Reassessing the Directional Signature of the Dark Matter Wind for DMica

MDvDM26@KIT

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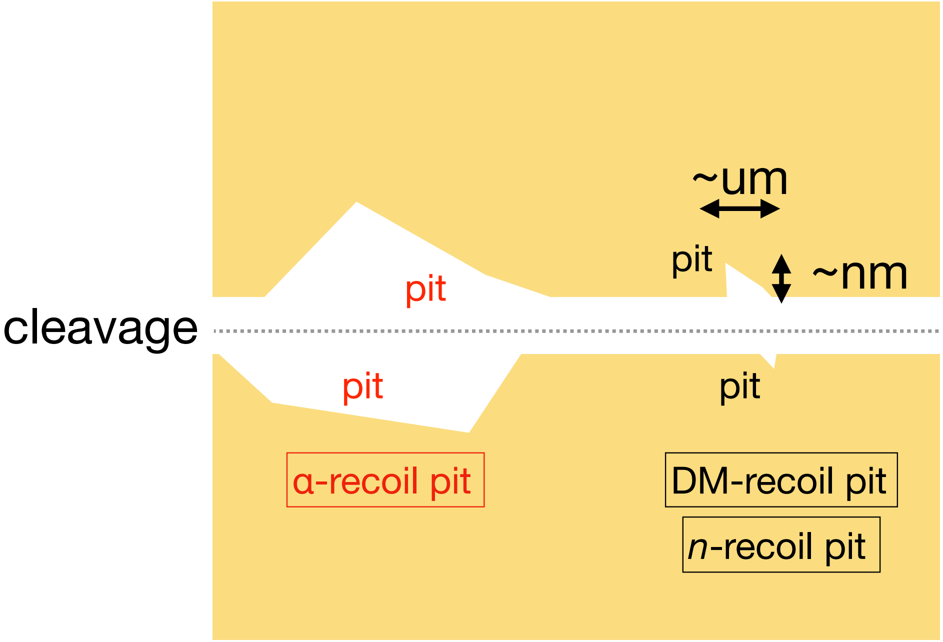
Method Overview: DMica searches DM signals in mica with the cleave-and-etch method



~um

~nm

cleavage

pit

pit

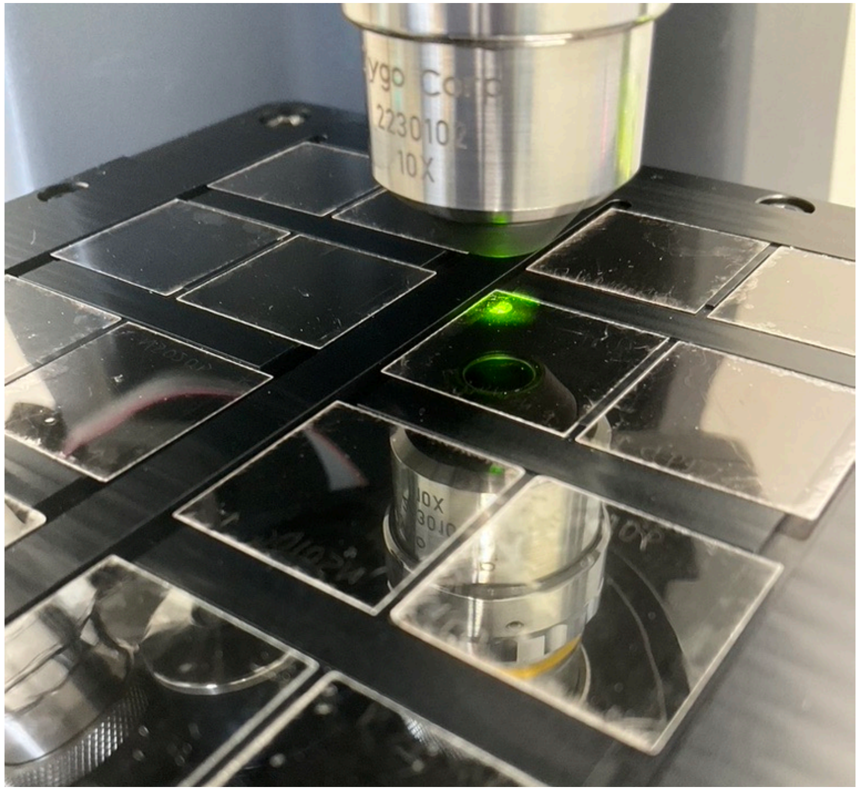
pit

pit

α-recoil pit

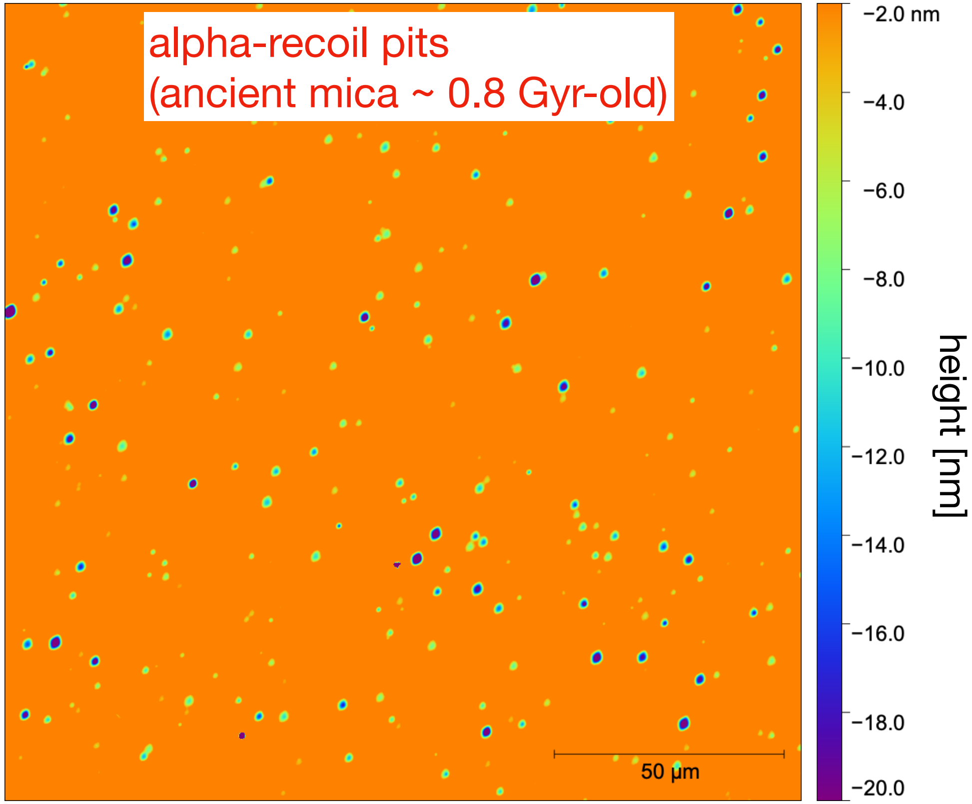
DM-recoil pit

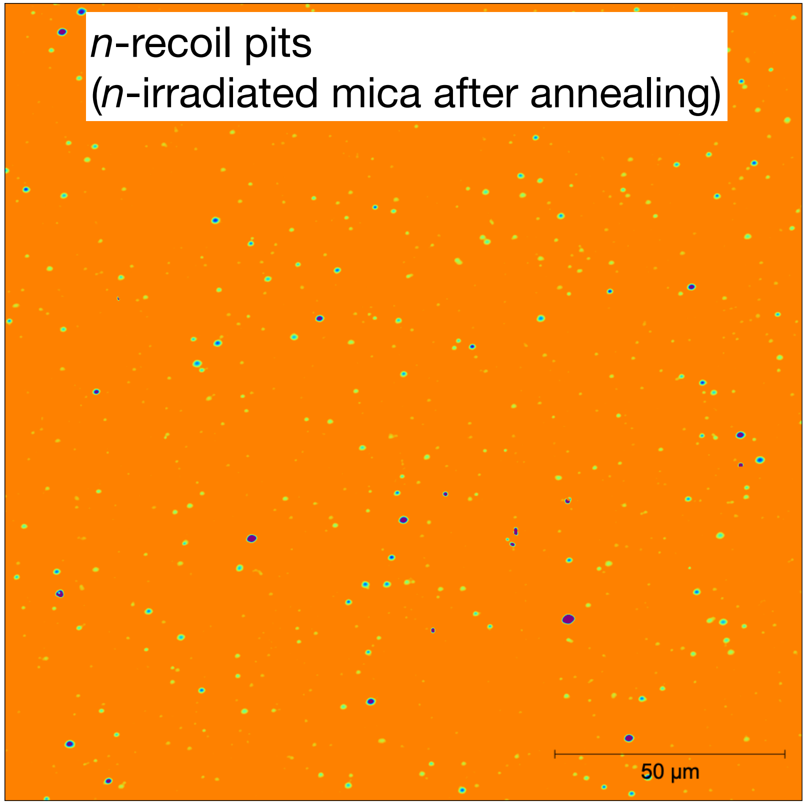
n-recoil pit



- Tracks intersecting cleavage are exposed as pits by chemical etching.
- The pits are counted with depth information using an optical profiler.

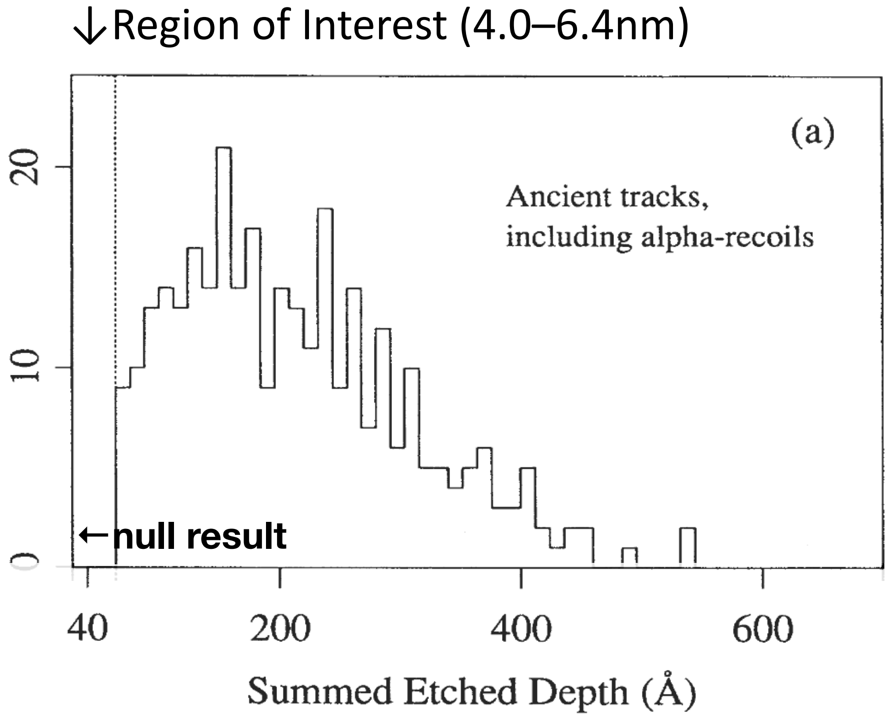
Pit examples: α-recoil vs. fast-neutron-recoil pits



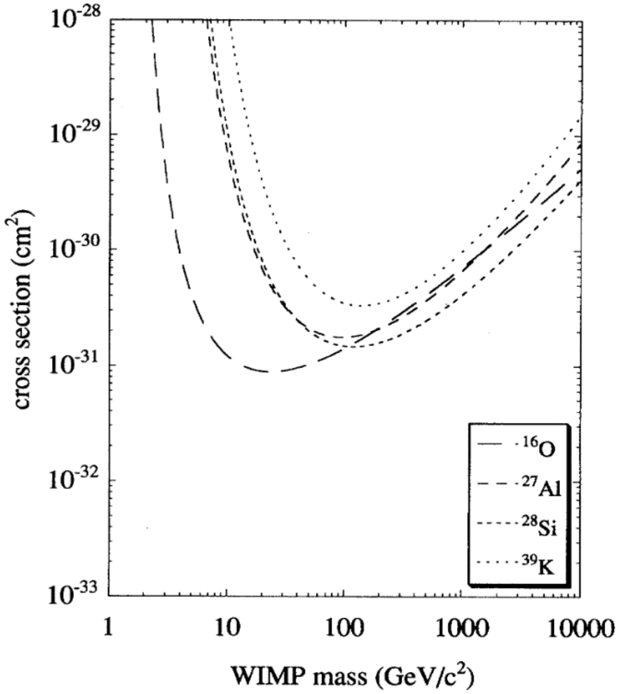


- Most abundant α-recoil pits in ancient micas are typically deeper than those expected from DM recoils.
- Fast-neutron recoils provide a useful experimental proxy for DM recoils, because both produce single nuclear-recoil tracks.

Snowden-Ifft et al. (1995): The First Mica DM Search


↓Region of Interest (4.0–6.4nm)

←null result



- Using AFM readout, SI95 built a pit-depth histogram from 0.08 mm² of 0.5-Gyr-old mica.
- The ROI at 4.0–6.4 nm was expected to contain DM-like pits, but no events were found.
- This null result was converted into an upper limit on the WIMP cross section.

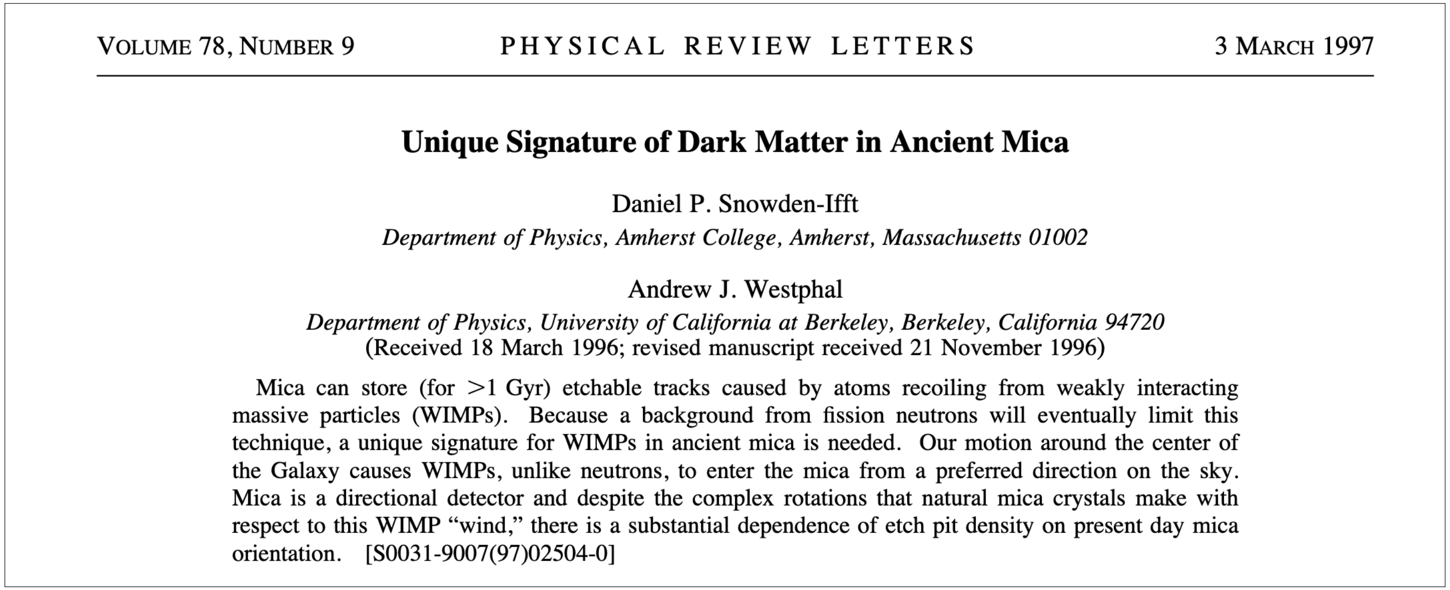
Scaling Up: From SI95 to DMICA via Optical Profiling

	Snowden-Ifft et al. 1995	**DMICA**
Exposure (Scan area)	1e-6 ton-year (0.08 mm^2)	**1 ton-year (800 cm^2)**
Readout (Scan speed)	Atomic force microscopy (48 hr/mm^2)	**Optical profiler (100 sec/mm^2)**
Nominal scan time	4 hours	**92 days**
Lateral sampling	0.156 um	**0.173 um**
Backgrounds in ROI	virtually no background because of small exposure	**radiogenic fast neutrons**

- Replacing AFM with fast optical-profiler readout opens a path toward a 1 ton-year exposure, about one million times larger than SI95.
- In this projected large-exposure regime, DM-wind directionality becomes a possible handle for discriminating signal from isotropic radiogenic-neutron backgrounds.

Scope of this talk:

Reassessing the SW97 directional signal



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Unique Signature of Dark Matter in Ancient Mica

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(Received 18 March 1996; revised manuscript received 21 November 1996)

Mica can store (for >1 Gyr) etchable tracks caused by atoms recoiling from weakly interacting massive particles (WIMPs). Because a background from fission neutrons will eventually limit this technique, a unique signature for WIMPs in ancient mica is needed. Our motion around the center of the Galaxy causes WIMPs, unlike neutrons, to enter the mica from a preferred direction on the sky. Mica is a directional detector and despite the complex rotations that natural mica crystals make with respect to this WIMP "wind," there is a substantial dependence of etch pit density on present day mica orientation. [S0031-9007(97)02504-0]

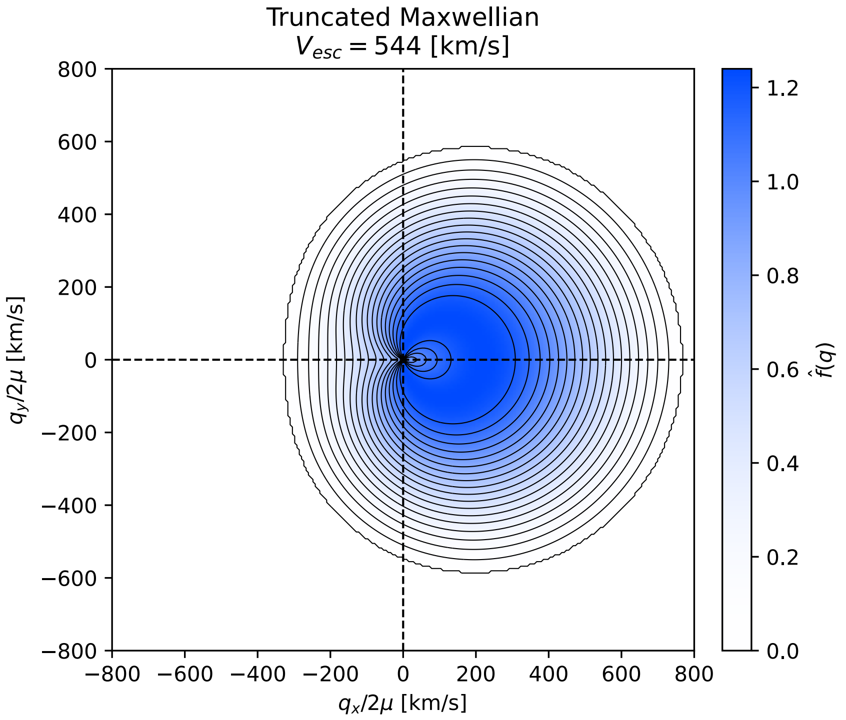
- First step: SW97-style background-free directional framework
- In this framework, the directional contrast is approximately $s(m,t) \approx \omega(m)\,\xi(t)$.
  1. $\omega(m)$: intrinsic directional response of mica, as a function of DM mass, m
  2. $\xi(t)$: geological-time degradation, as a function of sample age, t
  3. The output is an updated background-free directional reach.

1. $\omega(m)$: intrinsic directional response of mica

DM wind: What is the dark matter wind?

220km/s

wind



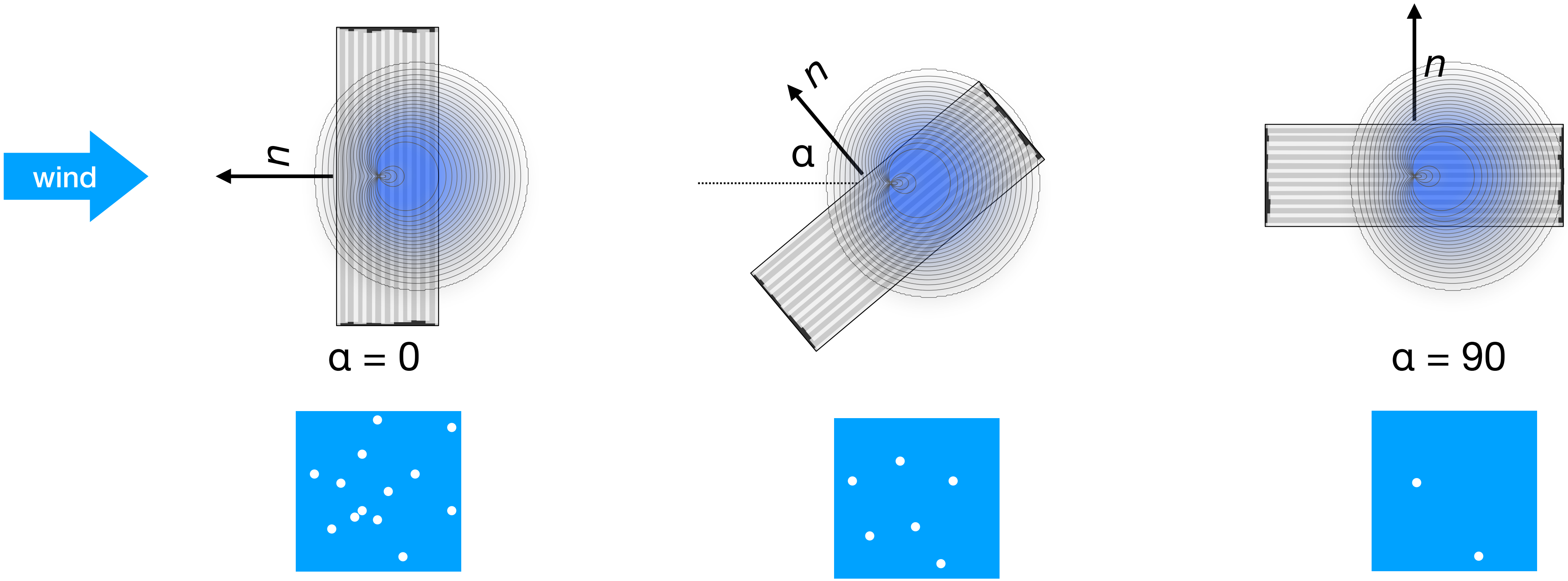
directional recoil kernel

- Dark matter is approximately isotropic in the halo rest frame.
- The Solar System moves through the halo at ~220 km/s, shifting the distribution in our frame.
- This produces an apparent dark matter wind, seen here as an anisotropic directional recoil kernel.

Directional idea:

Pit number depends on the angle to the DM wind

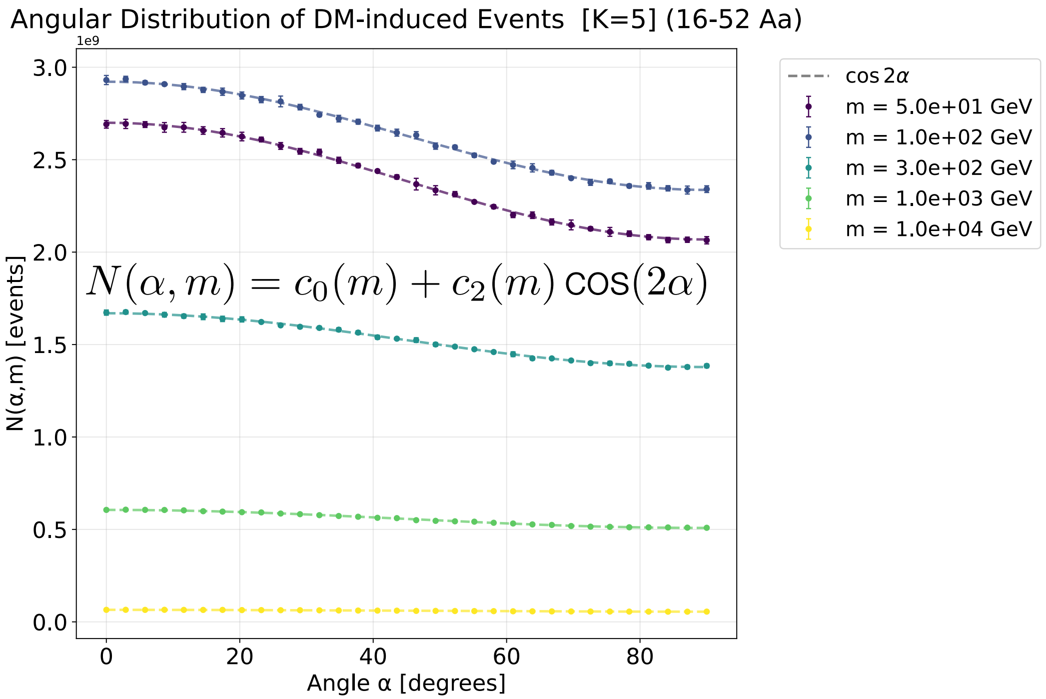
- α is the angle between the mica (cleavage) normal and the DM wind.
- More recoil tracks cross the cleavage plane at smaller α.
- Therefore, the pit number carries directional information about the DM wind.

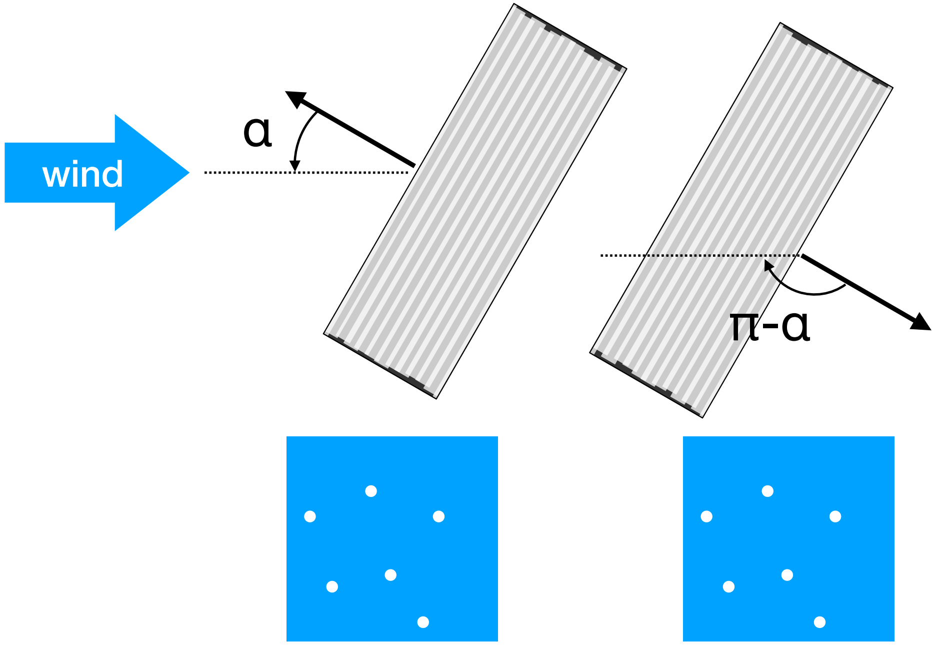


α = 0

α = 90

Angular Dependence of Pit Number from MC Simulations





N(α) = N(π-α)

- MC simulations confirm the angular dependence of the pit number N(α,m) and show a clearer dependence for lighter DM masses.
  - The MC results are well fitted by $N(\alpha,m) = c_0(m) + c_2(m)\cos(2\alpha)$.
  - This form respects N(α) = N(π-α) and is smooth at α = 90°.

Intrinsic directional response of mica: ω(m)

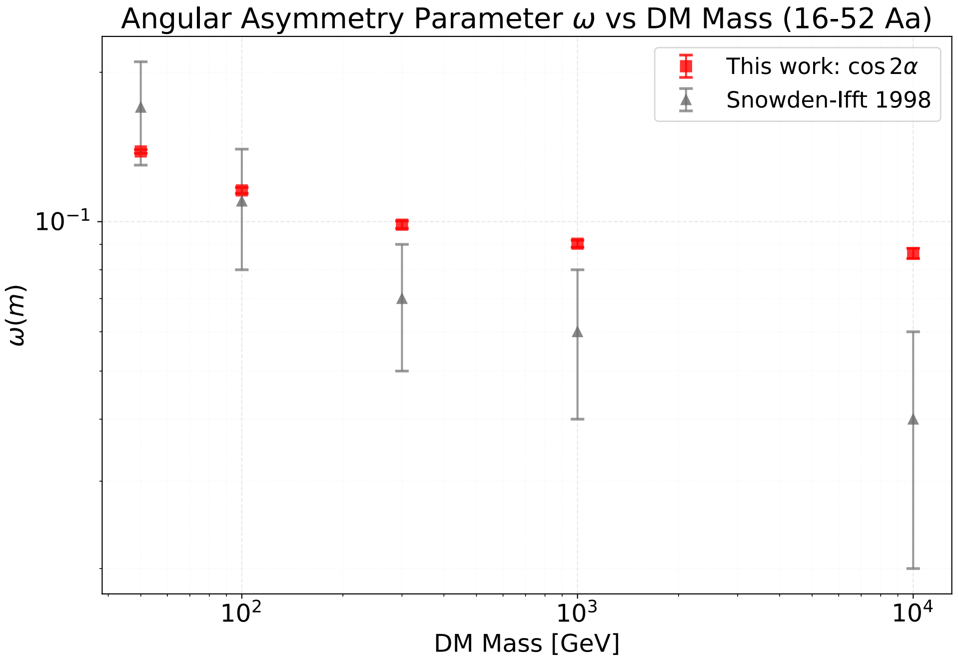
- The maximal signal contrast is given by the contrast between $\alpha = 0$ and $\alpha = 90$:

$$s_{\text{max}}(m) = \frac{N(0,m) - N(90,m)}{N(0,m) + N(90,m)} = \frac{c_2(m)}{c_0(m)}$$

- The intrinsic asymmetry factor is then defined as:

$$\omega(m) \equiv \frac{s_{\text{max}}(m)}{1 - s_{\text{max}}(m)/3}.$$

- $\omega(m)$ is at the 10% level and decreases for heavier DM.



2. $\xi(t)$: geological-time degradation

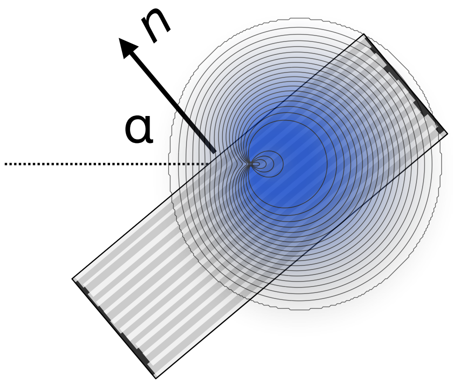
Definition of s(m,t) and the history degradation ξ(t)

$$s(m,t) \equiv \frac{\mathsf{max}_\alpha N(\alpha(t,\boldsymbol{n}_0),m) - \mathsf{min}_\alpha N(\alpha(t,\boldsymbol{n}_0)),m)}{\mathsf{max}_\alpha N(\alpha(t,\boldsymbol{n}_0)),m) + \mathsf{min}_\alpha N(\alpha(t,\boldsymbol{n}_0)),m)} \approx \omega(m)\xi(t)$$

$$\omega(m) \equiv \frac{s_{\mathsf{max}}(m)}{1 - s_{\mathsf{max}}(m)/3}$$

$$\xi(t) \equiv \frac{1}{2}\left(\underset{\boldsymbol{n}_0}{\mathsf{max}} \left\langle\left\langle \mathsf{cos}\, 2\alpha \right\rangle\right\rangle (t,\boldsymbol{n}_\mathbf{0}) - \underset{\boldsymbol{n}_0}{\mathsf{min}} \left\langle\left\langle \mathsf{cos}\, 2\alpha \right\rangle\right\rangle (t,\boldsymbol{n}_0)\right)$$

$$\left\langle\left\langle \mathsf{cos}\, 2\alpha \right\rangle\right\rangle (t,\boldsymbol{n}_0) \equiv \frac{1}{t}\int_0^t \mathsf{cos}\, 2\alpha(t,\boldsymbol{n}_0)dt$$

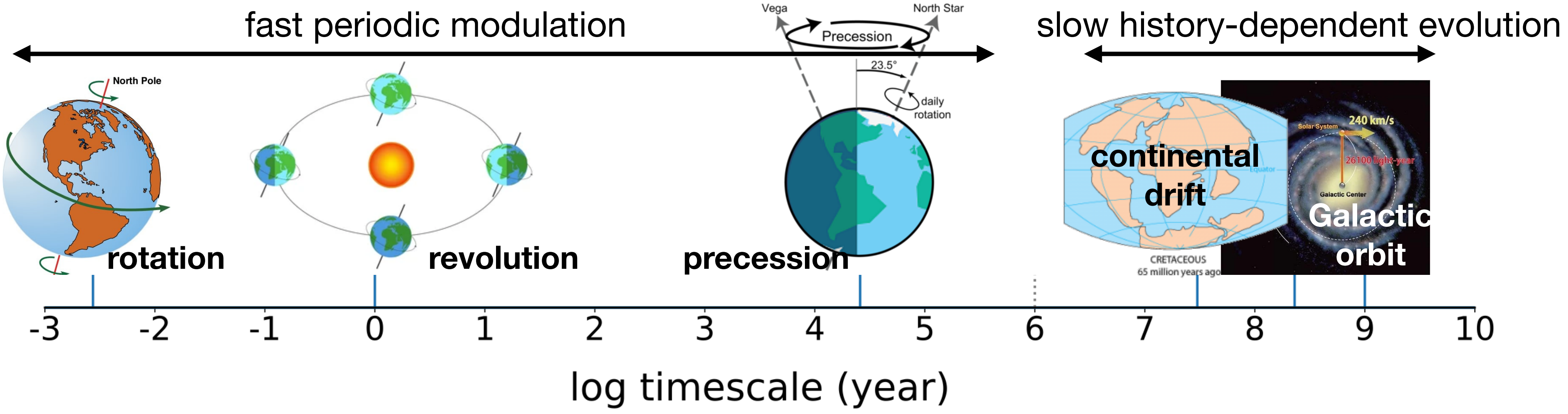


- n_0: present-day (mined) mica normal
- α = α(t, n_0): DM-wind angle for a sample of age t is a function of n_0.
- Since N(α,m) = c_0(m) + c_2(m) cos(2α), ξ(t) is written in terms of cos2α.

Two-step averaging of cos2α over the many-timescale evolution of α

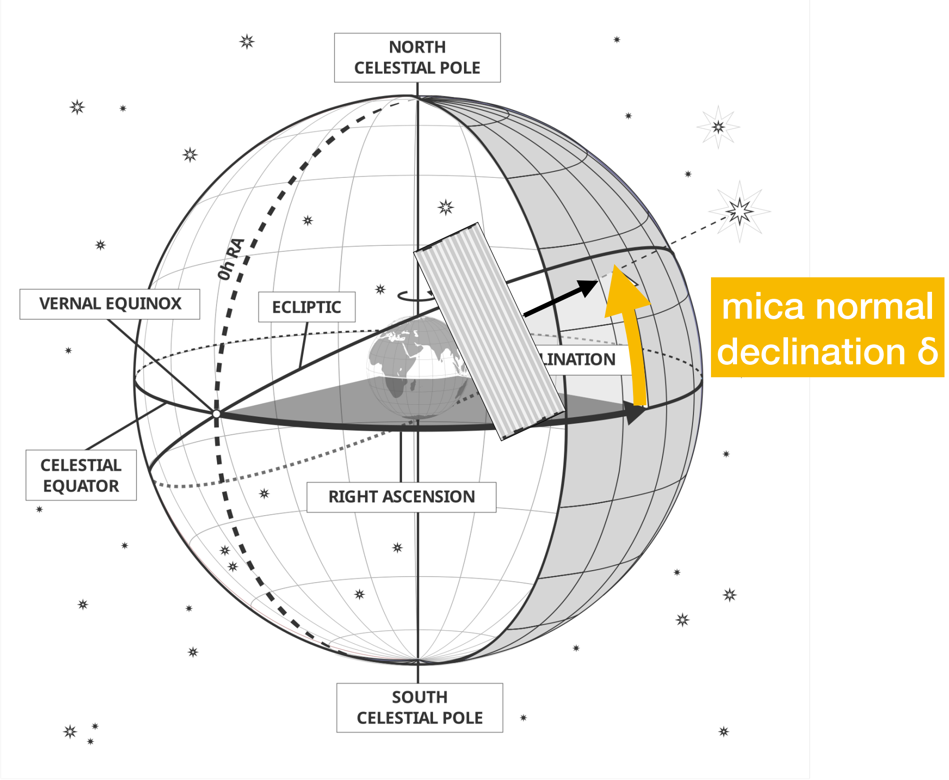
$$\langle\langle \cos 2\alpha \rangle\rangle (t, \boldsymbol{n}_0) \equiv \frac{1}{t}\int_0^t \cos 2\alpha(t,\boldsymbol{n}_0)dt \approx \frac{1}{t}\sum_{\text{slow}} \langle \cos 2\alpha\rangle_{\text{fast}} \Delta t_{\text{slow}}$$

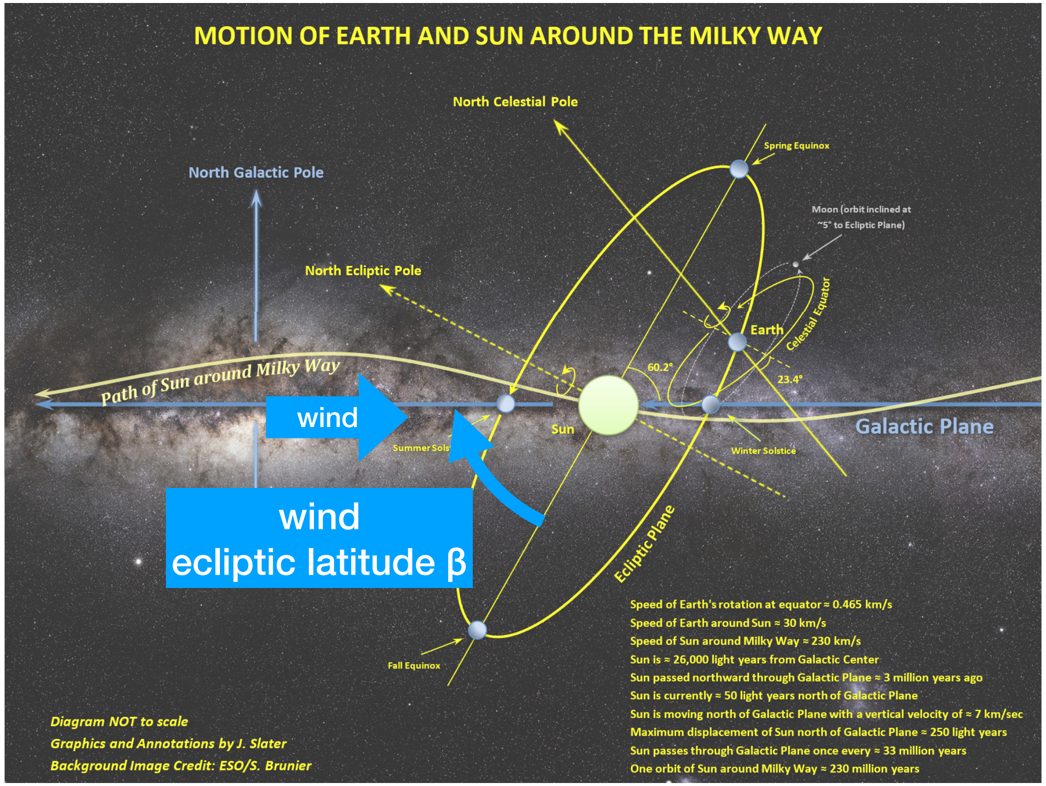
- Fast periodic modulation comes from Earth’s rotation, revolution, and precession.
- Slow history-dependent evolution comes from continental drift and Galactic orbit.



Two slow variables: δ for mica normal, β for the DM wind

- After averaging over the fast periodic motions, the response $\langle\cos 2\alpha\rangle_{\mathrm{fast}}$ is described by two slow variables:
  - Continental drift changes the mica-normal declination δ.
  - Galactic orbit changes the wind ecliptic latitude β.

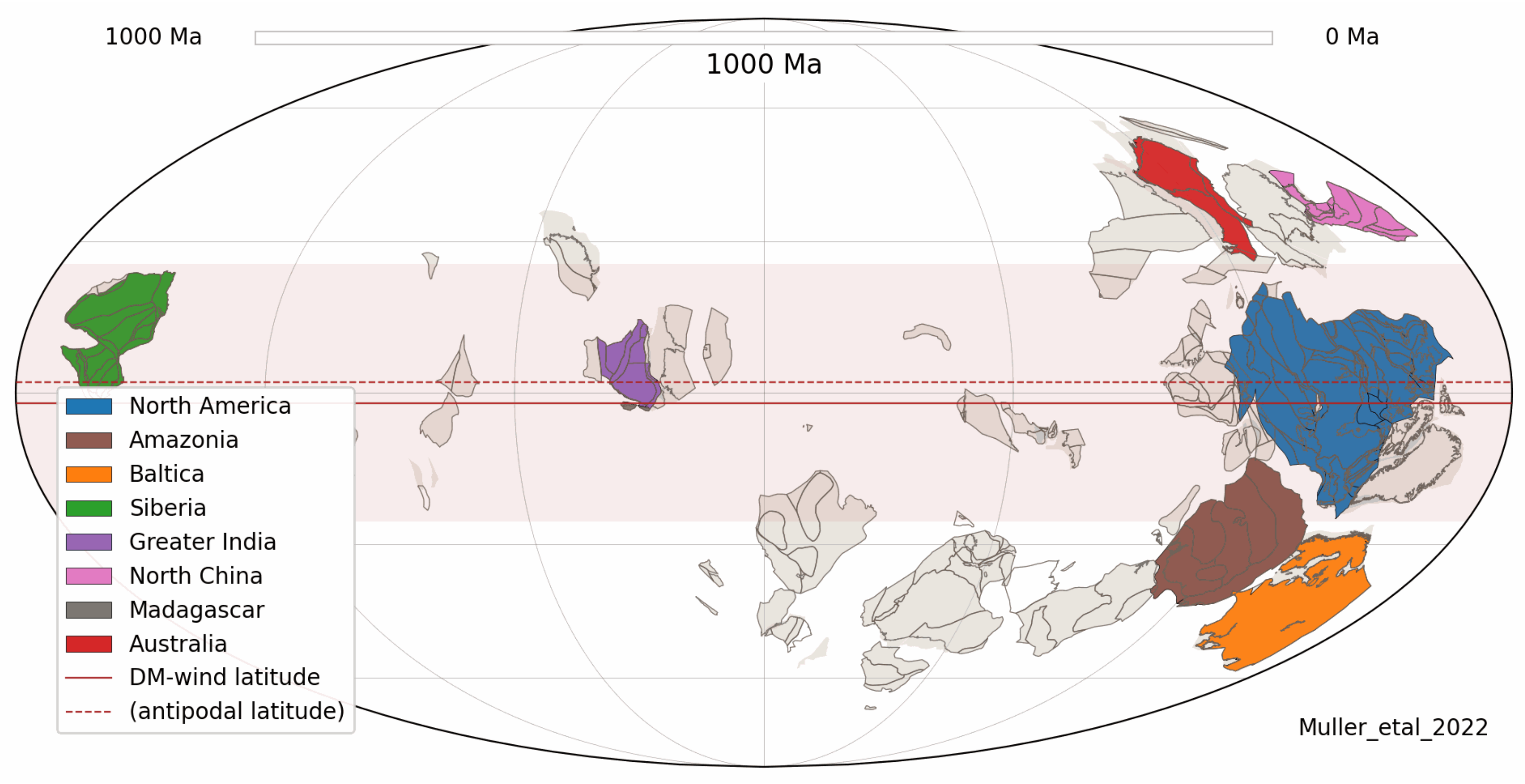




Speed of Earth's rotation at equator ≈ 0.465 km/s
Speed of Earth around Sun ≈ 30 km/s
Speed of Sun around Milky Way ≈ 230 km/s
Sun is ≈ 26,000 light years from Galactic Center
Sun passed northward through Galactic Plane ≈ 3 million years ago
Sun is currently ≈ 50 light years north of Galactic Plane
Sun is moving north of Galactic Plane with a vertical velocity of ≈ 7 km/sec
Maximum displacement of Sun north of Galactic Plane ≈ 250 light years
Sun passes through Galactic Plane once every ≈ 33 million years
One orbit of Sun around Milky Way ≈ 230 million years

Diagram NOT to scale
Graphics and Annotations by J. Slater
Background Image Credit: ESO/S. Brunier

Cratons provide reconstructable mica-normal histories

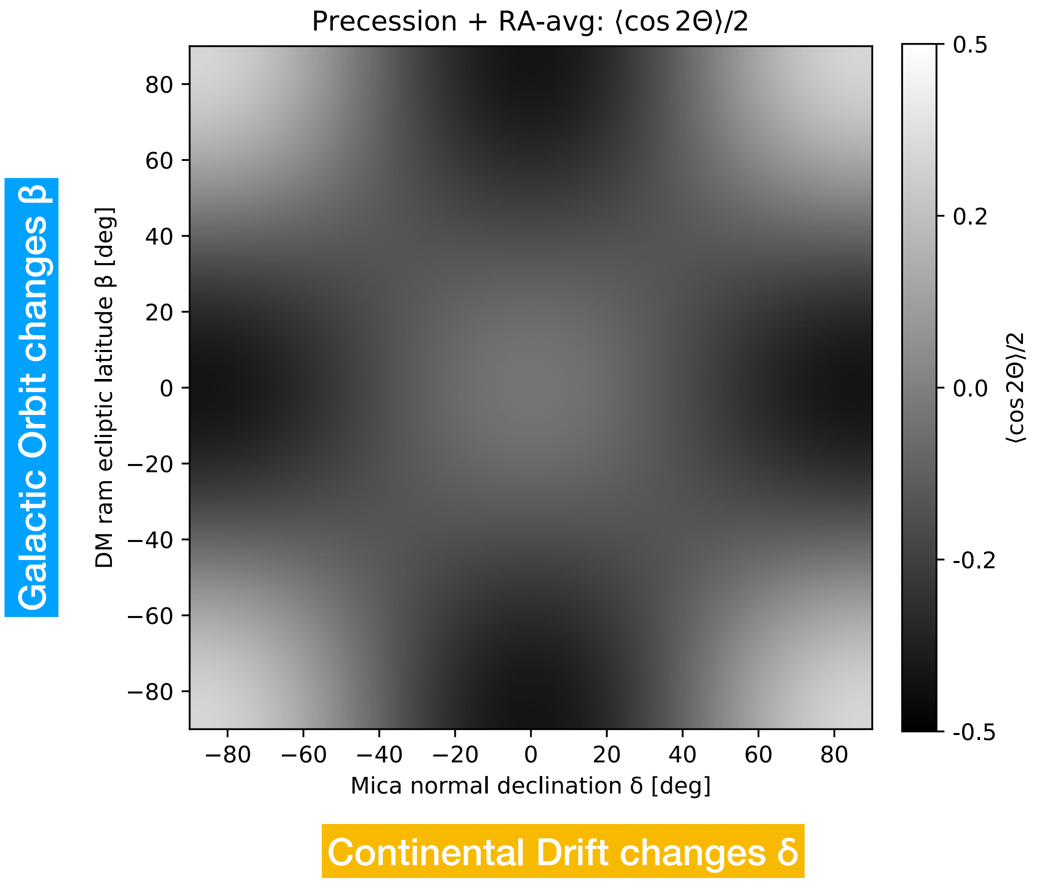


Muller_etal_2022

- Cratons approximately undergo rigid-body rotations through continental drift.
- Therefore, δ(t) can be reconstructed from paleomagnetic-based rotation models.

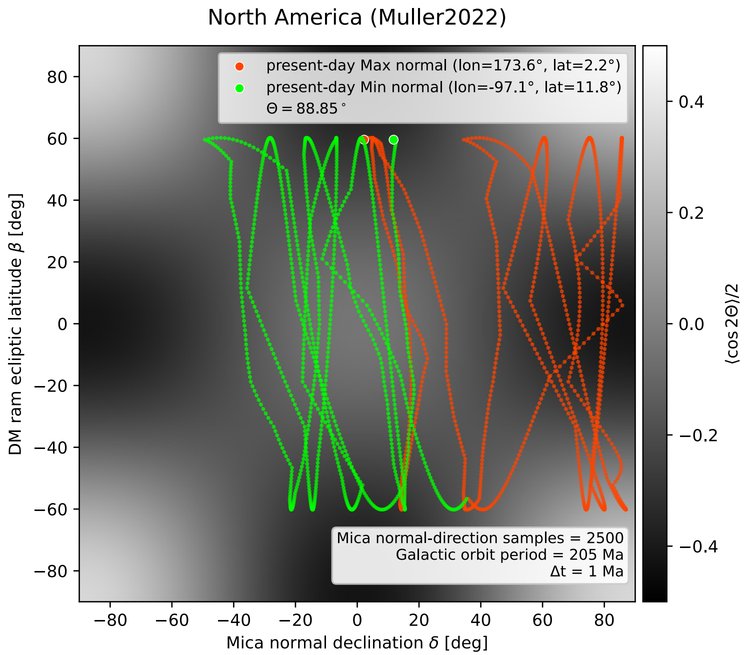
Fast-averaged response <cos2α>$_{\text{fast}}$ in the (δ, β) plane

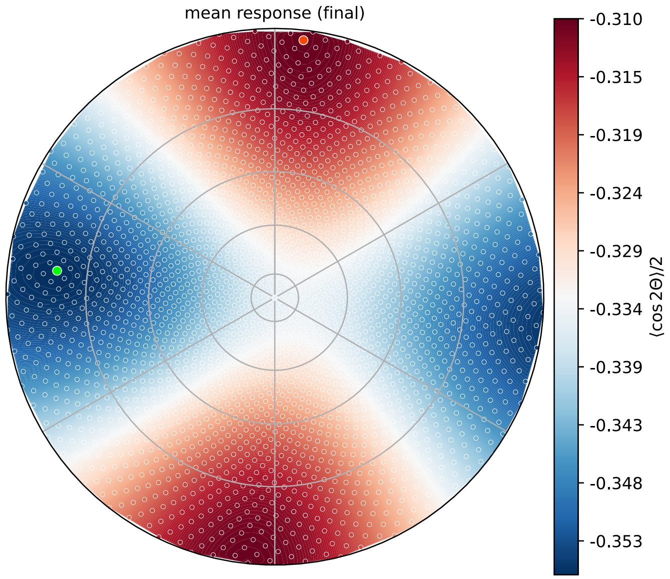
- After fast averaging, the response depends only on the two slow variables δ and β.
- This map of ⟨cos2α⟩$_{\text{fast}}$ provides the building block for geological-time averaging.
- The next step is to integrate ⟨cos2α⟩$_{\text{fast}}$ along the slow evolution of each present-day mica normal n_0 to obtain the full time average ⟨⟨cos2α⟩⟩(t, n_0).



How ξ(t) is computed in practice

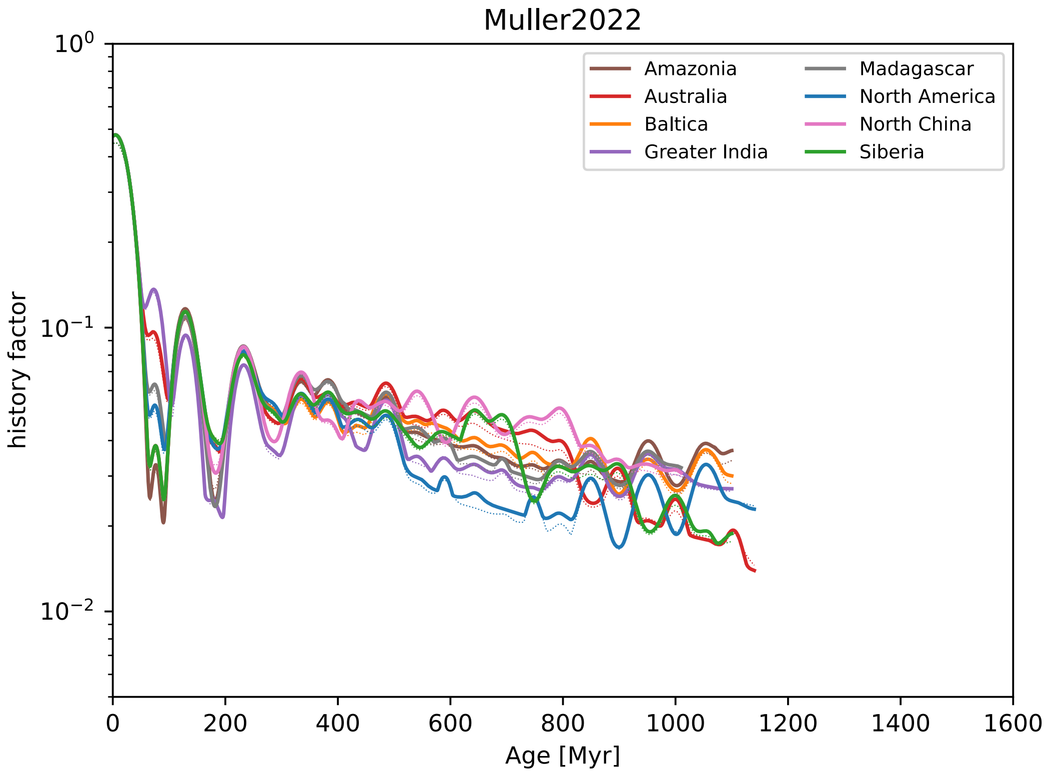
$$\xi(t) \equiv \frac{1}{2}\left(\max_{\boldsymbol{n}_0} \langle\langle \cos 2\alpha \rangle\rangle \left(t, \boldsymbol{n_0}\right) - \min_{\boldsymbol{n}_0} \langle\langle \cos 2\alpha \rangle\rangle \left(t, \boldsymbol{n}_0\right)\right)$$

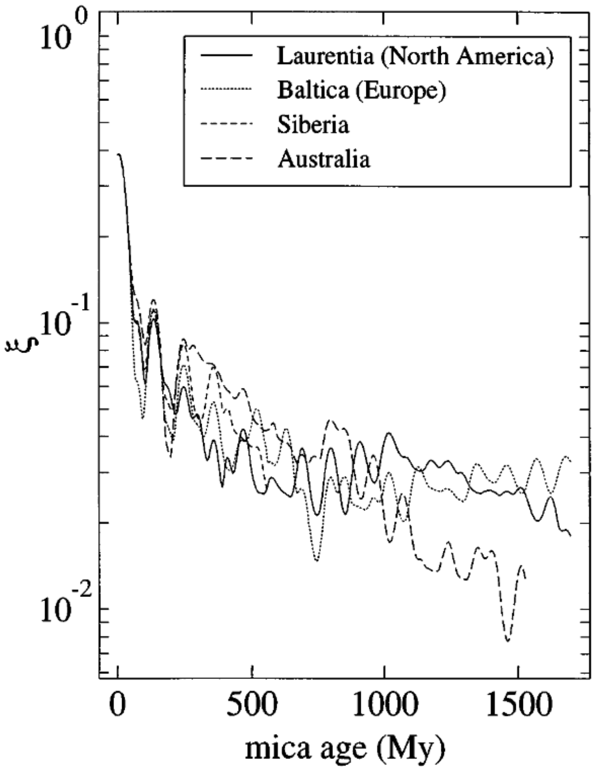




- For a fixed age t, 2500 present-day mica normals n_0 are sampled on a Fibonacci grid.
- For each n_0, the path in the δ–β plane gives the full time-averaged response $\langle\langle \cos 2\alpha \rangle\rangle(t, n_0)$.
- Then ξ(t) is the difference between the maximum and minimum responses.

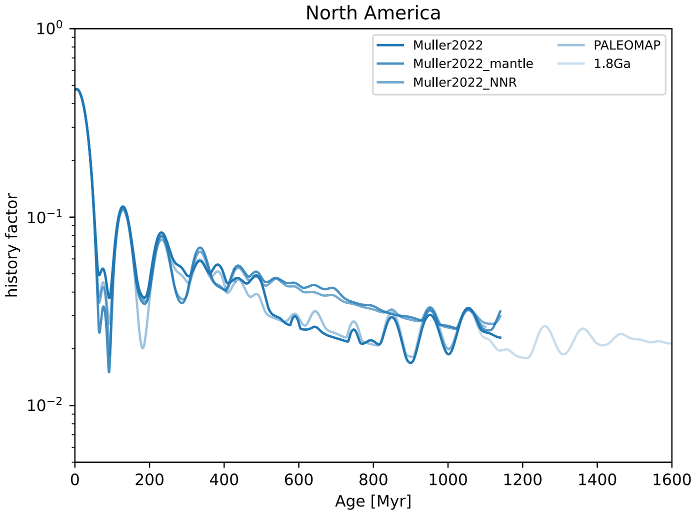
History degradation factor ξ(t): craton-by-craton

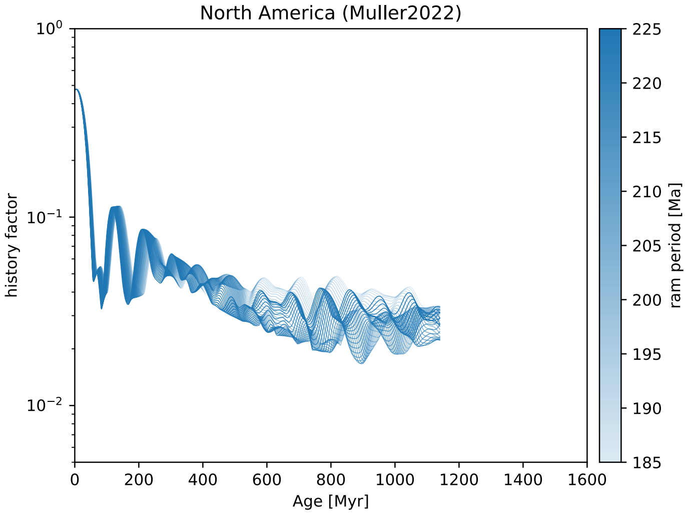


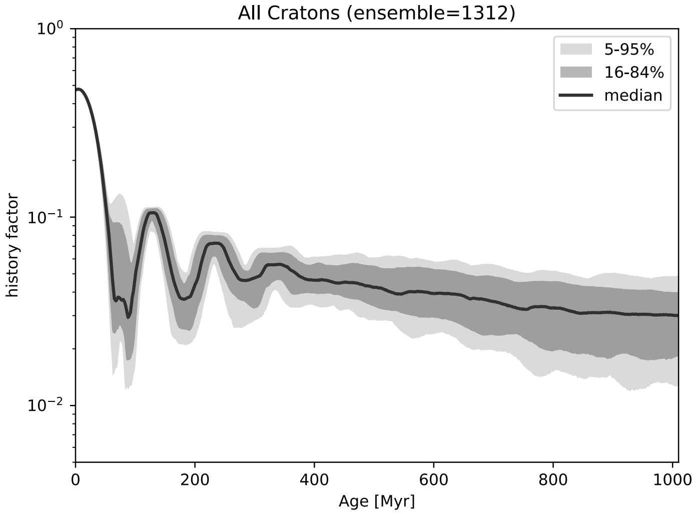


- The left panel shows ξ(t) for individual cratons based on the Muller2022 rotation model and Galactic orbital periods of 205Myr.
- The right panel reproduces the SW97 result for comparison, and the agreement is broadly good.

History degradation factor ξ(t): dependence on models and Galactic orbital periods



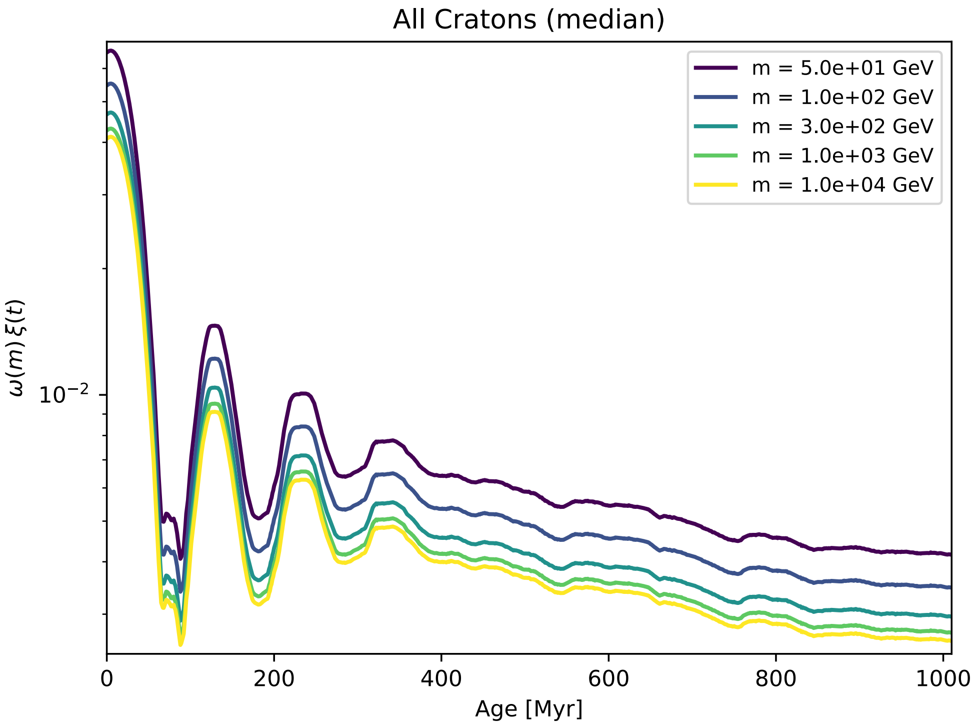


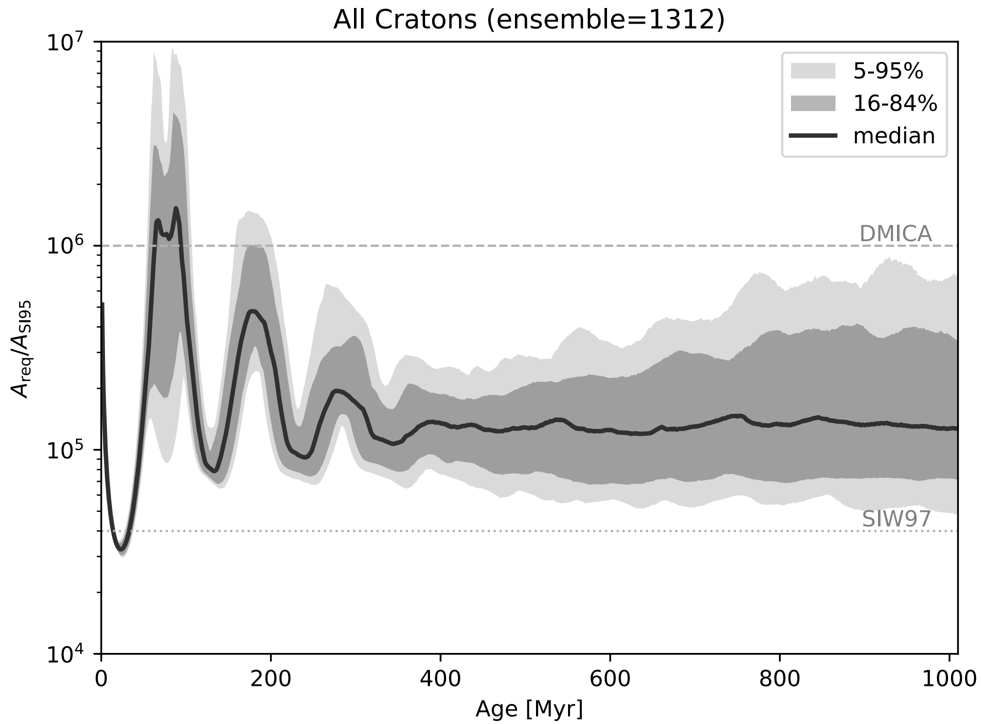


- The left panel shows the dependence on rotation models.
- The middle panel shows the dependence on the Galactic orbital period.
- The right panel shows the equal-weight ensemble over all cratons, models, and orbital periods; this will be the reference result in the next part.

3. (background-free) directional reach

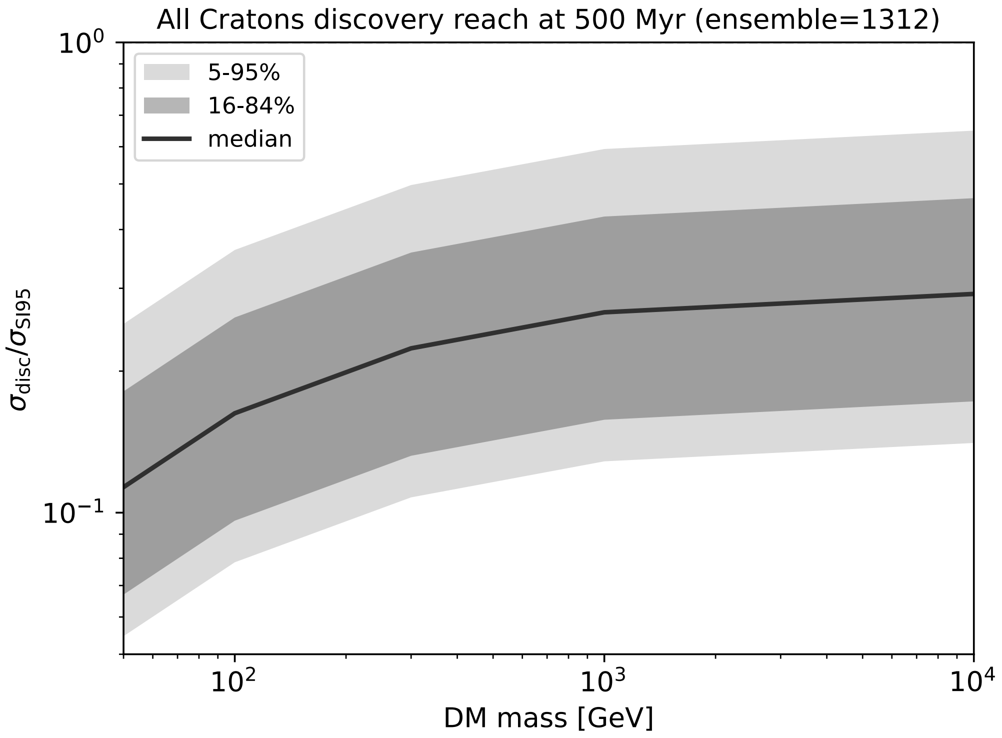
Final signal strength and required exploration area





- Using the ensemble ξ(t), the final signal decreases toward older ages because ξ(t) becomes smaller, but longer integration partly compensates for this.
- Assuming a cross section equal to the SI95 exclusion value, the required exploration area, in units of the SI95 area, is only weakly age-dependent.

Directional discovery reach at 500 Myr



- At 500 Myr, the 3σ directional discovery threshold, normalized to the SI95 exclusion value, is shown as a function of DM mass.
- Lower values indicate better directional sensitivity.
- The best sensitivity is obtained around $m = 50$ GeV; for heavier DM, it becomes worse because $\omega(m)$ decreases and then tends to saturate.

Summary

- Mica has an intrinsic directional response ω(m) at the ~10% level, with a stronger effect for lighter DM masses.
- Geological-time averaging reduces this response through the history factor ξ(t), which is ~0.04 for 500-Myr-old samples.
- The reassessment shows that the background-free directional reach remains within the projected large-exposure scope of DMica, assuming a cross section equal to the SI95 exclusion value.
- This work clarifies the benchmark directional potential of mica as a paleo-directional probe, complementary to present-day searches.

Outlook

- A natural next step is to include explicit background models and explore hybrid analyses that combine directional pit counting with pit-depth histogram information.