The spectral lineshape of gradient-coupled bosonic dark matter in our galaxy

Arne Wickenbrock, Alexander Gramolin et al.
for the CASPEr collaboration

PATRAS conference, 18.06.2021

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Nuclear Magnetic Resonance Meets Dark Matter

The Cosmic Axion Spin Precession Experiment (CASPEr)

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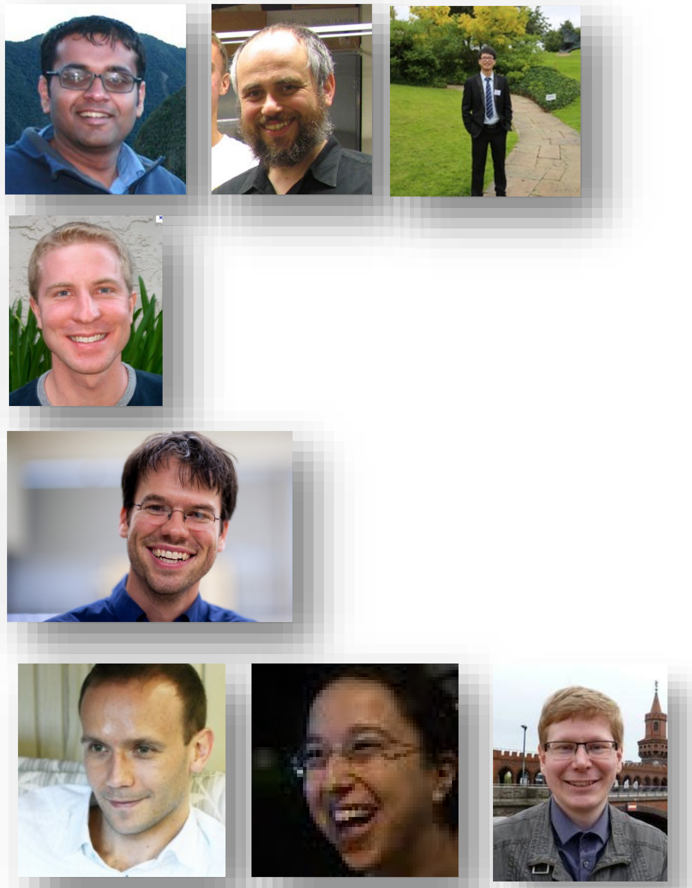
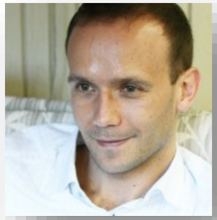
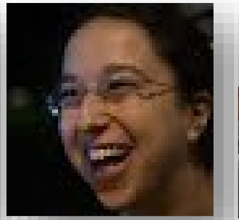
Acknowledgements

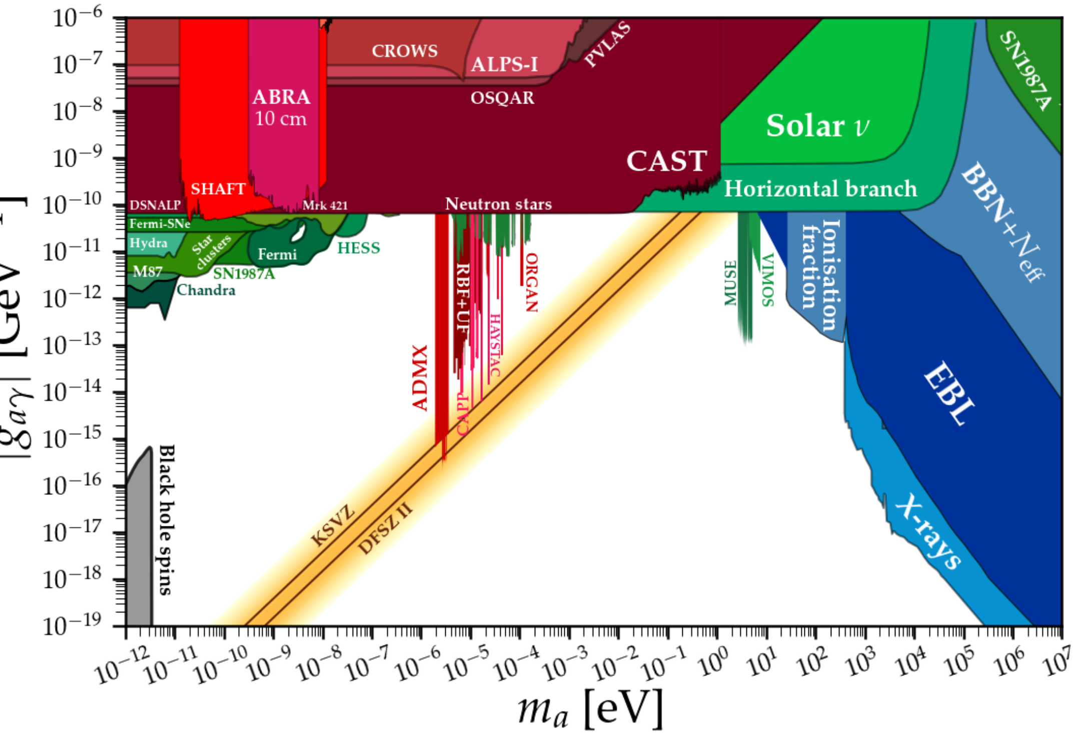


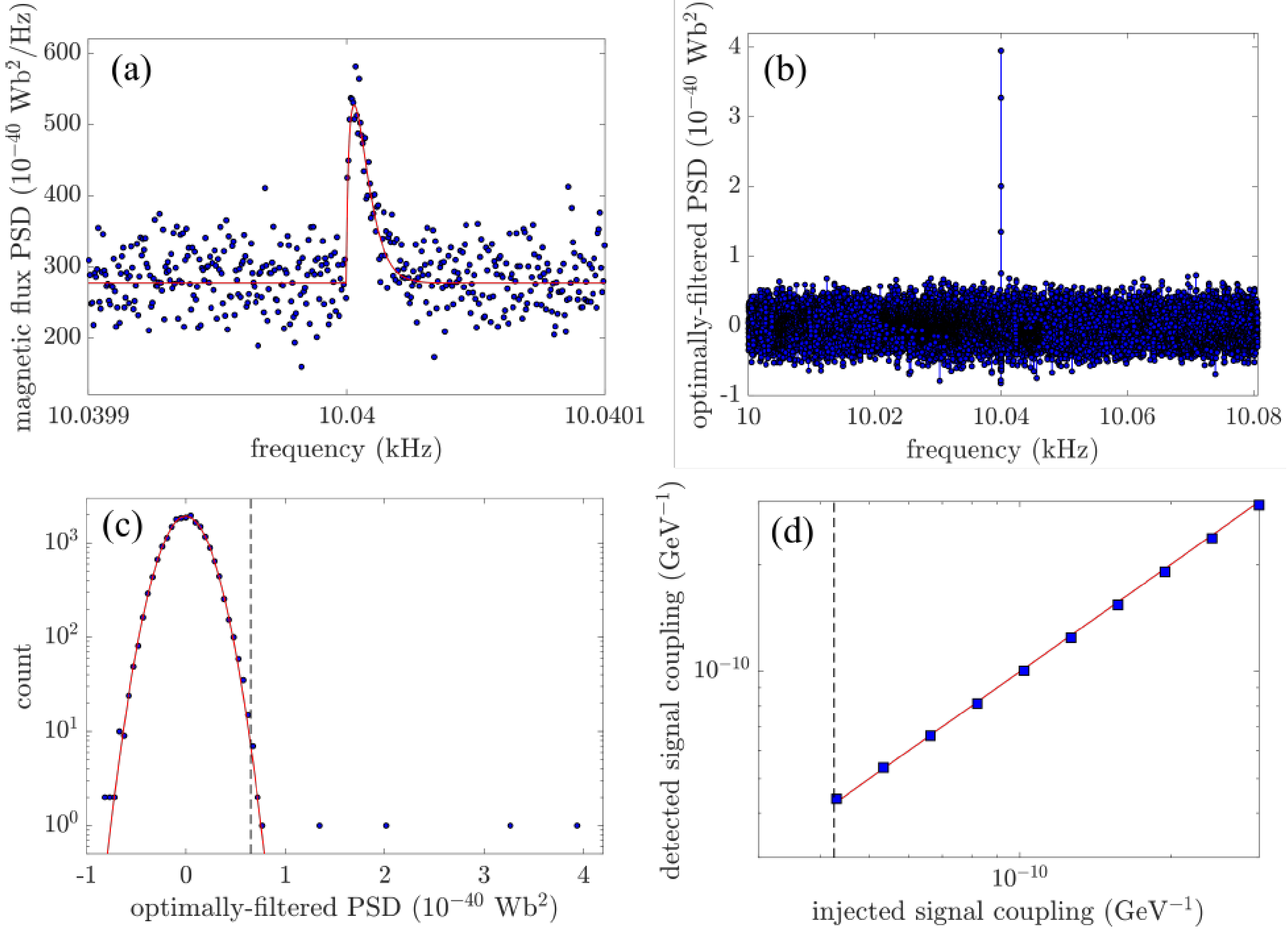
Arian Dogan

Why is the lineshape relevant?


Improving limits by optimally filtering the power spectrum data in SHAFT





Talk by Alex Sushkov (Thursday)

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Ciaran O'Hare: https://cajohare.github.io/AxionLimits/

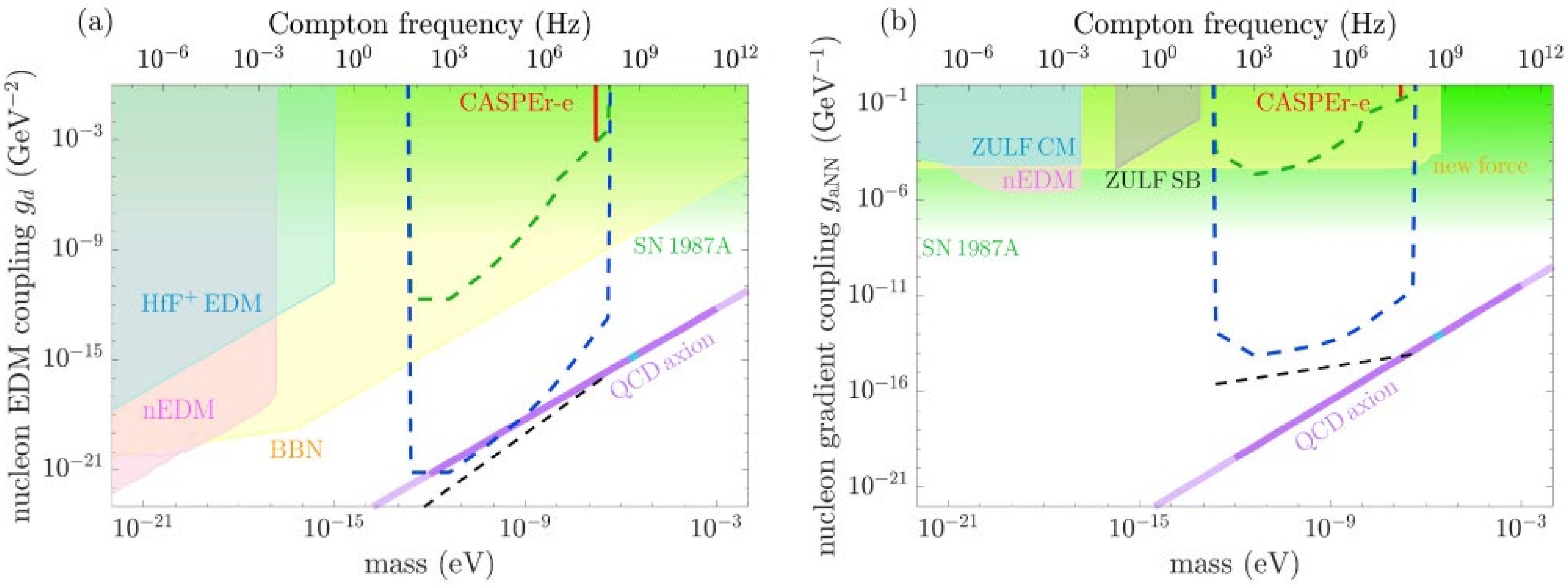
CASPEr Boston result

Talk by Deniz Aybas (Thursday)

Search for Axionlike Dark Matter Using Solid-State Nuclear Magnetic Resonance

Deniz Aybas, Janos Adam, Emmy Blumenthal, Alexander V. Gramolin, Dorian Johnson, Annalies Kleyheeg, Samer Afach, John W. Blanchard, Gary P. Centers, Antoine Garcon, Martin Engler, Nataniel L. Figueroa, Marina Gil Sendra, Arne Wickenbrock, Matthew Lawson, Tao Wang, Teng Wu, Haosu Luo, Hamdi Mani, Philip Mauskopf, Peter W. Graham, Surjeet Rajendran, Derek F. Jackson Kimball, Dmitry Budker, and Alexander O. Sushkov

Phys. Rev. Lett. **126**, 141802 – Published 9 April 2021



Optimal filtering in CASPEr-E Boston required the gradient coupling lineshape

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How to search for Axions (ALPs) ?

Axion (ALP) Interactions

Gravity

$+$

Gauge Fields

$$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} \qquad \frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

Most Searches

(CASPEr-E)

Fermions

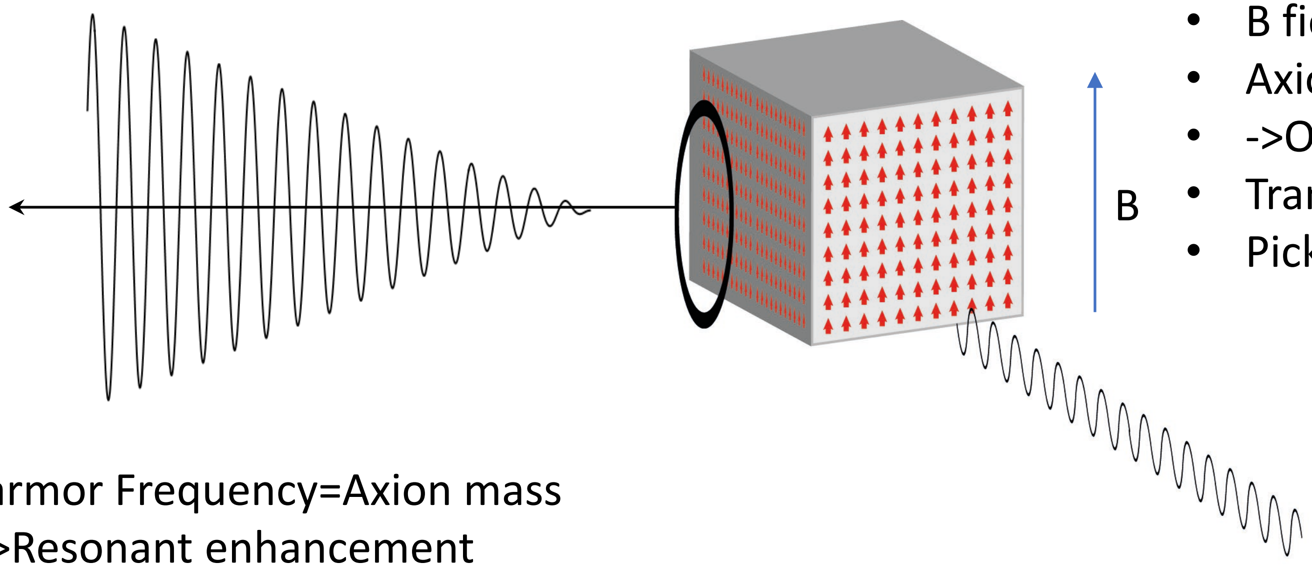
$$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

(CASPEr-Gradient, GNOME, QUAX)

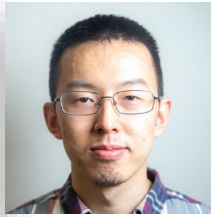
CASPEr – Gradient Mainz – idea

Detecting oscillating torque on nuclear xenon-129 spins from (0.01-4) MHz

$$\frac{\partial_\mu a}{f_a}\bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$



- Polarized nuclear spins
- B field
- Axion gradient couples to spins
- ->Oscillating torque on spins
- Transversal magnetization
- Pickup (somehow)


Larmor Frequency=Axion mass
=>Resonant enhancement

Talk by Hendrik Bekker (Thursday)

In Mainz: **Casper Gradient Low field 0.01-4 MHz**
Casper Gradient High Field 4-600 MHz

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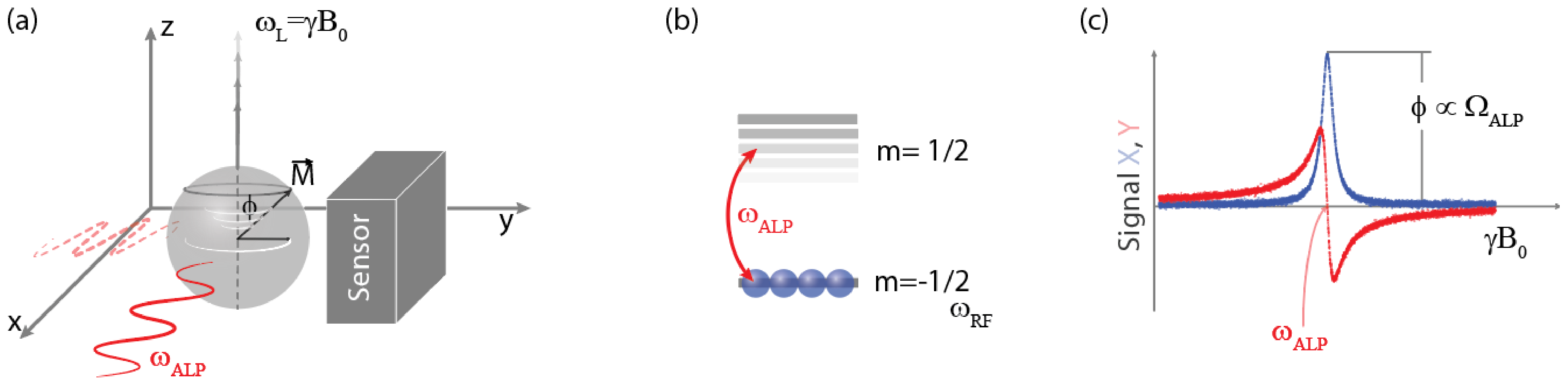
Two ways to search



Perp. To B
Sensitivity plane

Parallel to B
Sensitivity axis

Take home messages

1. **Gradient signal** = 3D pseudo magnetic field vector rotating in space with two independent phases
2. **Gradient line shape** fundamentally different (from the scalar lineshape)
3. Most power in the direction of movement (~ linear polarized signal)
4. Larger effect of annual and daily modulation
    1. On signal amplitude
    2. On signal frequency
5. Not new, but still: Virialized dark matter power spectra = modulated white noise

PHYSICAL REVIEW D 97, 123006 (2018)

Derivation of the **scalar** lineshape

Revealing the dark matter halo with axion direct detection

Joshua W. Foster,[1] Nicholas L. Rodd,[2] and Benjamin R. Safdi[1]
[1]*Leinweber Center for Theoretical Physics, Department of Physics, University of Michigan, Ann Arbor, Michigan 48109, USA*
[2]*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

(Received 19 January 2018; published 14 June 2018)

Axion field

$$\nu_n = \left(1+\frac{v_n^2}{2c^2}\right)\nu_a$$

Random acc. speed! Random!

$$a(\mathbf{r},t) = \frac{a_0}{\sqrt{N}}\sum_{n=1}^{N}\cos\left(2\pi\nu_n t - \mathbf{k}_n\cdot\mathbf{r}+\phi_n\right)$$

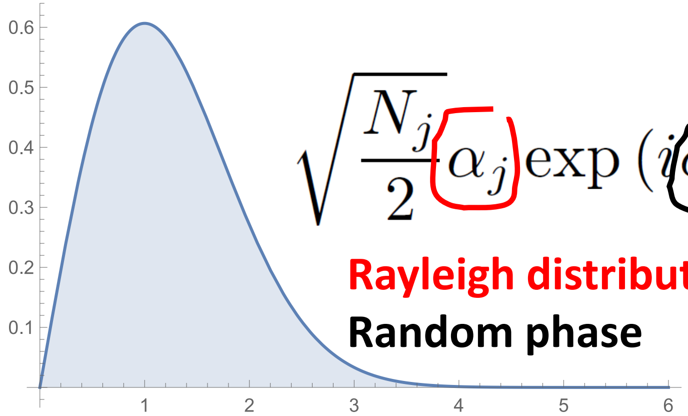
Axion field frequency class j

Oscillation Amplitude + Phase

$$a_j(t) = \frac{a_0}{\sqrt{N_j}}\sum_{i\in\Omega_j}\cos\left(\omega_j t+\phi_i\right) \propto \Re\left[\exp\left(i\omega_j t\right)\sum_{i\in\Omega_j}\exp\left(i\phi_i\right)\right]$$

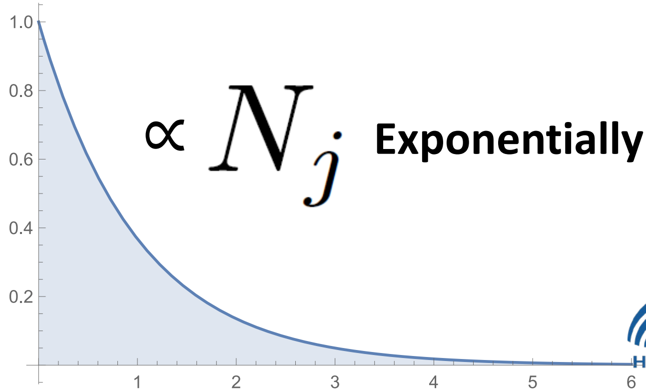
Central limit theorem:

$$\sum_{i\in\Omega_j}\exp\left(i\phi_i\right) =$$



$$\sqrt{\frac{N_j}{2}}\,\alpha_j\exp\left(i\phi_j\right)$$

Rayleigh distributed amplitude
Random phase



$\propto N_j$ **Exponentially distributed power!**

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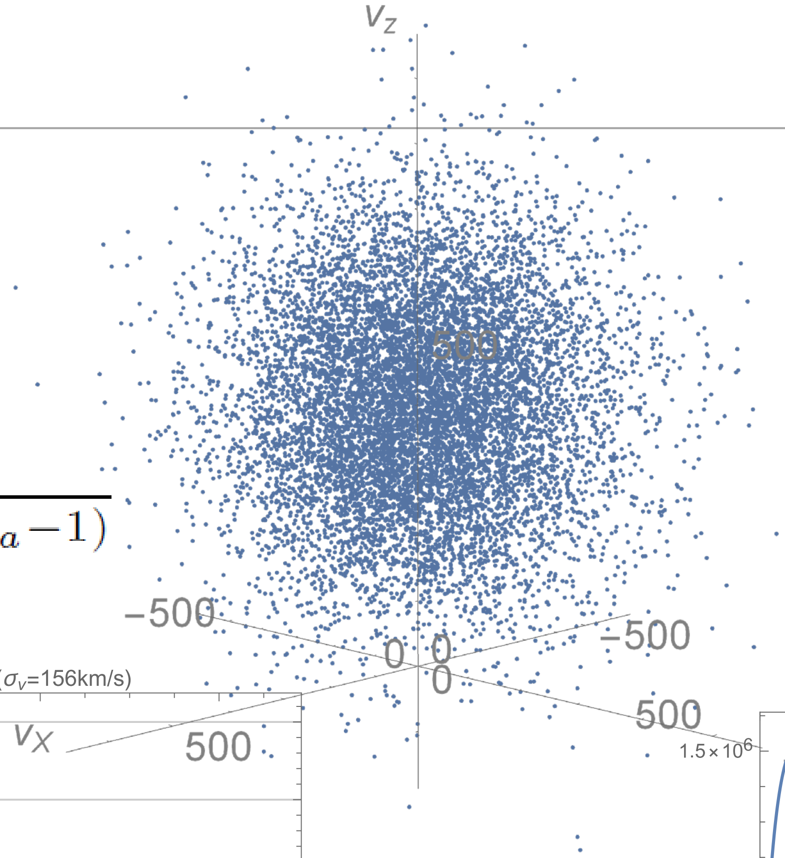
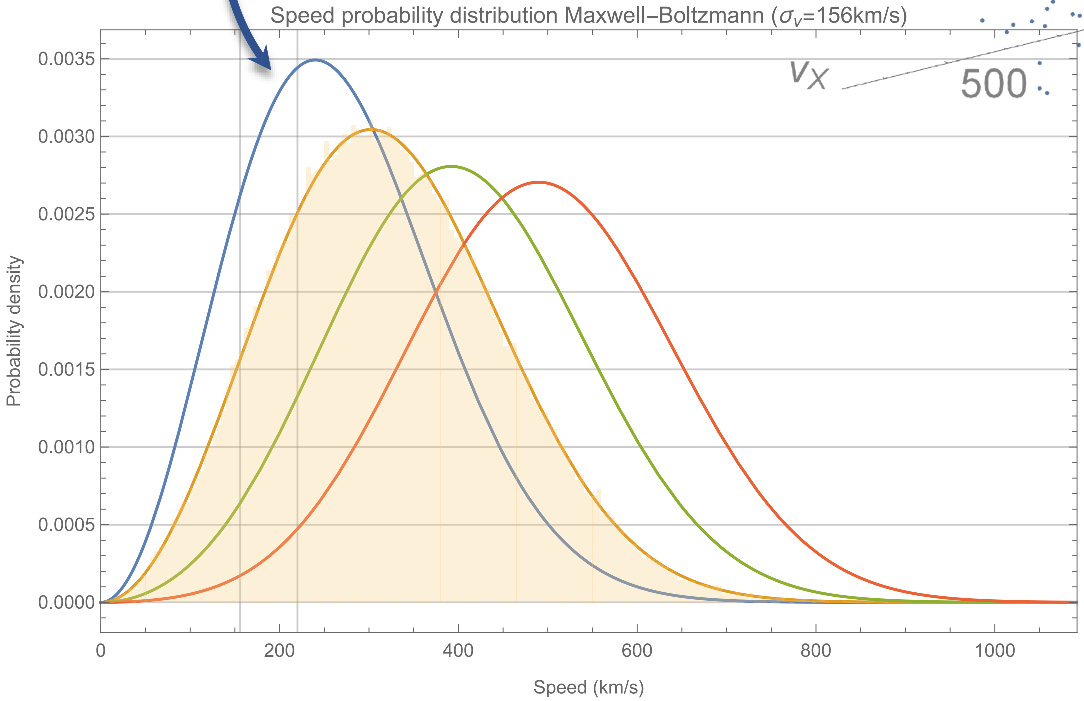
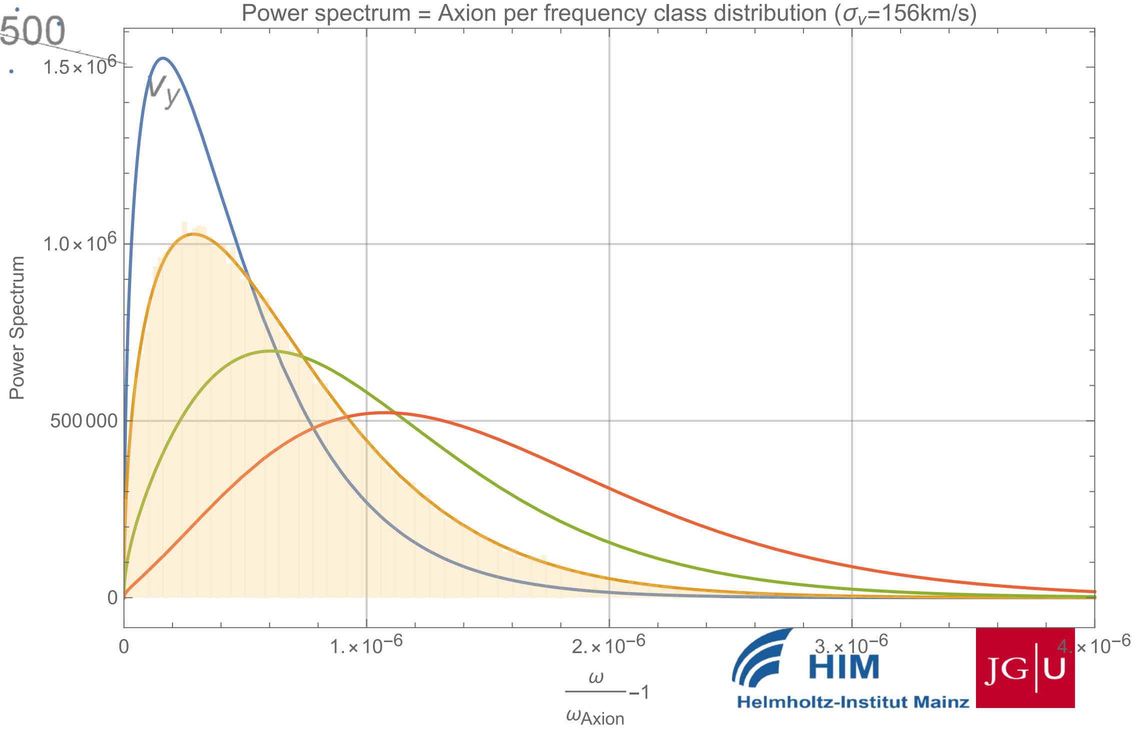
Scalar lineshape – ALP velocity distribution

$$\lambda(\nu) = f(v)\,\frac{dv}{d\nu}\bigg|_{v=c\sqrt{2(\nu/\nu_a-1)}}$$

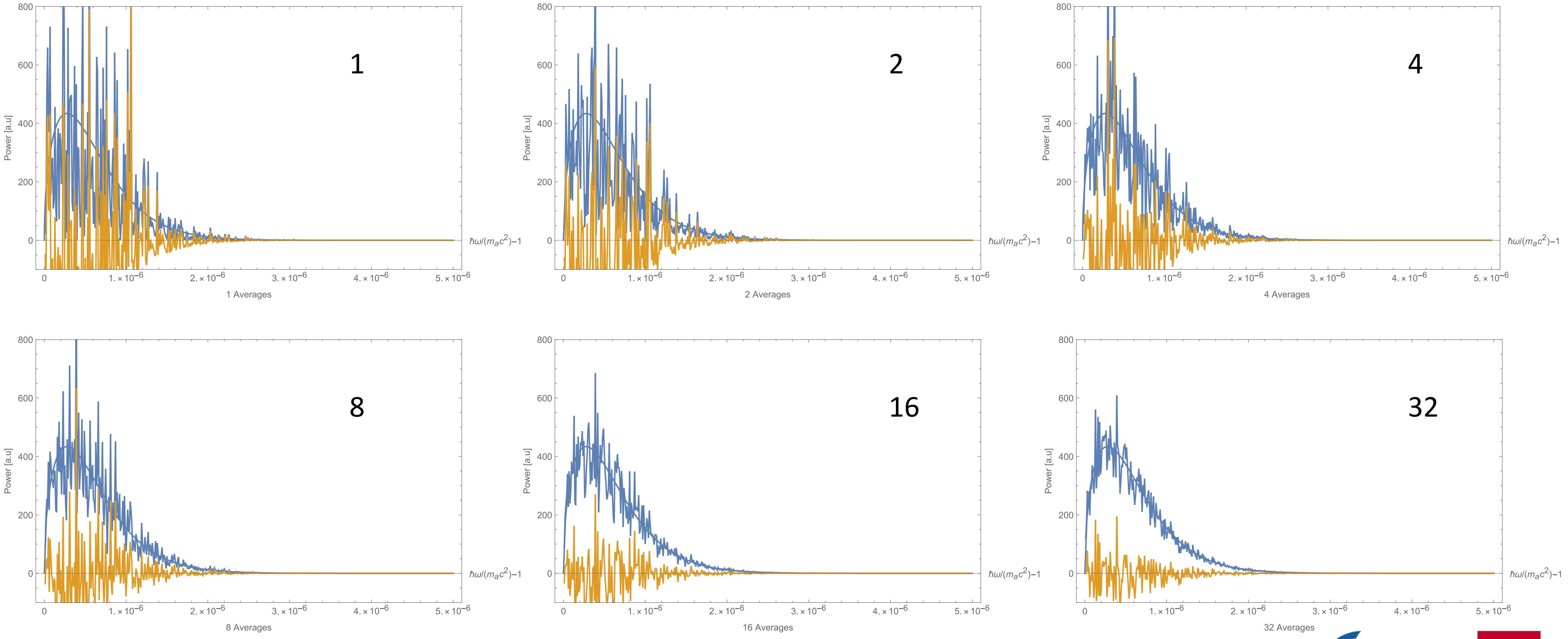






Ciaran O'Hare PHYSICAL REVIEW D 95, 063017 (2017)

Scalar lineshape – Power spectra , exponentially distributed in each bin.



Derivation of the **gradient** lineshape

Random 3D velocity

Random acc. speed!

Random!

Gradient Axion field

$$\nabla a(\mathbf{r},t) = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{c\sqrt{N}} \sum_{n=1}^{N} \mathbf{v}_n \sin\left(2\pi\nu_n t - \mathbf{k}_n \cdot \mathbf{r} + \phi_n\right)$$

<u>Gradient field frequency class j, x-direction</u>

Oscillation

Amplitude + Phase

$$\nabla a_{j,x}(t) \propto \Im\left[\exp\left(i\omega_j t\right) \sum_{i\in\Omega_j} v_{x,i} \exp\left(i\phi_i\right)\right]$$

New!

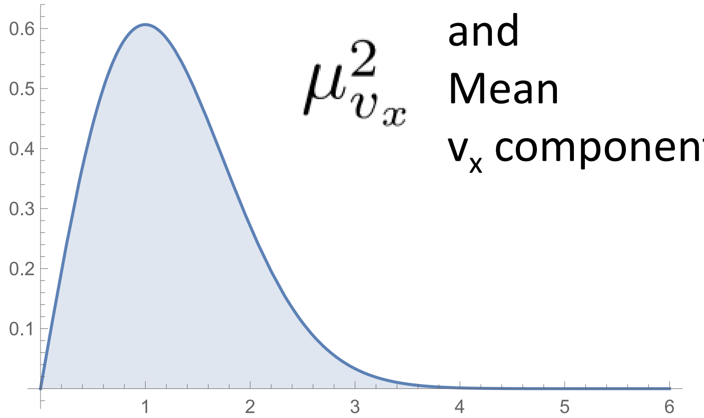
<u>Central limit theorem:</u>

$$\sum_{i\in\Omega_j} v_{x,i} \exp\left(i\phi_i\right) \propto \sqrt{N_j\left(\sigma_{v_x}^2 + \mu_{v_x}^2\right)}\,\alpha_j \exp\left(i\phi_j\right)$$

$\sigma_{v_x}^2$ Variance and

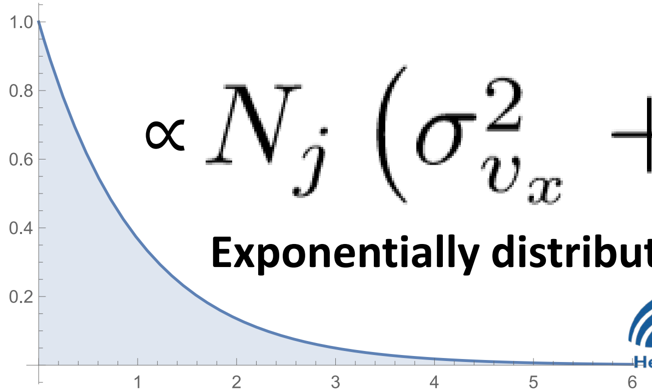
$\mu_{v_x}^2$ Mean

v_x component for a given frequency



Rayleigh distributed amplitude

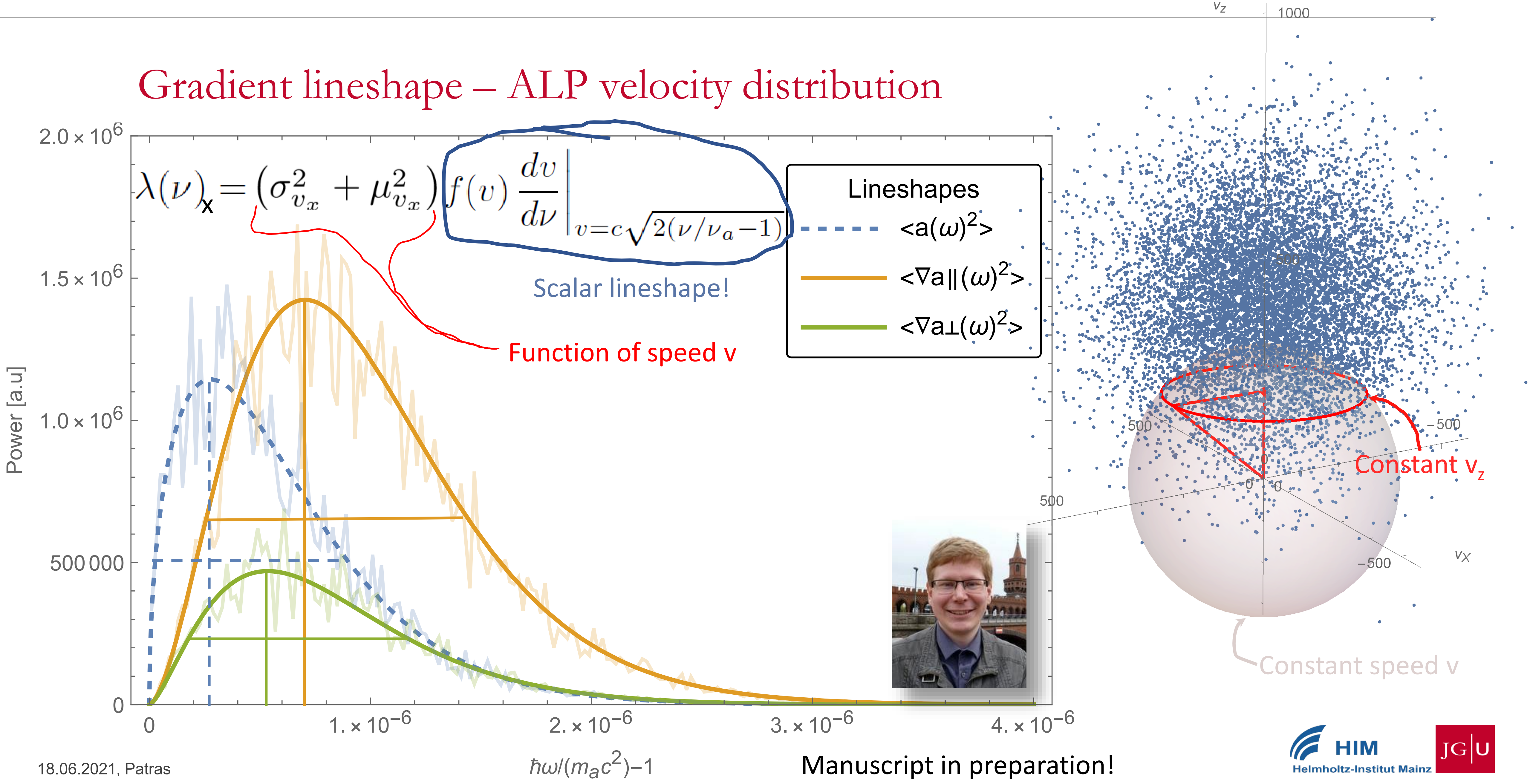
Random phase, different for different directions!



$$\propto N_j\left(\sigma_{v_x}^2 + \mu_{v_x}^2\right)$$

Exponentially distributed power!

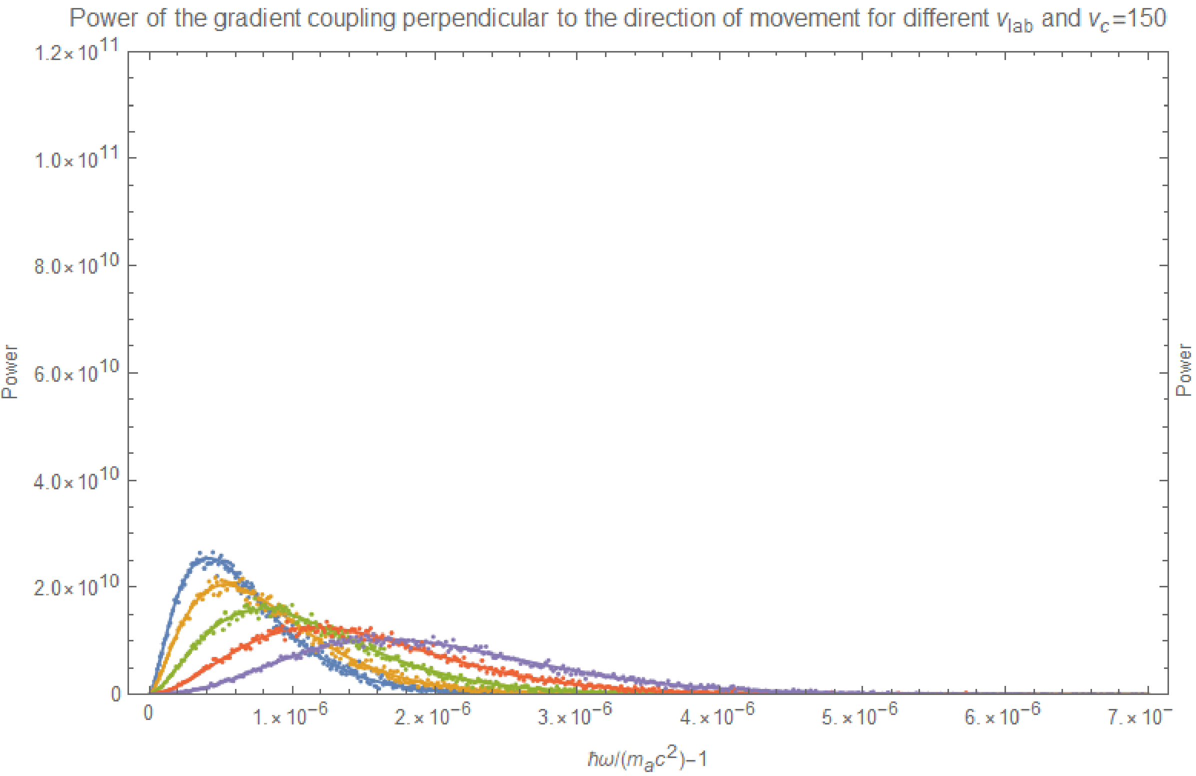
Gradient lineshape – ALP velocity distribution



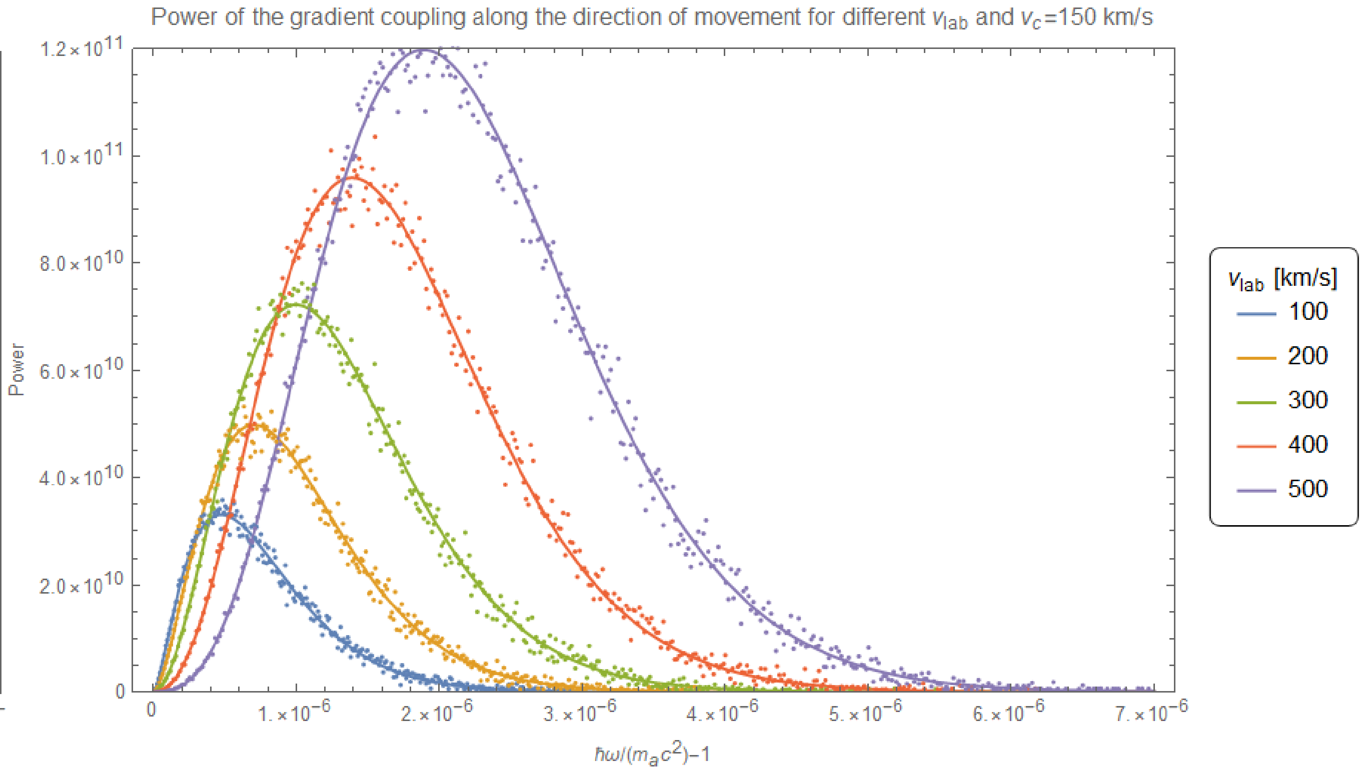
Manuscript in preparation!

Scaling with lab velocity

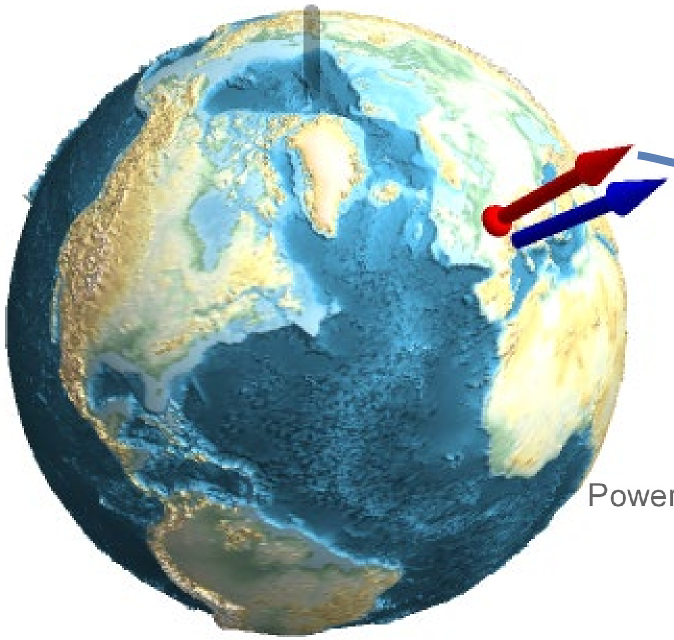
Perpendicular to the direction of movement

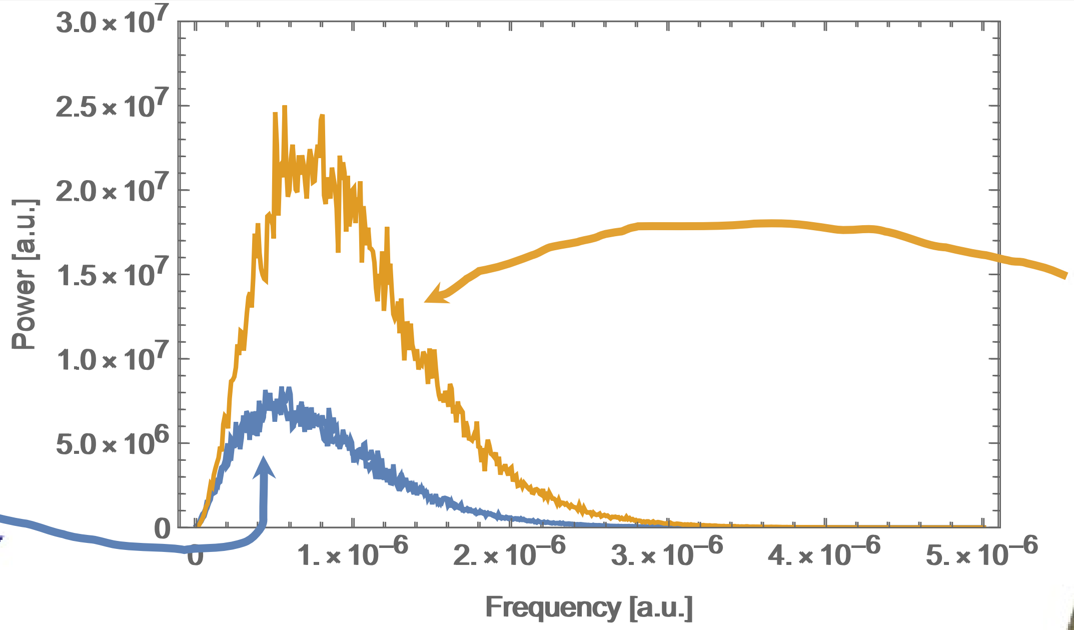


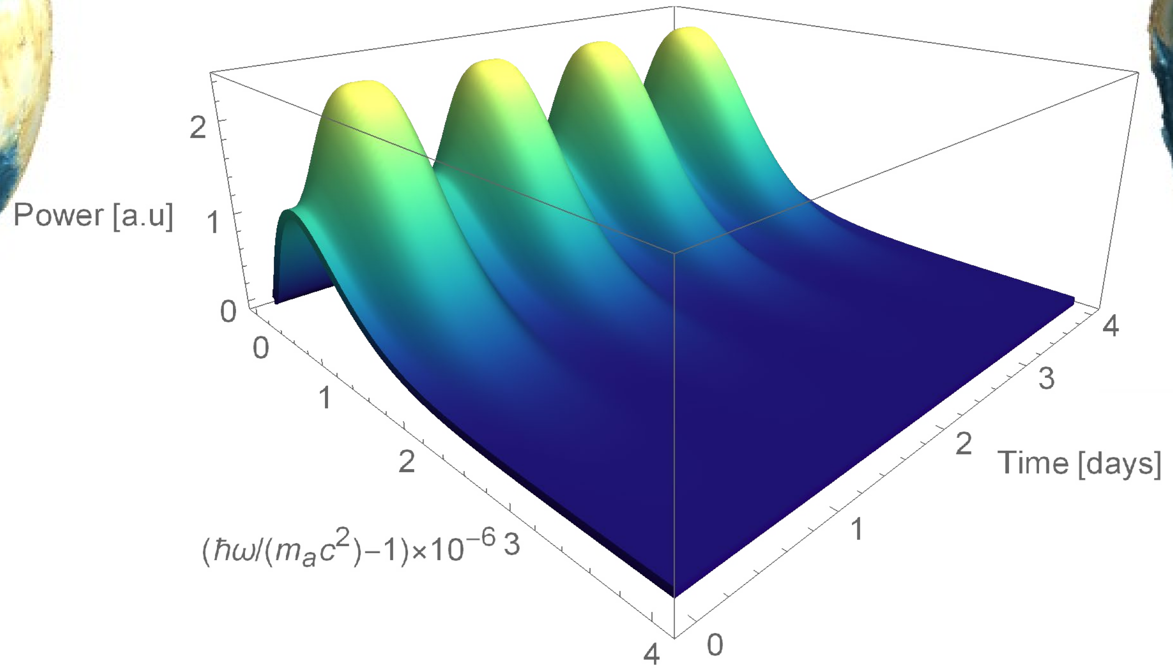
In the direction of movement

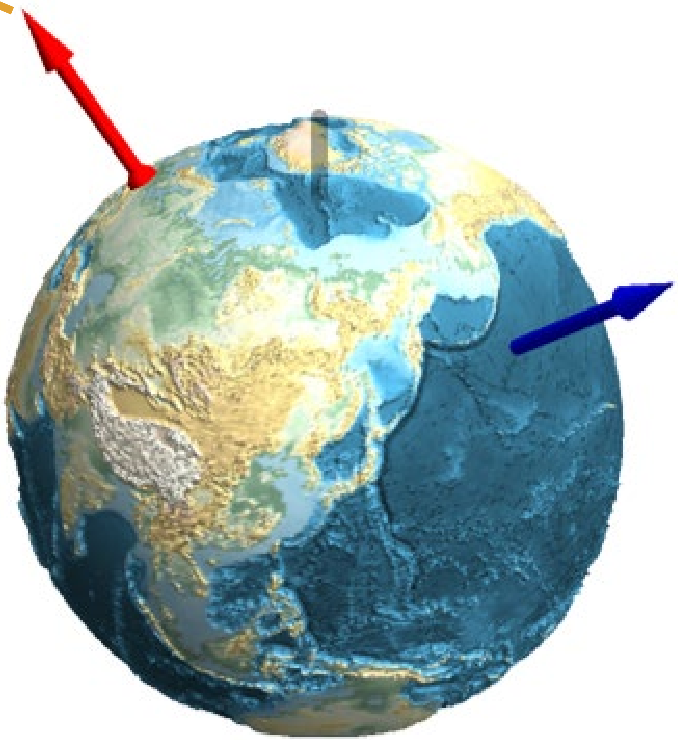


Daily modulation







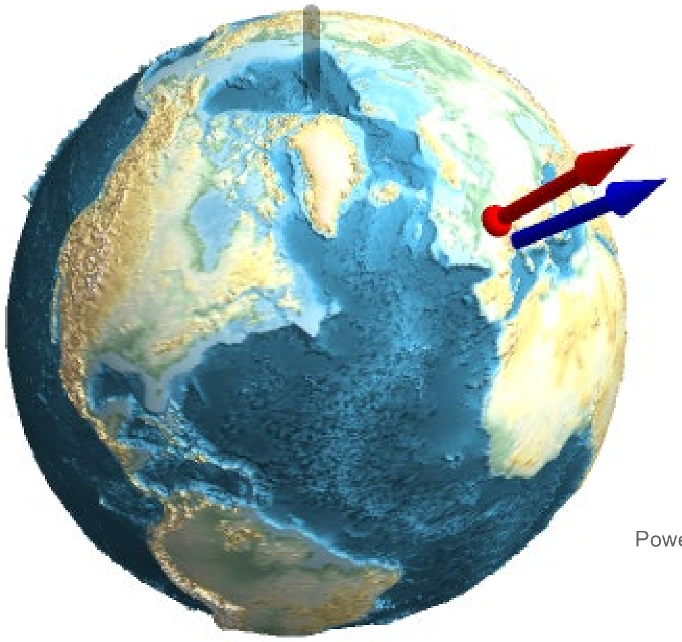


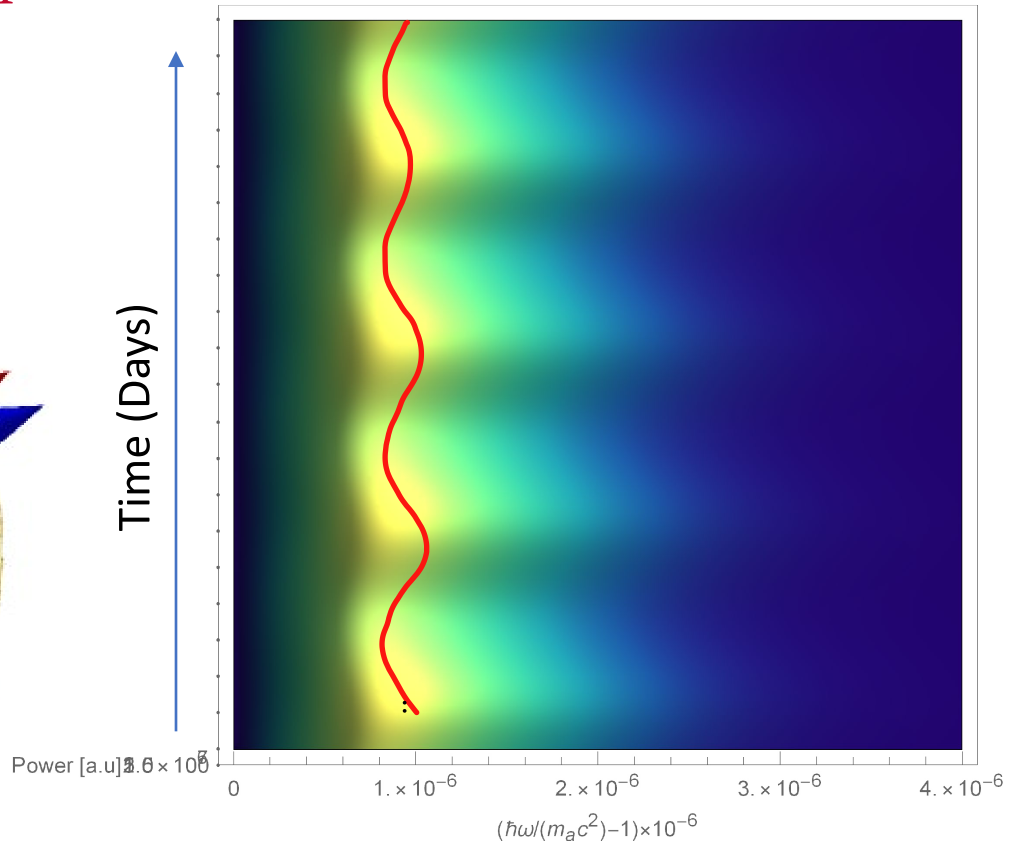
CASPEr Mainz B_0

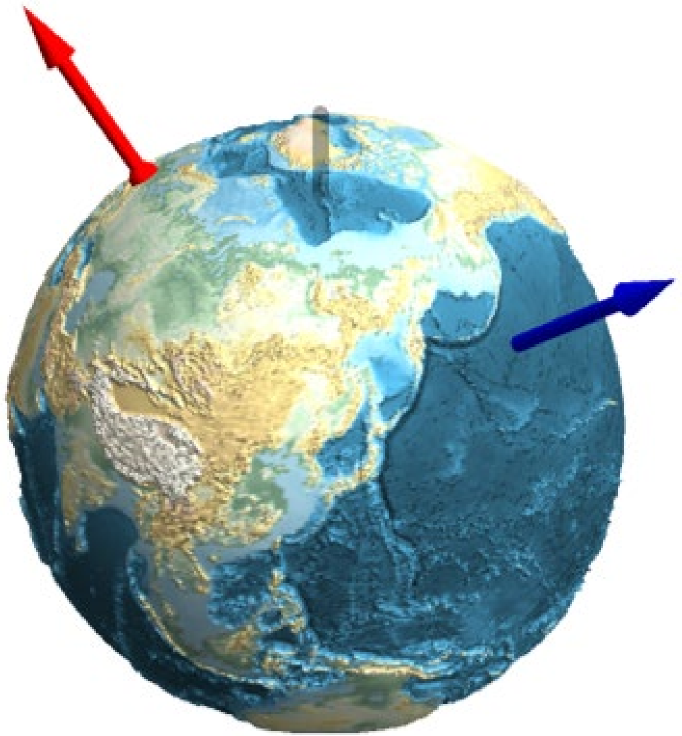
Earth velocity

Strong daily intensity modulation

Daily modulation







CASPEr Mainz B_0

Earth velocity

Strong daily intensity modulation
And
Daily frequency modulation! (10%-15% FWHM)

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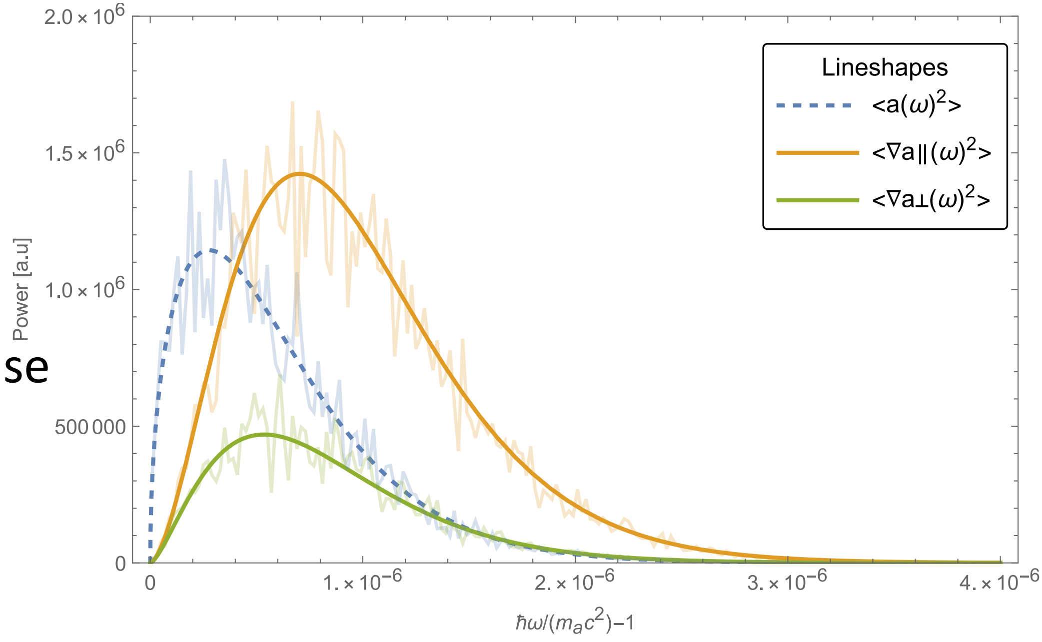
Virialized dark matter power spectra = modulated white noise



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Wavy Dark Matter summer in Mainz/Germany August 2022

Mon, 01nd **UDM** Bad Honnef	Tue, 02nd **UDM** Bad Honnef	Wed, 03th **UDM** Bad Honnef	Thu, 04th **UDM** Bad Honnef	Fri, 05th **UDM** Bad Honnef
Mon, 08th **PATRAS** Mainz	Tue, 09th **PATRAS** Mainz	Wed, 10th **PATRAS** Mainz	Thu, 11th **PATRAS** Mainz	Fri, 12th **PATRAS** Mainz
Mon, 15th **MITP** Mainz	Tue, 16th **MITP** Mainz	Wed, 17th **MITP** Mainz	Thu, 18th **MITP** Mainz	Fri, 19th **MITP** Mainz

Bad Honnef **Ultralight Dark Matter**

Summer school Scientific foundations and experimental searches

Mainz Institute of Theoretical Physics - Workshop

Searches for Wave-Like Dark Matter

Proposal! **with Quantum Networks**

Thank you