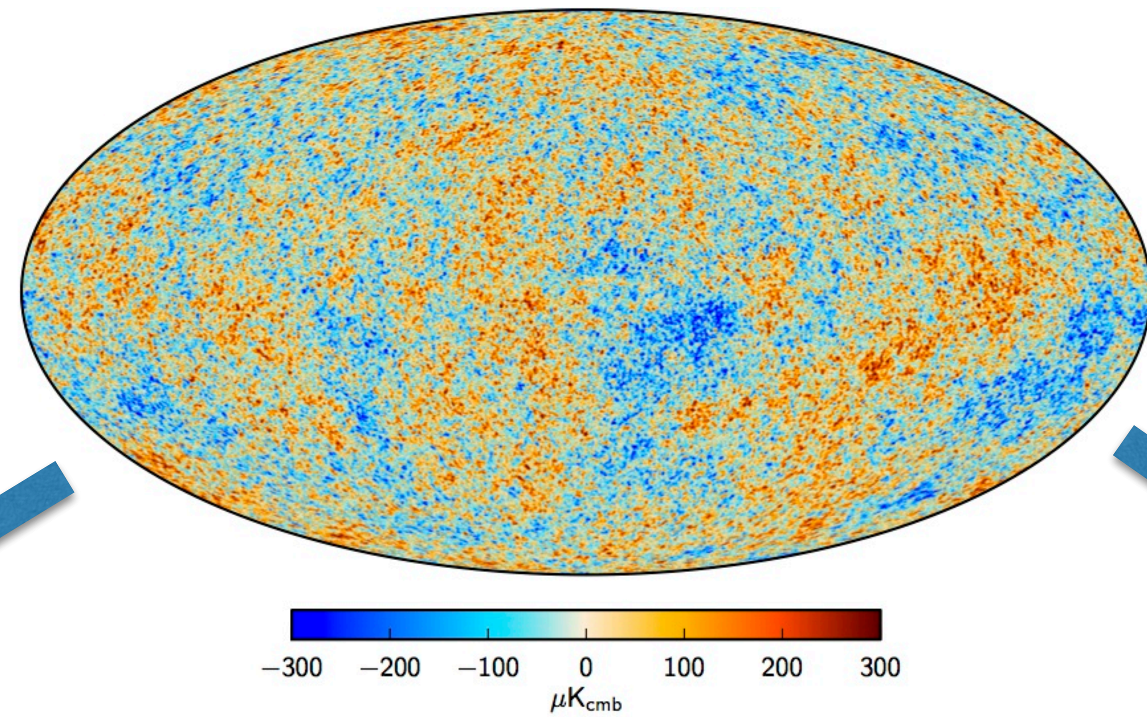
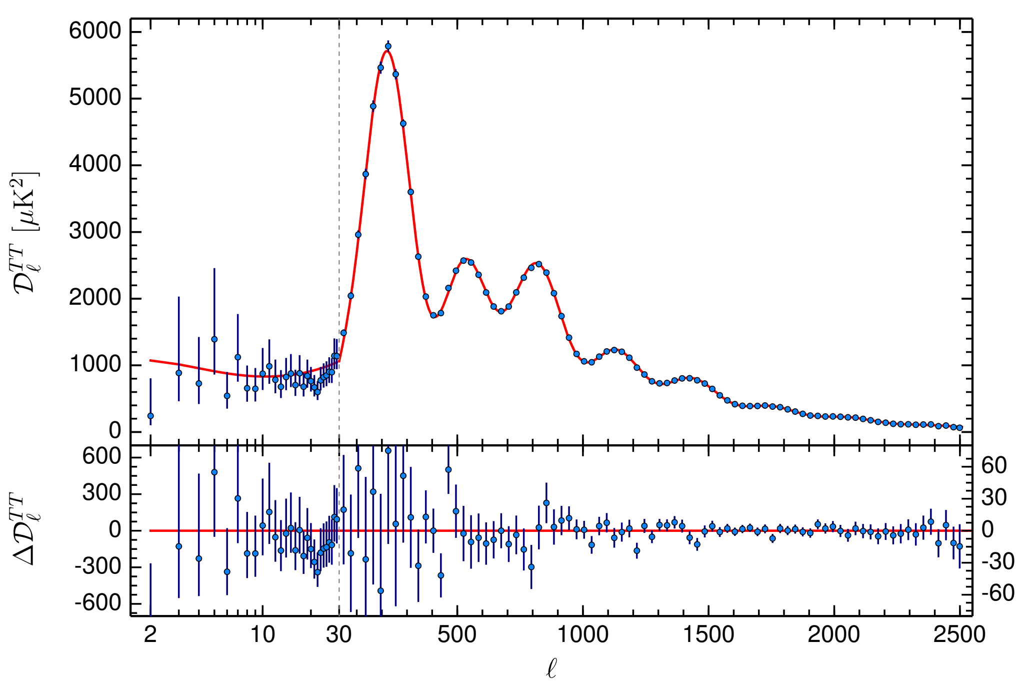
DM Radio-M^3
Theory Overview:
I. Coherent Field Basics

Yoni Kahn (UIUC)

Dark matter (DM) exists!



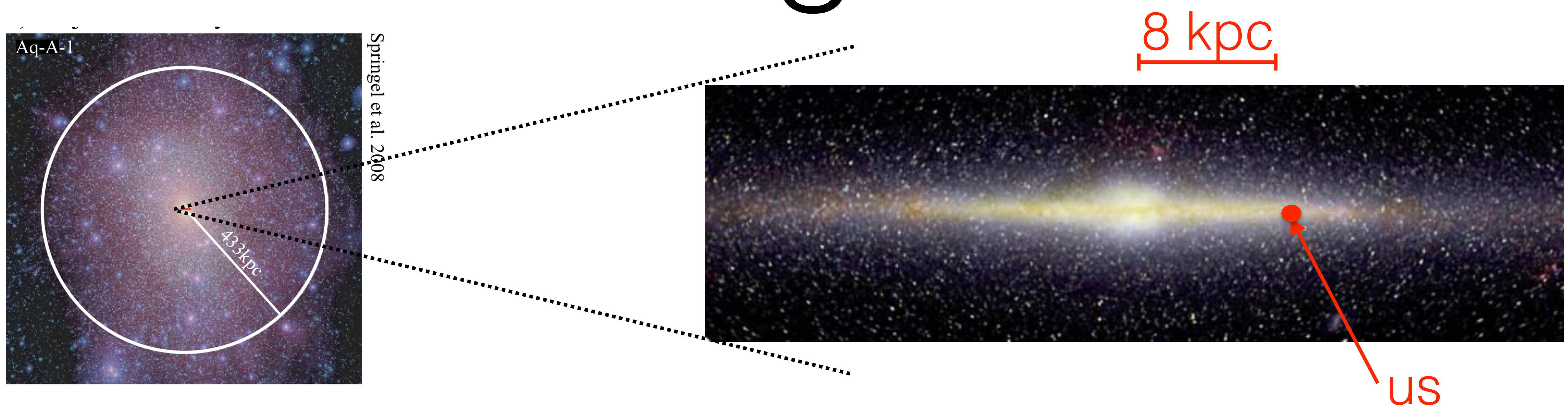


Parameter	[1] *Planck* TT+lowP
$\Omega_b h^2$	0.02222 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022
$100\theta_{MC}$	1.04085 ± 0.00047
τ	0.078 ± 0.019
$\ln(10^{10} A_s)$	3.089 ± 0.036
n_s	0.9655 ± 0.0062
H_0	67.31 ± 0.96
Ω_m	0.315 ± 0.013
σ_8	0.829 ± 0.014
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014

We have never observed a dark matter particle.

[Planck collab., A&A 2016]

DM in our neighborhood



Local measurements of stars tell us:

$$\rho_{\rm DM} \sim 0.3~{\rm GeV/cm^3}$$

$$\cancel{m_{\rm DM}} v_{\rm DM}^2 \sim \cancel{m_{\rm DM}} \frac{GM(<R)}{R}$$

$$\boxed{v_{\rm DM} \sim 10^{-3} c}$$

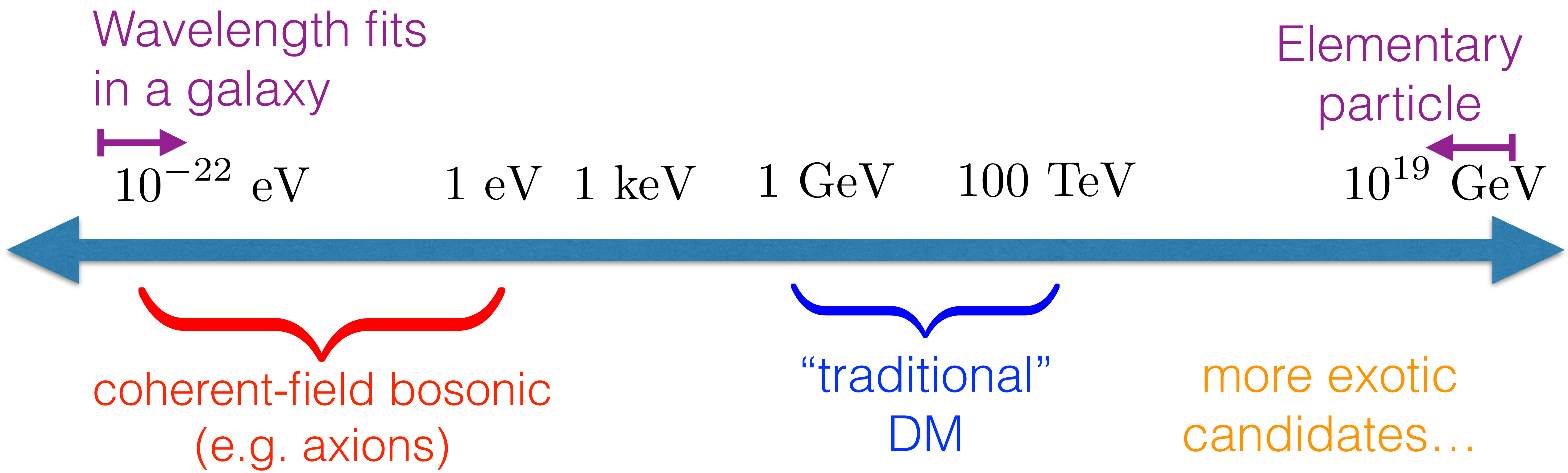
$$(\sim v_\odot \sim v_{\rm esc})$$

$$\rho_{\rm DM} = m_{\rm DM} \times n_{\rm DM}$$

Few heavy particles,
or lots of light particles…
what is DM mass?

[Read, J. Phys. G 2014; COBE/NASA; Springel et al. MNRAS 2008]

50 orders of magnitude!



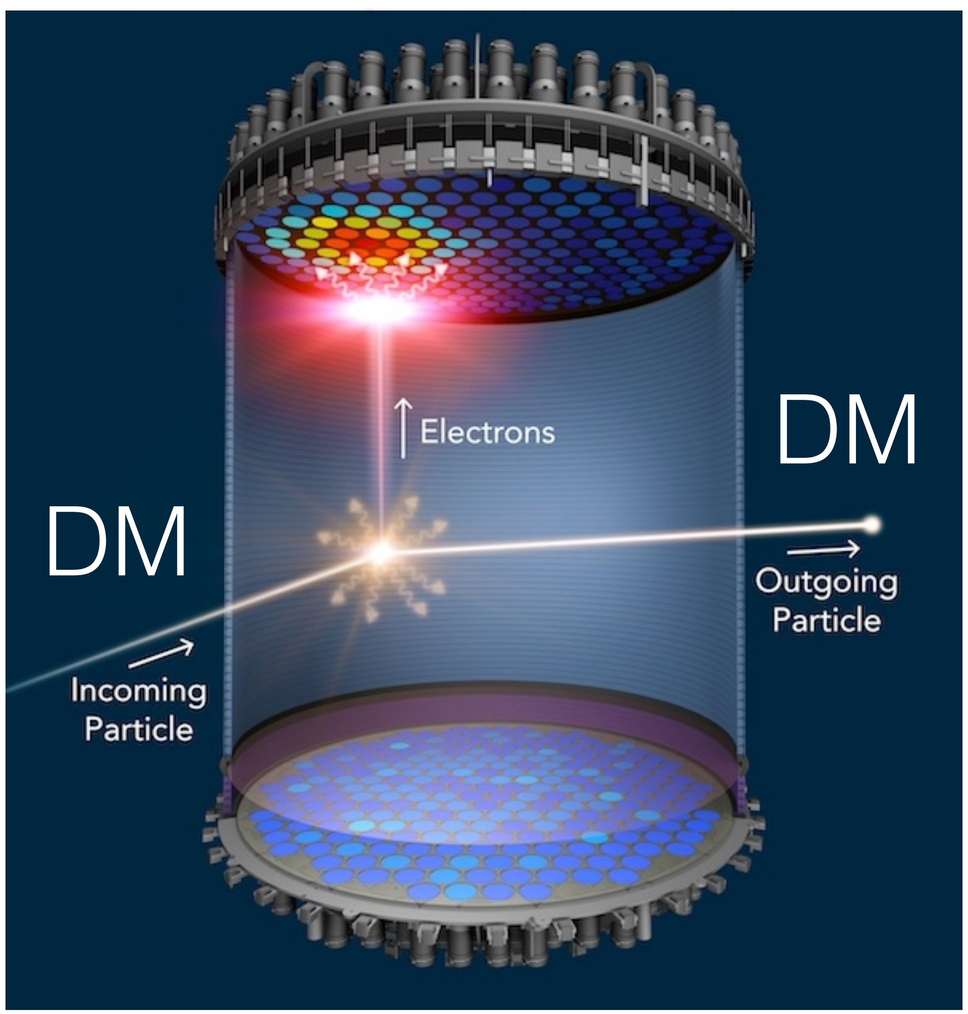
50 orders of magnitude

Wavelength fits in a galaxy

Elementary particle

10^{-22} eV   1 eV   1 keV   1 GeV   100 TeV 10^{19} GeV

"traditional" DM



$$n_{\mathrm{DM}}\lambda_{\mathrm{dB}}^{3} \ll 1$$

$$\mathrm{KE}_{\mathrm{DM}} = \frac{1}{2}m_{\mathrm{DM}}v_{\mathrm{DM}}^{2} > 1\ \mathrm{keV}$$

Rare collisions

[Goodman & Witten PRD 1985; Drukier, Freese, Spergel PRD 1986; image credit LZ collab.]

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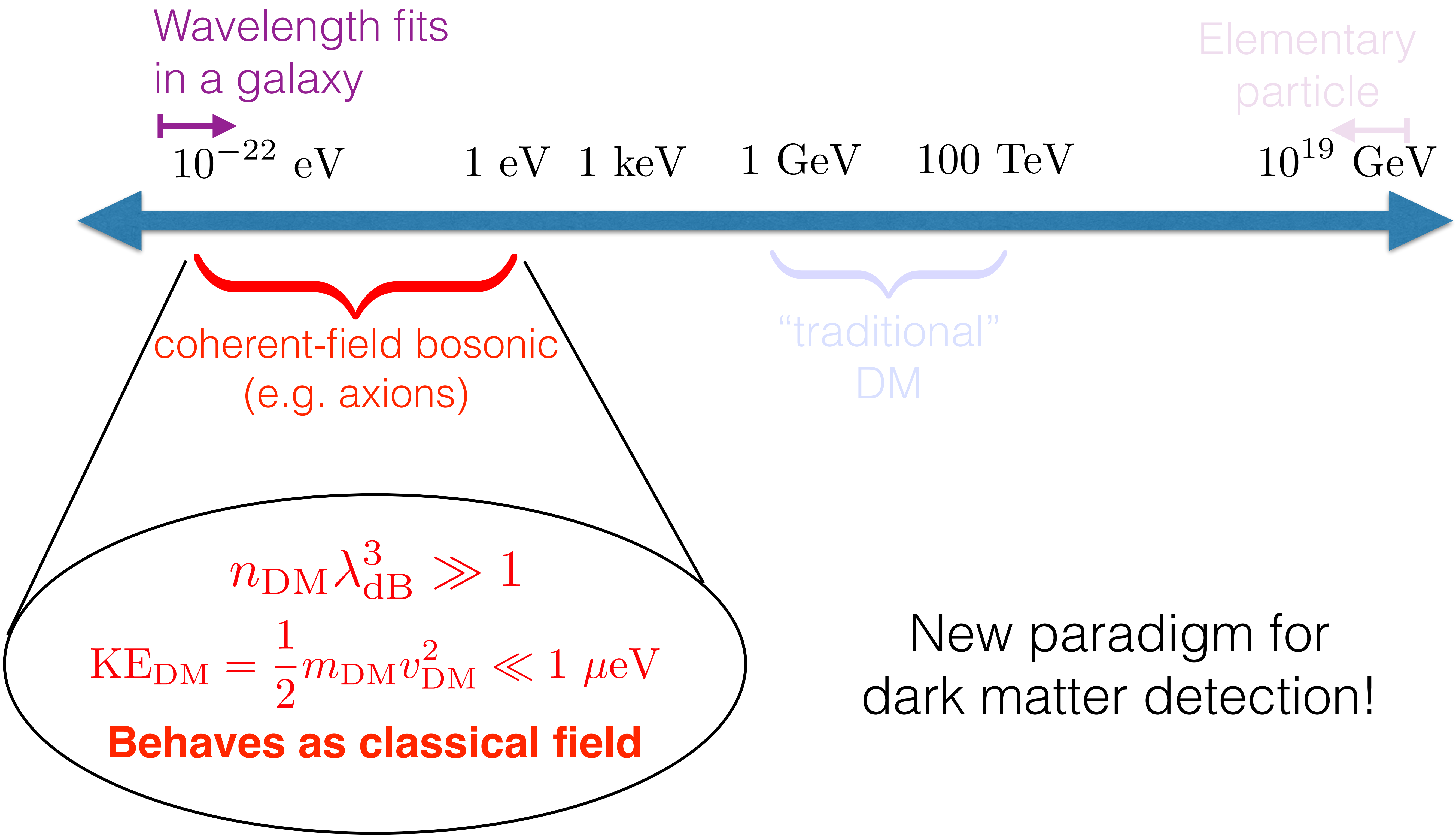


New paradigm for
dark matter detection!

Axion vitals

Mass: sub-eV
Spin: 0
Parity: odd
Charge: 0
Field value: angular

$$a(x^\mu) = f_a \theta(x^\mu)$$

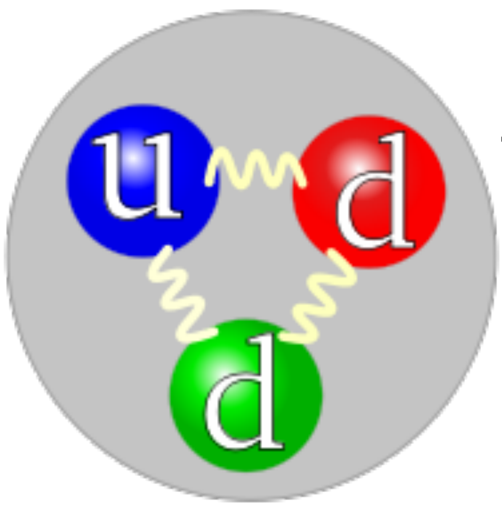
"axion decay constant"
or
"Peccei-Quinn (PQ) scale"

$\theta \in [-\pi, \pi]$ (dimensionless)

Who ordered that?

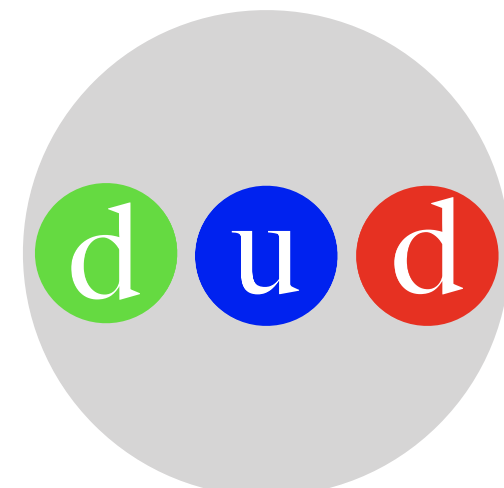
Wikipedia says neutron
looks like this:

+2/3 -1/3



-1/3

But experiments say
it looks like this!



-1/3 +2/3 -1/3

$d_n = 0$

This is the “strong-CP problem” of QCD

[Peccei & Quinn, Phys. Rev. Lett. 1977]

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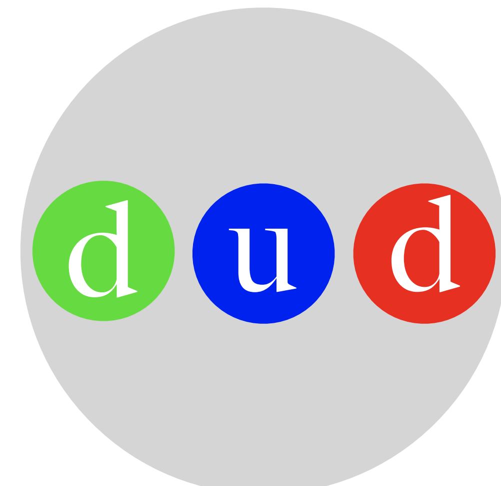


-1/3 +2/3 -1/3

$d_n = 0$

This is the “strong-CP problem” of QCD

Solution: QCD axion dynamically cancels the neutron EDM, thus “cleaning up” the strong CP problem [Wilczek]

[Peccei & Quinn, Phys. Rev. Lett. 1977]

Axion DM: here and now

$$a(\mathbf{x},t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_a}\cos(m_a t + \mathcal{O}(v_{\rm DM})\mathbf{x})$$

amplitude set
by local DM density

oscillates at frequency
set by DM mass

e.g. $m_a = 10^{-9}$ eV

$\lambda_{\rm Comp} \sim$ km

$\tau_{\rm Comp} \sim \mu$s

Local DM velocity → Spatial coherence → Temporal coherence

$\Delta v_{\rm DM} \sim v_{\rm DM} \sim 10^{-3}$ $\qquad \lambda_{\rm dB} = \frac{\lambda_{\rm Comp}}{v_{\rm DM}}$ $\qquad \tau_{\rm coh} = \frac{\tau_{\rm Comp}}{v_{\rm DM}^2}$

Classical physics is fine: $m_a = 10^{-9}$ eV $\implies N_a \sim 10^{18}/{\rm cm}^3$

[Graham and Rajendran, Phys. Rev. D88 (2013)]

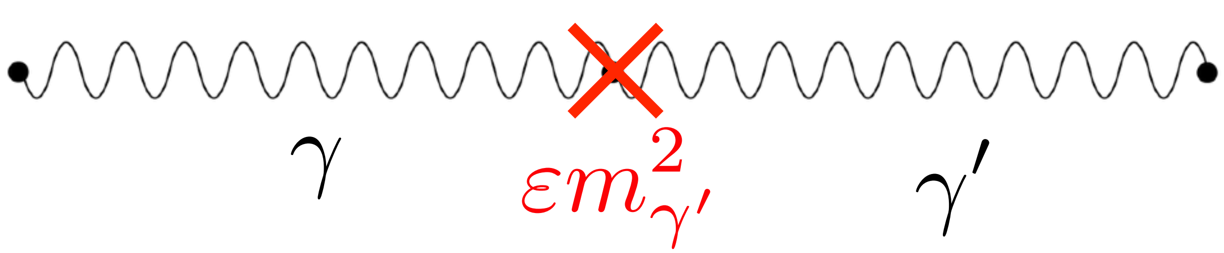
Hidden photons

Axions are (pseudo)scalars, but what if bosonic dark matter has spin 1?

$$\mathbf{A}'(\mathbf{x},t) = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_{\gamma'}}\hat{\mathbf{n}}(\mathbf{x},t)\cos(m_{\gamma'}t + \mathcal{O}(v_{\mathrm{DM}})\mathbf{x})$$

new ingredient: space- and time-dependent **polarization**

Can think of hidden photon DM as either:



mixing between ordinary and hidden photons: acts like a background current density

$$J^{\mu}_{\mathrm{EM}}\left(A_\mu + \varepsilon A'_\mu\right)$$

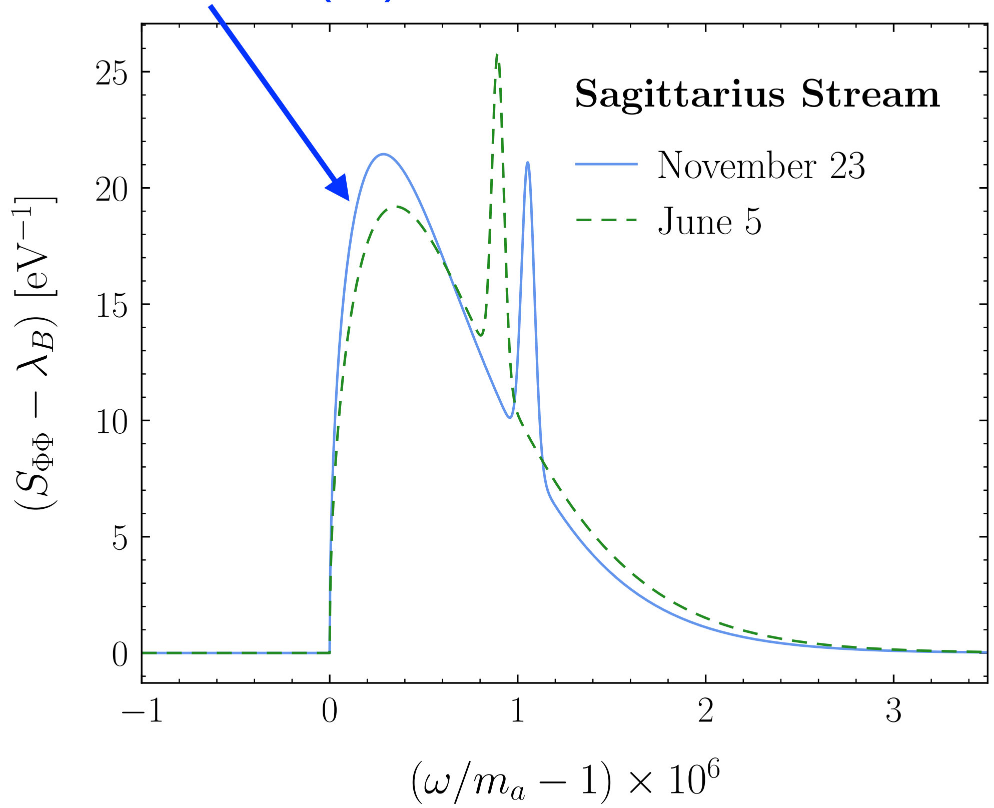
All charged particles feel an ε-suppressed "hidden Lorentz force"

Axion "halometry"

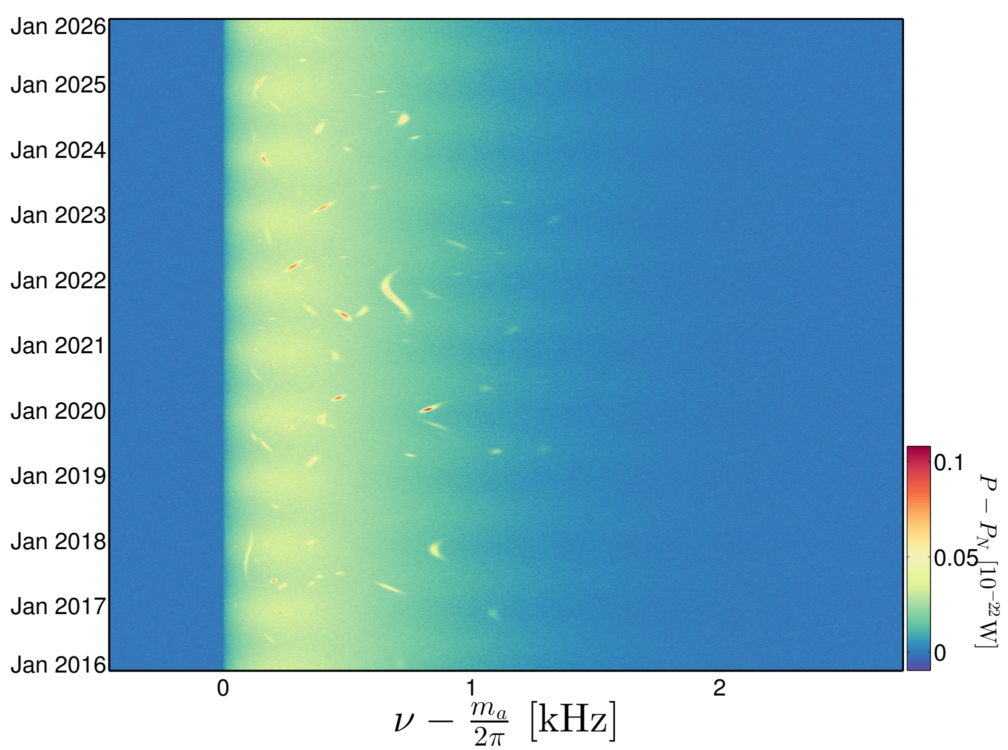
$$a(t) \sim \frac{\sqrt{2\rho_{\rm DM}}}{m_a} \int \sqrt{f(\mathbf{v}) d^3\mathbf{v}} \cos(\omega_{\mathbf{v}} t + m_a \mathbf{v} \cdot \mathbf{x})$$

$$\omega_{\mathbf{v}} = m_a(1 + \frac{1}{2}v^2 + \mathcal{O}(v^4))$$

proportional to a²:
traces out f(**v**)



Broadband-type (e.g. ABRA/DM-Radio)



Resonant-type (e.g. ADMX)

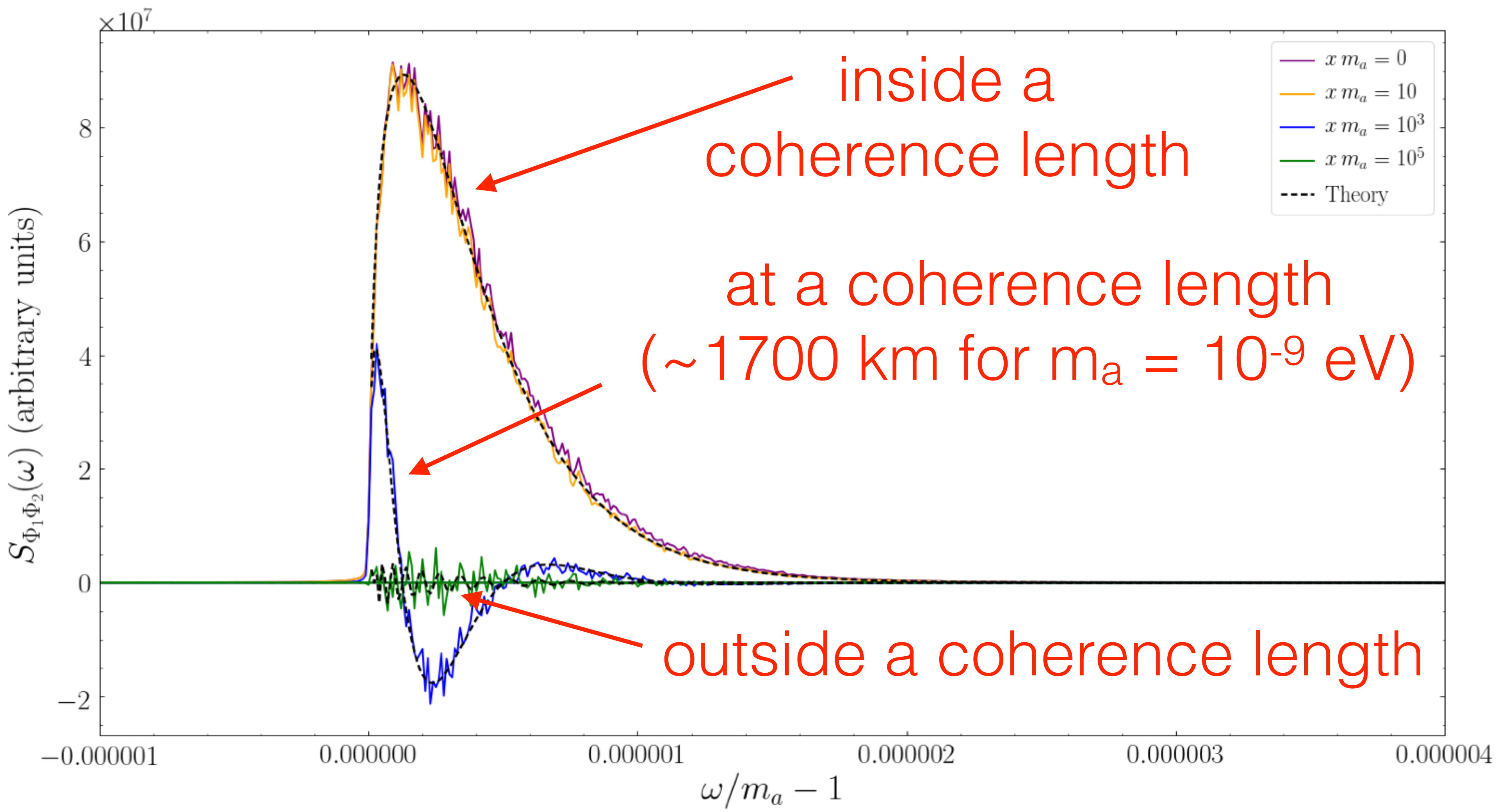
Much easier to identify structure in f(**v**) for axions than WIMPS

[O'Hare and Green, Phys. Rev. D95 (2017); Foster, Rodd, Safdi, Phys. Rev. D97 (2018)]

Coherence length effects

What about two detectors?

$$\langle S_{\Phi_1\Phi_2}(\omega)\rangle \propto \int d\Omega\, v\, f(\mathbf{v}) \cos(m_a \mathbf{v}\cdot\mathbf{x})\Big|_{v=\sqrt{2\omega/m_a-2}}$$



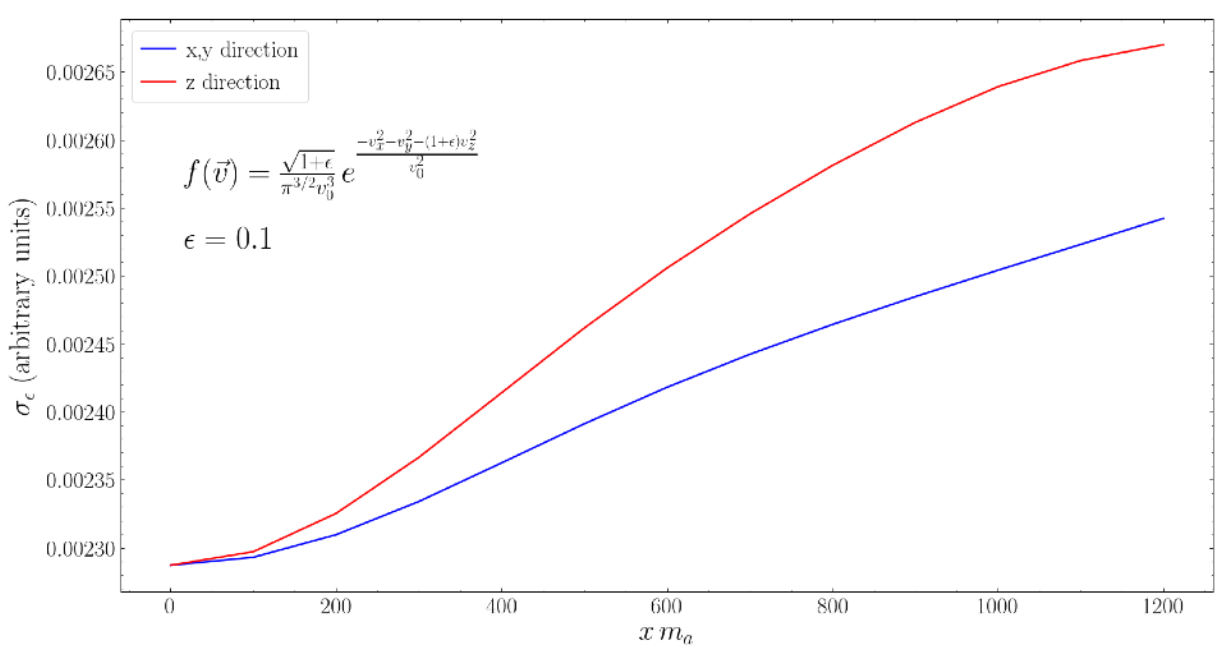
[ongoing work w/Rachel Nguyen, Josh Foster, Nick Rodd, Ben Safdi]

Mapping the 3D velocity distribution

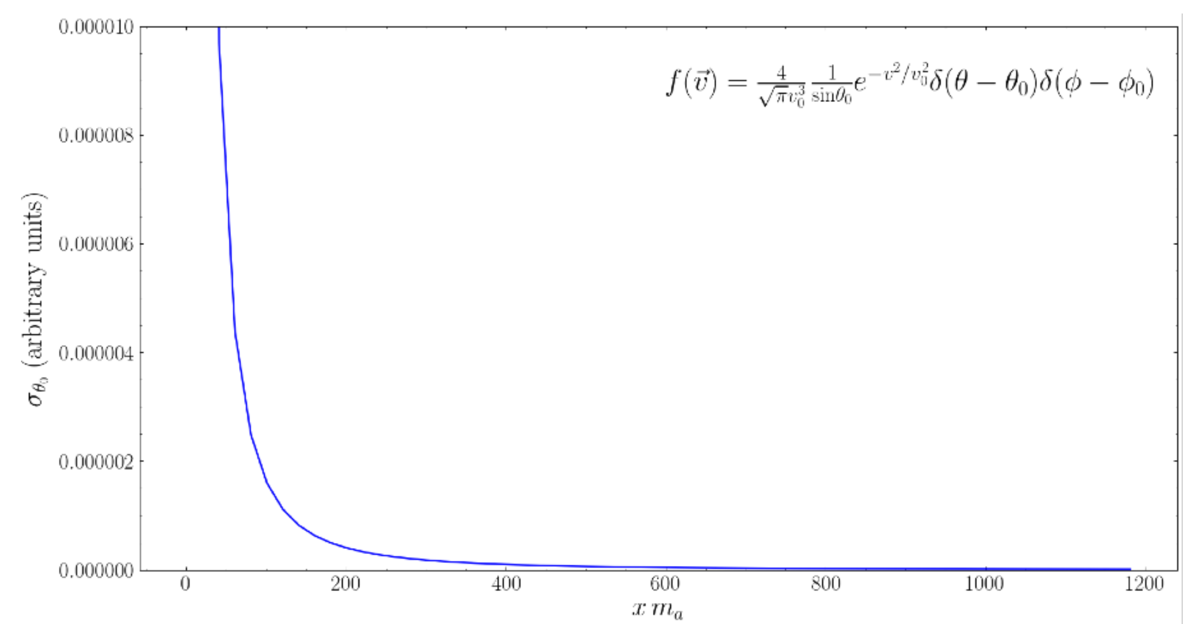
Axion power spectrum ➡ Likelihood framework ➡ extract params.

$$\sigma_\alpha^{-2} \propto \int \frac{dv}{v}\left[\int d\Omega_v\, \partial_\alpha f(\mathbf{v})(1+\cos(m_a \mathbf{v}\cdot\mathbf{x}))\right]^2$$

Mildly anisotropic DM "blob"



DM stream



If you want to know the **direction** of an anisotropy, you need (at least) two detectors, orthogonal to the anisotropy

[ongoing work w/Rachel Nguyen, Josh Foster, Nick Rodd, Ben Safdi]