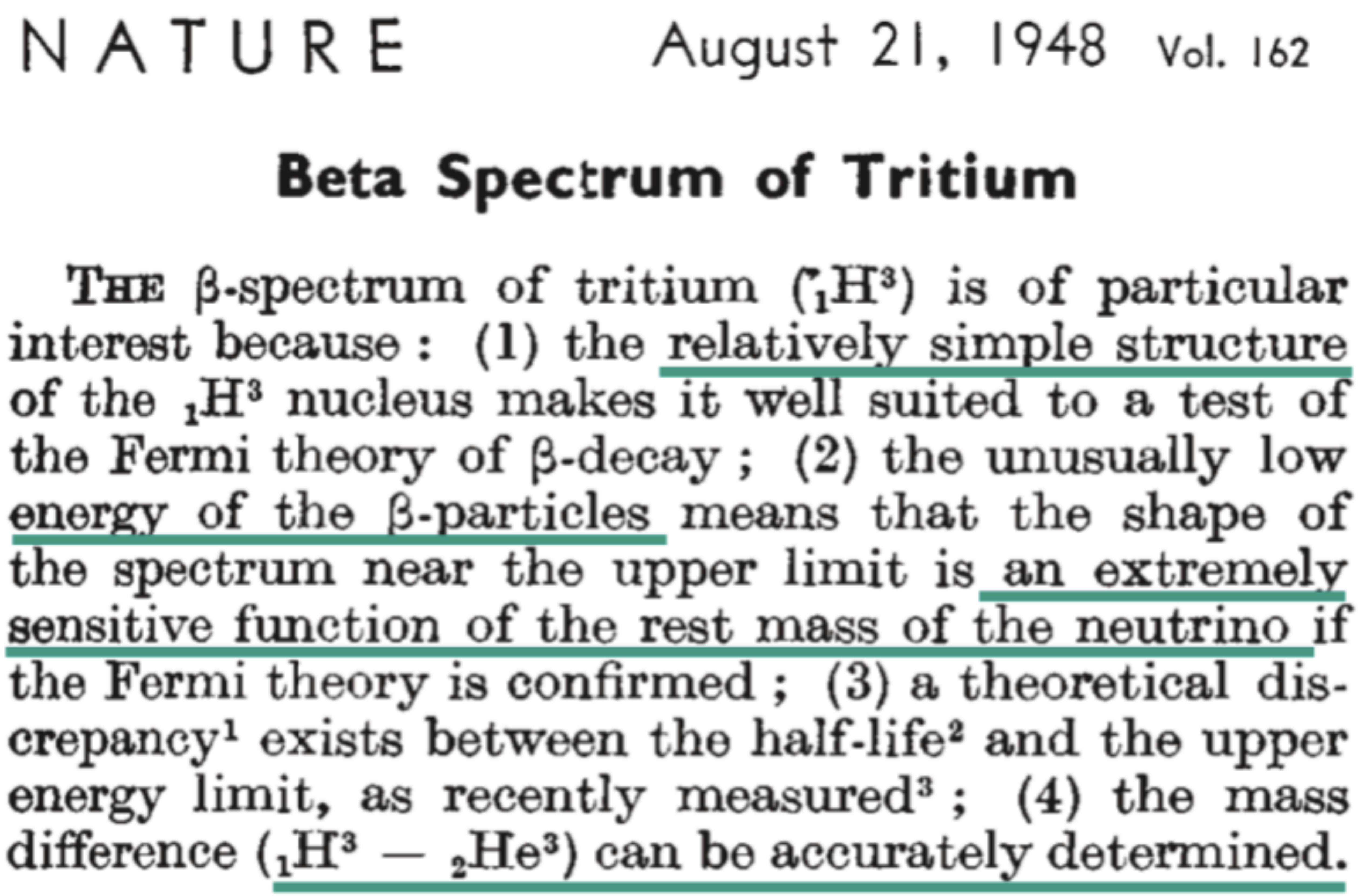
Neutrino mass

UCL

NATURE August 21, 1948 Vol. 162

Beta Spectrum of Tritium

THE β-spectrum of tritium (${}_1H^3$) is of particular interest because: (1) the relatively simple structure of the ${}_1H^3$ nucleus makes it well suited to a test of the Fermi theory of β-decay; (2) the unusually low energy of the β-particles means that the shape of the spectrum near the upper limit is an extremely sensitive function of the rest mass of the neutrino if the Fermi theory is confirmed; (3) a theoretical discrepancy[1] exists between the half-life[2] and the upper energy limit, as recently measured[3]; (4) the mass difference (${}_1H^3 - {}_2He^3$) can be accurately determined.



NATURE August 21, 1948 Vol. 162

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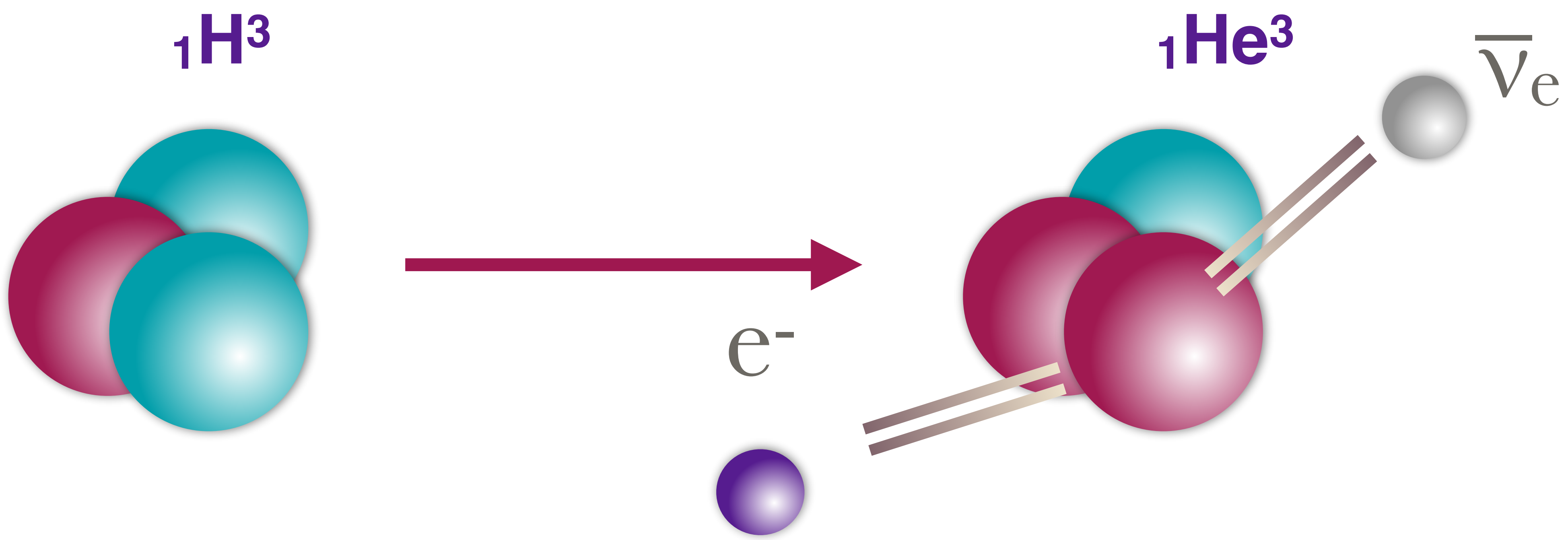

- **Simple structure** (1 proton, 2 neutrons) means **few nuclear effects**

Tritium: ^3H

NATURE — August 21, 1948 — Vol. 162

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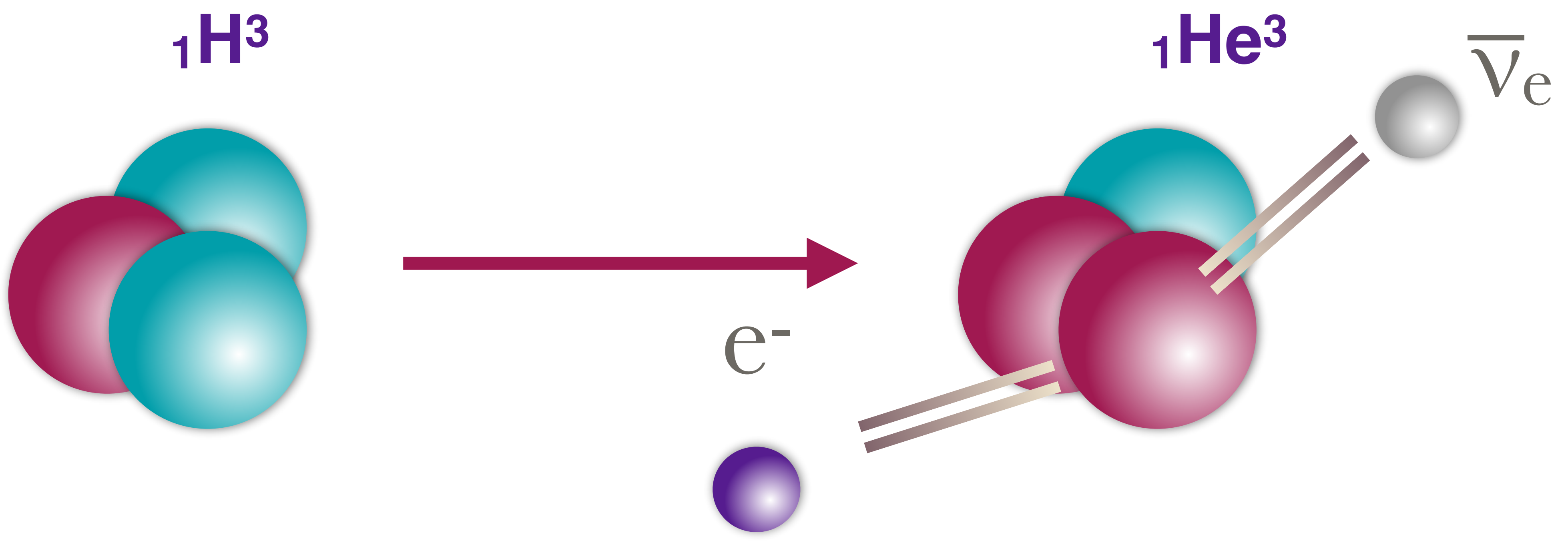

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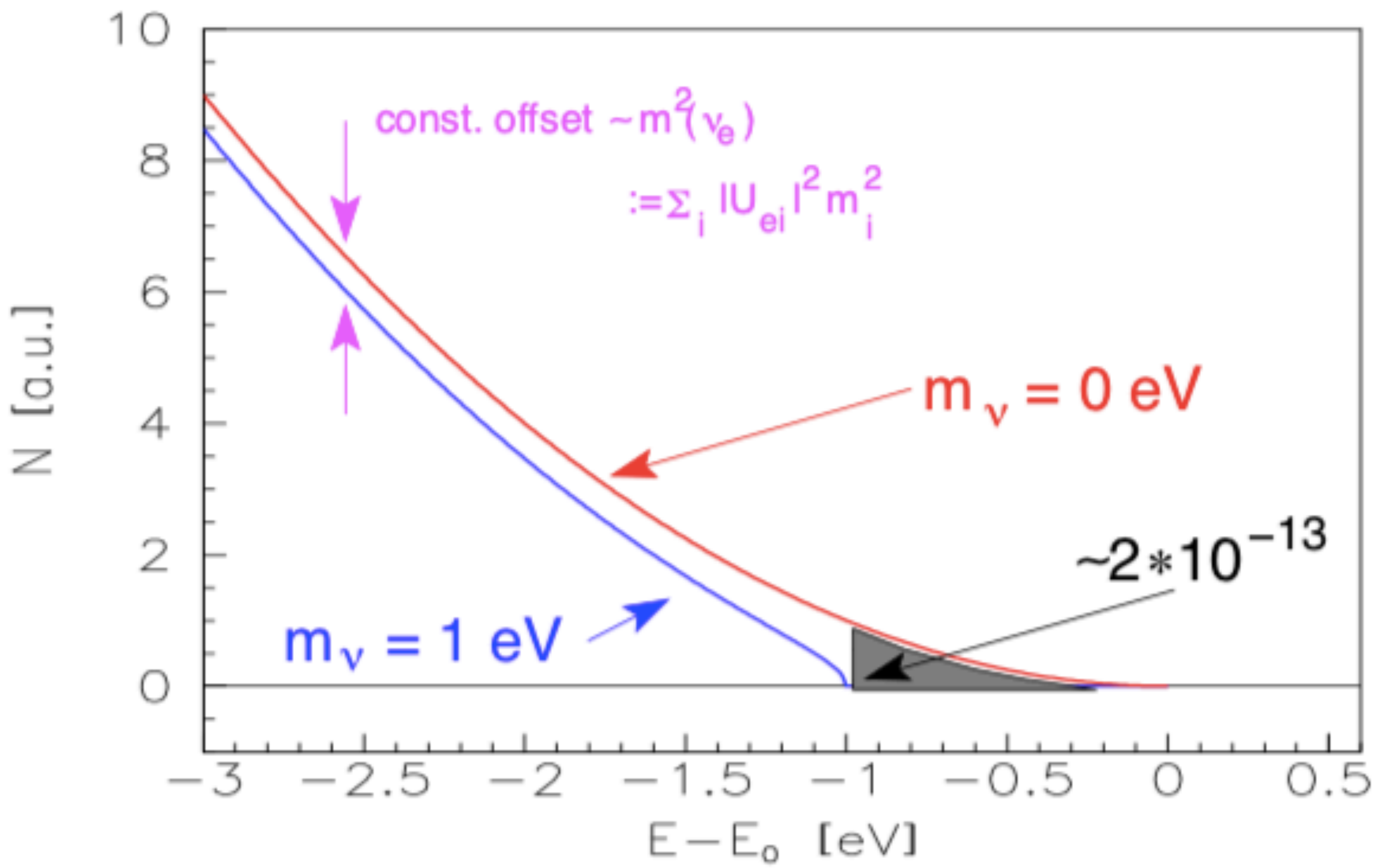
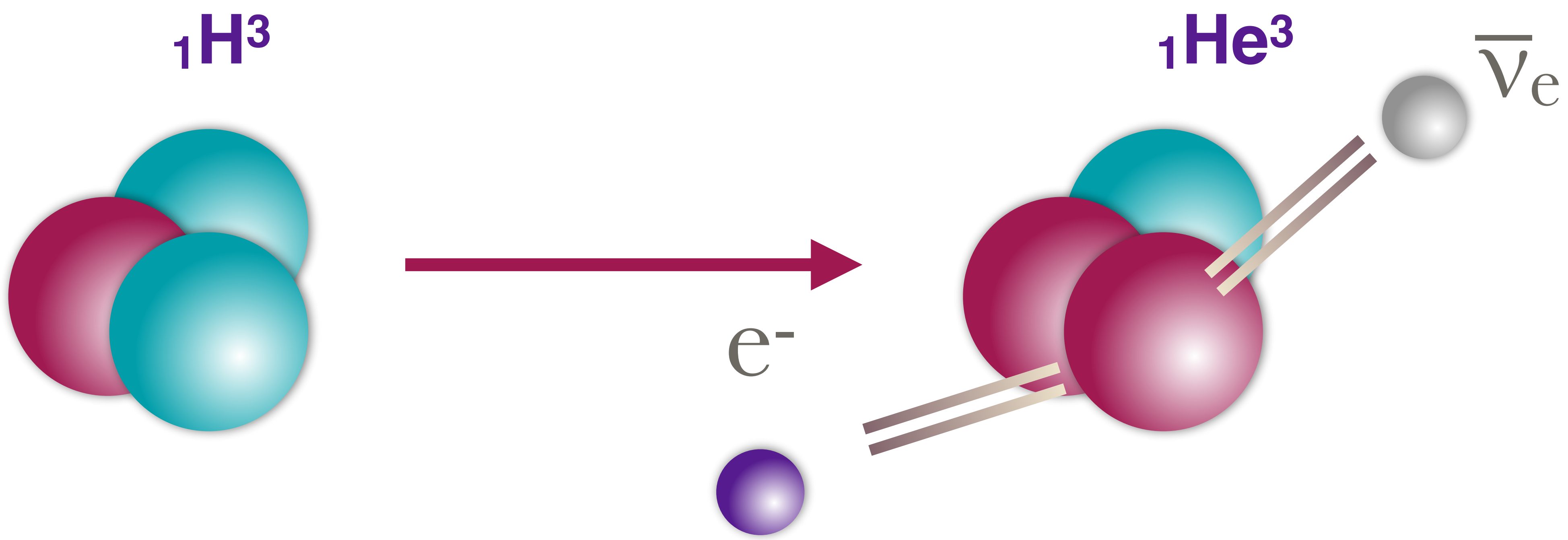
- **Super-allowed** decay = high activity: **$T_{1/2}$ = 12.3 years**

Tritium: ^3H





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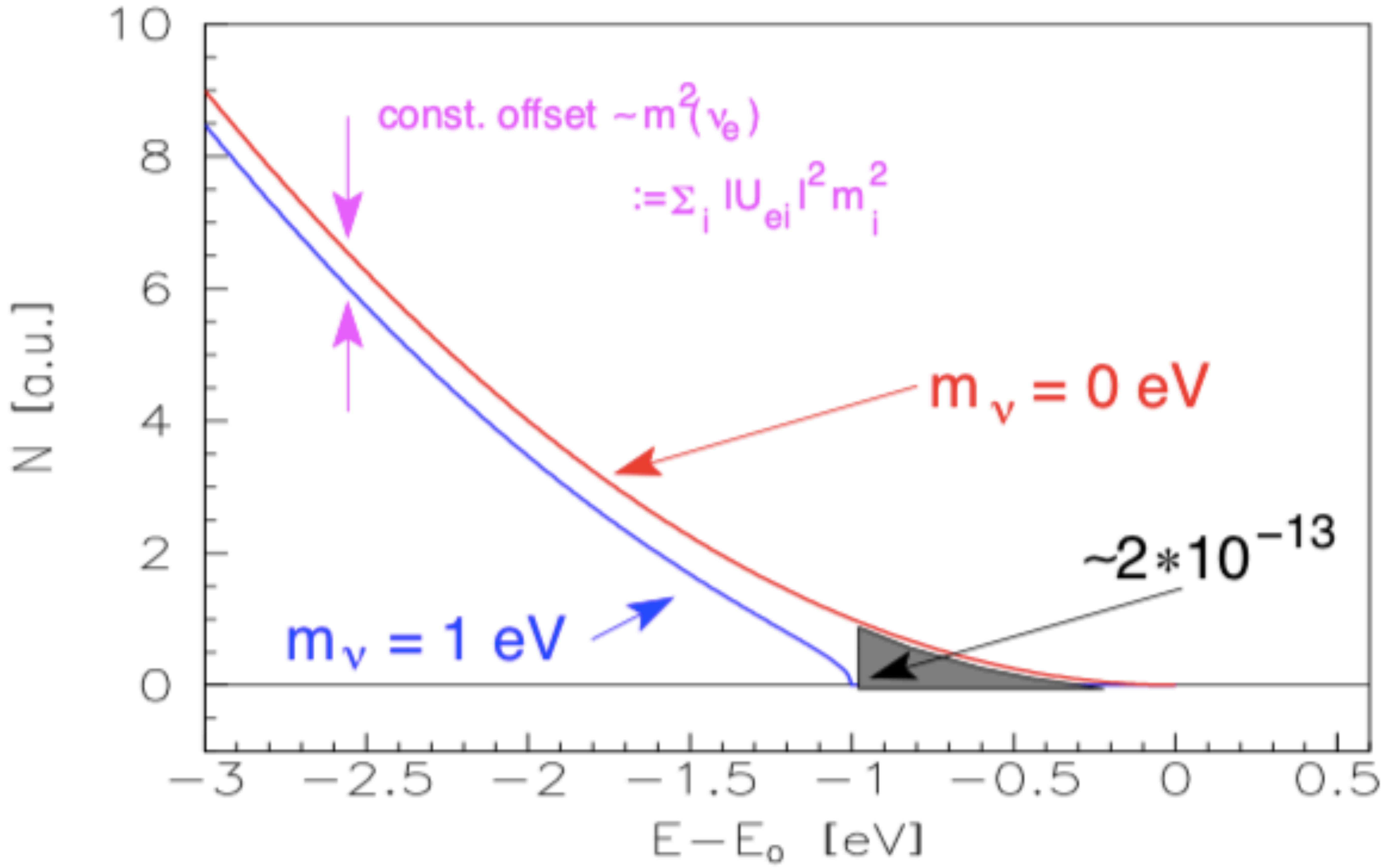

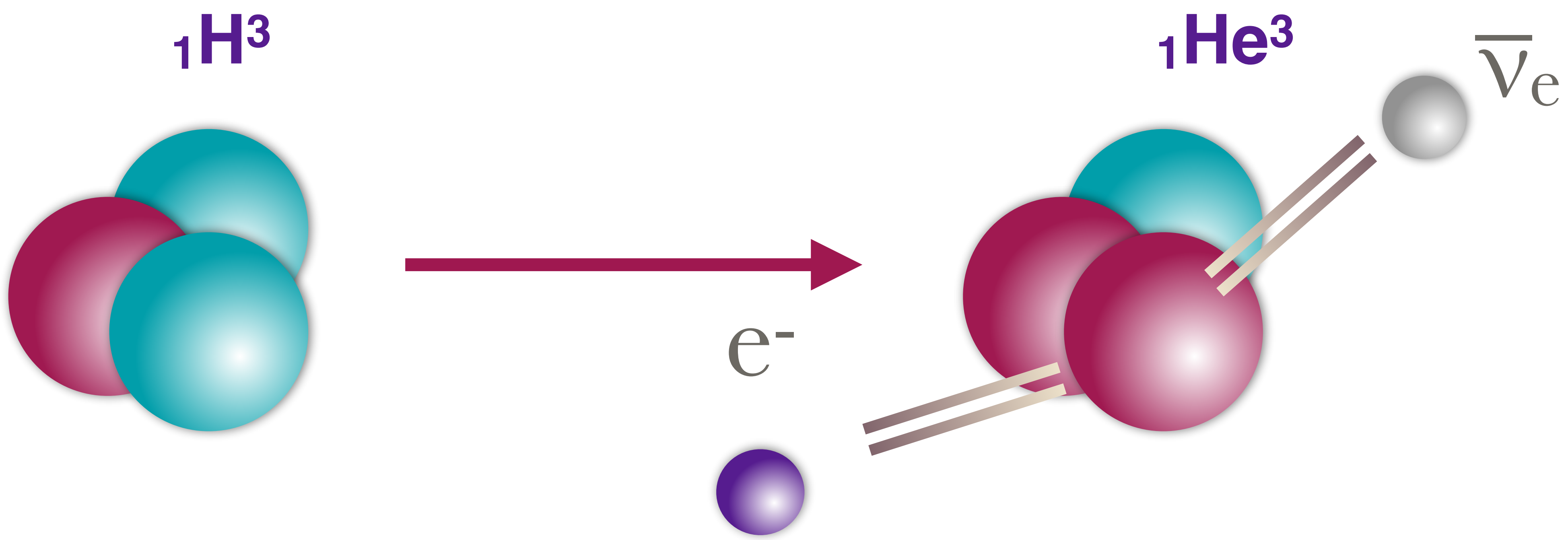

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Spectral distortion depends on an effective "**electron neutrino mass**" depending on PMNS matrix

$$m^2(\bar{\nu}_e) = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$$

The tritium electron energy spectrum in more detail

$$\frac{dN}{dE_e} = \frac{G_F^2 m_e^5 \cos^2\theta_C}{2\pi^3\hbar^7} \left|M_{\rm nuc}\right|^2 F(Z, E_e) p_e E_e$$

$$\times (E_{\rm max} - E_e) \sum_i \left|U_{ei}\right|^2 \sqrt{(E_{\rm max} - E_e)^2 - m_{\nu_i}^2}$$

$$\times \Theta(E_{\rm max} - E_e - m_{\nu_i})$$

*Phys. Rev. C **91**, 035505*

The tritium electron energy spectrum in more detail

Constant

G_F is Fermi constant
θ_C is Cabibbo angle

$$\frac{dN}{dE_e} = \boxed{\frac{G_F^2 m_e^5 \cos^2\theta_C}{2\pi^3\hbar^7}} \left|M_{\mathrm{nuc}}\right|^2 F(Z, E_e) p_e E_e$$

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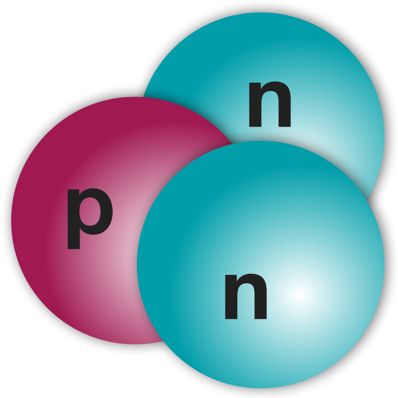
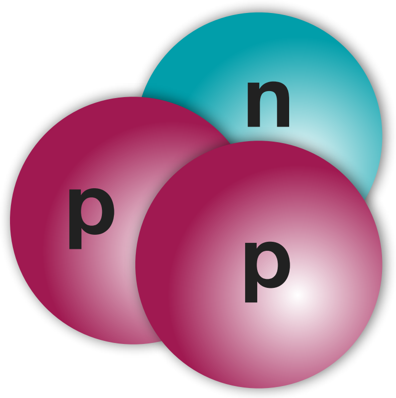
Phys. Rev. C ***91**, 035505*

The tritium electron energy spectrum in more detail

$_1\mathrm{H}^3$



$_1\mathrm{He}^3$



Nuclear matrix element is maximal because 3H and 3He are mirror nuclei

$$\frac{dN}{dE_e} = \frac{G_F^2 m_e^5 \cos^2\theta_C}{2\pi^3\hbar^7} \boxed{|M_{\mathrm{nuc}}|^2} F(Z, E_e) p_e E_e$$

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$$\times \Theta(E_{\mathrm{max}} - E_e - m_{\nu_i})$$

Phys. Rev. C ***91***, *035505*

The tritium electron energy spectrum in more detail

Fermi function corrects for electron-nucleus interaction

$$\frac{dN}{dE_e} = \frac{G_F^2 m_e^5 \cos^2\theta_C}{2\pi^3\hbar^7} |M_{\text{nuc}}|^2 \boxed{F(Z, E_e)} p_e E_e$$

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Phys. Rev. C ***91****, 035505*

The tritium electron energy spectrum in more detail

$$\frac{dN}{dE_e} = \frac{G_F^2 m_e^5 \cos^2\theta_C}{2\pi^3\hbar^7} |M_{\rm nuc}|^2 F(Z, E_e) \boxed{p_e E_e}$$

Electron momentum and energy

$$\times (E_{\rm max} - E_e) \sum_i |U_{ei}|^2 \sqrt{(E_{\rm max} - E_e)^2 - m_{\nu_i}^2}$$

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Phys. Rev. C ***91****, 035505*

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Energy conservation step function

Phys. Rev. C ***91****, 035505*

The tritium electron energy spectrum in more detail

$$\frac{dN}{dE_e} = \frac{G_F^2 m_e^5 \cos^2\theta_C}{2\pi^3\hbar^7} |M_{\text{nuc}}|^2 F(Z, E_e) p_e E_e$$

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The neutrino bit!

$$\times \Theta(E_{\max} - E_e - m_{\nu_i})$$

Phys. Rev. C ***91****, 035505*

The tritium electron energy spectrum in more detail

$$\frac{dN}{dE_e} = \frac{G_F^2 m_e^5 \cos^2\theta_C}{2\pi^3\hbar^7} \left|M_{\mathrm{nuc}}\right|^2 F(Z, E_e) p_e E_e$$

Neutrino energy $\times (E_{\mathrm{max}} - E_e) \sum_i |U_{ei}|^2 \sqrt{(E_{\mathrm{max}} - E_e)^2 - m_{\nu_i}^2}$

$$\times \Theta(E_{\mathrm{max}} - E_e - m_{\nu_i})$$

Phys. Rev. C ***91***, *035505*

The tritium electron energy spectrum in more detail

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Neutrino energy

$$\times (E_{\text{max}} - E_e) \sum_i |U_{ei}|^2 \underbrace{\sqrt{(E_{\text{max}} - E_e)^2 - m_{\nu_i}^2}}_{\text{Neutrino momentum}}$$

$$\times \Theta(E_{\text{max}} - E_e - m_{\nu_i})$$

Phys. Rev. C ***91***, *035505*

The tritium electron energy spectrum in more detail

$$\frac{dN}{dE_e} = \frac{G_F^2 m_e^5 \cos^2\theta_C}{2\pi^3\hbar^7} \left|M_{\rm nuc}\right|^2 F(Z, E_e) p_e E_e$$

Sum over neutrino mass states i

Neutrino energy

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Neutrino momentum

Phys. Rev. C ***91***, *035505*

The tritium electron energy spectrum in more detail

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Electron component of PMNS matrix

Sum over neutrino mass states i

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Phys. Rev. C ***91***, *035505*

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Electron component of PMNS matrix

Sum over neutrino mass states i

Neutrino energy

Neutrino mass

Neutrino energy

$$\times \boxed{(E_{\mathrm{max}} - E_e)} \boxed{\sum_i} \boxed{|U_{ei}|^2} \underbrace{\sqrt{\boxed{(E_{\mathrm{max}} - E_e)^2} - \boxed{m_{\nu_i}^2}}}_{\text{Neutrino momentum}}$$

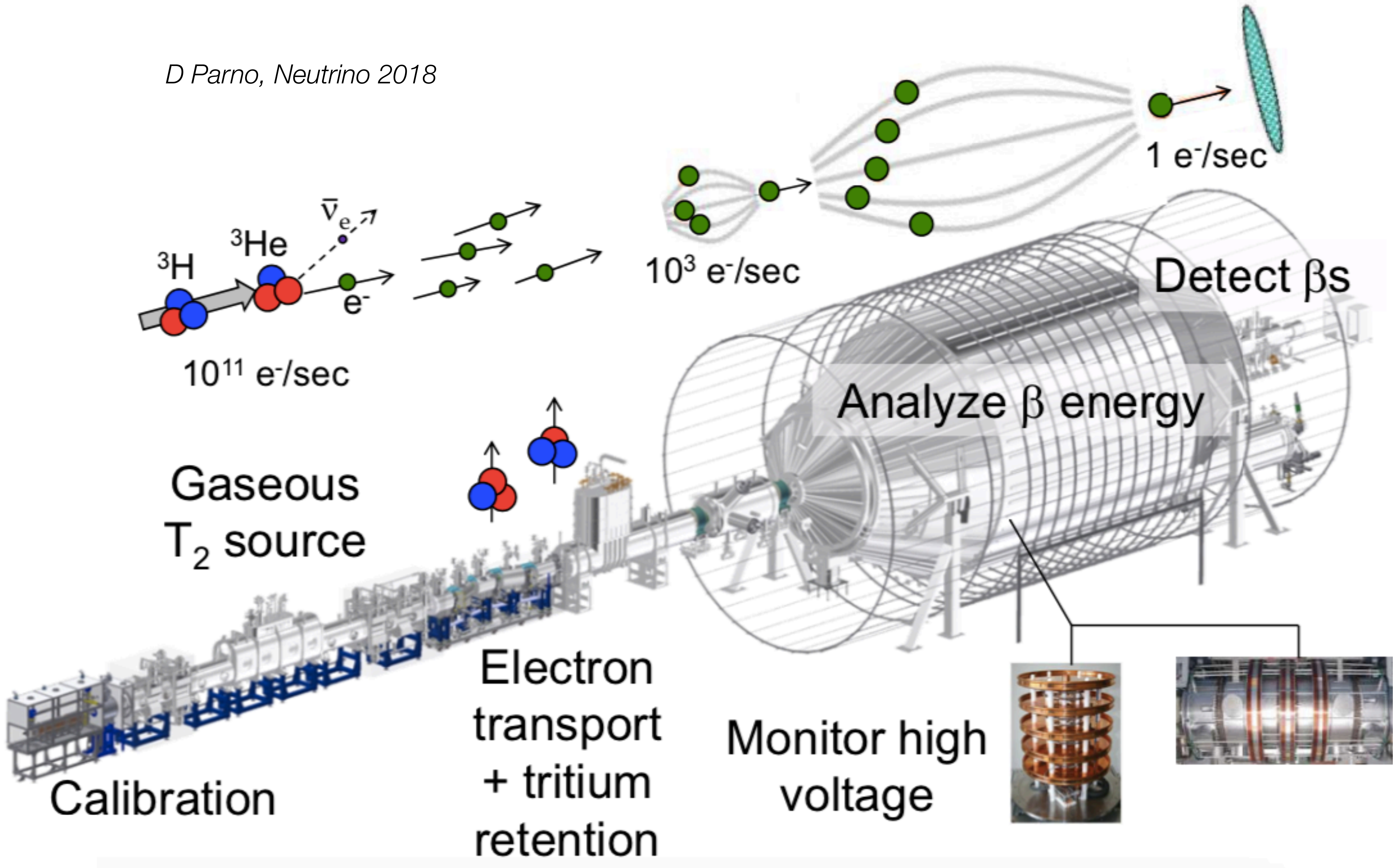
$$\times \Theta(E_{\mathrm{max}} - E_e - m_{\nu_i})$$

Phys. Rev. C ***91****, 035505*

Tritium β-decay experiment top trumps

KATRIN: Karlsruhe Tritium Neutrino Experiment

D Parno, Neutrino 2018



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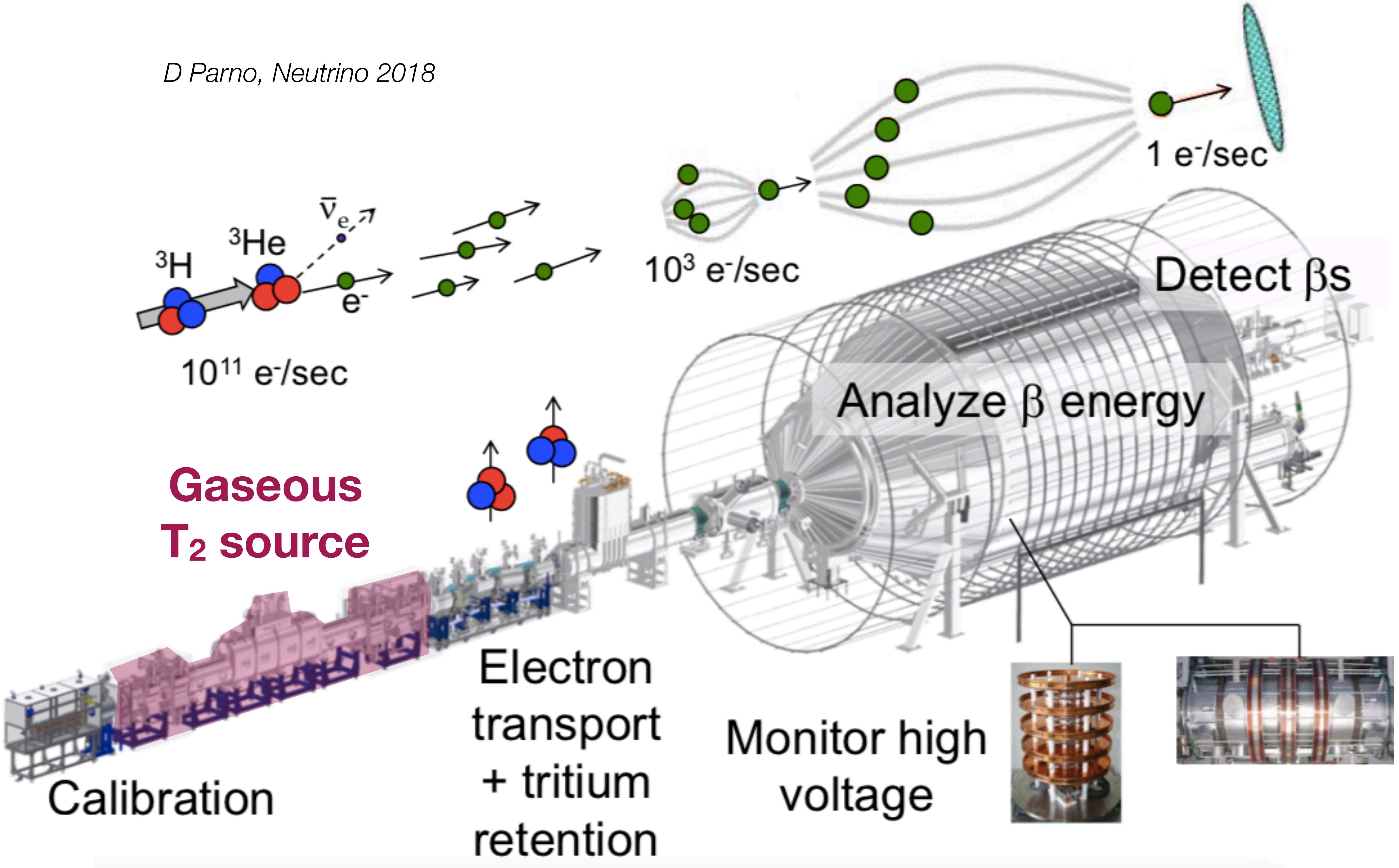
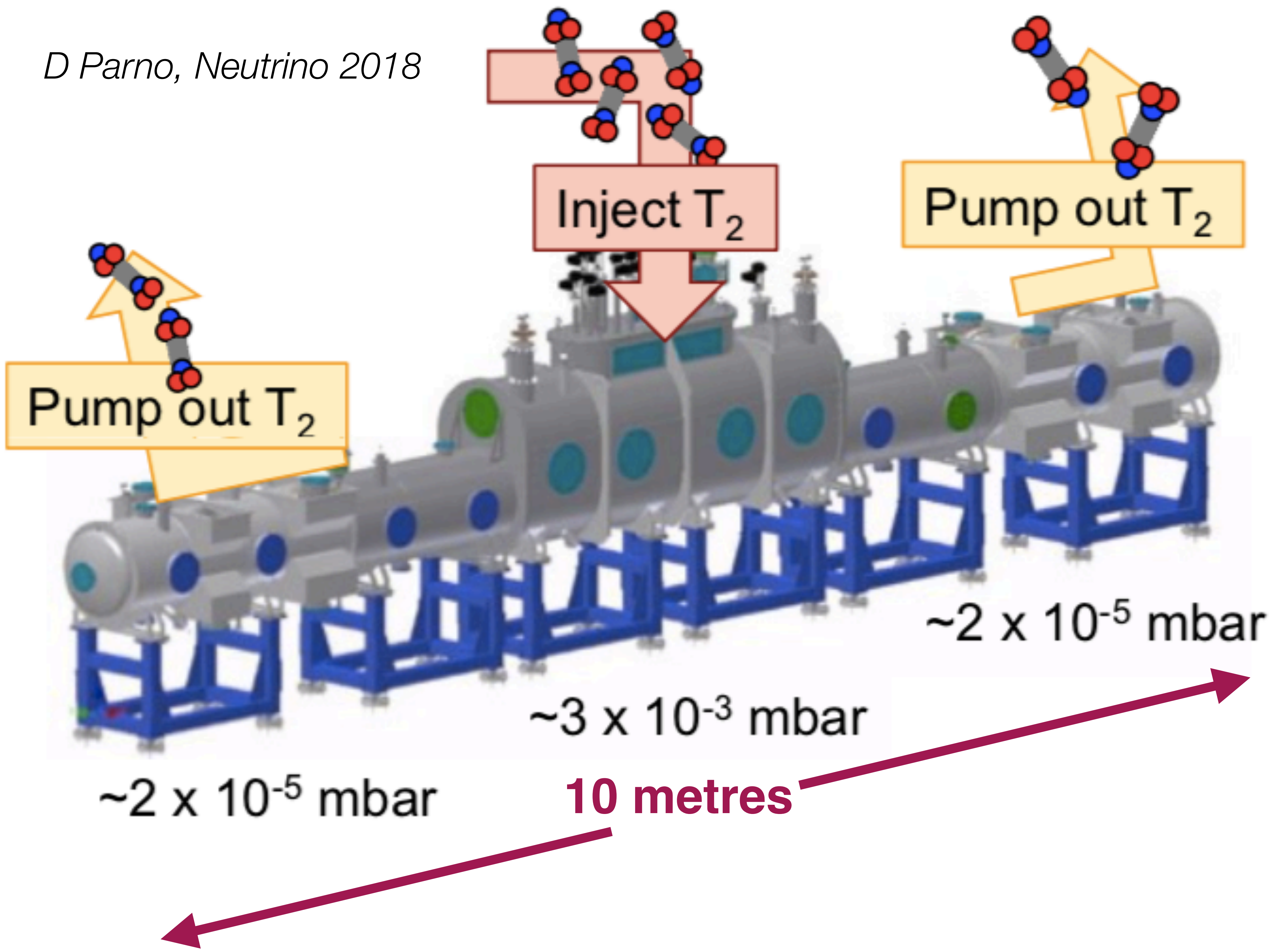


The Windowless, Gaseous Tritium Source

D Parno, Neutrino 2018



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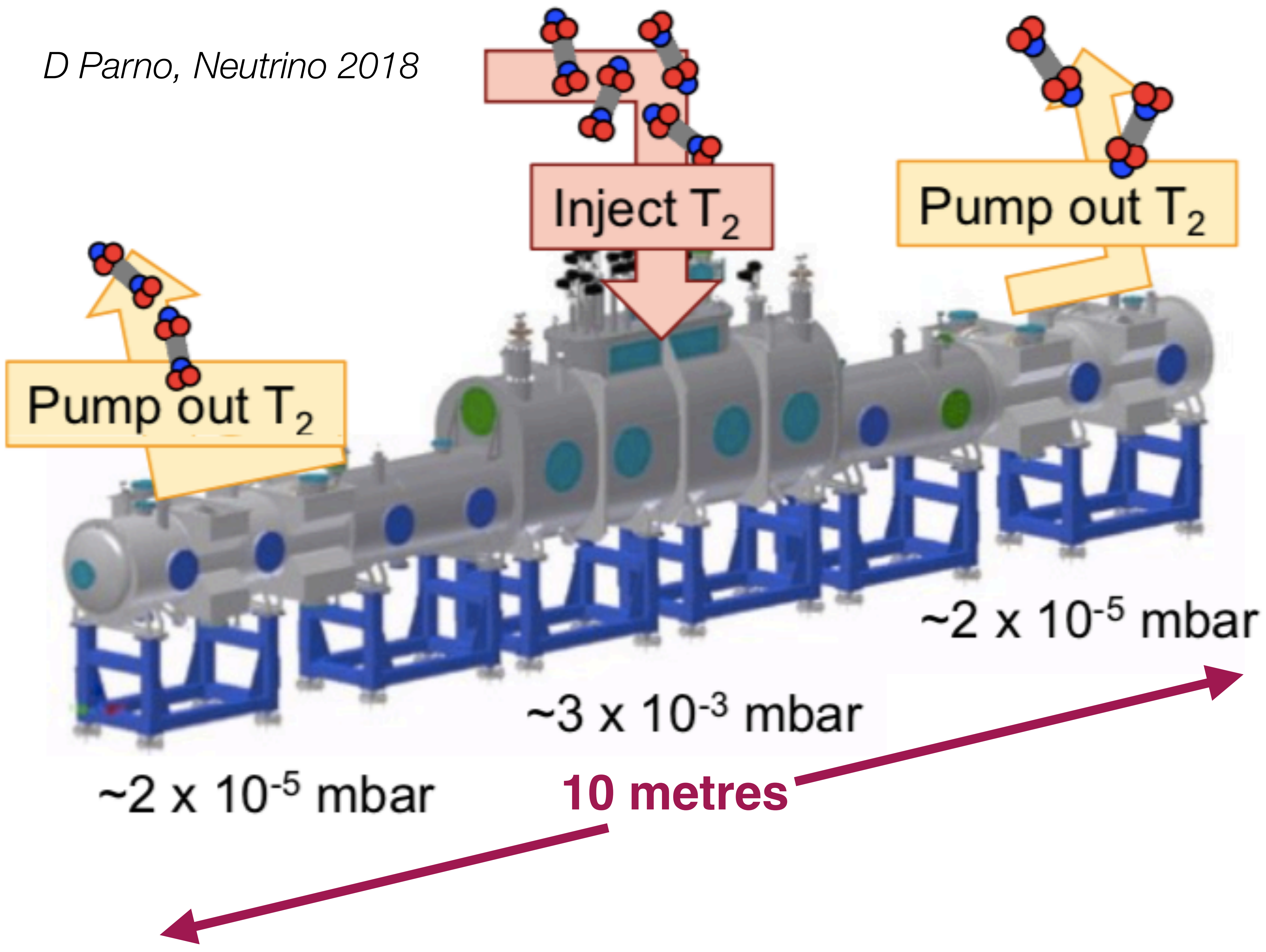
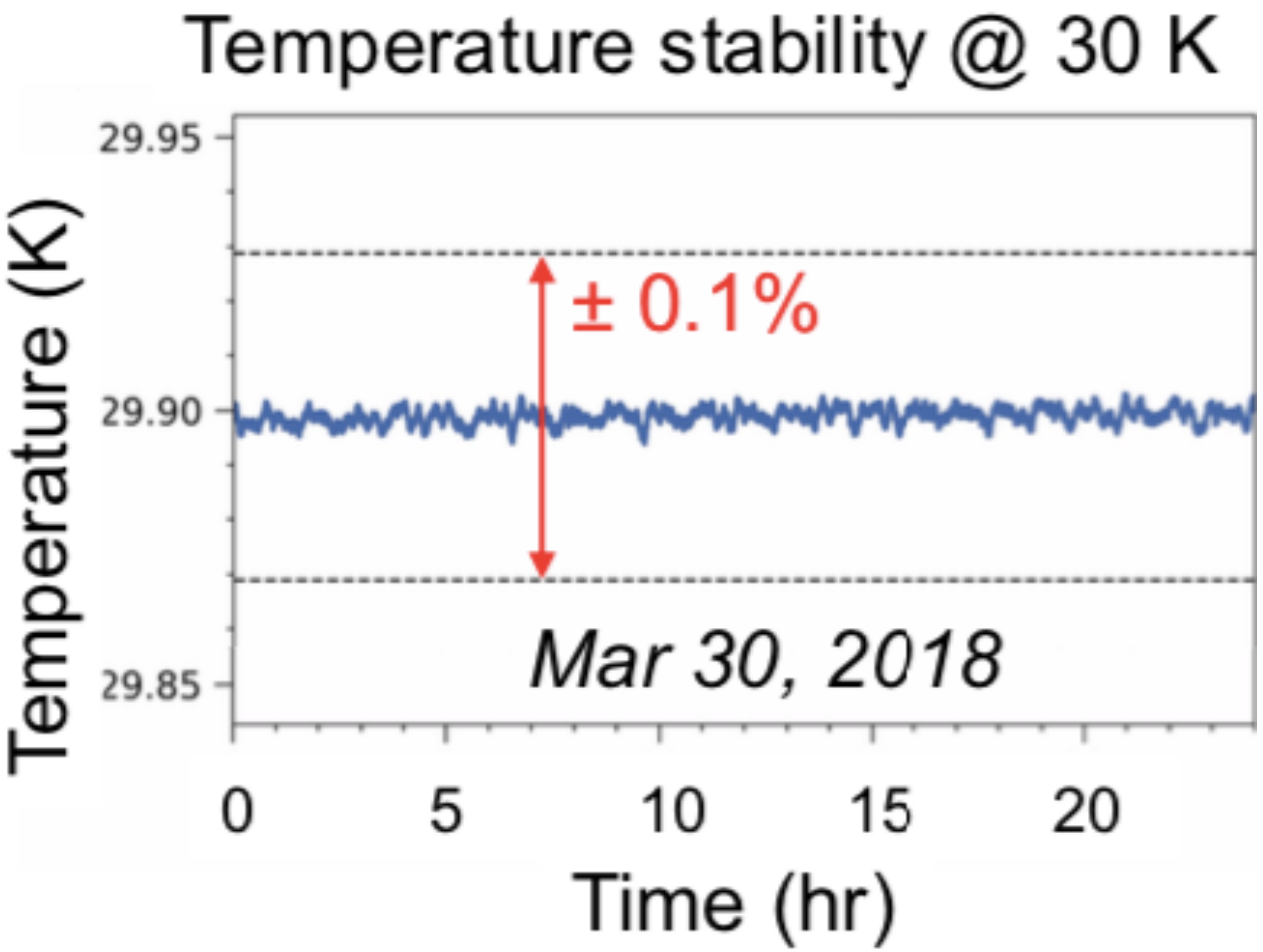
D Parno, Neutrino 2018

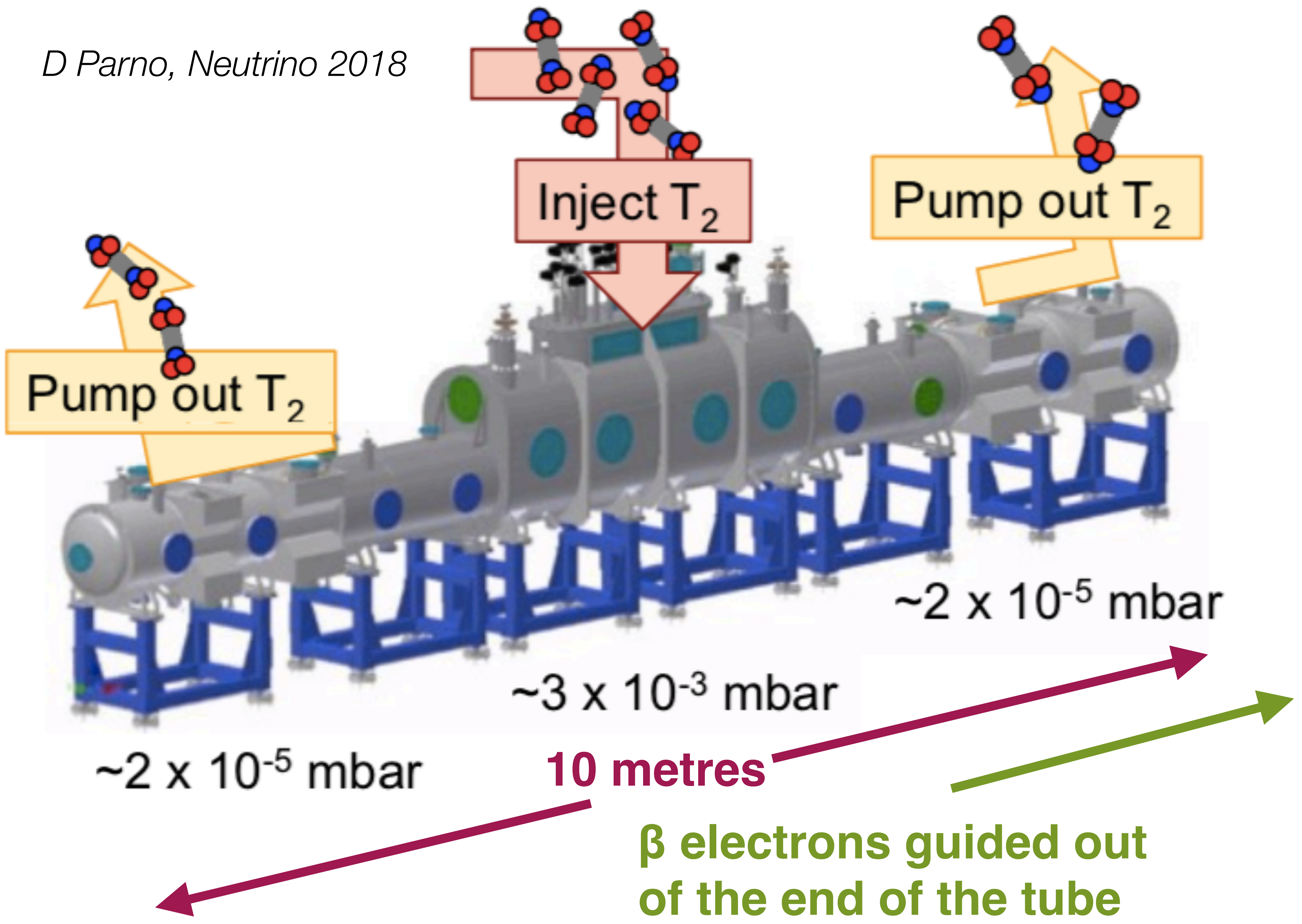


Temperature: 30 Kelvin



Two-phase Ne cooling: Cryogenics 49 (2009) 413

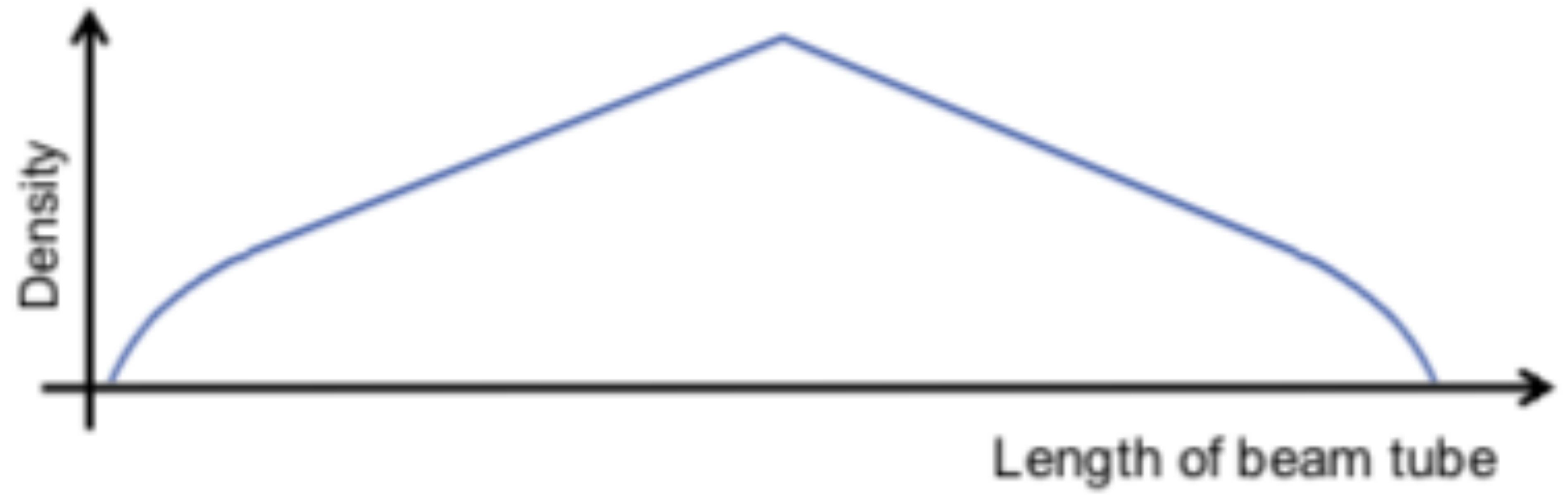
The Windowless, Gaseous Tritium Source



Temperature: 30 Kelvin

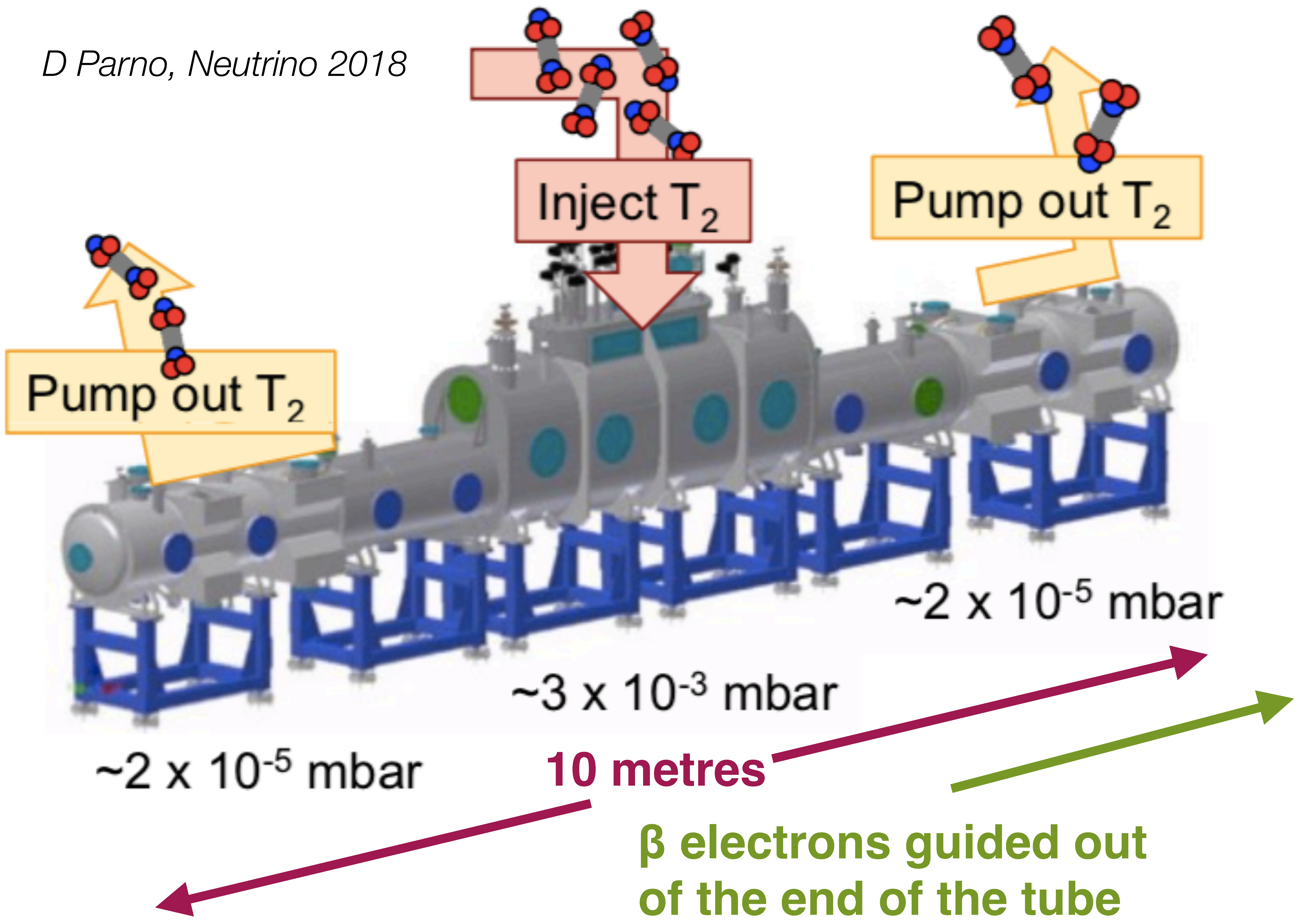
Activity: 100 GBq

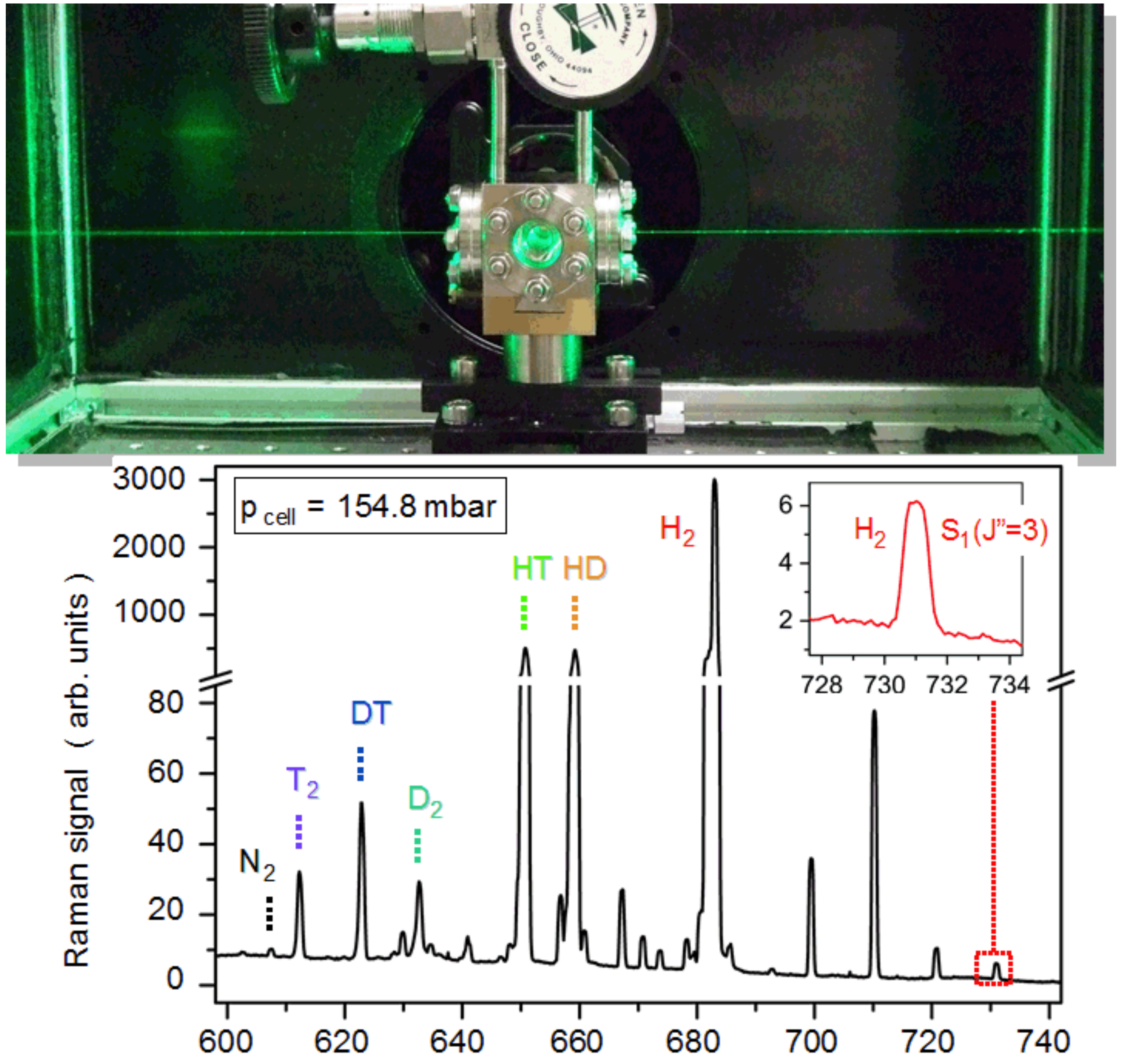
- Closed tritium cycle delivering **40g of T_2 per day**
- **9.9 X 10^{10} decays** per second
- Electrons guided out of ends of tube by **3.6 T magnetic field**
- Reduced **gas density** along tube protects against scattering and energy loss



The Windowless, Gaseous Tritium Source

D Parno, Neutrino 2018





Temperature: 30 Kelvin

Activity: 100 GBq

Isotopic Purity: 95% **molecular tritium**

Laser Raman Spectroscopy monitors isotopic content to 0.1% precision

KATRIN source: molecular tritium

Remember this?

Constant

Matrix element

Fermi function

Electron momentum and energy

$$\frac{dN}{dE_e} = \frac{G_F^2 m_e^5 \cos^2\theta_C}{2\pi^3\hbar^7} |M_{\rm nuc}|^2 F(Z, E_e) p_e E_e$$

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Neutrino energy and momentum

$$\times \Theta(E_{\rm max} - E_e - m_{\nu_i})$$

Energy conservation step function

Phys. Rev. C ***91***, *035505*

KATRIN source: molecular tritium

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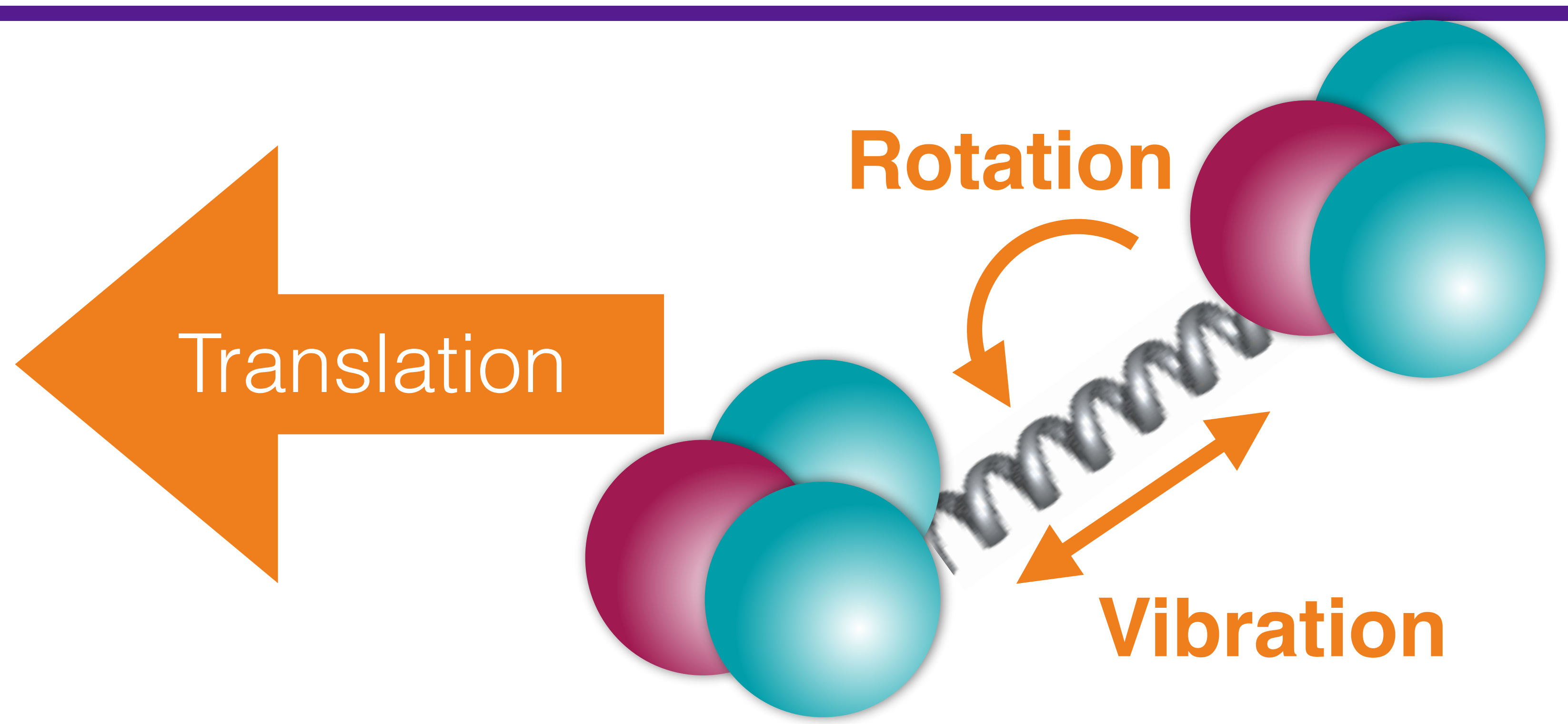
+



Phys. Rev. C ***91****, 035505*

KATRIN source: molecular tritium

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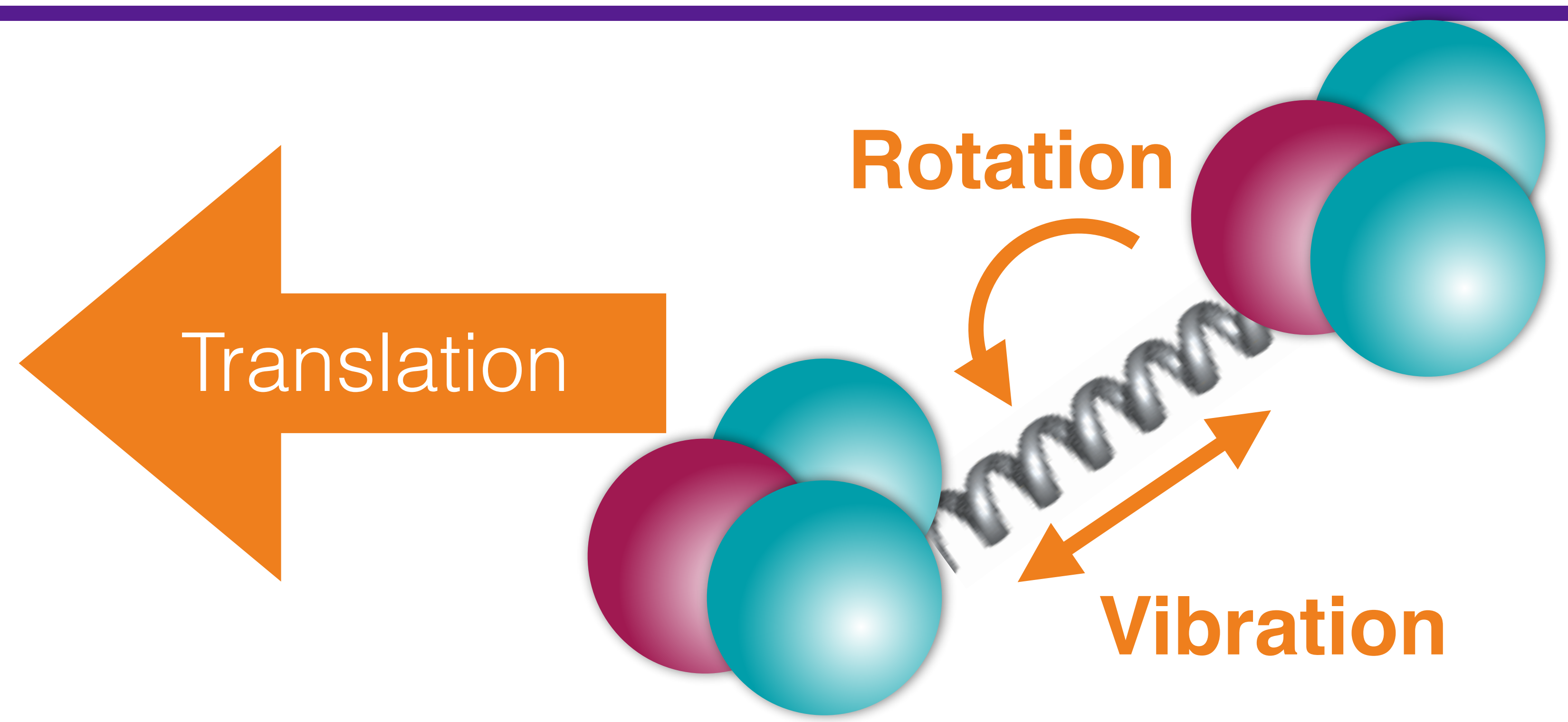

$$\times \sum_{ik} |U_{ei}|^2 P_k(E_{\max} - E_e - V_k)\sqrt{(E_{\max} - E_e - V_k)^2 - m_{\nu_i}^2}$$

Neutrino energy and momentum

$$\times\Theta(E_{\max} - E_e - V_k - m_{\nu_i})$$

Energy conservation step function

Phys. Rev. C ***91***, *035505*

KATRIN source: molecular tritium

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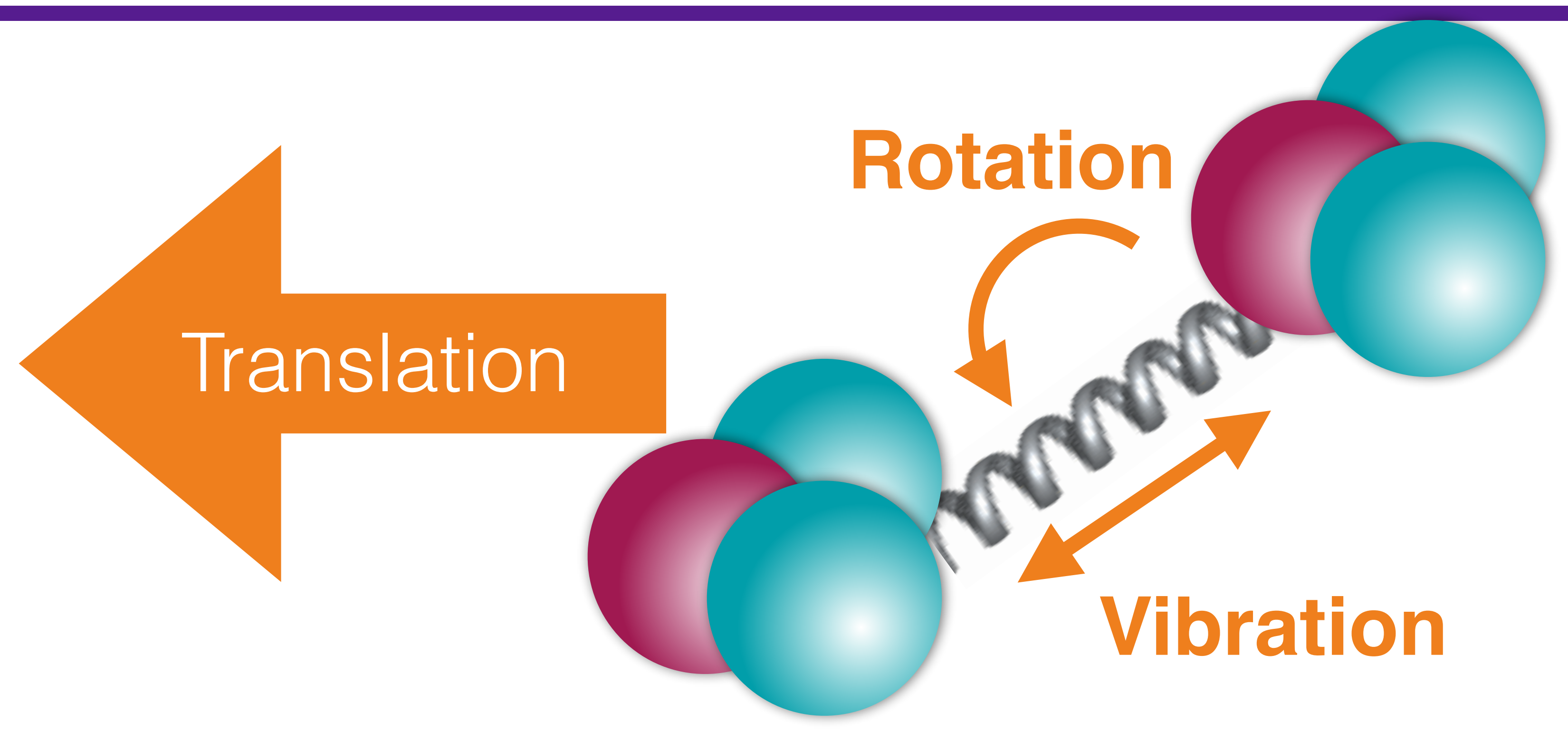

Probability of excited daughter state

$$\times \sum_{ik} |U_{ei}|^2 P_k (E_{\max} - E_e - V_k) \sqrt{(E_{\max} - E_e - V_k)^2 - m_{\nu_i}^2}$$

Sum over neutrino mass states i and excited states of daughter k

Energy of daughter state

$$\times \Theta(E_{\max} - E_e - V_k - m_{\nu_i})$$

Phys. Rev. C ***91****, 035505*

KATRIN source: molecular tritium

$$\frac{dN}{dE_e} = \frac{G_F^2 m_e^5 \cos^2\theta_C}{2\pi^3\hbar^7}|M_{\text{nuc}}|^2 F(Z,E_e)p_e E_e$$

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Sum over neutrino mass states i and excited states of daughter k

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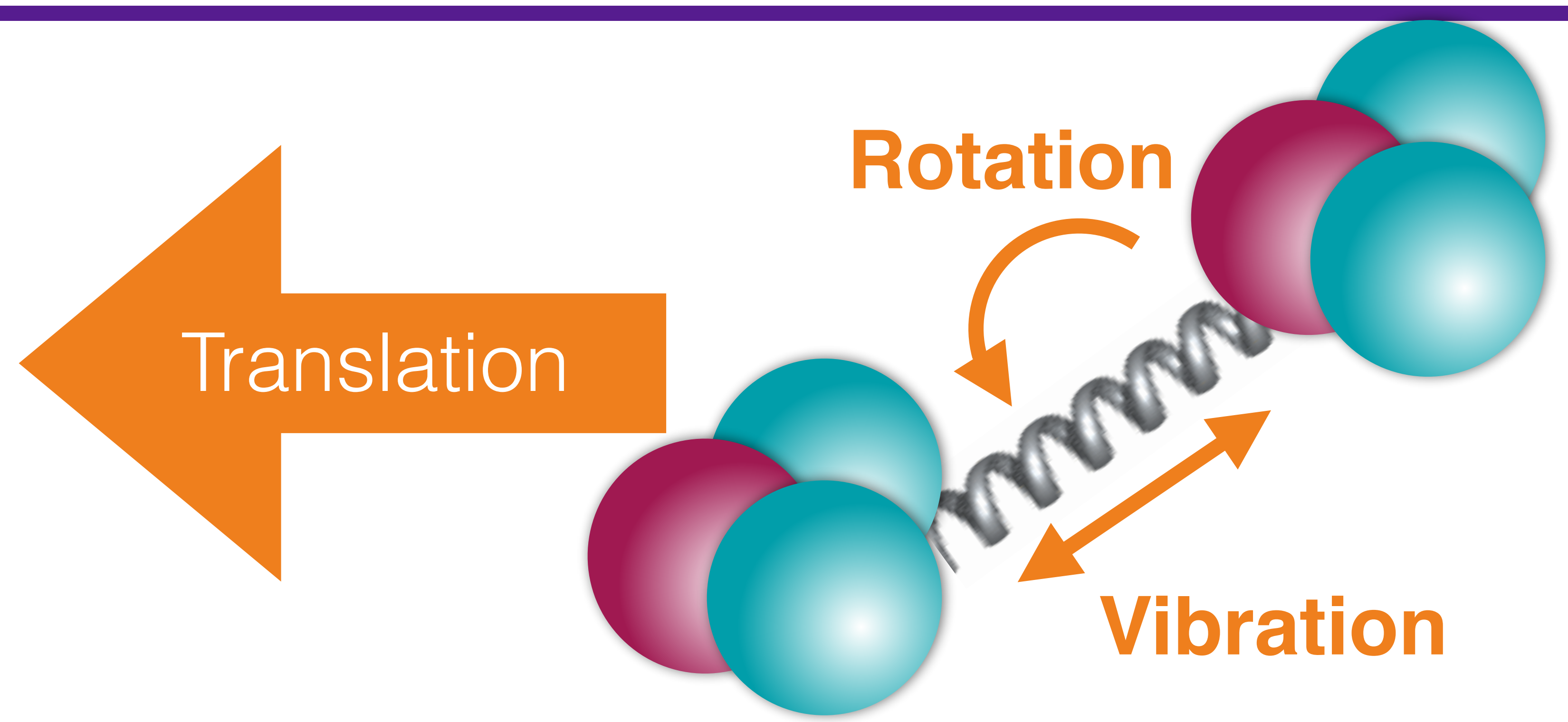
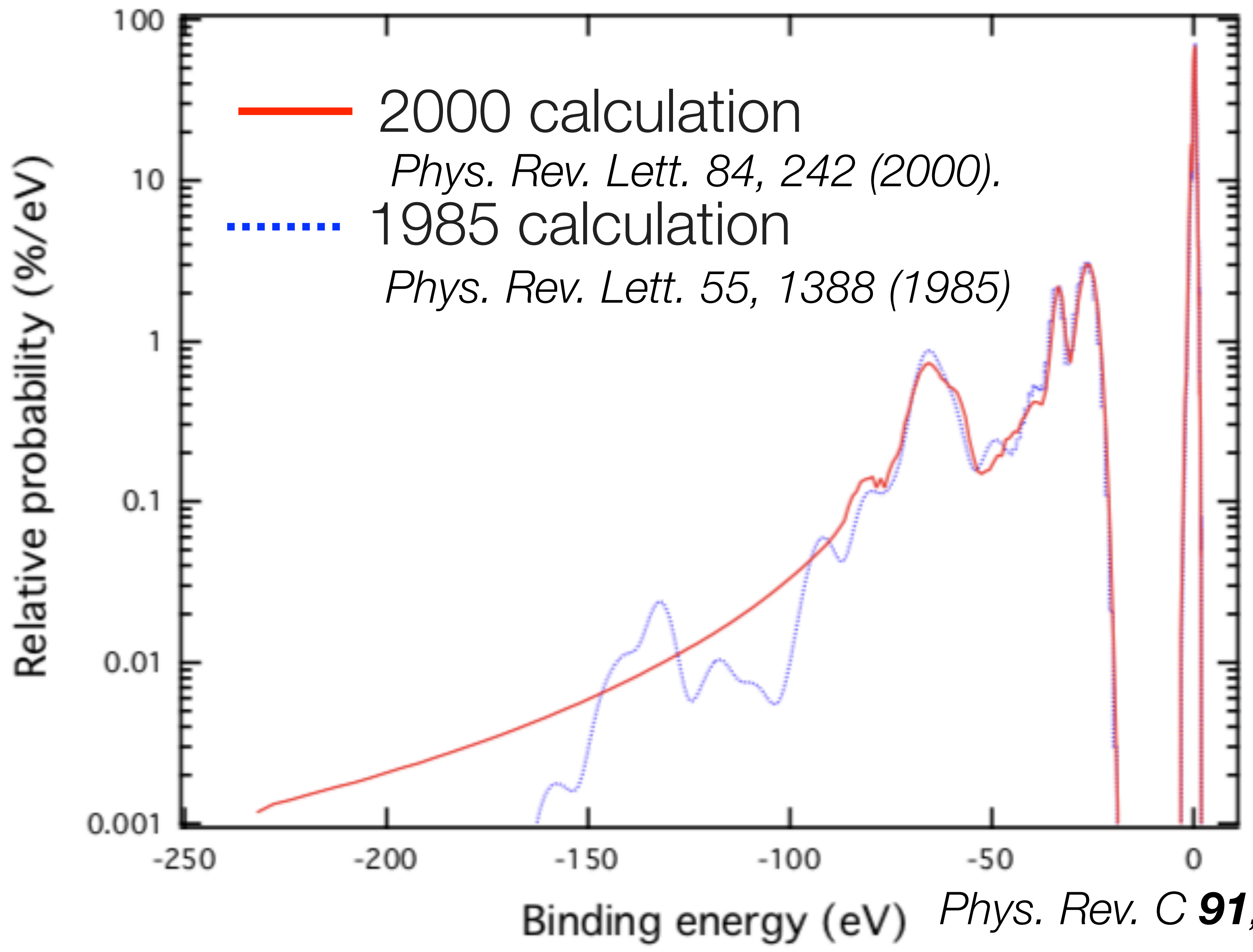
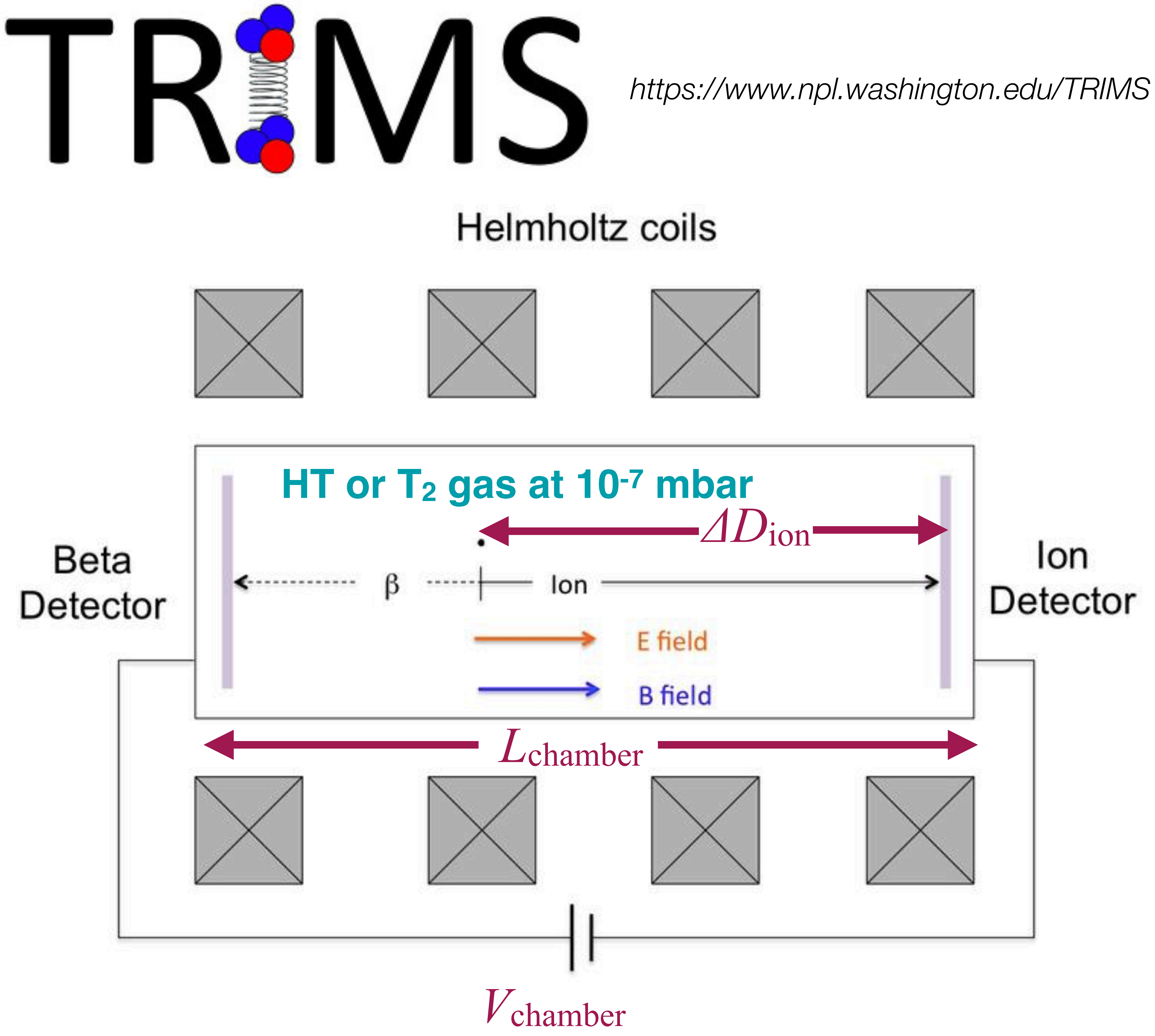


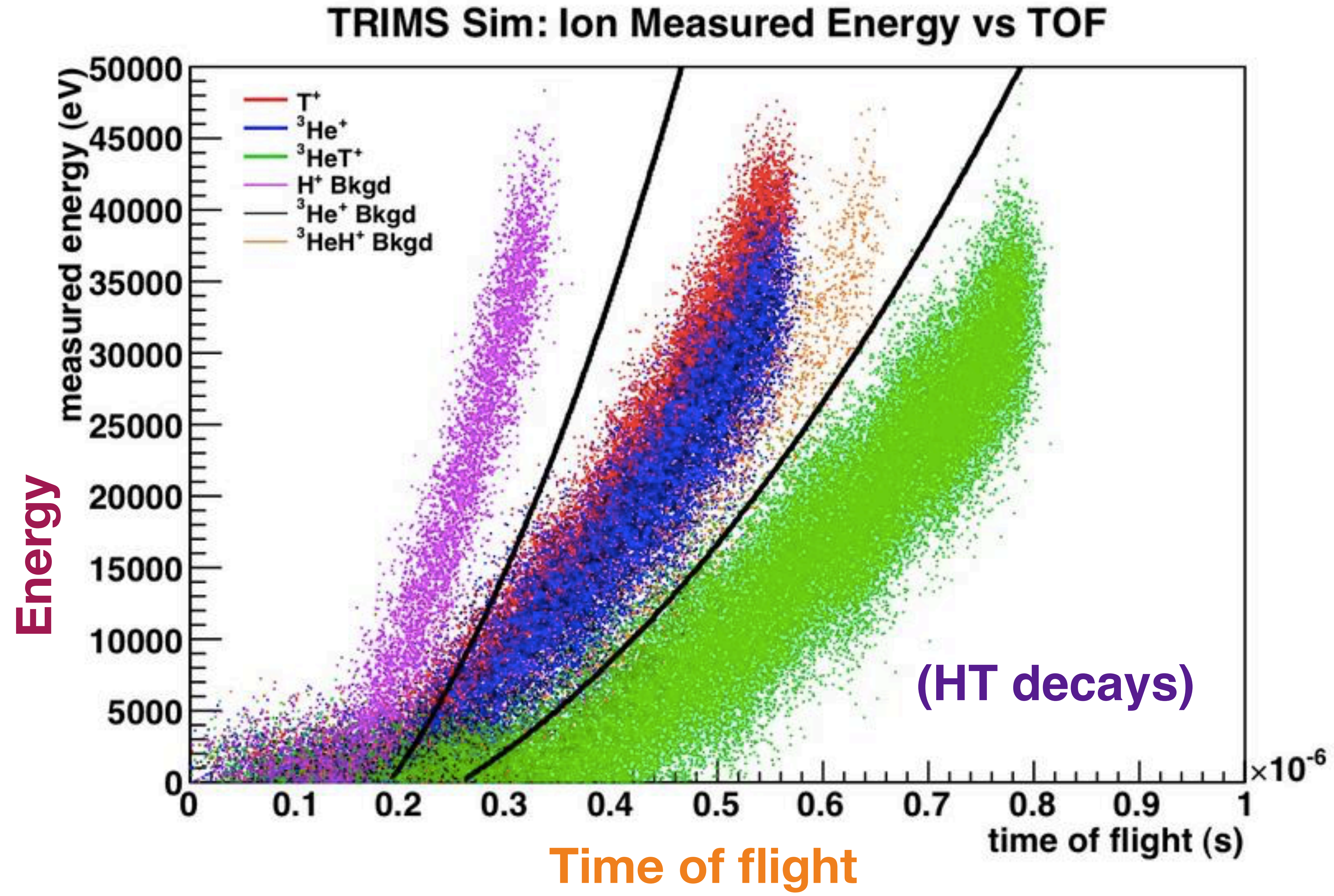
Calculated final-state molecular spectrum



Phys. Rev. C ***91****, 035505*

Tritium Recoil-Ion Mass Spectrometer



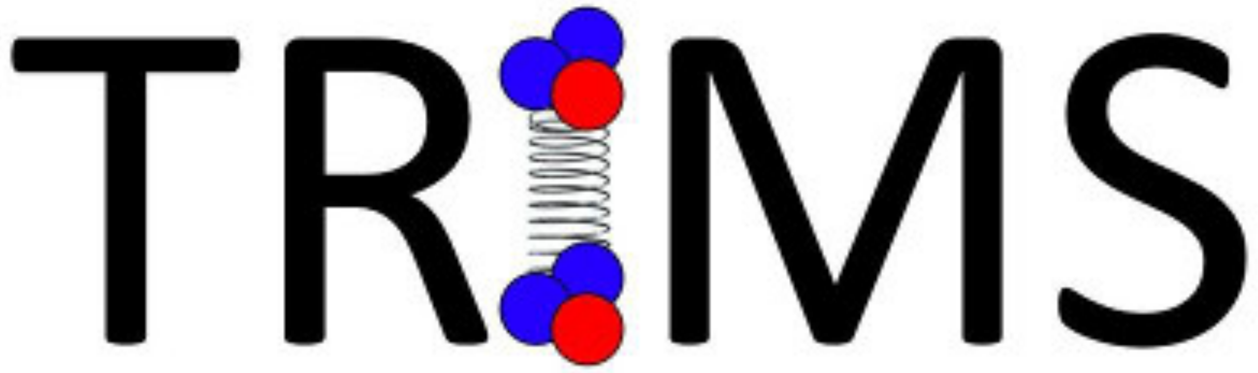


$$E_{\text{ion}} \sim \frac{qV_{\text{chamber}}\Delta D_{\text{ion}}}{L_{\text{chamber}}}$$

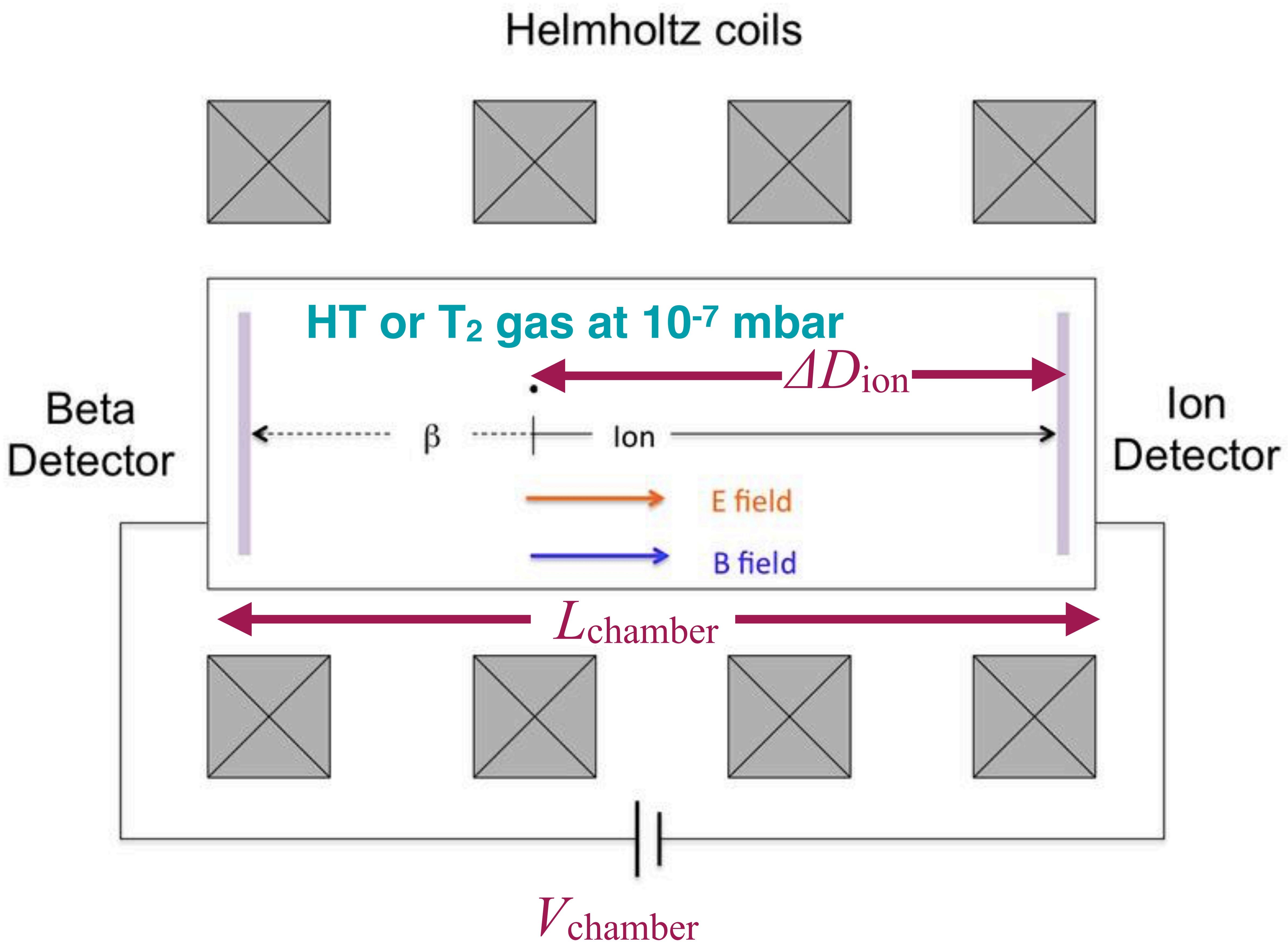
$$t_{\text{drift}} \sim \sqrt{\frac{2mL_{\text{chamber}}\Delta D_{\text{ion}}}{qV_{\text{chamber}}}}$$

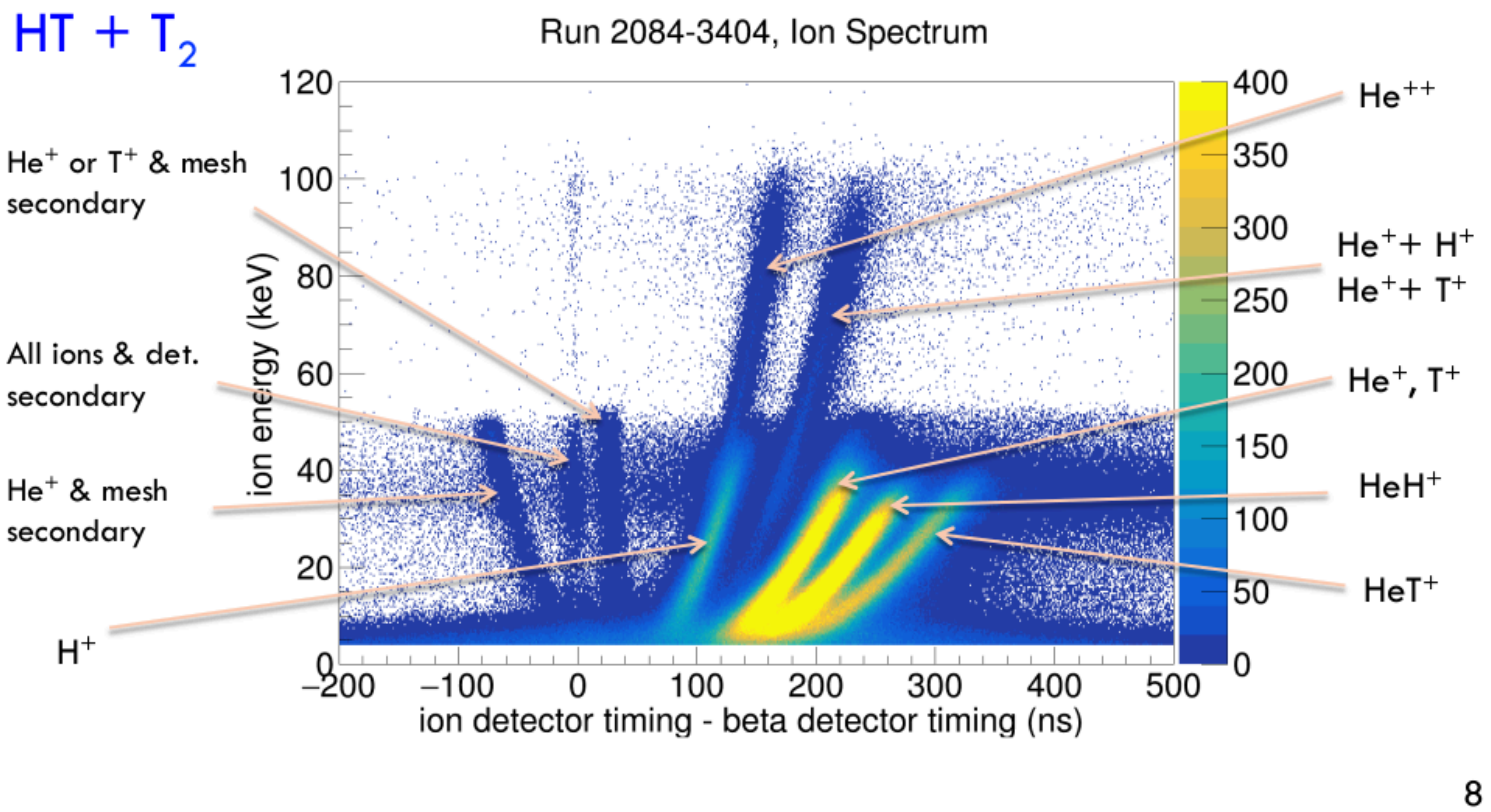
Energy and **time of flight** separate final states so **branching ratio** can be calculated

Tritium Recoil-Ion Mass Spectrometer



https://www.npl.washington.edu/TRIMS





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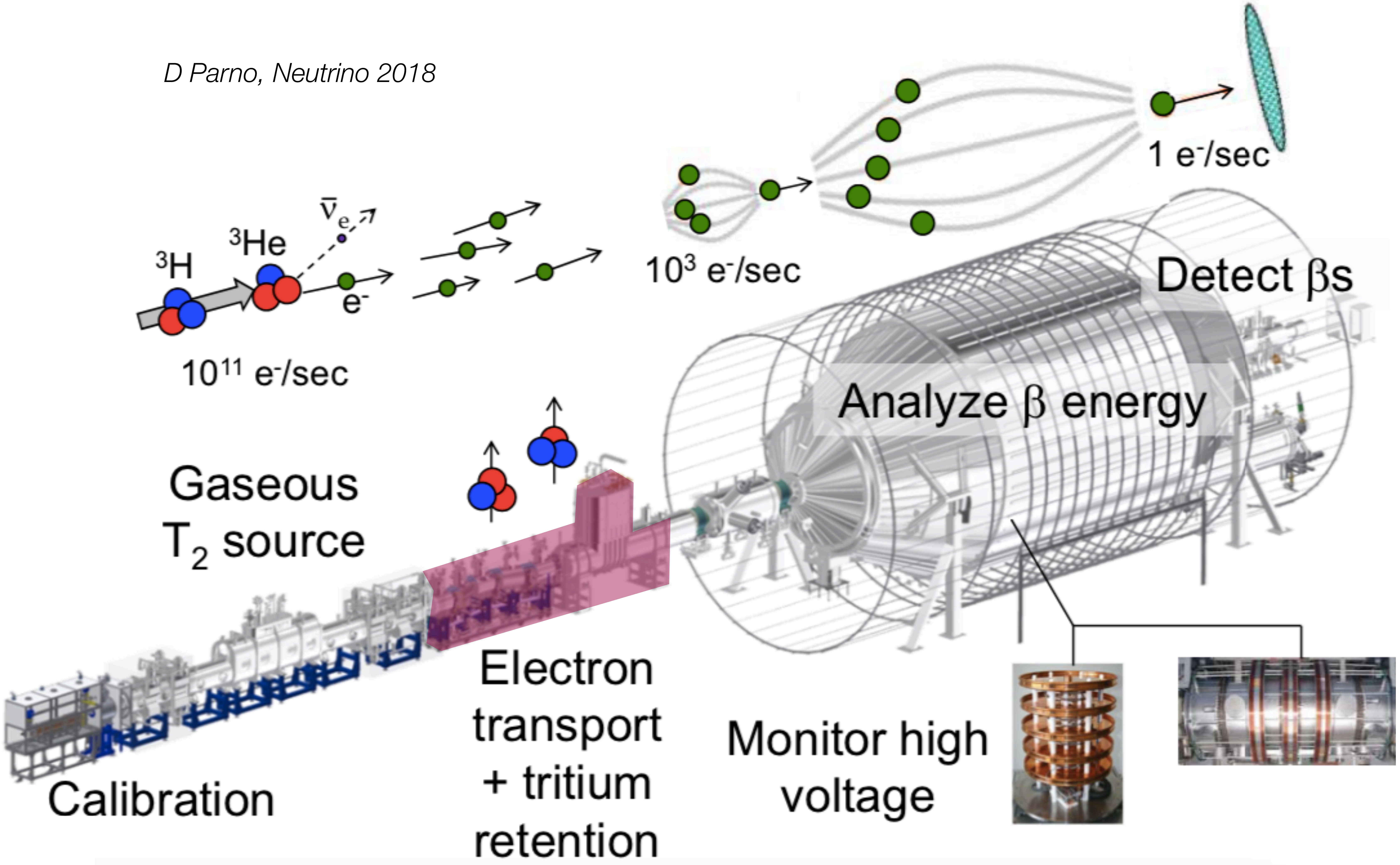
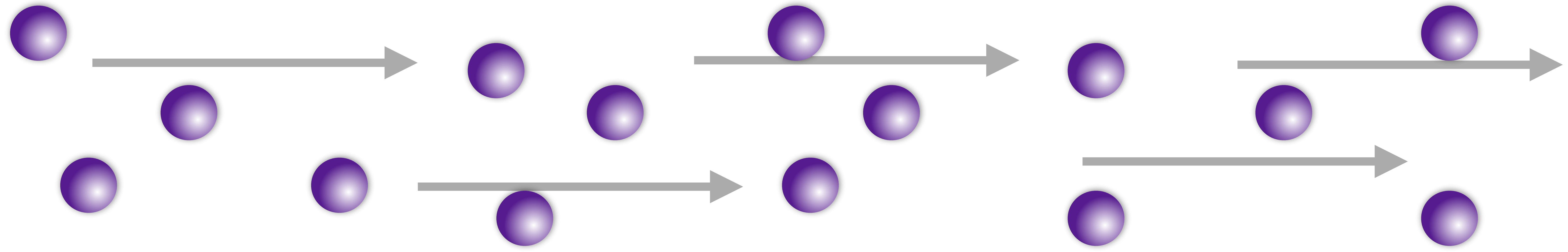


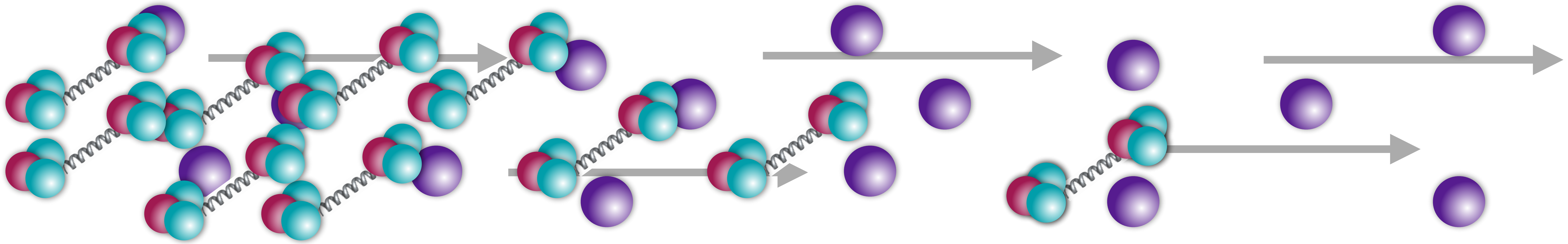
Electron transport and tritium removal

Electron transport and tritium removal



Electrons are guided adiabatically towards the spectrometers…

Electron transport and tritium removal

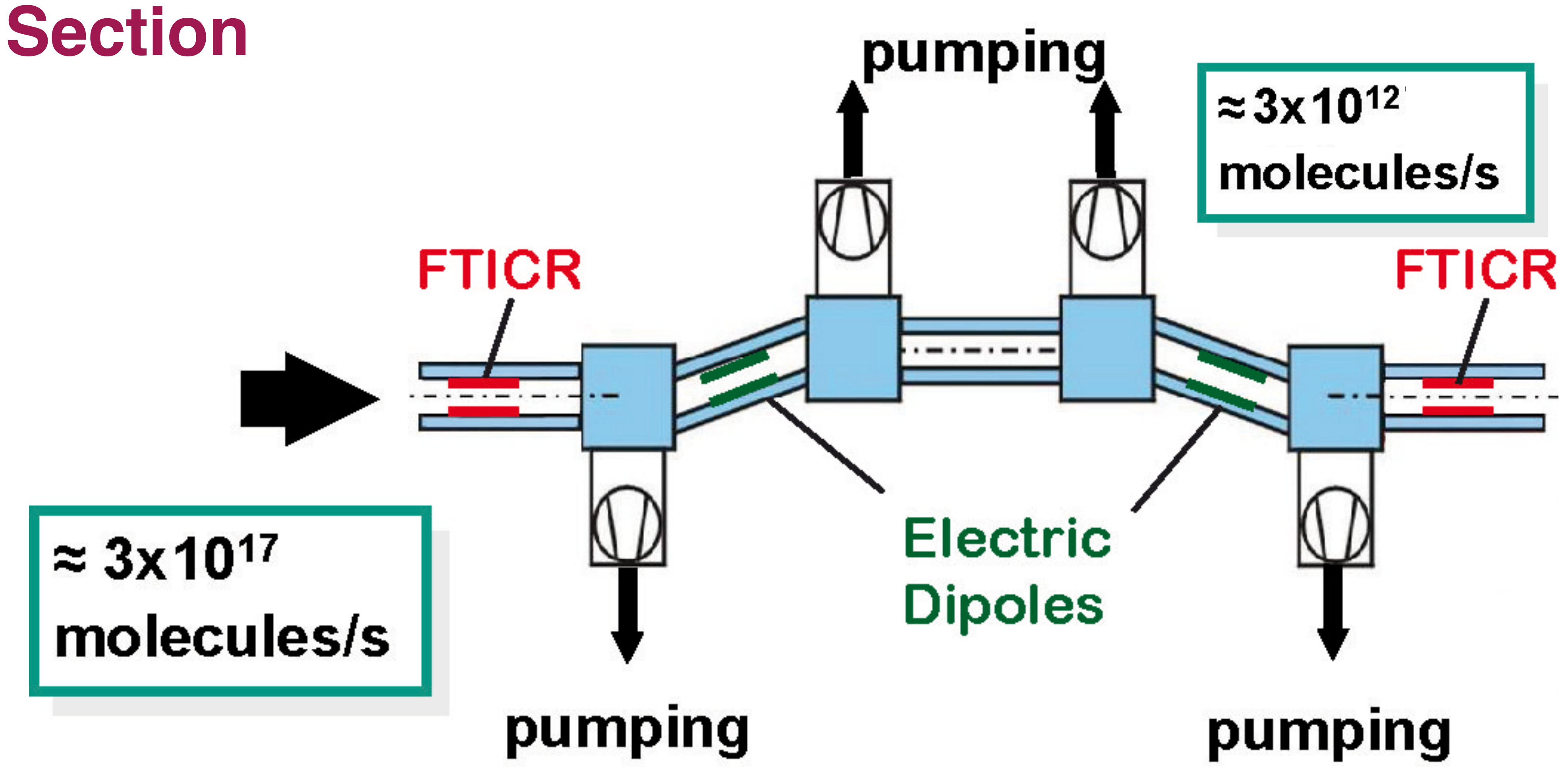


Electrons are guided adiabatically towards the spectrometers…

… while any remaining tritium is suppressed by a factor of 10^9

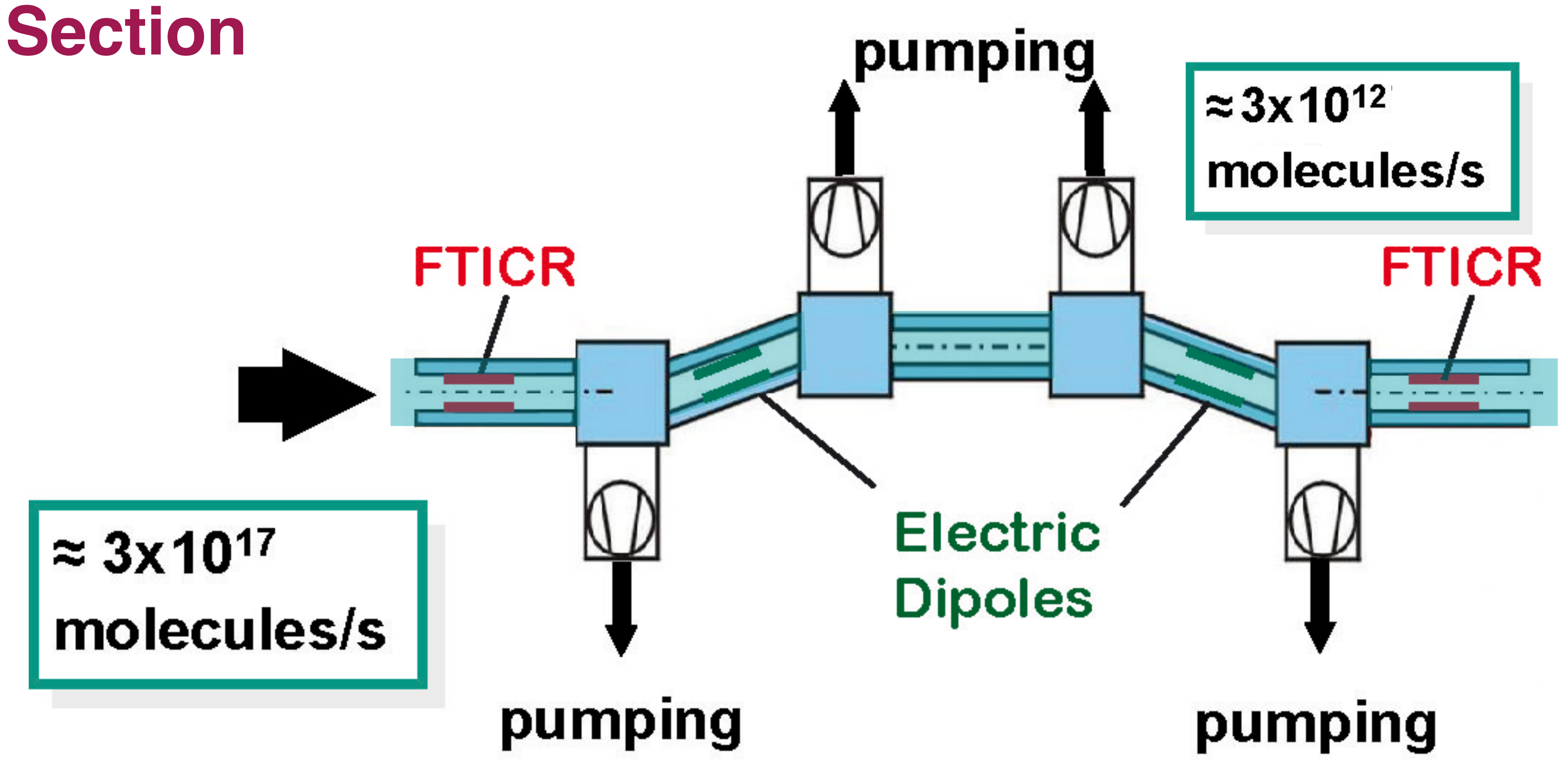
Electron transport and tritium removal

Differential Pumping Section



Electron transport and tritium removal

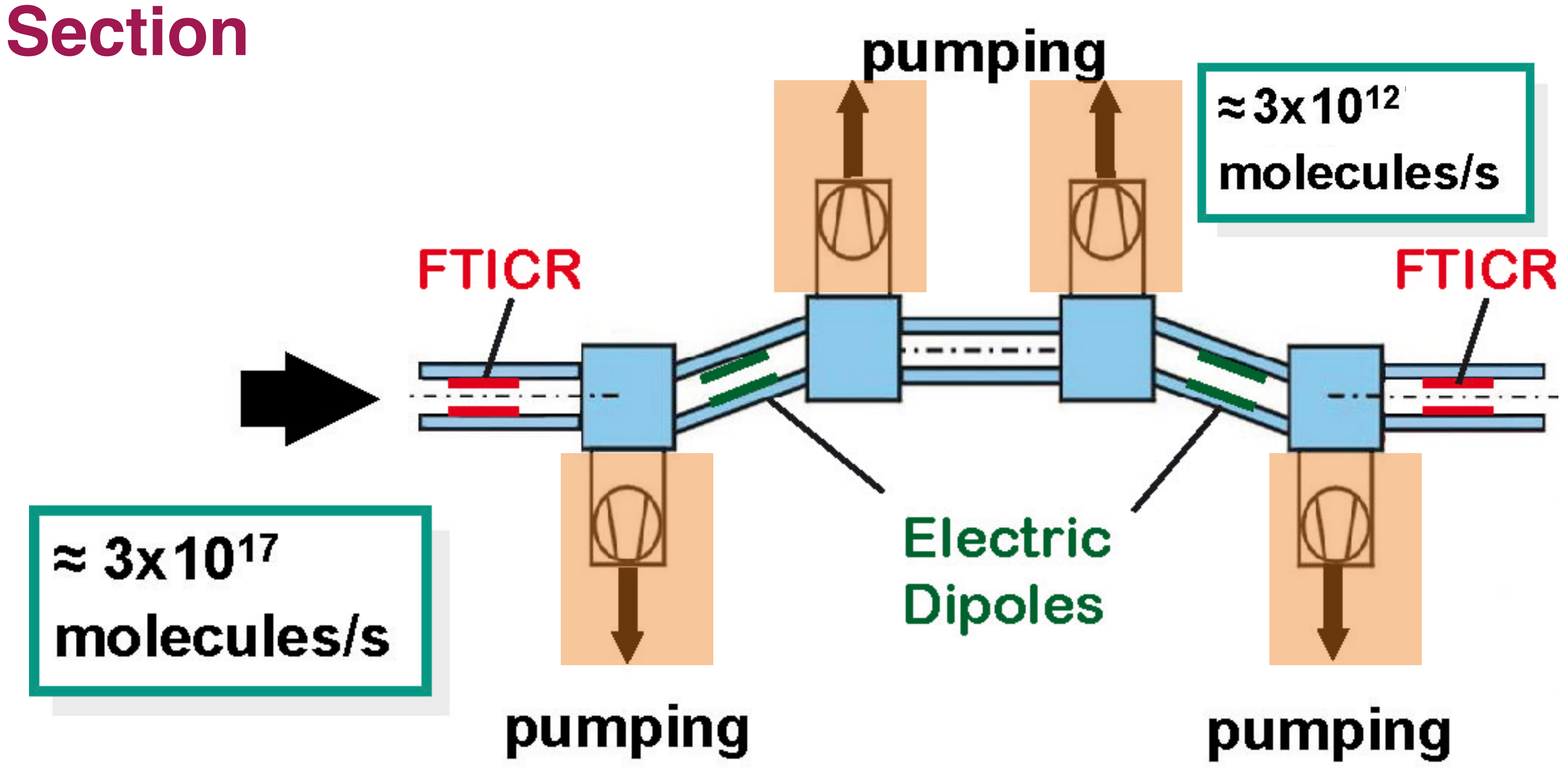
Differential Pumping Section



- Five 1-metre tubes with 20 degree tilt to block line of sight for **neutral molecules**

Electron transport and tritium removal

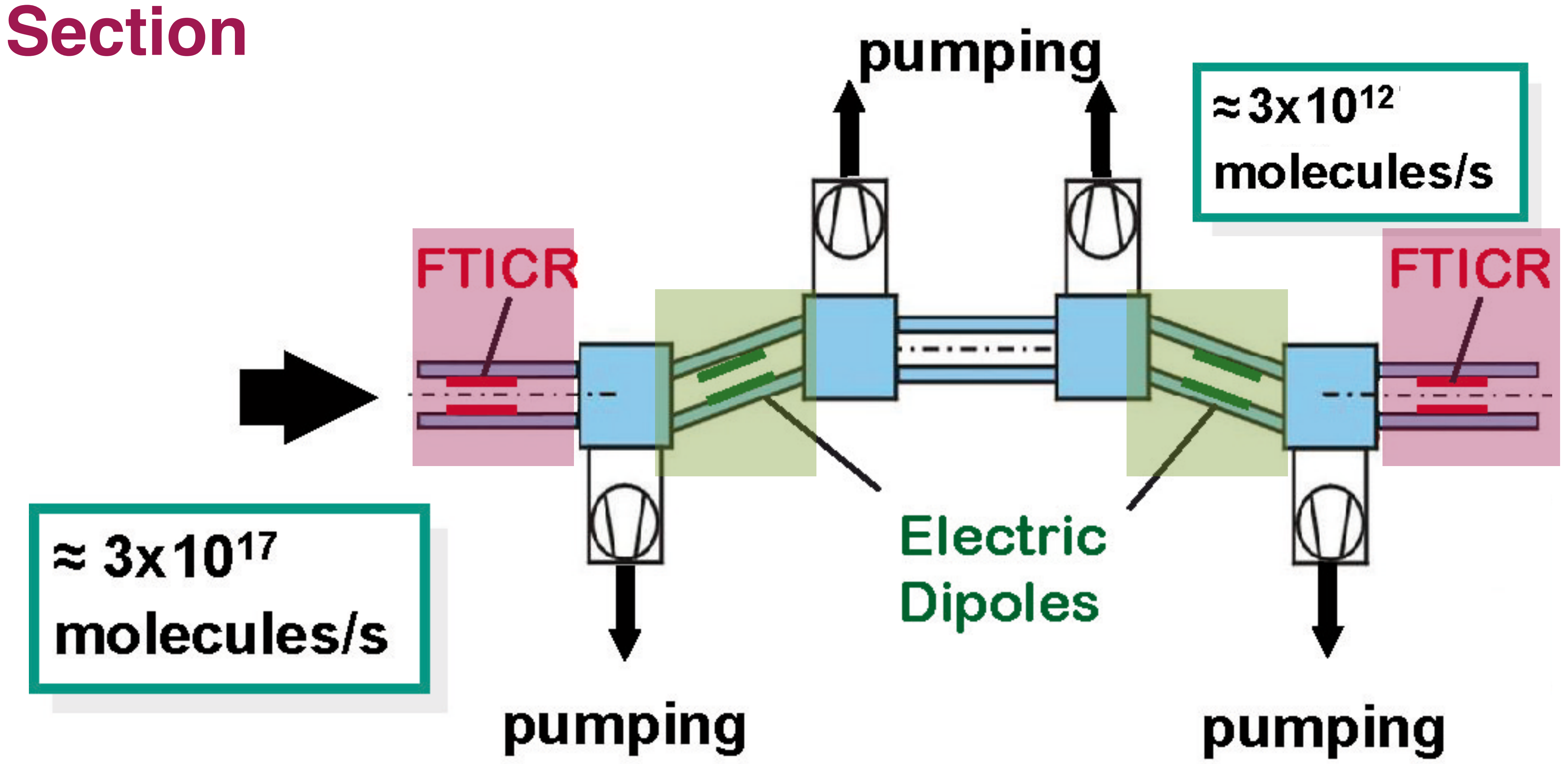
Differential Pumping Section



- Five 1-metre tubes with 20 degree tilt to block line of sight for **neutral molecules**
- **Turbo-molecular pumps** reduce tritium flow by 2.5×10^4

Electron transport and tritium removal

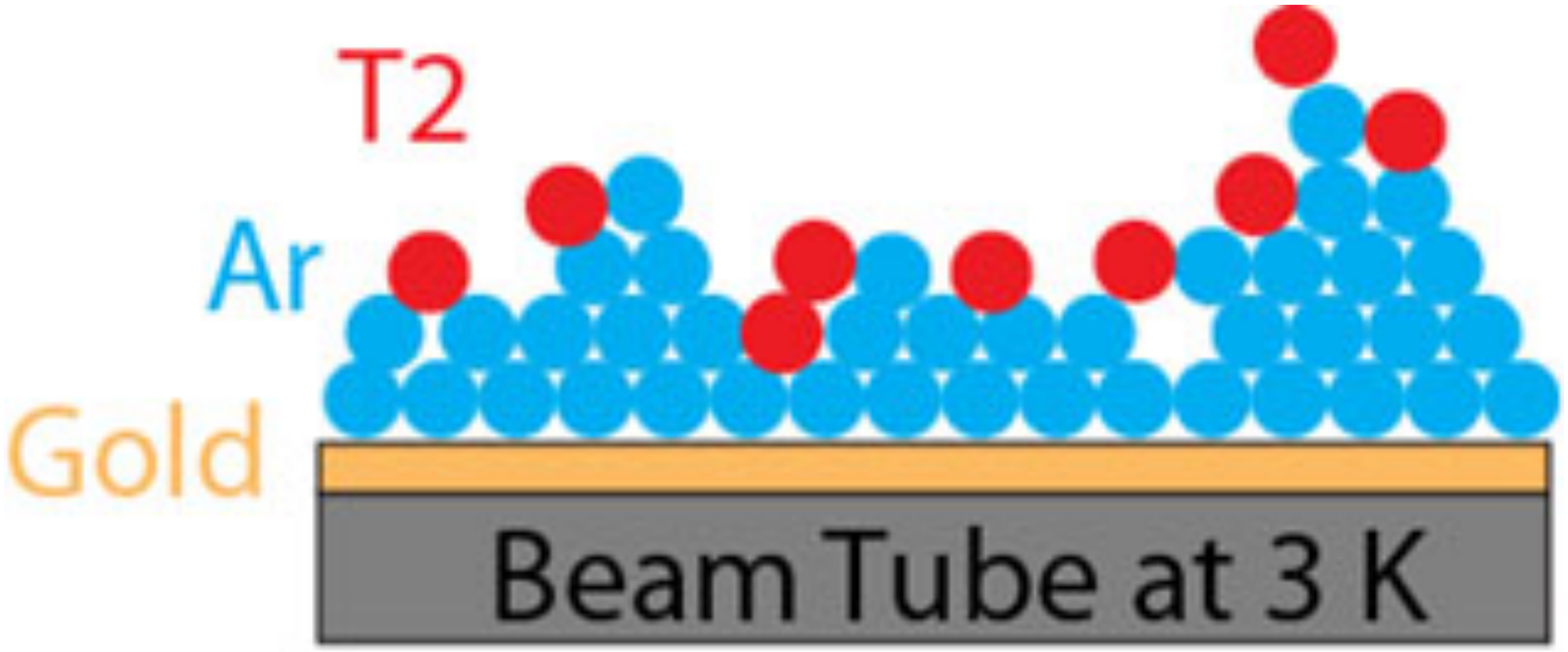
Differential Pumping Section



- Five 1-metre tubes with 20 degree tilt to block line of sight for **neutral molecules**
- **Turbo-molecular pumps** reduce tritium flow by 2.5×10^4
- **Dipole electrodes** and **Fourier-transform ion cyclotron resonators** remove positive ions

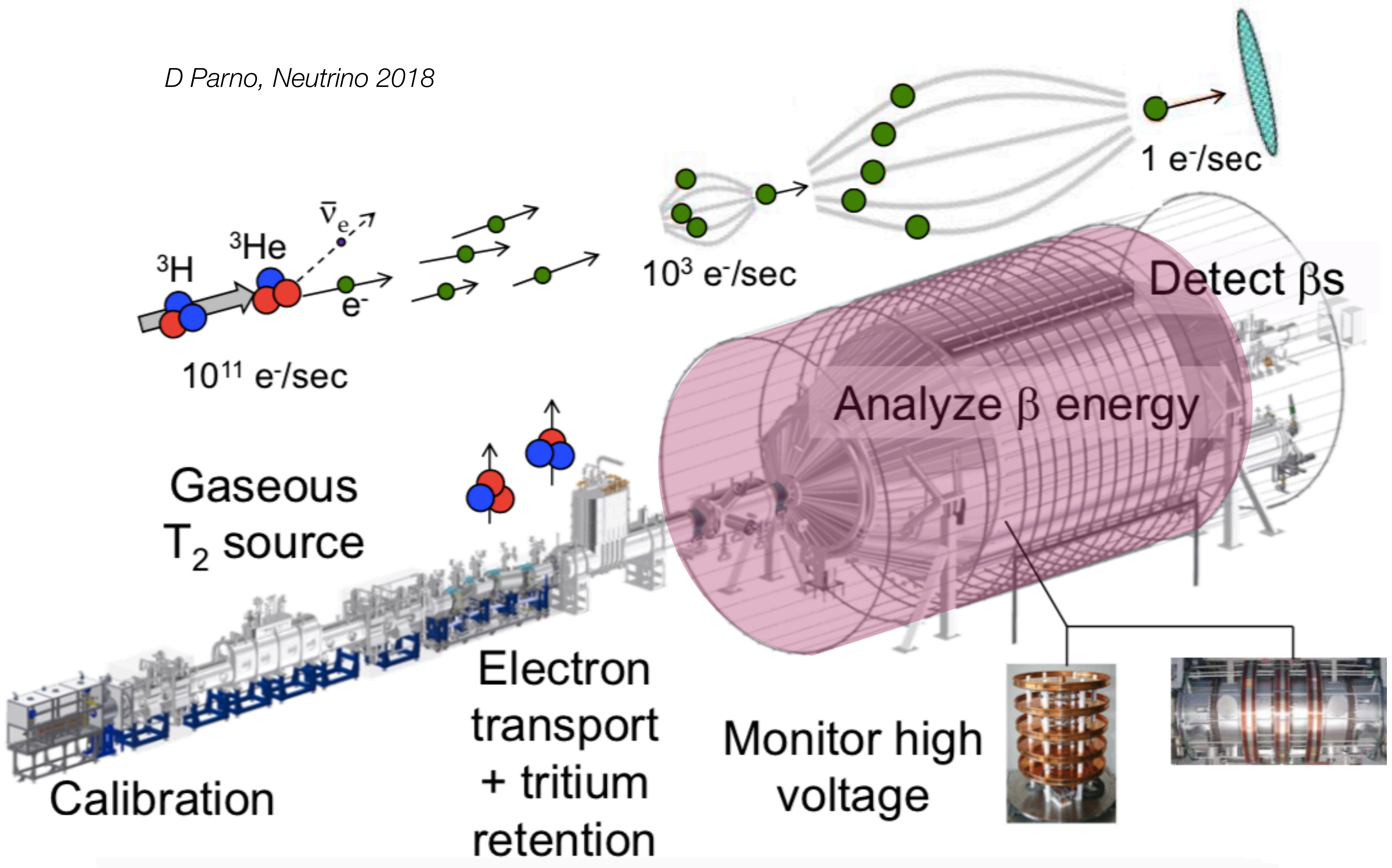
Electron transport and tritium removal

Cryogenic pumping section

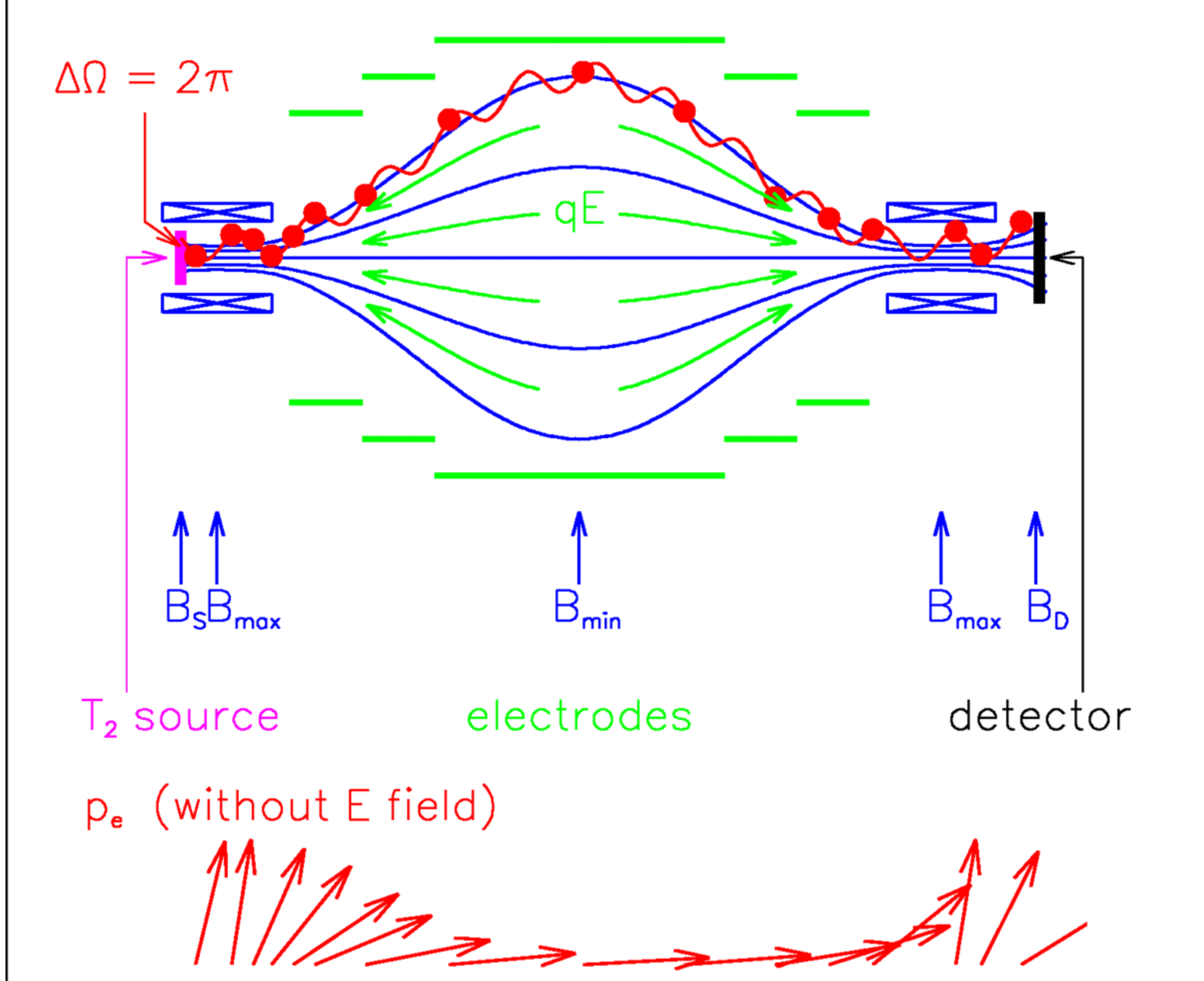


- Beam pipe coated with **argon frost**
- Remaining **tritium** is trapped by **cryo-sorption**
- After 60 days, surface is **saturated** - **heat** to 100 K to release tritium and **pump** it away
- Tritium suppressed by **12 orders of magnitude** relative to source inlet

KATRIN: Karlsruhe Tritium Neutrino Experiment



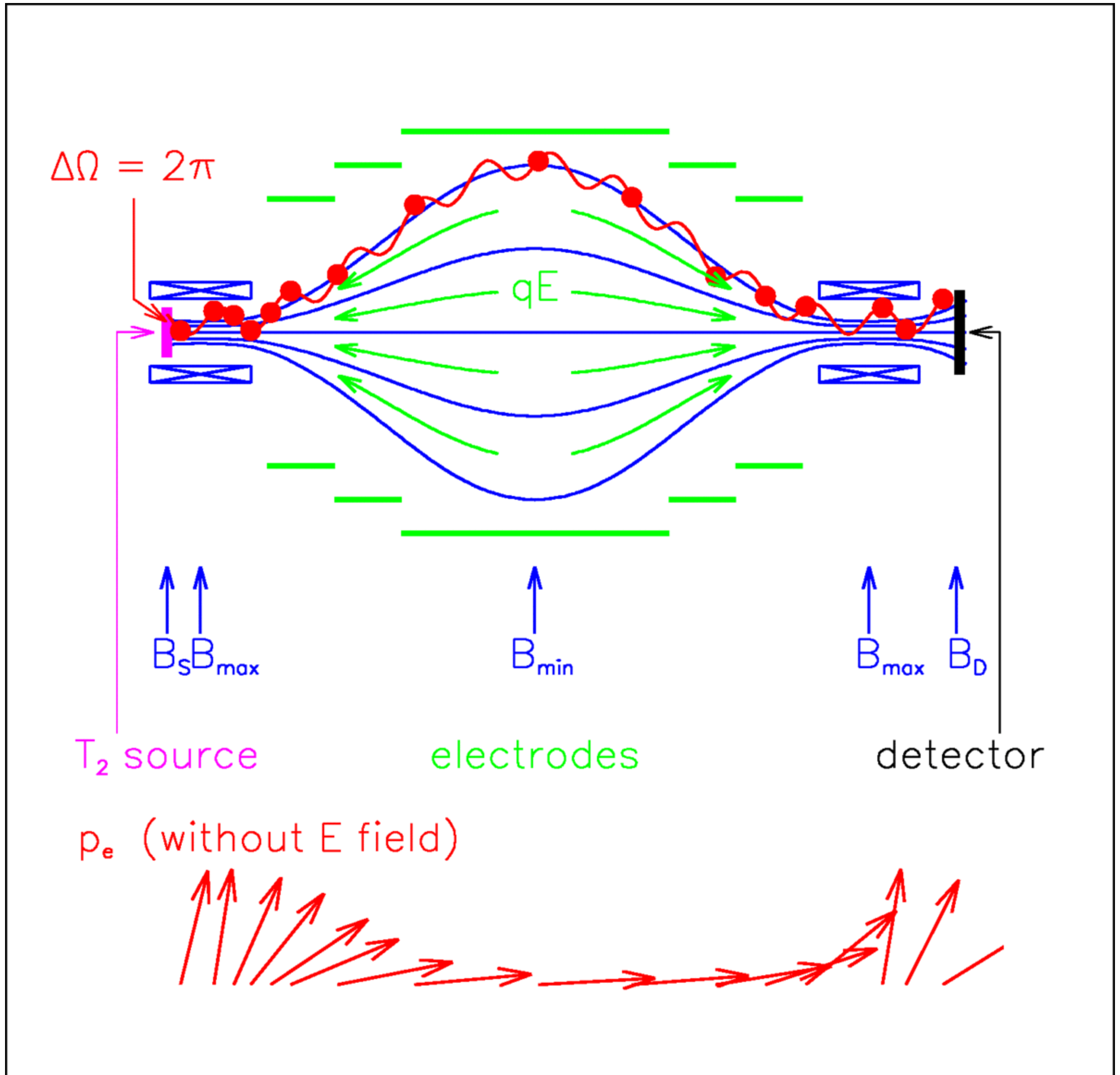
KATRIN's superpower - the MAC-E filter



https://www.katrin.kit.edu/

Kleesiek et al., arXiv:1806.00369

KATRIN's superpower - the MAC-E filter

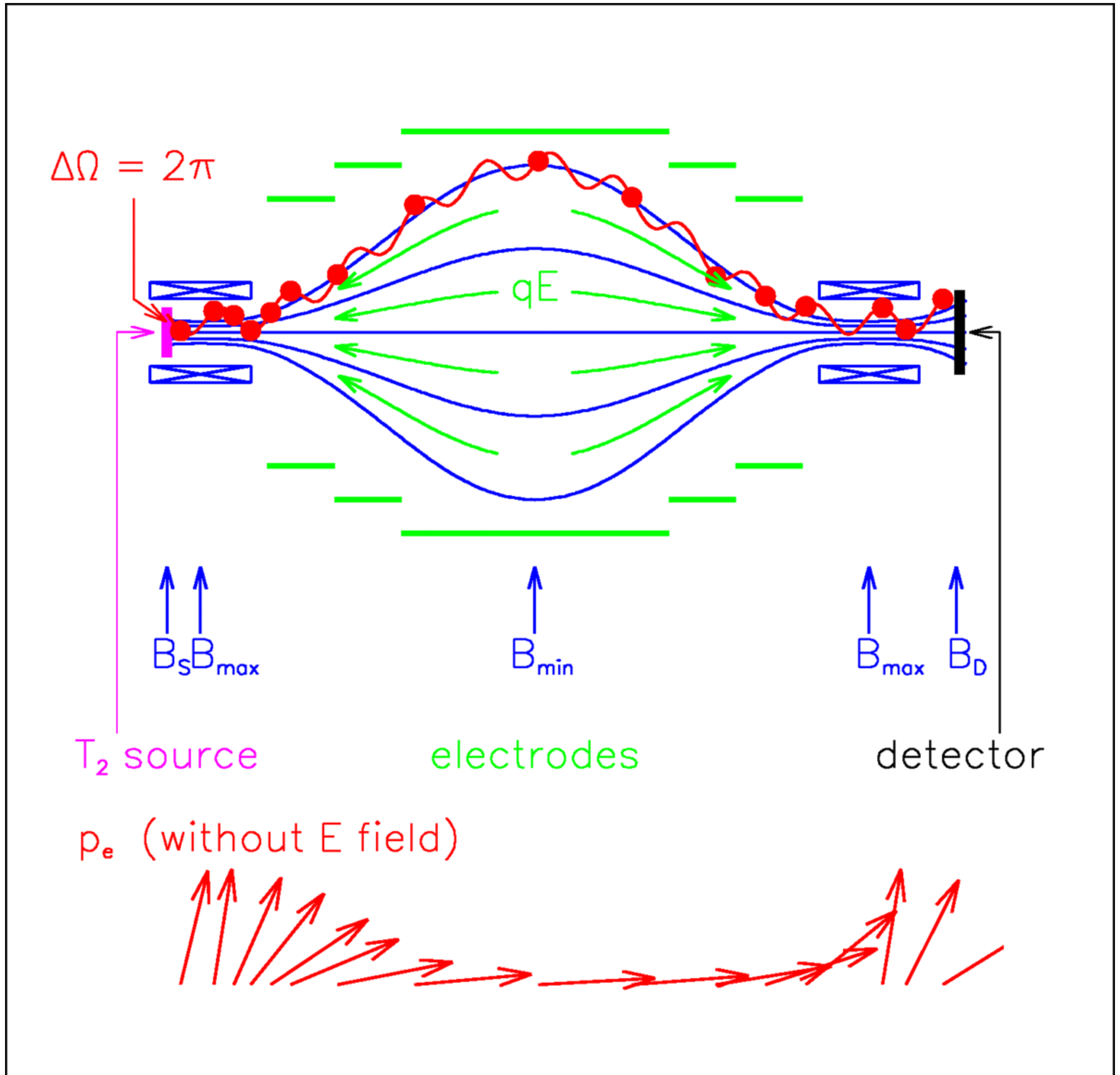


https://www.katrin.kit.edu/

Magnetic

Kleesiek et al., arXiv:1806.00369

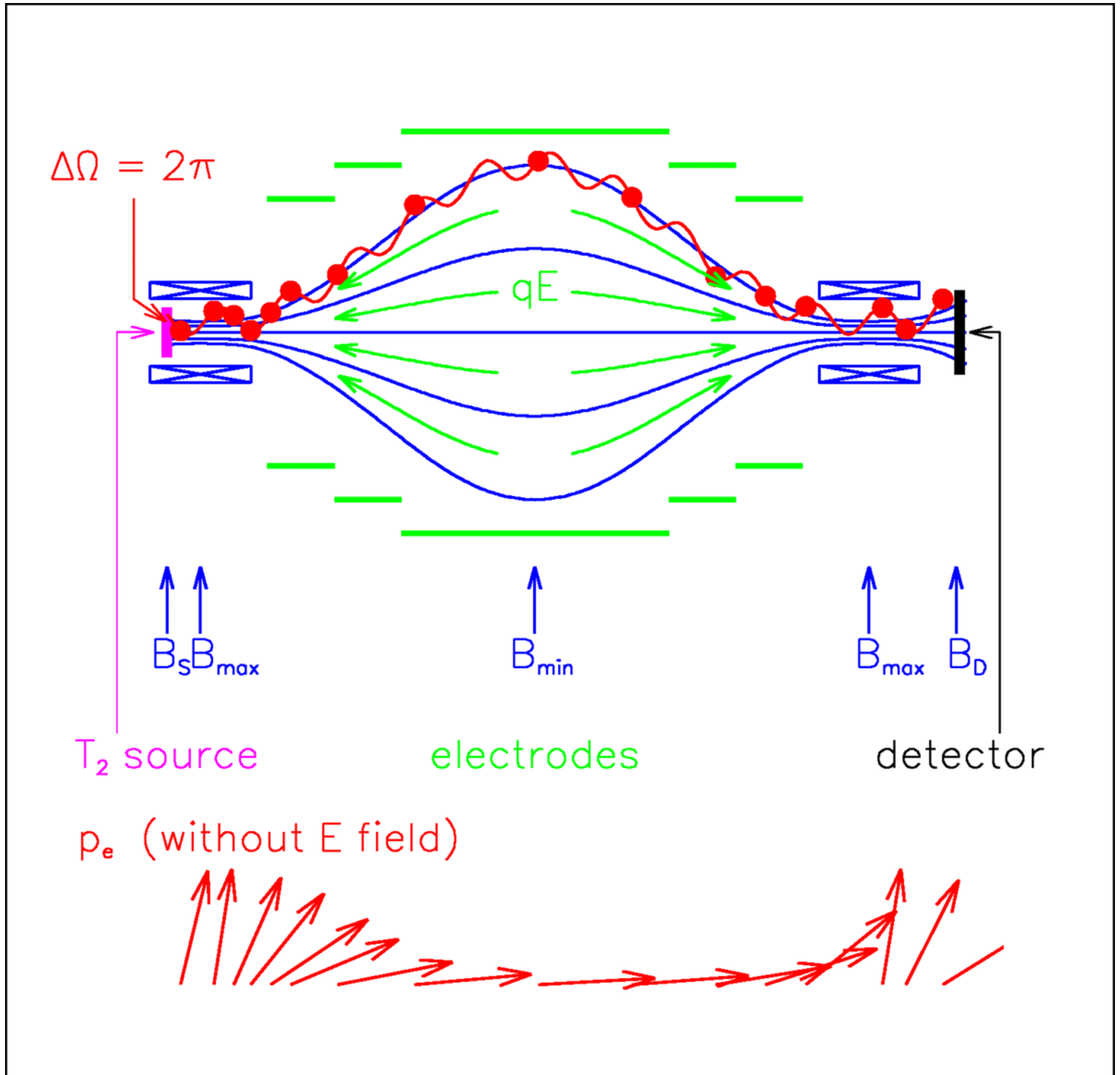
KATRIN's superpower - the MAC-E filter



https://www.katrin.kit.edu/

Magnetic **A**diabatic

Kleesiek et al., arXiv:1806.00369

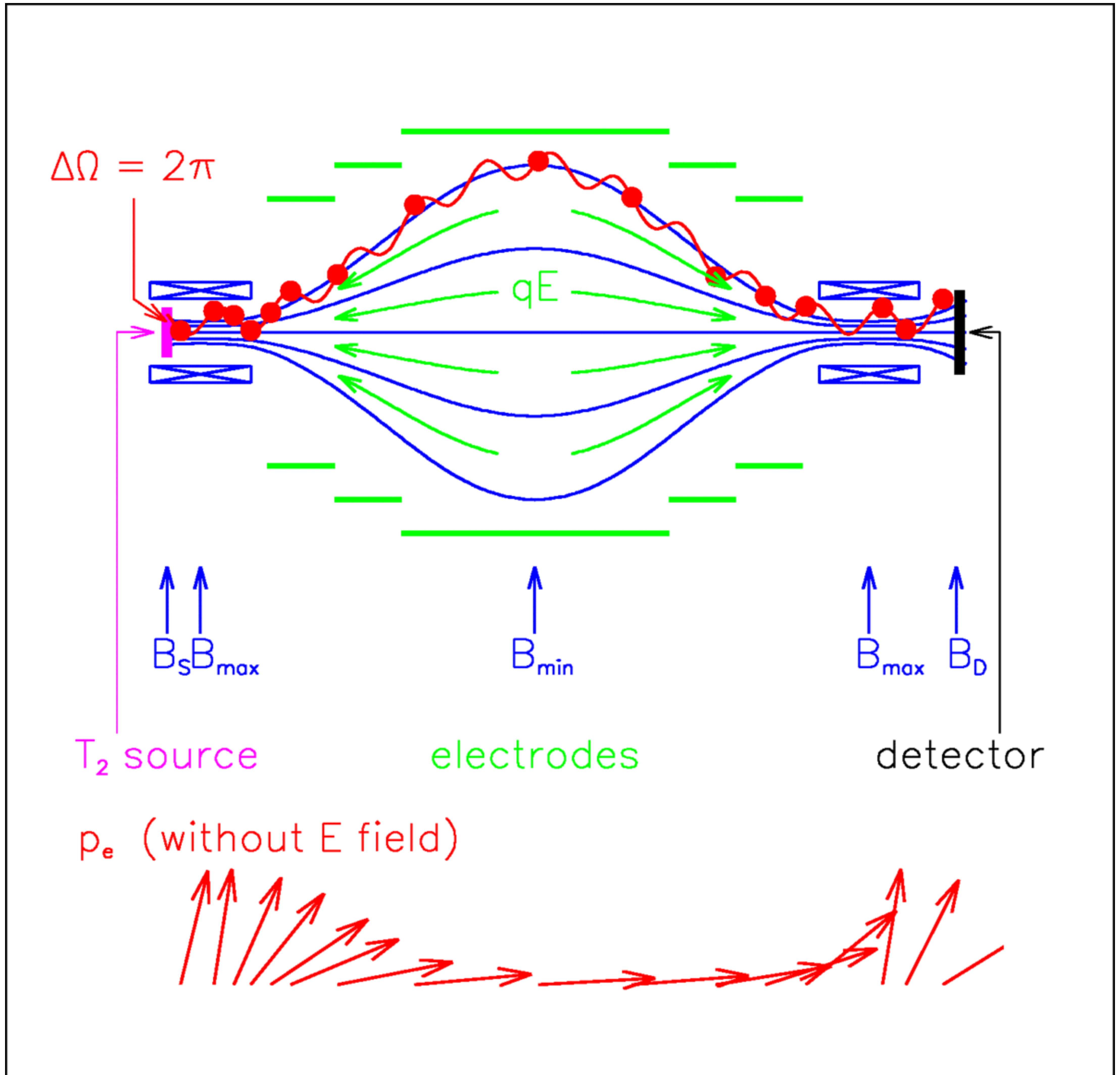


https://www.katrin.kit.edu/

Magnetic **A**diabatic **C**ollimation with an

Kleesiek et al., arXiv:1806.00369

KATRIN's superpower - the MAC-E filter

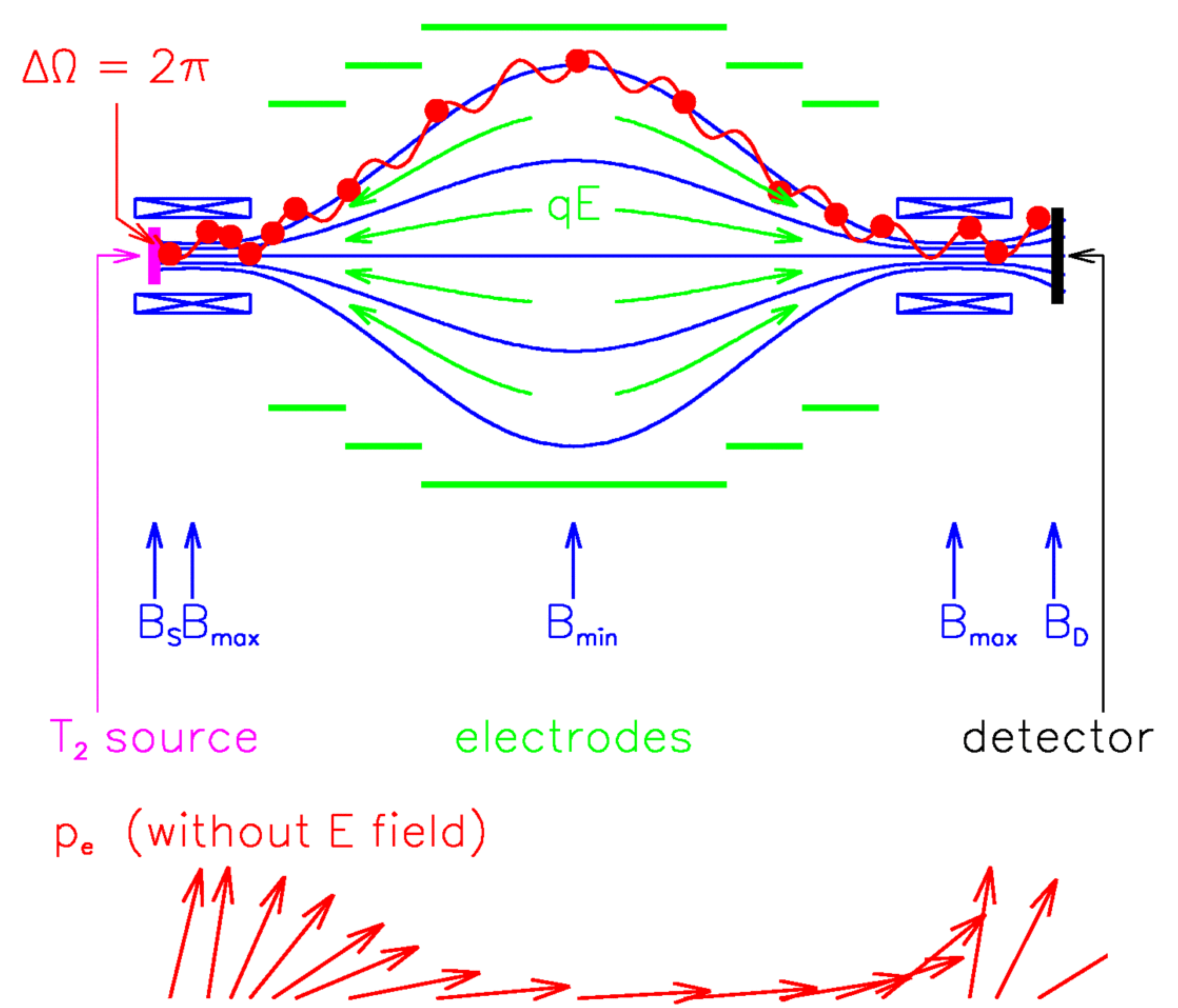


https://www.katrin.kit.edu/

Magnetic **A**diabatic **C**ollimation with an **E**lectrostatic Filter

Kleesiek et al., arXiv:1806.00369

KATRIN's superpower - the MAC-E filter



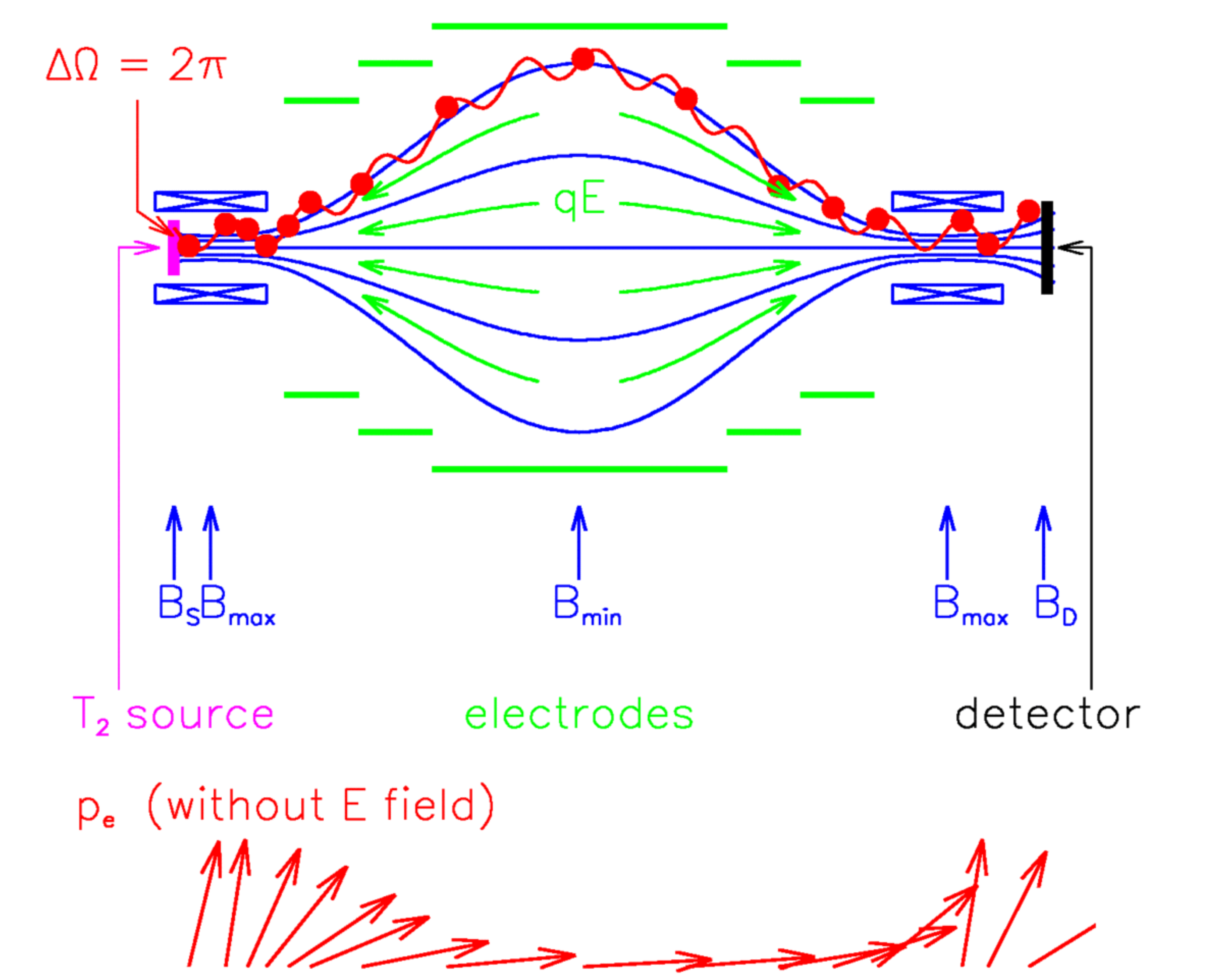
https://www.katrin.kit.edu/

Magnetic **A**diabatic **C**ollimation with an **E**lectrostatic Filter

- Two **superconducting solenoids** produce a guiding field **B.**
- Any forward-going **β electrons** from the **tritium source** are guided in **cyclotron motion** along the **B-field lines**, towards the **detector,** giving angular acceptance ~ 2π.

Kleesiek et al., arXiv:1806.00369

KATRIN's superpower - the MAC-E filter



https://www.katrin.kit.edu/

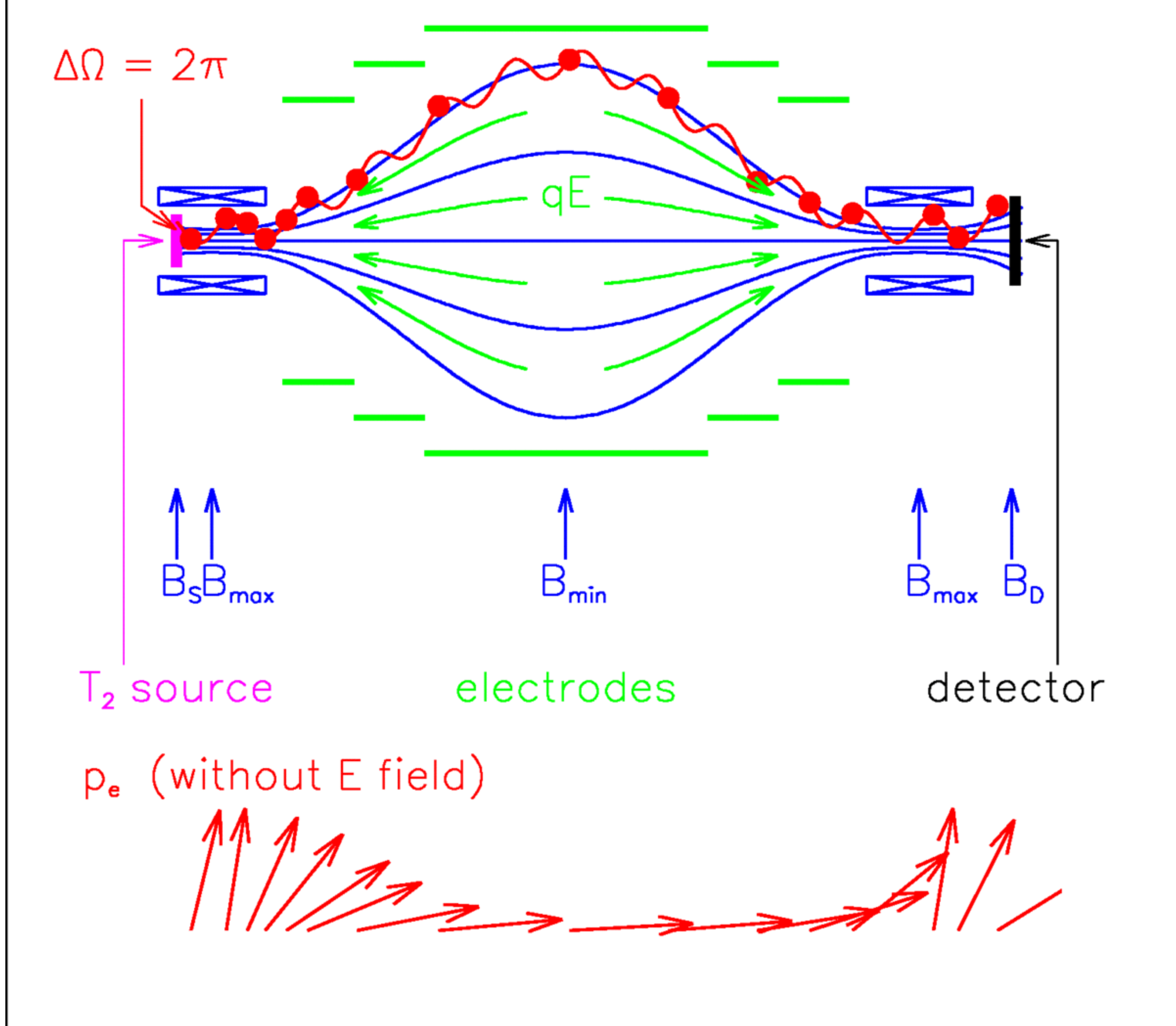
Magnetic **A**diabatic **C**ollimation with an **E**lectrostatic Filter

- The **magnetic field** varies through the spectrometer - strongest at the solenoids near source and detector, orders of magnitude weaker in the middle.
- Cyclotron motion is transformed to longitudinal motion in the middle of the spectrometer : isotropic β electrons become **parallel electron beam**
- The slow variation of field means transformation is **adiabatic**: constant magnetic moment

$$\mu = \frac{E_\perp}{B} = \text{const}$$

Kleesiek et al., arXiv:1806.00369

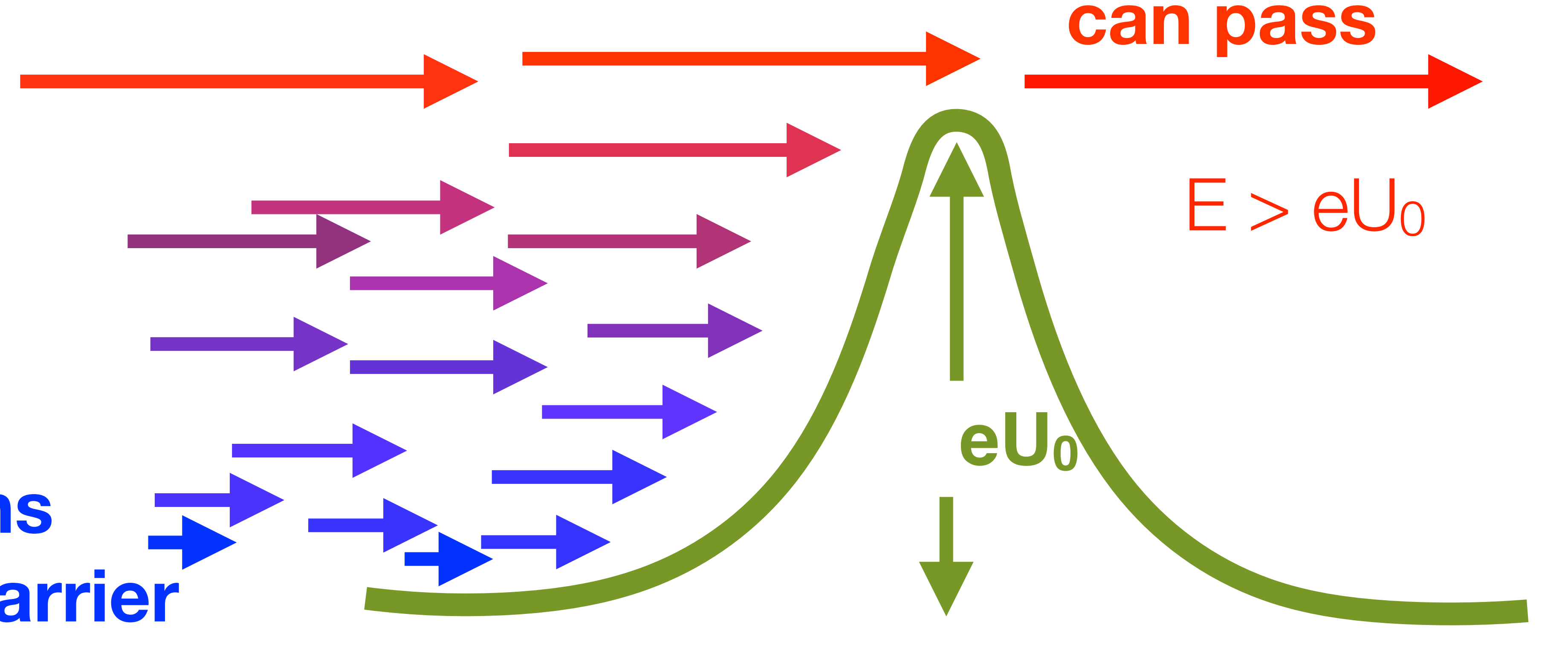
KATRIN's superpower - the MAC-E filter



https://www.katrin.kit.edu/

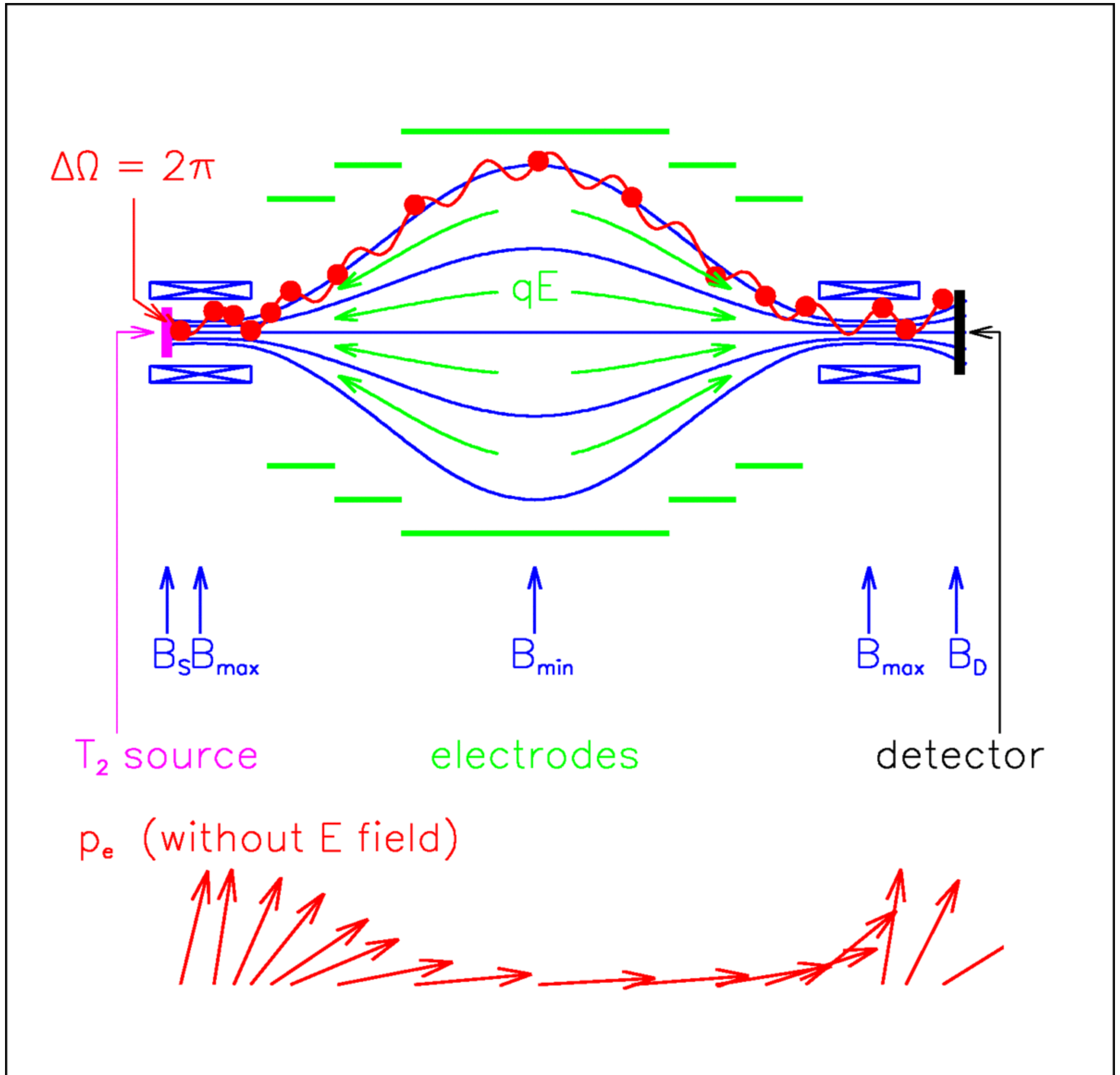
Magnetic **A**diabatic **C**ollimation with an **E**lectrostatic Filter

- Cylindrical **electrodes** create an electrostatic potential
- This acts in the opposite direction from the **electron beam**
- Only the **highest energy electrons** can pass through the **electrostatic barrier**



Kleesiek et al., arXiv:1806.00369

KATRIN's superpower - the MAC-E filter



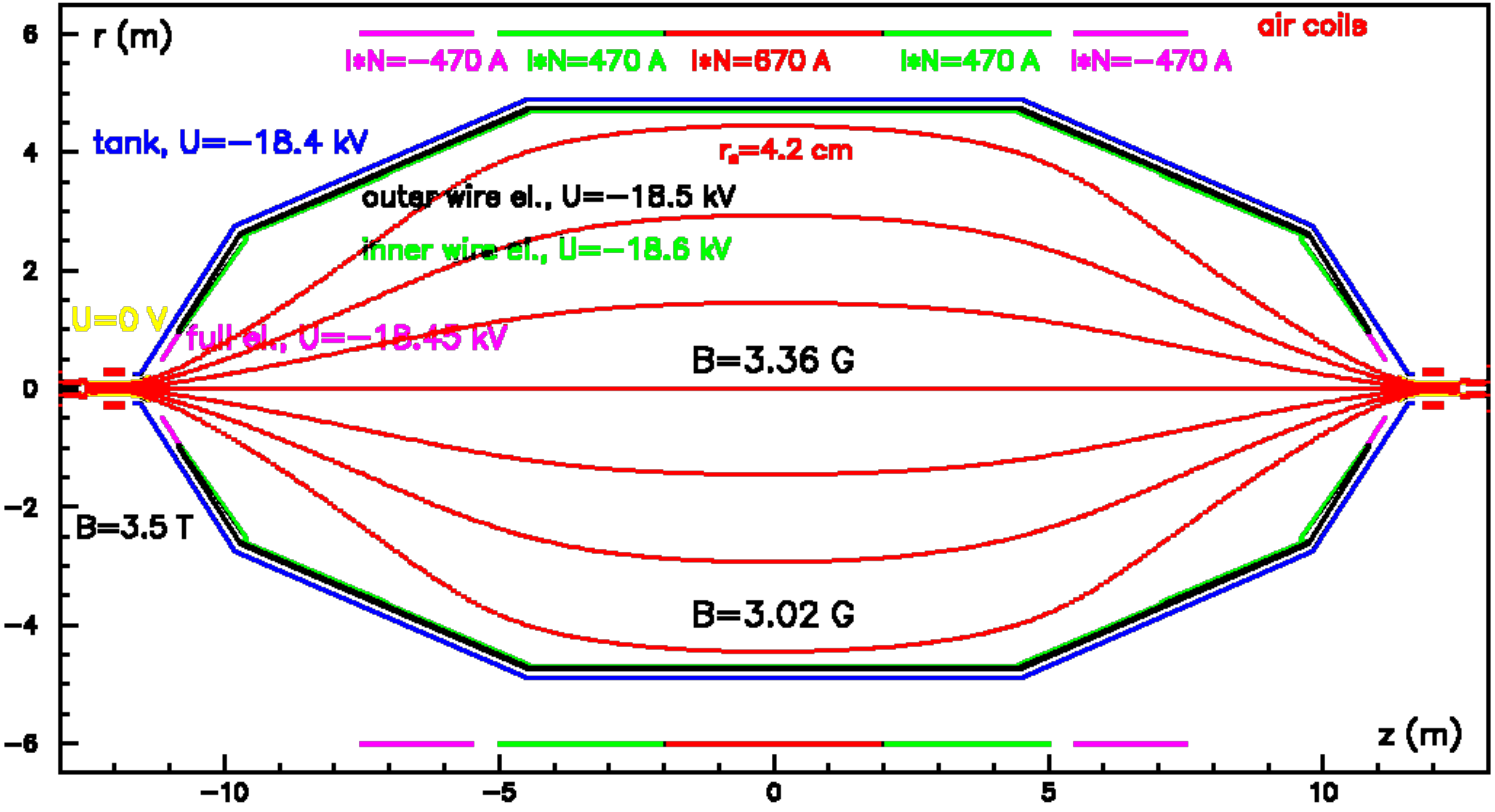
Magnetic Adiabatic Collimation with an Electrostatic Filter

- Surviving electrons are re-accelerated and **collimated** on the **detector**
- By measuring the count that make it through the high-pass energy filter at different **electrostatic potentials**, we can measure an **integrated electron energy spectrum.**
- Sharpness of filter given by

$$\frac{\Delta E}{E} = \frac{B_{min}}{B_{max}}$$

Kleesiek et al., arXiv:1806.00369

Fields in the MAC-E filter



(1 Tesla = 10^4 Gauss)

KATRIN's spectrometer: 2006 vacation pics

Deggendorf

Karlsruhe

- 10 metres wide, 200 tons
- Half a mile of specialist welding at **Deggendorf**
- Destination: **Karlsruhe**

Photos from symmetry magazine

KATRIN's spectrometer: 2006 vacation pics

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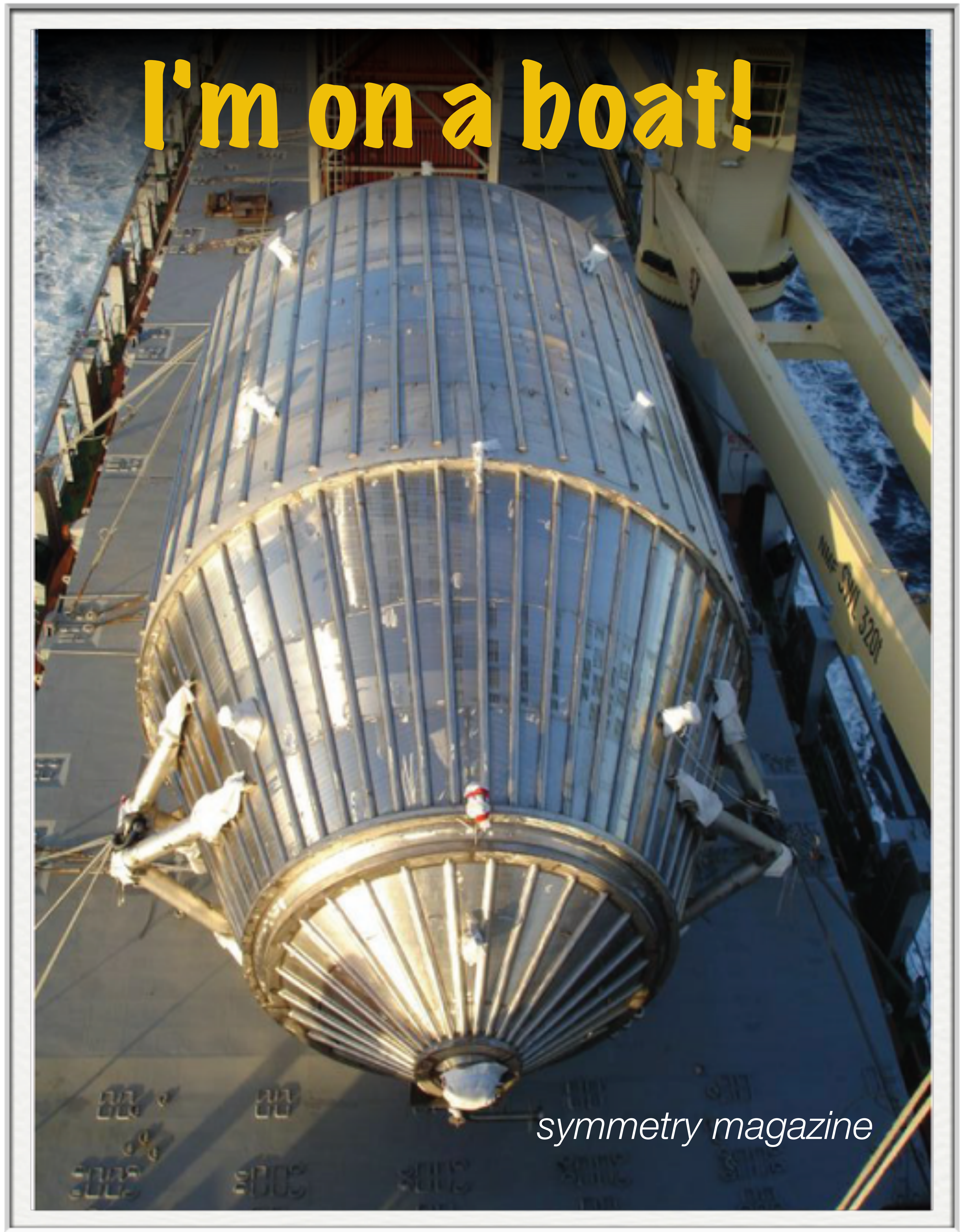

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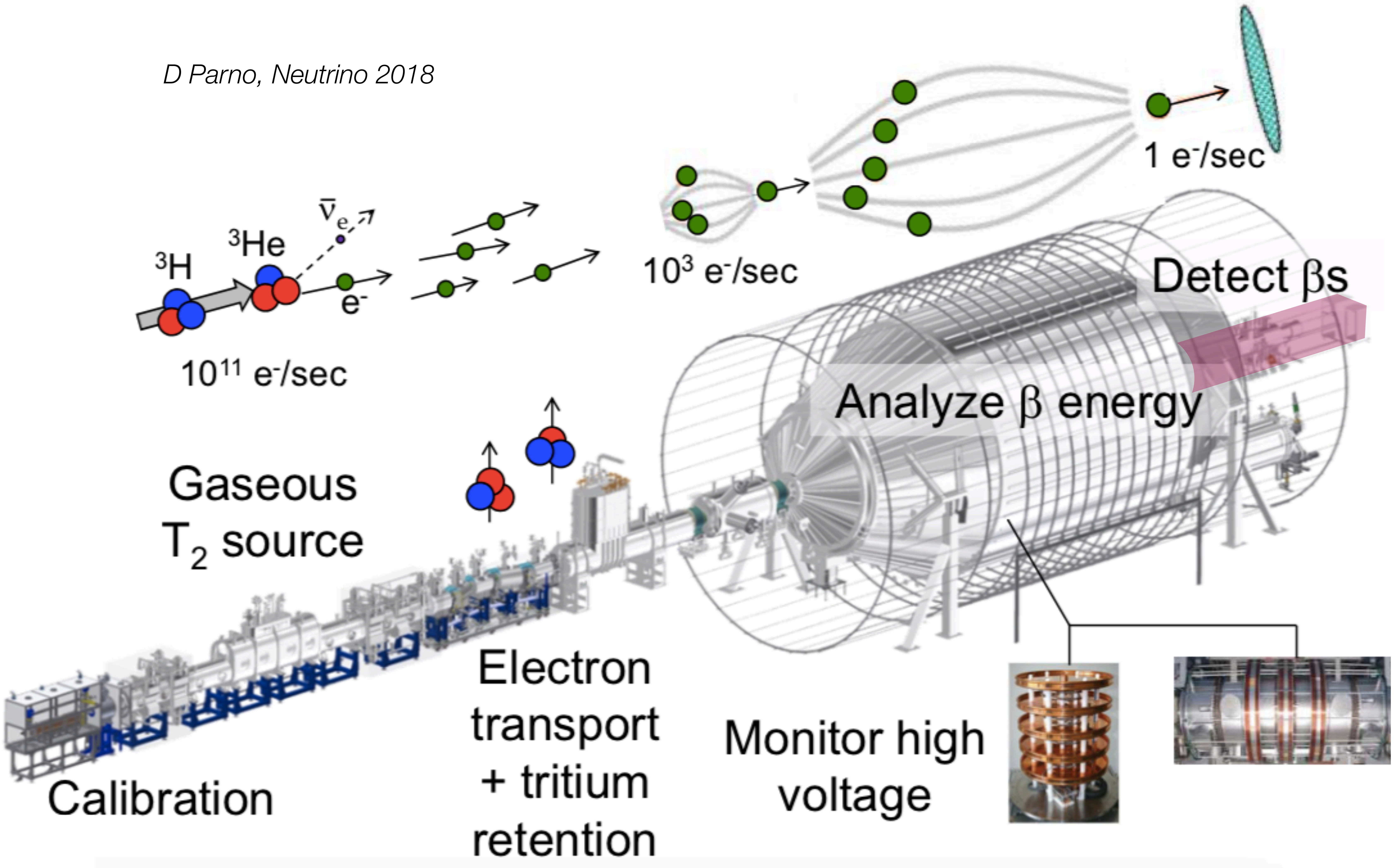
KATRIN: Karlsruhe Tritium Neutrino Experiment

D Parno, Neutrino 2018



Focal-plane detector system

Multi-pixel **silicon** PIN diode array with high **energy resolution** and thin entrance window, in second of two superconducting **magnets**

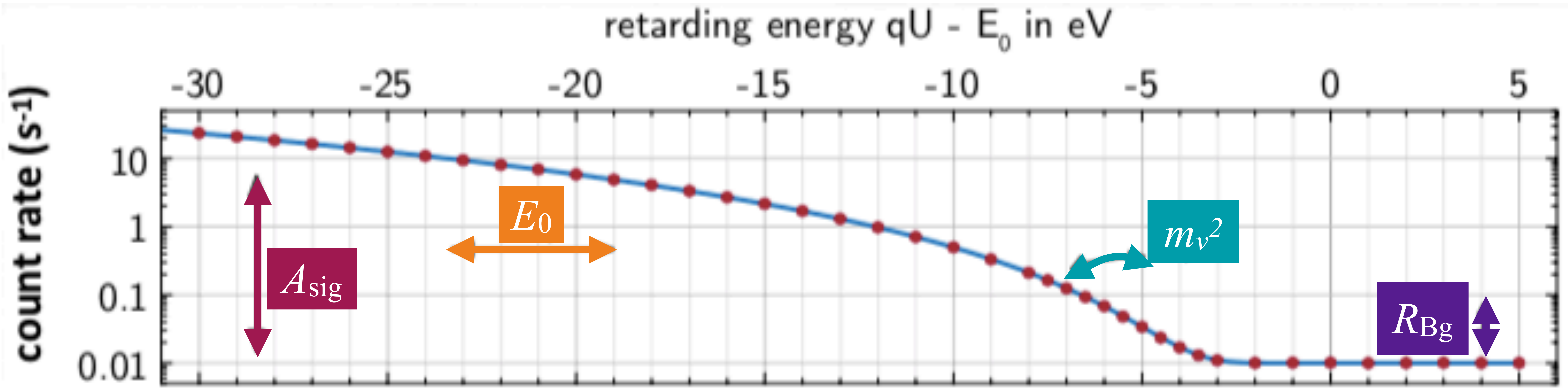
Radial position is affected by the shape of the electrostatic potential - use this to calibrate

Use position data to map source **shape**

Backgrounds can also be position-dependent e.g. cosmics (but **energy** is key discriminiator)

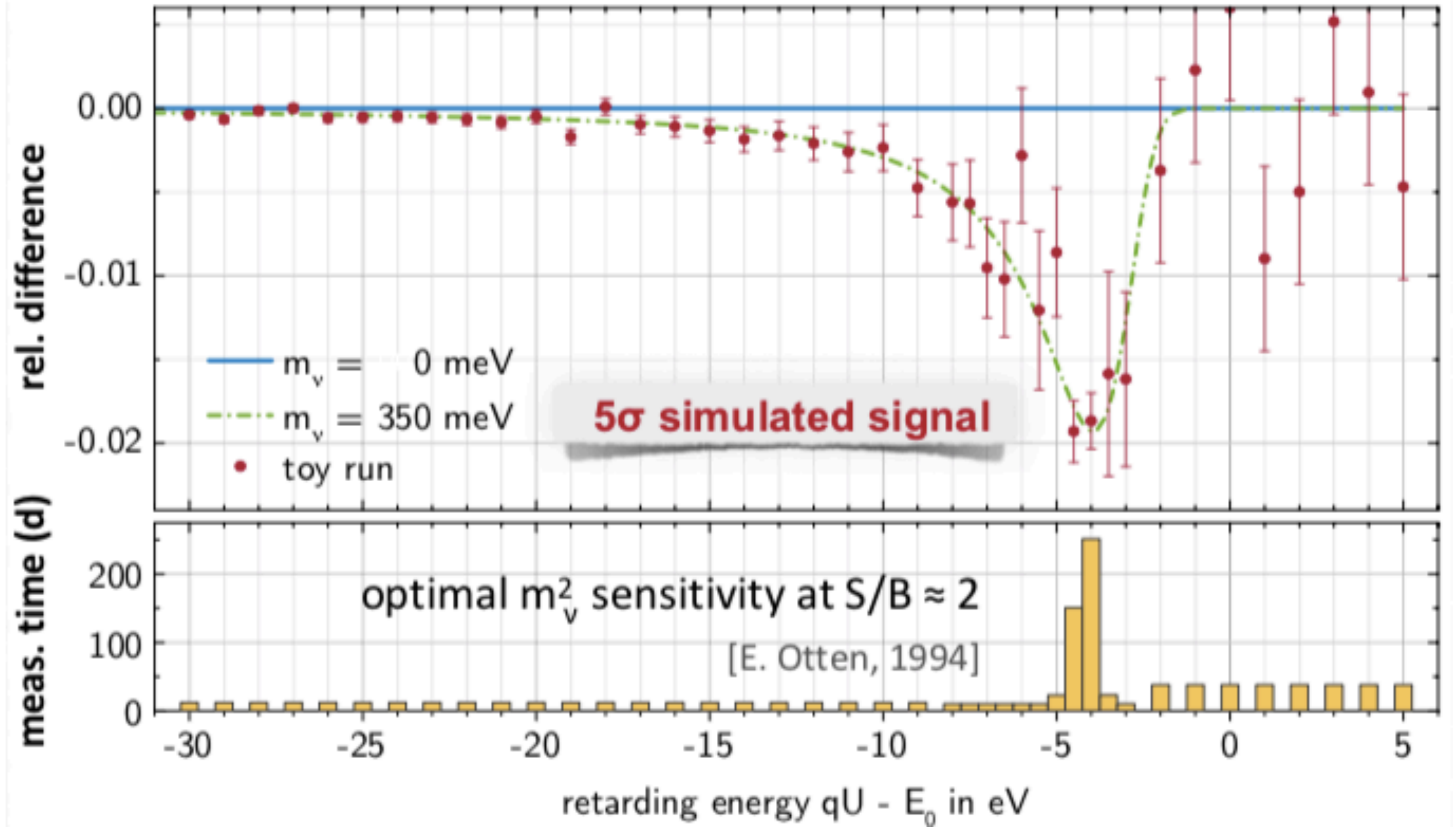
KATRIN design report 2004 FZKA-7090

Measuring the neutrino mass

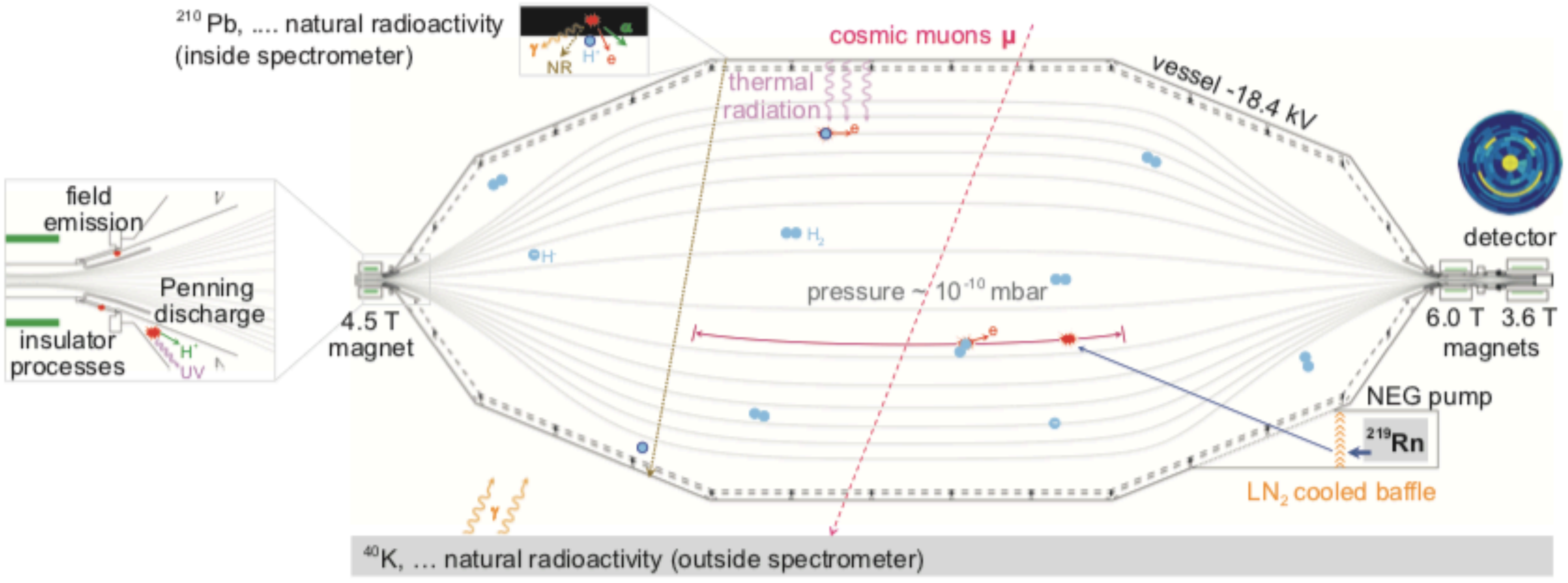


Simultaneous fit of **integrated** spectrum for 4 parameters:

- **Spectrum amplitude A_{sig}**
- **Endpoint energy E_0**
- **Background rate R_{Bg}** should be independent of retarding potential
- **Squared neutrino mass m_ν^2** affects the shape

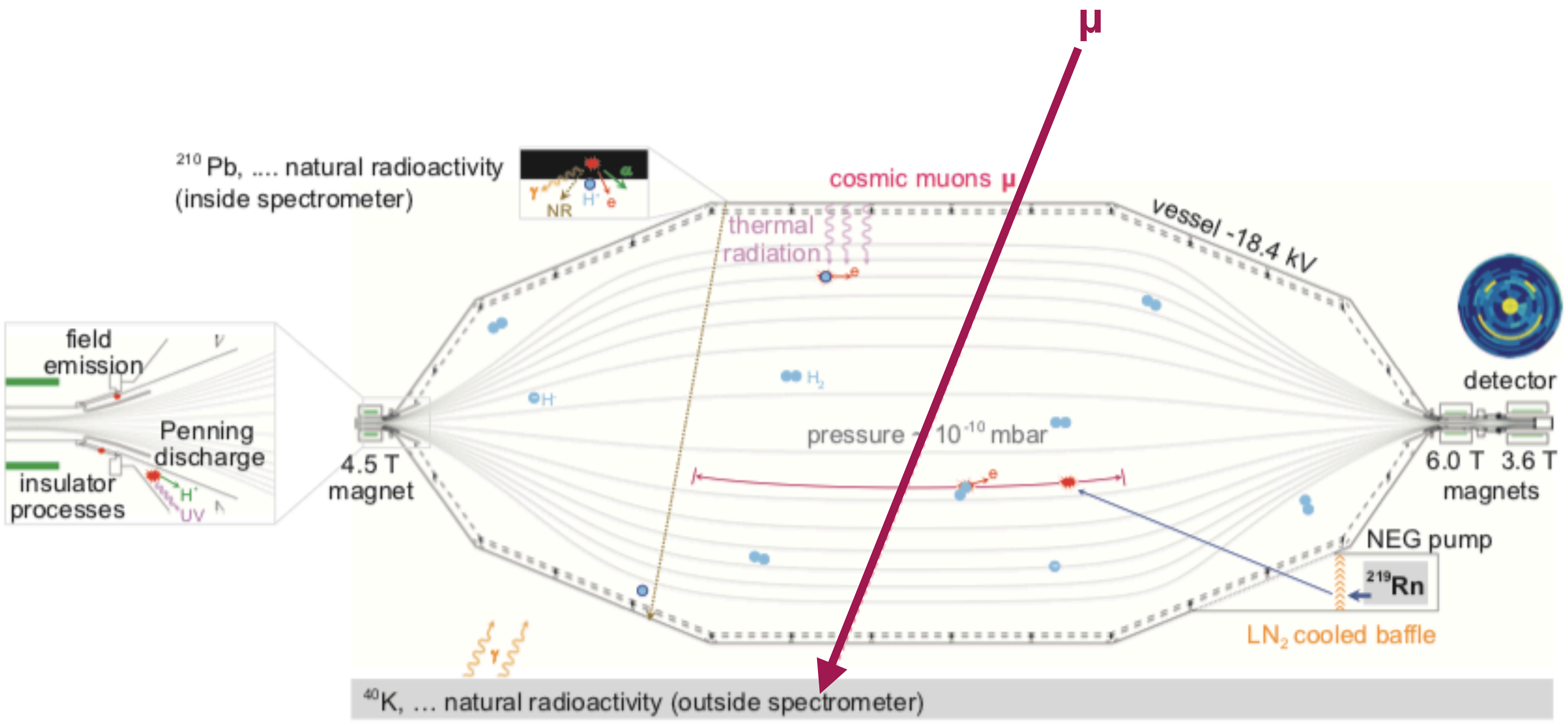


Backgrounds - and how KATRIN avoids them



Backgrounds - and how KATRIN avoids them

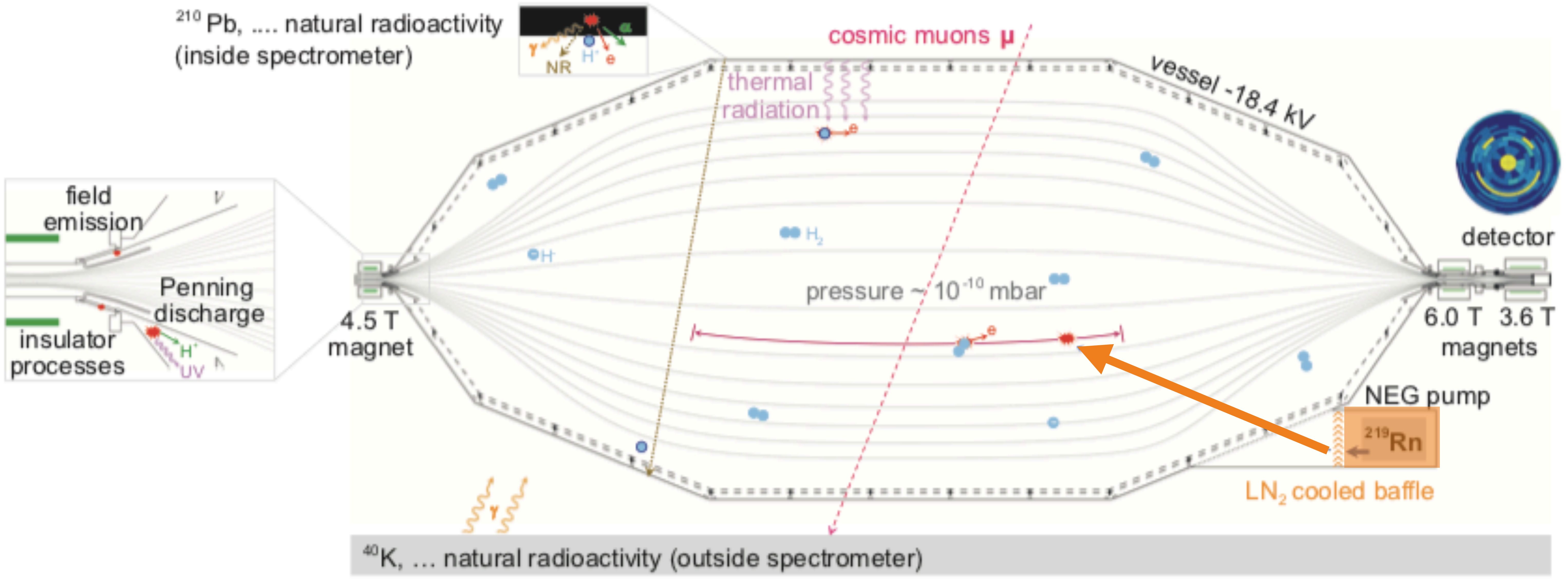
Cosmic muons



Problem
Can produce secondary electrons
Fixed by
Magnetic shielding by electron-guiding field

Cosmic muons

Radon in components



Problem

Electrons from decay chain get trapped in spectrometer & generate secondaries

Fixed by

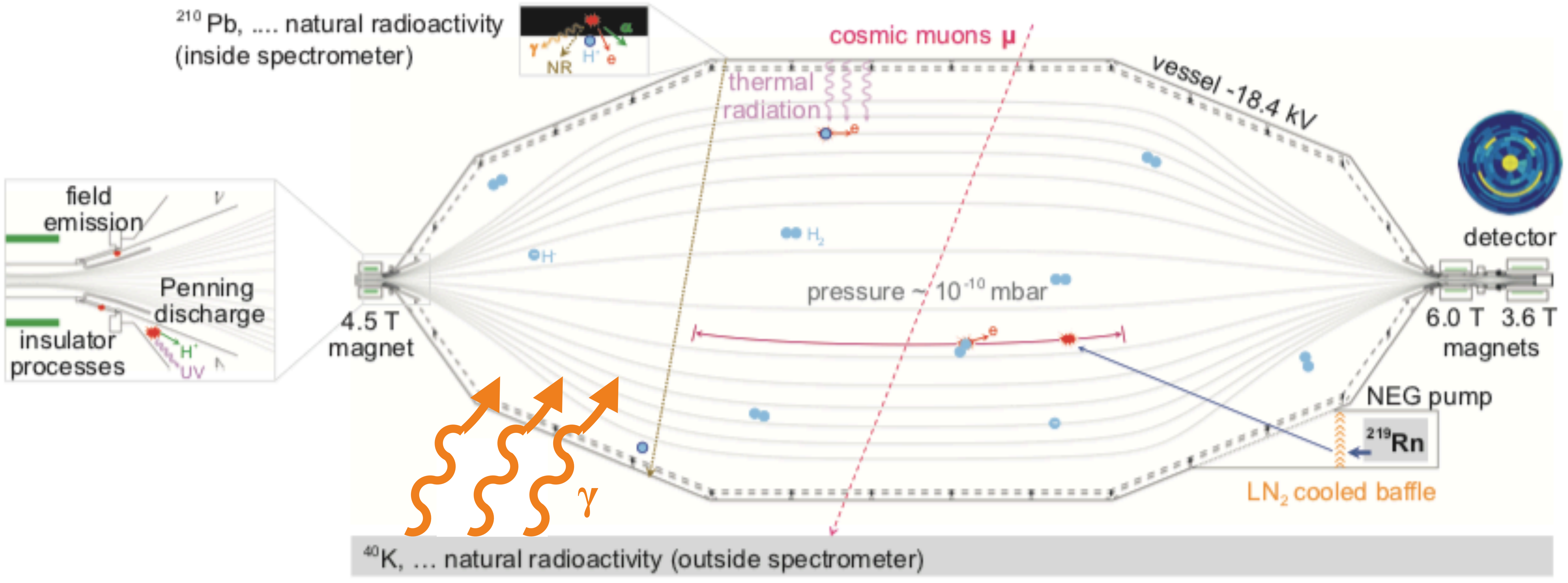
Baffle to clean radon from main source (“NEG” pump)

Backgrounds - and how KATRIN avoids them

Cosmic muons

Radon in components

External radioactivity



Problem
Gammas from ^{40}K outside spectrometer
Fixed by
Spectrometer shielding

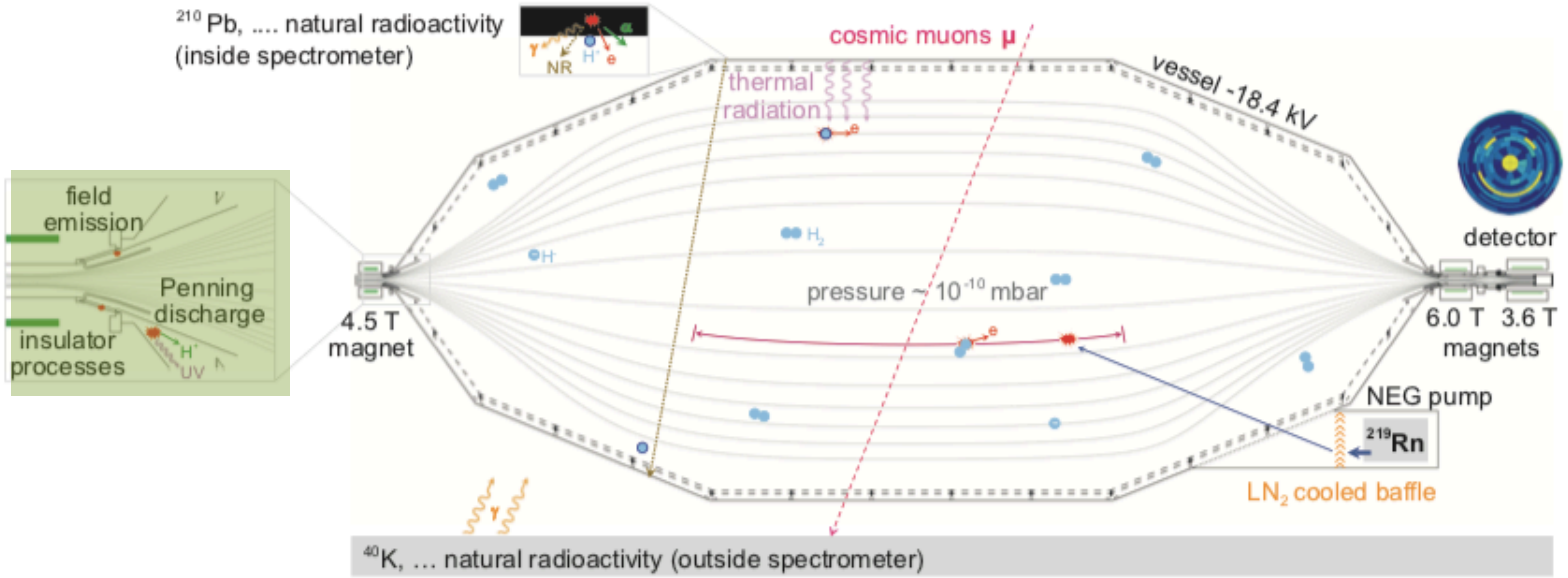
Backgrounds - and how KATRIN avoids them

Cosmic muons

Radon in components

External radioactivity

Penning discharge



Problem
Ionization at entrance to spectrometer where fields are strong

Fixed by
Careful electrode design

Backgrounds - and how KATRIN avoids them

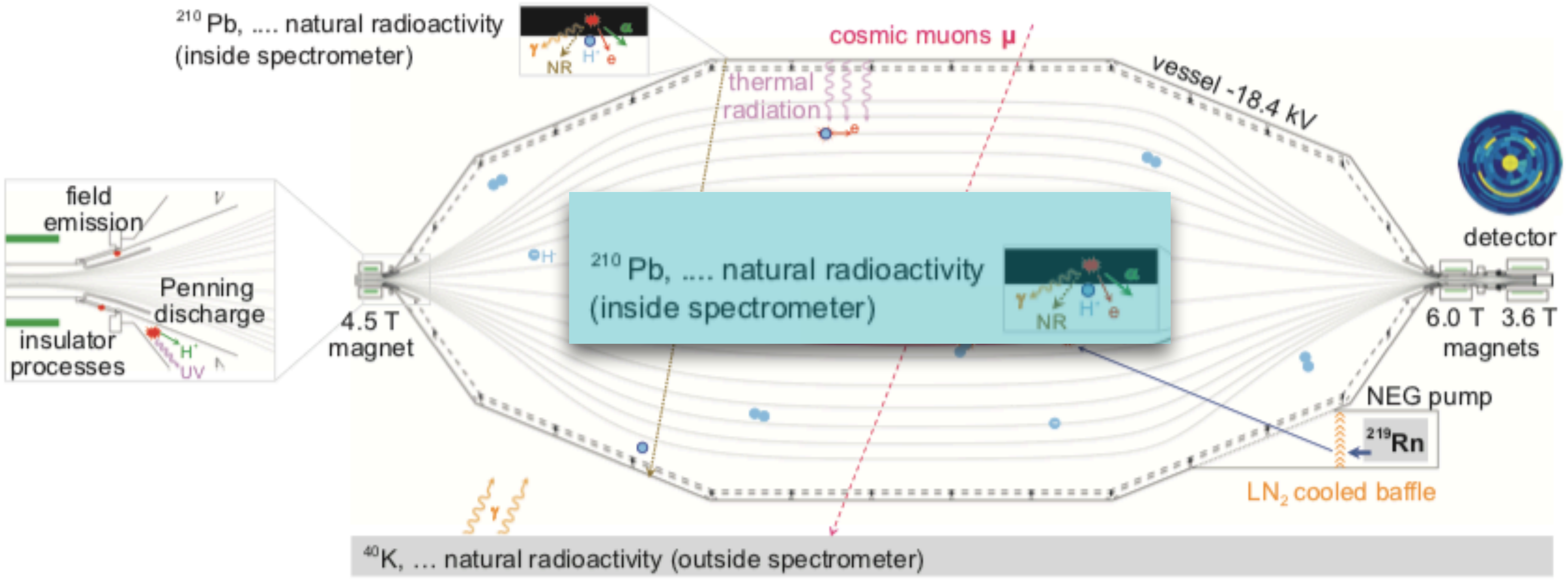
Cosmic muons

Radon in components

External radioactivity

Penning discharge

Internal ^{210}Pb decays



Problem
Decay products include Rydberg atoms, which are ionised by thermal radiation

Fixed by
Biggest background - not affected by shielding

Backgrounds - and how KATRIN avoids them

Cosmic muons

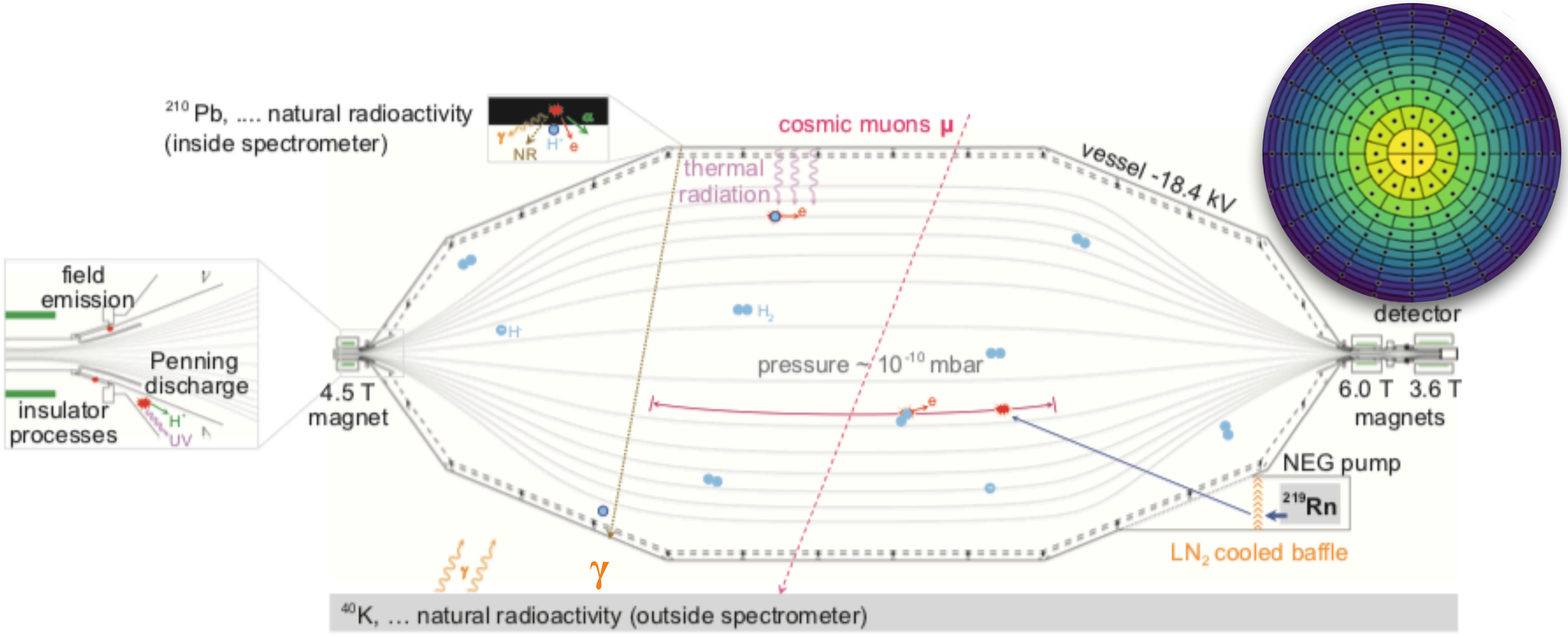
Radon in components

External radioactivity

Penning discharge

Internal ^{210}Pb decays

Detector backgrounds



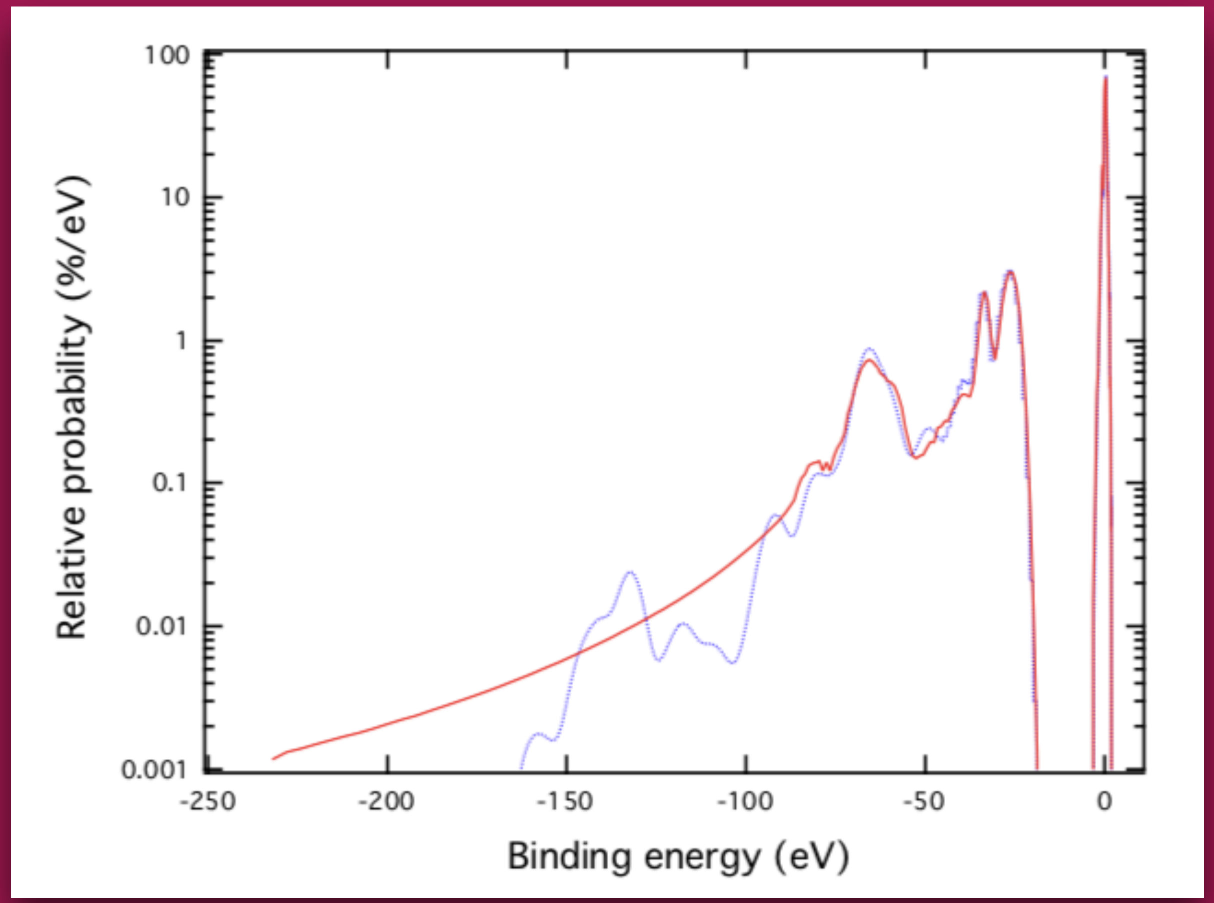
Problem

Electrons from sources other than the spectrometer

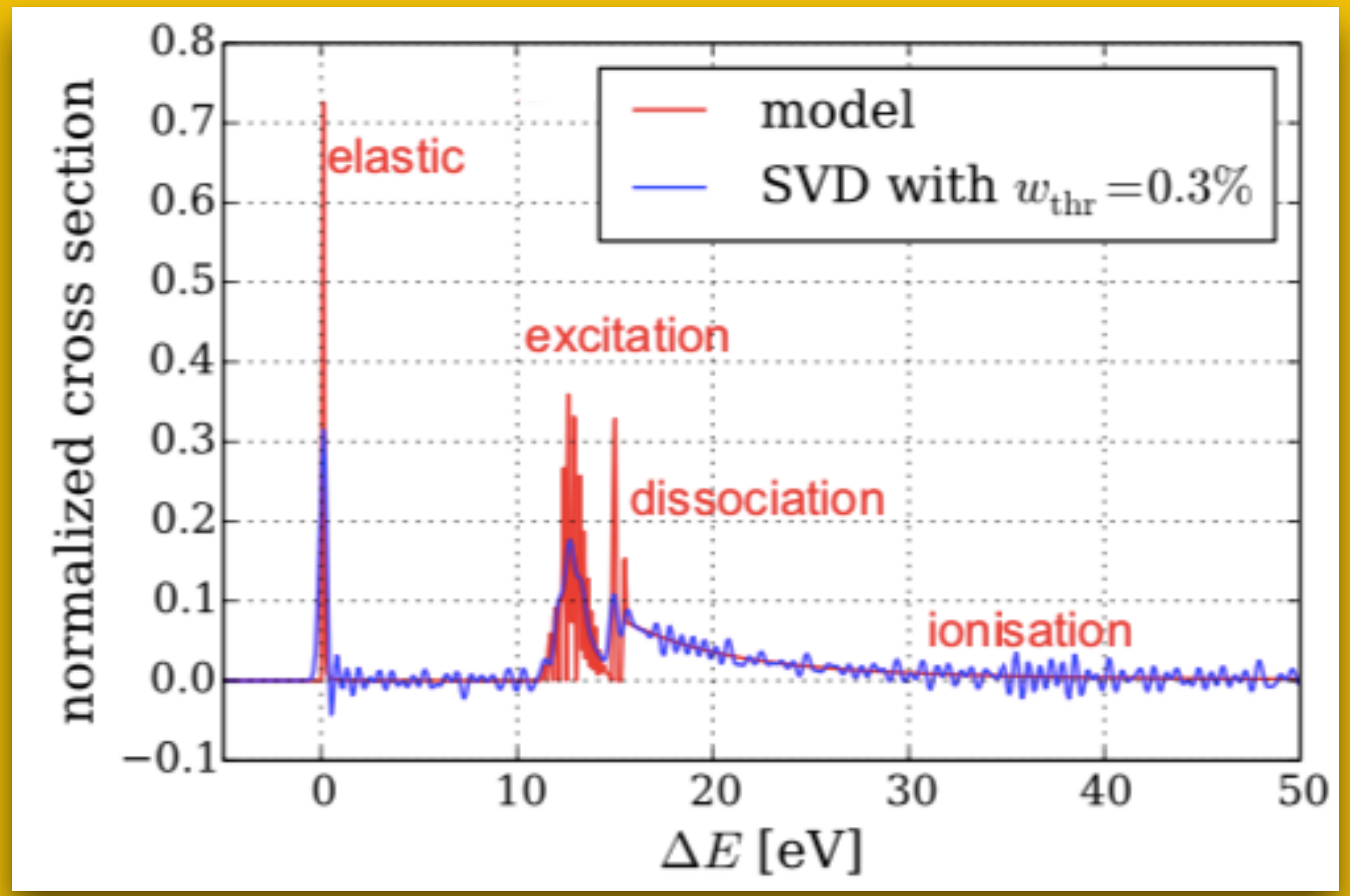
Fixed by

Lead and copper shielding; scintillator veto for cosmics

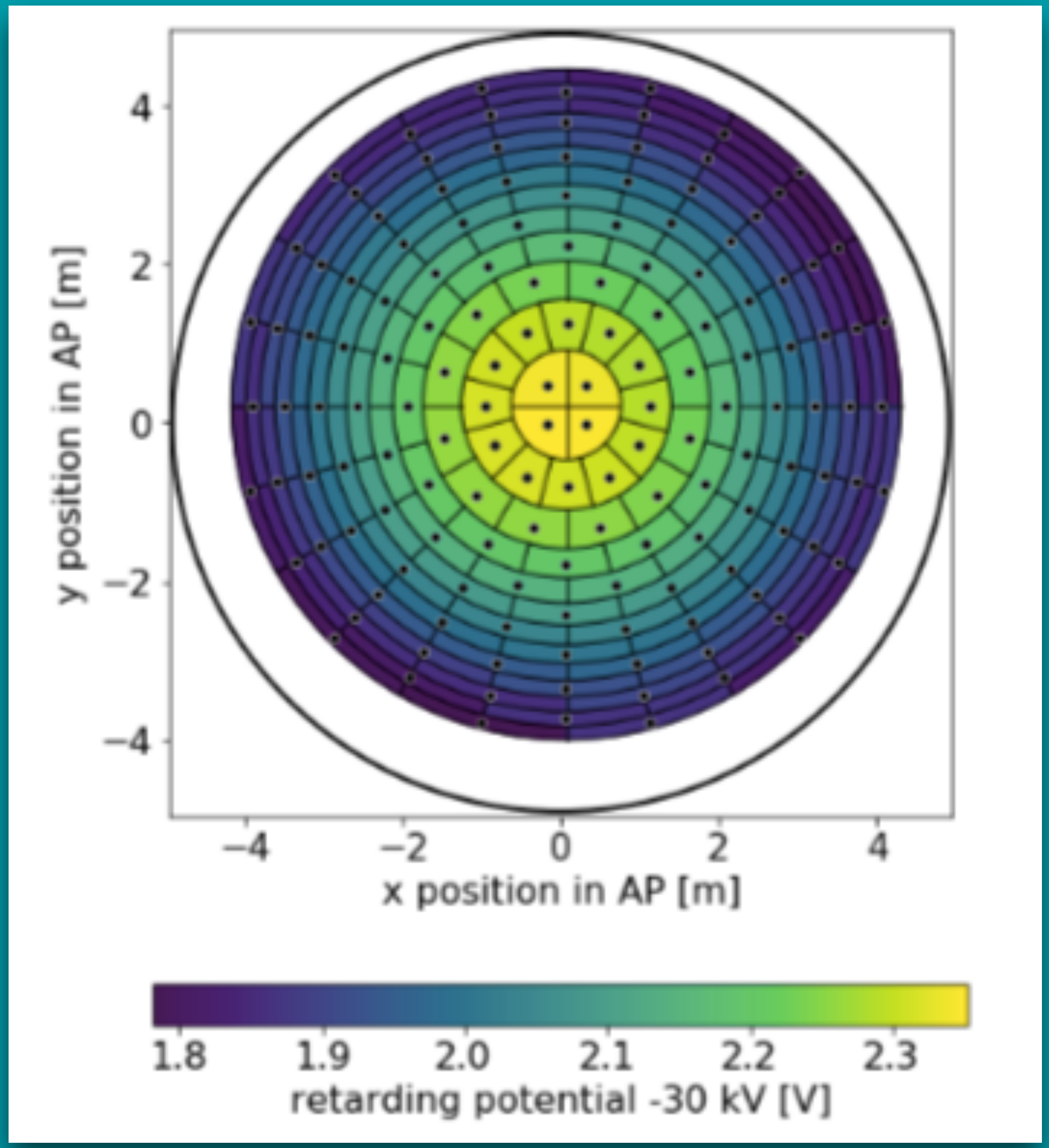
Sources of systematic uncertainty



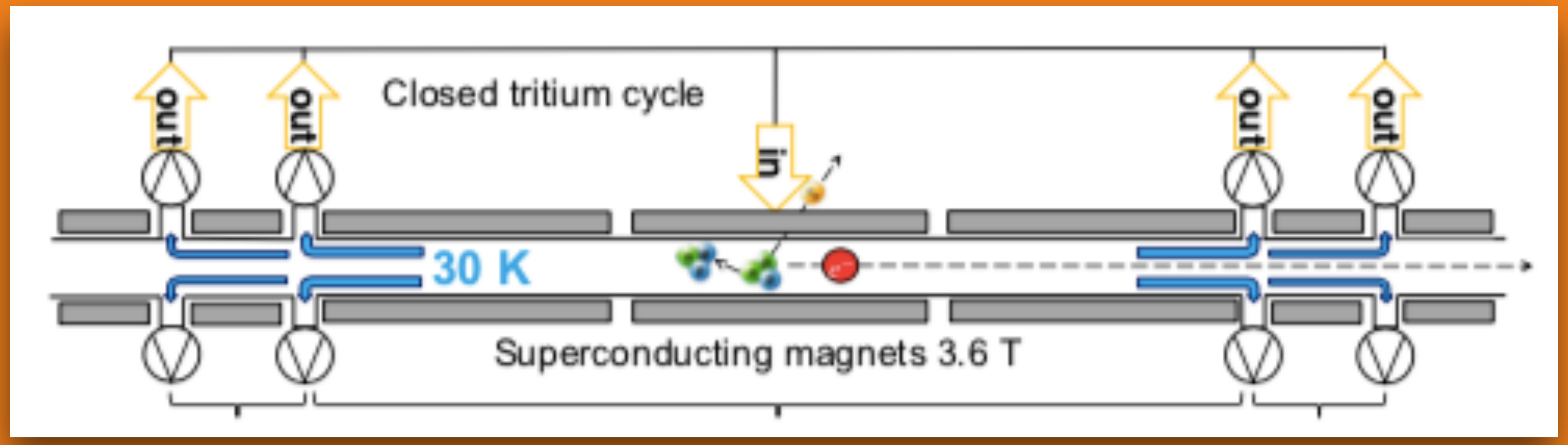
β decay model and final state ion distributions



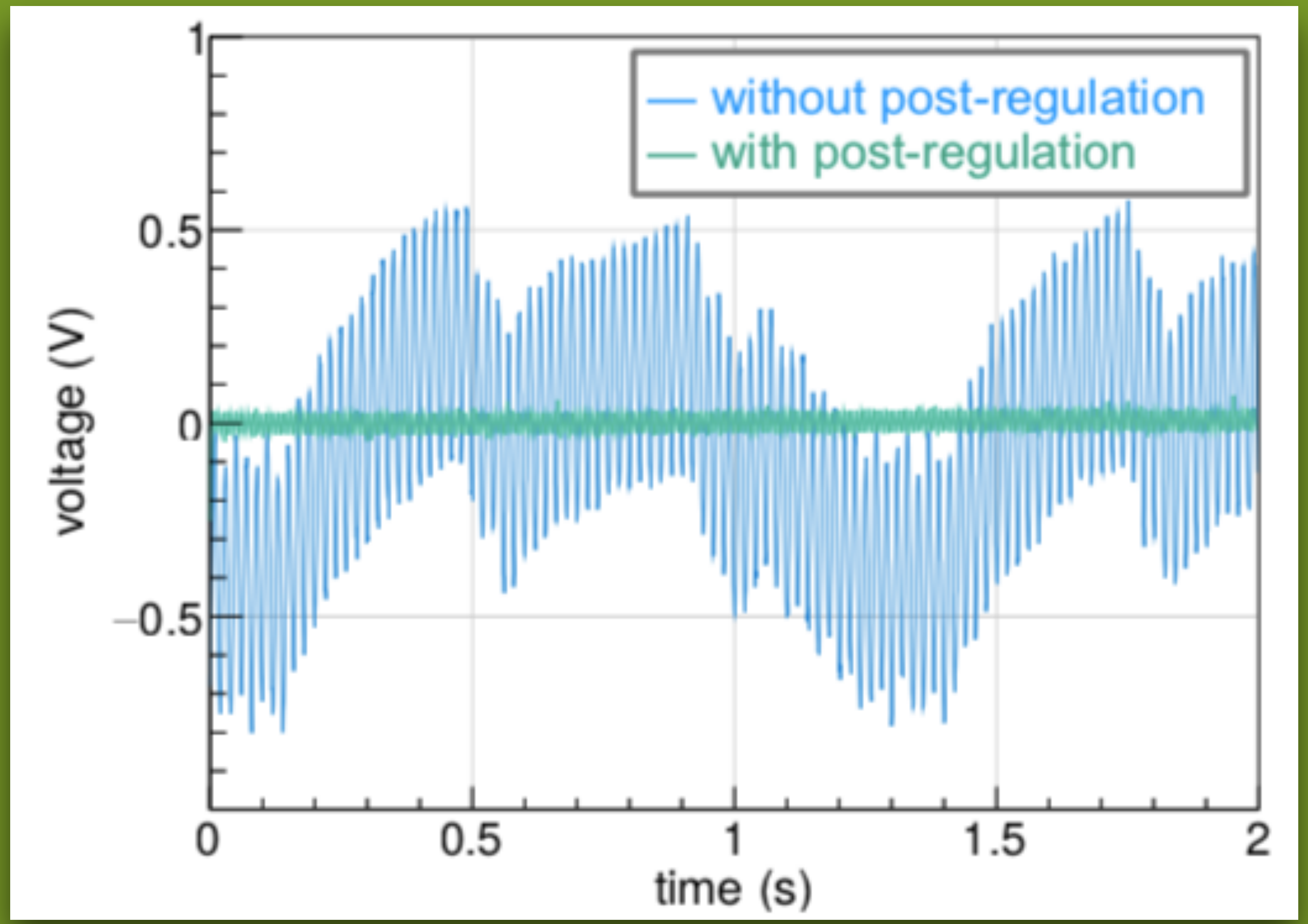
β-electron scattering and energy loss



Field homogeneity in the analyzing plane



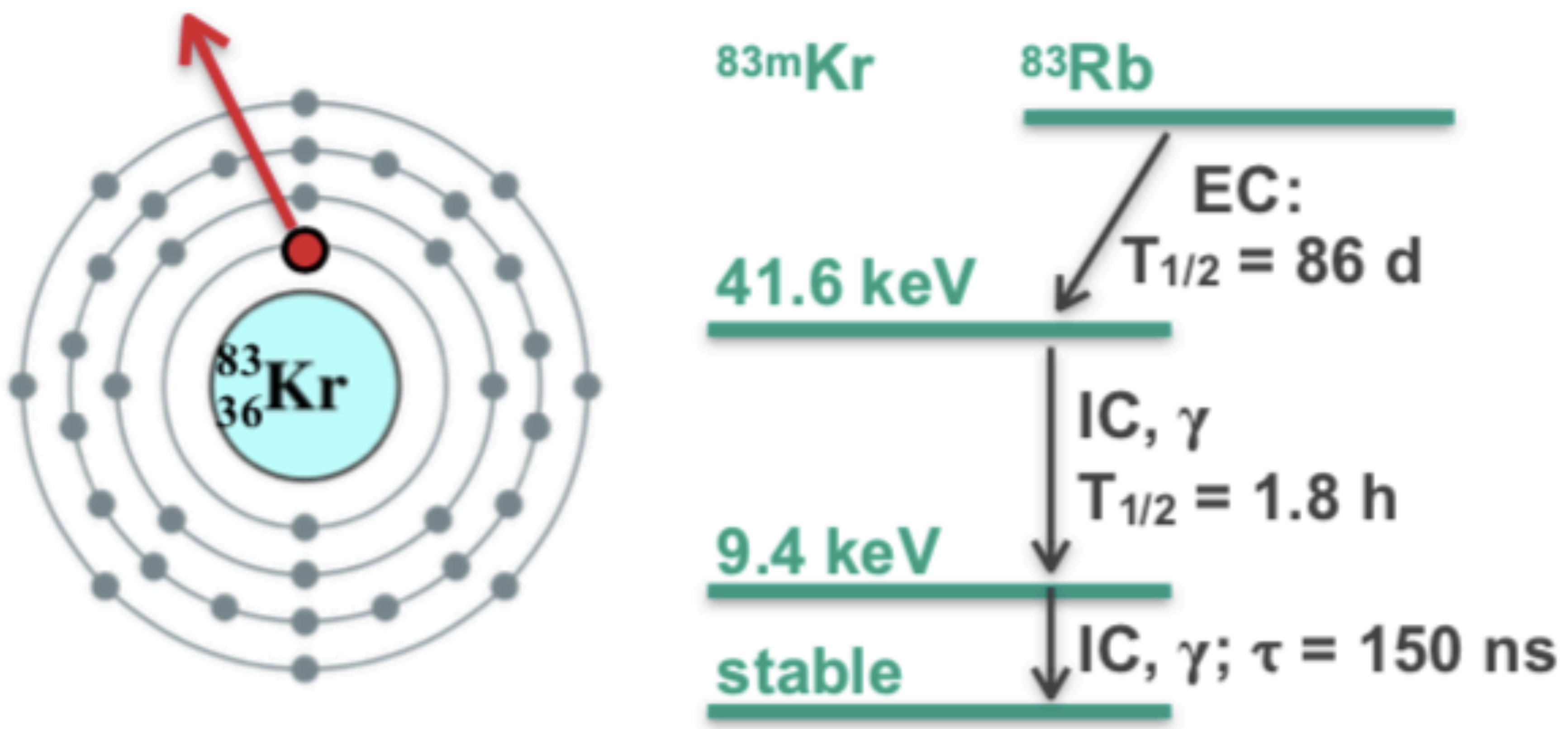
Source gas dynamics

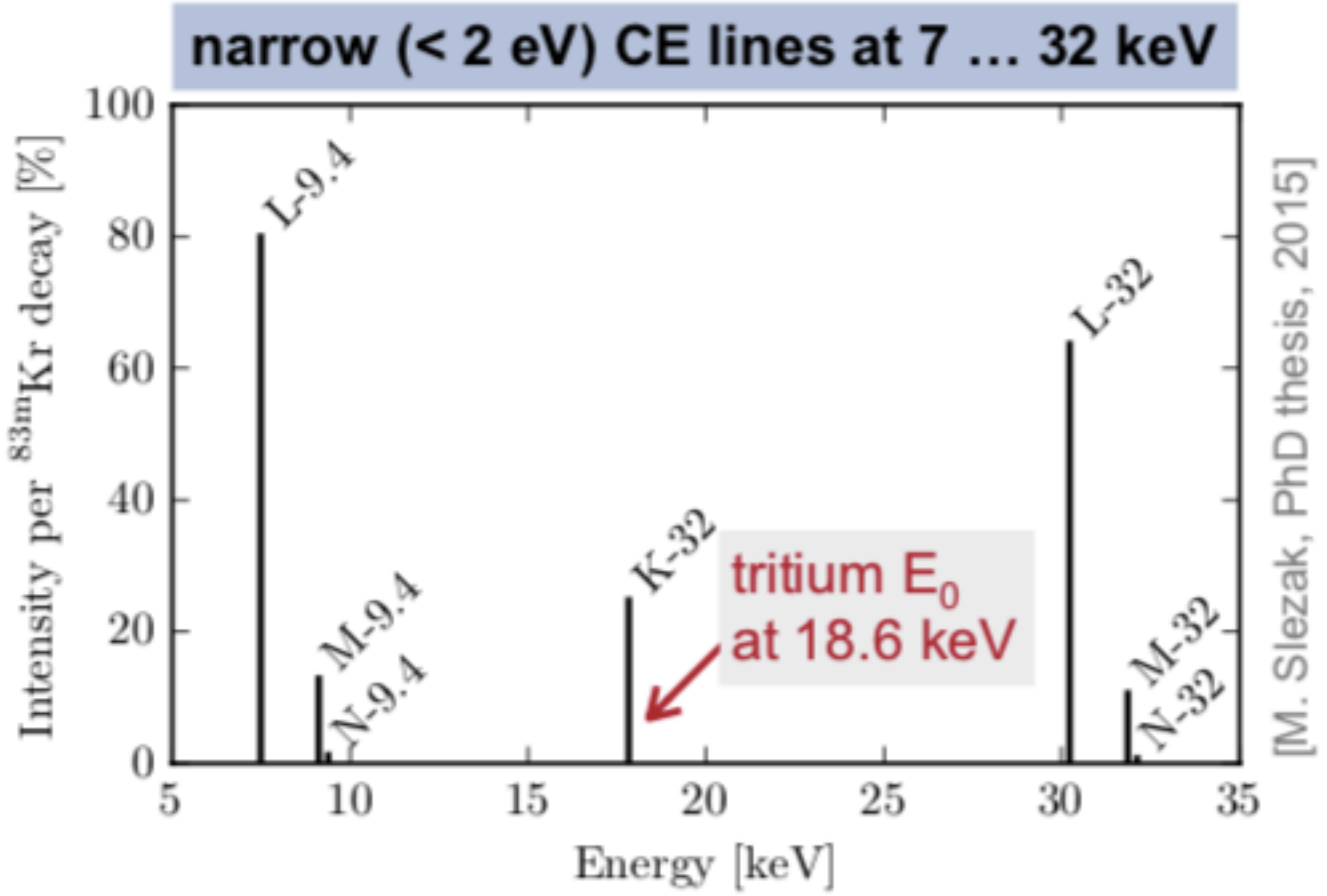


High voltage stability and calibration

Systematic uncertainties > statistical uncertainties after 3 beam years (5 calendar years)

Testing KATRIN - ^{83m}Kr spectroscopy in July 2017





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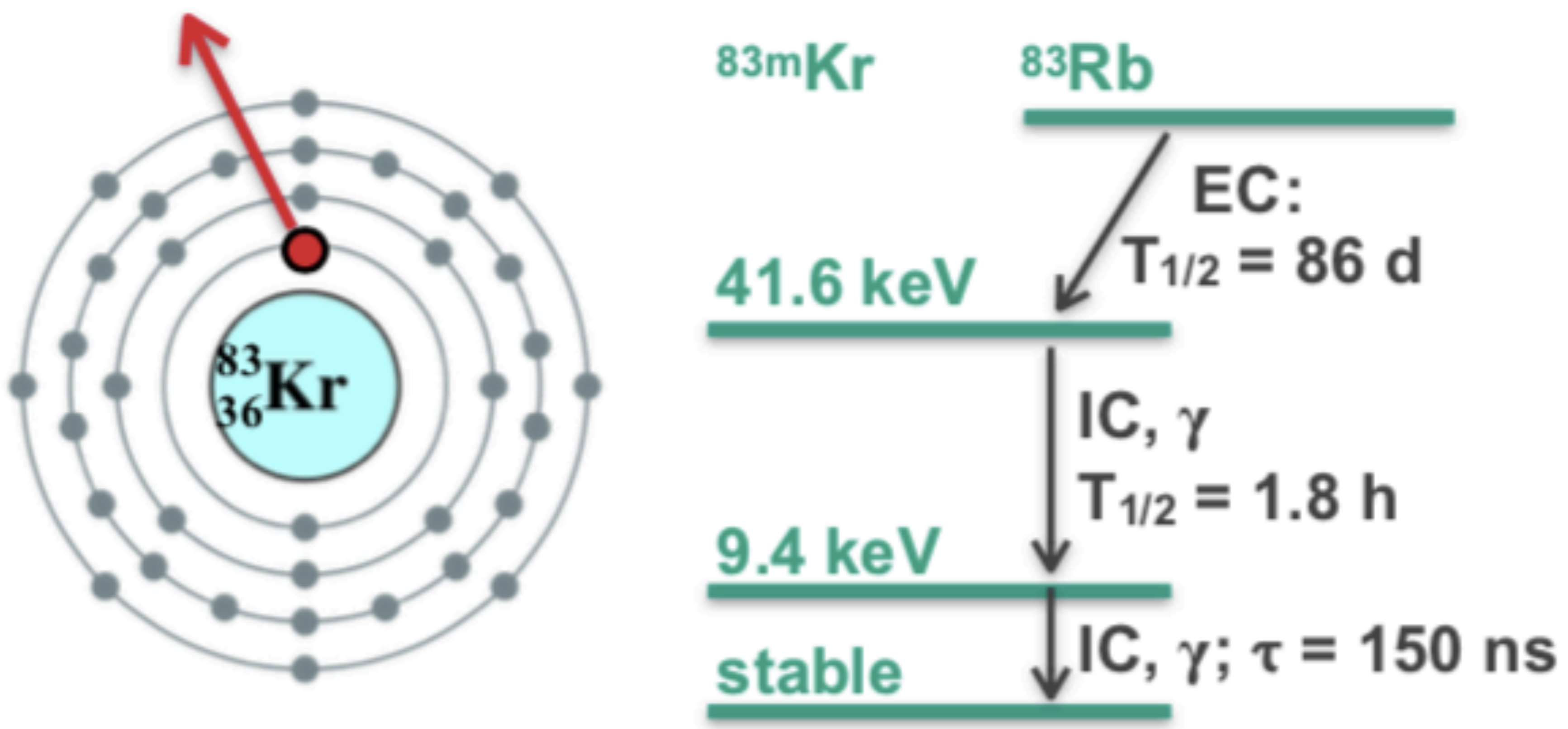

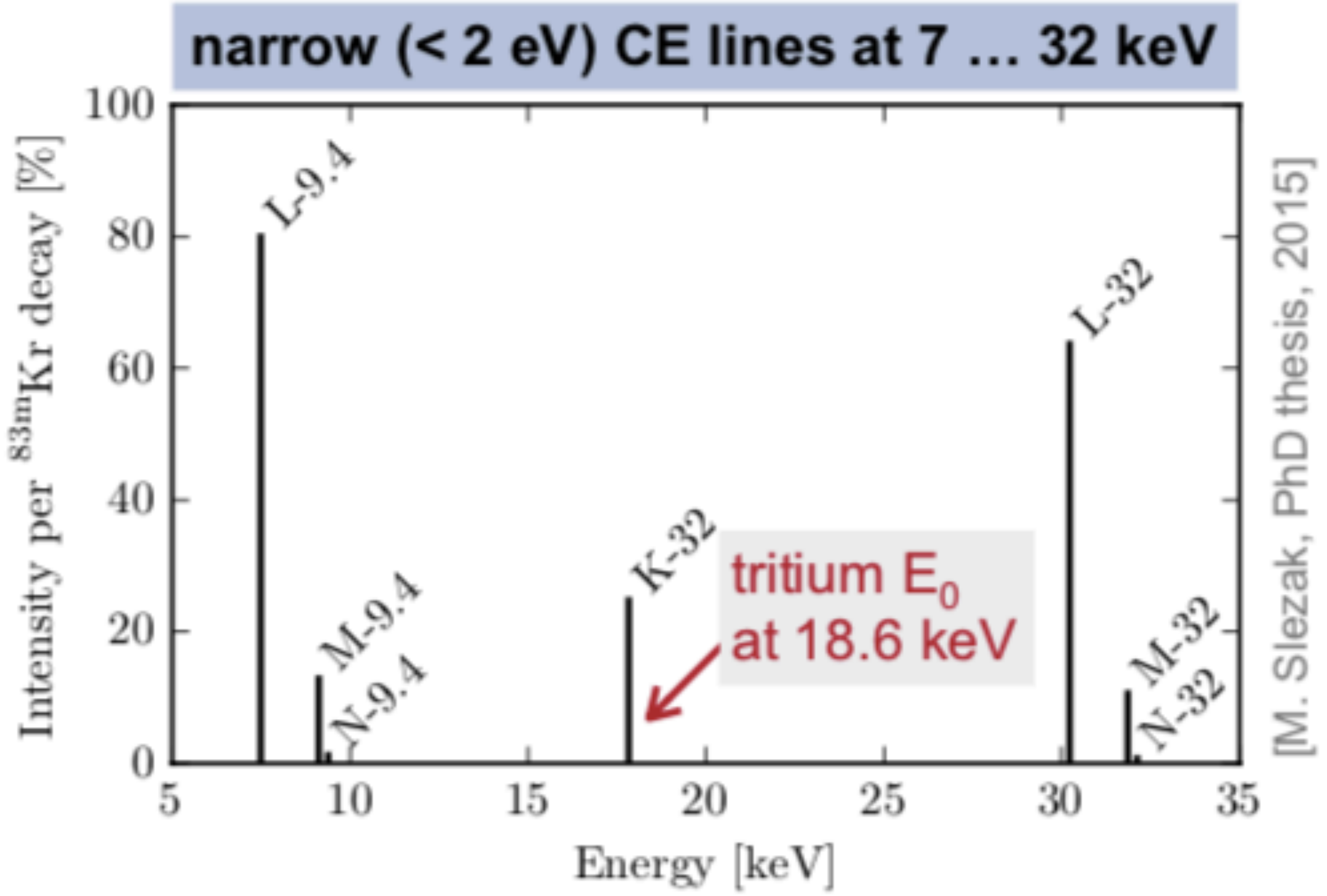

- **Energy scans**
- **Hardware** testing/commissioning
- Test of **data acquisition/analysis** pipeline
- System **characterization** (e.g. confirm sub-eV resolution)
- Calibration

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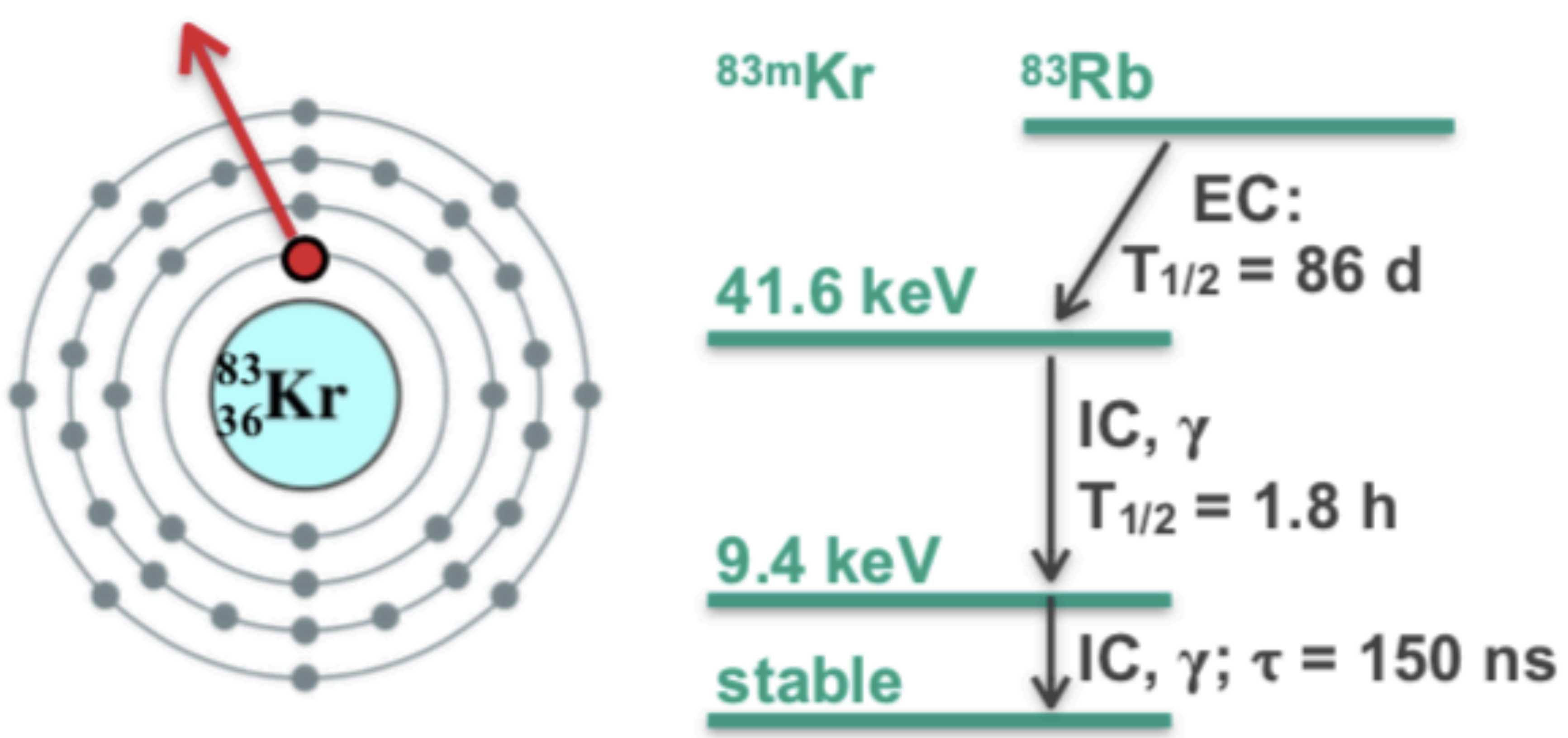

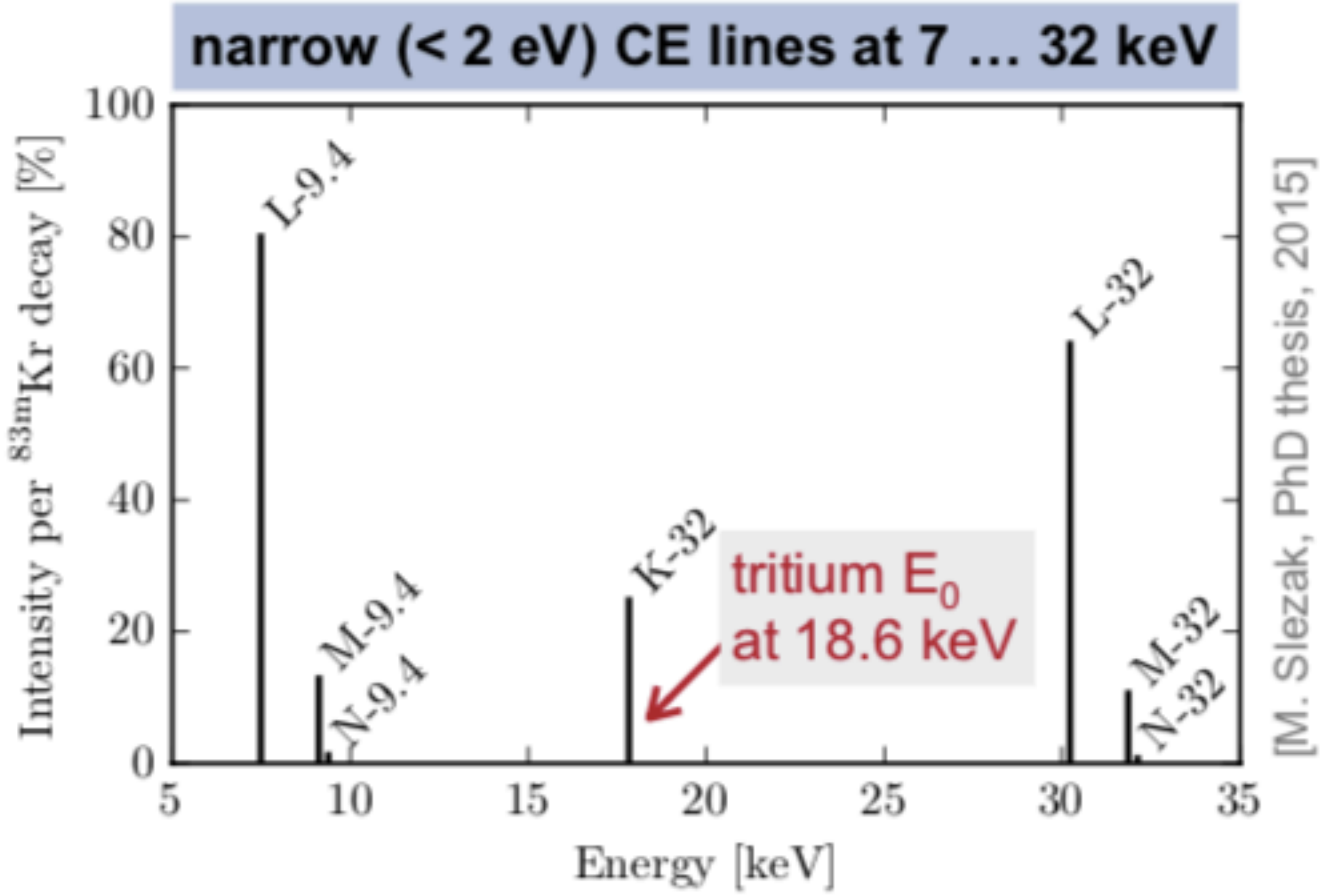

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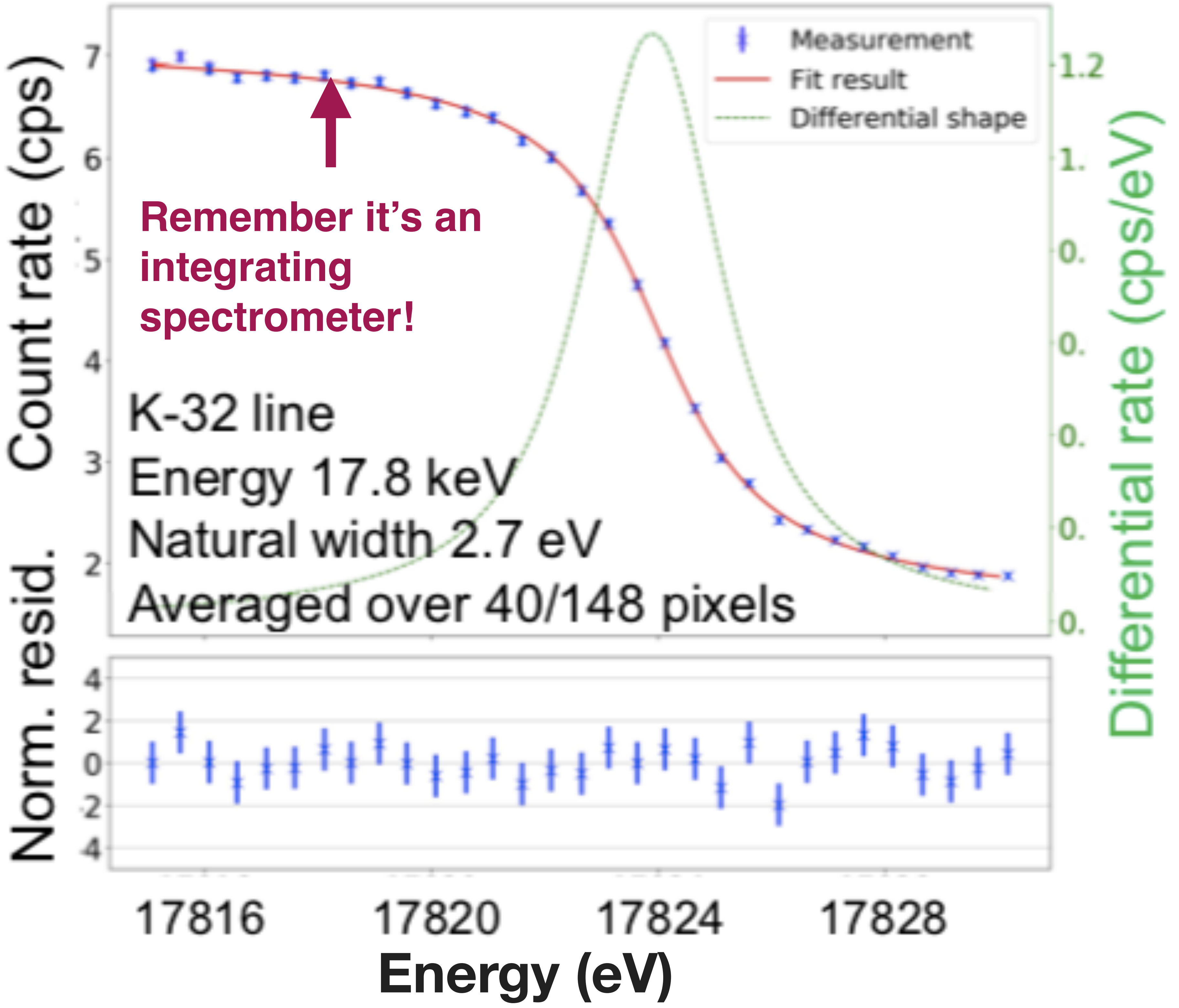
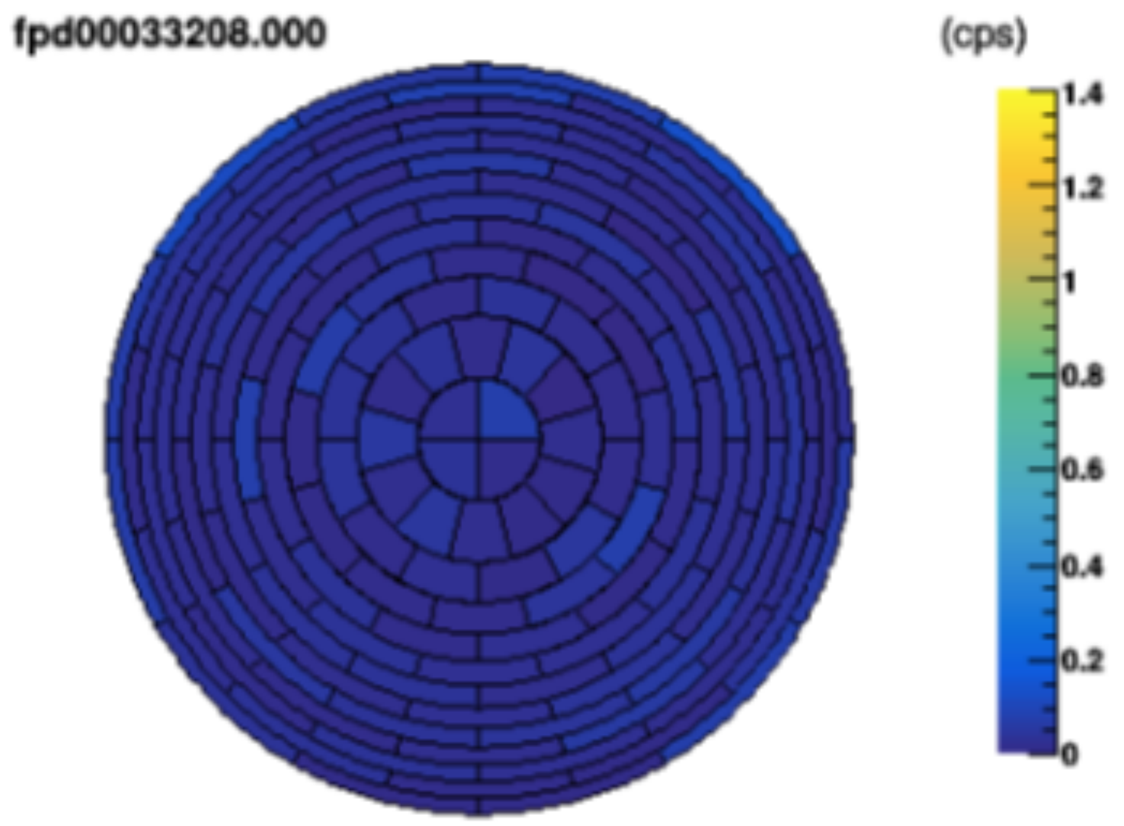




Real data from KATRIN!

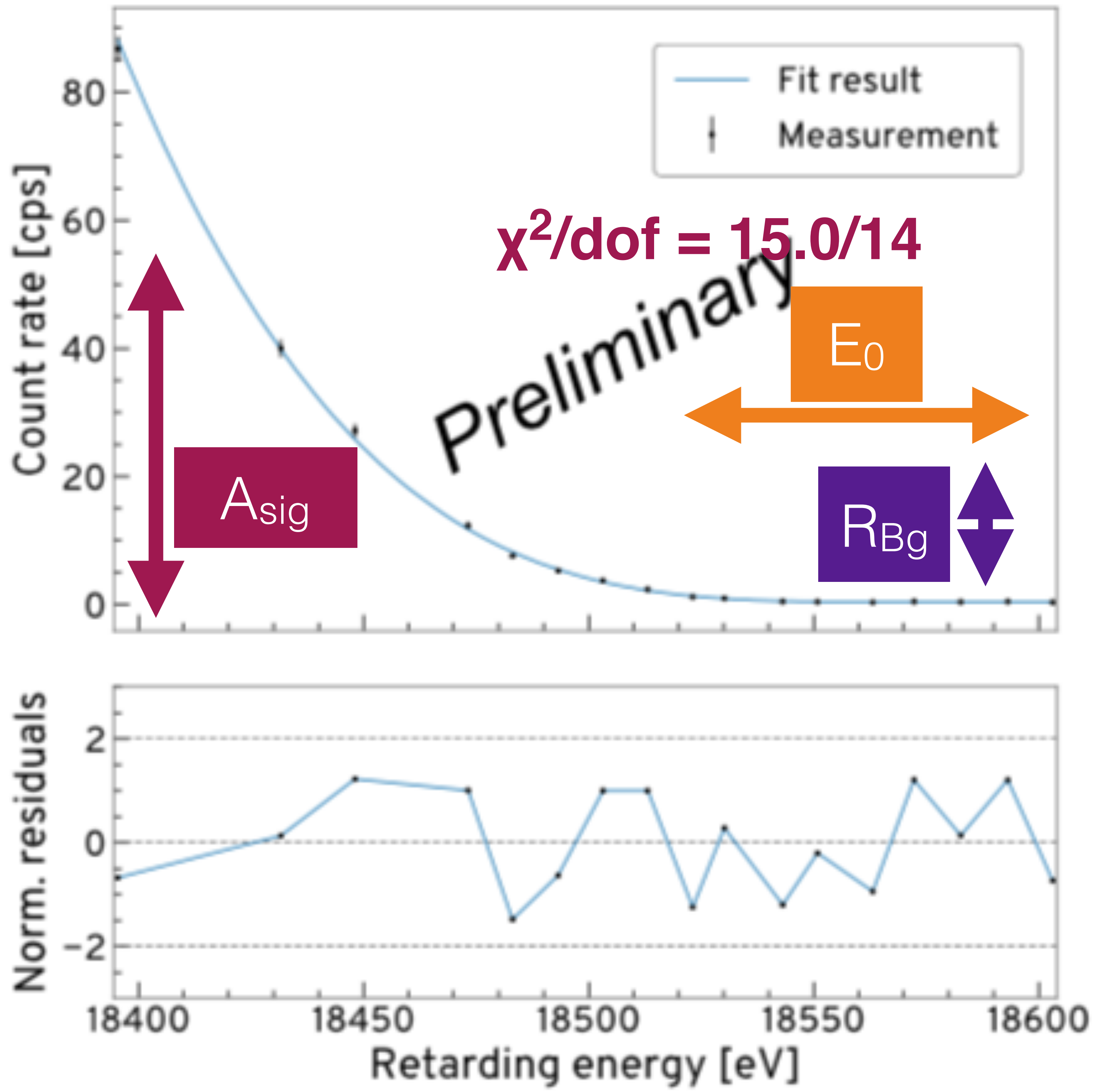
EPJ C 78 368 (2018)

JINST 13 P04020 (2018)

First tritium data June 2018

Test with D_2 at 90% nominal density, with 0.5% T atoms

First measurement of tritium spectrum



Fitted for

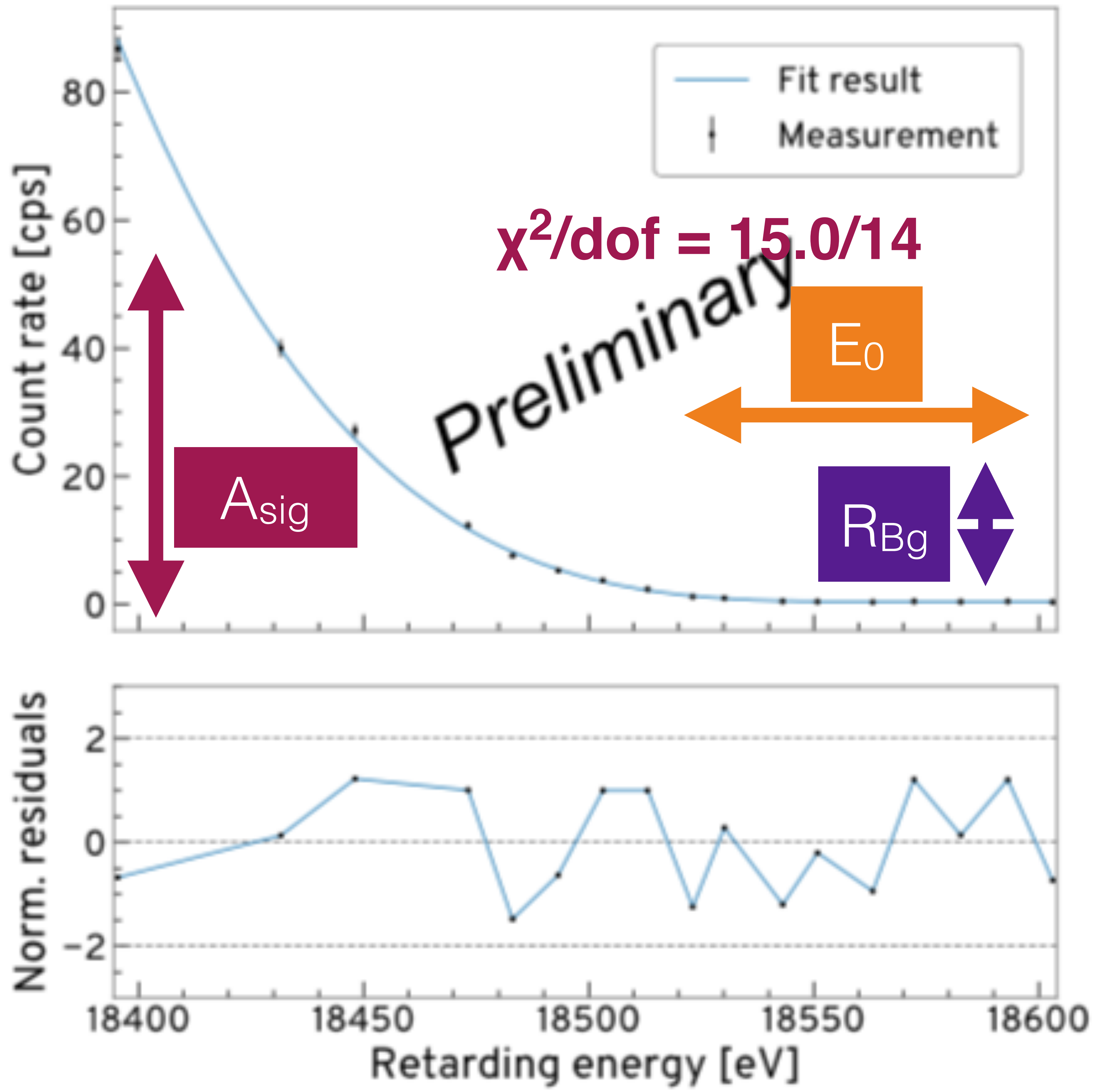
Activity A_{sig} **Endpoint energy E_0**

Background rate R_{Bg}

First tritium data June 2018

Test with D_2 at 90% nominal density, with 0.5% T atoms

First measurement of tritium spectrum



Fitted for

Activity A_{sig} **Endpoint energy E_0**

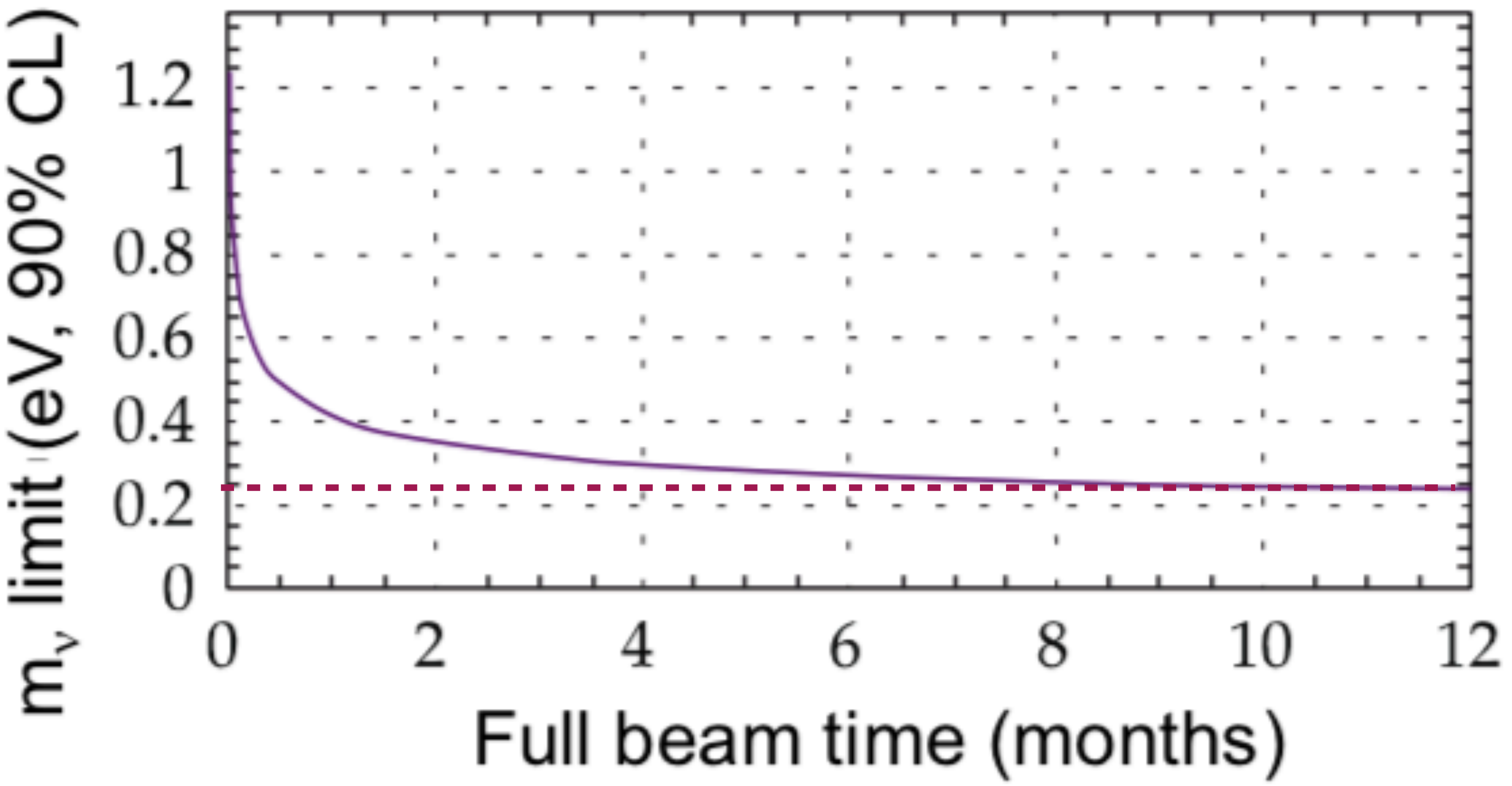
Background rate R_{Bg}

KATRIN Timeline	
June 5th–18th, 2018	First Tritium run: 81 hours of data
March-May 2019	"KNM1" with higher tritium concentration. First data usable for neutrino mass measurement
2020	Plan to start 3-year run at nominal settings
2025	Analysis becomes systematics limited. Should reach design sensitivity 0.2eV.

arXiv:1906.10168

Sensitivity and discovery potential

Sensitivity - if KATRIN measures zero mass

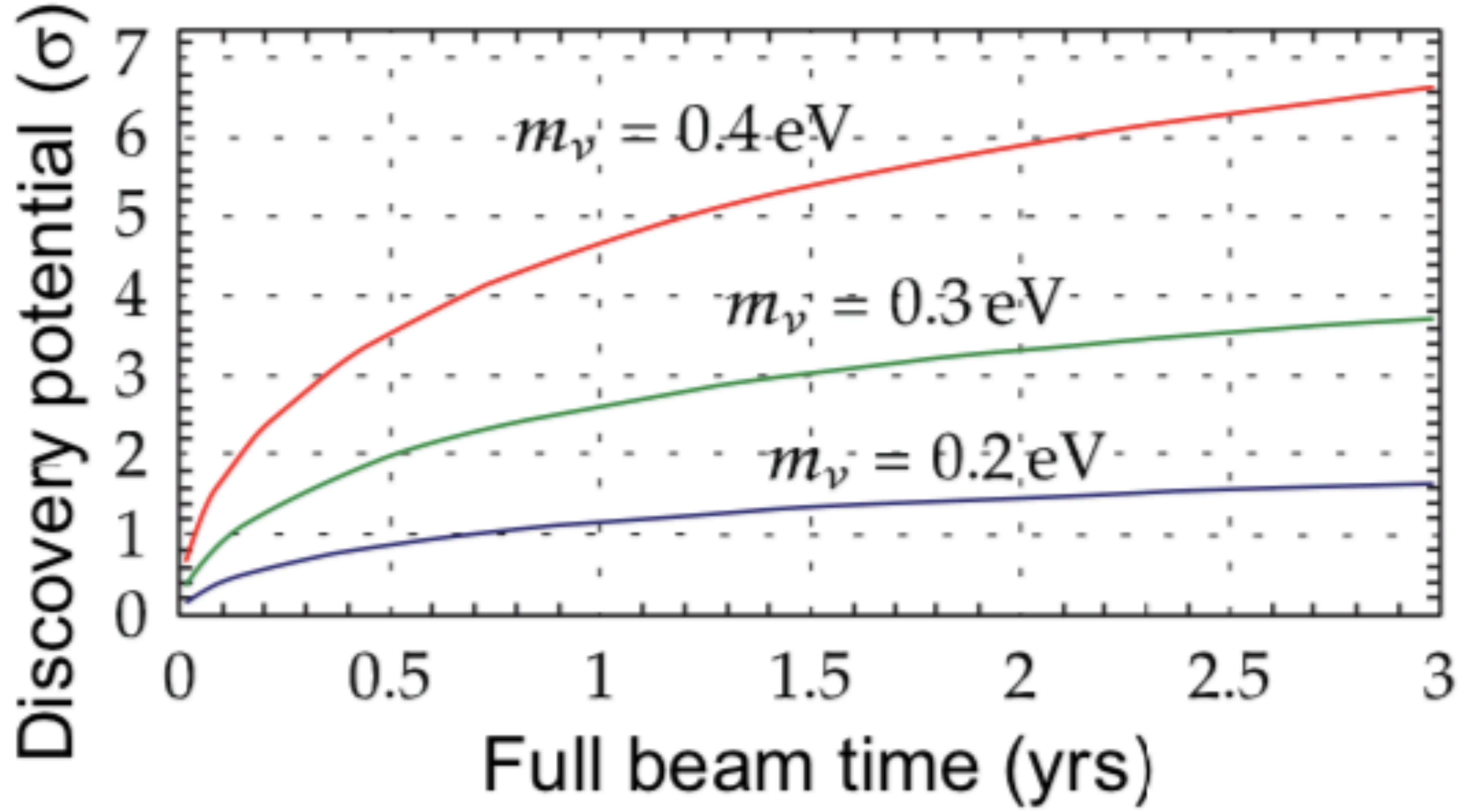


m_ν **< 0.24 eV at 90% confidence**

Jargon: **sensitivity**

The upper limit on the measured value (neutrino mass) if the mass is measured to be zero. Typically quoted with 90% confidence.

Discovery potential - if KATRIN measures a non-zero mass



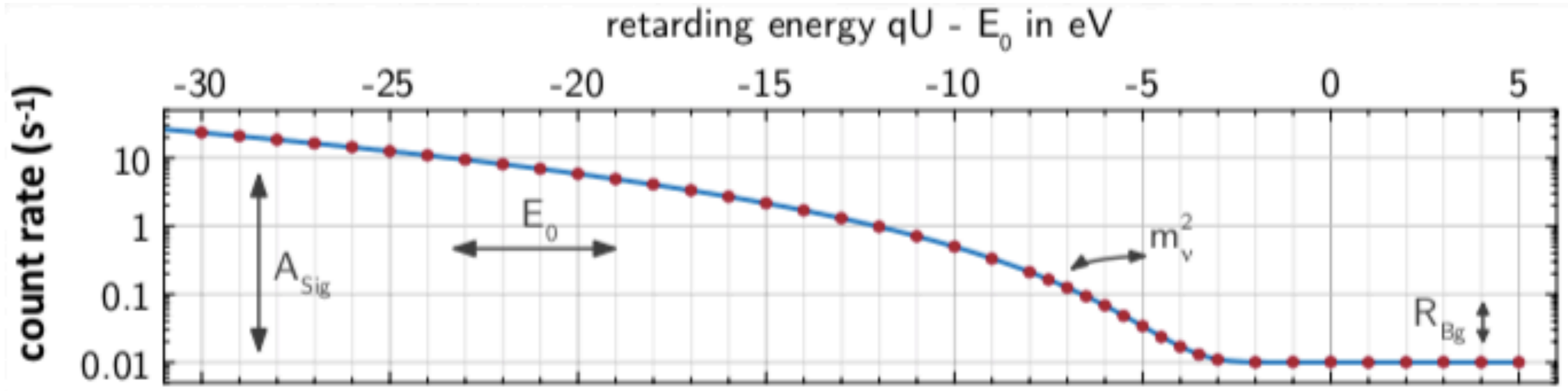
$m_\nu =$ **0.35 eV at 5σ significance**

$m_\nu =$ **0.3 eV at 3σ significance**

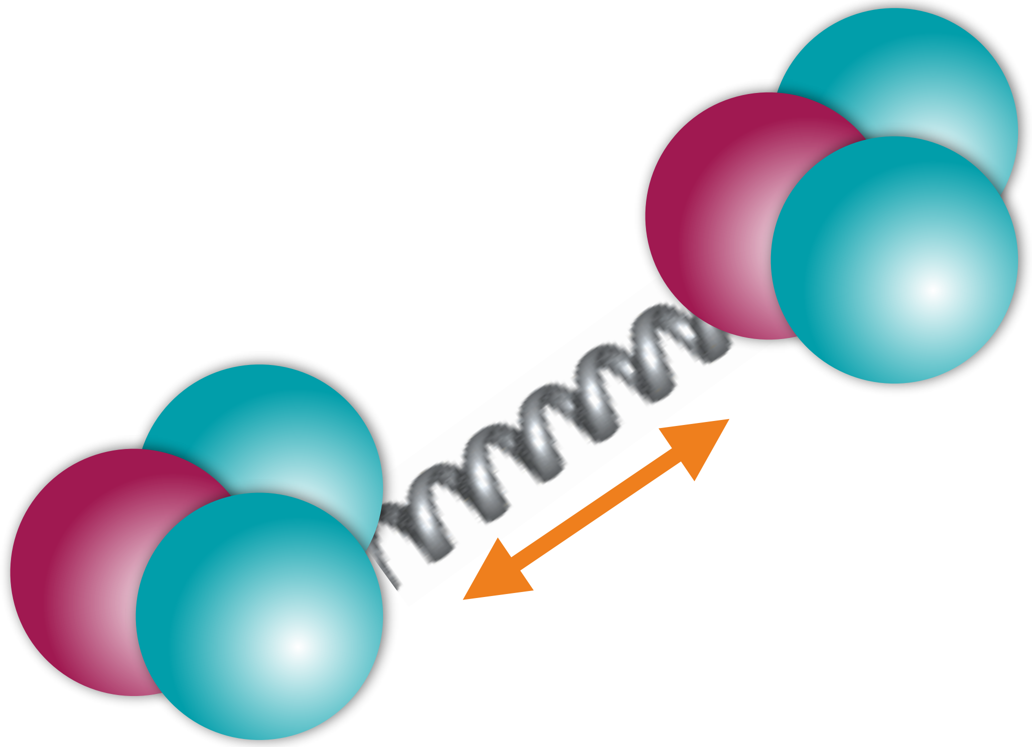
Systematic uncertainties > statistical uncertainties after 3 years (5 calendar years)

Challenges for future MAC-E experiments

Spectrometer already as big as is practical - can't improve resolution



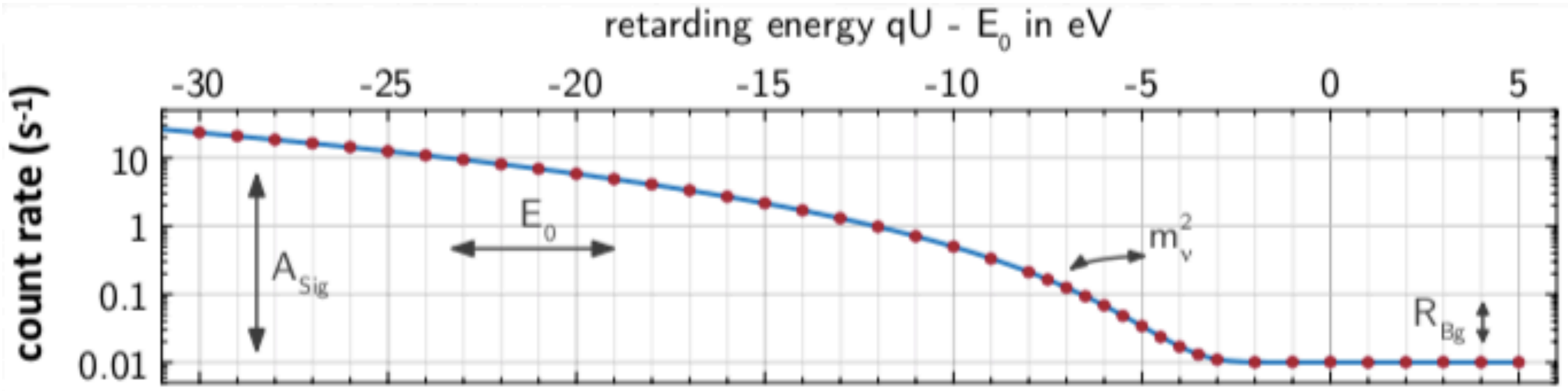
Integrated β spectrum means throwing away spectrum information



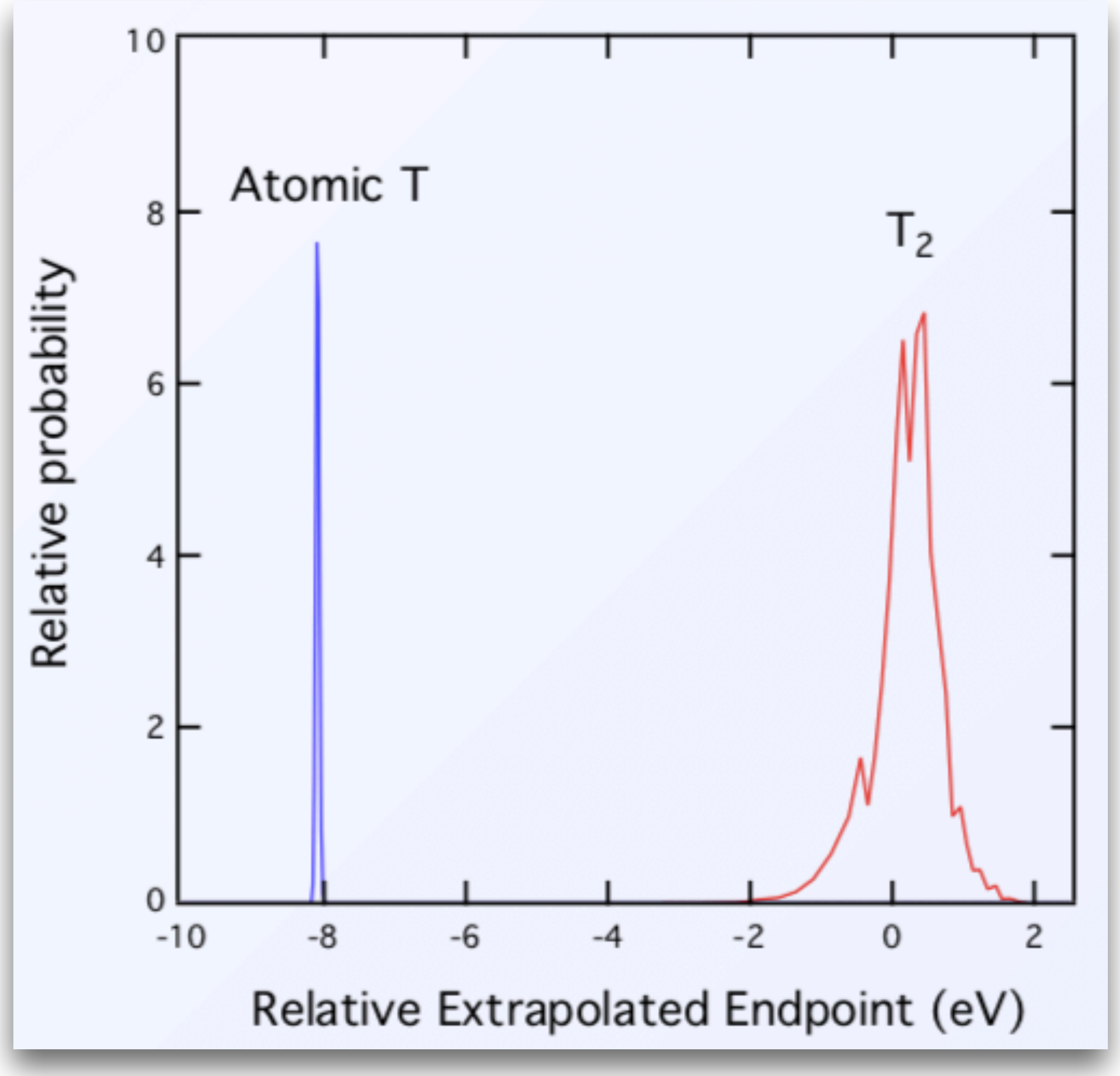
Molecular final state excitations / vibrations set ultimate T_2 limit

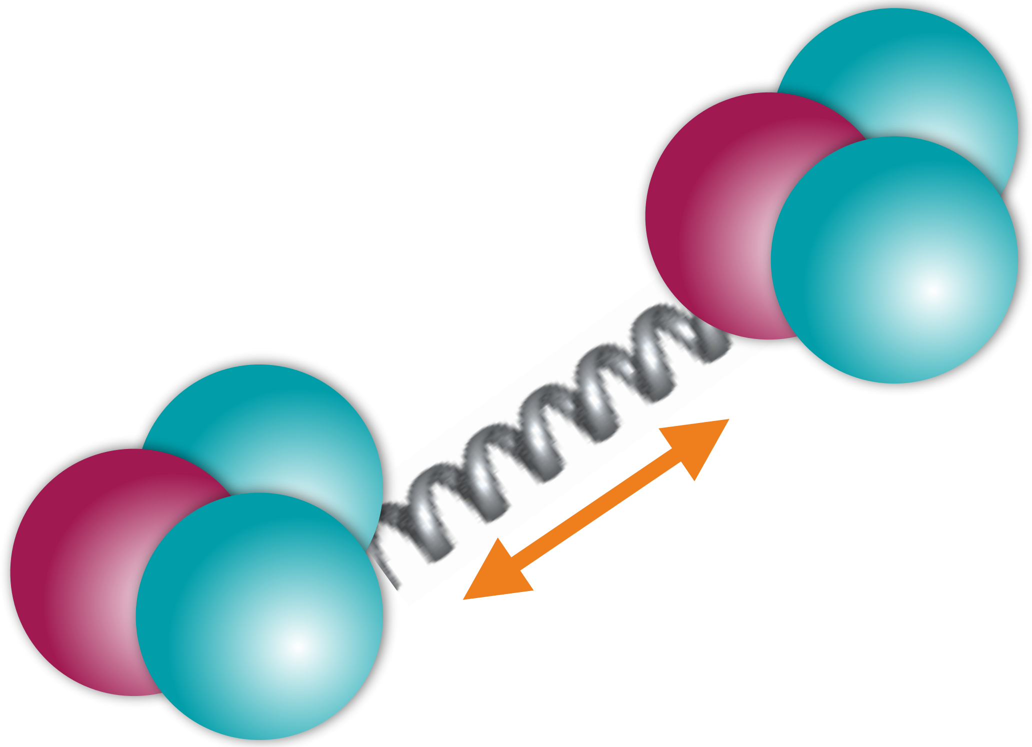
Challenges for future MAC-E experiments

Spectrometer already as big as is practical - can't improve resolution



Integrated β spectrum means throwing away spectrum information

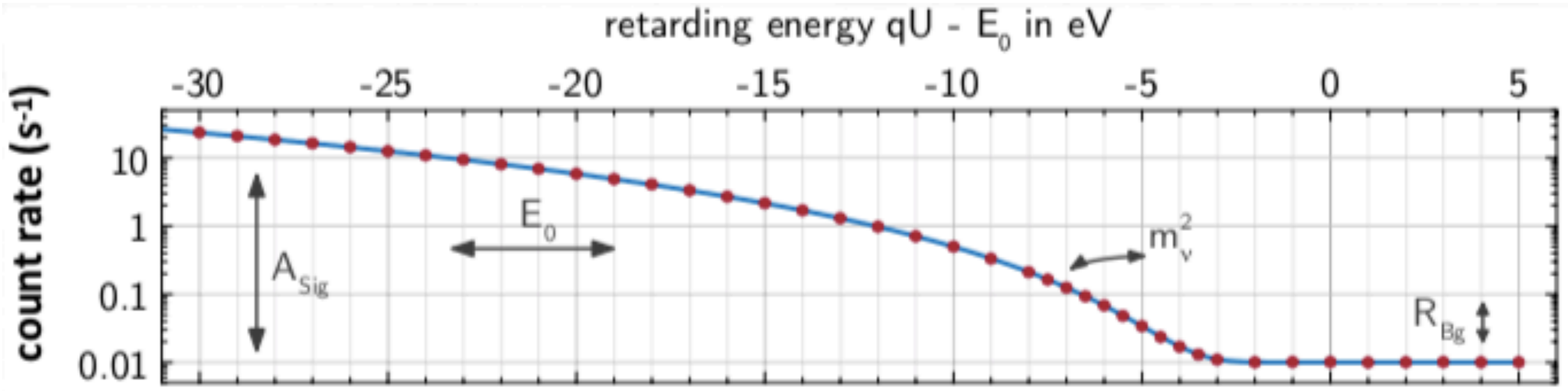




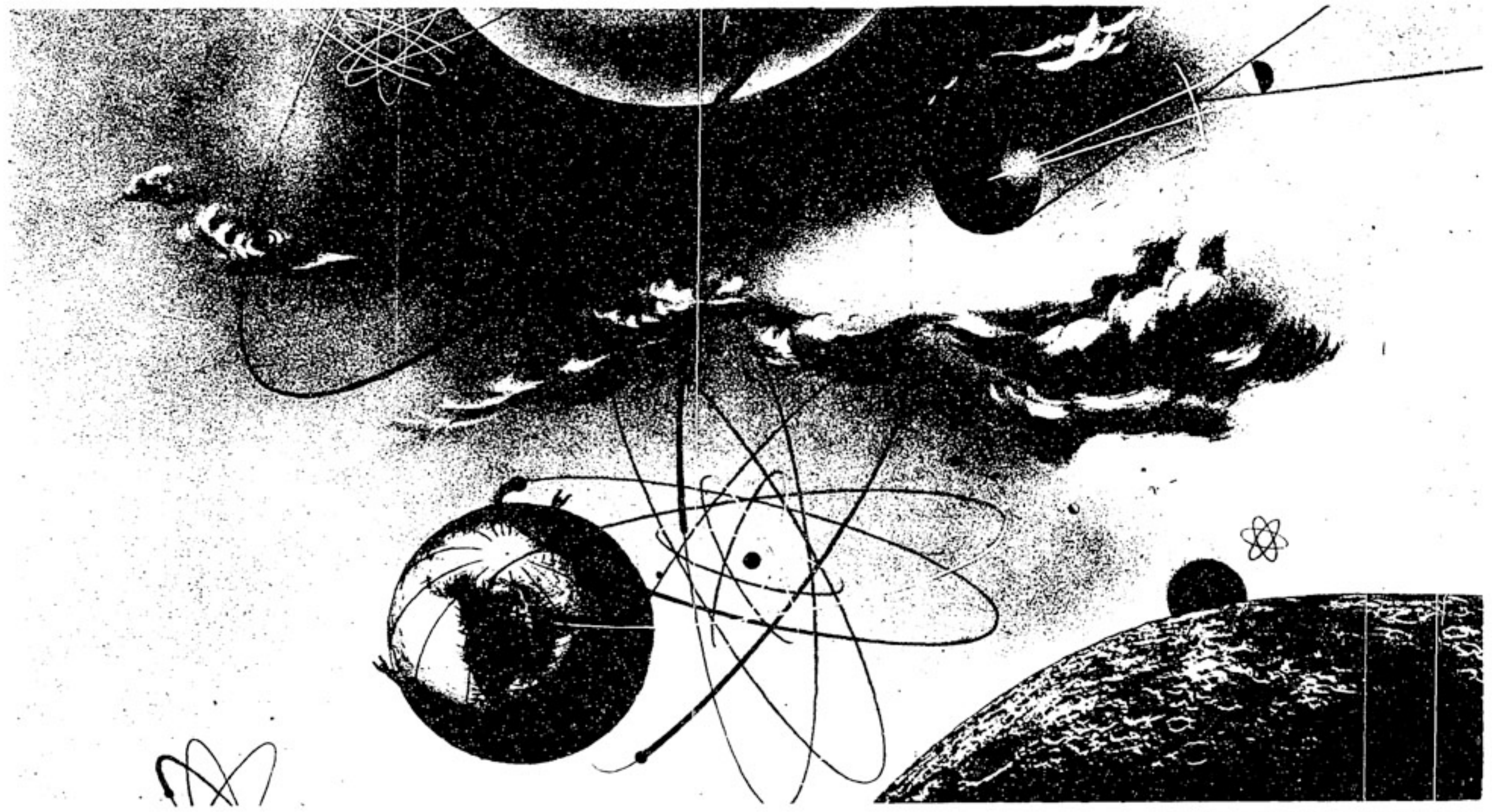
Molecular final state excitations / vibrations set ultimate T_2 limit

Challenges for future MAC-E experiments

Spectrometer already as big as is practical - can't improve resolution



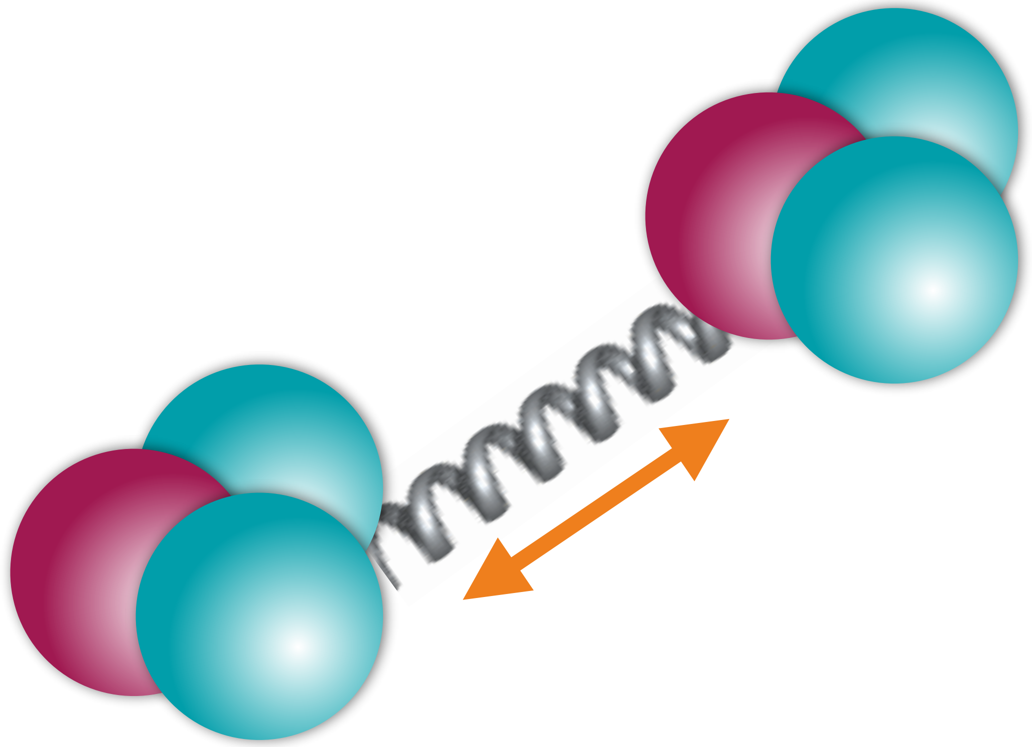
Integrated β spectrum means throwing away spectrum information


The New York Times Magazine

"In the world around us, atomic energy is working on a tremendous scale."

Drawing by Herbert Bayer, © General Electric Co.

We Enter a New Era—the Atomic Age



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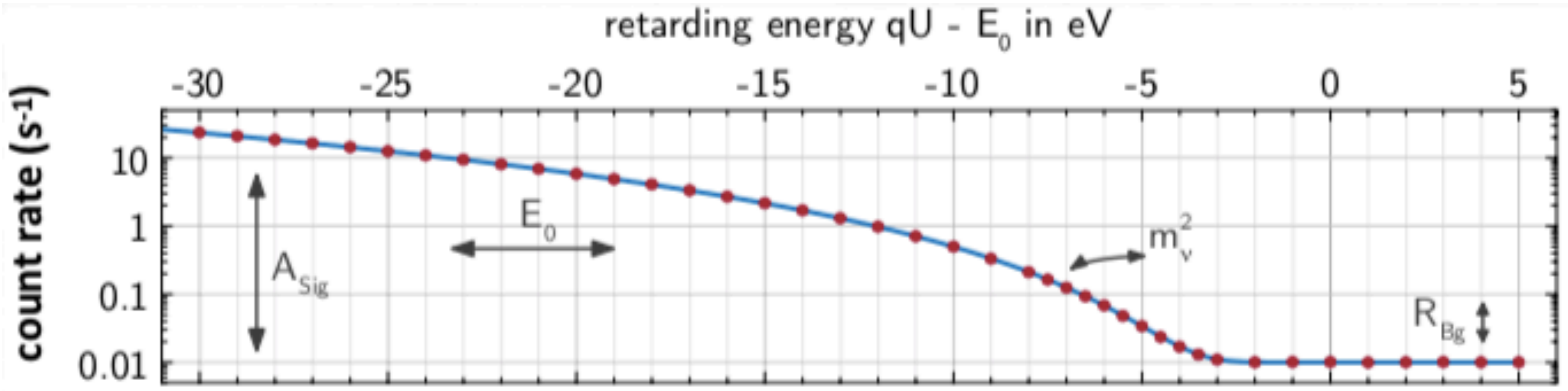

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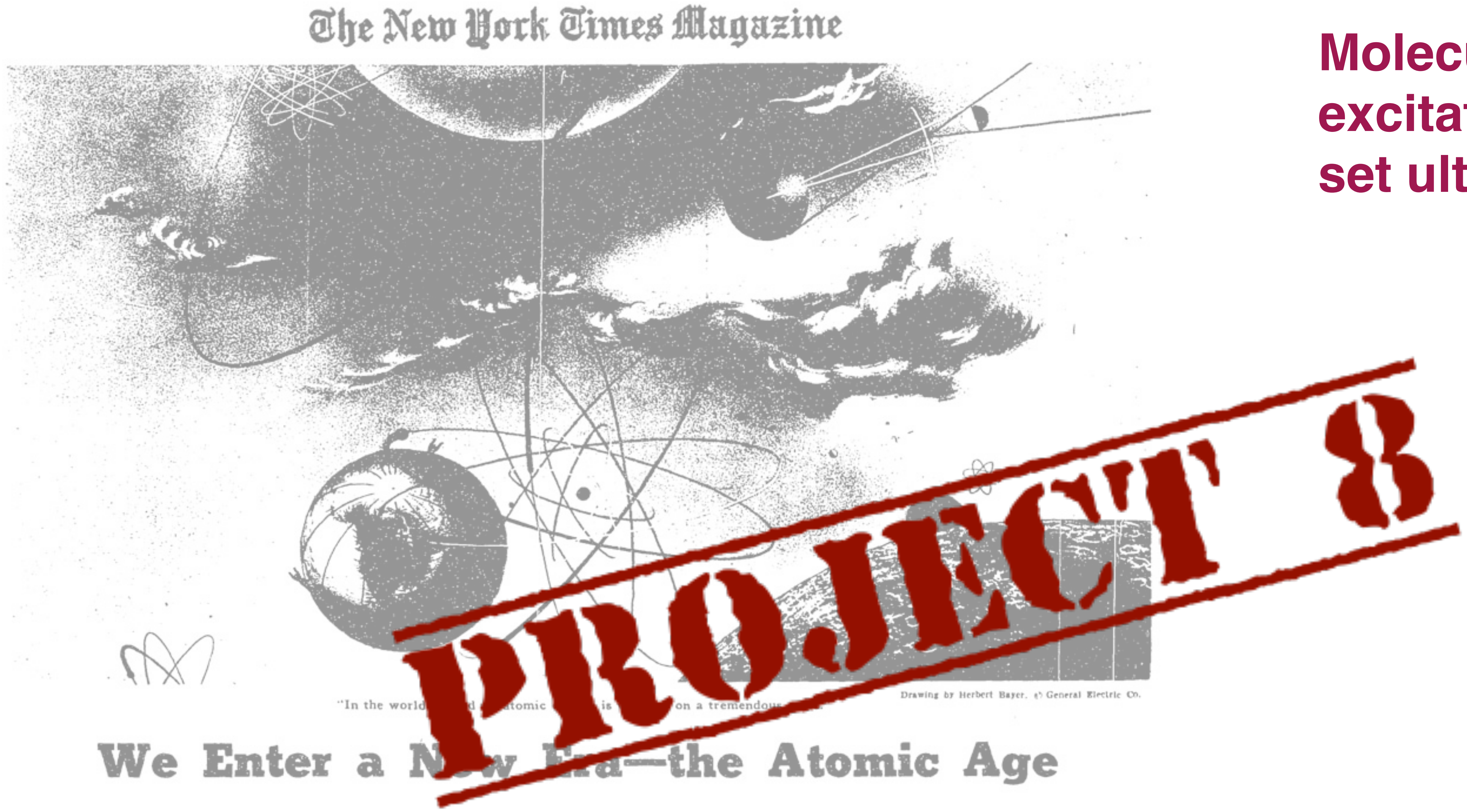
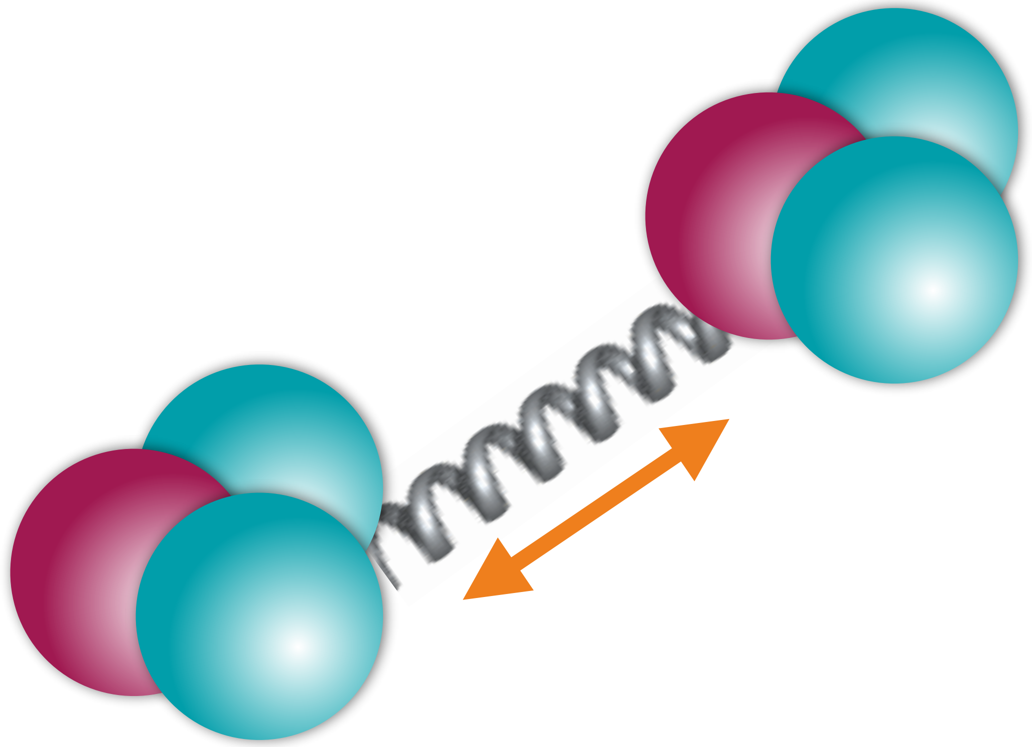




Molecular final state excitations / vibrations set ultimate T_2 limit

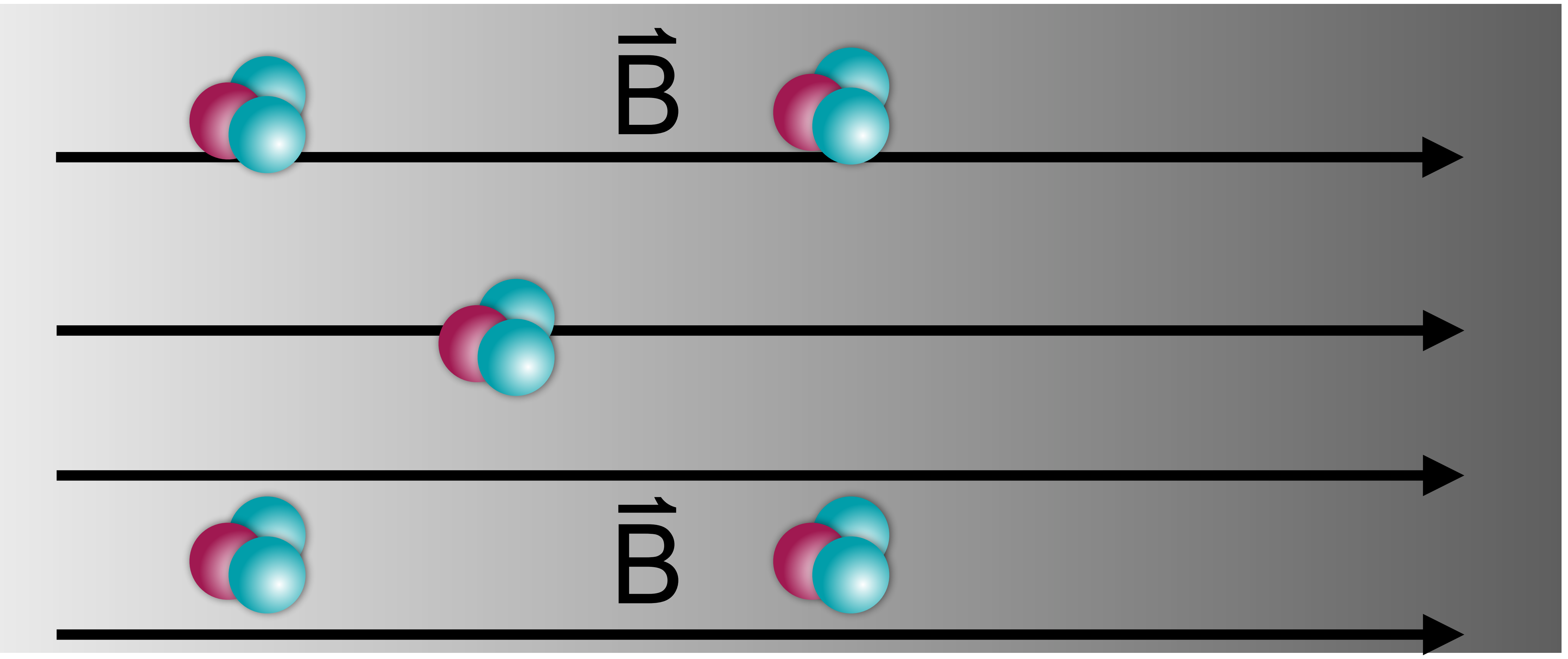
PROJECT 8 Cyclotron Radiation Emission Spectroscopy

UCL

Arthur Schawlow

"Never measure anything but frequency!"

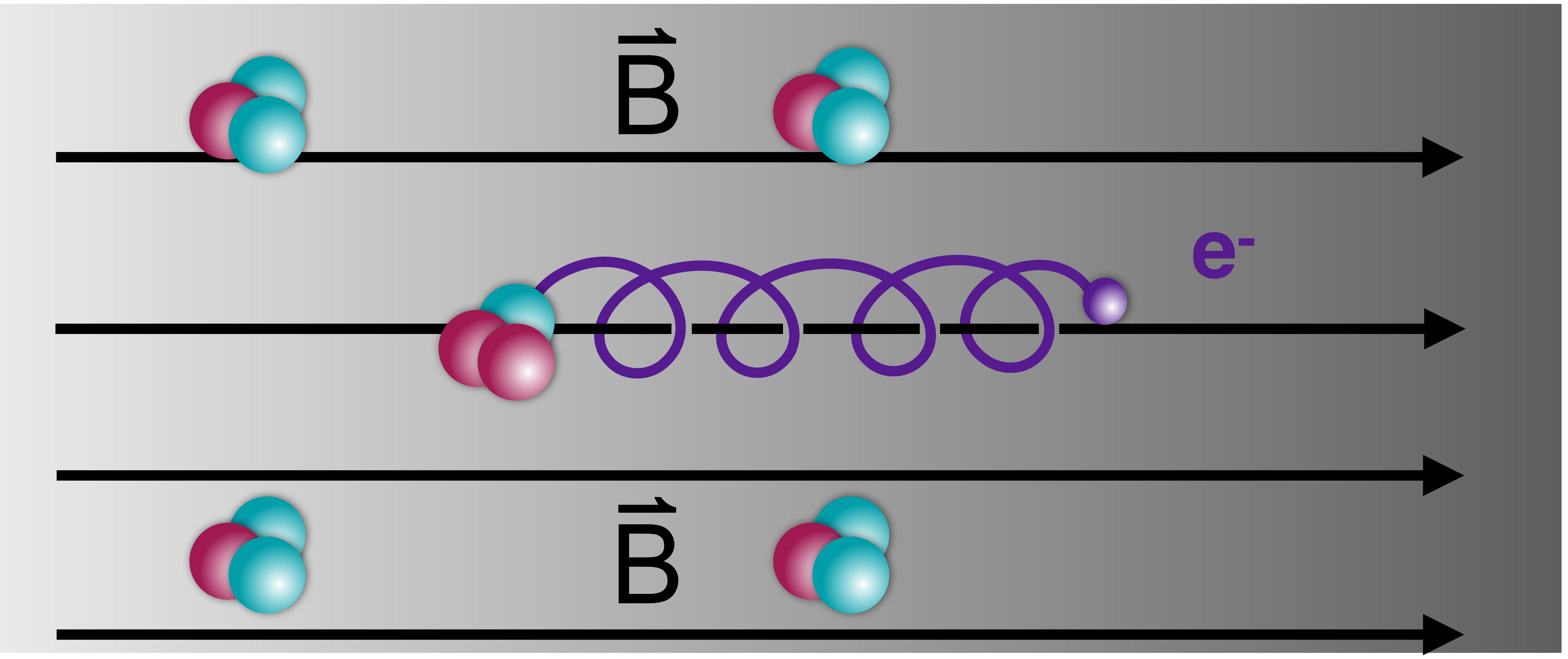
Cyclotron Radiation Emission Spectroscopy



J. Formaggio and B. Monreal, Phys. Rev D 80:051301 (2009)

Trapped low-temperature **tritium atoms** in uniform magnetic field

Cyclotron Radiation Emission Spectroscopy



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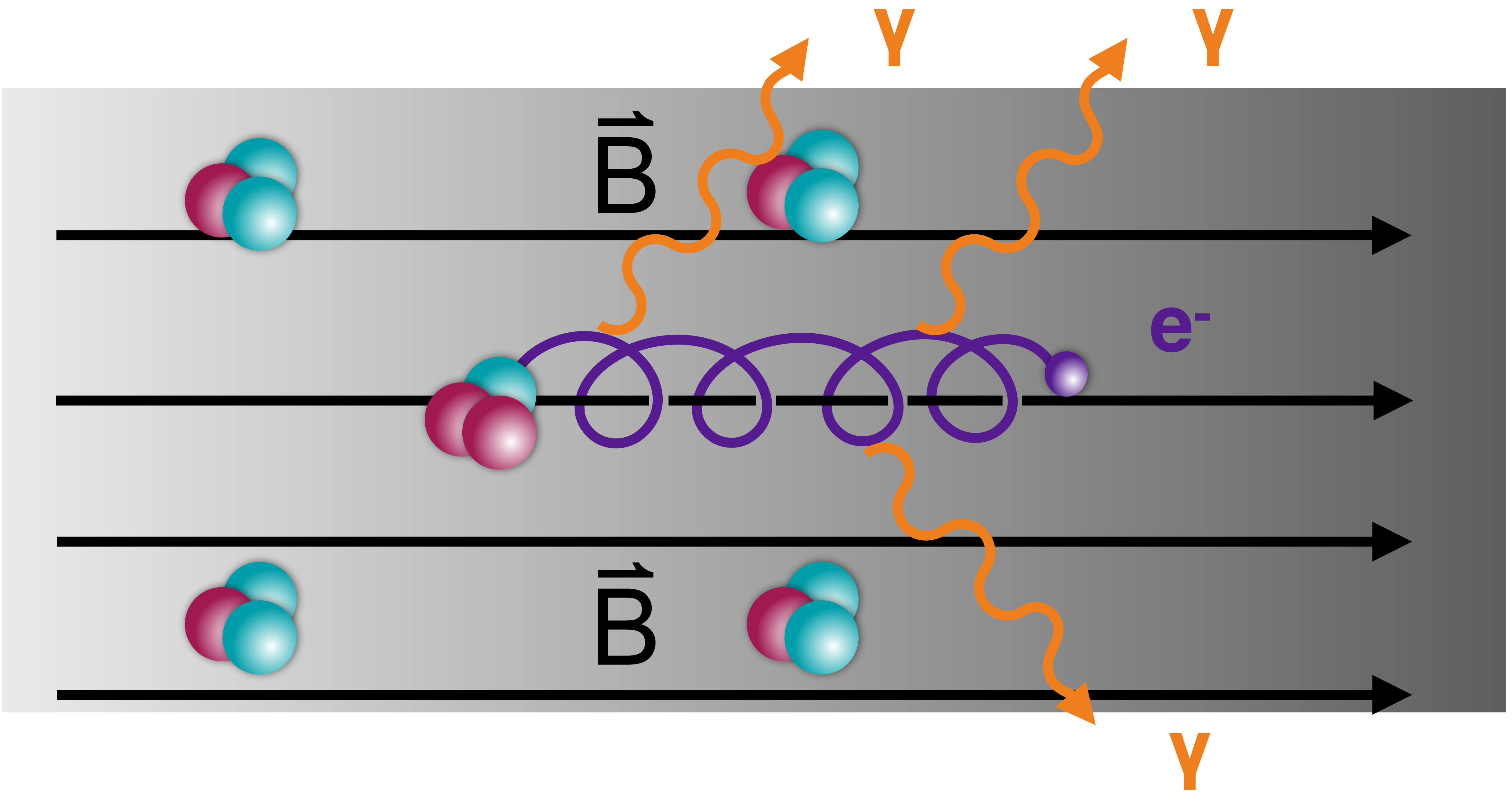
Trapped low-temperature **tritium atoms** in uniform magnetic field

β-decay electrons exhibit **cyclotron motion** around the field

Cyclotron Radiation Emission Spectroscopy



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Trapped low-temperature **tritium atoms** in uniform magnetic field

β-decay electrons exhibit **cyclotron motion** around the field

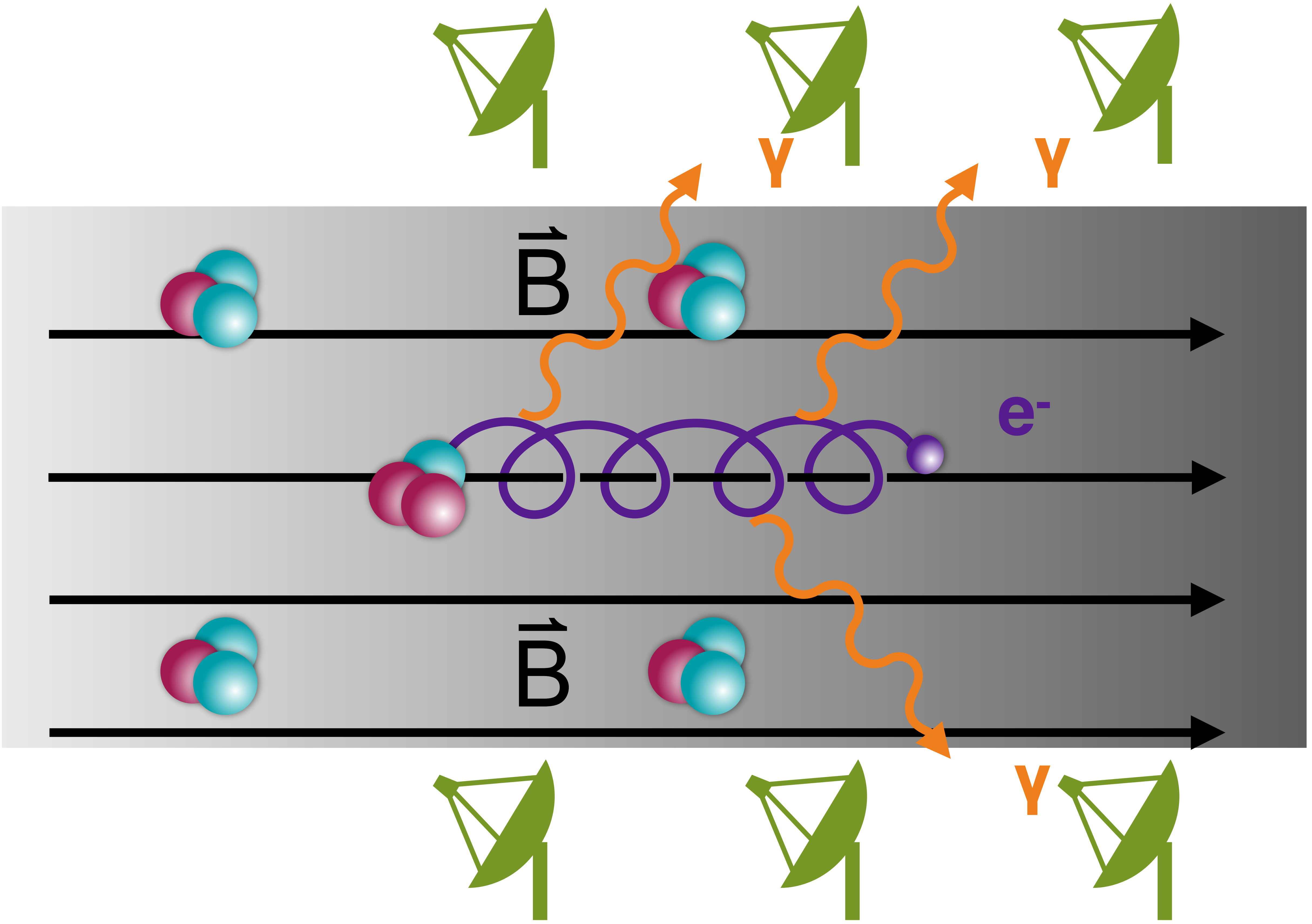
The spiralling electrons emit **cyclotron radiation**

$$\boxed{f_\gamma} \equiv \frac{\omega_c}{2\pi\gamma} = \frac{1}{2\pi}\frac{eB}{m_e + \boxed{K_e}/c^2}$$

Cyclotron frequency

Electron kinetic energy

Cyclotron Radiation Emission Spectroscopy



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Trapped low-temperature **tritium atoms** in uniform magnetic field

β-decay electrons exhibit **cyclotron motion** around the field

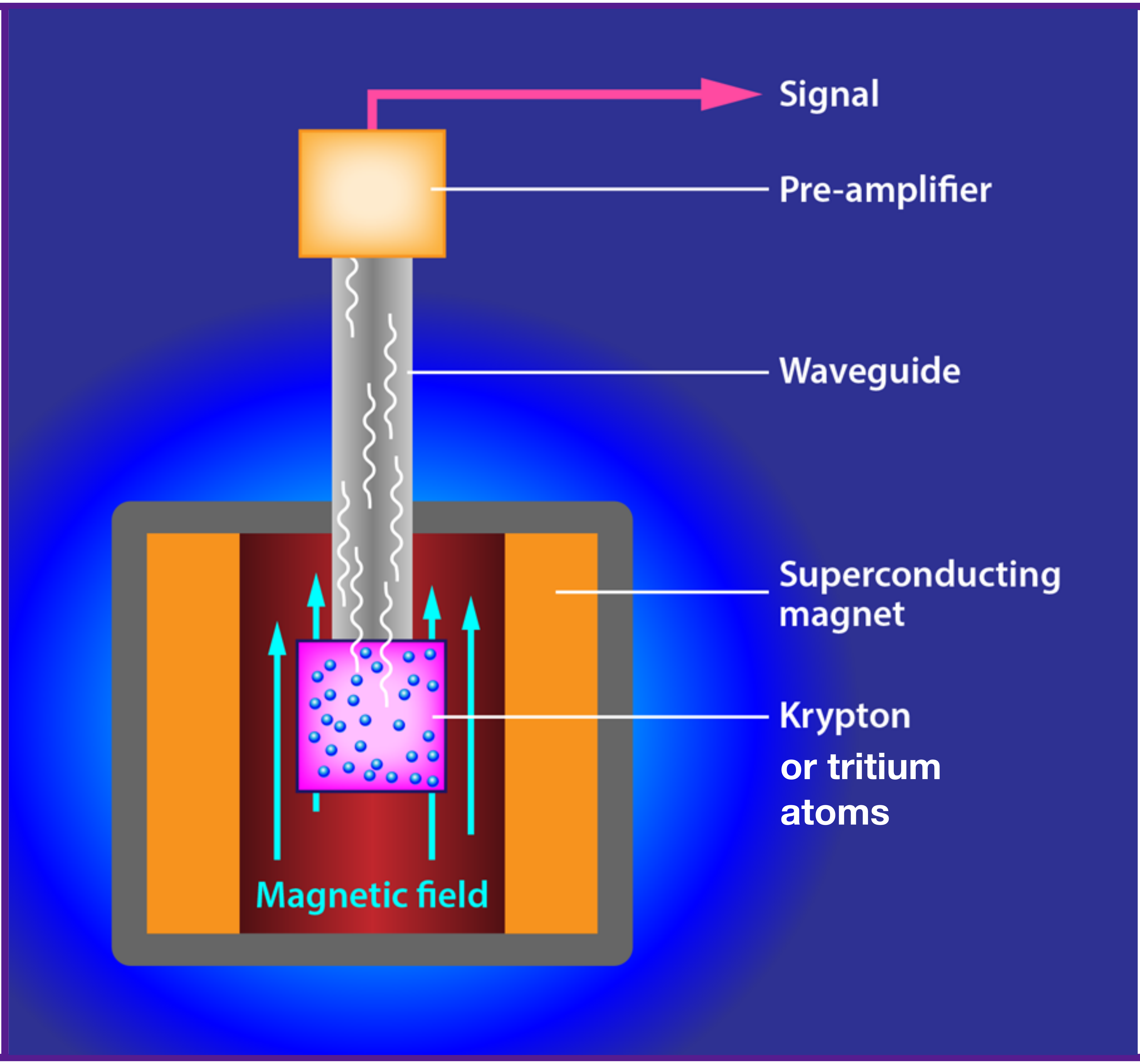
The spiralling electrons emit **cyclotron radiation**

Measure gamma frequency to reconstruct **electron energy**

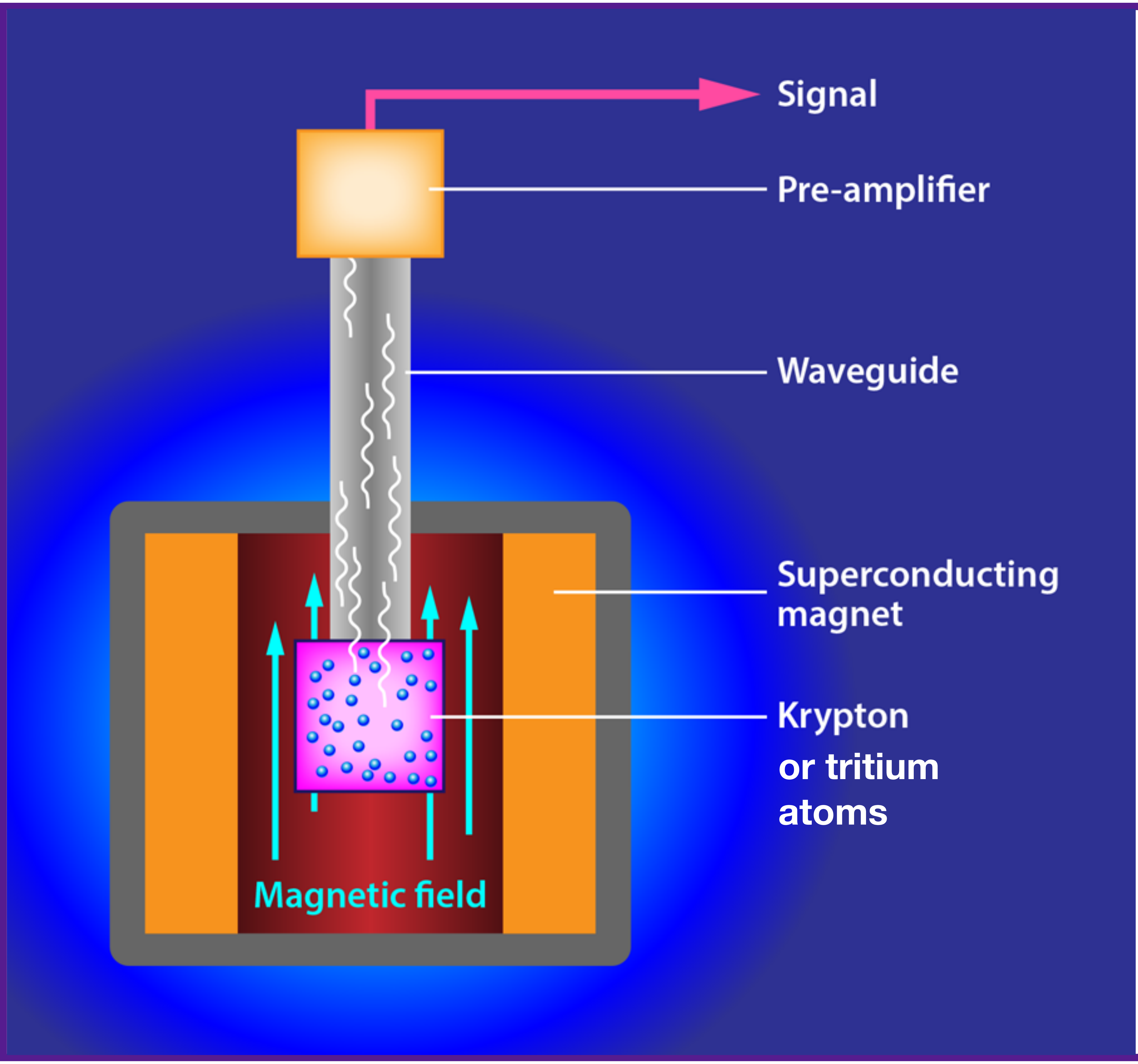
PROJECT 8

Project 8 by the numbers

UCL



Magnetic field: ~ 1 Tesla



PROJECT 8

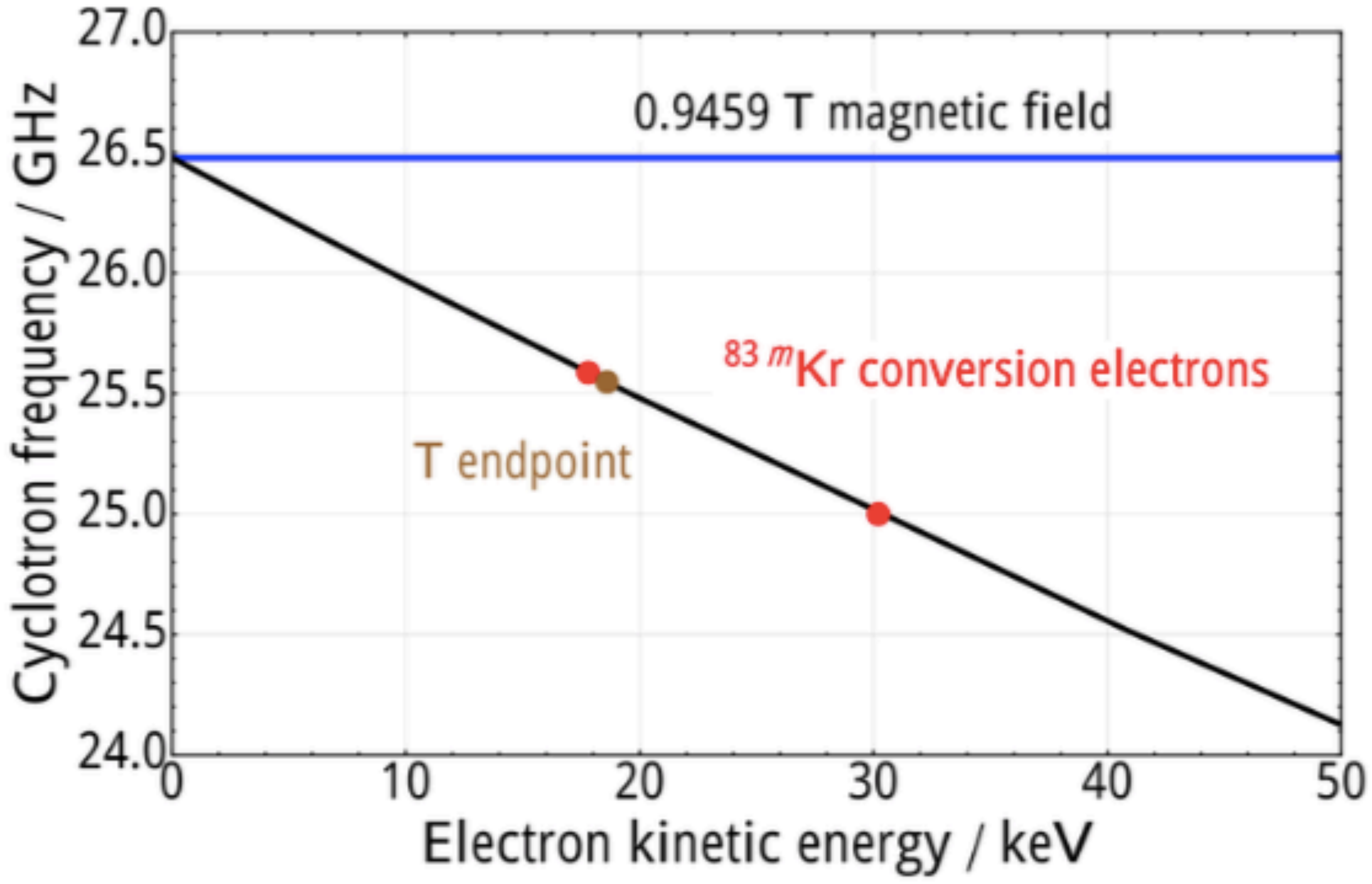
Project 8 by the numbers

UCL

Magnetic field: ~ 1 Tesla

Cyclotron frequency range 25-26.5 GHz (microwave)

Tritium endpoint 18.6 keV
(0 - 30keV for ^{83m}Kr spectrum)



Project 8 by the numbers

Magnetic field: ~ 1 Tesla

Cyclotron frequency range 25-26.5 GHz (microwave)

Tritium endpoint 18.6 keV
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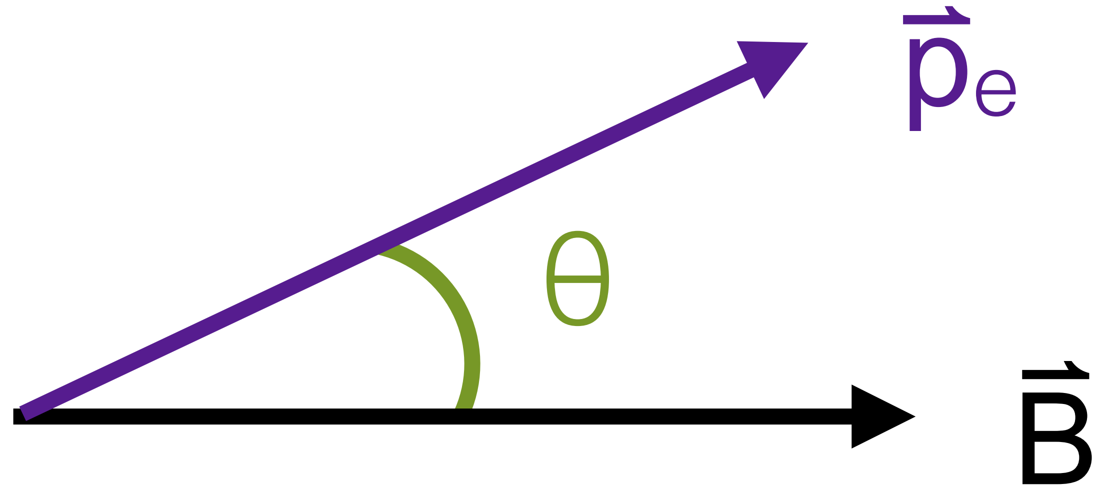
Power in femtowatt range

Larmor formula

$$P(\gamma,\theta) = \frac{1}{4\pi\epsilon_0}\frac{2}{3}\frac{e^4}{m_e^2}B^2(\gamma^2-1)\sin^2\theta$$



Depends on transverse momentum

$$P(K_e,m_e,\theta) = \frac{1}{4\pi\epsilon_0}\frac{2}{3}\frac{e^4}{m_e^2}B^2(K_e^2+2K_e m_e c^2)\sin^2\theta$$

$$P\,(\mathbf{18.6\ keV}, \mathbf{1T}, 90°) = 1\mathrm{fW}$$

PROJECT 8

Project 8 by the numbers

UCL

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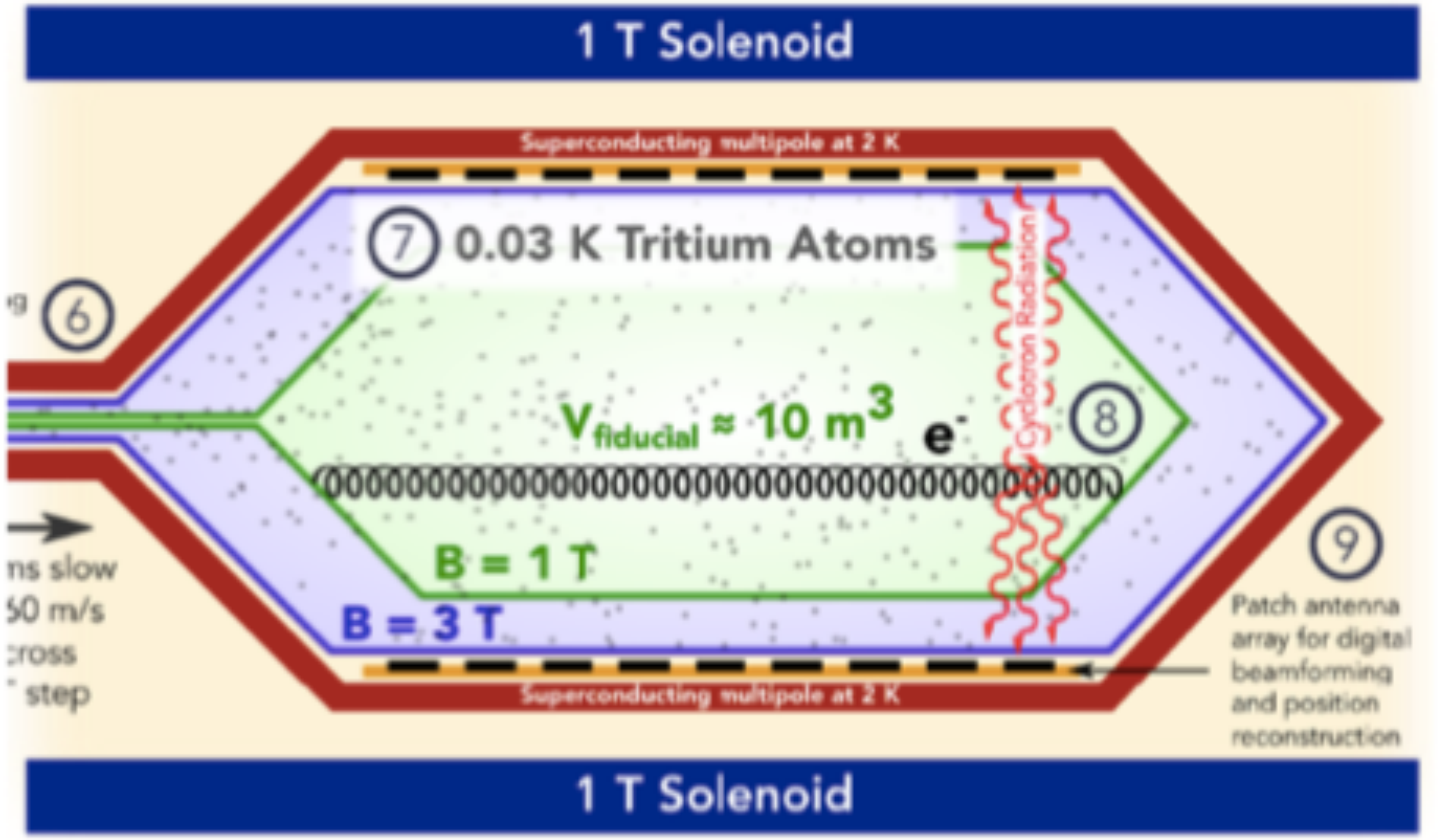
Gas volume 10m³ (final phase)



PROJECT 8

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Tritium endpoint 18.6 keV
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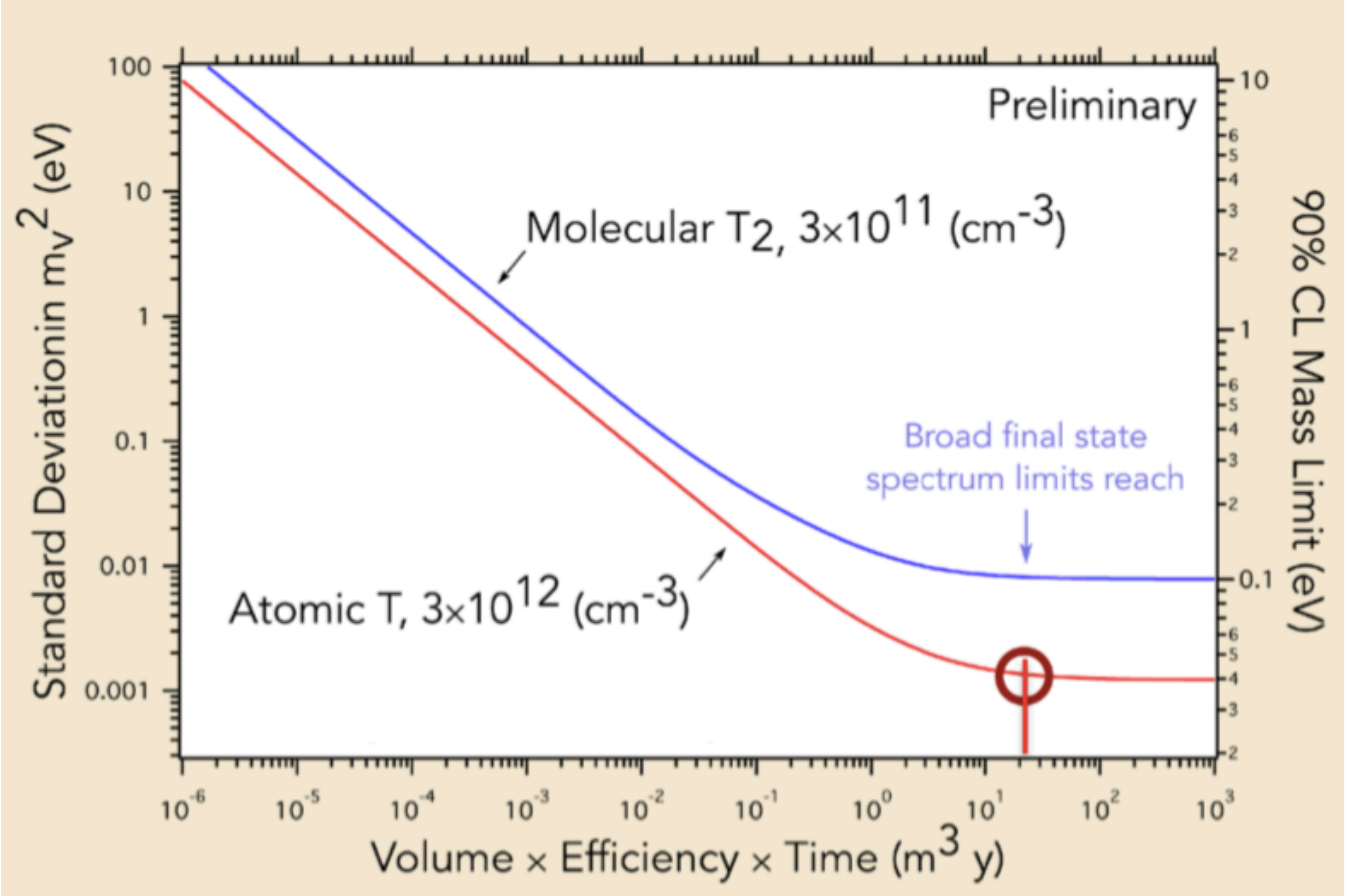
Power in femtowatt range

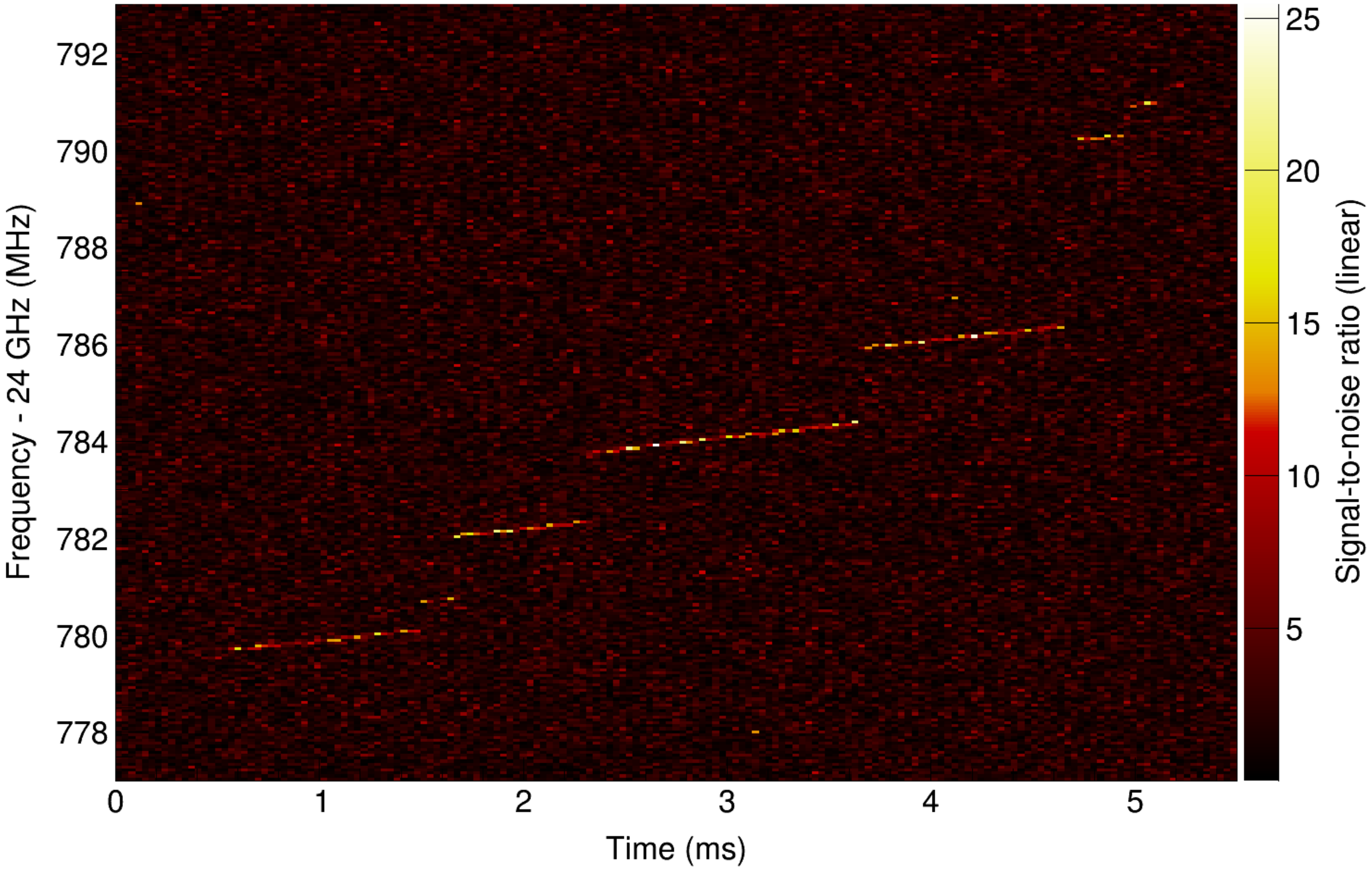
Gas volume 10m³ (final phase)

Projected m_ν sensitivity 40 meV



Project 8 phase I (2015-16) - demonstrate CRES with ^{83m}Kr

Phys. Rev. Lett. 114, 162501 (2015)



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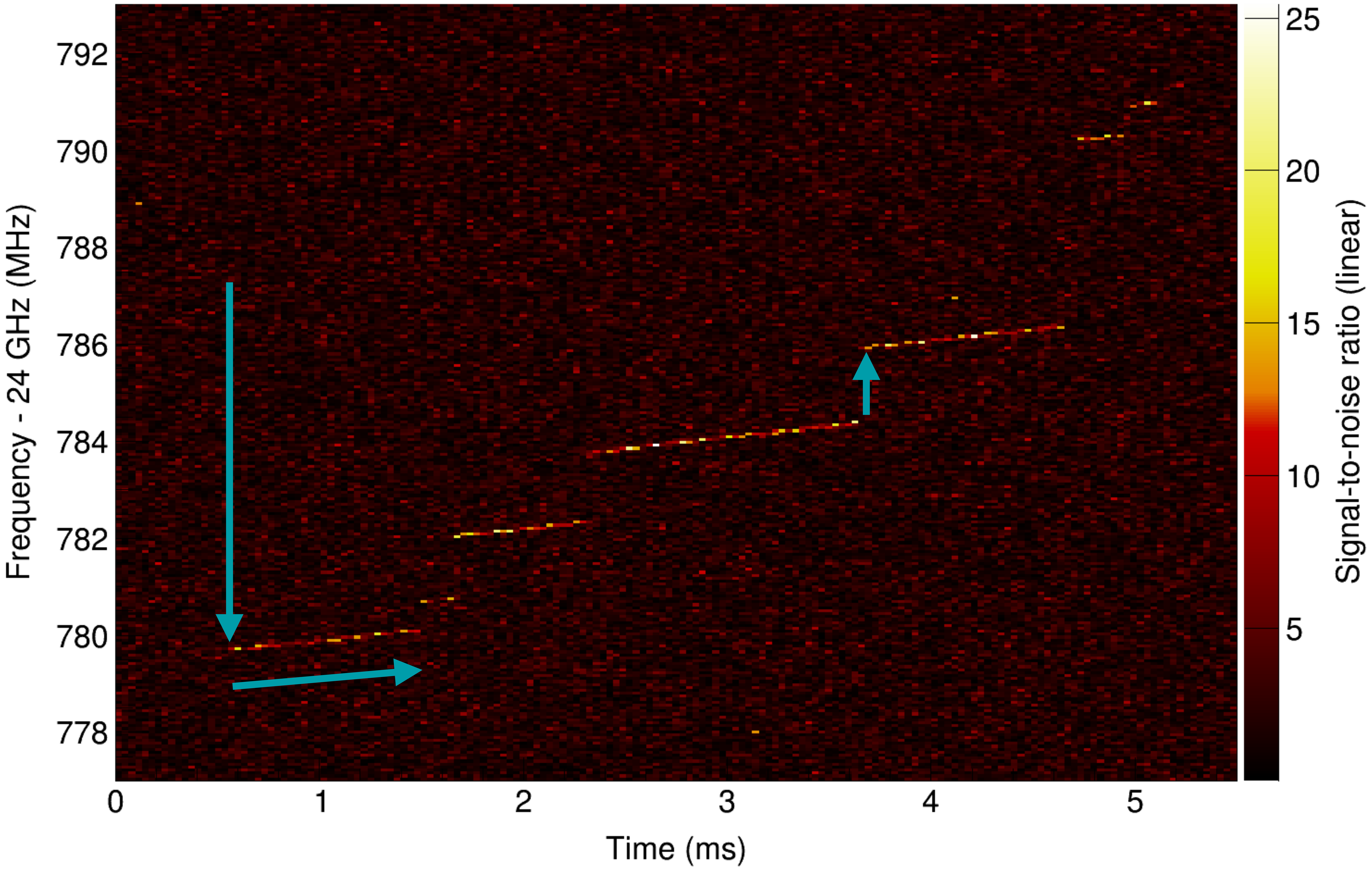

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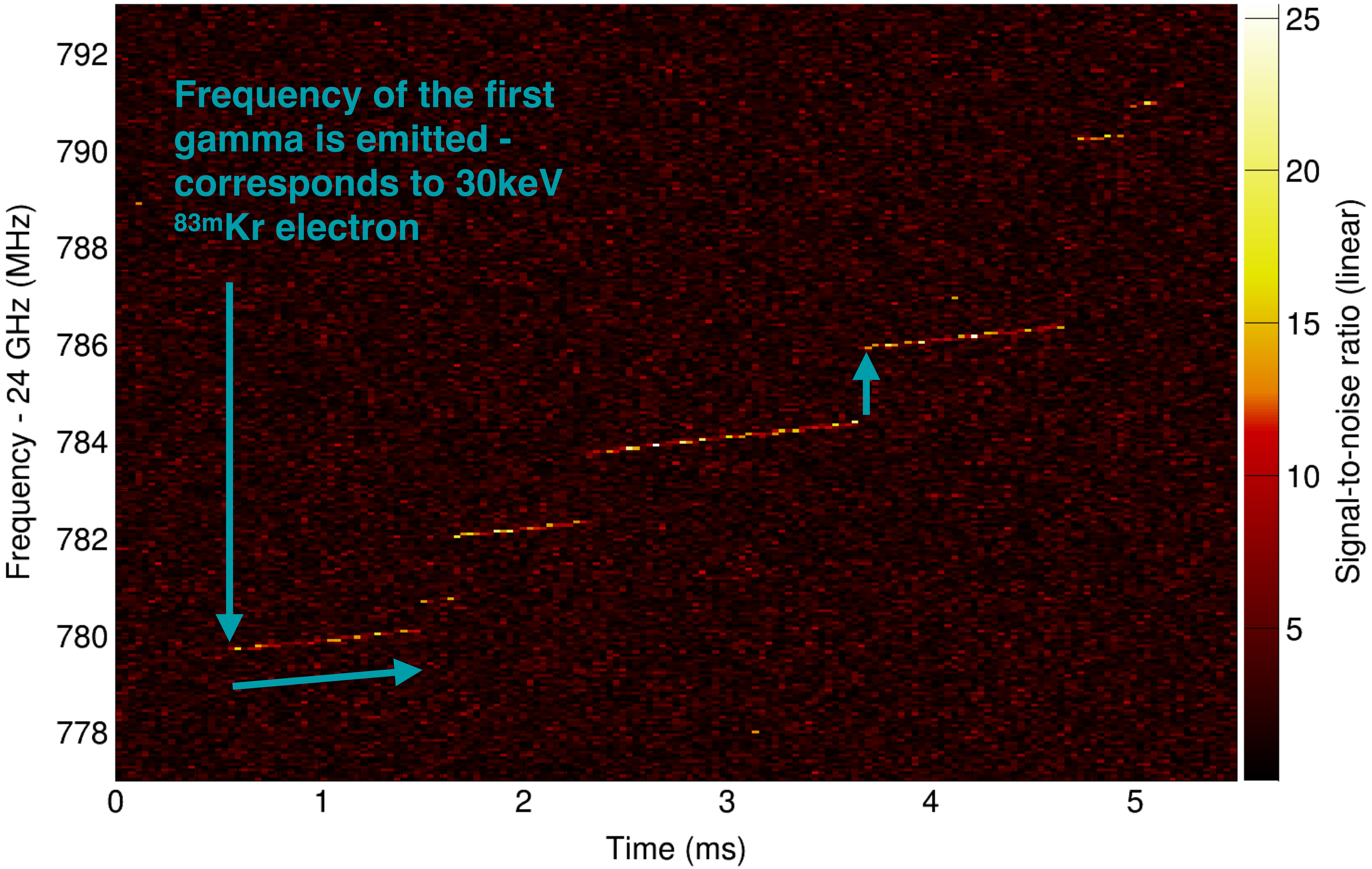

PROJECT 8

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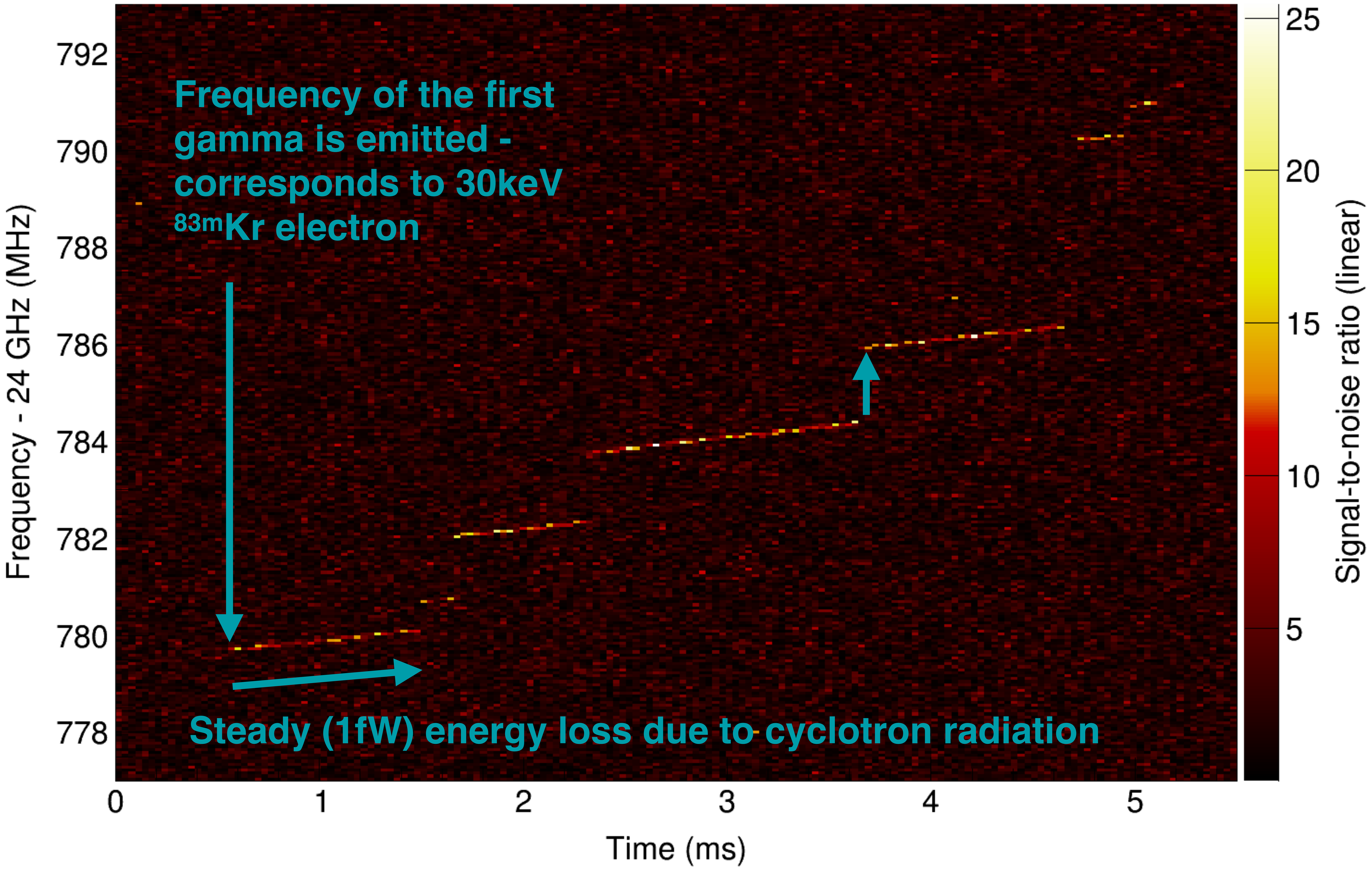

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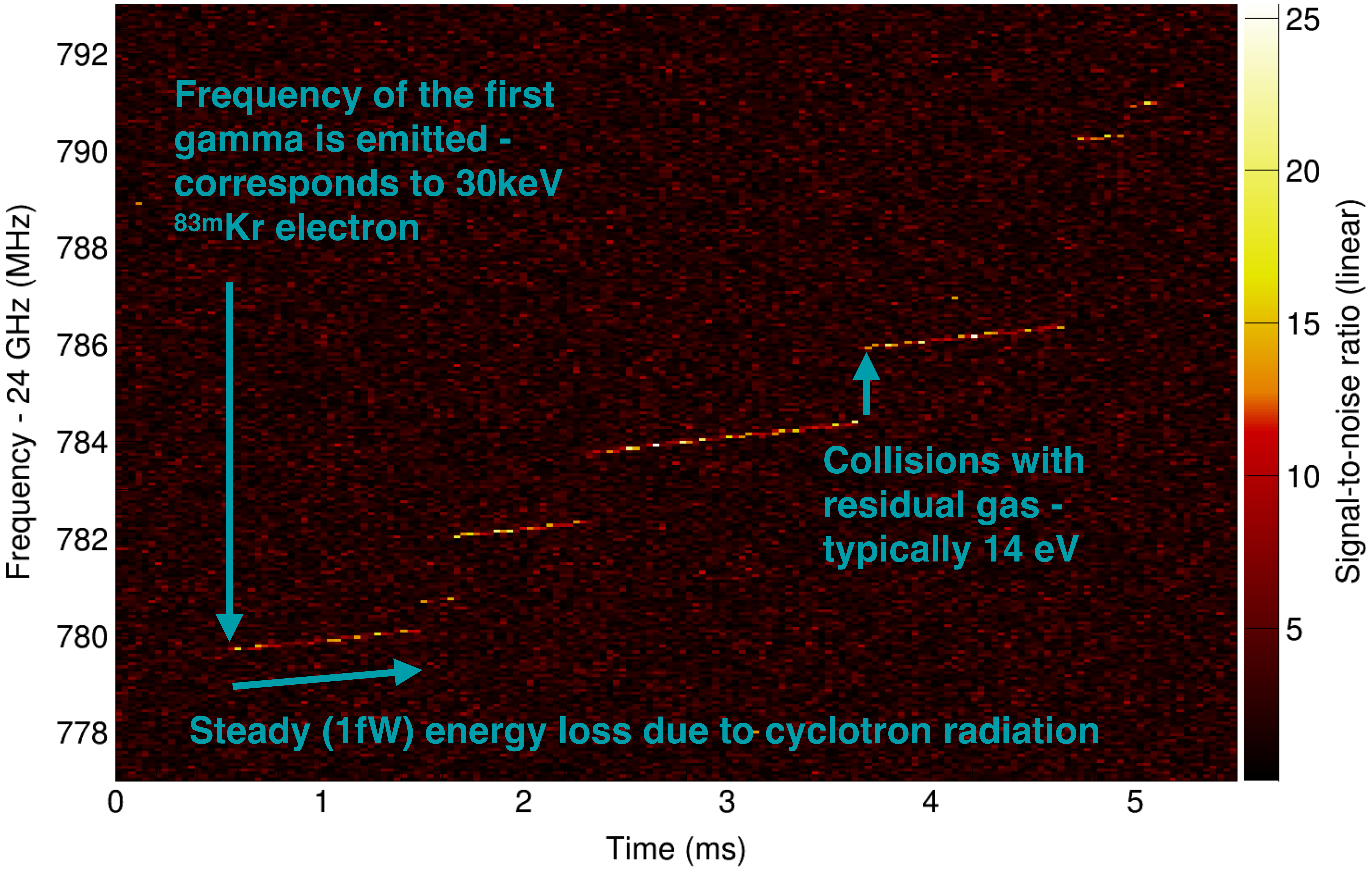

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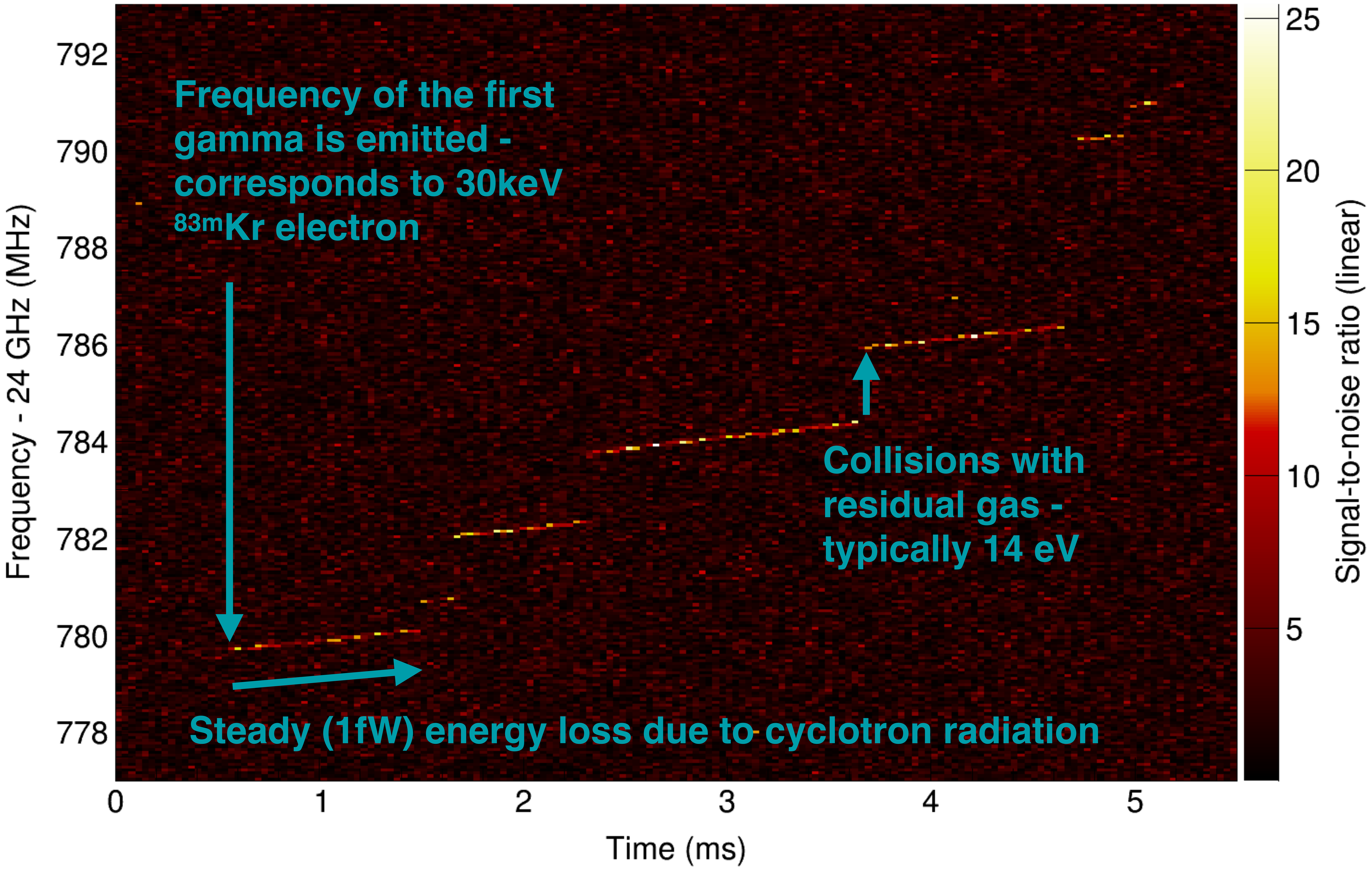

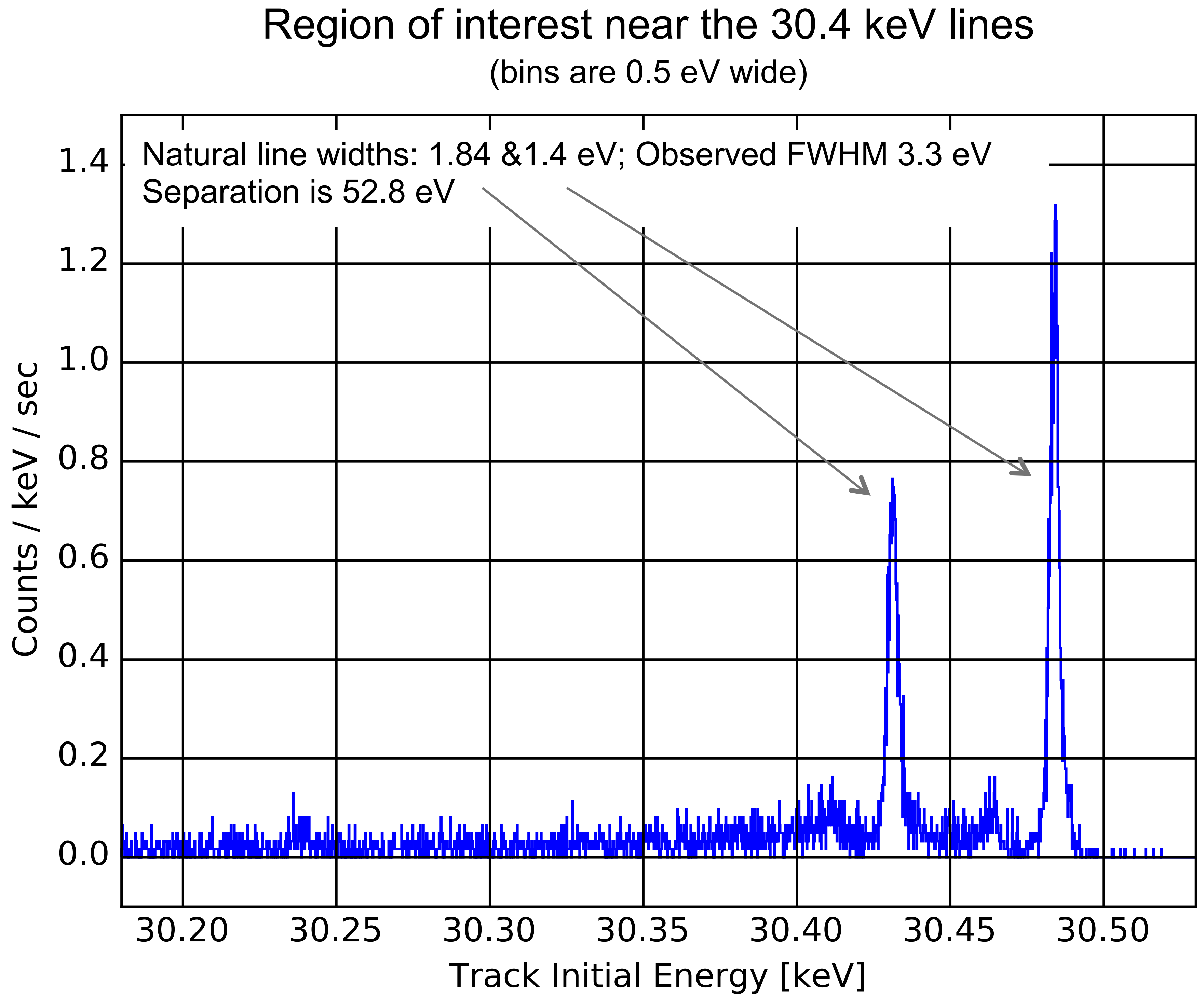

30.4 keV ^{83m}Kr lines resolved with FWHM 3.3 eV (actual widths 1.84 & 1.4 eV)

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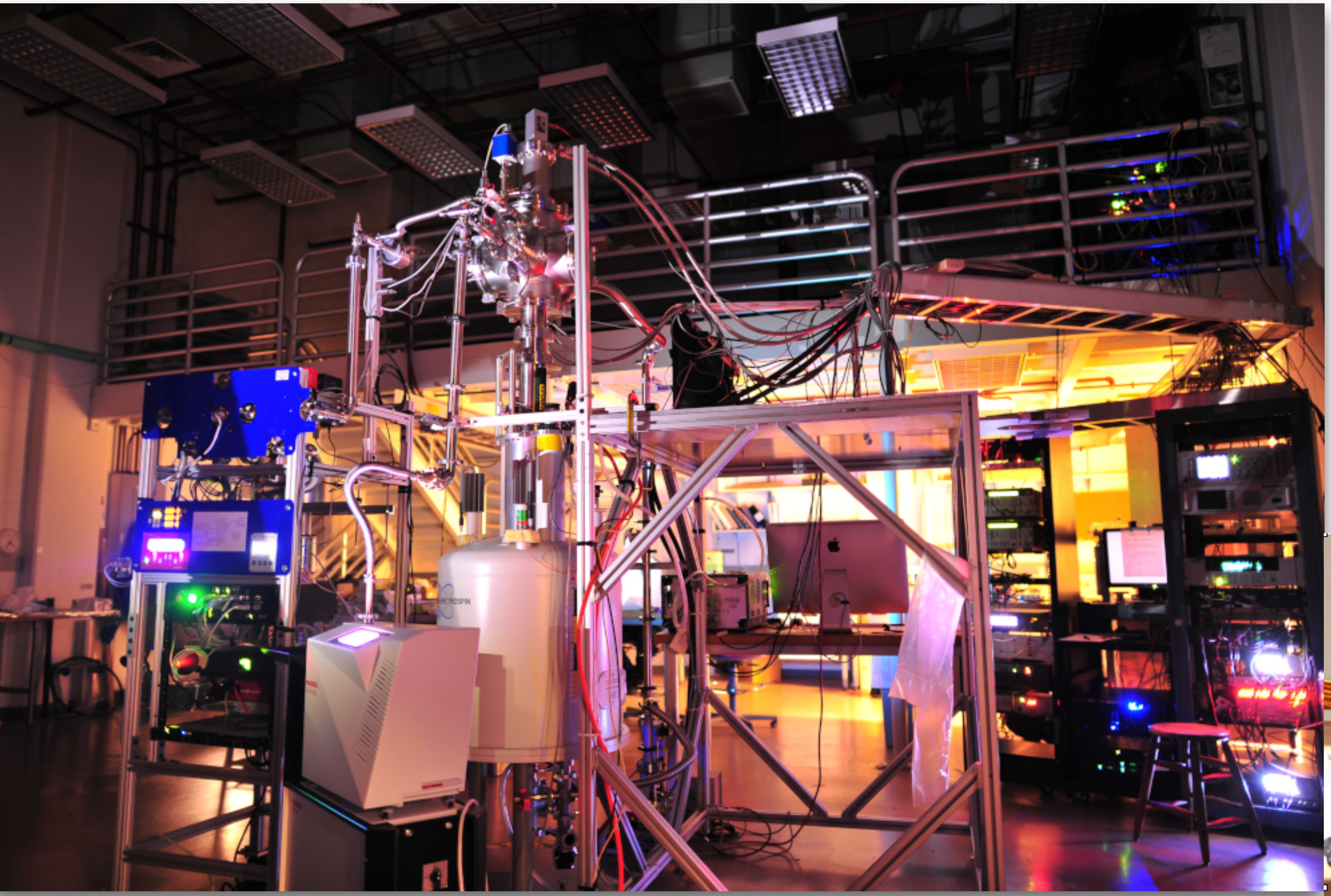
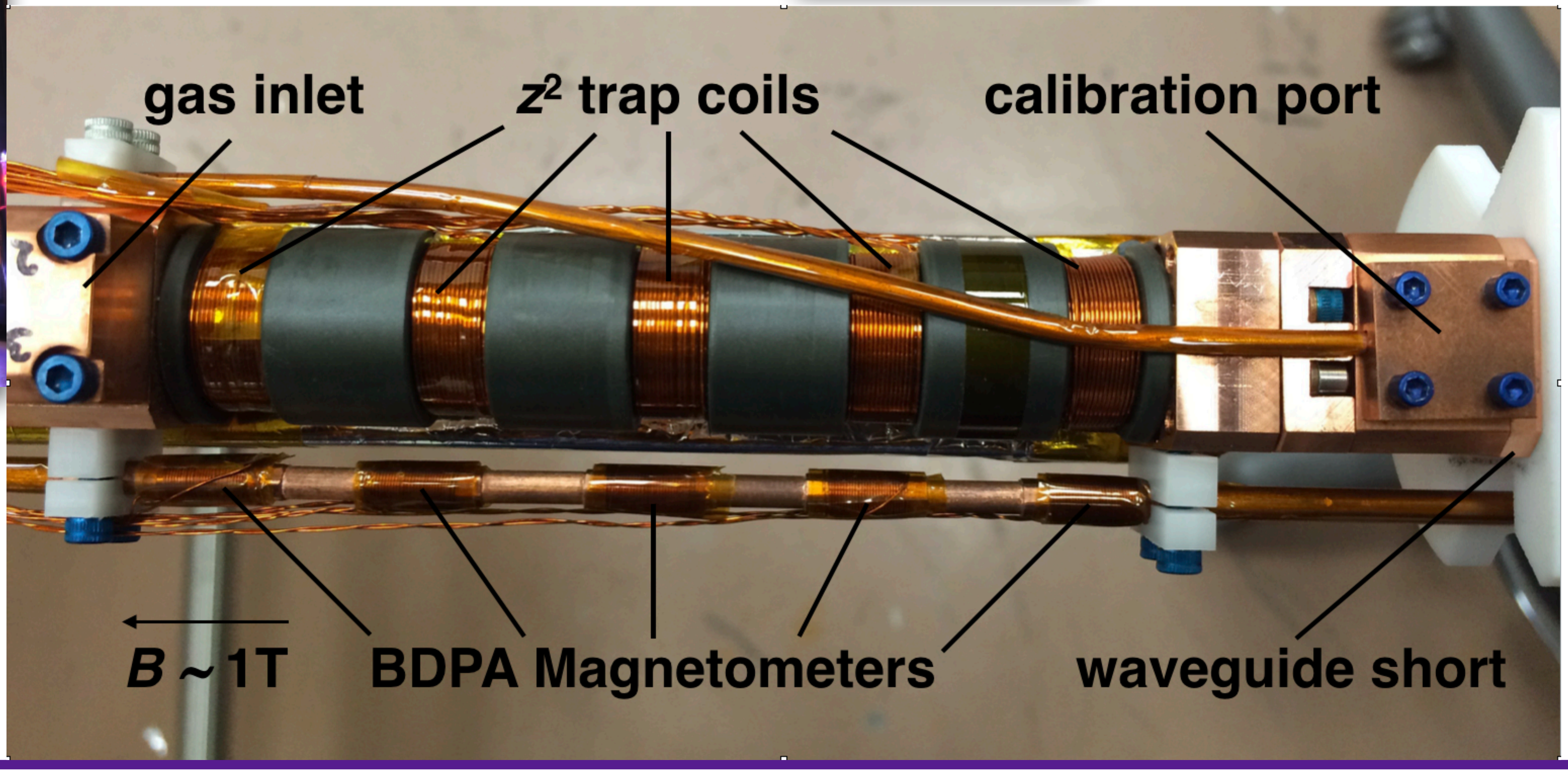
Project 8 phase II (2015-18) - molecular tritium

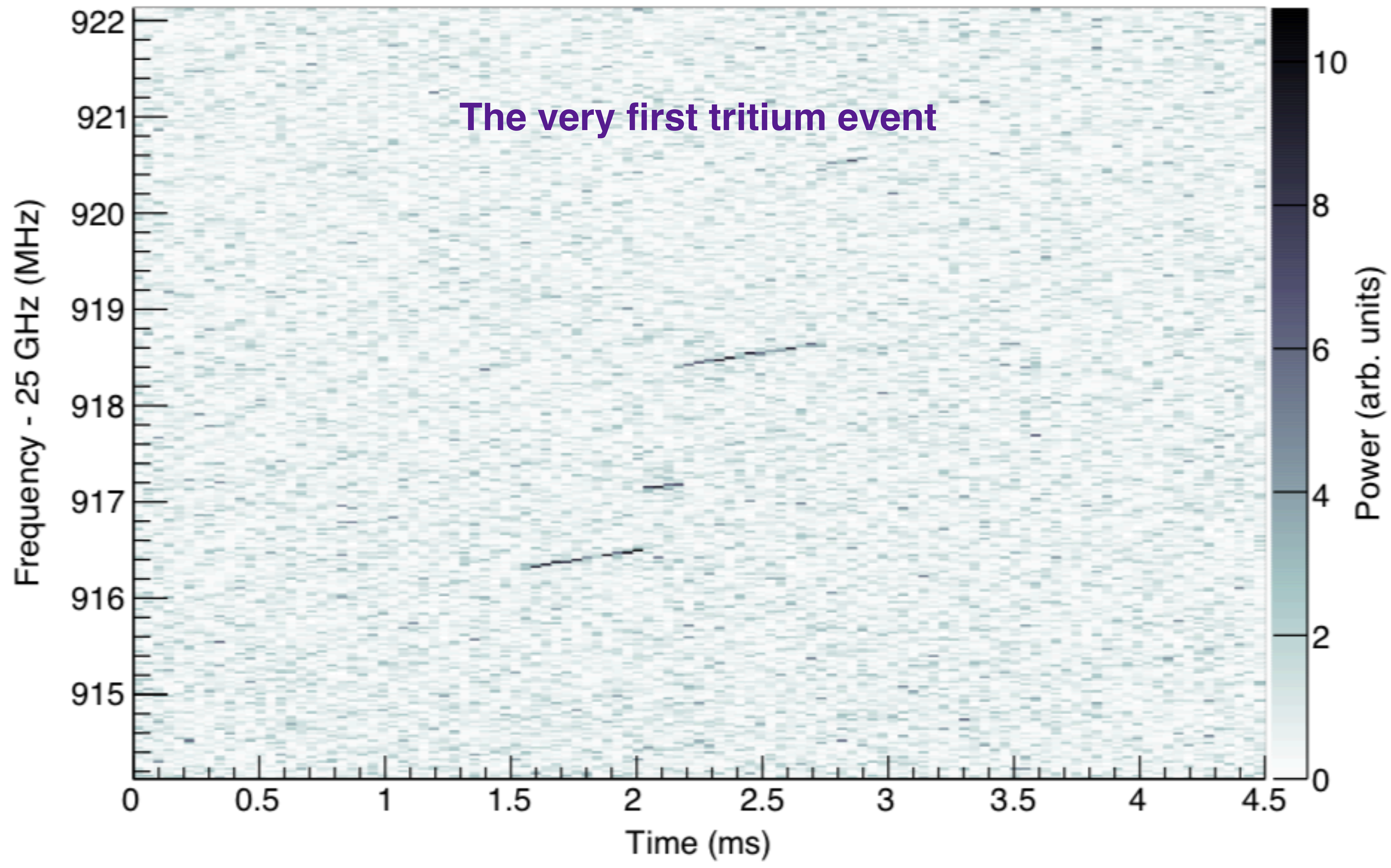


Project 8, phase II

Tritium!

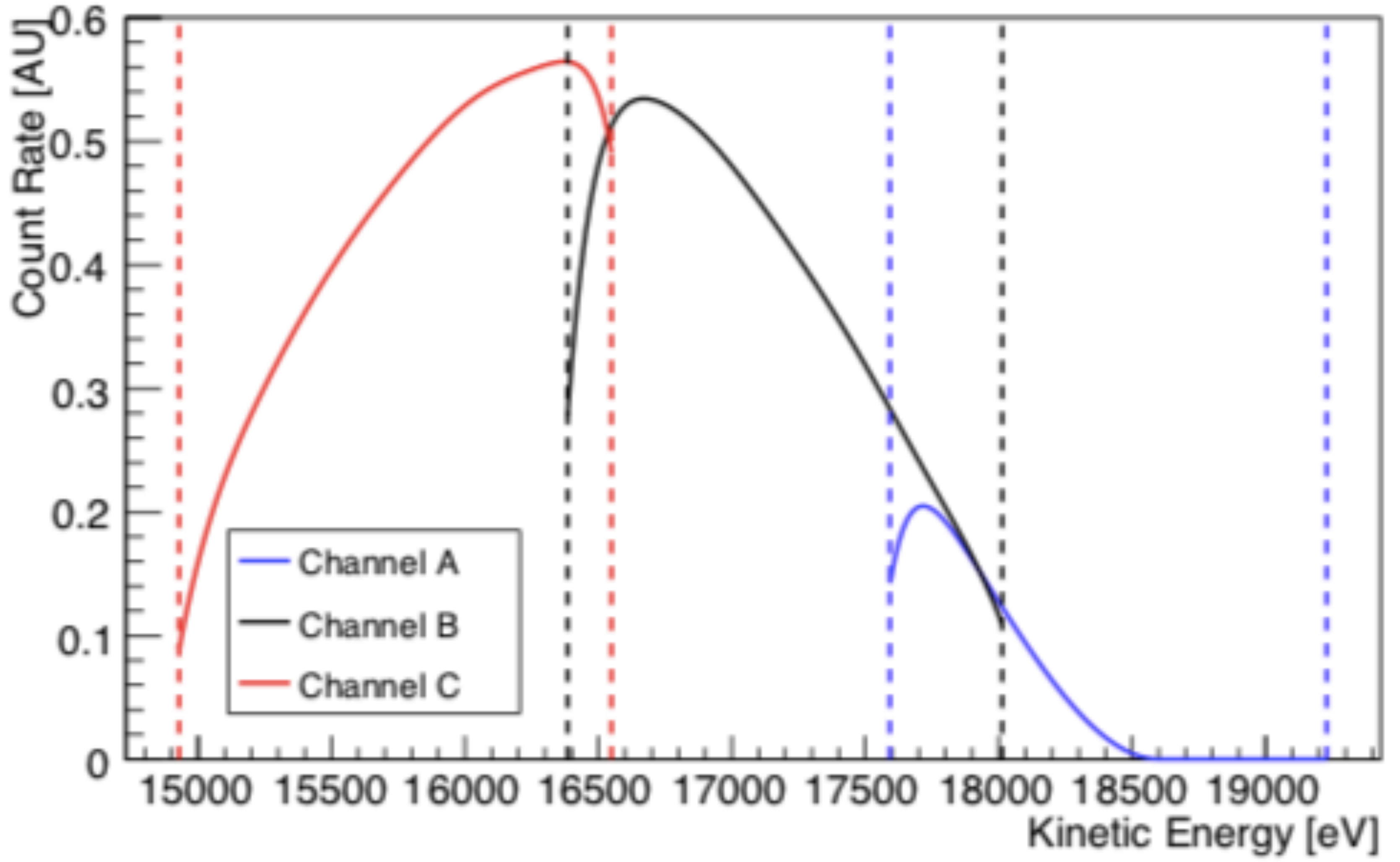


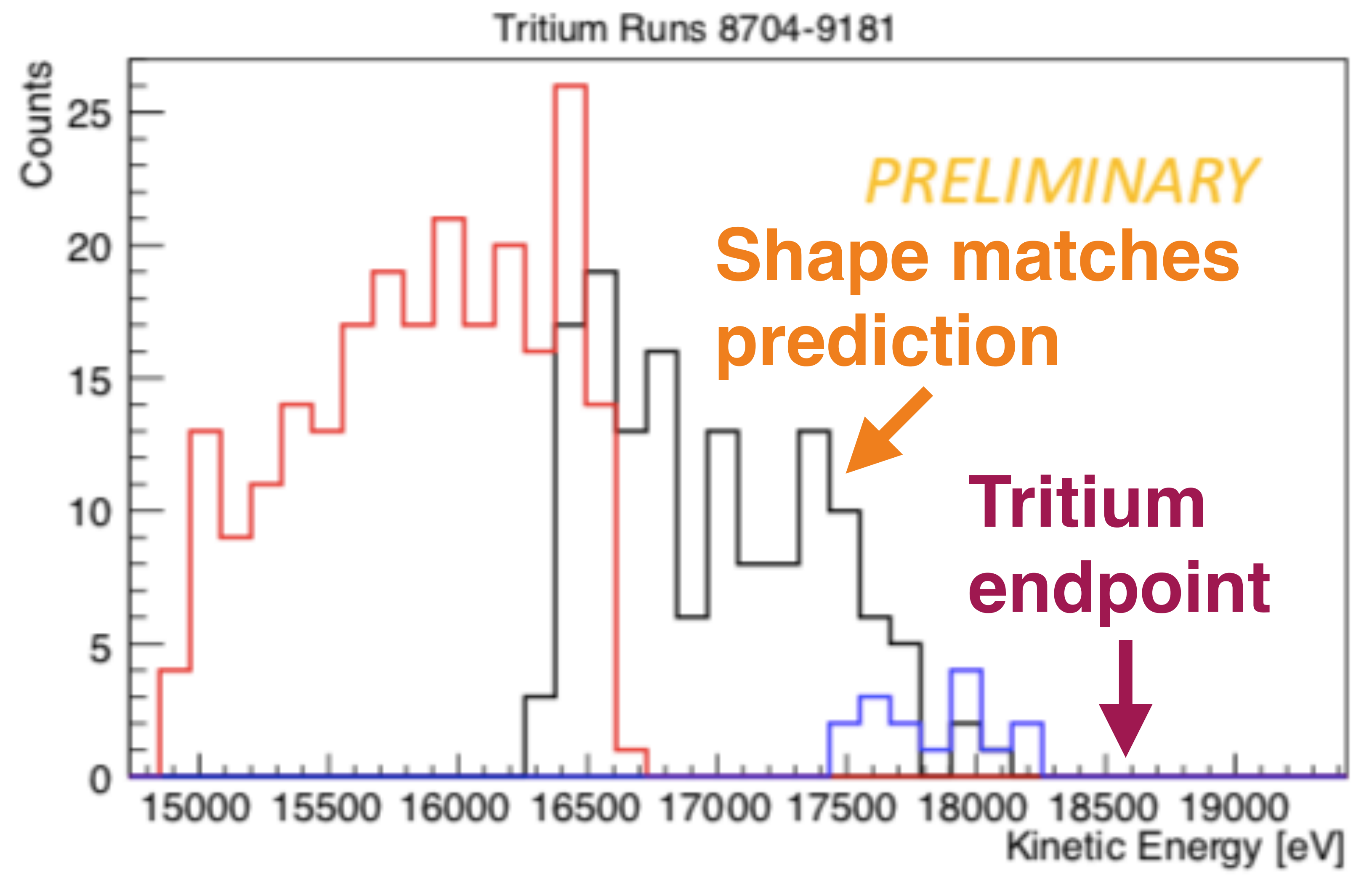
First tritium events!



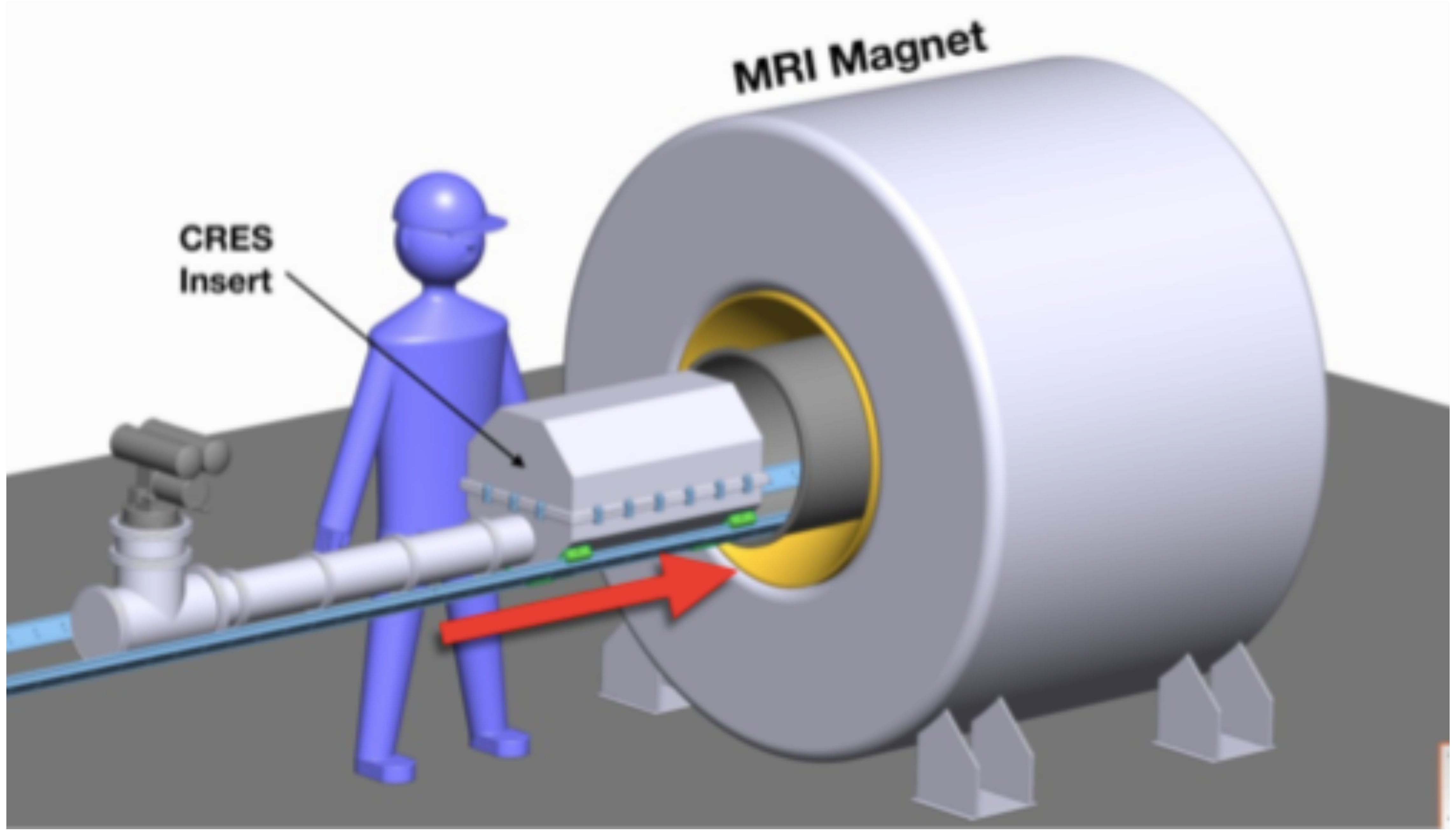
W Pettus, APS/JPS 2018, Waikoloa, HI

417 tritium events





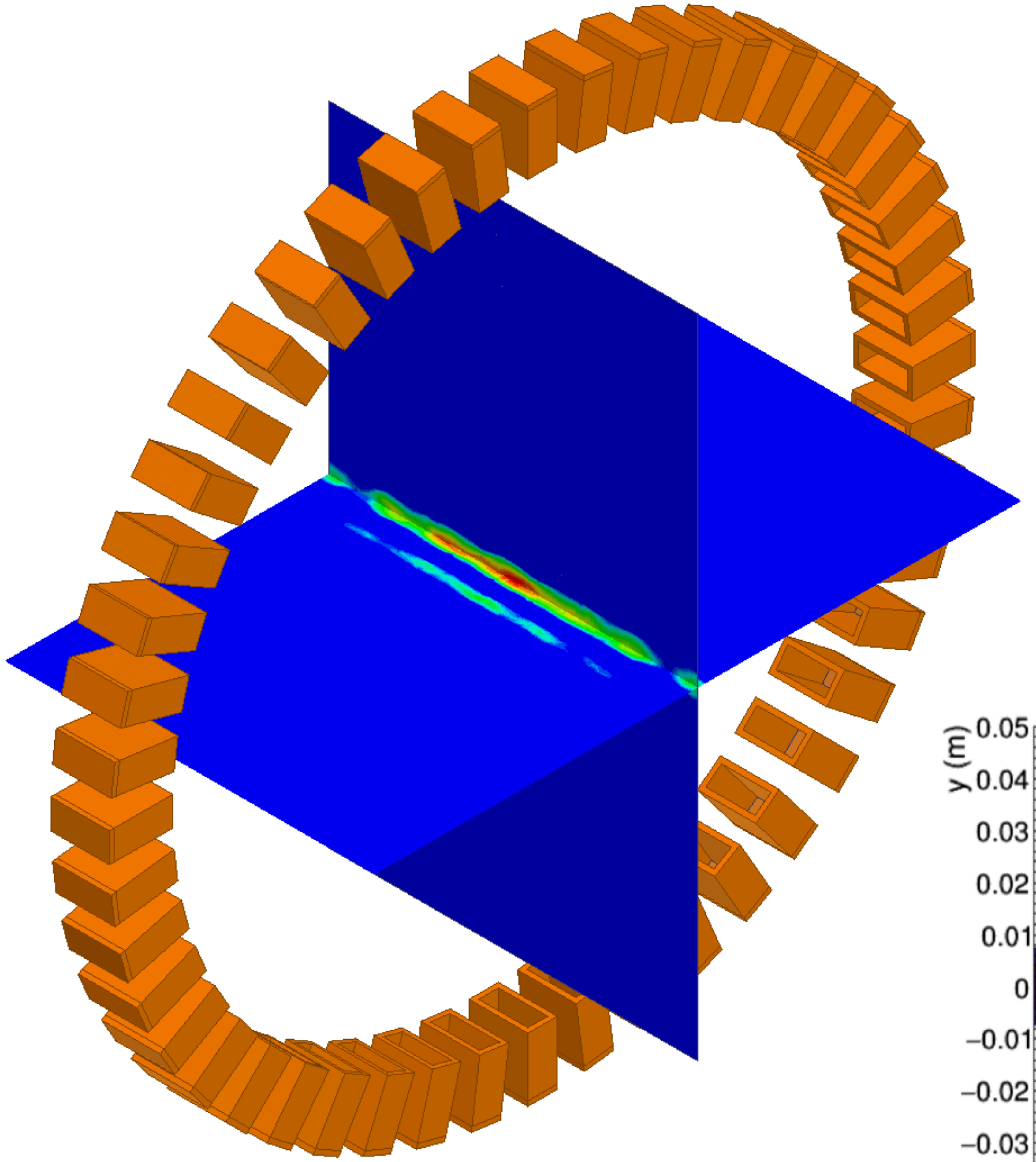
Project 8 phase III (R&D phase)- large volume detector with T_2



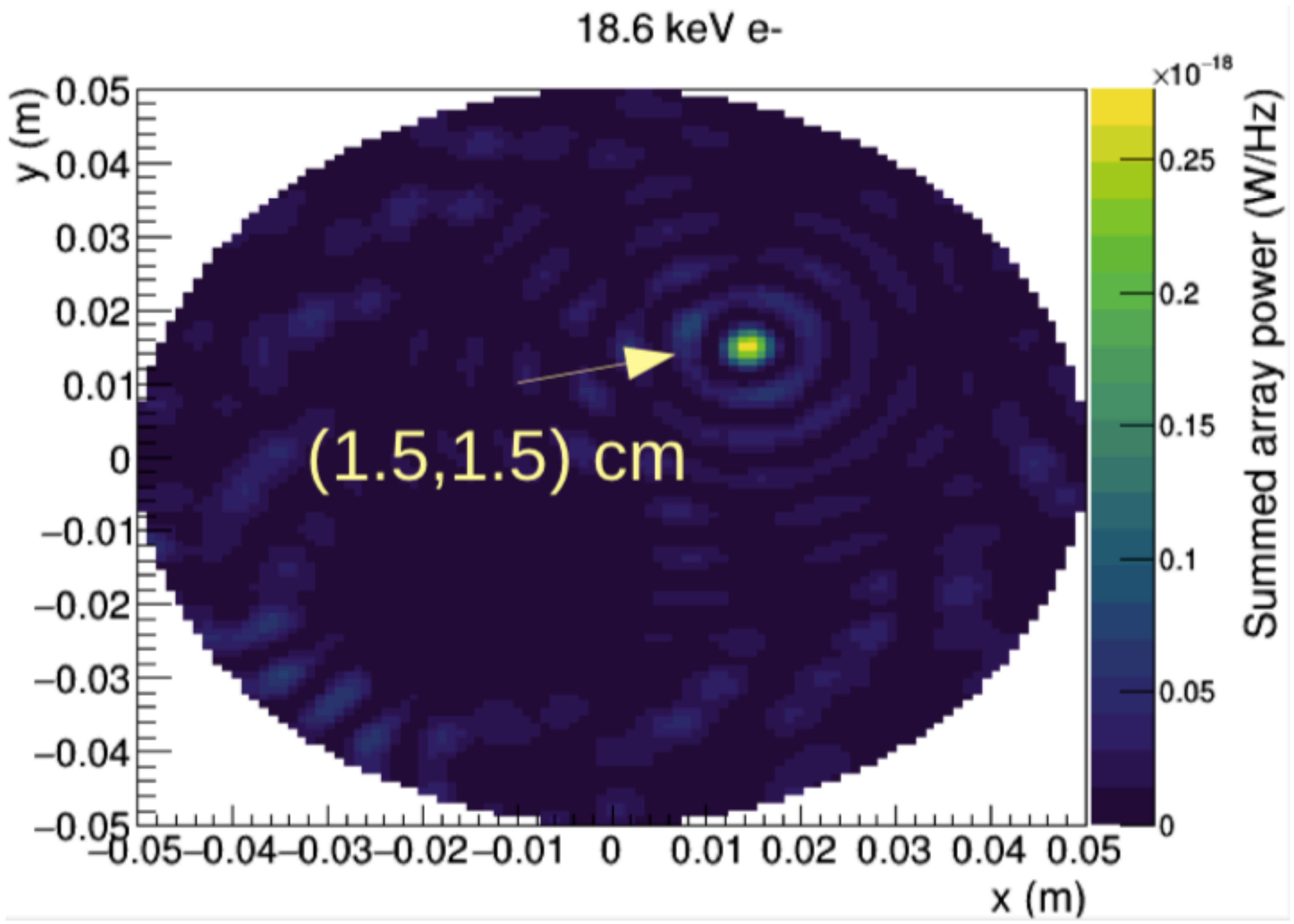
P Slocum, APS/JPS 2018, Waikoloa, HI

- **1 T** CRES field (MRI magnet)

Project 8 phase III (R&D phase)- large volume detector with T_2

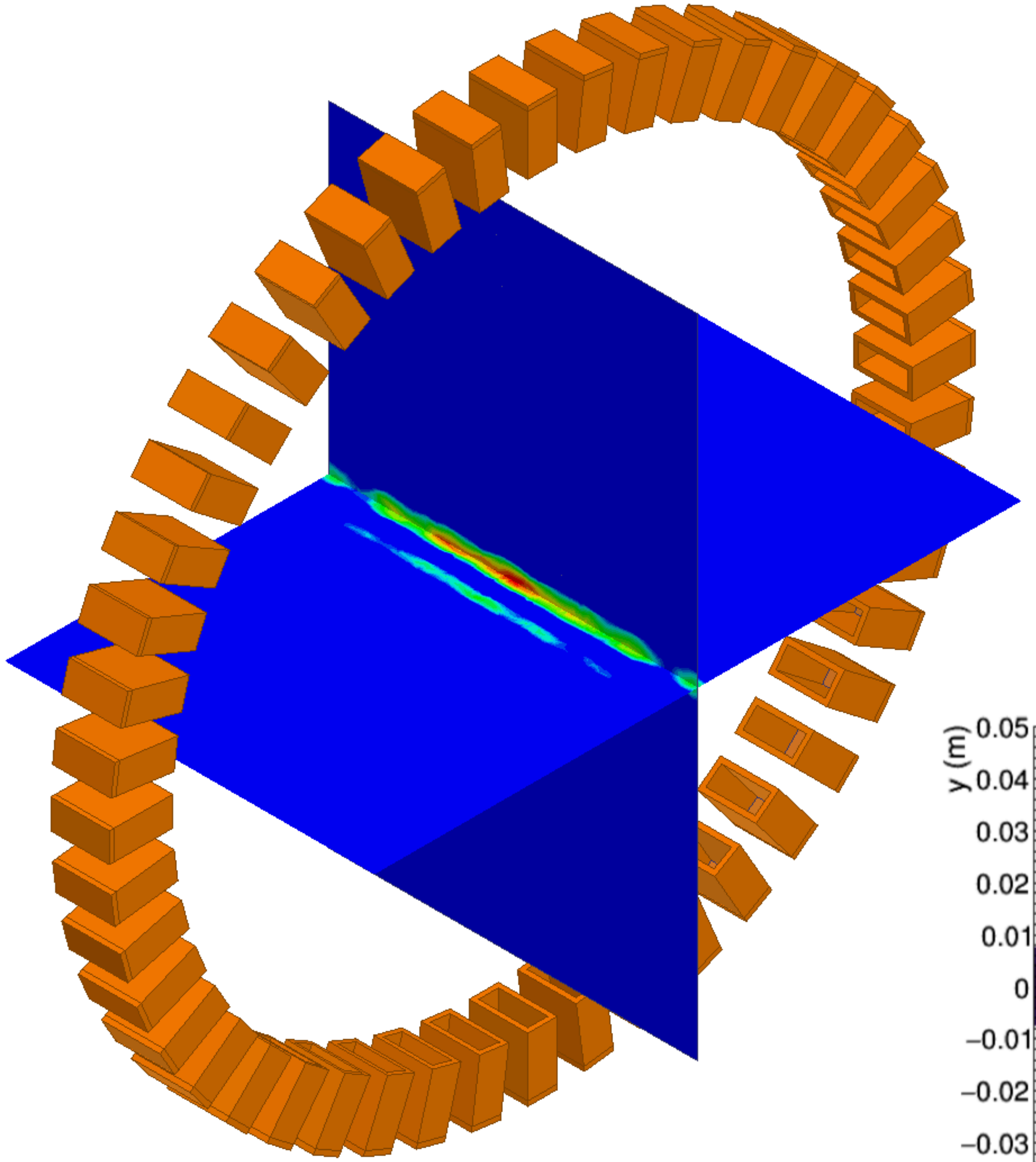


P Slocum, APS/JPS 2018, Waikoloa, HI



- **1 T** CRES field (MRI magnet)
- **200cm^3** gas volume
  - No waveguide
  - Electrons radiate into free space
  - Phased array of waveguide antenna elements

Project 8 phase III (R&D phase)- large volume detector with T_2



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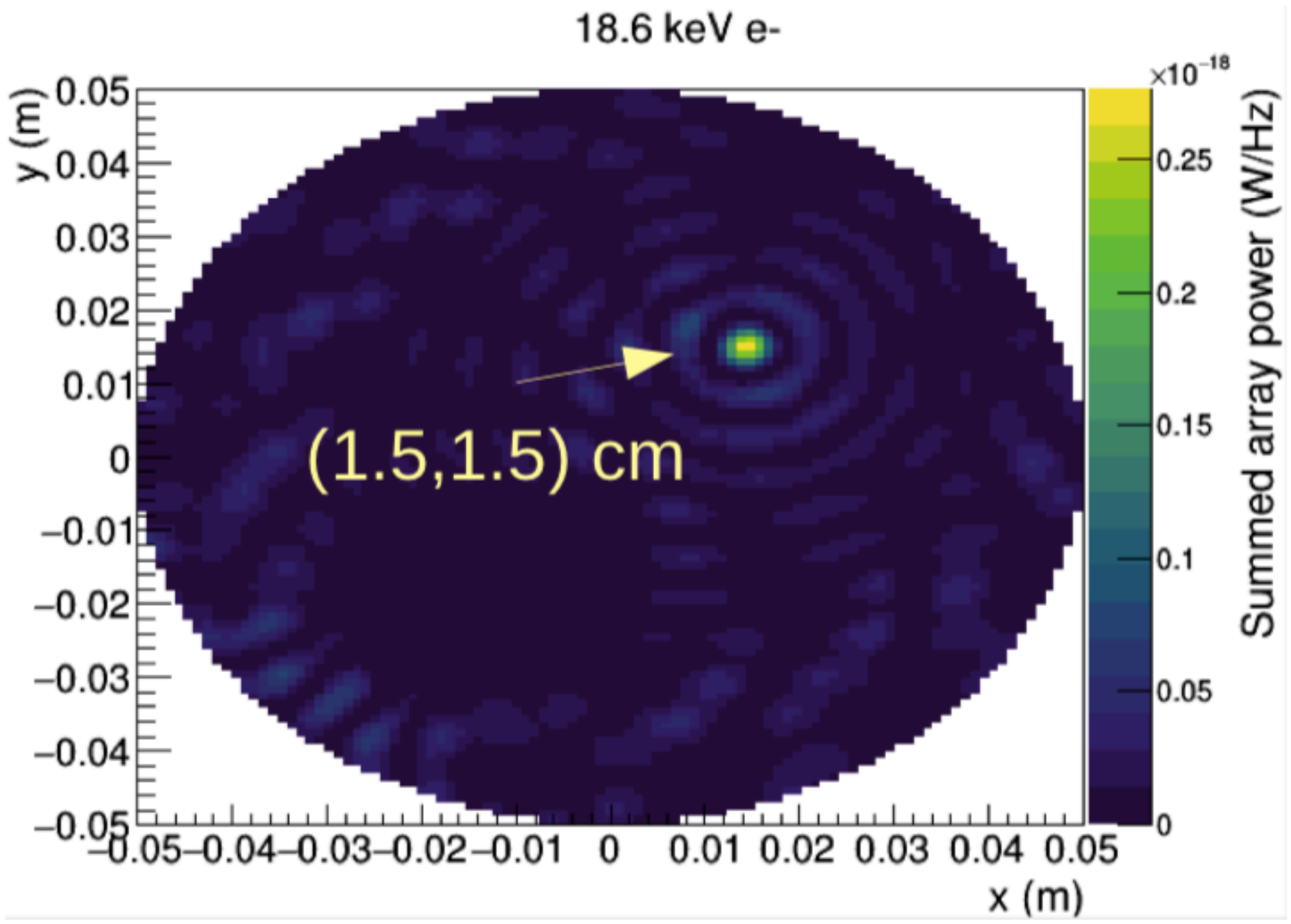
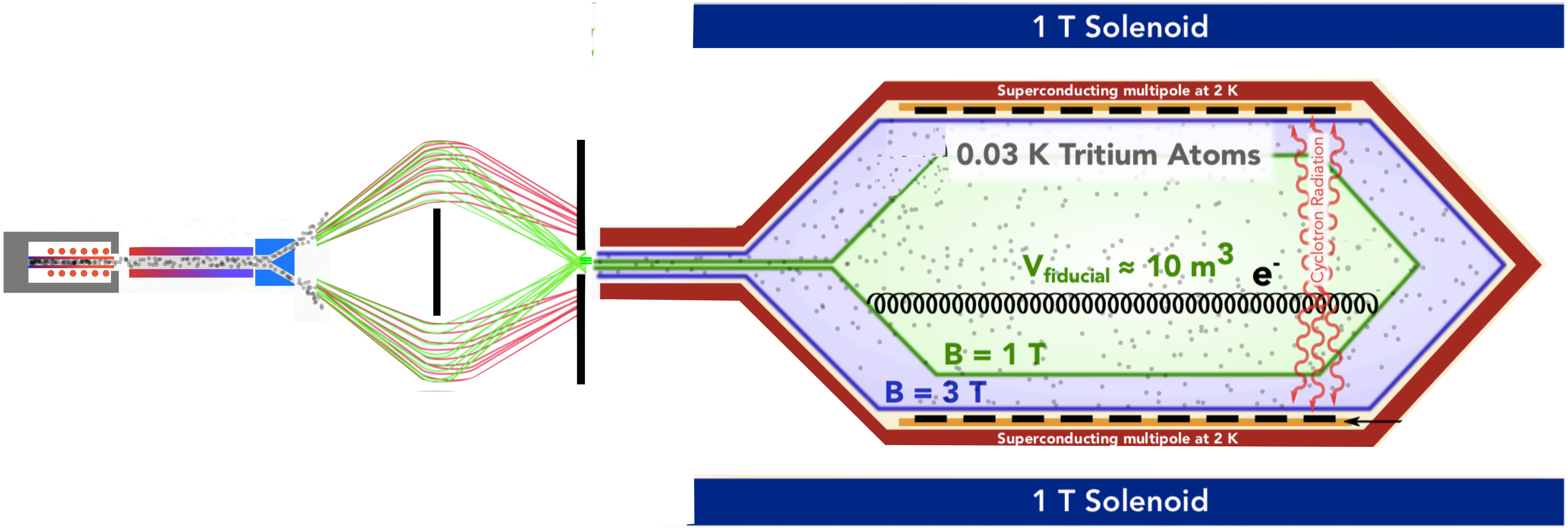


- **1 T** CRES field (MRI magnet)
- **200cm³** gas volume
  - No waveguide
  - Electrons radiate into free space
  - Phased array of waveguide antenna elements

- Electron energy resolution **1eV**
- Sensitivity m_ν **< 2 eV**
- Efficiency **10%**

PROJECT 8

Phase IV (R&D): atomic tritium



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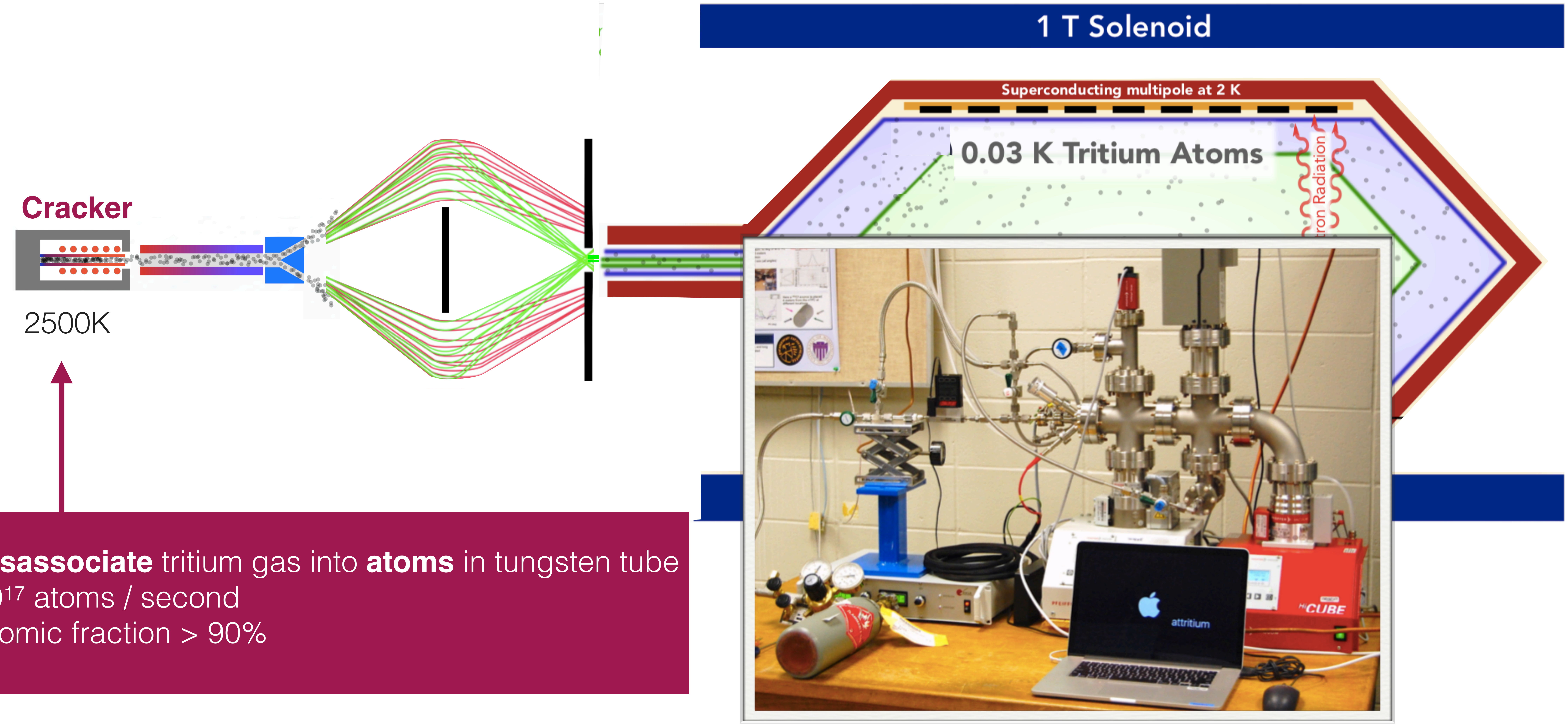
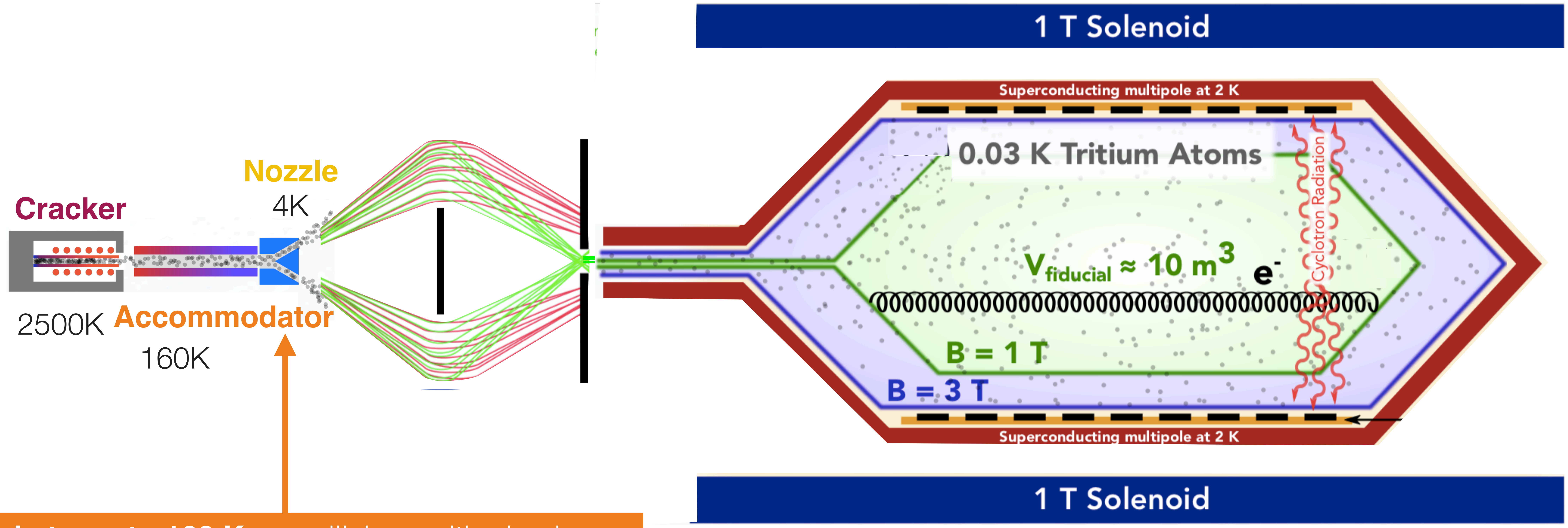


- **Disassociate** tritium gas into **atoms** in tungsten tube
- 10^{17} atoms / second
- Atomic fraction > 90%

Deuterium Cracker test stand

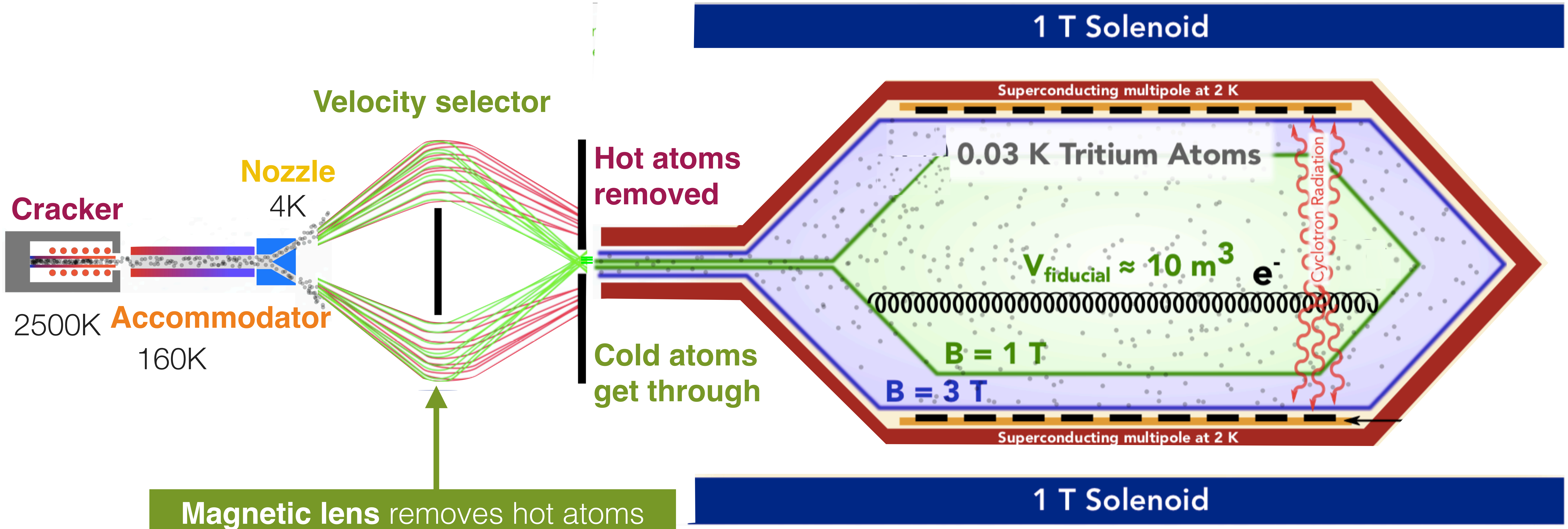
Phase IV (R&D): atomic tritium



Cool atoms to 160 K on collisions with aluminum then to 4K on a **frozen deuterium** film

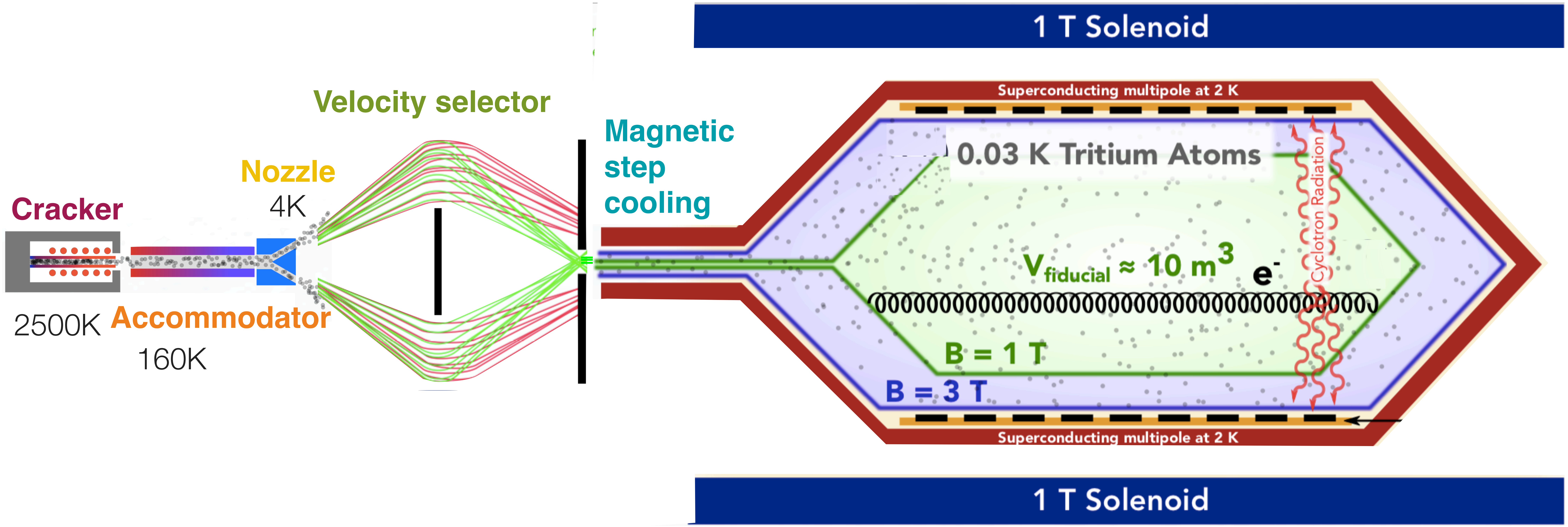
Deuterium Cracker test stand

Phase IV (R&D): atomic tritium



Magnetic lens removes hot atoms and residual molecules

Phase IV (R&D): atomic tritium



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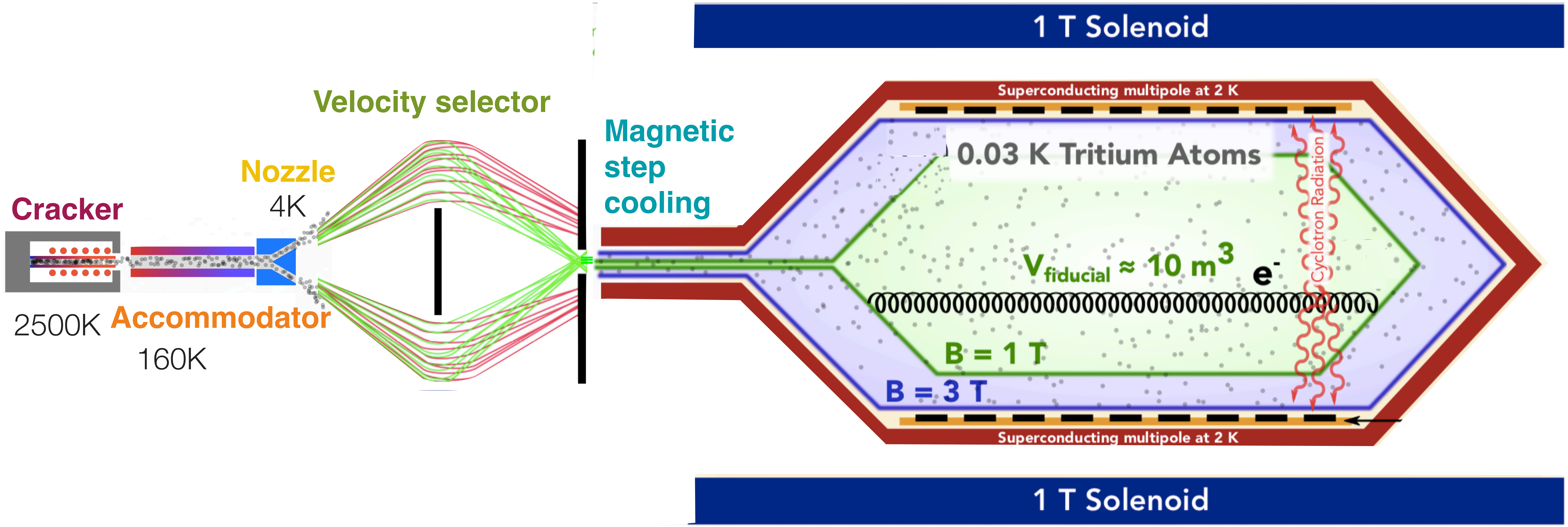

T atoms trapped in potential well (Ioffe trap) due to magnetic moment
T_2 molecules freeze to walls

PROJECT 8

Phased approach

UCL

KATRIN: Commissioning

KATRIN: Tritium Run ($m_\nu < 0.2$ eV/c^2)

Project 8.I (^{83m}Kr)

Project 8.II (T_2 ; $m_\nu < 10$—100 eV/c^2)

Project 8.III (T_2; $m_\nu < 2$ eV/c^2): Design

Project 8.III (T_2; $m_\nu < 2$ eV/c^2): Operation

Project 8.IV (T; $m_\nu < 0.04$ eV/c^2): R&D

Planck+BOSS, Planck +DES ($M_\nu < 0.1$ eV/c^2)

Euclid, ground-based LSST ($M_\nu < 0.05$ eV/c^2)

Planck + FFTT ($M_\nu < 0.0075$ eV/c^2)

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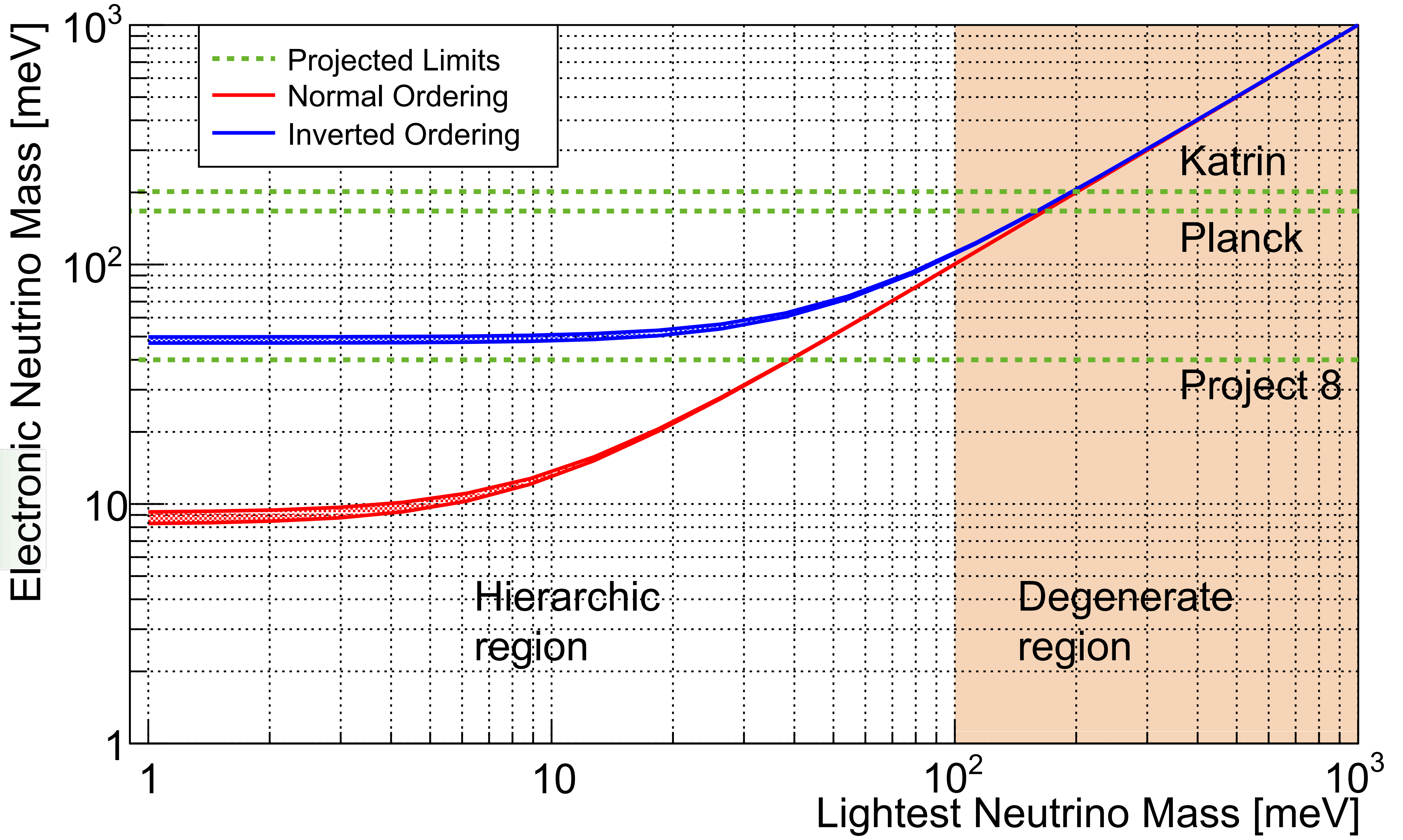
2015 2016 2017 2018 2019 2020 2021 2022



Phased approach

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JPhysG 44 (2017) 5

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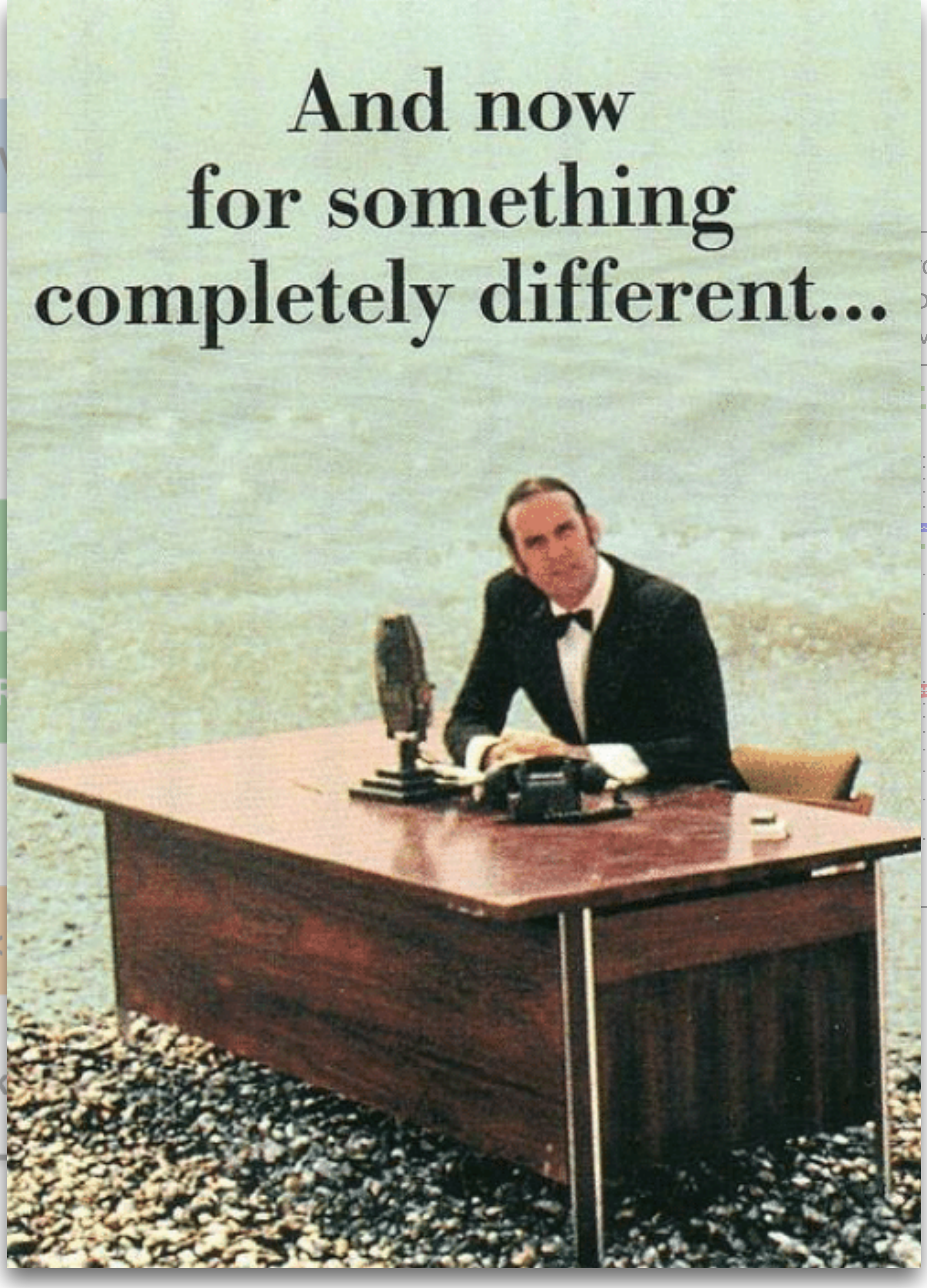
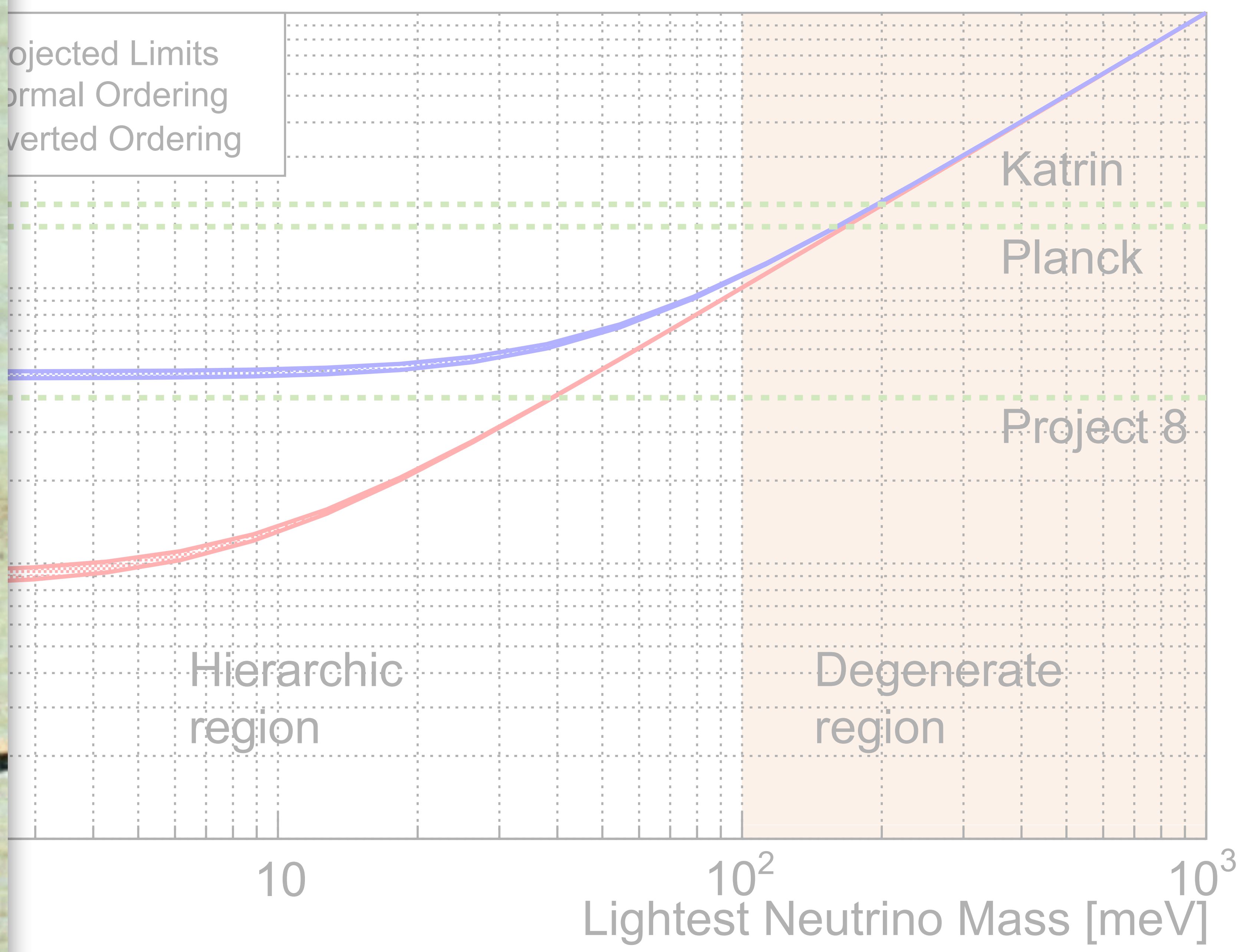




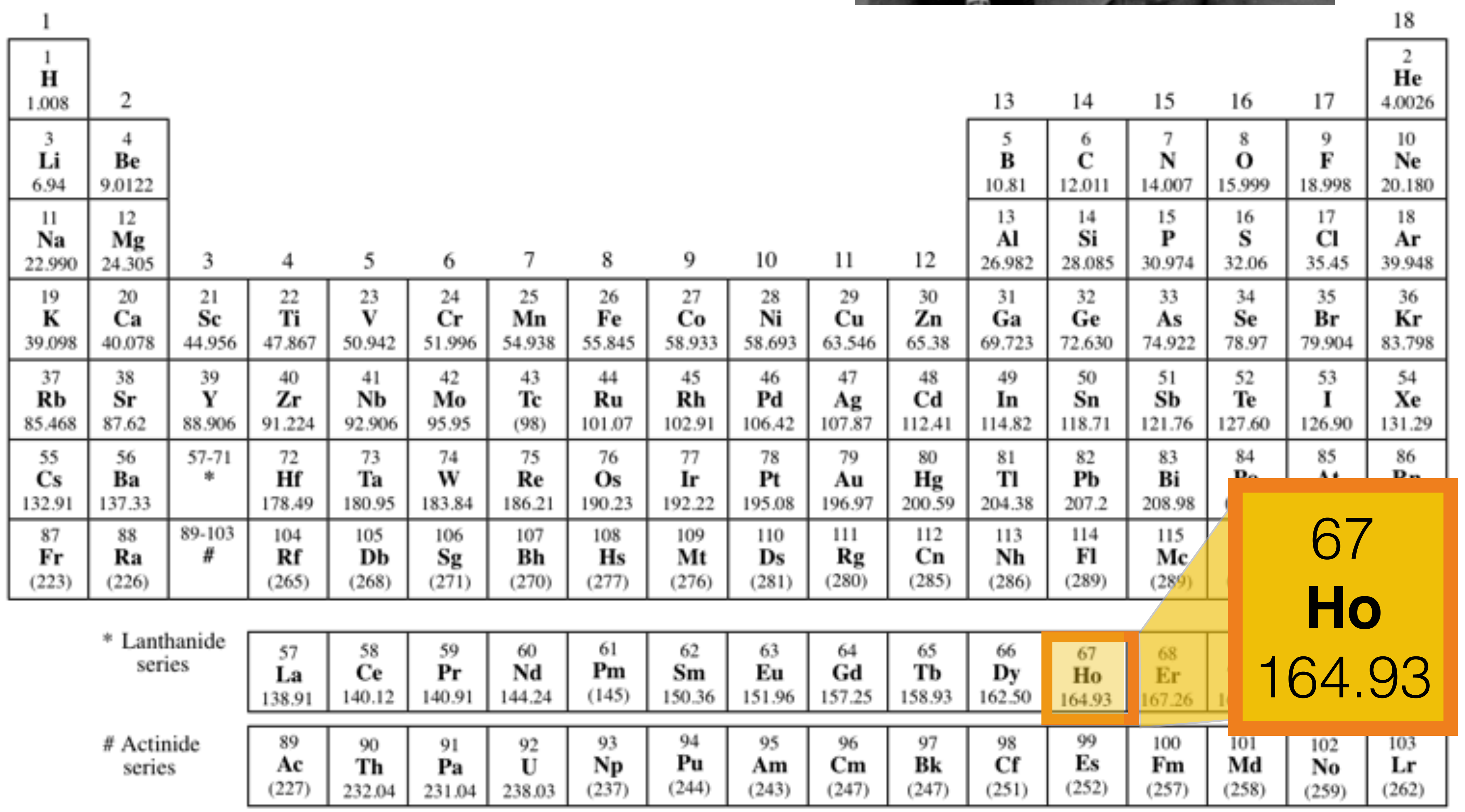
Electron-capture on holmium-163

What on Earth is holmium?

What on Earth is holmium?

- Rare earth metal, with highest magnetic moment of all elements
- Named for the city Stockholm
- Used to colour cubic zirconia, in lasers, as a neutron absorber in nuclear reactors, and in MRI machines
- Only one natural, stable isotope, ^{165}Ho

Per Teodor Cleve discovered holmium



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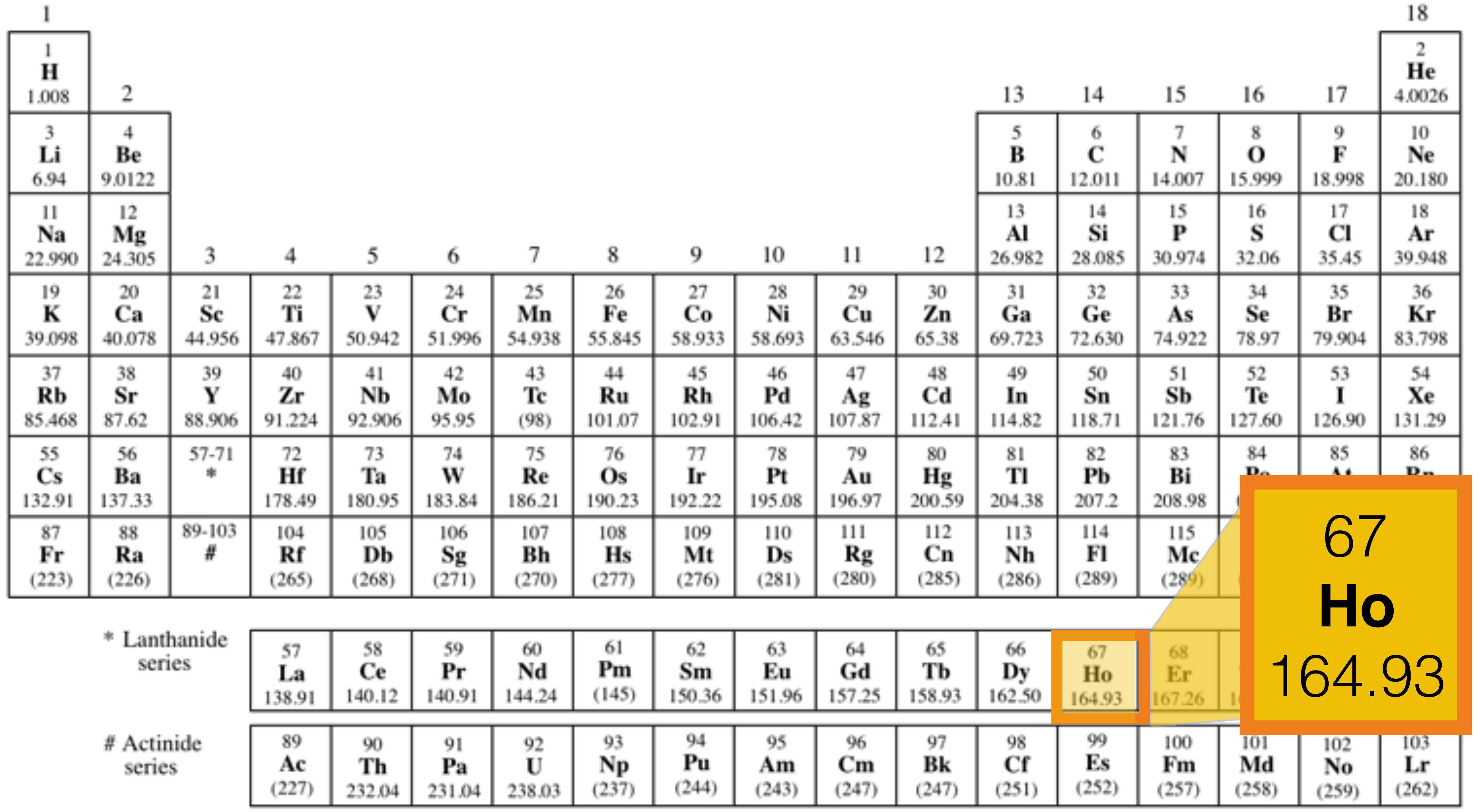

^{163}Ho decays via electron capture to ^{163}Dy with half-life 4570 years

Why ^{163}Ho?

Álvaro de Rújula

"The relation between experimentalists and theorists is often one of healthy competition for truth and less healthy competition for fame."

"Science is what we do when we don't know what we're doing."

Why ^{163}Ho?

Álvaro de Rújula

The proximity of the spectral endpoint to an atomic resonance makes the fraction of events that are sensitive to a non-zero neutrino mass superior in ^{163}Ho decay than in tritium decay. *Physics Letters B Volume 118, Issues 4–6, 9 December 1982, Pages 429-434*

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$$^{163}Ho + e^{-} \rightarrow ^{163}Dy + \nu_e \qquad \text{(Q} \sim 2.8\text{ keV)}$$

Lowest known Q-value (c.f. tritium 18.6 keV)

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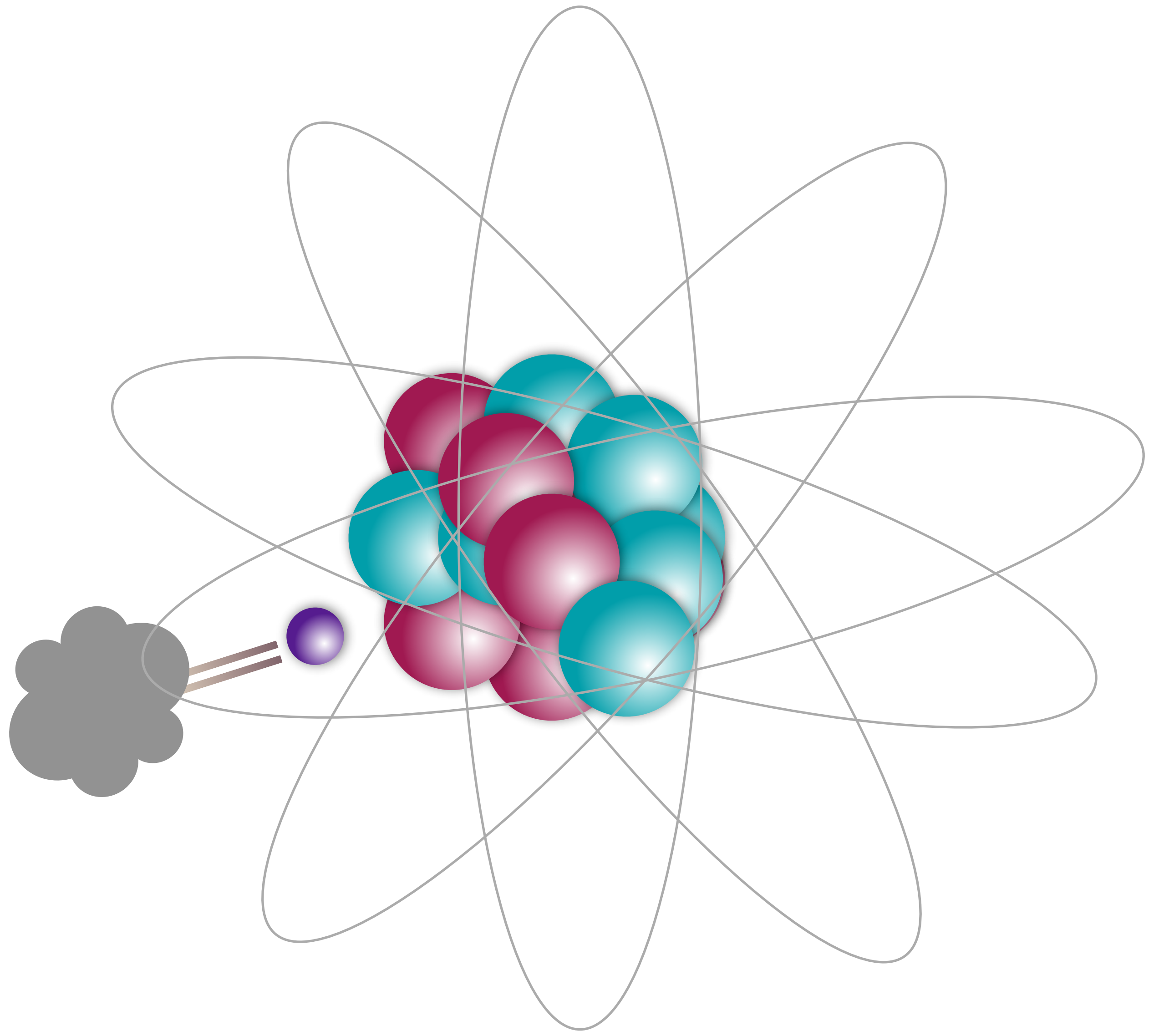

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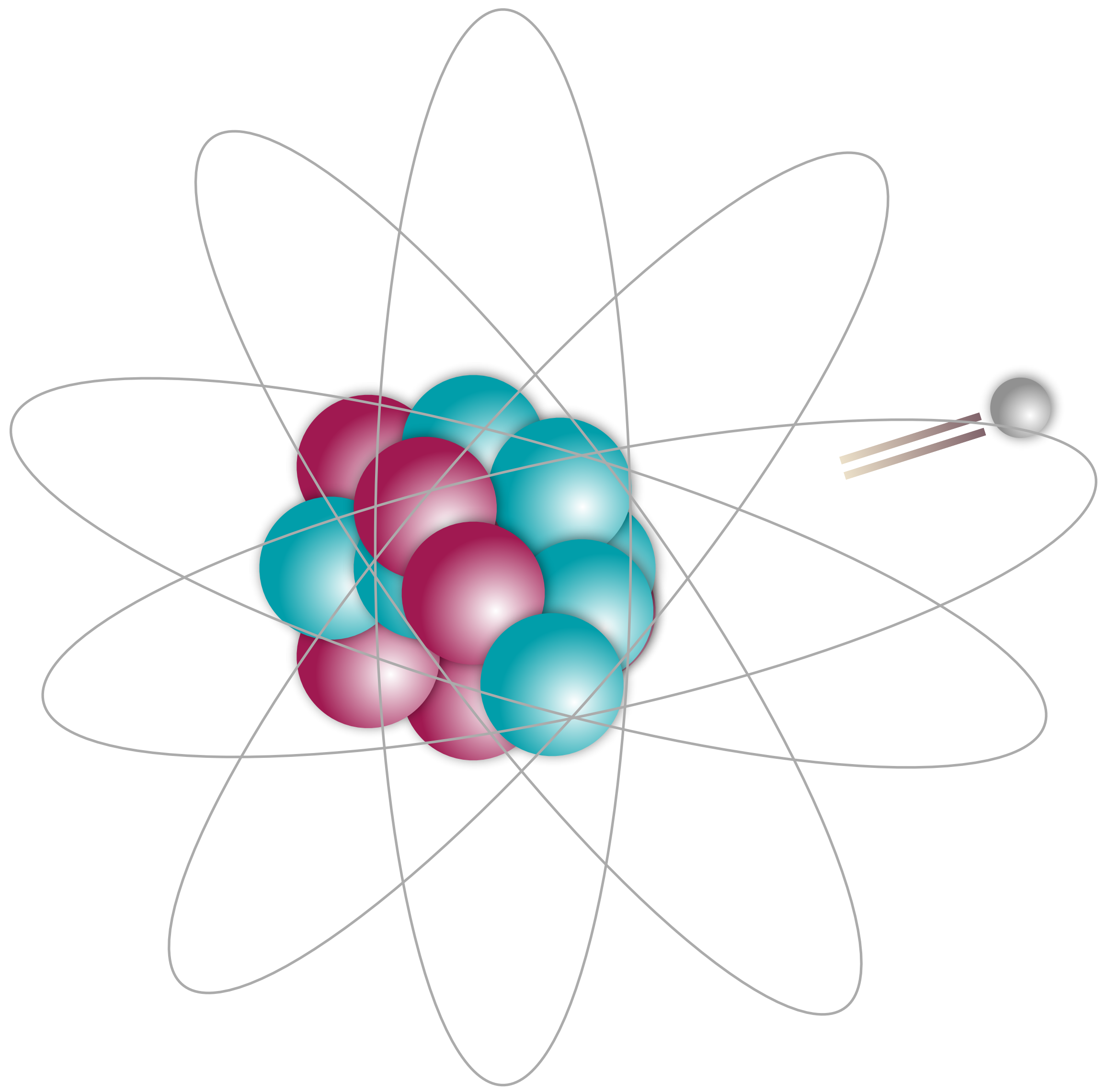

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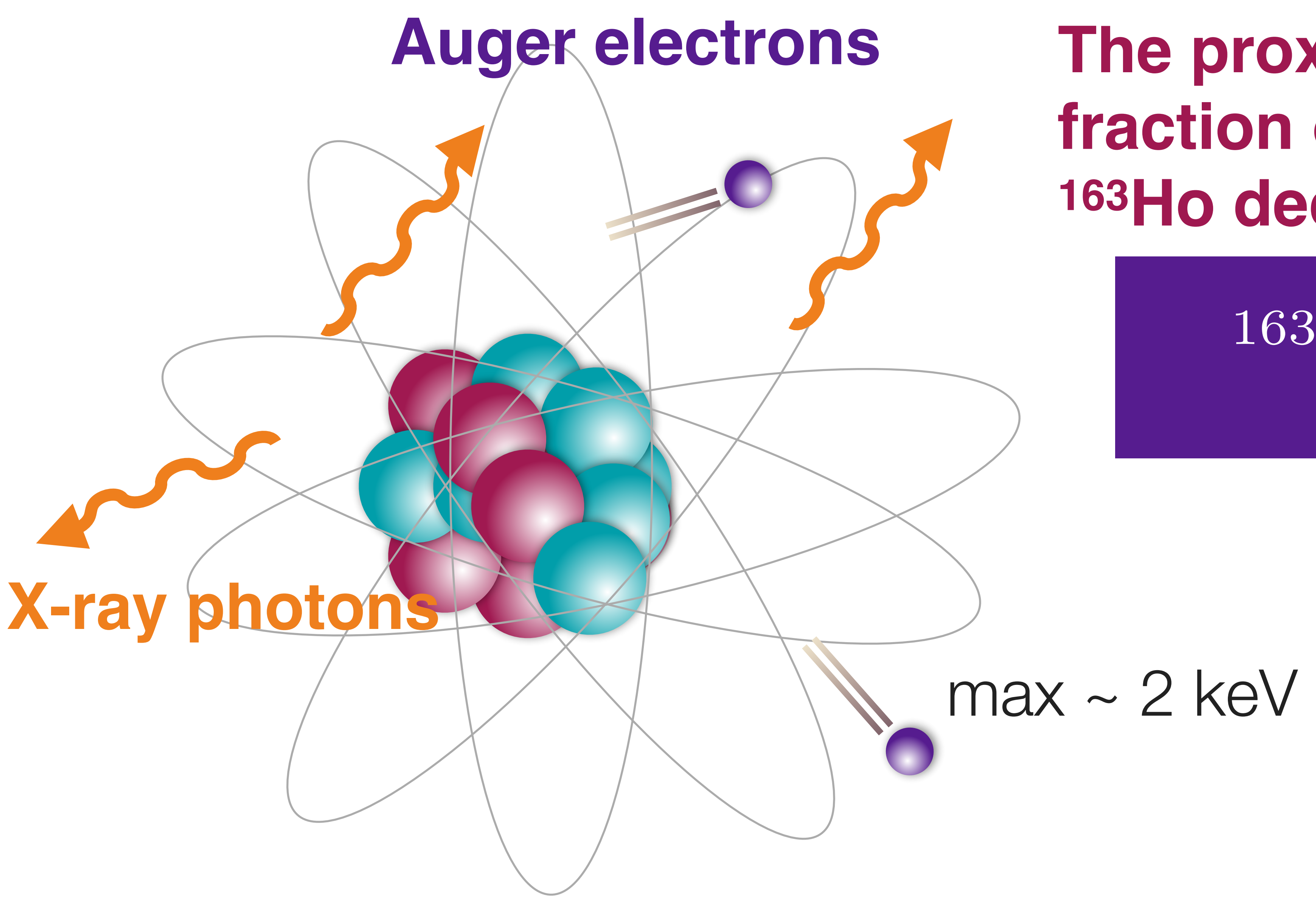
Why ^{163}Ho?



The proximity of the spectral endpoint to an atomic resonance makes the fraction of events that are sensitive to a non-zero neutrino mass superior in ^{163}Ho decay than in tritium decay. *Physics Letters B Volume 118, Issues 4–6, 9 December 1982, Pages 429-434*

$$^{163}Ho + e^- \rightarrow ^{163}Dy + \nu_e$$ (Q ~ 2.8 keV)

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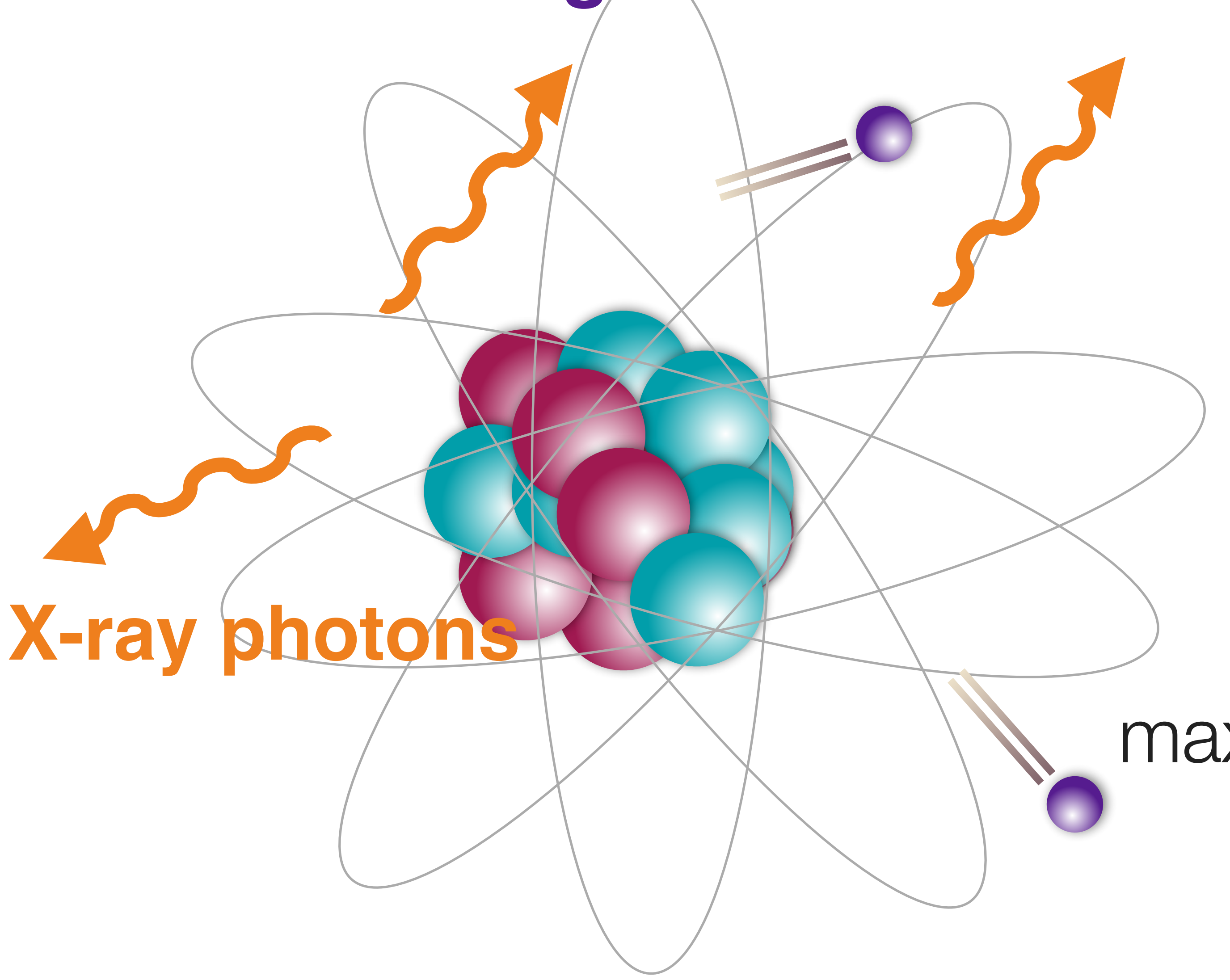

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Total calorimetric energy

Energy spectrum

$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q - E_c)\sqrt{(Q - E_c)^2 - m_\nu^2} \times \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi} \frac{1}{(E_c - E_i)^2 + \Gamma_i^2/4}$$

Eur Phys J C Part Fields. 2015; 75(3): 112

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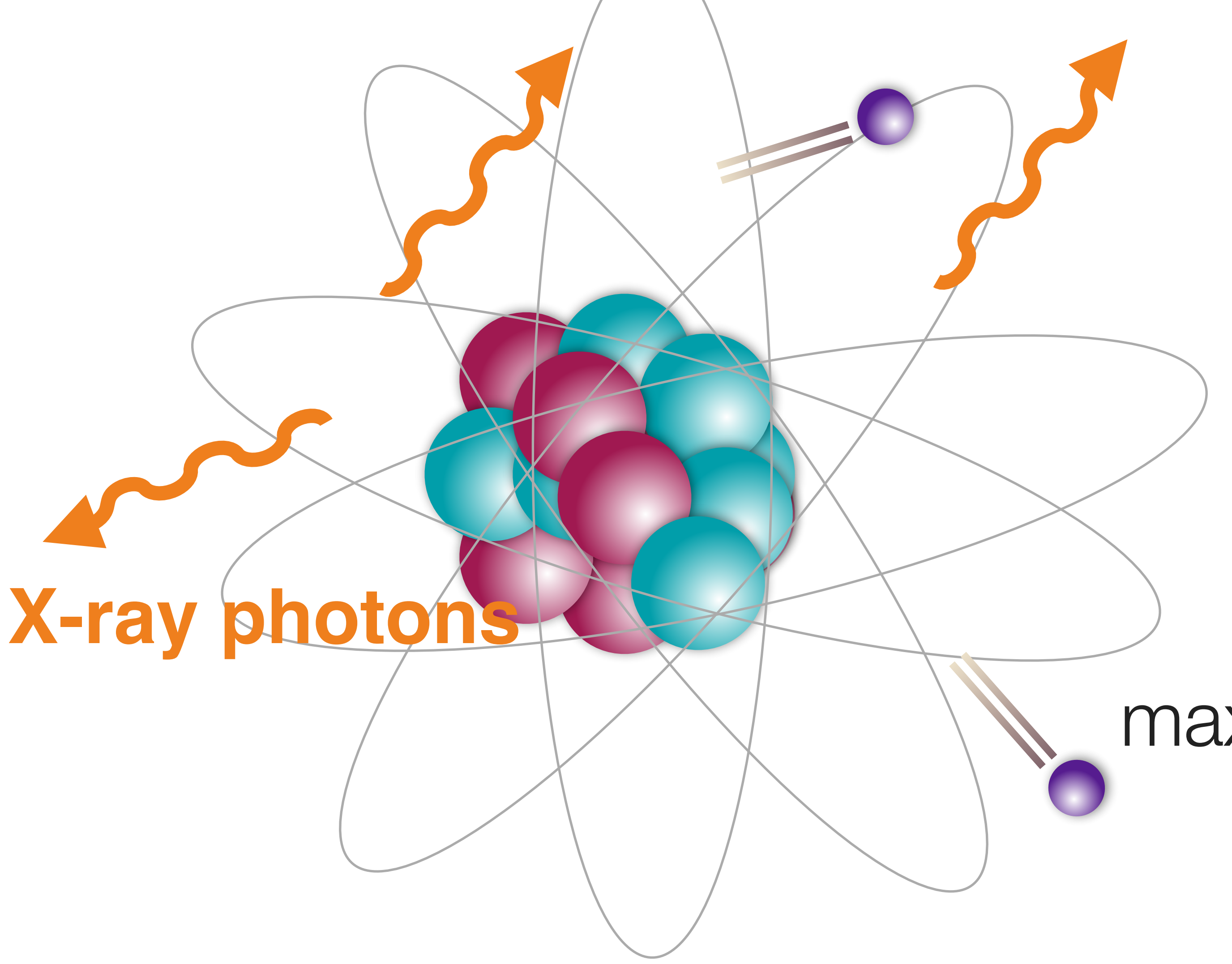

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Neutrino energy **Neutrino momentum**

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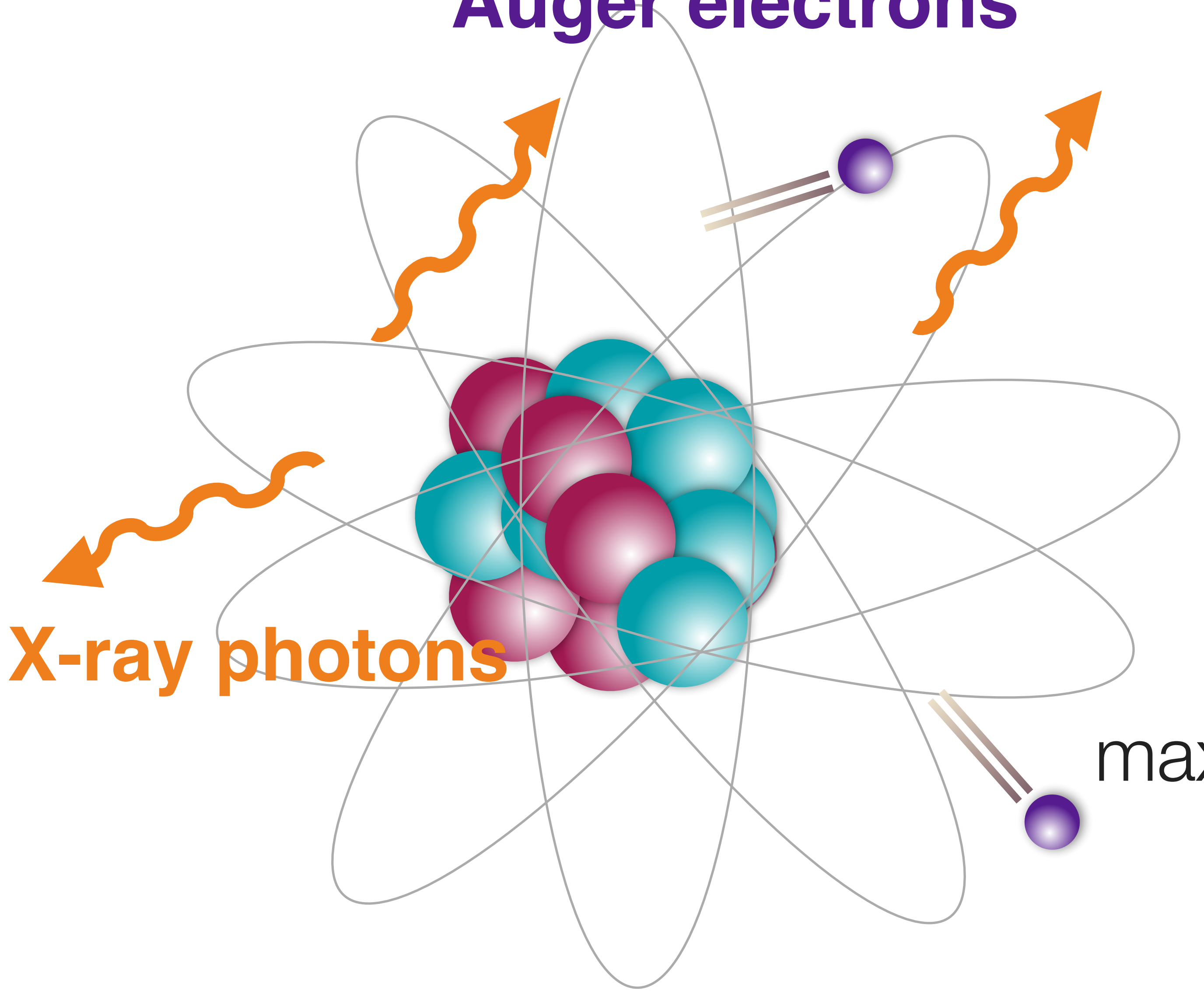

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Parameters of ionization spectral lines

Eur Phys J C Part Fields. 2015; 75(3): 112

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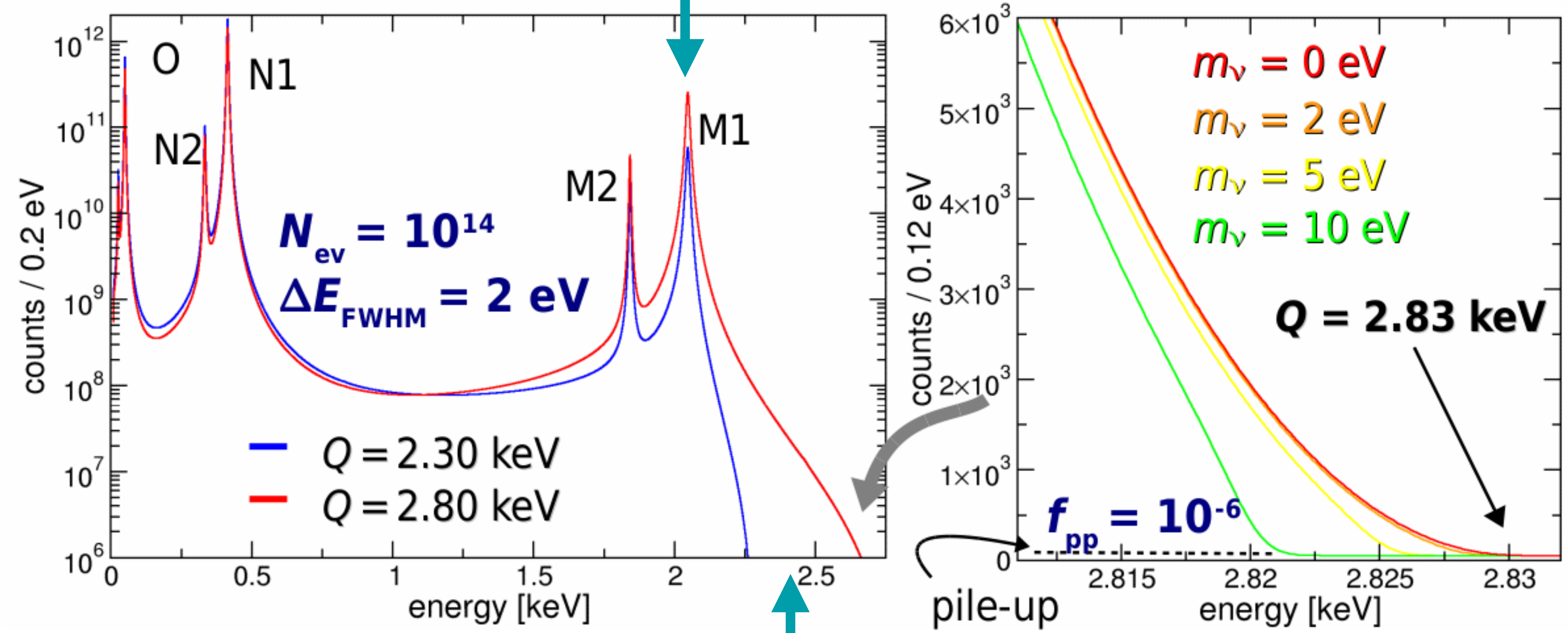
Enhancement near endpoint = even better chance of seeing neutrino mass effects



Low Q value increases neutrino mass effects (end point rate $\sim 1 / Q^3$)

https://holmes0.mib.infn.it/holmes/

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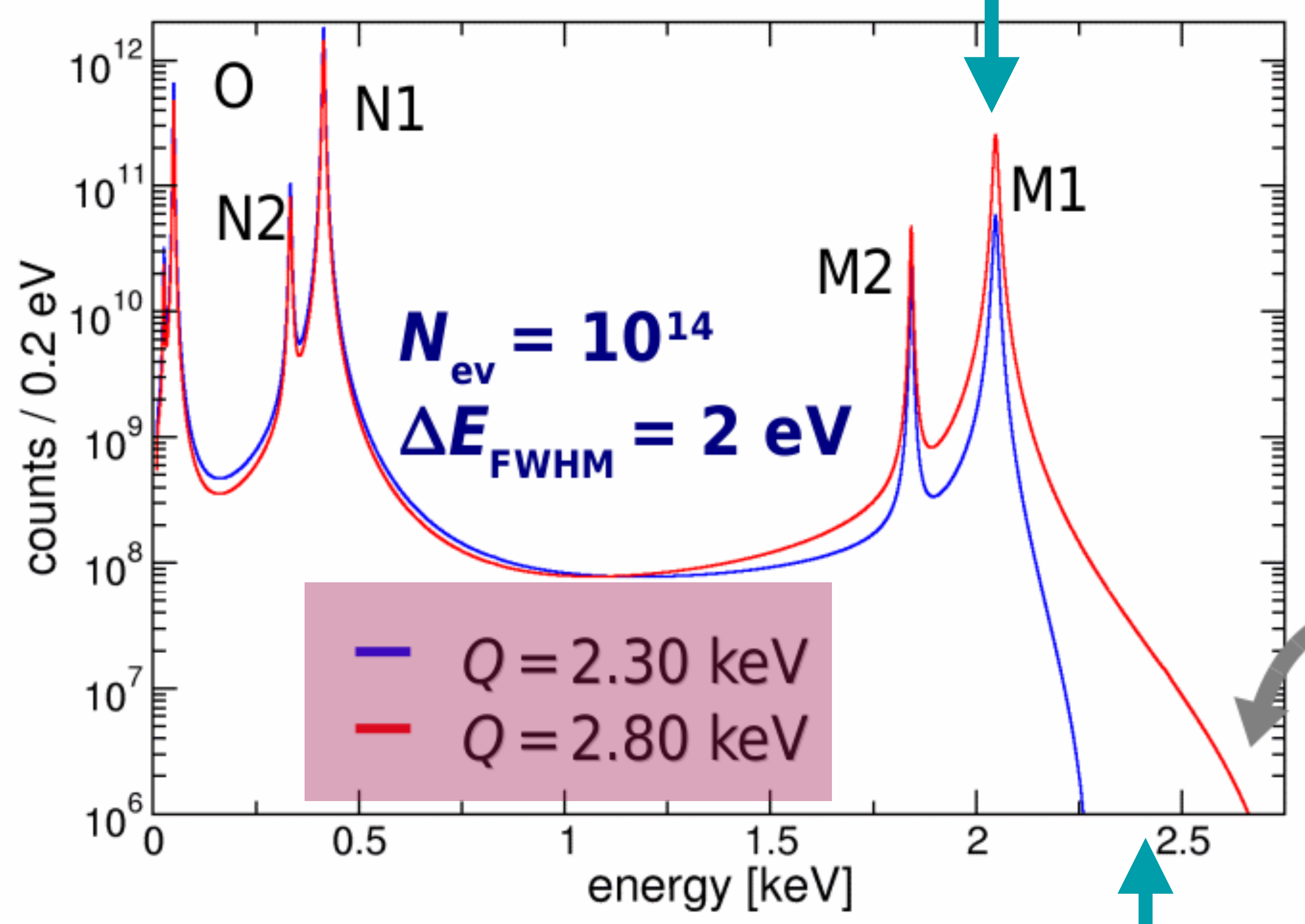

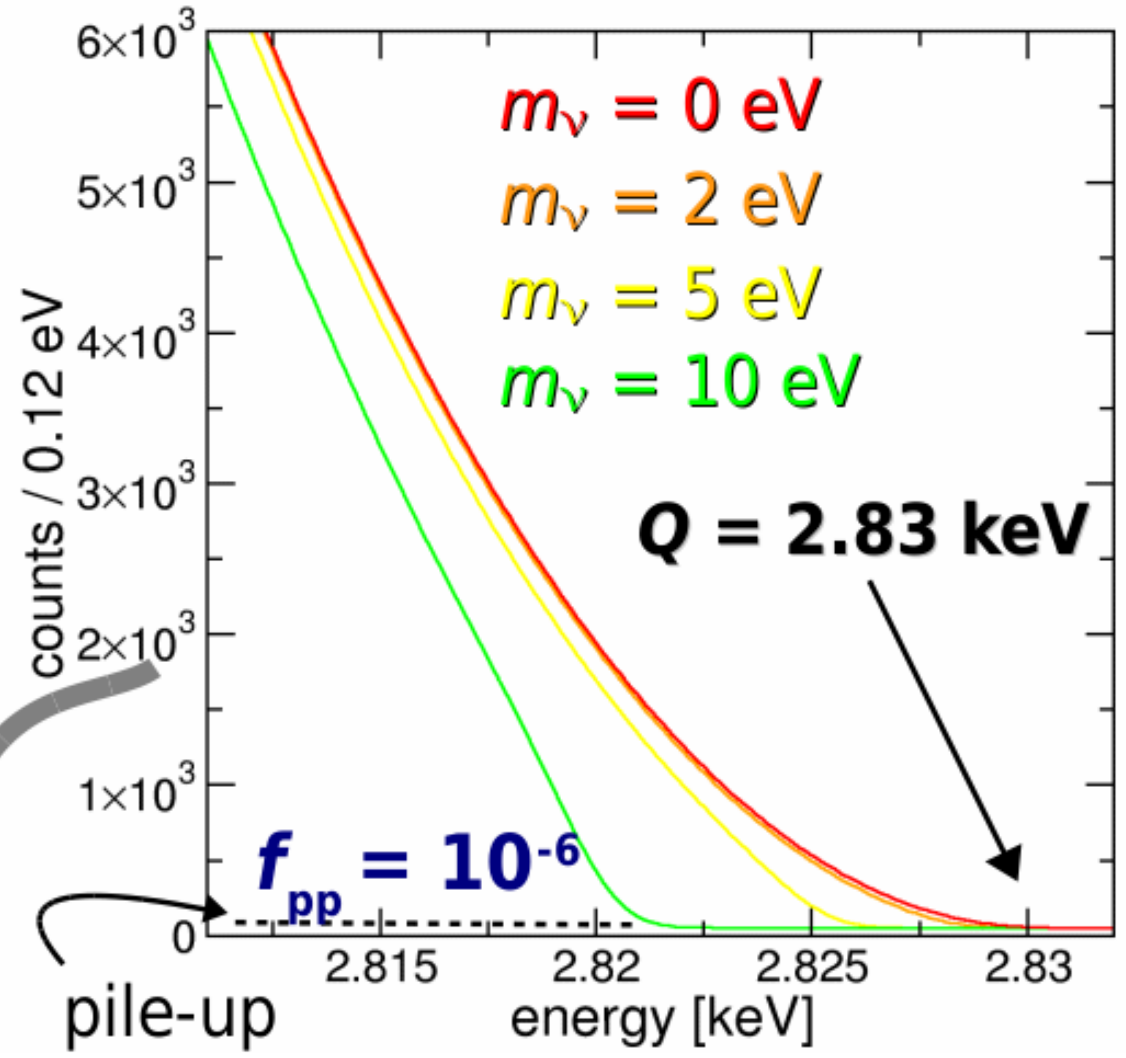

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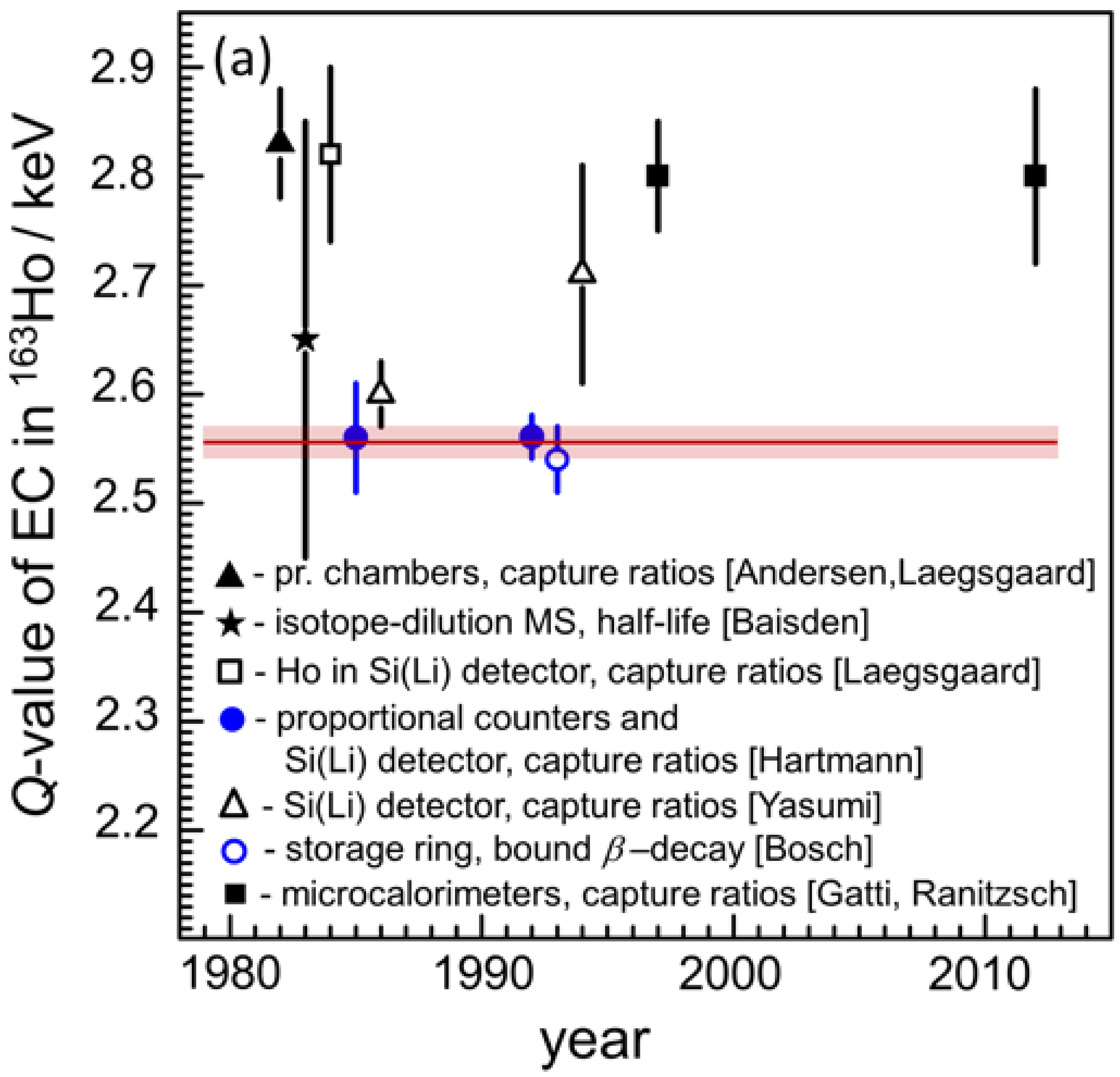
Eur Phys J C Part Fields. 2015; 75(3): 112

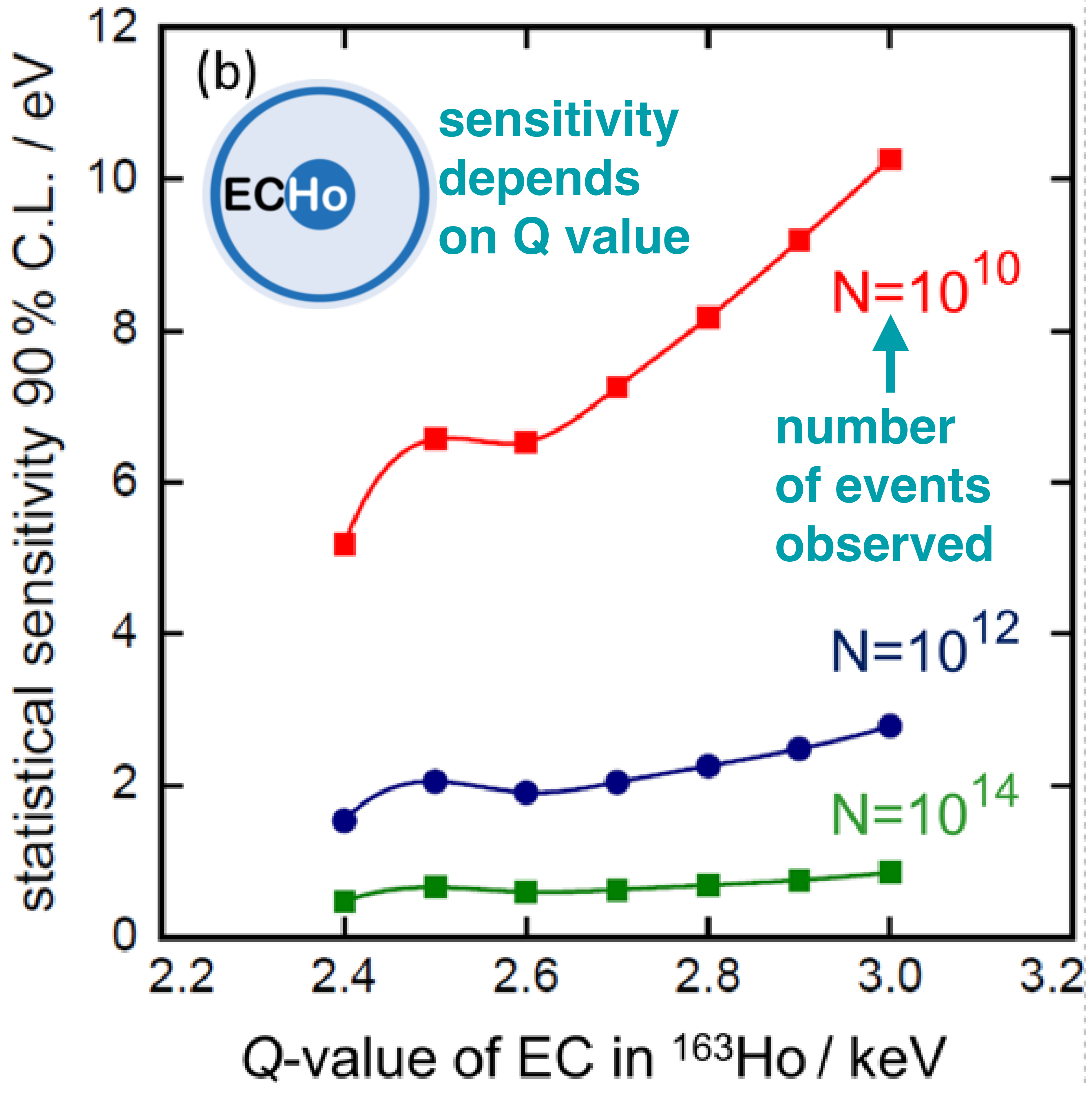
The question of Q

Electron capture spectrum results disagree with accepted value

Accepted Q-value

Proportional counter and storage ring measurements averaged to give accepted value





PRL115,062501 (2015)

Enter SHIPTRAP - Penning ion trapping facility

$$^{163}Ho + e^- \rightarrow ^{163}Dy + \nu_e$$

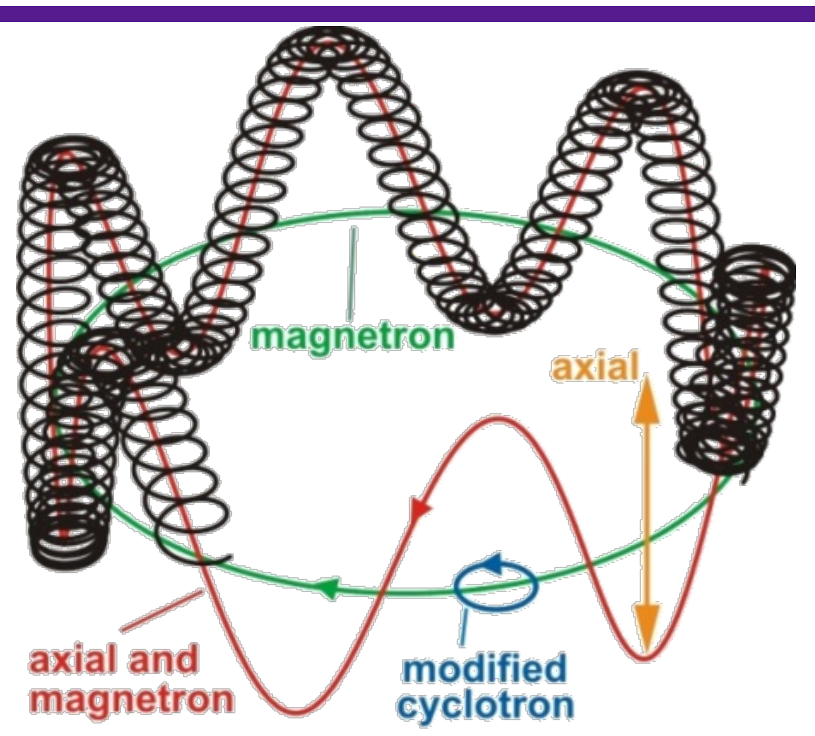
Look for mass difference by measuring the cyclotron-frequency ratio of ^{163}Ho and ^{163}Dy ions

magnetron frequency

$$\nu_c = \frac{qB}{2\pi m} = \nu_- + \nu_+$$

ion mass

modified cyclotron frequency



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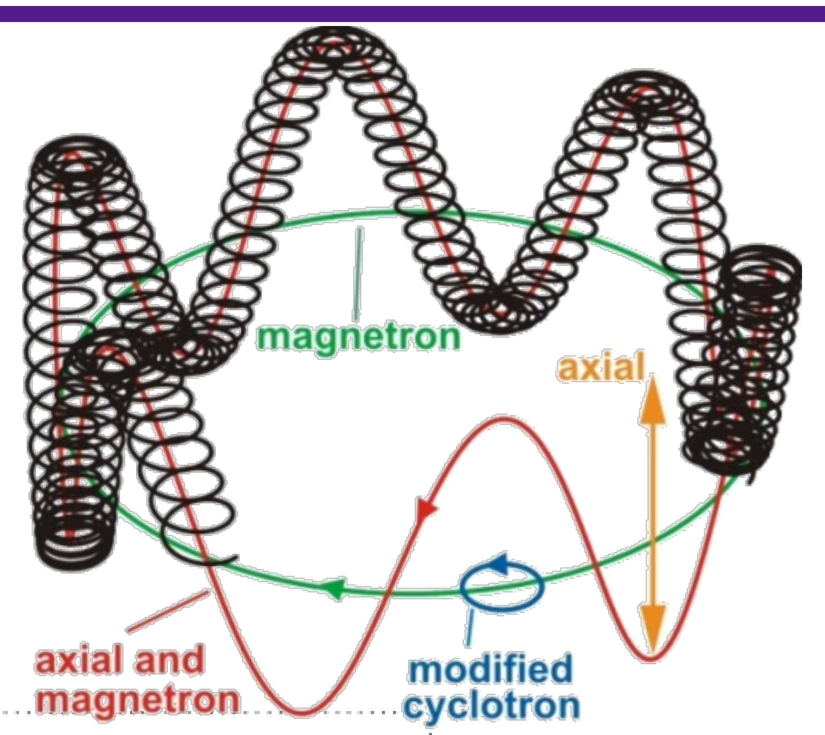
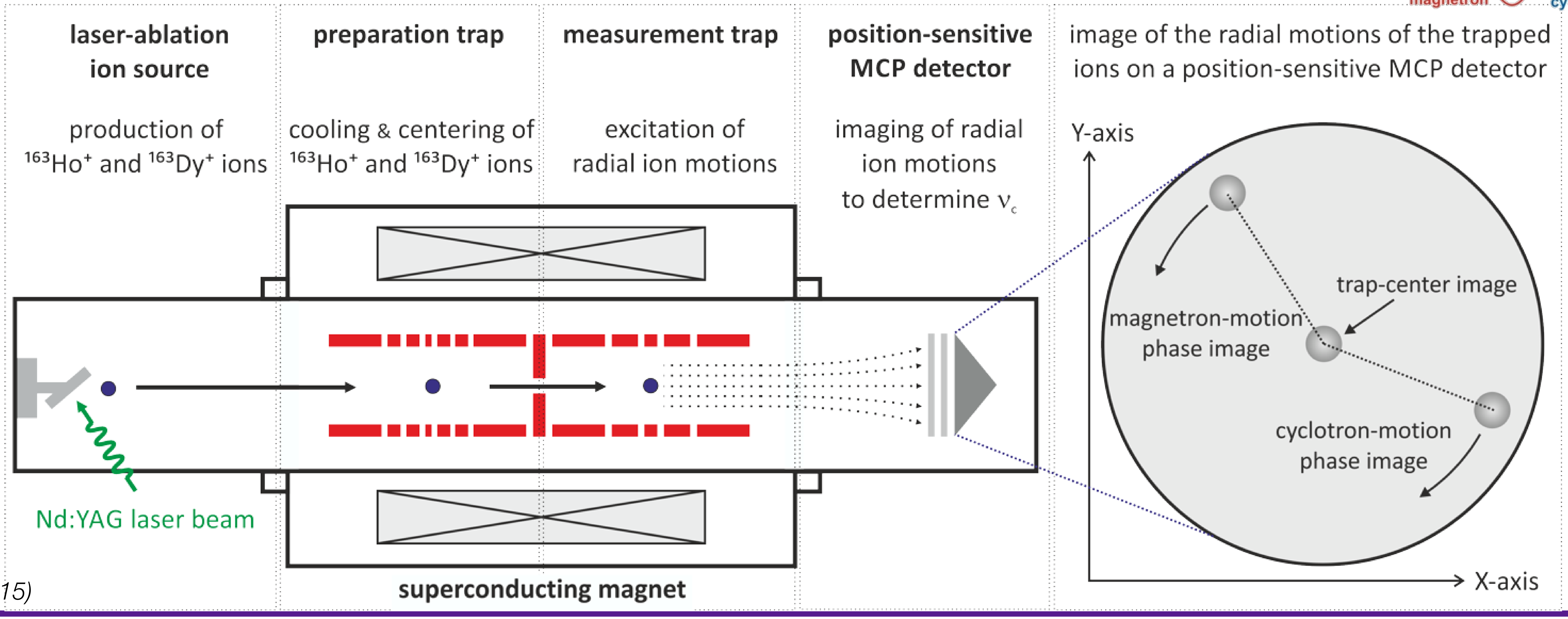
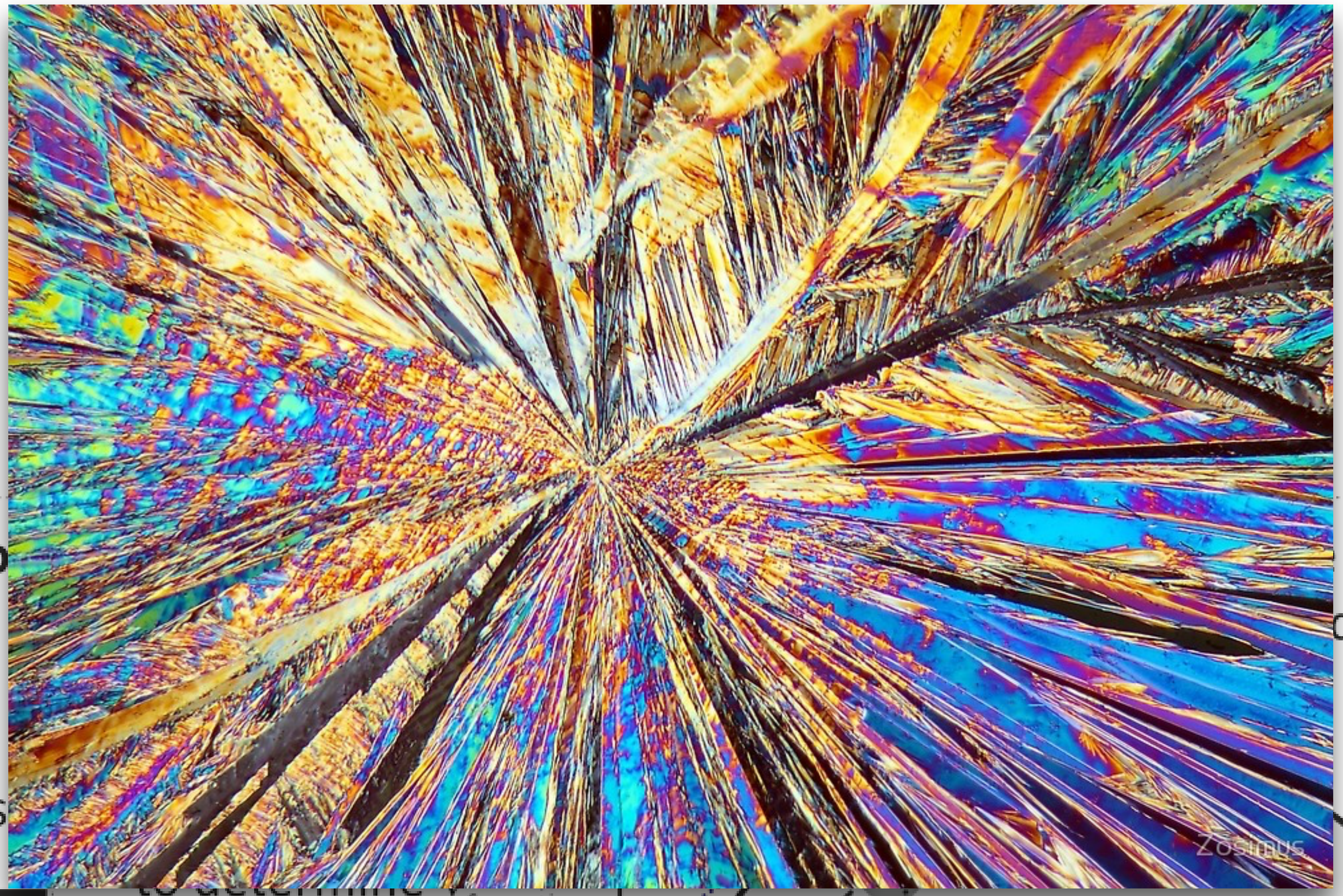




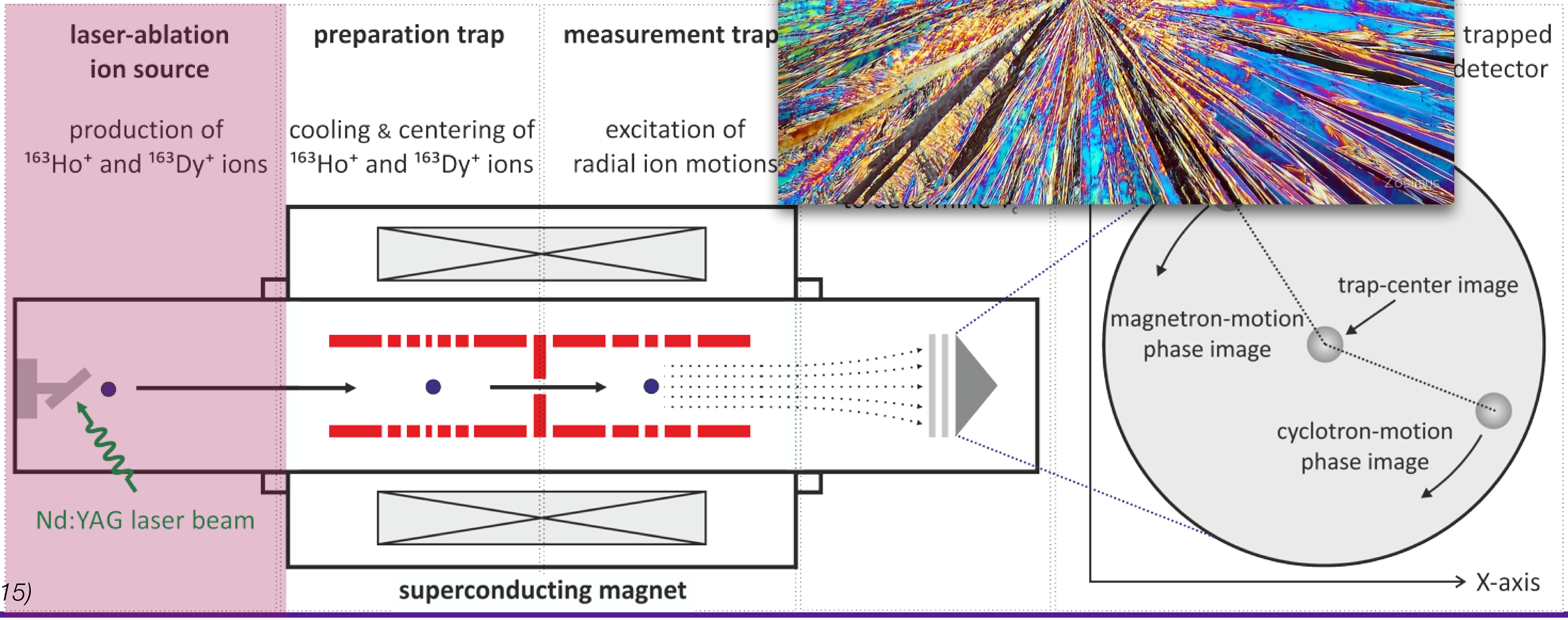
PRL115,062501 (2015)

Enter SHIPTRAP - Penning ion trapping facility

- ^{163}Ho nitrate on a titanium base (**10^{16} ^{163}Ho atoms**)
- Nd:YAG **laser** produces ^{163}Ho^{+} ions
- Repeat with natural Dy



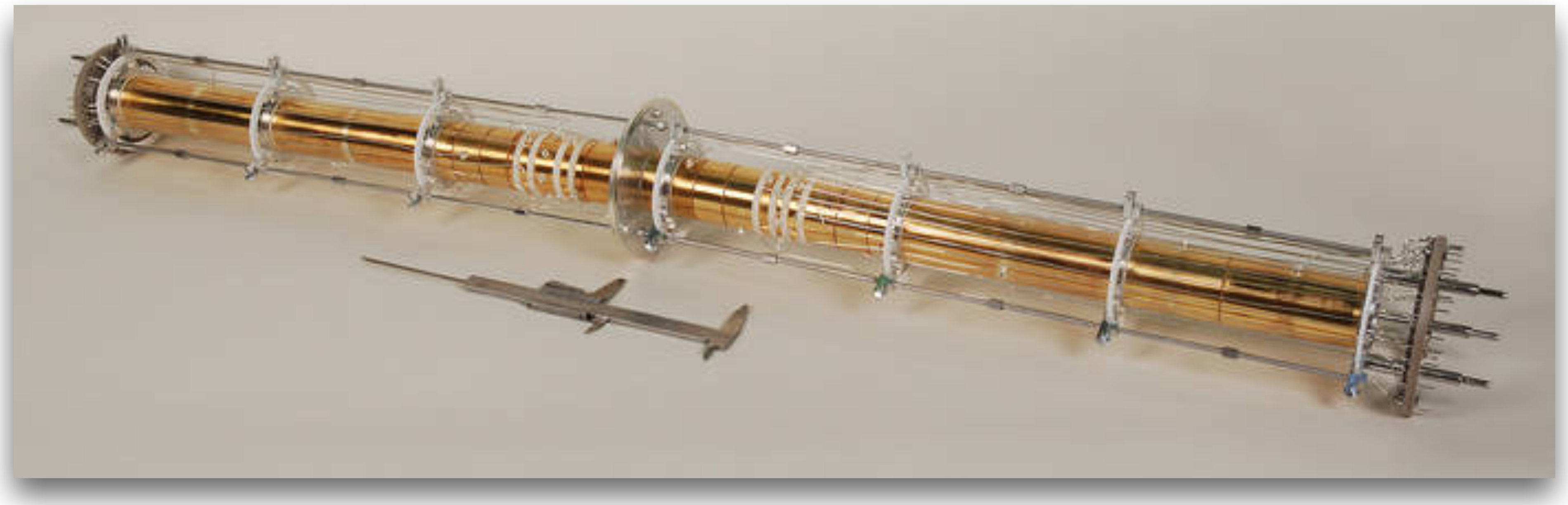
Holmium nitrate, Redbubble



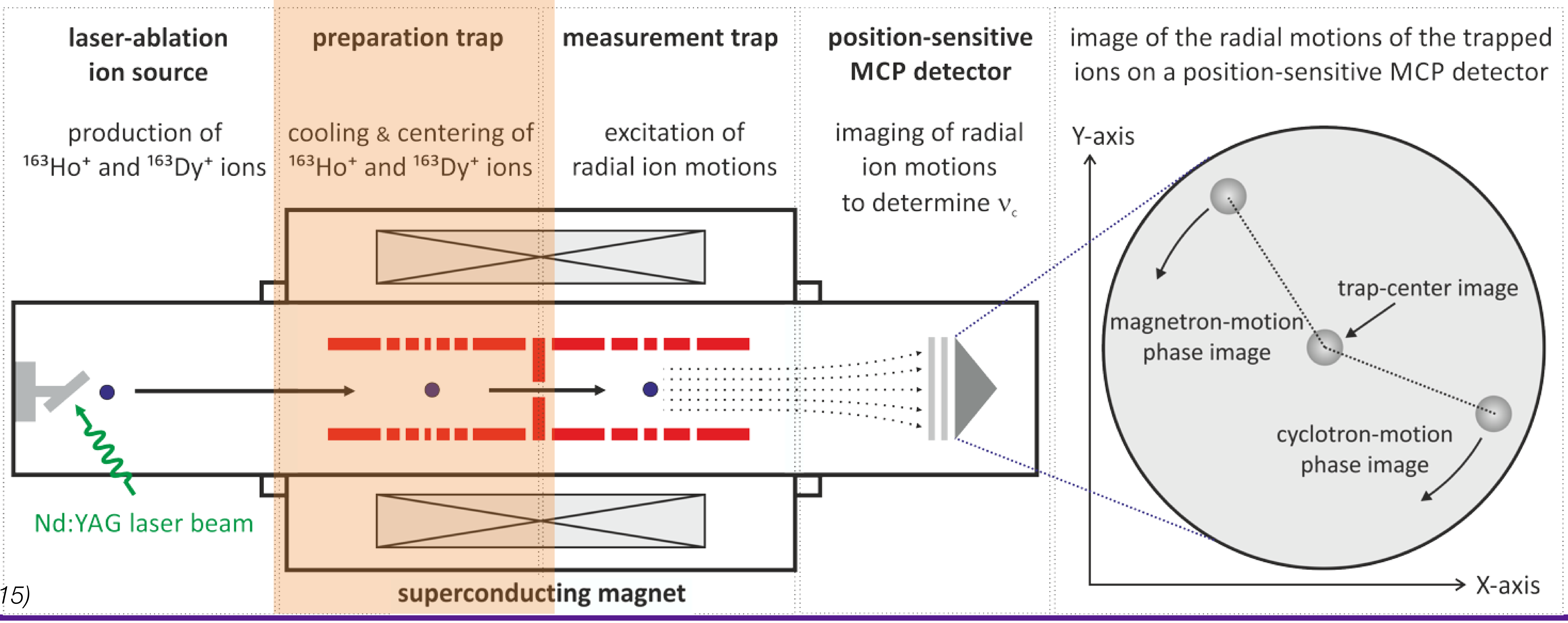
PRL115,062501 (2015)

Enter SHIPTRAP - Penning ion trapping facility

- **Cool** and **centre** ions
- Remove **impurities**
- Increase **cyclotron radius** to **0.5mm**



gsi.de



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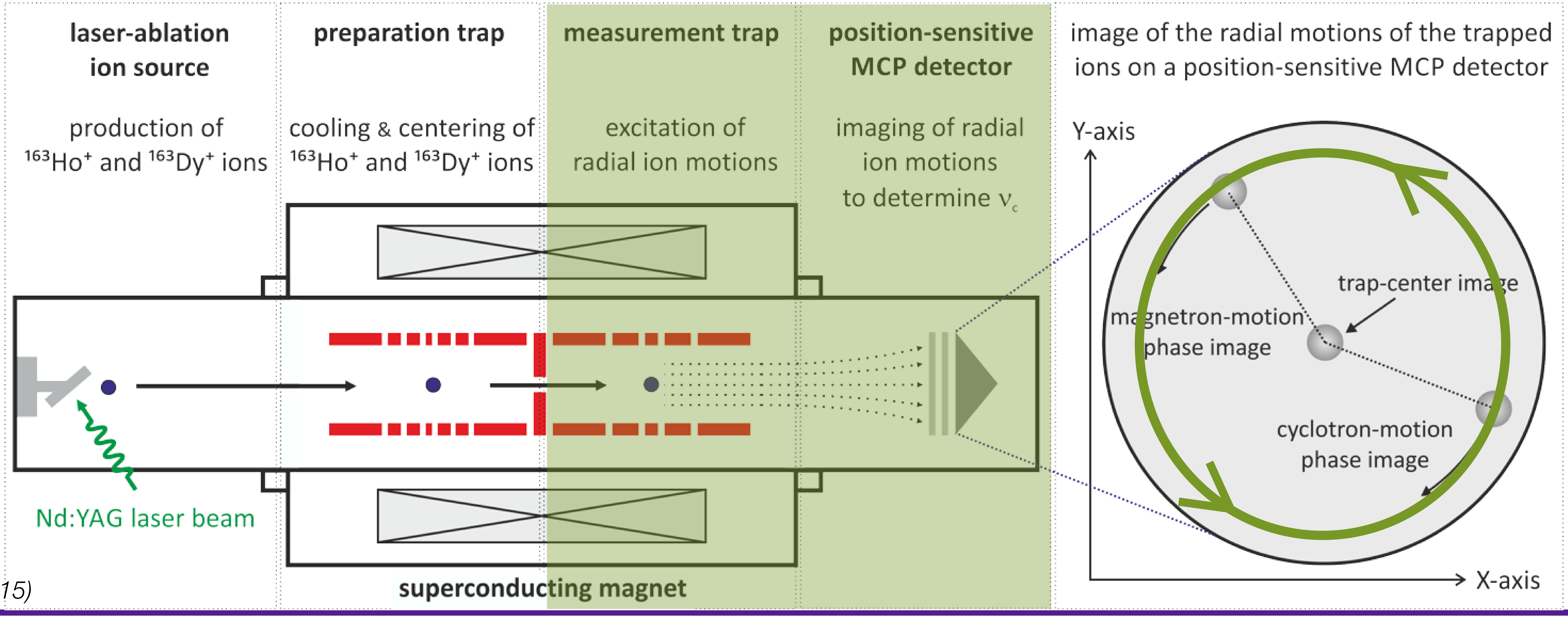

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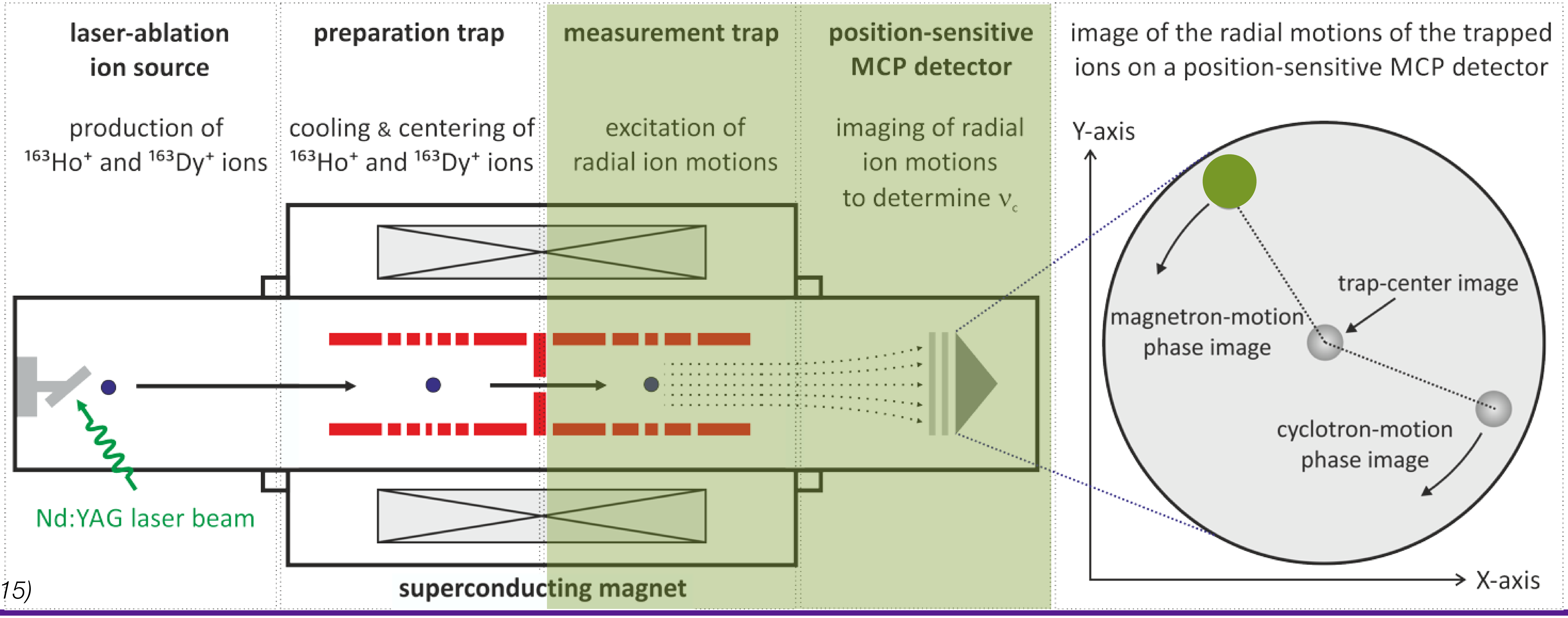

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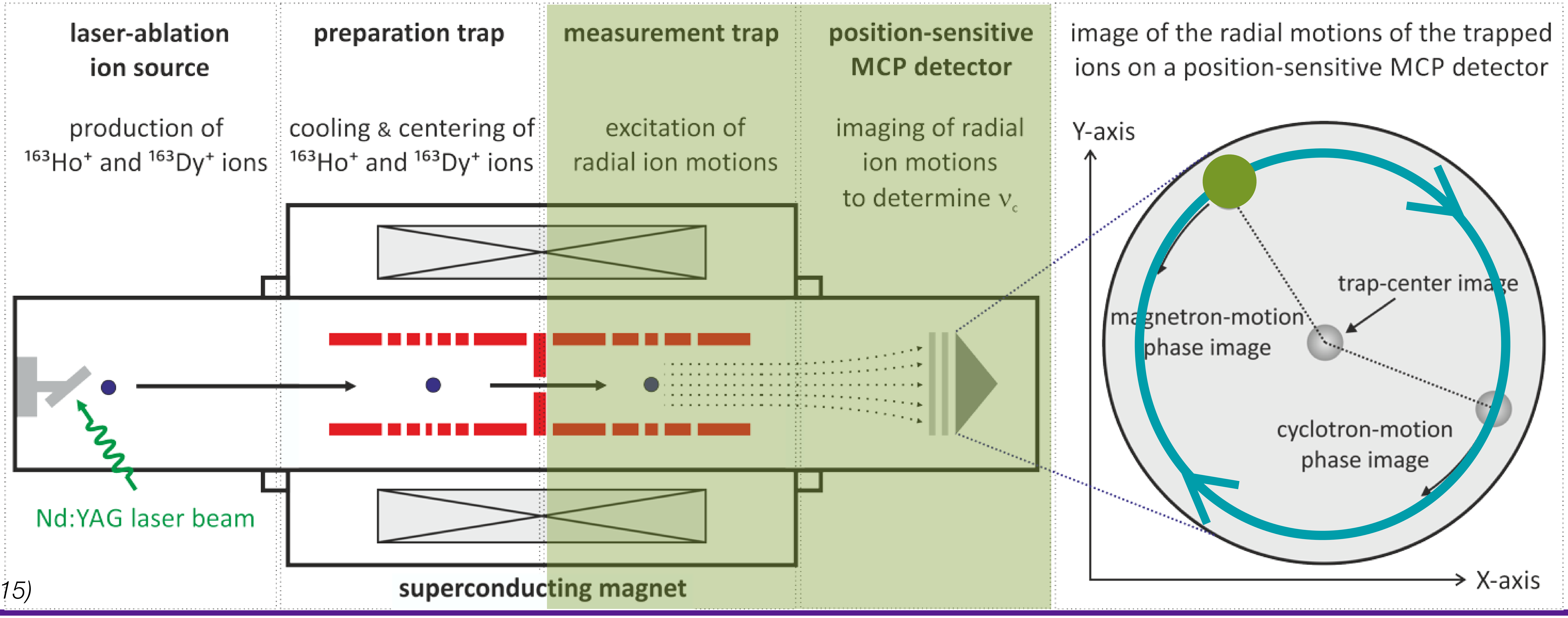

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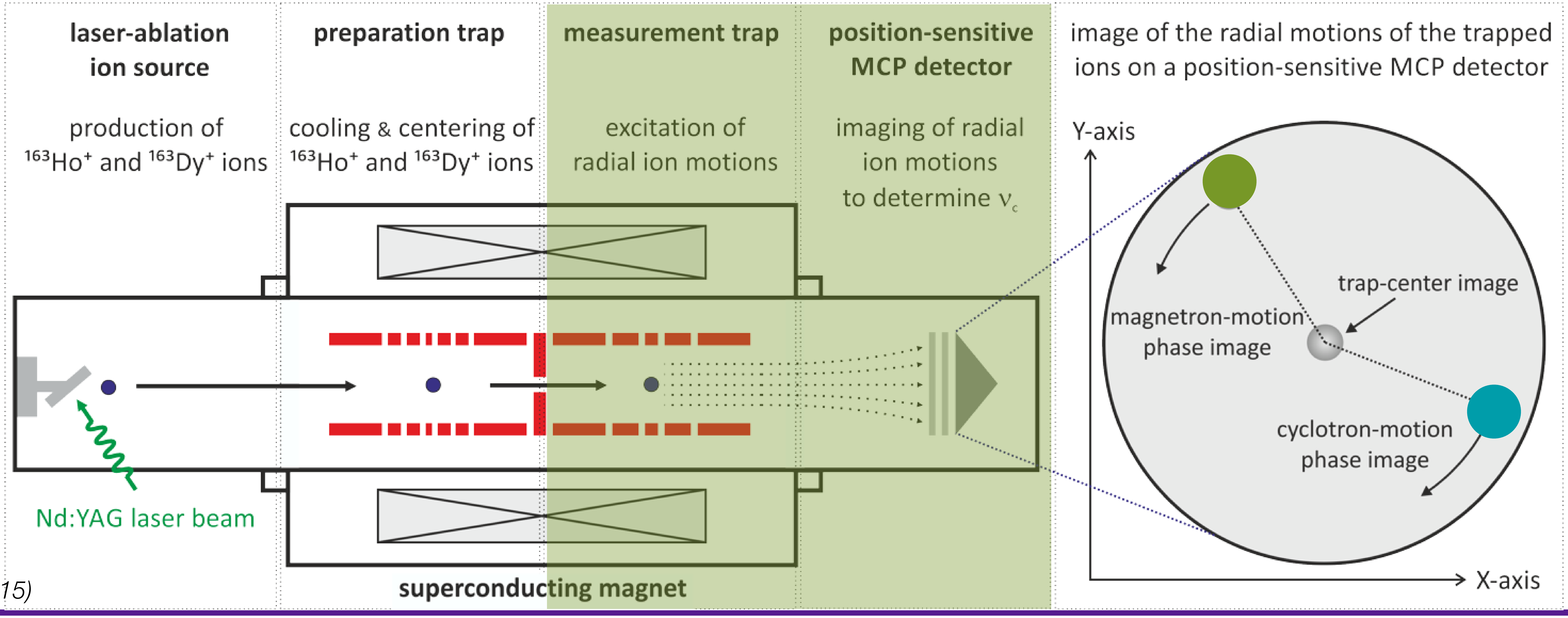

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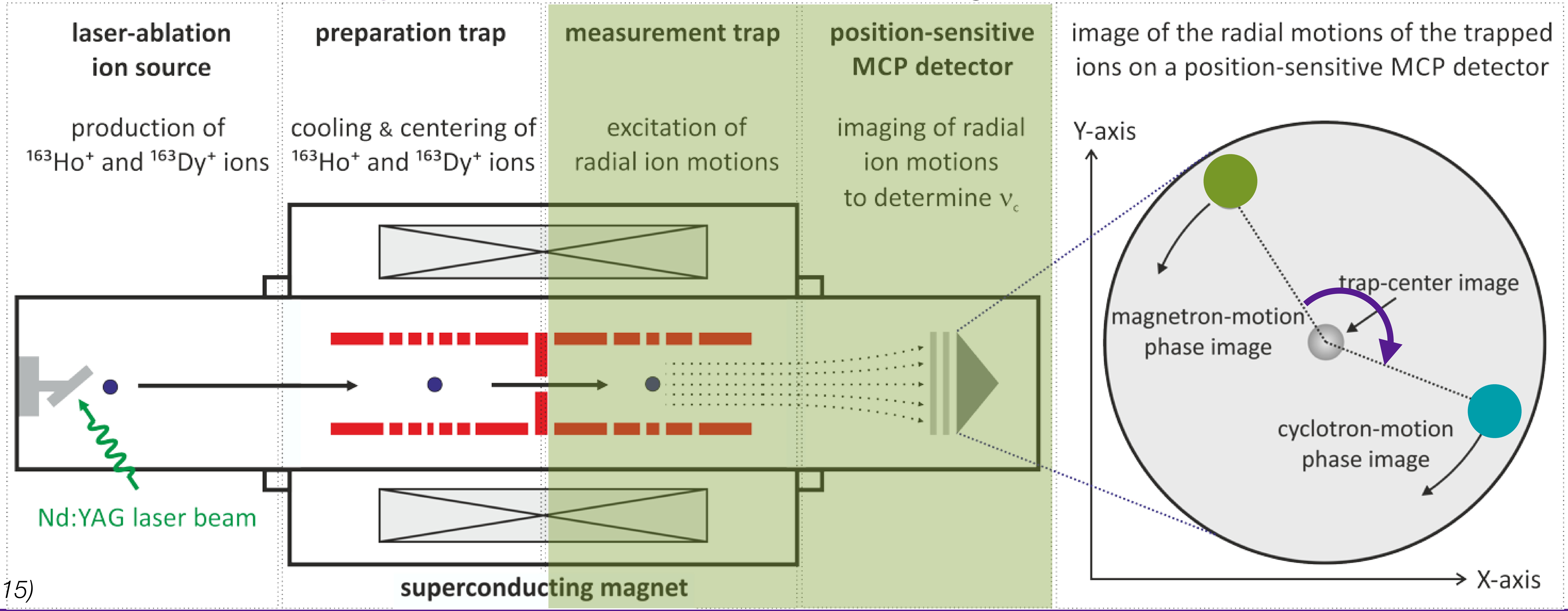

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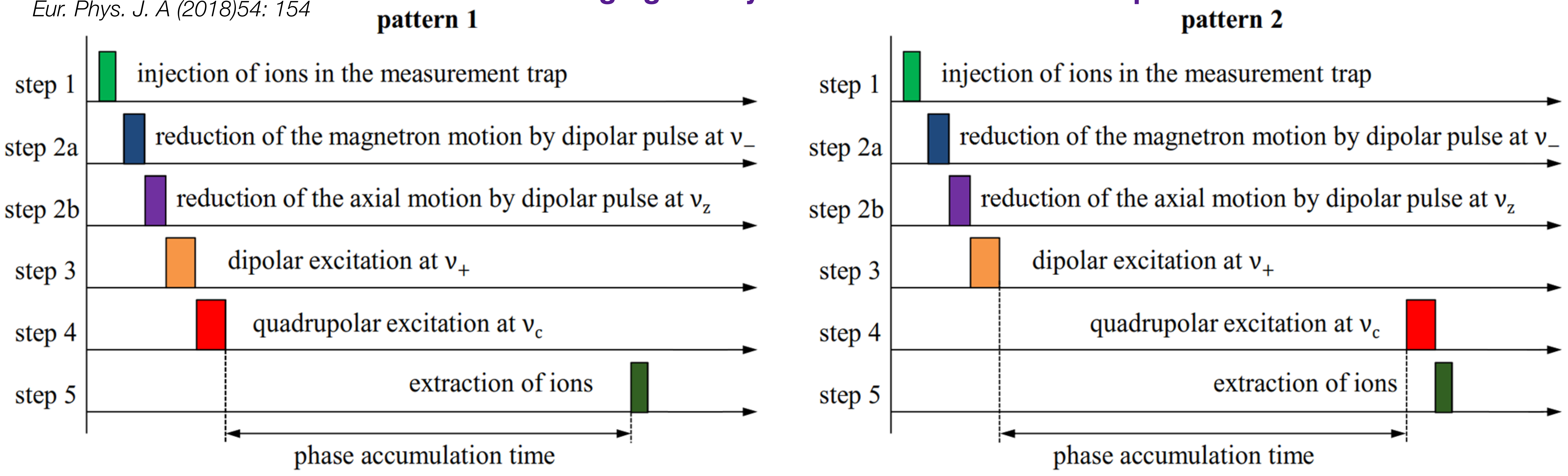
Phase-Imaging Ion-Cyclotron-Resonance technique

Eur. Phys. J. A (2018)54: 154



PRL115,

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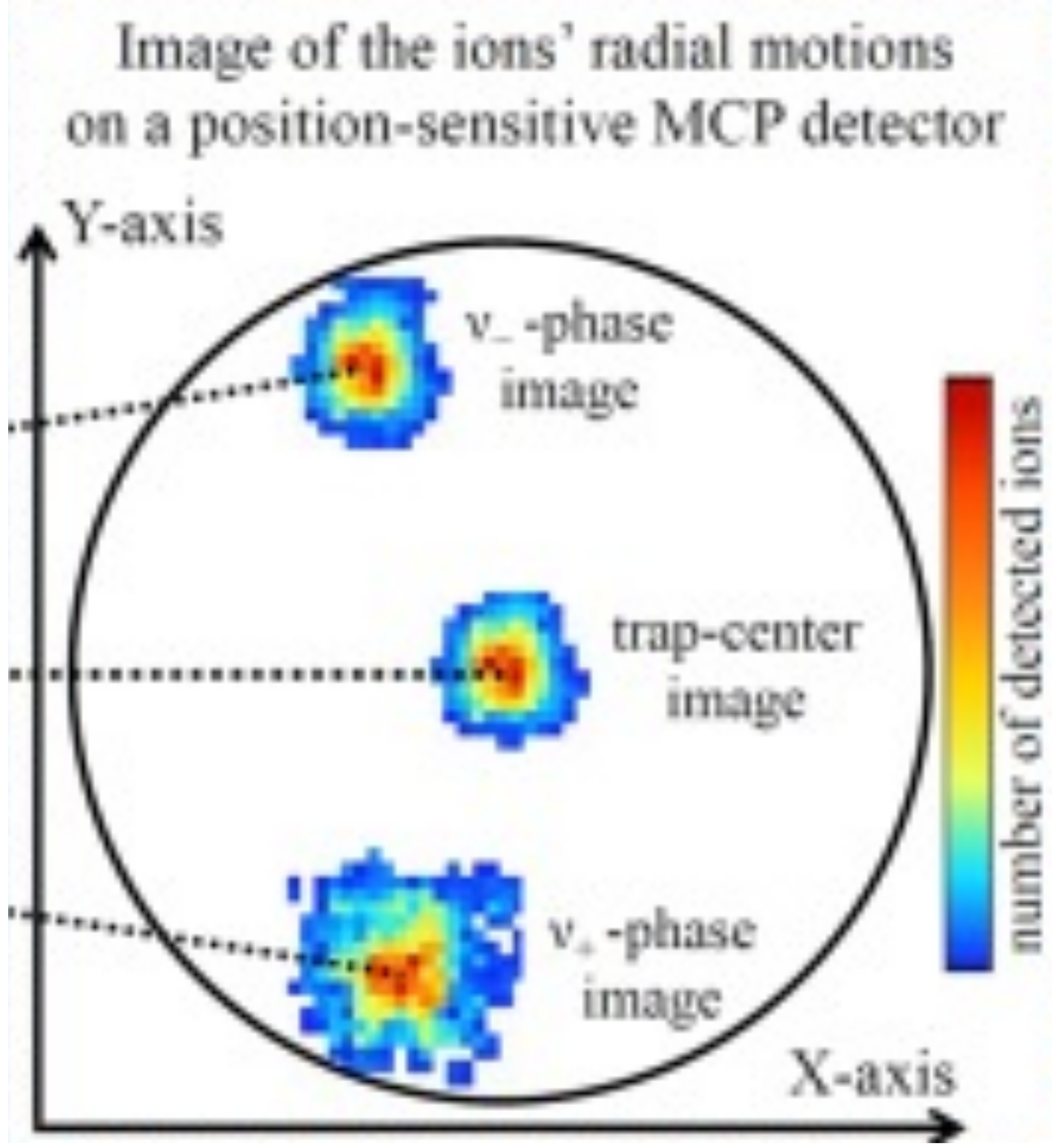
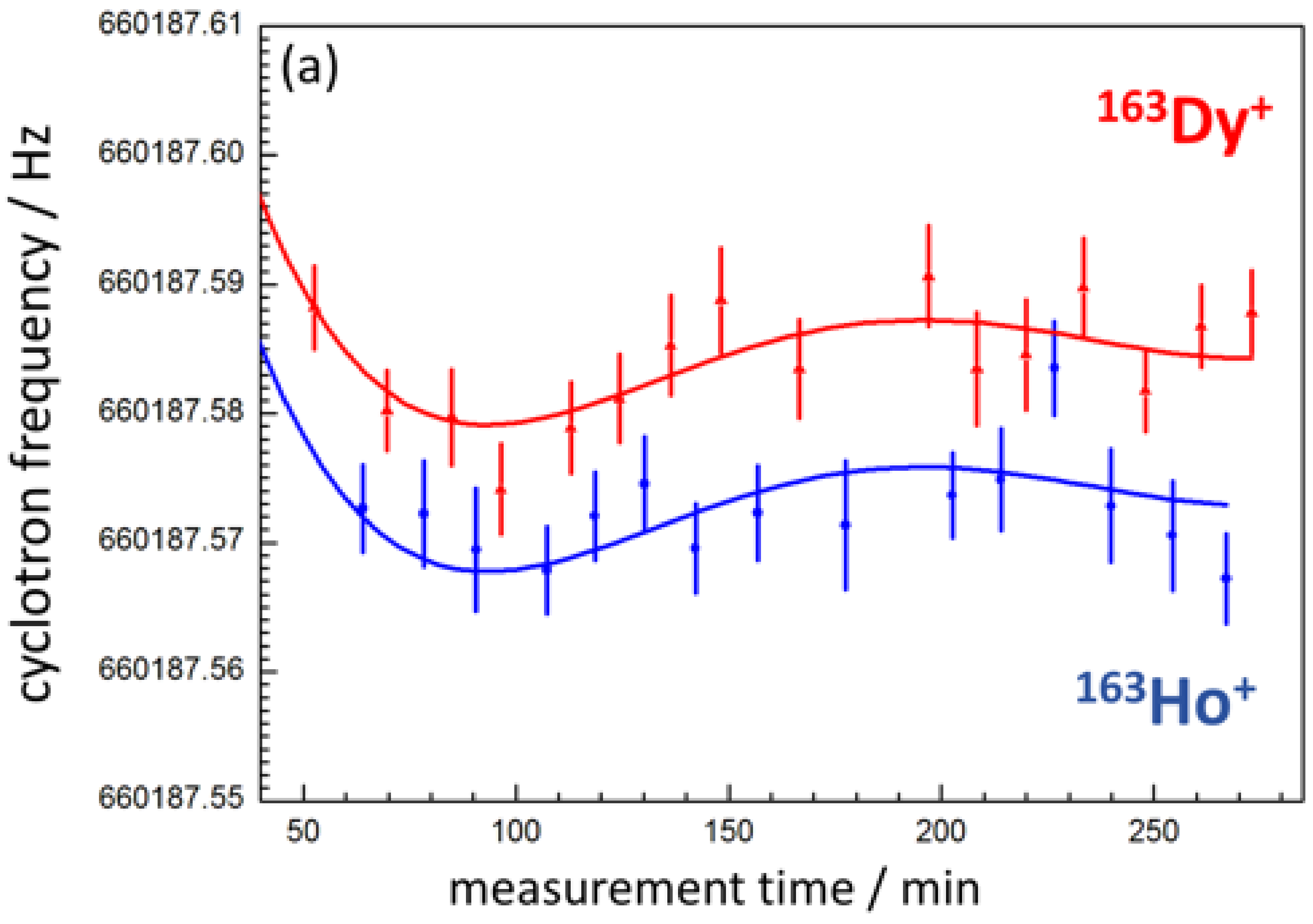


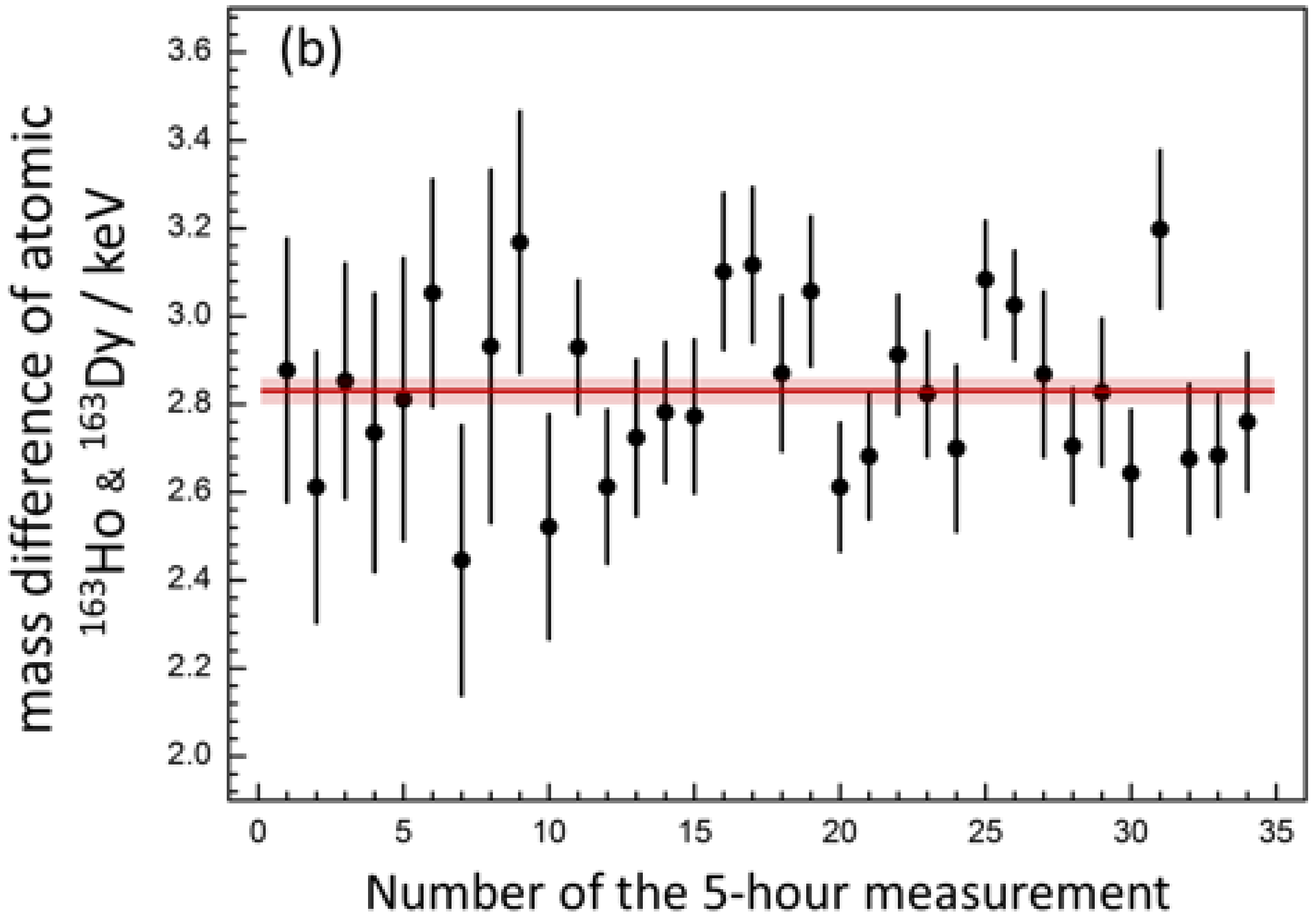
^{123}Te SHIPTRAP image

Physics Letters B 758(C) (2016)

PR

SHIPTRAP has the answer



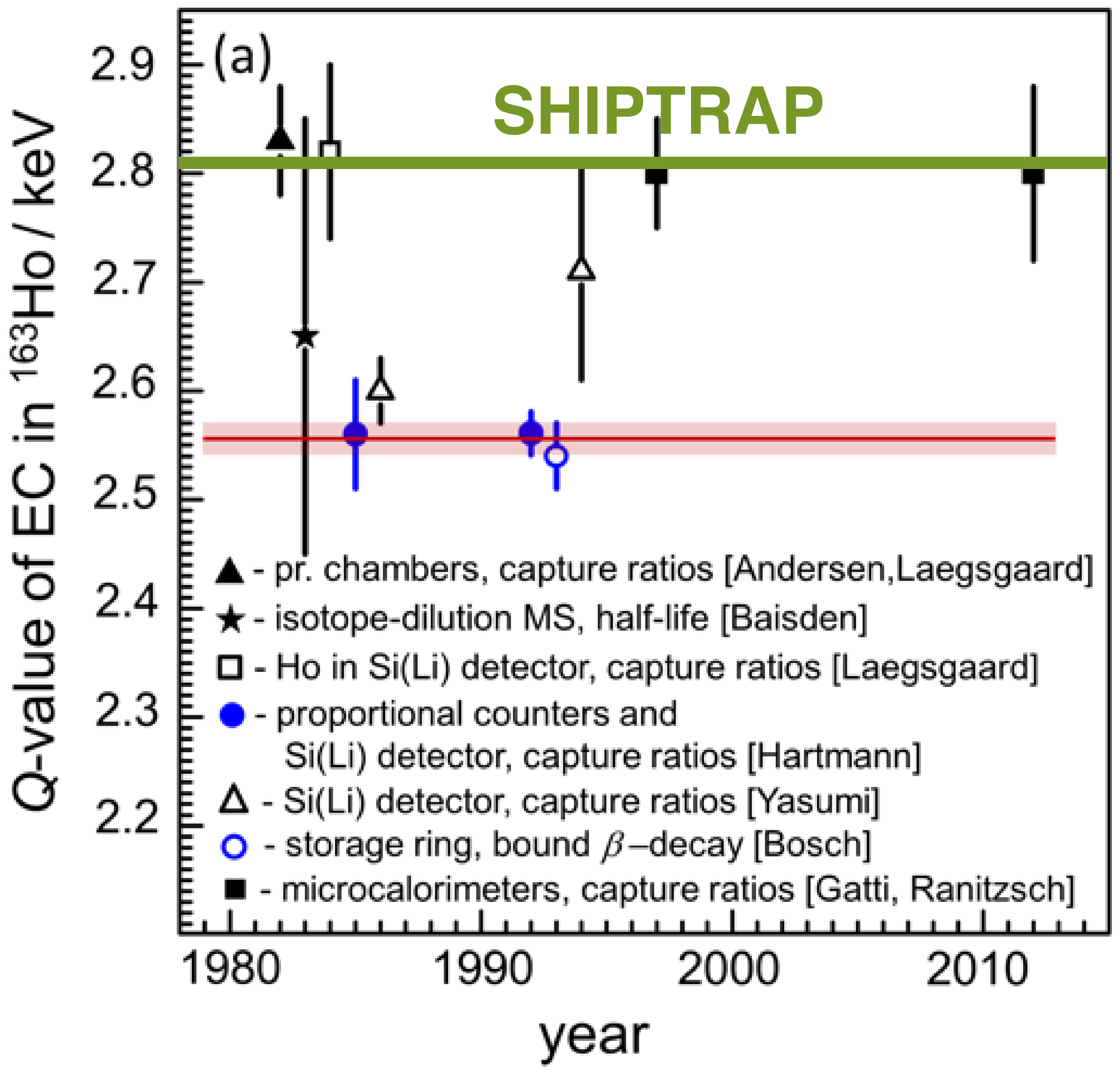


PPB measurement of frequency ratio

$$R = \frac{M_{^{163}\mathrm{Ho}}}{M_{^{163}\mathrm{Dy}}} = 1.00000001867(20_{\mathrm{stat}})(10_{\mathrm{sys}})$$

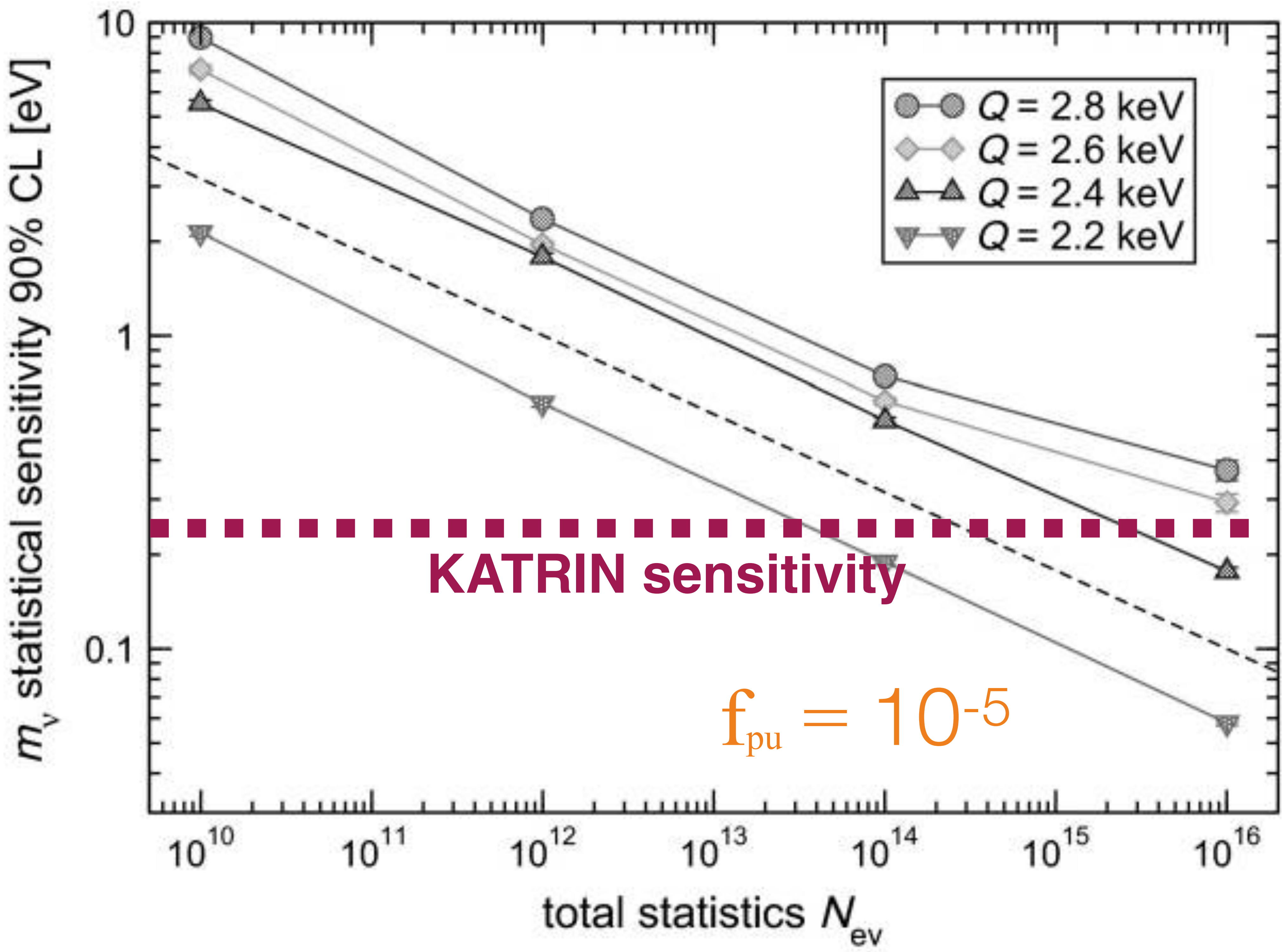
Mass difference agrees with micro calorimeter experiments

$$\Delta M = Q_{\mathrm{EC}} = 2833(30_{\mathrm{stat}})(15_{\mathrm{sys}})\mathrm{eV}/c^2$$



PRL115,062501 (2015)

How much ^{163}Ho do we need?



HOLMES

Eur Phys J C Part Fields. 2015; 75(3): 112.

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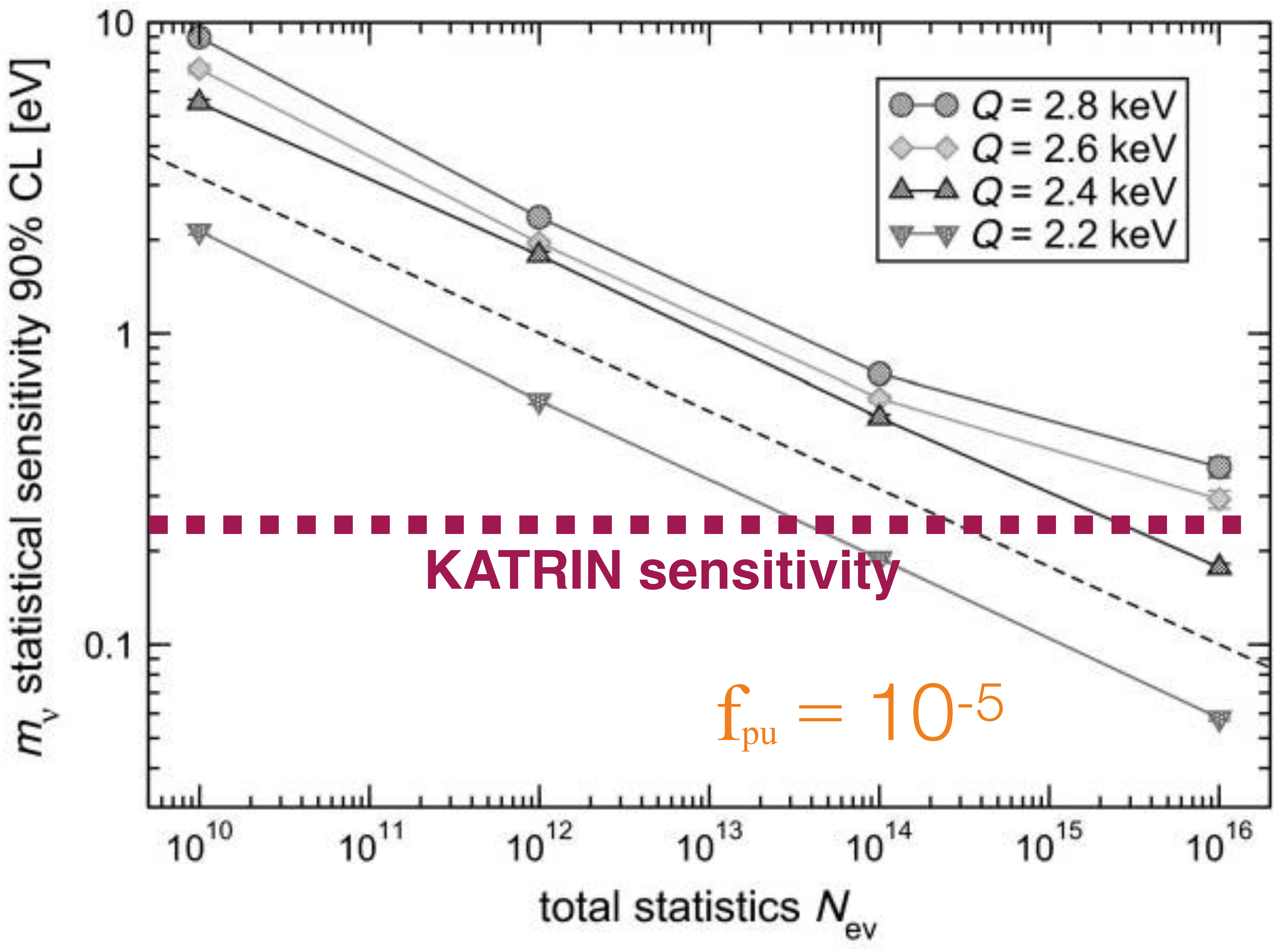

- For competitive m_ν sensitivity, we need ~ **10^{14} decays**
  - **~ MBq** activity for few-year run-times
  - 2 x 10^{11} atoms = 1Bq; we need ~ 10^{17} atoms

$$f_{pu} = A_{EC}\tau_R$$

2-event pile-up probability

activity in the detector

time resolution

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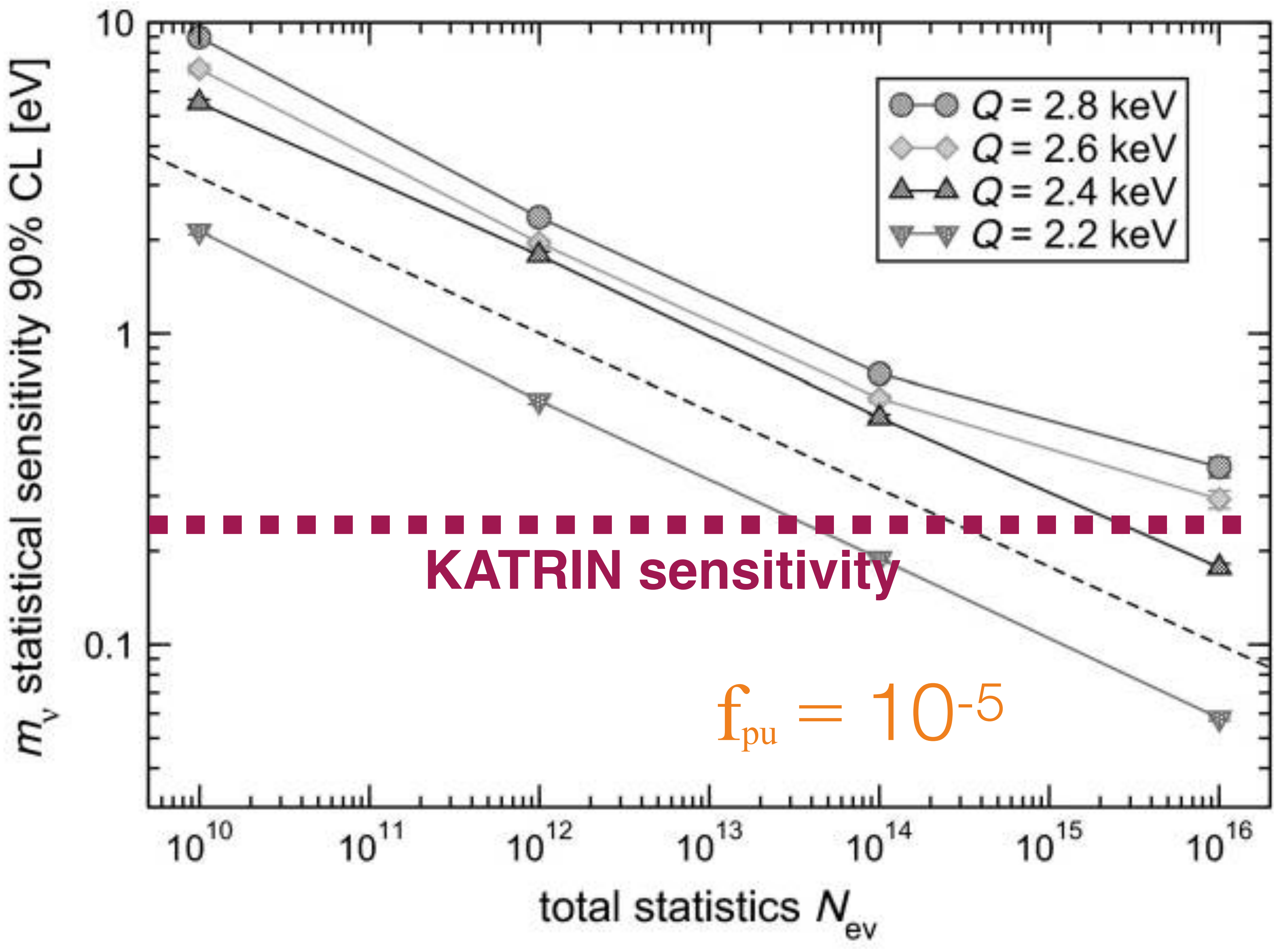

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We need $f_{pu} < 10^{-5}$

Typical τ_R ~ μs

Do we have a problem?

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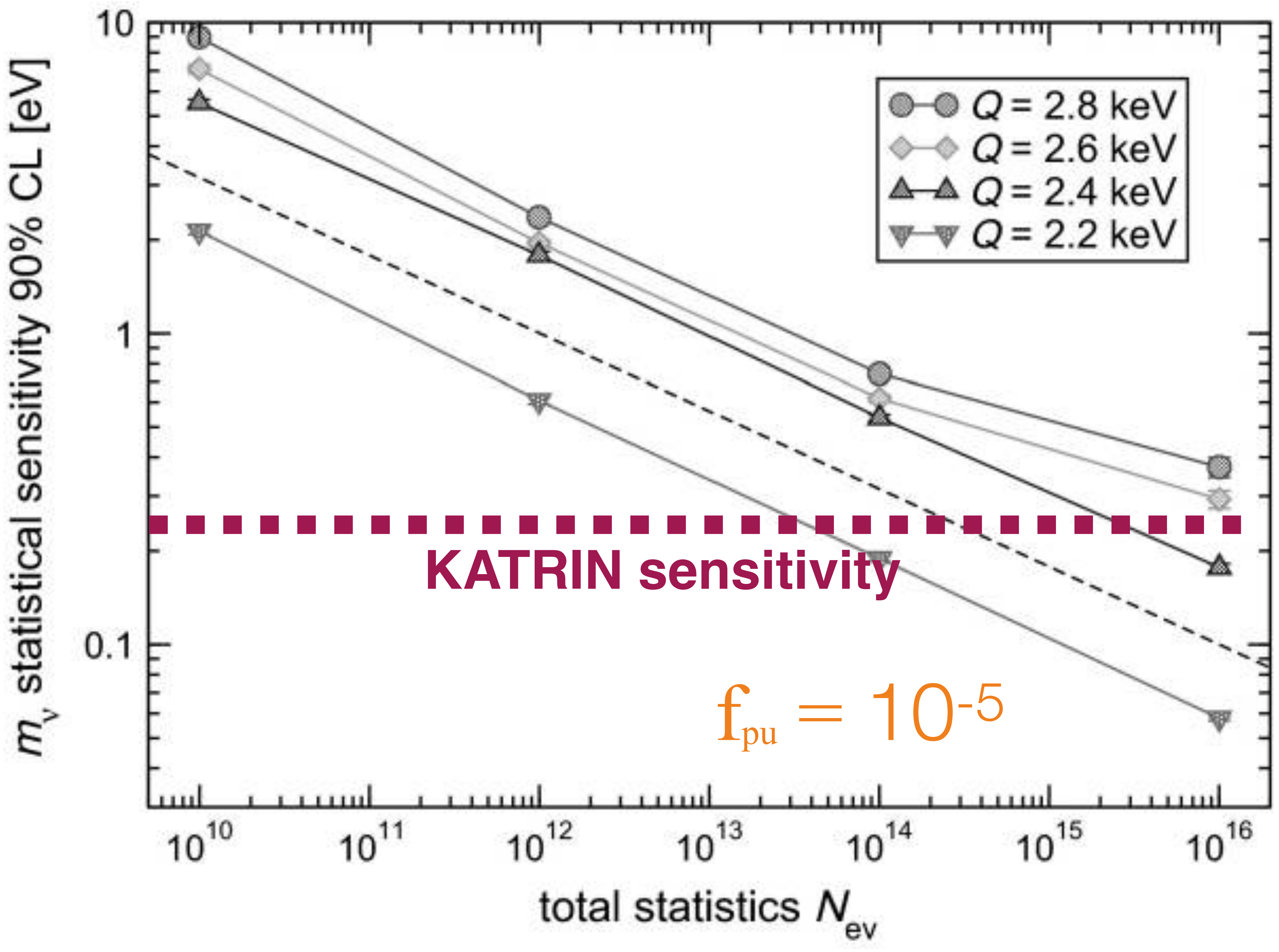

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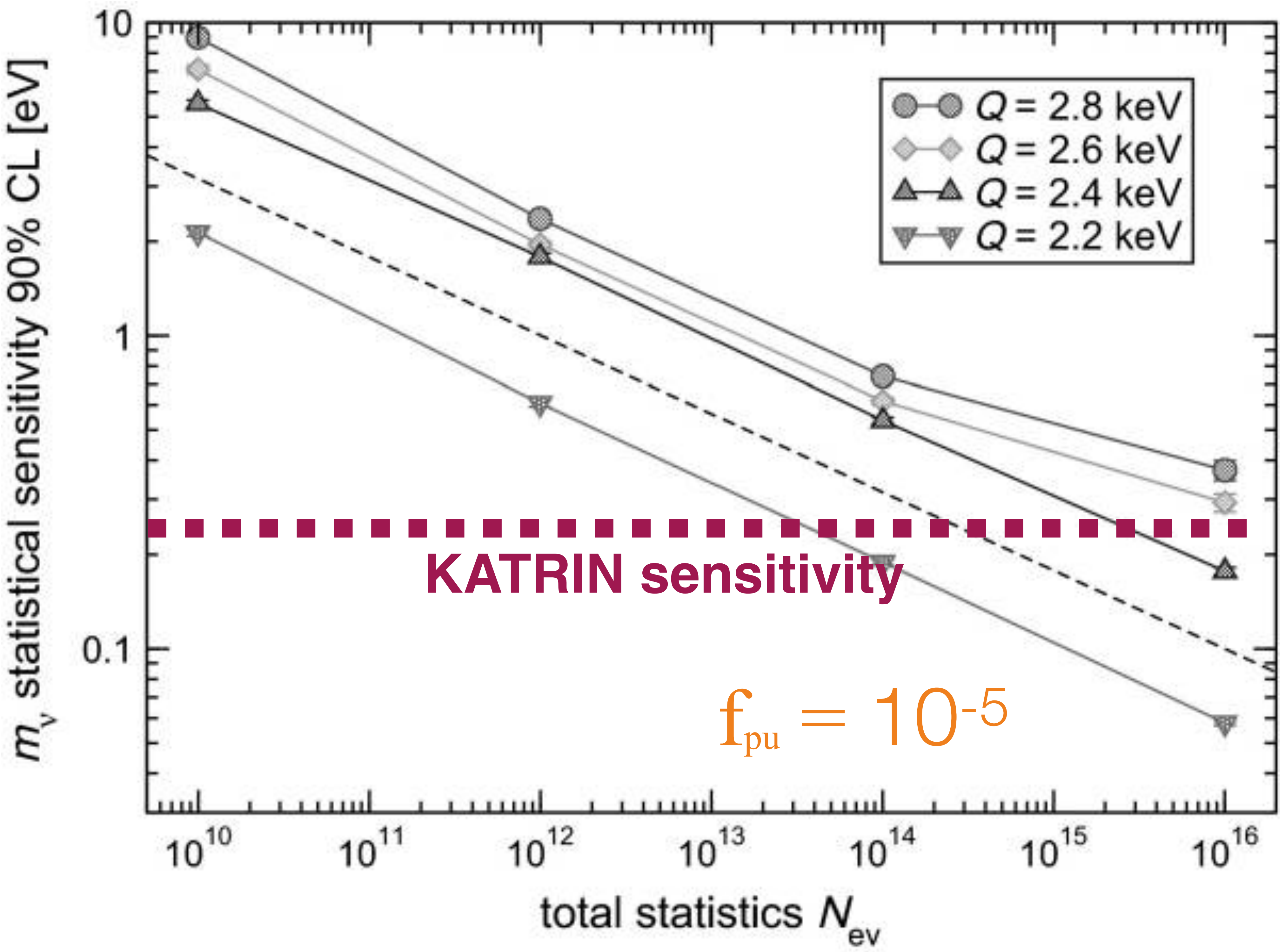

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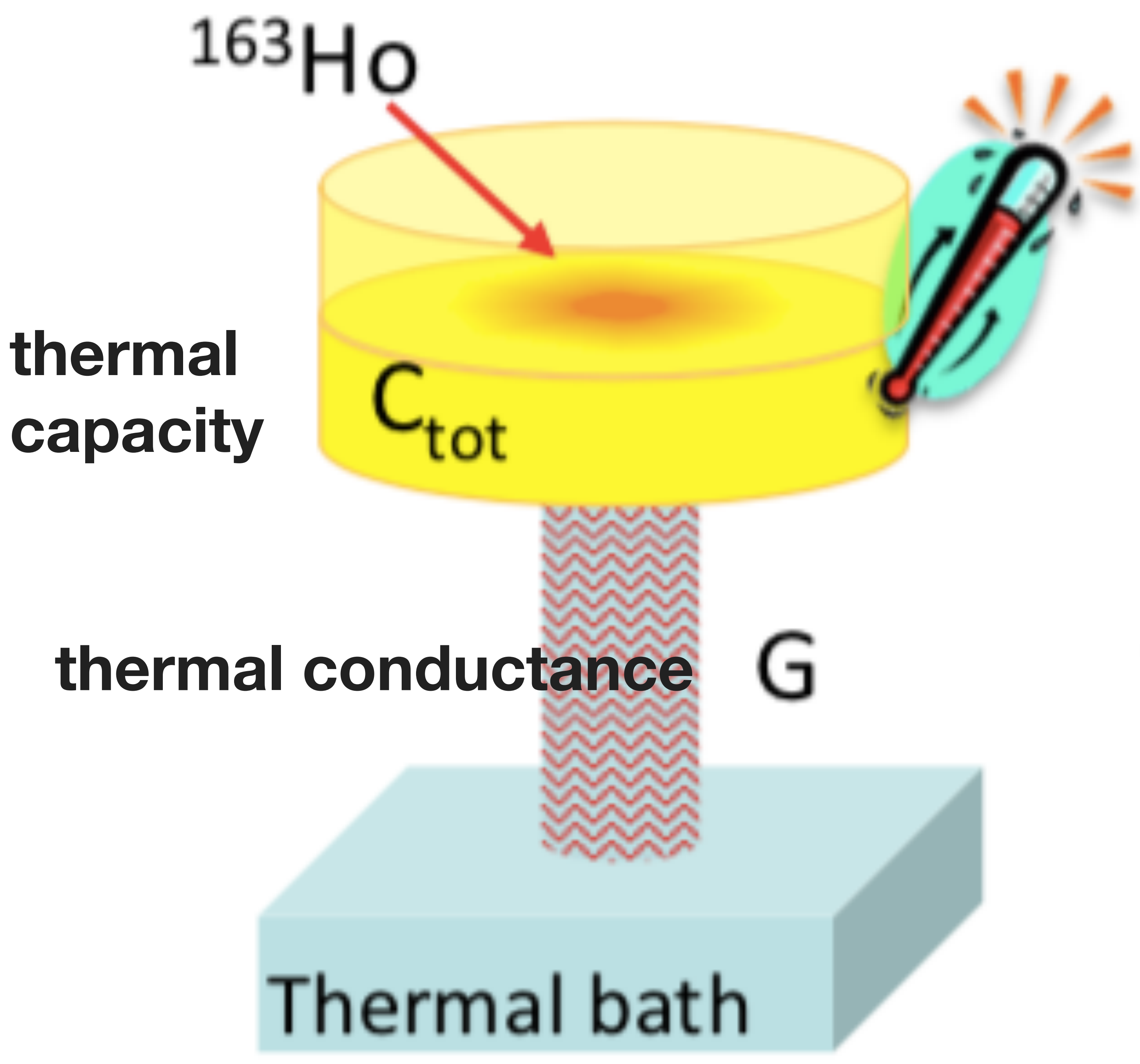
- **Pile-up** can be a limiting factor
  - Separate detector into **micro-calorimeter pixels**
- Energy resolution **ΔE < 3 eV**
- **Backgrounds** < 10^{-5} events/eV/detector/day

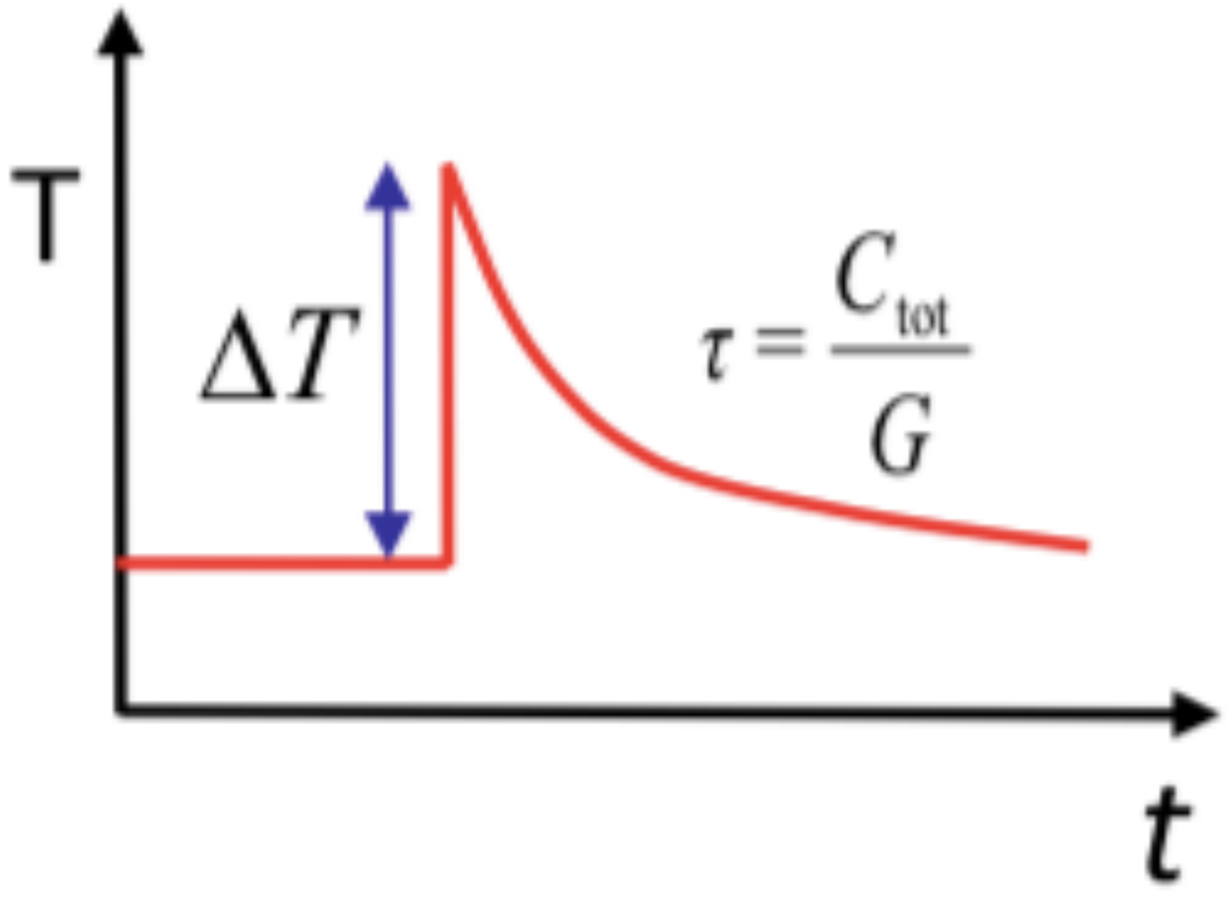
HOLMES

Eur Phys J C Part Fields. 2015; 75(3): 112.

Pixel detectors: low-temperature microcalorimeters



$$\Delta T \cong \frac{E}{C_{tot}}$$



- $\mathcal{O}(10^3$ to $10^6)$ individual detectors
- $\mathcal{O}(10^{14})$ ^{163}Ho atoms per detector
- Very small volume
- Working temperature < 100 mK
  - Low specific heat
  - Reduce thermal noise
- Very sensitive temperature sensor

L Gastaldo, Neutrino 2018
doi: 10.5281/zenodo/1286949

HOLMES: transition-edge sensors

JINST 12 C02046 2017

^{163}Ho isotope production → ^{163}Ho source embedding → Single detector optimization → Holmes array → **Full HOLMES**

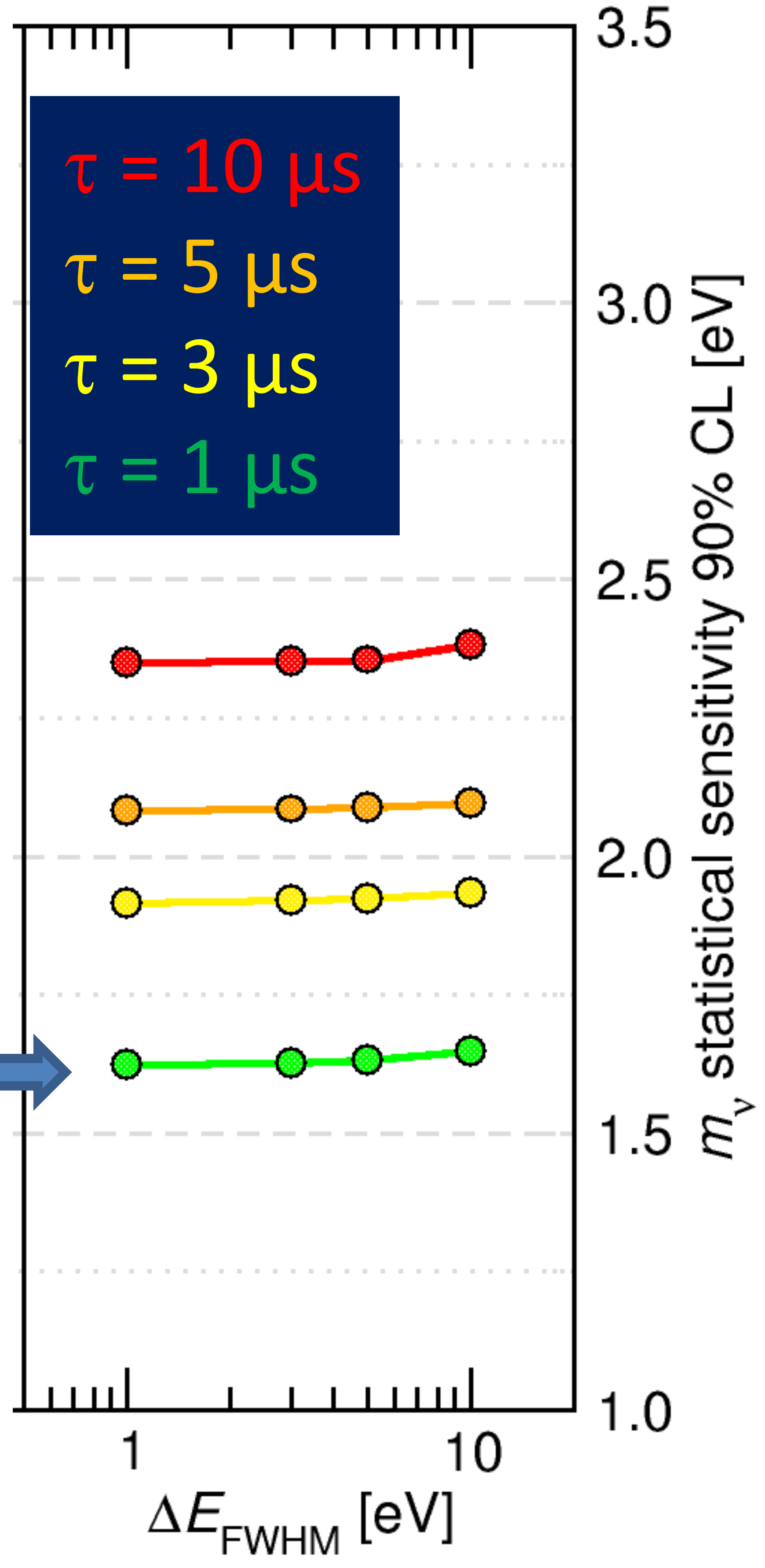
1024 detectors (16 arrays)

6.5 x 10^{16} ^{163}Ho nuclei(18 μg)

3 x 10^{13} events

3 x 10^{13} events (300Bq / pixel)

ΔE_{FWHM} ~ 3-5eV; Δt ~ 10 μ s



HOLMES

HOLMES: transition-edge sensors

UCL

JINST 12 C02046 2017

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H

(I

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Enriched erbium(III) oxide

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$16\ \mathrm{Er}(n,\gamma) \rightarrow\ \mathrm{Er}$

$^{163}\mathrm{Er} + e^- \rightarrow {}^{163}\mathrm{Ho} +$

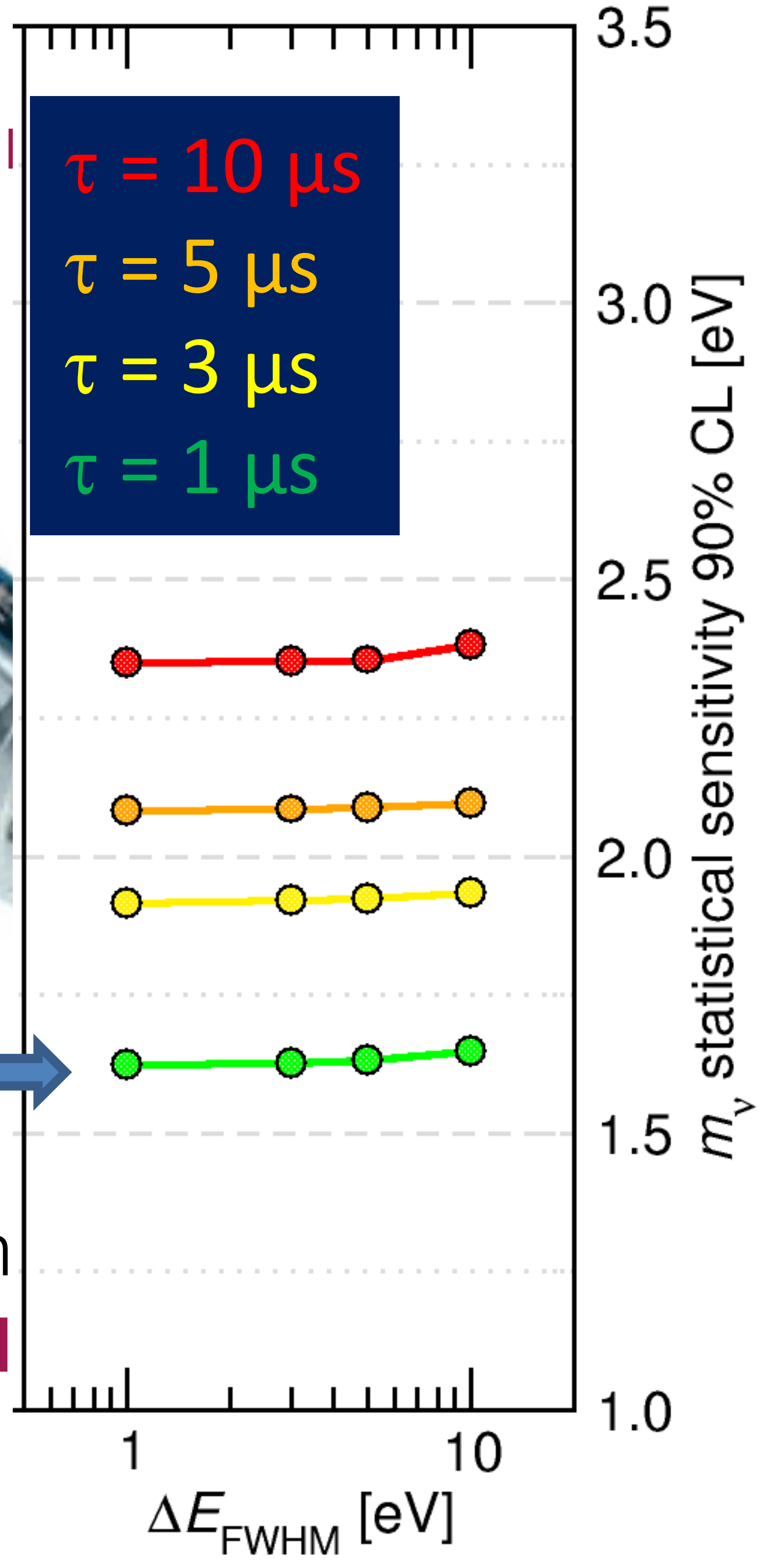
ΔE_{FWHM} ~ 3-5eV; Δt ~ 10 μ s

NEUTRONS FOR SOCIETY

Extract

650m

65 M



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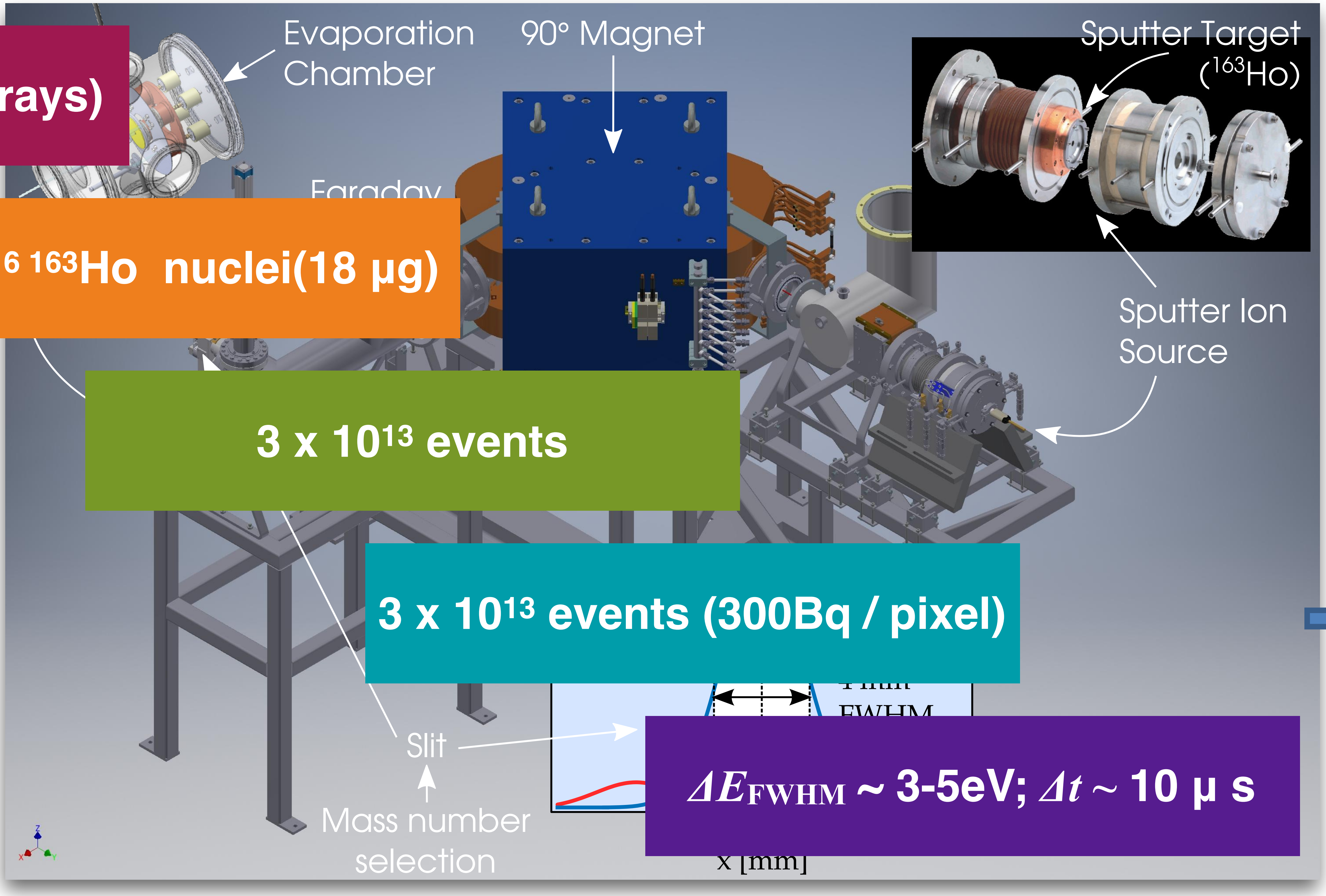
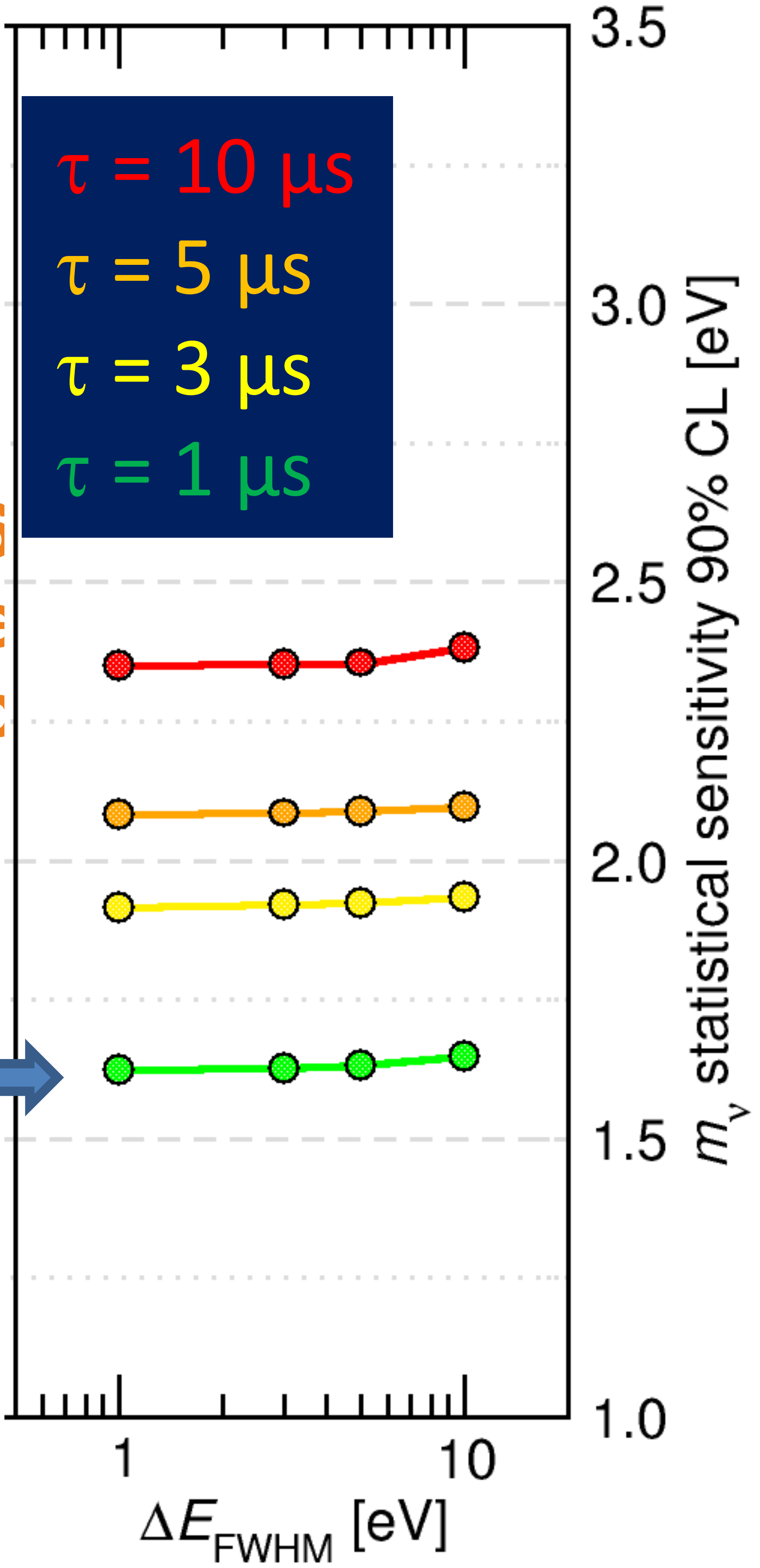
ΔE_{FWHM} ~ 3-5eV; Δt ~ 10 μ s

Mass separator - remove ^{166m}Ho (β-emitter)





HOLMES: transition-edge sensors

JINST 12 C02046 2017

^{163}Ho isotope production → ^{163}Ho source embedding → Single detector optimization → Holmes array → Full HOLMES

Si_2N_3 membrane

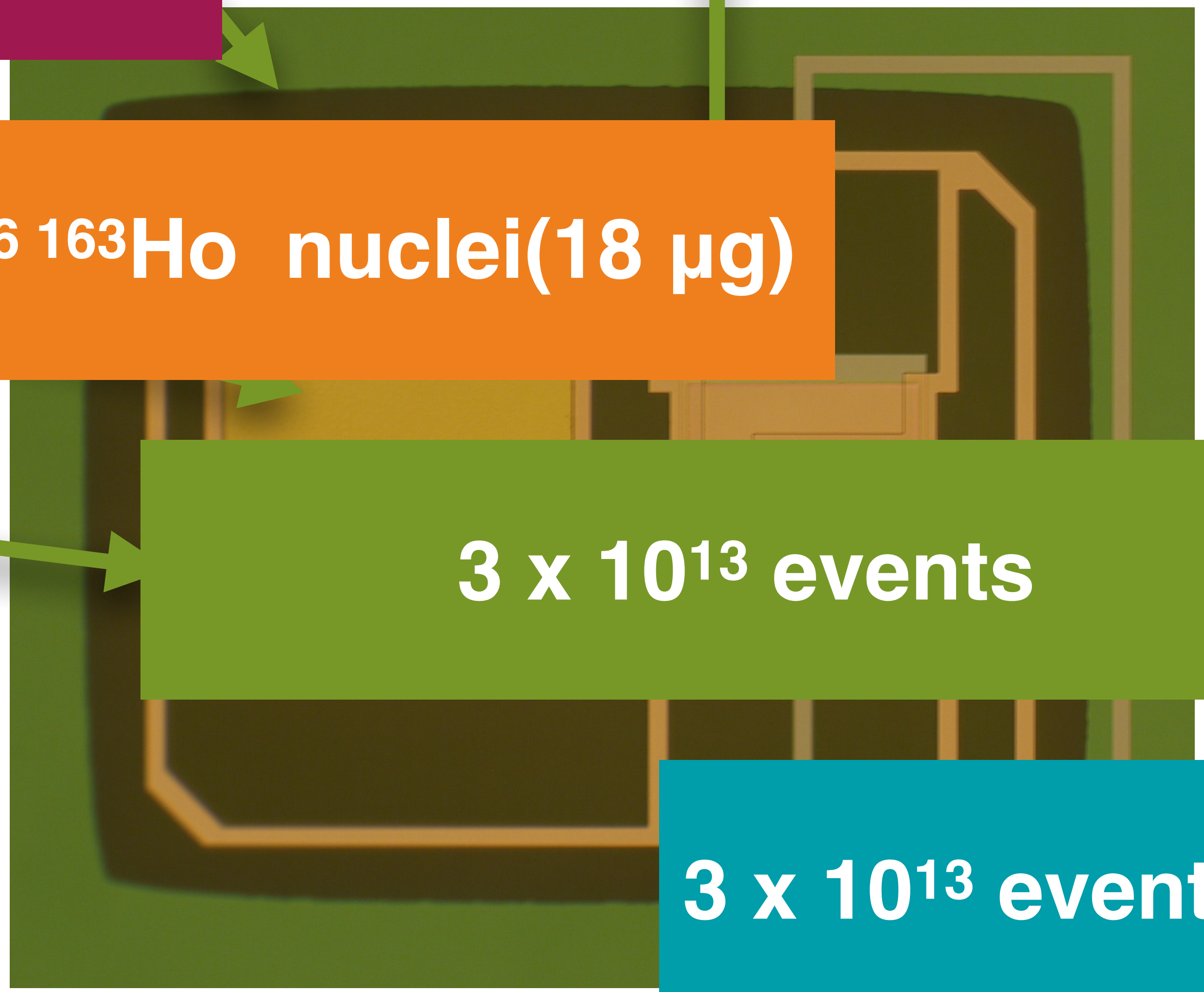
1024 detectors (16 arrays)

MoCu bilayer TES

gold absorb

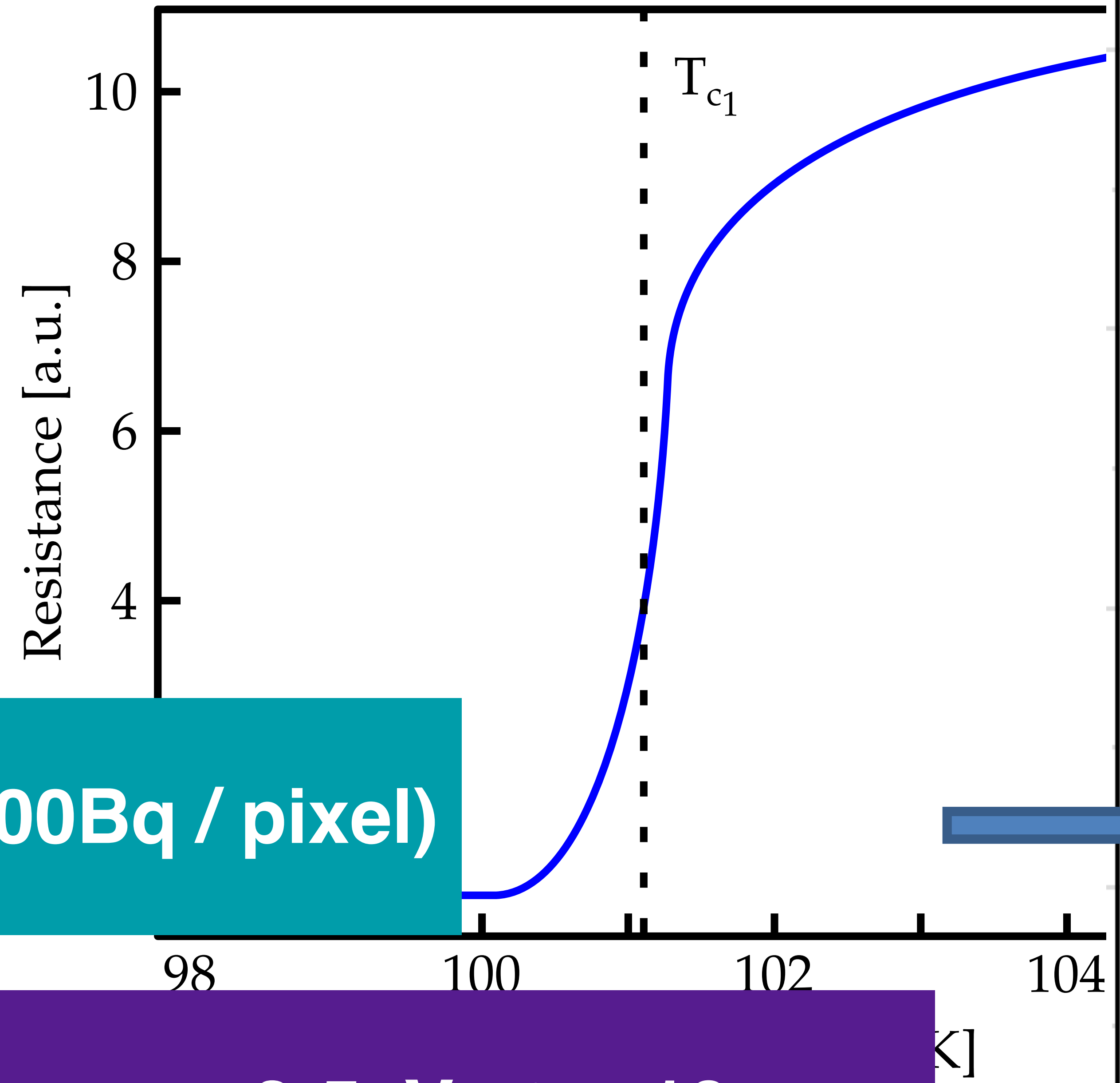
6.5 x 10^{16} ^{163}Ho nuclei(18 µg)

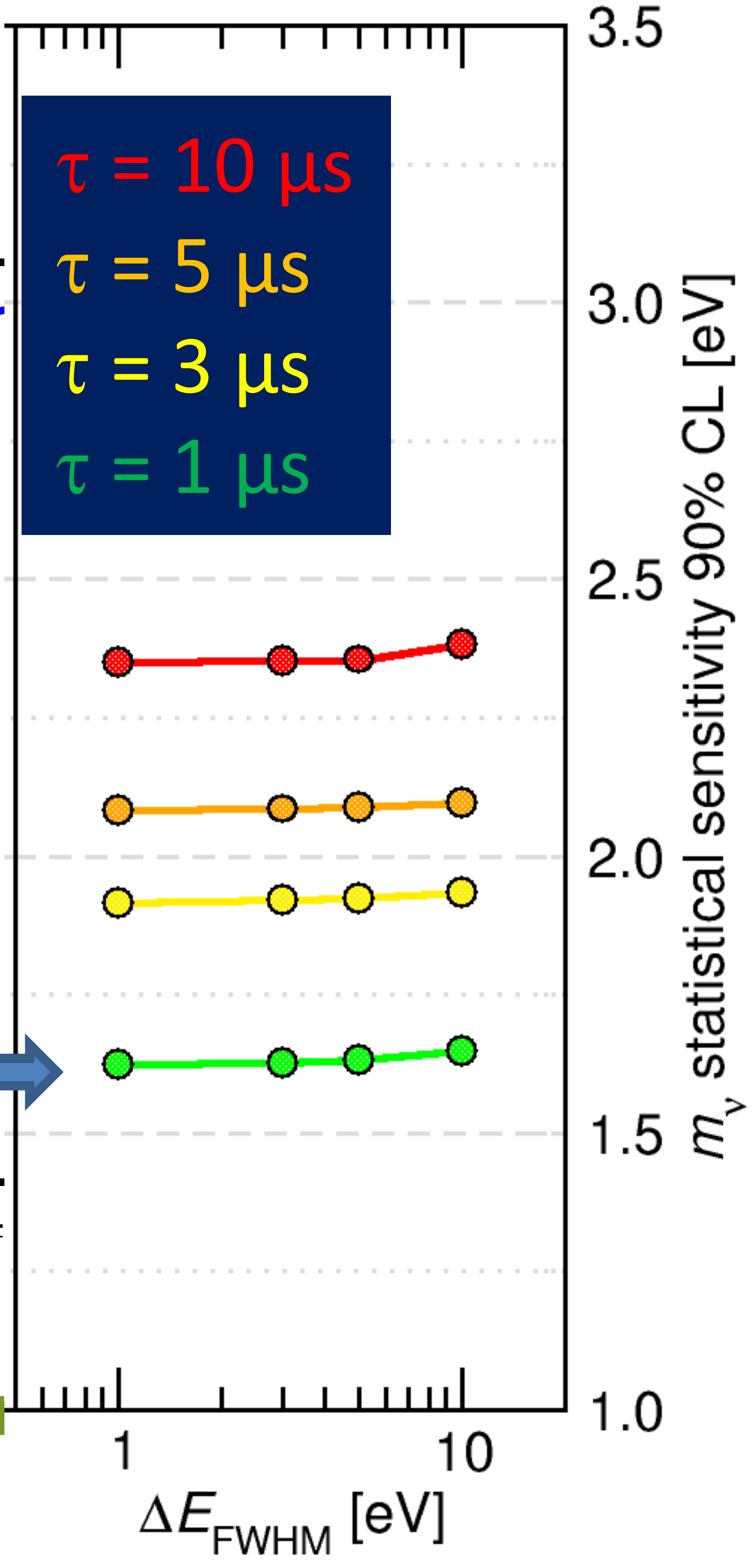
thermal radiating perimeter increases *G*



3 x 10^{13} events

3 x 10^{13} events (300Bq / pixel)



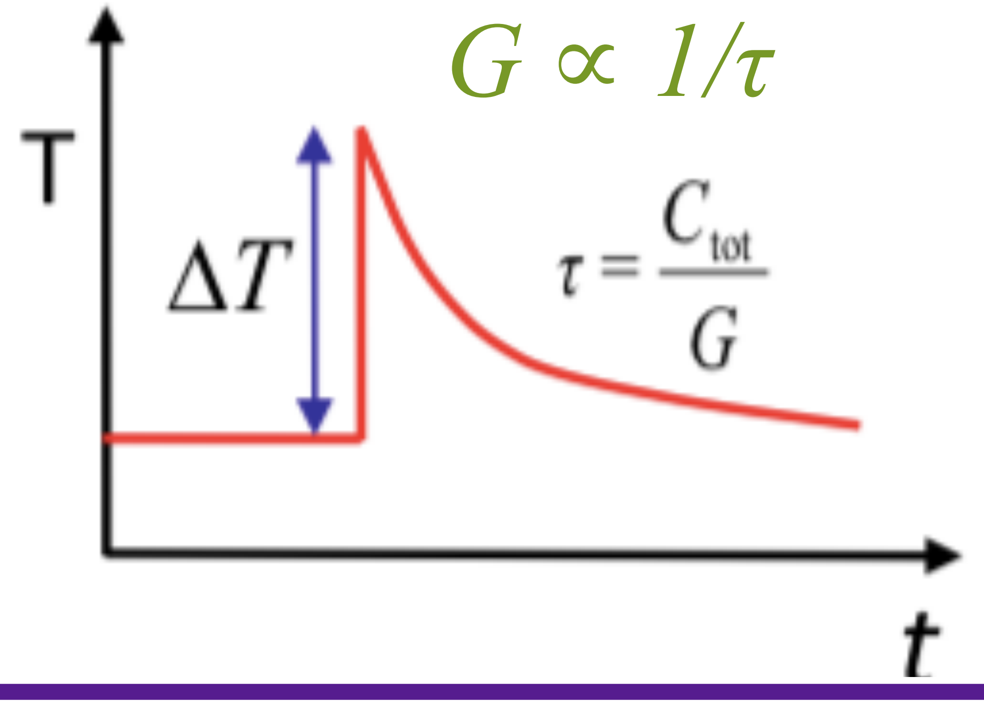


ies with
t super-
se

100r

ΔE_{FWHM} ~ 3-5eV; Δt ~ 10 µ s

$G \propto 1/\tau$



HOLMES: transition-edge sensors

JINST 12 C02046 2017

^{163}Ho isotope production → ^{163}Ho source embedding → Single detector optimization → **HOLMES array** → **Full HOLMES**

1024 detectors (16 arrays)

6.5 x 10^{16} ^{163}Ho nuclei(18 μg)

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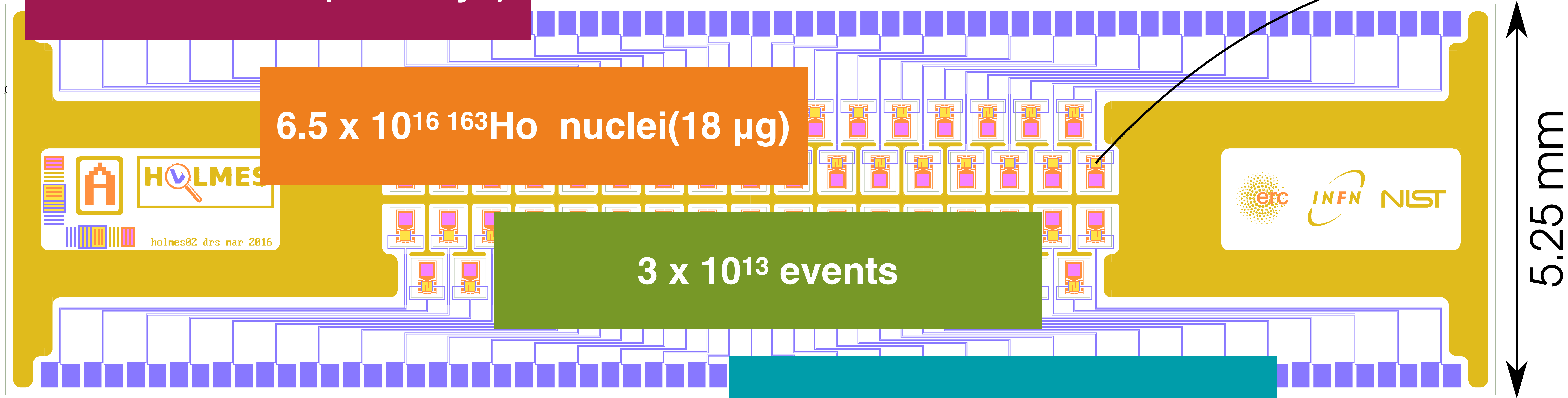

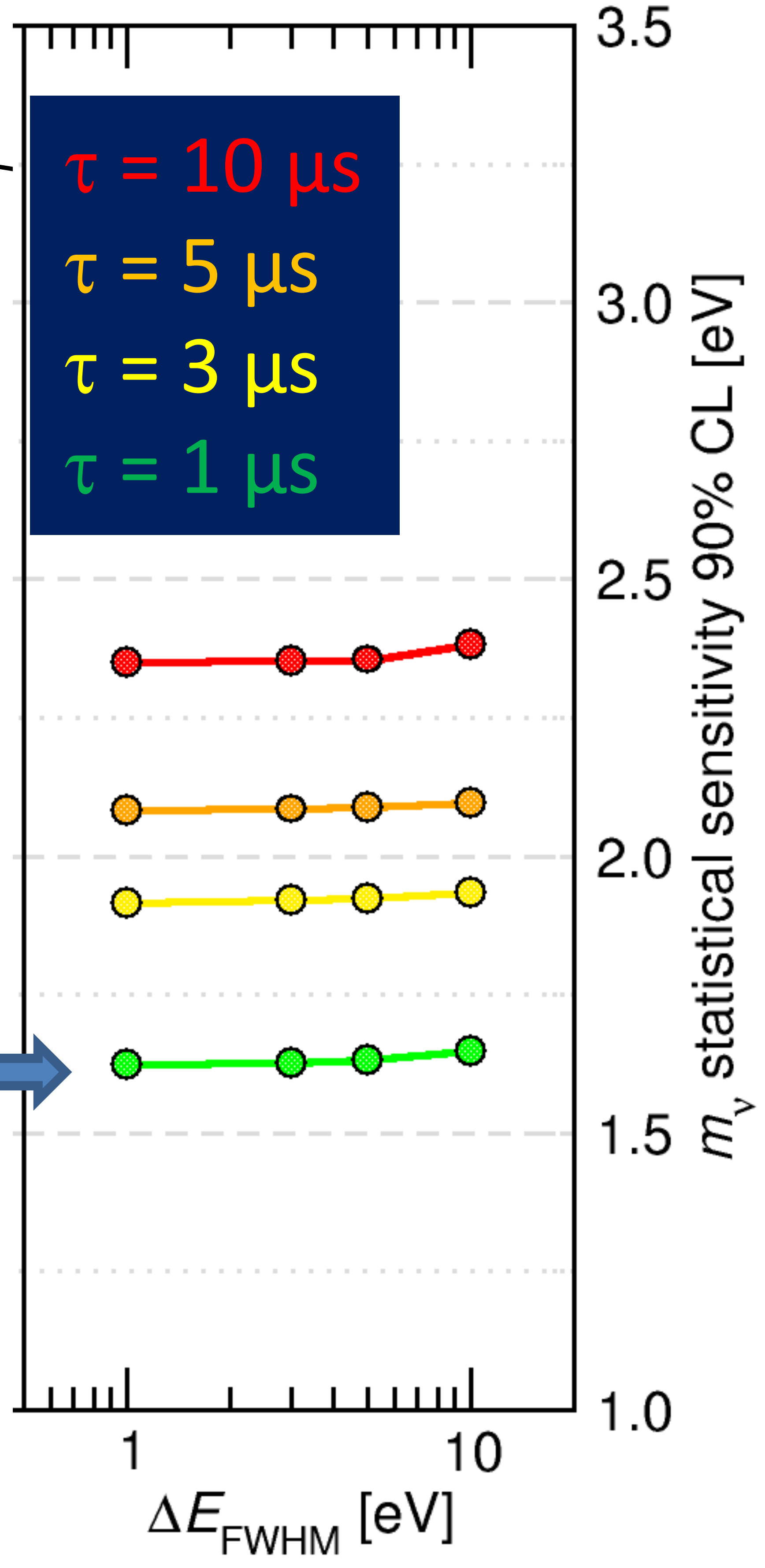

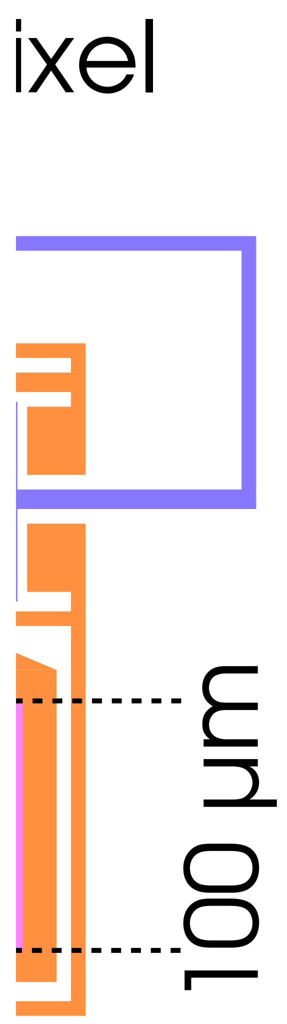

- TES current converted and modulated using **rf-SQUID**
- Each channel at different frequency
- **4x16 detector** prototype

ΔE_{FWHM} ~ 3-5eV; Δt ~ 10 μ s

HOLMES: transition-edge sensors

JINST 12 C02046 2017

^{163}Ho isotope production → ^{163}Ho source embedding → Single detector optimization → Holmes array → **Full HOLMES**

1024 detectors (16 arrays)

6.5 x 10^{16} ^{163}Ho nuclei (18 μg)

3 x 10^{13} events

3 x 10^{13} events (300Bq / pixel)

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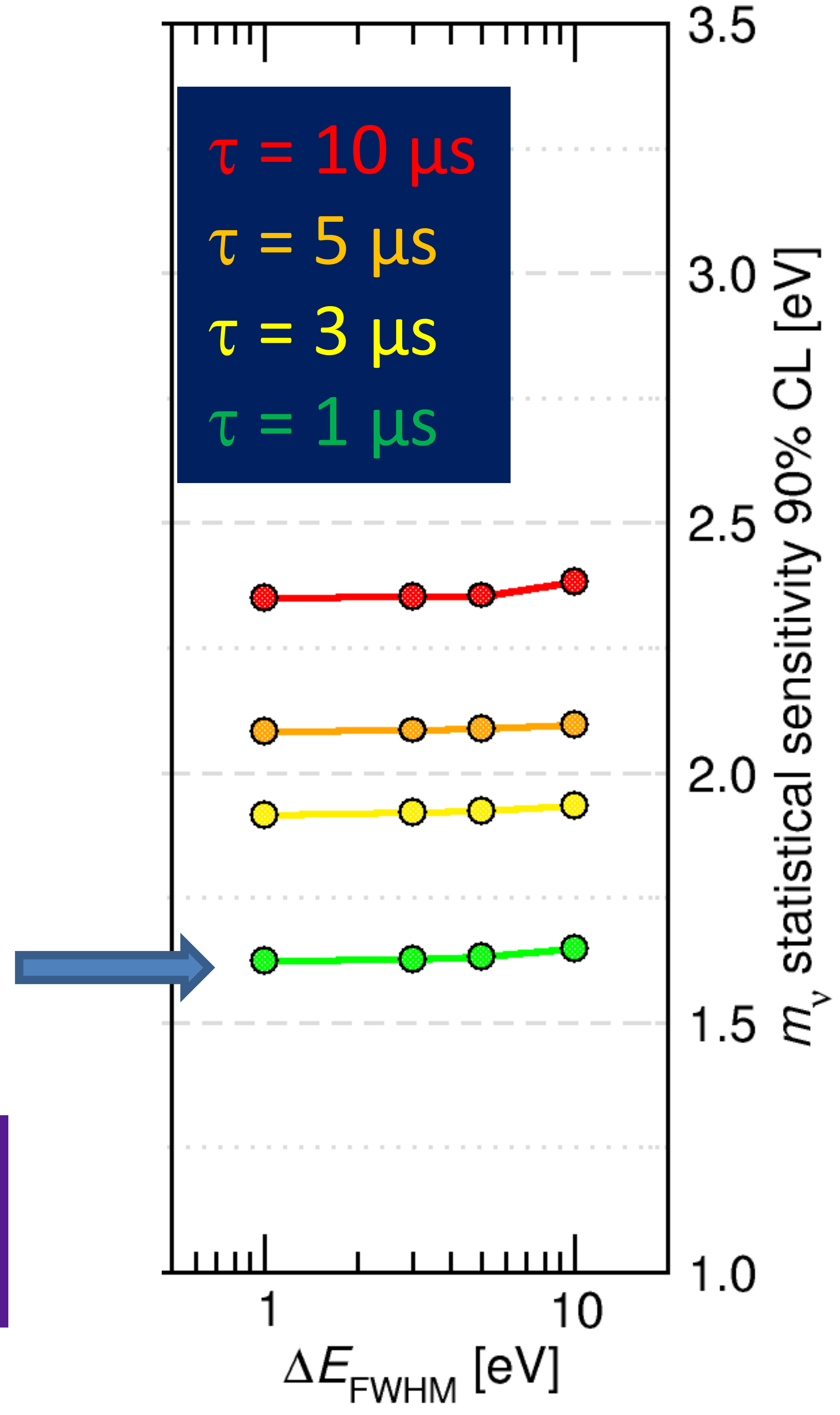
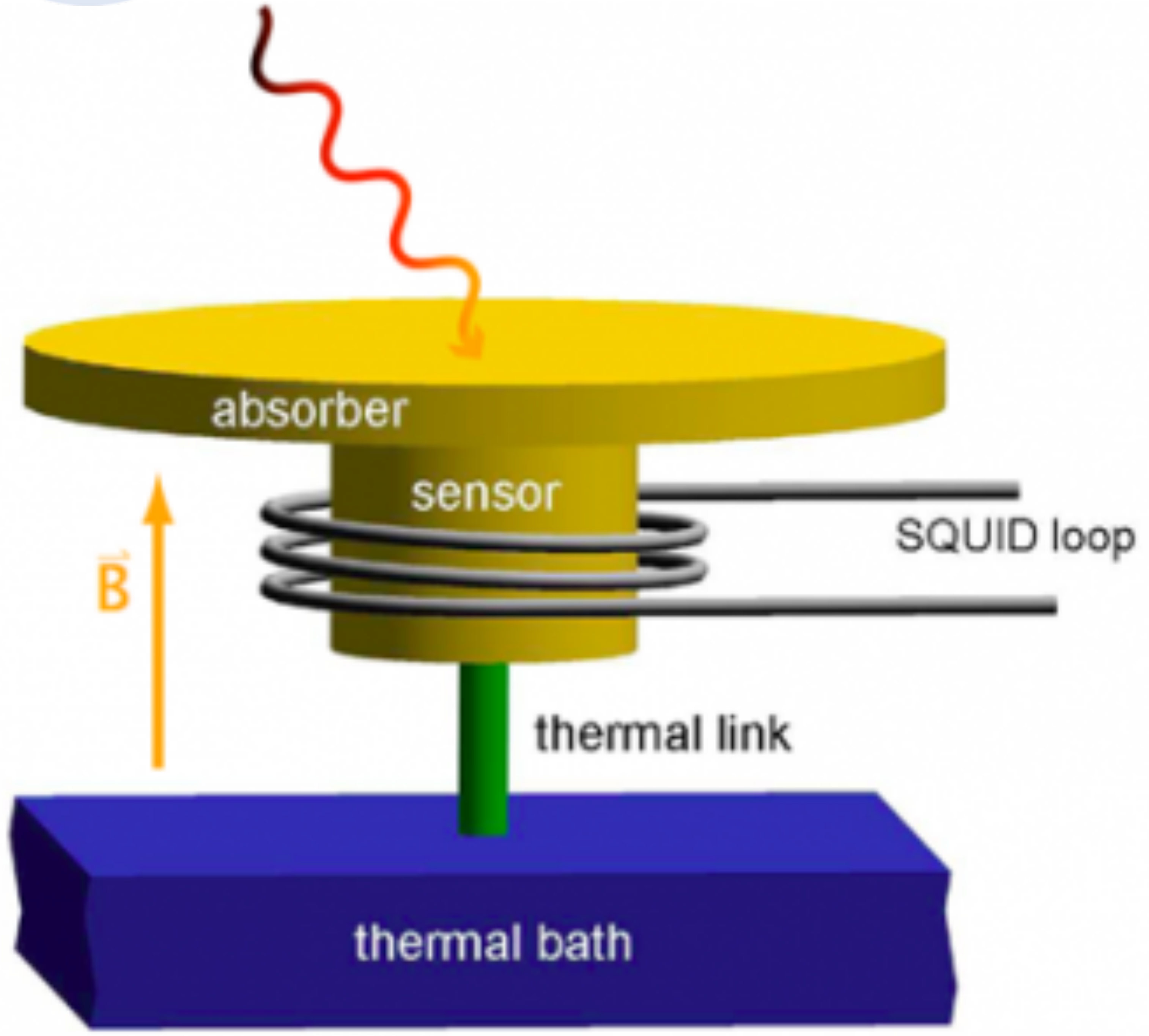


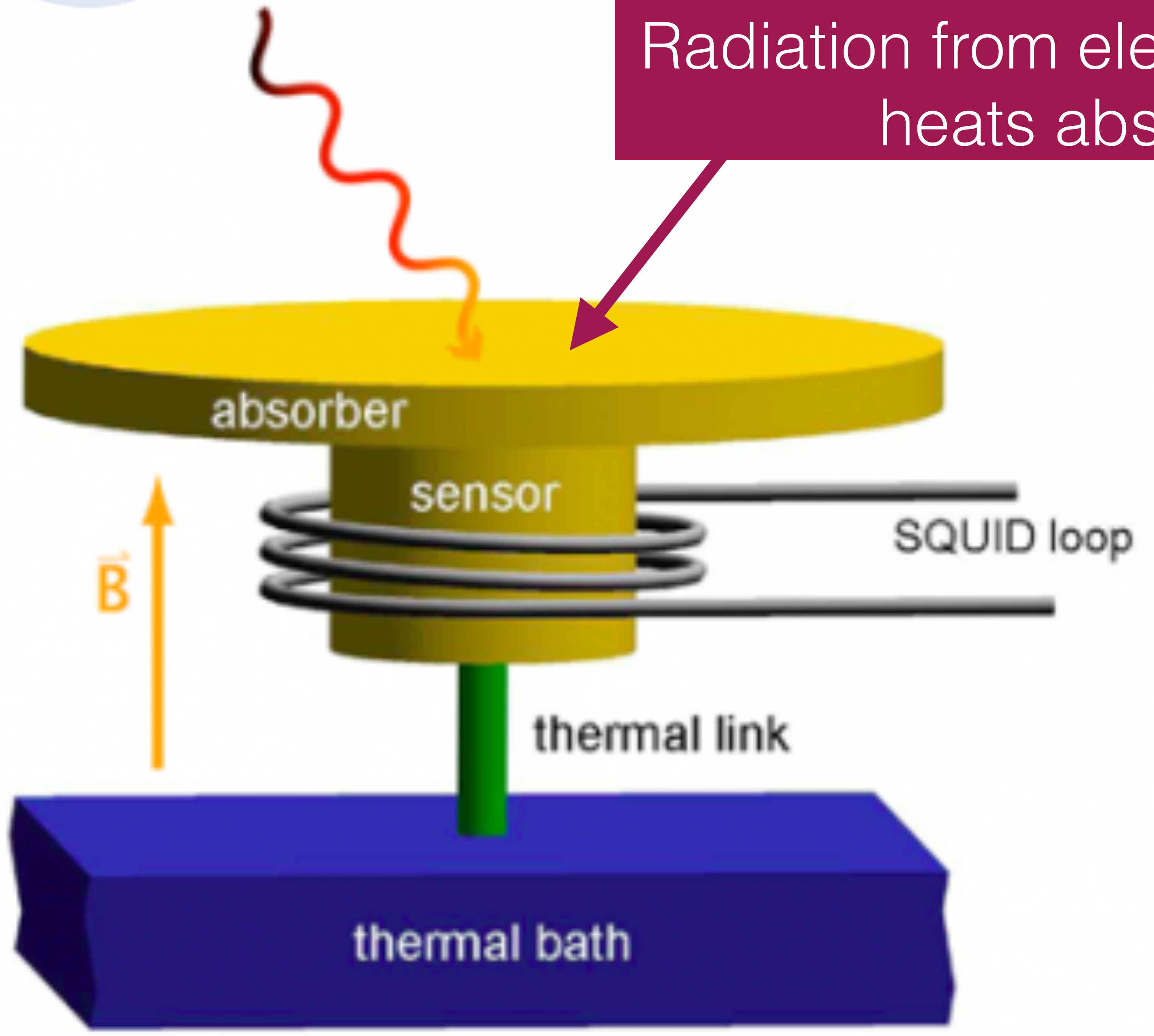
ECHo: metallic magnetic calorimeters



AIP Conf. Proc. 1185, 571, (2009)

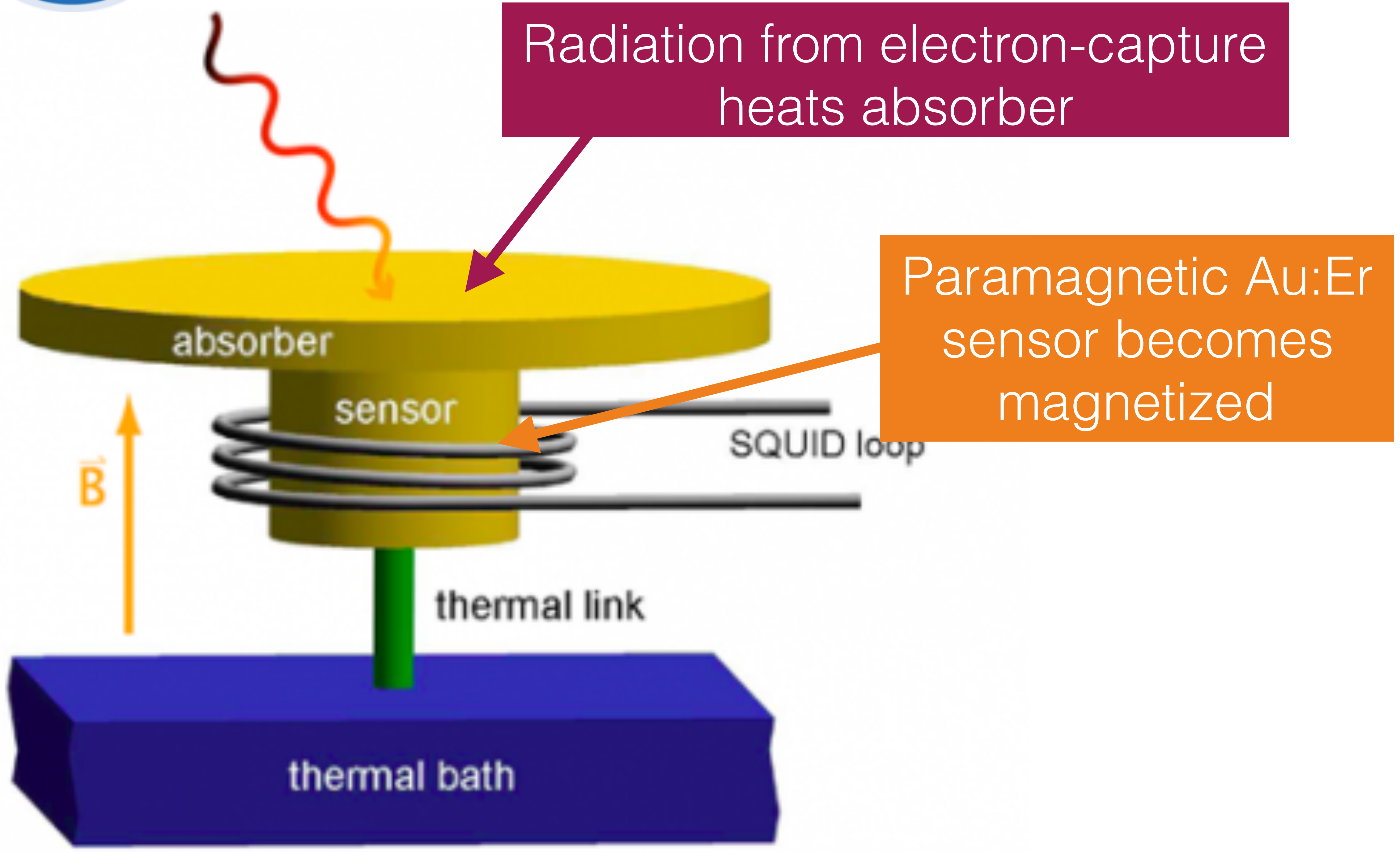
ECHo: metallic magnetic calorimeters

Radiation from electron-capture heats absorber



AIP Conf. Proc. 1185, 571, (2009)

ECHo: metallic magnetic calorimeters



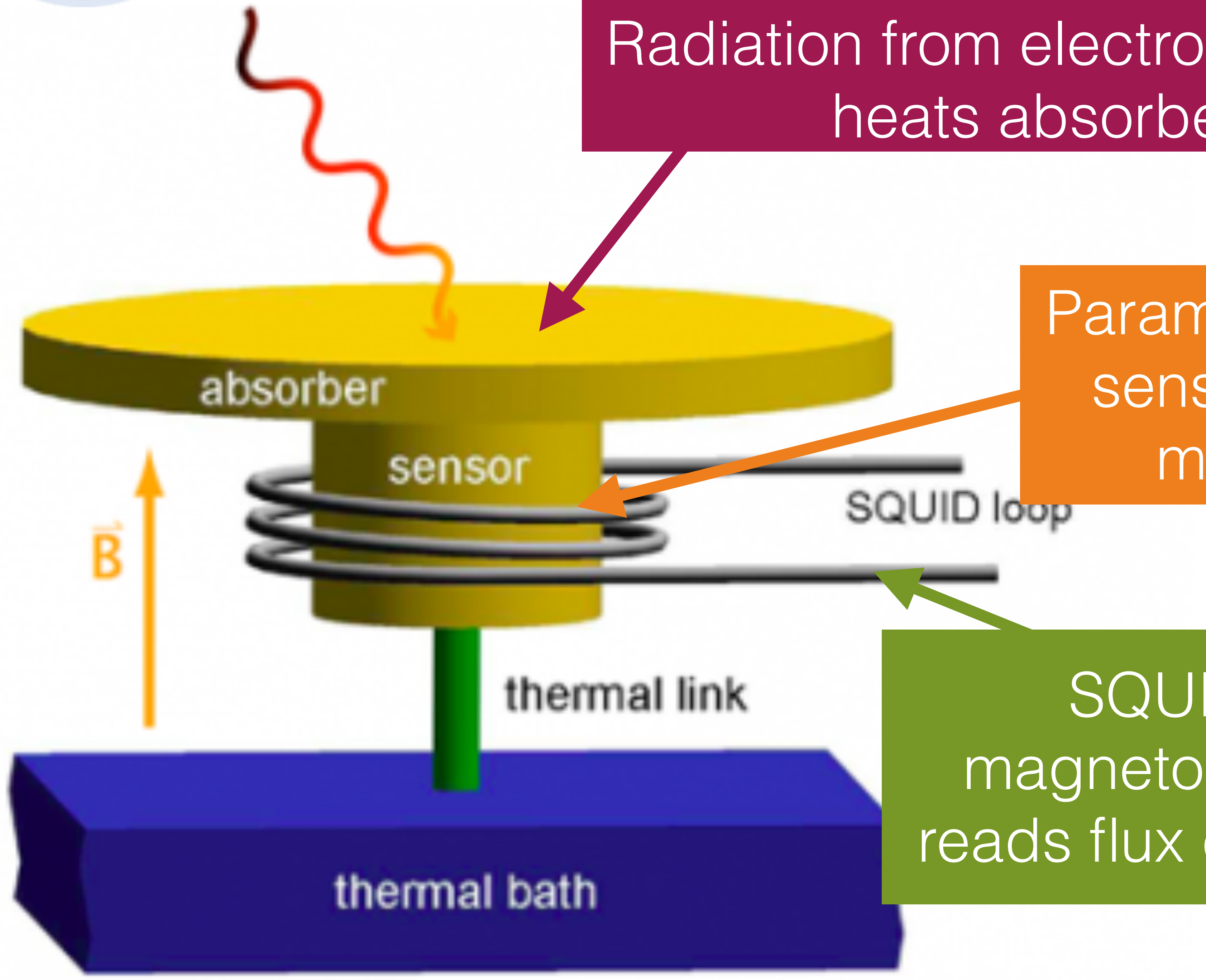
AIP Conf. Proc. 1185, 571, (2009)

ECHo: metallic magnetic calorimeters

Radiation from electron-capture heats absorber

Paramagnetic Au:Er sensor becomes magnetized

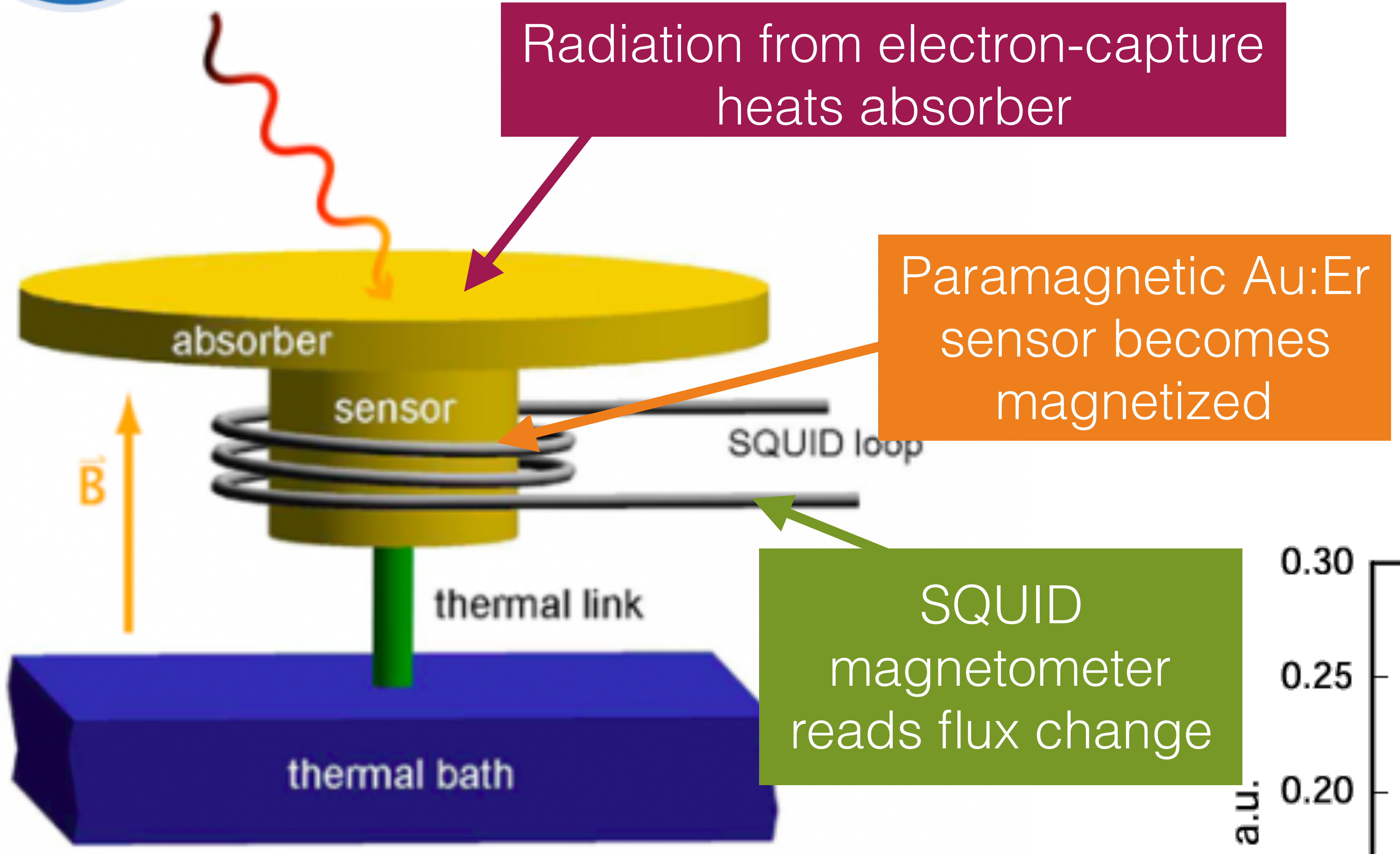
SQUID magnetometer reads flux change



$$\Delta\Phi_S \propto \frac{\partial M}{\partial T}\Delta T \rightarrow \Delta\Phi_S \propto \frac{\partial M}{\partial T}\frac{E}{C_{sens}+C_{abs}}$$

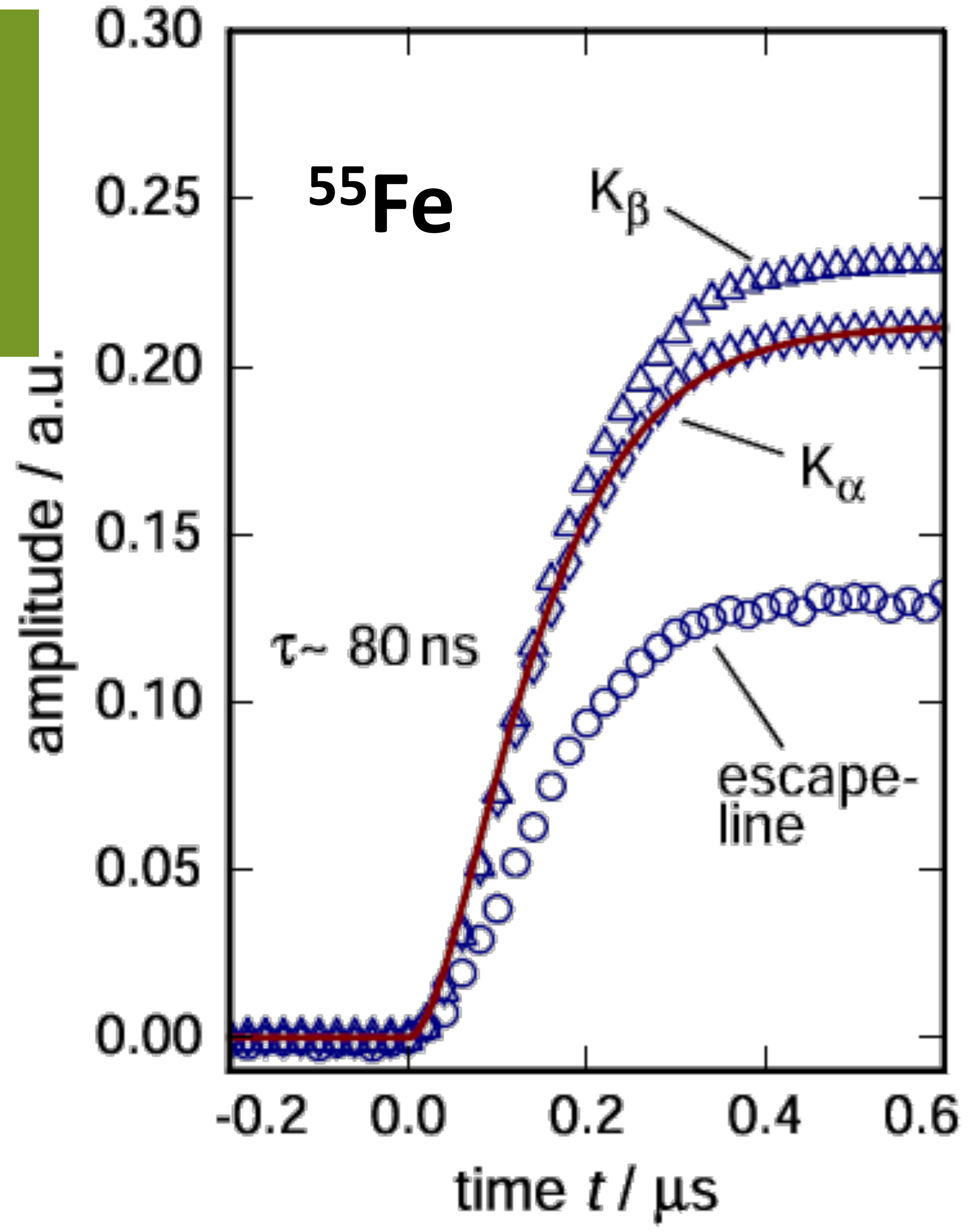
AIP Conf. Proc. 1185, 571, (2009)

ECHo: metallic magnetic calorimeters



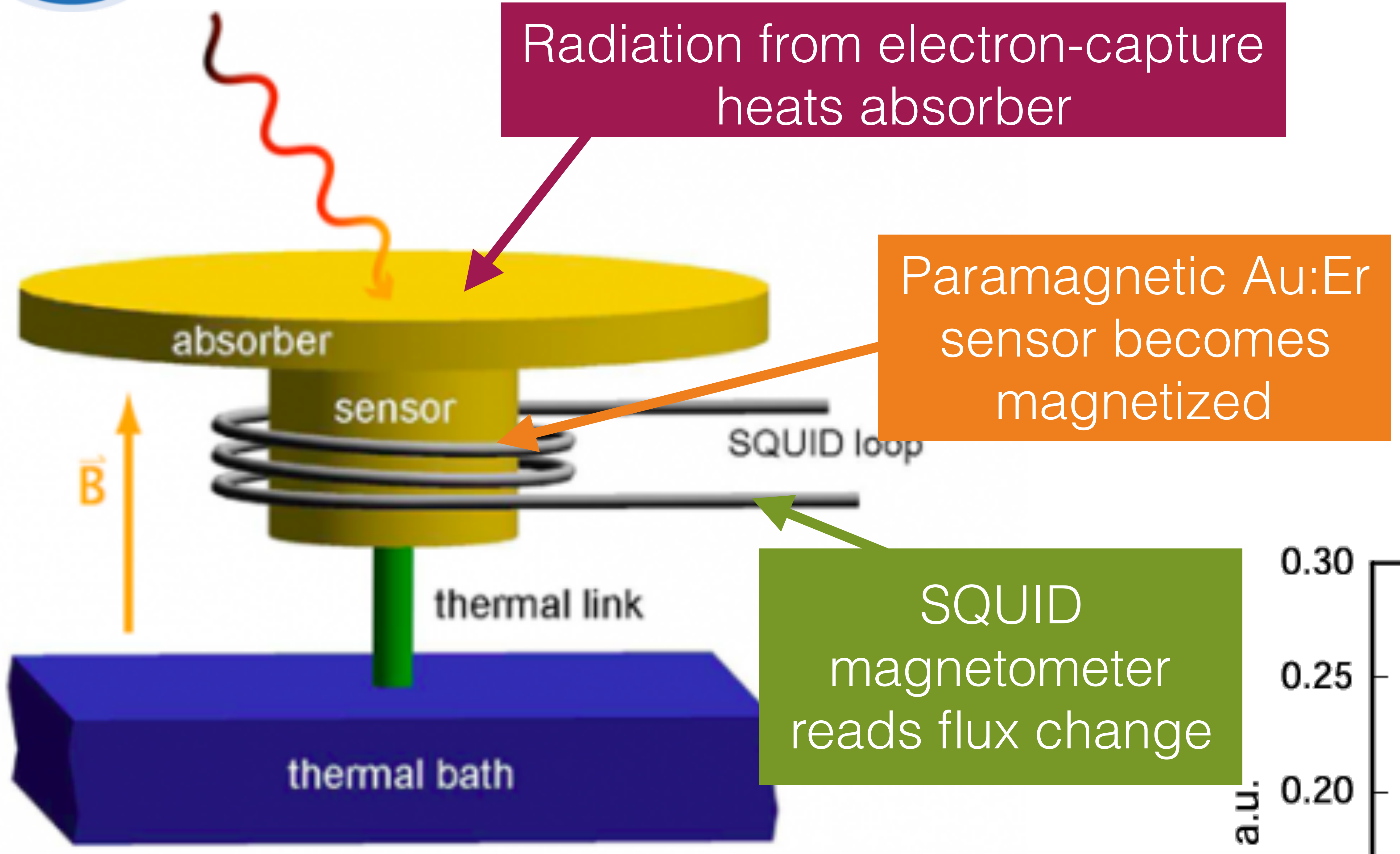
$$\Delta\Phi_S \propto \frac{\partial M}{\partial T}\Delta T \rightarrow \Delta\Phi_S \propto \frac{\partial M}{\partial T}\frac{E}{C_{sens}+C_{abs}}$$

Fast rise time reduces pile-up



AIP Conf. Proc. 1185, 571, (2009)

ECHo: metallic magnetic calorimeters



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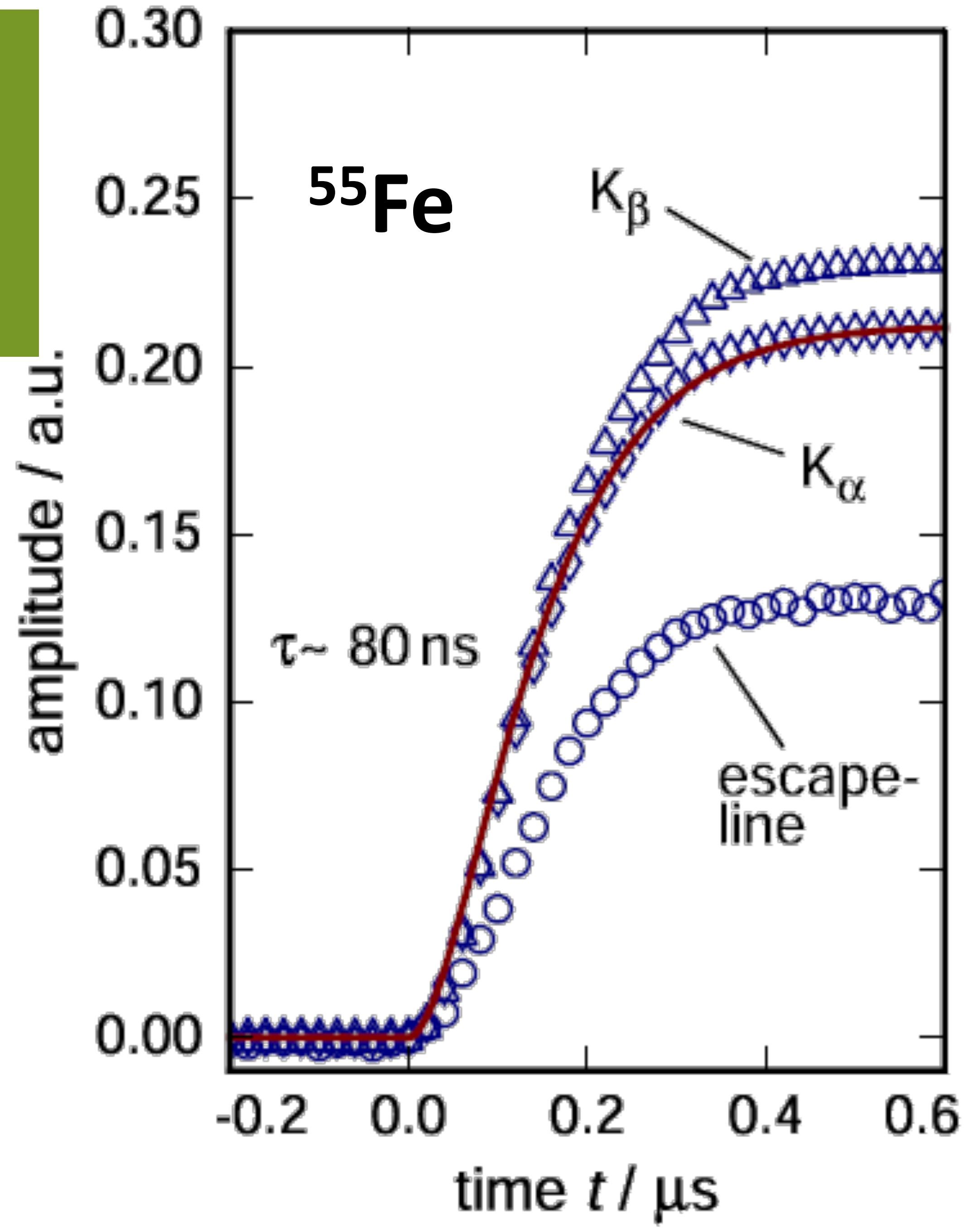
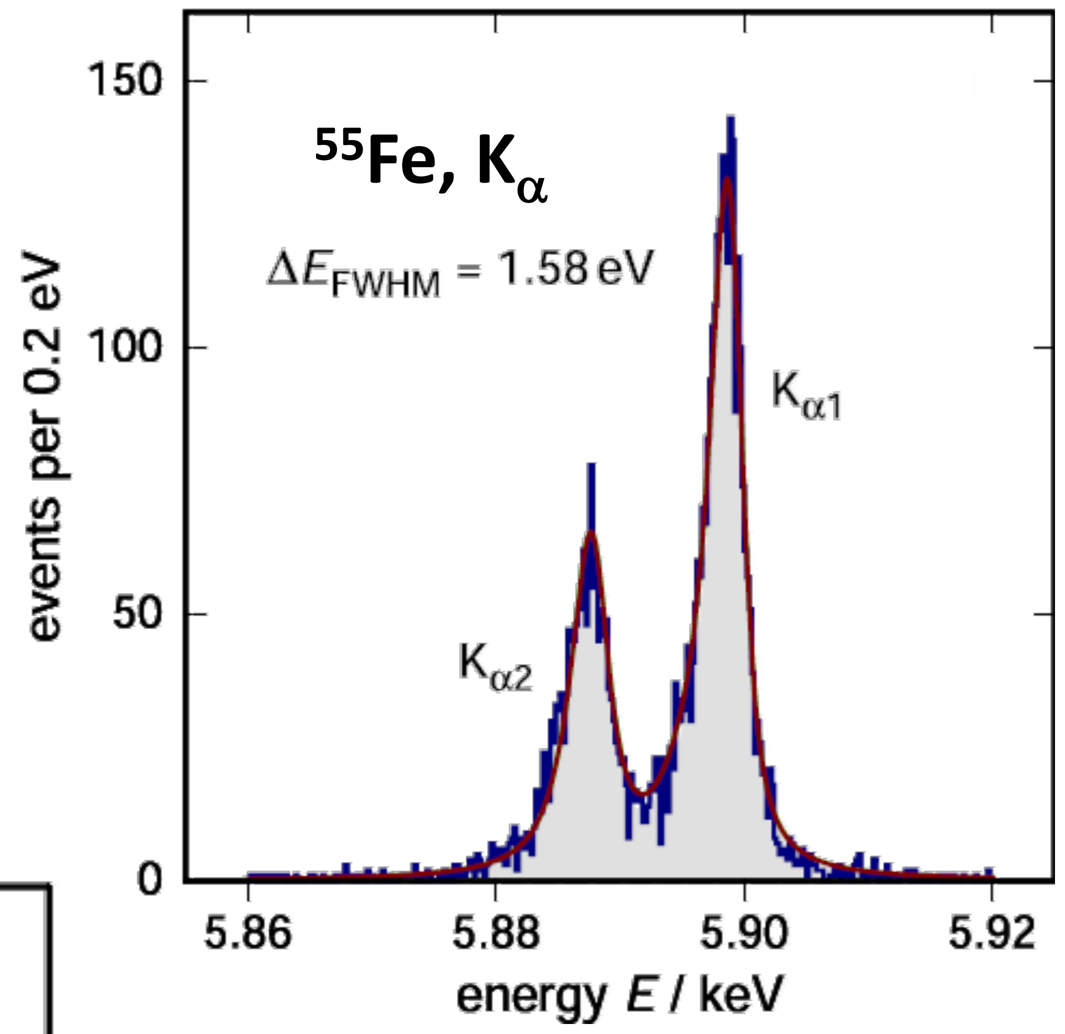
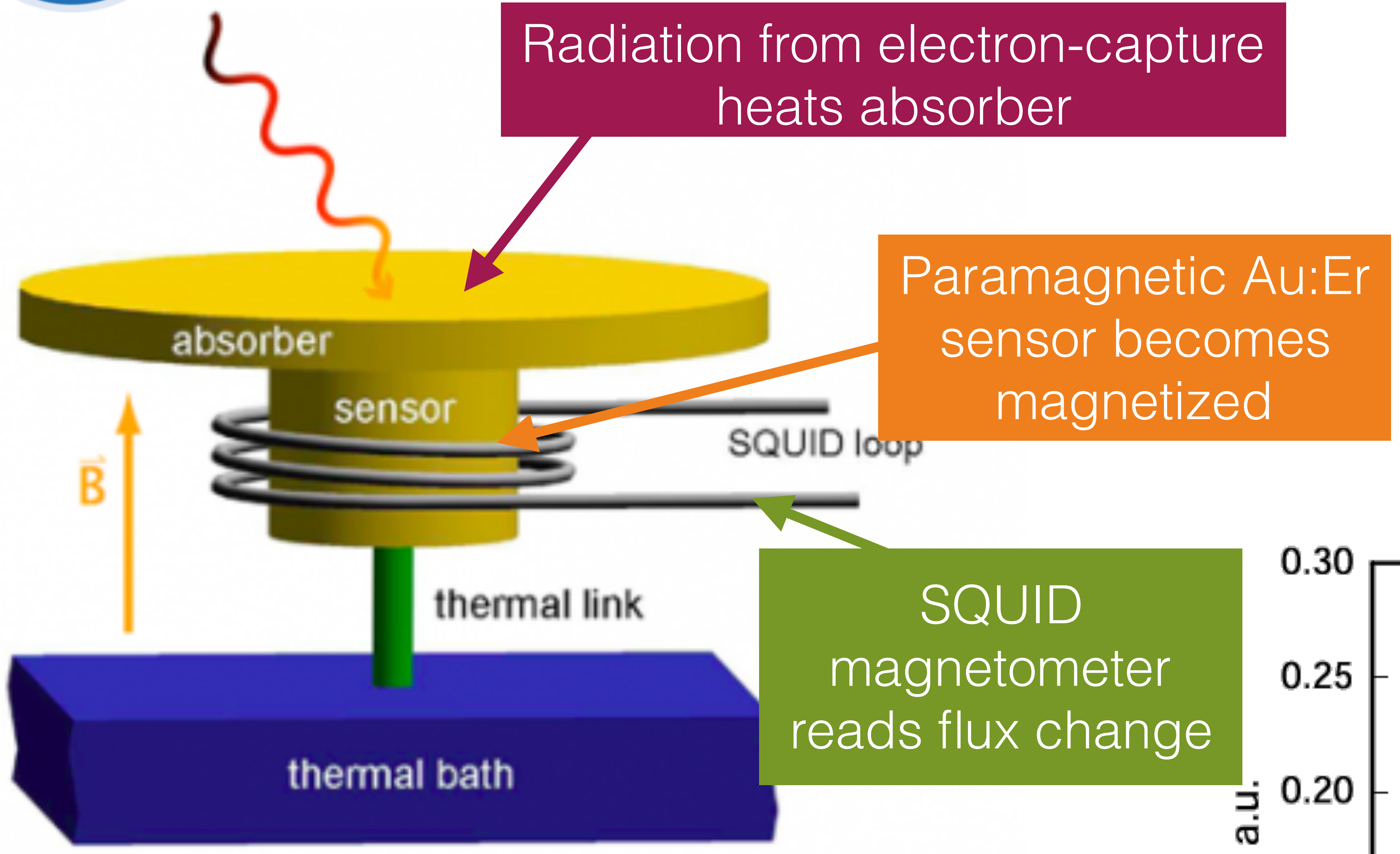




Excellent energy resolution

$\Delta E_{FWHM} \sim 1.6$ eV

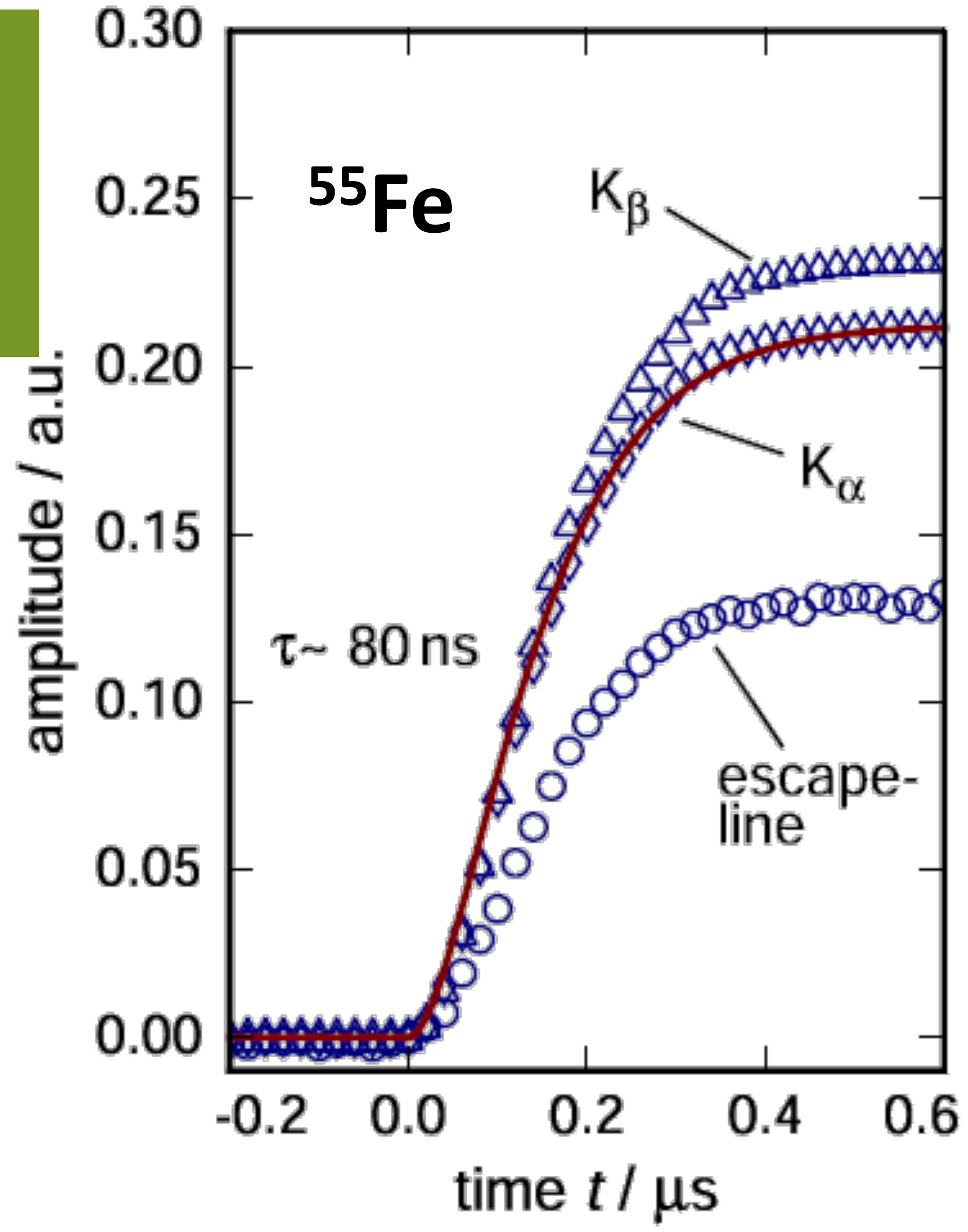
ECHo: metallic magnetic calorimeters

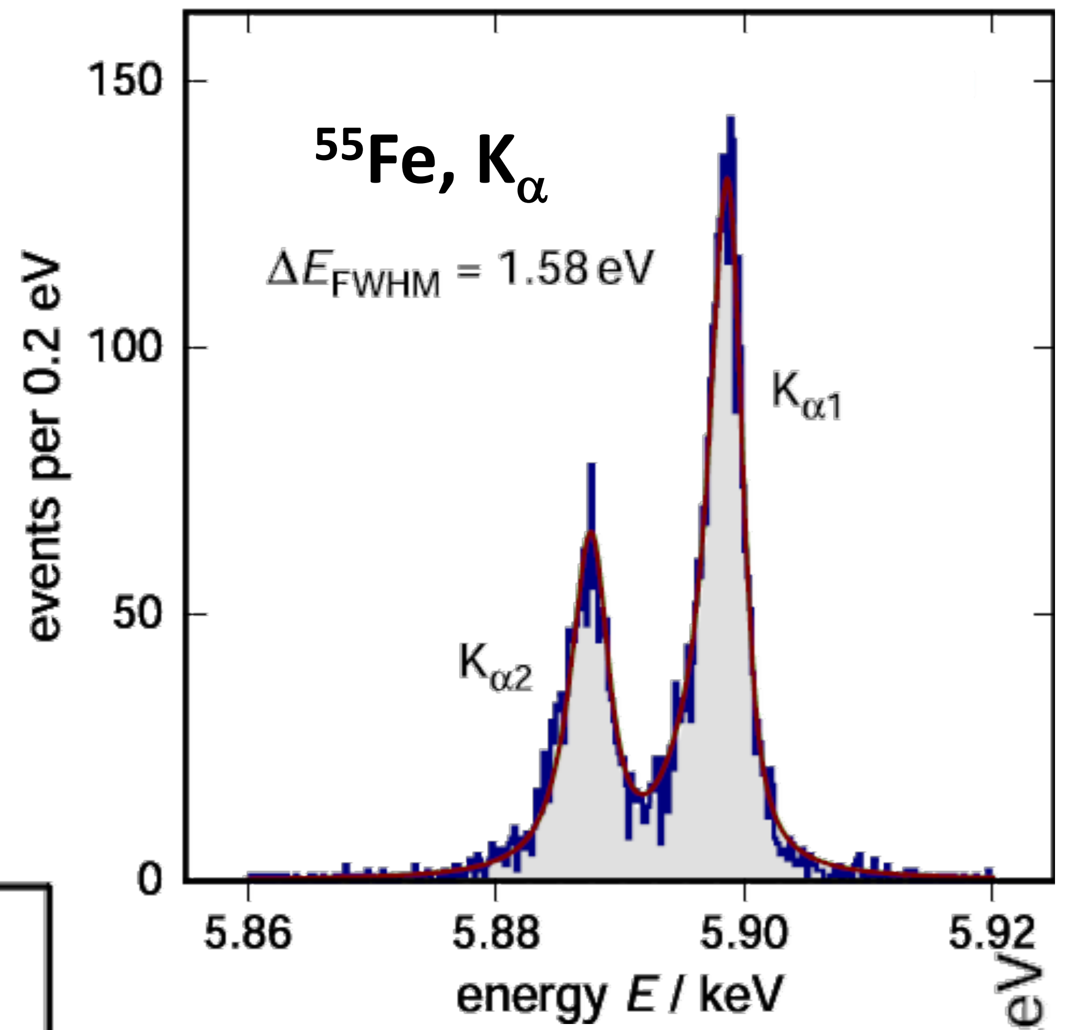


$$\Delta\Phi_S \propto \frac{\partial M}{\partial T}\Delta T \rightarrow \Delta\Phi_S \propto \frac{\partial M}{\partial T}\frac{E}{C_{sens}+C_{abs}}$$

AIP Conf. Proc. 1185, 571, (2009)

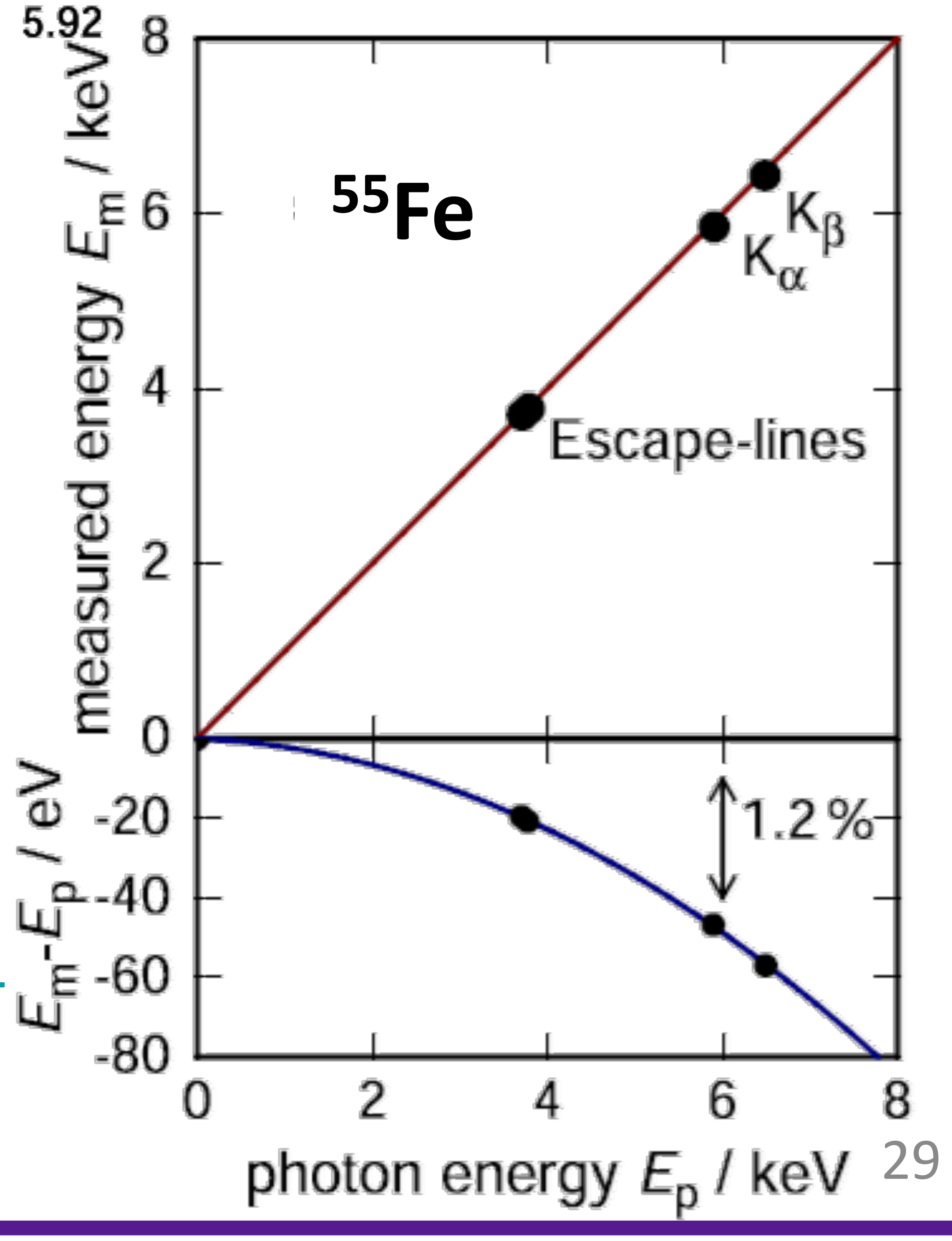
Fast rise time
reduces pile-up



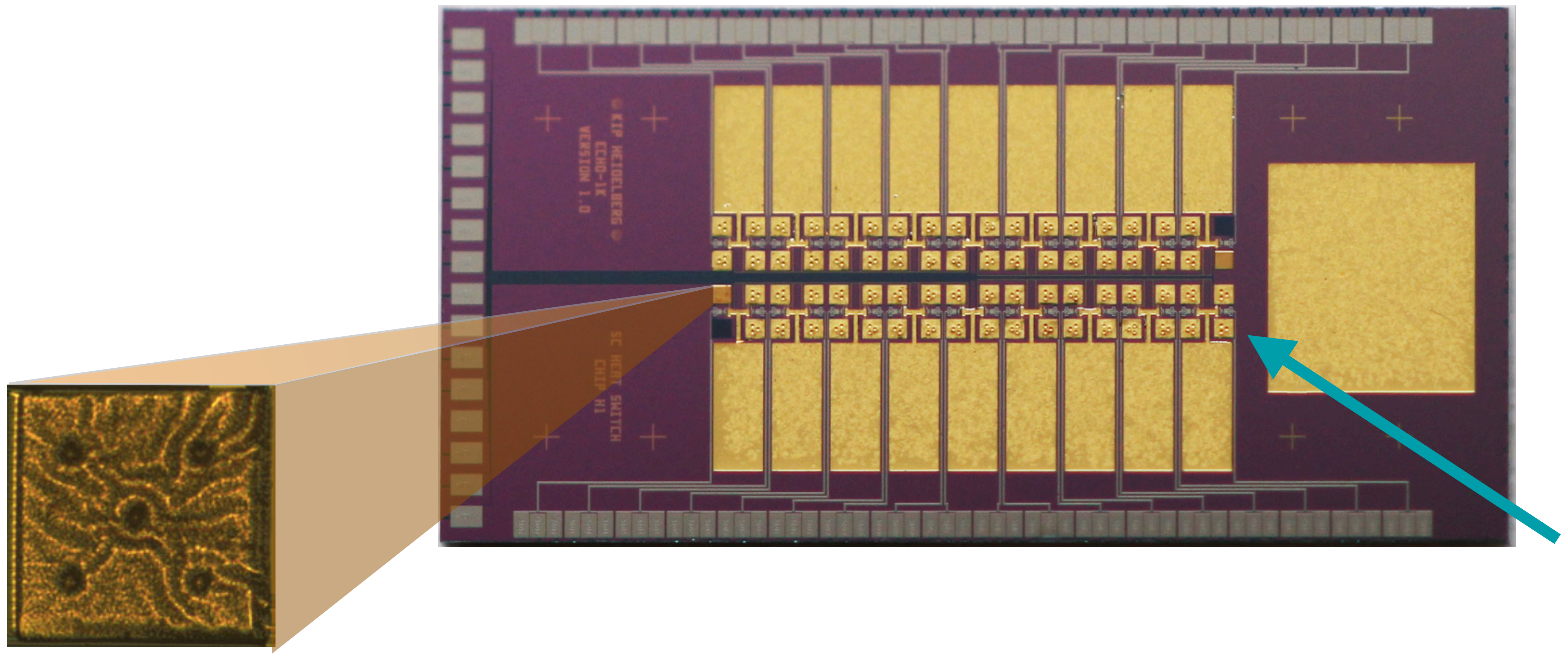


Excellent energy resolution
$\Delta E_{FWHM} \sim 1.6$ eV

Linear response
Energy scale well-understood



ECHo 1k detector

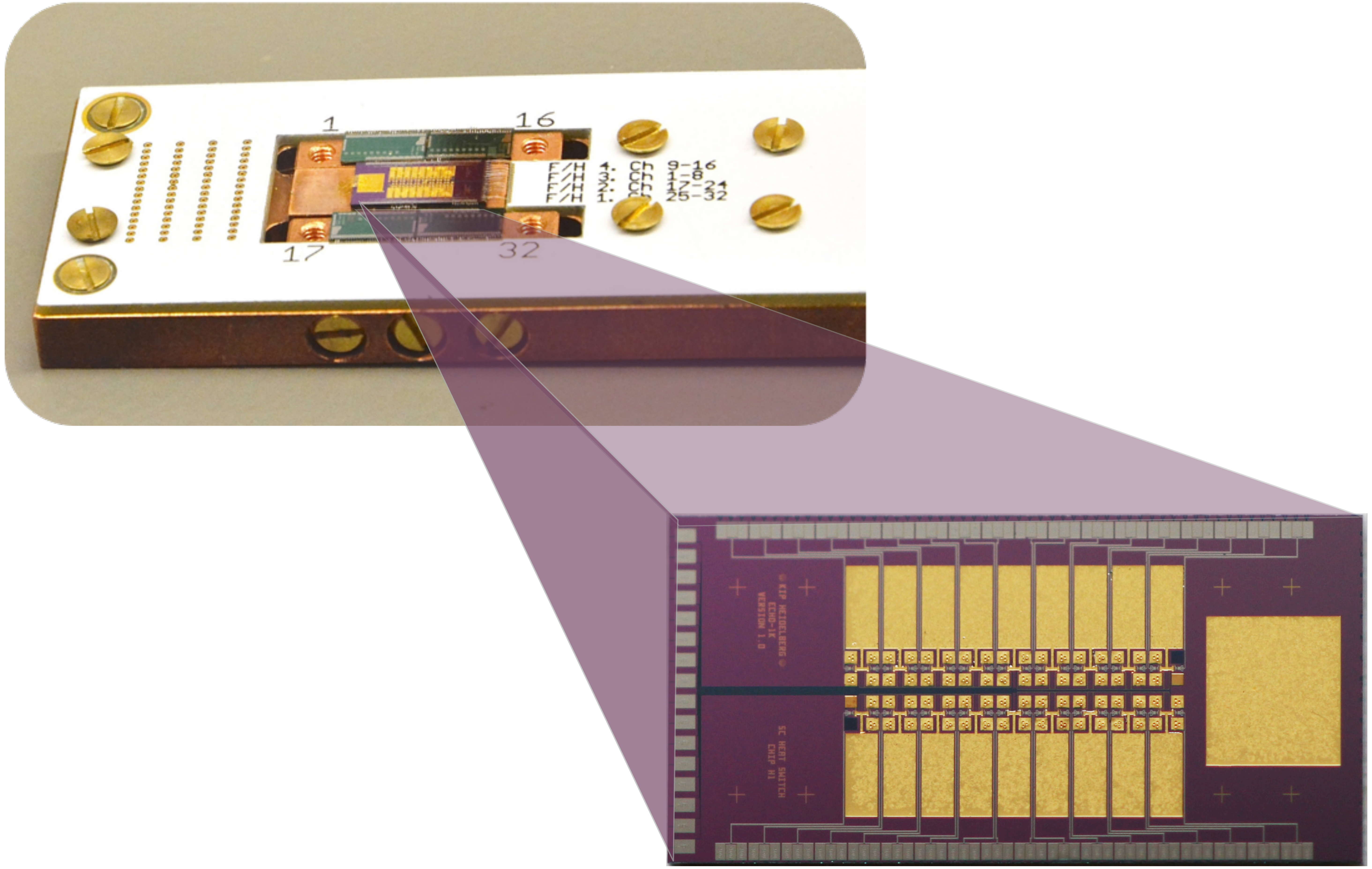


60 pixels with ^{163}Ho sandwiched between (+4 for diagnostics)

L Gastaldo, Neutrino 2018
doi: 10.5281/zenodo/1286949

ECHo 1k detector

100Bq 64-pixel prototype at RISIKO (Mainz)



L Gastaldo, Neutrino 2018
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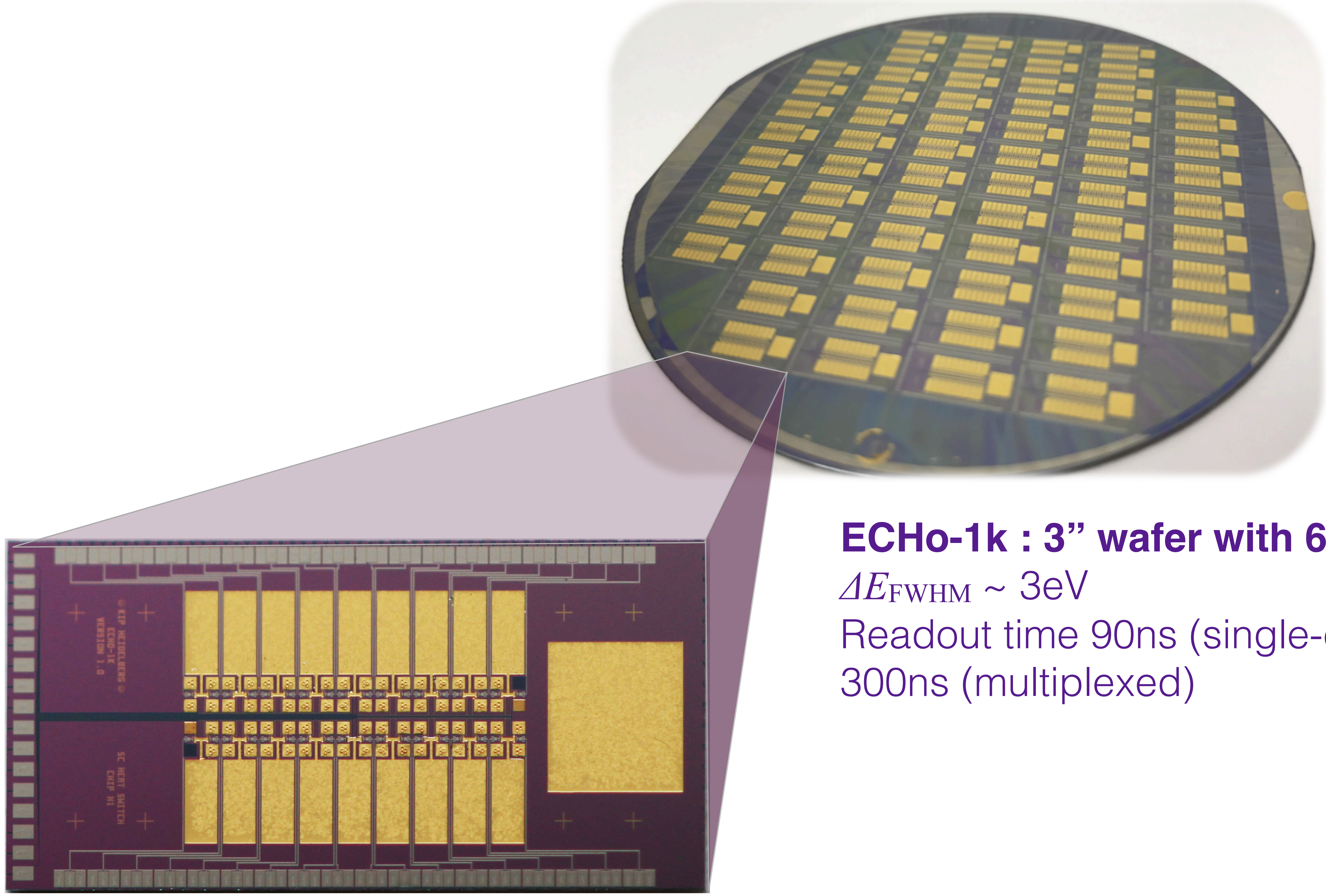
ECHo 1k detector



ECHo-1k : 3” wafer with 64 chips
ΔE_{FWHM} ~ 3eV
Readout time 90ns (single-channel)
300ns (multiplexed)

L Gastaldo, Neutrino 2018
doi: 10.5281/zenodo/1286949

The future: ECHo 1M detector

Scale up

- Total activity **1MBq**
- Neutrino mass sensitivity < **1eV**
- Approximately **50 wafers of ~1000 detectors** each

Holmium production

- Chemical separation for **bigger Er samples**
- Improved ^{162}Er **enrichment**
- Study ^{163}Ho(n,γ) reaction to optimise **irradiation time**

Optimise design with ECHo-1k

- Optimal activity per pixel (target $f_{pu} < 10^{-6}$)
- Study different **absorber** materials
- **Signal processing** algorithms for more detectors
- Improve **background** model (10^{-6} counts/eV/det/day)

Eur. Phys. J. Special Topics 226, 1623–1694 (2017)

^{163}Ho demonstrators

Advances in High Energy Physics 2016 (9) *L Gastaldo (Neutrino 2018)*	ECHo ECHo-1k	HOLMES Proof of concept	
Technology	Metallic magnetic calorimeters	Transition edge sensors	
^{163}Ho production	^{162}Er (n,γ)	^{162}Er (n,γ)	
Number of detectors	60	64	
Activity per detector	5 Bq	300 Bq	
Energy resolution	< 5eV	target 1 eV	
Run time	1 year	1 month	1eV goal
Neutrino mass sensitivity	< 10 eV	< 10 eV	

^{163}Ho demonstrators

UCL

Advances in High Energy Physics 2016 (9) *L Gastaldo (Neutrino 2018)*	ECHo ECHo-100k	HOLMES Full design	NuMECS
Technology	**Metallic magnetic calorimeters**	**Transition edge sensors**	**Transition edge sensors**
^{163}Ho production	**^{162}Er** (n,γ)	**^{162}Er** (n,γ)	**Dy** $(p,)$
Number of detectors	**12000**	**1000**	**4096**
Activity per detector	**10 Bq**	**300 Bq**	**100 Bq**
Energy resolution	**< 5eV**	**target 1 eV**	
Run time	**3 years**	**3 years**	**1 year** 1eV goal
Neutrino mass sensitivity	**< 1 eV**	**< 1 eV**	**1 eV**

Did you spot the pictures?

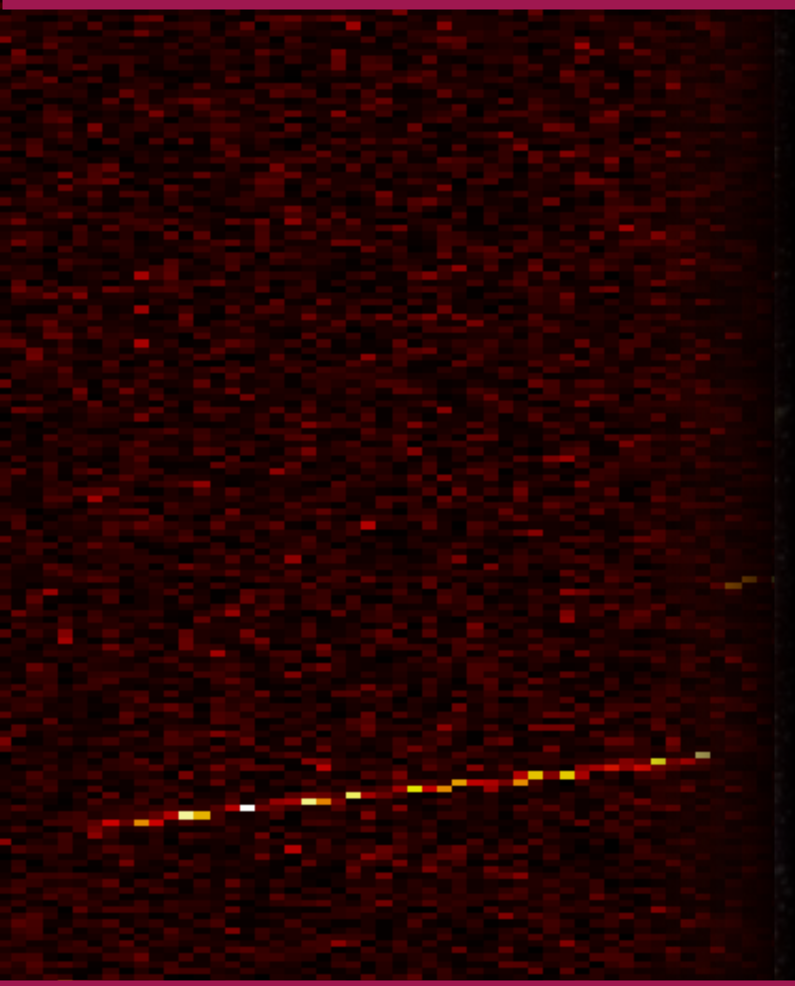
Project 8 event display

Did you spot the pictures?

Project 8 event display

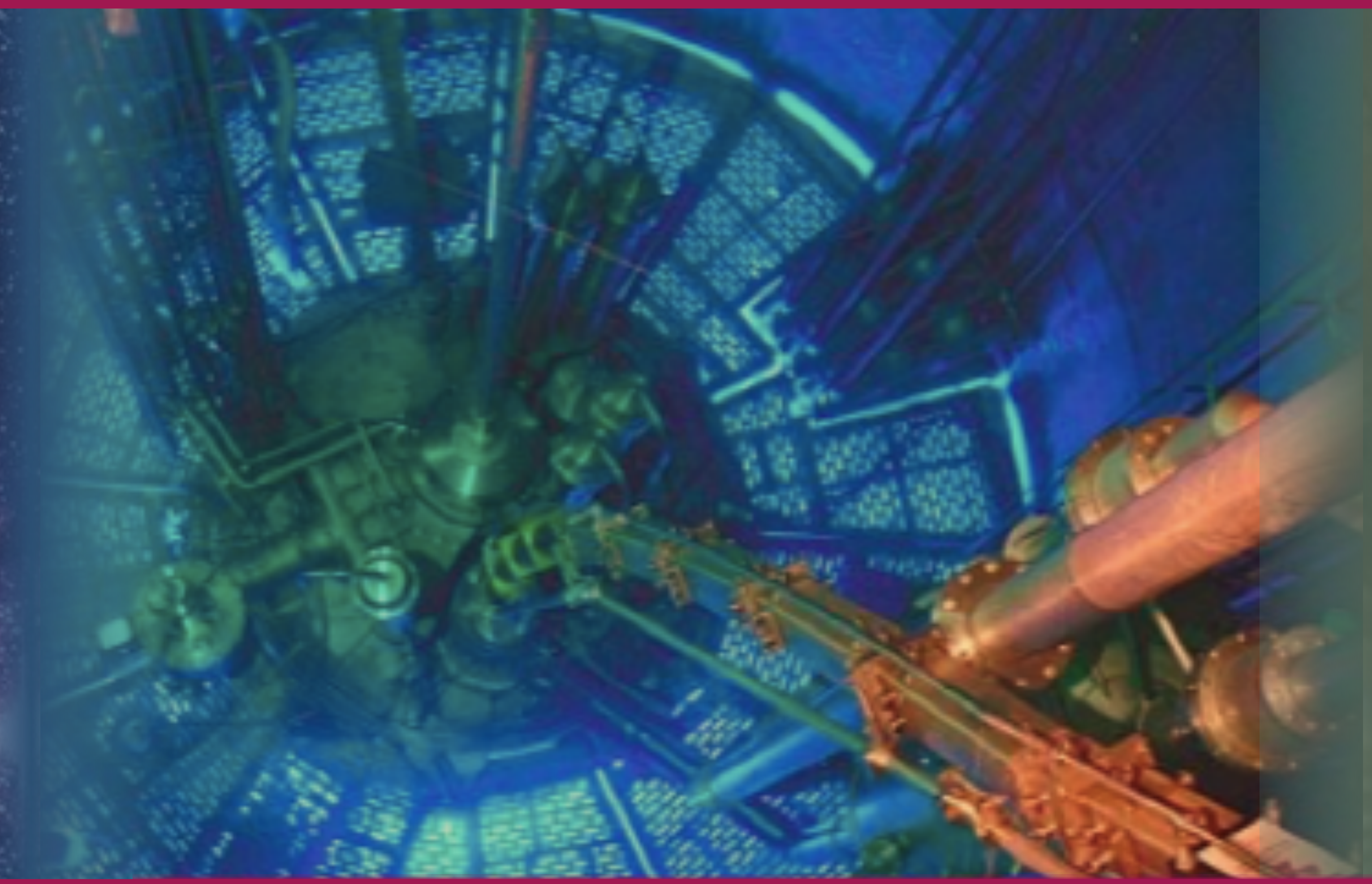
Supernova 1987A

Did you spot the pictures?



Project 8 event display

Supernova 1987A



ILL reactor making ^{163}Ho for ECHo

Did you spot the pictures?

Project 8 event display

Supernova 1987A

ILL reactor making ^{163}Ho for ECHo

KATRIN spectrometer

Did you spot the pictures?