Listening for ultra-heavy DM with underwater acoustic detectors

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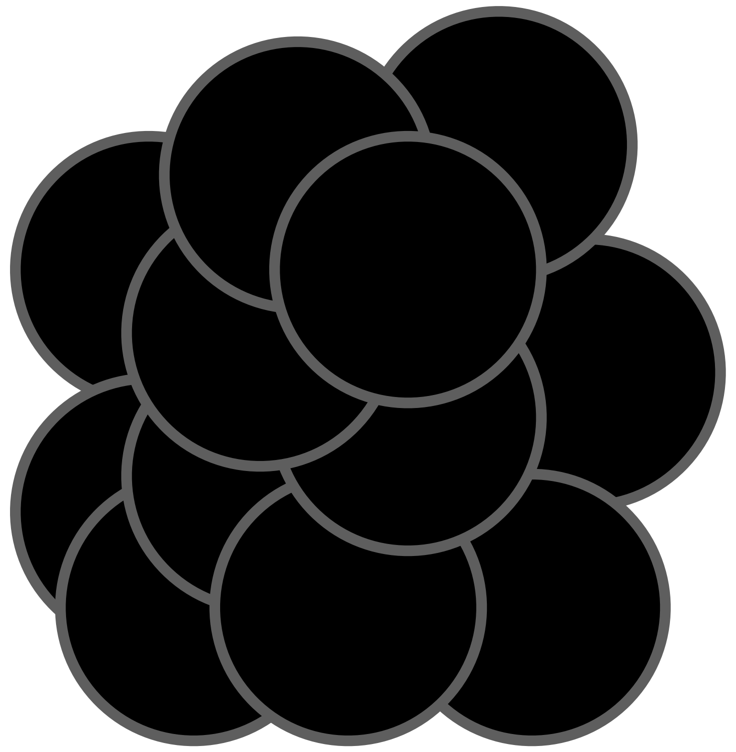
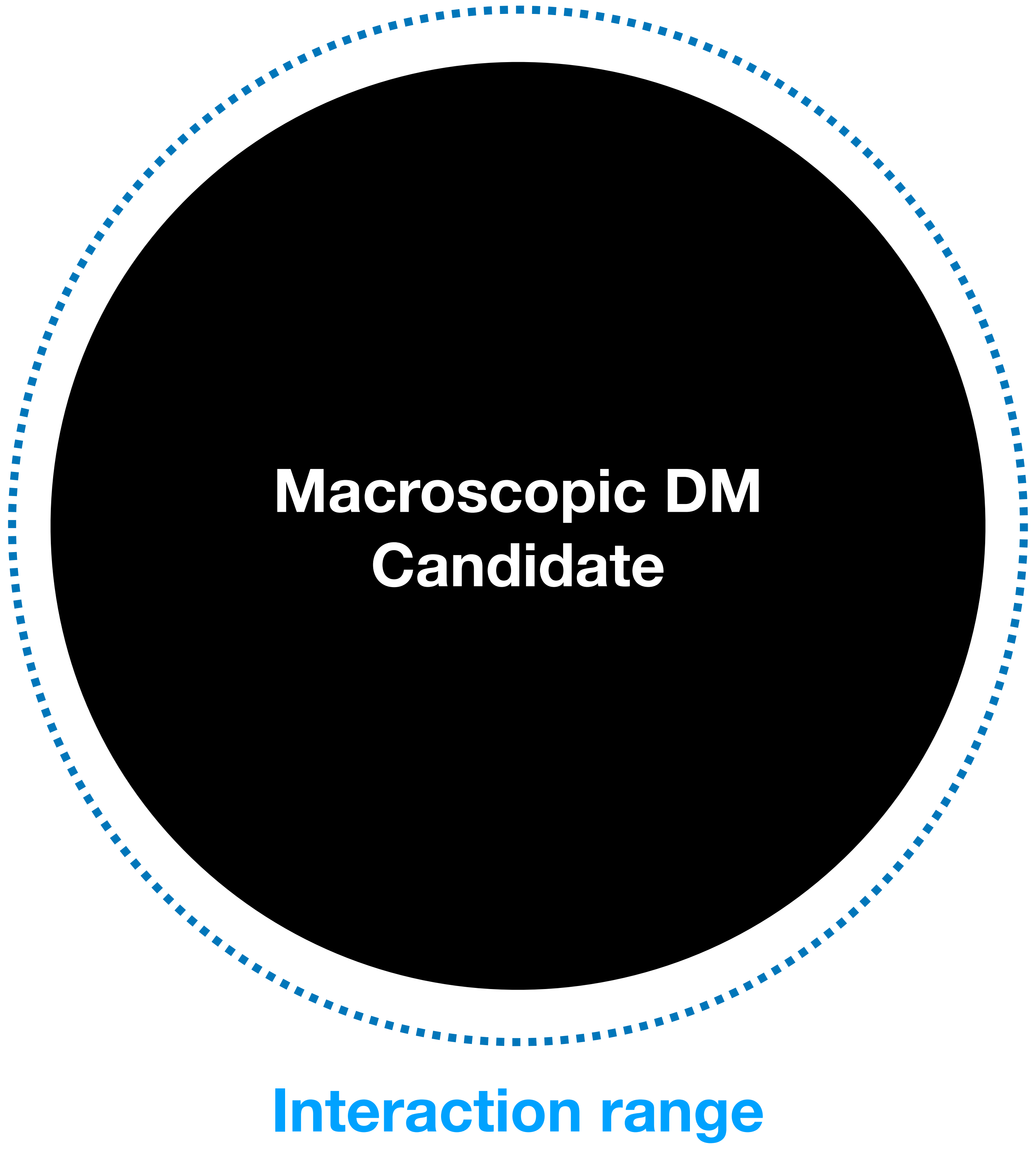
Ultra-heavy Dark Matter

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



Macros

- 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!



Macro Direct Detection

- Macro's often parameterised in grams (g)

- DM Flux: $\phi_\chi \approx 6 \left(\frac{1 \text{ g}}{m_\chi} \right) \text{km}^{-2} \text{ yr}^{-1}$

- Need a *very* large detector (or very long integration time) to have significant number of events.

Macro Kinematics

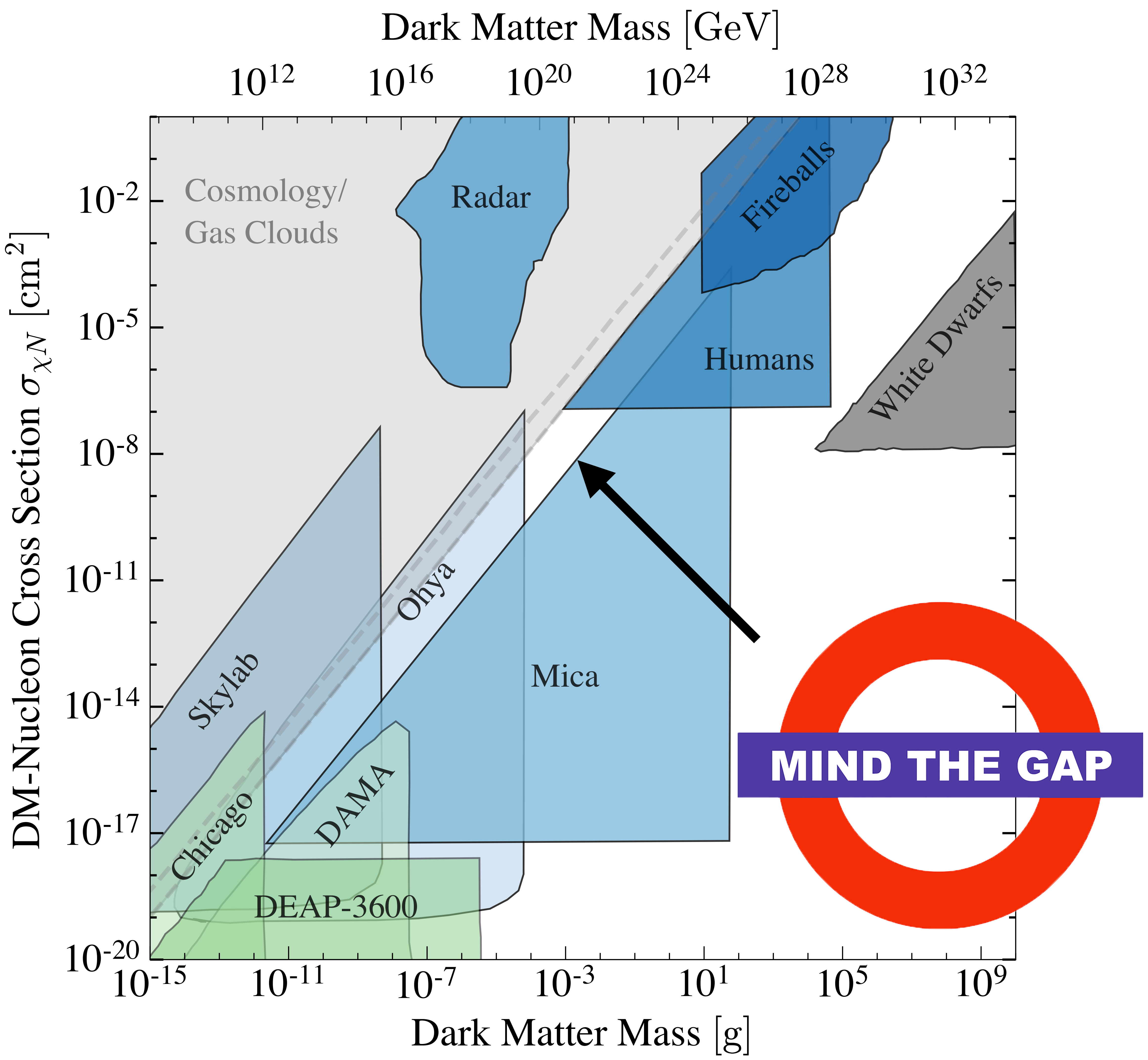
Total energy after traversing path length L in detector given by (determined by classical scattering):

$$E_{\chi f}(L) = \frac{1}{2} m_\chi v_{\chi,SL}^2 \exp\left(-2\frac{\sigma_{\chi N}}{m_\chi}\rho_{\rm med} L\right)$$

Differentiating, can find the energy deposition rate into the medium:

$$\frac{dE}{dL} = -\frac{dE_\chi}{dL} = \rho_w \sigma_{\chi N} v_{\chi,\rm SL}^2 \exp\left(-2\frac{\sigma_{\chi N}}{m_\chi}\rho_{\rm med} L\right)$$

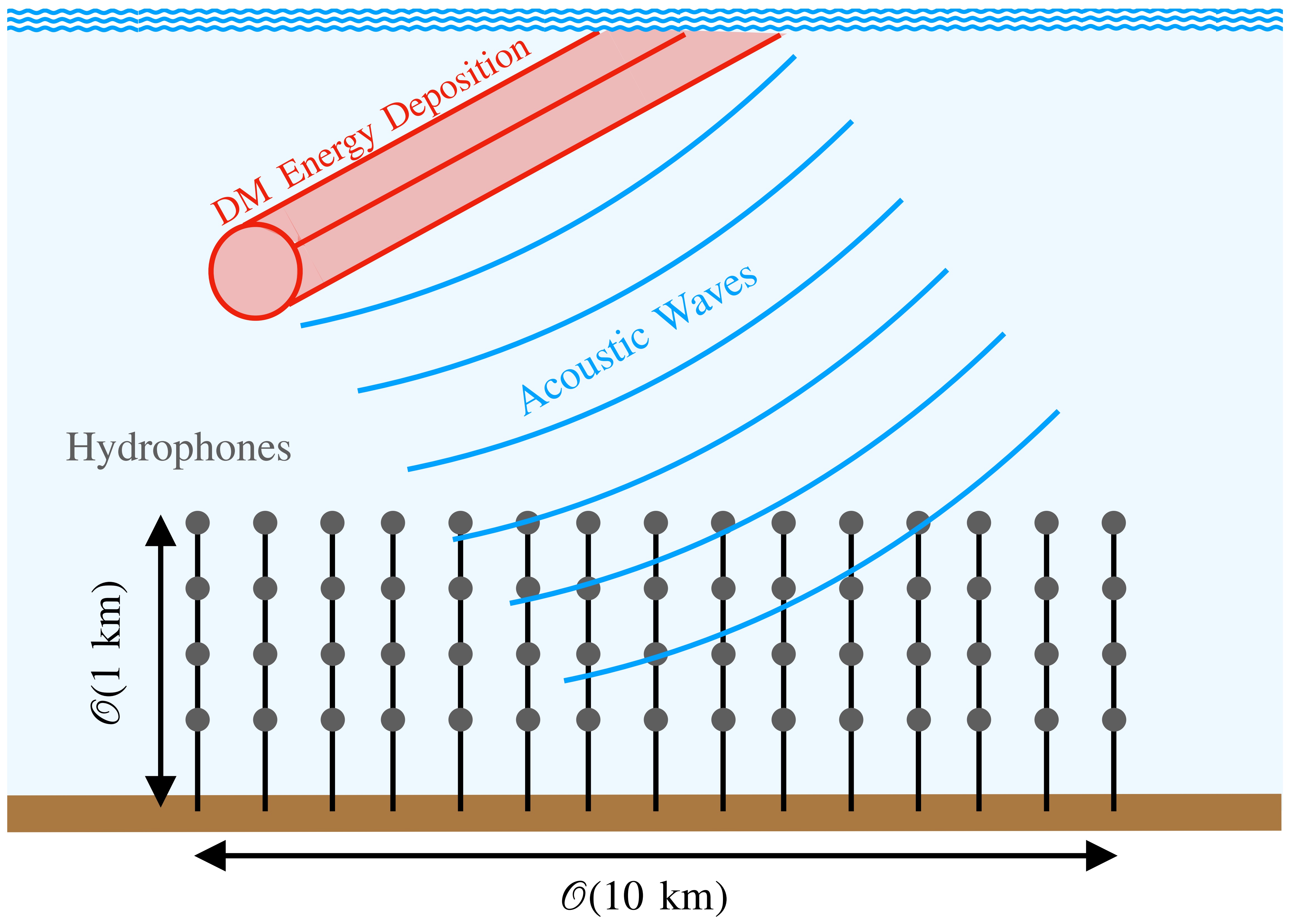
Current Constraints



- 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 in the ocean [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 required
- Energy deposition comes from particle showers

What is the signal?

Pressure waves created from **thermo-acoustic heating.**
[Learned, 1979]

Energy Deposition Density

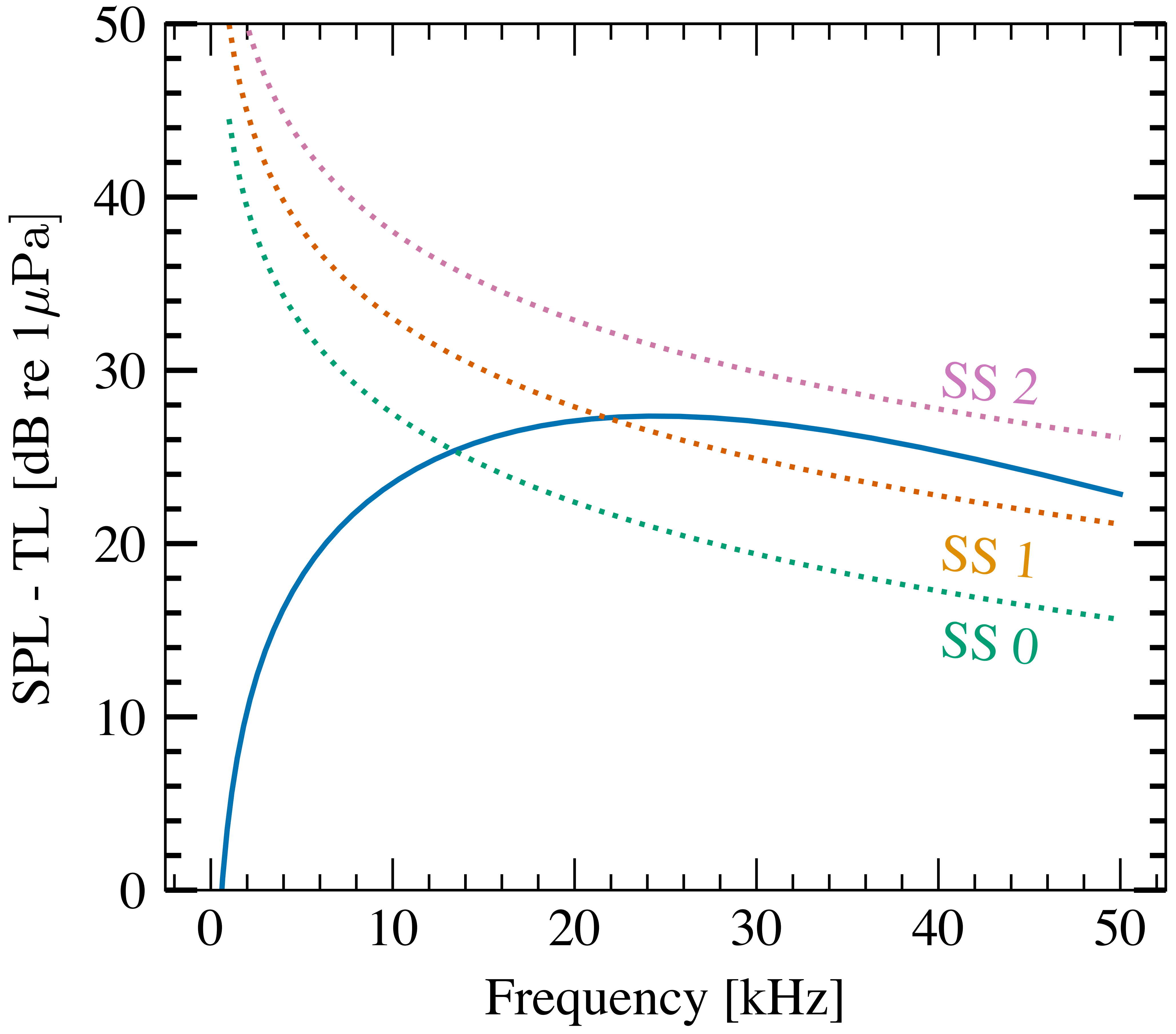
$$\nabla^2 P(\mathbf{r}, t) - \frac{1}{c_s^2} \frac{\partial^2 P(\mathbf{r}, t)}{\partial t^2} = -\frac{\alpha}{C_p} \frac{\partial^2 q(\mathbf{r}, t)}{\partial t^2}$$

Acoustic pressure

General solution to this equation given by:

$$P(\vec{r}, t) = \frac{\alpha}{4\pi C_p} \int_V \frac{dV'}{|\vec{r} - \vec{r'}|} \frac{\partial^2}{\partial t^2} q\left(\vec{r'}, t'\right), \quad t' = t - \frac{|\vec{r} - \vec{r'}|}{c_s}$$

Signal and Noise Characteristics



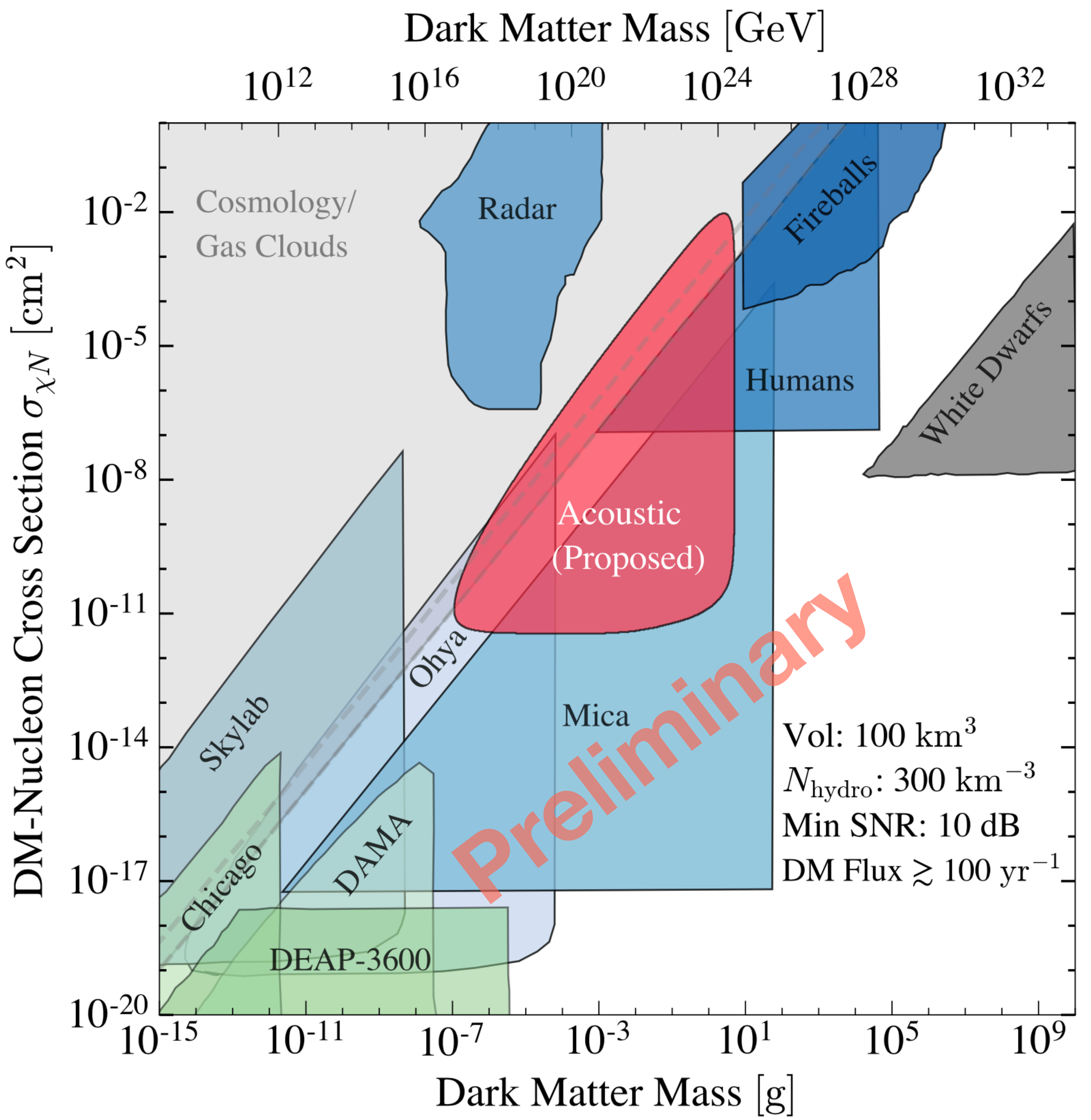
- The signal is **broadband**
- After transmission losses**, signal power greatest in 10-30kHz band**
- Dominant ambient noise in this band is **sea-state noise (surface agitation from wind)**

What we require

DM signal is:

- Larger than the typical hydrophone threshold (approx 1 μPa @ 15kHz) after propagation losses.
- Carries a minimum SNR to sea-state noise (conservatively defaulted to 10).
- Each hydrophone signal can be coherently summed to integrate the signal i.e. a $\sqrt{N_{\text{hydro}}}$ enhancement to the signal.

Preliminary Sensitivities



- Assuming proposed acoustic neutrino experiment parameters, **could constrain the gap!**
- Complementary to Humans, Mica, Ohya and Cosmological Bounds

Punchline

Future acoustic neutrino experiments could detect (or constrain) ultra-heavy dark matter

Any Questions

Backup Slides

Decibel Formalism

The pressure wave will have some **frequency dependent absorption** due to the chemical content of the sea water

Convenient to use a **decibel formalism,** as this is most often used in acoustics. Sound pressure level:

$$SPL = 20 \log_{10} \left(\frac{P}{P_{\text{ref}}} \right)$$

$$P_{\text{ref}} = 1 \mu\text{Pa}$$

Transmission Loss Model

The Transmission loss over a propagation distance r, is given by a frequency dependent parameter α

$$TL = \alpha r$$

$$\alpha = 0.106 \frac{f_1 f^2}{f^2 + f_1^2} e^{(\mathrm{pH}-8)/0.56} + 0.52 \left(1 + \frac{T}{43}\right) \left(\frac{S}{35}\right) \frac{f_2 f^2}{f^2 + f_2^2} e^{-D/6} + 0.00049 f^2 e^{-(T/27 + D/17)},$$

[Ainslie, McColm 1998]

Dependent on the temperature T, salinity S, depth D and pH. Frequency here in kHz. **After transmission losses, DM signal peaks at ~15kHz**

Sea State Noise

The dominant background noise source 10-100 kHz band is **sea state noise (surface agitation due to wind etc).** Parameterised by Knudsen curves:

$$\mathrm{NL}(f, n_s) = n_s - 10\log_{10}\left(f^{-5/3}\right)$$

There will also be transient noise sources from ocean wildlife e.g. dolphins and sperm wales. **Assume differentiable from DM signal** using algorithms being developed for neutrino detection.

Yearly and Daily Modulations