Physics beyond the Standard Model with IceCube

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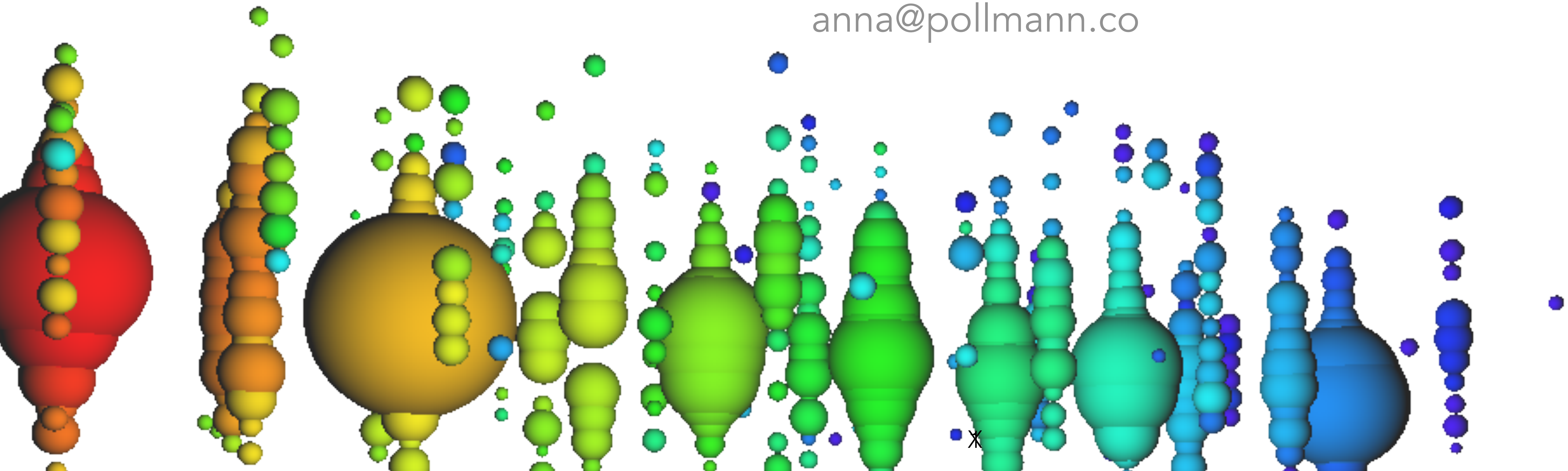


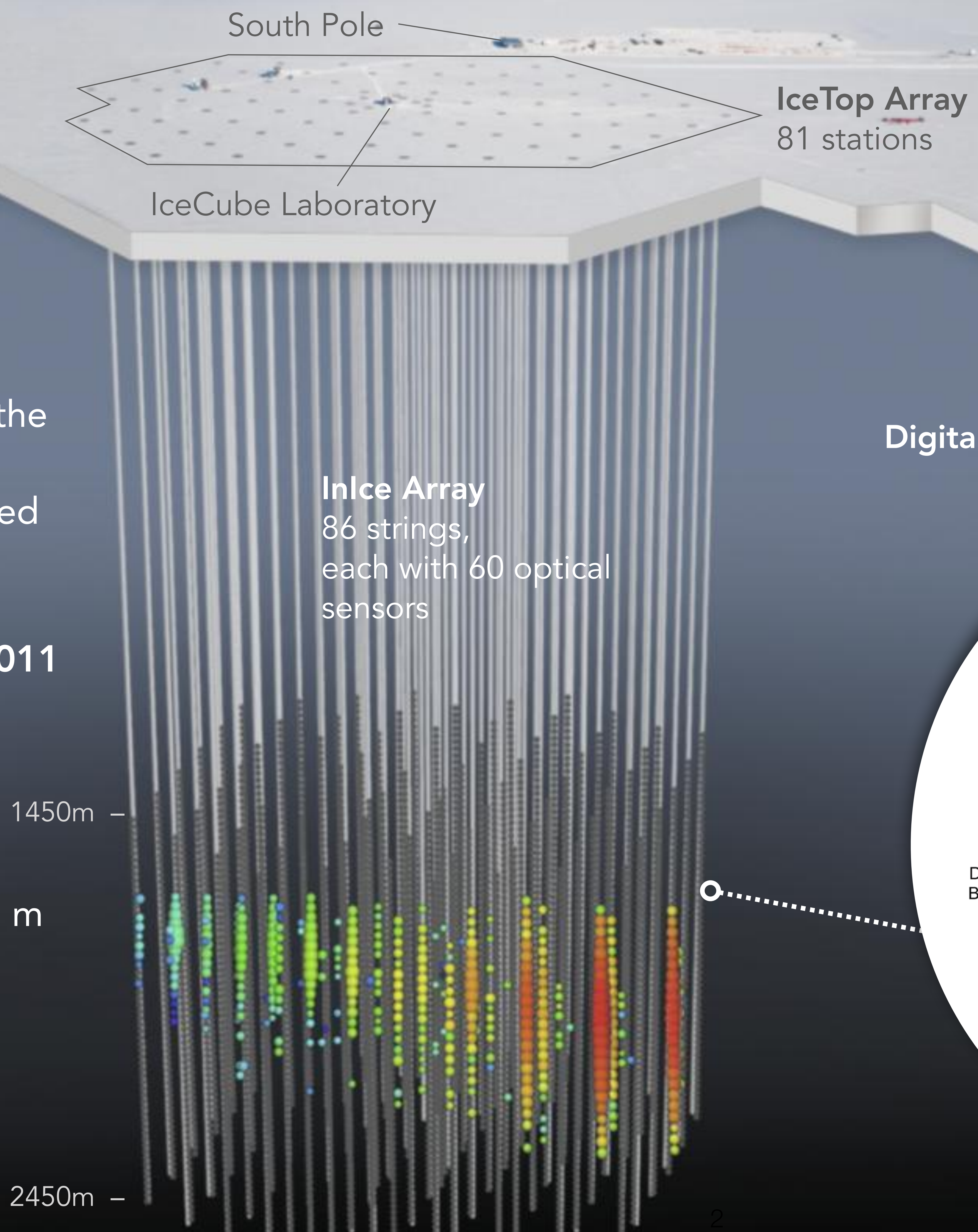
IceCube

IceCube

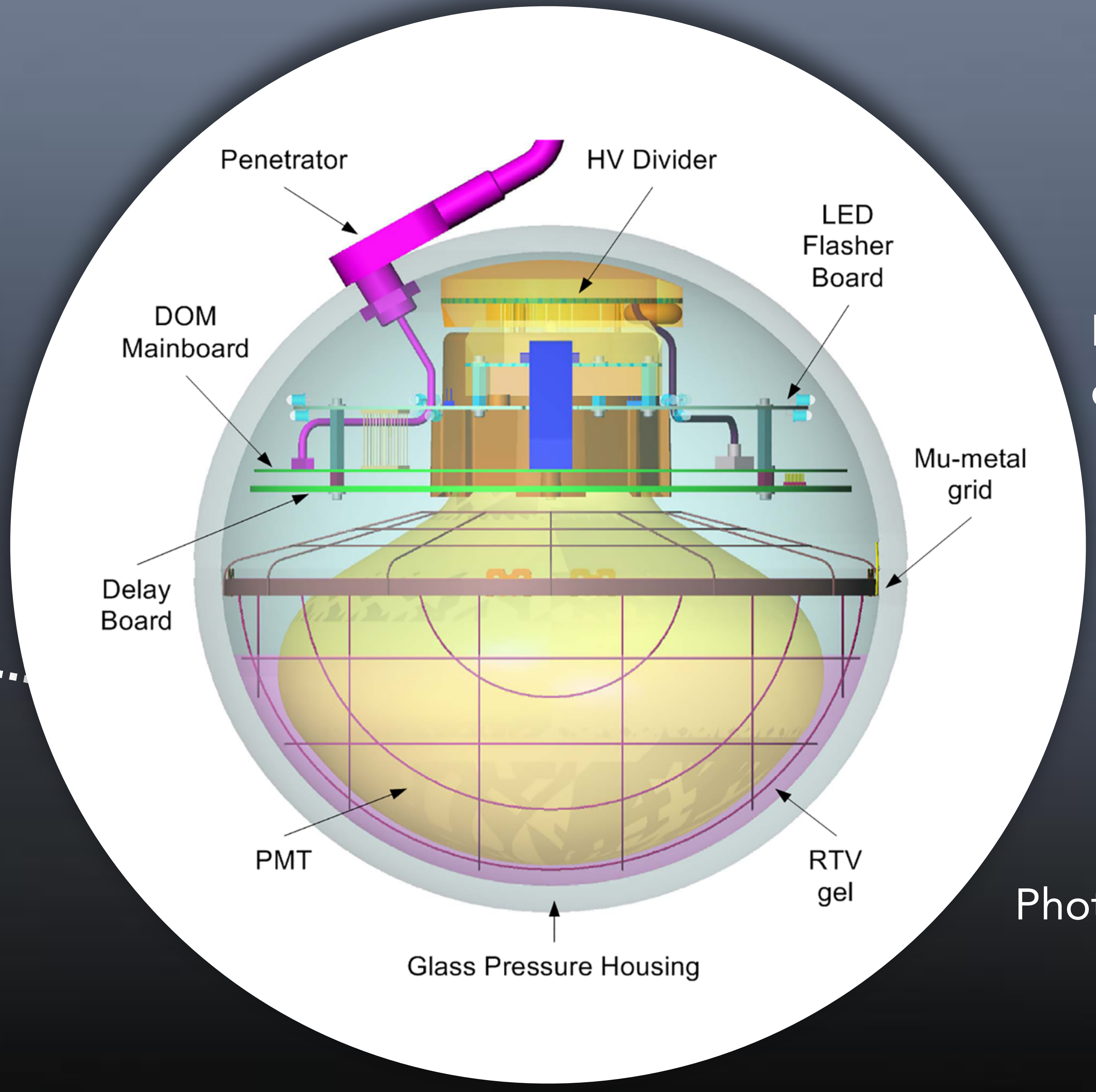
Working principle
- Particles interact with the deep clear ice
- Emitted light is detected by sensors

Fully operational since 2011

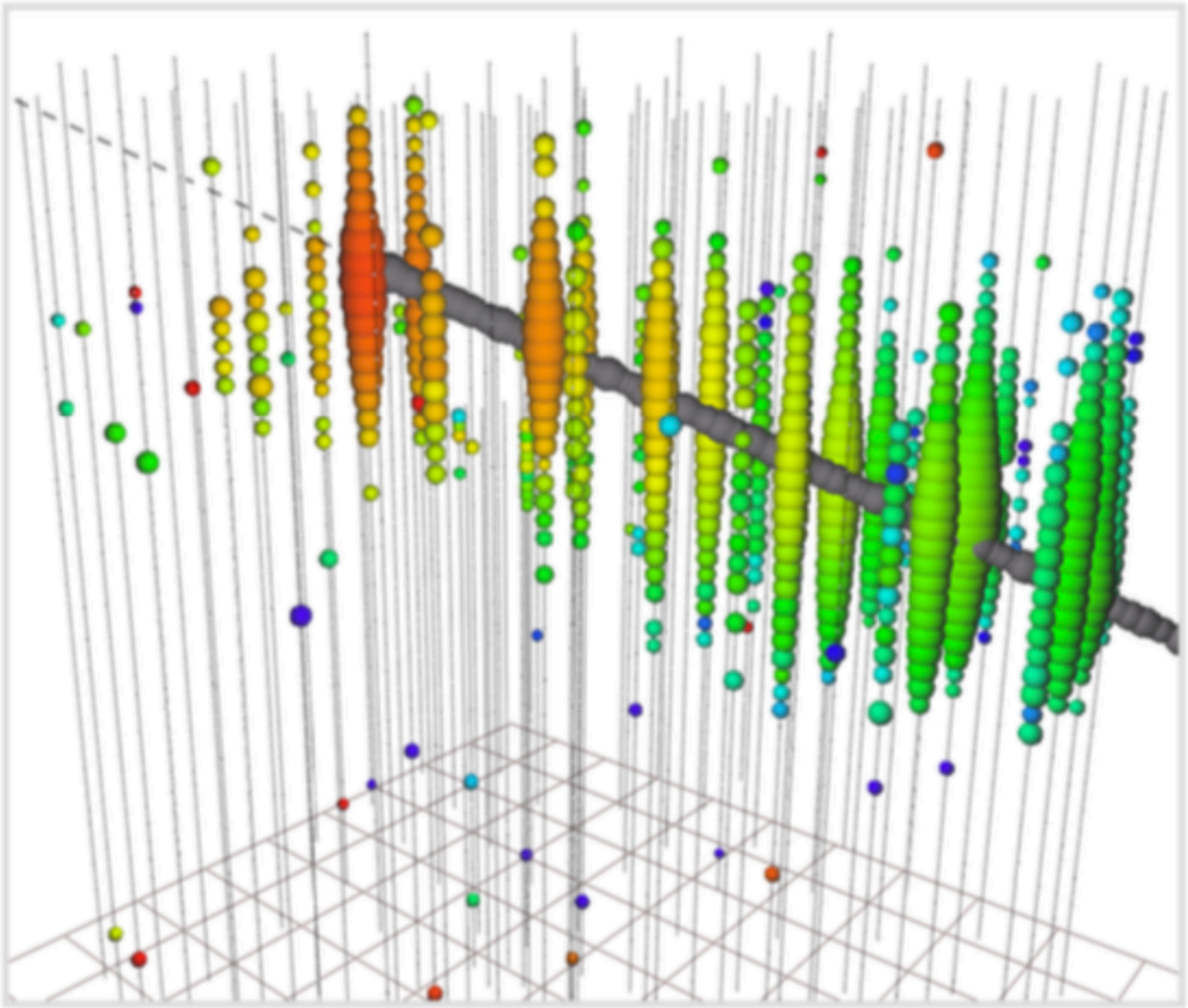
Geometry
- volume 1 km^3
- vertical spacing 17 m
- horizontal spacing 125 m

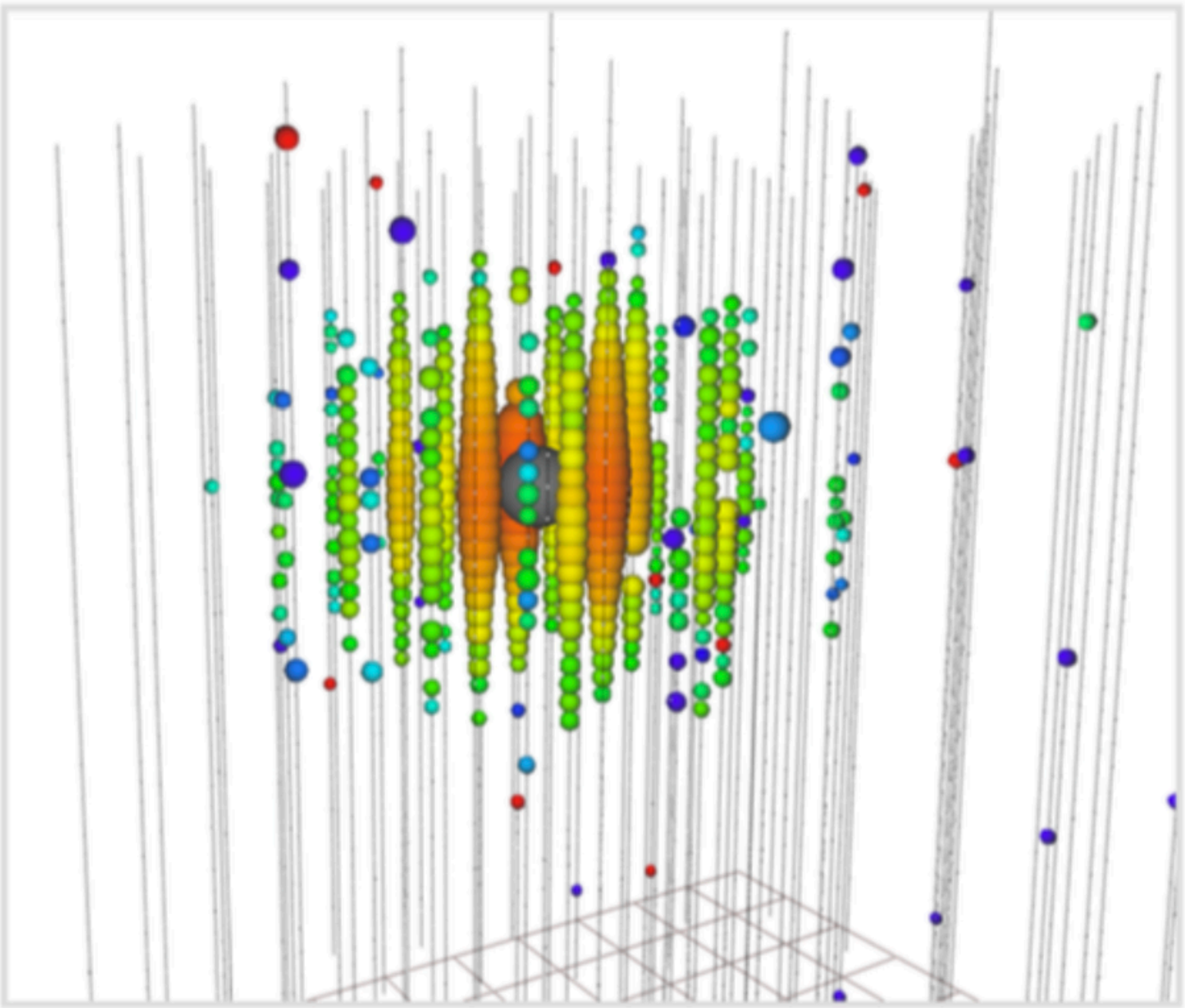


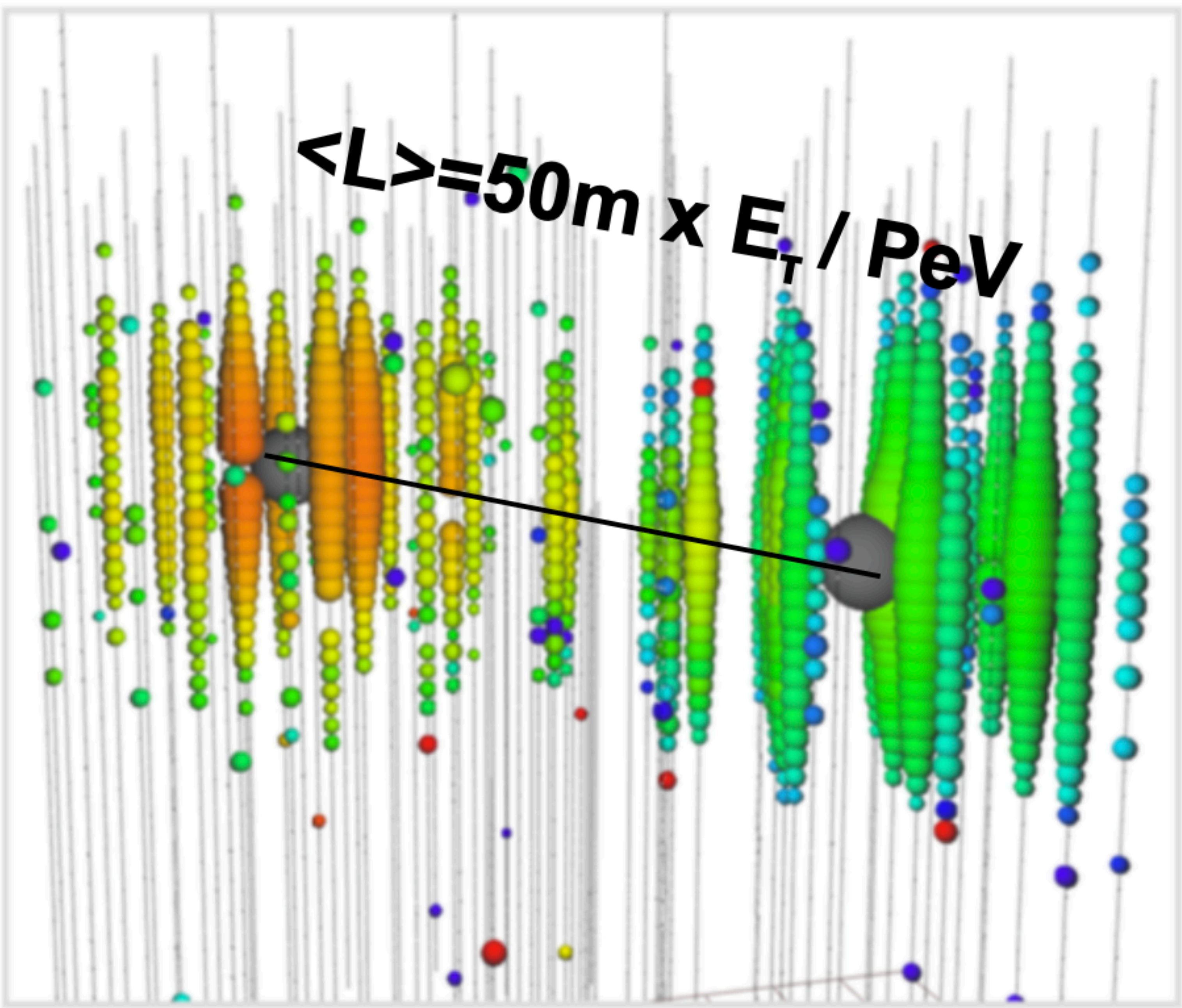
Digital Optical Module (DOM)



Neutrino signatures







Muon neutrinos:
track-like events

$$\nu_\mu + N \to \mu + X$$

angular resolution ~ 0.5°
energy resolution ~ 25%

Electron neutrinos:
isolated cascades

$$\nu_e + N \to e + X$$
$$\nu_x + N \to \nu_x + X$$

angular resolution ~ 10°
energy resolution ~ 15%

Tau neutrinos:
"double bang"

$$\nu_\tau + N \to \tau + X$$

~ 2 expected events
in 6 years

Beyond standard model searches in IceCube

fundamental laws

Indirect detection

- new physics influences propagation/development of particle fluxes
- exotic source of particles contributes to particle flux

sterile ν

ν inter-actions

… and many more

dark matter

partially charged particles

Direct detection

- IceCube detects what
  - reaches the detector
  - induces light production in ice

Q-balls / nuclearites

… and many more (not even thought off)

magnetic monopoles

Advantages to use ν-detectors for exotic physics

- large detector volume
- **for indirect detection:** high statistics
- **for direct detection:** few conditions on particle properties

Dark Matter from the Sun

„Standard"

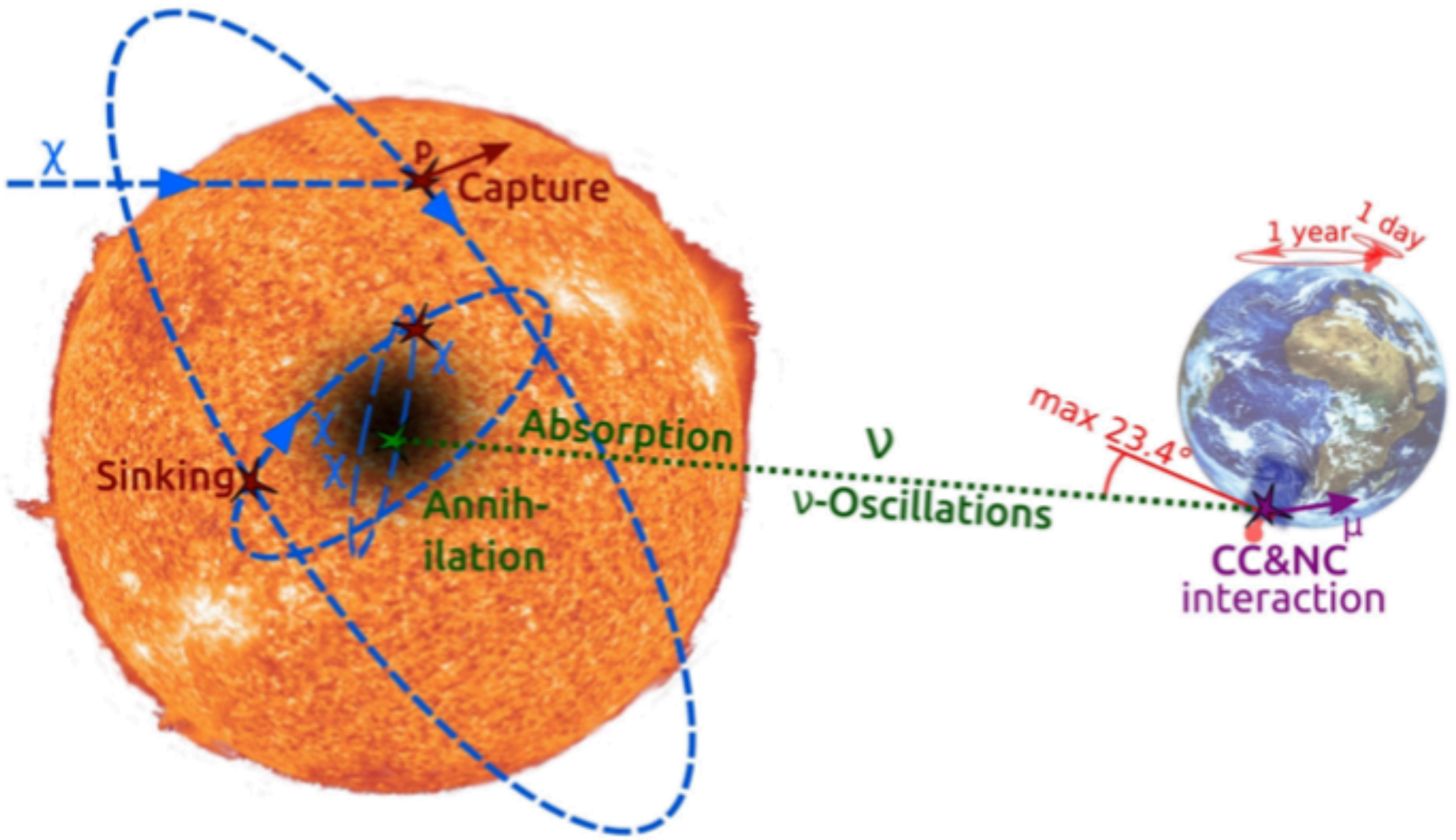
- DM from galactic halo gravitationally bound in potential of body
- weak scattering off nuclei in Sun decelerates DM towards center → $\sigma_{\chi\text{-}p}$
- DM self-annihilates at center with SM particle emission → different spectra *(only of neutrinos)*
- neutrino rate & energy at detector depends on
  - DM mass & annihilation cross section
  - DM halo density spectrum

Secluded DM

- annihilation via long-lived mediator decaying into SM particles outside sun

equilibrium!

$$\Phi_\nu^{limit} \rightarrow \Gamma_A \rightarrow C_c \rightarrow \sigma_{\chi-N}$$



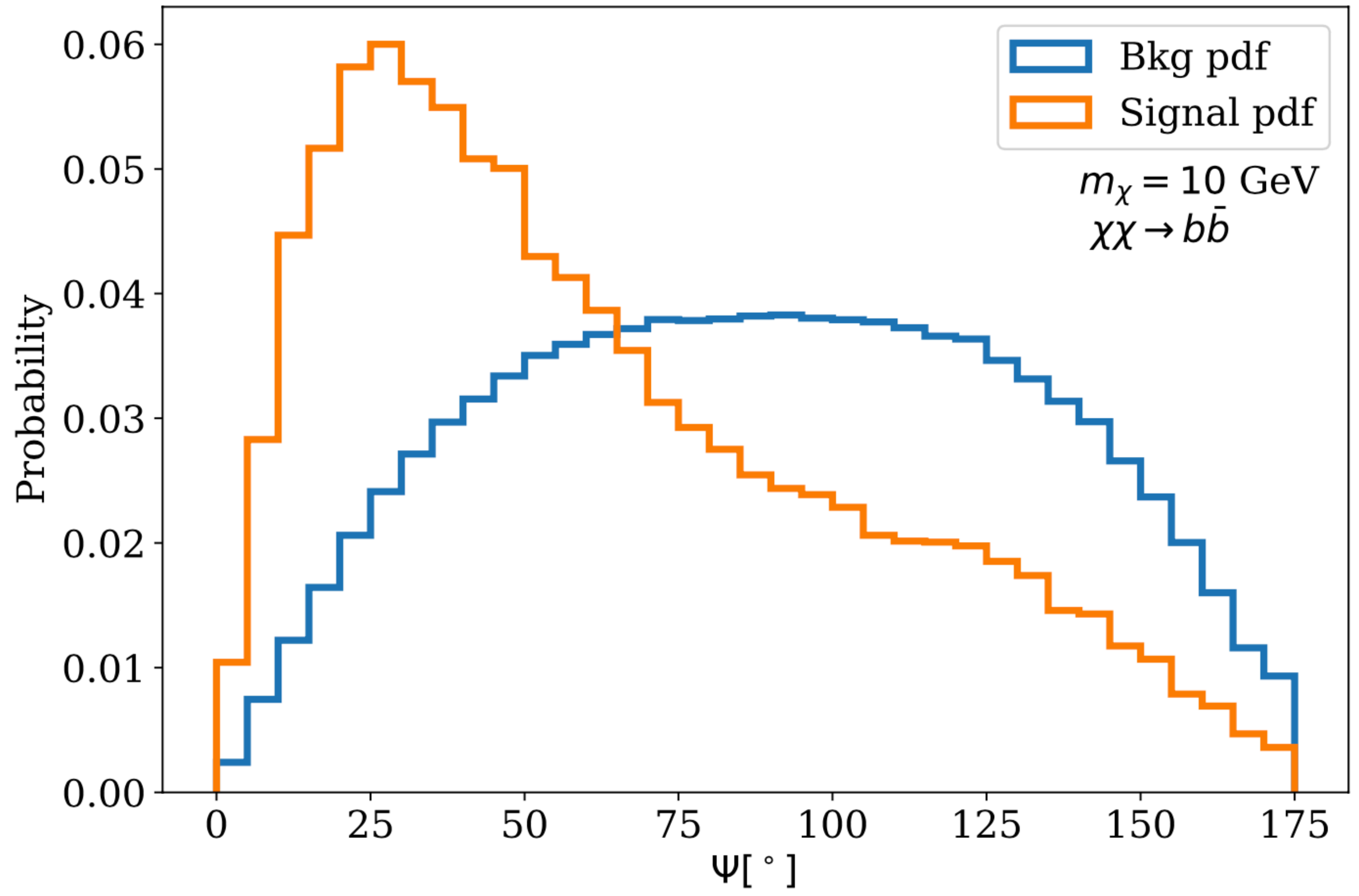
Dark Matter from the Sun

arXiv:2111.09970
Accepted by Phys. Rev. D

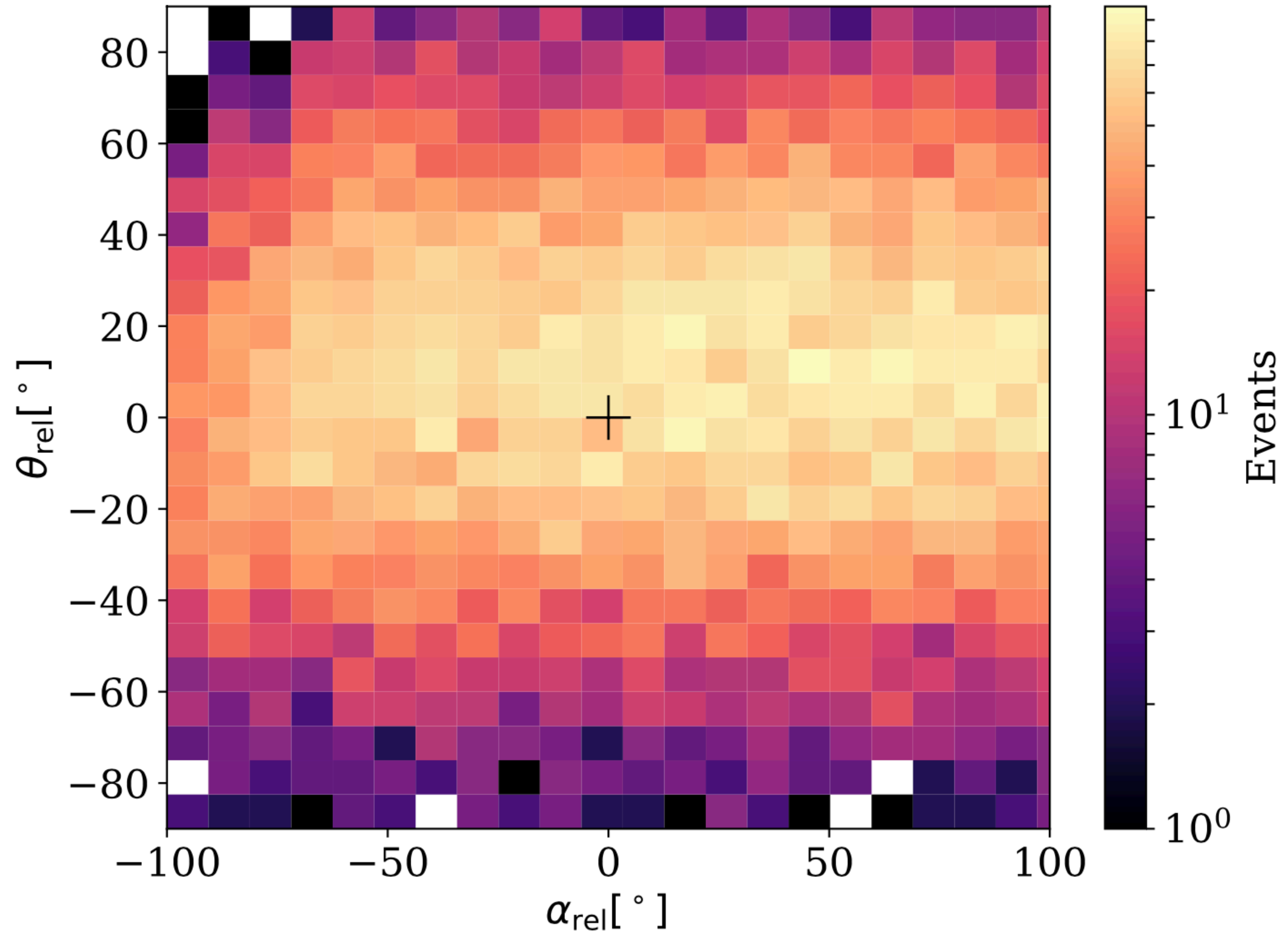
Analysis strategy:

- use low energy sub-detector *DeepCore*
- use standard IceCube as veto
- distinguish muon tracks and cascade-like signatures
- reconstruct direction (angular resolution 5-35°)
- unbinned LLH

Expectation / Model:



Observation



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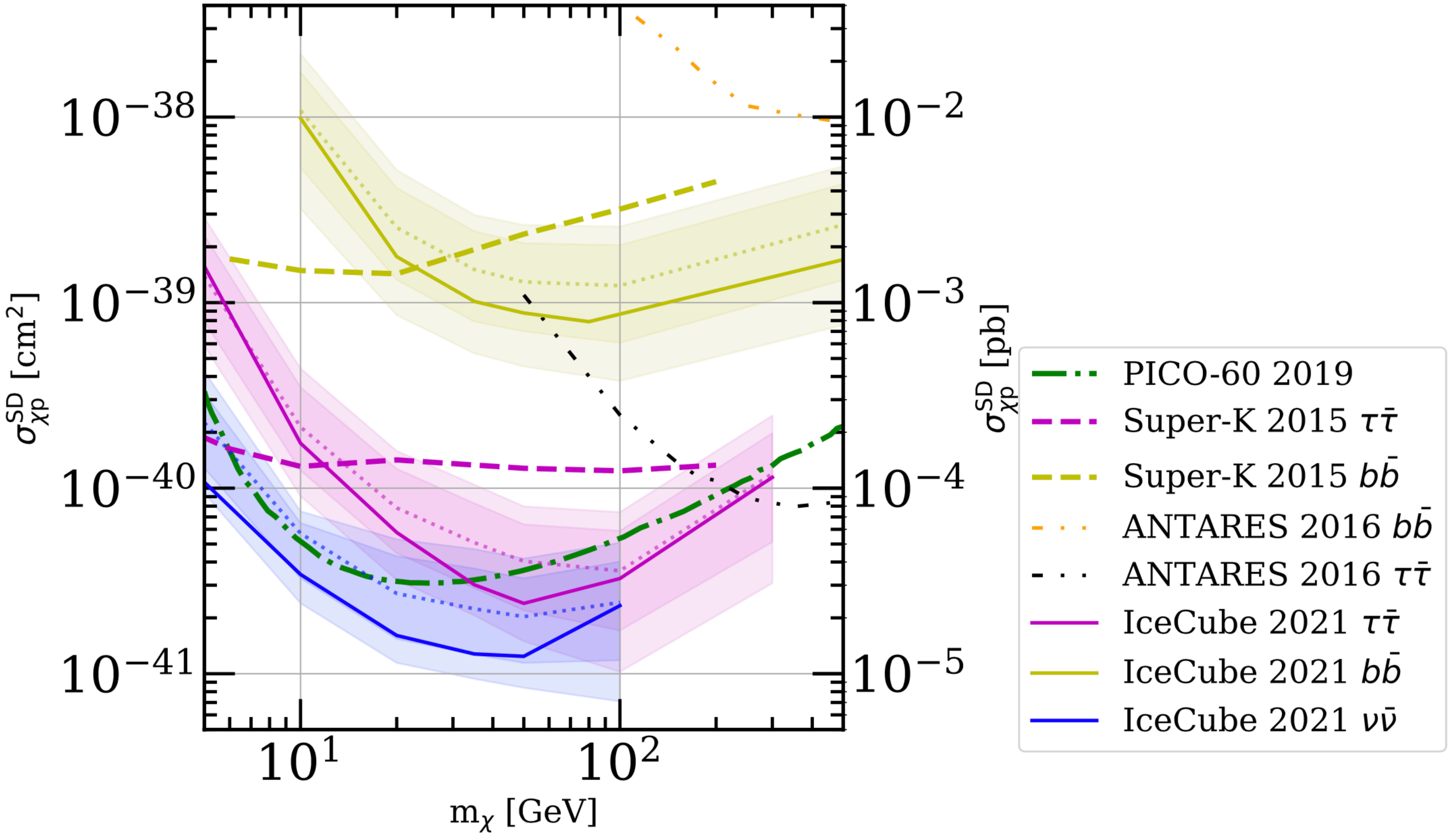


Dark Matter from the Sun

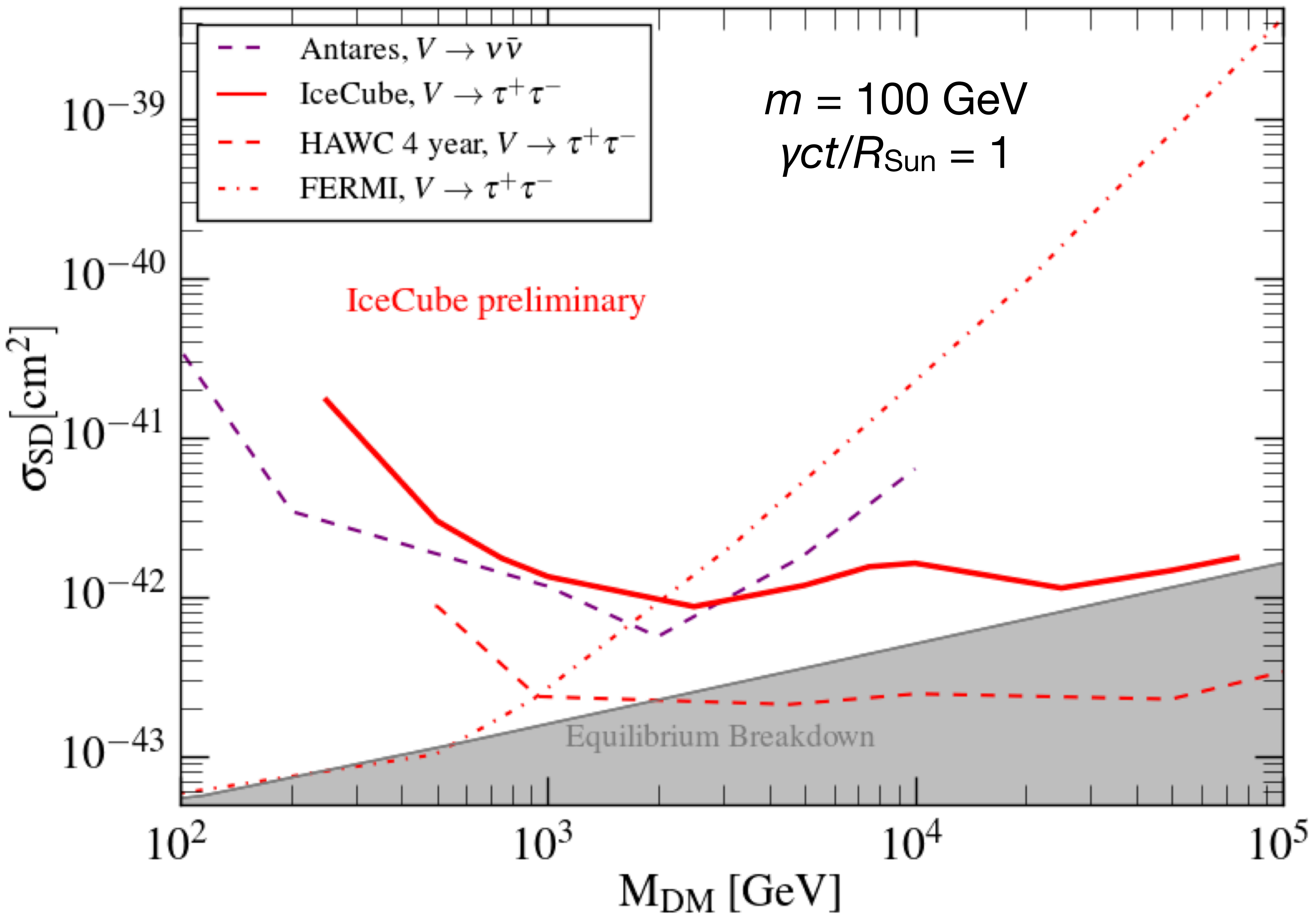
arXiv:2107.10778

Secluded Dark Matter

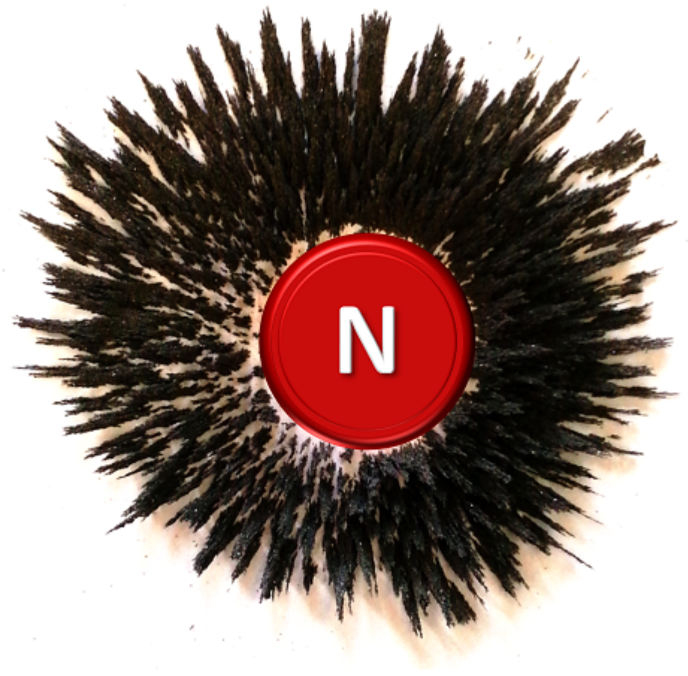
- mediator decays into ν outside sun, no signal attenuation
- signal at higher energies

Analysis strategy:

- consider muon tracks ”from below“
- unbinned LLH



Magnetic monopoles



1864

$$\nabla \cdot \mathbf{D} = 4\pi\rho_e$$
$$\nabla \cdot \mathbf{B} = 4\pi\rho_m$$

$$\nabla \times \mathbf{E} - c^{-1}\,\dot{\mathbf{B}} = 4\pi c^{-1}\,\mathbf{j}_m$$
$$\nabla \times \mathbf{H} - c^{-1}\,\dot{\mathbf{D}} = 4\pi c^{-1}\,\mathbf{j}_e$$

James Clerk Maxwell

1931

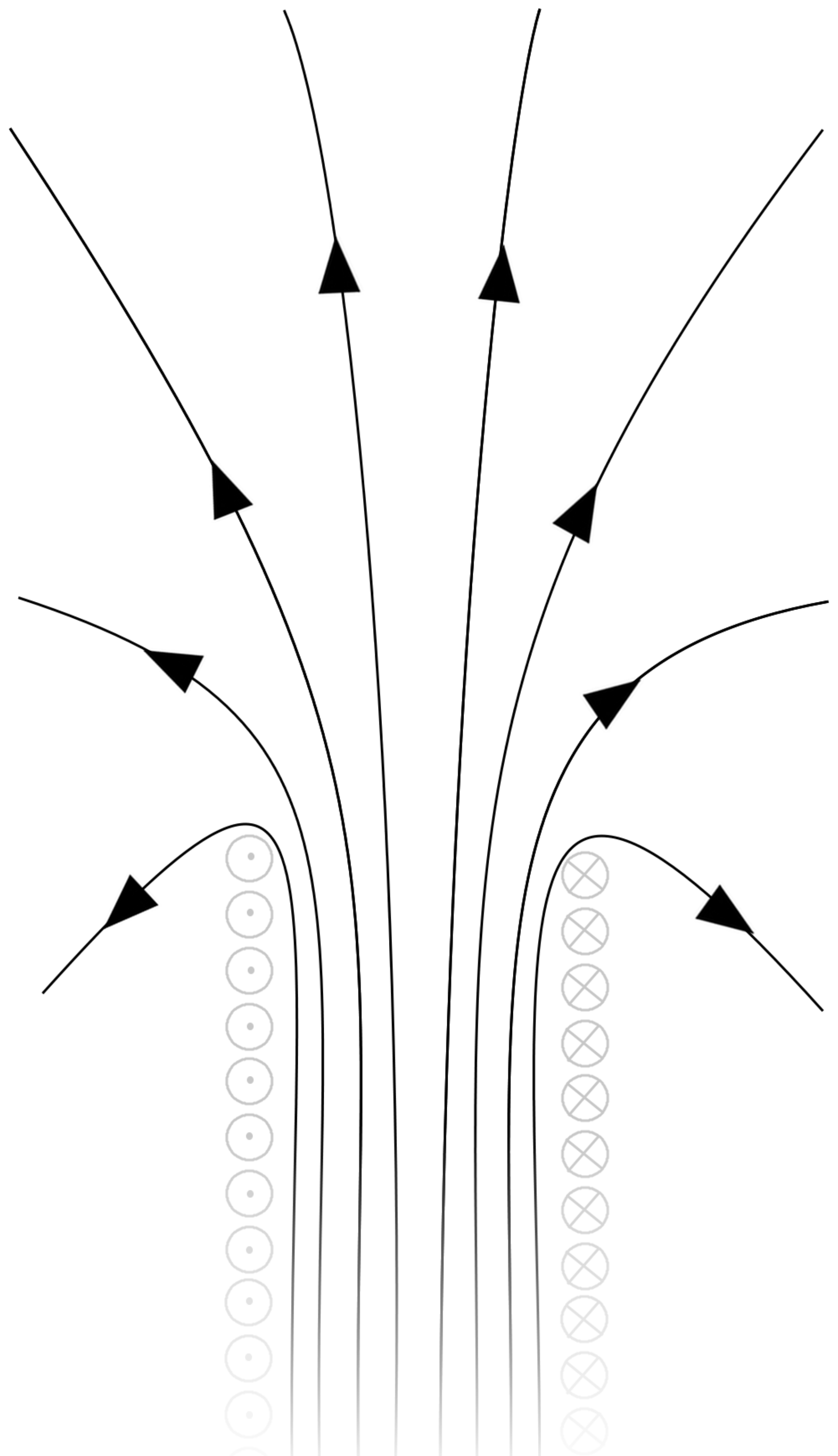
Search: Quantization of electric charge e

$$e = \sqrt{\hbar c \alpha}$$

Result: Dependence on a magnetic charge g

$$\mathbf{g} = \mathbf{k}\,\frac{\mathbf{e}}{2\alpha} \approx 68.5\ e$$

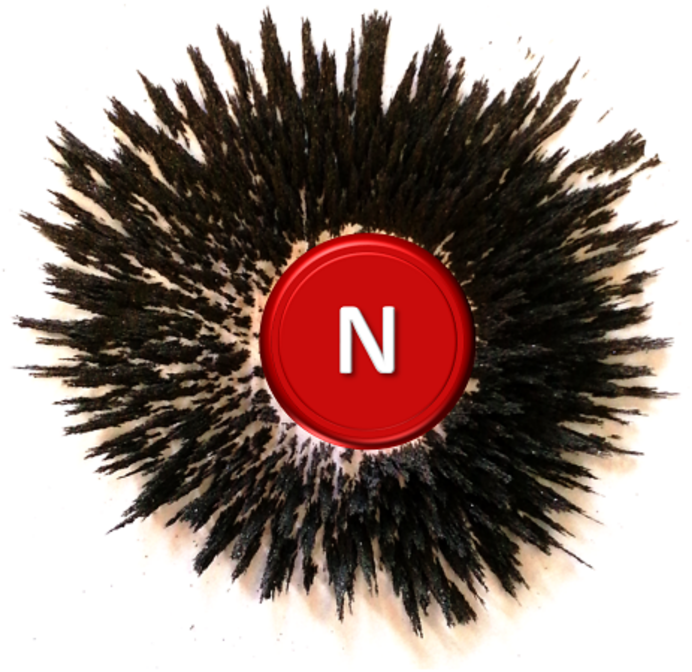
Paul Dirac



Field of a magnetic monopole (analogous to the end of a solenoid)

http://sse.royalsociety.org/2015/media/8749/mq_iron_filings-full-size.png

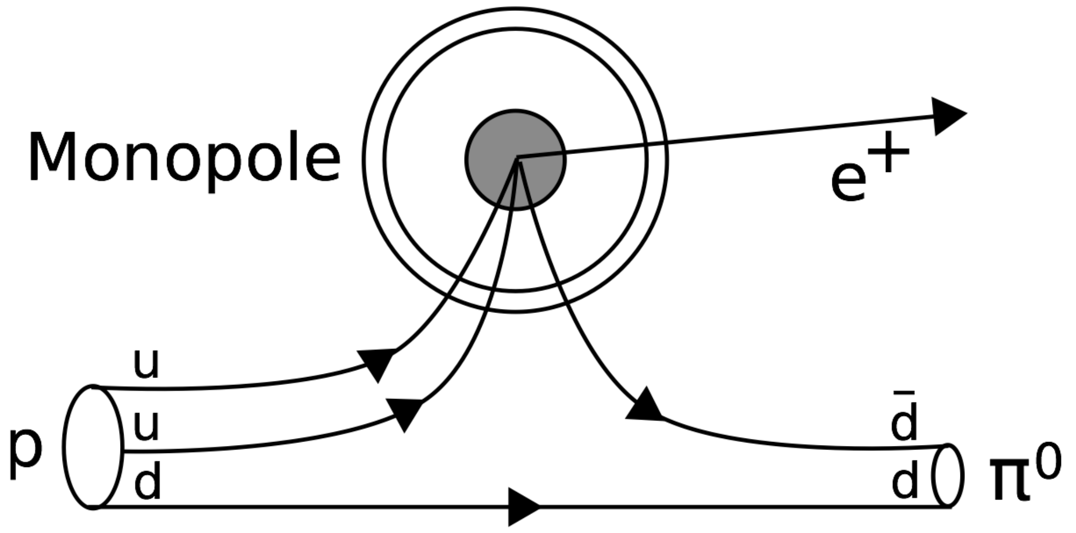
Detection of Magnetic Monopoles



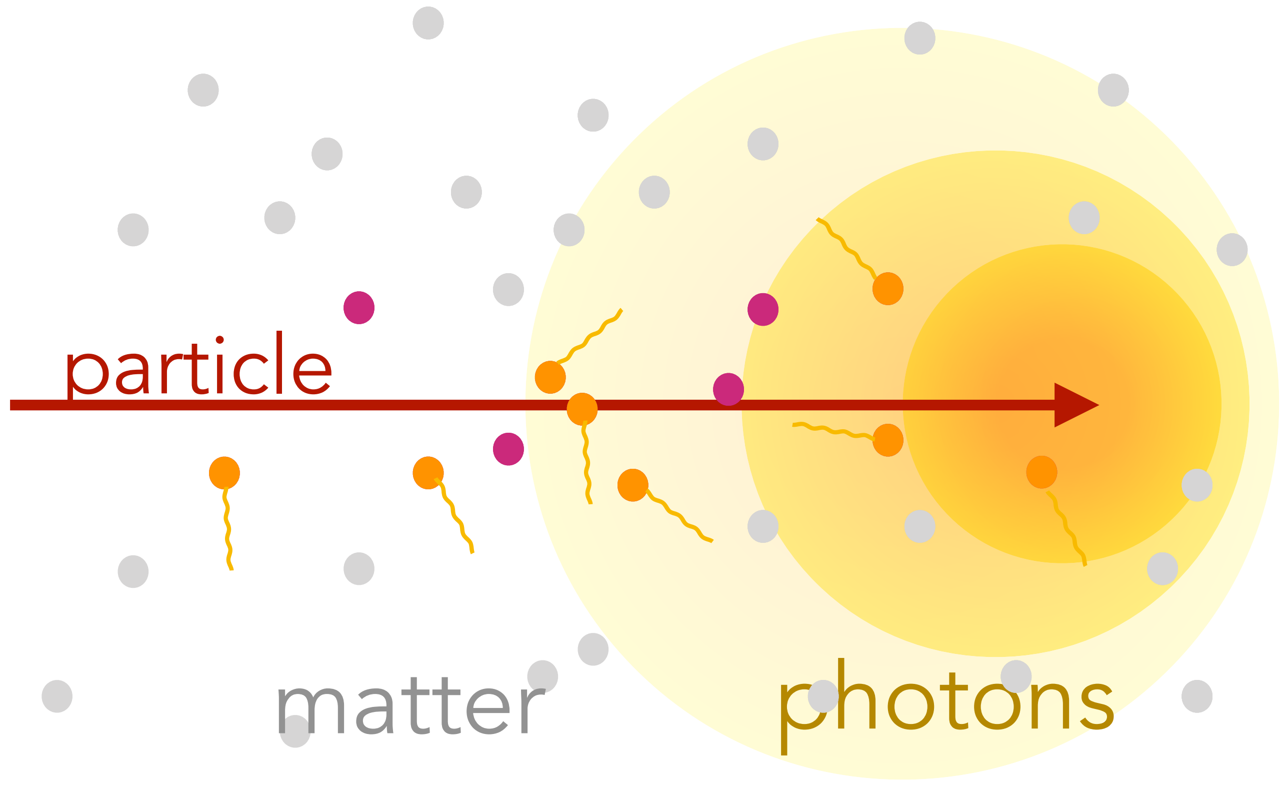
predicted by many BSM theories

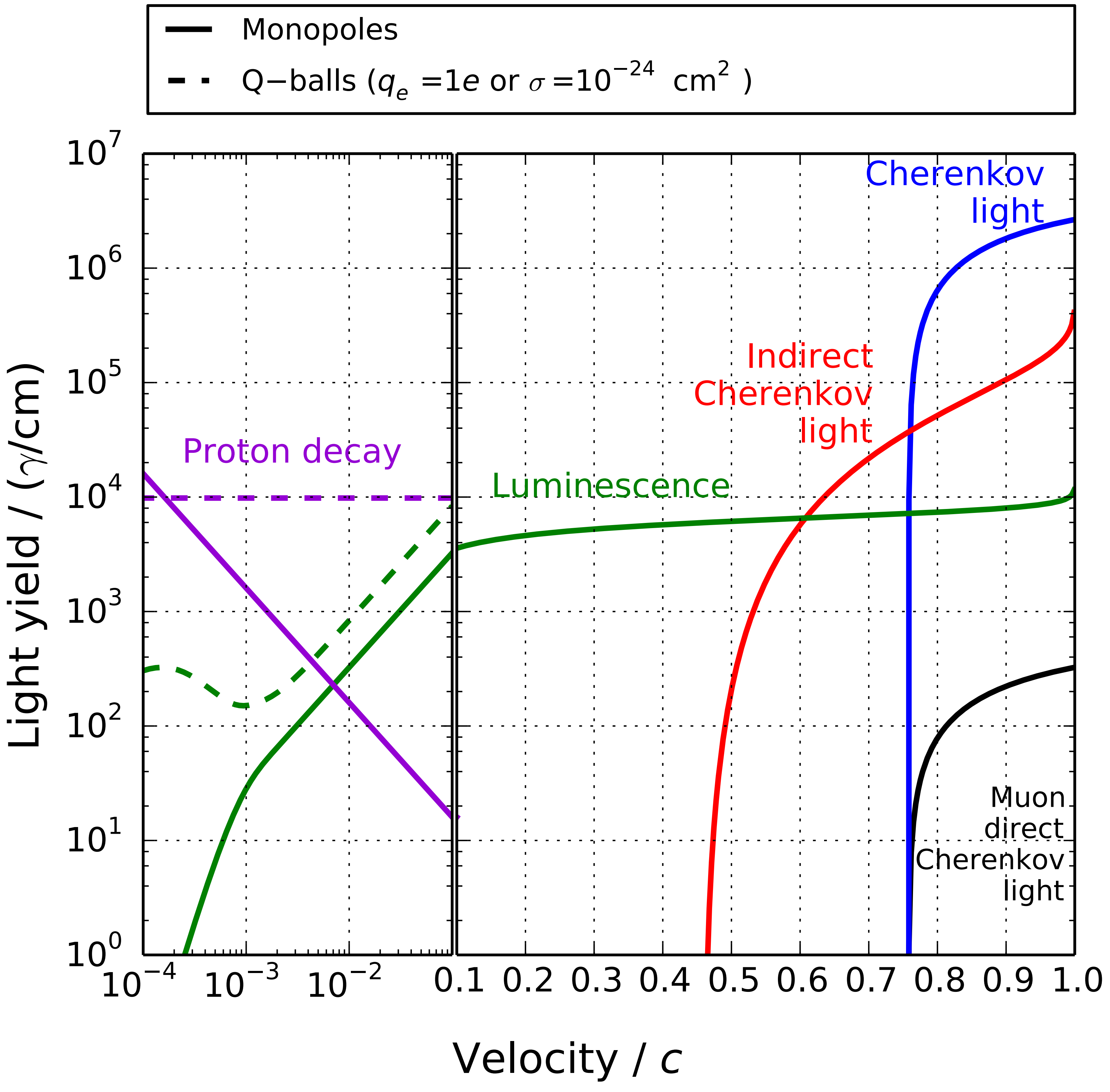
- isolated magnetic charge (~n x 68·*e*)
- massive (up to 10^{19} GeV)
- slow or relativistic
- low flux possible
- highly ionising

Proton decay



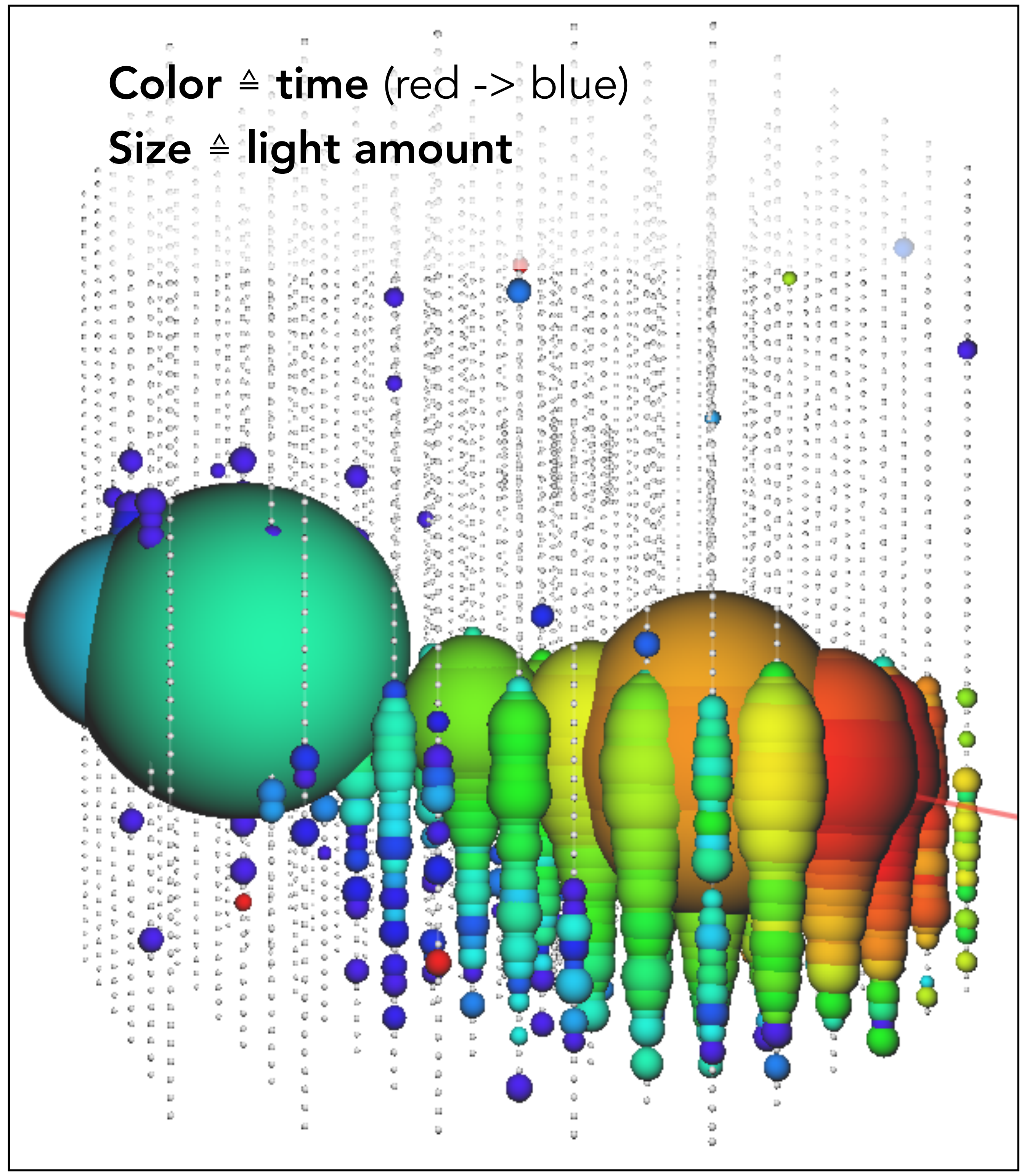
Luminescence light emission





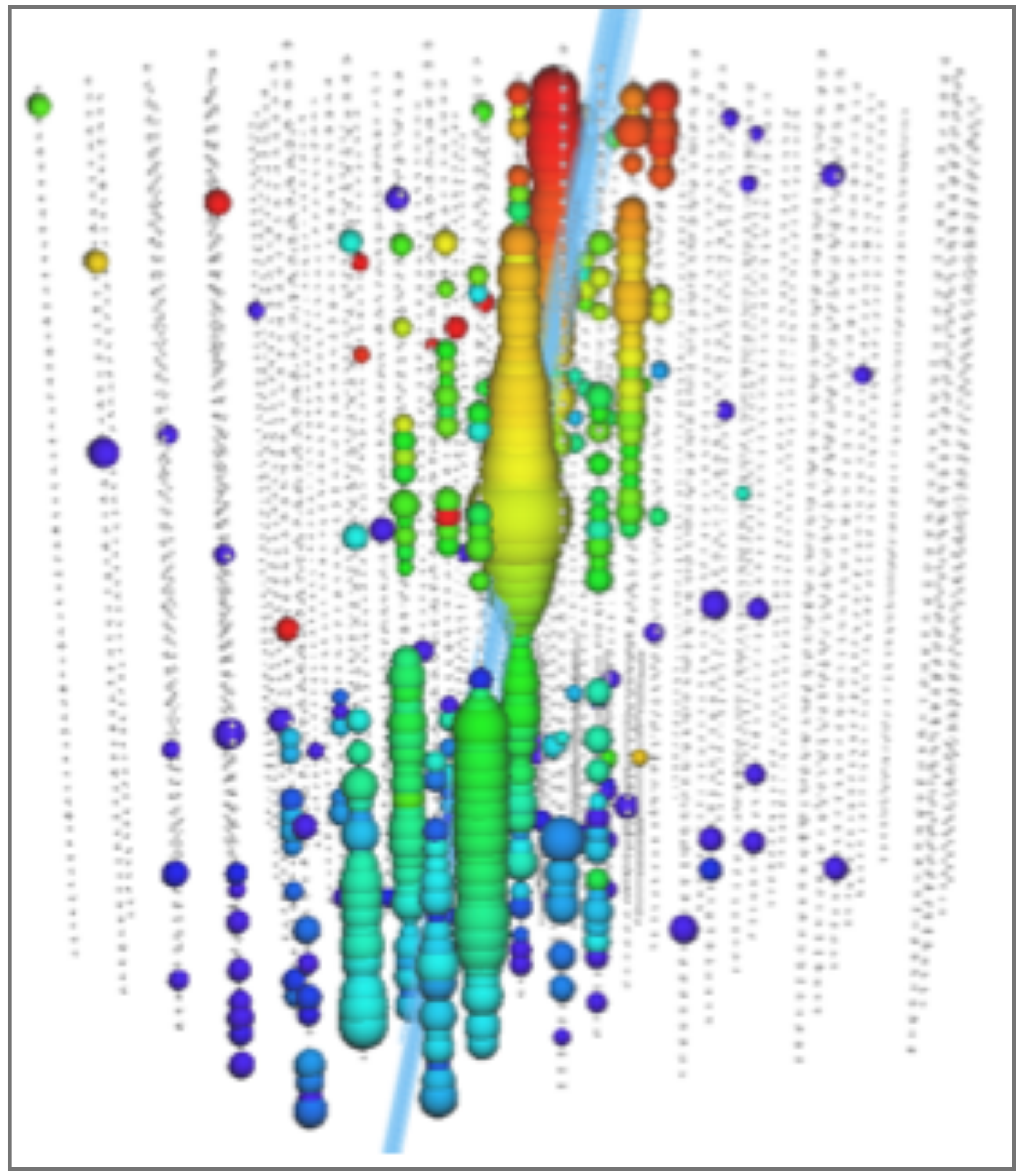
Event signatures of bright tracks

μ-neutrino
2.6 ± 0.3 PeV

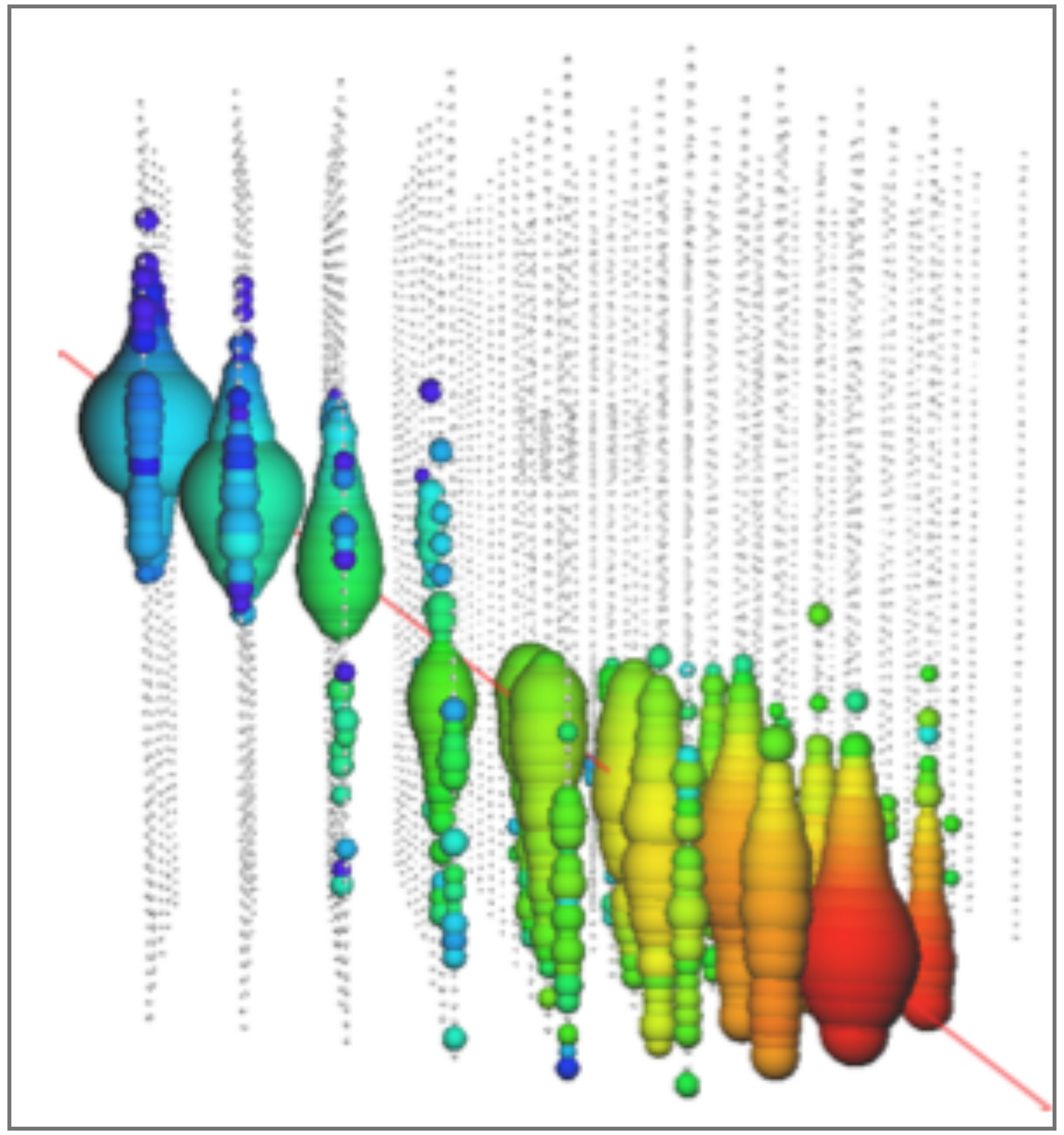


Astrophys.J. 833 (2016) 1

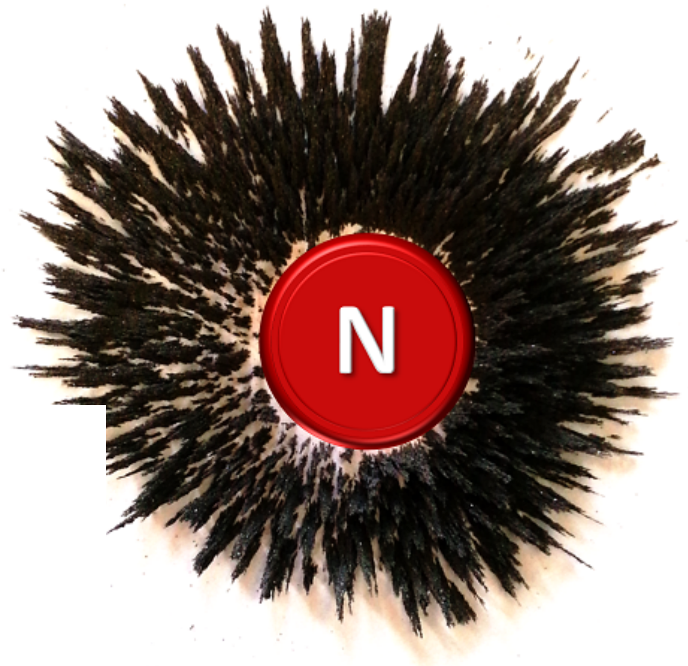
μ-bundle
from cosmic rays



Simulation of a monopole
with 0.99 *c*



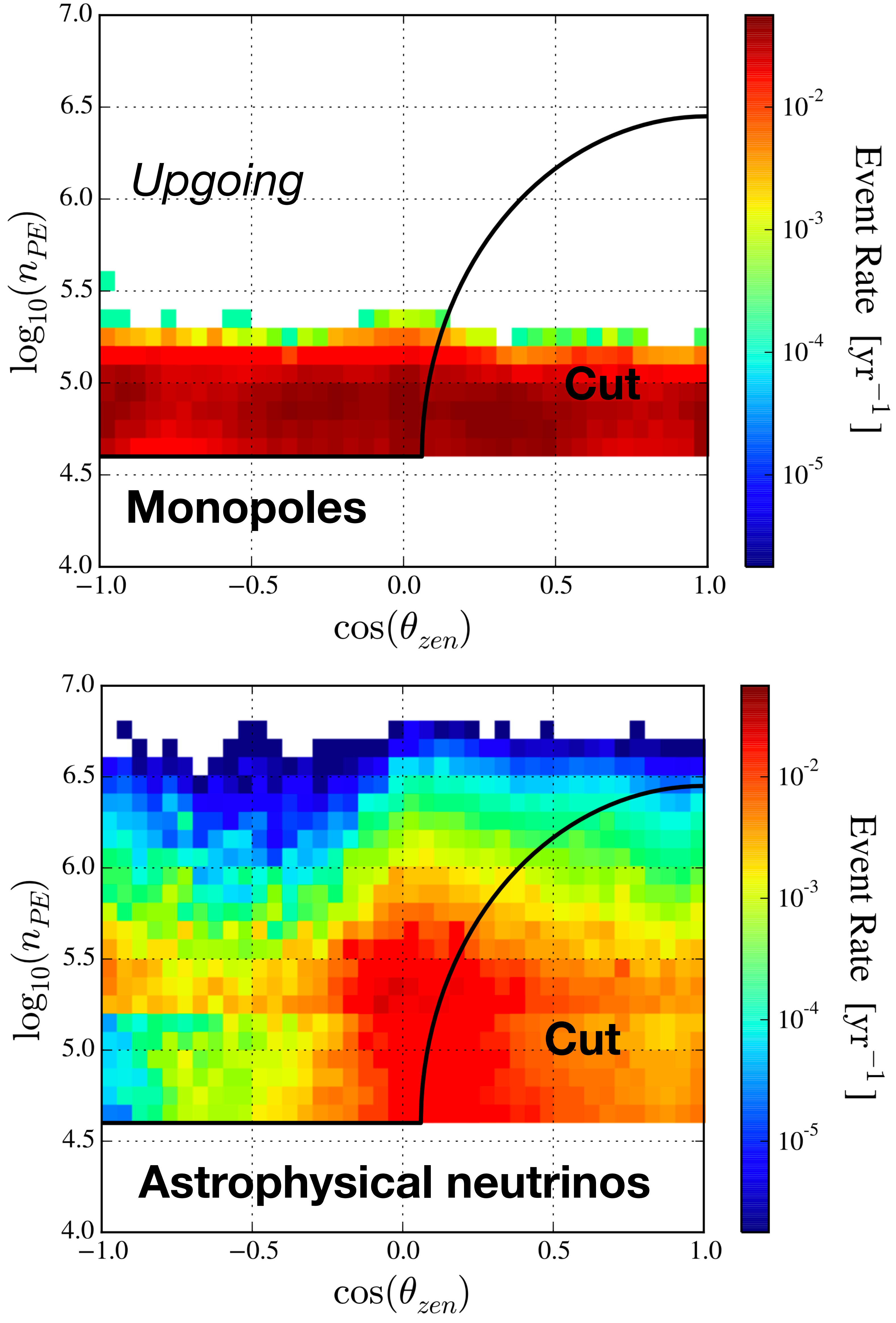
Bright relativistic magnetic monopoles



Event signature: similar to astrophysical muon neutrinos

Analysis:

- step 1: copy standard astro-ν search
- step 2: work out distinct features of monopoles:
  - zenith distribution
  - tracks
  - homogeneous brightness
  - speed



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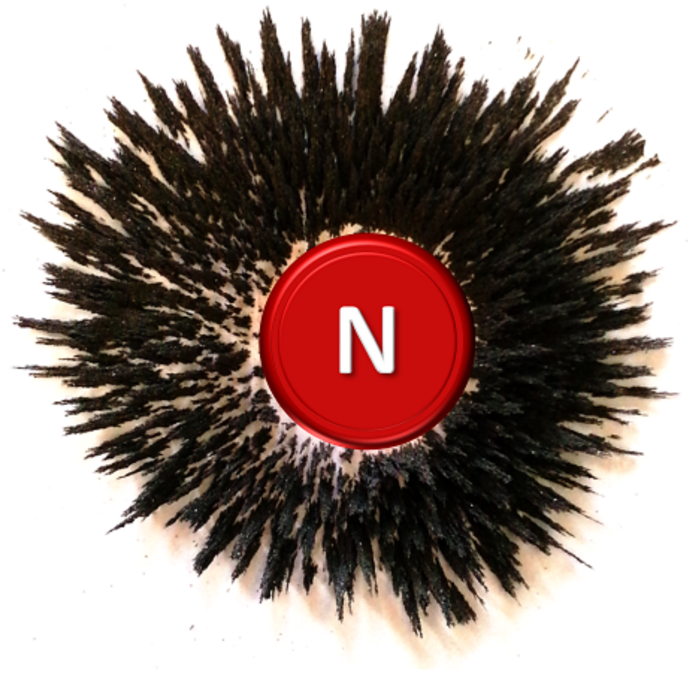

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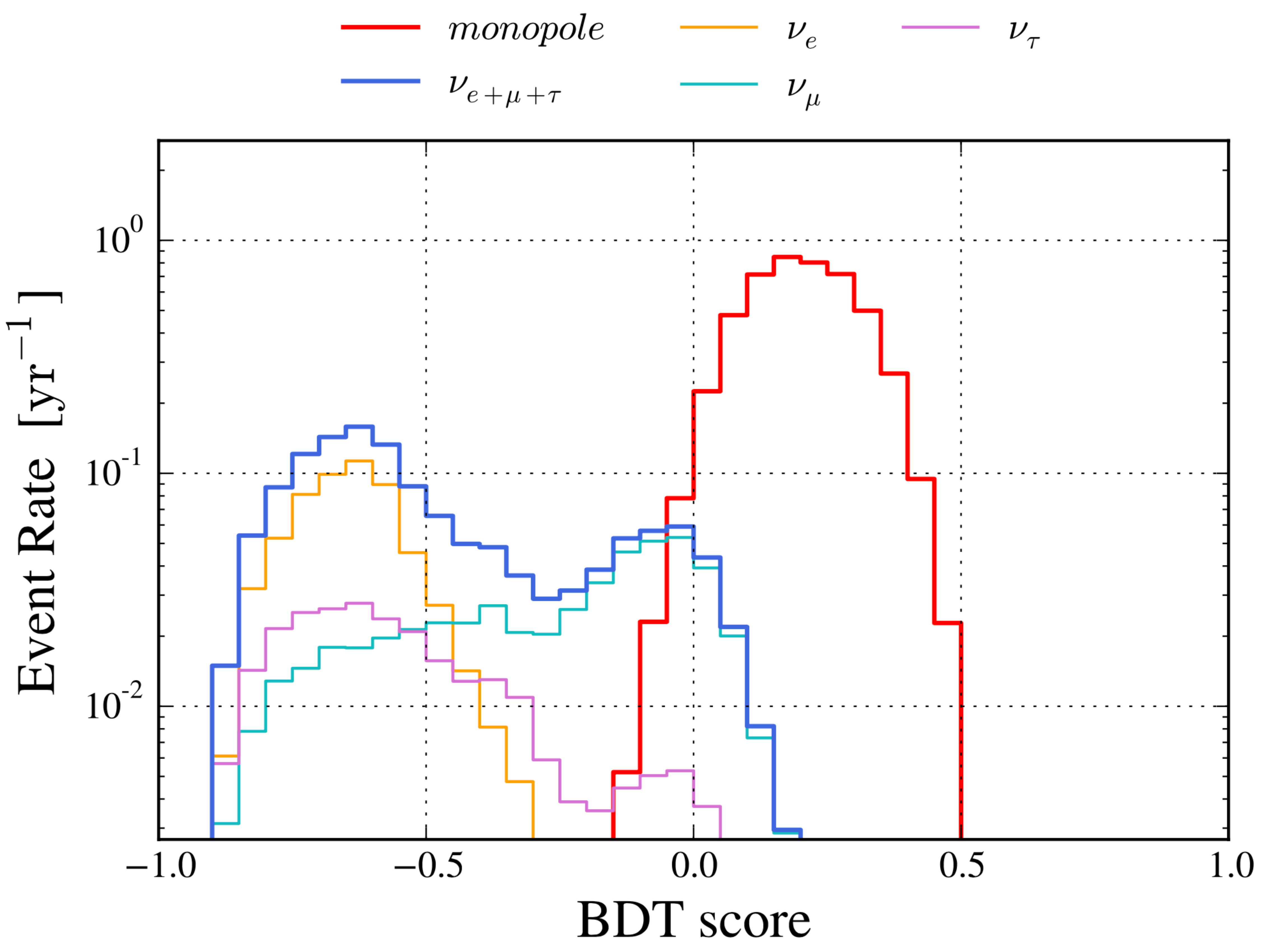

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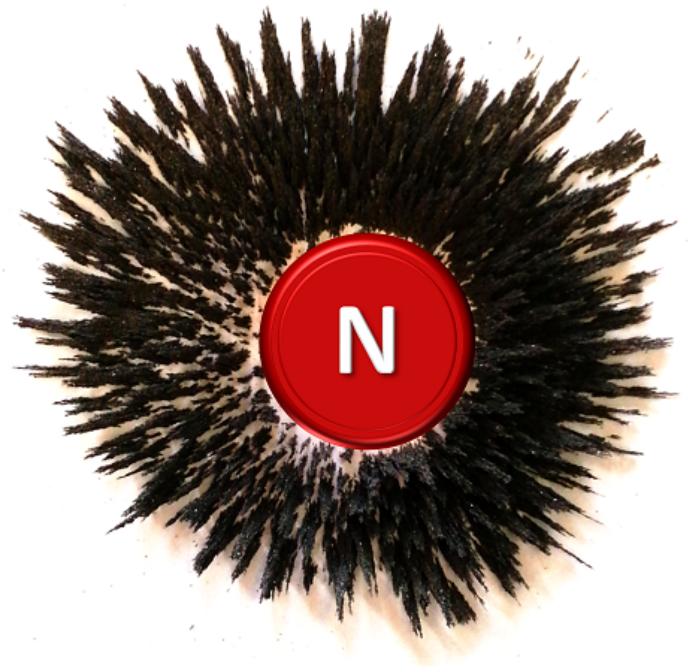

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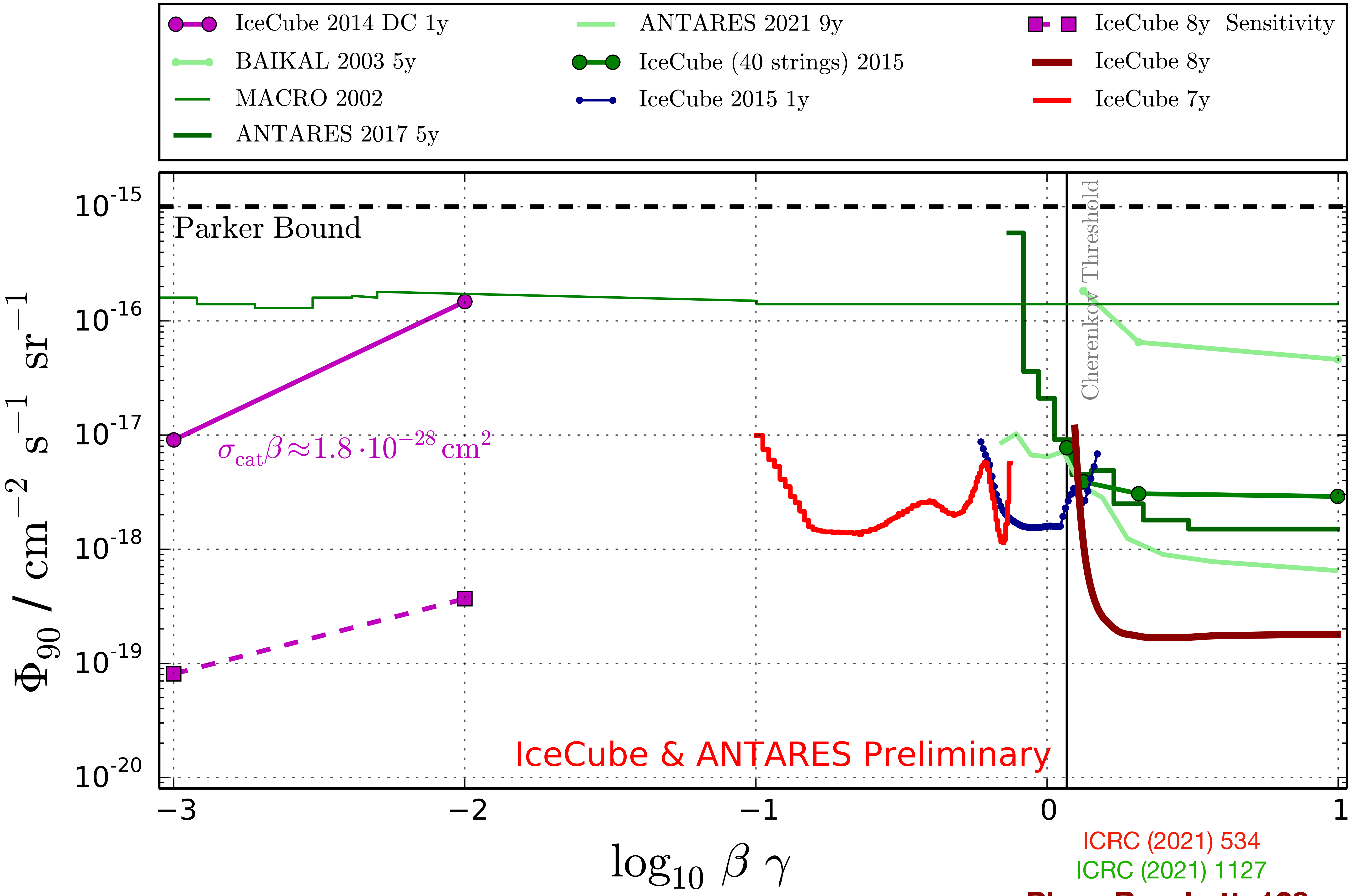
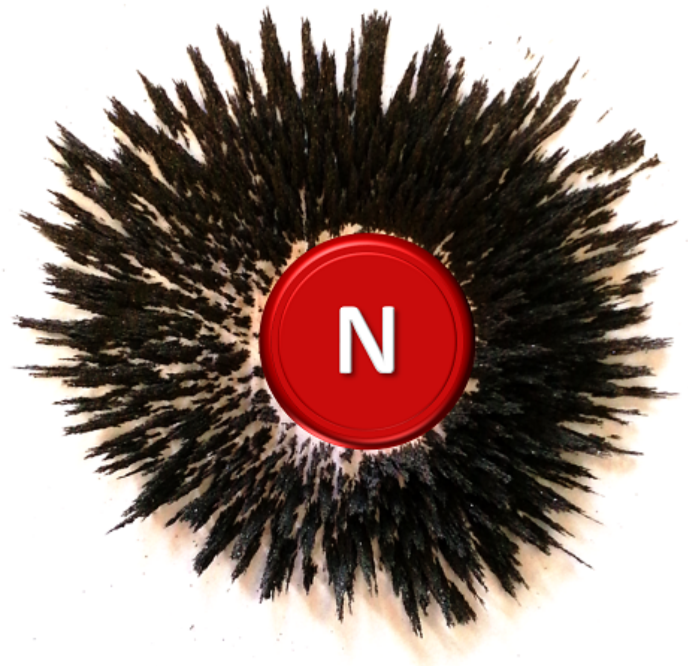


ICRC (2021) 534
ICRC (2021) 1127
Phys. Rev. Lett. 128, 051101 (2022)
(Arxiv: 109.13719)

Detection of Magnetic Monopoles



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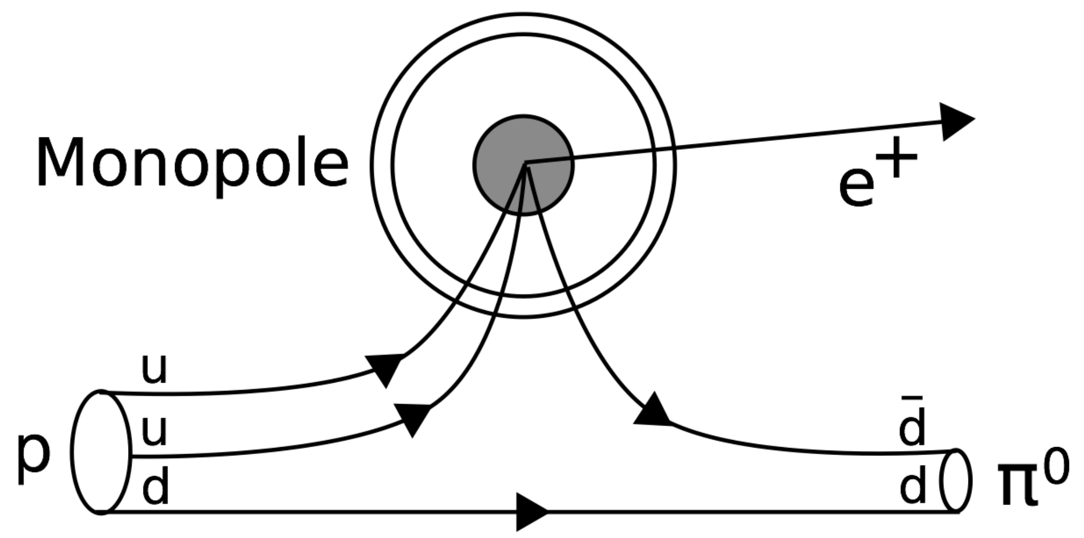

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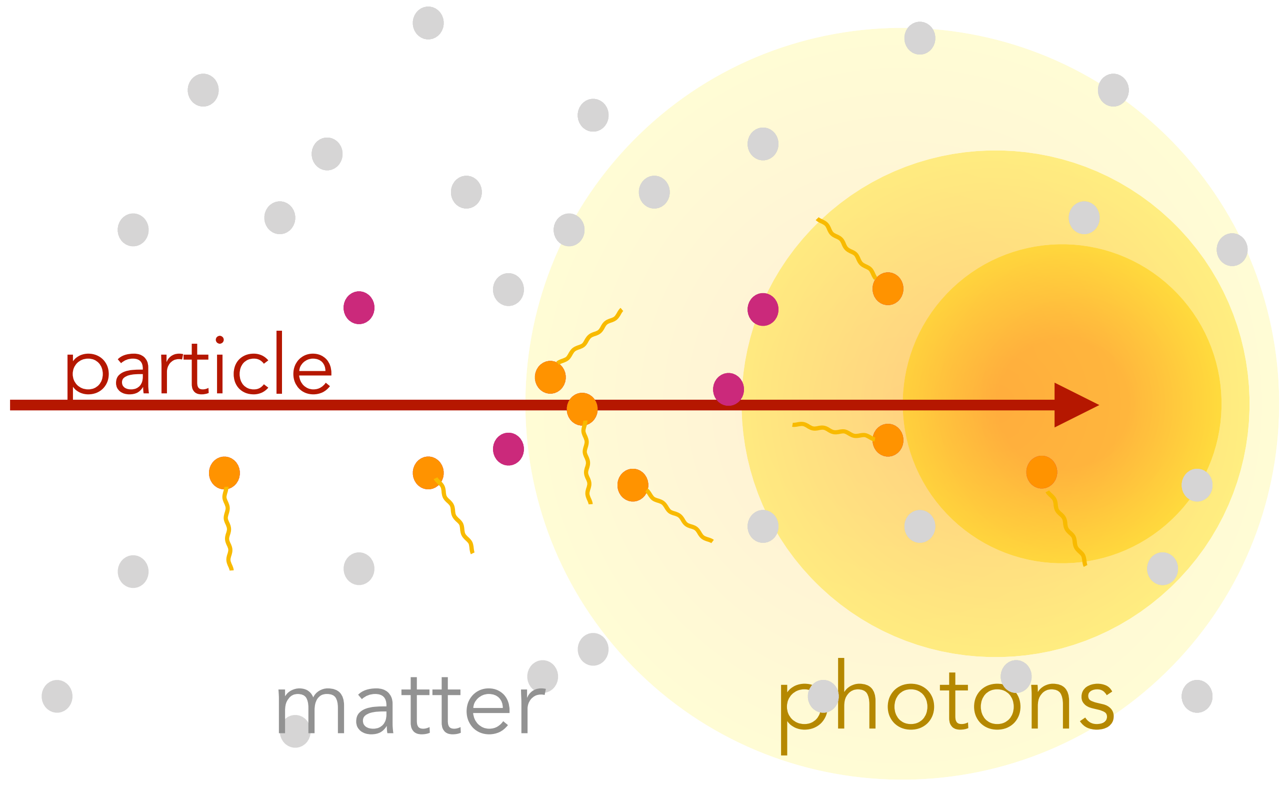
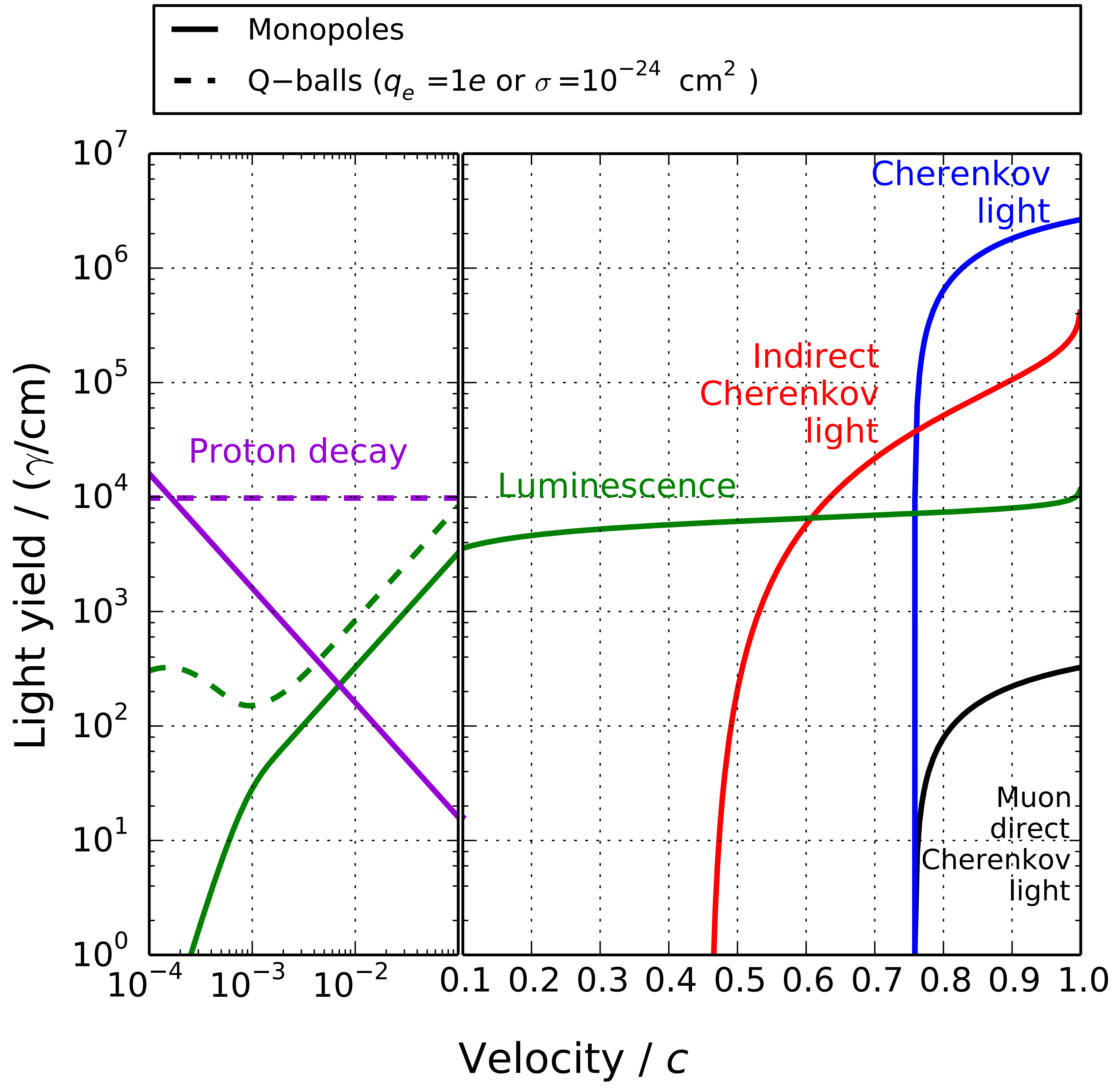
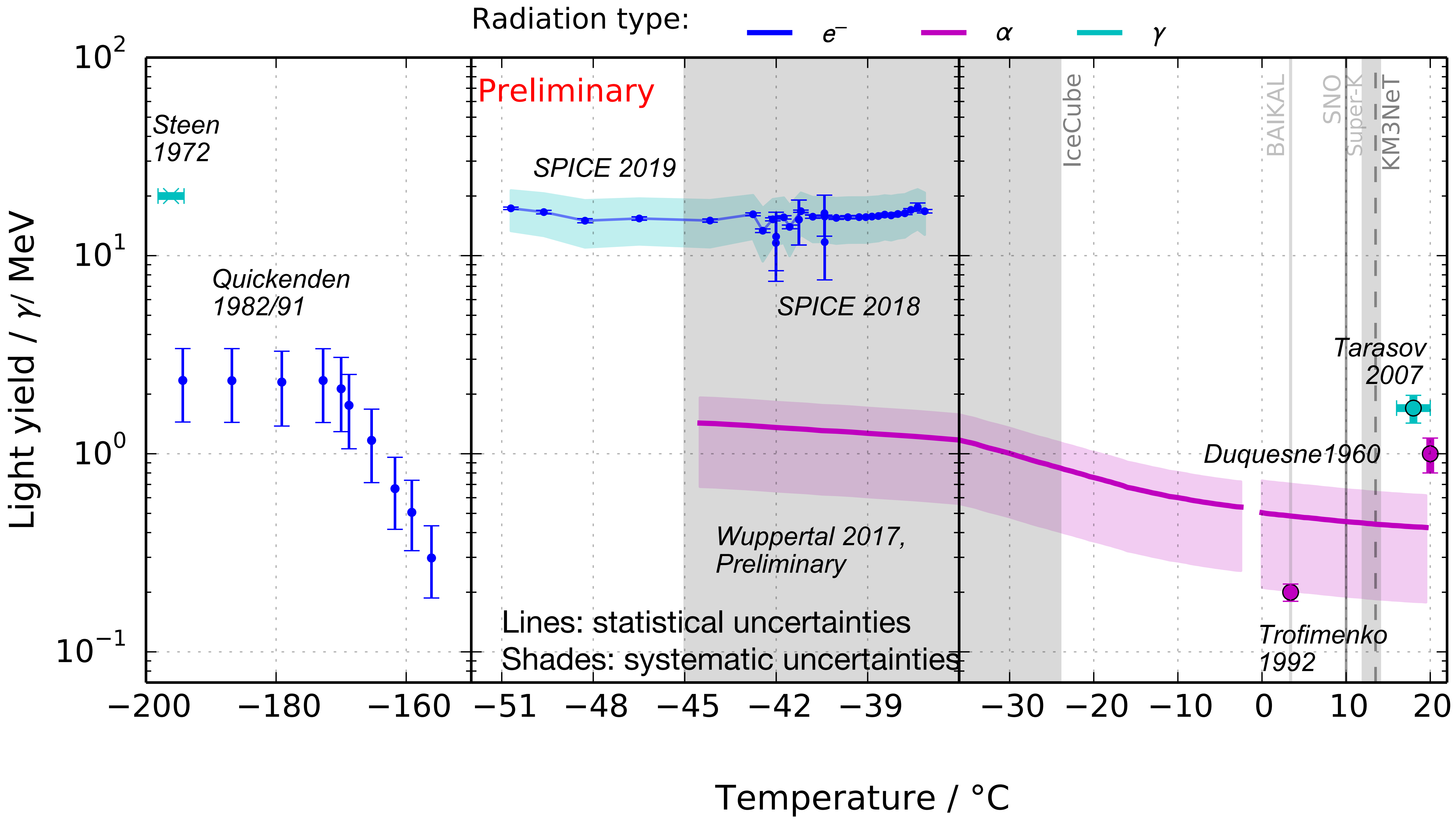


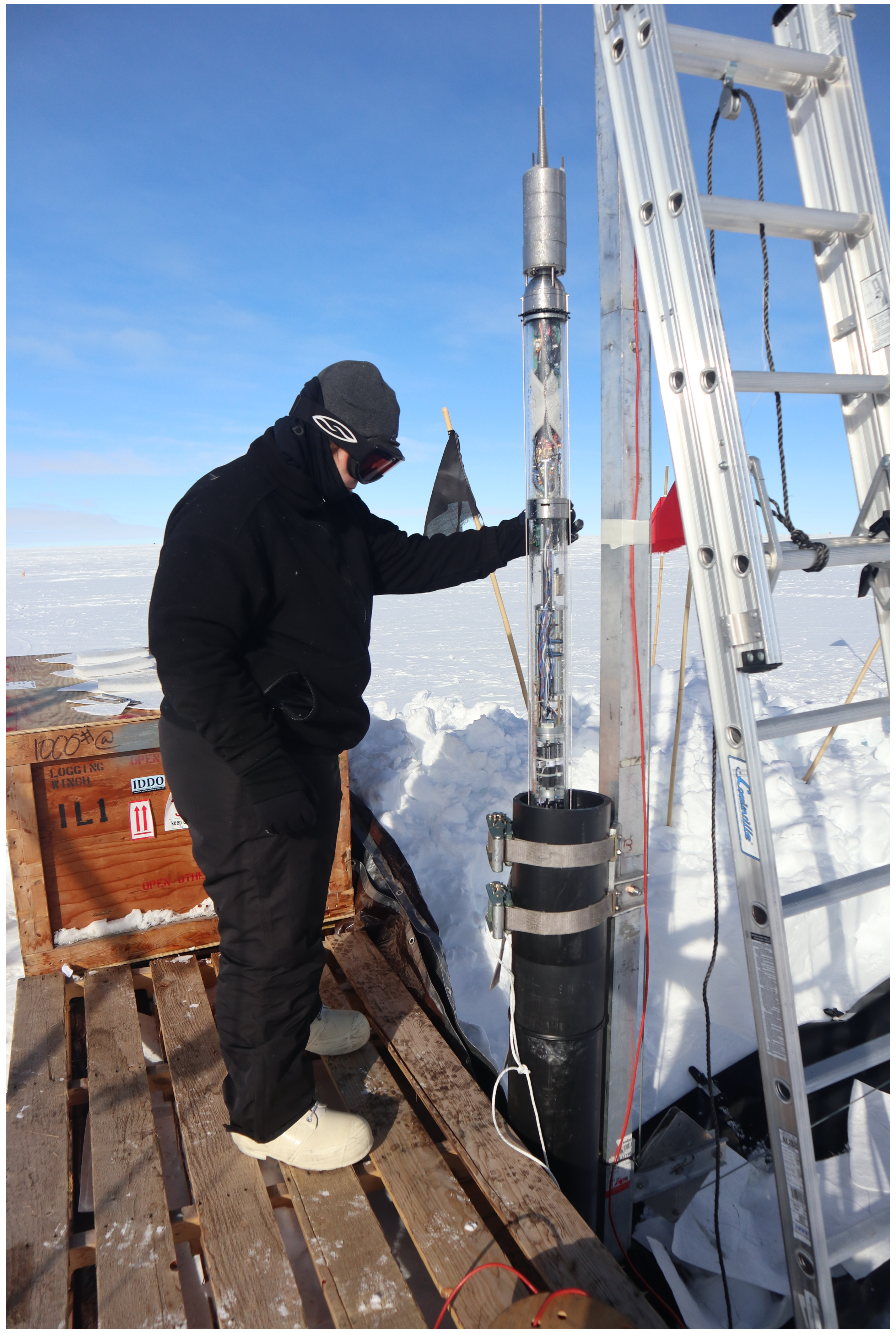


Luminescence of water and ice

- few previous measurements
- conducted laboratory and in-situ measurements
- measured properties are sufficient for use at neutrino telescopes



In Situ measurement @ IceCube 2019



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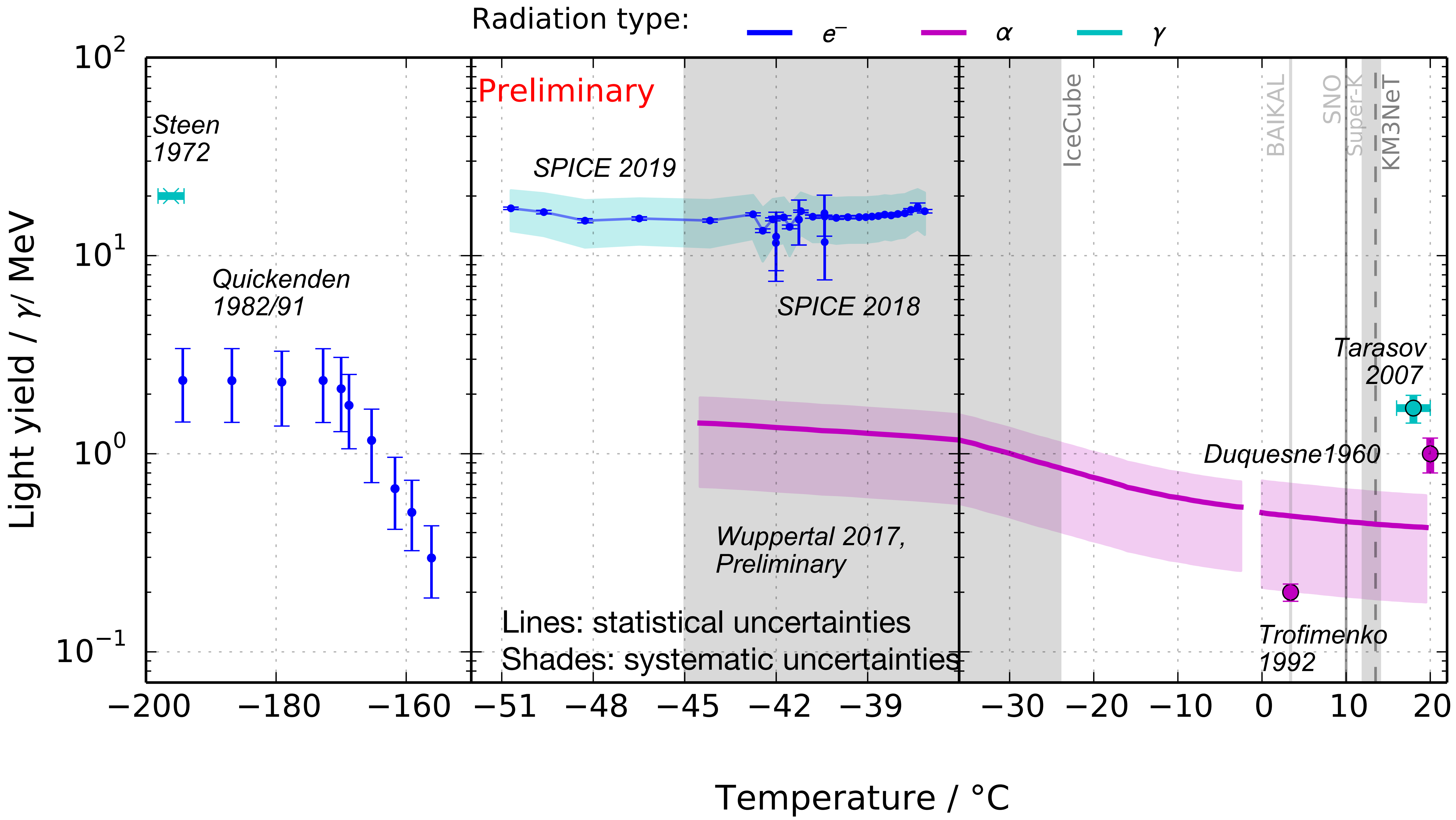
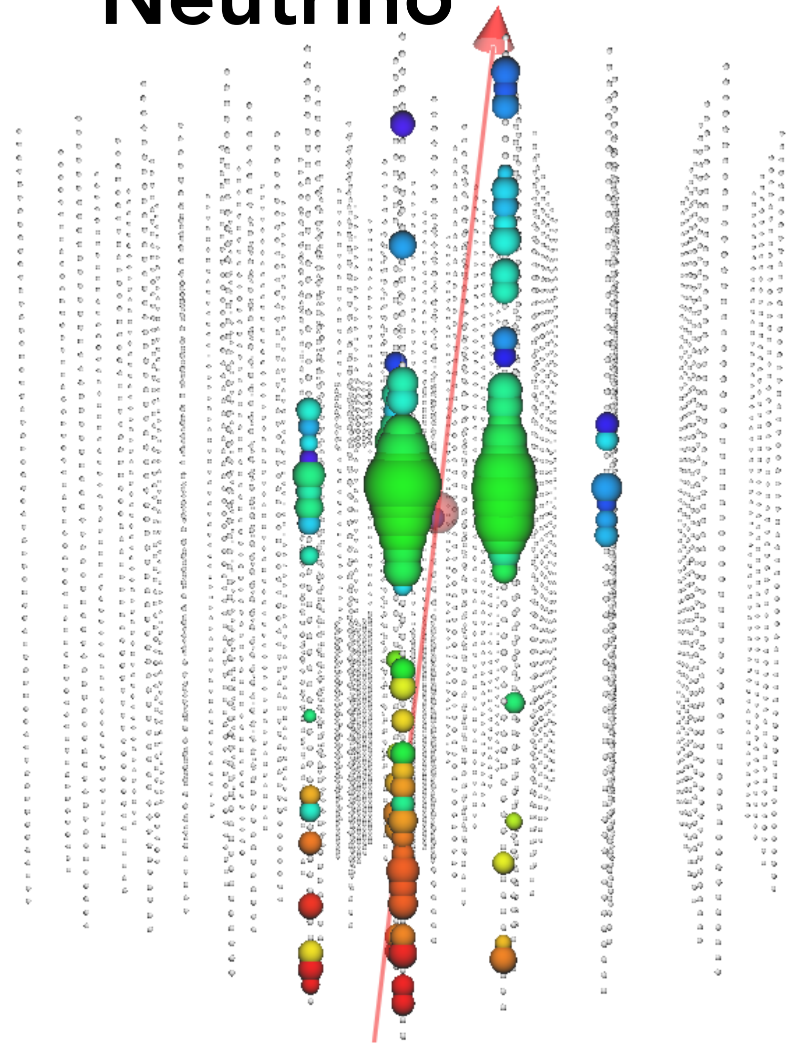
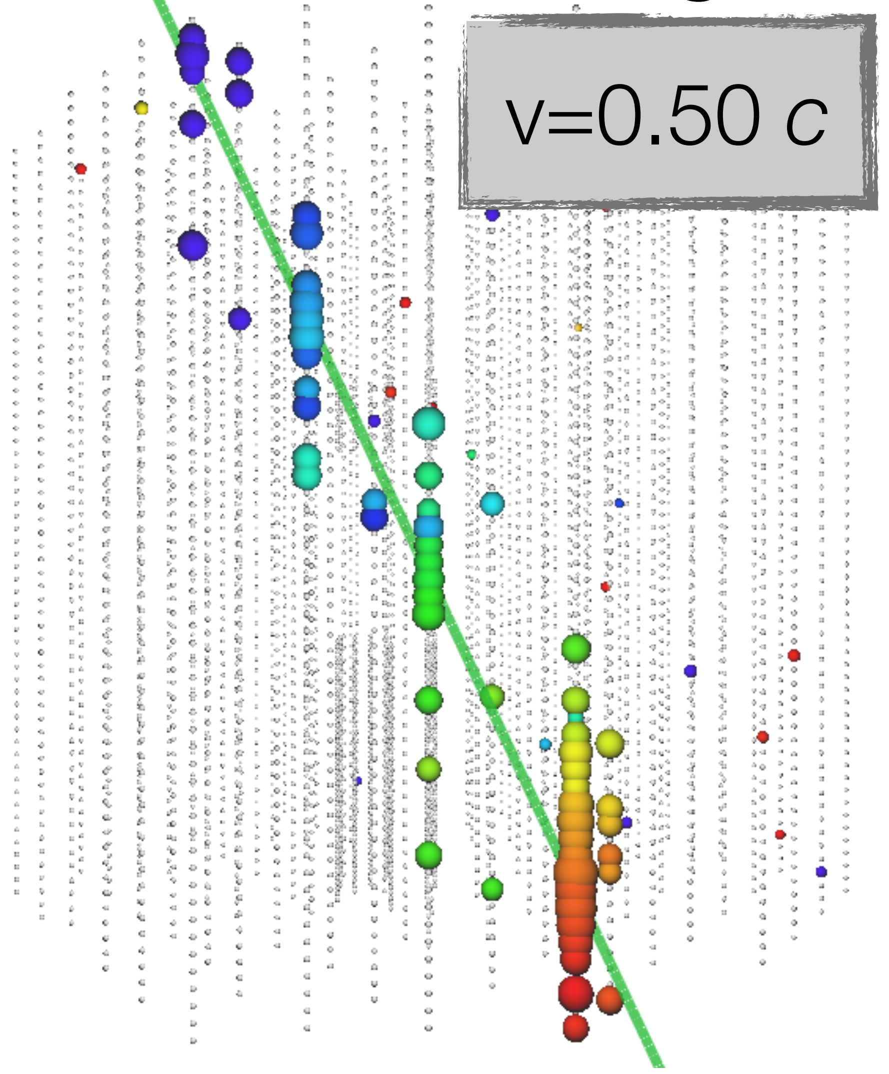


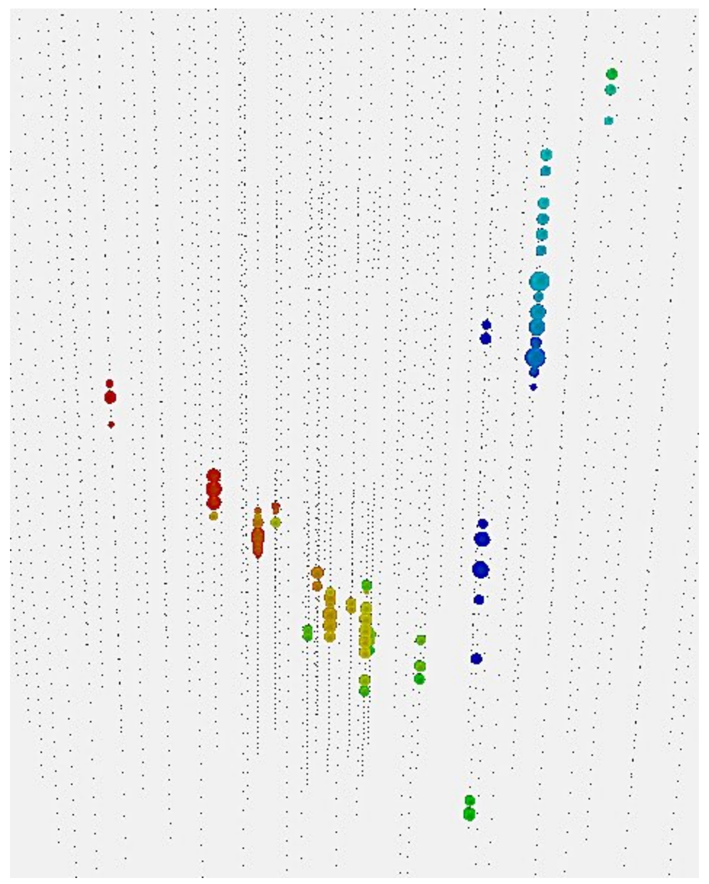
Neutrino



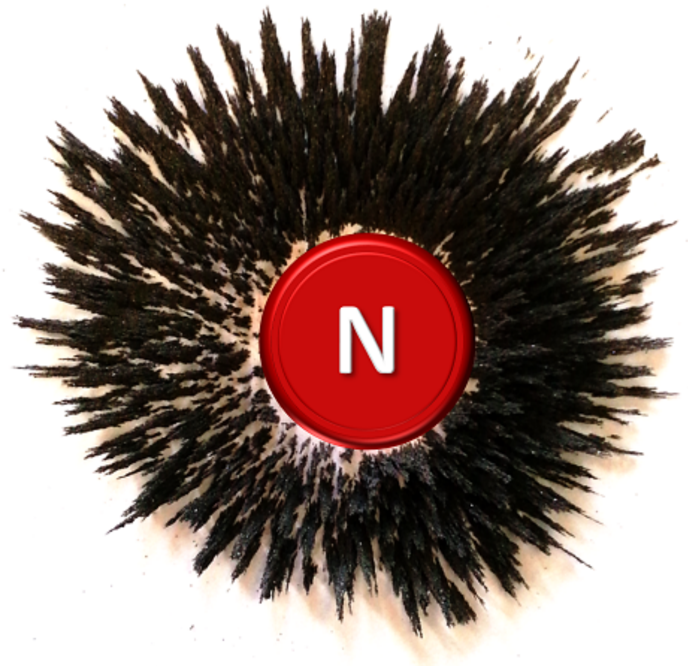
Monopole emitting luminescence light



Coincident Muons



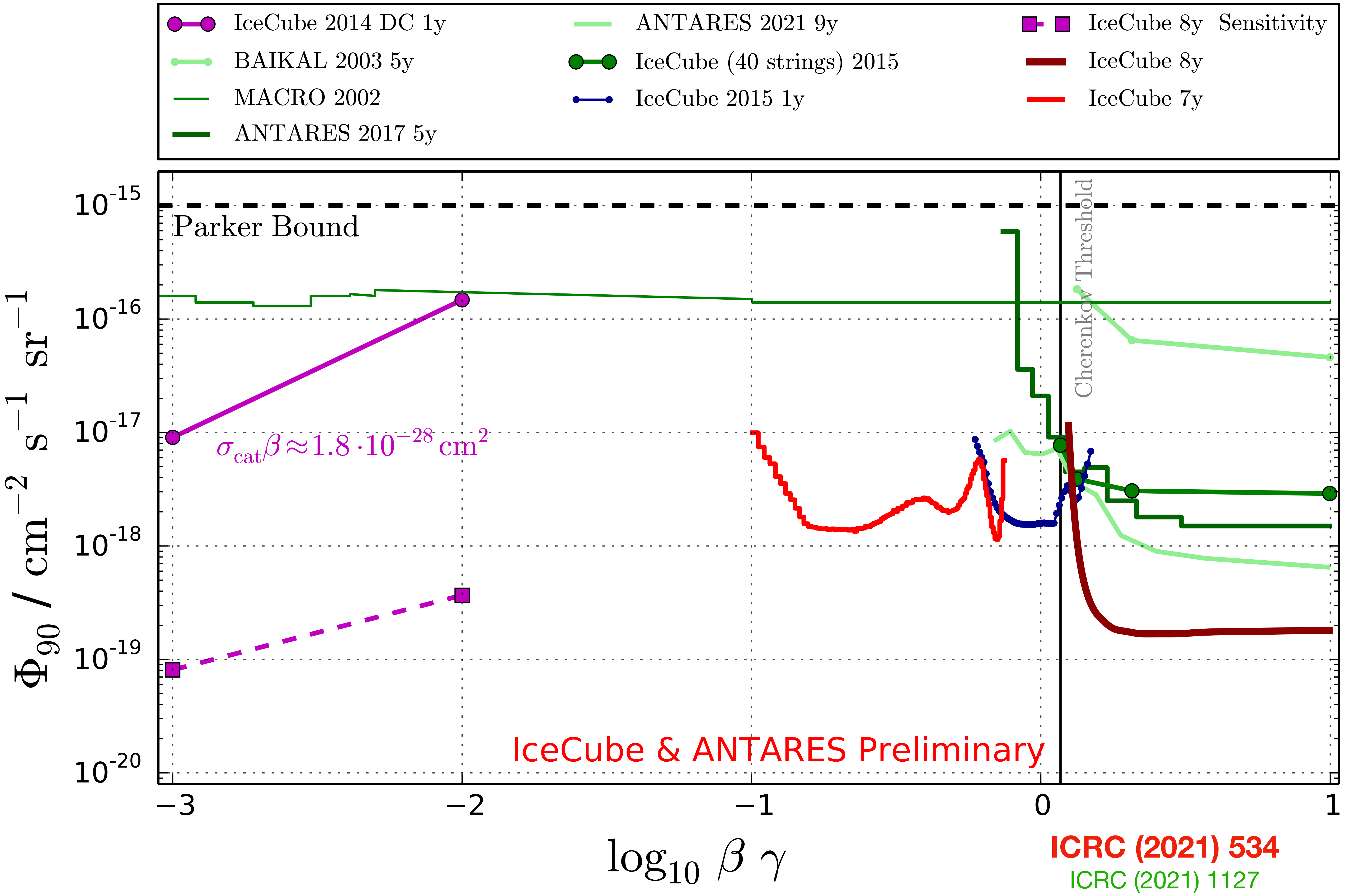
Low relativistic magnetic monopoles



Event signature: similar to atmospheric muon neutrinos or coincident muons from air showers

Analysis:

- work out distinct features of monopoles:
  - tracks
  - homogeneous brightness
  - speed
- model background with ~boot strapping algorithm



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Outlook

- ongoing search for heavy long lived (anomalously) charged particles
- searching for new detection mechanisms or particles
  - Q-balls → luminescence
  - nuclearites → thermal shock wave (experiments needed)
- detector upgrades new detector devices
  - open new parameter spaces, esp. at high energies
  - new detector devices