A Record of past Cosmic Rays from Carbon-14 in Antarctic ice

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University of Rochester

in collaboration with Segev BenZvi, Vasilii Petrenko, Alexander Ihle, Christo Buizert (Oregon State), et al.

MELIORA

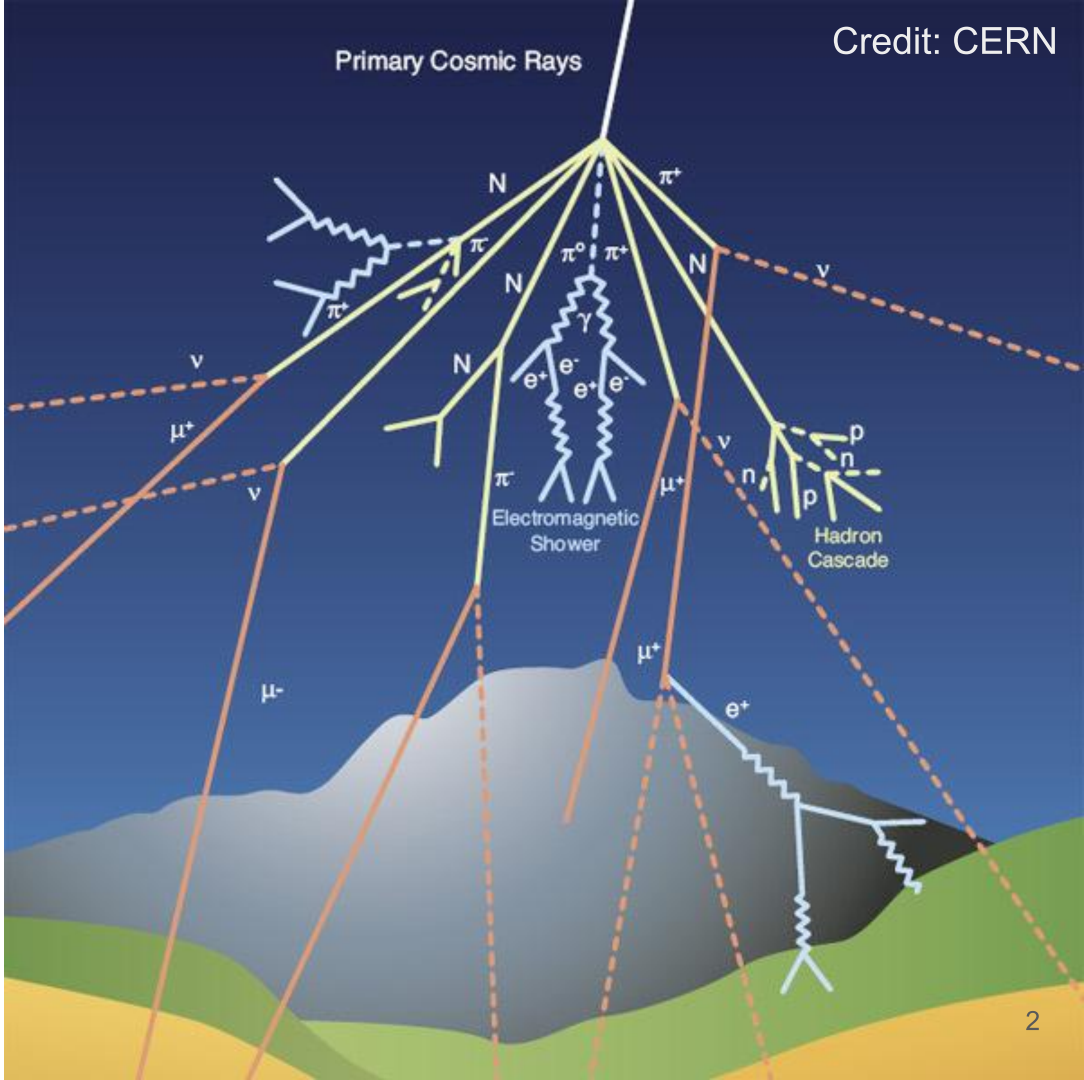
Motivation

Galactic Cosmic Rays (GCRs) are an important background in the study of solar activity

Radionuclides in meteorites support **constant GCR within 30% on million-year timescales**.

But, normalization and spectral index could be affected by:

- A nearby transient
- Motion of the solar system through the ISM



Credit: CERN

Project Goal

What:

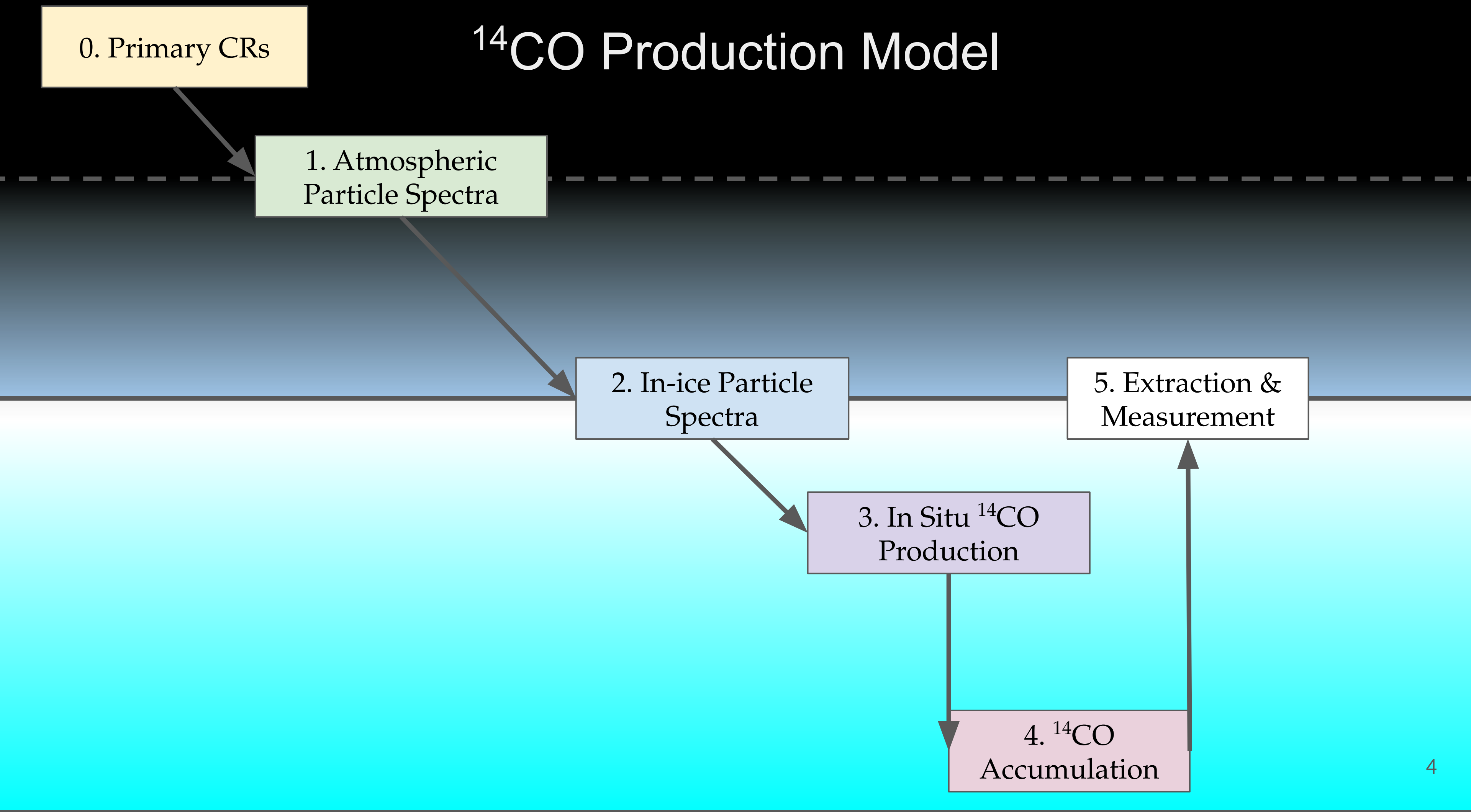
- Constrain galactic cosmic ray time dependence

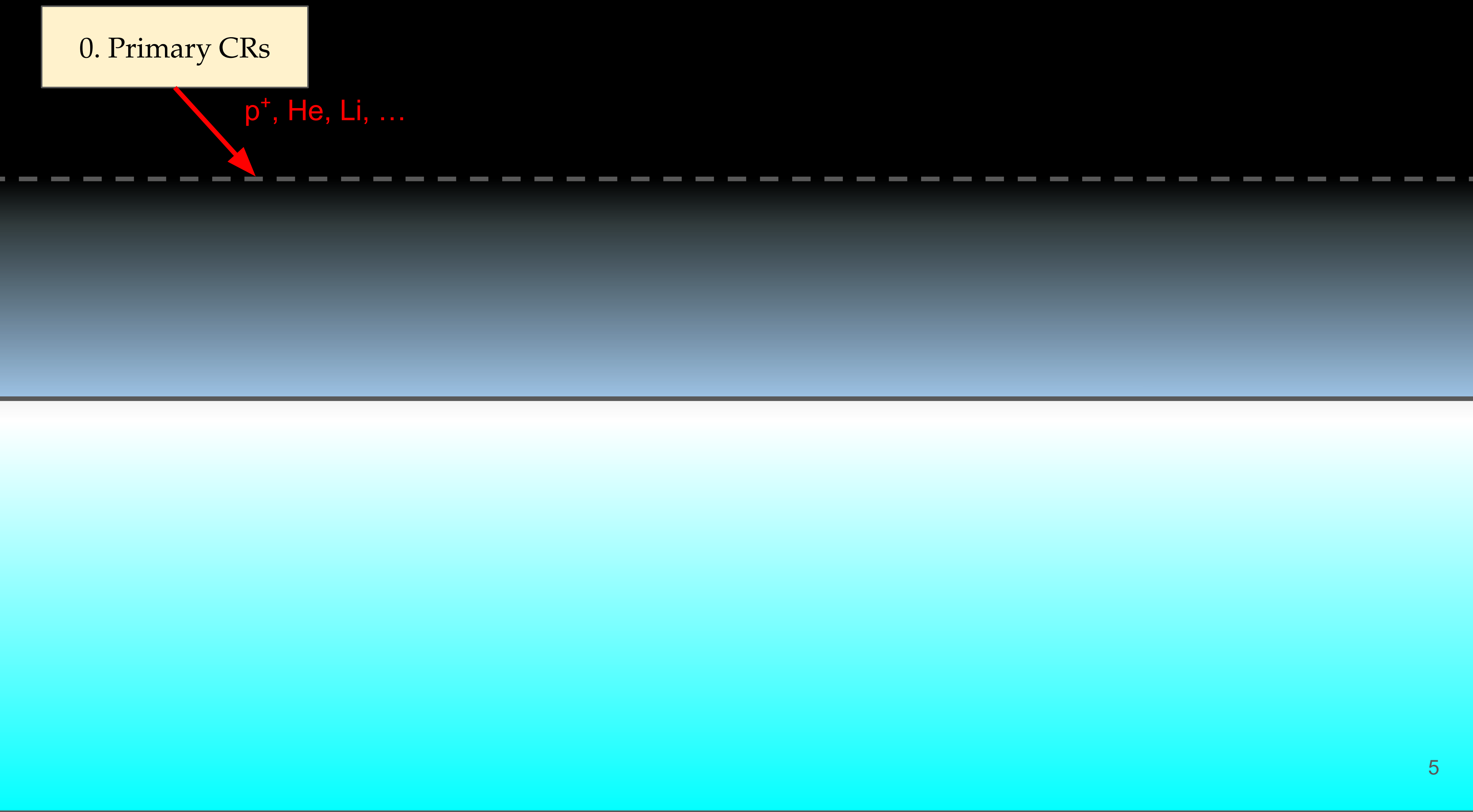
How:

- Cosmogenic ^{14}CO in ice cores from Dome C, Antarctica
  - Can improve upon uncertainties compared to existing data
  - Sensitive to past ~7 kyrs, with thousand-year rather than million-year time resolution
  - Also, jointly constrain ^{14}C production rates & cross-sections

See Petrenko, BenZvi, Dyonisius, et al., Cyrosphere 18:3439, 2024, https://tc.copernicus.org/articles/18/3439/2024/

^{14}CO Production Model

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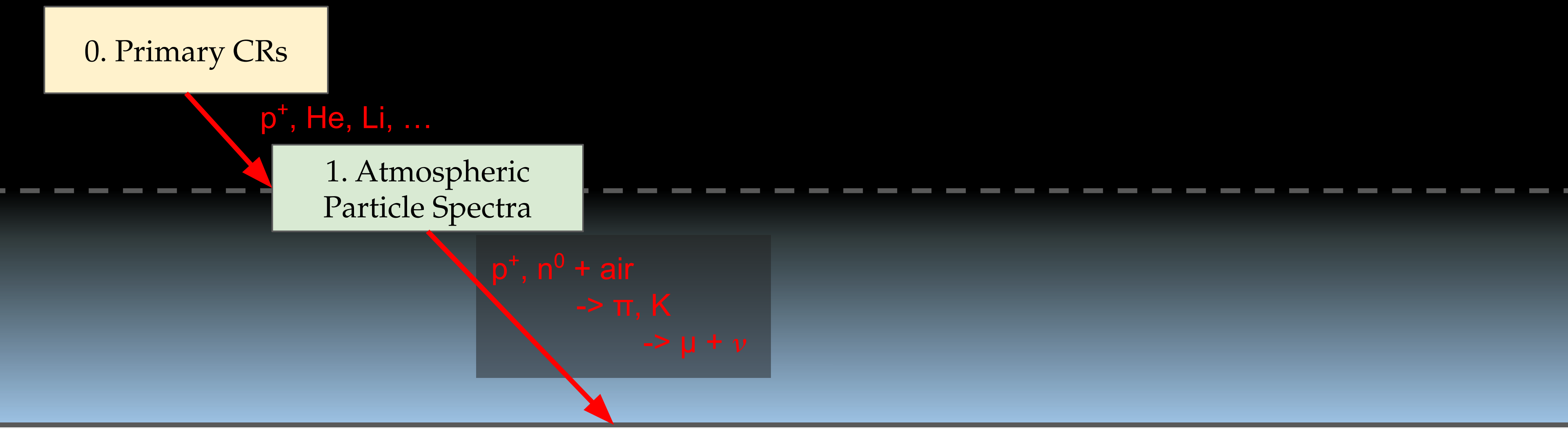
p^+, He, Li, …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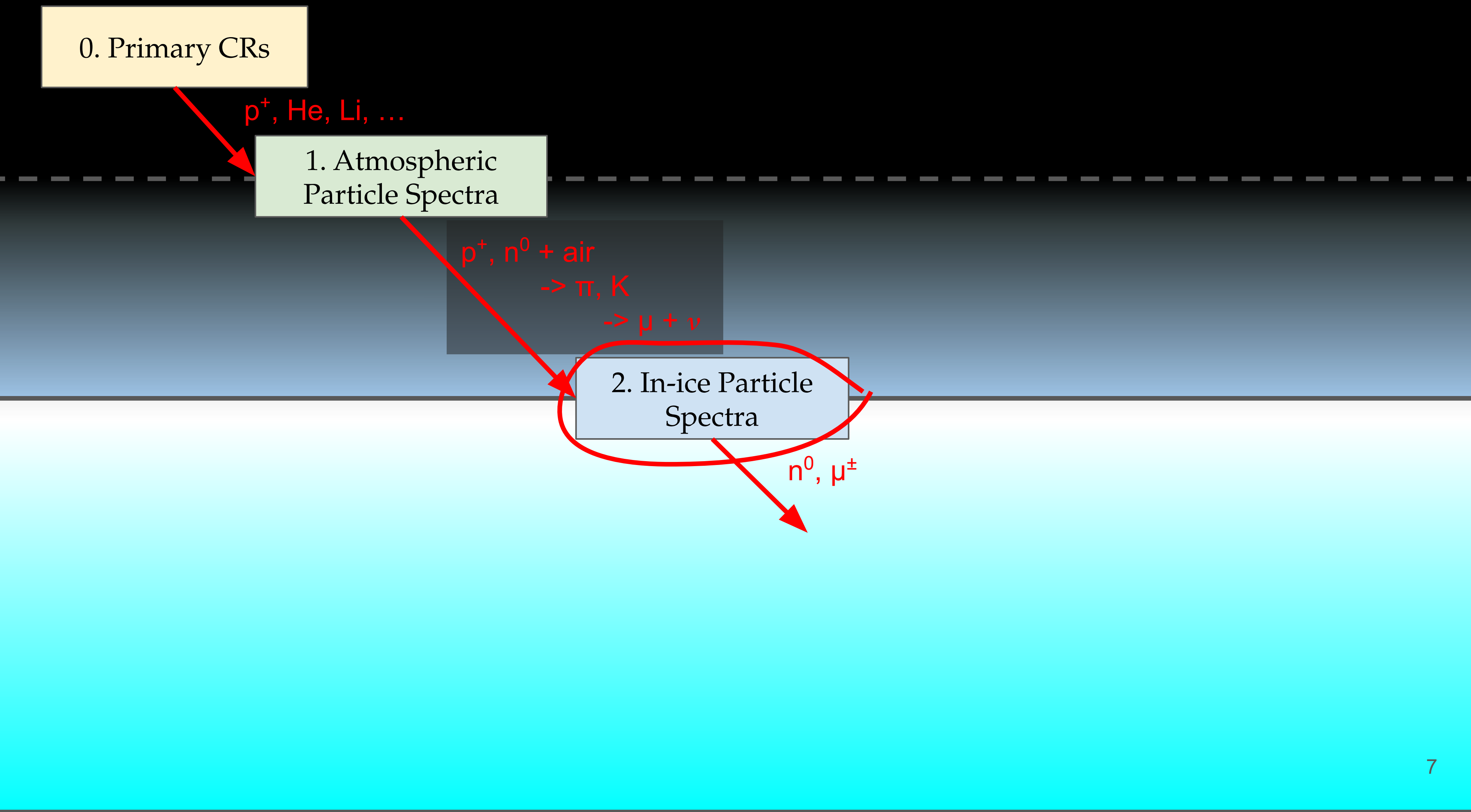
1. Atmospheric Particle Spectra
p+, n0 + air
-> π, K
-> μ + ν



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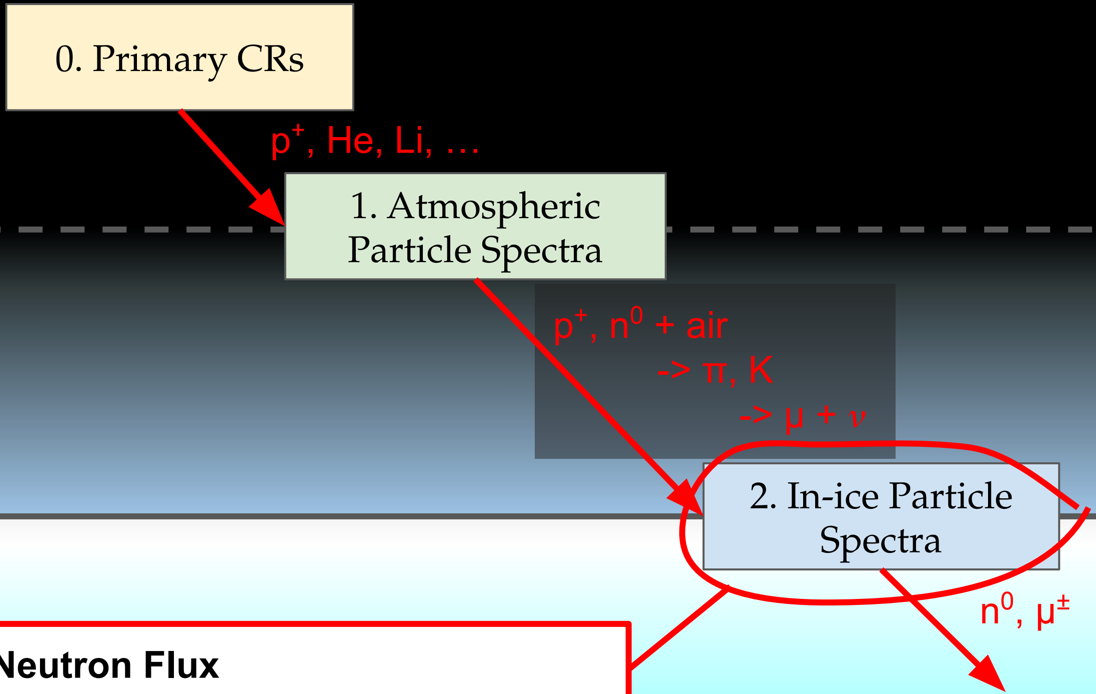
n0, μ±



Neutron Flux

Exponential Attenuation w/ depth

$$\Phi^{n^0}(h) = \Phi_0 \exp(-h/\Lambda)$$

$\boldsymbol{\Phi}_0$: Sea-level flux scaled to site

Λ : Attenuation length

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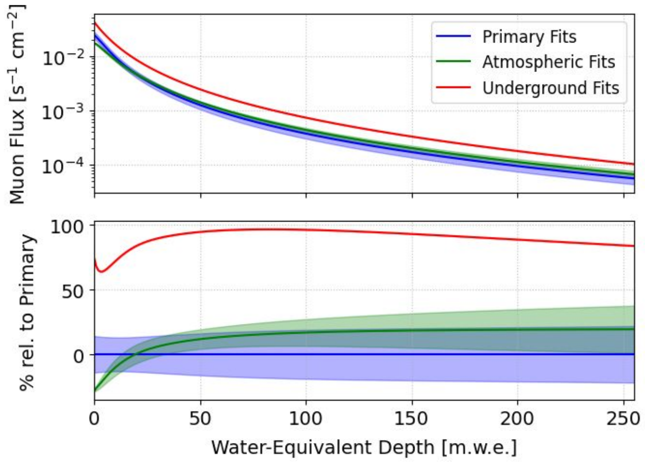
n^0, $\mu^\pm$

Underground Muon Spectrum

3 starting points for estimating spectrum:

- **Empirical Fits** to Primary, Atmospheric (sea-level), or Underground (Pb/Fe) Spectra
- **Matrix Cascade Equations (MCEq)** integrate interactions & decays through Atmosphere
- **Continuous Energy Loss (dE/dX)** below ice



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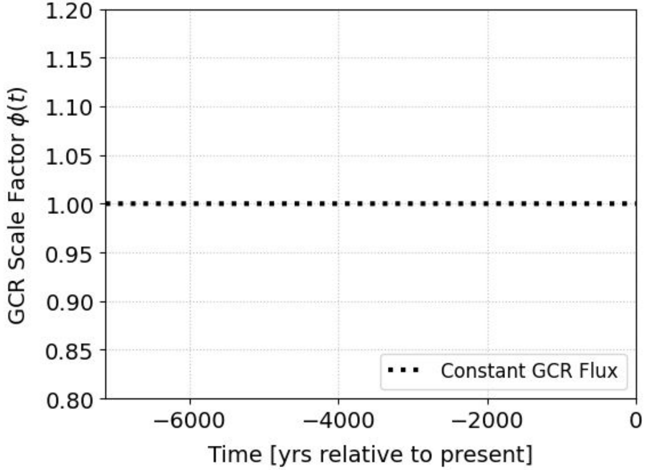
CR History Scale Factor (Time Dependence)

Scale CR normalization over time, to test effect of time dependence



$$\Phi^{n^0,\mu^\pm}(h,t) = \Phi(h)\phi(t)$$

Φ : present-day flux

$\phi(t)$: CR History

(examples shown in plot)

n^0, $\mu^\pm$

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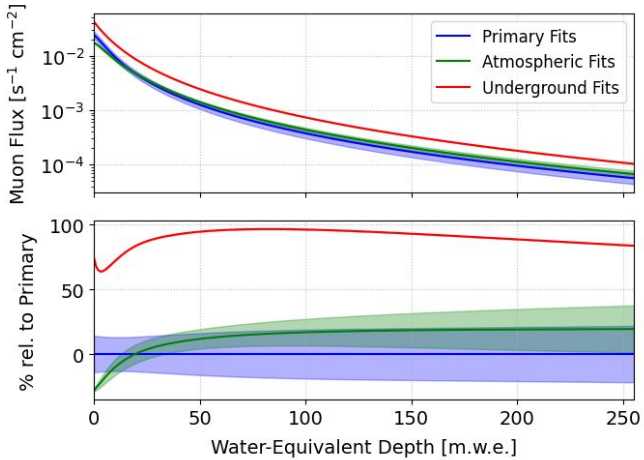

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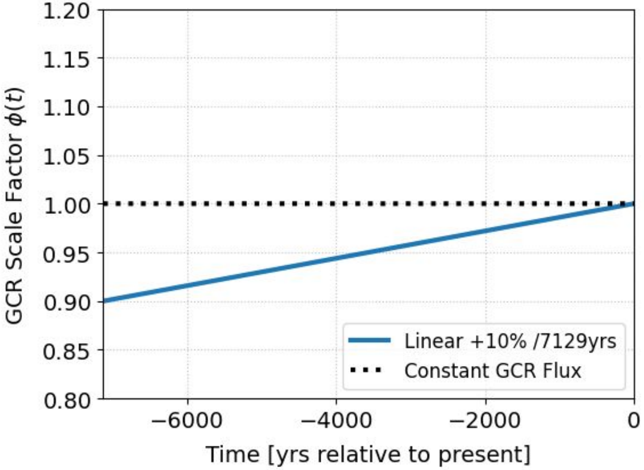

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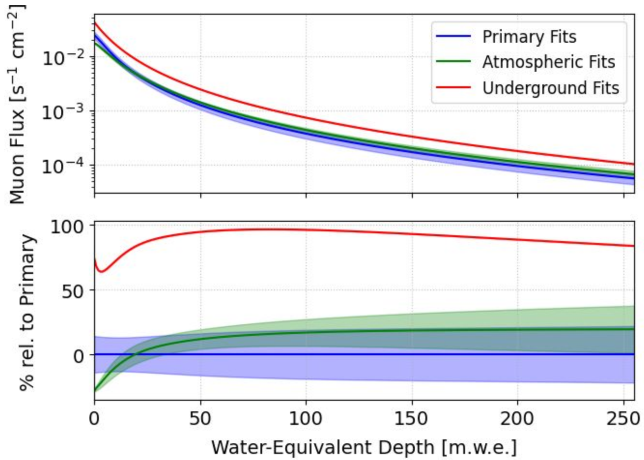

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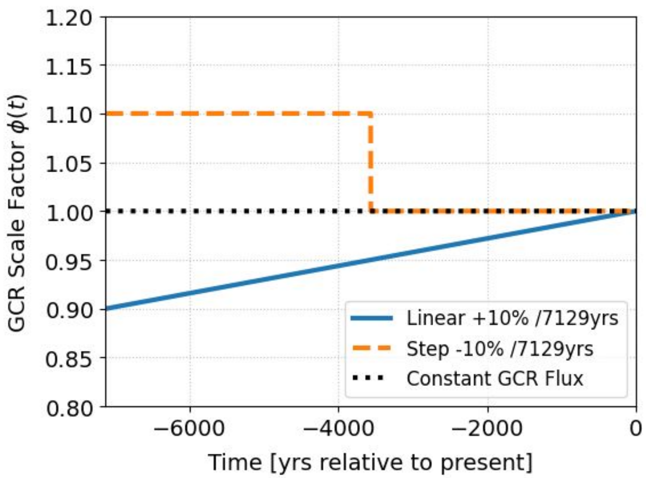

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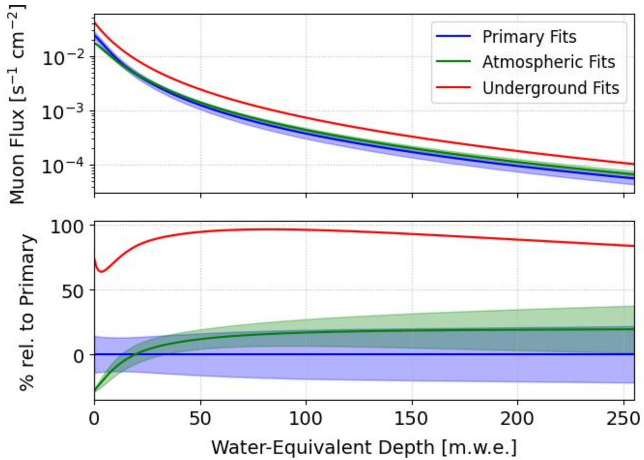

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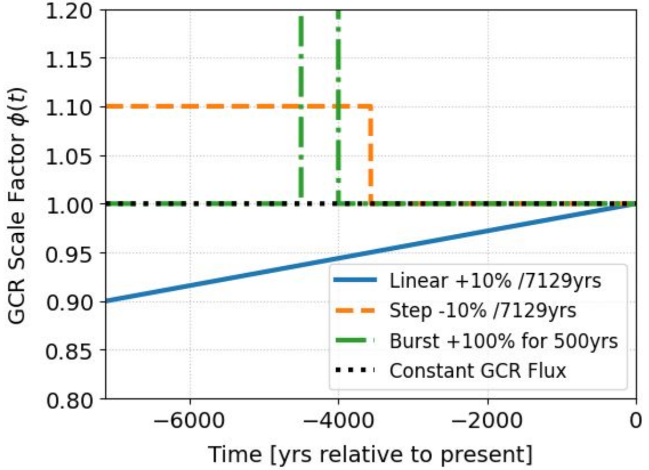

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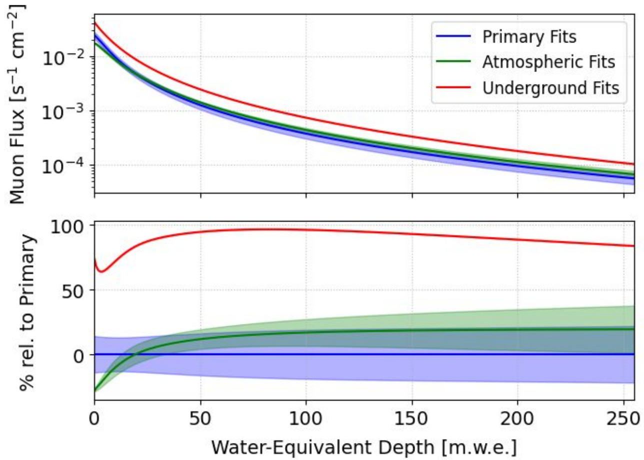

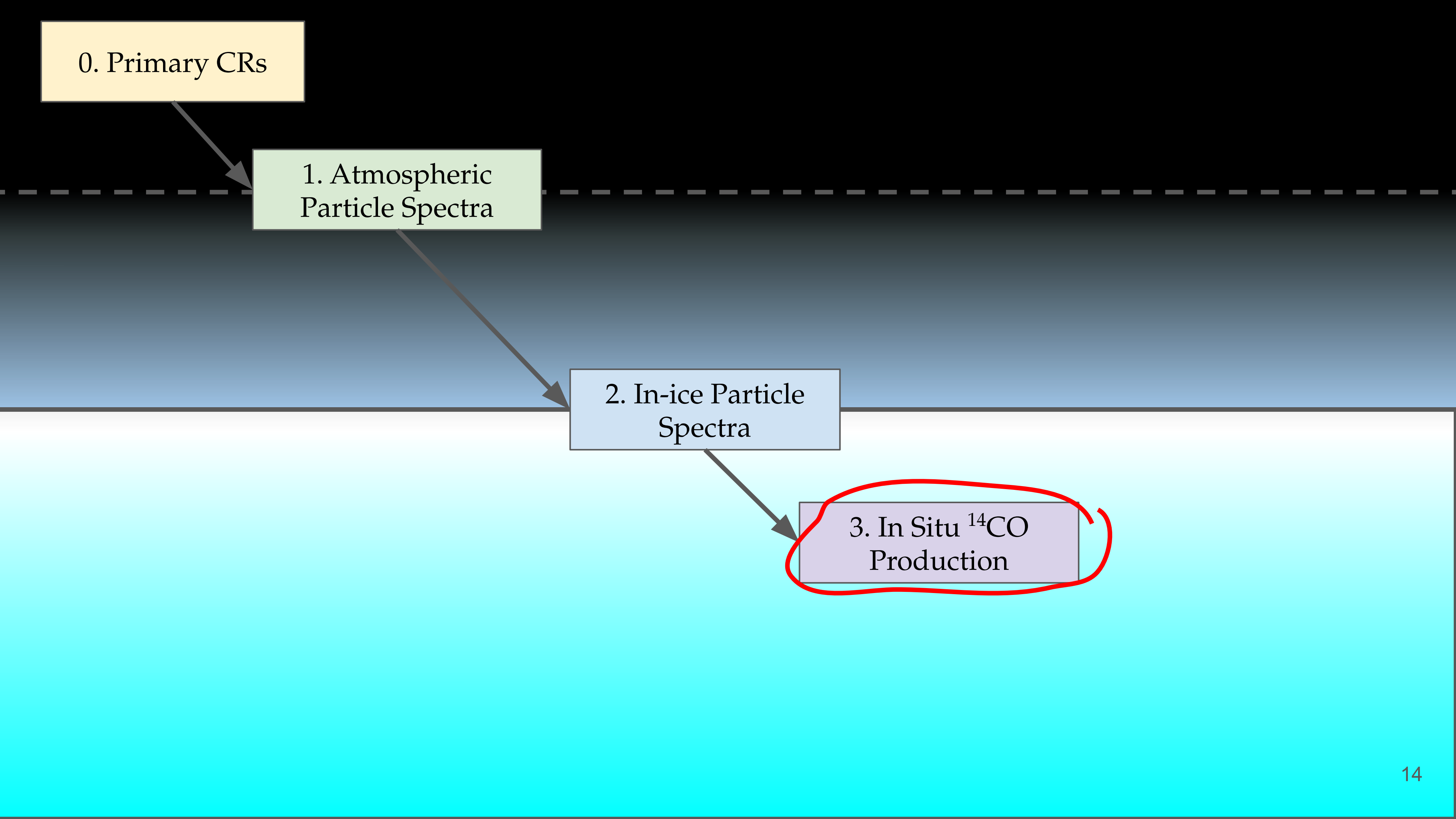
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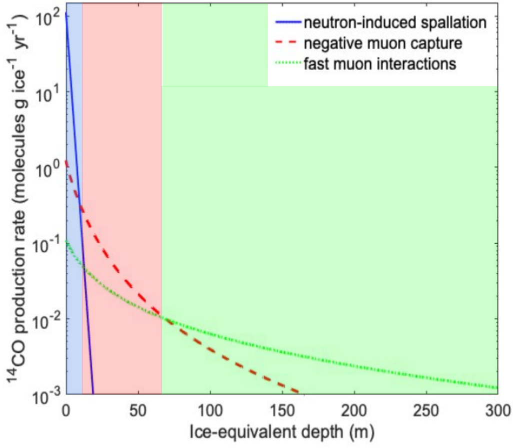
3. In Situ ^{14}CO Production

Neutron Spallation

$$P_{n^0}^{^{14}\mathrm{C}}(h) = N\sigma\Phi_{n^0}(h)$$

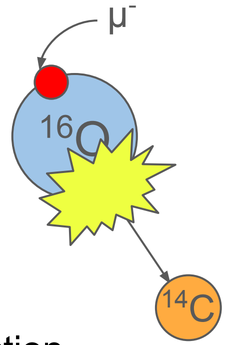
N: target (^{16}O) density
σ : cross-section
Φ(h) : total neutron flux
Falls off exponentially w/ depth, **insignificant below first ~20 meters**



Credit: Petrenko et al. (2024)

Negative Muon Capture

Stopped μ^- captured by p^+ in ^{16}O nucleus, inducing spallation



$$P_{\mu^-}^{^{14}C} = f_{tot} R_{\mu^-}(h)$$

f_{tot} : eff. probability of ^{14}C production
$R_{\mu-}(h)$: negative muon stopping rate

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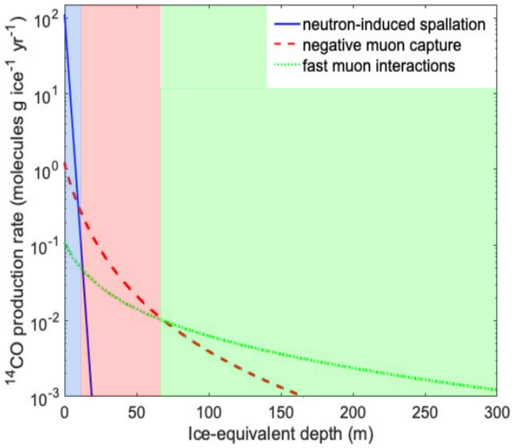

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Spectra

3. In Situ ^{14}CO Production

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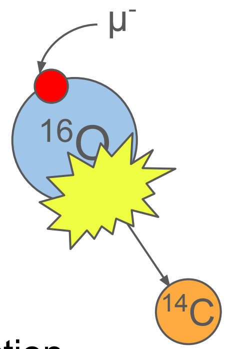

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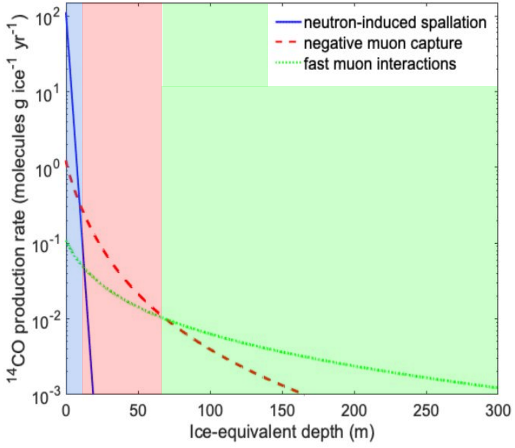

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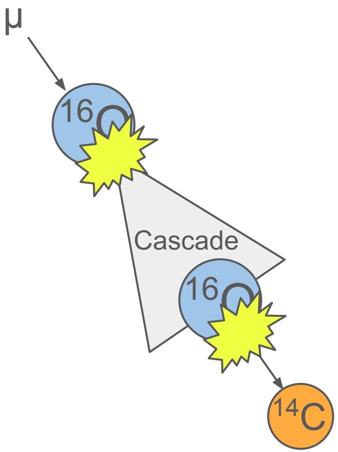
Fast Muon Interactions



High energy muon impacts ^{16}O nucleus, causing a particle cascade

$$P_{\mu_f}^{^{14}C} = N\overline{\sigma}(E)\Phi_{\mu^\pm}(h)$$

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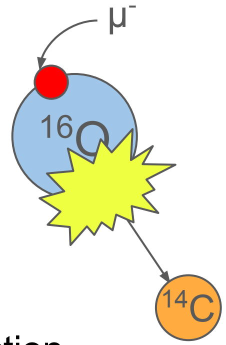

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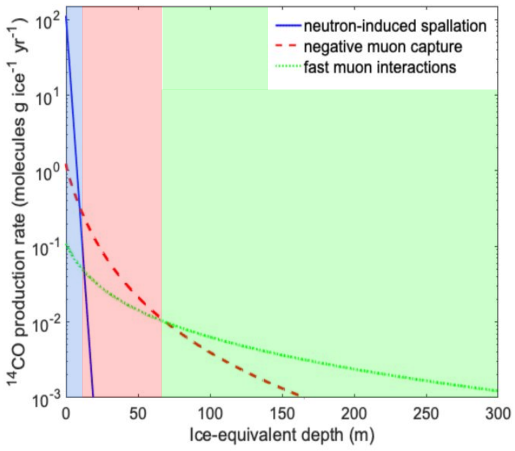

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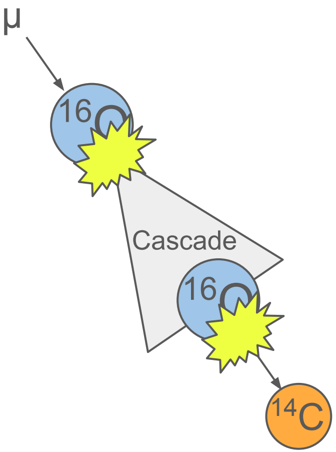

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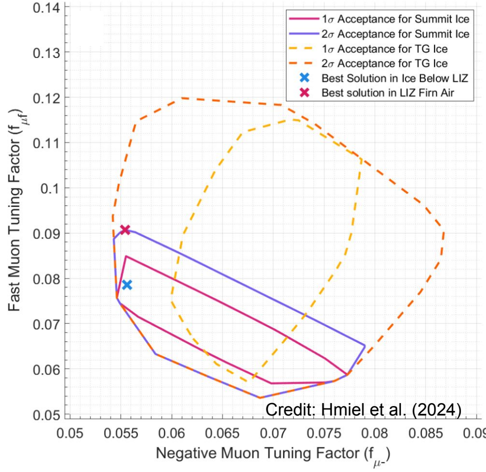
Tuning Factors (f_{n0}, $f_{\mu-}$, $f_{\mu f}$)

Rescale production rates for ^{14}CO fraction & uncertainties

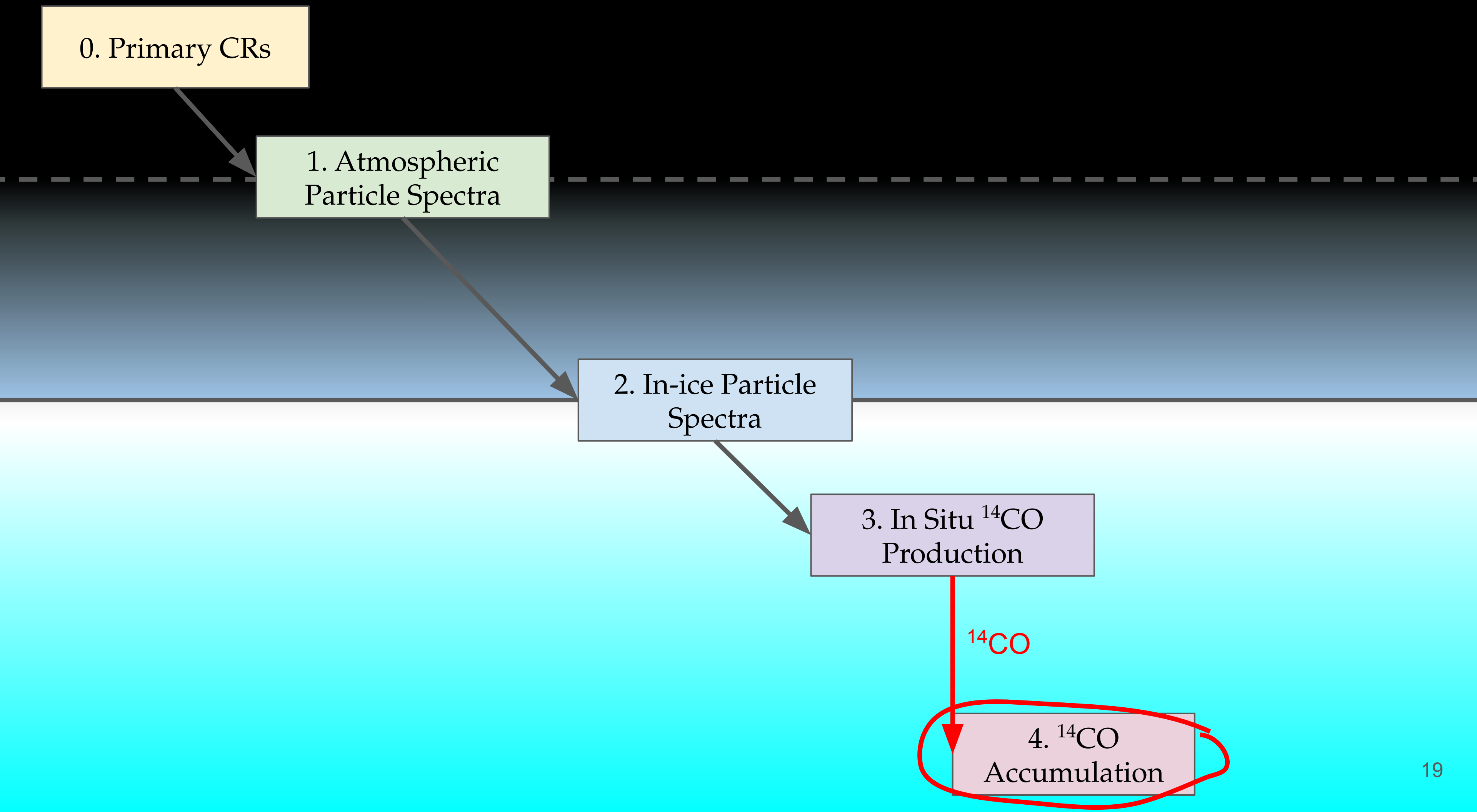
$$P^{^{14}CO} = P^{^{14}C} \cdot \vec{f}$$

$$\vec{f} = \Omega^{CO}\vec{\sigma}^*/\vec{\sigma}$$

Ω^{CO} : $^{14}CO/^{14}C$ fraction (~0.3)
σ* : true cross-sections
σ : literature cross-sections



Credit: Hmiel et al. (2024)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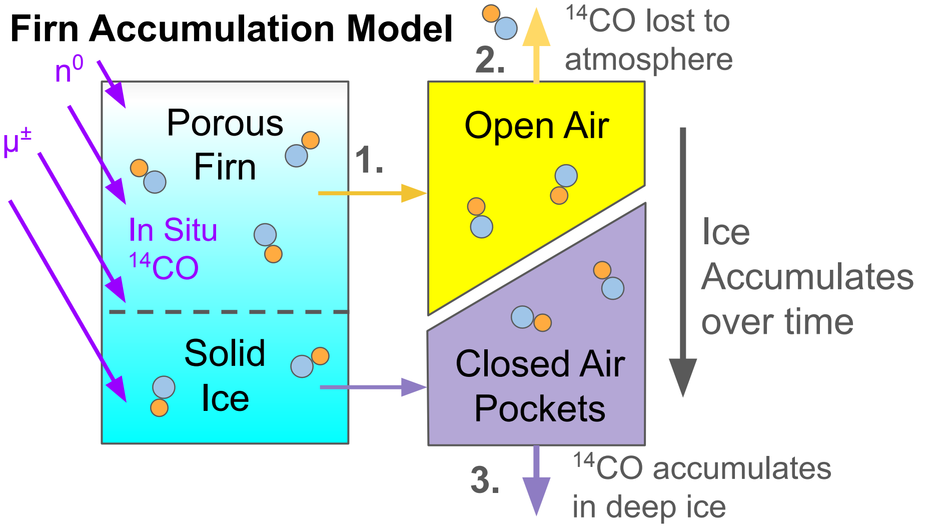
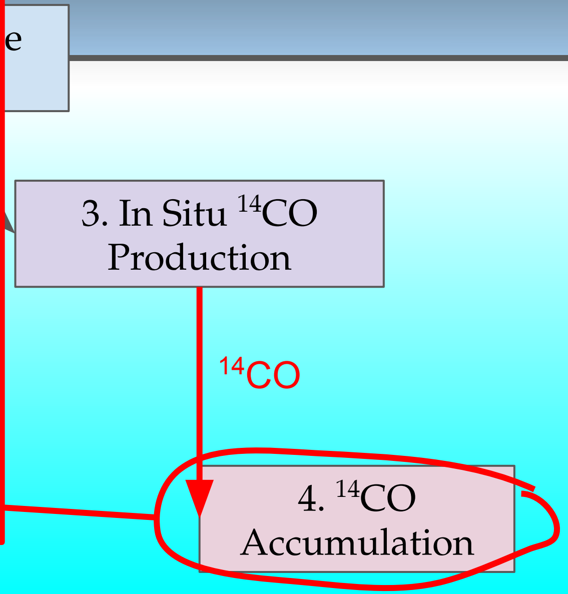
1. Atmospheric Particle Spectra
2. In-ice Particle Spectra
3. In Situ ^{14}CO Production
^{14}CO
4. ^{14}CO Accumulation

0. Primary CRs

Firn Accumulation Model



1. **New ^{14}CO** leaks from ice grains into air pockets
2. **Near the surface**, ^{14}CO diffuses out through open porosity into the atmosphere
3. **Below ~100m**, air bubbles close off, trapping & accumulating ^{14}CO over time as the ice sinks deeper



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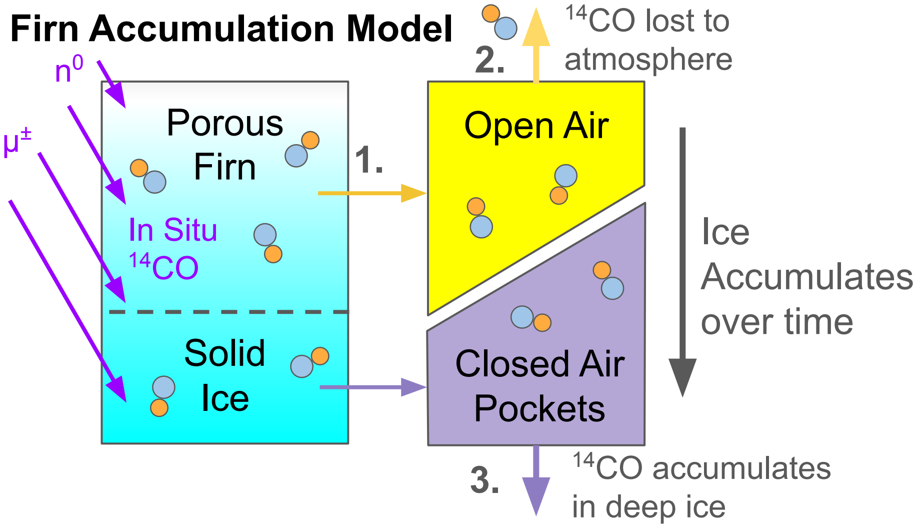

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Integration

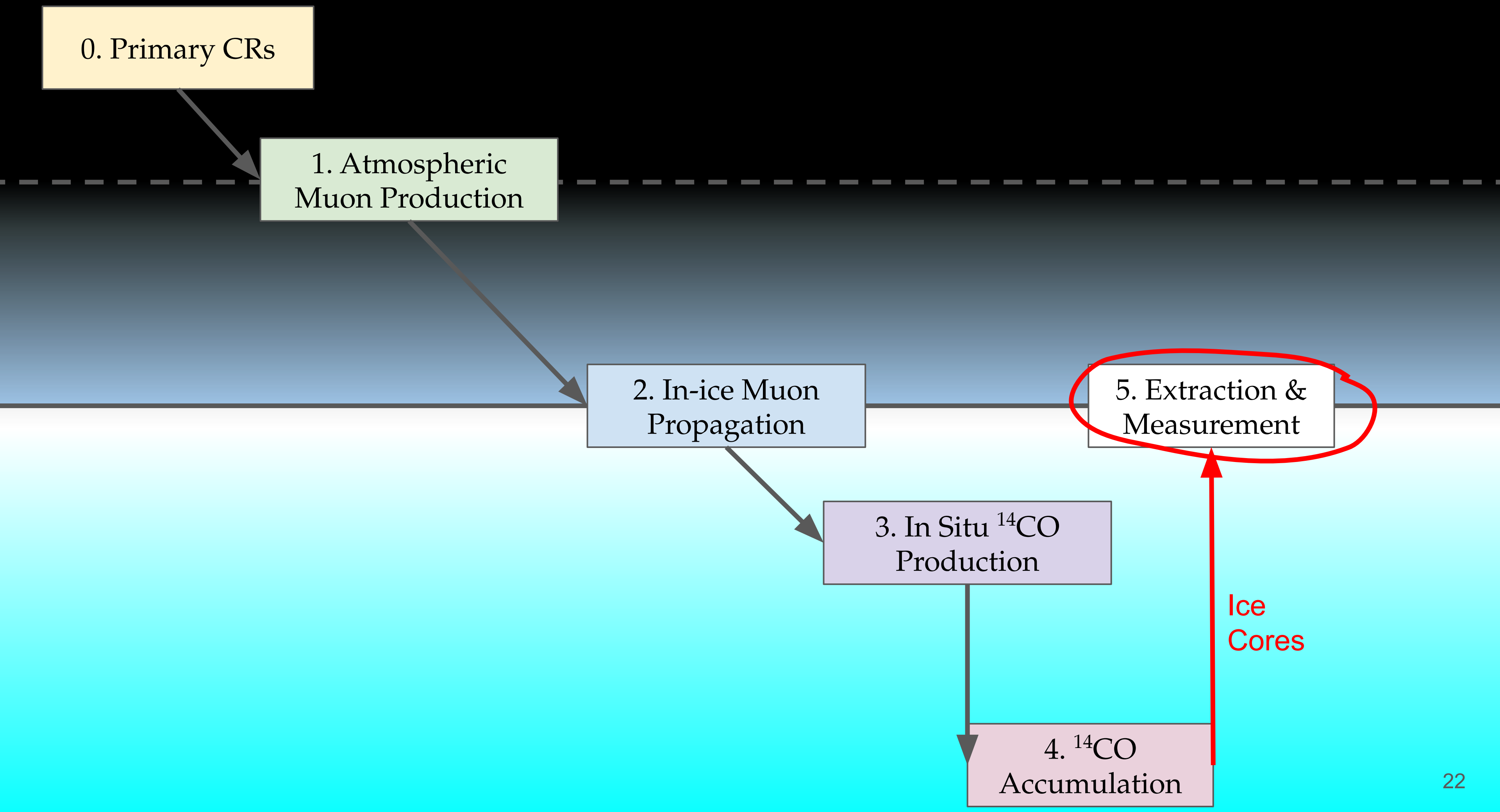
Integrate ^{14}CO production and loss along ice grain paths to get final concentrations

$$\frac{d}{dt}\,{}^{14}\mathrm{CO} = \mathrm{Production} - \mathrm{Leak} - \mathrm{Decay}$$

3. In Situ ^{14}CO Production

^{14}CO

4. ^{14}CO Accumulation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1. Atmospheric Muon Production
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5. Extraction & Measurement
Ice Cores

Ice Core Team:
Vas Petrenko, Alexander Ilhe, and Sebastian Miller

Ice cores extracted from Dome C, Antarctica over Austral summer 2024-2025.

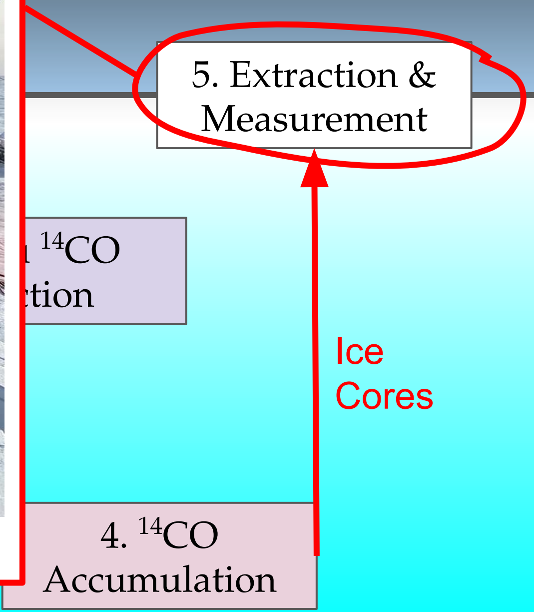
14 samples over 10 depths, top 4 depths repeated

Core depths: 100 - 300 m
Ice age range: ~2.5 - 9.5 kyr

Ice cores melted, gas collected and analyzed for ^{14}CO content.

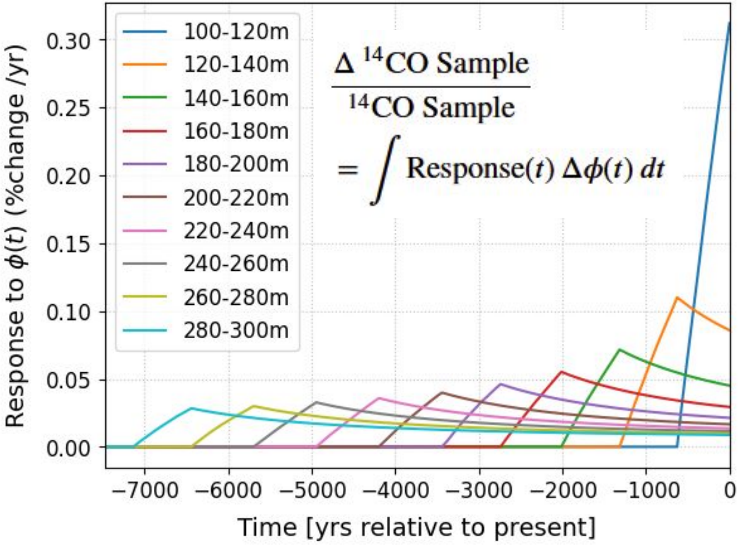
Measurements are in!

Credit: Vasilii Petrenko



Sensitivity to GCR Flux History

Upper plot shows sensitivity ranges (normalized response functions) for each ice core sample to changes in the GCR flux over time



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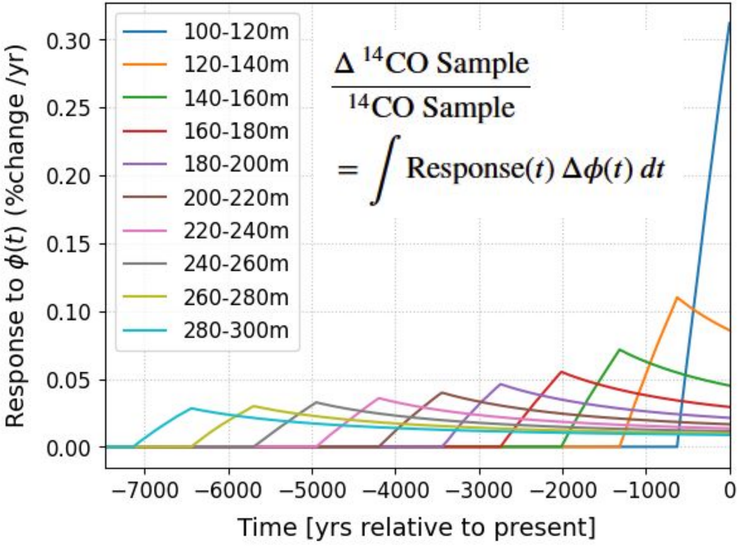
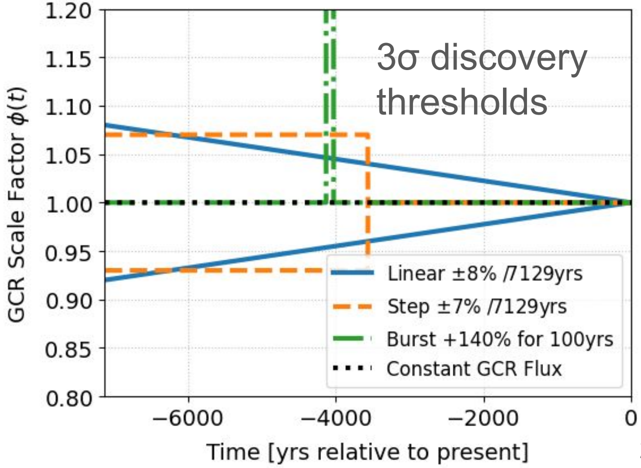


Lower plot shows magnitudes of simulated non-constant CR histories which lead to 3σ discoveries in at least 50% of cases



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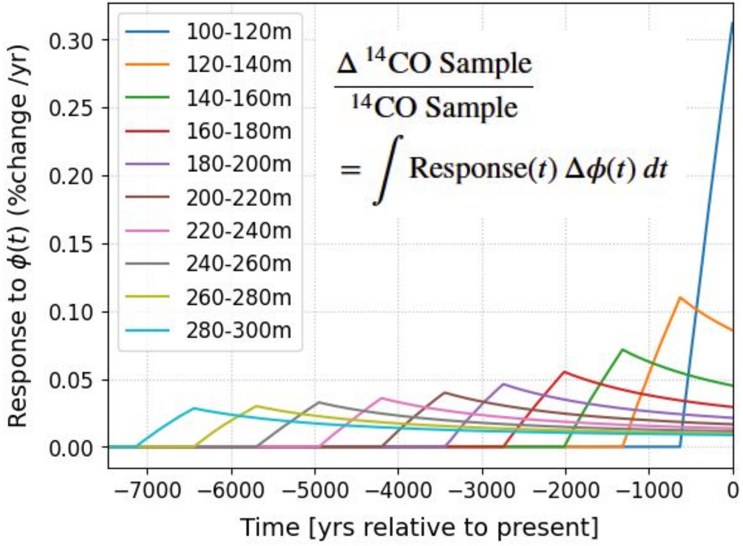

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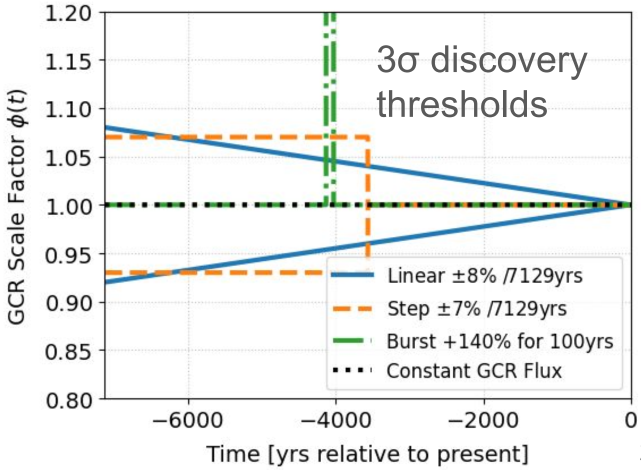
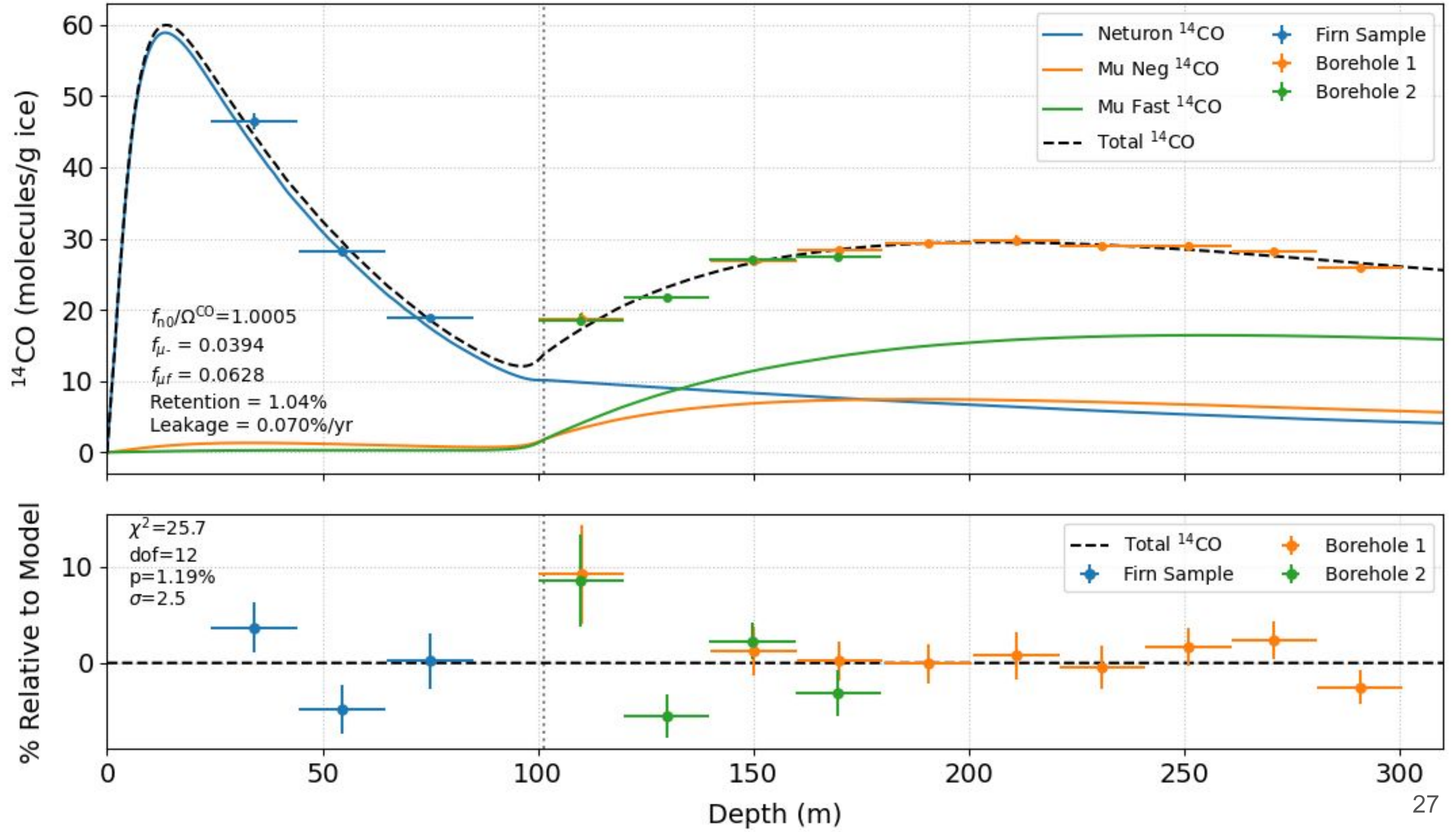


We expect 3σ(5σ) discovery from changes averaging >8%(12%)
over ~7kyr timeframe, w/ ~700-year resolution

Preliminary Results

^{14}CO measurements w/ simple χ^2 fit to data, assuming constant GCR history



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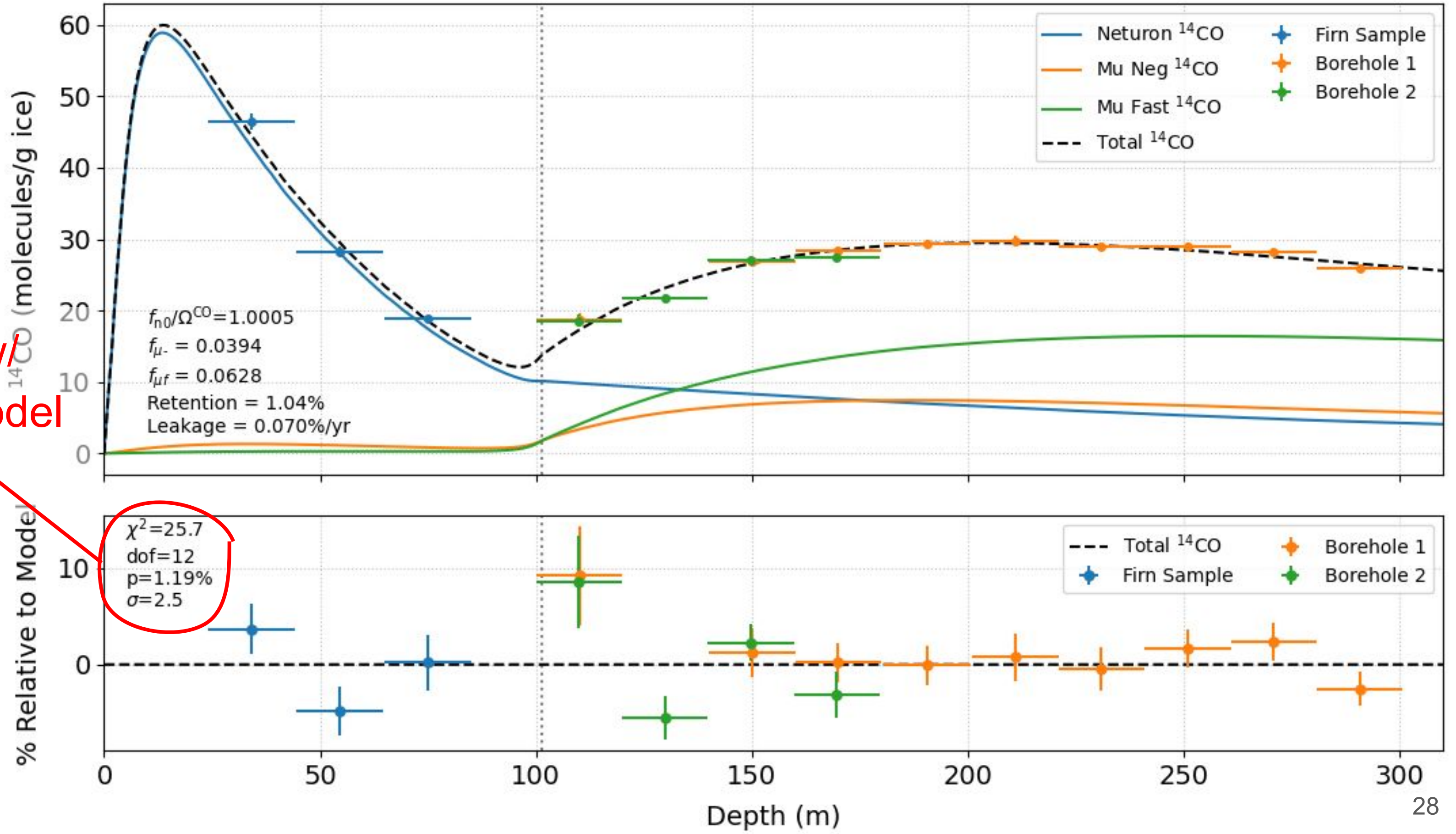

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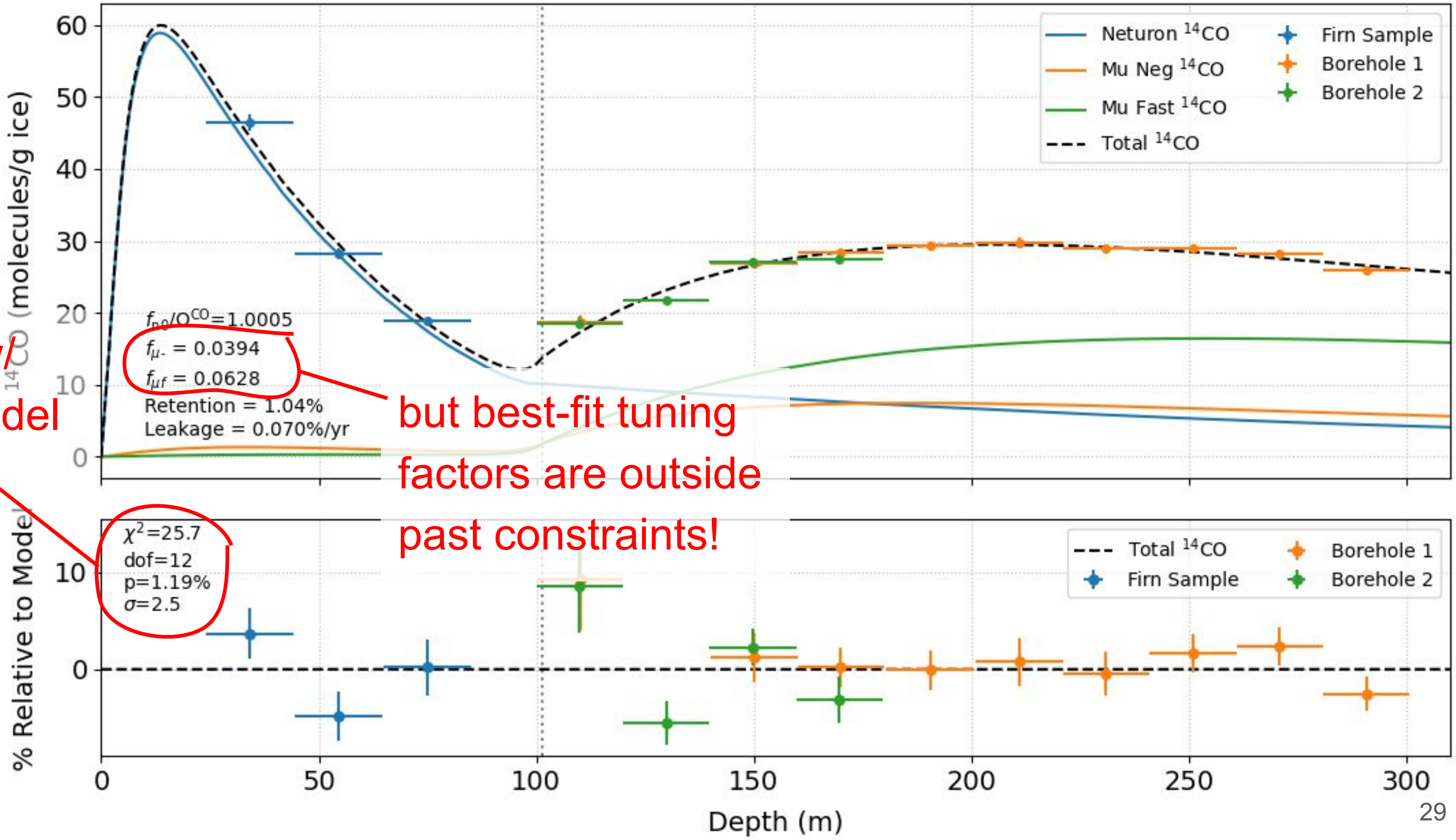

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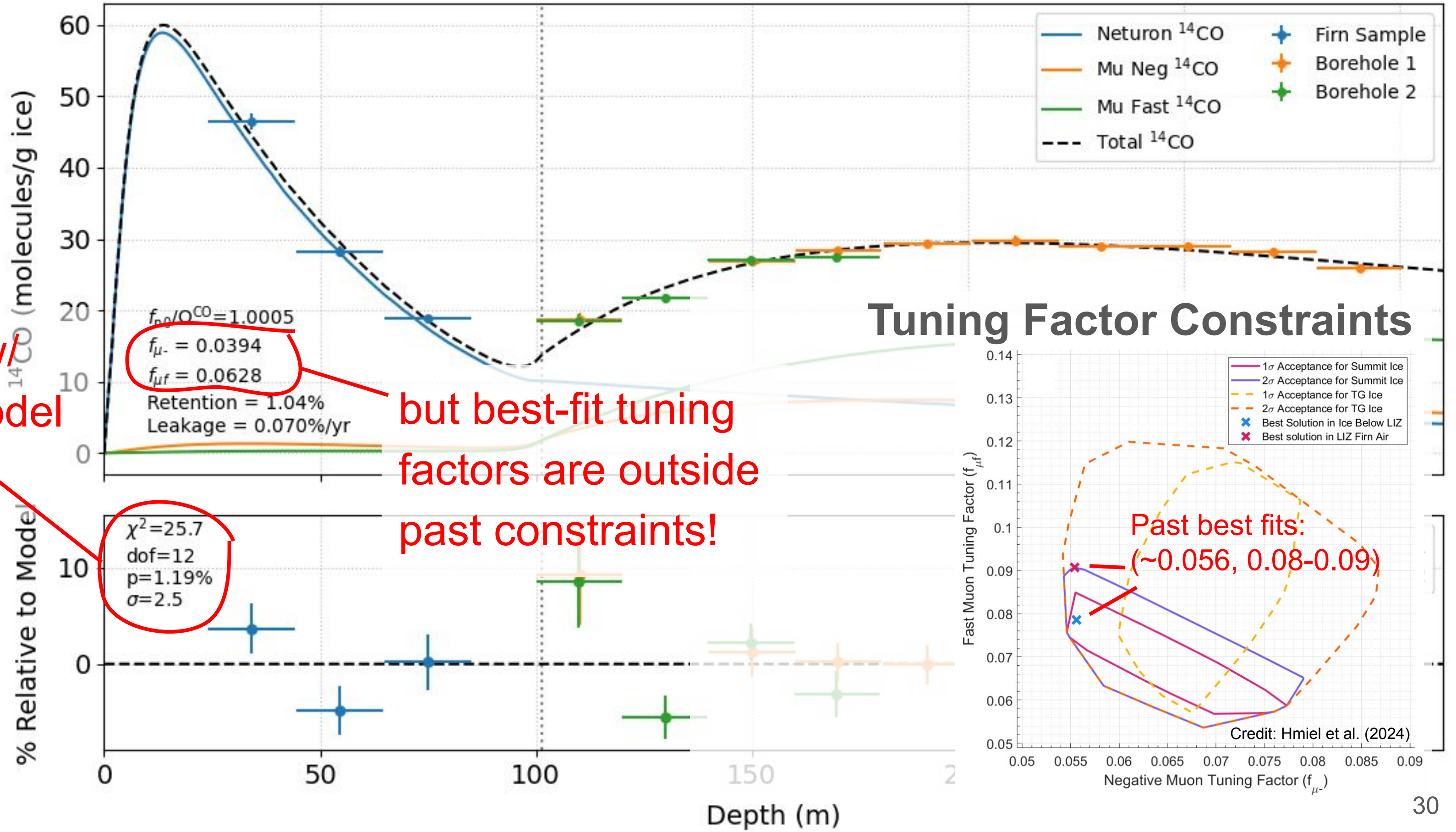

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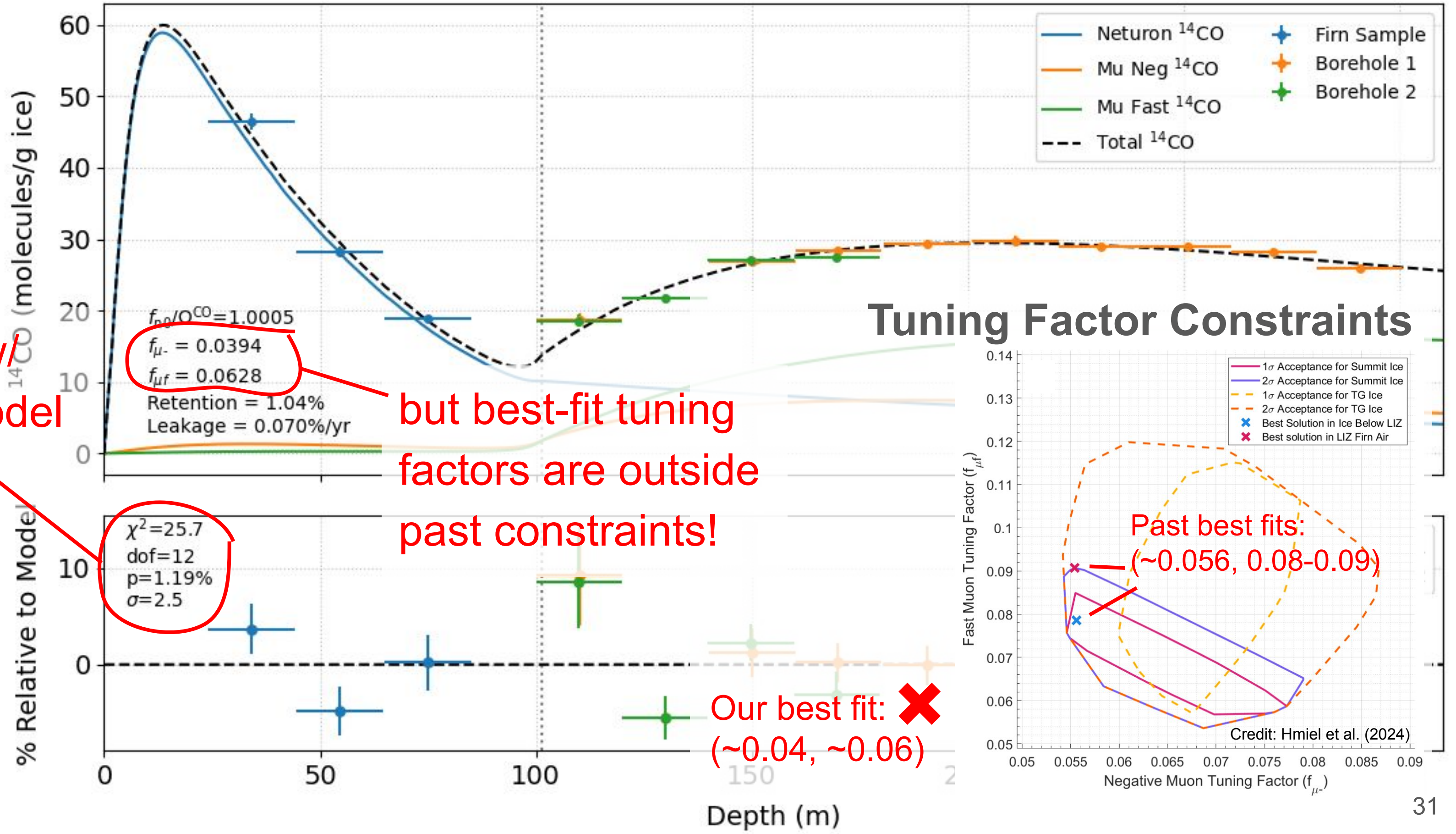

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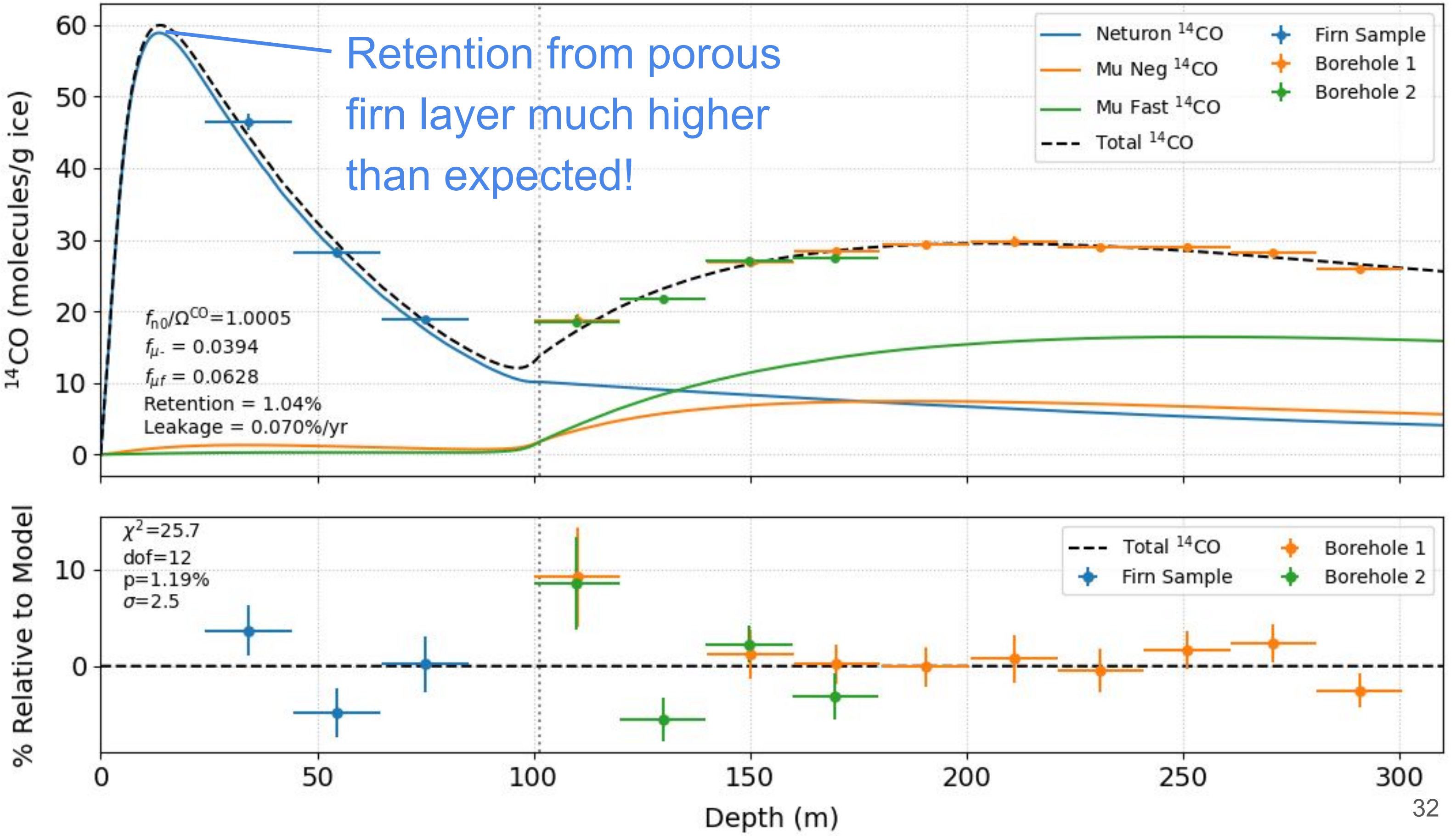
Our best fit: ✖ (~0.04, ~0.06)

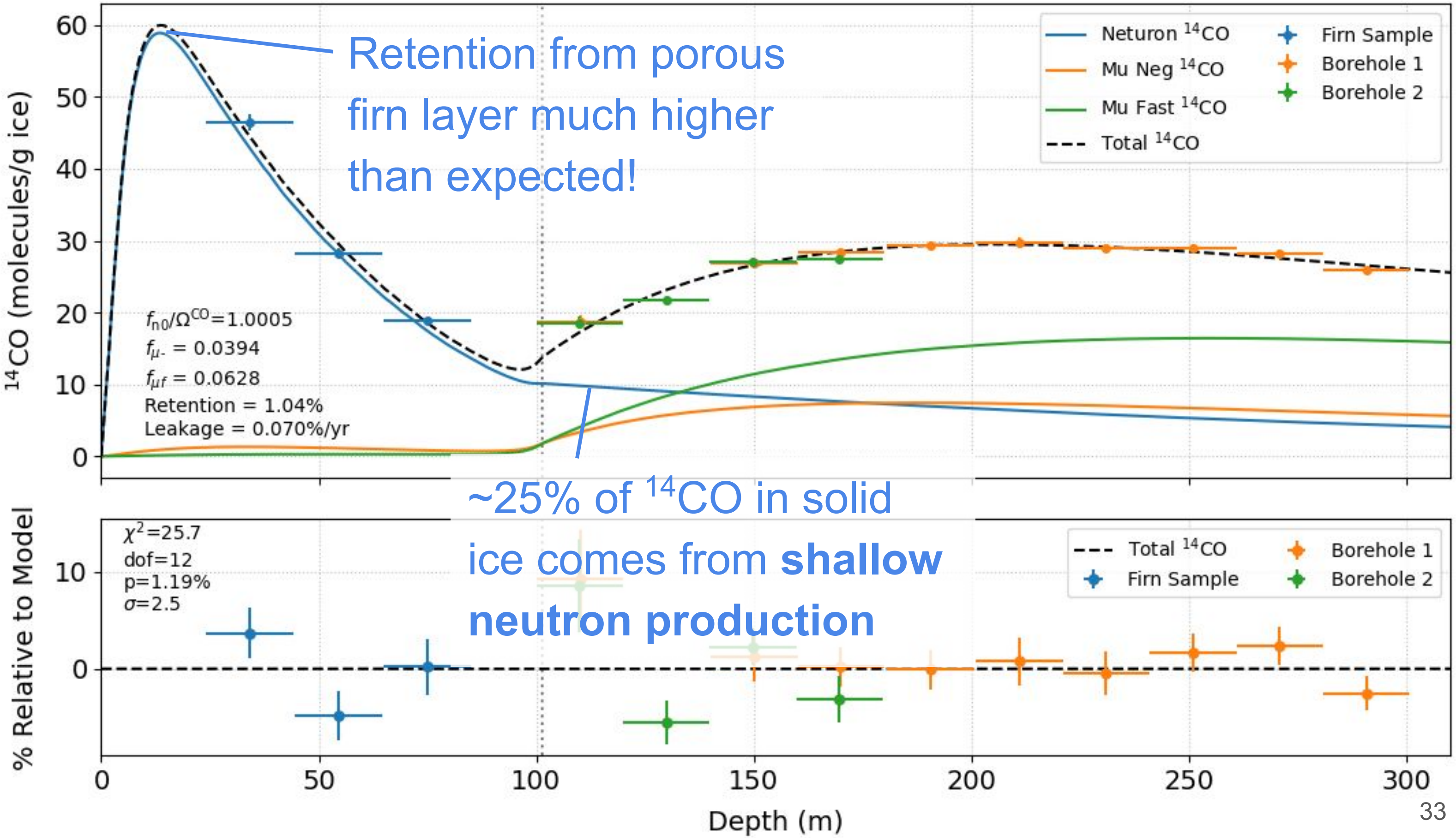
Preliminary Results

^{14}CO measurements w/ simple χ^2 fit to data, assuming constant GCR history



Preliminary Results

^{14}CO measurements w/ simple χ^2 fit to data, assuming constant GCR history

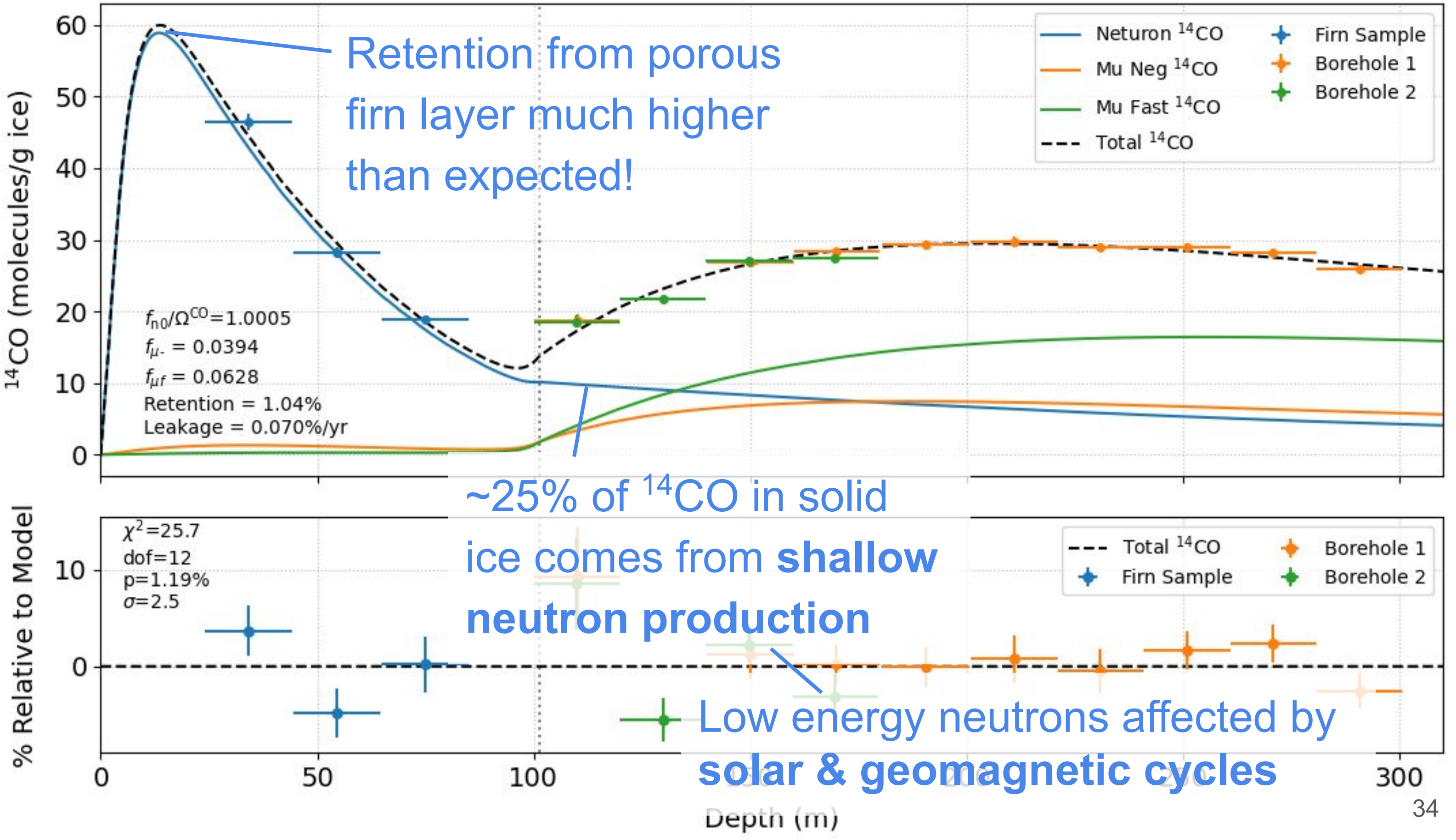


Retention from porous firn layer much higher than expected!

~25% of ^{14}CO in solid ice comes from **shallow neutron production**

Preliminary Results

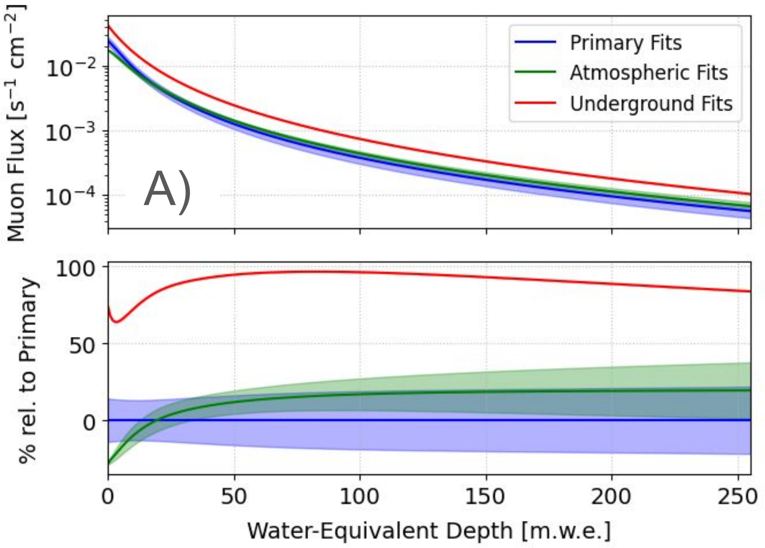
^{14}CO measurements w/ simple χ^2 fit to data, assuming constant GCR history



Systematic Uncertainties

Production Rate Uncertainties:

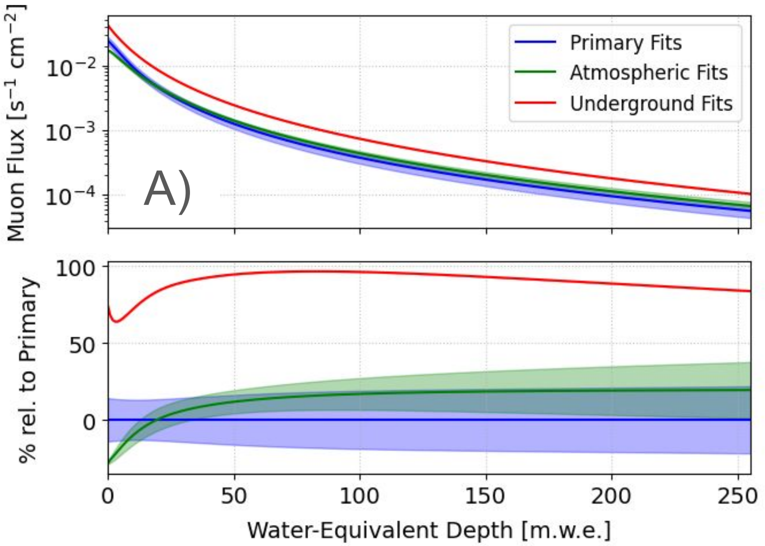
A) Underground muon spectrum

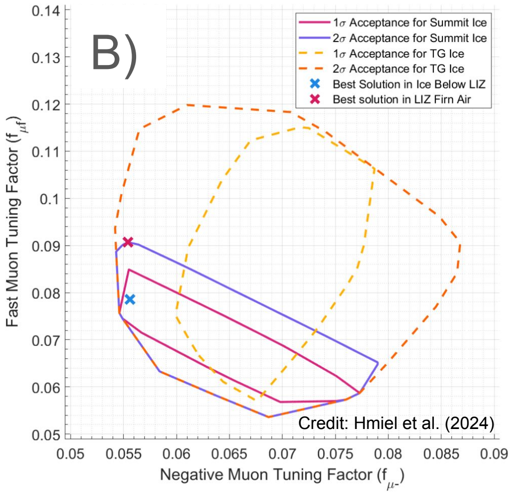


Systematic Uncertainties

Production Rate Uncertainties:

A) Underground muon spectrum
B) ^{14}CO Production tuning factors





Credit: Hmiel et al. (2024)

Our best fit: ✖
(~0.04, ~0.06)

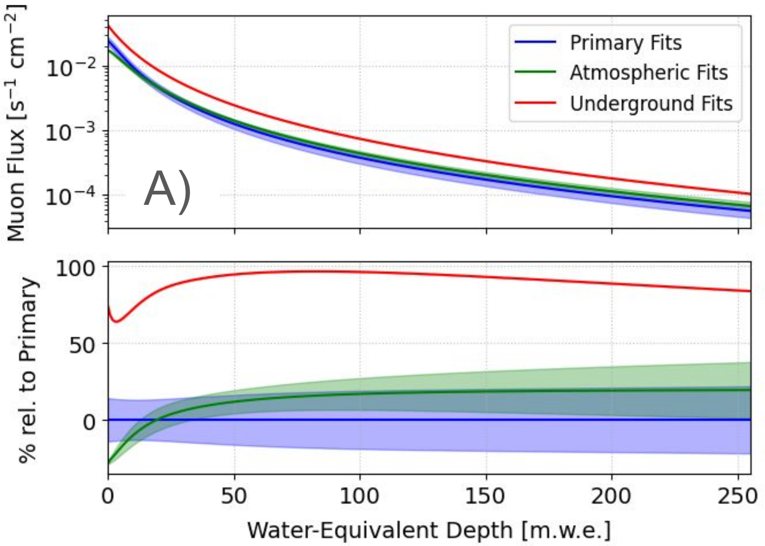
Systematic Uncertainties

Production Rate Uncertainties:

A) Underground muon spectrum
B) ^{14}CO Production tuning factors

Accumulation Uncertainties:

C) Retention & leakage from shallow firn layer



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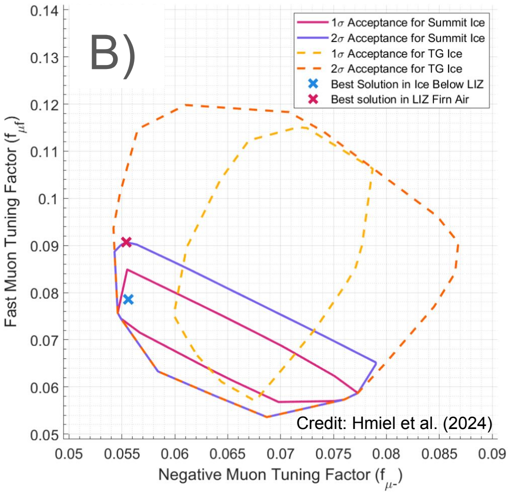


Systematic Uncertainties

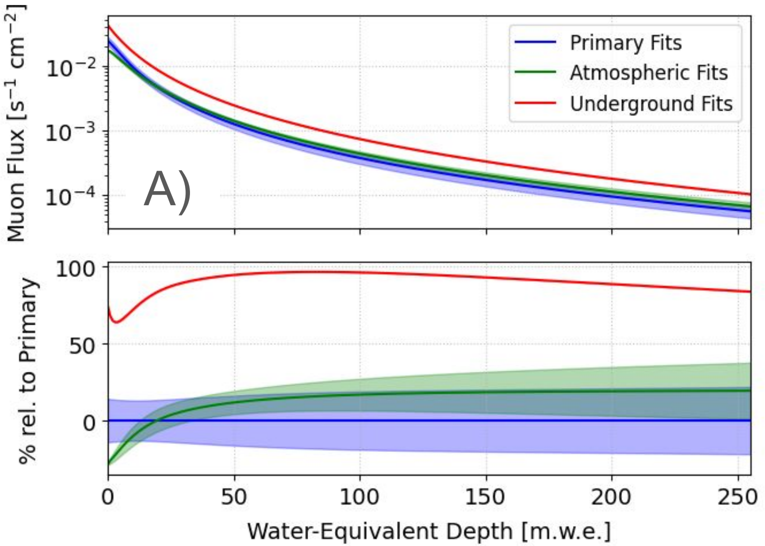
Production Rate Uncertainties:

A) Underground muon spectrum
B) ^{14}CO Production tuning factors

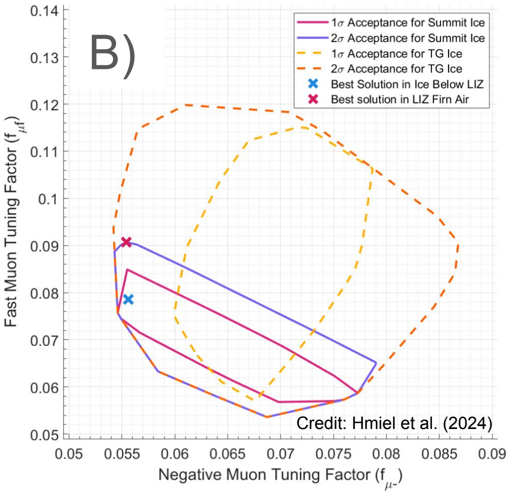
Accumulation Uncertainties:

C) Retention & leakage from shallow firn layer

Plan to address uncertainties:
Incorporate additional data from past studies at Taylor Glacier, Antarctica & Summit, Greenland



Our best fit: ✖ (~0.04, ~0.06)



Summary

Goal: Constrain galactic cosmic ray time dependence with ^{14}CO in Antarctic ice

3σ(5σ) Sensitivity: ~8%(12%) over past ~7,000 yrs, w/ ~700-year resolution

Preliminary analysis appears consistent w/ constant GCR History,
but requires production rates outside expected range

Next Steps:

- ➢ Incorporate existing data from Taylor Glacier, Antarctica & Summit, Greenland
- ➢ Propagate systematic uncertainties
- ➢ Final null hypothesis p-value & σ
- ➢ Best fits & constraints on parameters

Acknowledgements

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References

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- B. Heisinger et al. Earth Plan. Sci. Lett. 200 no. 3, (2002) 357–369.
- V. V. Petrenko et al. Cryosphere 18 no. 8, (2024) 3439–3451.

Image Source: ESA

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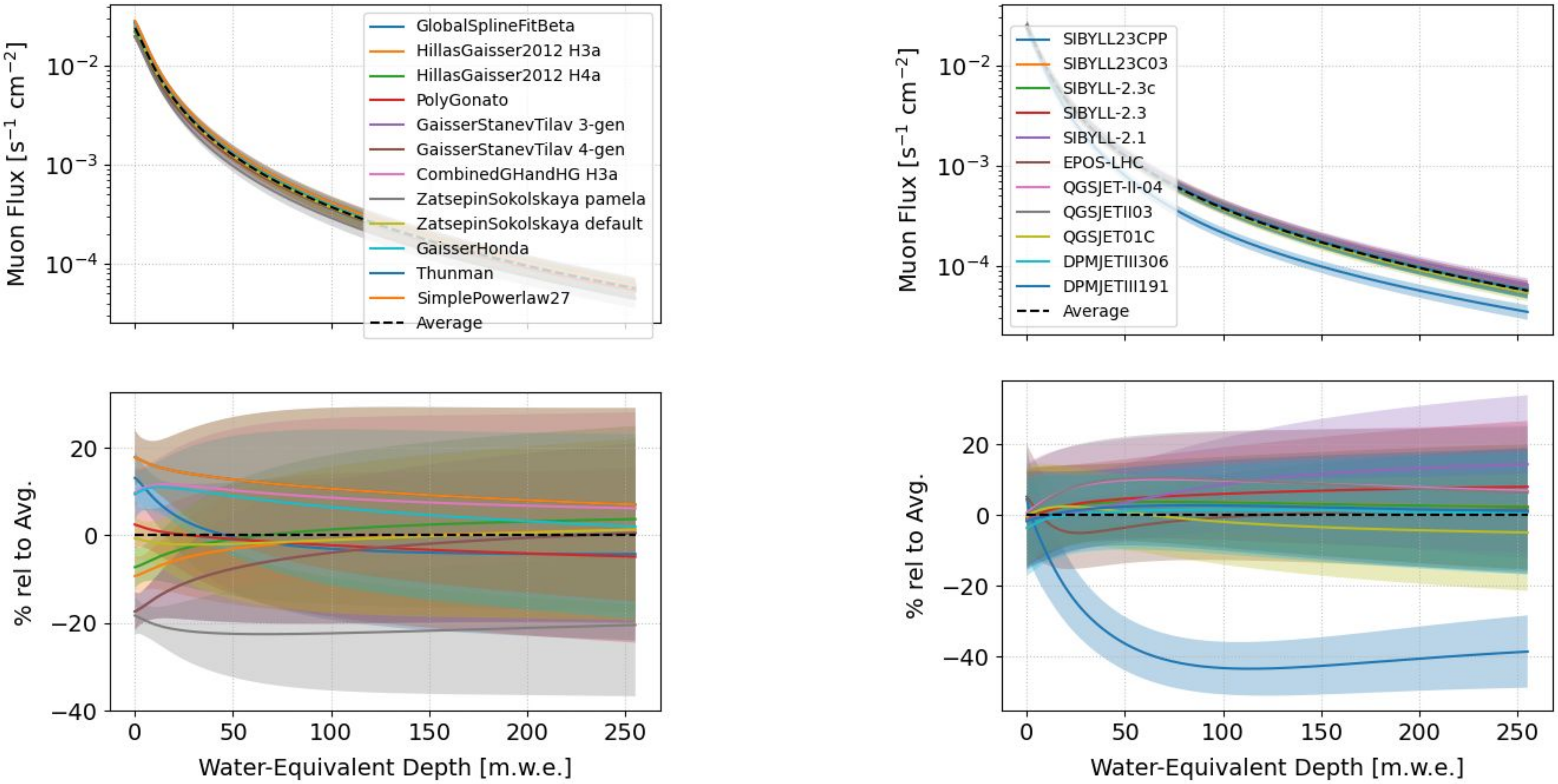
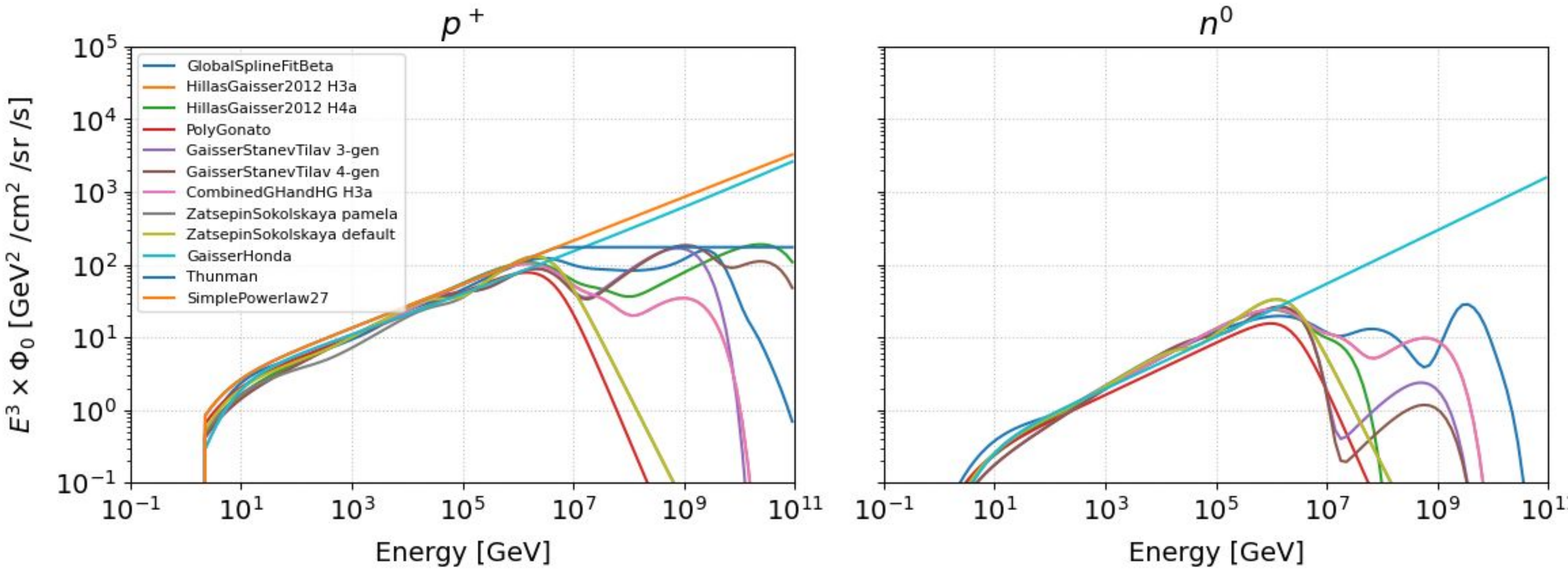
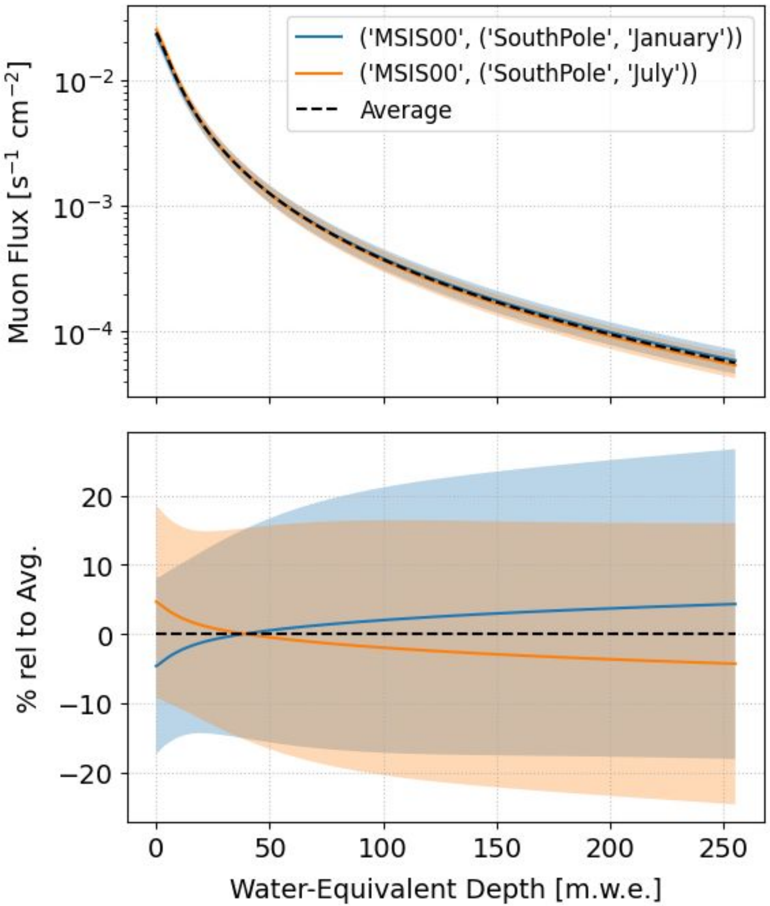
MCEq Parameterization Uncertainties

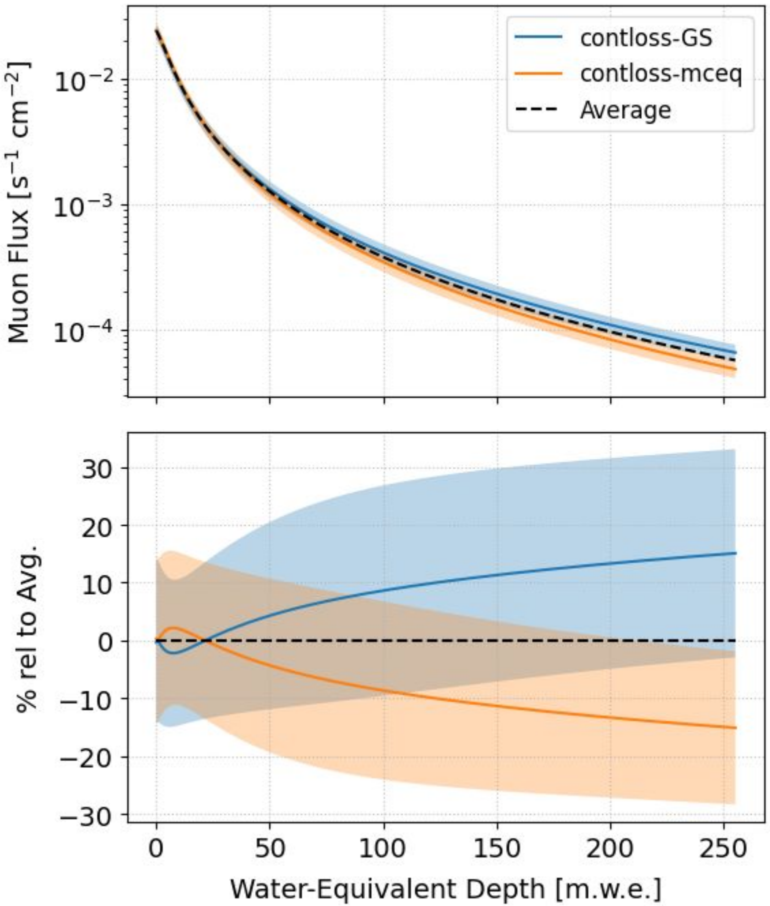


Primary CR Spectrum Fits (MCEq built-in)



MCEq Parameterization Uncertainties cont.





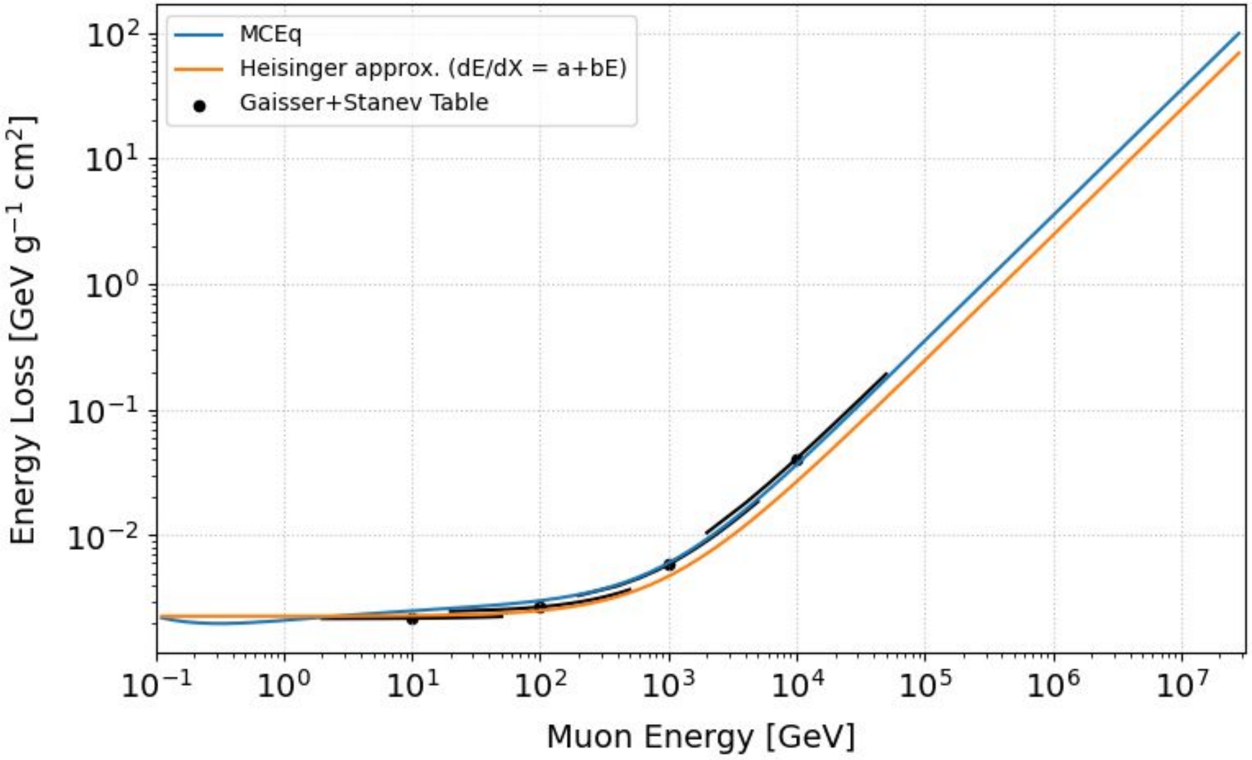
Muon Continuous Energy Loss (dE/dX)

$$-\frac{dE_\mu}{dX} = a + b\,E_\mu$$

Table 24.2: Average muon range R and energy loss parameters calculated for standard rock [53]. Range is given in km-water-equivalent, or 10^5 g cm^{-2}.

E_μ GeV	R km.w.e.	a MeV g^{-1} cm^2	$b_{\rm brems}$	$b_{\rm pair}$ 10^{-6} g^{-1} cm^2	$b_{\rm nucl}$	$\sum b_i$	$\sum b(\rm ice)$
10	0.05	2.17	0.70	0.70	0.50	1.90	1.66
100	0.41	2.44	1.10	1.53	0.41	3.04	2.51
1000	2.45	2.68	1.44	2.07	0.41	3.92	3.17
10000	6.09	2.93	1.62	2.27	0.46	4.35	3.78

T.K. Gaisser and T. Stanev
“Cosmic Rays”,
Phys Review D, revised 2007



Questions for IceCube

1. Which primary models are most reliable?
2. Which interaction models are most reliable?
3. Citation/Source for MCEq built-in muon energy loss function?
4. Does daemonflux have settings for location & altitude, or just sea-level?
5. Any datasets of spectra I should know about?
   Antarctica, ~3km, under <300m ice