Backgrounds at KATRIN and mitigation strategies

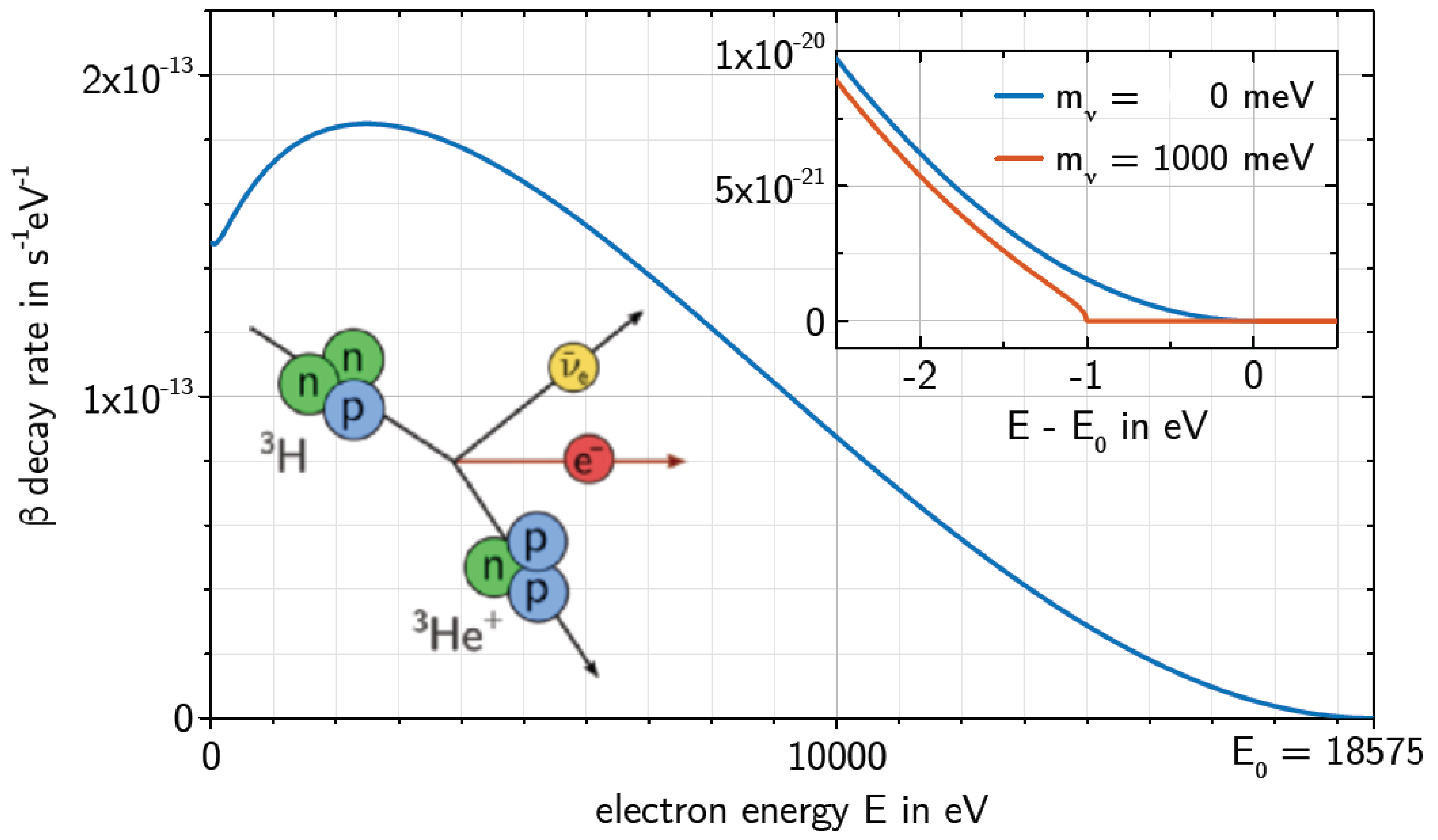
Joscha Lauer (Institute for Astroparticle Physics (IAP), KIT)
for the KATRIN Collaboration

- Introduction
- Sources of background and mitigation
- The remaining background
- Summary and outlook

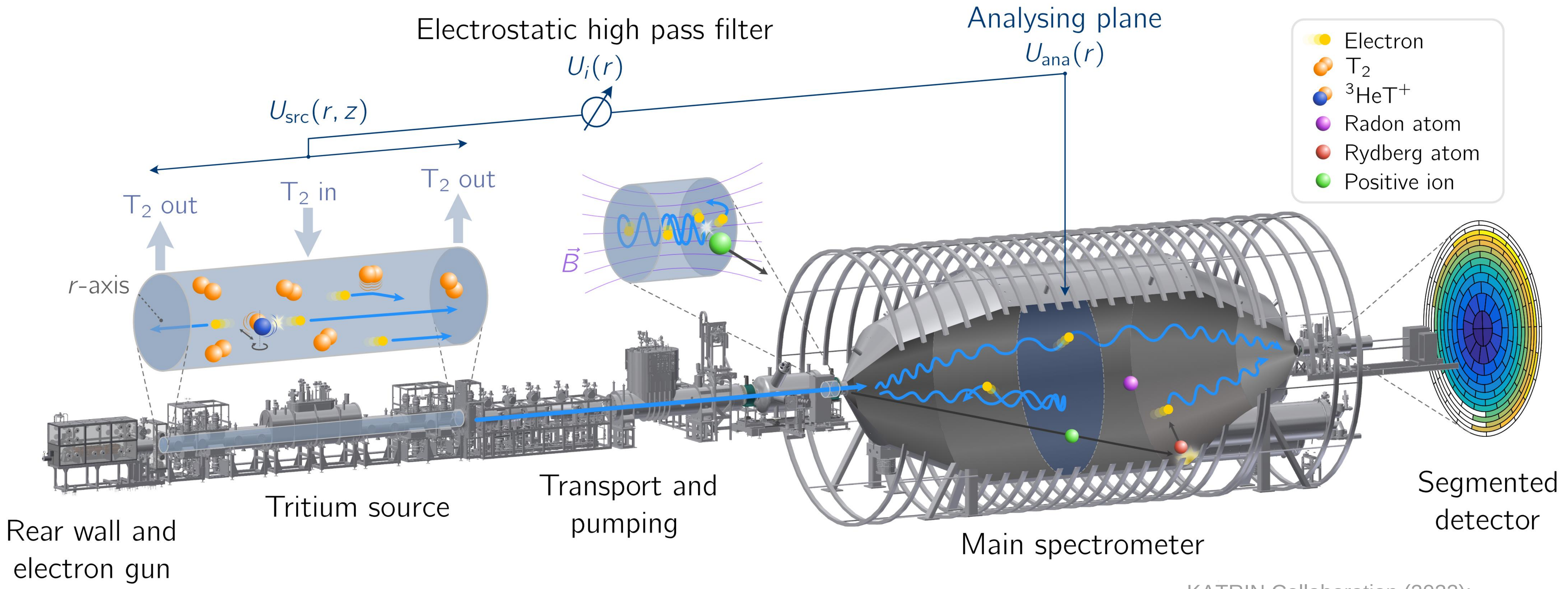
February 26th, 2024 – NuMass 2024, Genoa

The KATRIN experiment

K. Valerius (2023)



- $\frac{\mathrm{d}R}{\mathrm{d}E}(E, m_\nu^2) = C \cdot (E + m_e) \cdot p \cdot E_\nu \cdot \sqrt{(E_0 - E)^2 - m_\nu^2} \cdot F(Z, E)$
- $m_\nu^2 = \sum_i |U_{ei}|^2 m_i^2$



KATRIN Collaboration (2022): 10.1038/s41567-021-01463-1

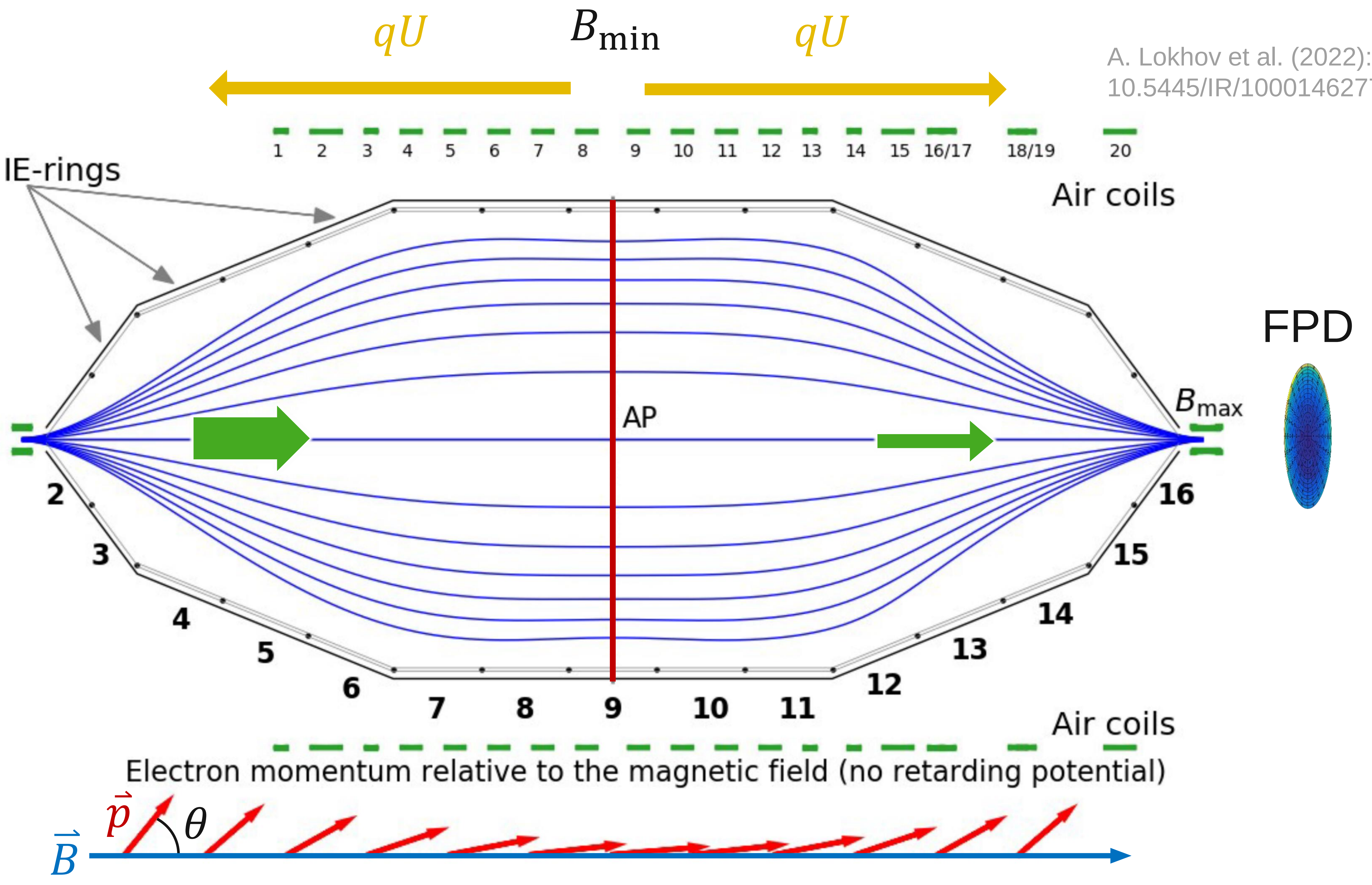
MAC-E – Magnetic Adiabatic Collimation + Electrostatic Filter

- Magnetic moment conservation:

  $\mu \approx \frac{E_\perp}{B} = \text{const.}$ (non-relativistic)

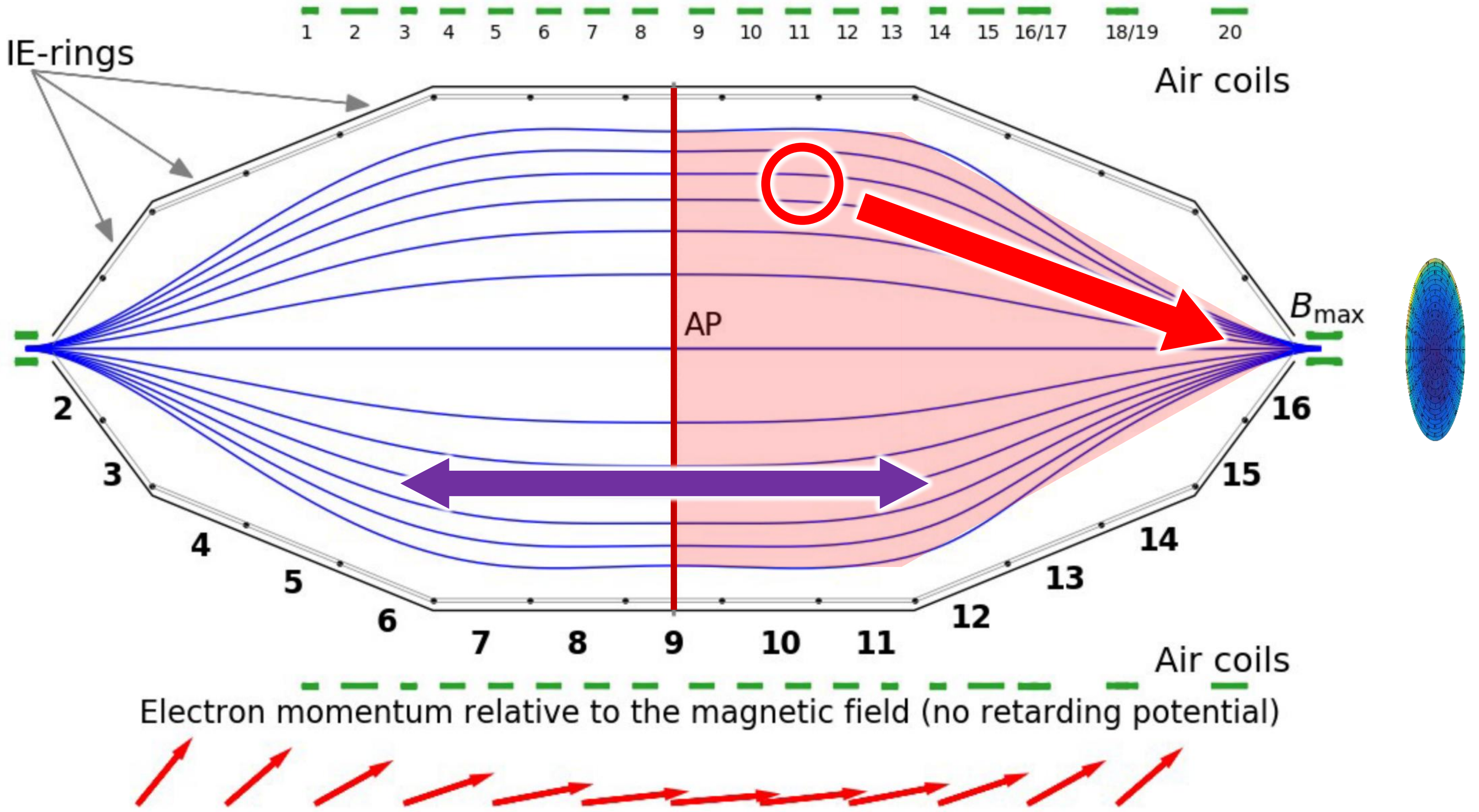
- Adiabatically: $E_\perp \rightarrow E_\parallel \rightarrow E_\perp$
- Remaining $E_\perp$ at analyzing plane (AP) defines ΔE ($\mathcal{O}(1)$ eV at 18.6 keV)

$$E = \underbrace{E\sin^2(\theta)}_{E_\perp} + \underbrace{E\cos^2(\theta)}_{E_\parallel}$$



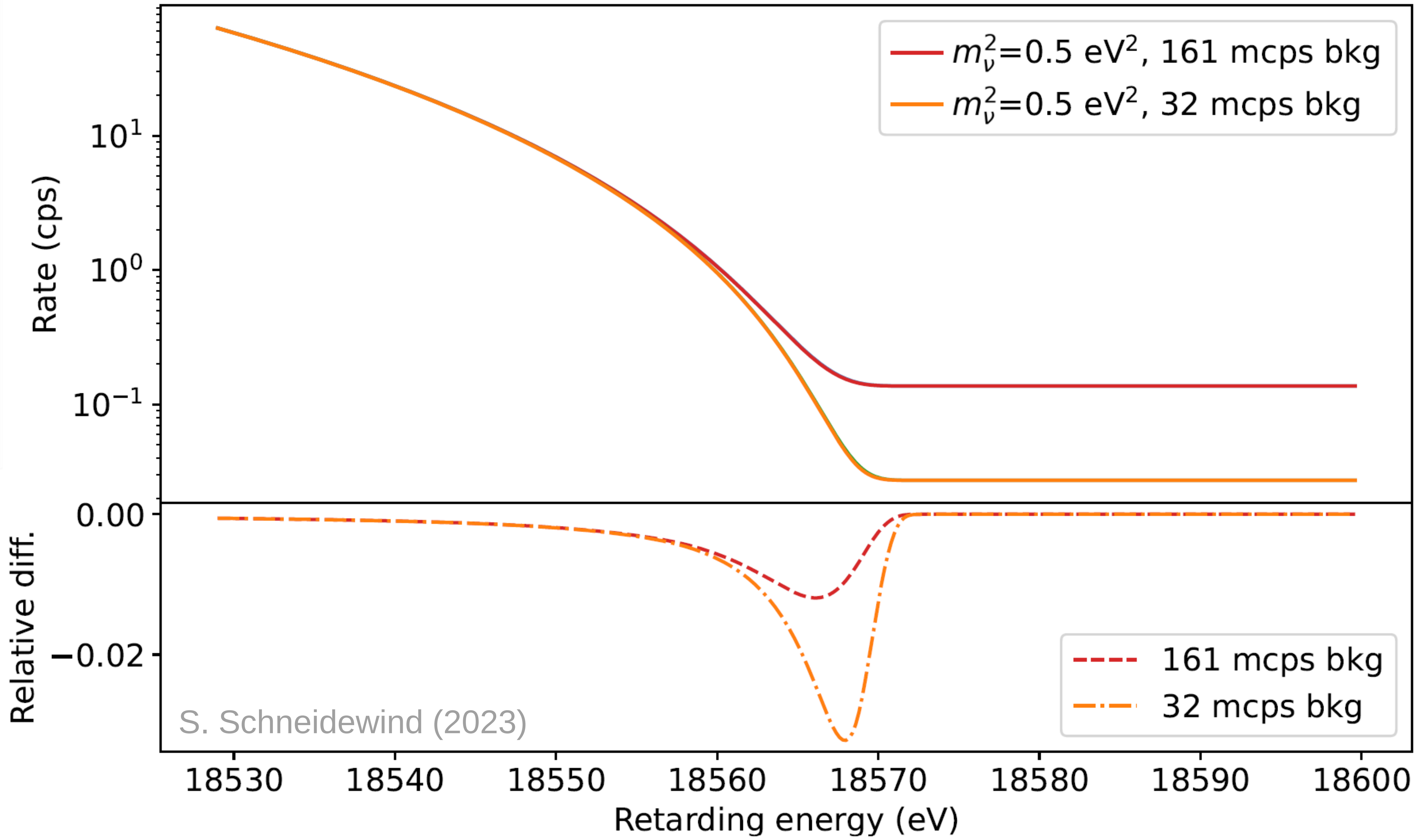
A. Lokhov et al. (2022): 10.5445/IR/1000146277

Background in the tritium β-spectrum



- $R = \mathrm{Amp} \cdot \int_{qU}^{E_0} \frac{\mathrm{d}R}{\mathrm{d}E}(E, m_\nu) f(E - qU) \mathrm{d}E + R_{\mathrm{Bg}}$
- → background rate R_{Bg}: $\mathcal{O}(100)$ mcps
- m_ν^2 sensitive region: $\mathrm{Sig}/\mathrm{Bg} \sim 1$

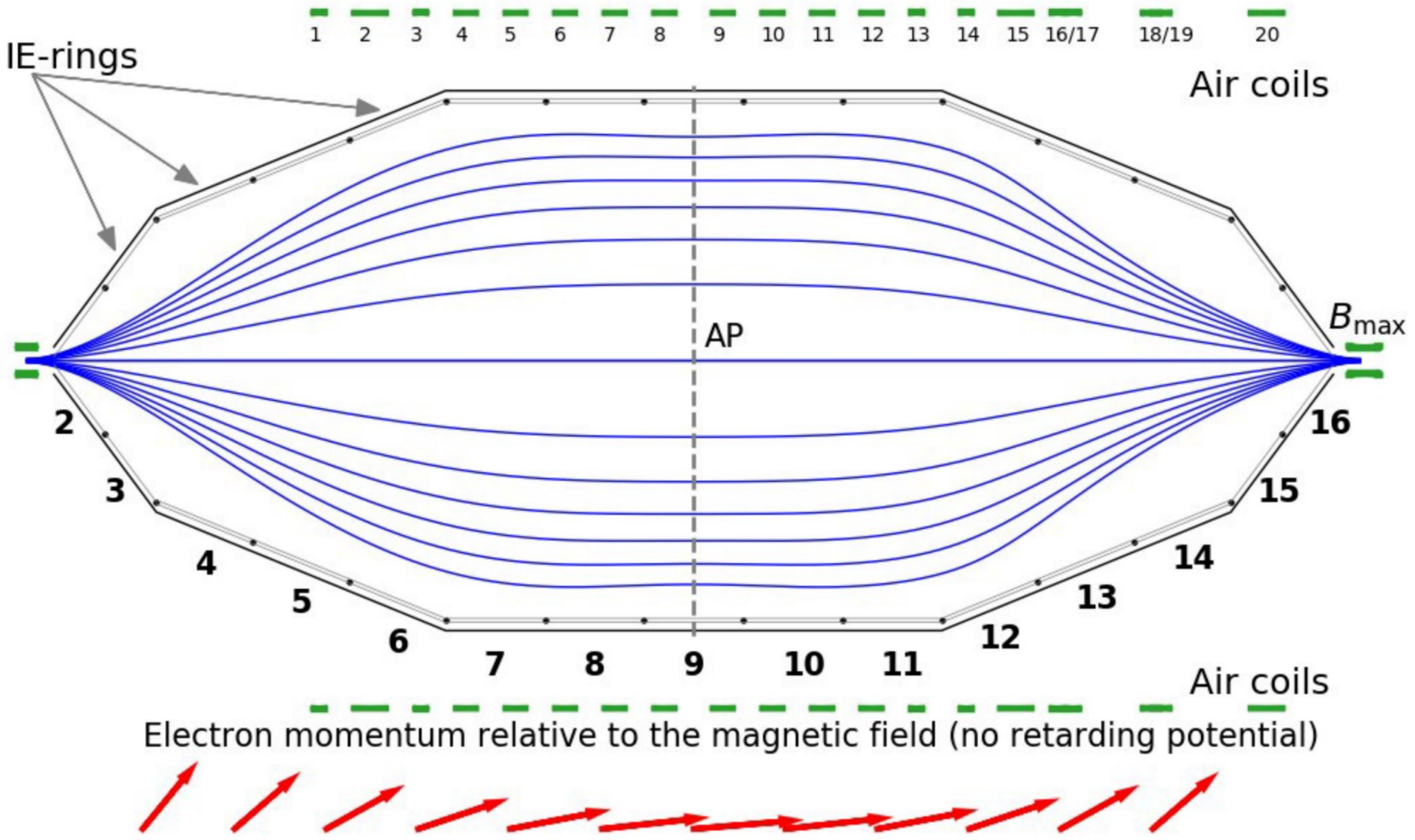
goal: $R_{\mathrm{Bg}} = 10$ mcps

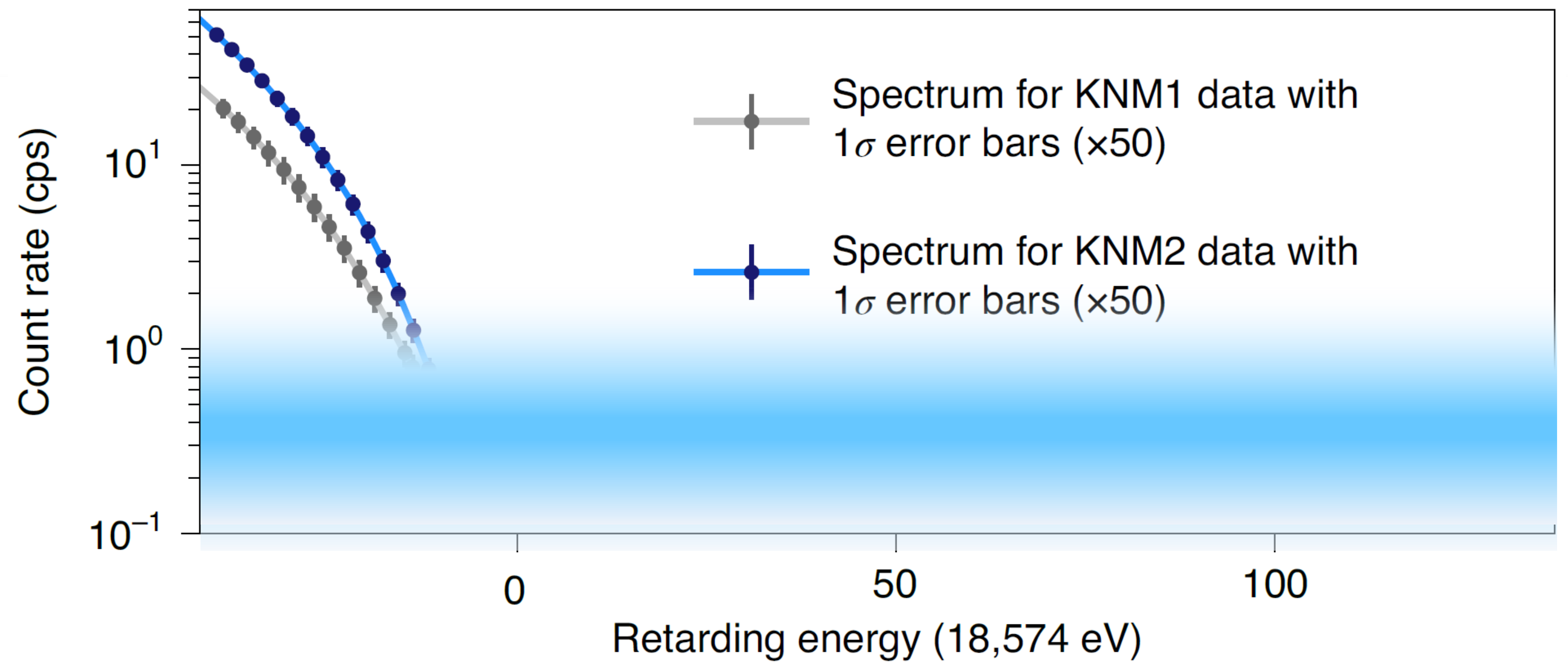


Background sources

- **External background:**
  - Muons
  - External radioactivity
- **Intrinsic background:**
  - Scattering and ions
  - Penning traps
  - Intrinsic radioactivity:
    - Radon
    - Remaining background

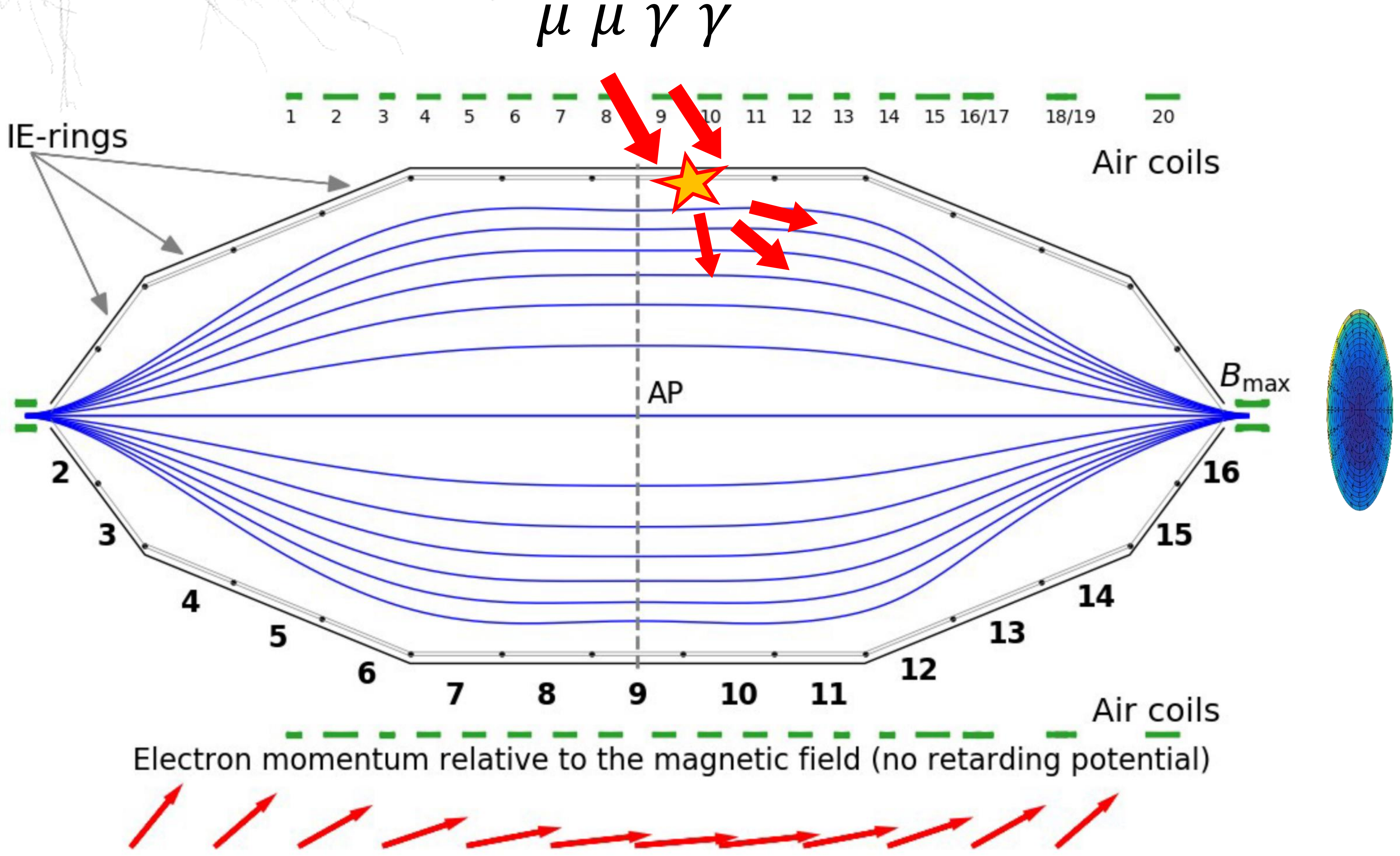
Main Spectrometer (**MS**)



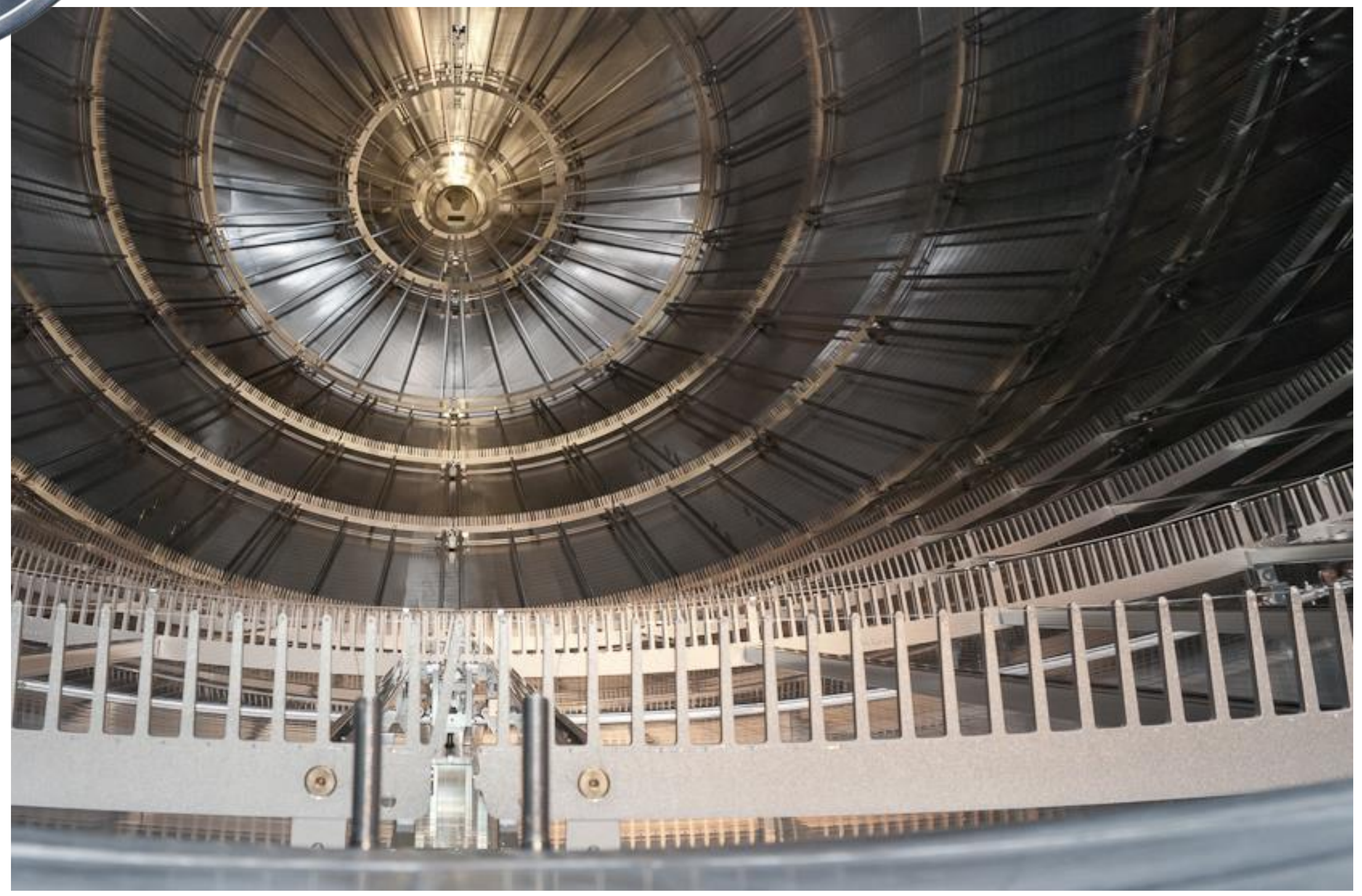


External background

- Cosmic muons, γ flux from ambient radionuclides
- → air coil system
- → inner wire electrodes



air coils

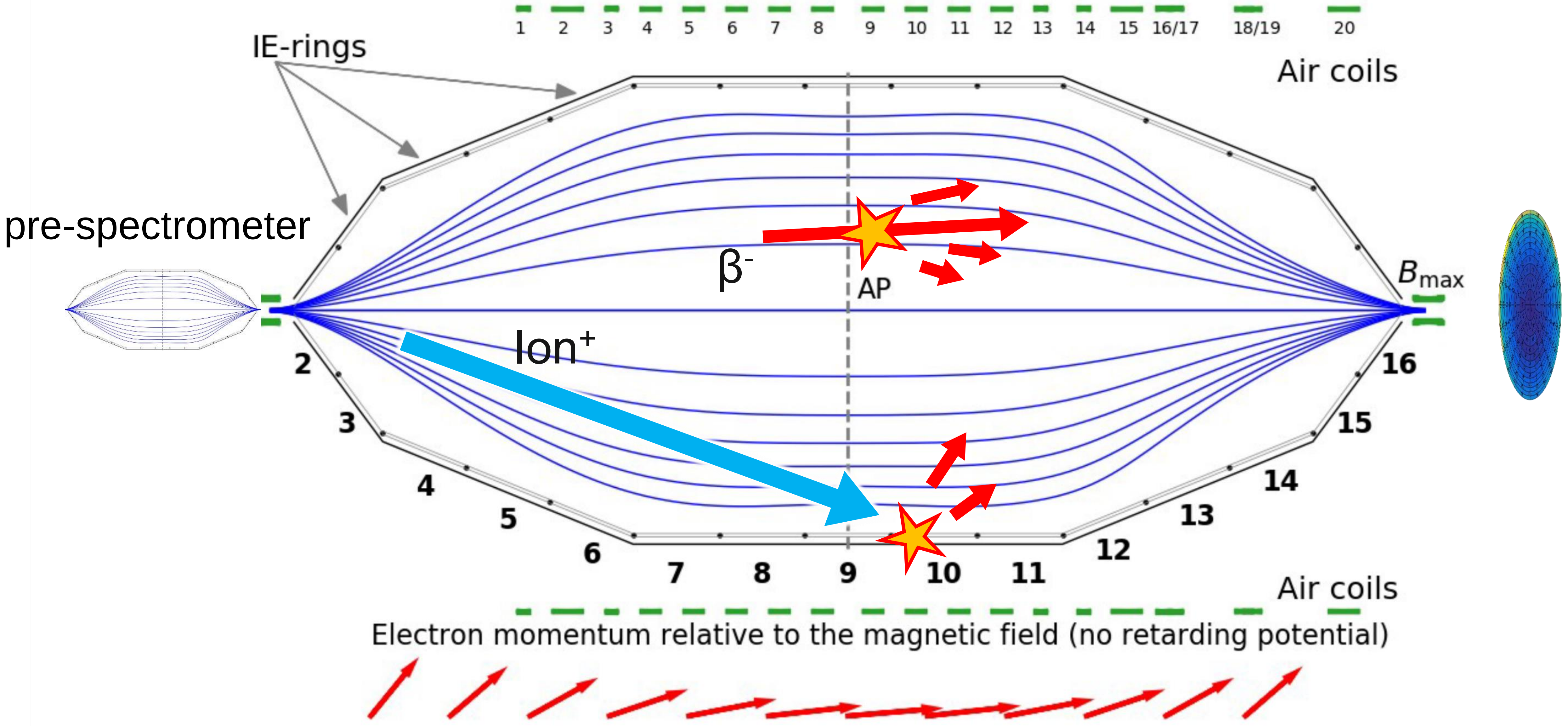


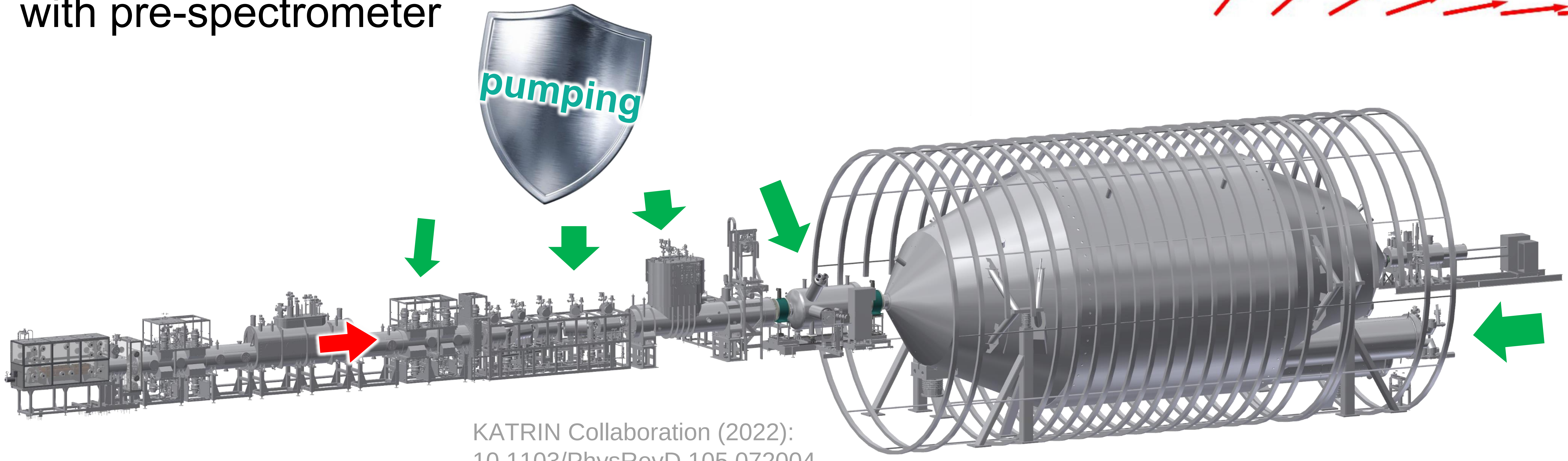
wire electrodes

M. Zacher (2012)

Ions and scattering

- Remaining positive ions
- Residual gas scattering
- → excellent ion/tritium flux reduction $\mathcal{O}(10^{-12})$
- → UHV conditions in MS: $\mathcal{O}(10^{-11})$ mbar
- → option: reduce flux of β-electrons into MS with pre-spectrometer

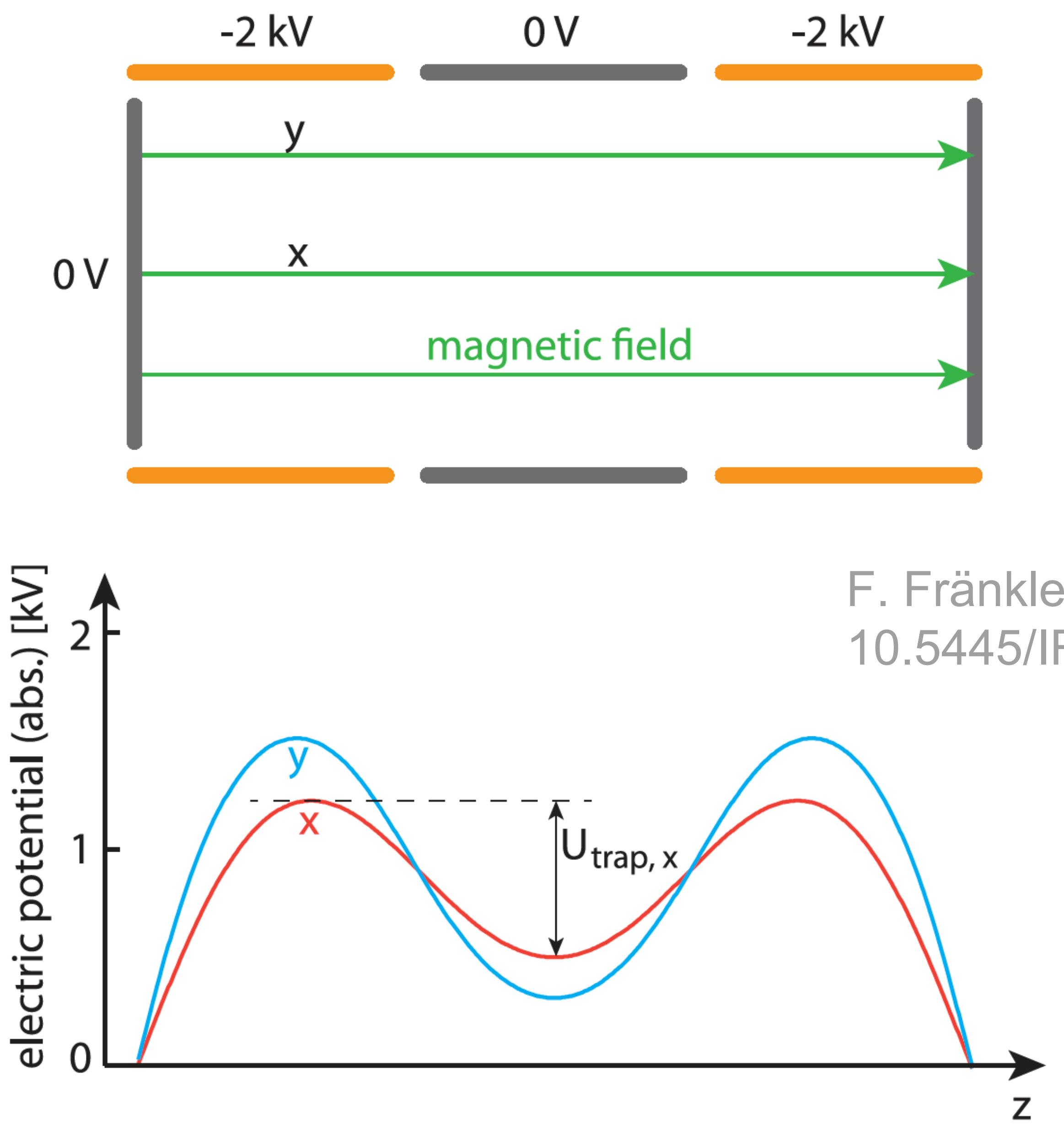




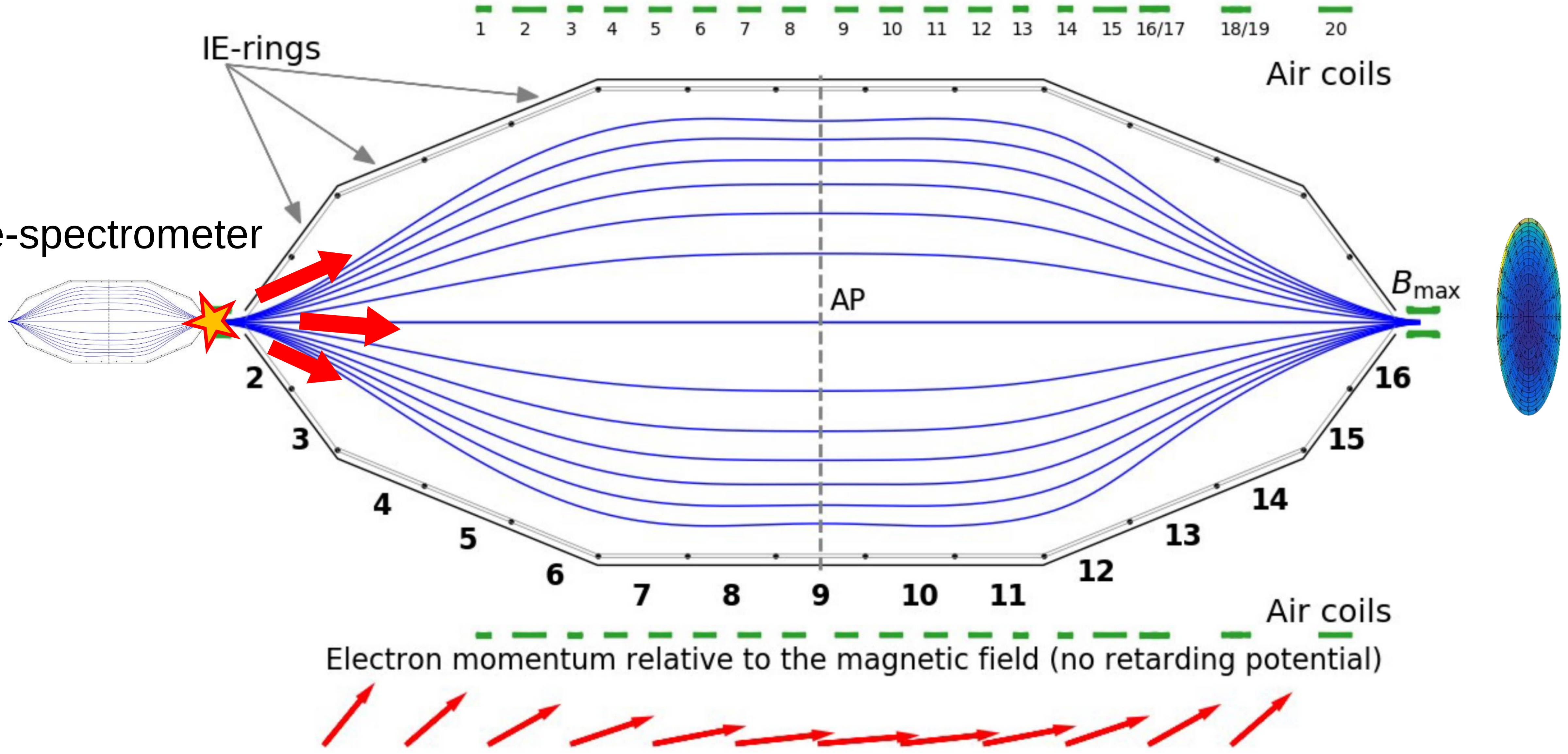
KATRIN Collaboration (2022): 10.1103/PhysRevD.105.072004

Penning traps

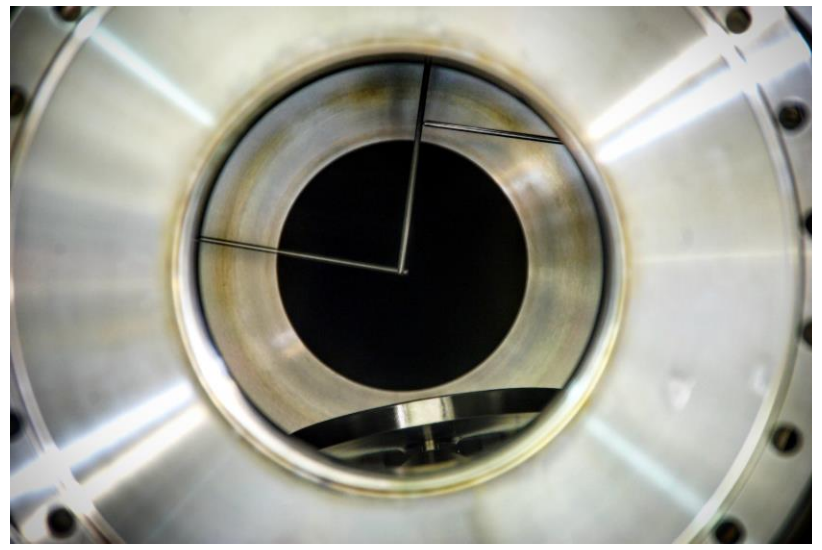
- Electron confinement due to EM trapping
- Residual gas ionization by trapped electrons
  → secondary emission
- Trap between pre- and main spectrometer
- → Penning wiper / grounding



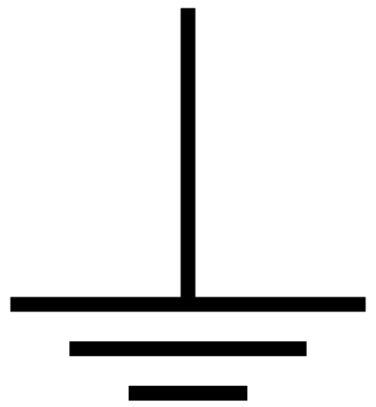
F. Fränkle (2010): 10.5445/IR/1000019392



KATRIN Collaboration (2020): 10.1140/epjc/s10052-020-8278-y



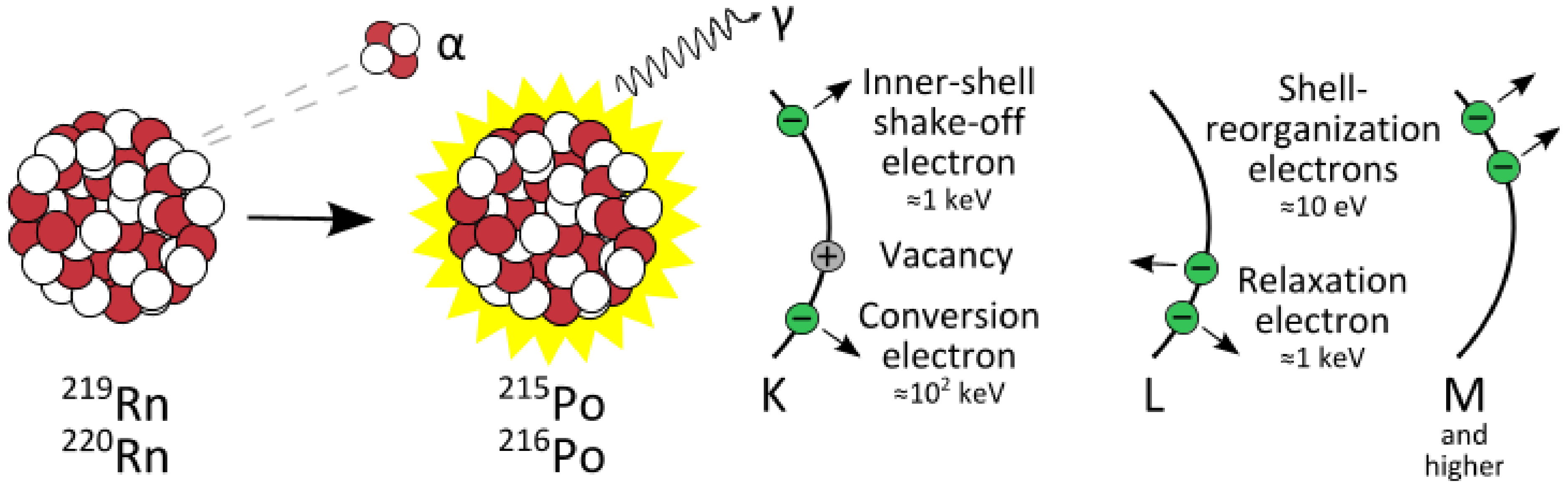
"Penning wiper"



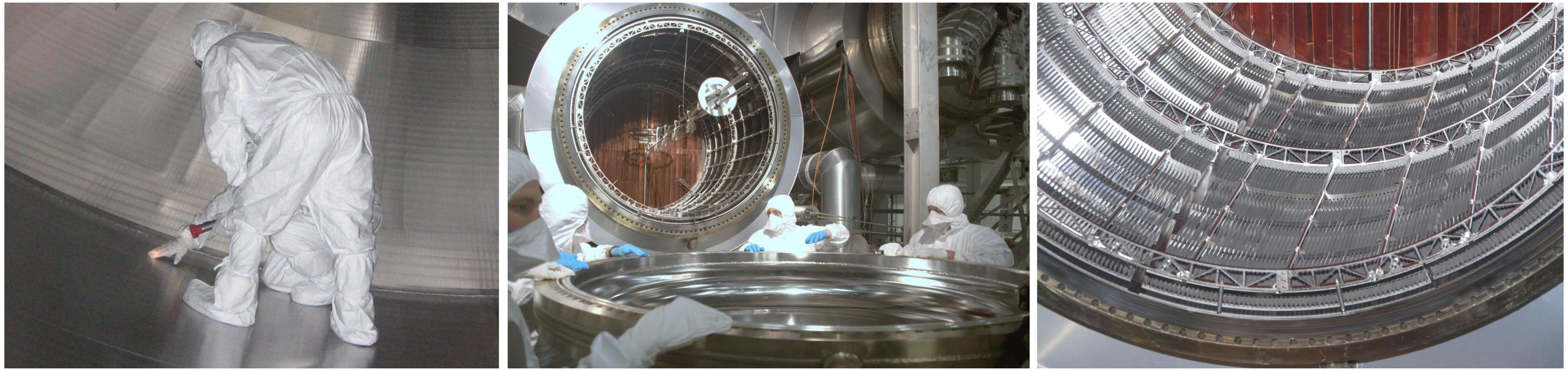
Intrinsic Radioactivity

KATRIN Collaboration (2016):
10.5445/IR/1000055291

- Non-evaporable getter pumps and welding seams: radon emanation
- Neutral particle: no shielding, no efficient pumping (short-lived)
- → keV electron emission in fluxtube



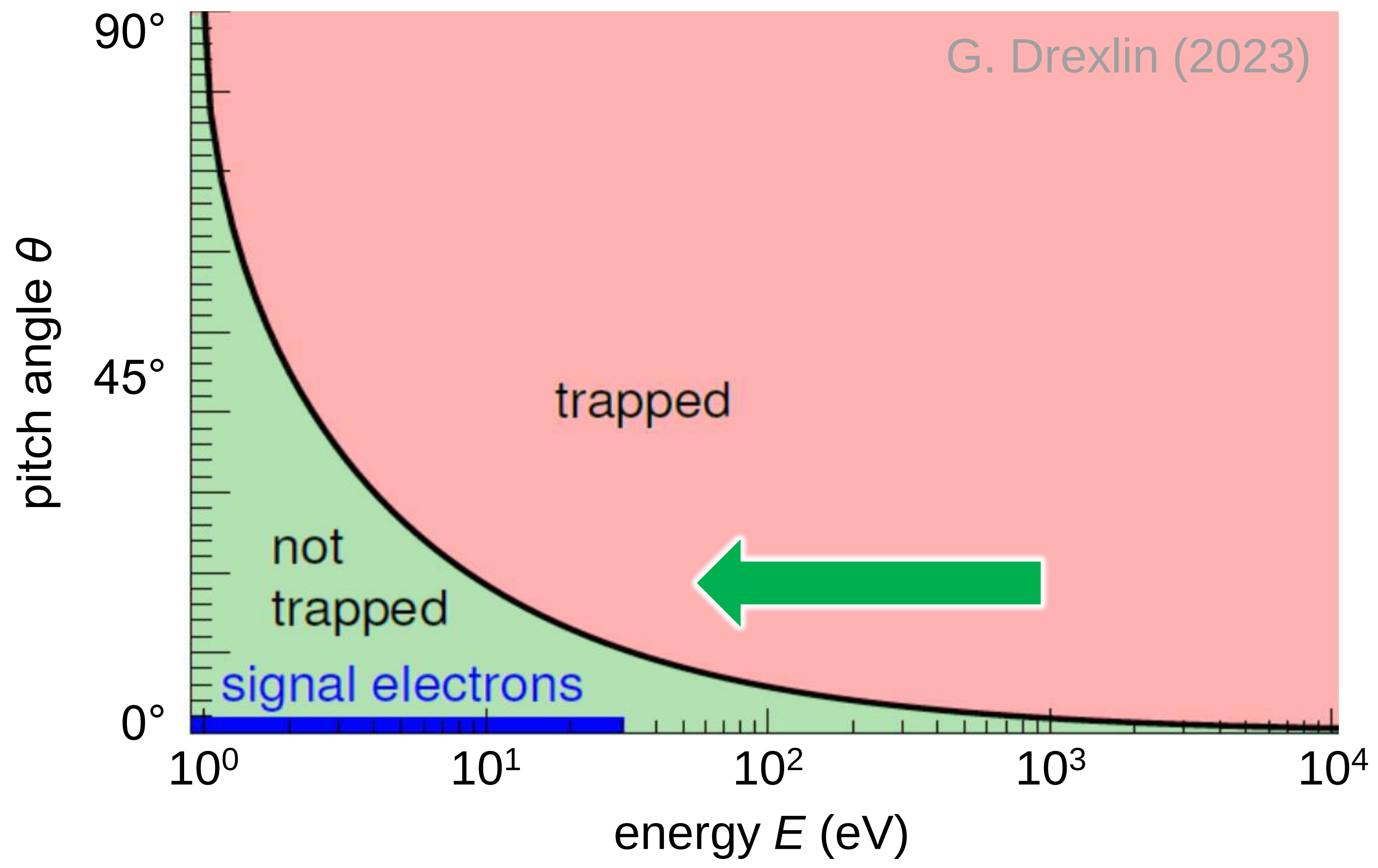
F. Harms (2015):
10.5445/IR/1000050027



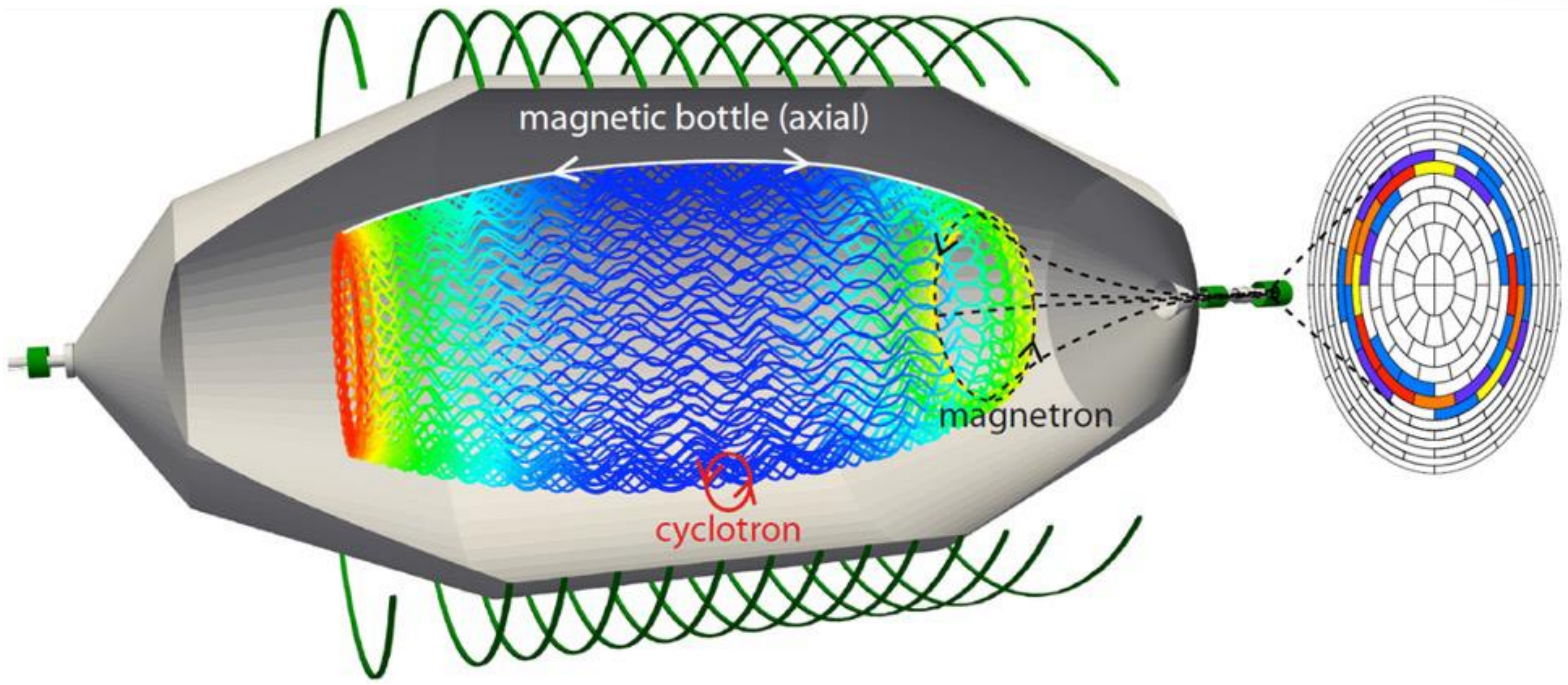
KATRIN Collaboration (2016):
10.5445/IR/1000055291

Radon-induced background

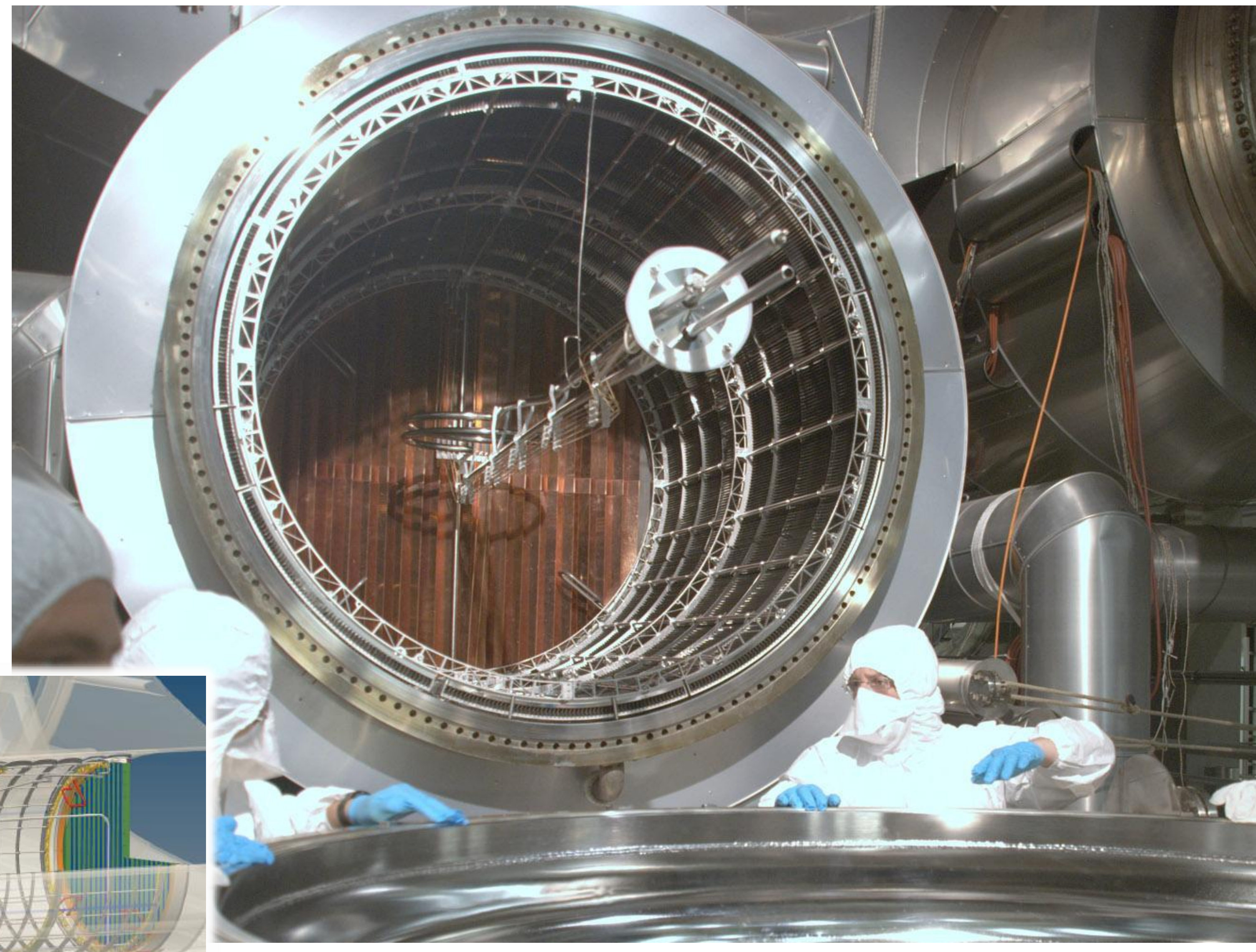
- Magnetic bottle → electron trapping up to hours
- Energy loss due to residual gas scattering
- → LN_2-cooled Cu baffles block radon by adsorption

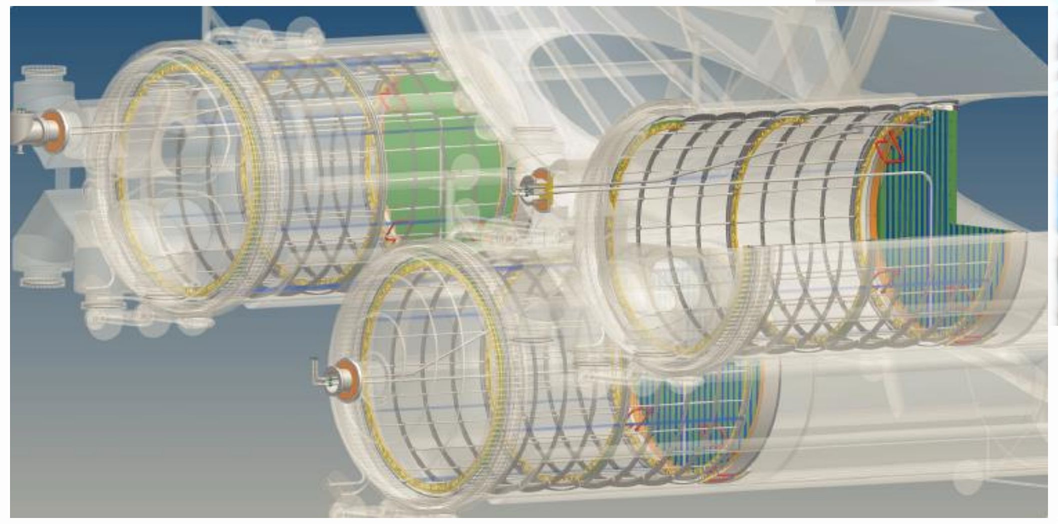


$$\theta(\vec{r}) = \arcsin\left(\sqrt{\frac{E(\vec{r}_0)}{E(\vec{r})}\frac{|\vec{B}(\vec{r})|}{|\vec{B}(\vec{r}_0)|}}\sin(\theta_0)\right)$$



G. Drexlin (2023)

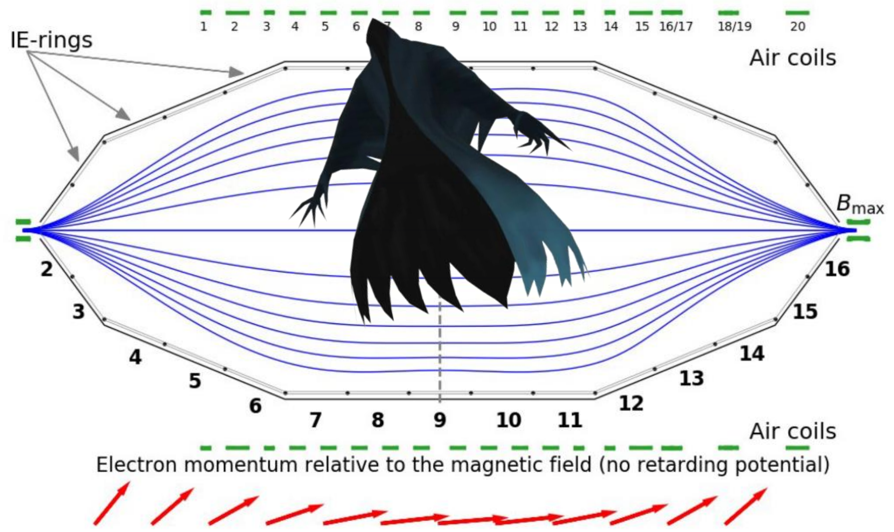


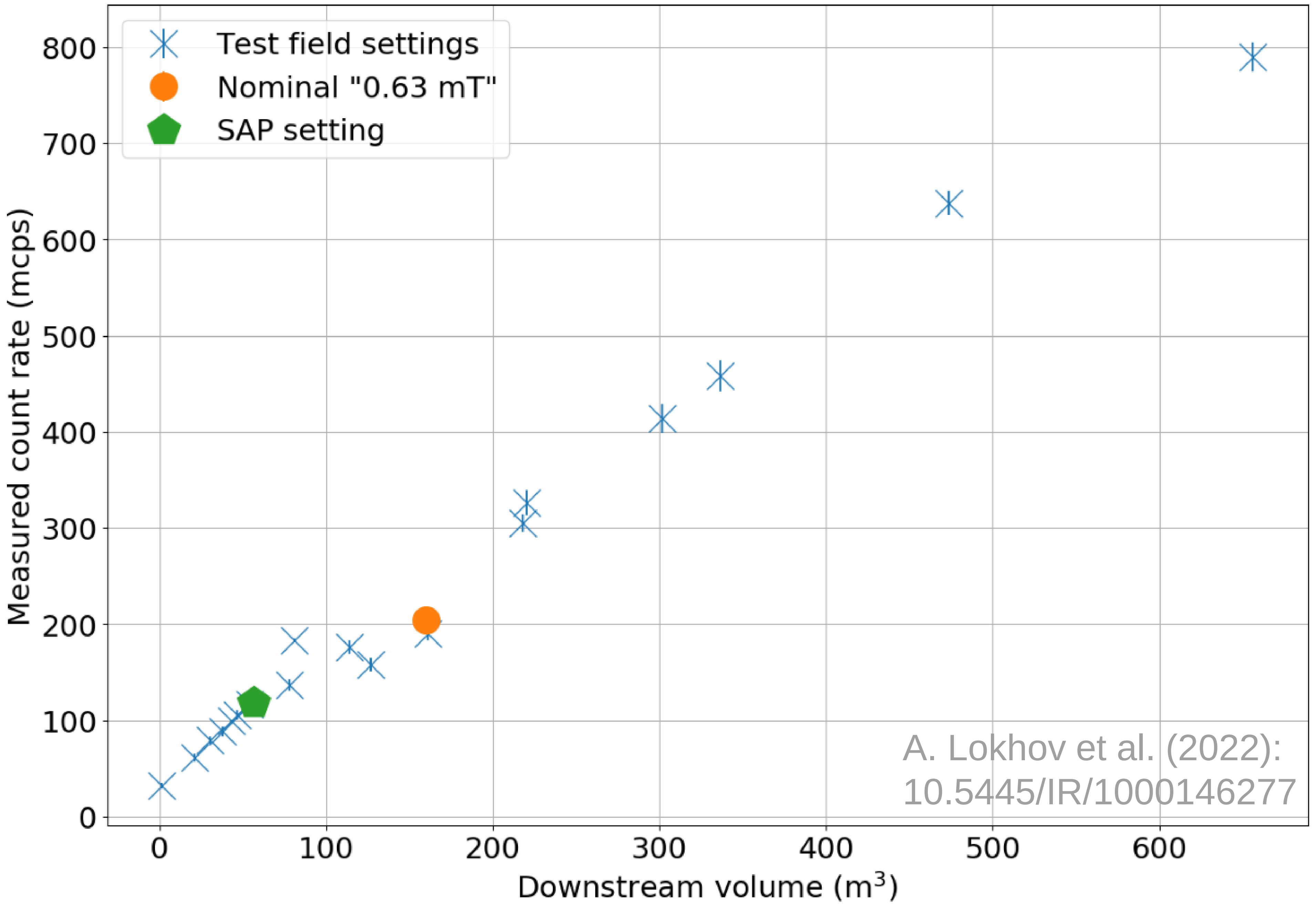


→ 95% retention

Remaining background

- After all steps: **~ 300 mcps** bg. (design: **10 mcps**)
- *Characteristics*:
  - Volume dependence
  - Spatial profile
  - Temperature dependence
  - Bake-out
  - …



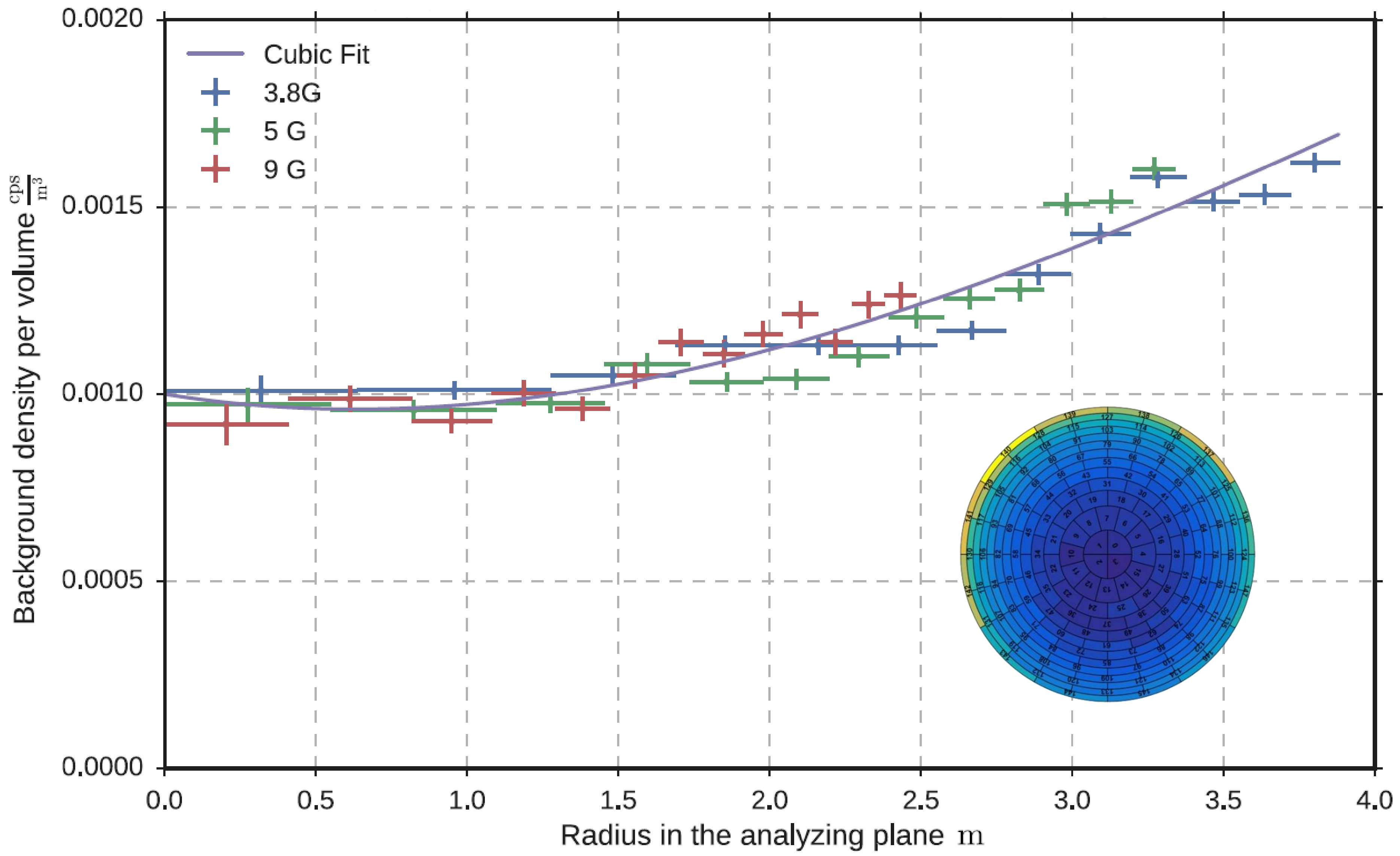


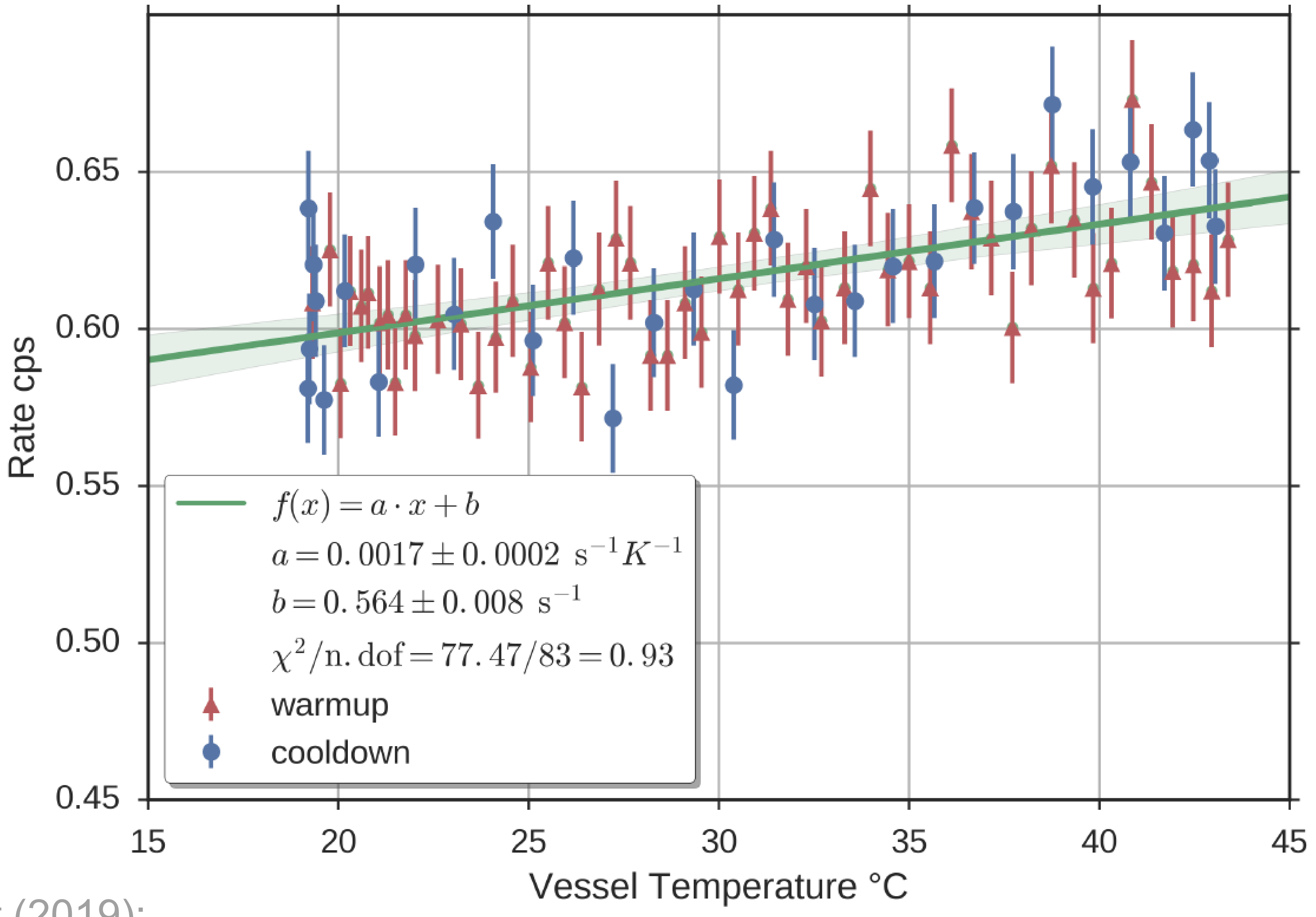
A. Lokhov et al. (2022): 10.5445/IR/1000146277

→ neutral mediators

→ Bg originating from vessel walls

→ thermal energy increases rate

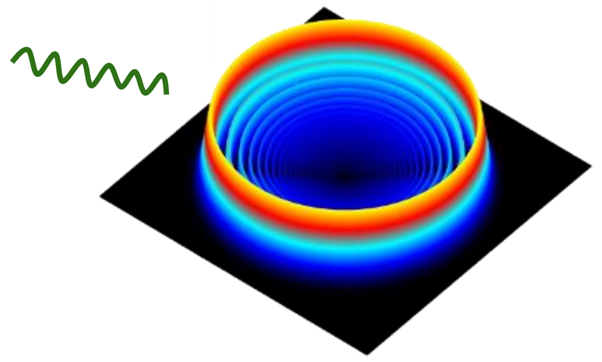


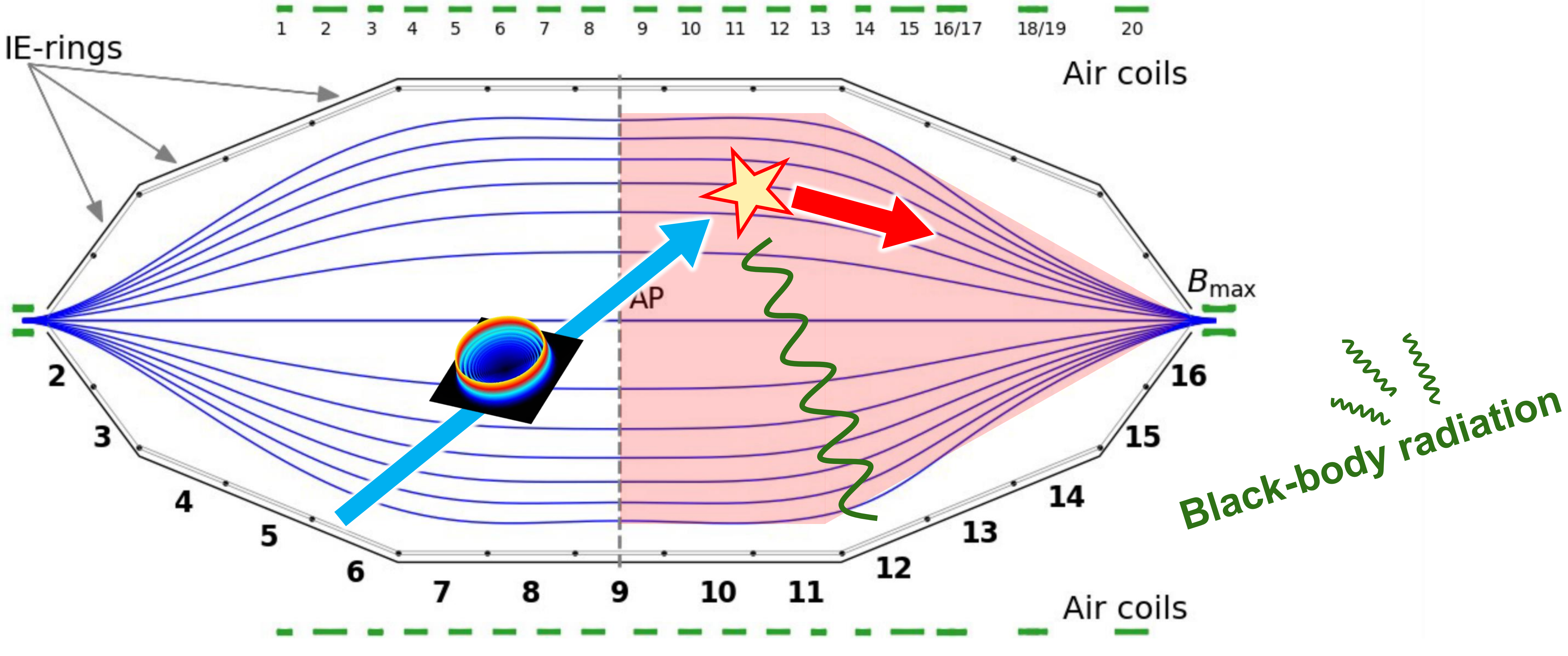


N. Trost (2019): 10.5445/IR/1000090450

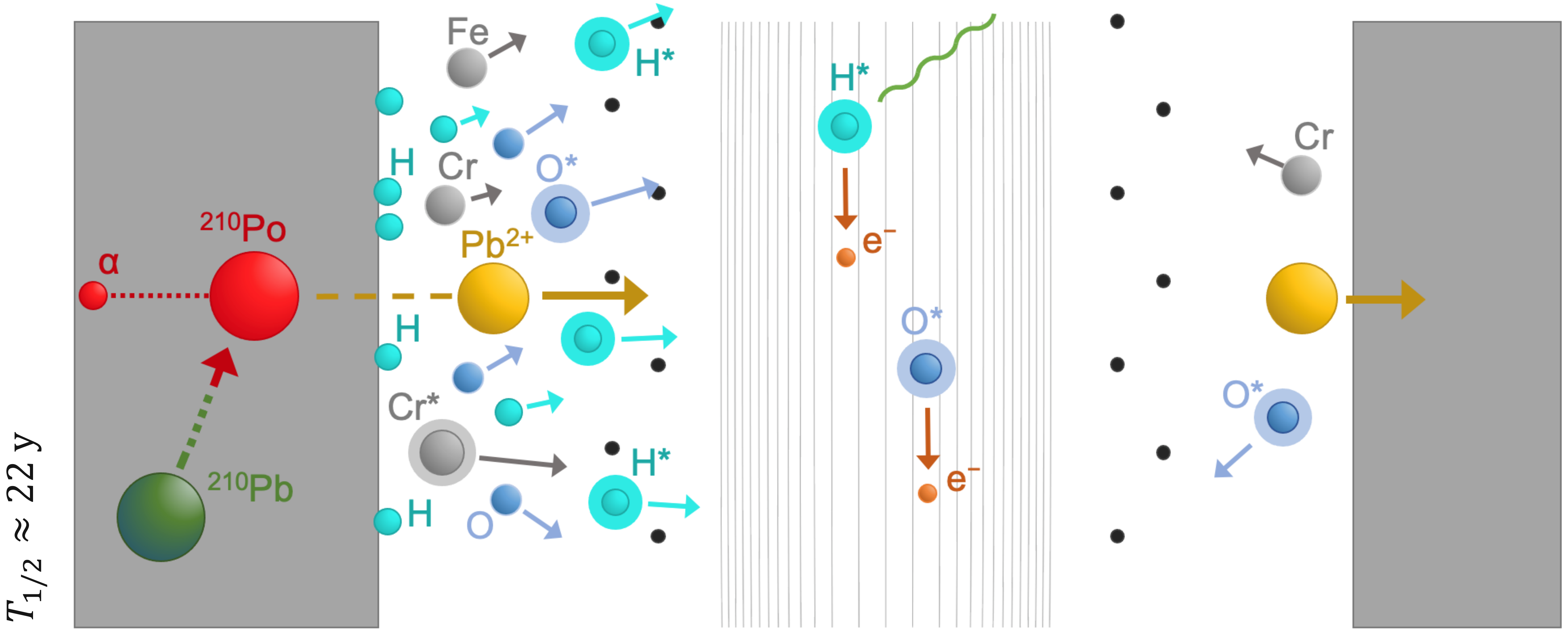
The Rydberg model

- Long-term ambient air (^{222}Rn) ventilation
- ^{210}Pb implanted into steel surface
- α-decay: excited mediators sputtered into MS volume → Rydberg states of e.g. H
- $\mathcal{O}(10)$ meV black-body radiation (room temp.) sufficient for ionization





M. Zacher (2012)



adapted D. Hinz

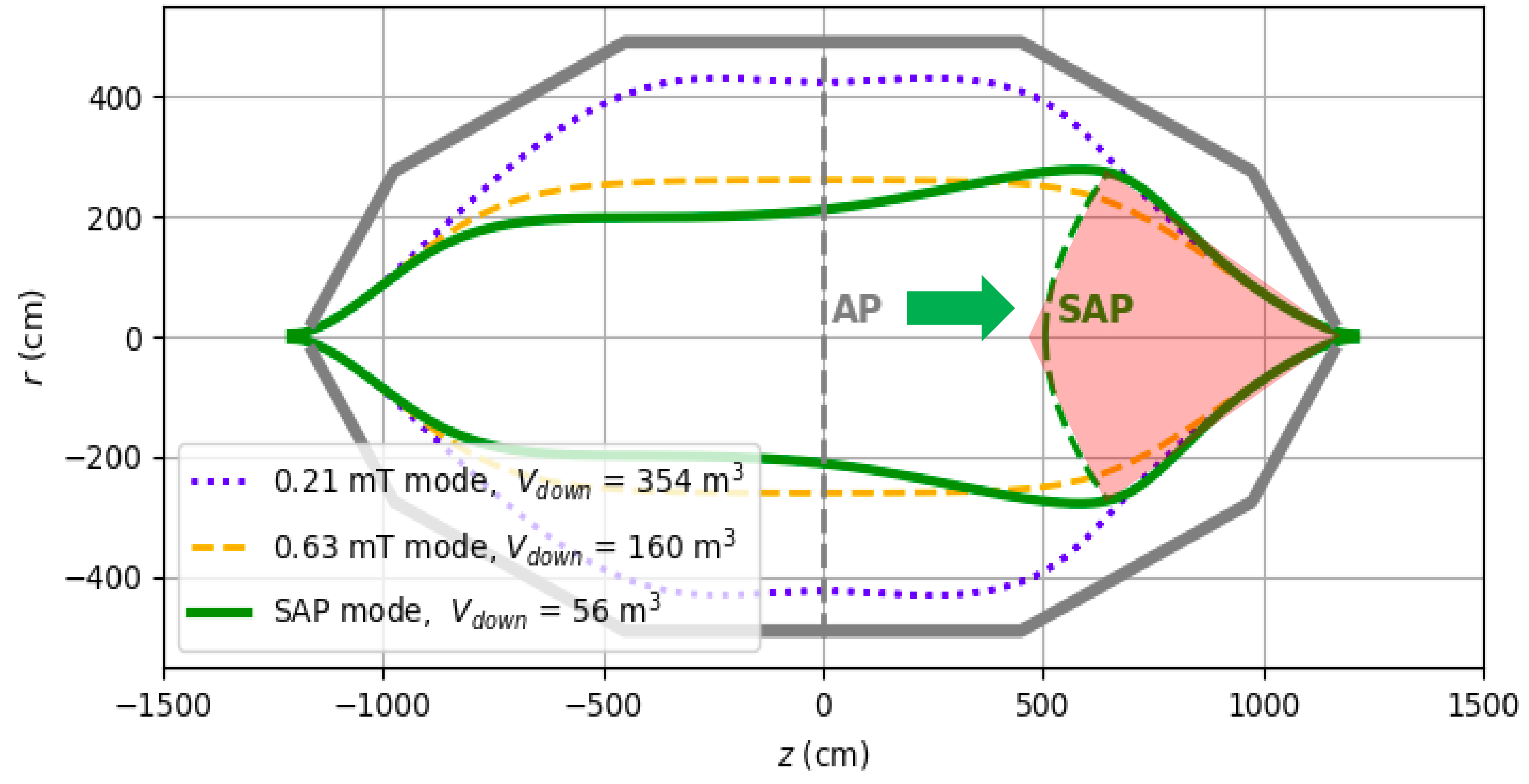
“Rydberg” background mitigation (pt. 1)

Volume dependence

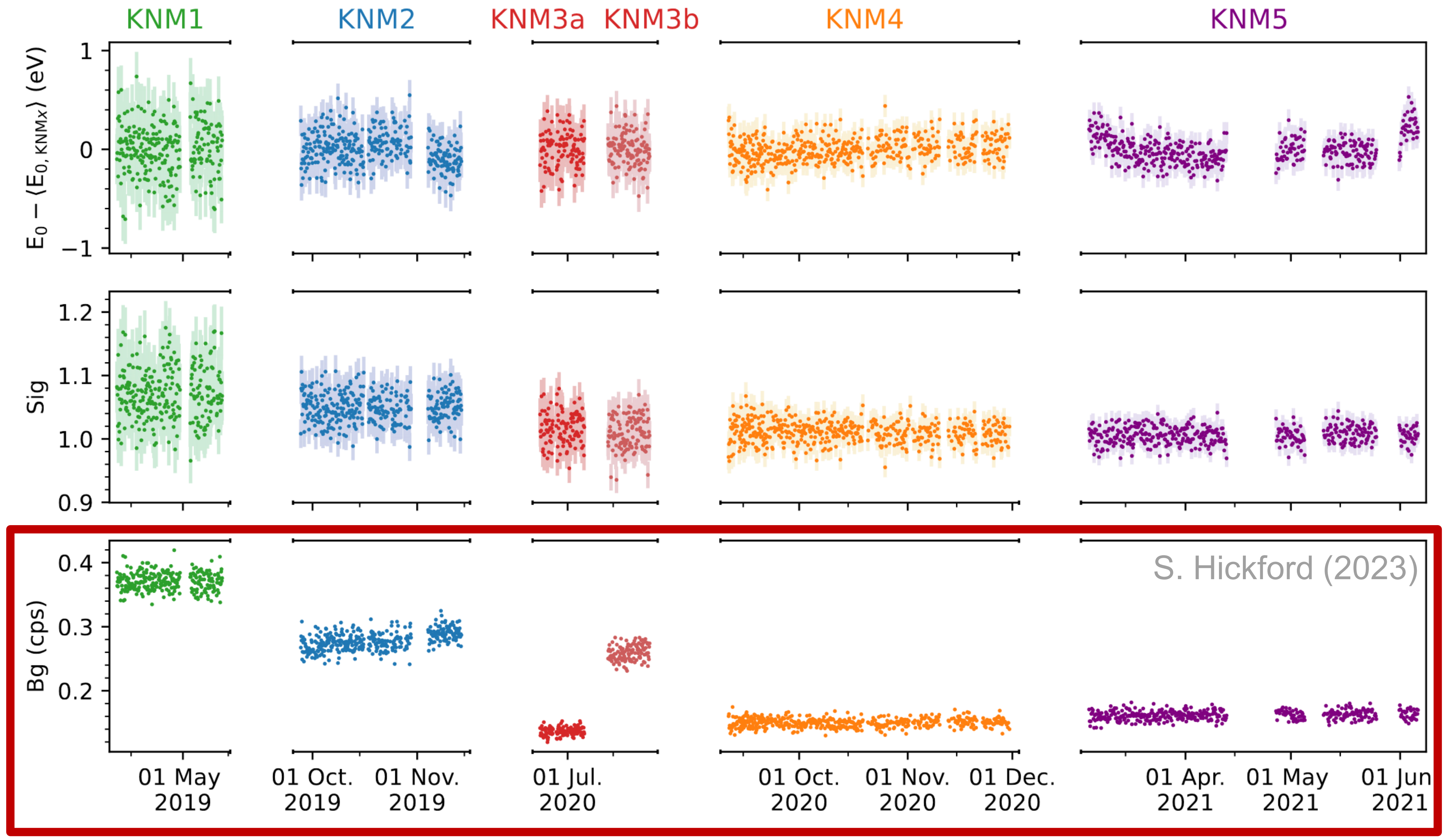
- → reduce “fiducial volume” by shifting AP

~ 1/3 volume → ~ 1/2 Bg

A. Lokhov et al. (2022): 10.5445/IR/1000146277



Shifted Analyzing Plane (**SAP**)

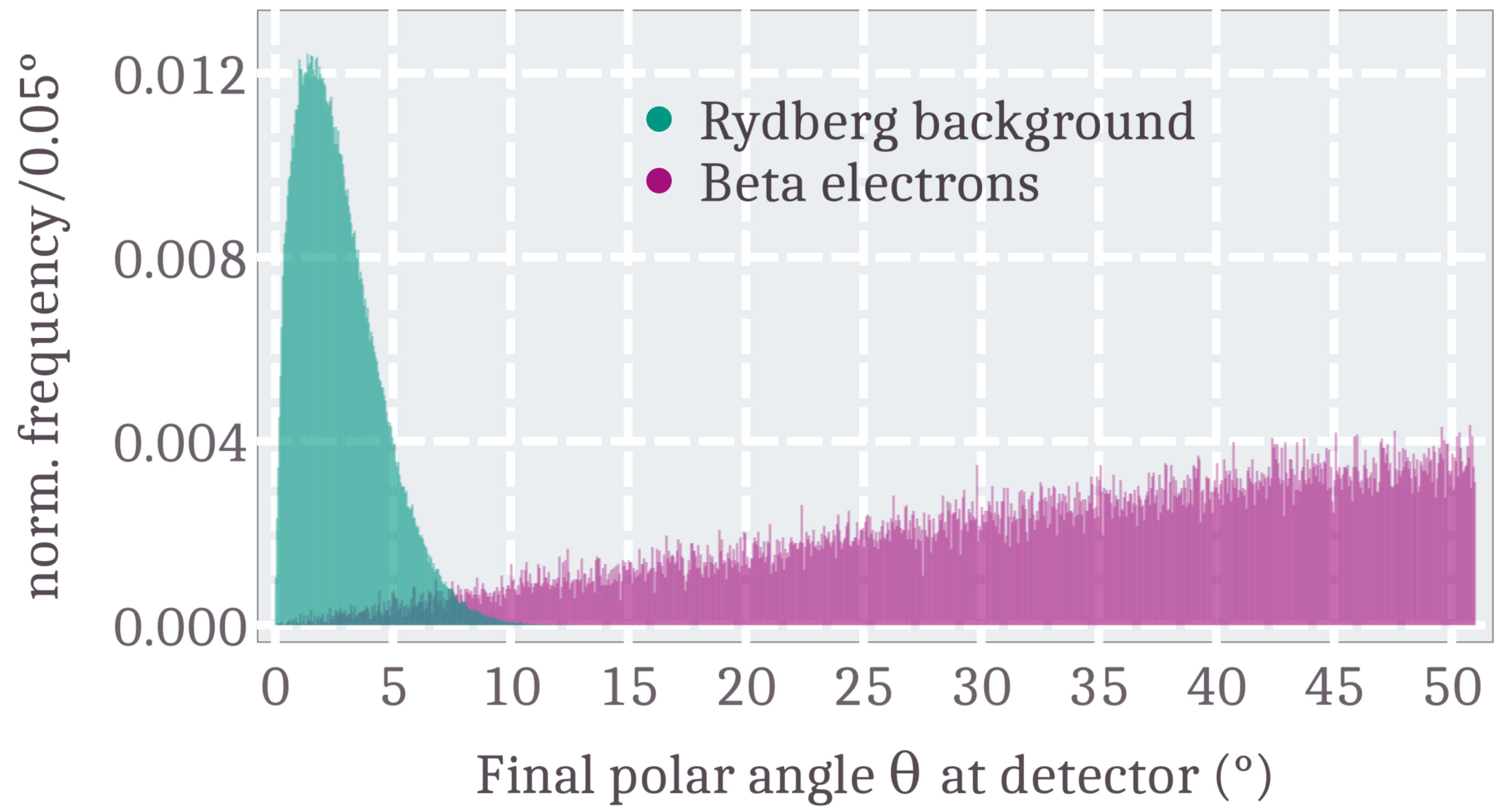


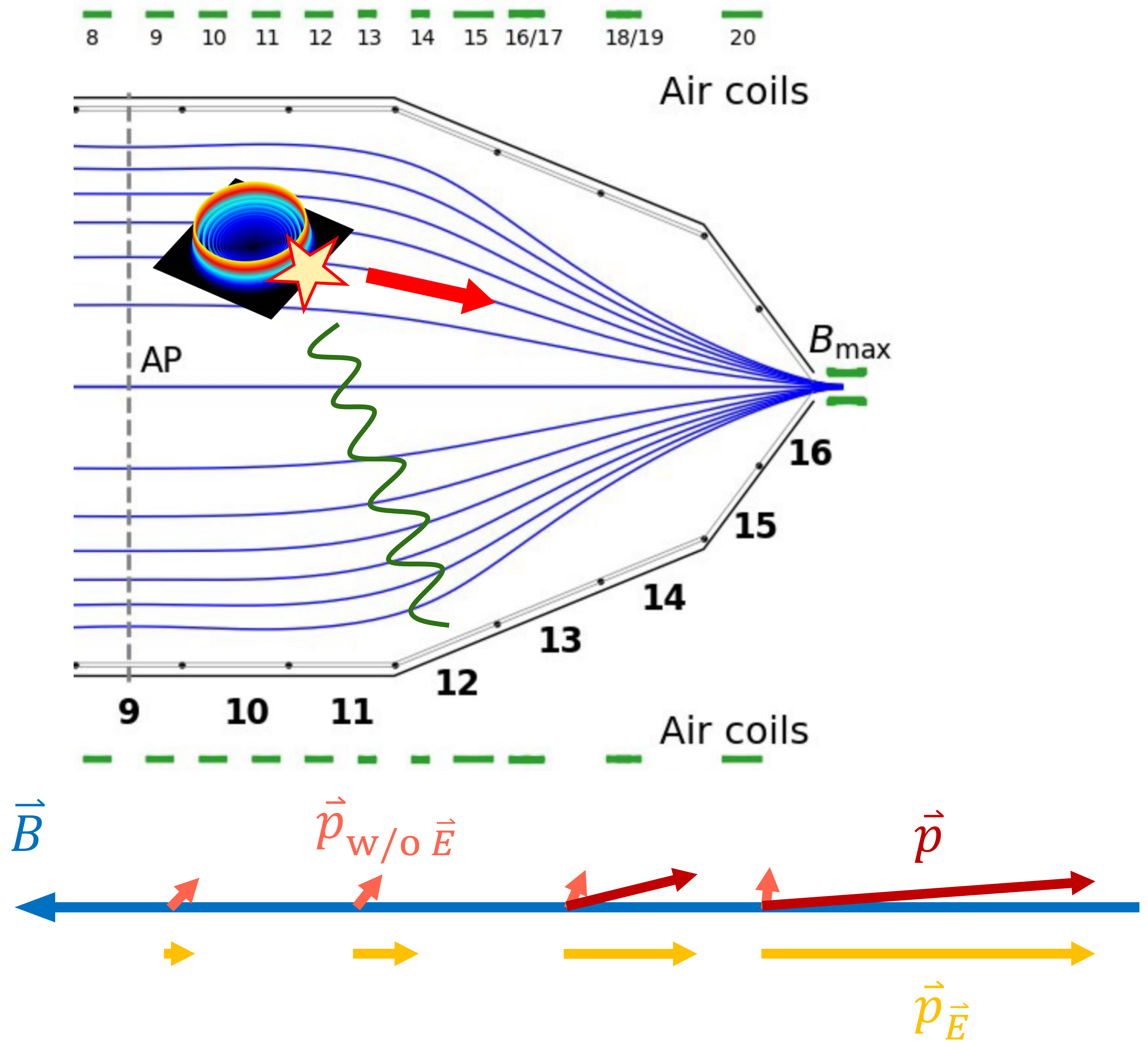
“Rydberg” background mitigation (pt. 2)

Propagation characteristics

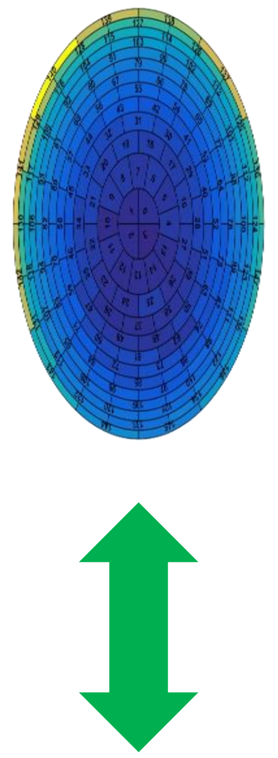
- Initial energies $\sim 1\ \mu\mathrm{eV} - 100\ \mathrm{meV} \rightarrow \mathcal{O}(10)\ \mathrm{keV}$ at FPD
- Low pitch / polar angles θ at FPD

D. Hinz (2022): 10.5445/IR/1000151022





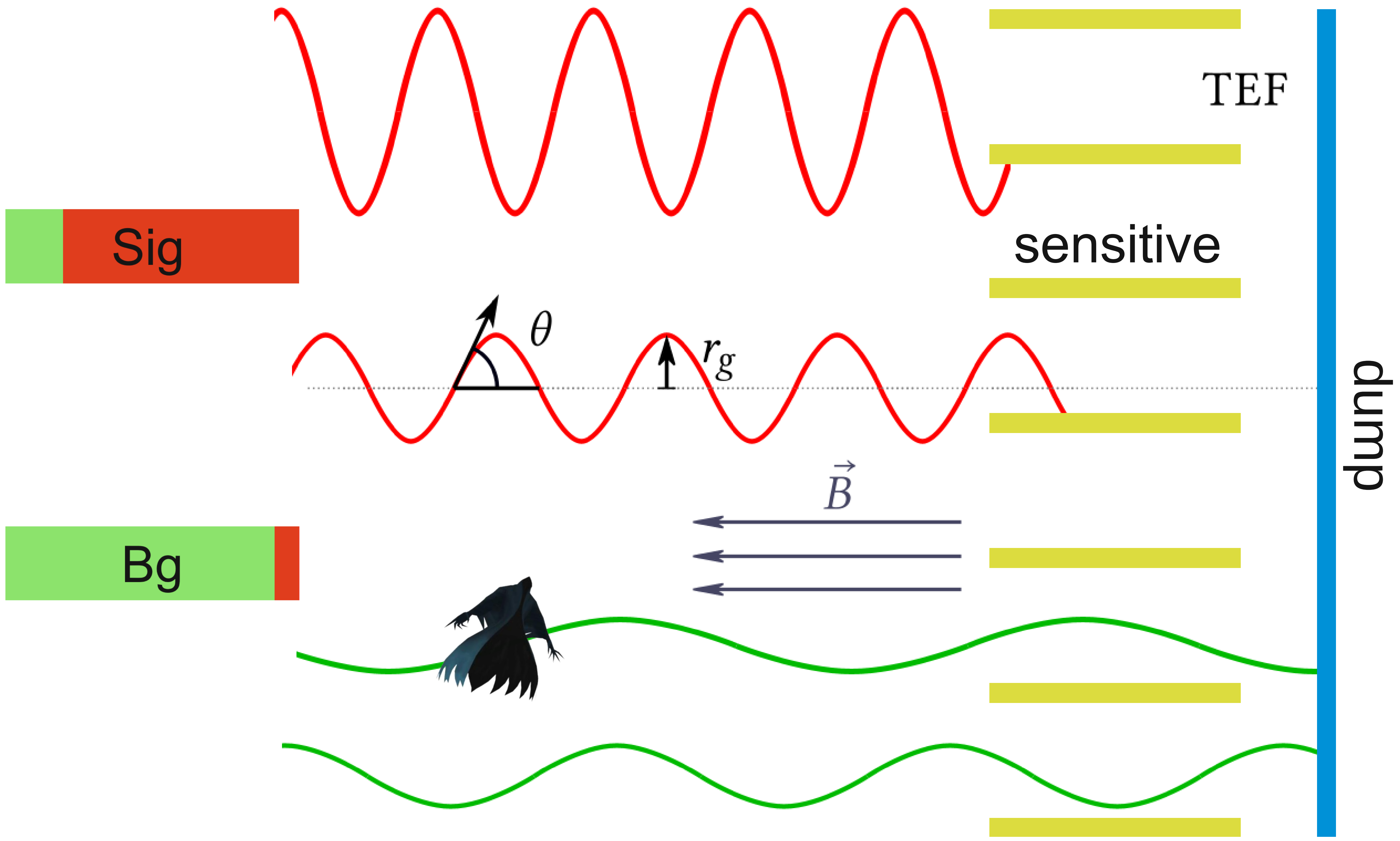
Transverse Energy Filters (TEFs)



Mitigation with an *active TEF*

- Only detect high-angle fraction (Sig) using micron-scaled 3d channels
- Larmor radius r_g: $\mathcal{O}(10-100)\ \mu\mathrm{m}$
  Bg ⟷ Sig

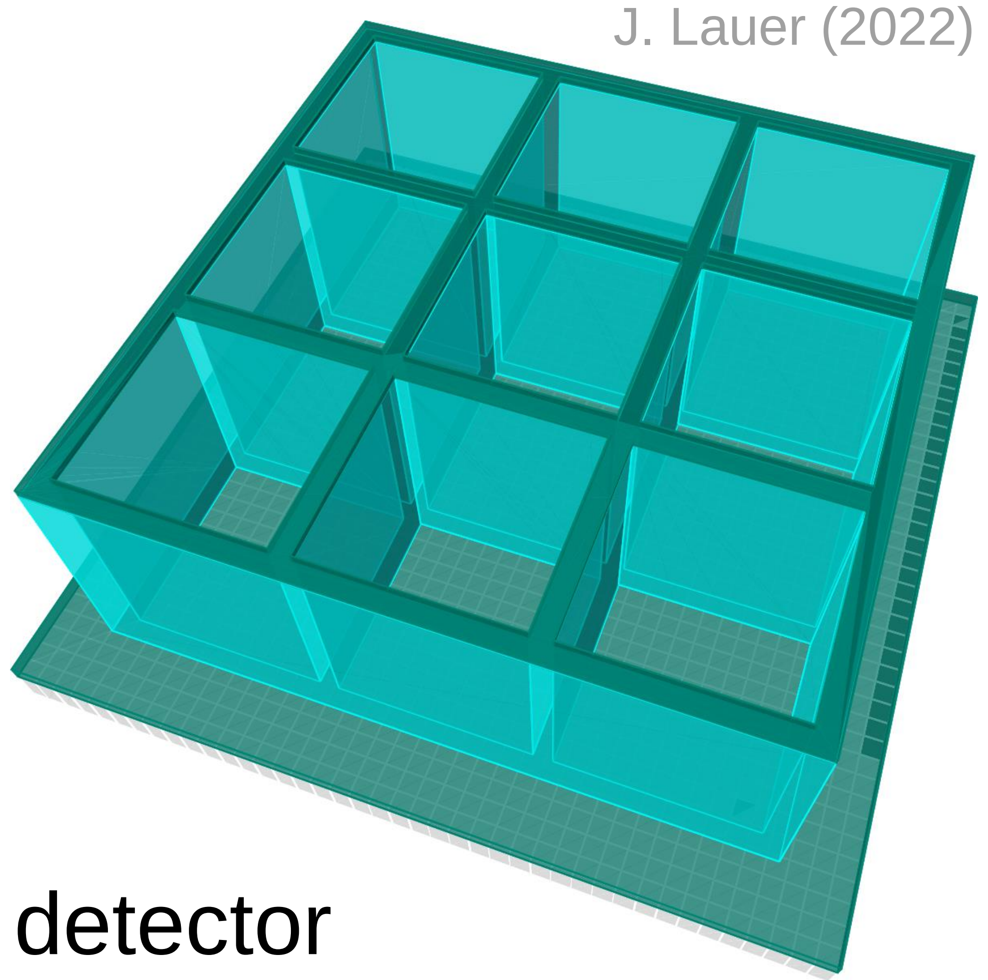
R. G. H. Robertson
C. Weinheimer



J. Lauer (2022)

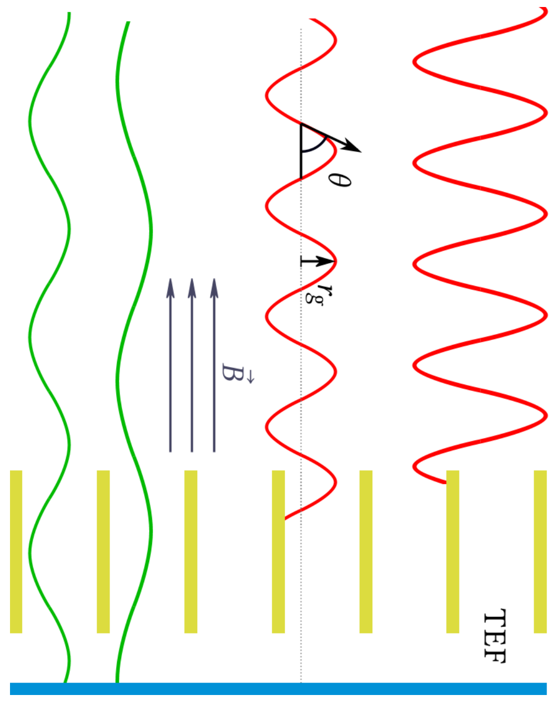
Two R&D approaches to aTEF

J. Lauer (2022)

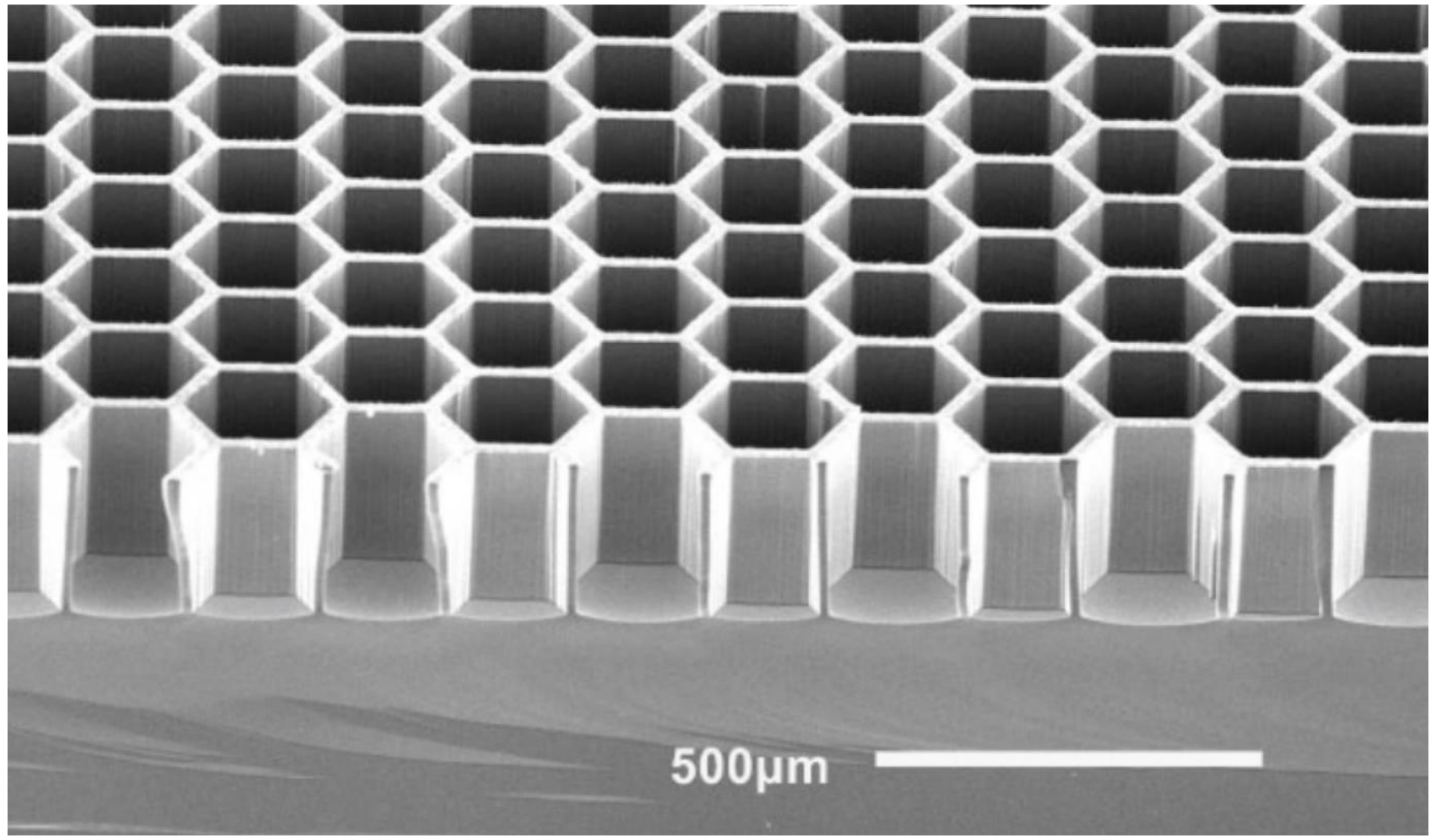


***Silicon** aTEF*

- Etched PIN diode
- → challenges: etching and noise

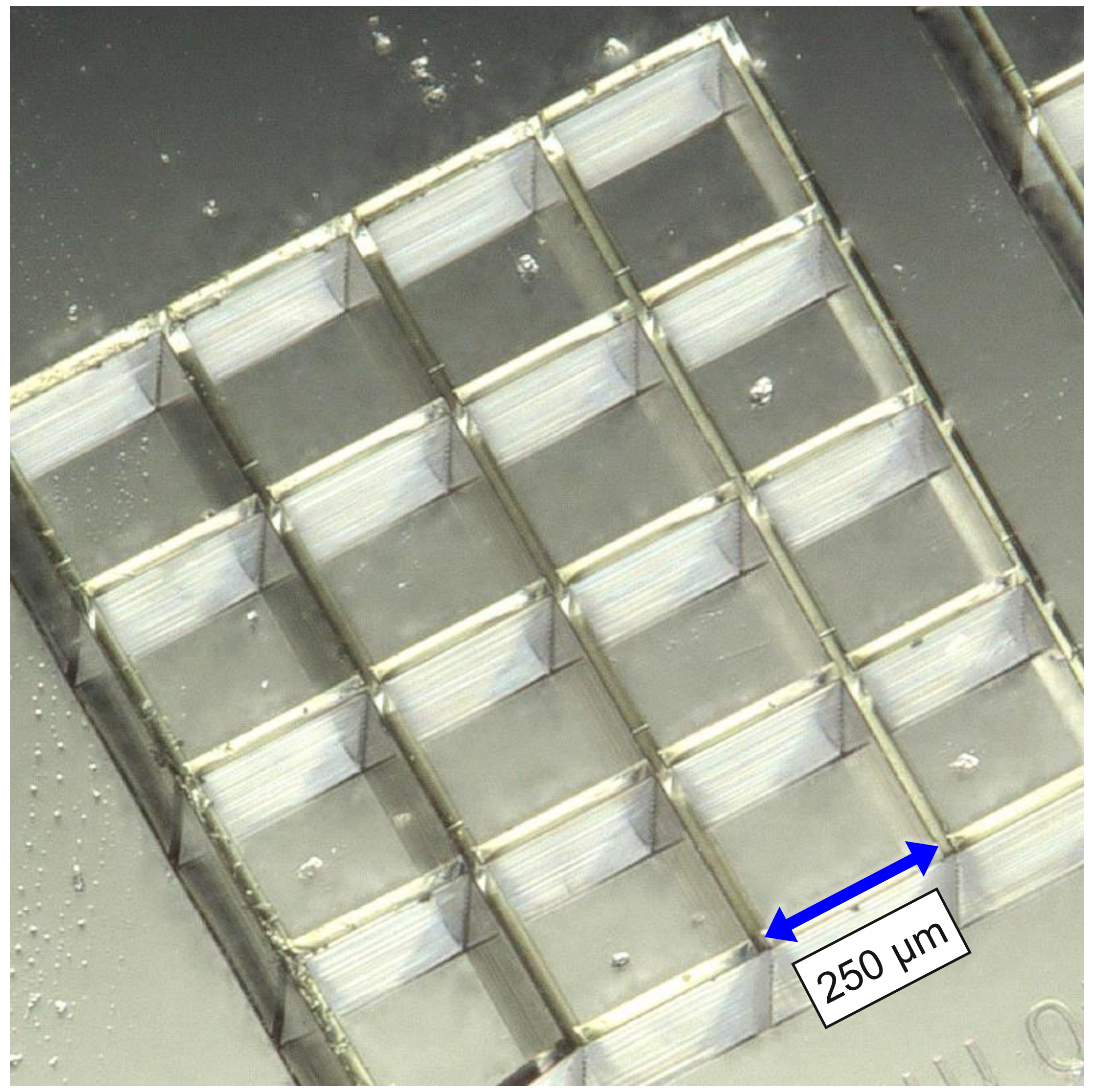


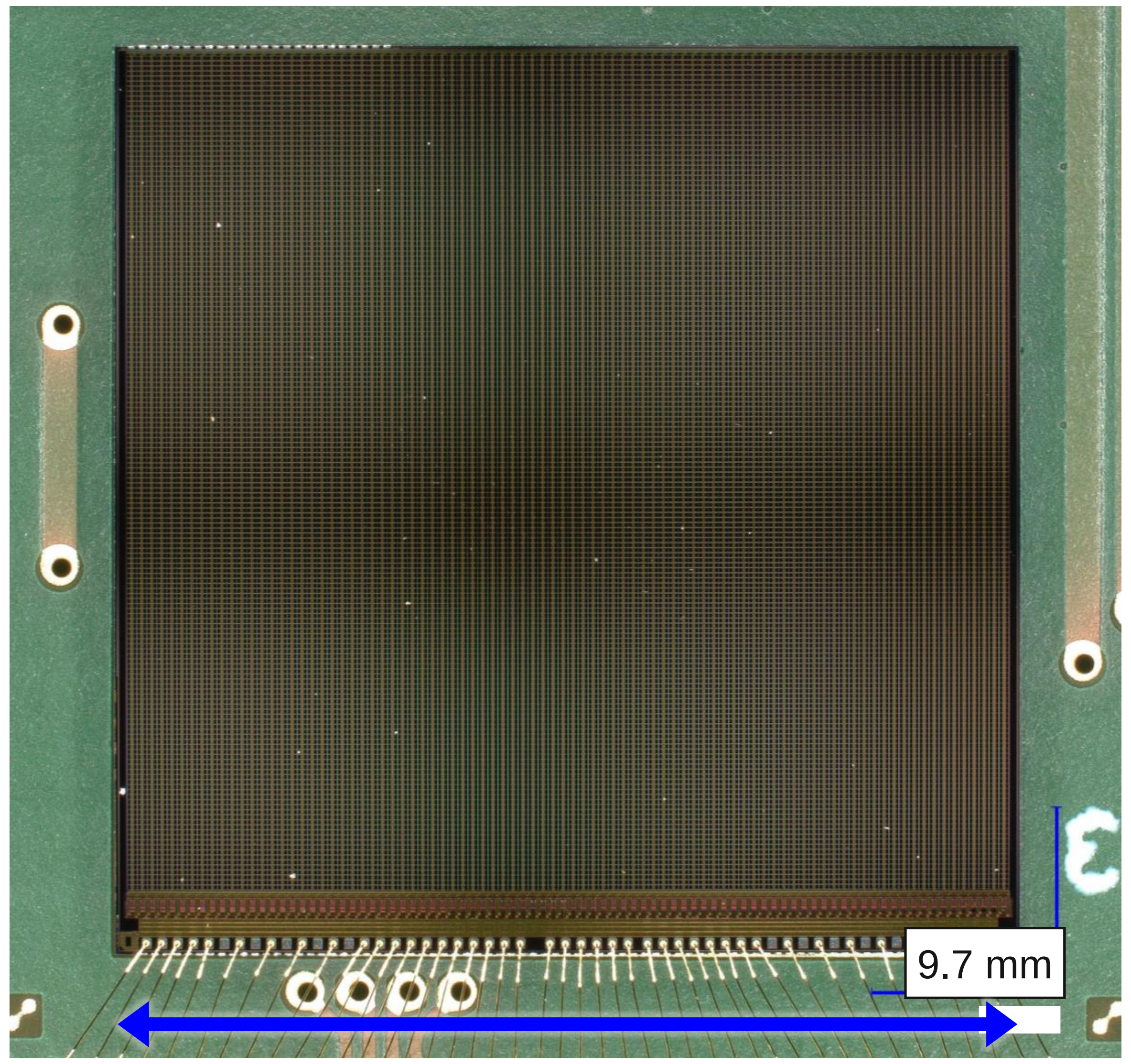
K. Gauda et al. (2022):
10.1140/epjc/s10052-022-10858-0



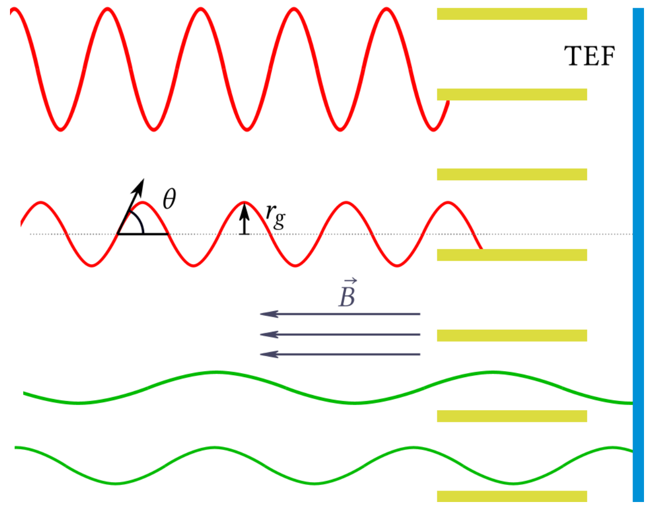
***scintillating** aTEF*

- scintillator grid and single-photon detector
- → challenges: micron-scale precision 3D printing of plastic scintillators, readout of detector array



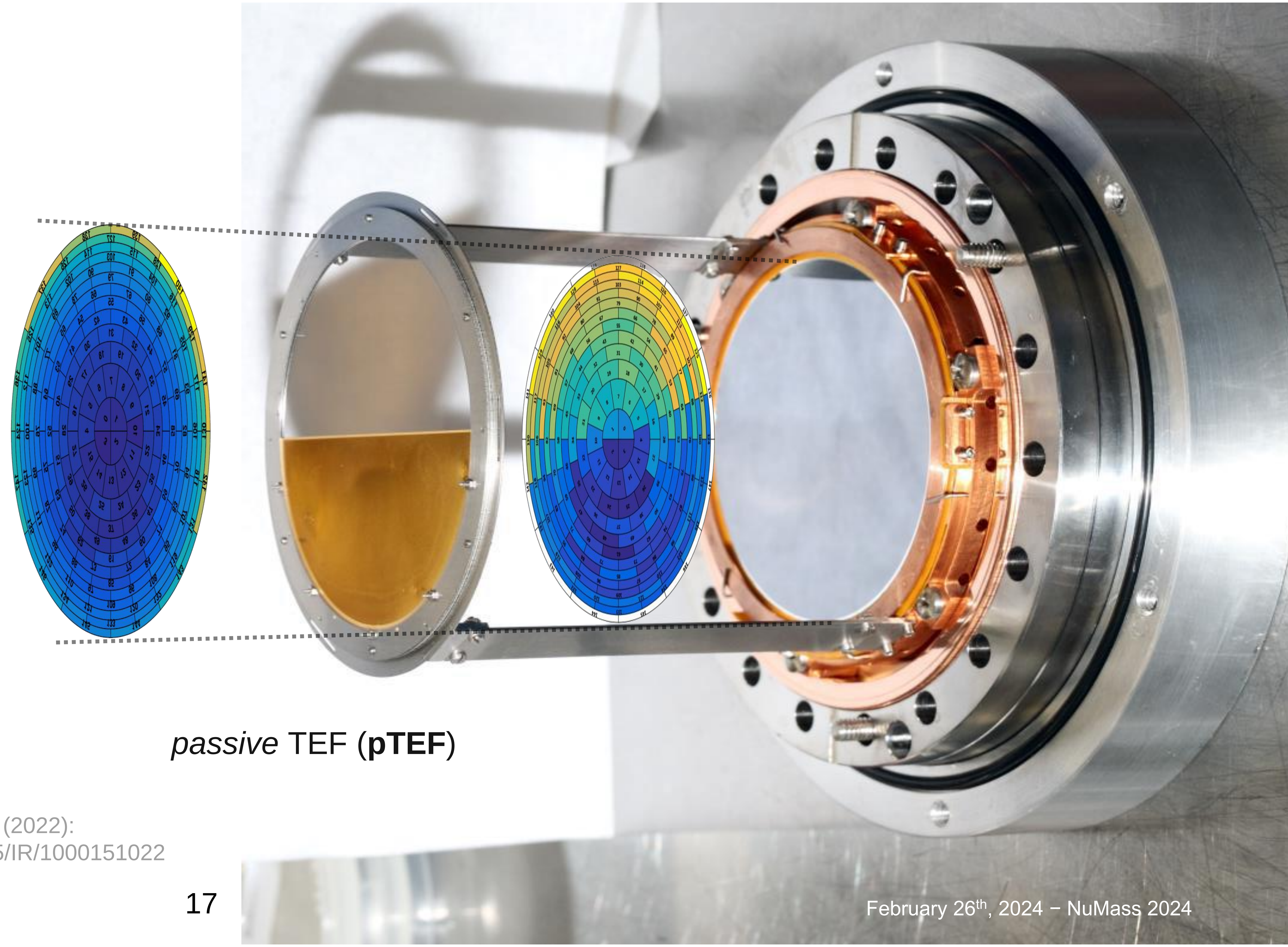


Proof of concept

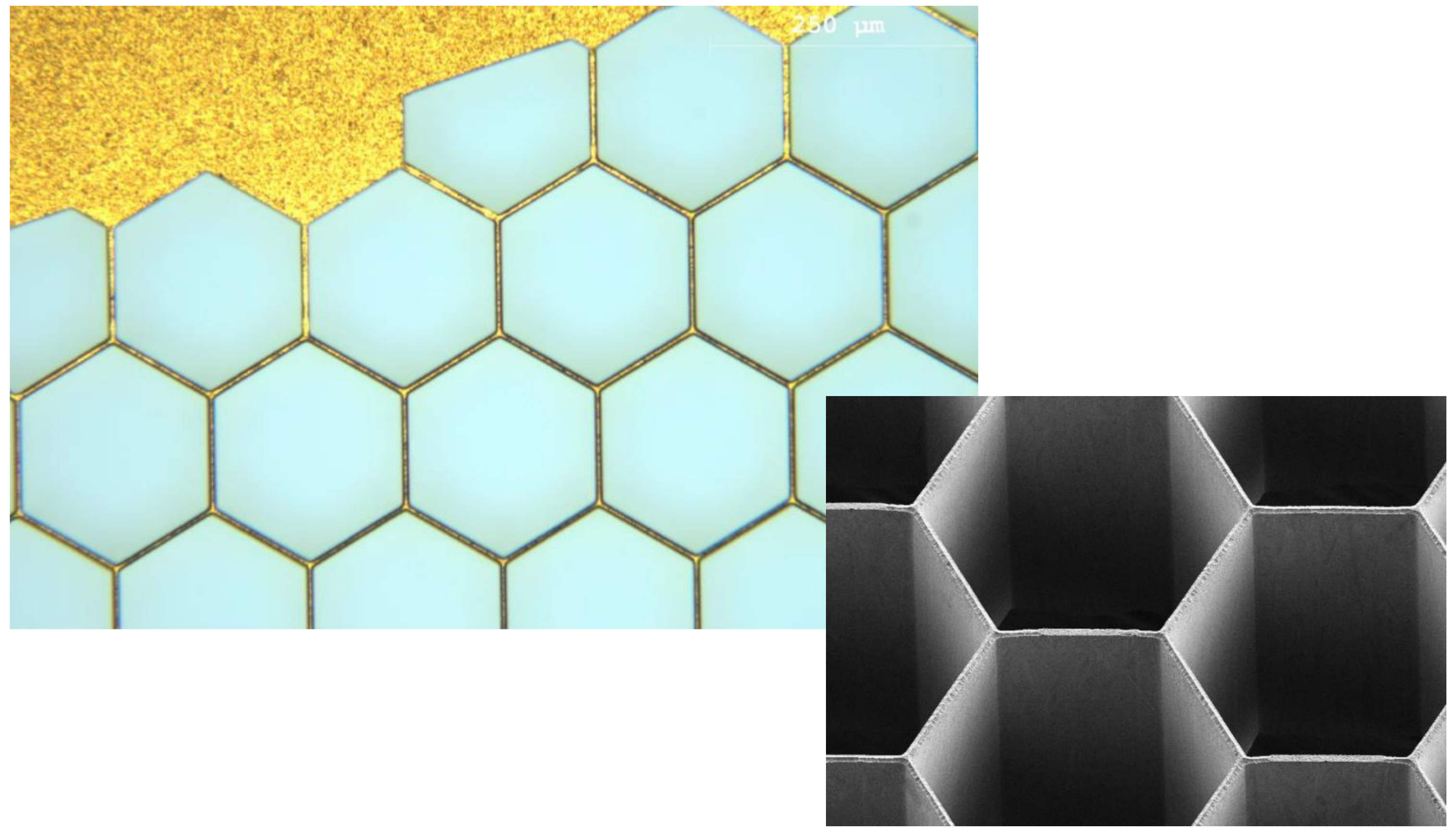


J. Wolf (2021)

- **Required** for design: **initial energies** & **angular distribution**
- Investigation: TEF principle + FPD
- Transmission → angular distribution



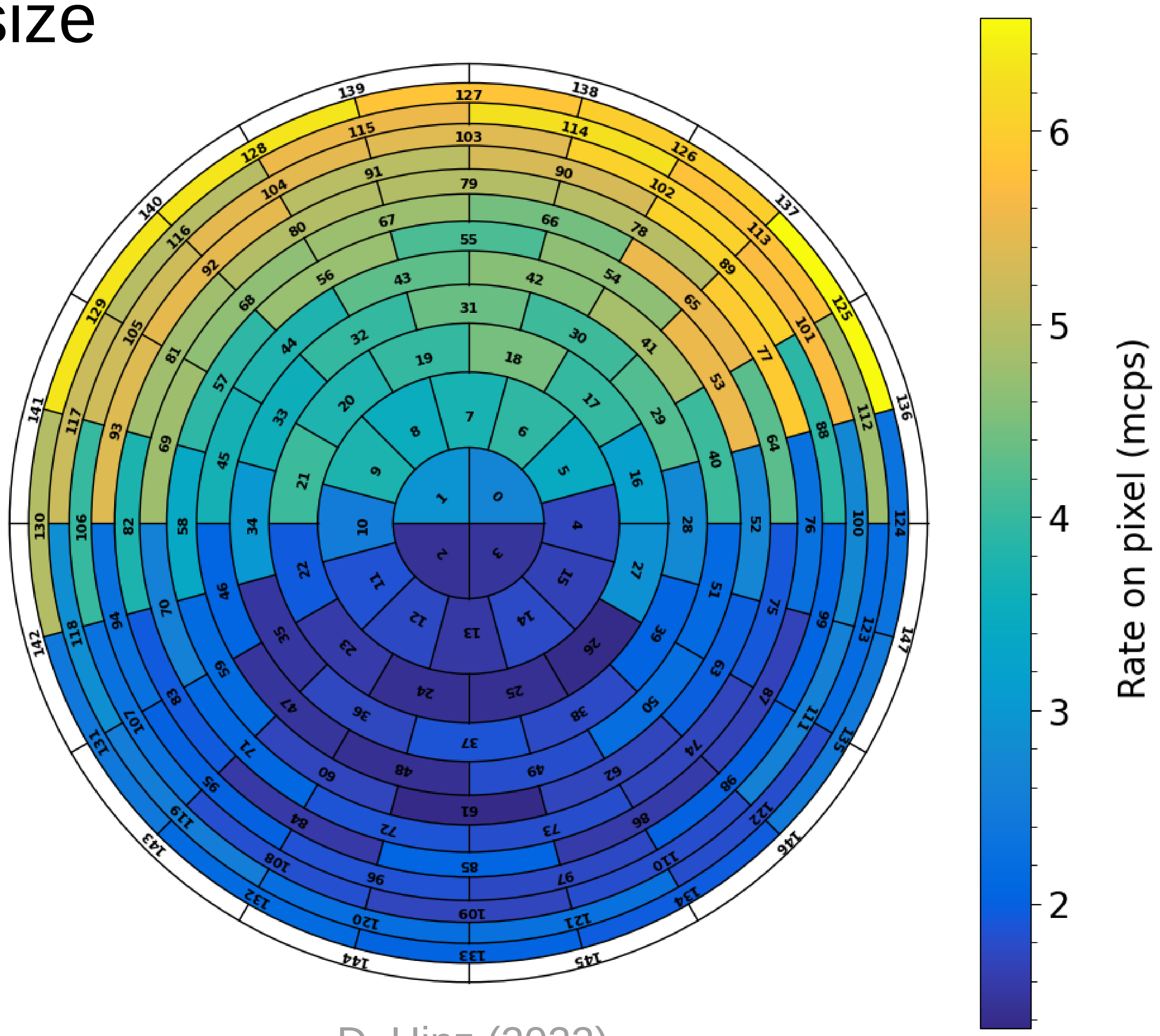
passive TEF (**pTEF**)



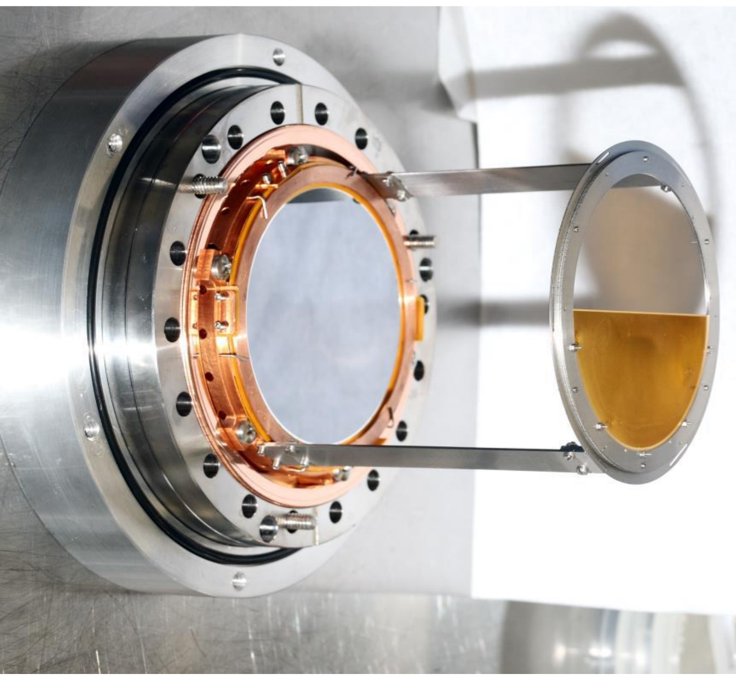
D. Hinz (2022): 10.5445/IR/1000151022

Background characterization

- pTEF Bg transmission depends on:
  - Electron inital energy
  - Magnetic field setting
  - Channel size

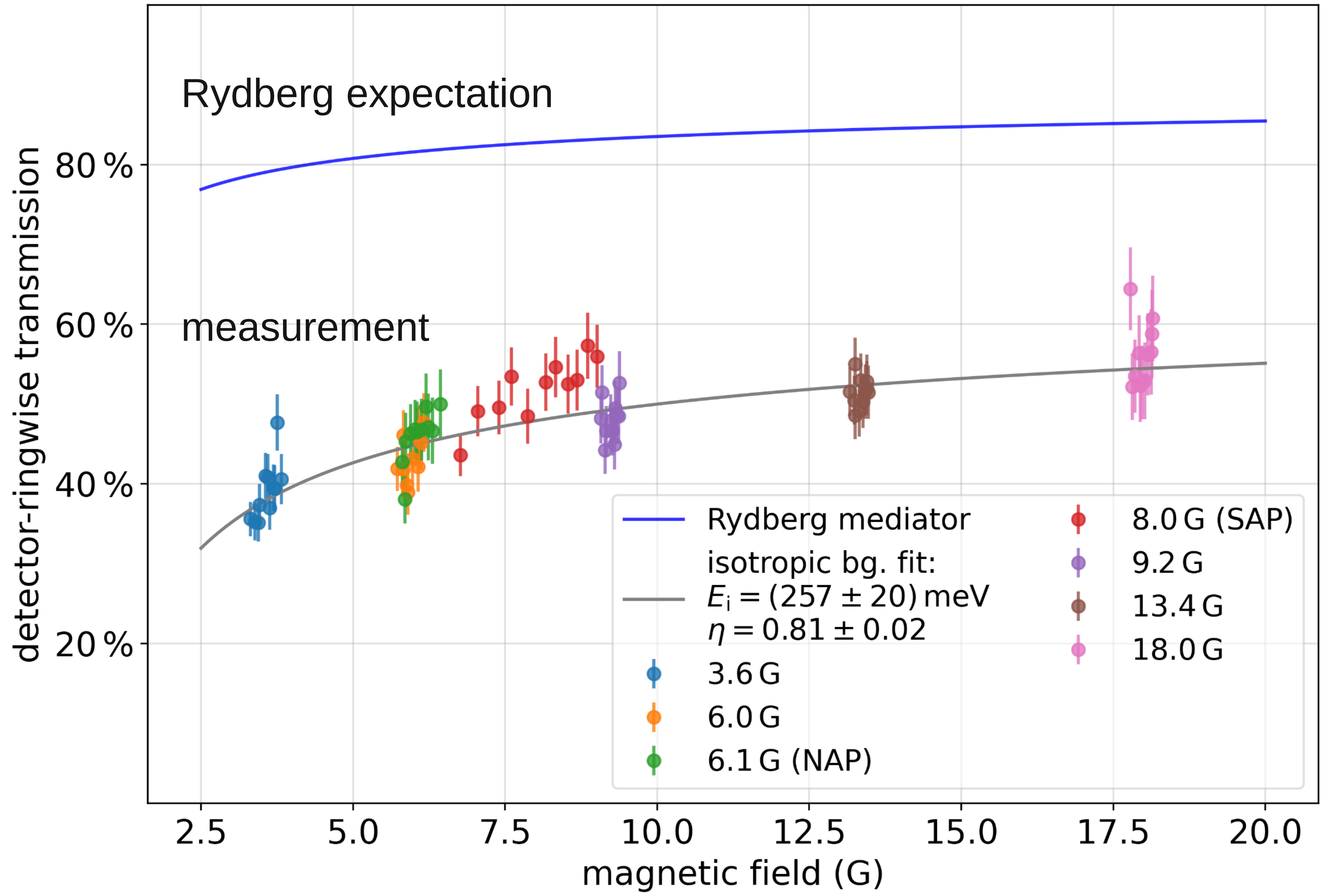


D. Hinz (2022)

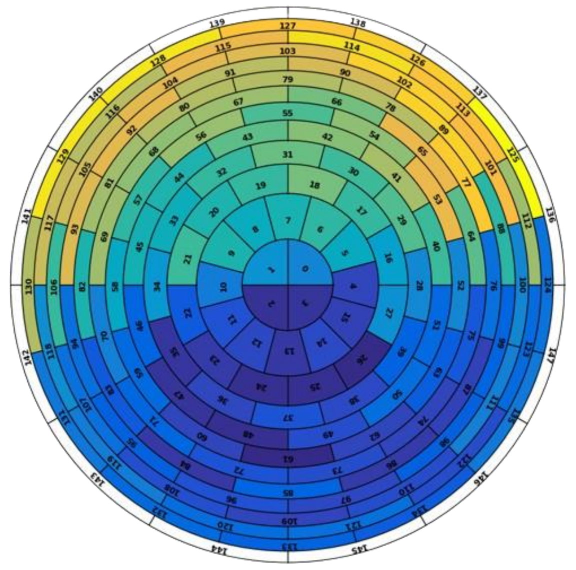


- Simulations: clear tension of pure “Rydberg” model simulation and observation
- Higher initial energies ($> 200\ \mathrm{meV}$) required

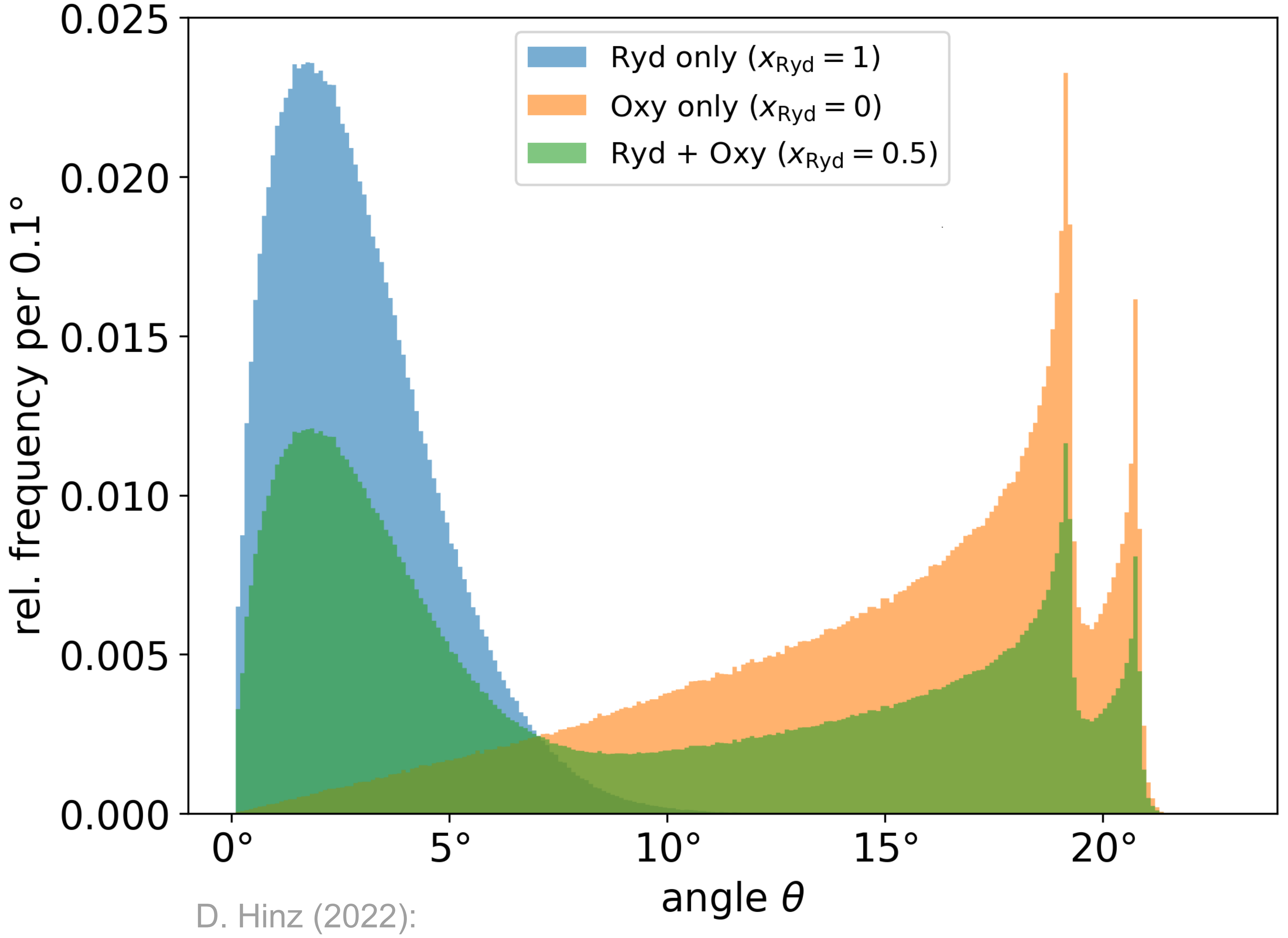
D. Hinz (2022): 10.5445/IR/1000151022



Implications of the pTEF campaign

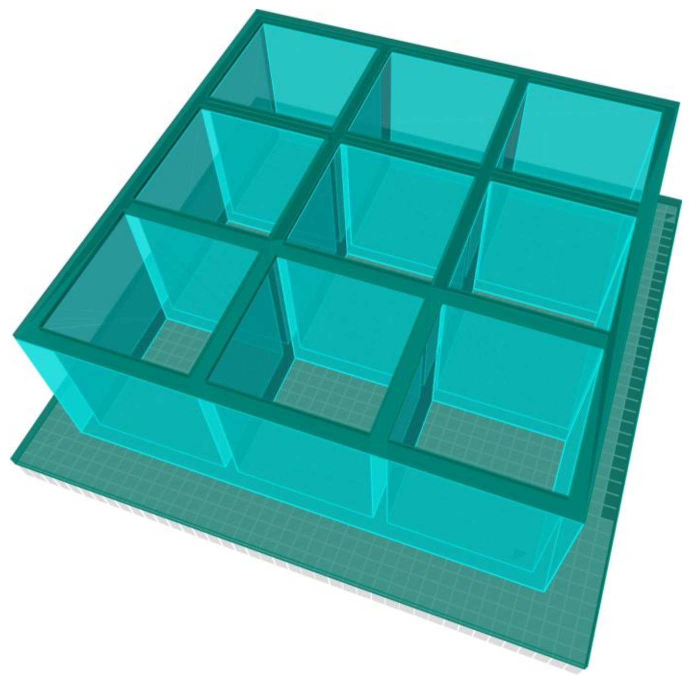


initial energy $E \Rightarrow$ angle θ at detector



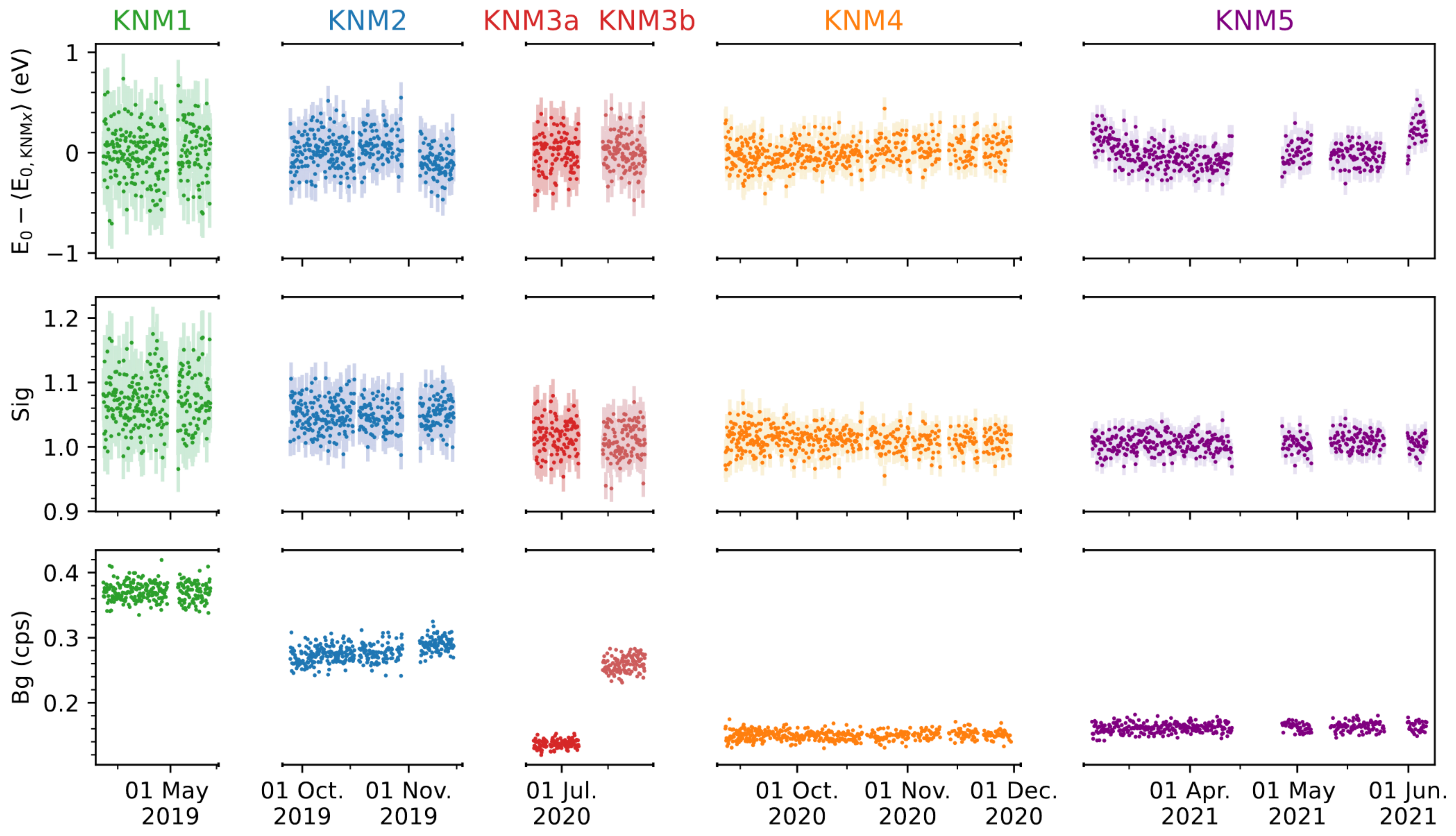
D. Hinz (2022): 10.5445/IR/1000151022

- Higher initial energies than expected from Rydberg mechanism
- → higher pitch angles and reduced mitigation effect of an aTEF
- “Rydberg” background needs **model extension**
  → candidate: **auto-ionizing** states of **oxygen**
- Likely constituted of different components, e.g. “Ryd + Oxy”



Summary and outlook

- Excellent understanding of background sources in KATRIN
- Background mitigation: ~ 1 cps → ~ 0.13 cps
- Mitigation strategies R&D:
  - aTEF
  - THz radiation
  - ToF



Acknowledgements

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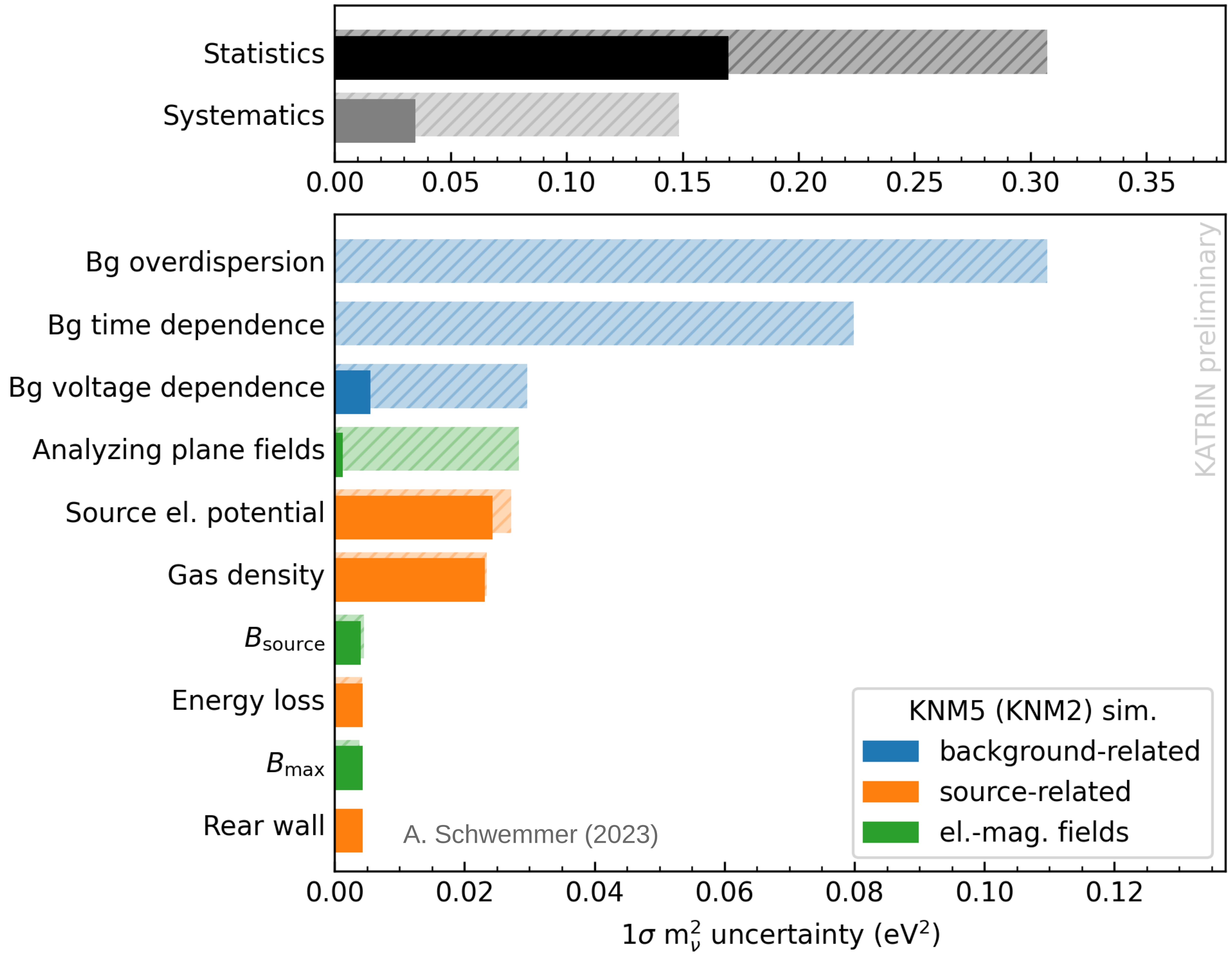
Backup

Systematics comparison

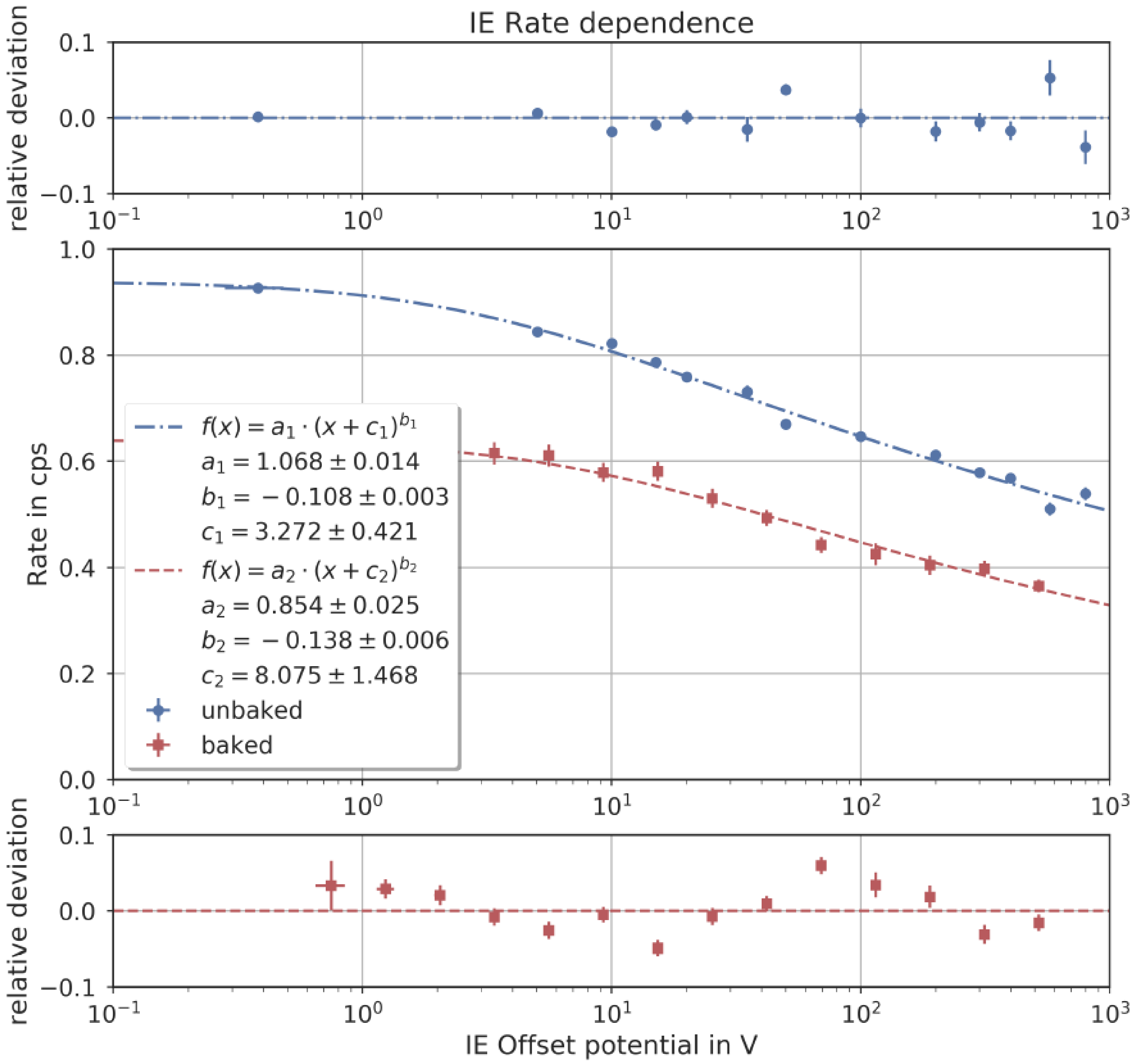
- Comparison: 2nd and 5th measurement campaign
- SAP fields measured with high precision
- → reduced overdispersion in SAP setting
- → less “efficient” radon decays



Rydberg model – evidence

Artificial contaminations of the MS

- Thorium measurement in Dec. 2016:
  - Verification of decay rate: observation of evolution according to half-life of lead-212
- Radium measurement in Oct. 2018:
  - Verification of inner electrode voltage dependence

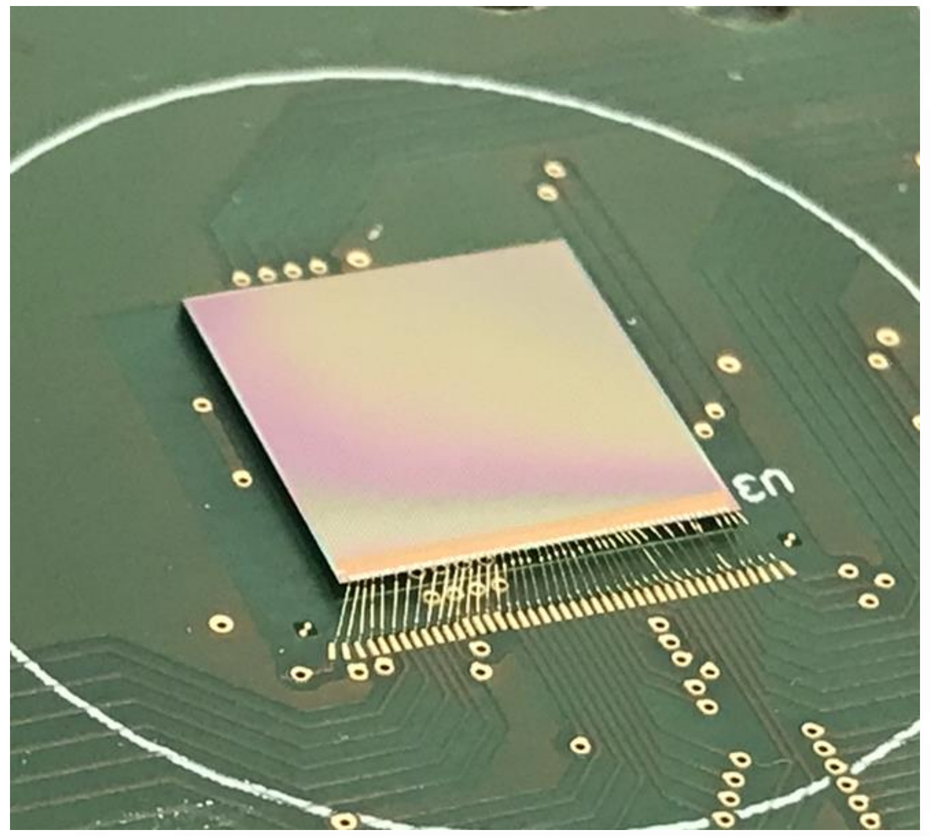


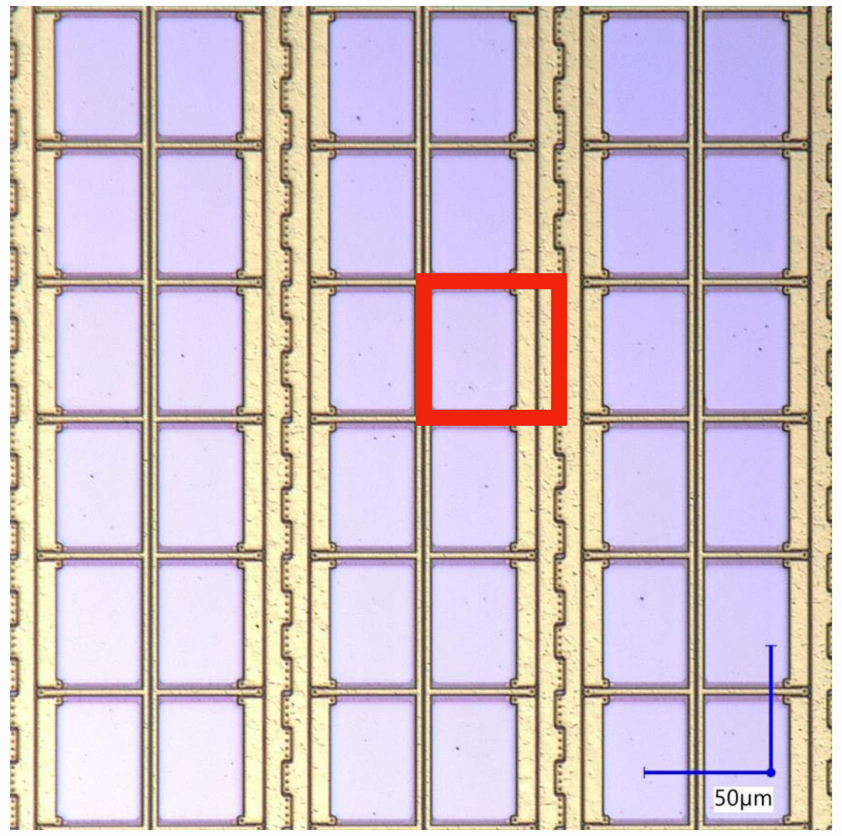
N. Trost (2019): 10.5445/IR/1000090450

$$^{228}\mathrm{Th} \xrightarrow[1.9\,\mathrm{a}]{\alpha} {}^{224}\mathrm{Ra} \xrightarrow[3.7\,\mathrm{d}]{\alpha} {}^{220}\mathbf{Rn} \xrightarrow[56\,\mathrm{s}]{\alpha} {}^{216}\mathrm{Po} \xrightarrow[0.15\,\mathrm{s}]{\alpha} {}^{212}\mathrm{Pb} \xrightarrow[10.6\,\mathrm{h}]{\beta^-} {}^{212}\mathrm{Bi} \left\{ \begin{array}{l} (64\,\%) \xrightarrow[61\,\mathrm{min}]{\beta^-} {}^{212}\mathrm{Po} \xrightarrow[310\,\mathrm{ns}]{\alpha} \\ (36\,\%) \xrightarrow[61\,\mathrm{min}]{\alpha} {}^{208}\mathrm{Tl} \xrightarrow[3.1\,\mathrm{min}]{\beta^-} \end{array} \right\} {}^{208}\mathrm{Pb}, \quad (3.7)$$

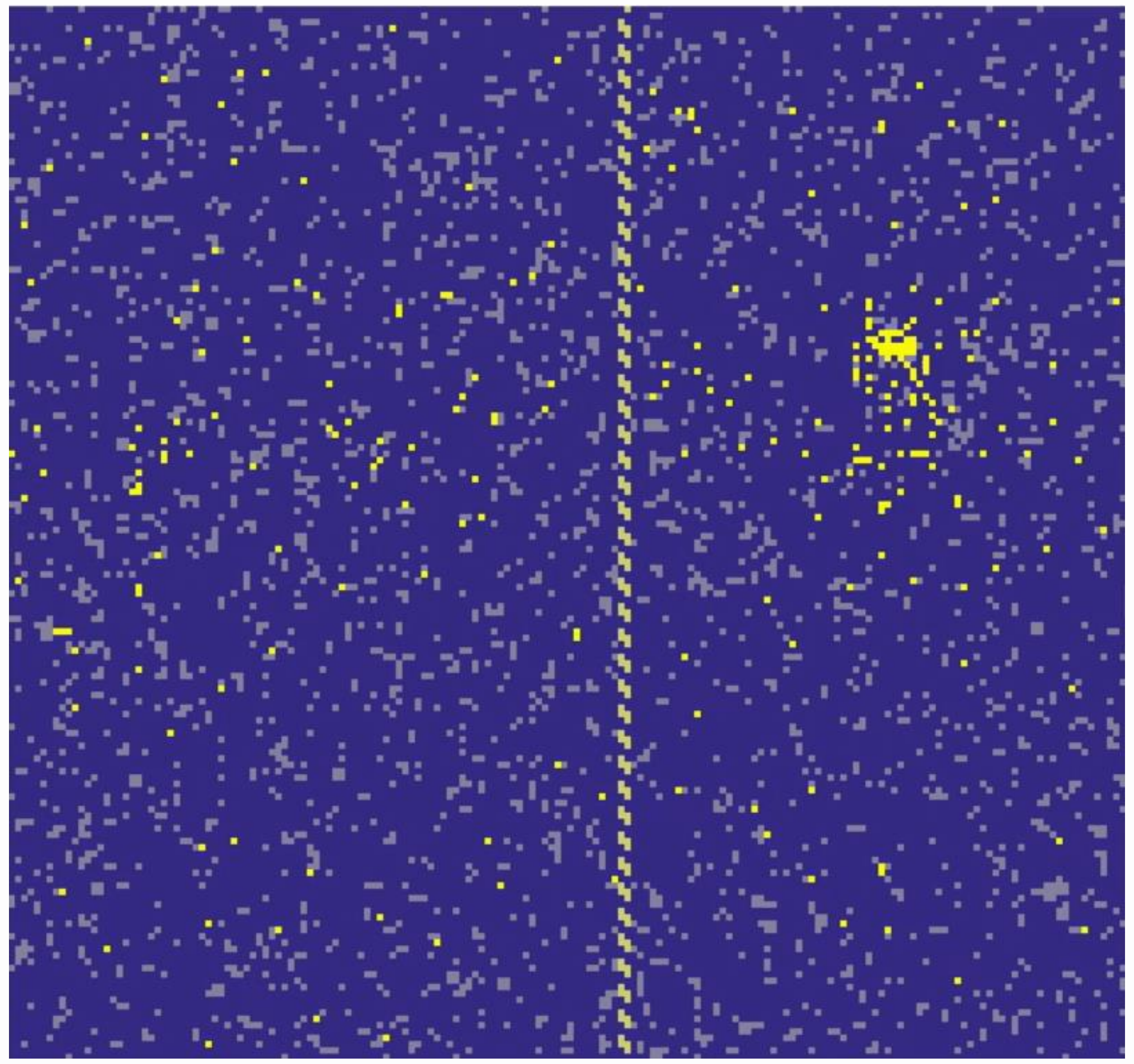
$$^{223}\mathrm{Ra} \xrightarrow[11\,\mathrm{d}]{\alpha} {}^{219}\mathbf{Rn} \xrightarrow[4\,\mathrm{s}]{\alpha} {}^{215}\mathrm{Po} \xrightarrow[1.8\,\mathrm{ms}]{\alpha} {}^{211}\mathrm{Pb} \xrightarrow[36\,\mathrm{min}]{\alpha} {}^{211}\mathrm{Bi} \xrightarrow[2.1\,\mathrm{min}]{\alpha} {}^{207}\mathrm{Tl} \xrightarrow[4.8\,\mathrm{min}]{\beta^-} {}^{207}\mathrm{Pb}, \quad (3.8)$$

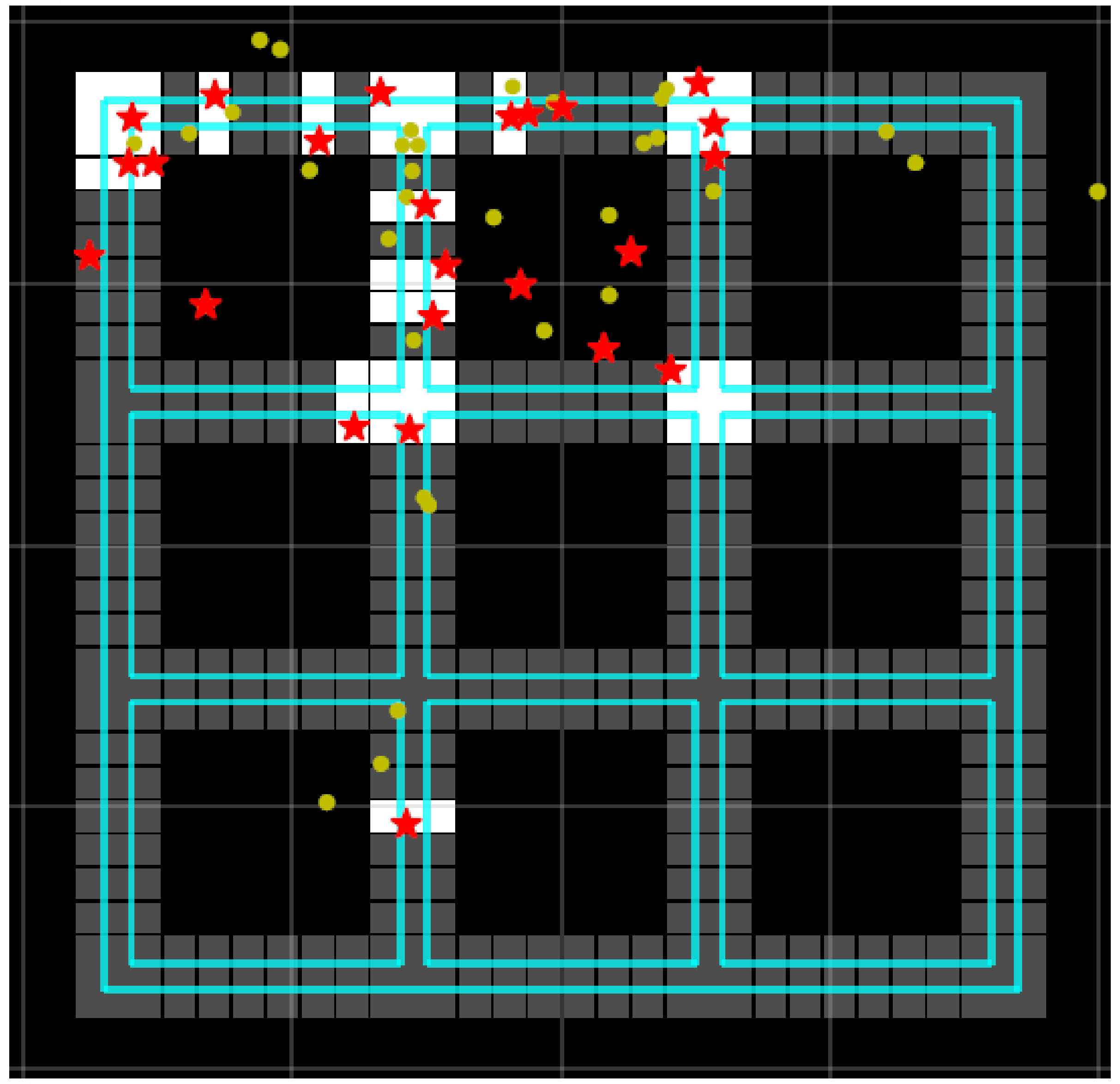
scintillating aTEF

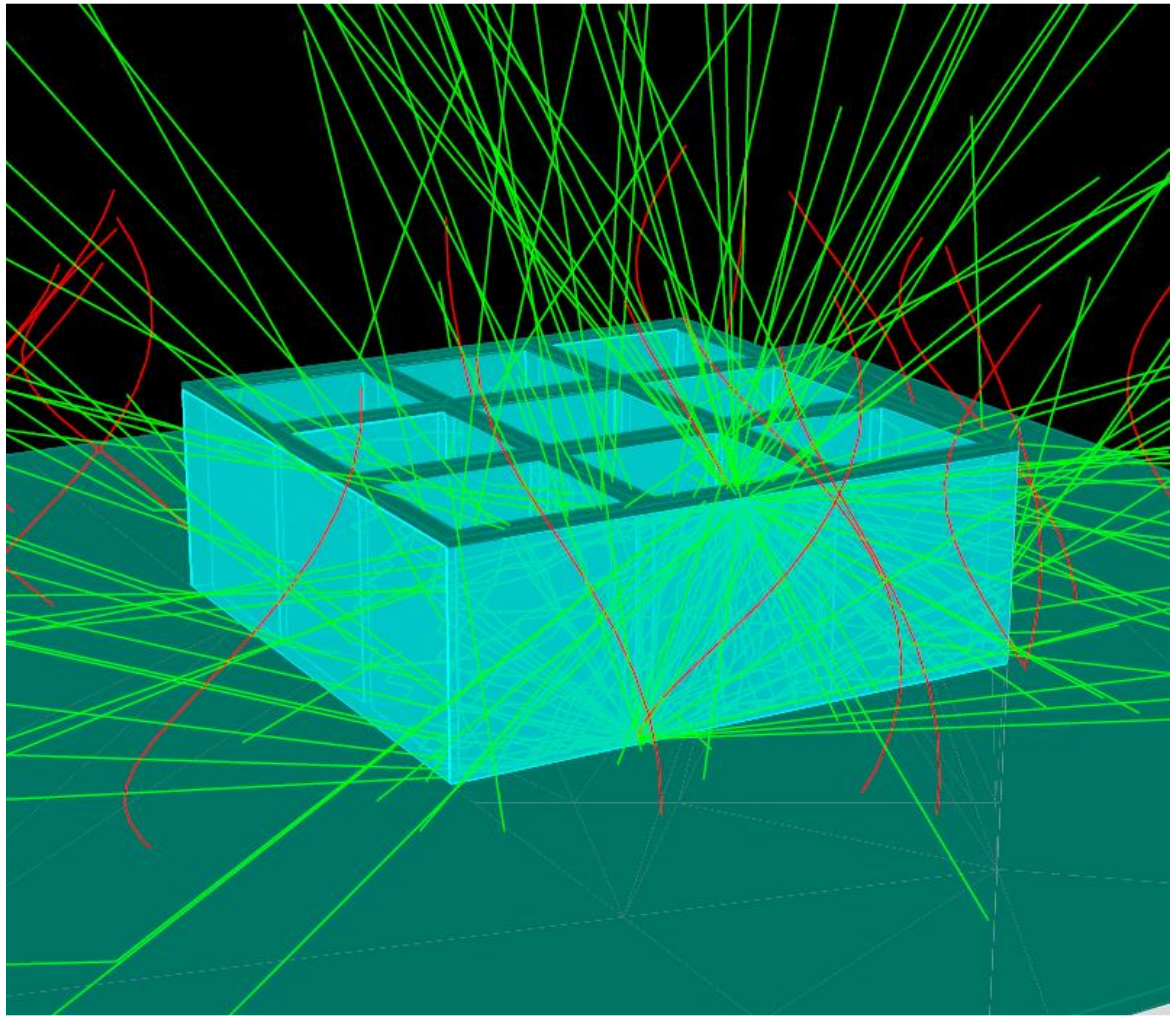




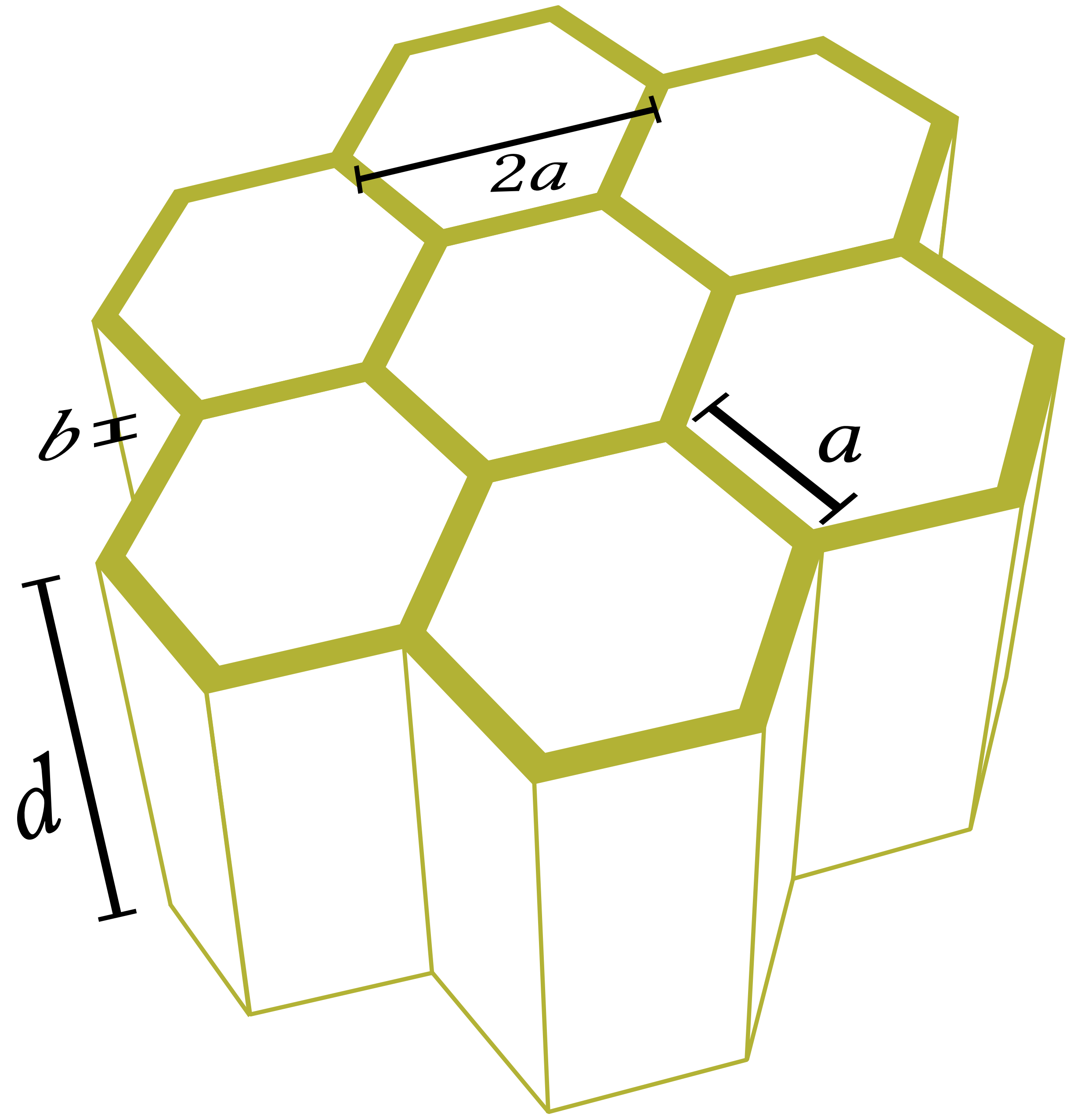
J. Lauer (2022)

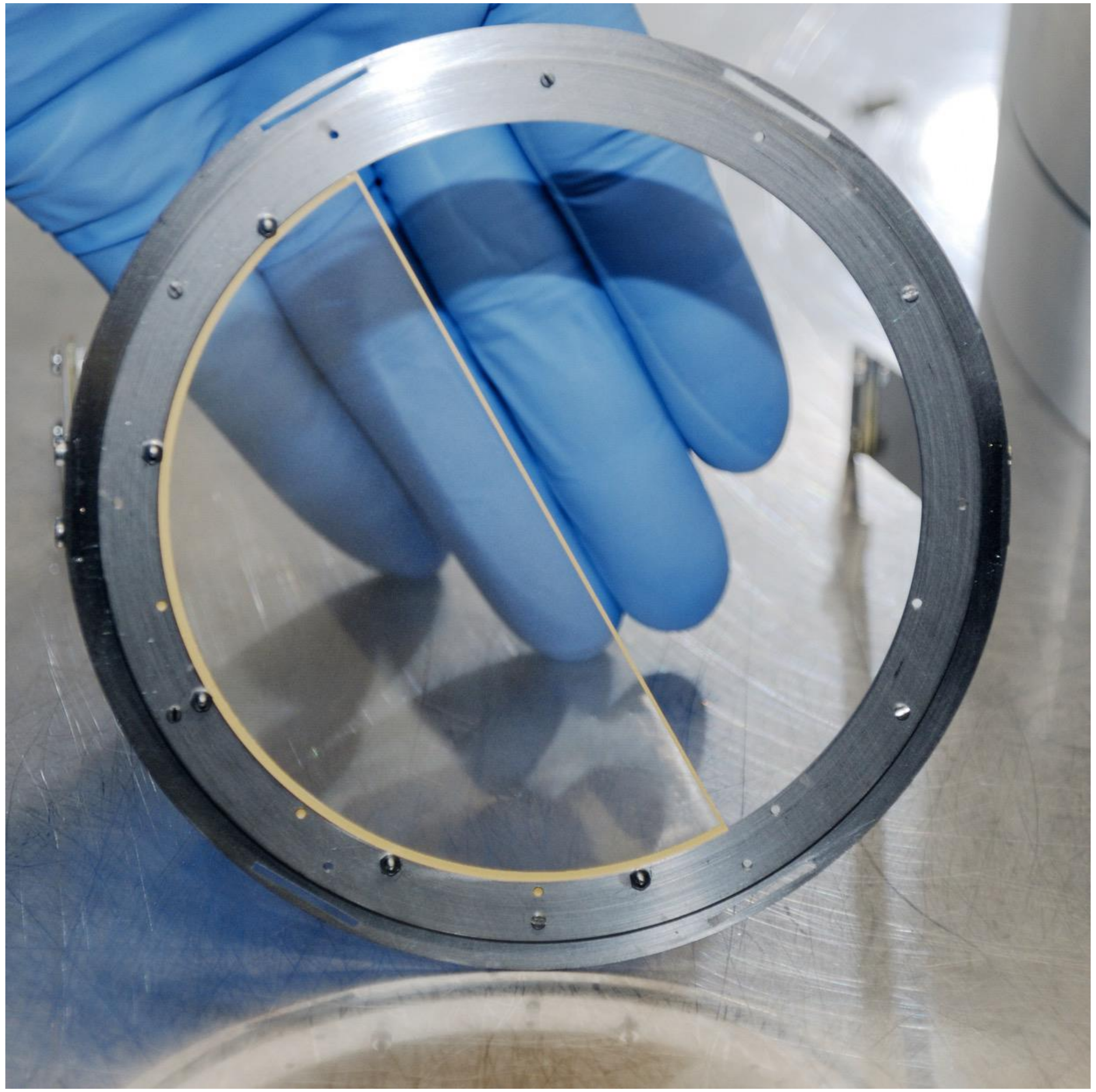






pTEF





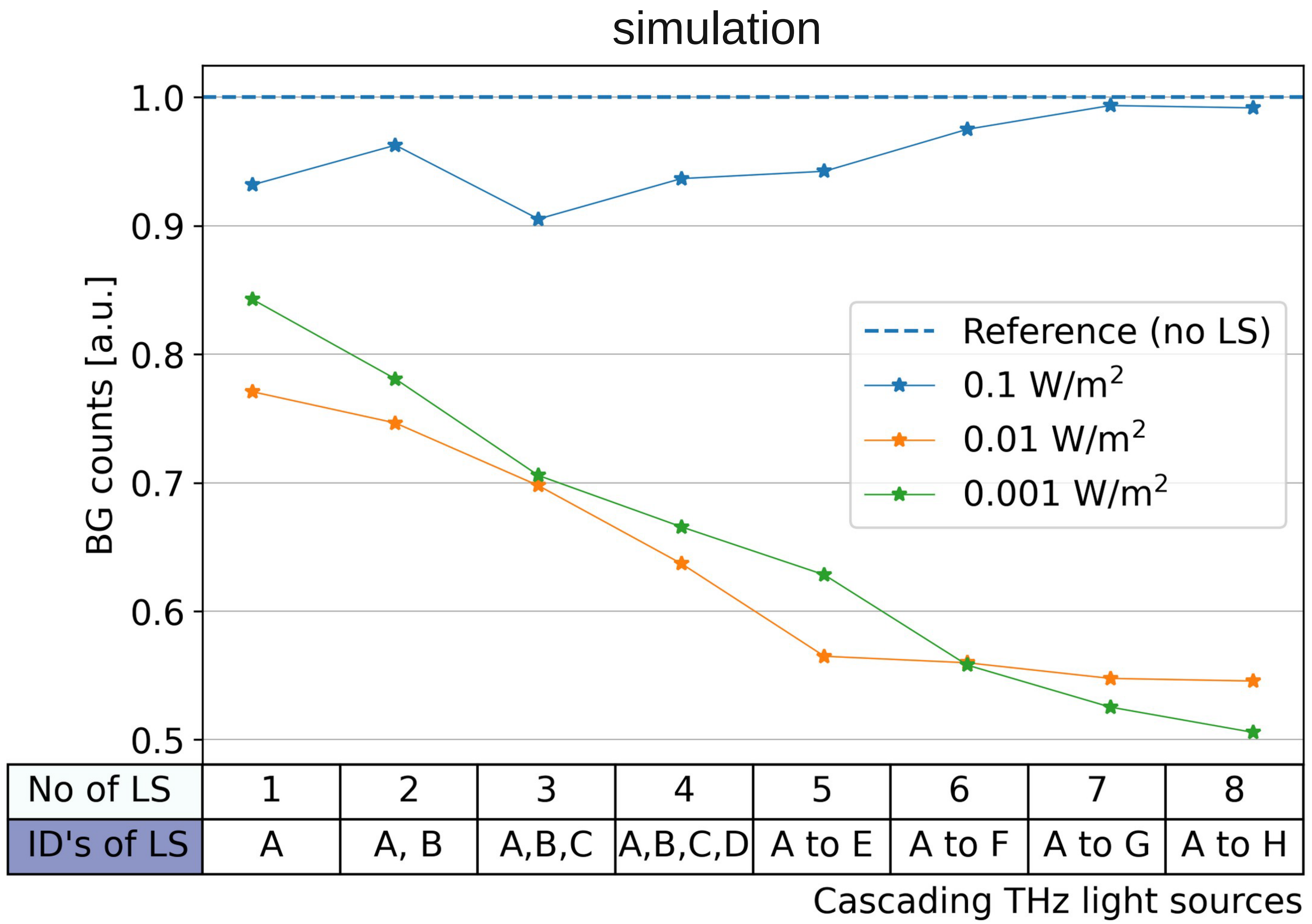
J. Lauer (2022)

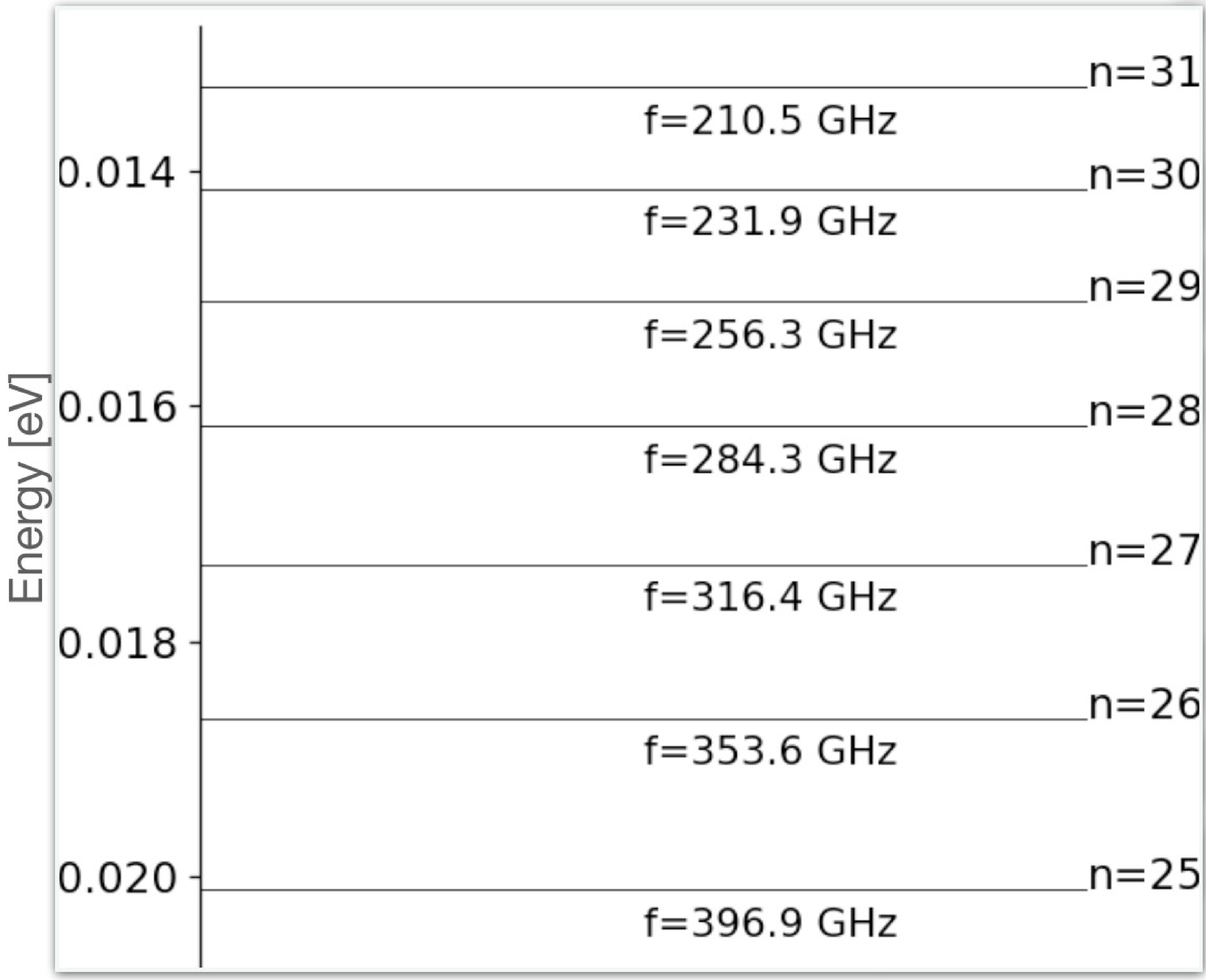
“Rydberg” background mitigation (pt. 3)

THz radiation

- Manipulating atomic transitions using EM radiation
- Radiation: $\mathrm{THz} \sim 1\ \mathrm{meV}$ → example: 8 THz source

K. Helbing (2023)





“Rydberg” background mitigation (pt. 4)

Time of flight: electron tagging

- Tagging of electrons entering MS:
  - Cyclotron radiation (low-noise waveguide or cavity amplifier)
  - SQUID resonator readout
- → discrimination of all electrons from MS volume
- → also interesting for differential measurement