Listening for ultra-heavy DM with underwater acoustic detectors

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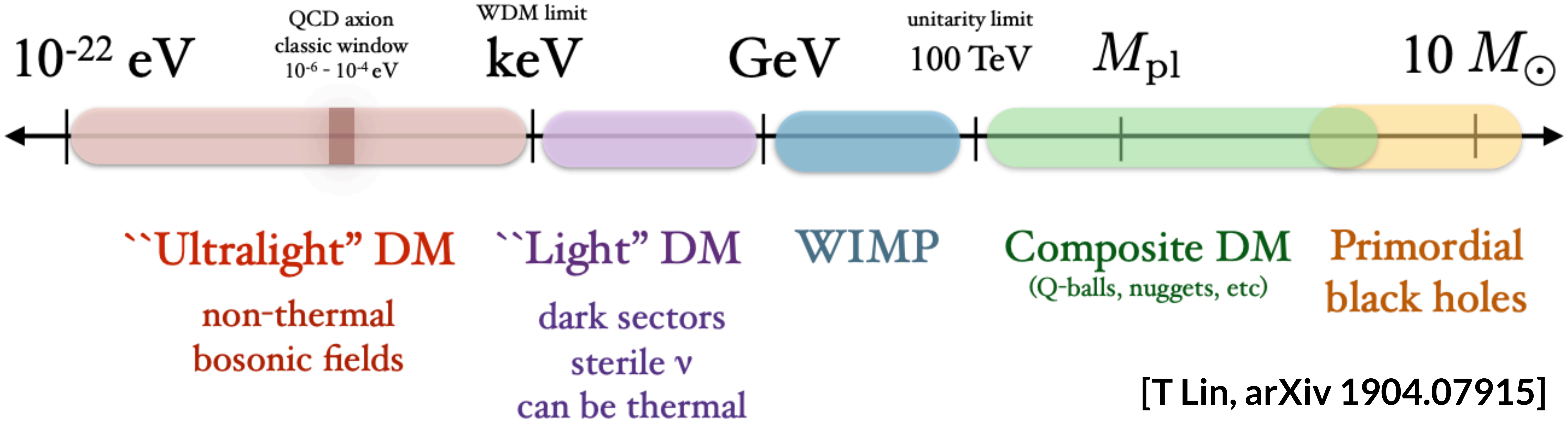
Based on arXiv:2502.17593 (PRD in review)

Where in the DM spectrum are we focused?

$$\Omega_{\mathrm{CDM}} h^2 \sim 0.120 \pm 0.001$$

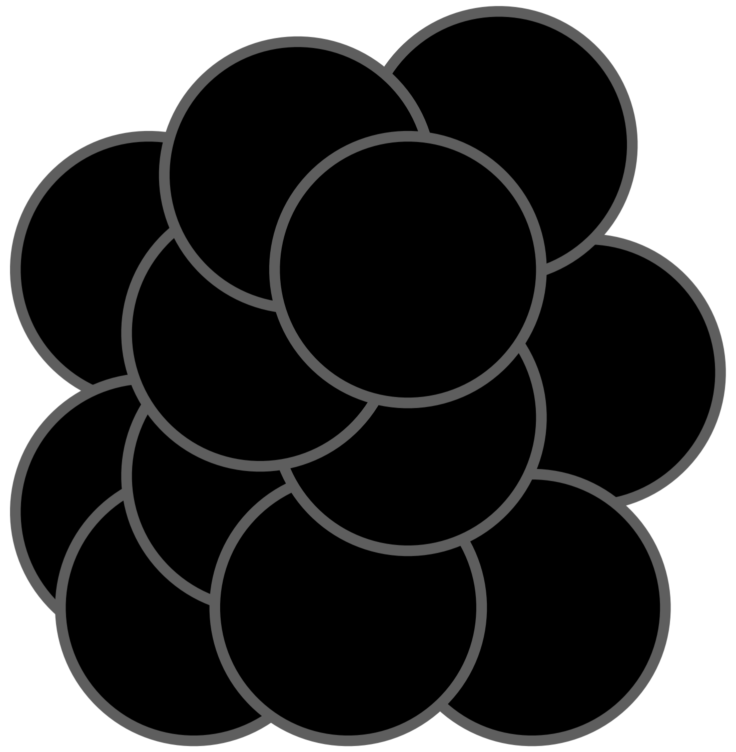
[Planck, 2018]



[T Lin, arXiv 1904.07915]

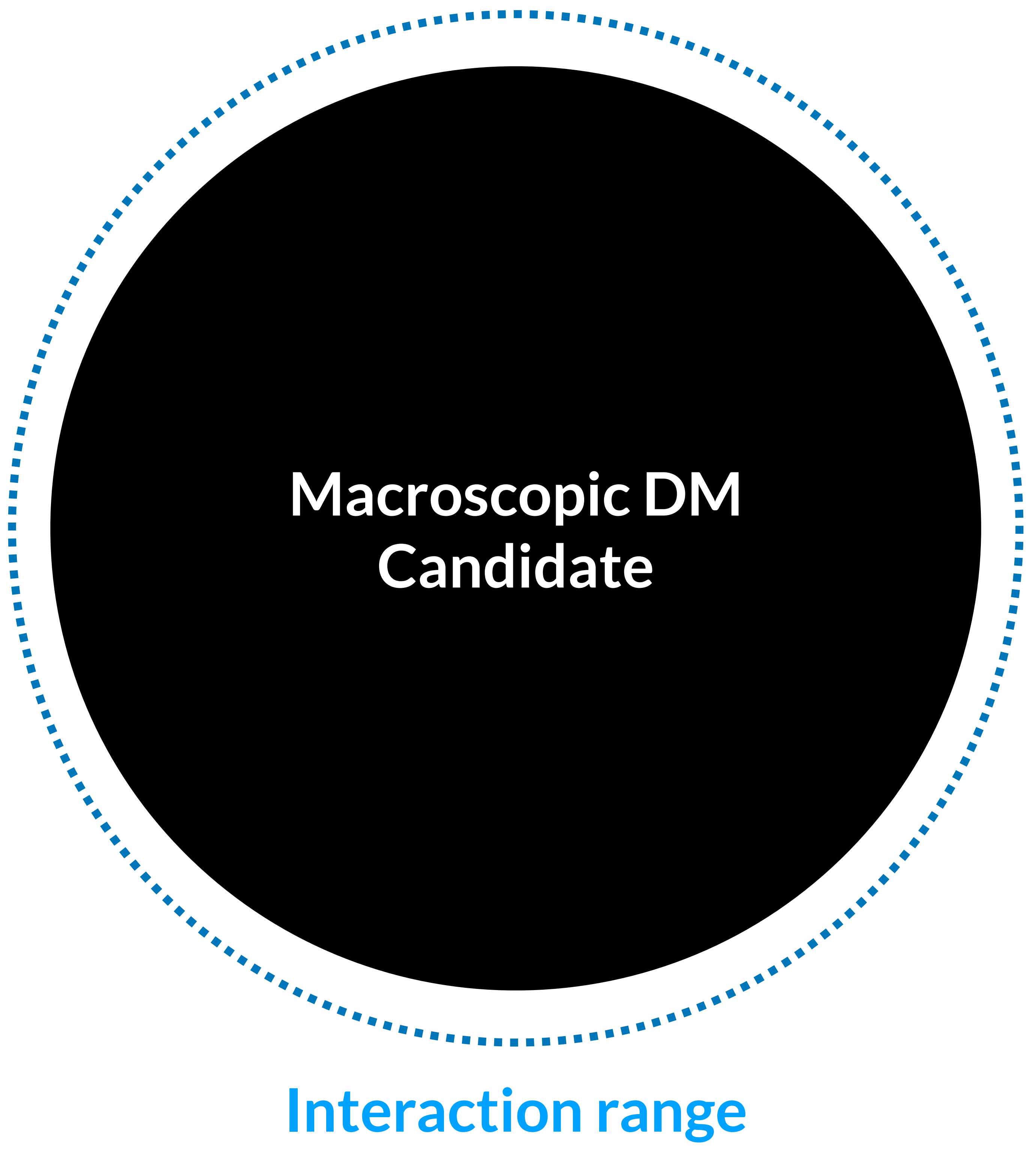
Ultra-heavy Dark Matter

- Ultra-heavy dark matter is necessarily composite (if thermally produced) due to s-wave unitarity
- Many different models for UHDM
  - PBH, Nuggets, Blobs, WIMPonium, Q-Balls etc…
- Is there a nice model-independent way to treat them?
- Answer: **Yes** (for some parts of parameter space)



Geometric UHDM

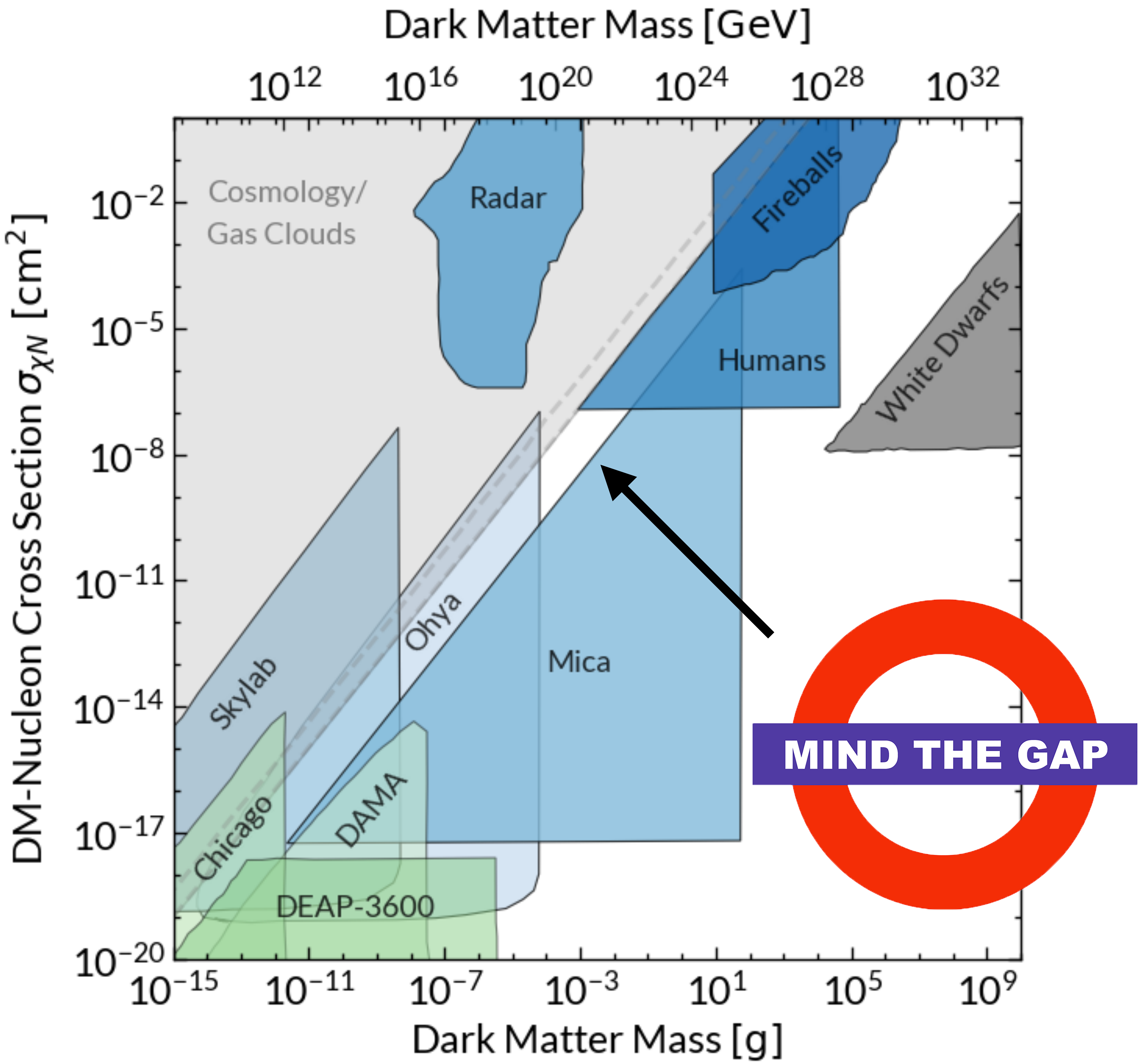
- Consider parameters of models where:
  - The DM is Planck-mass or larger
  - DM Radius R_χ much larger than interaction length scale
  - Geometric cross section dominates i.e. $\sigma_\chi \approx \pi R_\chi^2$
  - Parameterise the interaction in terms of R_χ -> set by the theory -> make experimental statements about multiple models!



UHDM Direct Detection

- We parametrise UHDM in grams (g)
- DM Flux: $\phi_\chi \approx 6 \left(\frac{1\ \mathrm{g}}{m_\chi} \right) \mathrm{km}^{-2}\ \mathrm{yr}^{-1}$
- Need a *very* large detector (or very long integration time) to have significant number of events.
- No hope for conventional detectors (LUX-ZEPLIN, XENONnT etc.)

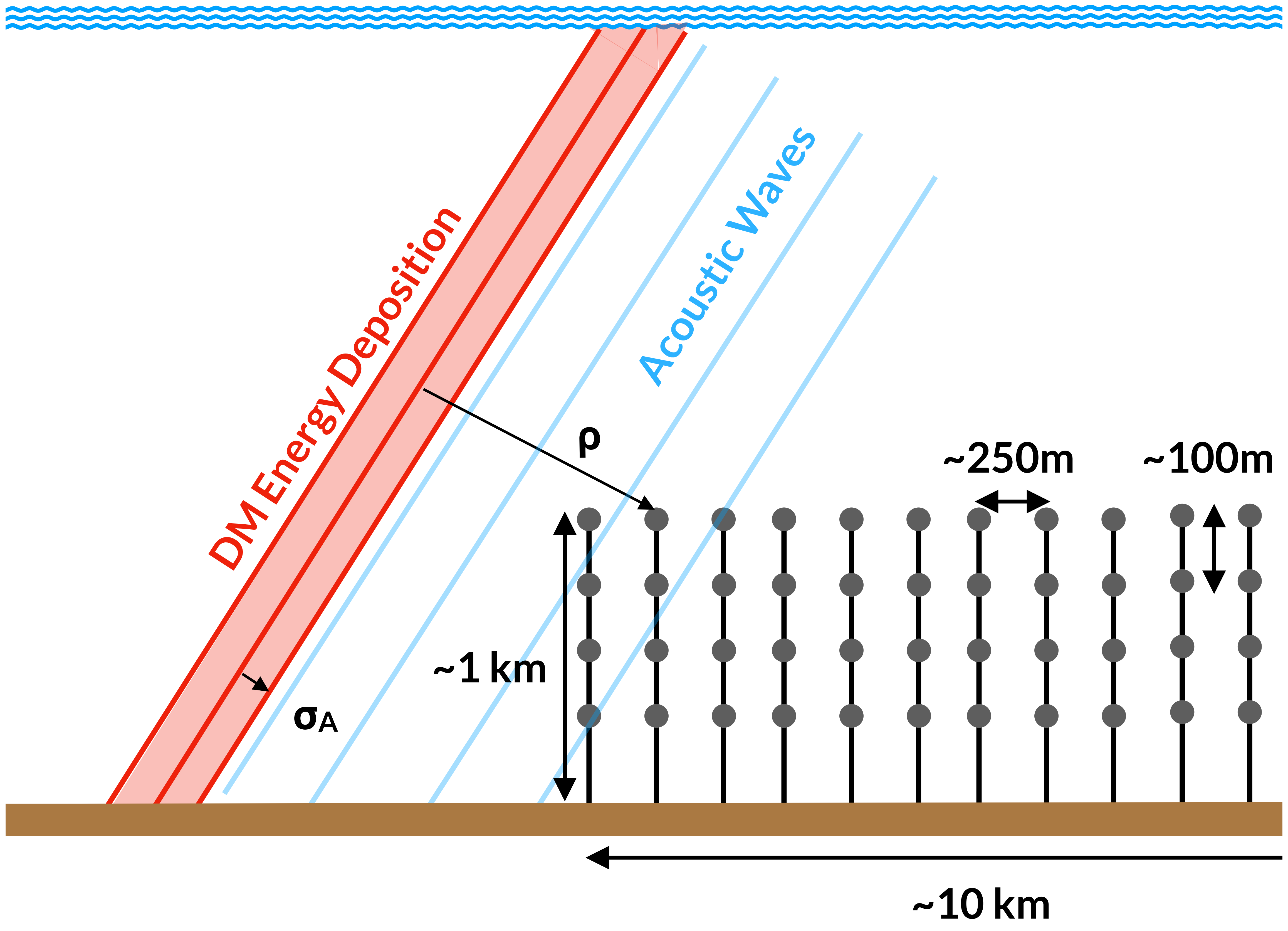
Current Constraints



- Annoying "gap" in constraints
- Mica underground - too much overburden
- Radar not sensitive enough - not enough ionisation
- **What phenomena could we use to constrain this region?**

Acoustic Detection

- Idea: DM is weakly interacting enough to make it through the atmosphere
- Reaches much more dense medium: **the ocean**
- DM deposits energy into the ocean creating pressure waves
- Detect pressure waves using **a large hydrophone array**



Neutrino Experiments

- Propositions for acoustic neutrino experiments with $\mathcal{O}(100\ \mathrm{km}^3)$ hydrophone arrays [Lahmann, 2016]

- Detect UHE neutrinos. Similar number density issues, but similarly high cross section

- Acoustic propagation distance in water much greater than light -> less dense instrumentation

- Energy deposition comes from **hadronic showers**

Thermo-acoustic heating

Pressure waves come from thermo-acoustic heating, which obeys the following DE:

Energy Deposition Density

$$\nabla^2 p - \frac{1}{c_s^2}\frac{\partial^2 p}{\partial t^2} = -\frac{\alpha}{c_p}\frac{\partial^2 q(r,t)}{\partial t^2}$$

Acoustic pressure

General Solution: $$p(r,t) = \frac{\alpha}{4\pi c_p}\int \frac{\mathrm{d}^3 r'}{|r - r'|}\frac{\partial^2 q(r',t')}{\partial t^2}$$

$$t' = t - |r - r'|/c_s$$

What is q for UHDM?

Taking a geometric cross section only and taking the number of scatters to infinity:

$$\frac{\mathrm{d}E_\chi}{\mathrm{d}z} = -\rho_{\mathrm{sea}}\sigma_\chi v_\chi^2 \exp\left(-\frac{z}{\ell_{\mathrm{sea}}}\right)$$

Where ℓ_{sea} is the characteristic length of the energy deposition:

$$\ell_{\mathrm{sea}} = \frac{m_\chi}{2\rho_{\mathrm{sea}}\sigma_\chi} \simeq 480\,\mathrm{km} \times \left(\frac{m_\chi}{10^{-2}\,\mathrm{g}}\right)\left(\frac{10^{-10}\,\mathrm{cm}^2}{\sigma_\chi}\right)$$

ℓ_{sea} can be very long, in this case: $$\frac{\mathrm{d}E_\chi}{\mathrm{d}z} \simeq -\rho_{\mathrm{sea}}\sigma_\chi v_\chi^2 = \mathrm{const}$$

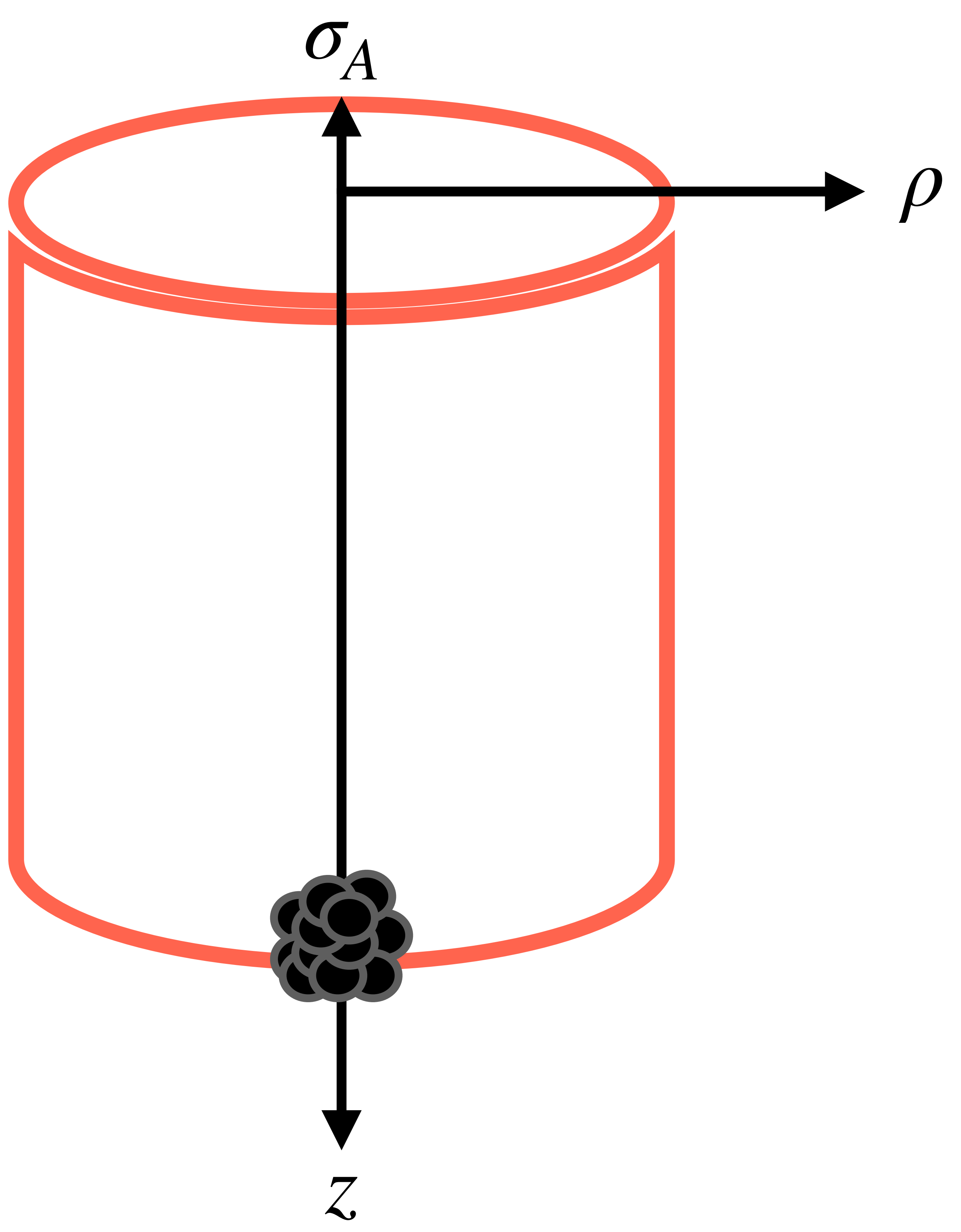
What is q for UHDM?

Model energy deposition rate as Gaussian cylinder:

$$q(r) = \sum_{A=\{H,O\}} \frac{1}{2\pi} \frac{dE_A}{dz} \frac{1}{\sigma_A^2} \exp\left(-\frac{\rho^2}{2\sigma_A^2}\right)$$

Where σ_A is the characteristic scattering length of species A (found using SRIM software package).

Gaussian allows us to find analytic solutions for the pressure - turns out to be enough to capture the physics



What is the pressure solution?

Take infinitely long line track (good for large ℓ_{DM}), instantaneous energy deposition and take width much smaller than detection distance $\sigma_A \ll \rho$:

$$p(r,t;\sigma_A \ll \rho) = \frac{\alpha}{2\pi c_p}\frac{dE}{dz}\frac{c_s^2}{\sqrt{2\pi\sigma_A^3}}\frac{1}{\sqrt{\rho}}\, I_p\left(\frac{t-\rho/c_s}{\sigma_A/c_s}\right)$$

$$I_p(A) = \int_0^\infty dY \sqrt{Y} \exp\left(-\frac{Y^2}{2}\right) \cos\left(A\,Y + \frac{\pi}{4}\right)$$

$$= -\frac{\pi A}{4\sqrt{2}(A^2)^{1/4}} \exp\left(-\frac{A^2}{4}\right)\left[\left(A+\sqrt{A^2}\right)\left(I_{1/4}\left(\frac{A^2}{4}\right) - I_{3/4}\left(\frac{A^2}{4}\right)\right) + \frac{\sqrt{2}}{\pi}\left(\sqrt{A^2}K_{1/4}\left(\frac{A^2}{4}\right) - AK_{3/4}\left(\frac{A^2}{4}\right)\right)\right]$$

What does p look like?

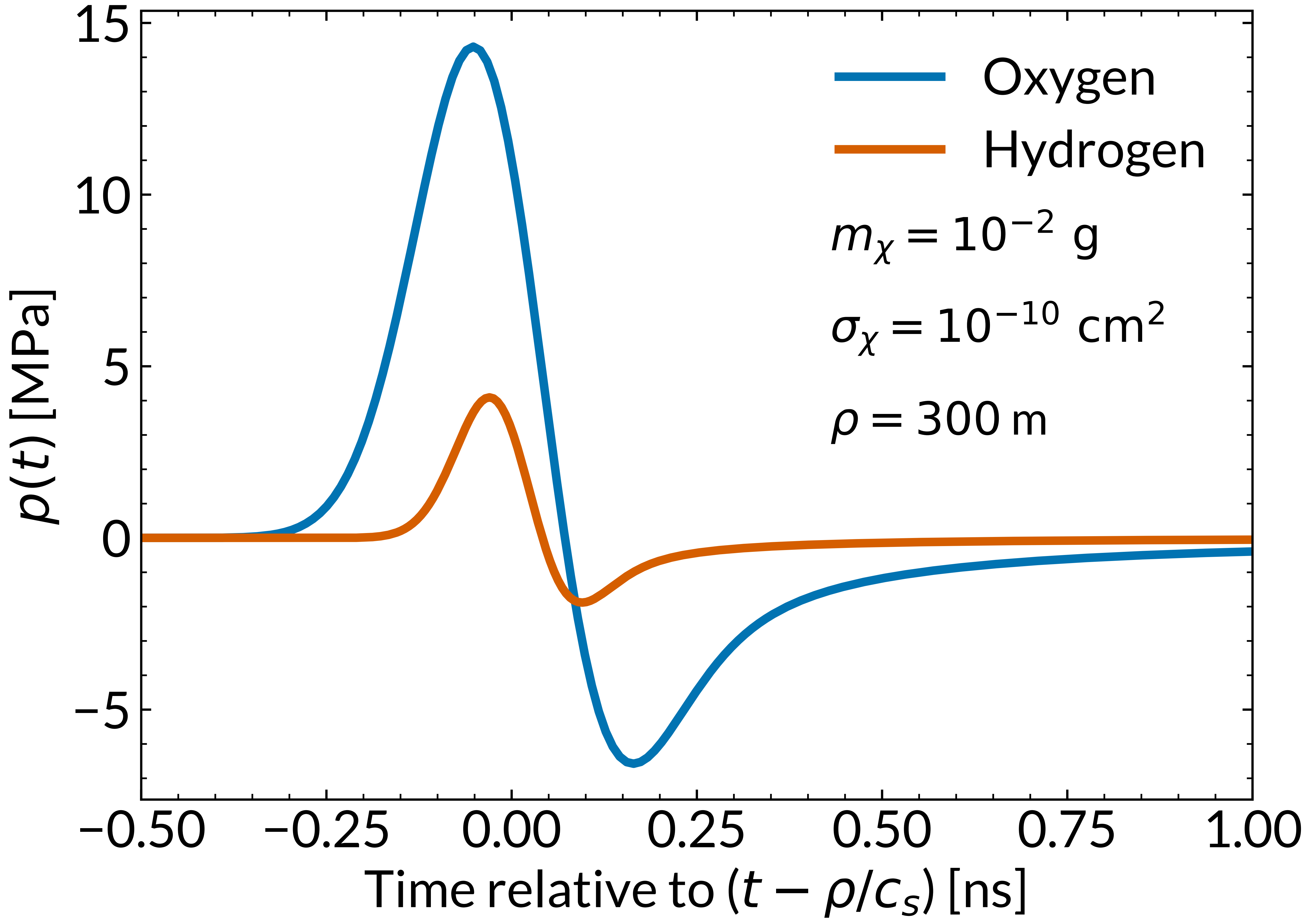
$$p(r, t; \sigma_A \ll \rho) = \frac{\alpha}{2\pi c_p}\frac{dE}{dz}\frac{c_s^2}{\sqrt{2\pi\sigma_A^3}}\frac{1}{\sqrt{\rho}} I_p\left(\frac{t - \rho/c_s}{\sigma_A/c_s}\right)$$

Shape determined by $I_p \sim \mathcal{O}(1)$.

Solution is **bi-polar**

Large MPa signal for UHDM in target parameter regions - **determined by pre-factor**

Full pressure solution is sum of O and H contributions.



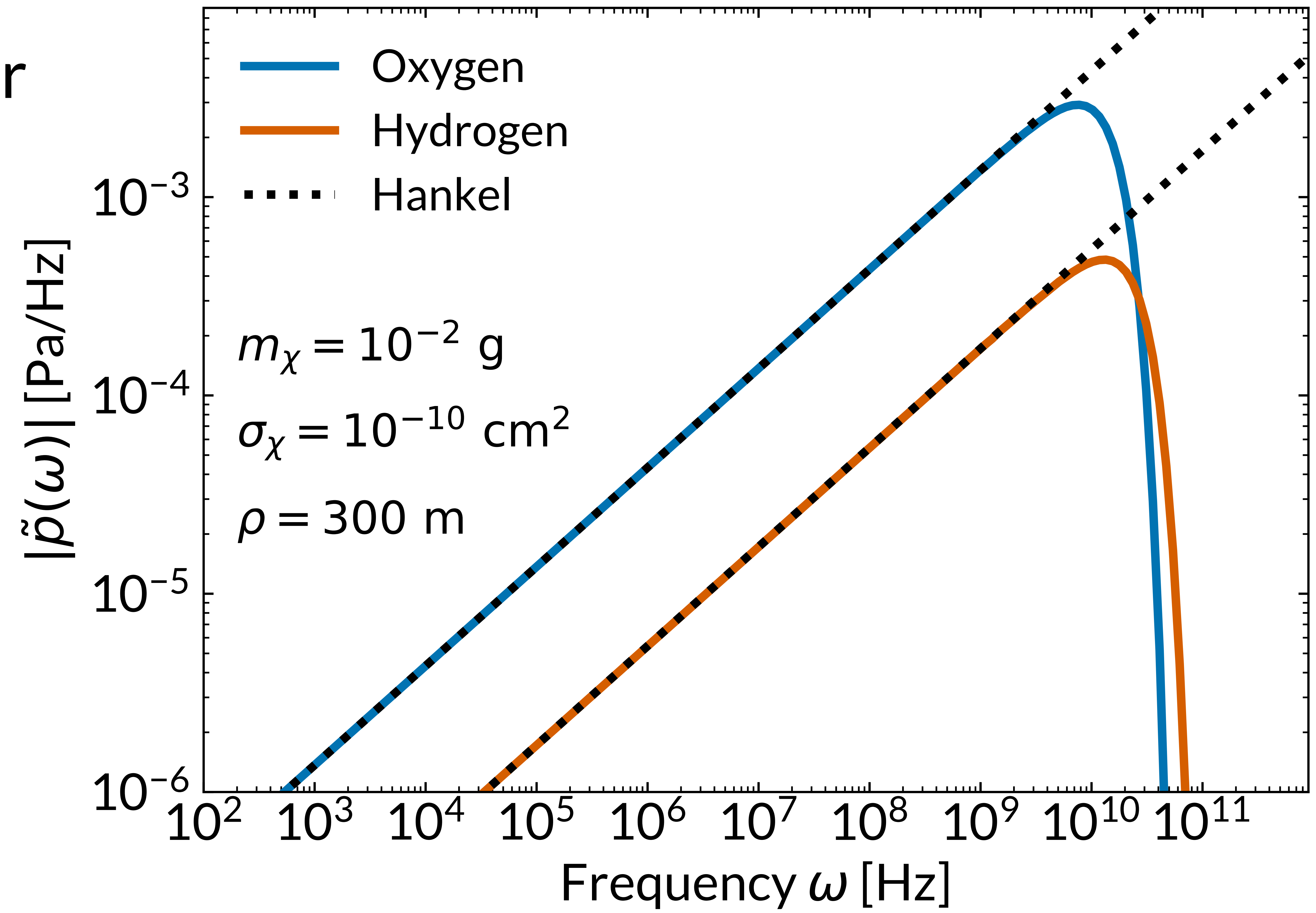
What does p look like?

Can also find full frequency solution (must be solved numerically) by Fourier transform.

Frequency cut-off set by c_s/σ_A

Can "integrate out" width σ_A to get an analytic approximation at lower freq:

$$\tilde{p}_A(\rho,\omega) \approx \frac{\omega\alpha}{2\pi c_p}\frac{dE_A}{dz}\frac{\pi}{2}H_0^{(2)}\left(\frac{\rho\,\omega}{c_s}\right)$$



Is this the full story?

Need to account for other attenuation effects! Packaged into an absorption coefficient $\tilde{a}(\omega)$:

$$\tilde{a}(\omega) = \frac{\omega^2}{\omega_0 c_s} + \frac{2}{\lambda_1}\frac{i\omega}{\omega_1 + i\omega} + \frac{2}{\lambda_2}\frac{i\omega}{\omega_2 + i\omega}$$

Chemical Relaxation Effects

$$\omega_0 = 5.32 \times 10^{11}\,\mathrm{kHz}$$

Viscous Absorption

$$\lambda_1 = 64.4\,\mathrm{km}, \lambda_2 = 152.7\,\mathrm{m}$$

$$\omega_1 = 8.37\,\mathrm{kHz}, \omega_2 = 582.7\,\mathrm{kHz}$$

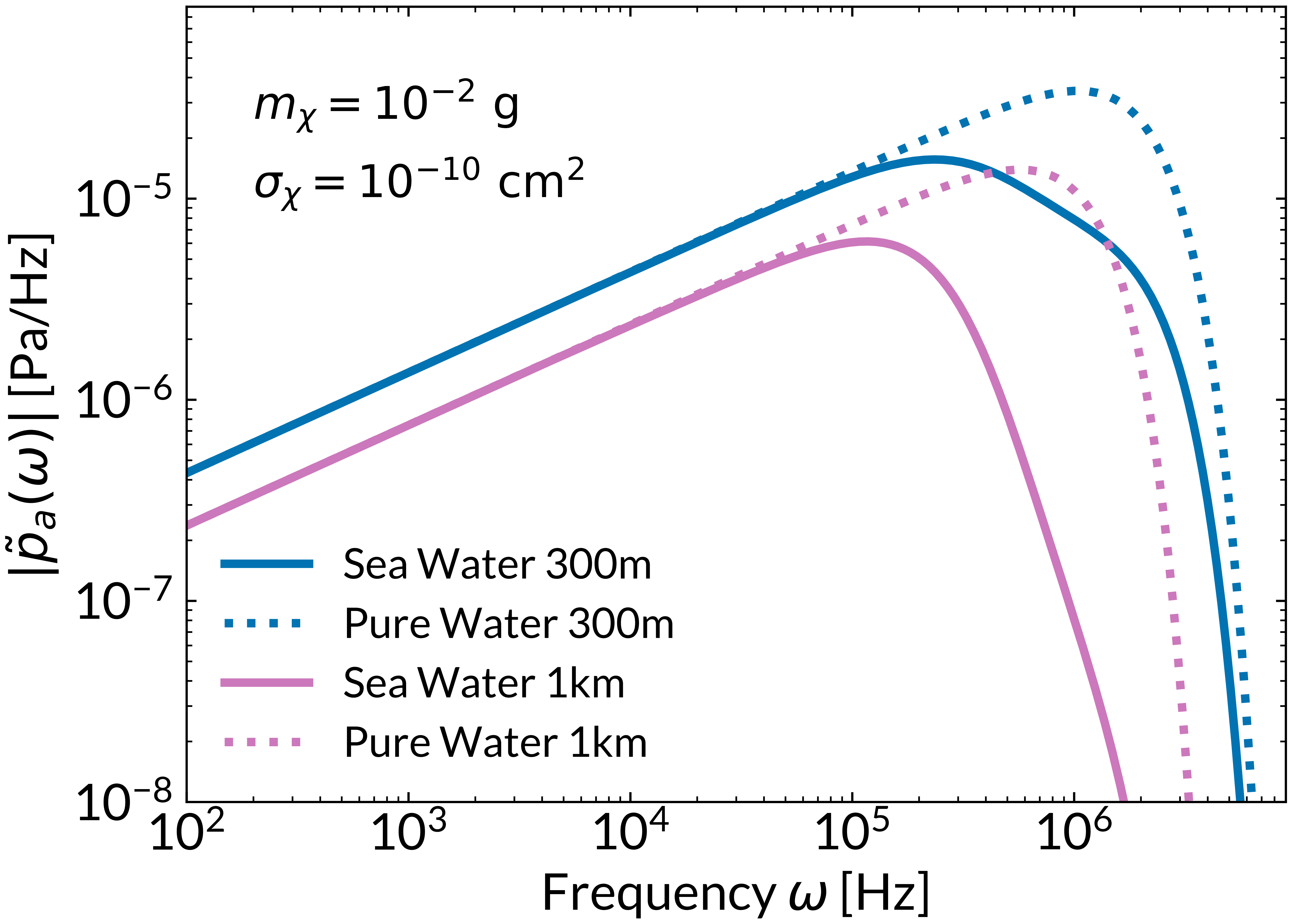
The pressure in frequency space becomes:

$$\tilde{p}_a(\rho, \omega) = \exp\left(-\frac{\tilde{a}(\omega)\rho}{2}\right)\tilde{p}(\rho, \omega)$$

Is this the full story?

Takes frequency cut-off from $\mathcal{O}(10^{11}\,\mathrm{Hz})$ to $\mathcal{O}(10^{5}\,\mathrm{Hz})$.

Cut-off profile is not Gaussian at certain characteristic distances for full sea water model.



Pure water vs Sea Water

Pure water: can be solved analytically (IFT) **and still contains I_P!** Retains shape but different width $\sigma_A \rightarrow \sqrt{\rho c_s/\omega_0}$.

Pure Water

$$p_a^{\text{pure}}(\rho, t) = \frac{\alpha}{2\pi c_p}\frac{dE}{dz}\frac{c_s^2}{\sqrt{2\pi}}\frac{1}{\sqrt{\rho}}\left(\sqrt{\frac{\rho c_s}{\omega_0}}\right)^{-3/2} I_p\left(\frac{t-\rho/c_s}{\sqrt{\rho c_s/\omega_0}/c_s}\right)$$

Un-attenuated case

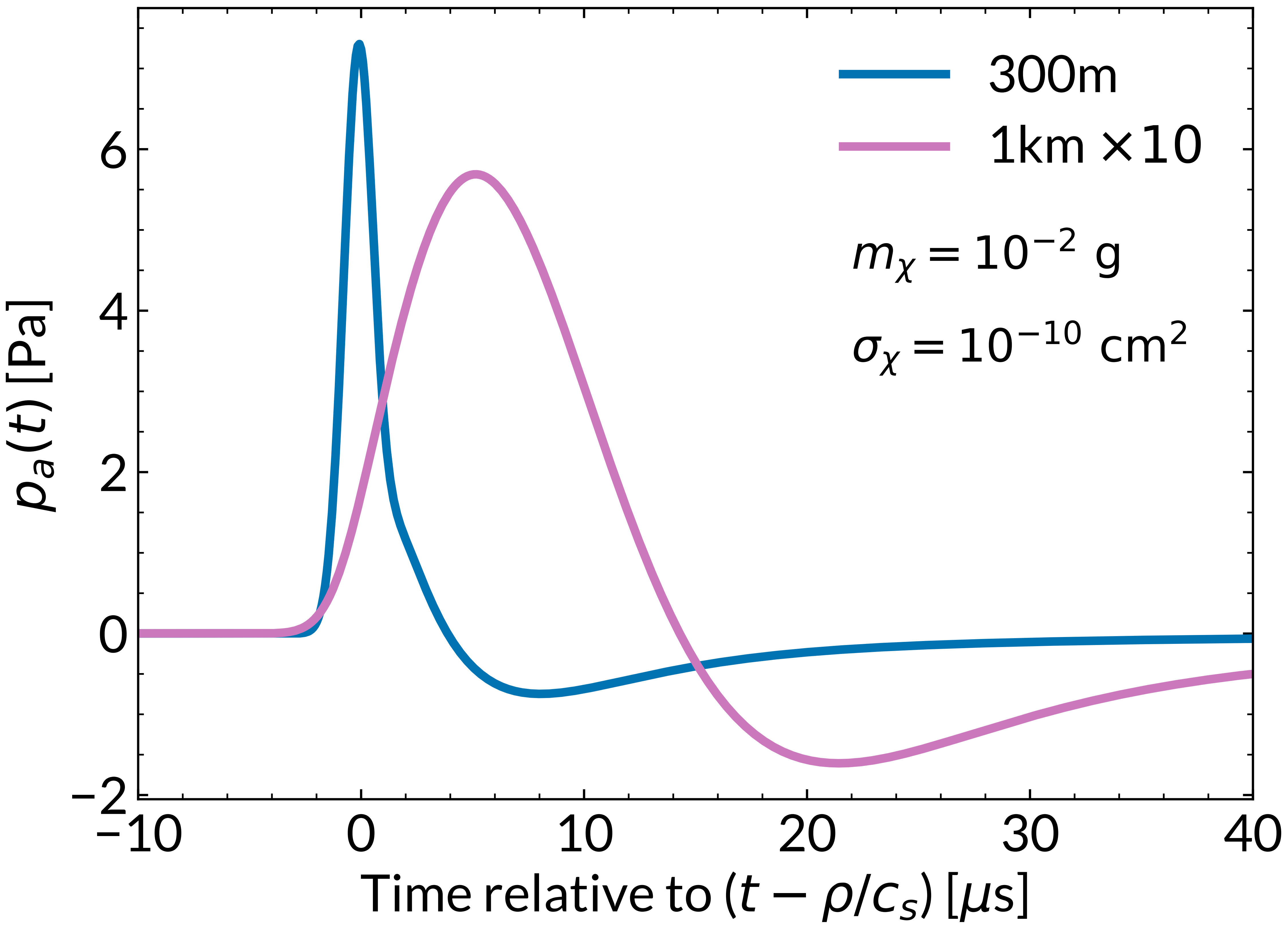
$$p(r, t; \sigma_A \ll \rho) = \frac{\alpha}{2\pi c_p}\frac{dE}{dz}\frac{c_s^2}{\sqrt{2\pi\sigma_A^3}}\frac{1}{\sqrt{\rho}} I_p\left(\frac{t-\rho/c_s}{\sigma_A/c_s}\right)$$

Sea Water: Must be solved numerically

What does the new pulse look like?

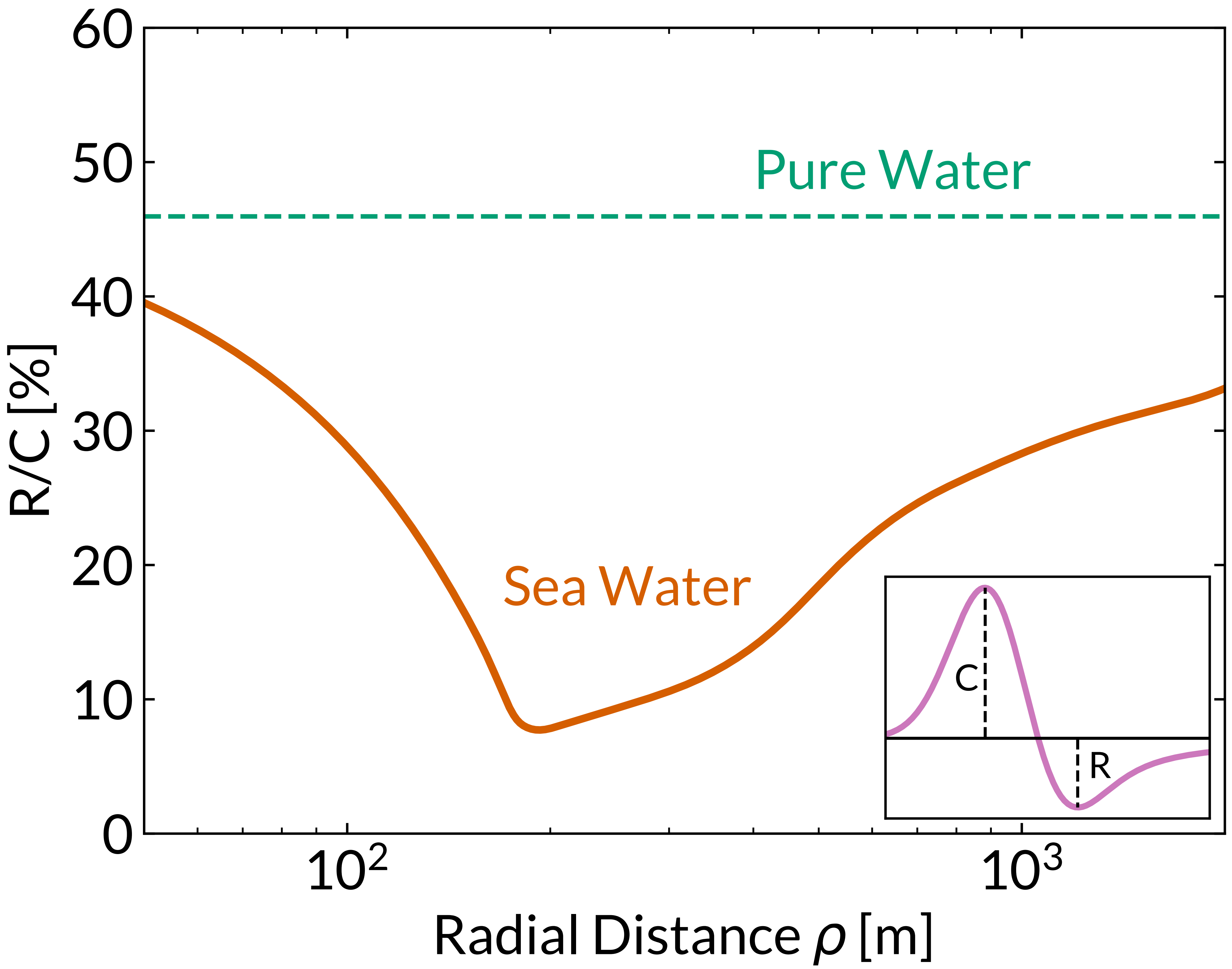
Nano-second pulse of MPa amplitude has become **micro-second pulse at Pa amplitude**

Frequency dependent distortions in freq. domain -> modifications in bipolar pulse structure



Pulse Asymmetry

- Pure water: same shape no matter the distance -> constant asymmetry
- Pulse gets more asymmetry from non-Gaussian cut-off shape in freq space.
- Maximal asymmetry near the characteristic absorption scale of magnesium sulphate ($\lambda_2 = 152.7$m)



Sensitivity Analysis

Characterise the sensitivity of a hydrophone array by the number of detectable events:

$$N_{\text{events}} = \phi_\chi(m_\chi) \cdot \mathrm{A}_{\text{array}} \cdot \eta\left(\frac{dE}{dz}\left(\sigma_\chi, v_\chi\right); p_{\text{thr}}\right)$$

DM Flux

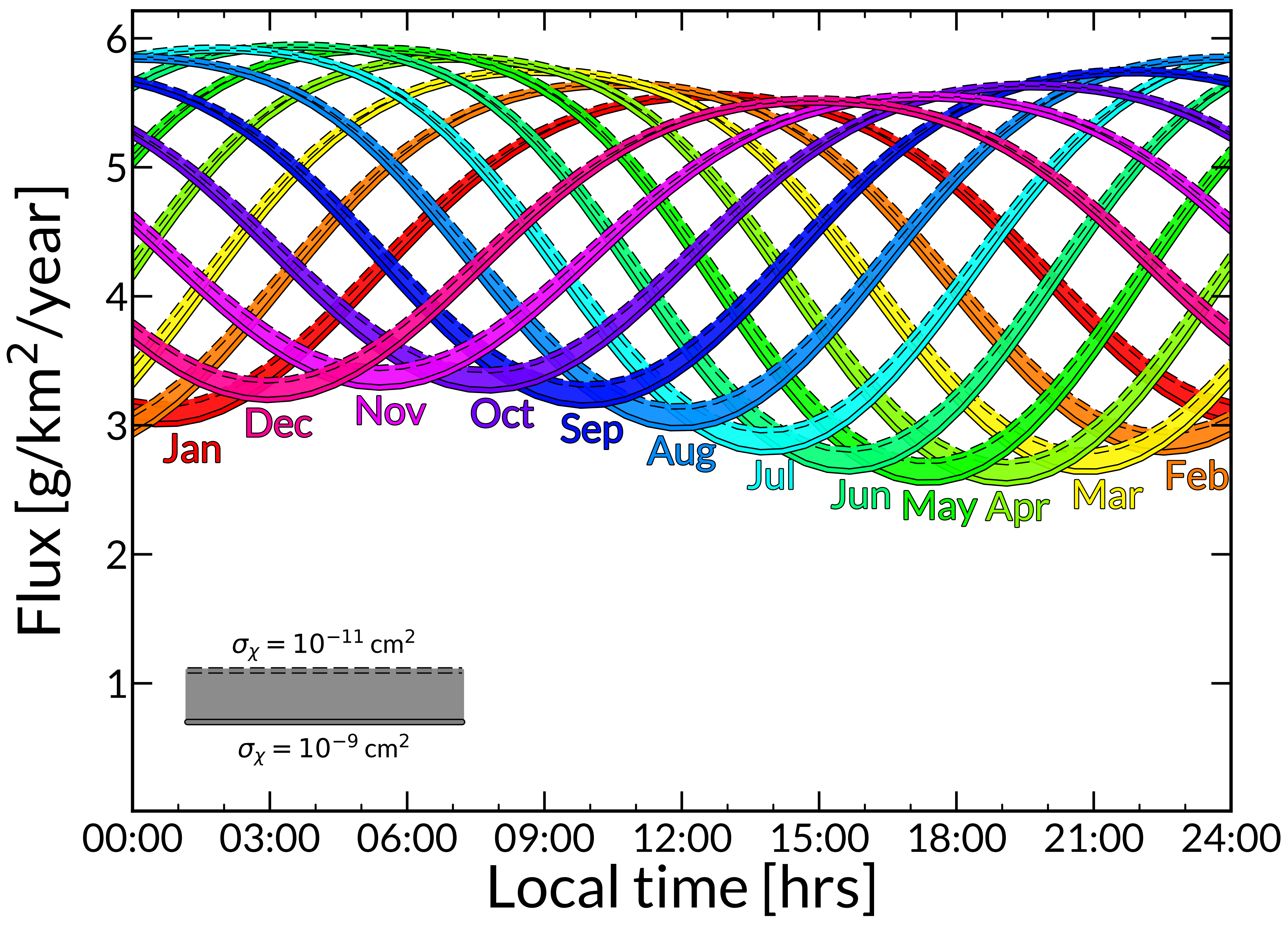
Array area

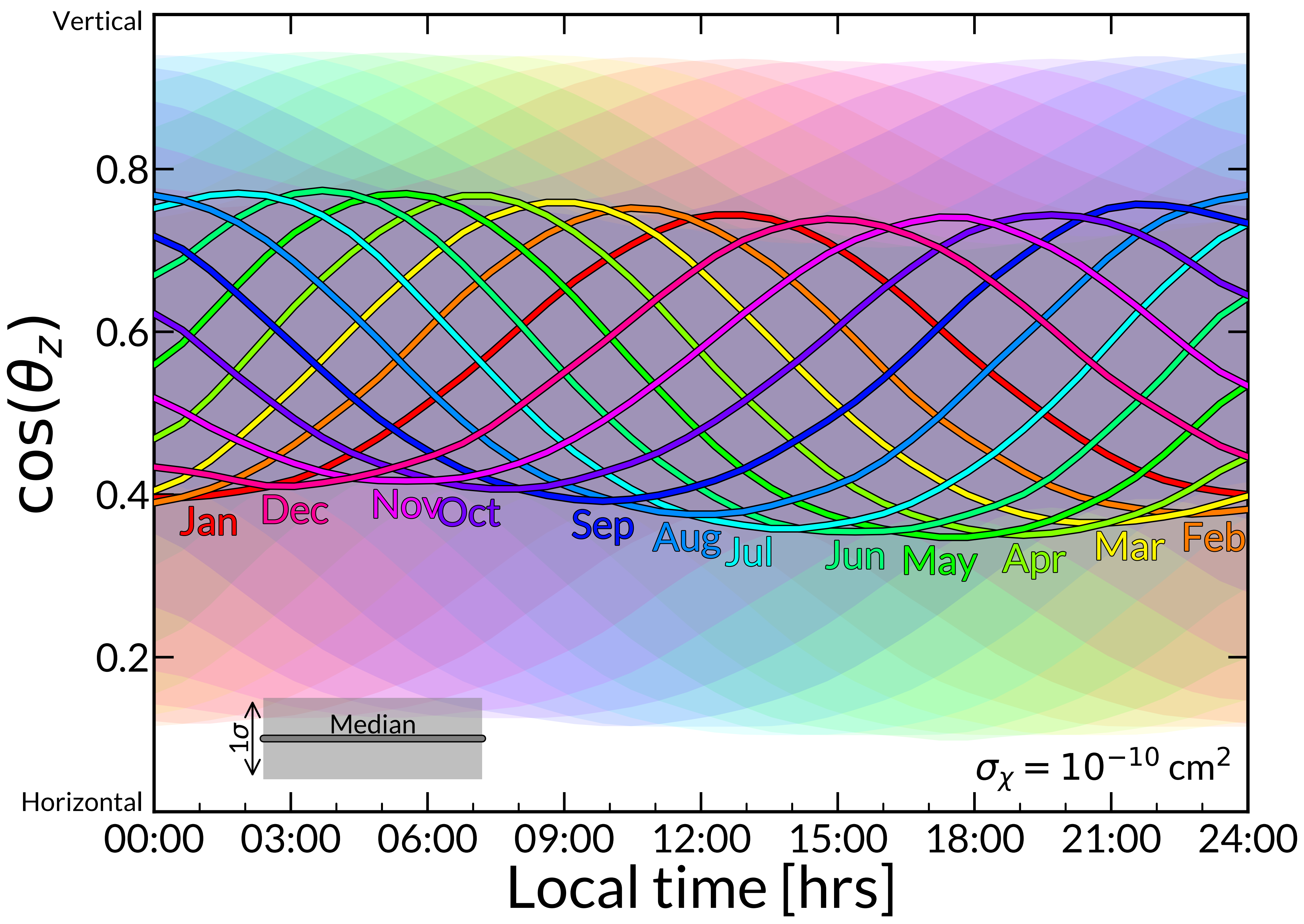
Detection efficiency

Detection threshold

We now summarise how each parameter is calculated

Sensitivity Analysis: $\phi_\chi(m_\chi)$





- DM arriving from below detector -> stopped by Earth
- Maximal DM flux when hydrophone array has constellation Cygnus above
- Distinct daily modulation -> different than UHE neutrinos!

- Modulation in the zenith angle distribution
- Broad distribution -> less distinctive than flux modulation

Sensitivity Analysis: $\mathrm{A}_{\mathrm{array}}$

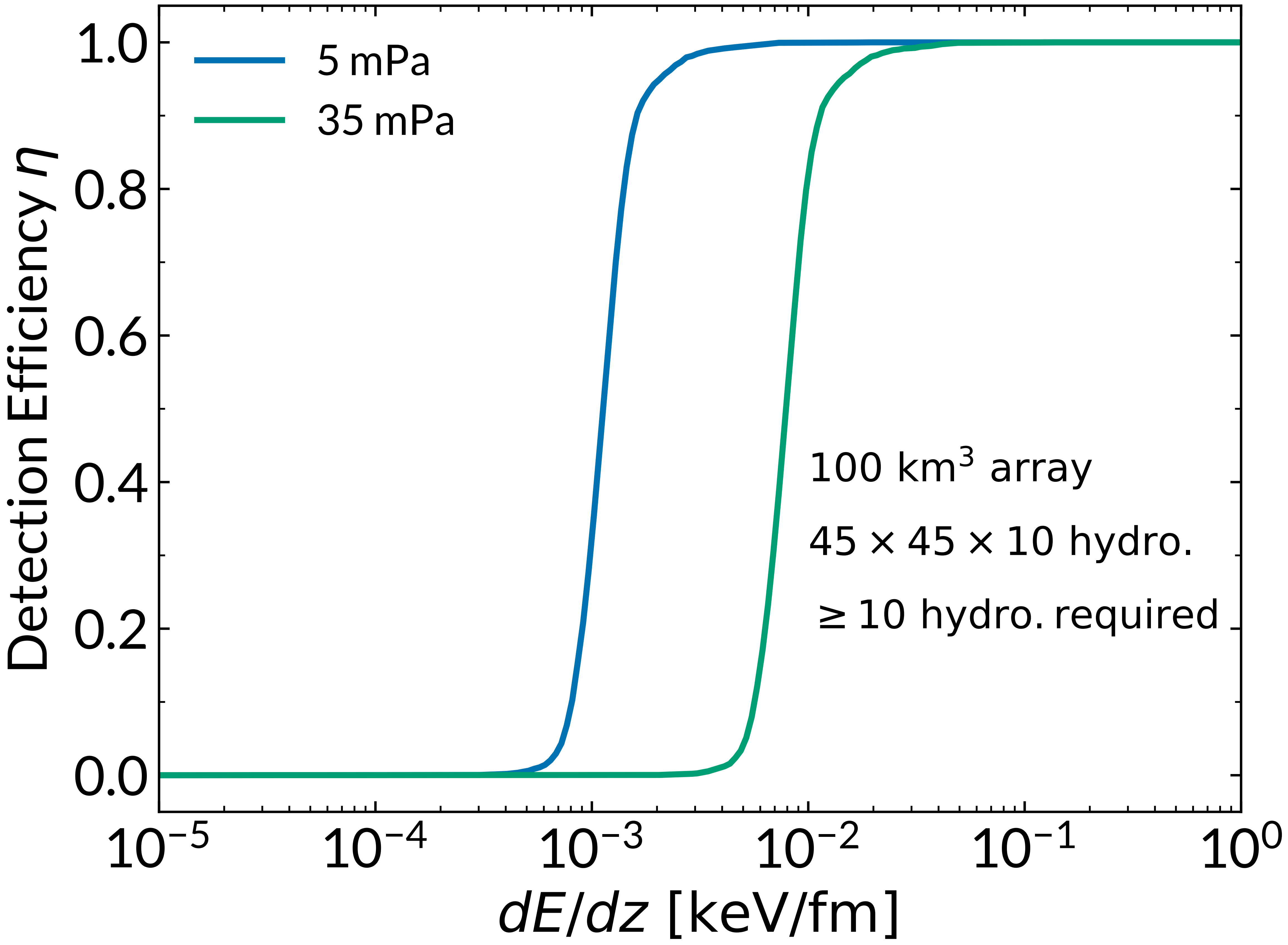
- DM Flux: $\phi_\chi \approx 4 \left(\frac{1\ \mathrm{g}}{m_\chi} \right) \mathrm{km}^{-2}\ \mathrm{yr}^{-1}$, Need km scale dimensions
- Aligns with UHE neutrino detection with proposals with $\mathcal{O}(100\ \mathrm{km}^3)$ dimensions
- We take 10km x 10km x 1km array in Mediterranean at depth 1.2km
- Hydrophone distribution 45 x 45 x 10 grid -> lower end of neutrino studies
- To account for edge effects, we extend $\mathrm{A}_{\mathrm{array}} = 10.5\ \mathrm{km} \times 10.5\ \mathrm{km}$

Sensitivity Analysis: p_{thr}

- Threshold for detection **determined by noise levels in the experiment**
- Hydrophones optimised in 10-100 kHz range
- Here, dominated by sea surface agitations due to weather conditions -> **sea state noise.** States 0-9, increasing in noise level.
- Hydrophone self noise equivalent to **sea state 0,** always sea state limited
- Mediterranean average sea noise level at 2km depth recorded as **approx. 5 mPa** in the 20 - 43 kHz band -> take this as a baseline

Sensitivity Analysis: η

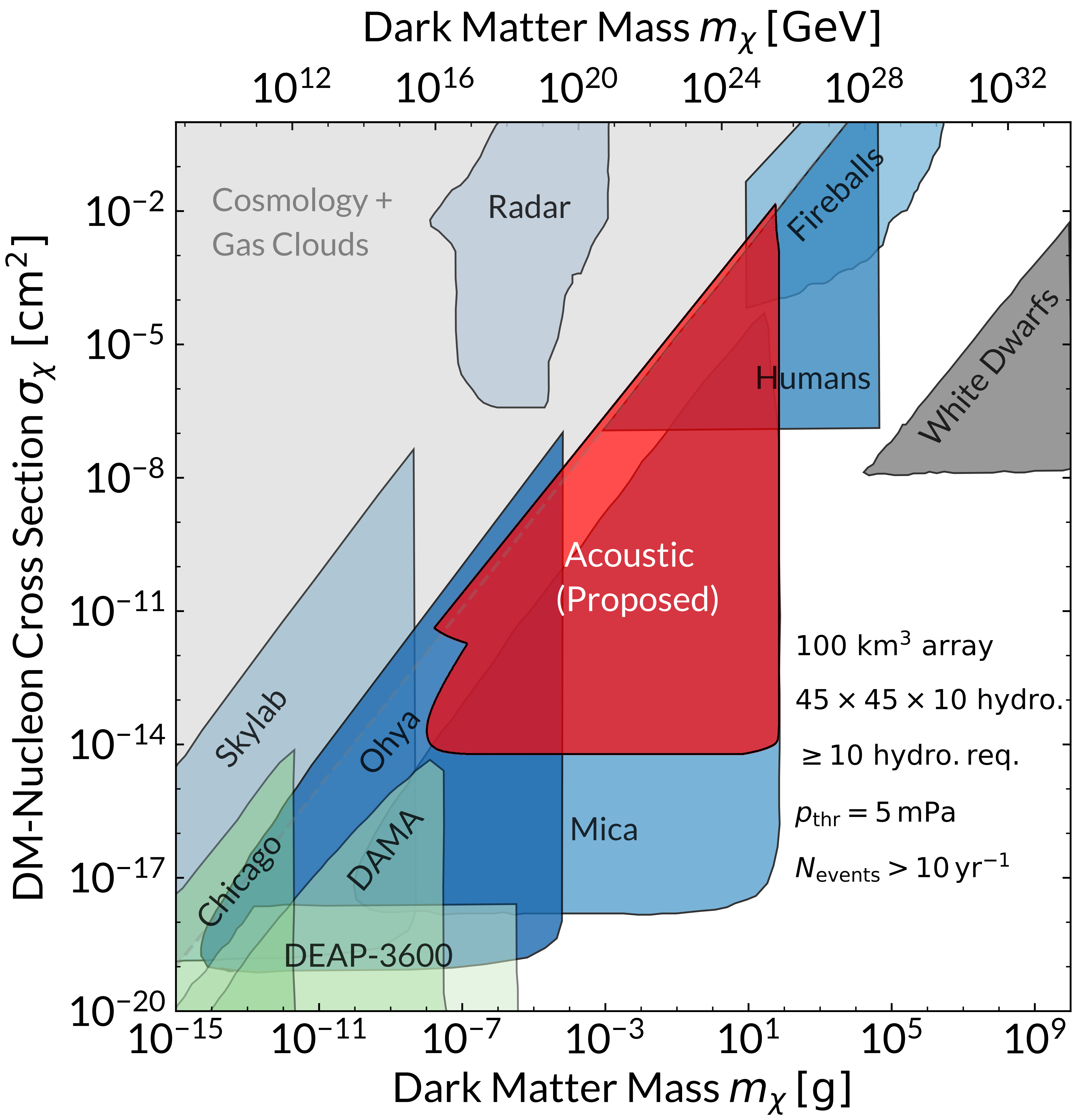
- Monte Carlo simulation for $\mathcal{O}(10^5)$ tracks
- Calculate pressure in all hydrophones in array
- If $p > p_{\rm thr}$ for at least 10 hydrophones, count track as detected
- Used optimistic scenario $p_{\rm thr} = 5\ \rm mPa$ and pessimistic $p_{\rm thr} = 35\ \rm mPa$. Leads to factor 7 reduction in sensitivity in dE/dz



Sensitivity Analysis: N_{events}

- We make a choice that $N_{\text{events}} > 10\ \text{yr}^{-1}$ is required for detection
- Somewhat arbitrary, but comparable rates to UHE neutrino studies
- Linear changes to N_{events} leads to linear changes in σ_χ or m_χ sensitivity, so making other choices doesn't change sensitivity significantly

Sensitivities



- Can put all this together to get a projected sensitivity for the array
- Assuming proposed acoustic neutrino experiment parameters, **could constrain the gap!**
- Complementary to Humans, Mica, Ohya and Cosmological Bounds
- Also sensitive to spin dependent cross section through hydrogen, Ohya is not!

Punchline:

Future acoustic neutrino experiments could have the power to constrain UHDM candidates

Thank you for listening!
Any Questions?

Based on arXiv:2502.17593 (PRD in review)

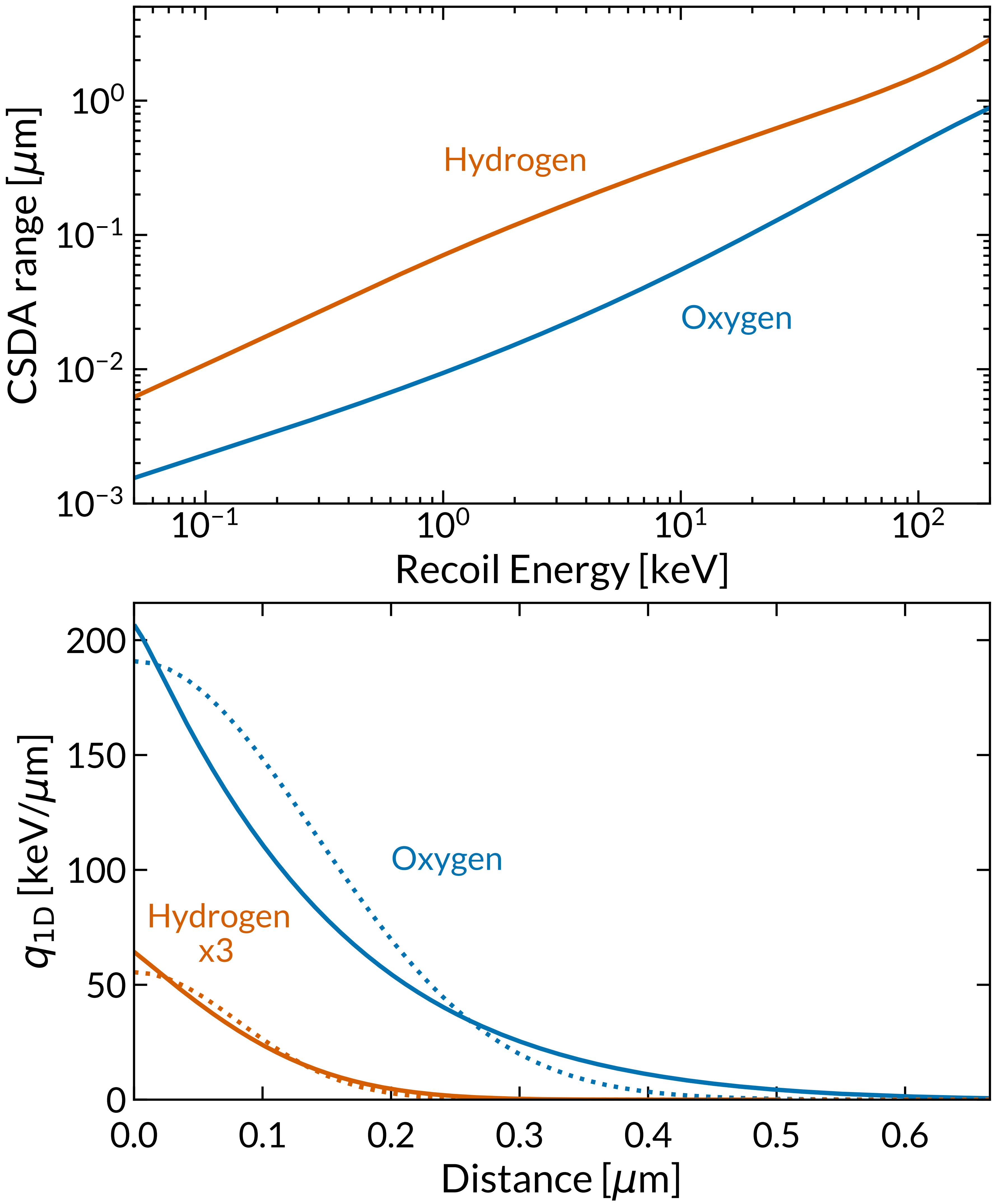
Backup slides

Track Width + Gaussian Approx

- Calculate range using slowing down approximation range of H and O using SRIM software package.

- Find at typical recoil energy of $\overline{E_O} = 30.2$ keV and $\overline{E_H} = 1.9$ keV, the fit widths are $\sigma_O = 0.14\,\mu\mathrm{m}$ and $\sigma_H = 0.082\,\mu\mathrm{m}$

- While Gaussian is not an excellent fit, the true nature of the distribution is irrelevant after attenuation



Short Track Case

If we let the DM energy deposition evolve in z direction but with no track width:

$$q(\rho', \phi', z') = \frac{1}{2\pi}\frac{\delta(\rho')}{\rho'}\frac{dE}{dz'}\bigg|_0 \exp\left(-\frac{z'}{\ell}\right)$$

We find a pressure solution:

$$p(\rho, z, t) = \frac{\alpha}{2\pi c_p}\frac{dE}{dz'}\bigg|_0 \exp\left(-\frac{z}{\ell}\right)\frac{\partial}{\partial t}\left[\frac{\Theta\left(t - t_0\right)}{\sqrt{t^2 - t_0^2}}\cosh\left(\frac{c_s\sqrt{t^2 - t_0^2}}{\ell}\right)\right].$$

Same pre-factor as constant dE/dz case
but with extra exponential factor

$\mathcal{O}(1)$ over μs scales

$$\cosh\left(\frac{c_s\sqrt{t^2 - t_0^2}}{\ell}\right) \approx \cosh\left(\sqrt{\frac{t - t_0}{\Delta(\ell, \rho)}}\right)$$

$$\Delta(\ell, \rho) = \frac{\ell^2}{2\rho c_s} \approx 10^4\,\mu s \times \left(\frac{\ell}{100\,\mathrm{m}}\right)^2\left(\frac{300\,\mathrm{m}}{\rho}\right)$$

Detection Efficiency for Short Tracks

- We extend the detection efficiency calculation to varying track length $\ell_{\rm DM}$
- Track lengths of $\mathcal{O}(20\ \mathrm{km})$ match the constant dE/dz calculation
- Using these detection efficiencies leads to the second "bump" in the sensitivity region