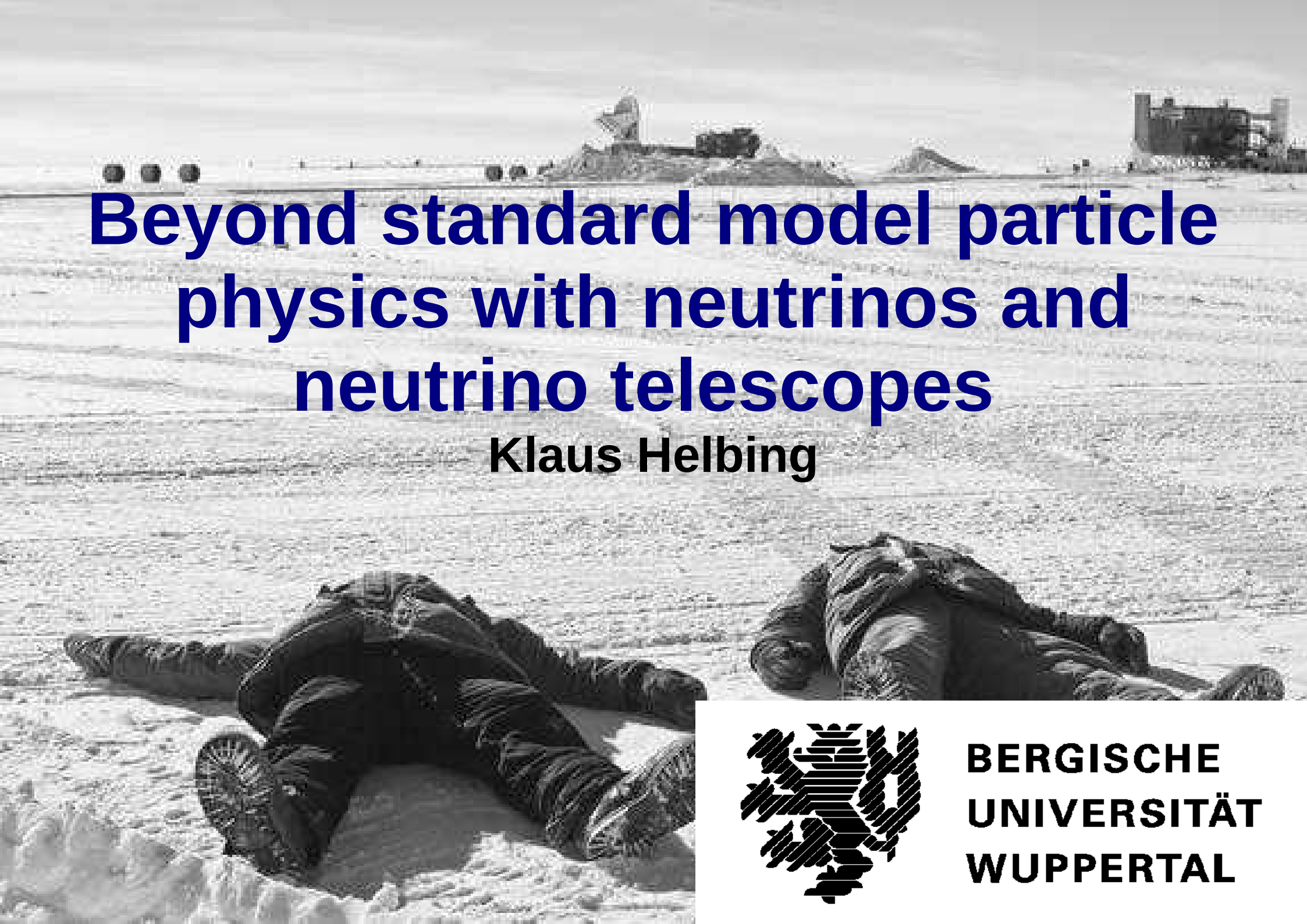


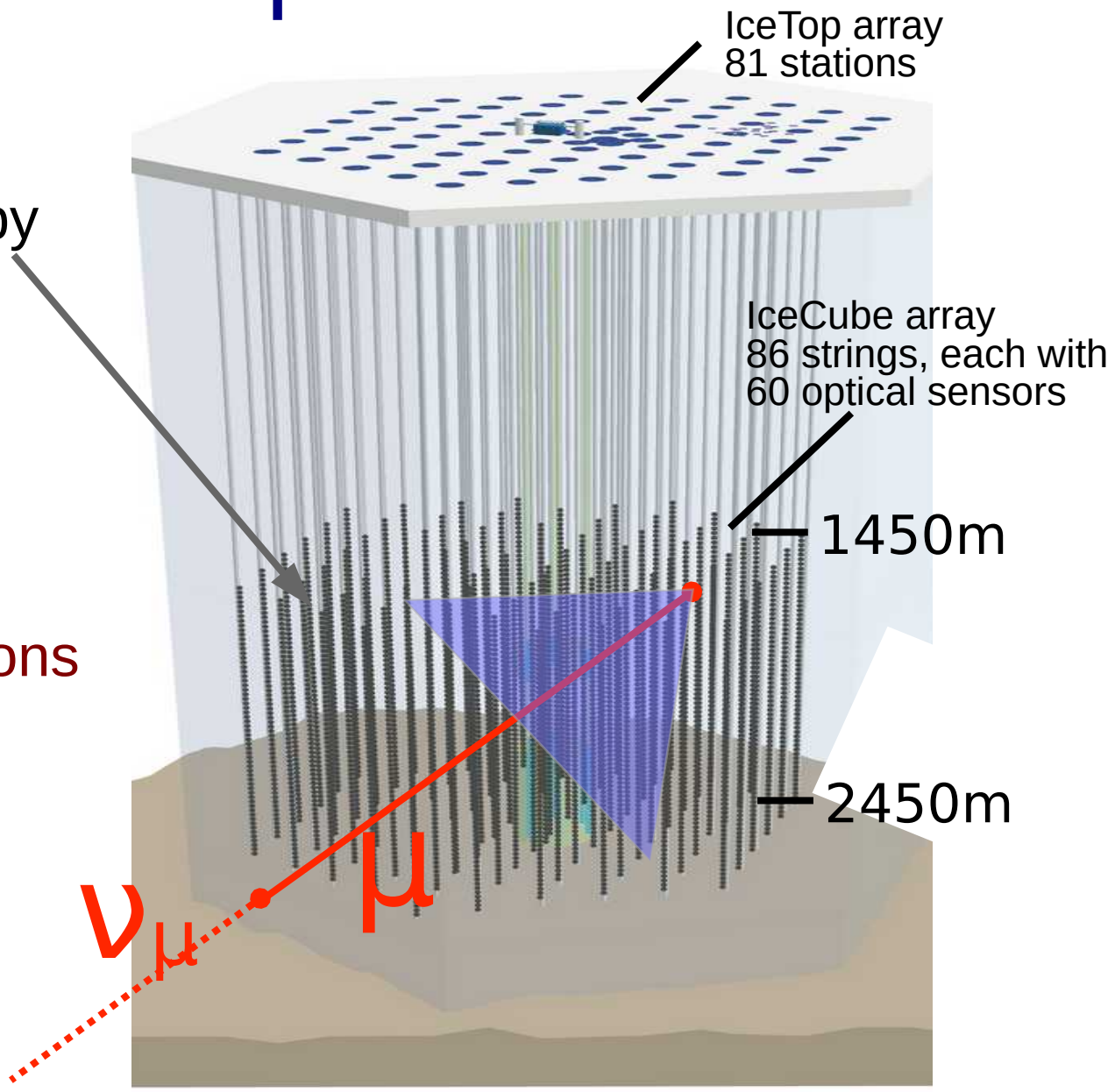
Beyond standard model particle physics with neutrinos and neutrino telescopes

Klaus Helbing

BERGISCHE UNIVERSITÄT WUPPERTAL

Primary working principle of Neutrino Telescopes

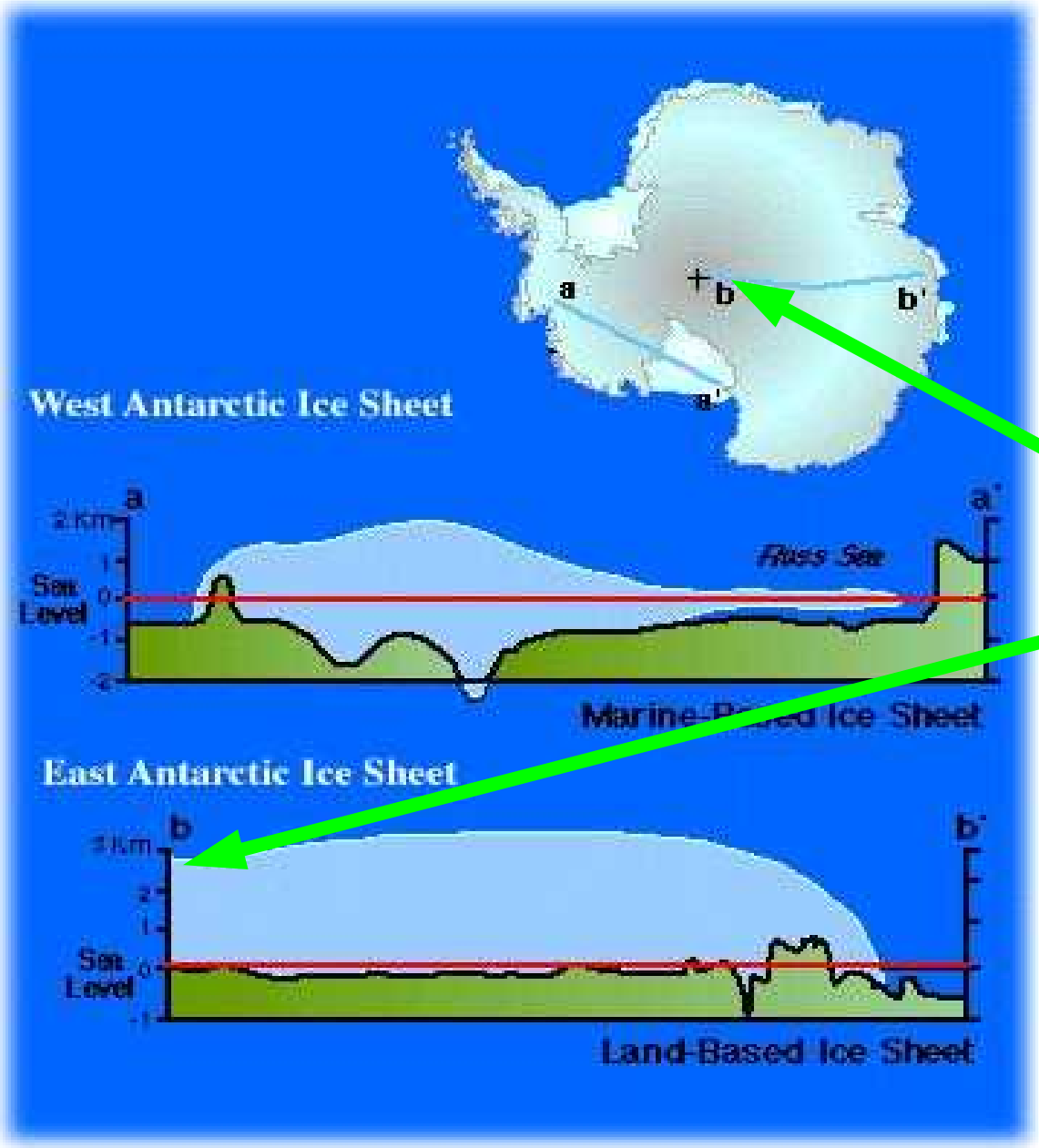
- Particles interact with the deep clear ice
- Emitted light is detected by sensors
  - Cherenkov Light
  - Bremsstrahlung
  - Pair production
  - Photonuclear interactions
  - Luminescence



Neutrino Telescope Sites

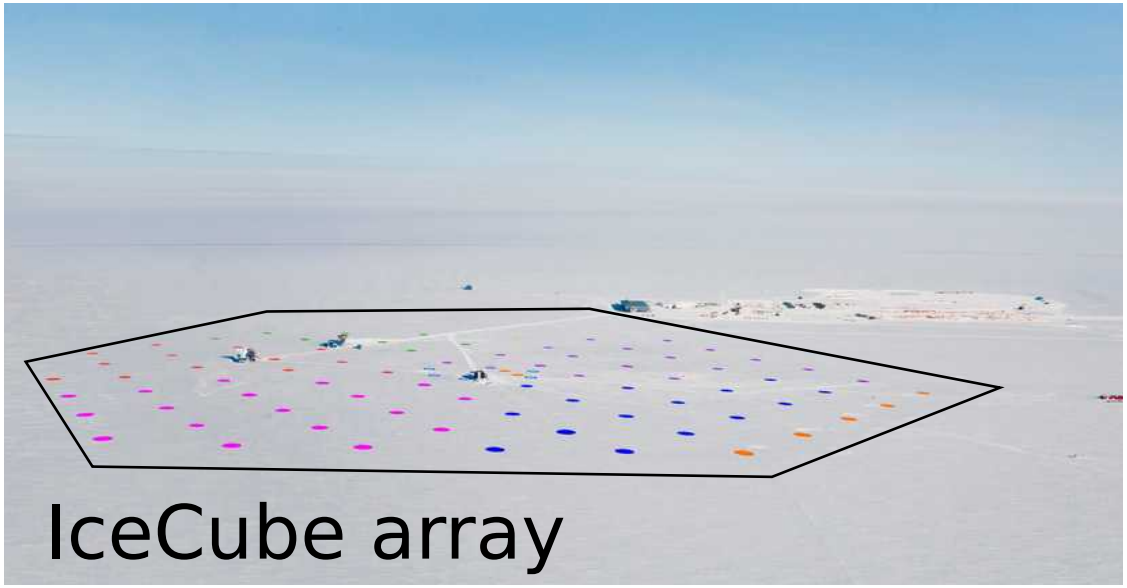
Deep natural sites with water or ice

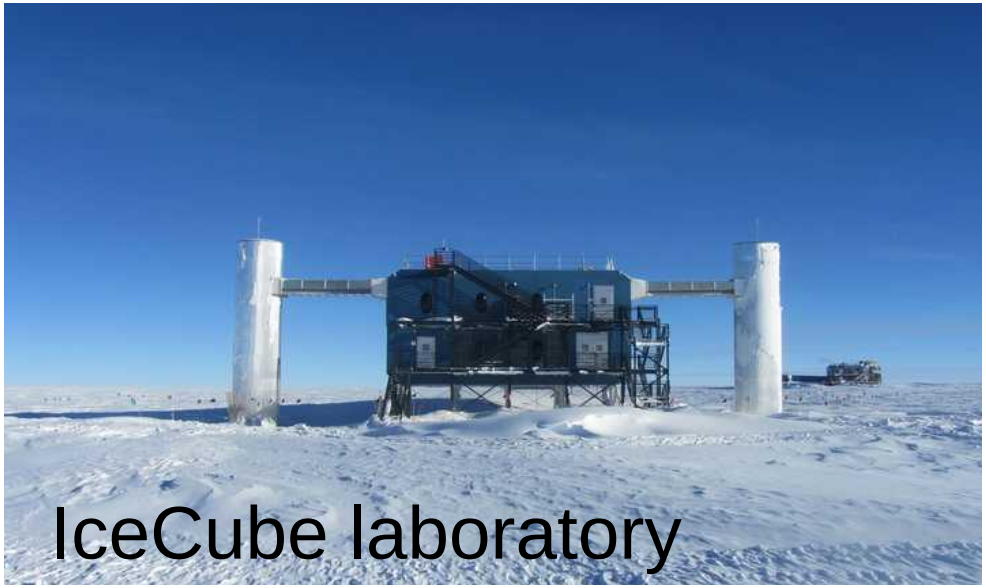
South Pole ice



South Pole

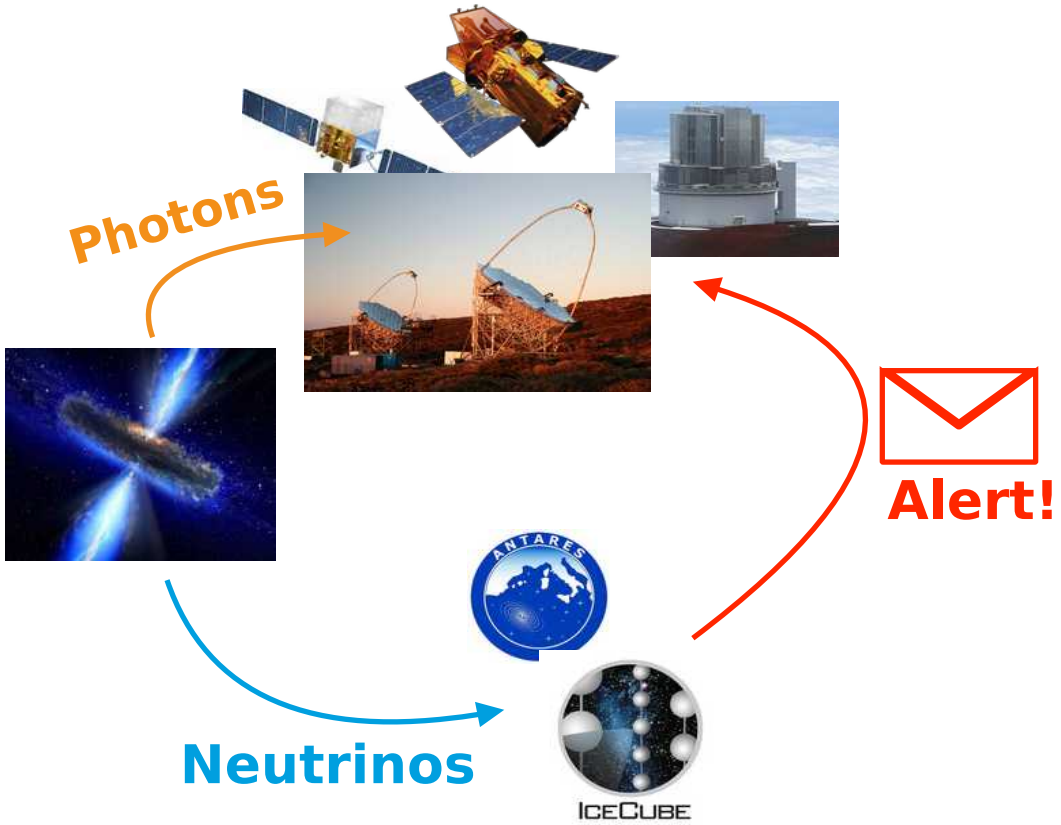
IceCube Neutrino Observatory

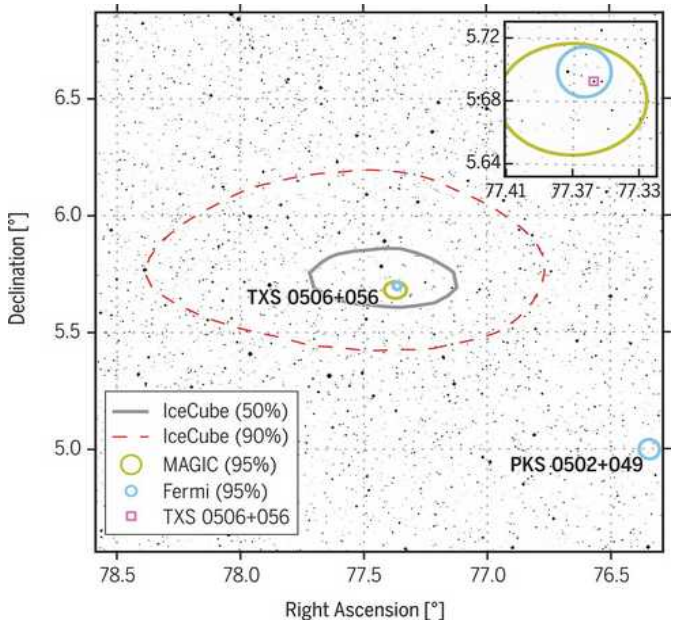




First evidence for a neutrino source!

Real-time alerts





3σ correlation of IC-170922A (~300 TeV) with the flaring blazar TXS 0506+056

This is not what this talk is about ...

… but signatures of BSM physics

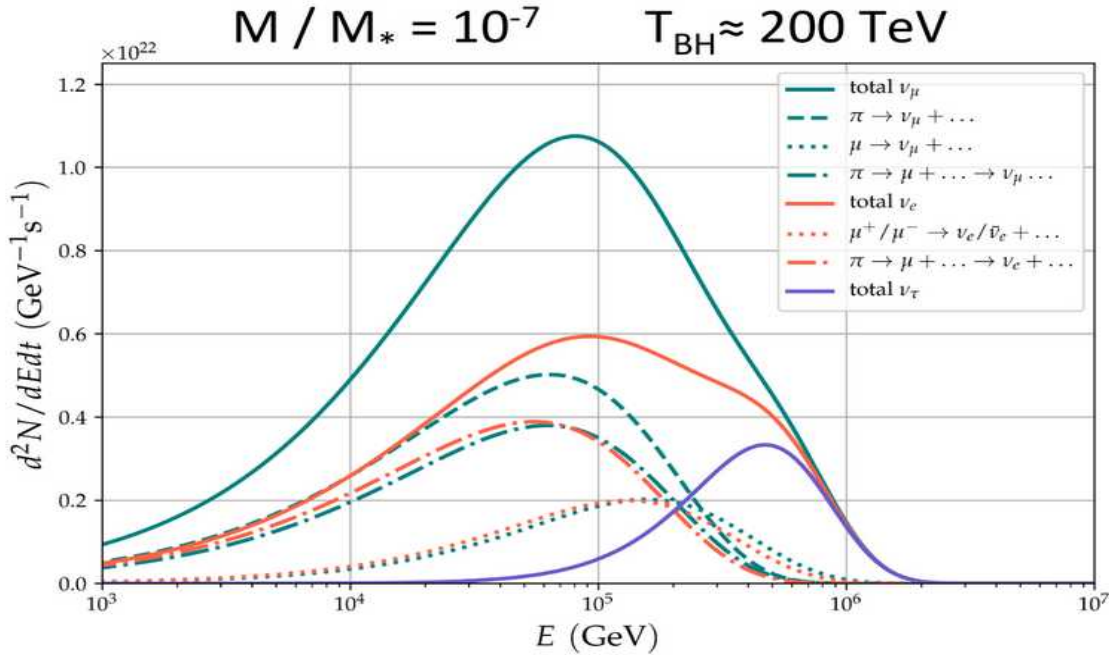
- In IceCube
  - black hole evaporation
  - Magnetic Monopoles
  - Q-Balls, Nuclearites
  - Fractional charges
- In KATRIN
  - Direct neutrino mass
  - Relic neutrinos
  - LIV
- and – Deexcitation of Rydberg atoms

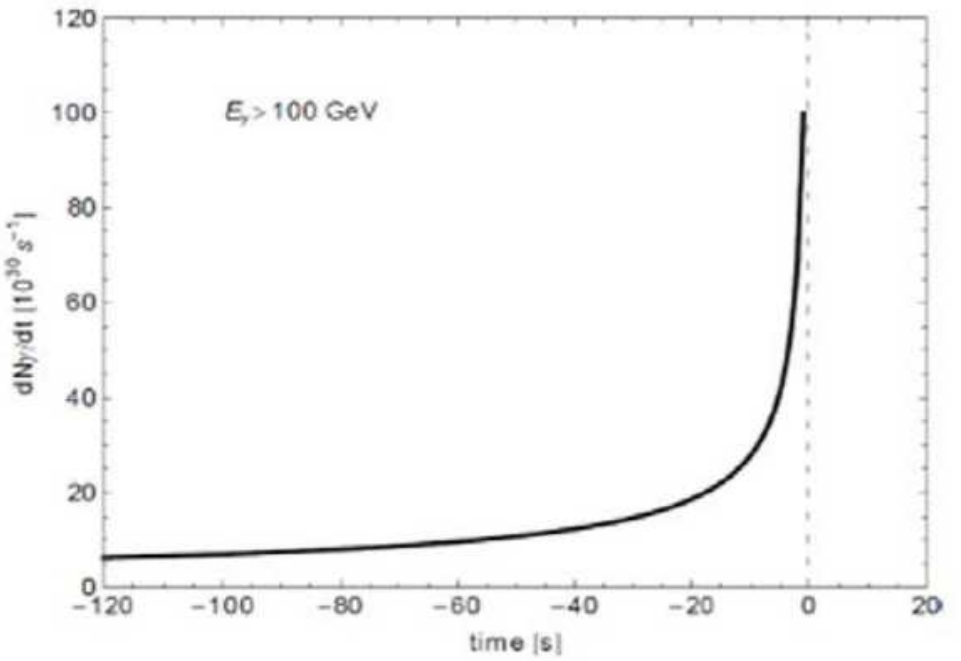
… sorry, need to skip over oscillations

more by Markus Ackermann tomorrow

Evaporating primordial black holes as flaring point sources

Today might be the ideal cosmological epoch





Signature:
Hawking radiation of neutrinos
→ chirp with increasing energy

Interested? Join us!

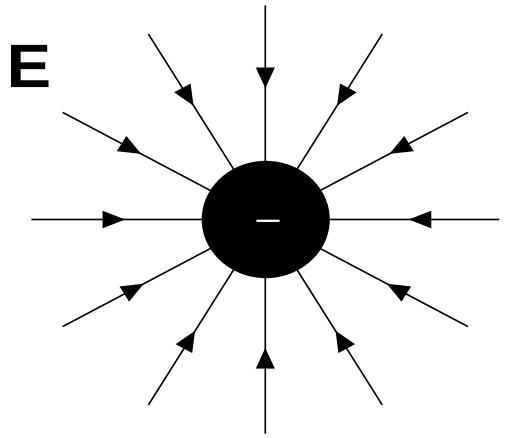
Symmetric Maxwell equations – classical field theory

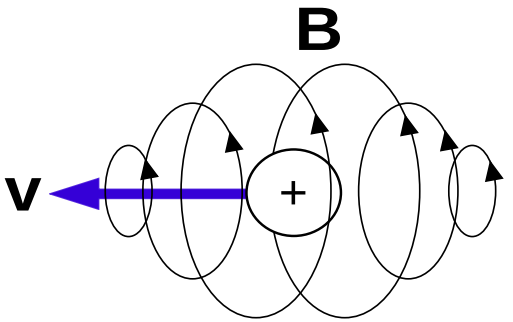
$$\vec{\nabla} \cdot \vec{E} = \rho_{\mathrm{E}}$$

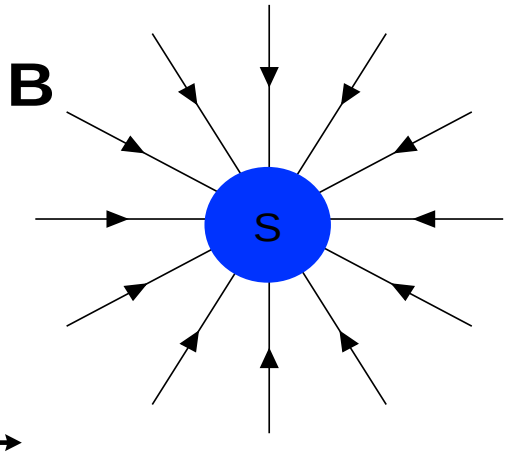
$$\vec{\nabla} \cdot \vec{B} = \rho_{\mathrm{M}}$$

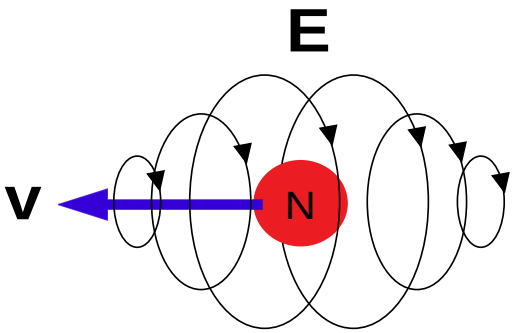
$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} - \vec{j}_{\mathrm{M}}$$

$$\vec{\nabla} \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + \vec{j}_{\mathrm{E}}$$





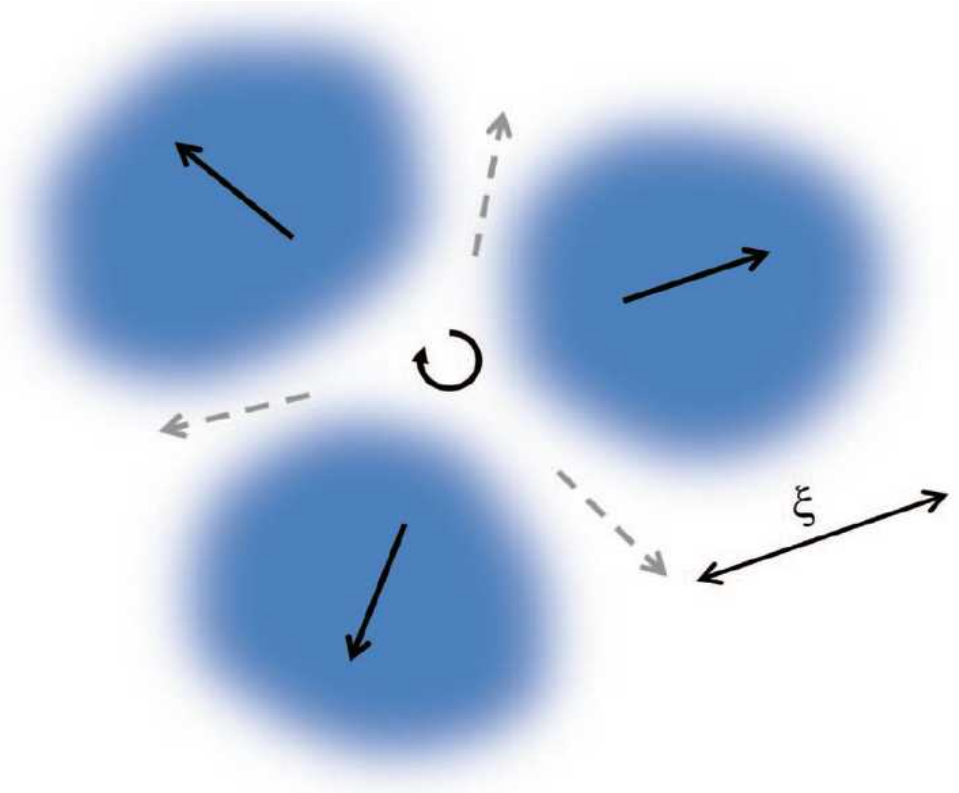




vector potential $\vec{A}$: $\vec{\nabla} \times \vec{A} = \vec{B}$

Cosmic Monopoles

- Hot big bang:
  GUT symmetry breaks in a phase transition
- Higgs field chooses direction randomly but monotonous within interaction horizon.
- Kibble: Monopoles form at least one per horizon volume
  → “Monopole Problem”
- Inflationary phase of the Universe

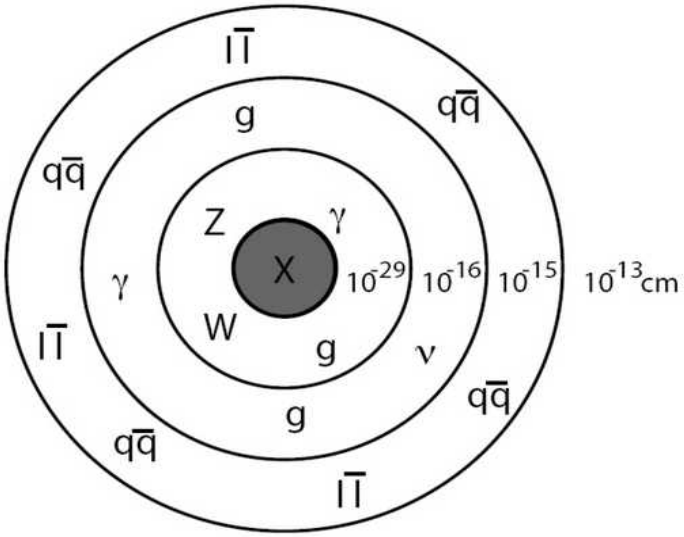


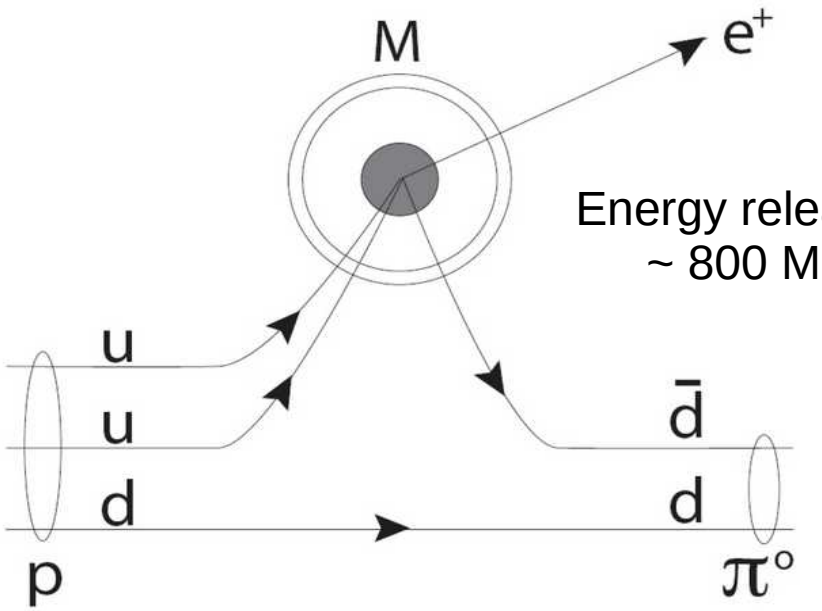
$$\rho^{\#}_{mon} \simeq 10^{-13}\,\mathrm{m}^{-3}$$

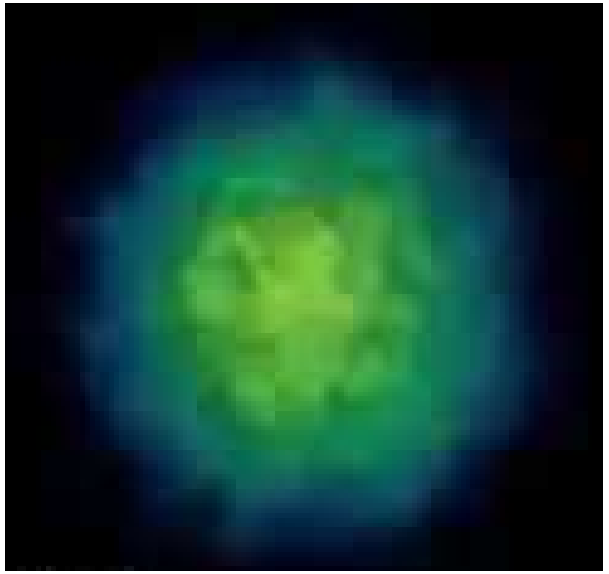
$$\rho_{mon} \simeq 10^{+4}\,\mathrm{GeV\ m}^{-3}$$

GUT Monopoles

- Generic predictions of GUTs
- Mass typically 10^{17} GeV
- May catalyze proton decay



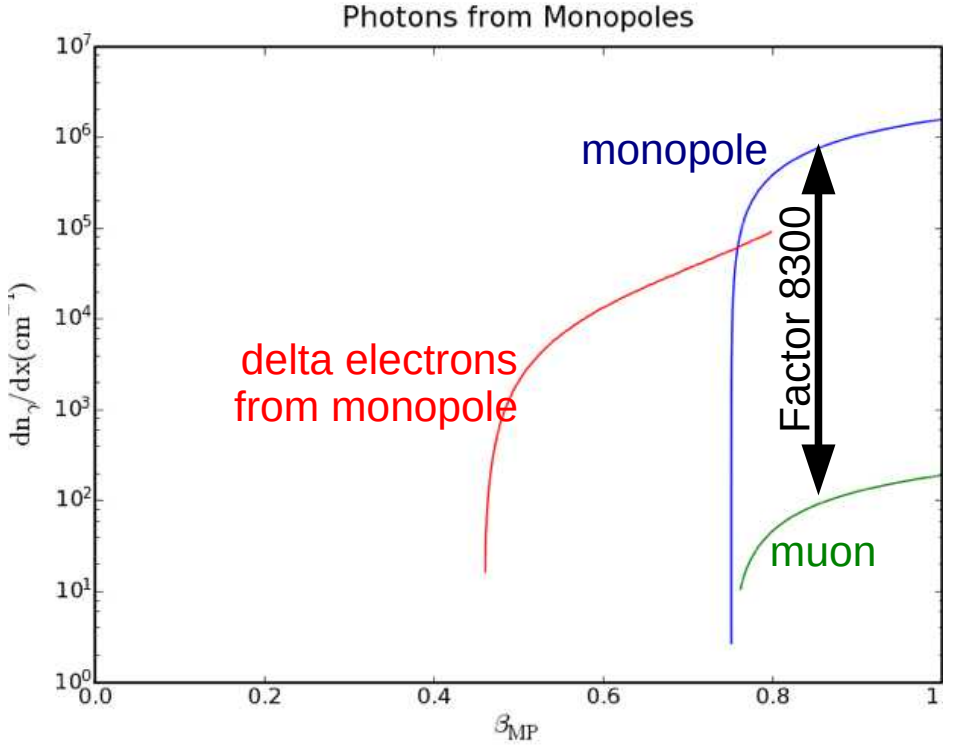


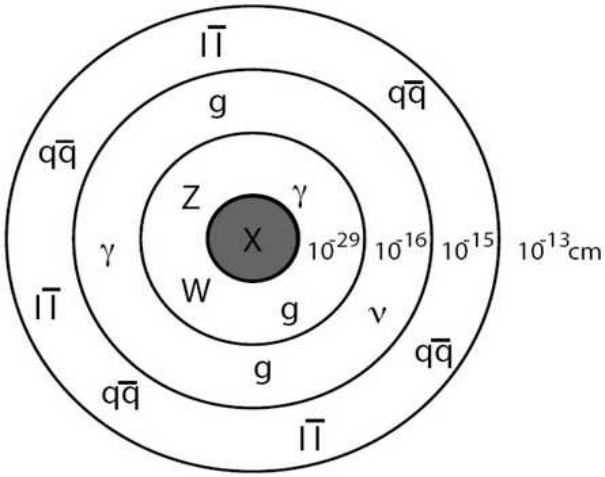


Lattice field theory simulation (A. Rajantie)

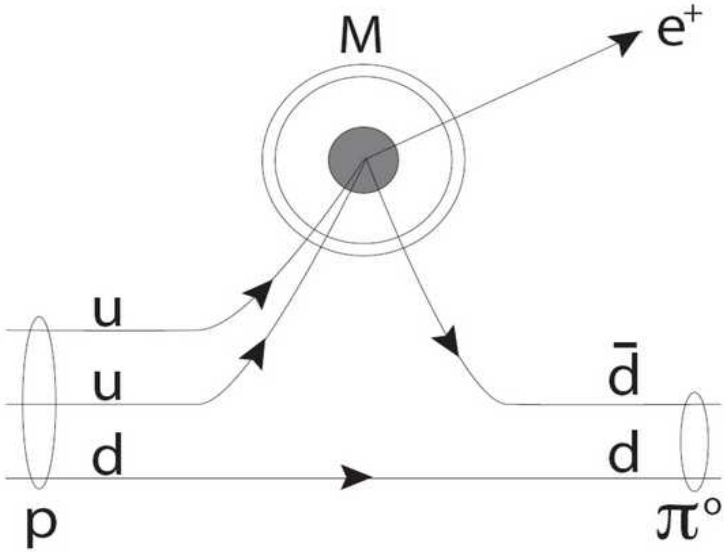
Detection of monopoles

- Charge:
  $g \approx N \cdot 68.5\, e$
- Mass:
  $m = 10^4 - 10^{17}$ GeV
- Kinetic energy:
  $T = 10^9 - 10^{16}$ GeV
- **Cherenkov light:**
  $N_\gamma \propto (g \cdot n / e)^2$
  $\propto$ **8300** $N_\gamma(\mu)$





GUT monopole:
Onion like structure containing the whole world of GUT
→ nucleon decay catalysis



Monopole detection techniques

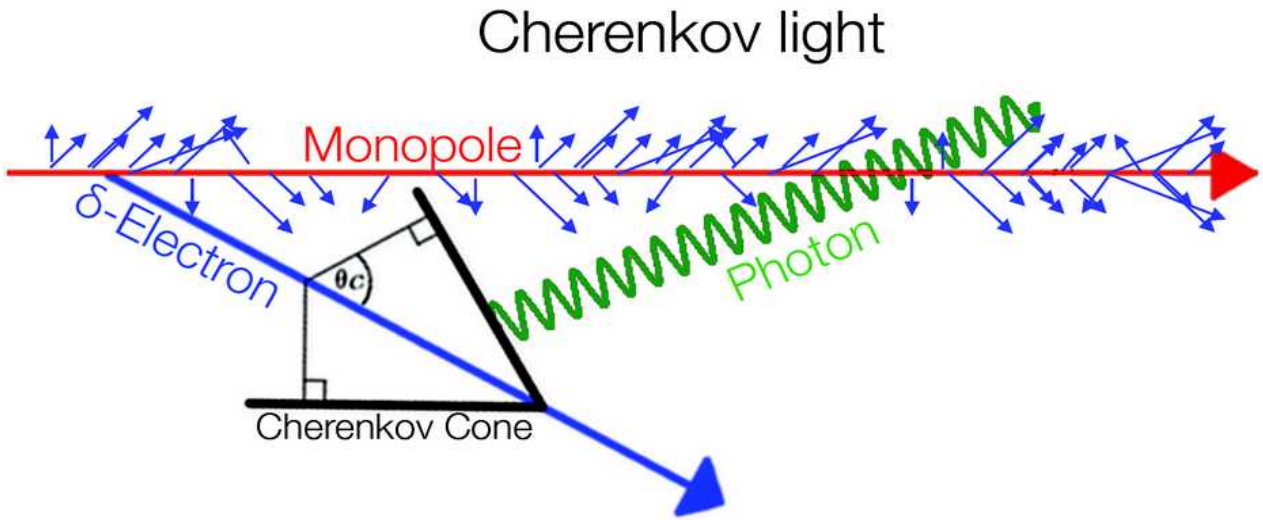
β > 0.76: direct Cherenkov light:

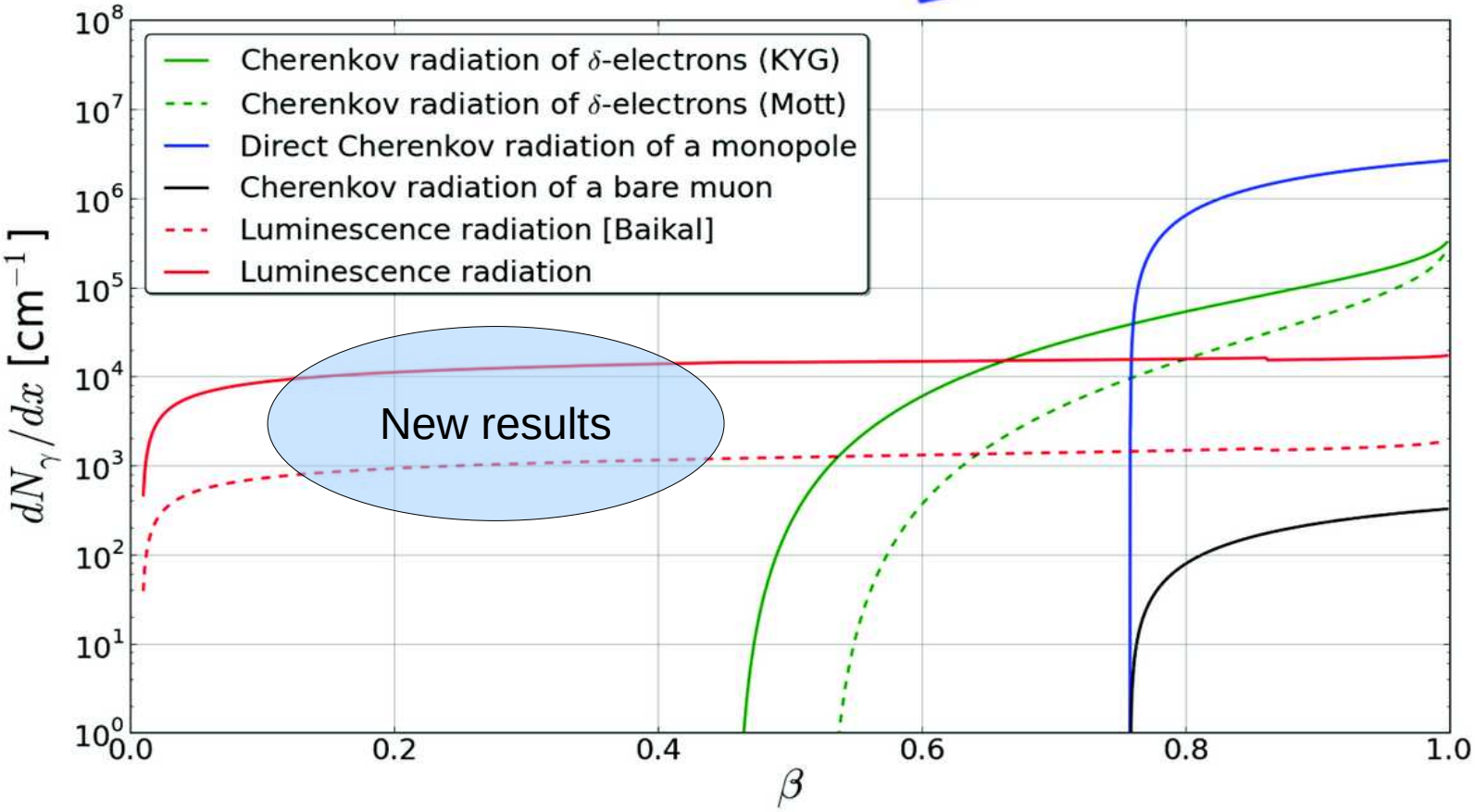
$N\gamma \propto (g \cdot n / e)^2 \propto 8300\, N_\gamma(\mu)$

... i.e. dead simple

Monopoles with β > 0.5: indirect Cherenkov

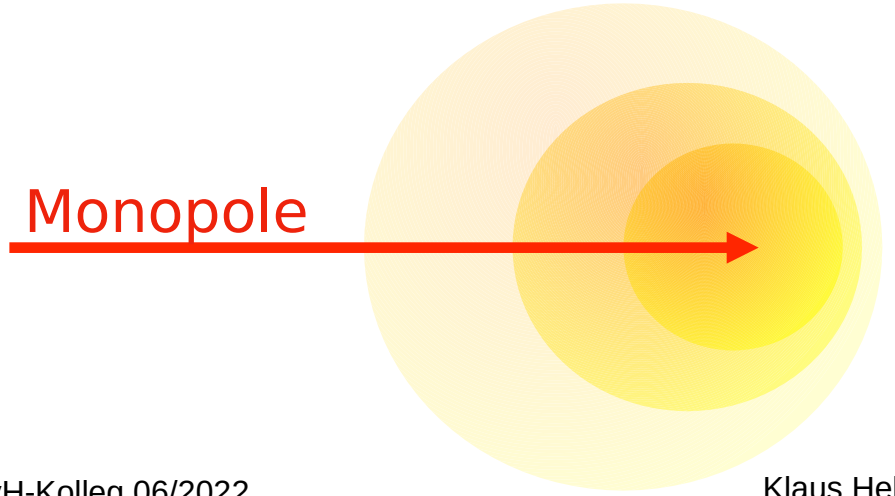
Monopoles with β < 0.5:
– Nucleon decay catalysis
– **Radio-luminescence**



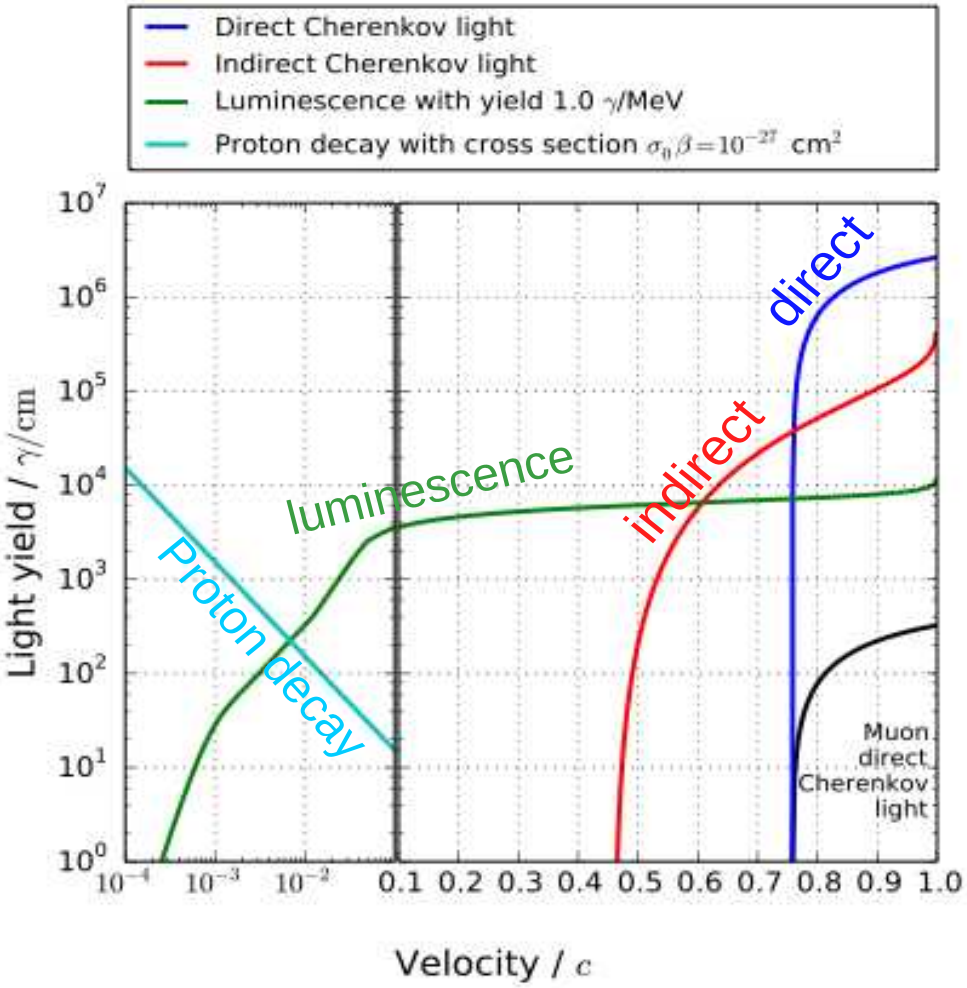


Radio-Luminescence

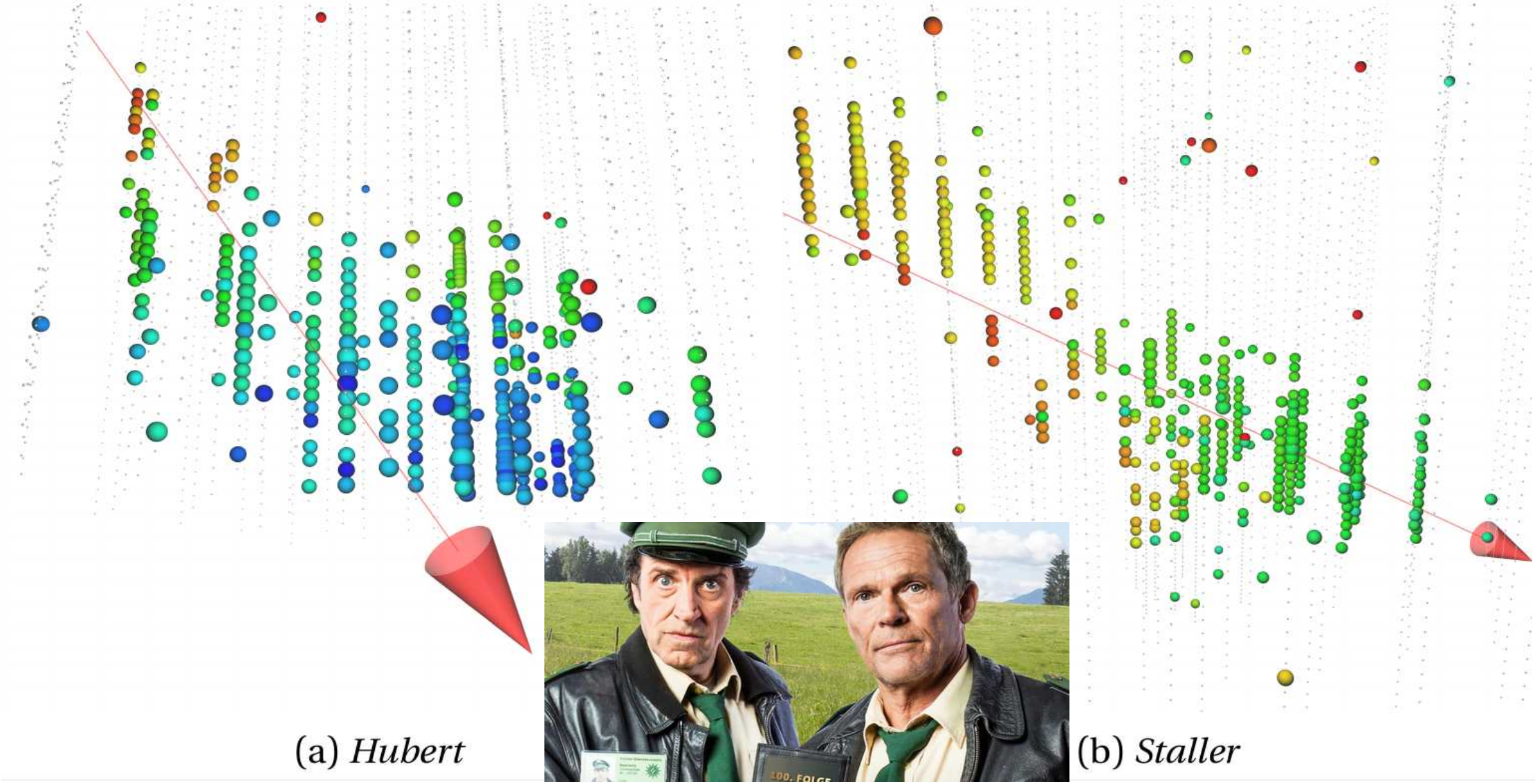
- highly ionizing, multiply charged particle
- excites surrounding matter
- photon release at relaxation … basically very slow scintillation



Monopole light yield



2 remaining events in the box

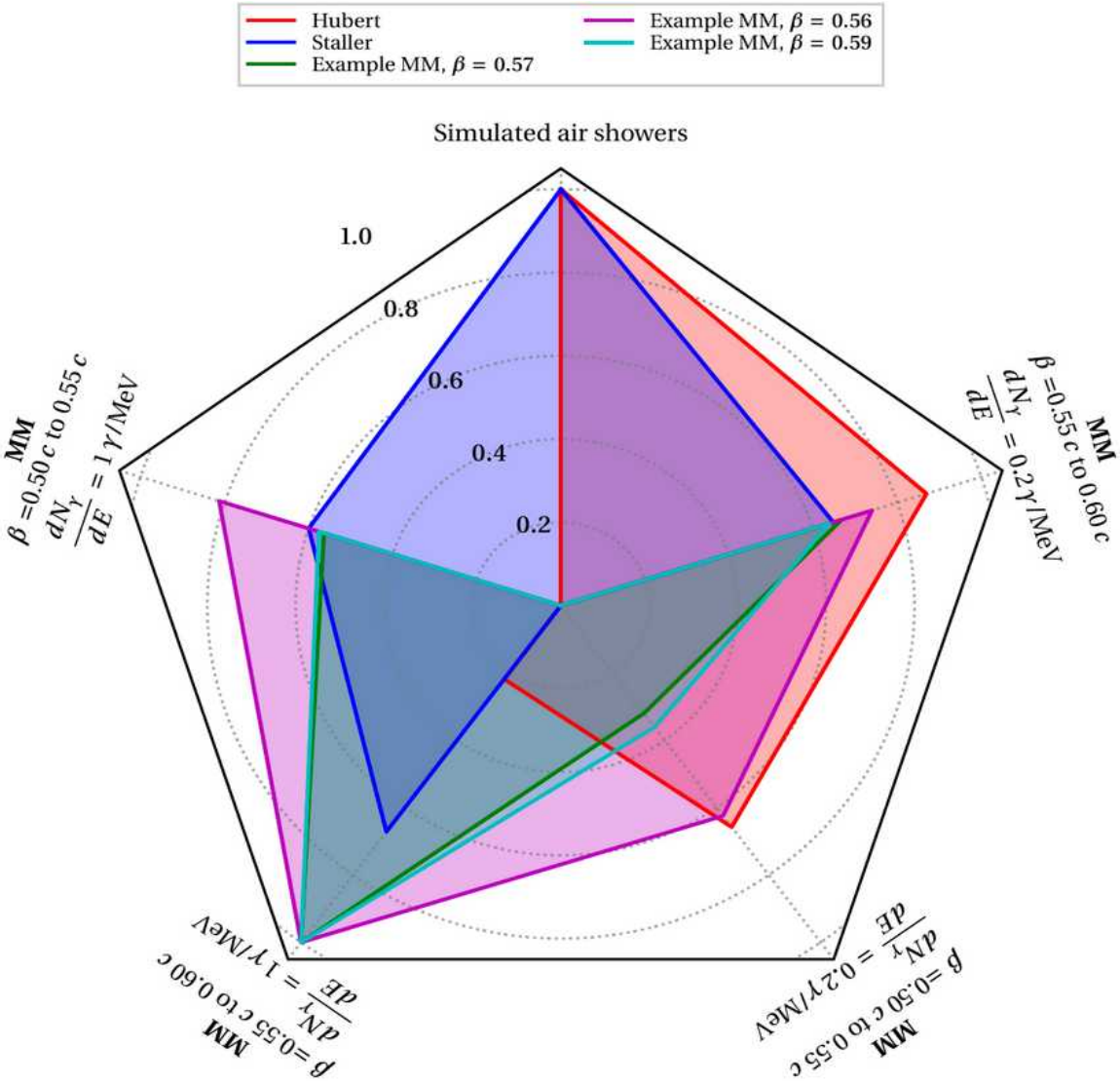


(a) *Hubert*

(b) *Staller*

Name	Velocity / c	Azimuth / °	Zenith / °	Date
Hubert	0.564 ± 0.009	38 ± 6	38 ± 1	September 19, 2013
Staller	0.54 ± 0.01	246 ± 5	62 ± 1	March 14, 2018

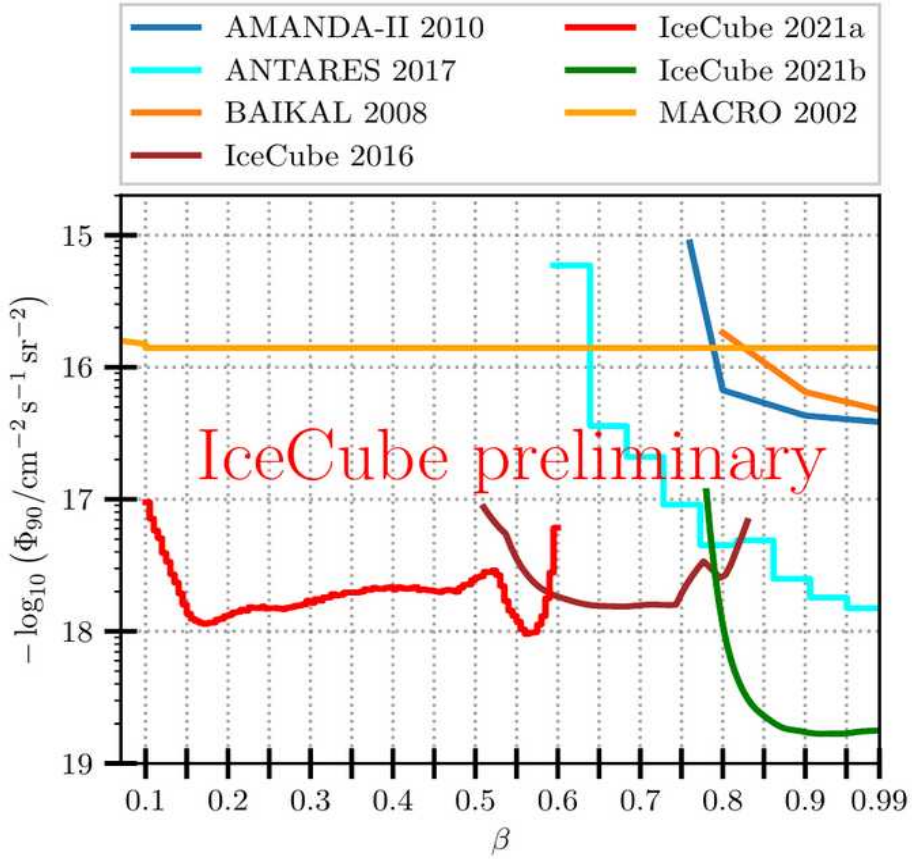
Event Origin



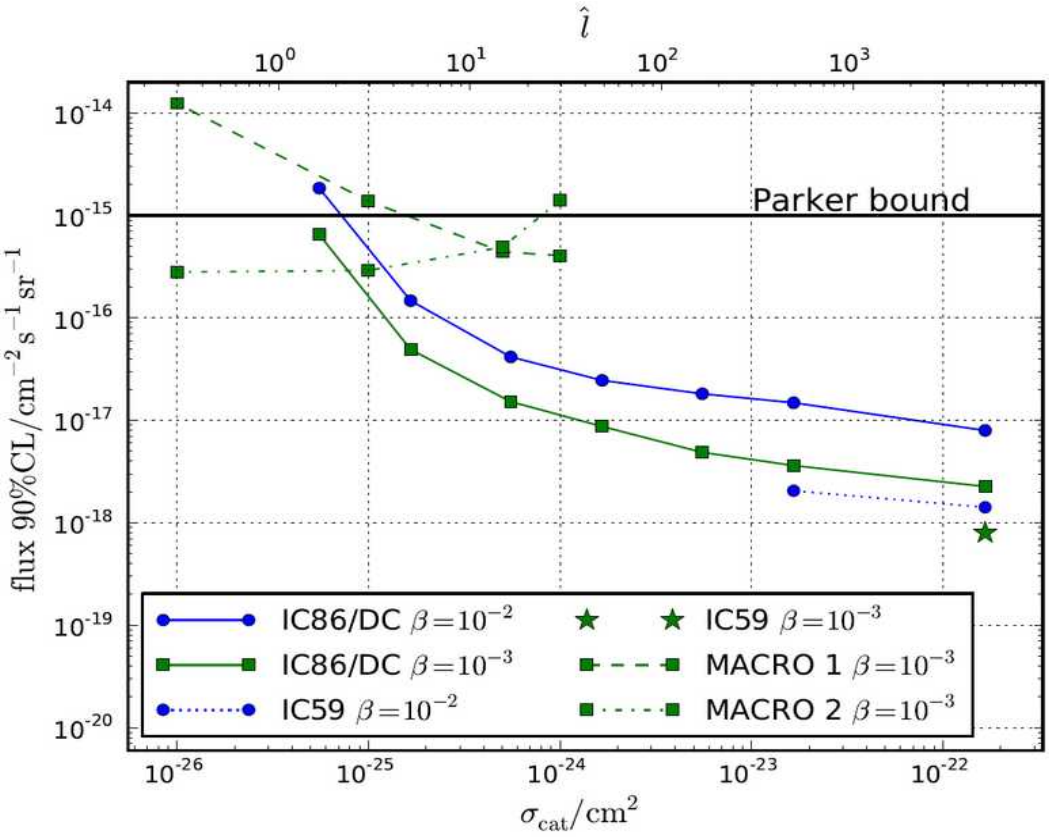
- Corners: probability from KDEs (kernel density estimator)
- Hubert & Staller slightly more compatible with air shower origin
- Treated as background

Monopole limits

Mildly and highly relativistic

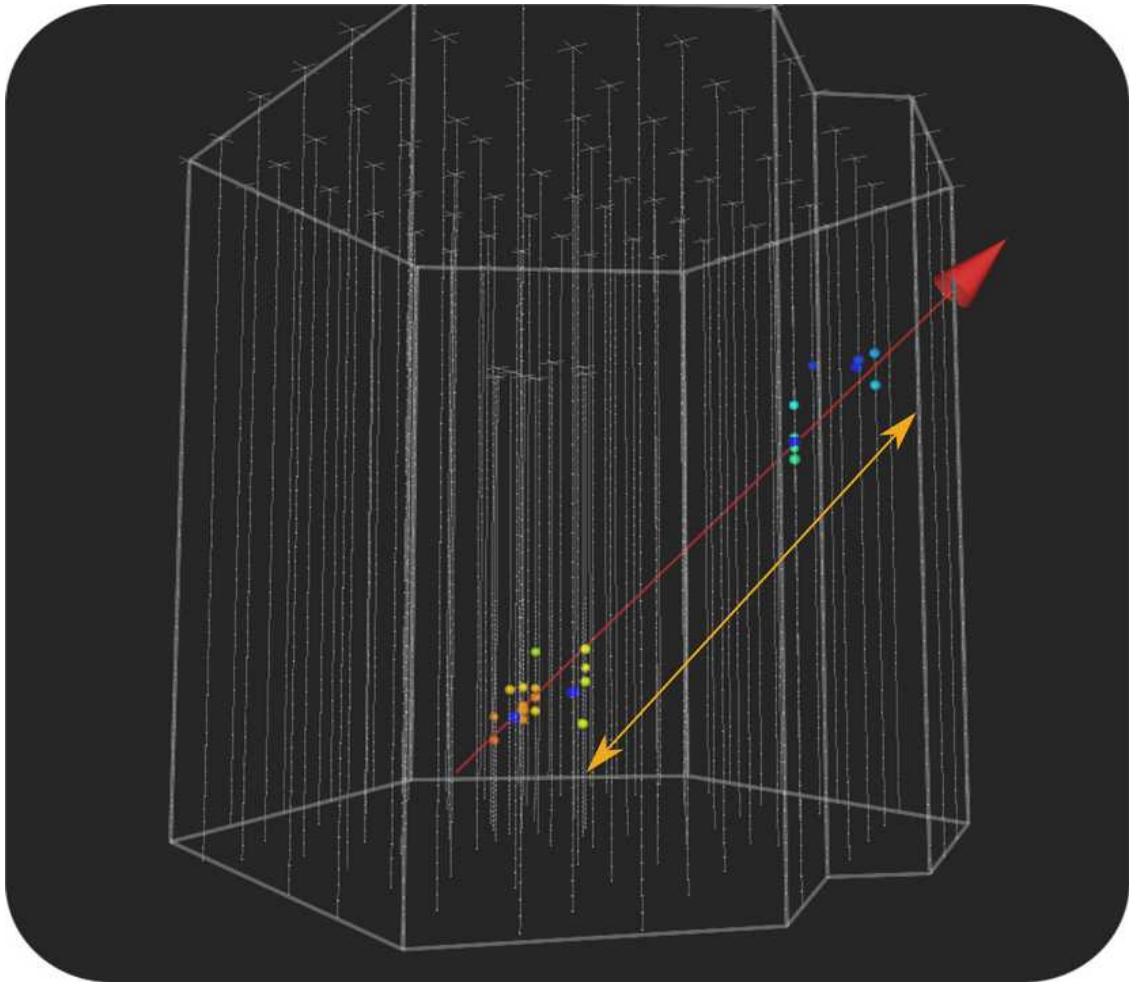


Nucleon decay catalysis

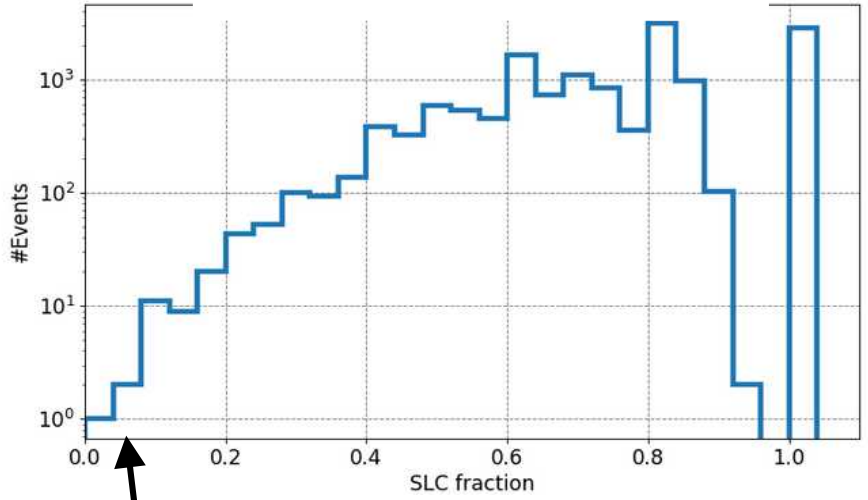


Odd enough: astrophysical neutrinos significant background to relativistic monopoles! … Statler and Waldorf

Fractional charges

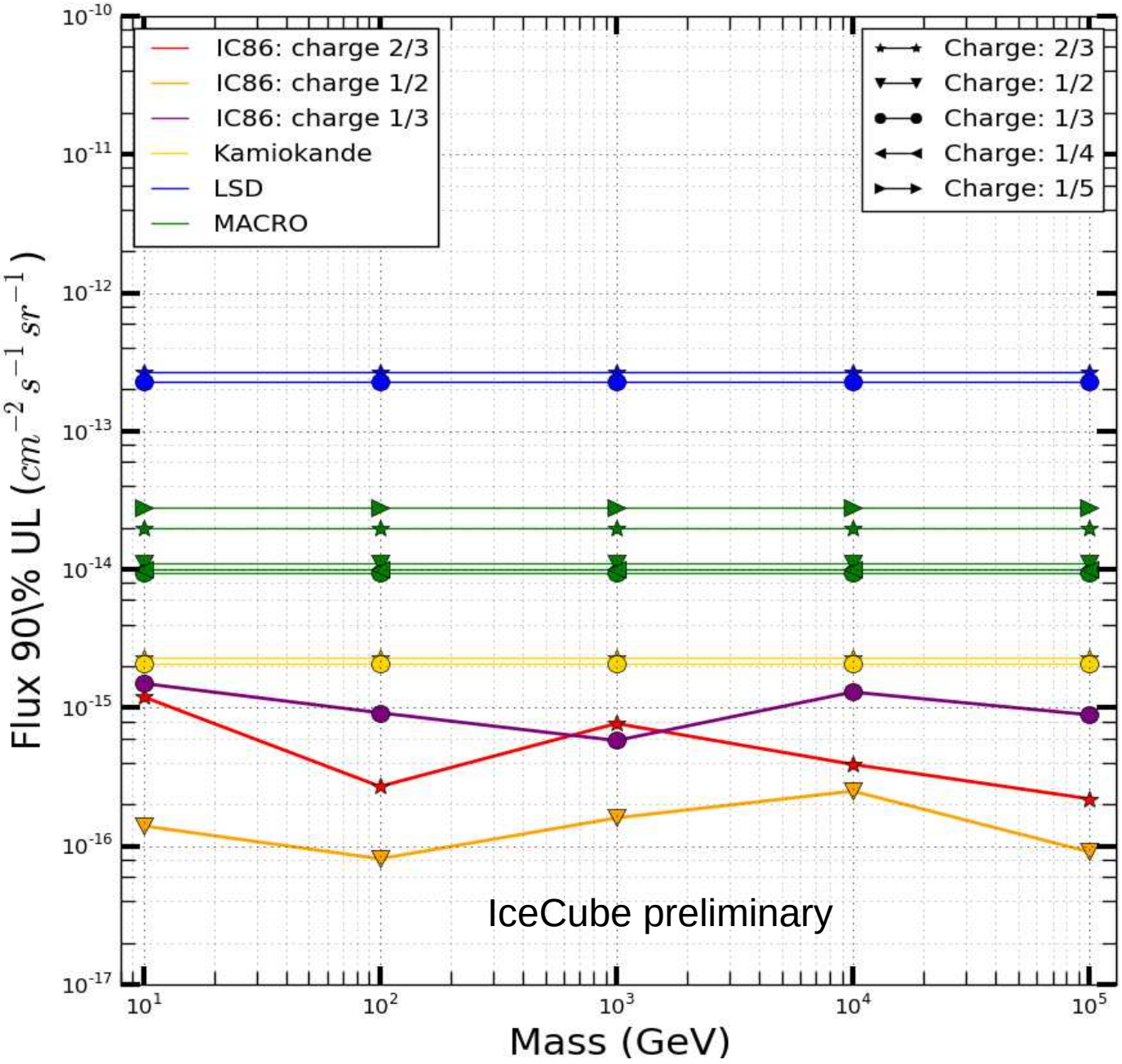


Fraction of isolated hits



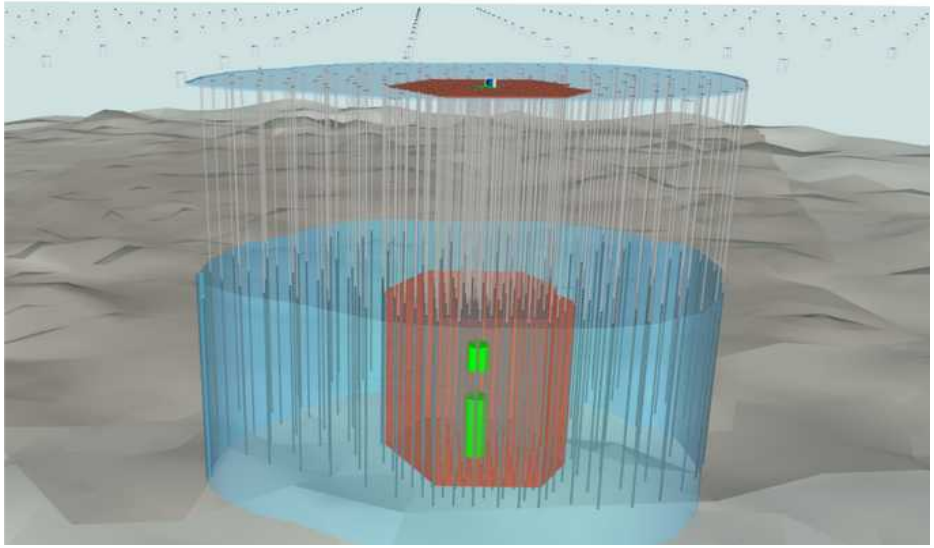
Existing trigger primarily works on locally clustered detector hits

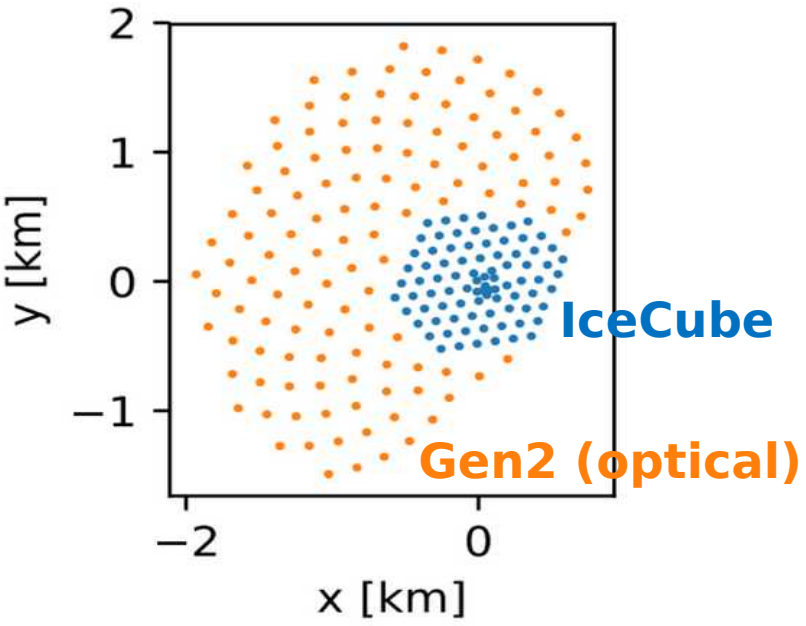
Limits for Fractional Charges



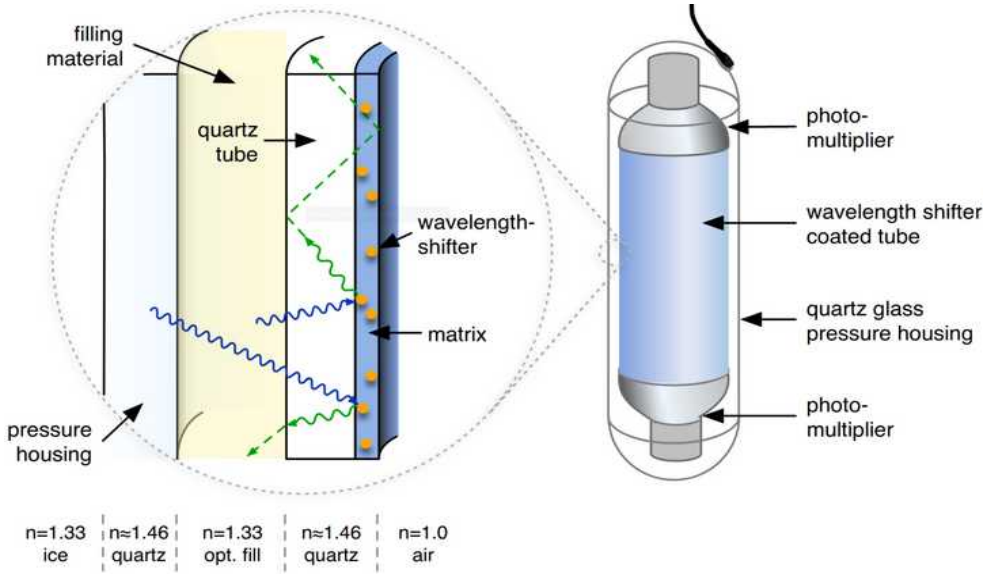
3 ways to improve further

Bigger detector: IceCube Gen2





Sensitive sensors

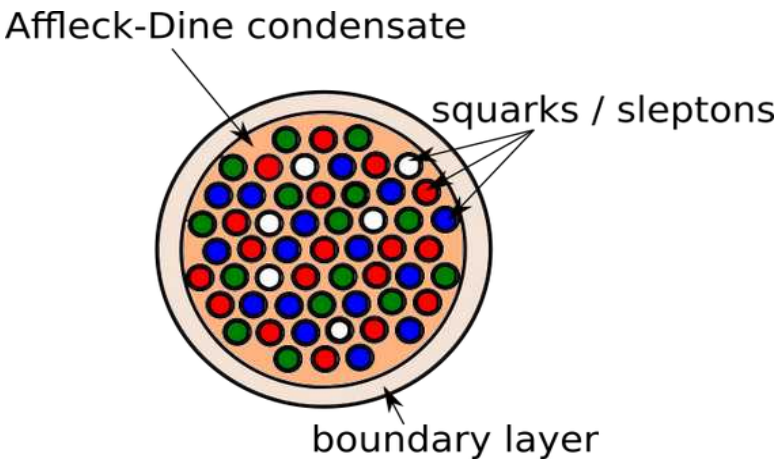


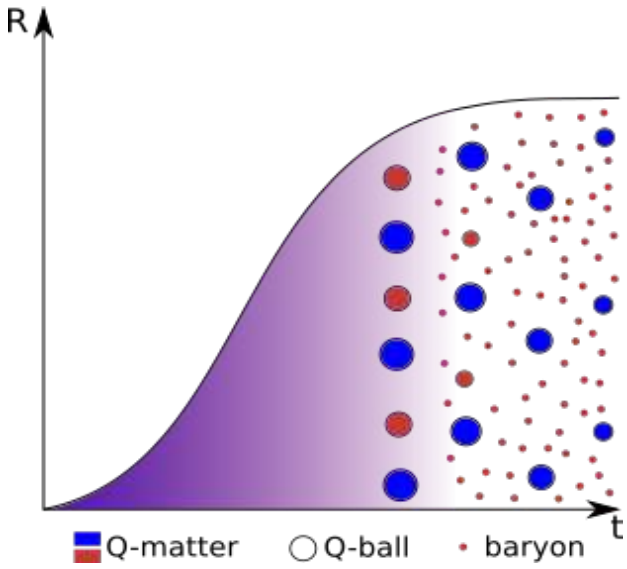
New trigger

hit time sorting and directional matching of hits can be done in real time in FPGA.

Q-Balls

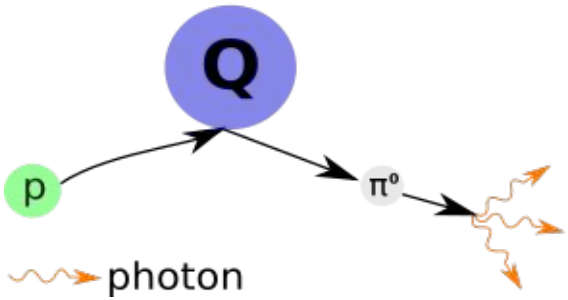
- Q-balls arise in all supersymmetric extensions of the standard model
- Charge Q is baryon or lepton number: $Q = 10^{12} – 10^{38}$
- Electric charge $0 \leq Z \leq 137$
- Q-balls are filled with squarks and sleptons
- They could have been produced in the early Universe
  → Affleck-Dine baryogenesis
- Q-balls can be entirely stable
  → dark matter candidate

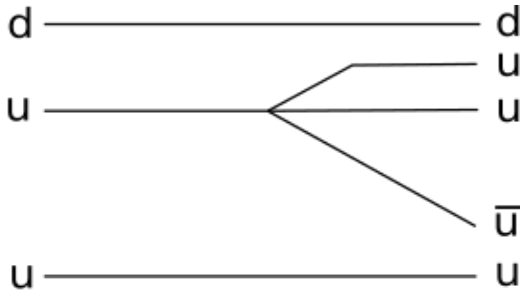




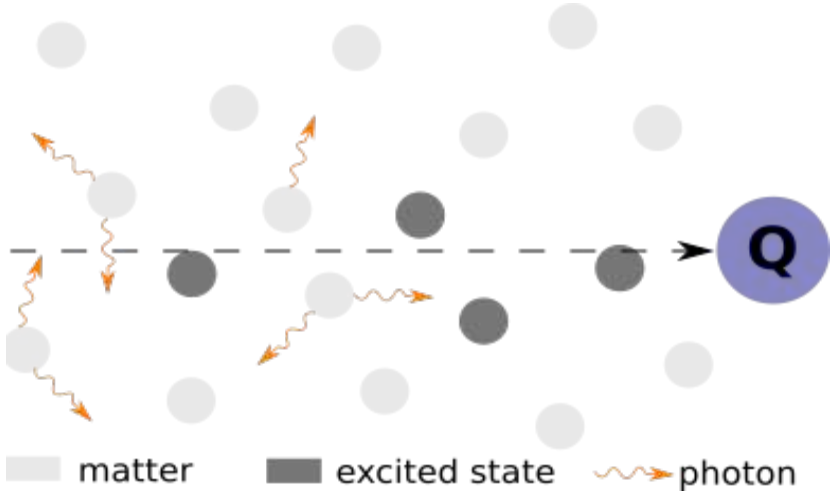
Interaction with matter
Main light production mechanisms

→ nucleon decay
(KKST-process)





→ luminescence

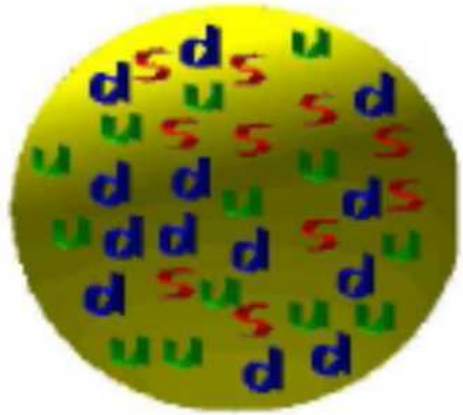


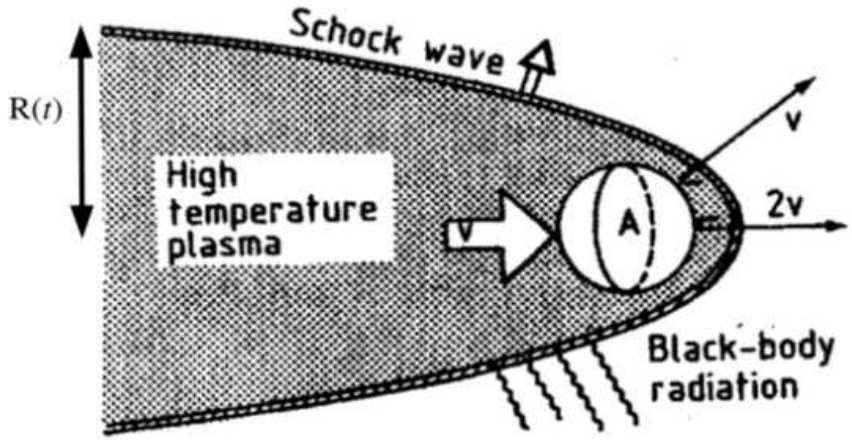
→ similar to magnetic monopoles

Interested? Join us!

Nuclearites

- The particle
  - nuggets of strange quark matter surrounded by electron shell
    → atom-like neutral system
  - stable states in SM in thermodynamic processes
  - heavy stable object of u-, d-, s-quarks
  - almost neutral
  - produced after Big Bang or as lumps of neutron stars
- Detection
  - Intense elastic collisions
  - thermal shock wave

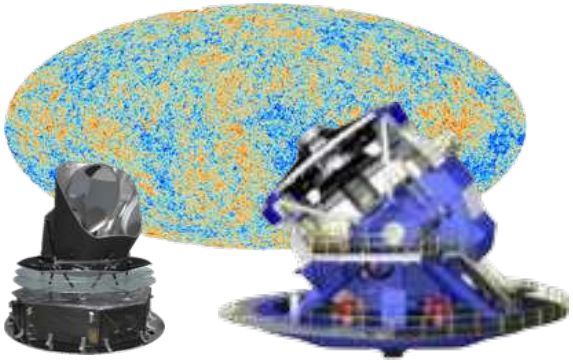


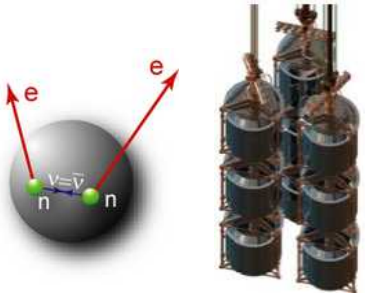


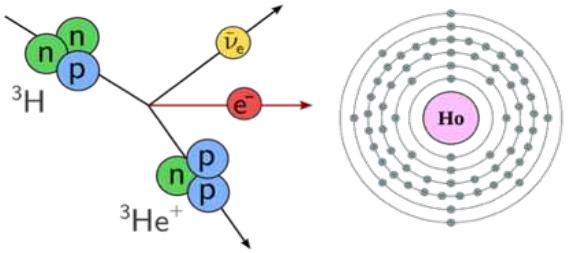
Interested? Join us!

The absolute neutrino mass

Truly !

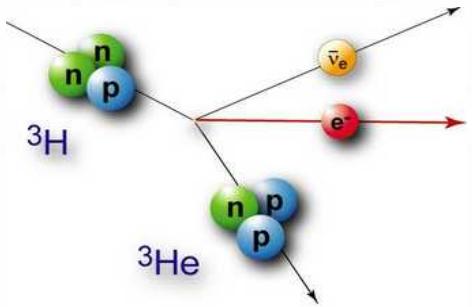






	Cosmology	Search for 0νββ	β-decay & electron capture
Observable	$M_\nu = \sum_i m_i$	$m^2_{\beta\beta} = \left\lvert \sum_i U^2_{ei}\, m_i \right\rvert^2$	$m^2_\beta = \sum_i \lvert U_{ei} \rvert^2 m^2_i$
Present upper limit	0.12 – 1 eV	0.2 – 0.4 eV	2 eV
Potential	15 – 50 meV	15 – 50 meV	200 meV
Model dependence	Multi-parameter cosmological model	- Majorana ν: LNV - BSM contributions other than m(ν)? - nucl. matrix elements - Incl. interferences	**Direct,** only kinematics; no cancellations in incoherent sum

KATRIN beam line: 70 m



Source & transport monitoring

diagnostics

tritium source

differential pumping

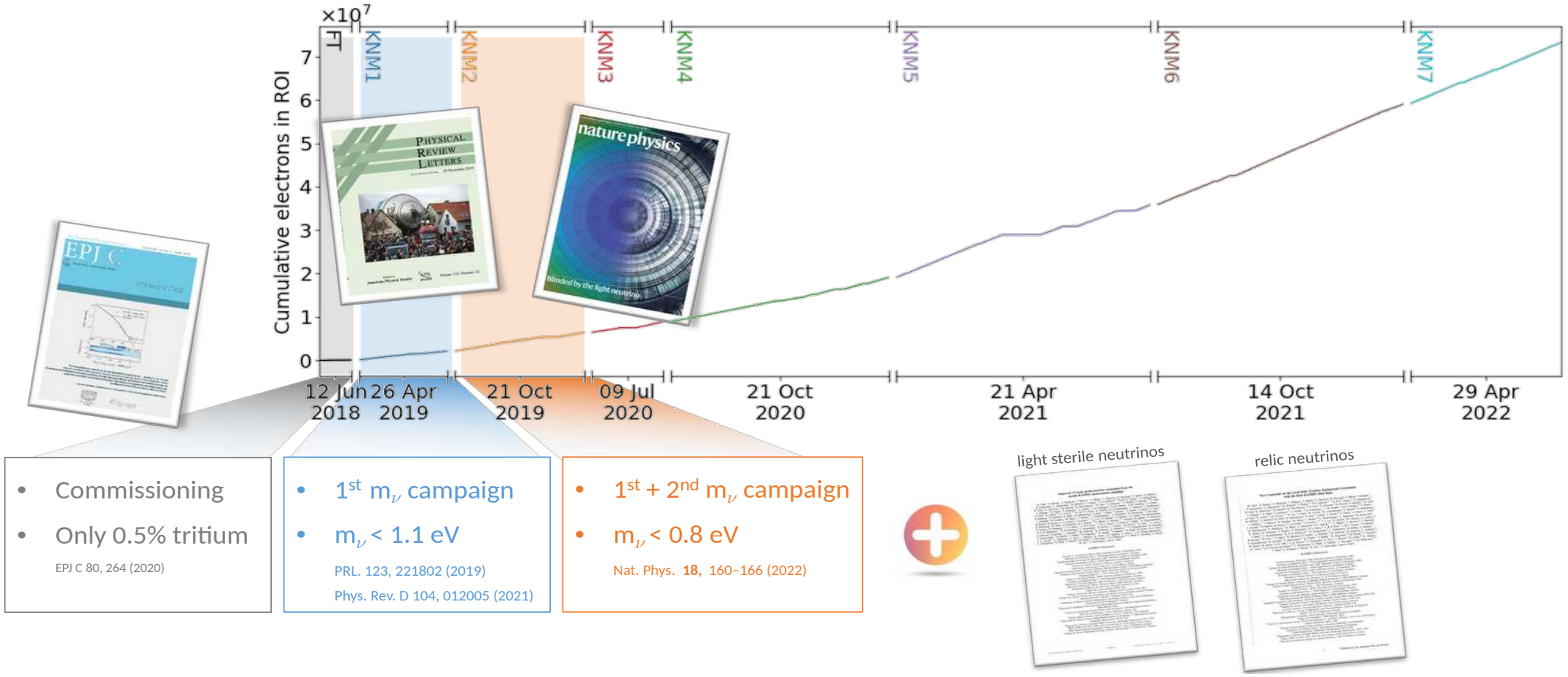
cryogenic pumping

integral energy analysis

electron counting

Recycling the tritium
Removing ions

KATRIN status



- Commissioning
- Only 0.5% tritium

EPJ C 80, 264 (2020)

- 1st m_ν campaign
- $m_\nu < 1.1$ eV

PRL. 123, 221802 (2019)
Phys. Rev. D 104, 012005 (2021)

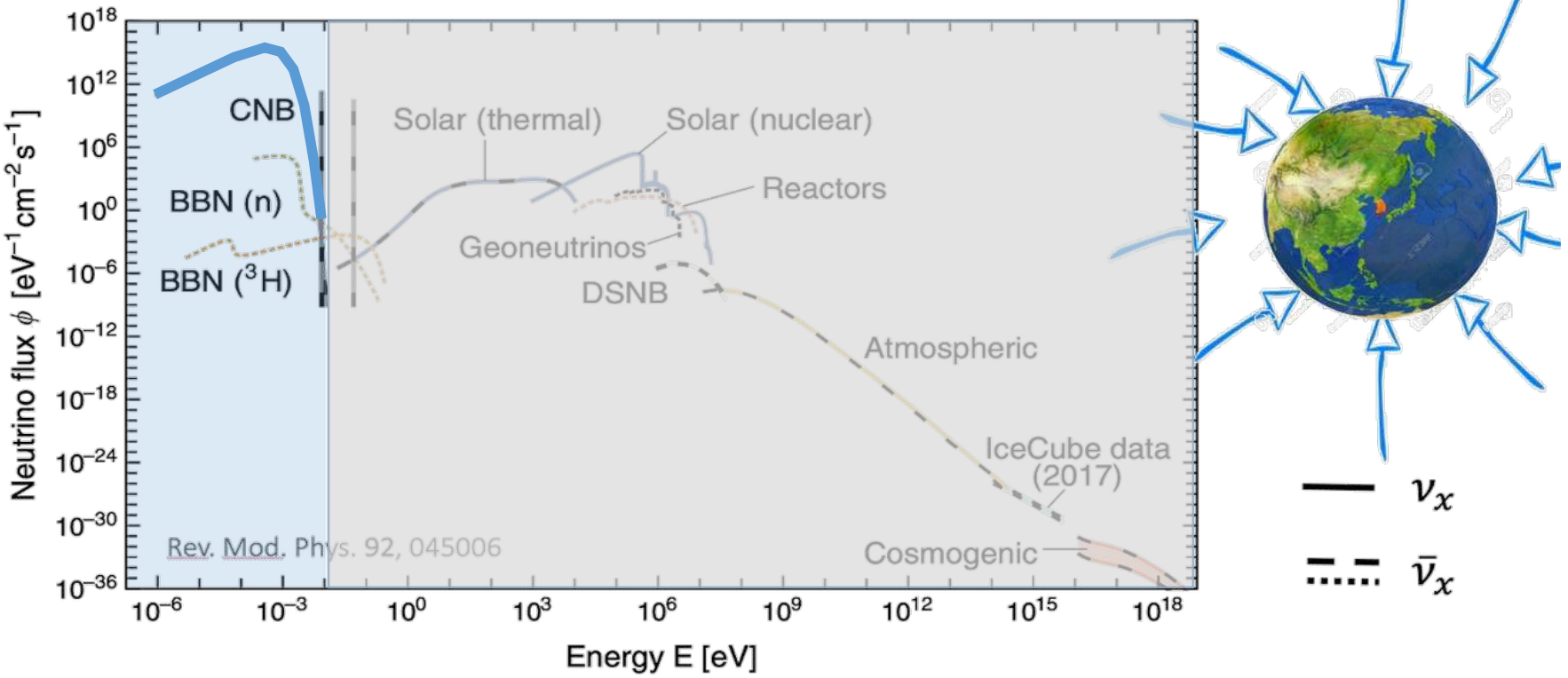
- 1st + 2nd m_ν campaign
- $m_\nu < 0.8$ eV

Nat. Phys. **18,** 160–166 (2022)

Cosmic relic neutrinos

- Early Universe: ν's are in thermal equilibrium with matter
- Big-Bang+1 sec (1 MeV): ν decouple
  → Relic (Cosmic) Neutrino Background emission

340 relic neutrinos of all species /cm^3 in the Universe



KATRIN restricts the maximum overdensity ratio on Earth η

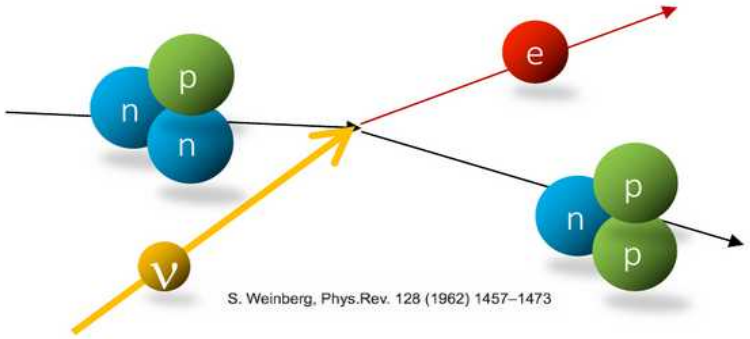
Relic neutrino capture in KATRIN

meV relic neutrinos…

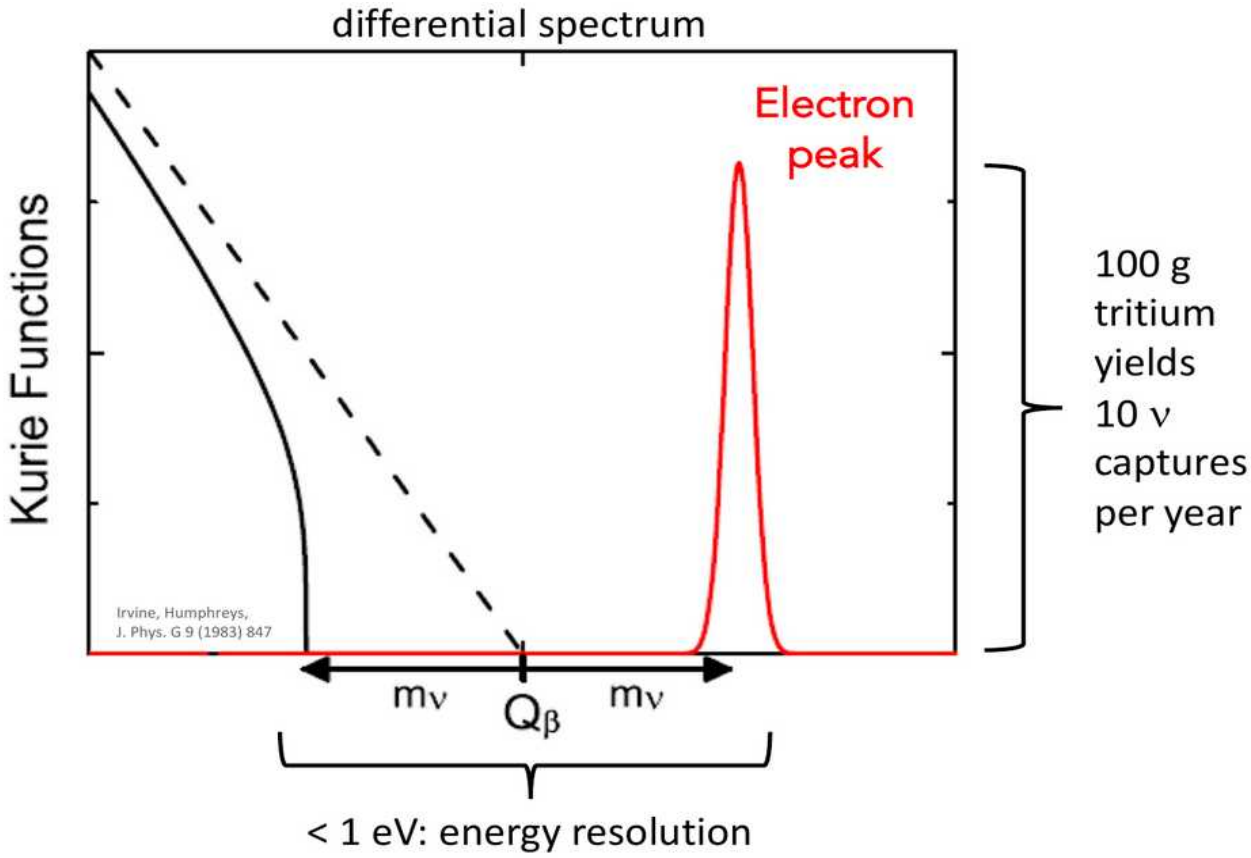
neutrino capture on tritium:

$$^3\mathrm{H} + \nu_e \longrightarrow {}^3\mathrm{He}^+ + e$$

no energy threshold

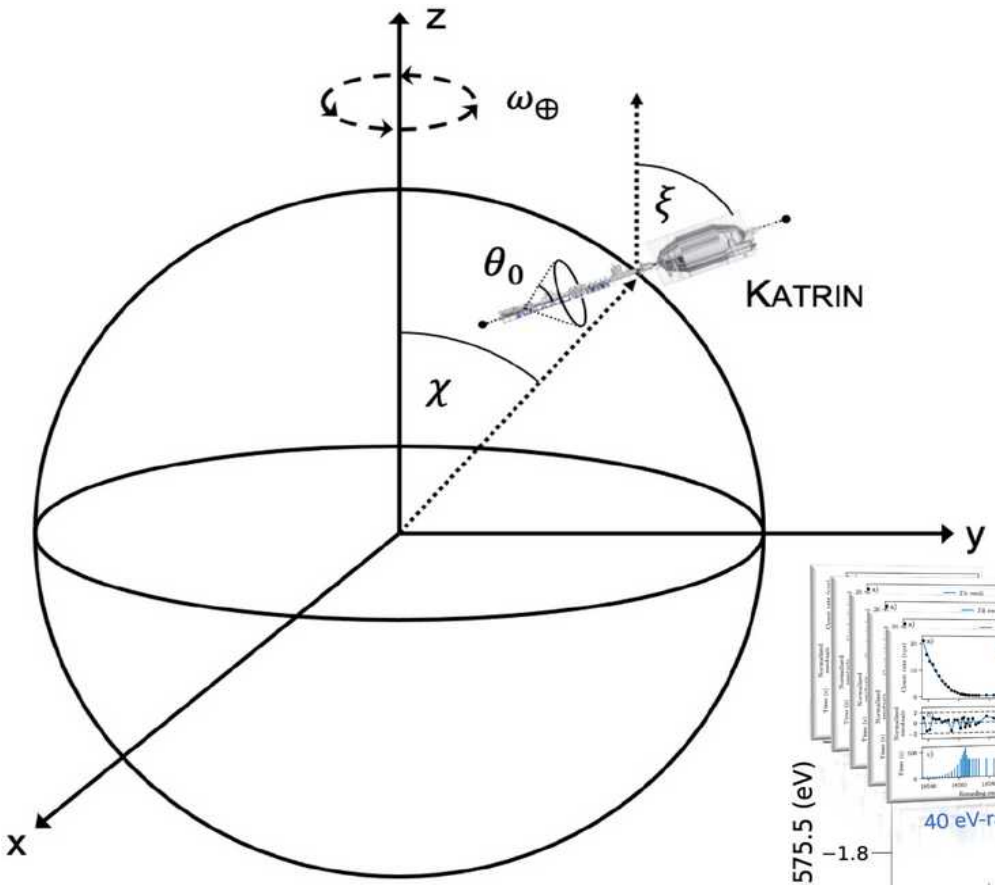


electron peak right above endpoint
(in the differential spectrum)

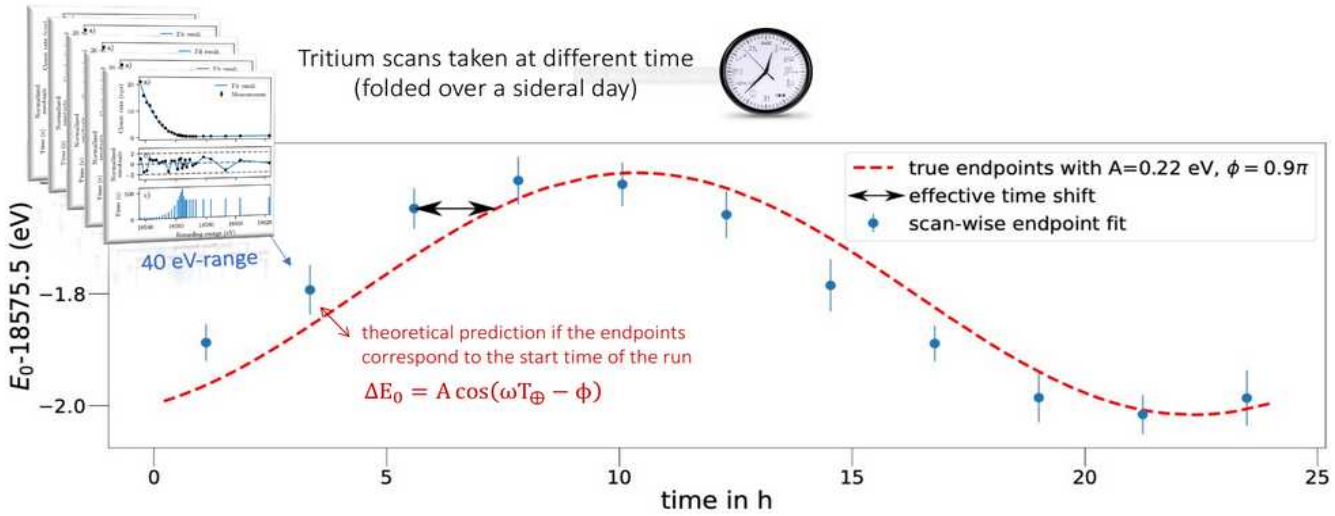


No electron peak observed → over-density < ~10^{10}

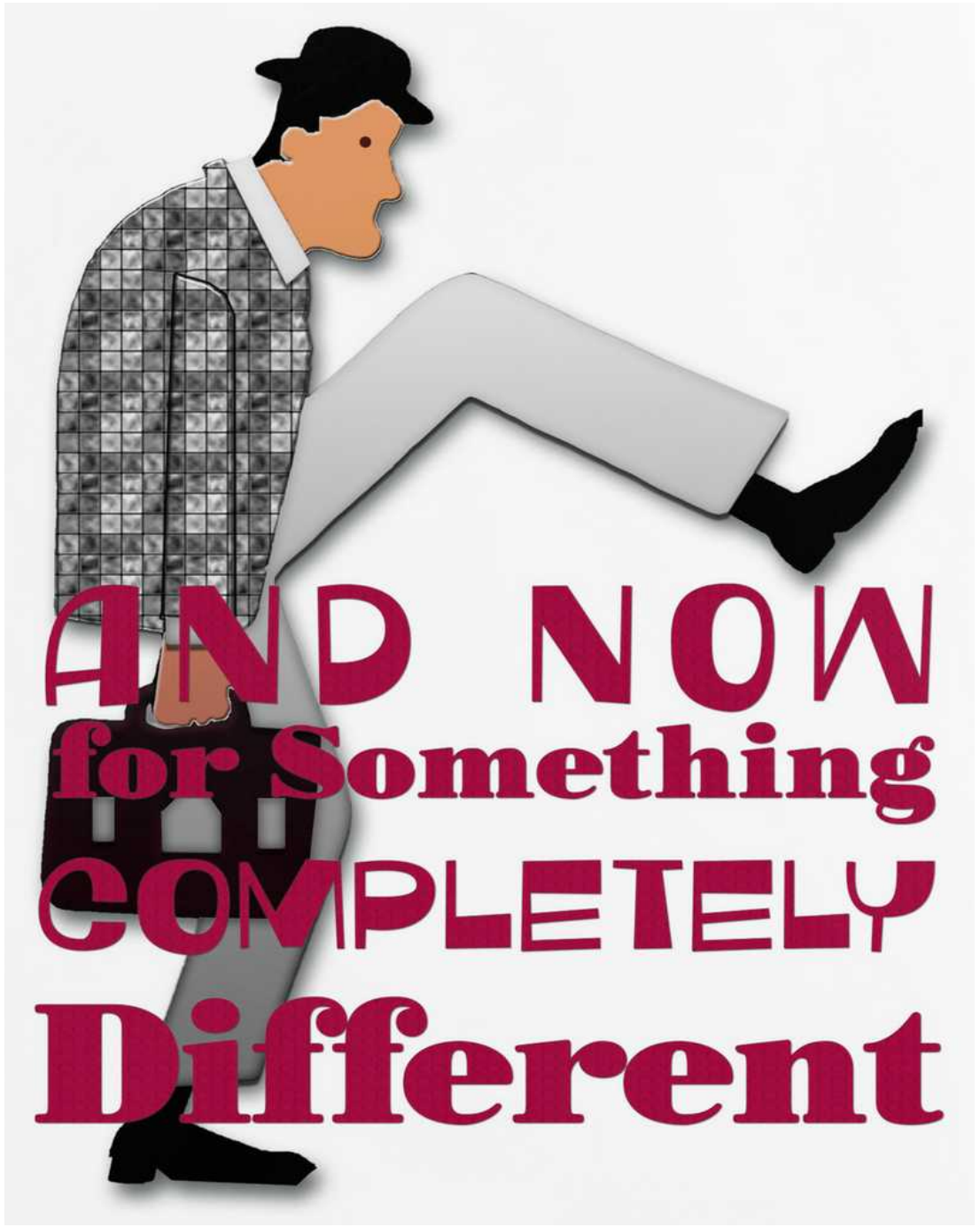
Lorentz-Invarianz Violation



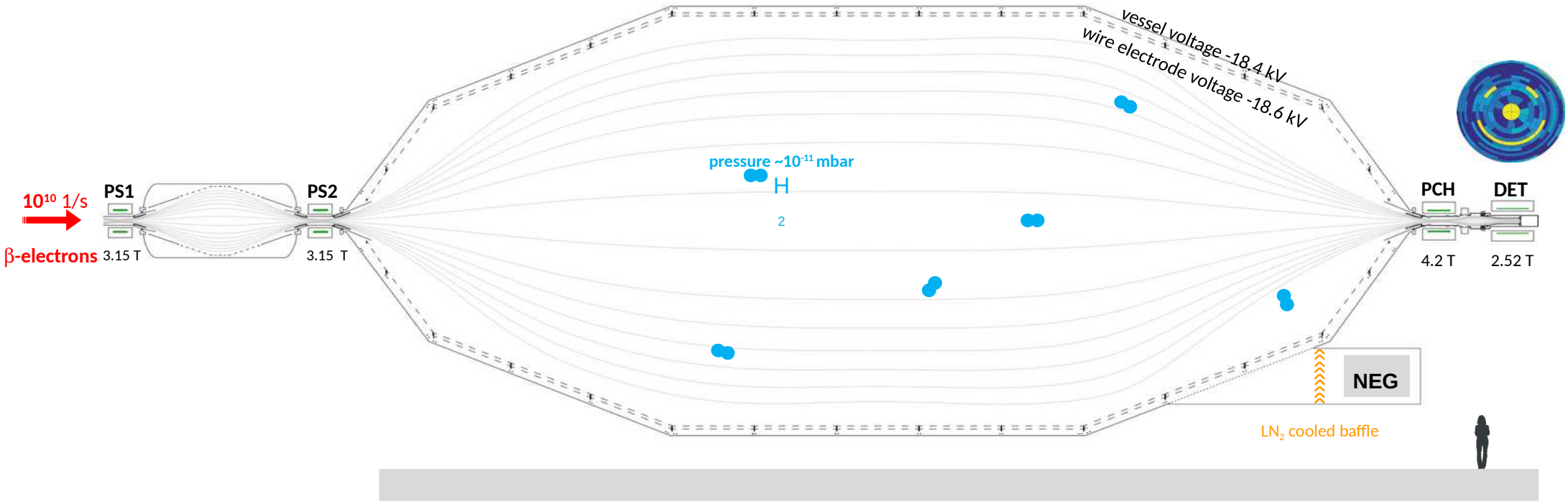
- Anisotropic LV: KATRIN source acceptance angle introduces preferred “direction”
- As the earth is rotating, relative direction of KATRIN to the LV-violating vector changes
  → search for oscillation of Tritium endpoint with sidereal frequency (23h 56 min)



Results forthcoming!

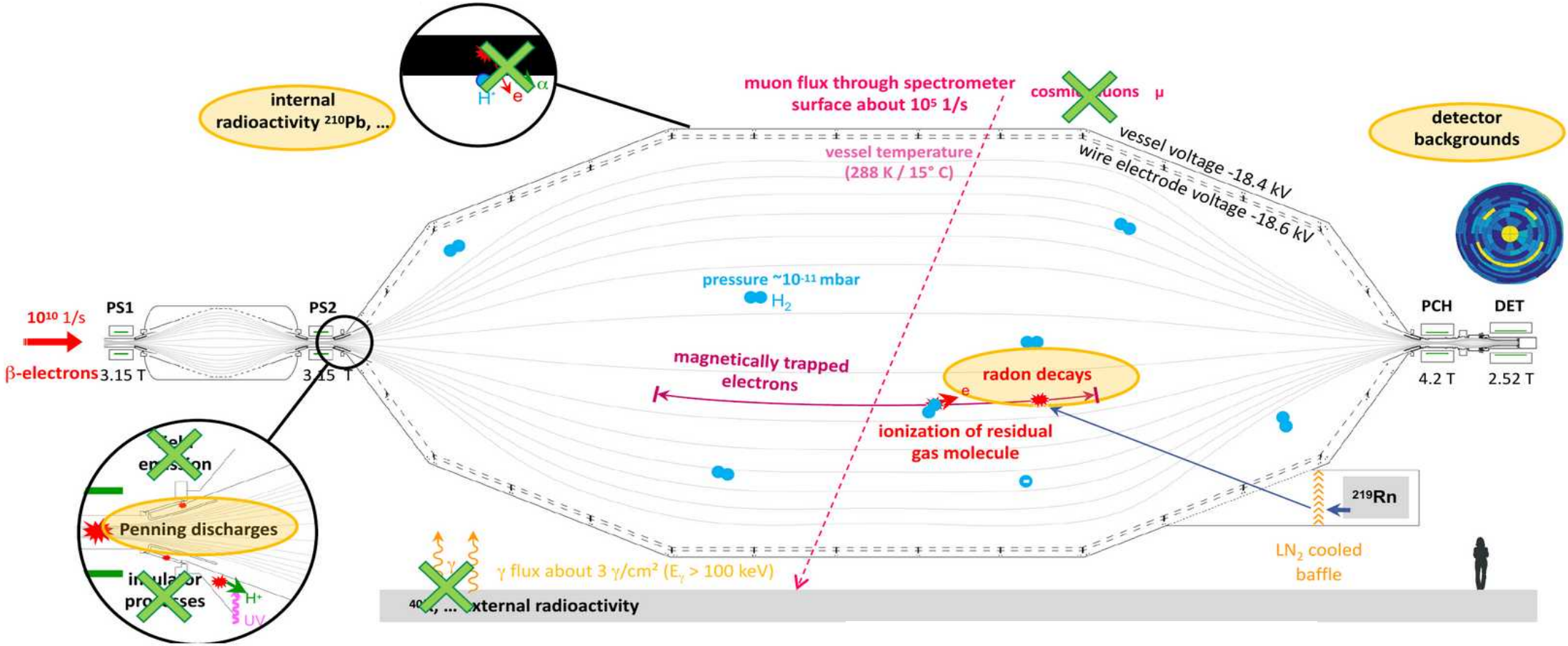

AND NOW
for Something
COMPLETELY
Different

Background rate in KATRIN



- Design goal of KATRIN: Background rate R < 10 mcps in ROI (25.72 keV to 30.72 keV)
- But the current background level is 204 mcps

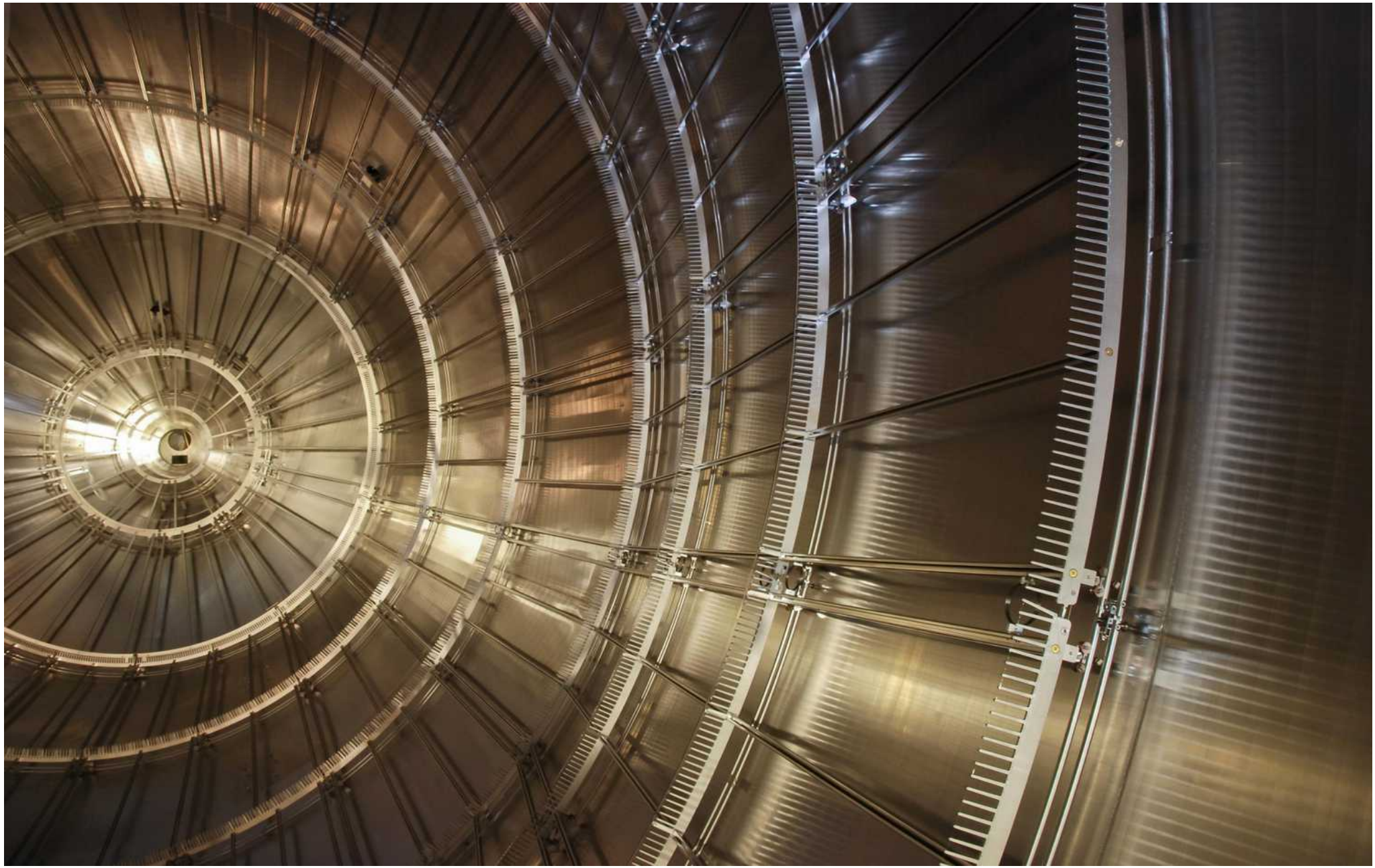
Background sources in KATRIN



All known background sources excluded!
No stored-particle signature, not pressure dependent
extremely low kinetic energies observed extending to below 1 eV
Spatial distribution of background electrons approximately homogeneous.

Main spectrometer

Ernst Otten: “feels like entering the Cologne Cathedral”

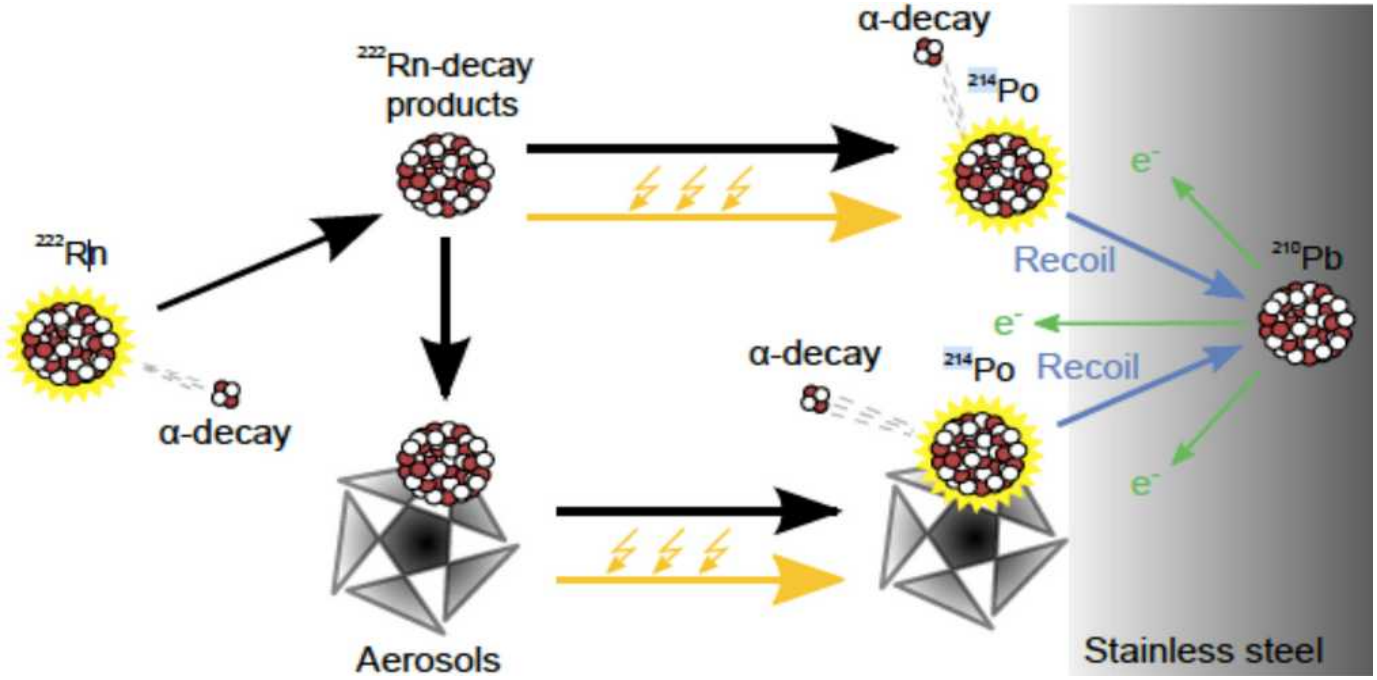


Idea: Rydberg atoms

- “Messenger-particle” between radioactive decay on the surface and the low-energy electrons in the volume
  - cannot be charged (shielded by the magnetic field)
  - needs to originate and be caused by the alpha-chain radioactivity on the vessel surface
- Rydberg atoms produced in sputtering process in the vessel wall.
  - Rydberg atom is excited atom with one or more electrons with very high principal quantum number n
  - extremely large Radius ~1 µm
  - Neutral Rydberg atoms travel through the whole spectrometer and get ionized by BBR
  - resulting free electron is accelerated to the detector

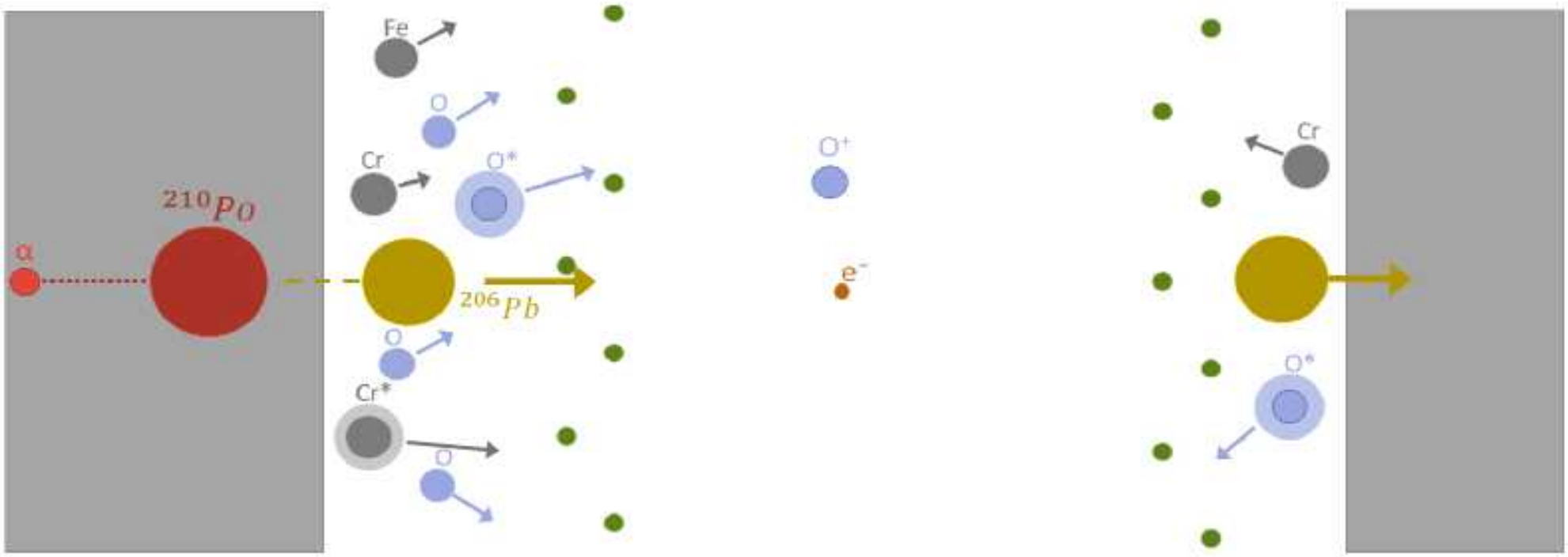
Rydberg production: Implatation

- ^{222}Rn (3.8 d half-life) contamination due to spec at ambient air for 5 years
- Short lived daughter nuclei (^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po) settle on the vessel wall surface
- ^{241}Po decays into the long-life ^{210}Pb (22.2 y, α)
- Efficiently (88%) implanted with 146 keV recoil energy into the vessel wall surface in mean depth of 12 nm.



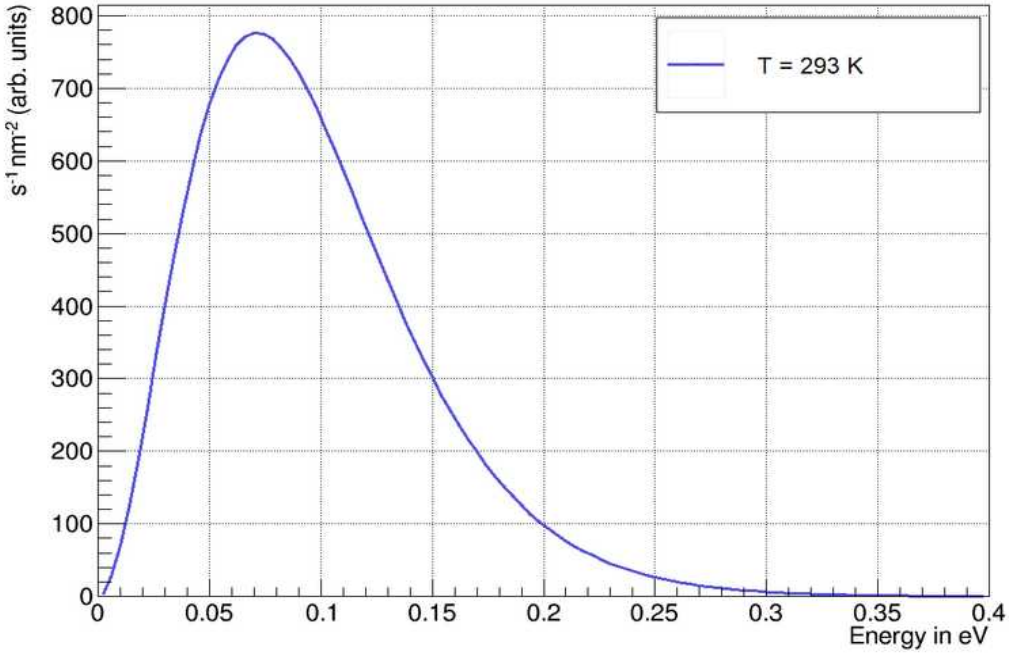
Rydberg production: emanation

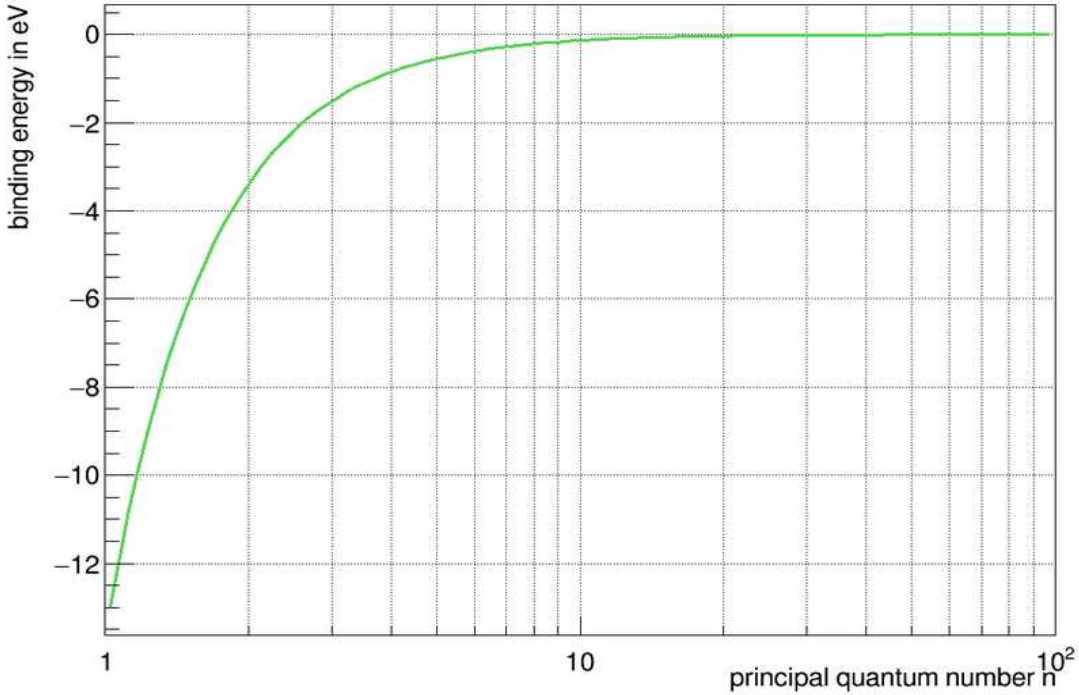
- From ^{210}Po to ^{206}Pb via alpha decay with 103 keV recoil energy
- explantation and re-implantation (on the other side of the spectrometer)
- Process produces sputter products (sputter yield)



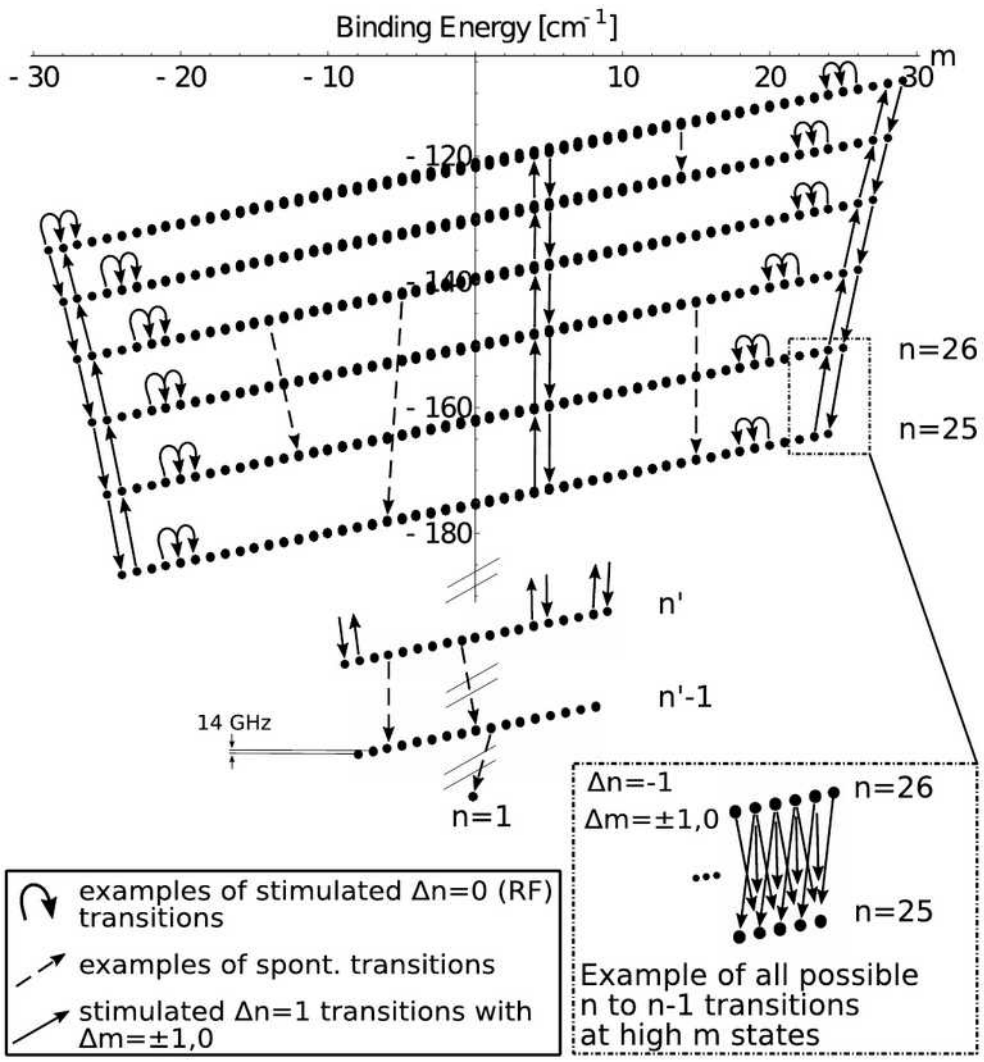
Rydberg ionization

- Spontaneous Decay
- Photoionization by thermal black body radiation
  - Ionization by room temperature BBR
  - → very low kinetic energies (below 0.15 eV)
  - below the energy resolution of E = 0.95 eV of KATRIN





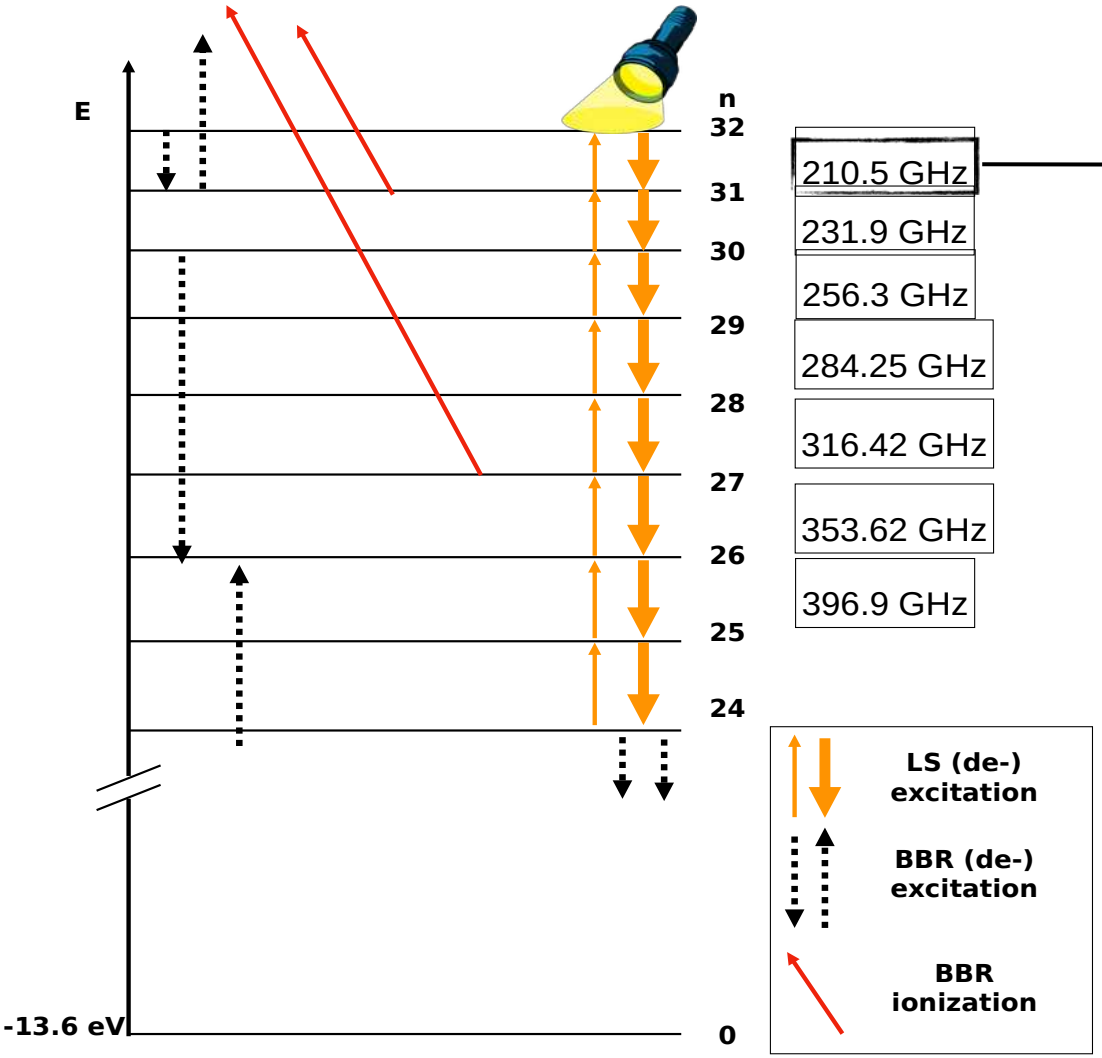
Idea inherited from ASACUSA – last Humboldt Kolleg

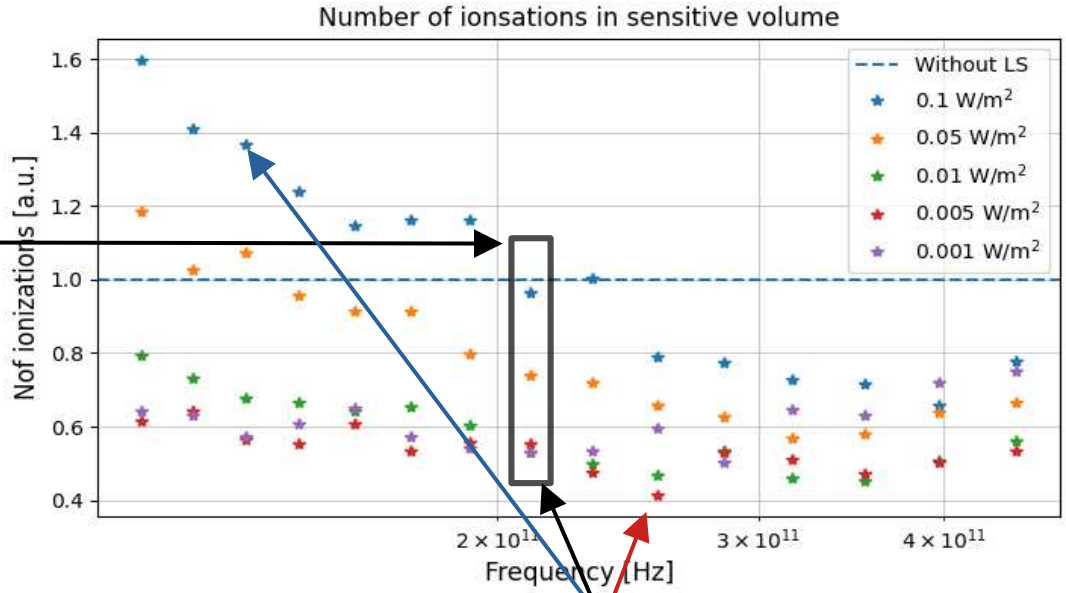


- Anti-Hydrogen formation:
  - drive newly bound anti-hydrogen down to ground state
  - More earlier this week: Chloe Malbrunot
- KATRIN:
  - Avoid random ionization in sensitive volume
  - manipulate state distribution with THZ radiation

THz treatment in KATRIN

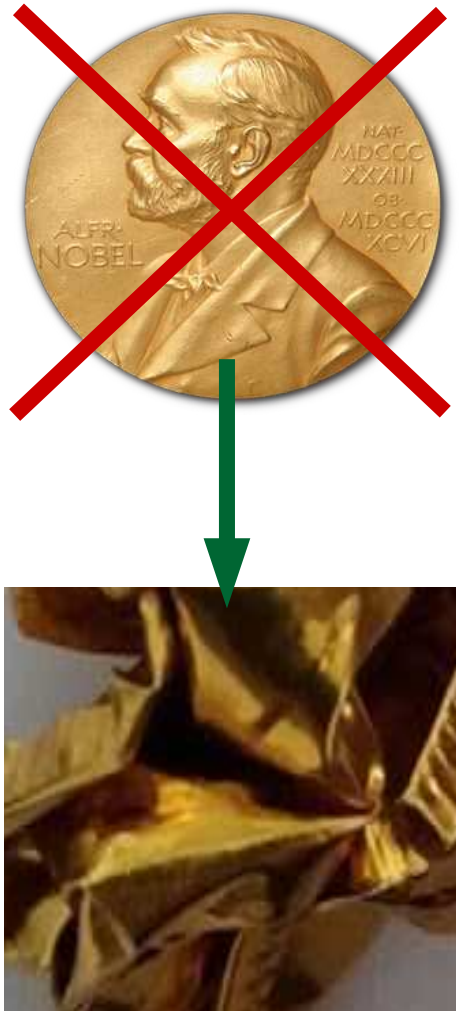
Full simulation in place with state distribution from sputtering





Approach:
- Eightfold Way:
  8 consecutive light sources drive down to n-8 e.g. 32 → 24
- choose intensity not to overdrive
- at least factor 2 reduction possible in simulation

Summary & Outlook



We are stretching IceCube and KATRIN far beyond design goals and initial ideas!

Fundament discoveries must be around the corner
… meanwhile entertaining ourselves with atomic physics ☺

Major research infrastructures