

# Collider in the Heavens

## *Exploration of Fundamental Physics*



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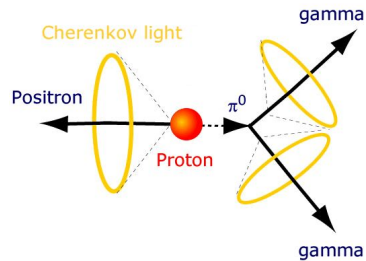
Kavli IPMU, University of Tokyo



# Super-Kamiokande

- 50 kton water Cherenkov multipurpose experiment (Japan), collecting data ~20+ years
- Originally built as most sensitive detector for nucleon decays  
→ unique tests of fundamental theories of unification of forces

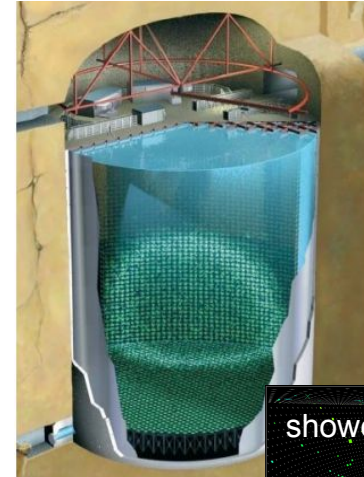
Decay Mode	Lifetime
$p \rightarrow e^+ \nu \nu$	$1.7 \times 10^{32}$ yrs
$p \rightarrow \mu^+ \nu \nu$	$2.2 \times 10^{32}$ yrs
$p \rightarrow e^+ X$	$7.9 \times 10^{32}$ yrs
$p \rightarrow \mu^+ X$	$4.1 \times 10^{32}$ yrs
$n \rightarrow \nu \gamma$	$5.5 \times 10^{32}$ yrs
$np \rightarrow e^+ \nu$	$2.6 \times 10^{32}$ yrs
$np \rightarrow \mu^+ \nu$	$2.0 \times 10^{32}$ yrs
$np \rightarrow \tau^+ \nu$	$3 \times 10^{31}$ yrs



[Takhistov+ (Super-K), *PRL*, 1409.1947]

[Takhistov+ (Super-K), *PRL*, 1508.05530]

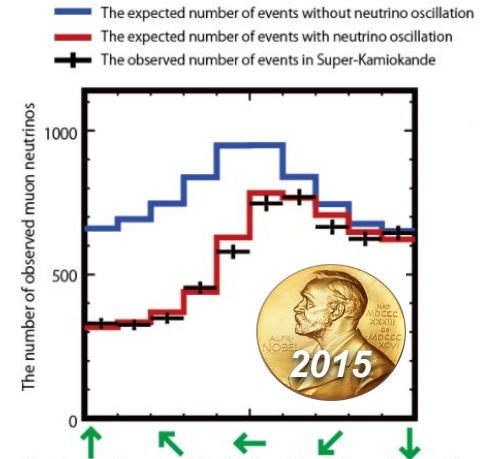
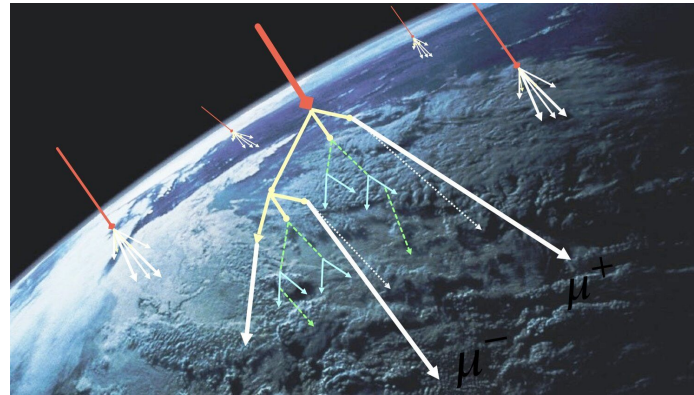
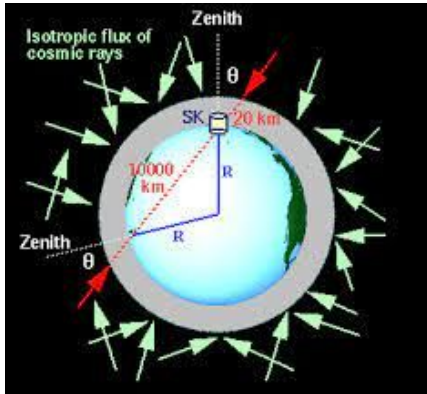
review of all SK searches: [Takhistov, 1605.03235]



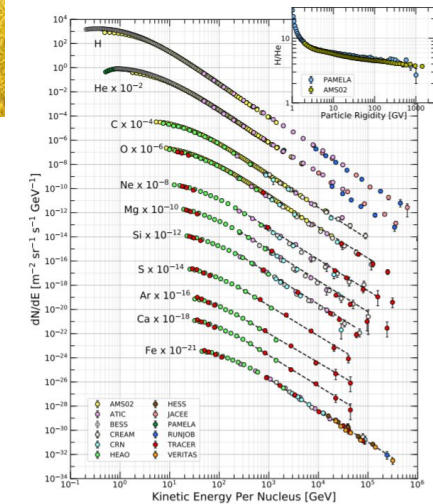
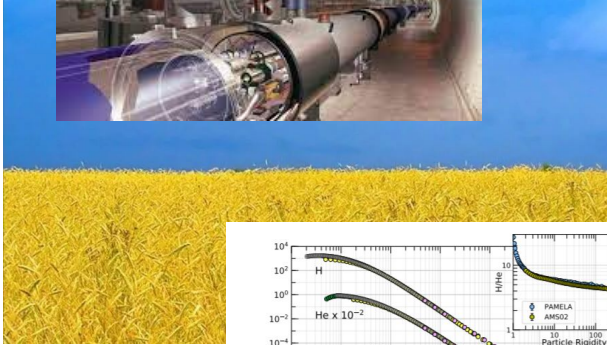
real data  
(1998)

# Atmospheric Neutrinos, briefly

- Cosmic rays isotropically bombarding atmosphere lead to copious production of neutrinos  
→ **discovery of neutrino oscillations** [Fukuda+ (Super-K), *PRL*, 1998]



# Atmospheric Collider



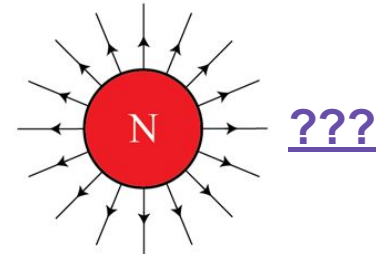
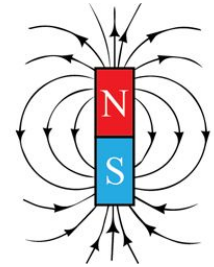
- Unique natural source of  $\sim p$  collisions
- “Beam” is always ON
- Robust flux for ALL terrestrial experiments
- Broad energy spectrum



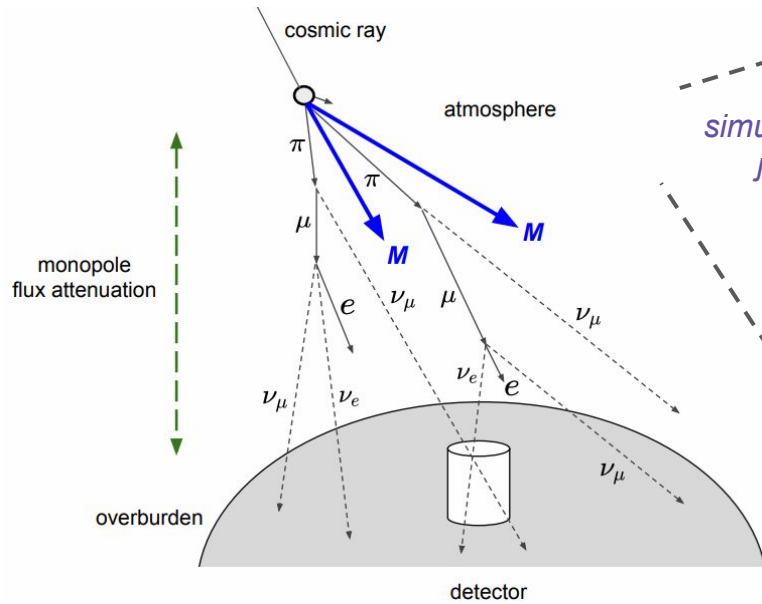
**unprecedented opportunities  
for exploration of new physics**

# Monopoles are *Back in Vogue*

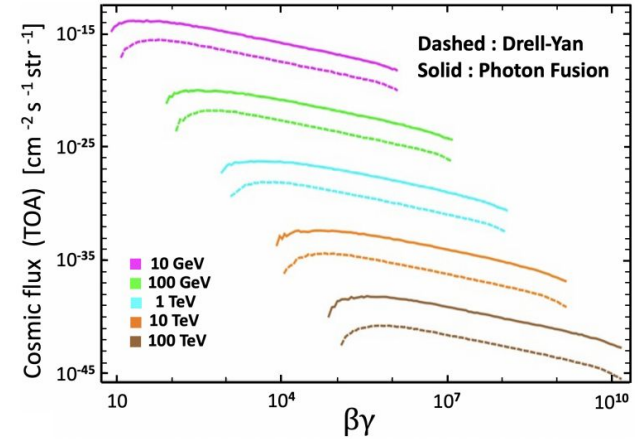
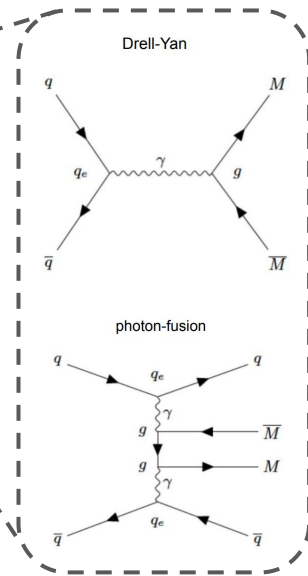
- 125+ years of history [Curie, 1894]
- Symmetrize Maxwell's equations, related to quantization [Dirac, 1931]
- Naturally appear in unification theories [t'Hooft, 1974; Polyakov, 1974]
- Cosmology production highly uncertain → *not predictive*  
[Kibble, 1976; Zurek, 1985]
- Plethora of experimental searches, often look for “ambient” unknown monopole flux
- Reinvigorated recent interest with models (e.g. [Ellis+, 2017]) for EW-scale monopoles  
[Acharya+, *Nature*, 2022; Acharya+ (MoEDAL), *PRL*, 2019; Aad+ (ATLAS), *PRL*, 2020]



# Monopoles from Atmospheric Collider

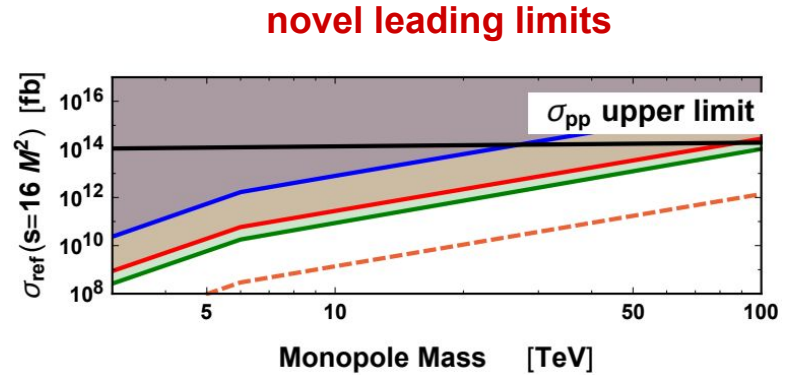
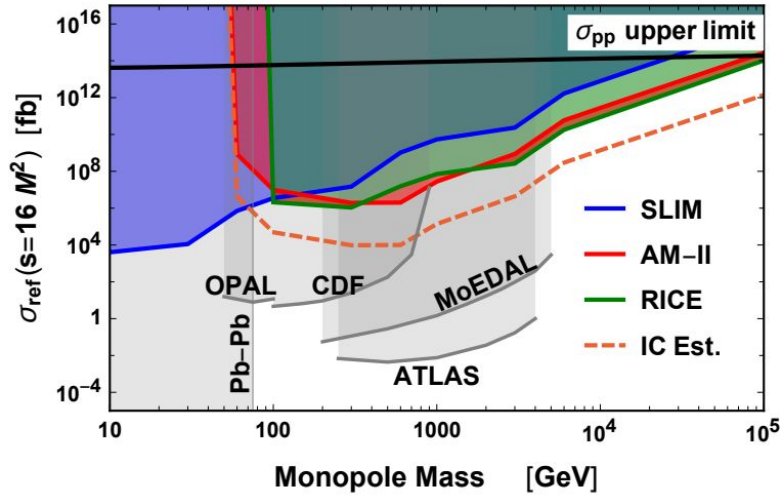


simulations  
just like  
LHC



[Iguro, Plestid, VT, *PRL*, 2111.12091]

# Monopoles from Atmospheric Collider



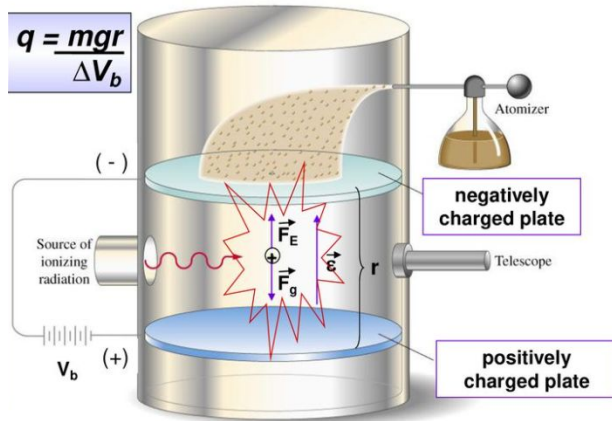
- Atm. collider gives robust universal flux source, sets leading bounds, connects historic studies

**resolve decades-old problem of interpreting ambient monopole searches !**

[Iguro, Plestid, VT, *PRL*, 2111.12091]

# Millicharge Particles

## Millikan oil-drops



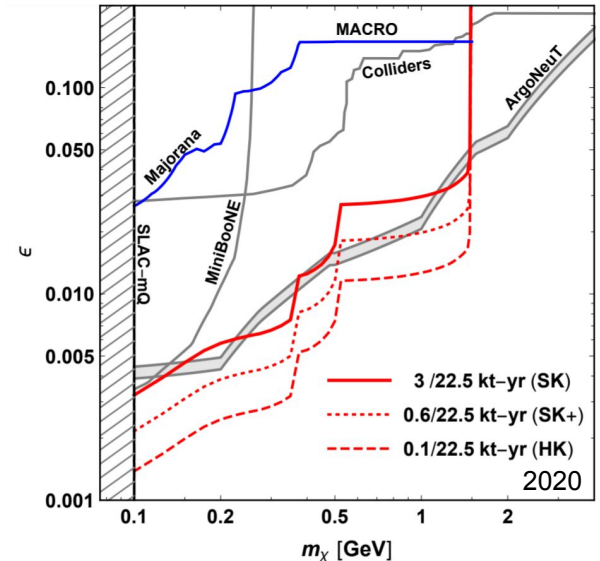
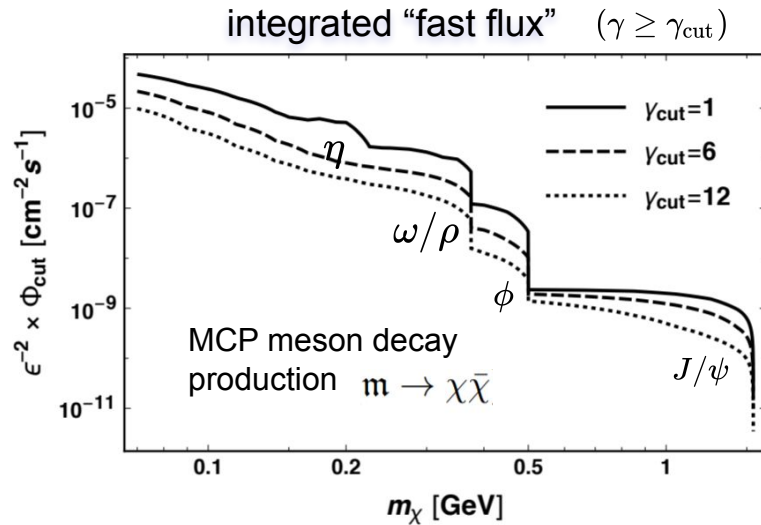
elementary  
charge unit  $e$

## Is charge *actually* quantized? How small?

- In Standard Model anomaly cancellation restricts  
→ but for 3 generations some freedom (e.g. [Foot+, 1992])
- Quantization motivates broader ideas (unification...)
- Quantum gravity link ? [Shiu+, *PRL*, 2013]
- Dark matter / dark sectors
- Connections with astronomy  
(e.g. EDGES anomaly [Barkana, *Nature*, 2018;...])



# Millicharge from Atmospheric Collider



- First quantitative exploration of idea → Super(Hyper)-K sets strong limits

\* *follow-up numerical simulations* [Argüelles, Kelly, Munoz, 2021]

[Pleštid, Takhistov+, *PRD*, 2002.11732]

# Light Dark Matter from Atmospheric Collider

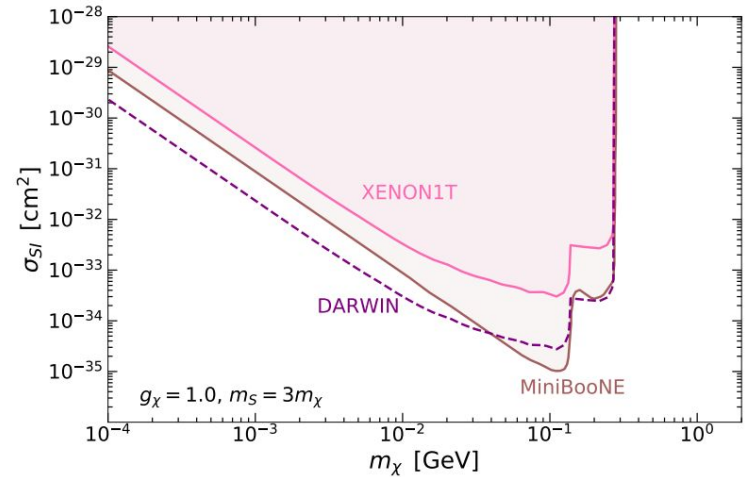
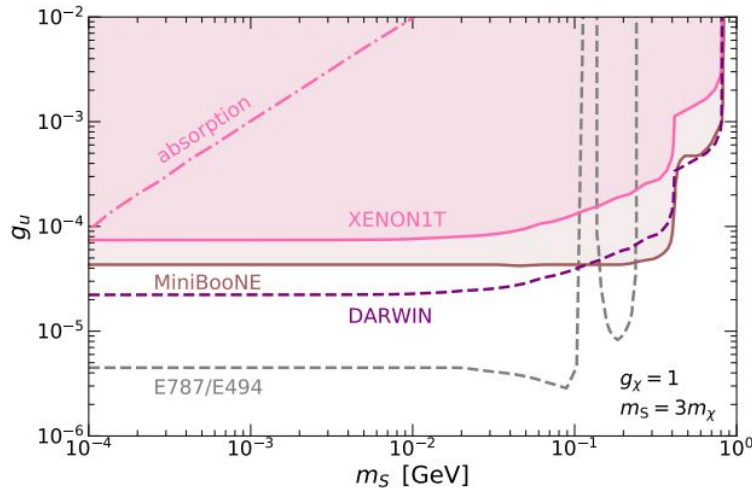
- Light (sub-GeV) DM challenging to search with usual direct detection, reduced recoils
- Atm. collider establishes persistent source of “boosted” DM → probe novel parameter space

$$\begin{aligned} \eta &\rightarrow \pi^0 S \\ \eta' &\rightarrow \pi^0 S \\ K^+ &\rightarrow \pi^+ S \end{aligned}$$



$$S \rightarrow \chi\chi$$

quark coupling



[Arguelles, Munoz, Shoemaker, VT, 2203.12630]

(also [Alvay+, 2020])

# Summary

- Atmospheric collider historically proven to be an invaluable tool to study neutrinos
- Unique source that is always ON, potentially accessible for ALL experiments



***General concept, broad opportunities  
for exploration of new physics ideas !***