Dark Cosmic Rays

Volodymyr Takhistov (UCLA)

SoCal BSM-2017 @ UC Riverside

Based on: Hu, Kusenko, VT. *Phys. Lett.* B (2017)
[arXiv:1611.04599]

Introduction

- Dark matter (DM) nature unknown beyond gravitational interactions
- Many DM candidates employ non-gravitational interactions for early universe production … plausible for DM to carry electric charge

Introduction

- Dark matter (DM) nature unknown beyond gravitational interactions

- Many DM candidates employ non-gravitational interactions for early universe production … plausible for DM to carry electric charge

- charged DM accelerated by supernovae remnants … or in other astrophysical accelerators [Chuzhoy,Kolb,08; Dimopoulos+,90]

Dark Cosmic Rays

Charged DM

Popular concrete realization: millicharged DM (mDM) [*long list*]

- extra gauge $\mathrm{U}(1)_X$ with charged fermions (DM)

[Holdom,86]

- kinetic mixing of $\mathrm{U}(1)_Y, \mathrm{U}(1)_X$ via $\tilde{\varepsilon} F'_{\mu\nu} F^{\mu\nu}$ $\rightarrow$ DM fermions get charge $\varepsilon\, e$

Charged DM

Popular concrete realization: millicharged DM (mDM) [*long list*]

- extra gauge $\mathrm{U}(1)_X$ with charged fermions (DM)

[Holdom,86]

- kinetic mixing of $\mathrm{U}(1)_Y, \mathrm{U}(1)_X$ via $\tilde{\varepsilon} F'_{\mu\nu} F^{\mu\nu}$ $\rightarrow$ DM fermions get charge $\varepsilon\, e$
- mediated by "dark photon"

[Shiu,Soler,Ye,13]

- *massive* : very constrained already, disfavored by general formal arguments
- *massless* : open parameter space

Opportunity!

Charged DM

Popular concrete realization: millicharged DM (mDM) [*long list*]

- extra gauge $\mathrm{U}(1)_X$ with charged fermions (DM)

[Holdom,86]

- kinetic mixing of $\mathrm{U}(1)_Y, \mathrm{U}(1)_X$ via $\tilde{\varepsilon} F'_{\mu\nu} F^{\mu\nu}$ $\rightarrow$ DM fermions get charge $\varepsilon\, e$
- mediated by "dark photon"

[Shiu,Soler,Ye,13]

- *massive* : very constrained already, disfavored by general formal arguments
- *massless* : open parameter space

- DM fermions reside in bound states ("dark atoms") or free ions [Cline,Liu,Xue,12]

Charged DM

Popular concrete realization: millicharged DM (mDM) [*long list*]

- extra gauge $\mathrm{U}(1)_X$ with charged fermions (DM)

[Holdom,86]

- kinetic mixing of $\mathrm{U}(1)_Y, \mathrm{U}(1)_X$ via $\tilde{\varepsilon} F'_{\mu\nu} F^{\mu\nu}$ $\rightarrow$ DM fermions get charge $\varepsilon\, e$
- mediated by "dark photon"

[Shiu,Soler,Ye,13]

  - *massive* : very constrained already, disfavored by general formal arguments
  - *massless* : open parameter space

- DM fermions reside in bound states ("dark atoms") or free ions [Cline,Liu,Xue,12]

[Cyr-Racine,Sigurdson,13; others] [Foot,14]

- ionization possibilities: primordial DM ions, starlight, past SN explosions, high redshift re-ionization sources (e.g. Pop. III stars, quasars) …

Overview

Goal: study dark cosmic rays (DCR) in general, don't commit to a model

Overview

Goal: study dark cosmic rays (DCR) in general, don't commit to a model

- Fermi acceleration
- Framework for analyzing dark cosmic rays

  a) robust spectrum prediction

  b) propagation in medium/energy loss

- Detection and signatures

→ novel search proposals for Super-Kamiokande !

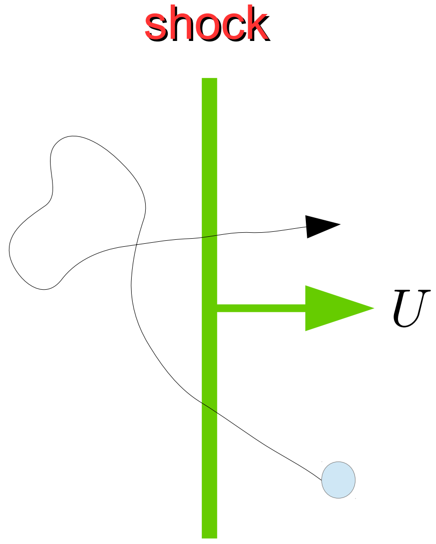
1^{st} Order Fermi (Diffusive-Shock) Acceleration

- Cosmic accelerators: supernovae, AGNs, GRBs, stellar winds, etc.

1^{st} Order Fermi (Diffusive-Shock) Acceleration

- Cosmic accelerators: supernovae, AGNs, GRBs, stellar winds, etc.

- Basic idea: gain energy from successive shock re-scattering



[Blandford, Ostriker,78]

$$\frac{\Delta E}{E} \sim U$$

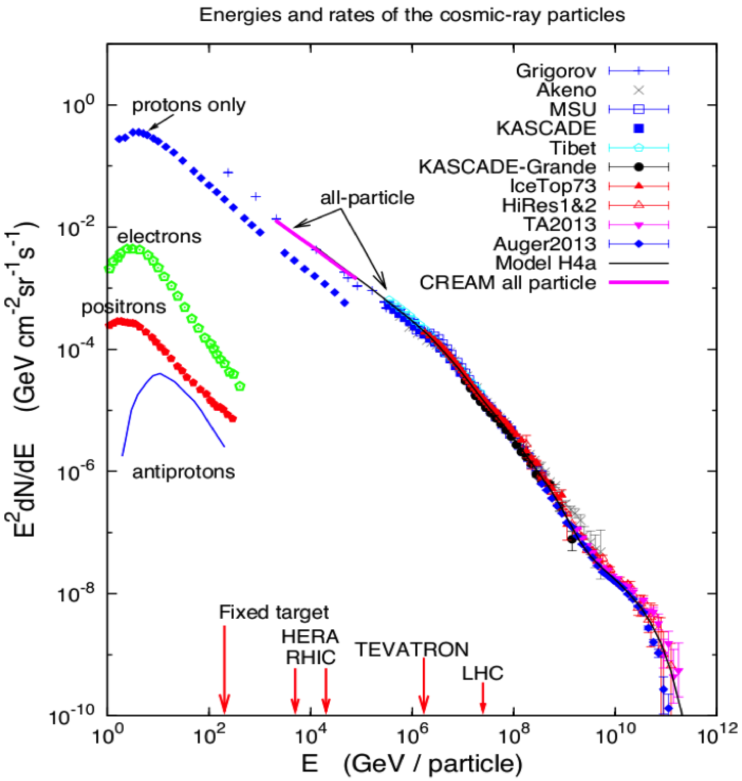
** complete details of mechanism very complicated (non-linear shock theory, etc.)*

1^{st} Order Fermi (Diffusive-Shock) Acceleration

- Cosmic accelerators: supernovae, AGNs, GRBs, stellar winds, etc.
- Basic idea: gain energy from successive shock re-scattering
- Predictions:

  → observed cosmic ray spectrum $\frac{dN}{dE} \sim E^{-\alpha}$

from IceCube

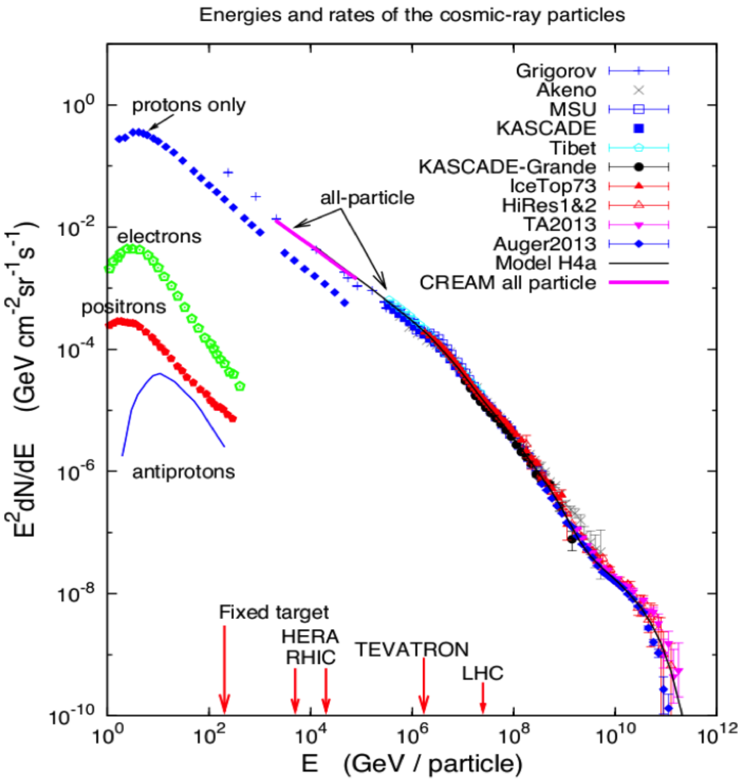


1^{st} Order Fermi (Diffusive-Shock) Acceleration

- Cosmic accelerators: supernovae, AGNs, GRBs, stellar winds, etc.
- Basic idea: gain energy from successive shock re-scattering
- Predictions:

→ observed cosmic ray spectrum $\frac{dN}{dE} \sim E^{-\alpha}$

from IceCube



observed CR (protons): $\alpha \approx 2.7$

→ 2 (Fermi) + 0.7 (diffusion)

1^{st} Order Fermi (Diffusive-Shock) Acceleration

- Cosmic accelerators: supernovae, AGNs, GRBs, stellar winds, etc.

- Basic idea: gain energy from successive shock re-scattering

- Predictions:

→ observed cosmic ray spectrum $$\frac{dN}{dE} \sim E^{-\alpha}$$

→ maximum energy (Hillas criterion) $E_{max} \sim eBUL$

[Hillas,84]

1^{st} Order Fermi (Diffusive-Shock) Acceleration

- Cosmic accelerators: supernovae, AGNs, GRBs, stellar winds, etc.
- Basic idea: gain energy from successive shock re-scattering
- Predictions:

for SN: $B \sim 0.5 \text{ mG}$
$U \sim 0.1$
$L \sim 0.3 \text{ pc}$

$\rightarrow$ observed cosmic ray spectrum $\dfrac{dN}{dE} \sim E^{-\alpha}$

$\rightarrow \quad E_{max} \sim 10^6 \text{ GeV}$

$\rightarrow$ maximum energy (Hillas criterion) $E_{max} \sim eBUL$

[Hillas,84]

DCR Flux

- How to predict flux for DCR?

  → use results from CR flux ion/charged dust contamination

[Malkov,98; Malkov,Diamond, Sagdeev,12]

DCR Flux

- How to predict flux for DCR?

  $\rightarrow$ use results from CR flux ion/charged dust contamination

[Malkov,98; Malkov,Diamond, Sagdeev,12]

- Acceleration actually depends on rigidity $R = p/Q$, not energy

  $\rightarrow$ at same rigidity DCR spectrum follows protons, differ by shock injection $\dfrac{e^{\mathrm{X}}_{\mathrm{inj}}}{e^{p}_{\mathrm{inj}}}$

DCR Flux

- How to predict flux for DCR?

  $\rightarrow$ use results from CR flux ion/charged dust contamination

[Malkov,98; Malkov,Diamond, Sagdeev,12]

- Acceleration actually depends on rigidity $R = p/Q$, not energy

  $\rightarrow$ at same rigidity DCR spectrum follows protons, differ by shock injection $\frac{e^{X}_{\rm inj}}{e^{p}_{\rm inj}}$

- DCR spectrum:

$$\frac{dN_X}{dE} \simeq \frac{(\rho_X/m_X)}{(\rho_p/m_p)} \frac{e^{X}_{\rm inj}}{e^{p}_{\rm inj}} \varepsilon^{(\alpha-1)} \frac{dN_p}{dE}$$

$$= 30\varepsilon^{(\alpha-1)} \left(\frac{\rm GeV}{m_X}\right)\left(\frac{E}{\rm GeV}\right)^{-\alpha} / ({\rm GeV cm^2 \; s \; sr})$$

DCR Flux

- How to predict flux for DCR?

  → use results from CR flux ion/charged dust contamination

[Malkov,98; Malkov,Diamond, Sagdeev,12]

- Acceleration actually depends on rigidity $R = p/Q$, not energy

  → at same rigidity DCR spectrum follows protons, differ by shock injection $\dfrac{e^{\rm X}_{\rm inj}}{e^{p}_{\rm inj}}$

- DCR spectrum:

$$\frac{dN_{\rm X}}{dE} \simeq \frac{(\rho_{\rm X}/m_{\rm X})}{(\rho_p/m_p)} \frac{e^{\rm X}_{\rm inj}}{e^{p}_{\rm inj}} \varepsilon^{(\alpha-1)} \frac{dN_p}{dE}$$

$$= 30\varepsilon^{(\alpha-1)} \left(\frac{\rm GeV}{m_{\rm X}}\right) \left(\frac{E}{\rm GeV}\right)^{-\alpha} / ({\rm GeV cm^2\ s\ sr})$$

experiment: ~2.7

analytic model: ~4

… for DM take NFW profile @ 1 kpc from GC, which has highest SN rate

DCR Flux

- How to predict flux for DCR?

  $\rightarrow$ use results from CR flux ion/charged dust contamination

[Malkov,98; Malkov,Diamond, Sagdeev,12]

- Acceleration actually depends on rigidity $R = p/Q$, not energy

  $\rightarrow$ at same rigidity DCR spectrum follows protons, differ by shock injection $\frac{e^{\mathrm{X}}_{\mathrm{inj}}}{e^{p}_{\mathrm{inj}}}$

- DCR spectrum:
$$\frac{dN_{\mathrm{X}}}{dE} \simeq 30\varepsilon^{1.7}\left(\frac{\mathrm{GeV}}{m_{\mathrm{X}}}\right)\left(\frac{E}{\mathrm{GeV}}\right)^{-2.7}/(\mathrm{GeV cm^2\ s\ sr})$$

- Maximum energy:
$$E_{max} \sim \varepsilon e B U L$$

- Anisotropy: when gyroradius ≥ 0.3 kpc Galactic disk height

  $\rightarrow$ pointing to GC, expect at $E \sim \varepsilon \cdot 10^{18}\ \mathrm{eV}$

Detection

- Depending on charge, DCR show
  - muon-like flux $(\varepsilon \gtrsim 10^{-2})$
  - neutrino-like flux $(\varepsilon \lesssim 10^{-2})$

Detection

- Depending on charge, DCR show → muon-like flux $(\varepsilon \gtrsim 10^{-2})$ / → neutrino-like flux $(\varepsilon \lesssim 10^{-2})$

→ **Cherenkov detectors!**

Detection

- Depending on charge, DCR show → muon-like flux $(\varepsilon \gtrsim 10^{-2})$ → neutrino-like flux $(\varepsilon \lesssim 10^{-2})$

→ **Cherenkov detectors!**

- Can exploit differences with real neutrinos: no oscillations, Glashow resonance …

Detection

- Depending on charge, DCR show
  - muon-like flux $(\varepsilon \gtrsim 10^{-2})$
  - neutrino-like flux $(\varepsilon \lesssim 10^{-2})$

→ **Cherenkov detectors!**

- Can exploit differences with real neutrinos: no oscillations, Glashow resonance …

- Interactions:

$$\text{(quasi-elastic)}\ \mathrm{QE}: \quad X + e^- \rightarrow X + e^-$$

$$\text{(photo-nuclear)}\ \mathrm{PN}: \quad X + N \rightarrow X + N'$$

$$\text{(deep inelastic scattering)}\ \mathrm{DIS}: \quad X + N \rightarrow X + N' + \text{hadrons}$$

Propagation in Medium

- Stopping power: $$-\langle\frac{dE}{dx}\rangle = a(E) + b(E)E$$

Propagation in Medium

- Stopping power: $$-\langle\frac{dE}{dx}\rangle = a(E) + b(E)E$$

critical energy:

$$\epsilon = a(\epsilon)/b(\epsilon)$$

ionization loss
(Bethe-Bloch formula)

radiative processes
(brems-strahlung, pair-production, photo-nuclear)

Propagation in Medium

- Stopping power: $$-\langle \frac{dE}{dx} \rangle = a(E) + b(E)E$$

critical energy:
$\epsilon = a(\epsilon)/b(\epsilon)$

- Relate DCR parameters to muons *(leading diagrams)* :

[Groom,Mokhov, Striganov,01]

$$\frac{a_{\rm X}}{a_\mu} \propto \varepsilon^2; \qquad \frac{b_{\rm X,brems}}{b_{\mu,\rm brems}} \propto \left(\frac{m_\mu}{m_{\rm X}}\right)^2 \varepsilon^4 \ ;$$

$$\frac{b_{\rm X,pair}}{b_{\mu,\rm pair}} \propto \left(\frac{m_\mu}{m_{\rm X}}\right)\varepsilon^2; \qquad \frac{b_{\rm X,nucl}}{b_{\mu,\rm nucl}} \propto \varepsilon^2 \ .$$

Propagation in Medium

- Stopping power: $$-\langle\frac{dE}{dx}\rangle = a(E) + b(E)E$$

critical energy:
$\epsilon = a(\epsilon)/b(\epsilon)$

- Relate DCR parameters to muons *(leading diagrams)* :

[Groom,Mokhov, Striganov,01]

$$\frac{a_X}{a_\mu} \propto \varepsilon^2; \qquad \frac{b_{X,\mathrm{brems}}}{b_{\mu,\mathrm{brems}}} \propto \left(\frac{m_\mu}{m_X}\right)^2 \varepsilon^4 \; ;$$
$$\frac{b_{X,\mathrm{pair}}}{b_{\mu,\mathrm{pair}}} \propto \left(\frac{m_\mu}{m_X}\right)\varepsilon^2; \qquad \frac{b_{X,\mathrm{nucl}}}{b_{\mu,\mathrm{nucl}}} \propto \varepsilon^2 \; .$$

- Approximately: $$\boxed{\frac{b_{X,\mathrm{total}}}{b_{\mu,\mathrm{total}}} \simeq \frac{1}{2}\left(\frac{m_\mu}{m_X}\right)\varepsilon^2 \quad ; \quad \frac{\epsilon_X}{\epsilon_\mu} \simeq 2\left(\frac{m_X}{m_\mu}\right) .}$$

Spectrum/Flux in Medium

- Spectrum (after x m.w.e): $E_X(x) = (E_{X,0} + \epsilon_X)e^{-b_X x} - \epsilon_X$

Spectrum/Flux in Medium

- Spectrum (after x m.w.e): $E_X(x) = (E_{X,0} + \epsilon_X)e^{-b_X x} - \epsilon_X$
- For flux $KE^{-\alpha}$, integrated vertical intensity after depth x :

$$I_X(x) = \frac{K\epsilon_X^{-\alpha+1}}{\alpha-1} e^{-(\alpha-1)b_X x}(1 - e^{-b_X x})^{-\alpha+1}$$

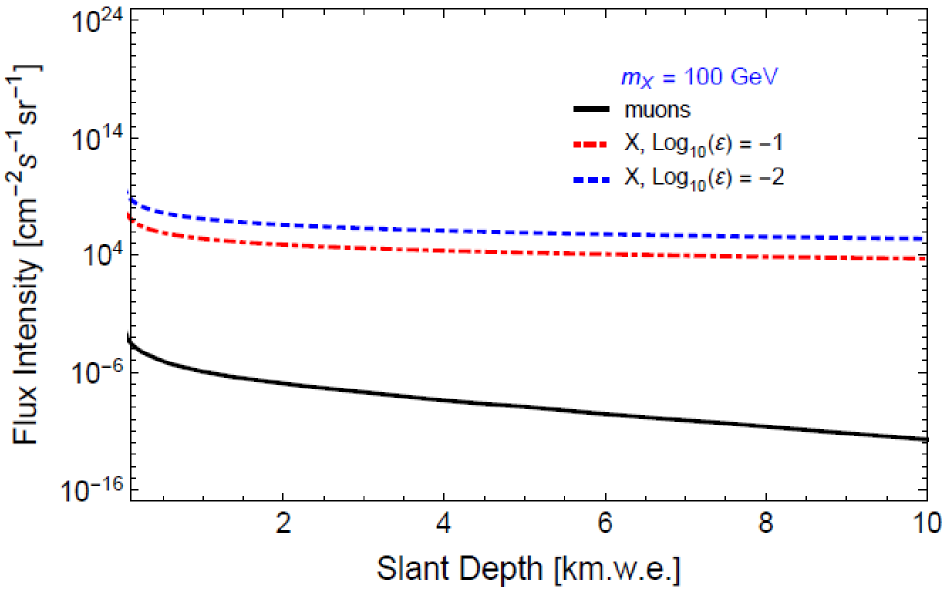
Spectrum/Flux in Medium

- Spectrum (after x m.w.e): $E_X(x) = (E_{X,0} + \epsilon_X)e^{-b_X x} - \epsilon_X$
- For flux $KE^{-\alpha}$, integrated vertical intensity after depth x :

$$I_X(x) = \frac{K\epsilon_X^{-\alpha+1}}{\alpha - 1} e^{-(\alpha-1)b_X x}(1 - e^{-b_X x})^{-\alpha+1}$$

- Atmosphere thin, propagate through rock only to underground lab

→ *compare with standard underground CR muon flux "Crouch curve"*



muons from [Reichenbacher, Je Dong,07]

DCR Cherenkov Radiation

- Charged particles travel in medium faster than light → *Cherenkov radiation*

DCR Cherenkov Radiation

- Charged particles travel in medium faster than light → *Cherenkov radiation*

- Cherenkov radiation:

Cherenkov angle

$$\frac{d^2N_X}{dx d\lambda} = \frac{2\pi\alpha_f\varepsilon^2}{\lambda^2}\left(1-\frac{1}{n^2\beta^2}\right) = \frac{2\pi\varepsilon^2\alpha_f}{\lambda^2}\sin^2\theta_C$$

light wavelength

DCR Cherenkov Radiation

- Charged particles travel in medium faster than light → *Cherenkov radiation*
- Cherenkov radiation:

$$\frac{d^2 N_X}{dx d\lambda} = \frac{2\pi\alpha_f \varepsilon^2}{\lambda^2}\left(1 - \frac{1}{n^2\beta^2}\right) = \frac{2\pi\varepsilon^2\alpha_f}{\lambda^2}\sin^2\theta_C$$

→ for DCR normalization changes as ε^2

→ light spectrum identical to non-fractional particles

DCR Cherenkov Radiation

- Charged particles travel in medium faster than light → *Cherenkov radiation*

- Cherenkov radiation:

$$\frac{d^2 N_X}{dx d\lambda} = \frac{2\pi\alpha_f \varepsilon^2}{\lambda^2}\left(1 - \frac{1}{n^2\beta^2}\right) = \frac{2\pi\varepsilon^2\alpha_f}{\lambda^2}\sin^2\theta_C$$

→ for DCR normalization changes as ε^2

→ light spectrum identical to non-fractional particles

- Cherenkov threshold (water):

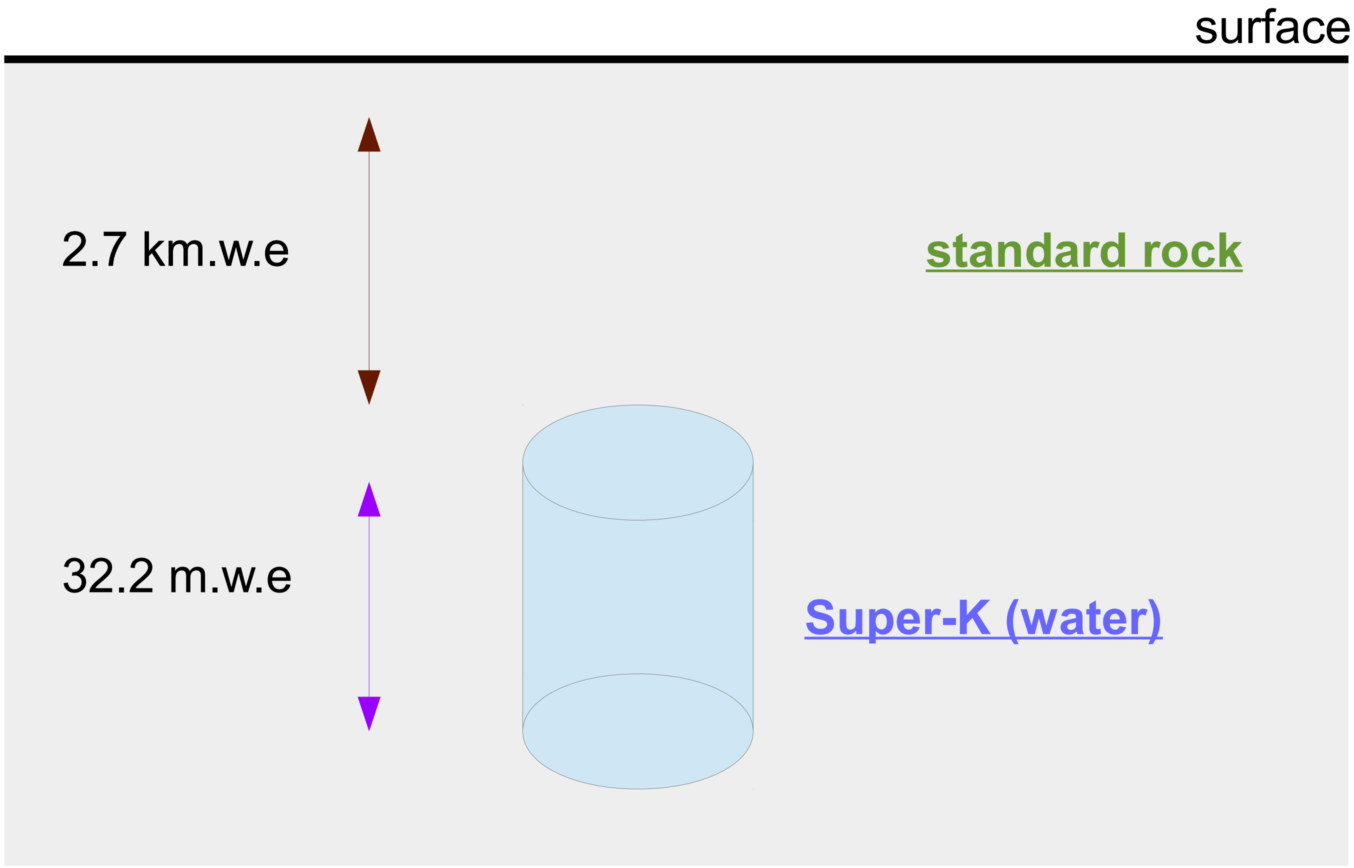
$$E_{\mathrm{th.}} > 1.52\ m_{\mathrm{X}}$$
$$p_{\mathrm{th}} > 1.14\ m_{\mathrm{X}}$$

New Super-K analysis I (μ-like): Energy Deposit

- CR muons deposit energy in Super-K → fraction. charged particles (e.g. DCR) also

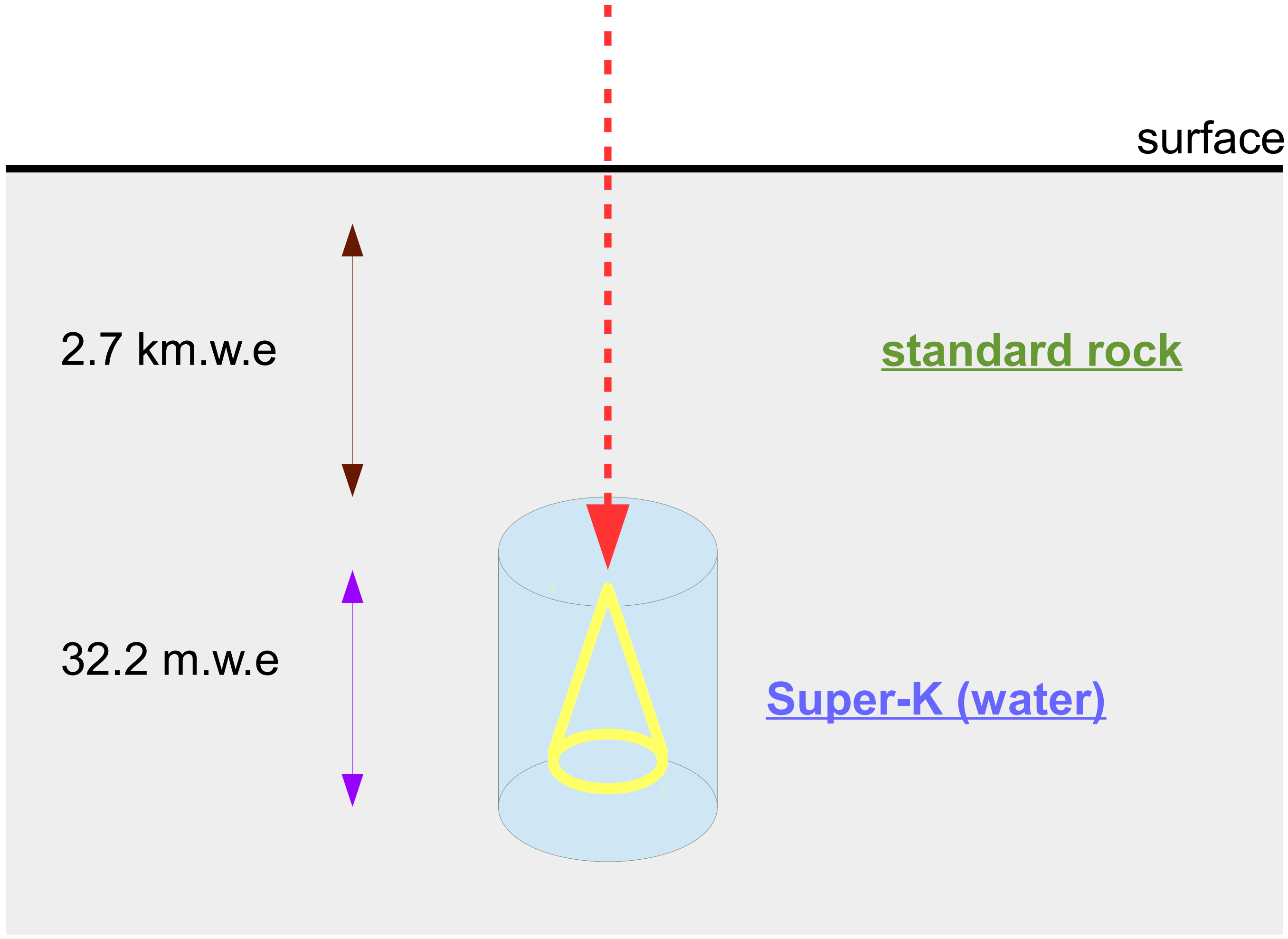
New Super-K analysis I (μ-like): Energy Deposit

- CR muons deposit energy in Super-K → fraction. charged particles (e.g. DCR) also



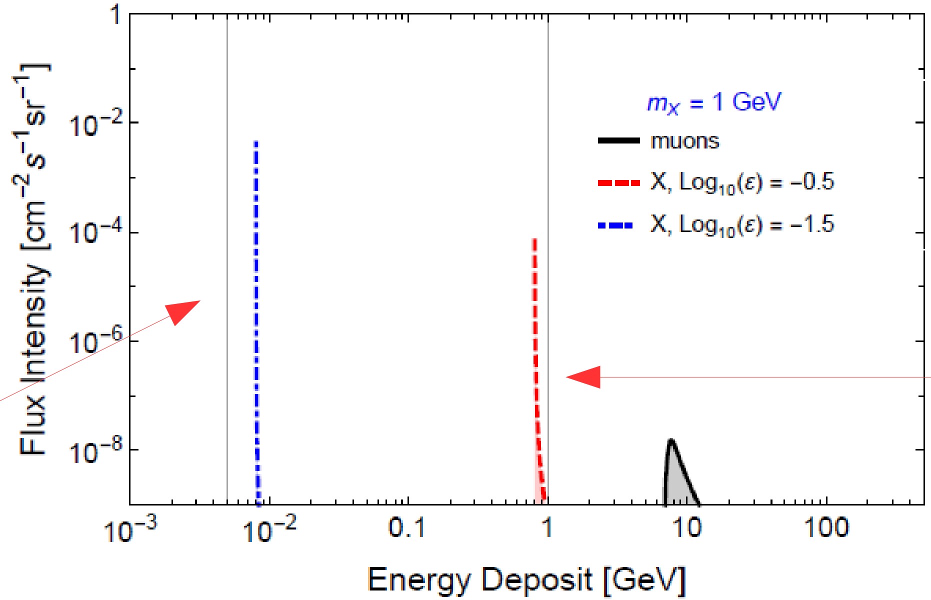
New Super-K analysis I (μ-like): Energy Deposit

- CR muons deposit energy in Super-K → fraction. charged particles (e.g. DCR) also



New Super-K analysis I (μ-like): Energy Deposit

- CR muons deposit energy in Super-K → fraction. charged particles (e.g. DCR) also
- Propagate DCR through standard rock, then through Super-K (water)
- Deposited energy:



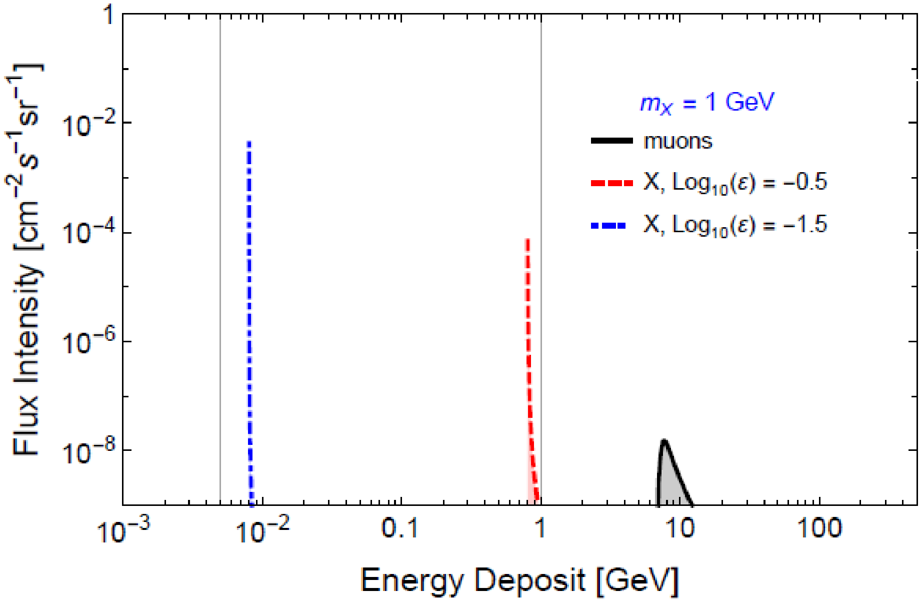
muons from [Li,Beacom,14]

SK now

upcoming SK Gadolinium upgrade

New Super-K analysis I (μ-like): Energy Deposit

- CR muons deposit energy in Super-K → fraction. charged particles (e.g. DCR) also
- Propagate DCR through standard rock, then through Super-K (water)
- Deposited energy:



muons from [Li,Beacom,14]

- Clean signal, upcoming SK Gadollium upgrade probes $\varepsilon \gtrsim 10^{-2}$

→ **novel general search for fractional particles** (DCR only determines flux)

→ **could be competitive with dedicated experiments like MACRO**

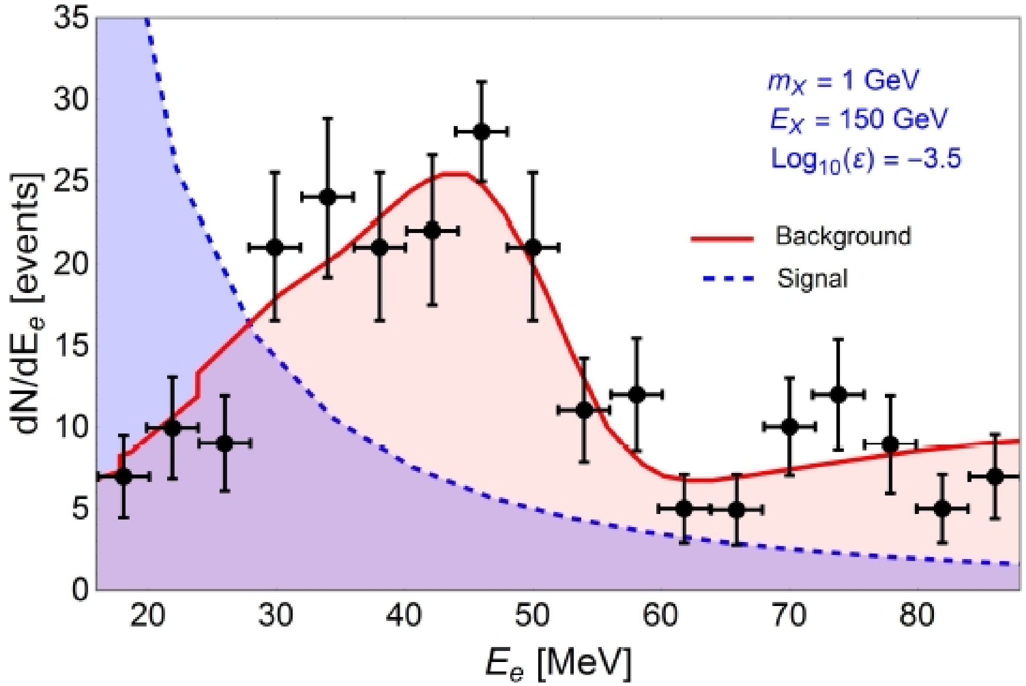
New Super-K analysis II (ν-like): Recoil Electron Spectrum

- Earth transparent for ν-like DCR

- Know: cross-section, flux, exposure, threshold → calculate recoil electron spectrum

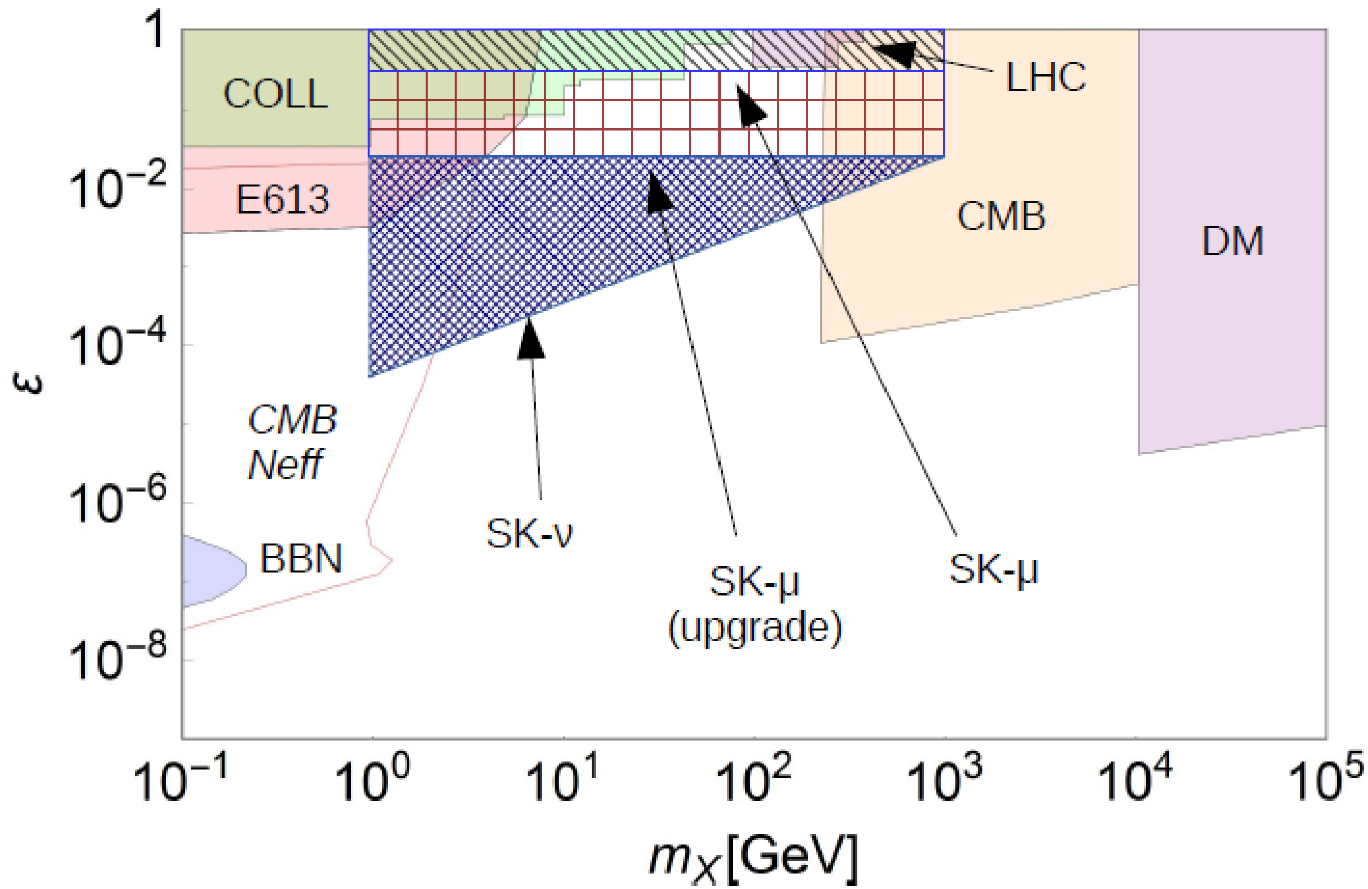
New Super-K analysis II (ν-like): Recoil Electron Spectrum

- Earth transparent for ν-like DCR
- Know: cross-section, flux, exposure, threshold → calculate recoil electron spectrum
- SK supernova relic neutrino sample sensitive to DCR with $\varepsilon \sim 10^{-5}$



data/MC from [Bays+(SK),12]

New Limits/Constraints for mDM



constraint summary
[Vinyoles,Vogel,16]

Summary

- General framework to study dark cosmic rays, results apply to broad class of models … some to fractionally charged particles in general

- Novel searches for Cherenkov experiment $\rightarrow$ new limits/constraints

Summary

- General framework to study dark cosmic rays, results apply to broad class of models … some to fractionally charged particles in general

- Novel searches for Cherenkov experiment $\rightarrow$ new limits/constraints

- Further development *(in preparation)* :

  - acceleration beyond Fermi mechanism

  - explanation of IceCube excess

  - atmospheric showers

  … etc.