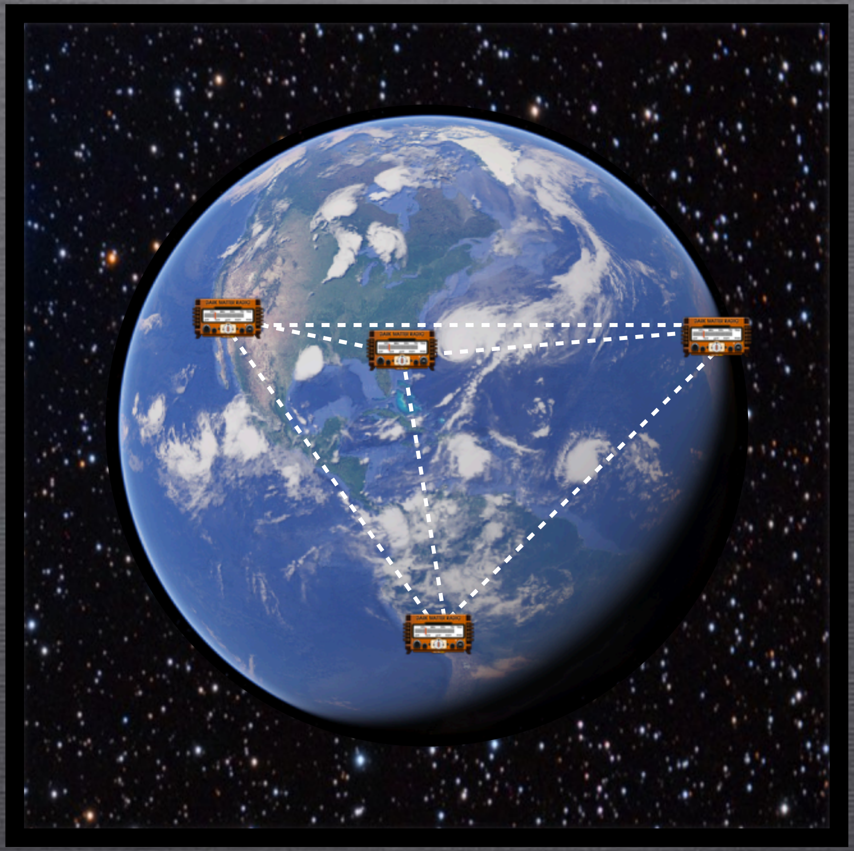
Dark Matter Interferometry

or why 2 detectors are better than 1



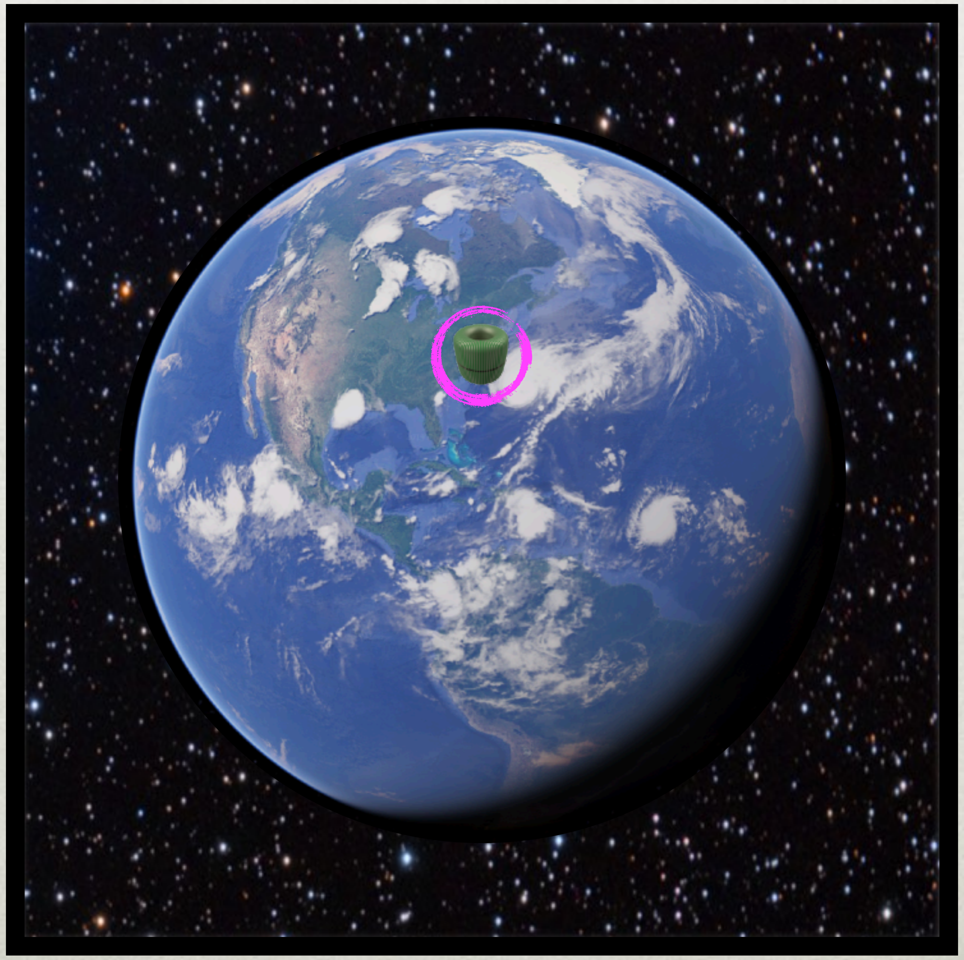
Nick Rodd

w/ Josh Foster, Yoni Kahn,
Rachel Nguyen, and Ben Safdi

DM Radio Collaboration Meeting, 14 August 2020

Basic Idea

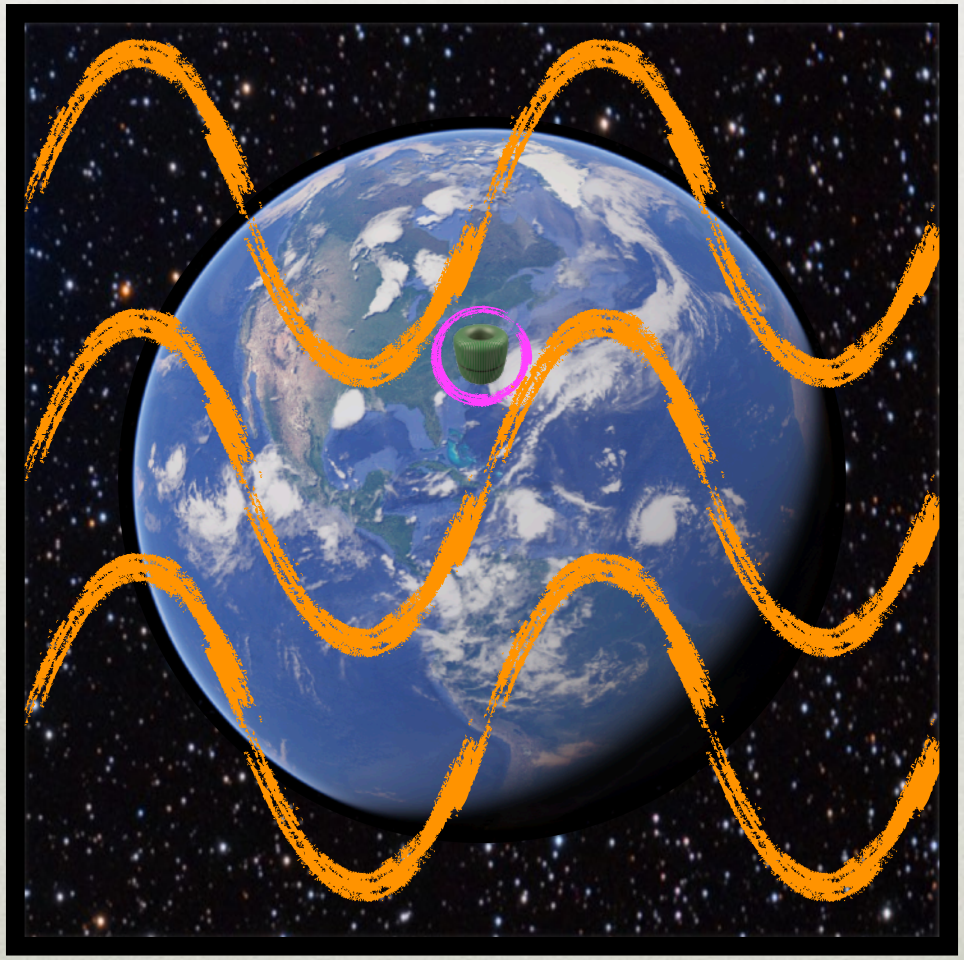
Wave-like DM



Basic Idea

Wave-like DM

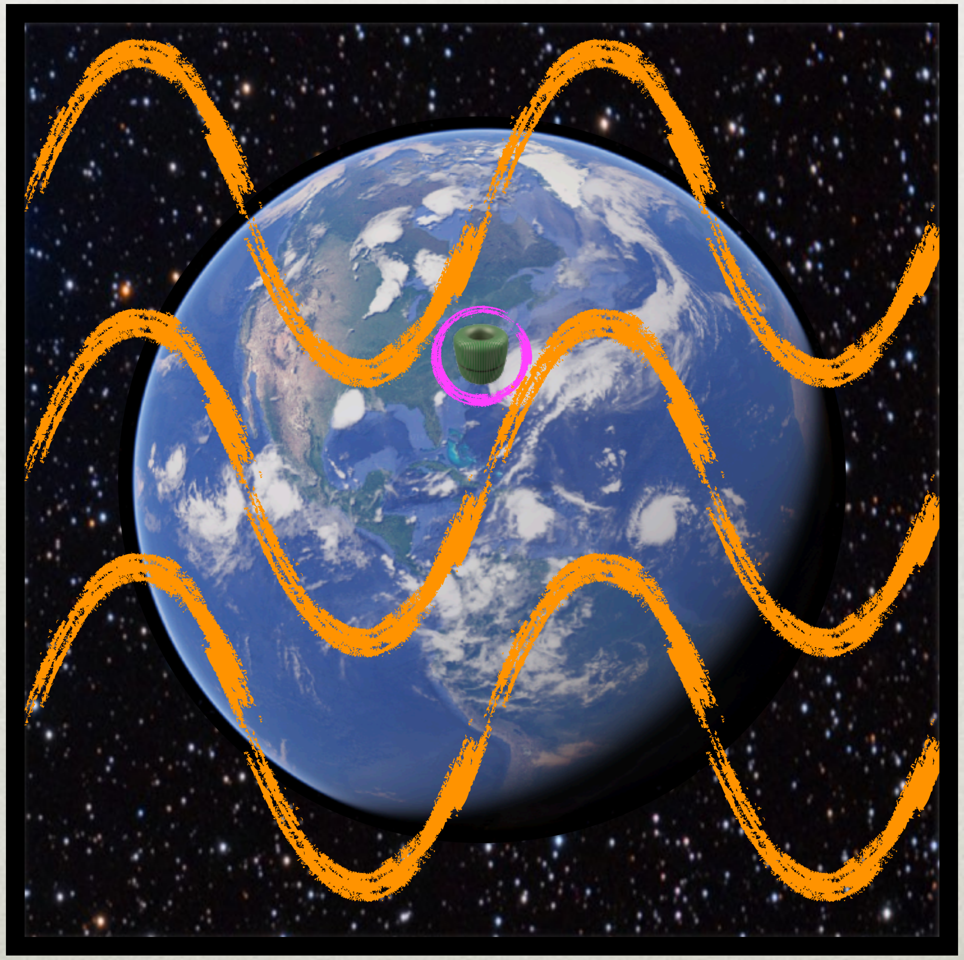
$$a \sim \cos(m_a t)$$



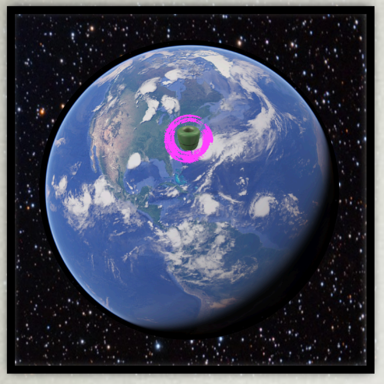
Basic Idea

Wave-like DM

$$a \sim \cos(\omega t - \mathbf{k} \cdot \mathbf{x})$$



Basic Idea

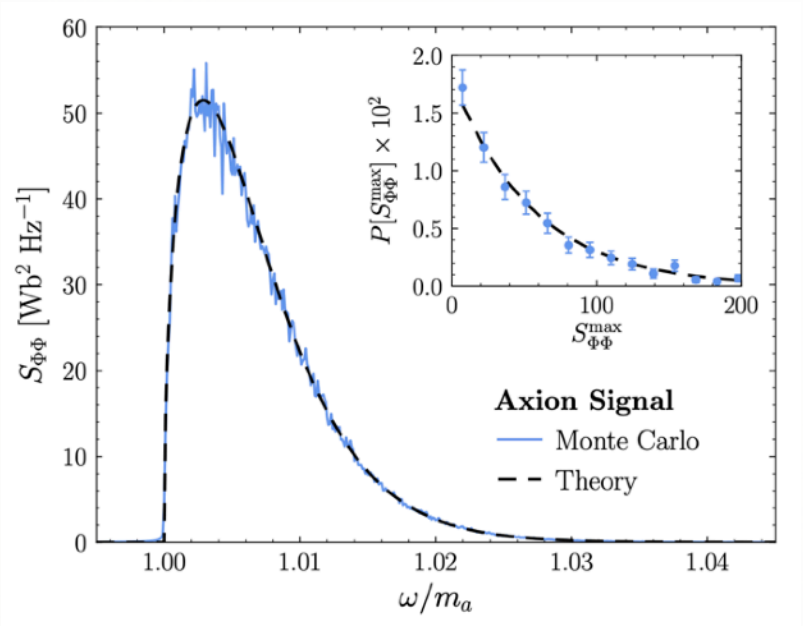


Wave-like DM

$$a \sim \cos(\omega t - \mathbf{k} \cdot \mathbf{x})$$

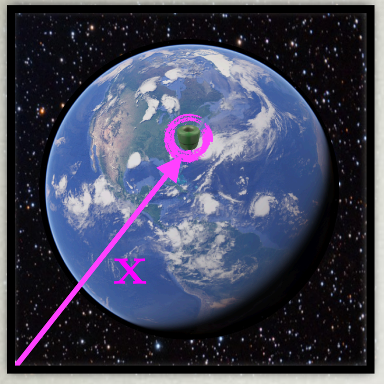
Speed $\omega \approx m_a(1 + |\mathbf{v}|^2/2)$

Determined by $f(v)$



[Foster, NLR, Safdi 17]

Basic Idea



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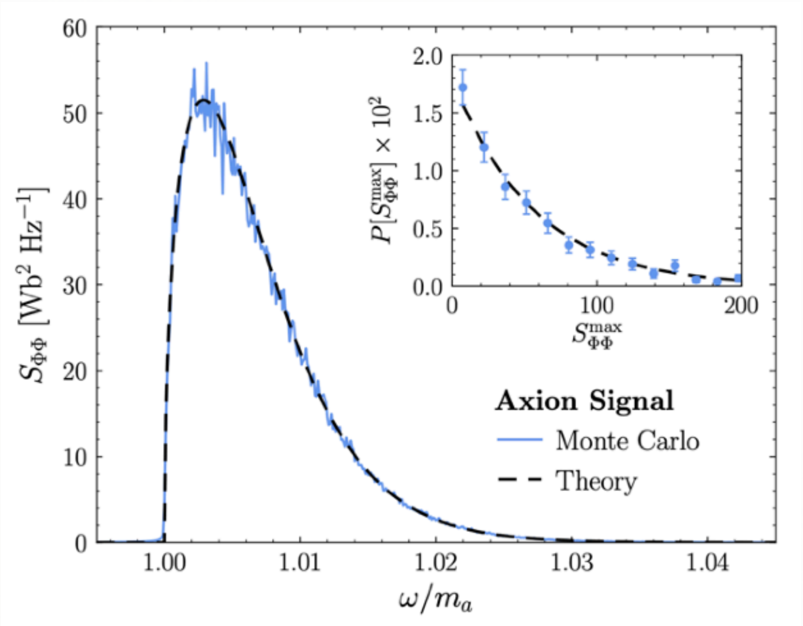


[Foster, NLR, Safdi 17]

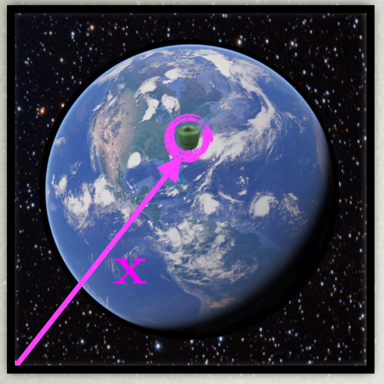
Velocity $\mathbf{k} = m_a \mathbf{v}$

Determined by $f(\mathbf{v})$

But usually invisible to detectors

1. $\nabla a \sim \mathbf{k} \ll \omega \sim \partial_t a$
2. For 1 experiment, can choose $\mathbf{x} = 0$

Basic Idea



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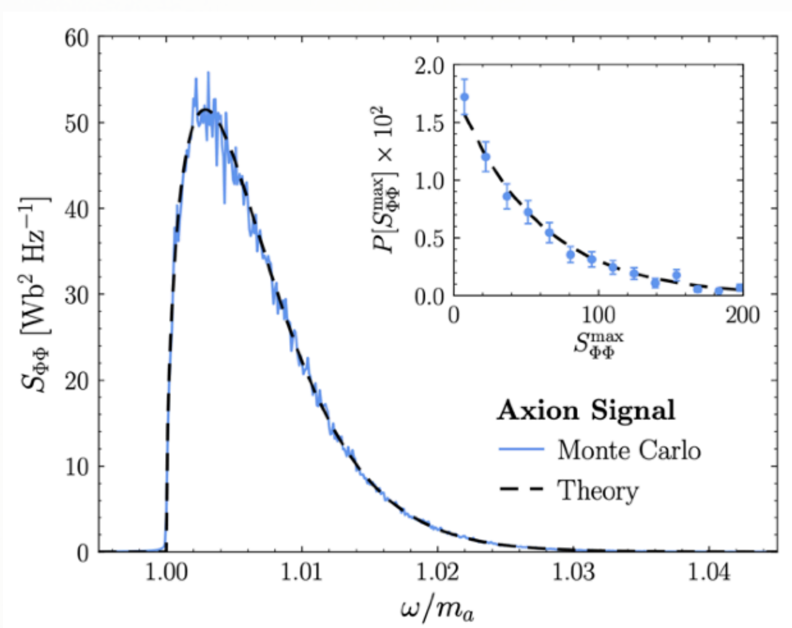

[Foster, NLR, Safdi 17]

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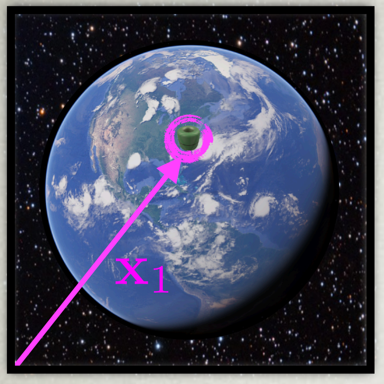
Our Aim

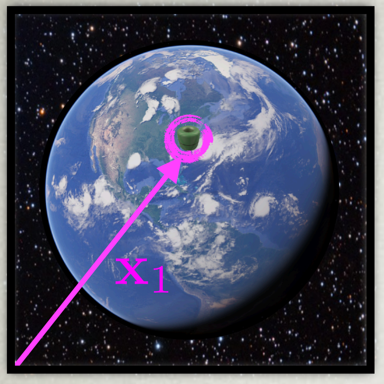


Basic Idea

Two Detectors

Measurement at MIT

$$\Phi_1 \sim a(\mathbf{x}_1, t) \sim \sum_{\mathbf{v}} \sqrt{f(\mathbf{v})} \cos[\omega_v t - \mathbf{k}_\mathbf{v} \cdot \mathbf{x}_1 + \phi_\mathbf{v}]$$



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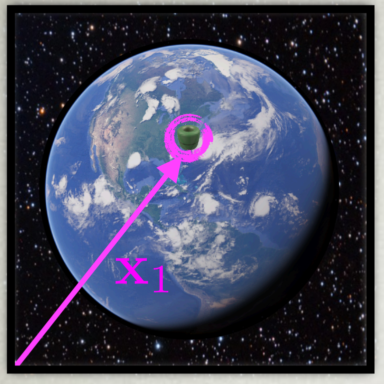
Superposition of velocities

$a_0 \propto \sqrt{\rho_{\rm DM}}$

Random phase

Basic Idea



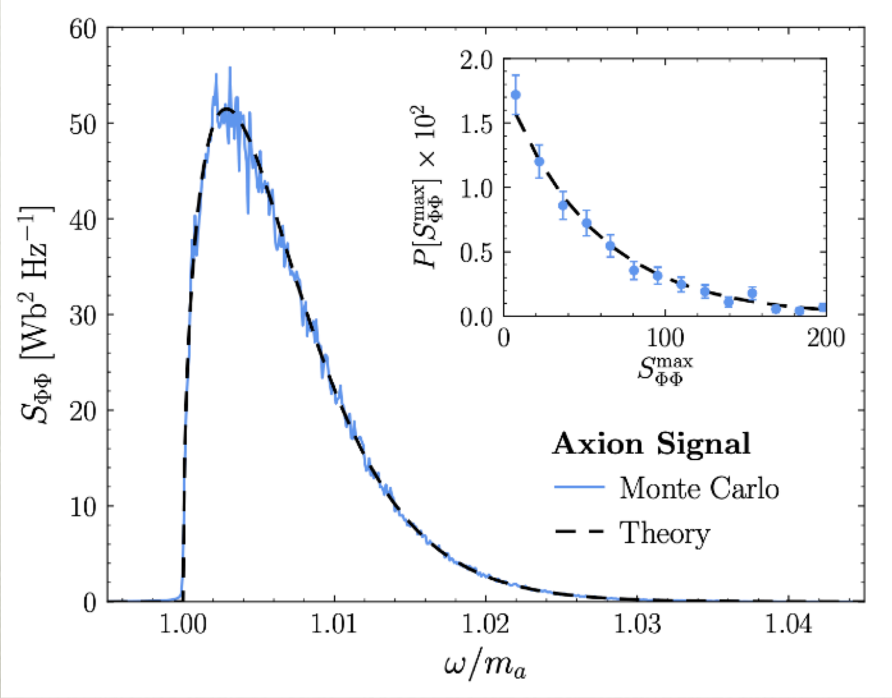
Two Detectors

Measurement at MIT

$$\Phi_1 \sim a(\mathbf{x}_1, t) \sim \sum_{\mathbf{v}} \sqrt{f(\mathbf{v})} \cos[\omega_v t - \mathbf{k}_{\mathbf{v}} \cdot \mathbf{x}_1 + \phi_{\mathbf{v}}]$$

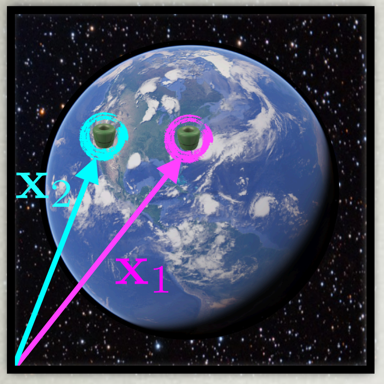
$$\Rightarrow S_{\Phi\Phi}(\omega) \sim \frac{f(v_\omega)}{v_\omega}$$

$$v_\omega = \sqrt{2\omega/m_a - 2}$$



[Foster, NLR, Safdi 17]

Basic Idea



Two Detectors

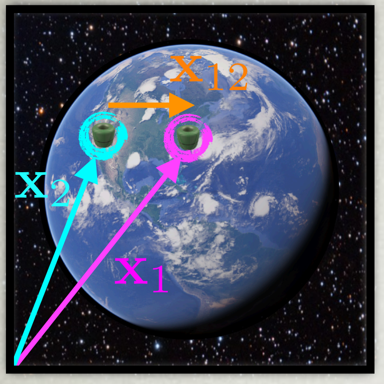
Measurement at MIT

$$\Phi_1 \sim a(\mathbf{x}_1, t) \sim \sum_{\mathbf{v}} \sqrt{f(\mathbf{v})} \cos[\omega_v t - \mathbf{k}_{\mathbf{v}} \cdot \mathbf{x}_1 + \phi_{\mathbf{v}}]$$

Measurement at SLAC

$$\Phi_2 \sim a(\mathbf{x}_2, t) \sim \sum_{\mathbf{v}} \sqrt{f(\mathbf{v})} \cos[\omega_v t - \mathbf{k}_{\mathbf{v}} \cdot \mathbf{x}_2 + \phi_{\mathbf{v}}]$$

Basic Idea



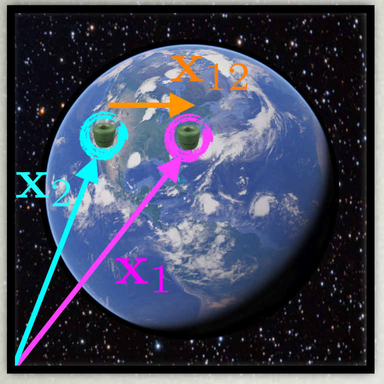
Two Detectors

Fruits of a collaboration*

$$\Phi_1 + \Phi_2 \sim \sum_{\mathbf{v}} \sqrt{f(\mathbf{v})} \cos[\omega_v t + \phi_{\mathbf{v}}] \cos[\mathbf{k}_{\mathbf{v}} \cdot \mathbf{x}_{12}/2]$$

$$\mathbf{x}_{12} = \mathbf{x}_1 - \mathbf{x}_2$$

*Requires μs-ns level synchronization (exact value depends on m)



Basic Idea

Two Detectors

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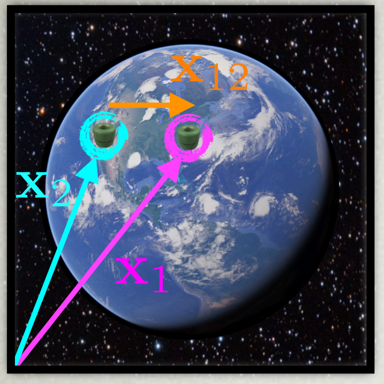
$$\Phi_1 + \Phi_2 \sim \sum_{\mathbf{v}} \sqrt{f(\mathbf{v})} \cos[\omega_v t + \phi_{\mathbf{v}}] \cos[\mathbf{k}_{\mathbf{v}} \cdot \mathbf{x}_{12}/2]$$

$$\Rightarrow S_{\Phi\Phi}(\omega) \sim \frac{4}{v_\omega} \int d^3\mathbf{v} f(\mathbf{v}) \cos^2[m_a \mathbf{v} \cdot \mathbf{x}_{12}/2] \delta[|\mathbf{v}| - v_\omega]$$

PSD remains exponentially distributed
⇒ full likelihood formalism

c.f. [Foster, **NLR**, Safdi 17]



Basic Idea

Two Detectors

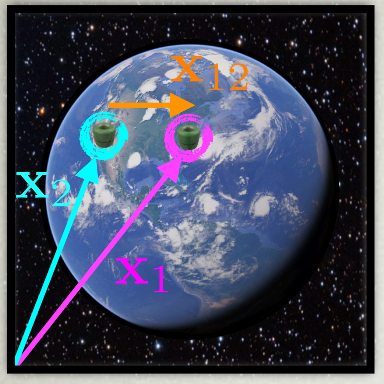
c.f. 1 detector PSD:

$$f(v) \to \mathcal{F}(v) = 4\int d^3\mathbf{v}\, f(\mathbf{v}) \cos^2[m_a \mathbf{v}\cdot \mathbf{x}_{12}/2]\delta[|\mathbf{v}| - v_\omega]$$

Interference leads to a modulated speed distribution

- ***Contains information invisible to one detector***
- Result varies with $\mathbf{x}_{12}$ - daily modulation
- Simple generalization to $\mathcal{N}$ detectors

Basic Idea



Two Detectors

c.f. 1 detecto

$$f(v) \to \mathcal{F}(\quad] \delta[|\mathbf{v}| - v_\omega]$$

Outline

(for the last few minutes)

1. Toy Example: scalings & intuition
2. Realistic Case: estimating $\mathbf{v}_\odot$

Interference leads to a modulated speed distribution

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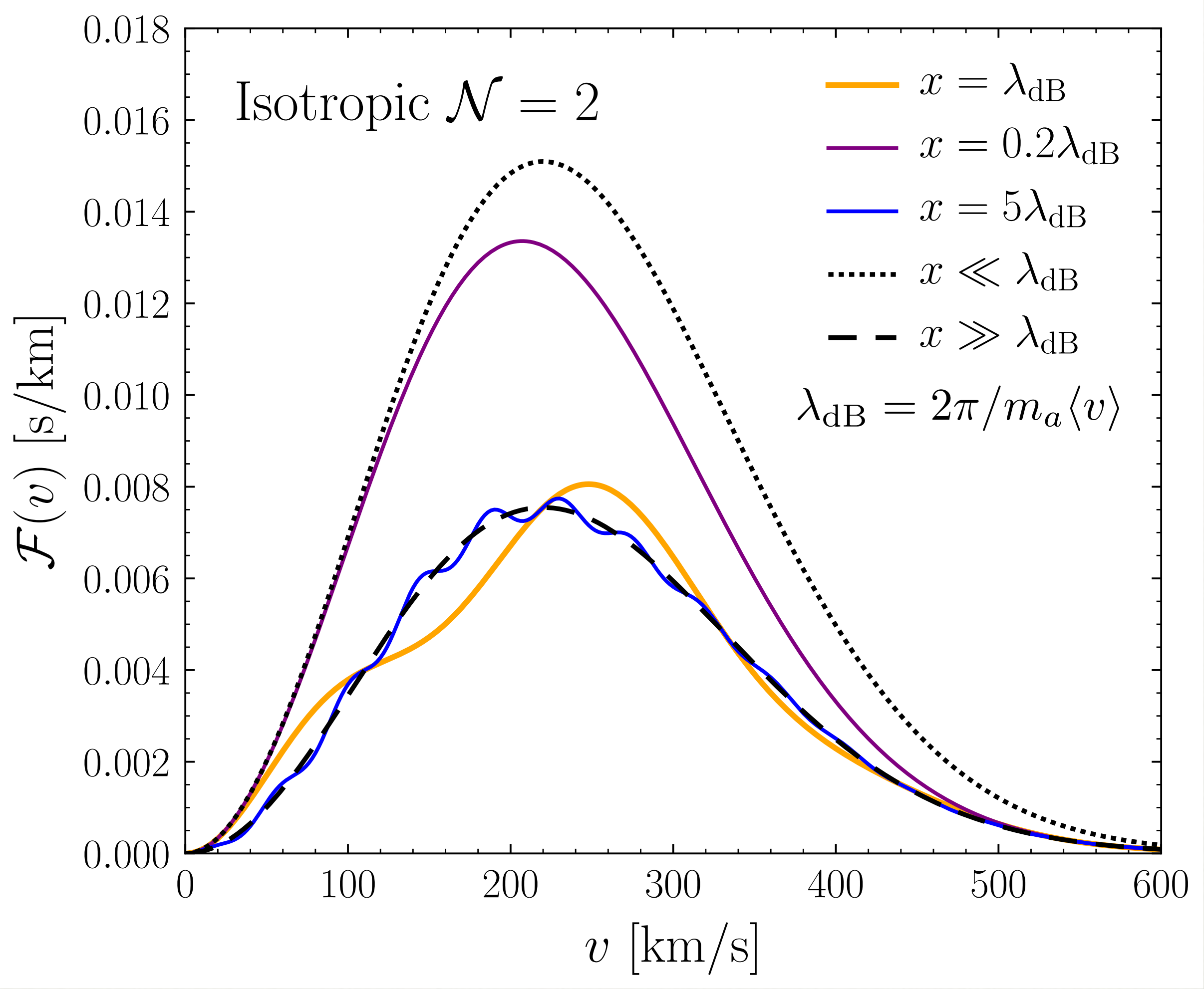
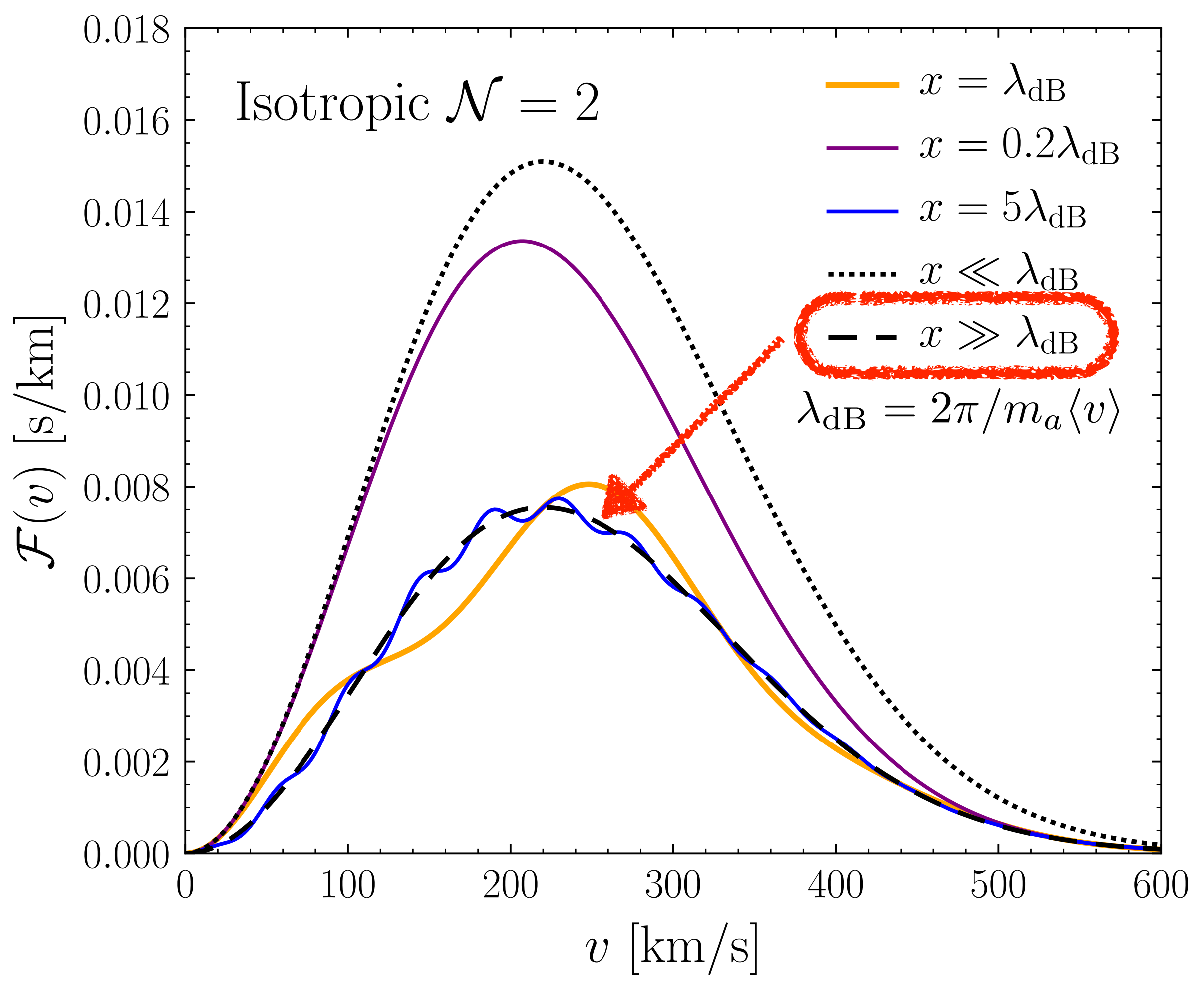
- Simple generalization to $\mathcal{N}$ detectors

Toy Example



$$\mathcal{F}(v) = 4\int d^3\mathbf{v} f(\mathbf{v}) \cos^2[m_a \mathbf{v}\cdot\mathbf{x}/2]\,\delta[|\mathbf{v}| - v]$$

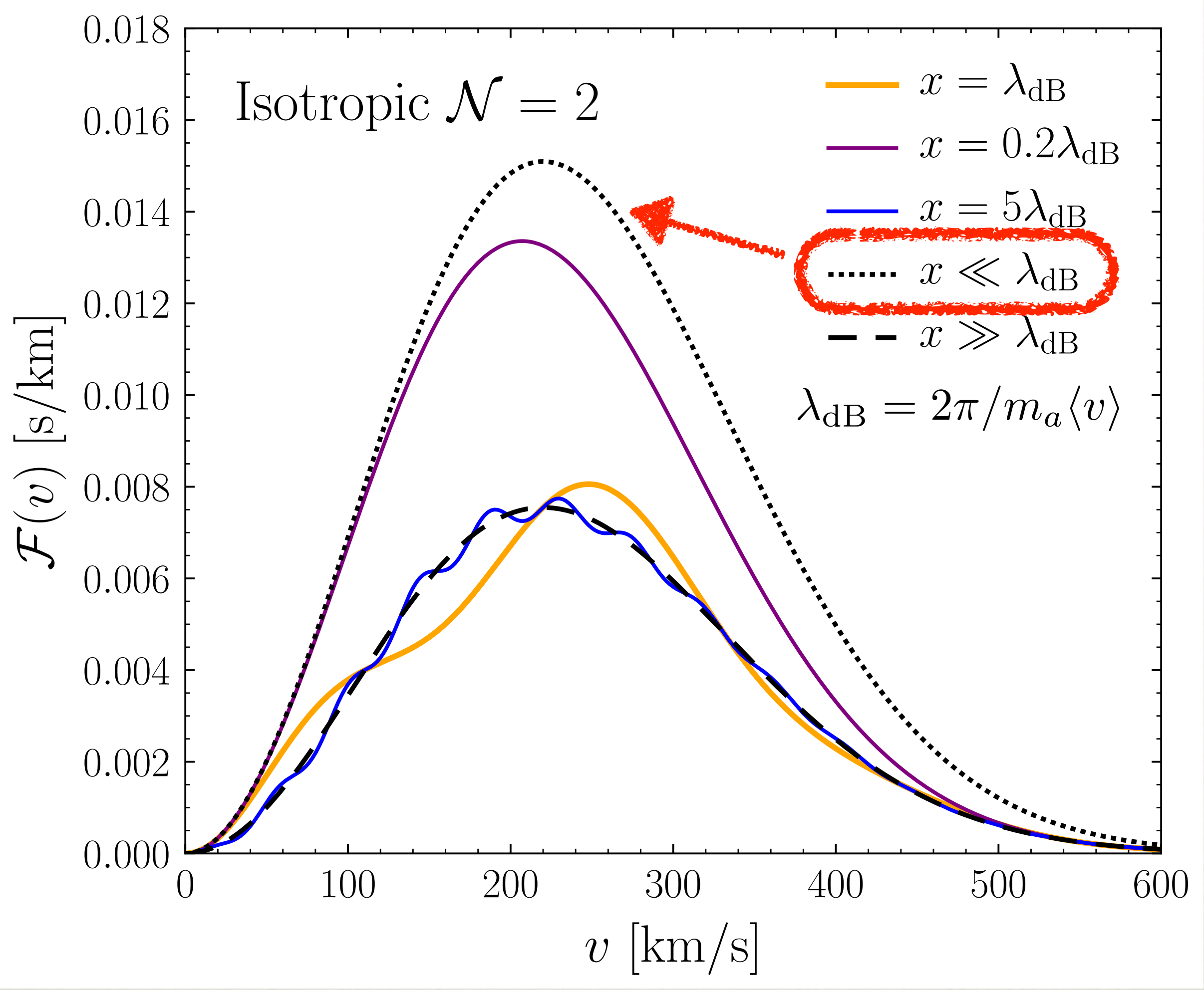
Toy Example



$$\mathcal{F}(v) = 4\int d^3\mathbf{v} f(\mathbf{v}) \underbrace{\cos^2[m_a \mathbf{v}\cdot\mathbf{x}/2]}_{\to 1/2} \delta[|\mathbf{v}| - v] = 2 f(v)$$

Incoherent

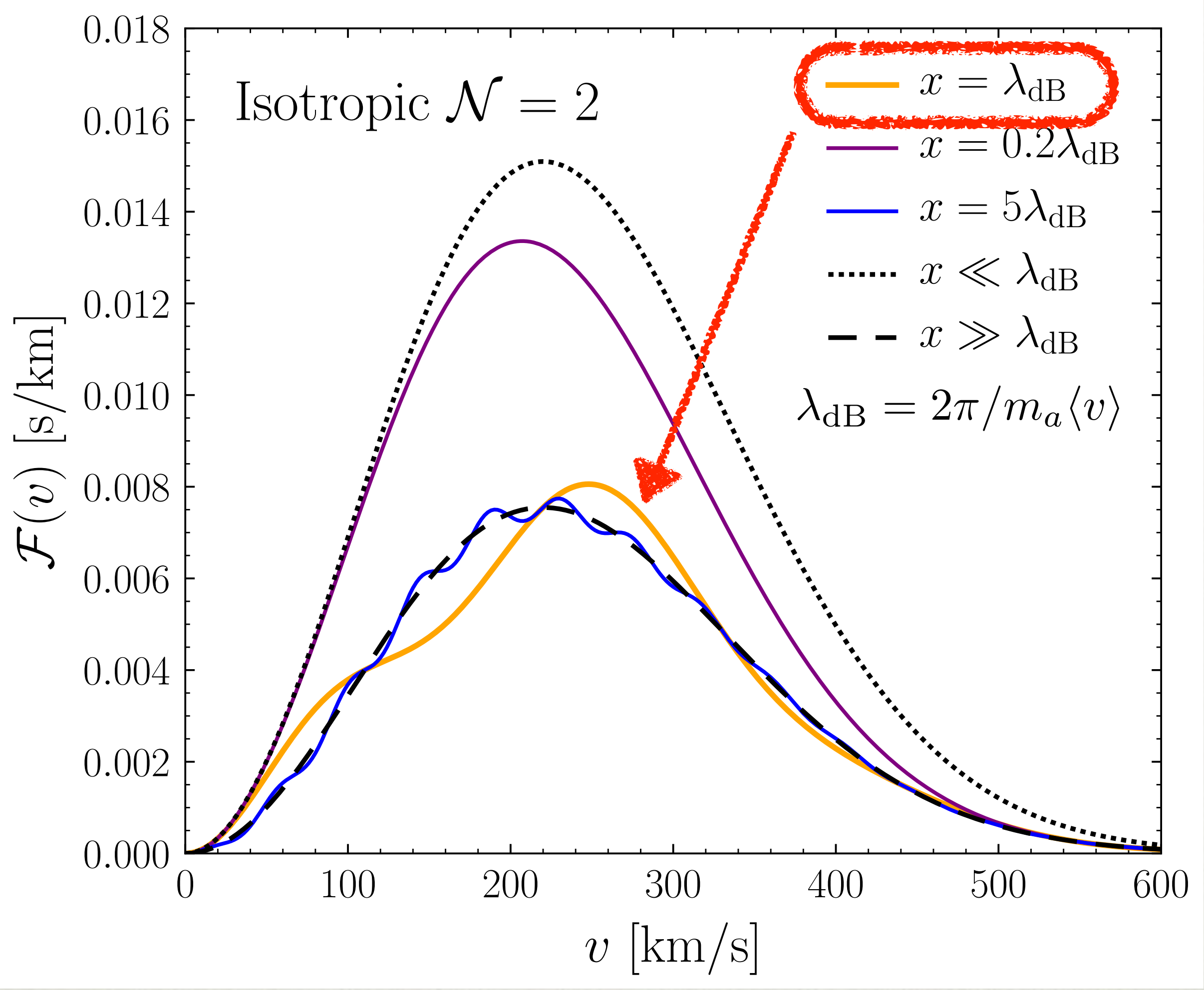
Toy Example



$$\mathcal{F}(v) = 4\int d^3\mathbf{v} f(\mathbf{v}) \underbrace{\cos^2[m_a \mathbf{v}\cdot\mathbf{x}/2]}_{\to 1} \delta[|\mathbf{v}| - v] = 4 f(v)$$

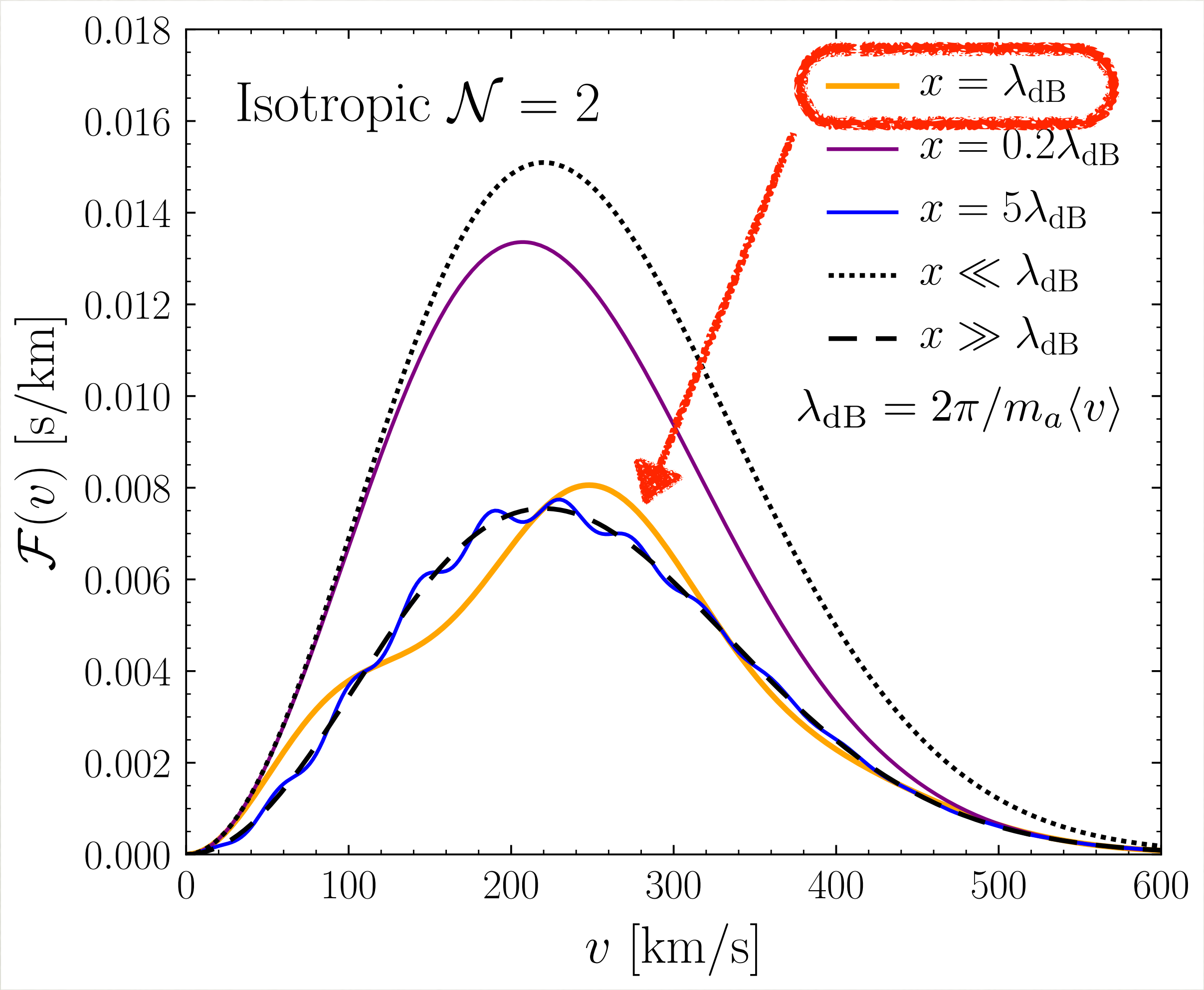
Coherent

Toy Example



$$\mathcal{F}(v) = 4\int d^3\mathbf{v} f(\mathbf{v}) \cos^2[m_a \mathbf{v}\cdot\mathbf{x}/2]\,\delta[|\mathbf{v}| - v] \propto f(v)$$

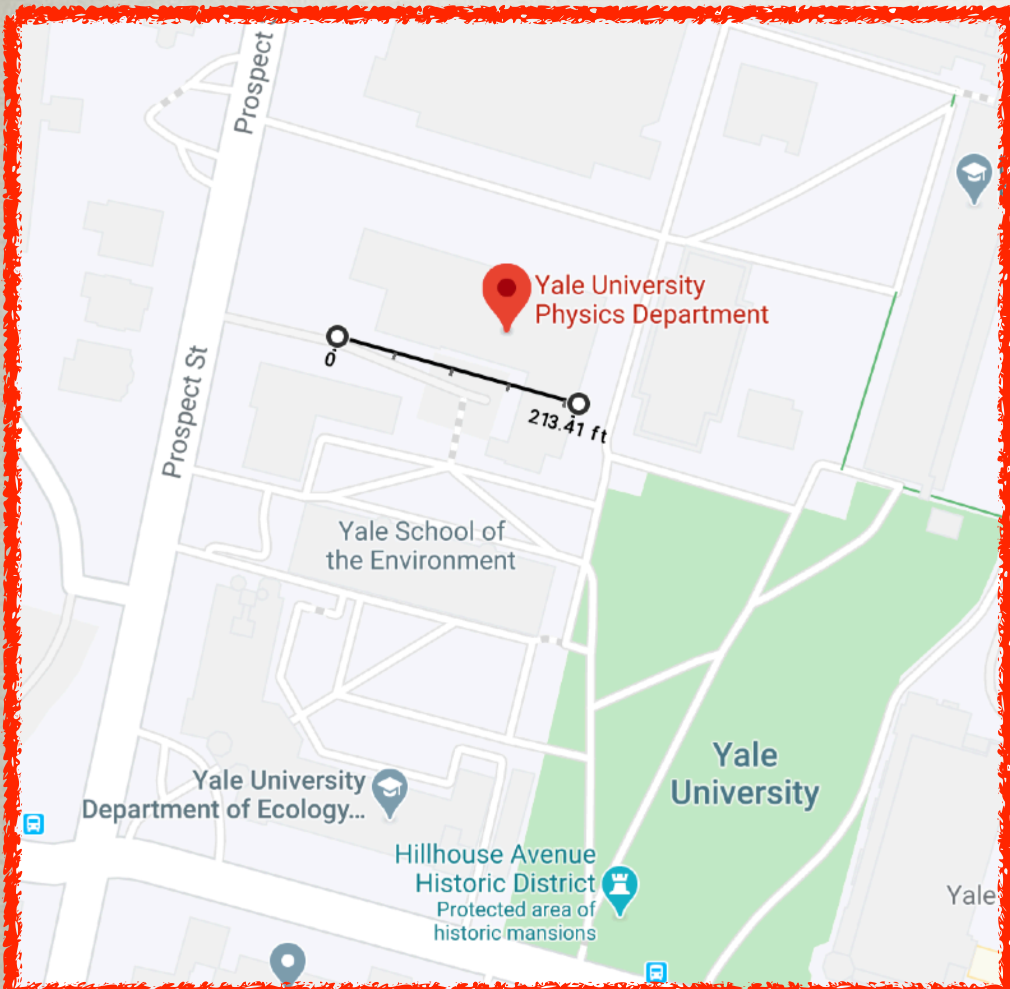
Toy Example

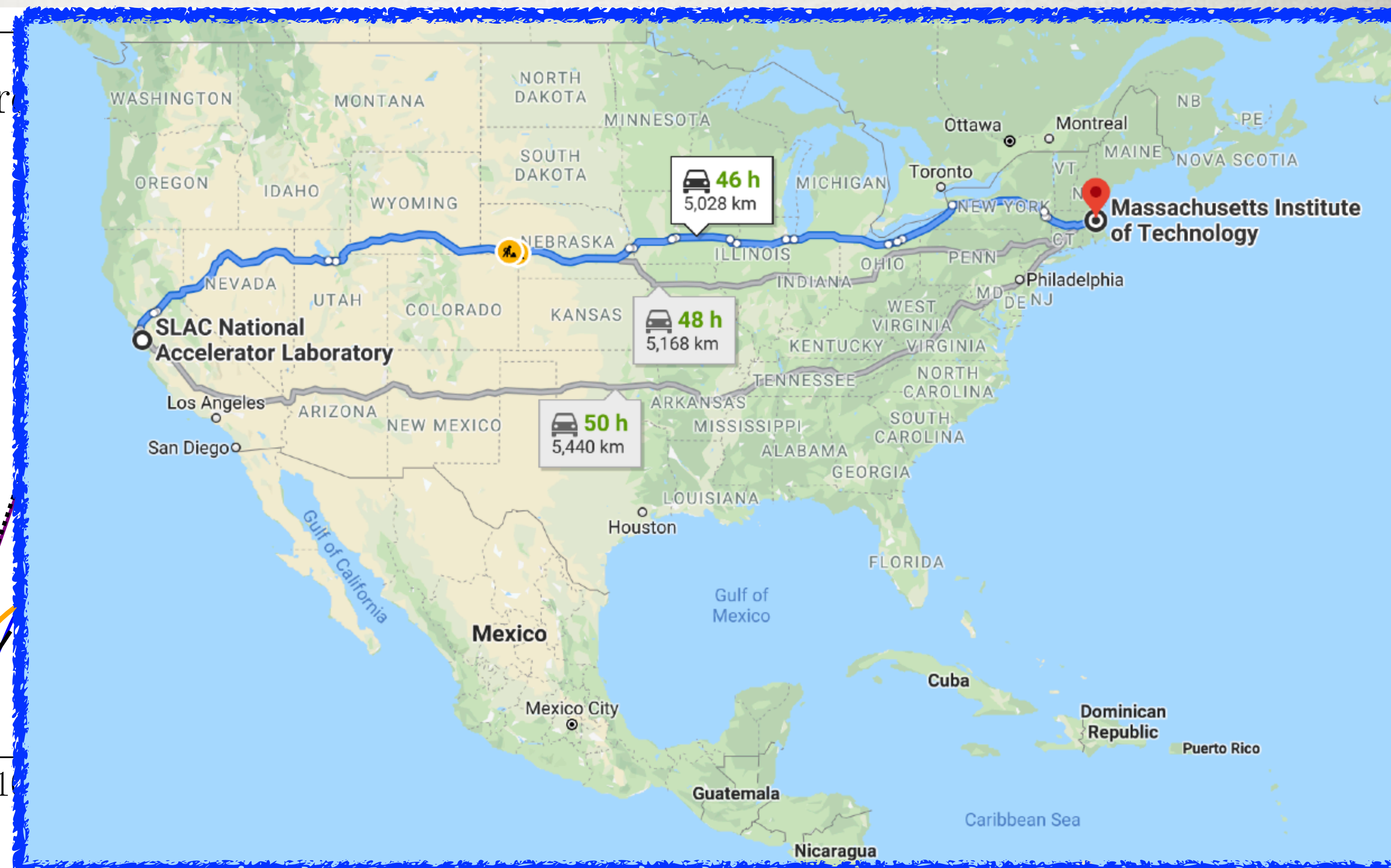


1. $m_a = 25\ \mu\text{eV} \Rightarrow \lambda_{dB} \approx 50\ \text{m}$
2. $m_a = 1\ \text{neV} \Rightarrow \lambda_{dB} \approx 2{,}000\ \text{km}$

Why 25 μeV? See [Buschmann, Foster, Safdi 20]

Toy Examples





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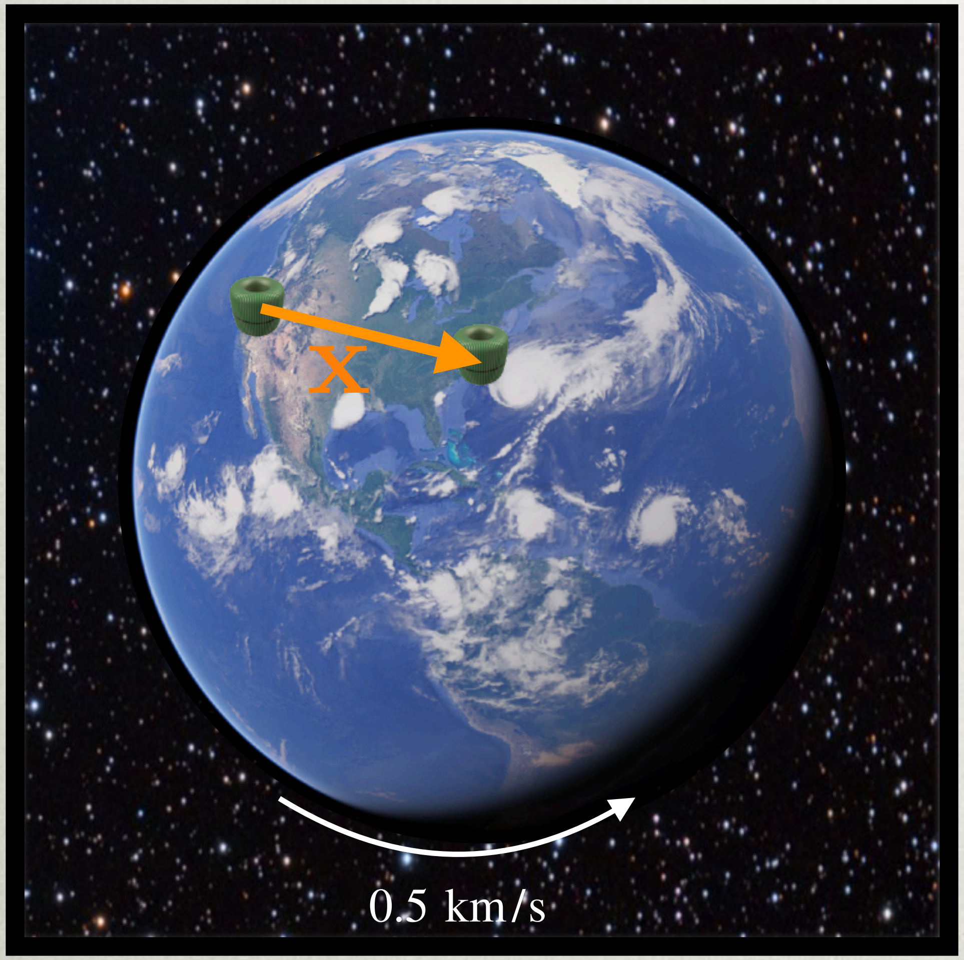
Daily Modulation

A Unique Wave Dark Matter Signal



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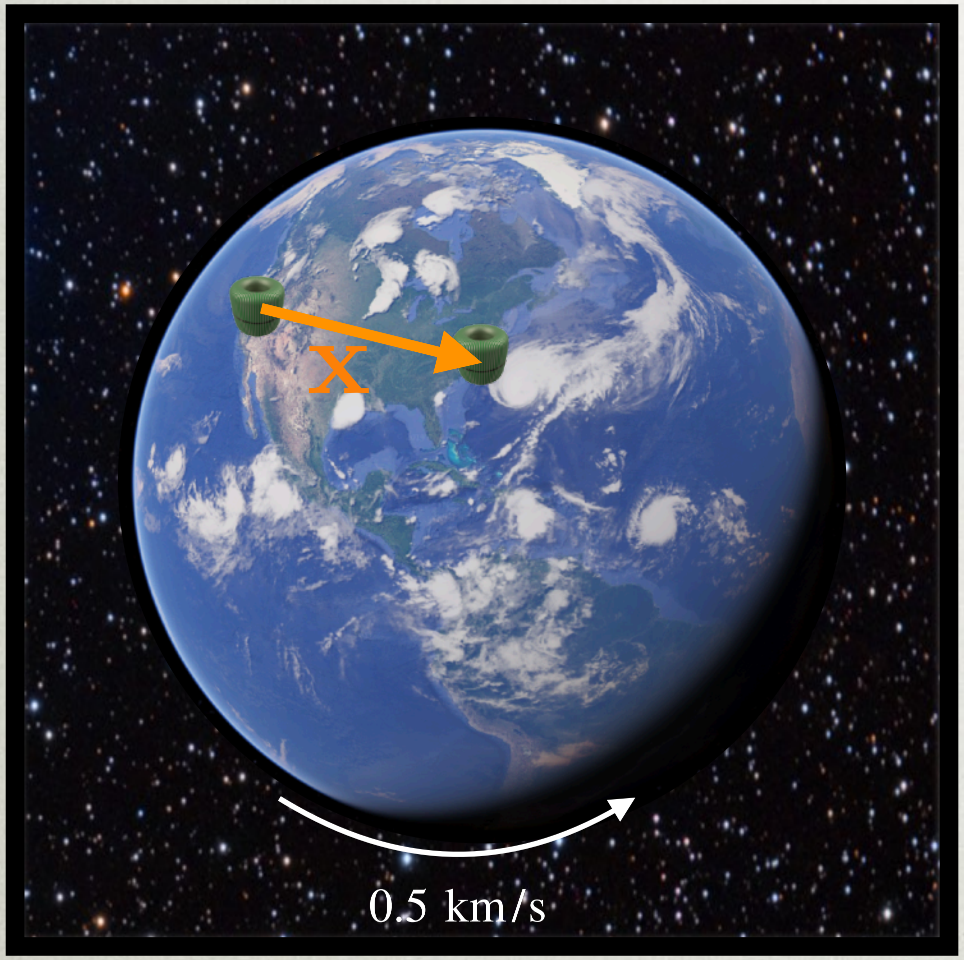

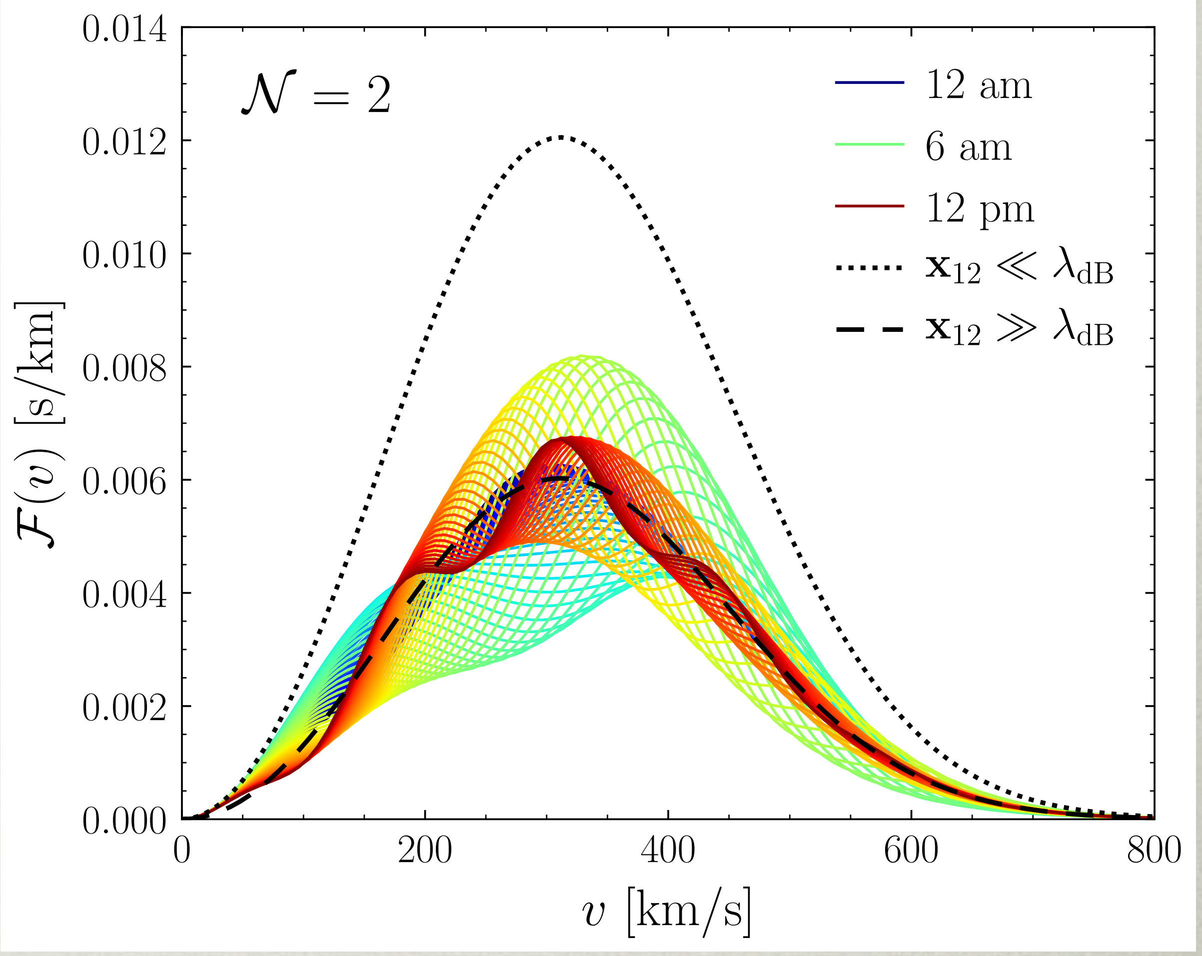

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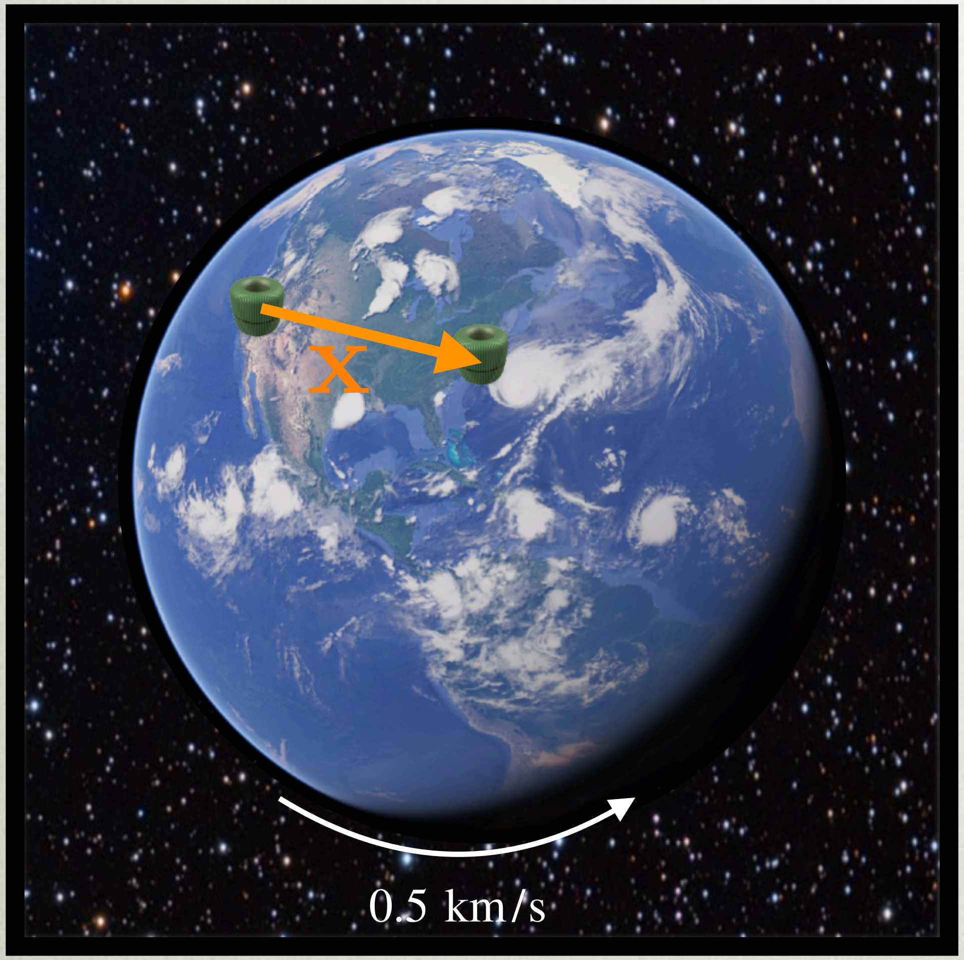
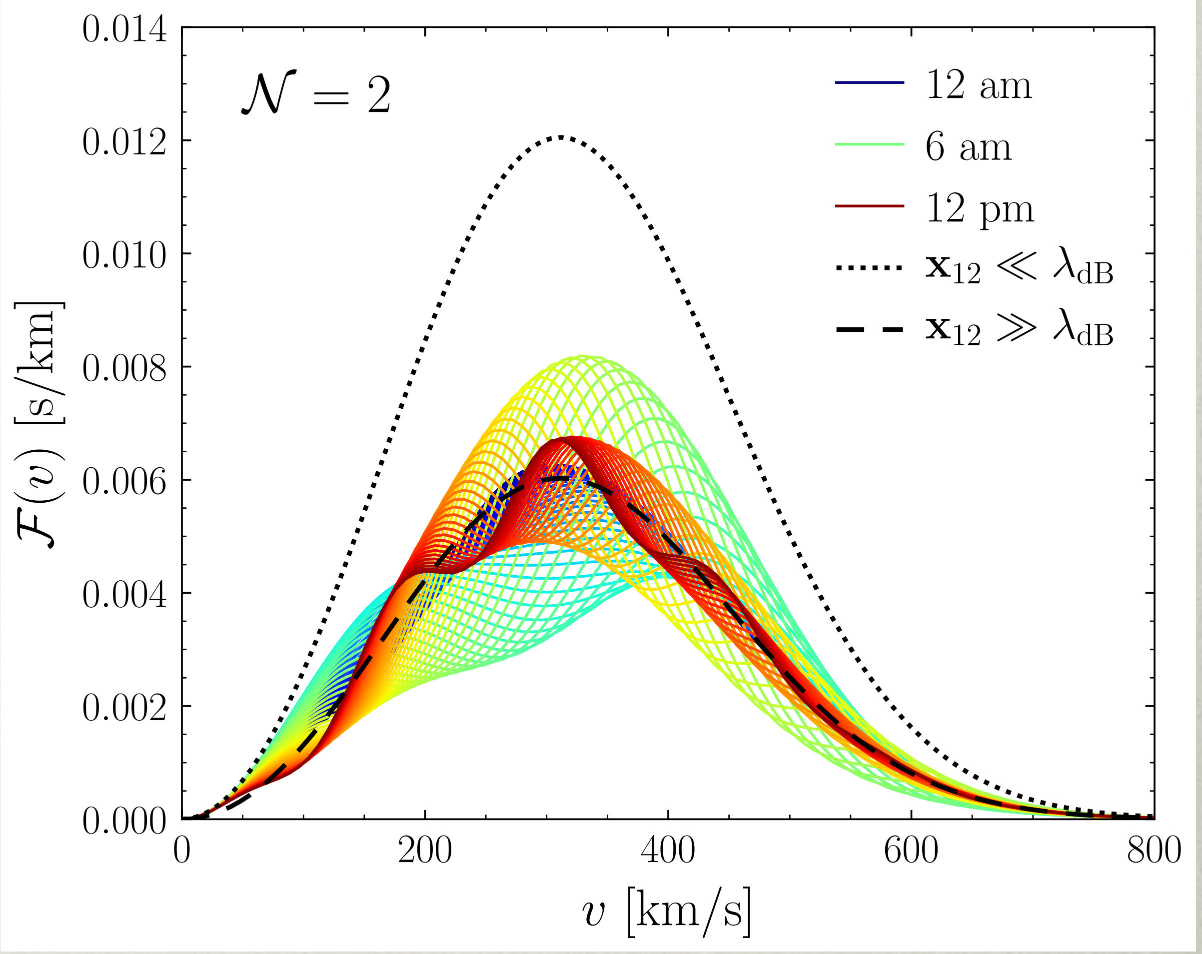


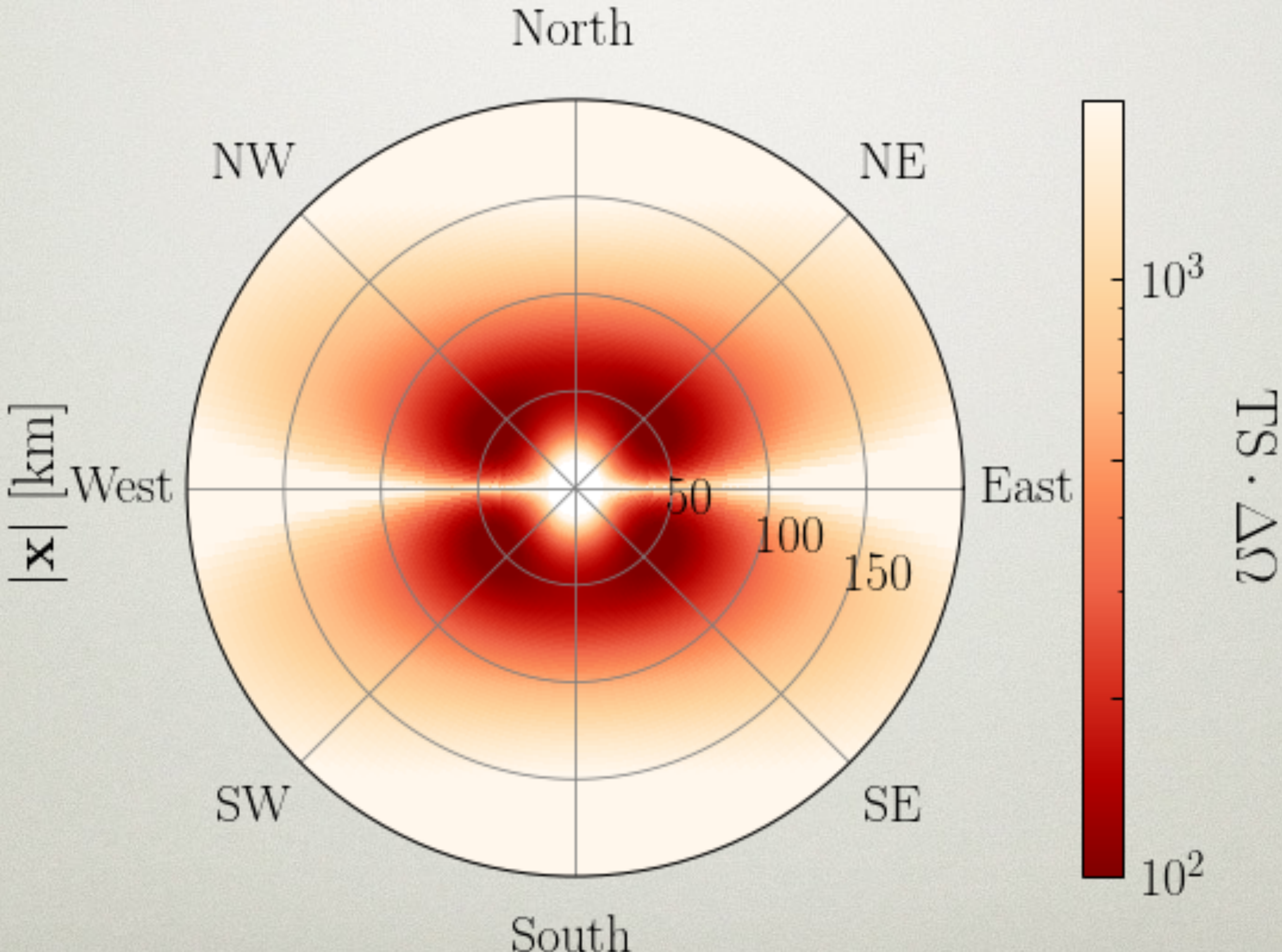


How well can we estimate the direction of $\mathbf{v}_{\odot}$?

Daily Modulation

A Unique Wave Dark Matter Signal

PRELIMINARY



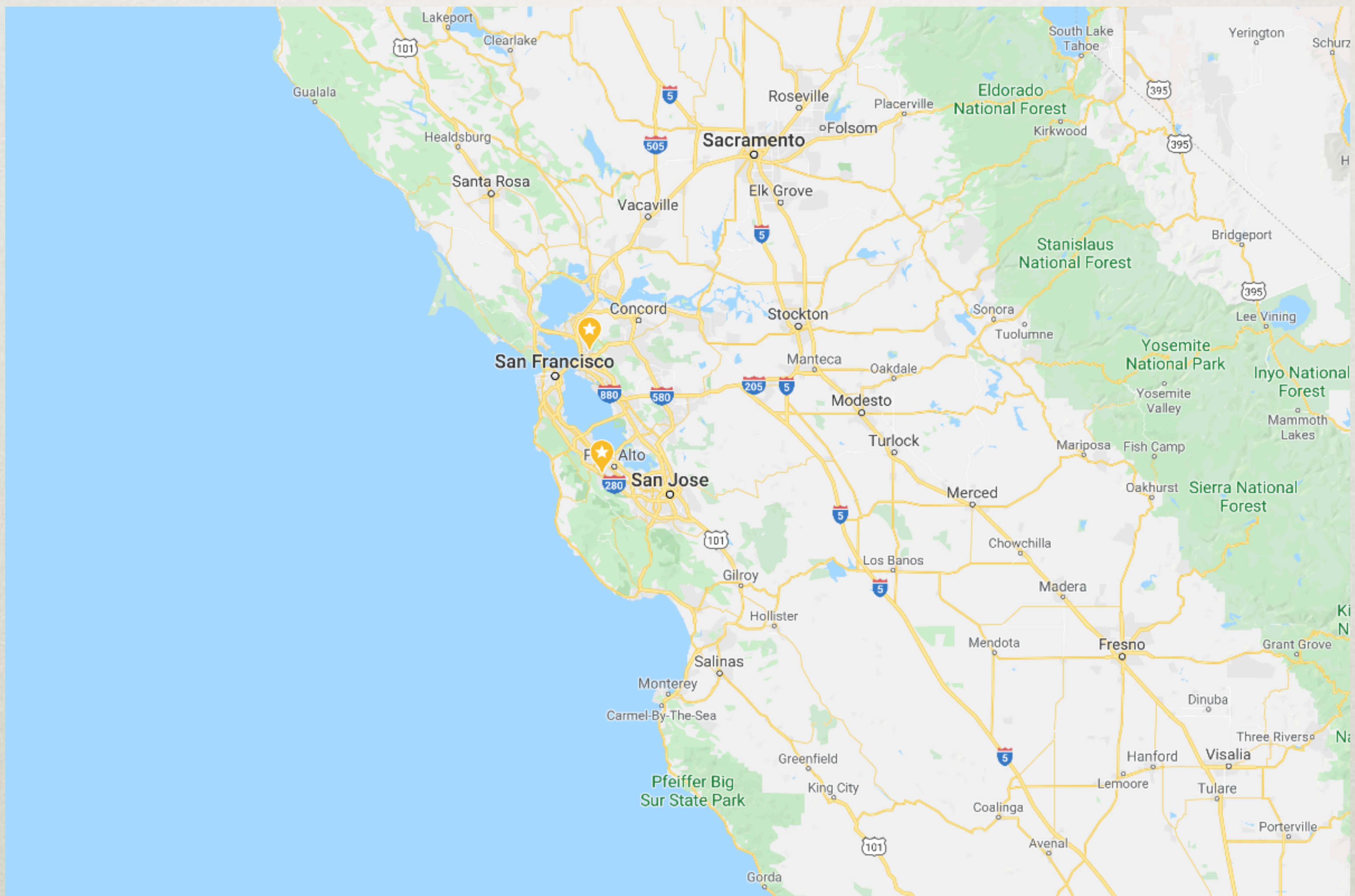
PRELIMINARY

$m_a = 10$ neV

Daily Modulation

A Unique Wave Dark Matter Signal

PRELIMINARY



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$$m_a = 10 \text{ neV}$$

Daily Modulation

A Unique Wave Dark Matter Signal

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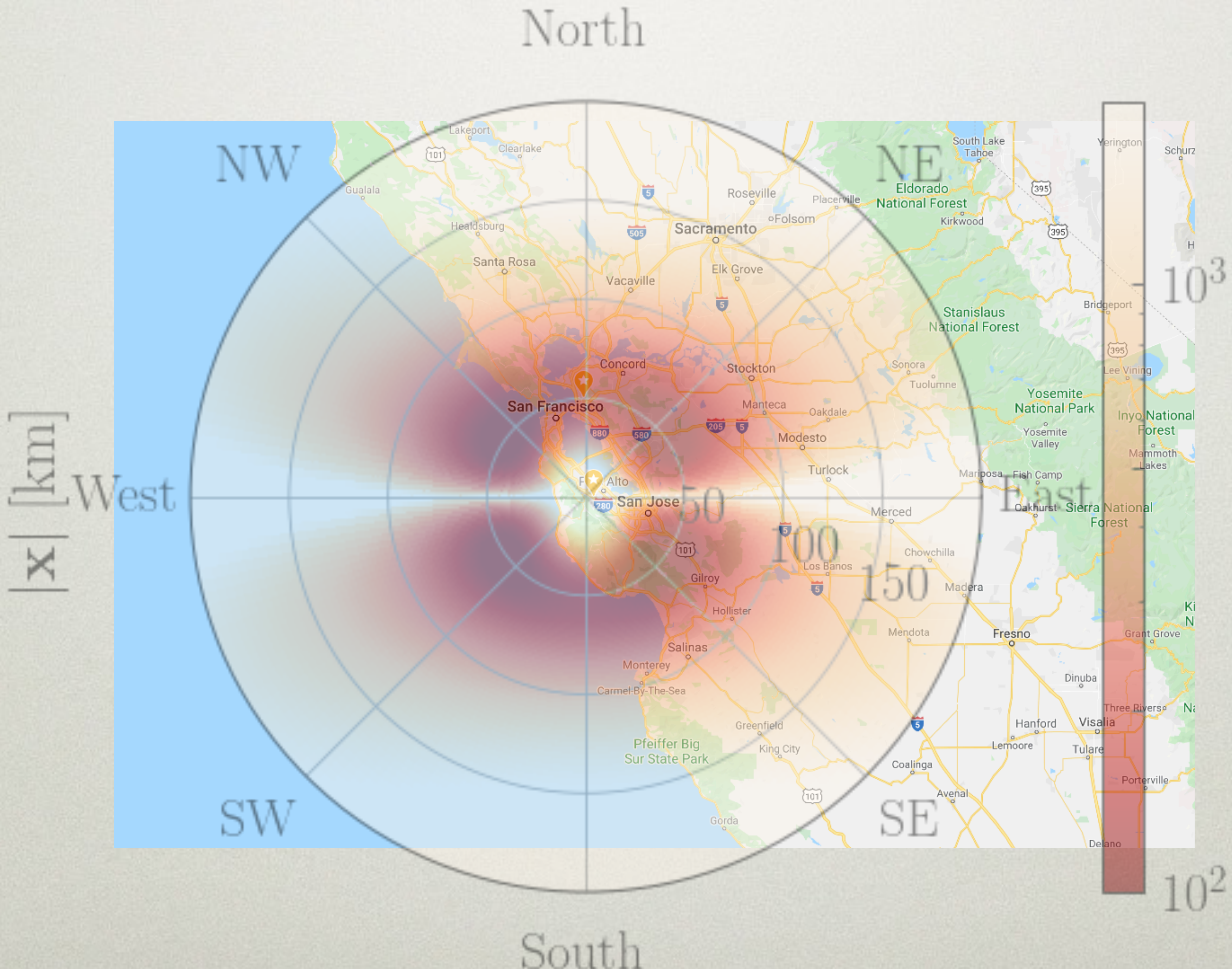


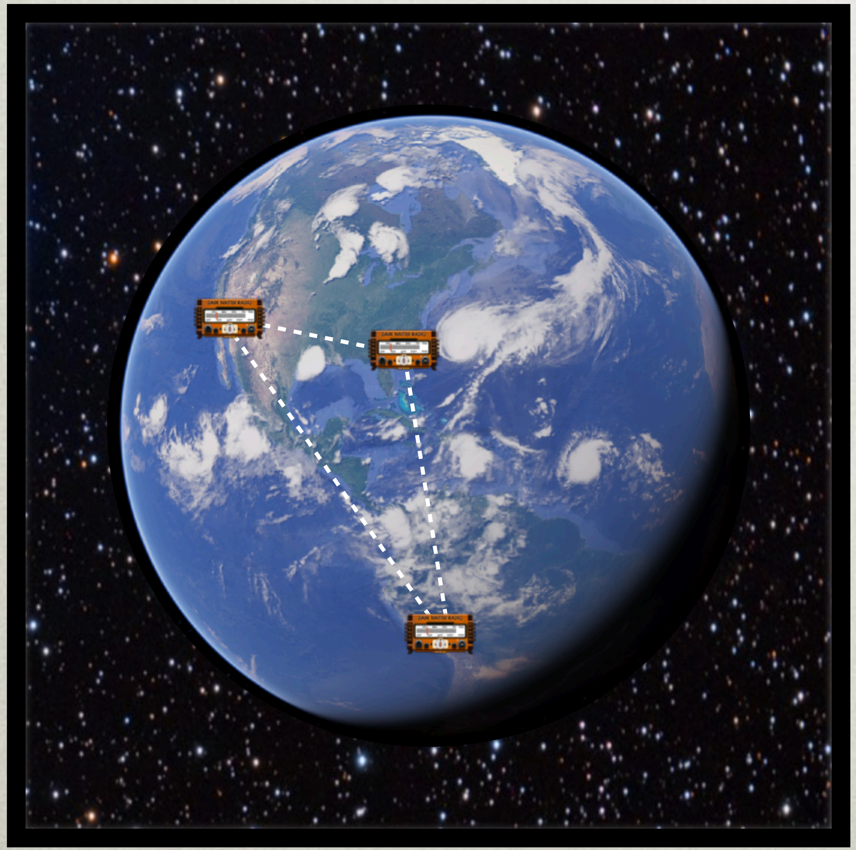
PRELIMINARY

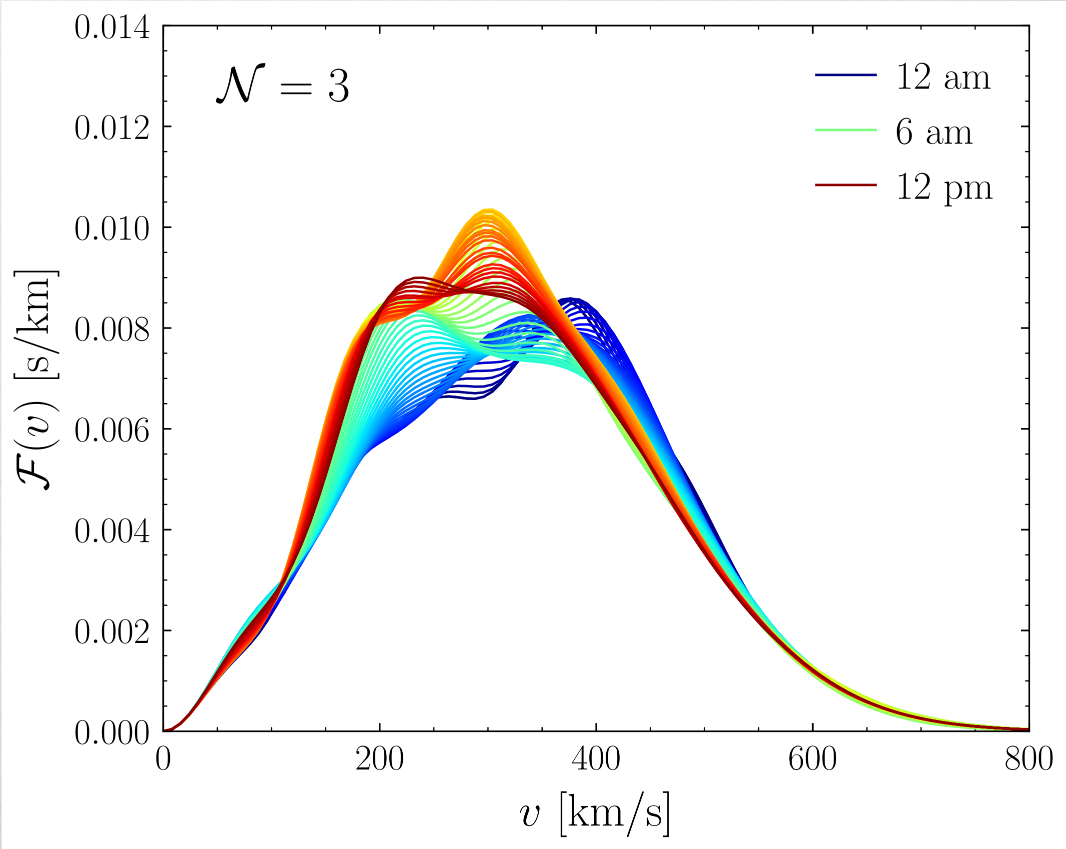
$m_a = 10$ neV

Conclusion

A Unique Wave Dark Matter Signal

- Encodes information invisible to 1 detector, e.g. $\mathbf{v}_\odot$
- Carries the unique fingerprint of dark matter





Backup Slides

Result for a General $\mathcal{N}$

$$\Phi(\mathbf{x},t) = \sqrt{A}a(\mathbf{x},t)$$

$$\langle S_{\Phi\Phi}(\omega)\rangle = A\frac{\pi\mathcal{F}(v_\omega)}{m_a v_\omega}$$

Exponentially Distributed

$$\mathcal{F}(v) = \mathcal{N}\int d^3\mathbf{v}\, f(\mathbf{v})\mathcal{X}(\mathbf{v})\delta[|\mathbf{v}|-v]$$

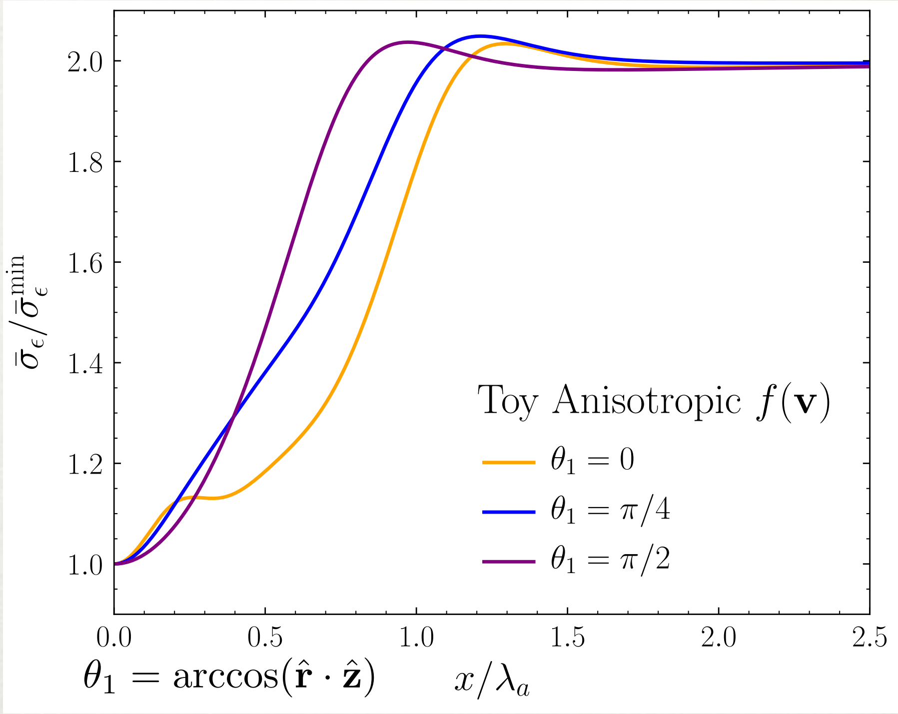
$$\mathcal{X}(\mathbf{v}) = 1 + \frac{2}{\mathcal{N}}\sum_{(ij)\in\mathcal{C}}\cos[m_a\mathbf{v}\cdot\mathbf{x}_{ij}]$$

Unique pairs

Toy Examples

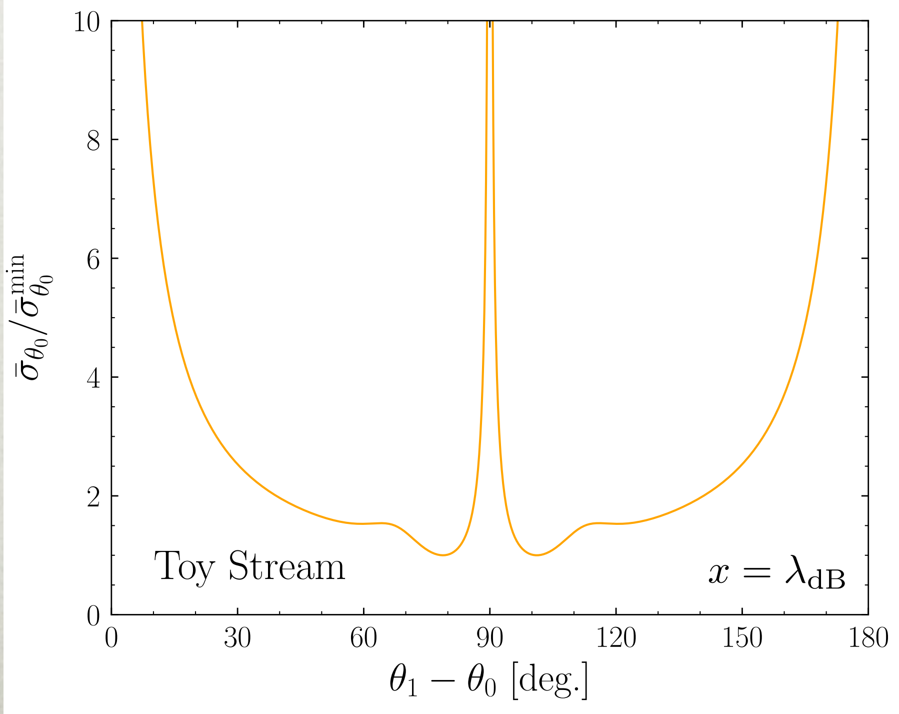
Anisotropy? Interferometry ✗

$$f(\mathbf{v}) = \frac{\sqrt{1+\epsilon}}{\pi^{3/2} v_0^3} e^{-(v_x^2+v_y^2+(1+\epsilon)v_z^2)/v_0^2}$$



Stream? Interferometry ✔

$$f(\mathbf{v}) = \frac{4}{\sqrt{\pi} v_0^3} \frac{e^{-v^2/v_0^2}}{\sin\theta_0} \delta(\theta - \theta_0)\delta(\phi)$$



Parameters for realistic case

- Data over 24 hours
- Read out every 30 minutes, 75 averages/read out
- 0.04 Hz resolution