Obtaining a History of the flux of Galactic Cosmic Rays using *in situ* ^{14}C Trapped in Polar Ice

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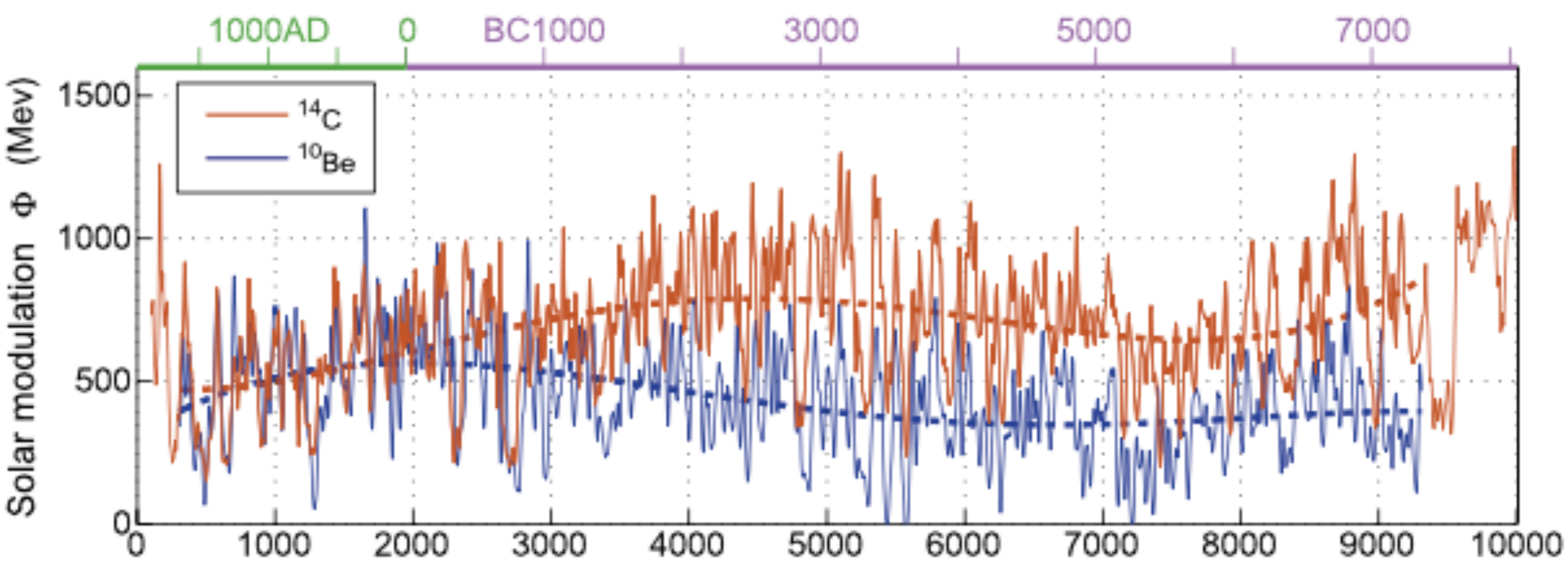
Overview

- Motivation: search for time variability in flux of cosmic rays above 100 GeV.
- *In situ* ^{14}C in ice as a potential tracer of the high-energy cosmic-ray flux.
  - ^{14}CO data from Taylor Glacier and Greenland Summit.
- Sensitivity to time variations in the cosmic-ray flux.
  - Investigation of simulated data sets, assuming several simple models of time-varying flux, at a location such as Dome C.
- Conclusions and future work.

Past Variations in Radionuclides

- E.g., measurements of ^{10}Be and ^{14}C: multiple episodes of past variability.

M. F. Knudsen et al., GRL **36**:2009, L16701.



- Solar behavior affecting cosmic rays below 10 GeV? If the "background" of Galactic cosmic rays is constant, these variations can be used to study changes to the heliosphere during the Holocene Epoch.

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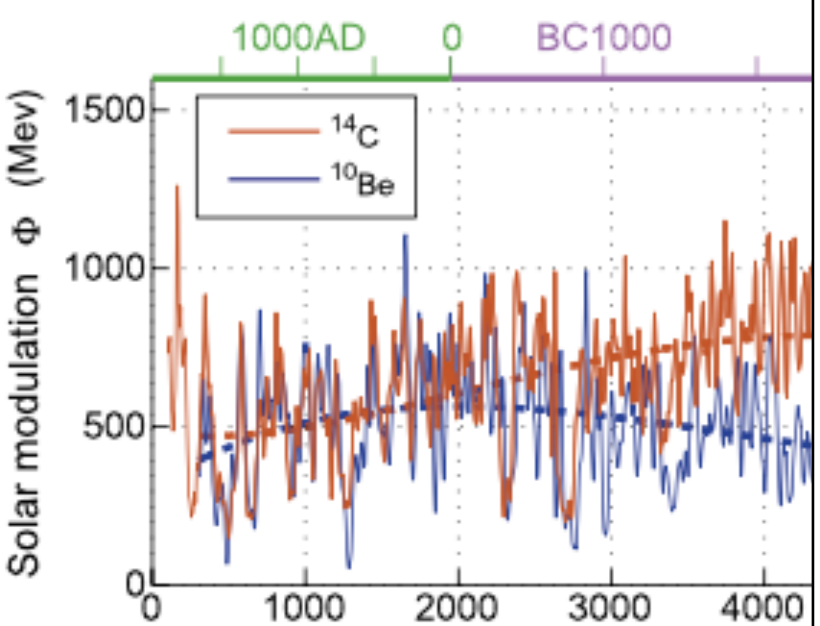
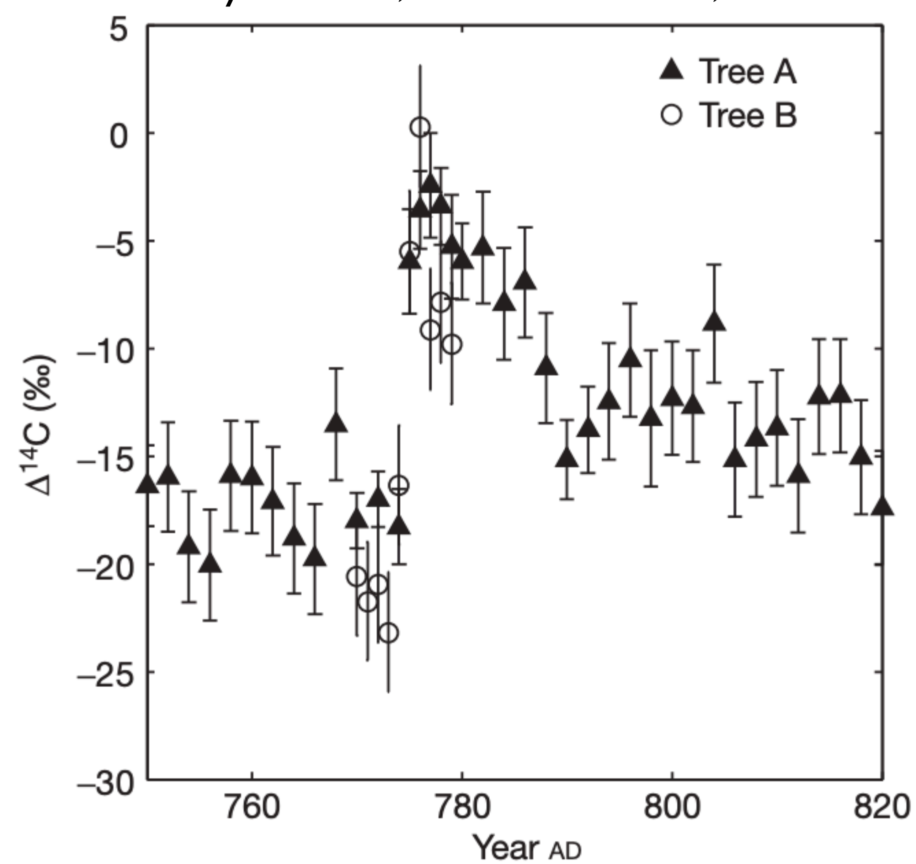
M. F. Knudsen et al., GRL **36**:2009, L16[…]



F. Miyake et al., Nature **486**:2012, 240-242



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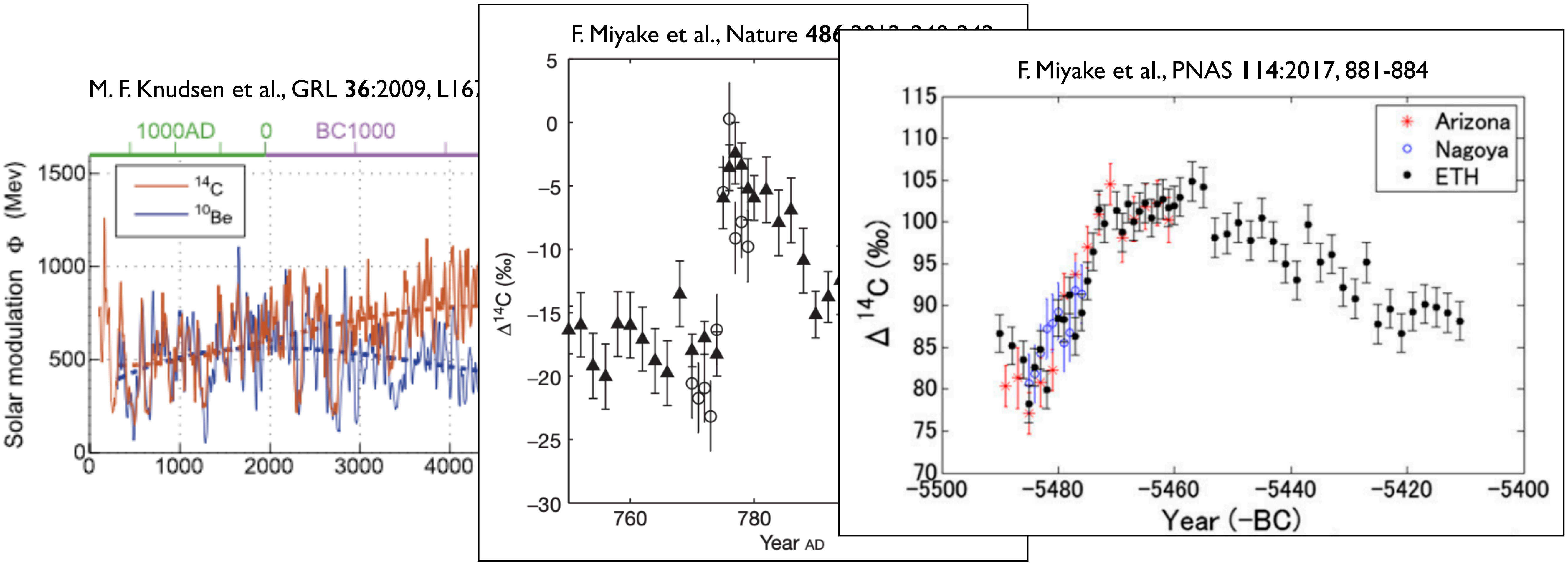

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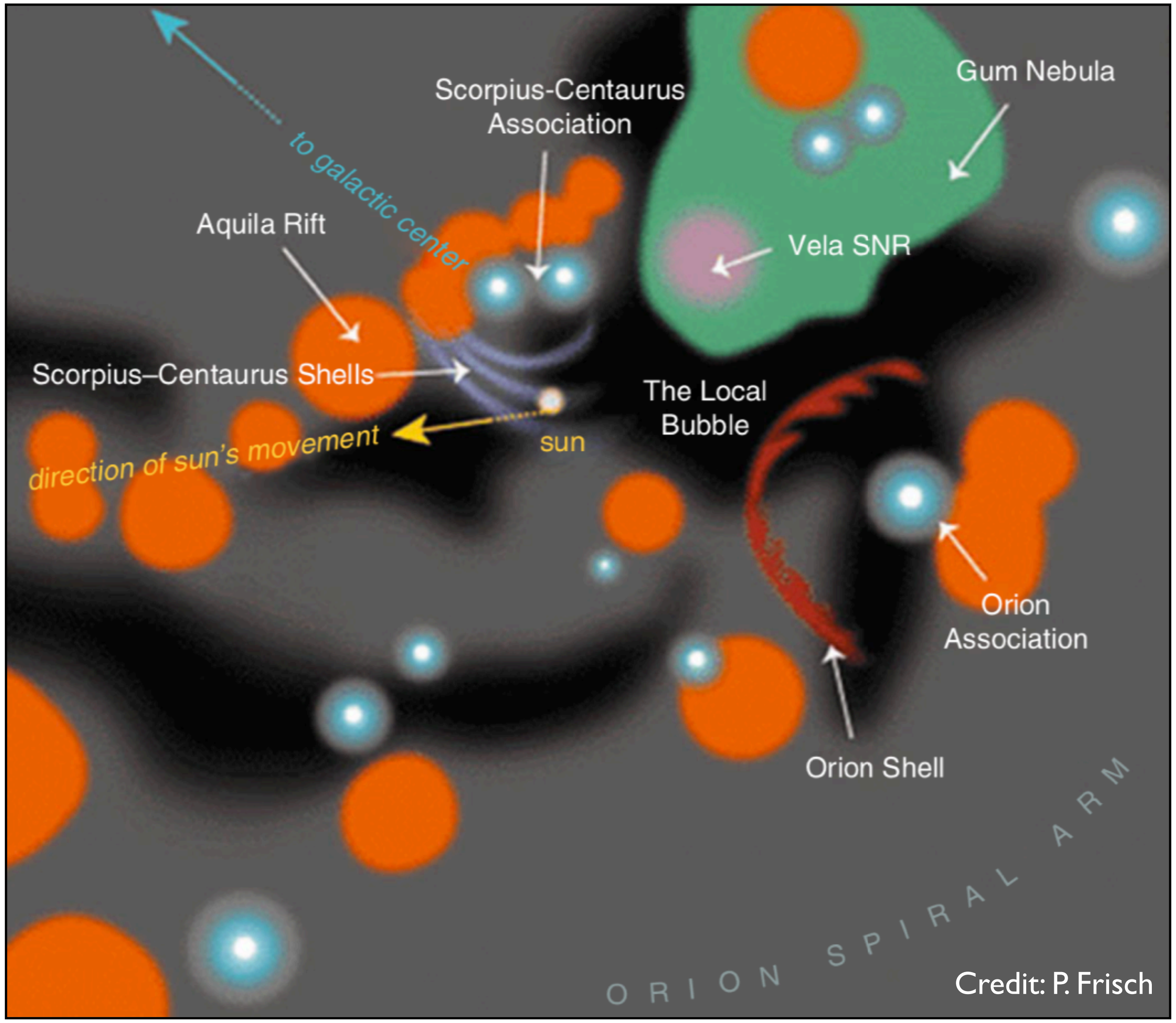
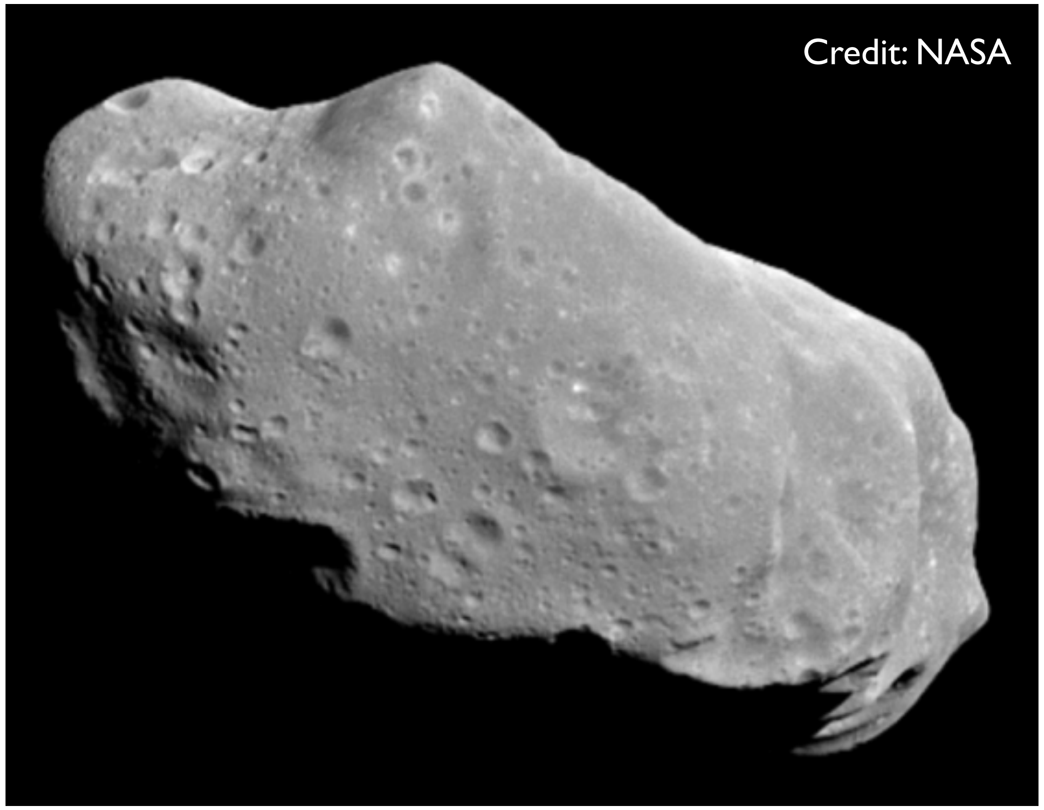
Is the Galactic CR Flux Constant?



- Local ISM & cosmic ray flux: see paper by P. Frisch and H. Mueller, Sp. Sci. Rev. (2010).

- CR flux *may* be constant to first order, though no *a priori* reason it *must* be.
- Possible perturbations:
  - Supernovae and remnants.
  - Motion of solar system through local bubbles & spiral arm of Milky Way.
  - Very long-term changes in MW star formation rate.
- Discussion in K. Scherer *et al.*, Sp. Sci. Rev. (2006).

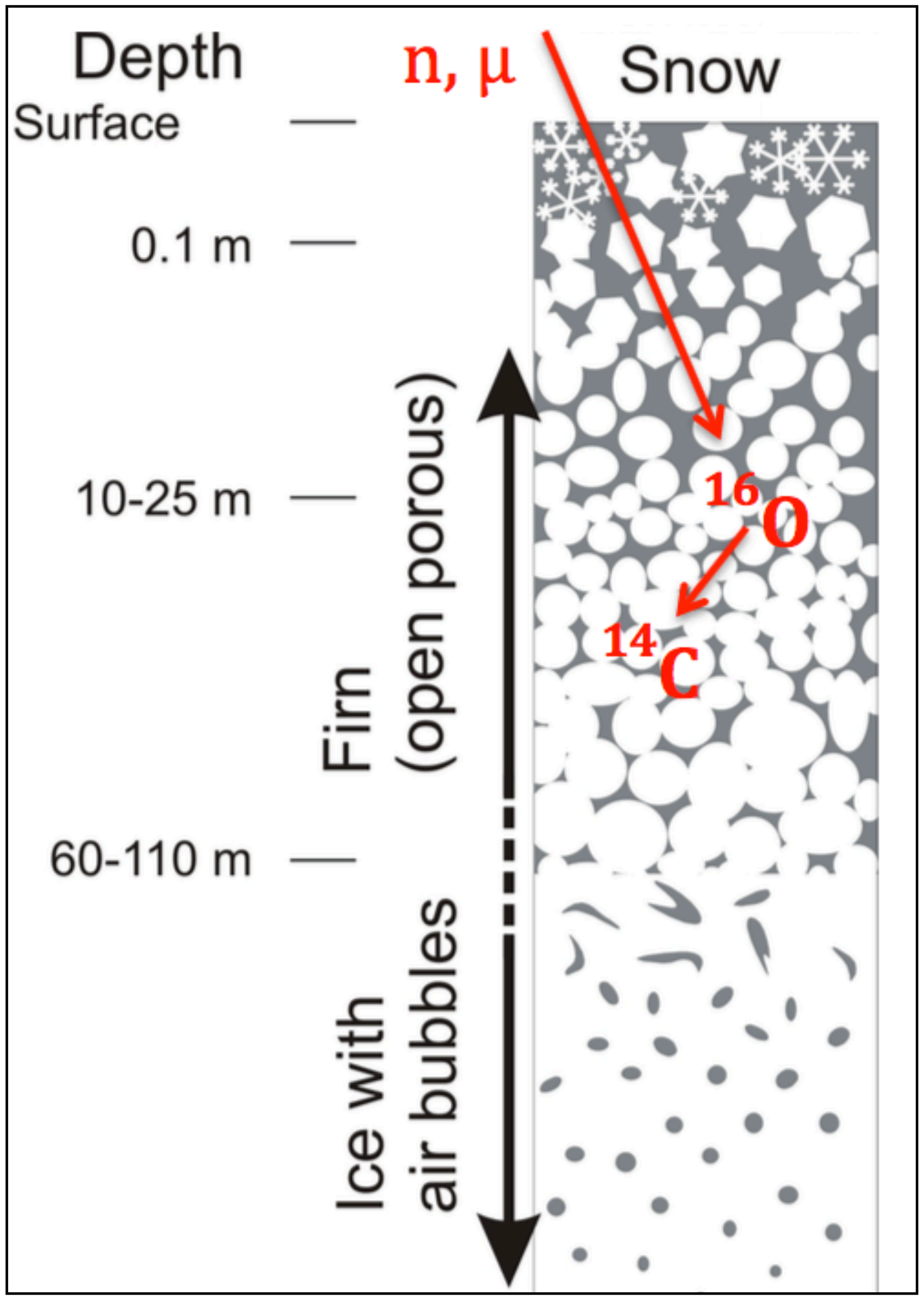
Flux Constraints from Meteoroids



- Meteoroids accumulate radionuclides with varying lifetimes, achieving "saturation" for some.
- Examples: ^{3}H, ^{10}Be, ^{14}C, ^{22}Na, ^{26}Al, ^{36}Cl, ^{39}Ar, ^{44}Ti, ^{53}Mn.

- Radionuclides constrain cosmic-ray flux over ~10^6 yr.
- Data suggest **constant CR flux**, to first order.
- Significant systematics:
  - Effect of solar modulation.
  - Meteoroid orbits.
  - Shielding effects of surface.
- Constant CR flux uncertain at ≳30%: R. Wieler *et al.*, Sp. Sci. Rev. (2011).

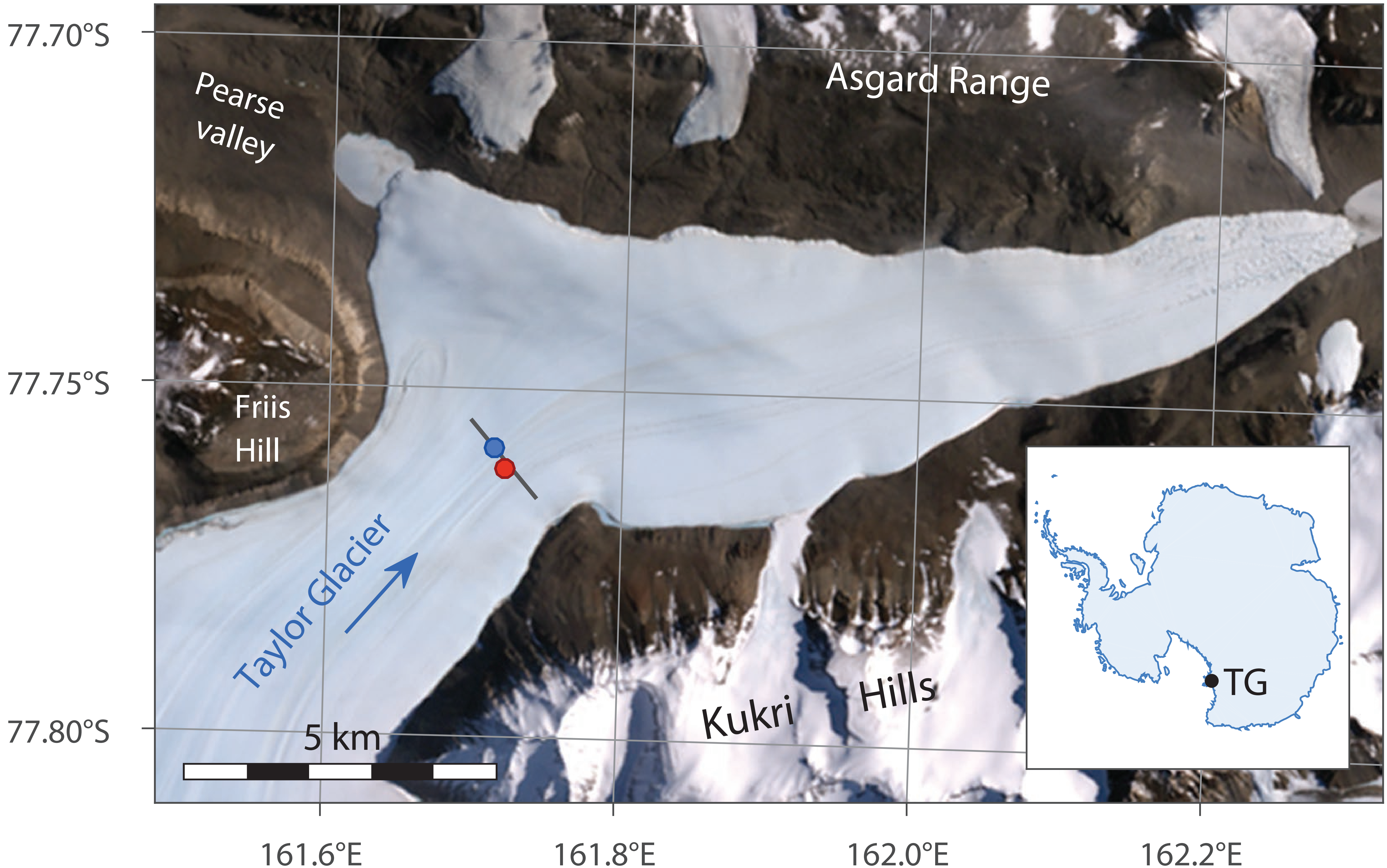
^{14}C in Ice Cores as a Flux Probe



After J. Schwander, "Gas Diffusion in Firn," 1996.

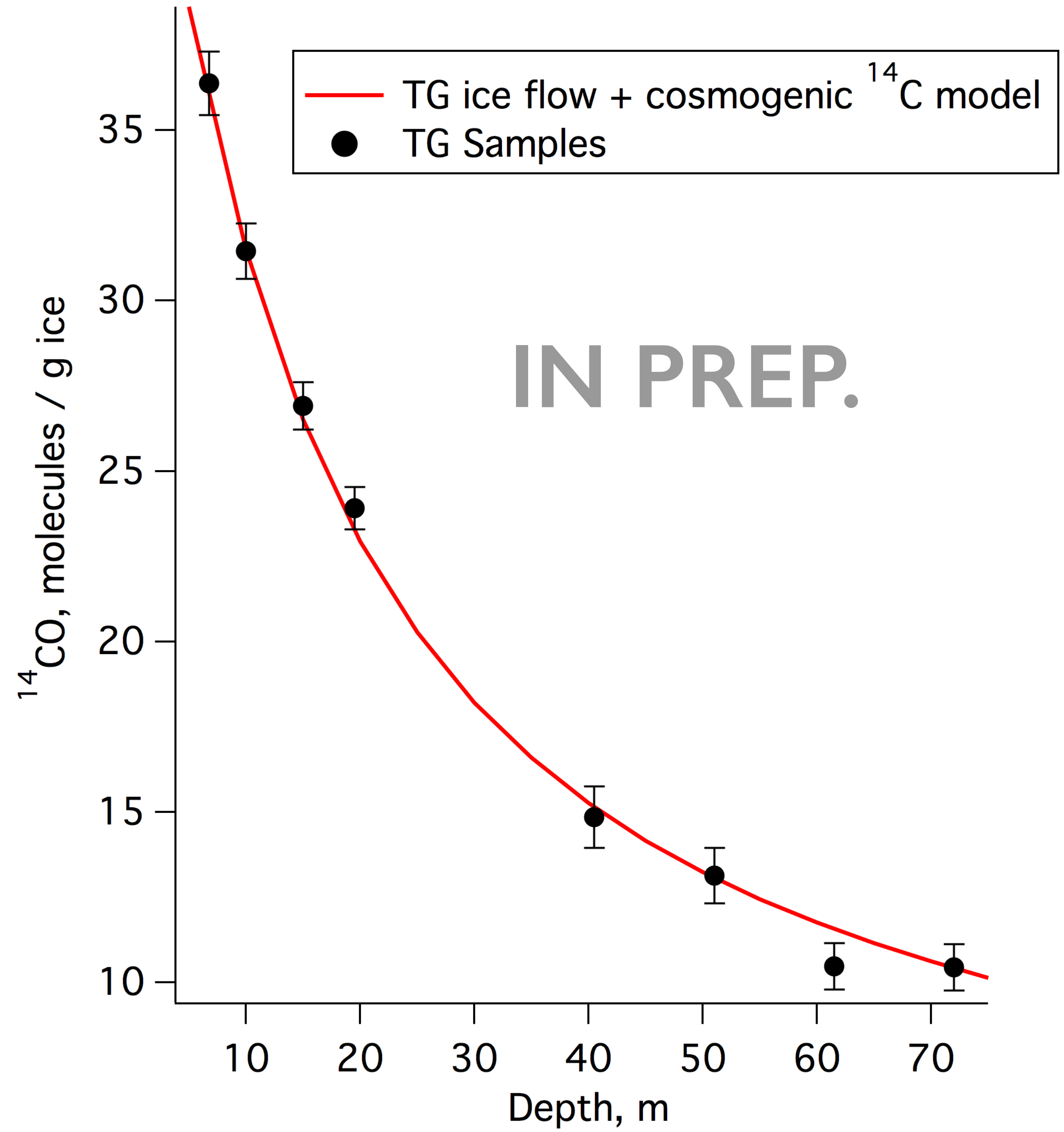
- Sources of ^{14}C in ice cores:
  1. Trapped air (CO_2, CO, CH_4).
  2. *In situ* cosmogenic production:
     A. Neutron (~1 MeV) spallation: $\mathcal{O}$(1 m) depth.
     B. Slow μ^- capture: $\mathcal{O}$(20 m) depth.
     C. Interactions with fast muons μ_f (>10 GeV); $\mathcal{O}$(≳60 m) depth.
- **Key points**: (1) *in situ* ^{14}C leaks from firn layer but is retained below; (2) cosmogenic ^{14}C dominates the CO phase at most sites.

In Situ ^{14}CO Production: Taylor Glacier



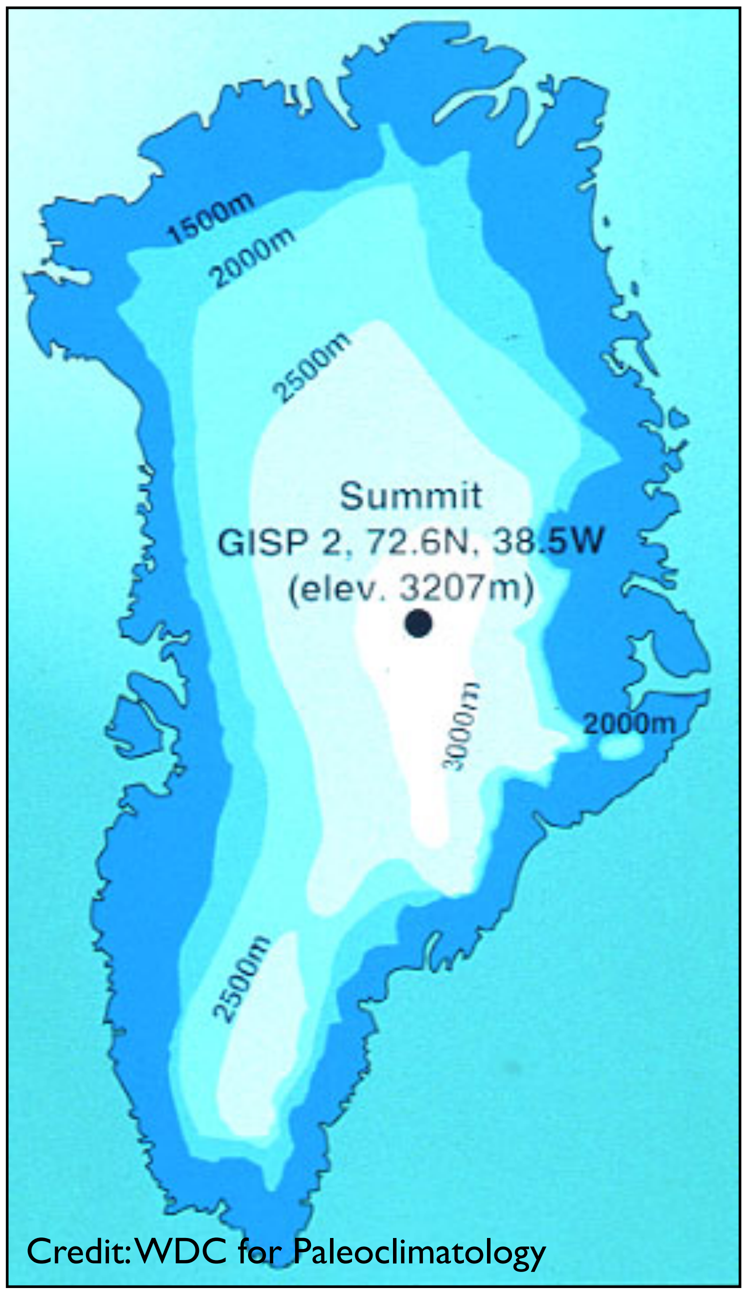
Measurements of ^{14}C at Taylor Glacier

- Preliminary ^{14}CO measurements: **M. Dyonisius** *et al.*, in preparation.
- ^{14}C is dominated by muon production at this site.
- **Fit**: adapted $^{10}Be + ^{26}Al$ production model in rock from Balco *et al.*, Quat. Geo. **3** (2008) + glacier ice flow model from Buizert *et al.*, JGR **117** (2012).
- Constraints on ^{14}CO production rates ***at the surface***:
  - $P_{0\mu^-} = 0.46 \pm 0.03$ mol./g/yr
  - $P_{0\mu_f} = 0.071 \pm 0.020$ mol./g/yr



In Situ ^{14}CO: Greenland Summit

- Constraints on cosmogenic ^{14}C in the firn layer.

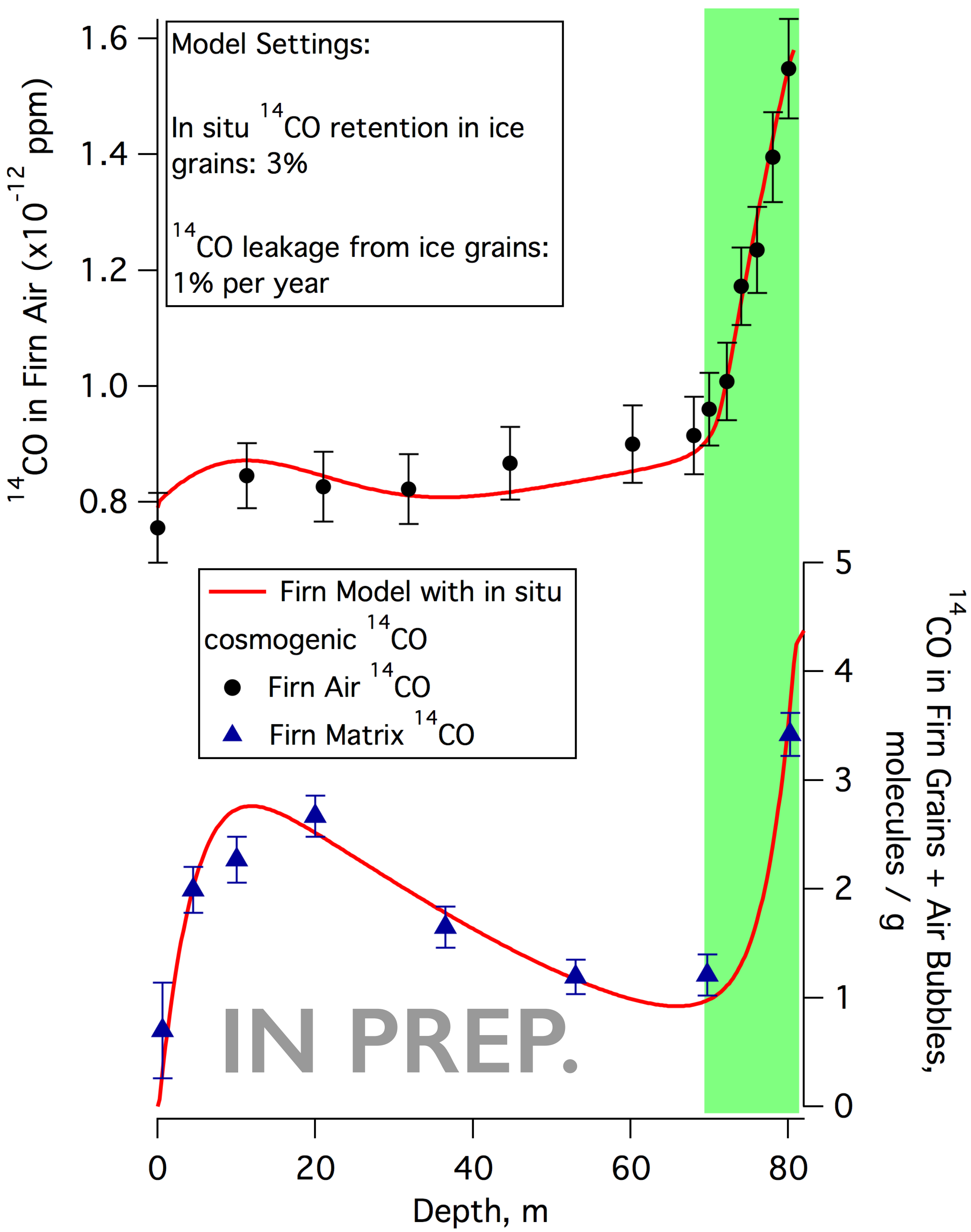


Credit: WDC for Paleoclimatology


Credit: Jon Edwards


Credit: Xavier Fain

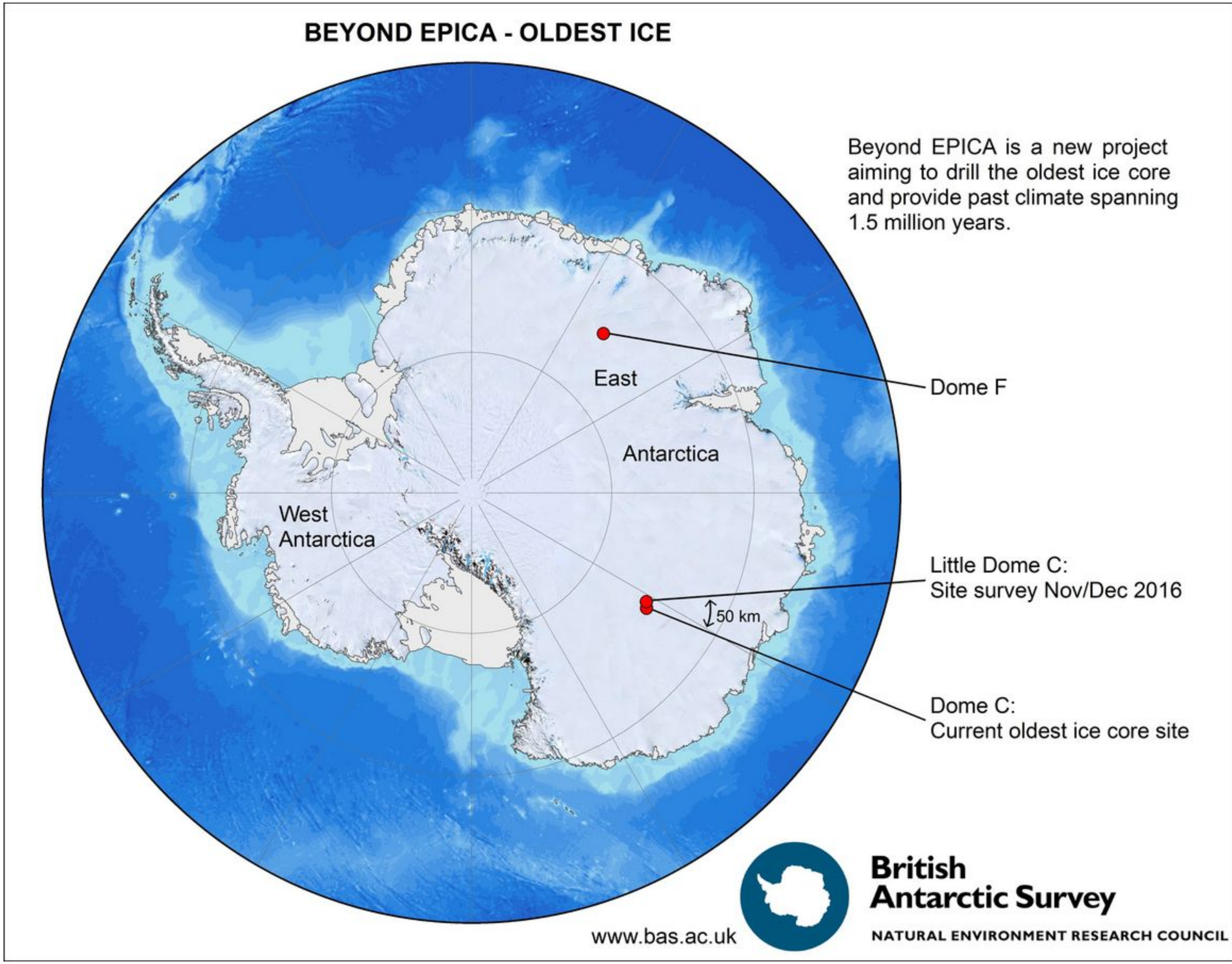
In Situ Cosmogenic ^{14}CO in Firn



- Preliminary ^{14}CO measurements: **B. Hmiel** *et al.*, in preparation.
- In firn, only ~3% of ^{14}CO produced is retained in the ice matrix.
- The retained ^{14}CO leaks out of the ice grains at ~1% yr^{-1}.
- *In situ* cosmogenic ^{14}C below the firn layer is almost entirely from fast muons.

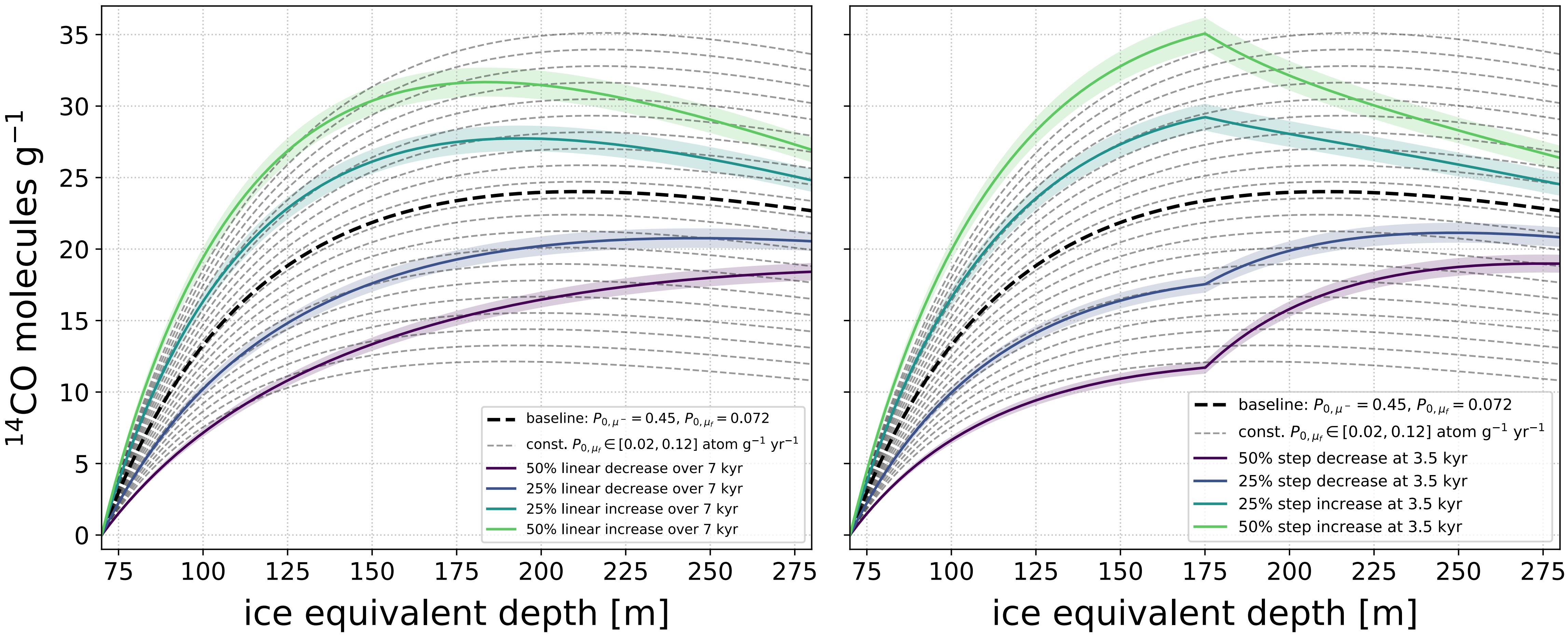
Cosmogenic ^{14}C at Dome C

- Stable & low accumulation rate: 3 cm ice equivalent yr^{-1}.
- Good CR exposure at shallow depths: expect large ^{14}C signal.
- Shallow dry-drilled ice cores provide access to ~7 kyr of data.



Simulated History of ^{14}CO

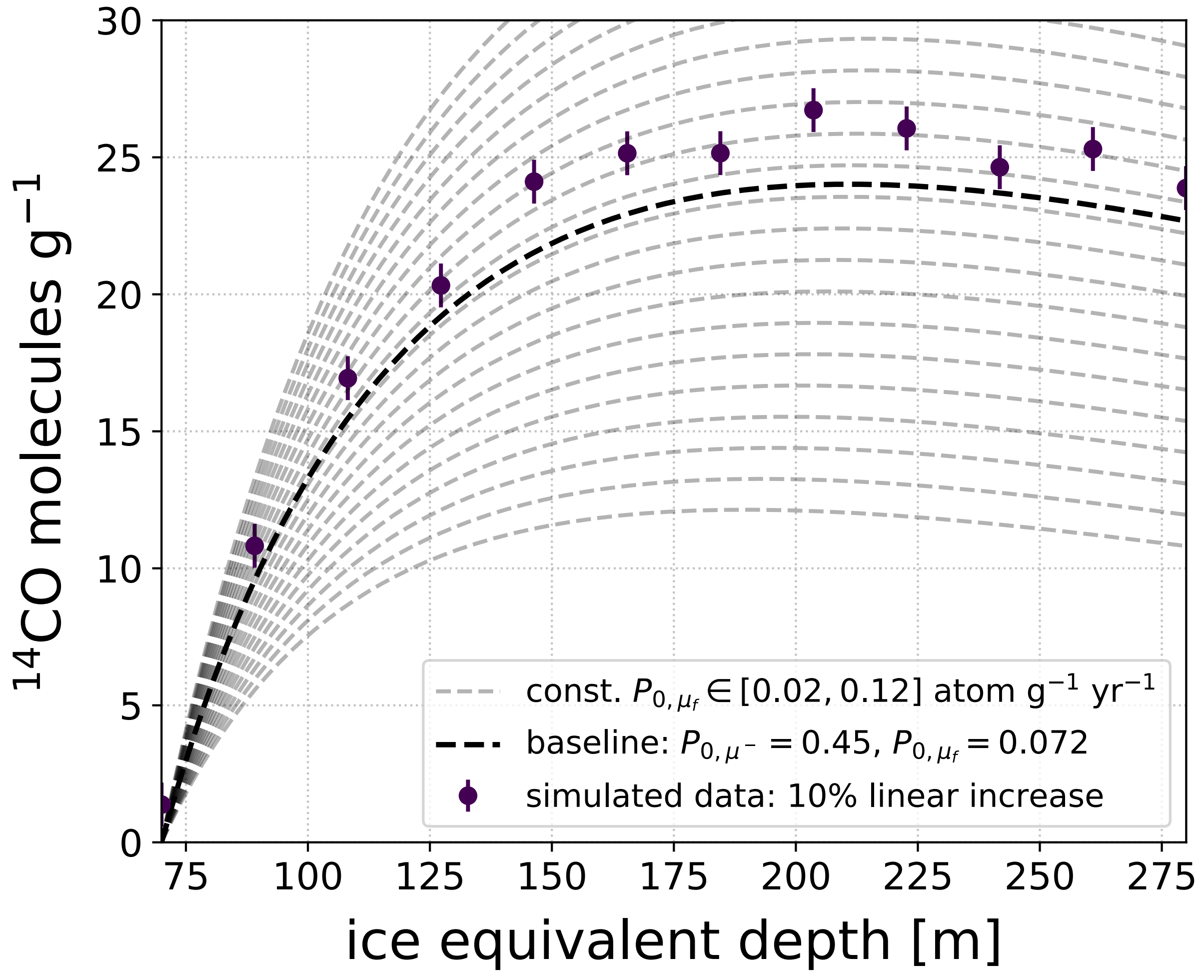
- Dashed line: ^{14}CO profile at depth at Dome C assuming constant production rates (values from best fits to TG data).

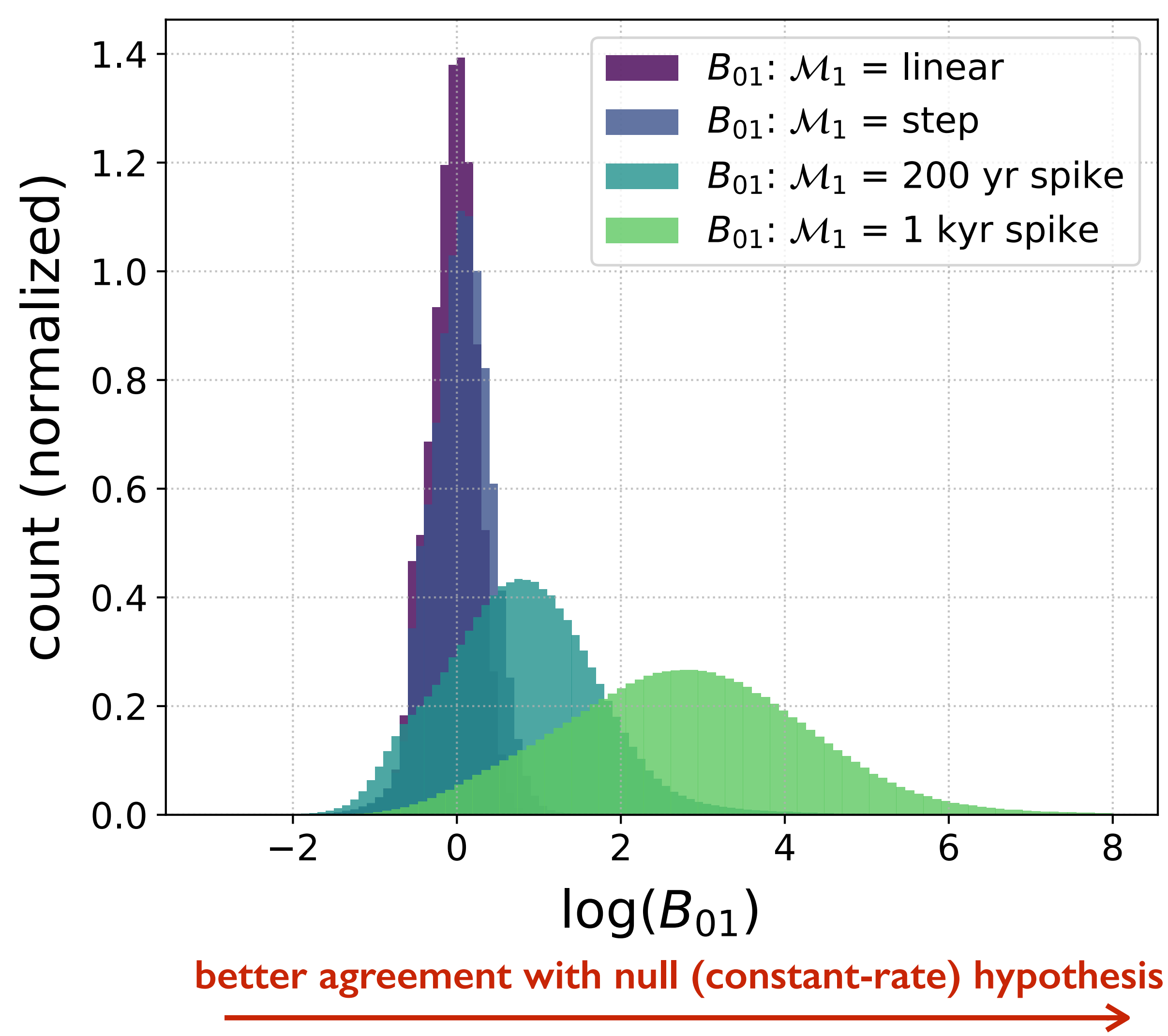


- Colored contours: ^{14}CO profiles from linear change in production rates (left) or abrupt change @ 3.5 kyr (right).

Dome C Sensitivity: Shape Analysis

- Left: simulated ^{14}CO profile with linear increase in rate P_{0,μ_f}.





- Right: distribution of Bayes Factor B_{01} in >10^6 simulated datasets with constant P_{0,μ_f}, for 4 time-varying alternative models.

Projected Sensitivity at Dome C

- Calculate prob. that a constant P_{0,μ_f} produces $B_{01} \ll 1$ by chance.
- Sensitivity: when $p \lesssim 10^{-3}$ (or $\lesssim 3\times10^{-7}$) at least 50% of the time.

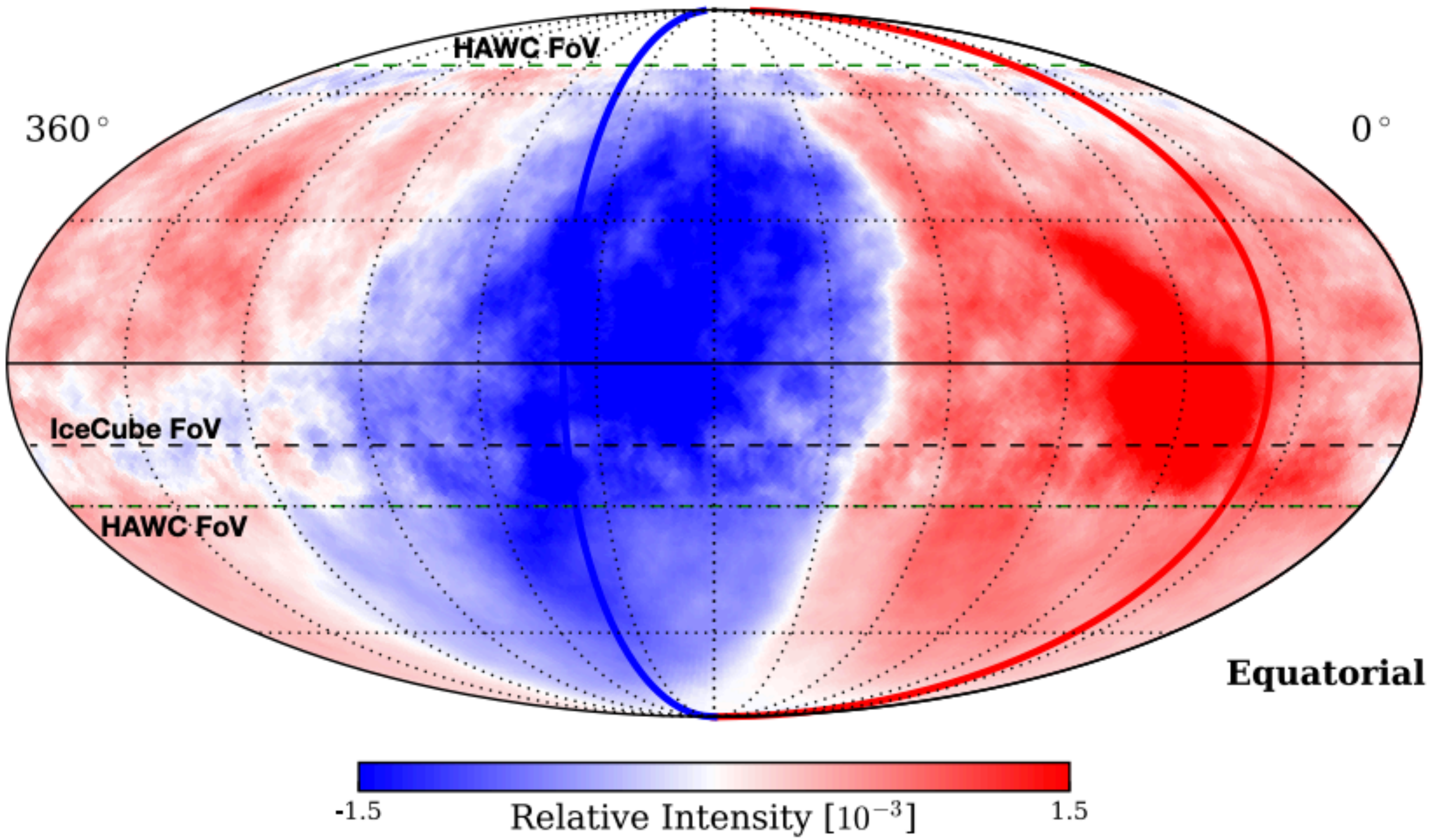
Difference from Baseline Model	Sensitivity at 3σ (>50% of trials)	Sensitivity at 5σ (>50% of trials)
Linear increase over 7 kyr	14%	21%
Abrupt step-like increase at 3.5 kyr	9%	15%
Impulsive increase: 200 yr @ 3.5 kyr	90%	152%
Impulsive increase: 1 kyr @ 3.5 kyr	17%	30%

Summary

- ^{14}CO locked into ice sheets could be a sensitive new probe of the historical cosmic-ray flux at energies > 100 GeV, beyond the range of solar modulation effects.
  - New test of variability in the flux of Galactic cosmic rays over timescales of $\sim 10^4$ yr.
  - First look at the **high-energy part of the spectrum**. Can separate out the effects of solar modulation on ice core ^{10}Be and atmospheric ^{14}C.
  - Conservative estimates of sensitivity to changes in historical flux are well below 30% uncertainties in flux.
- **Dome C** would be an excellent site to measure cosmogenic ^{14}C sensitive to high-energy cosmic rays. Exploring campaign during 2022/2023 drilling season.

Anisotropy of TeV CRs

- Evidence the local IMF and/or local over-density of CR accelerators creates a statistically significant cosmic ray anisotropy at 10 TeV.



HAWC Collaboration, IceCube Collaboration: ApJ **871**:96, 2019

^{14}CO as a Signature of *In Situ* Production

- Why is ^{14}C in the CO phase in ice known to be made *in situ*?
  - Atmospheric ^{14}C produced by thermal neutrons quickly reacts with oxygen and forms CO.
  - The CO in the atmosphere quickly forms CO_2.
  - ^{14}CO is produced exclusively within the ice, and is used to date trapped atmospheric CO_2.
- References:

  - Lal *et al.*, Nature **346**:350, 1990.
  - Lal & Jull, GRL **17**:1303, 1990.
  - van Roijen *et al.*, Radiocarbon **37**:165, 1995.

Flow Line Model at Taylor Glacier

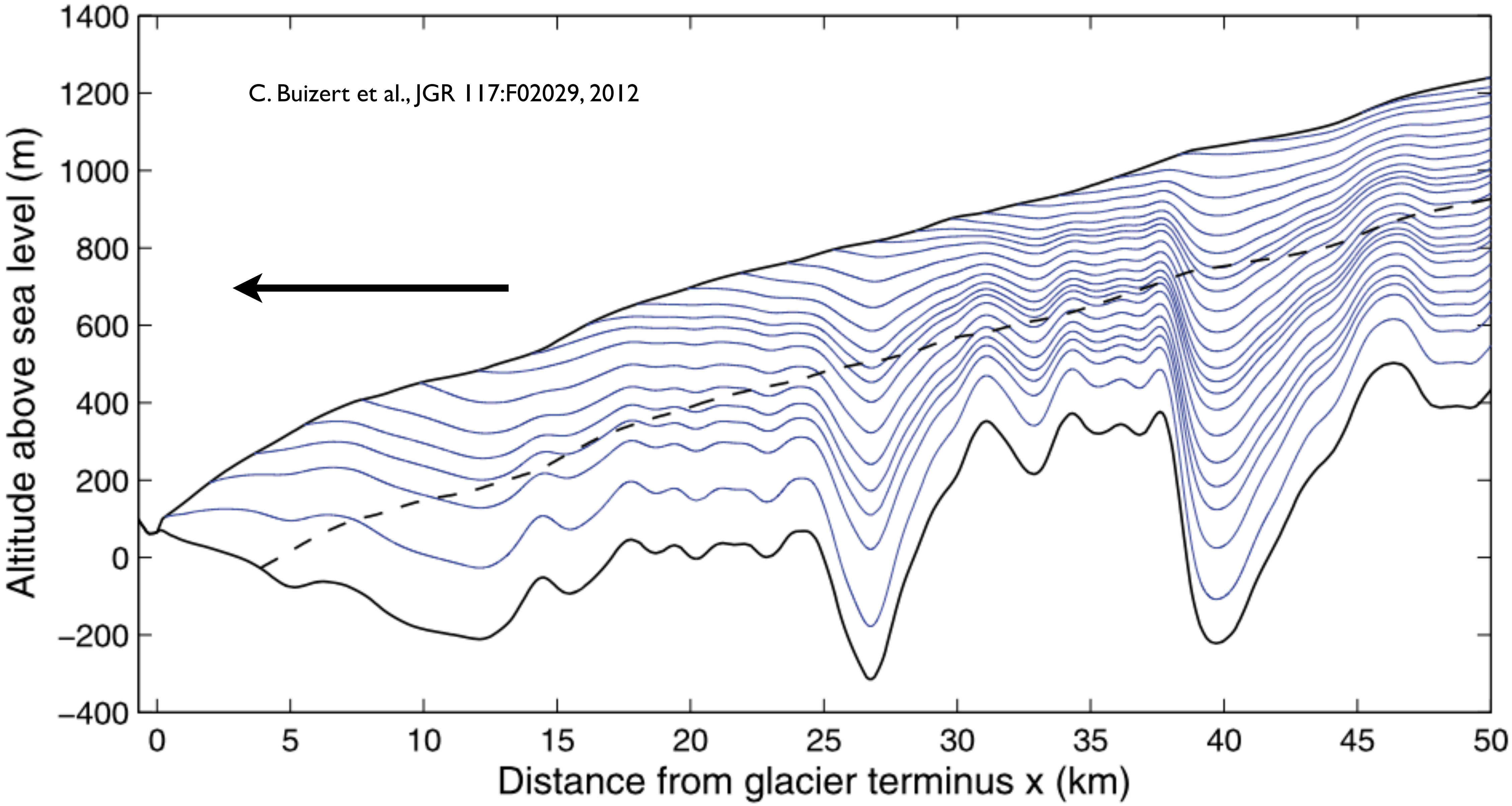
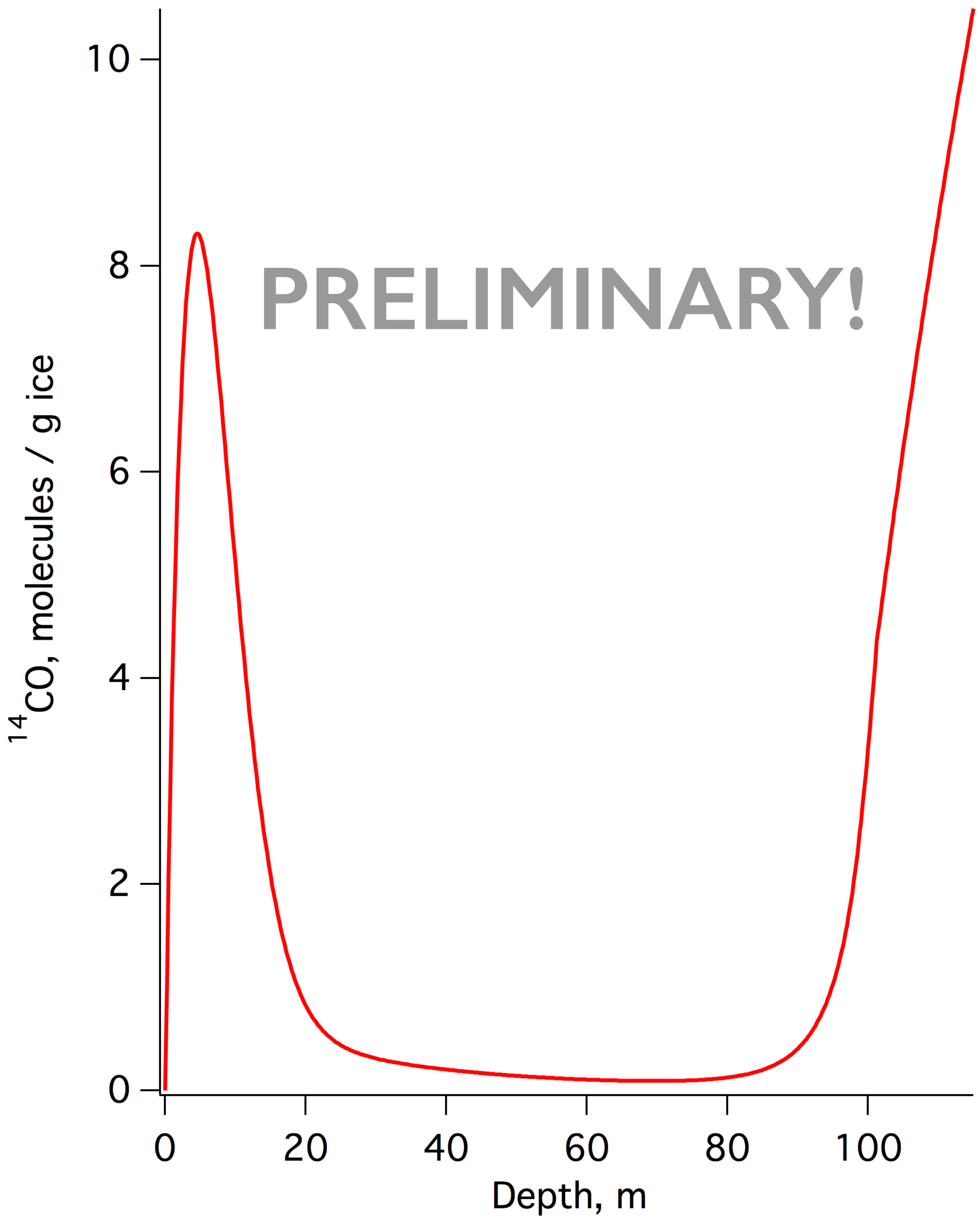


Figure 6. Modeled ice parcel trajectories along the center flow line. Model time step of 1 yr; parcels are traced 20 ka back in time. The dashed line indicates the 10 atoms g^{-1} equilibrium depth.

Predicted ^{14}CO in Dome C Firn Grains



- High surface production + long exposure.
- Almost all ^{14}CO leaks out of deeper firn.
- ^{14}CO in deep ice is due to muons >10 GeV, which arise from >100 GeV cosmic rays.
- Sensitive to high-energy Galactic CR flux; insensitive to solar modulation.
- New sensitive test of high-energy flux with radionuclides!

^{14}C Production Model at Dome C

- ^{14}CO depth-production rates used in simulations are based on the total muon production model from Balco *et al*., 2008 + glacier ice flow model of Buizert *et al*., 2012.

- For ease of computation, Balco's muon production model is fit using a 3-term exponential series. I.e.,

$$P_{\mu^{(-)}_{(f)}}(z_i) = \underbrace{P_{0,\mu^{(-)}_{(f)}}}_{\text{surface rate}} \cdot \sum_{j=1}^{3} f_{j,\mu^{(-)}_{(f)}} \exp\left(-\rho_{\text{ice}} \cdot z_j / \Lambda_{j,\mu^{(-)}_{(f)}}\right)$$

- The primary free parameters in the simulation are the muon production rates at the surface.

  - We use Taylor Glacier data as "baseline" values.

Sensitivity to Flux Variations at Dome C

- Compute Bayes Factor, sensitive to profile shape, between the "null" hypothesis assuming **constant** production rates and several alternative models assuming **time-varying** production rates.
- **Calibrate** using 3.5×10^6 constant-rate simulated data sets:
  - Assume ~20 m depth resolution of ice cores.
  - Assume conservative 3% relative uncertainties on measurements of ^{14}CO concentration vs. depth.
  - Use "baseline" Taylor Glacier rates in null hypothesis to produce the most conservative Bayes Factor for each trial.
- Generate $\mathcal{O}(10^4)$ data sets with time-varying models. **Sensitivity**: rate of change in production rate at which >50% of simulated sets can be discriminated from "null" hypothesis at 3σ and 5σ levels.

Method: Bayes Factor (1)

- We use the Bayes Factor to estimate the posterior odds that a measured ^{14}CO profile is sensitive to a constant flux model $\mathscr{M}_0$ or a time-varying flux model $\mathscr{M}_1$.

$$B_{01} = \frac{\Pr(\mathscr{M}_0 \mid {}^{14}\mathrm{CO})}{\Pr(\mathscr{M}_1 \mid {}^{14}\mathrm{CO})} = \frac{\Pr({}^{14}\mathrm{CO} \mid \mathscr{M}_0)}{\Pr({}^{14}\mathrm{CO} \mid \mathscr{M}_1)} \cdot \frac{\Pr(\mathscr{M}_0)}{\Pr(\mathscr{M}_1)}$$

- By allowing us to marginalize the unknown constant production rates or time variations in the production rates, B_{01} gives us sensitivity to the shape of the ^{14}CO profile.
- We can interpret B_{01} in terms of Bayesian posterior odds (Kass & Raftery 1995) or convert it to a frequentist test statistic using simulated data sets.

Method: Bayes Factor (2)

- Assuming there is no reason to favor one model over another *a priori*, B_{01} reduces to a likelihood ratio:

$$B_{01} = \frac{\Pr(^{14}\mathrm{CO} \mid \mathscr{M}_0)}{\Pr(^{14}\mathrm{CO} \mid \mathscr{M}_1)}$$

- If the parameters of the models are described by the vectors θ_0 and θ_1 — e.g., ^{14}CO production rates — we can marginalize them using their *a priori* distributions for each model. E.g.,

$$B_{01} = \frac{\int d\vec{\theta}_0 \ \Pr(^{14}\mathrm{CO} \mid \vec{\theta}_0, \mathscr{M}_0) \ \Pr(\vec{\theta}_0 \mid \mathscr{M}_0)}{\int d\vec{\theta}_1 \ \Pr(^{14}\mathrm{CO} \mid \vec{\theta}_1, \mathscr{M}_1) \ \Pr(\vec{\theta}_1 \mid \mathscr{M}_1)}$$

- Priors on θ_0 and θ_1 can be informed by external measurements.

Method: Bayes Factor (3)

- To be as conservative as possible, parameters such as the muon ^{14}CO production rates are marginalized using uninformative uniform priors. For example:

$$\Pr(P_{0,\mu_f} \,|\, \mathcal{M}_0) = \frac{1}{P_{0,\mu_f}^{\max} - P_{0,\mu_f}^{\min}} = \frac{1}{\Delta P_{0,\mu_f}}$$

- We parameterize the likelihood using 3% Gaussian measurement uncertainties for the ^{14}CO. E.g., for model $\mathcal{M}_0$,

$$\Pr(^{14}\mathrm{CO} \,|\, \mathcal{M}_0) = \int dP_{0,\mu^-} \int dP_{0,\mu_f} \, \frac{1}{\Delta P_{0,\mu^-}} \cdot \frac{1}{\Delta P_{0,\mu_f}} \cdot \prod_{j=1}^{N} \frac{1}{\sqrt{2\pi}\sigma_j} \exp - \frac{1}{2} \left(\frac{^{14}\mathrm{CO}_j - c(z_j \,|\, P_{0,\mu^-}, P_{0,\mu_f})}{\sigma_j} \right)^2$$

Interpretation of the Bayes Factor

- We calibrate B_{01} with simulated data sets to convert it to a frequentist test statistic.
- Conventional Bayesian interpretation — see R. Kass & A. Raftery, J. Am. Stat. Assoc. **90**:1995, 773-795:

$\log_{10}(B_{01})$	B_{01}	Strength of evidence favoring $\mathscr{M}_0$
0 - 0.5	1 - 3.2	Low/insubstantial
0.5 - 1	3.2 - 10	Substantial
1 - 2	10 - 100	Strong
>2	>100	Decisive