

# Fundamental Physics with Atmospheric Collisions

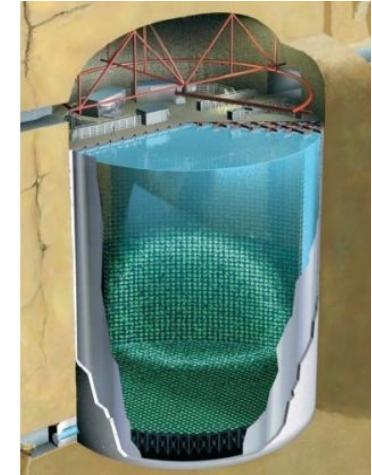
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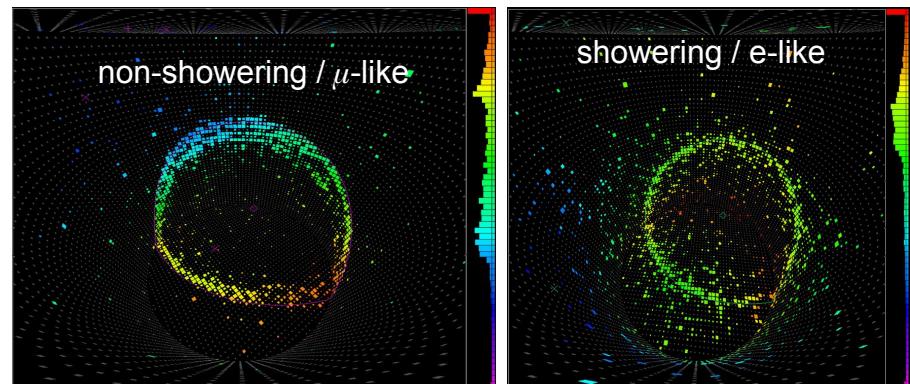
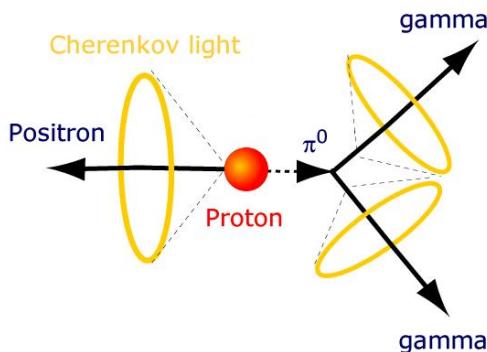


# Super-Kamiokande (SK)

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



*real SK data (1998)*



# Nucleon Decay



some  $> p > p$   $n \rightarrow \tau^+ \bar{\nu}_\tau$

$\tau(p n \rightarrow \tau^+ \bar{\nu}_\tau)$	$\tau(p n \rightarrow \mu^+ \bar{\nu})$	( $10^{30}$ years)	CL%	EVTS	BKGD EST			
		<b>&gt;29</b>		<b>90</b>				
	<i>LIMIT</i>	( $10^{30}$ years)	CL%	EVTS	BKGD EST			
<i>LIMIT</i> ( $10^{30}$ years)	$\tau(p \rightarrow e^+ \nu \nu)$	<b>&gt;200</b>		<b>90</b>				
$> 29$	<i>LIMIT</i>	( $10^{30}$ years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
		<b>&gt;170</b>	<b>p</b>		<b>90</b>		1 TAKHISTOV	14 SKAM
	• • • We do not use the following data for averages, fits, limits, etc. • • •							
<i>LIMIT</i>	( $10^{30}$ years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN	
<b>&gt;220</b>	<b>p</b>		<b>90</b>			1 TAKHISTOV	14 SKAM	

## Baryon Particle Listings

p

$\tau(n \rightarrow \nu\gamma)$					<b>T44</b>	
LIMIT ( $10^{30}$ years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
<b>&gt;550</b>		<b>90</b>			TAKHISTOV	15

$\tau(pn \rightarrow \mu^+ \bar{\nu})$	( $10^{30}$ years)	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
$>29$	<b>90</b>				TAKHISTOV_15	SKA

<u>LIMIT</u> ( $10^{30}$ years)	<u>CL%</u>	<u>EVTS</u>	<u>BKGD EST</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>	
<b>&gt;200</b>	<b>90</b>			TAKHISTOV	15	SKAM	TECN

LIMIT ( $10^{30}$ years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID	TECN
>170	p	90			1 TAKHISTOV	14 SKAM

• • • We do not use the following data for averages, fits, limits, etc. • • •

review of all Super-K searches:

[Takhistov, 1605.03235]

(originally as 51st Moriond Proceedings)

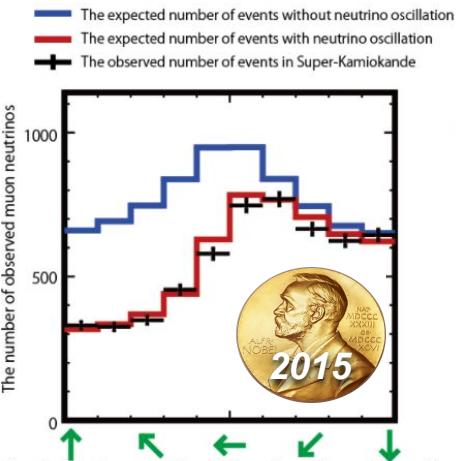
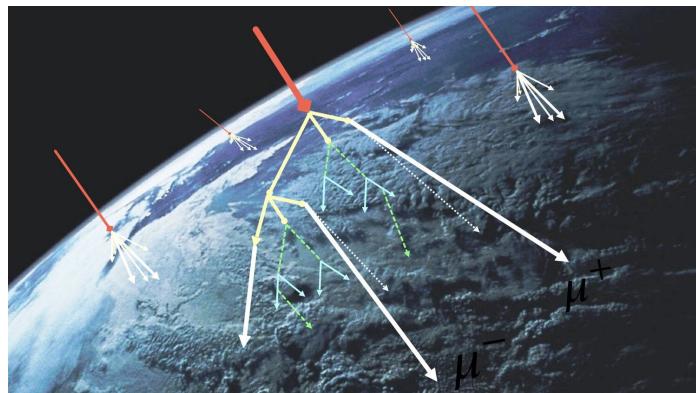
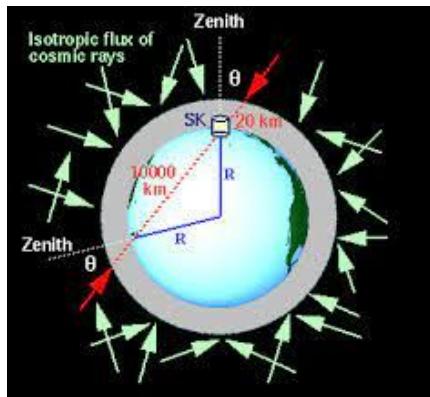
*Remain world best limits  
after almost 10 years !*

[Takhistov+ (Super-K), *Phys.Rev.Lett.*, 1409.1947]

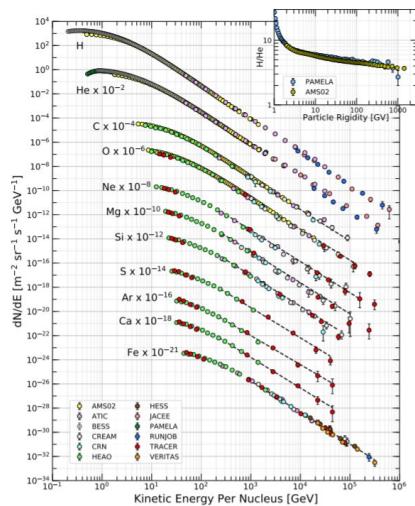
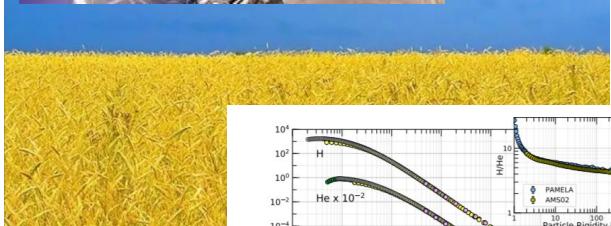
[Takhistov+ (Super-K), *Phys.Rev.Lett.*, 1508.05530]

# Atmospheric Neutrinos, briefly

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



\* With ongoing Gadolinium-doped SuperK-Gd experiment, aim to discover diffuse supernovae neutrino background soon ! (proposal: [Beacom, Vagins, *PRL*, 2003])



# Atmospheric Collider

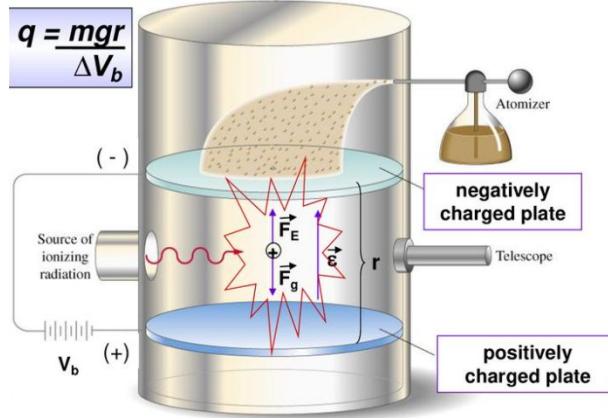
- Unique natural source of  $\sim p$  collisions
- “Beam” is always ON
- Robust flux for ALL terrestrial experiments
- Broad energy spectrum



unprecedented opportunities  
for exploration of  
fundamental physics

# Millicharge Particles

## Millikan oil-drops

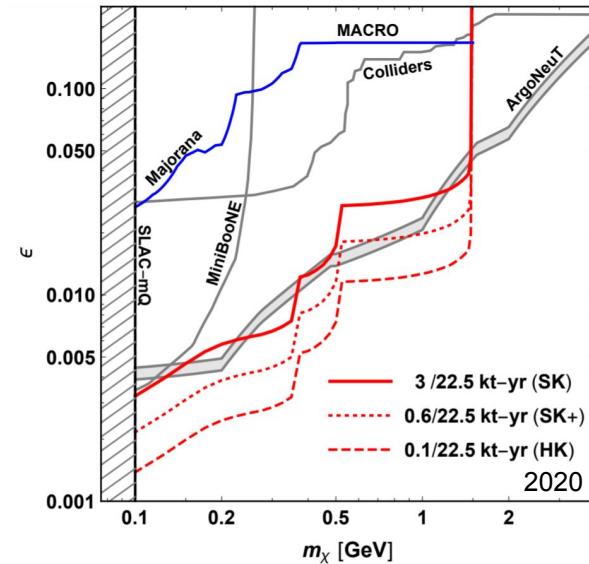
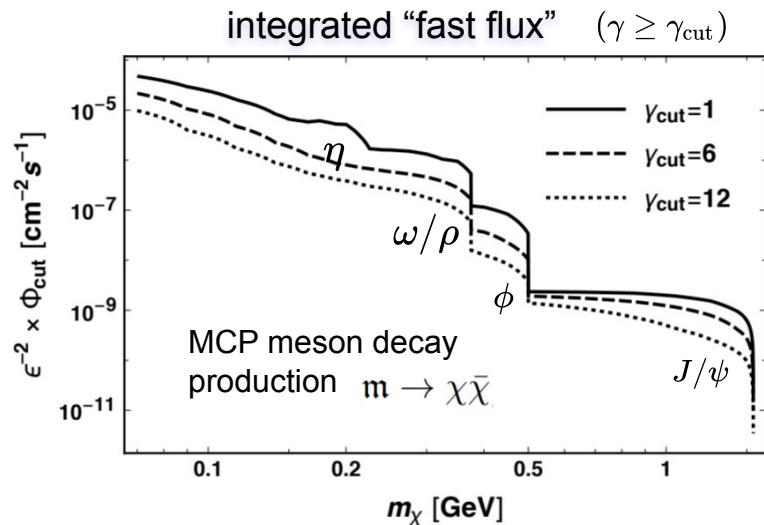


elementary  
charge unit  $e$

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

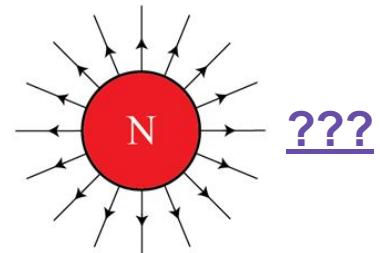
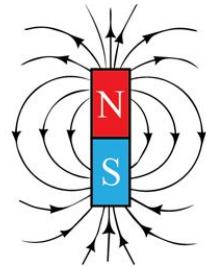


- First quantitative exploration of idea → Super(Hyper)-K probes broad parameter space
  - \* subsequent studies with numerical simulations [Argüelles, Kelly, Munoz, 2021]
  - \* further refinements suggested [Du+, 2022]

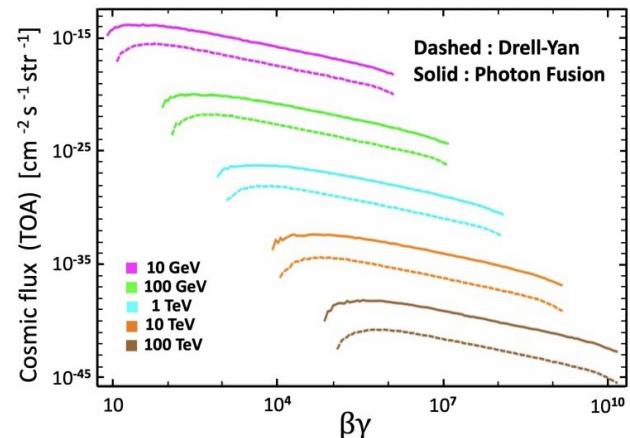
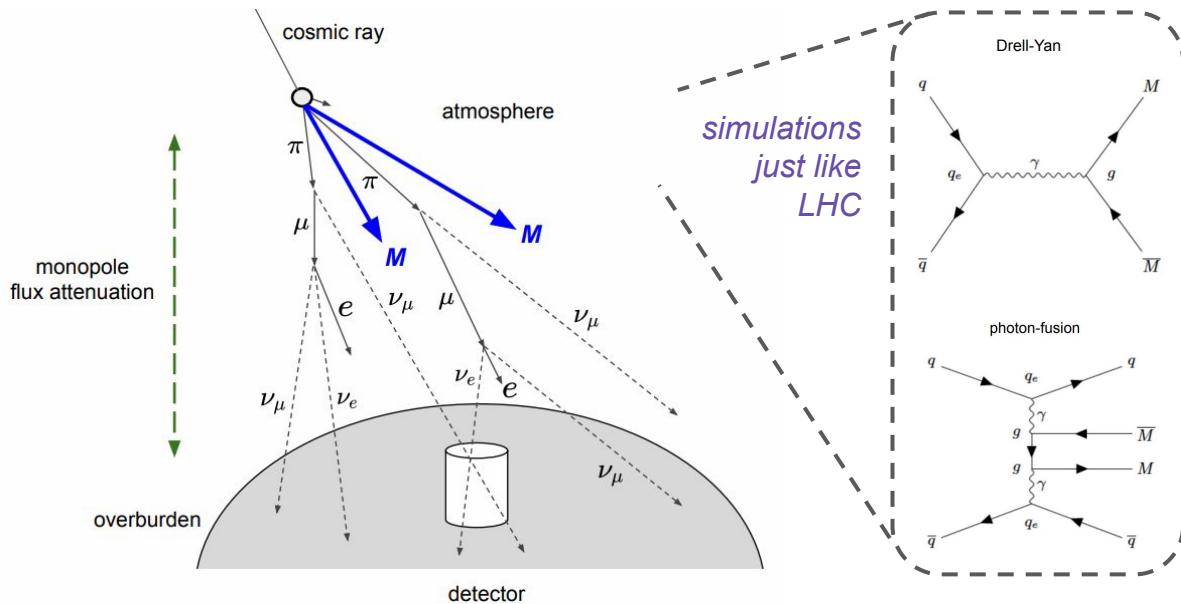
[Plestid, **Takhistov**, Tsai, Bringmann, Kusenko, Pospelov, *Phys. Rev. D*, 2002.11732]

# 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 really 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]

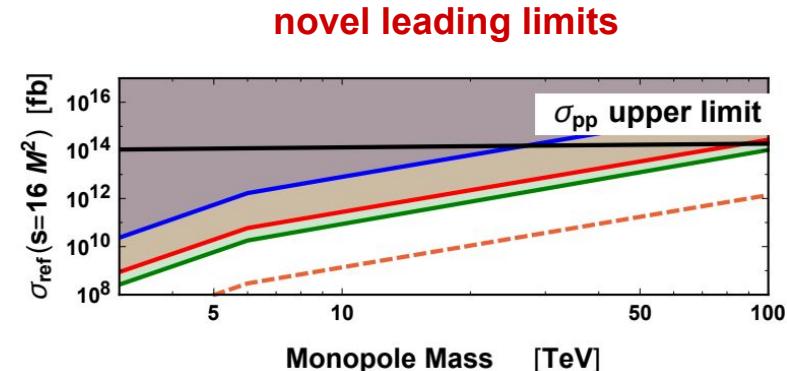
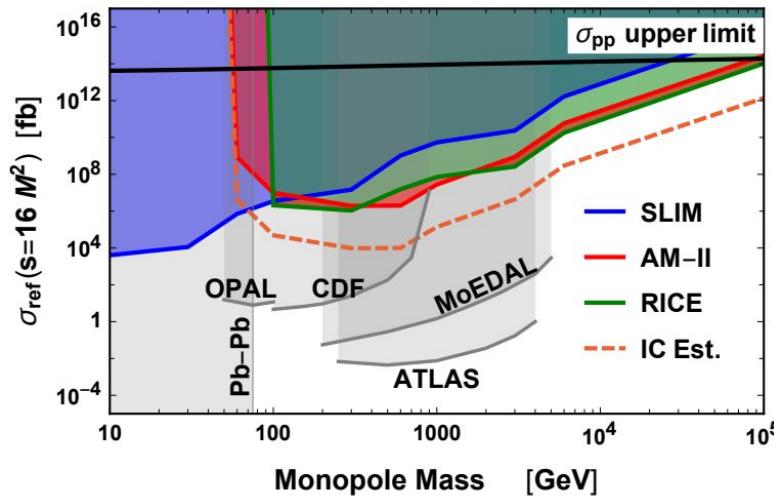


# Monopoles from Atmospheric Collider



[Iguro, Plestid, Takhistov, *Phys.Rev.Lett.*, 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, **Takhistov**, *Phys.Rev.Lett.*, 2111.12091]

.... *monopoles, asteroids,  
stay tuned !*

# Light Dark Matter from Atmospheric Collider

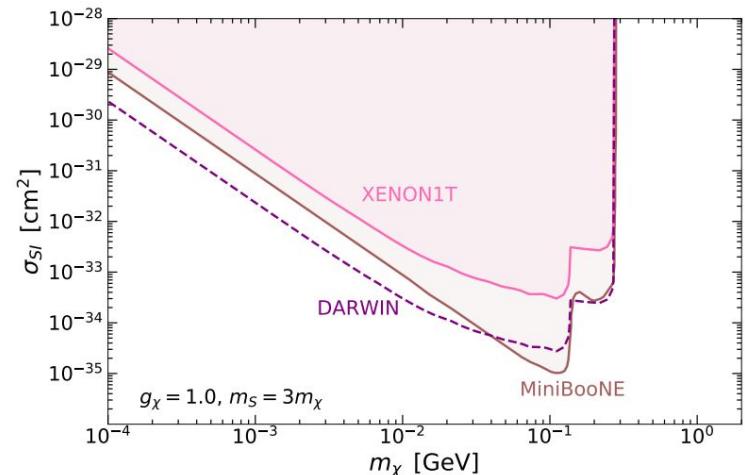
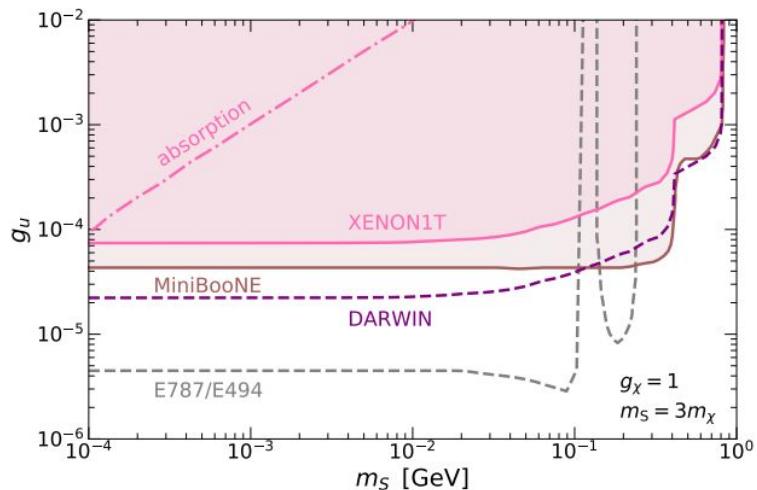
- Light (sub-GeV) DM challenging to search with usual direct detection, reduced recoils
- Atm. collider establishes persistent source of “boosted” DM → probe novel parameter space

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

↓

$$S \rightarrow \chi\chi$$

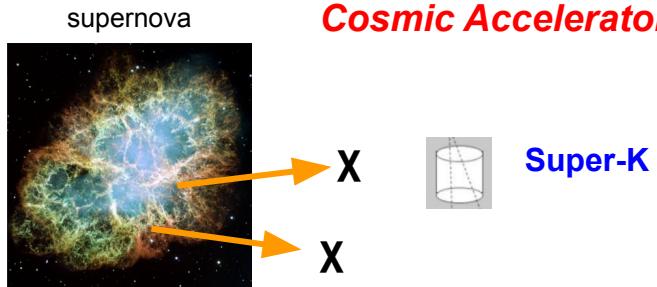
quark coupling



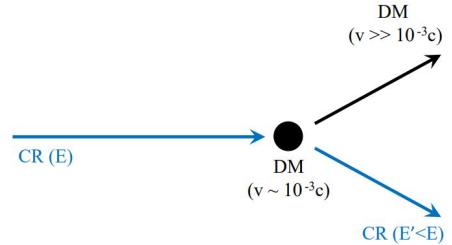
[Arguelles, Munoz, Shoemaker, Takhistov, *Phys.Lett. B*, 2203.12630]

(also [Alvay+, 2020])

# “Boosted” Dark Matter in Context, many neutrino experiment opportunities like...

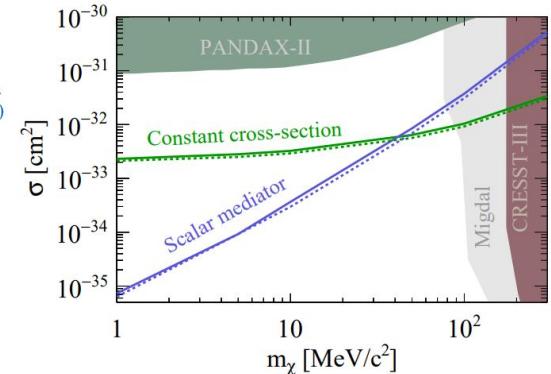


[Hu, Kusenko, Takhistov, *Phys.Lett.B*, 1611.04599]  
(also [Dunsky+, 2019; Li, Lin, 2019])



[Cappiello, Beacom, 2019;  
Bringmann, Pospelov, 2019;  
Ema+, 2019]

## Cosmic-ray Upscattering



[Abe+ (Super-K), *Phys.Rev.Lett.*, 2023]

With atmospheric collider, can explore an even broader BSM program...

e.g. heavy neutral leptons [Coloma, Hernandez, Munoz, Shoemaker, 2019]

# Summary

- Atmospheric collider (fixed target experiment in the sky) historically proven to be an invaluable tool for studying neutrinos
- Unique source that is always ON, potentially accessible for ALL experiments



*Natural laboratory in the sky with rich opportunities for exploration of new physics ideas !*