Listening for ultra-heavy DM with underwater acoustic detectors

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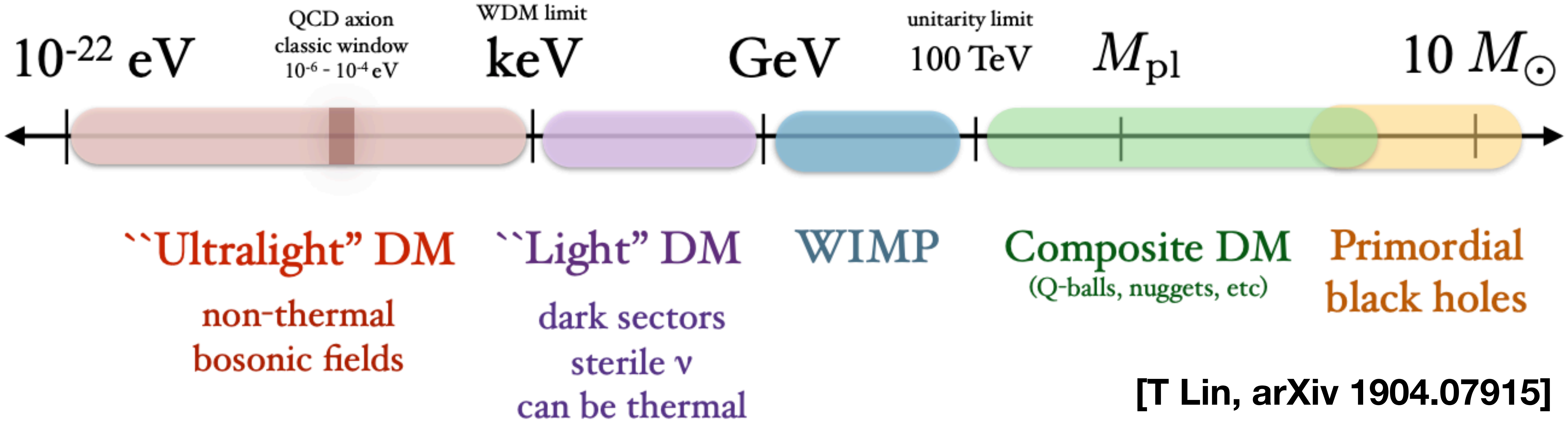
NeXT Workshop, 15/07/24

What is Dark Matter?

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

[Planck, 2018]



[T Lin, arXiv 1904.07915]

What (generic) DM properties do we need for DD?

Local DM Density

$$\rho_\chi \sim 0.3\ \text{GeV/cm}^3$$

Local DM Velocity

$$v_\chi \sim 220\ \text{km/s}$$

In truth, follows a (boosted) Maxwell Boltzmann distribution with peak v_χ

Ultra-heavy Dark Matter

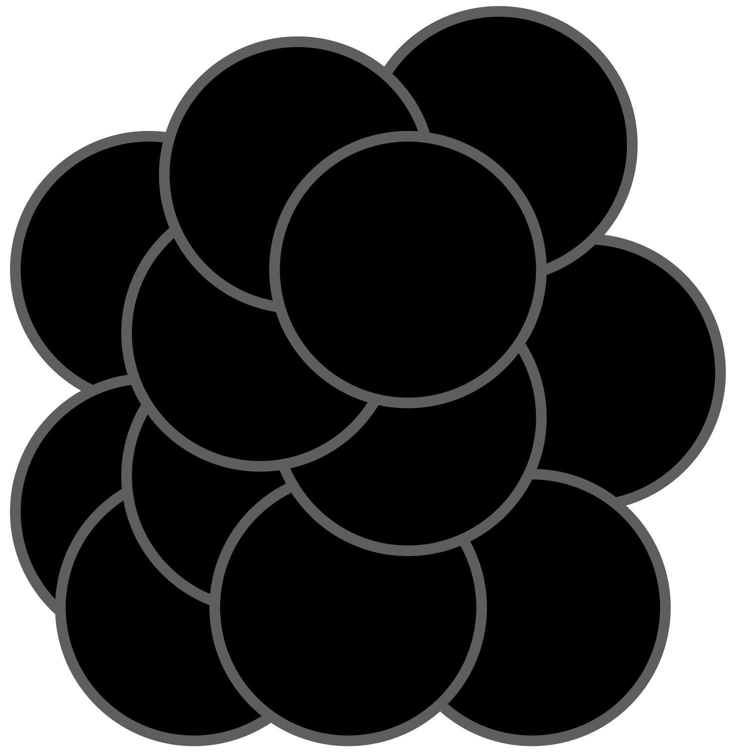
- Ultra-heavy dark matter is necessarily composite (if thermally produced) due to s-wave unitarity

- Many different models for UHDM

    - PBH, Nuggets, Blobs, WIMPonium, Q-Balls etc…

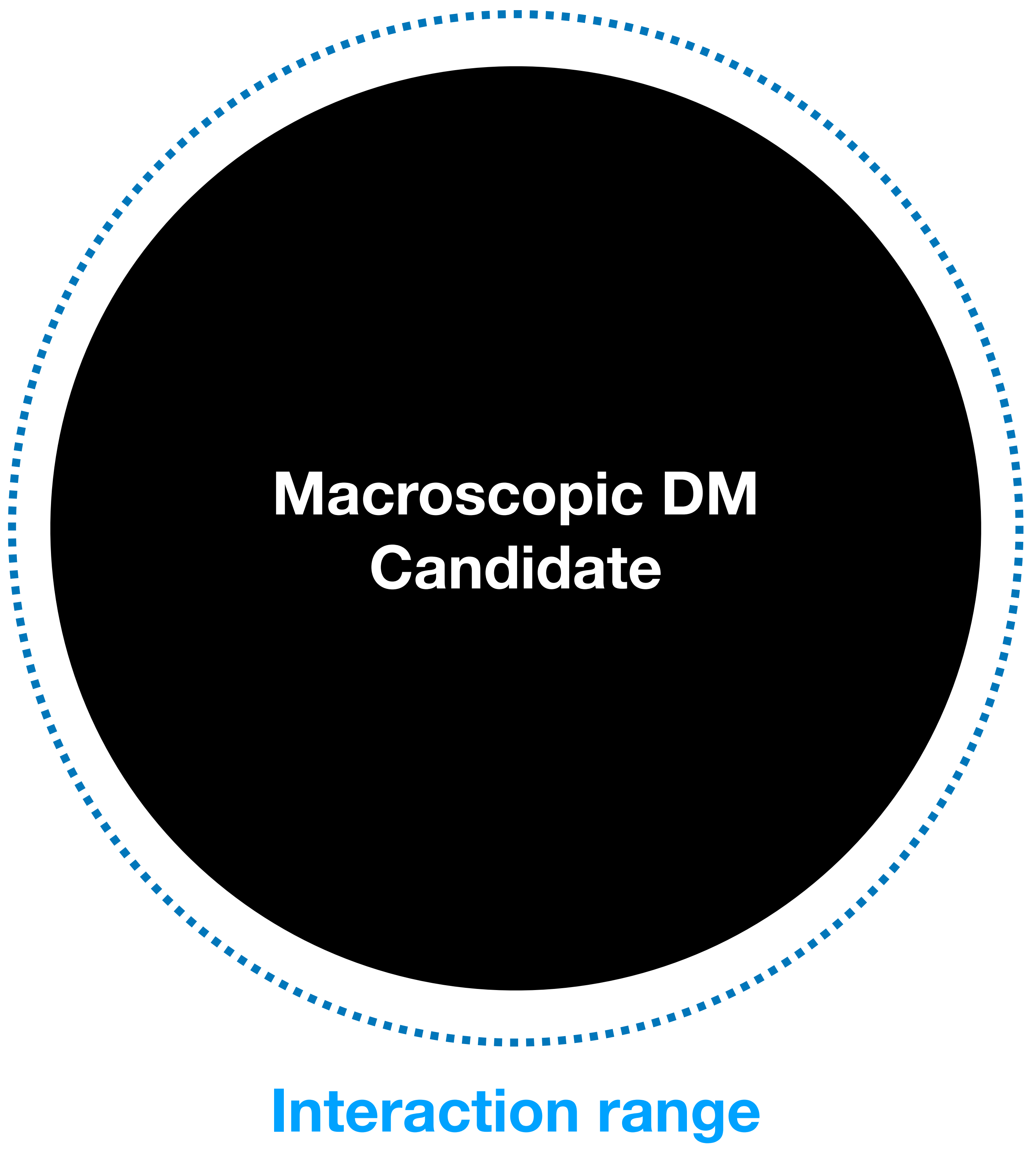
- Is there a nice model-independent way to treat them?

- Answer: **Yes** (for some parts of parameter space)



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.
- No hope for conventional detectors (LUX-ZEPLIN, XENONnT etc.)

Macro Kinematics

The energy of the macro after after traversing a path length L is given by:

$$E_\chi(L) = \frac{1}{2} m_\chi v_{\chi f}(L)^2$$

With the DM final velocity after N collisions:

$$v_{\chi f} \simeq v_{\chi i} \left(1 - 2\frac{m_A}{m_\chi}\right)^{\frac{N}{2}},$$

$$\simeq v_{\chi i} \exp\left(-N\frac{m_A}{m_\chi}\right).$$

Many collisions needed to slow down for $m_A \ll m_\chi$

Macro Kinematics

Using the relation for the mean free path $\lambda = m_A/(\rho_{\rm med}\sigma_{\chi N})$ and the number of scatters as $N = L/\lambda$ yields:

$$v_{\chi f} \simeq v_{\chi i} \exp\left(-\frac{\sigma_{\chi N}}{m_\chi}\rho_{\rm med} L\right)$$

This is only for a constant density medium, for the atmospheric overburden, use mass column density yields sea level velocity $v_{\chi,\rm SL}$:

$$v_{\chi,\rm SL} \simeq v_{\chi i} \exp\left(-\frac{\sigma_{\chi N}}{m_\chi} X_0 \sec\theta\right) \qquad X(h) = \int_h^\infty dh' \rho_0 e^{-h'/H} = X_0 e^{-h/H}$$

Macro Kinematics

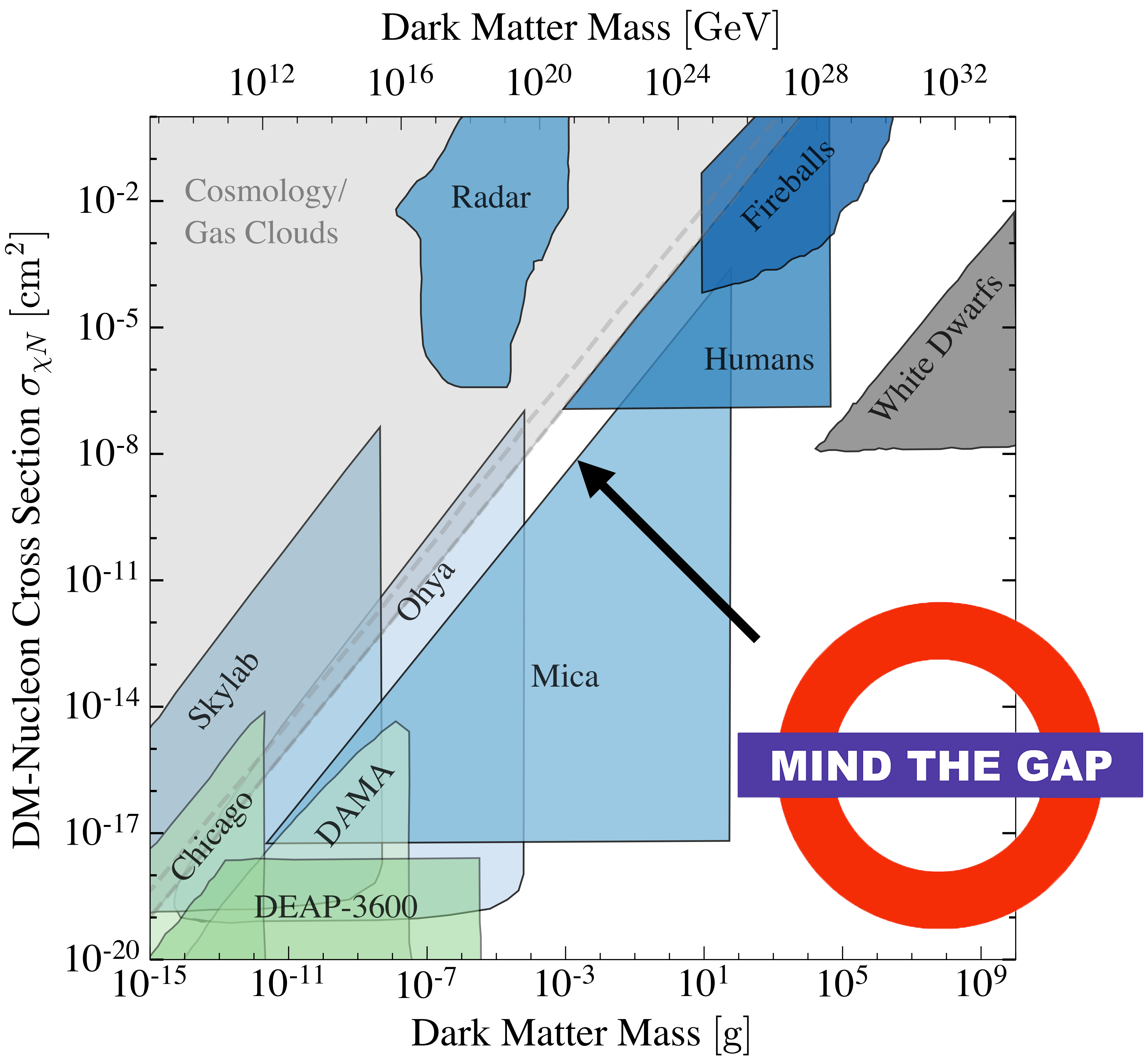
Total energy after traversing path length L in detector given by:

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

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

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

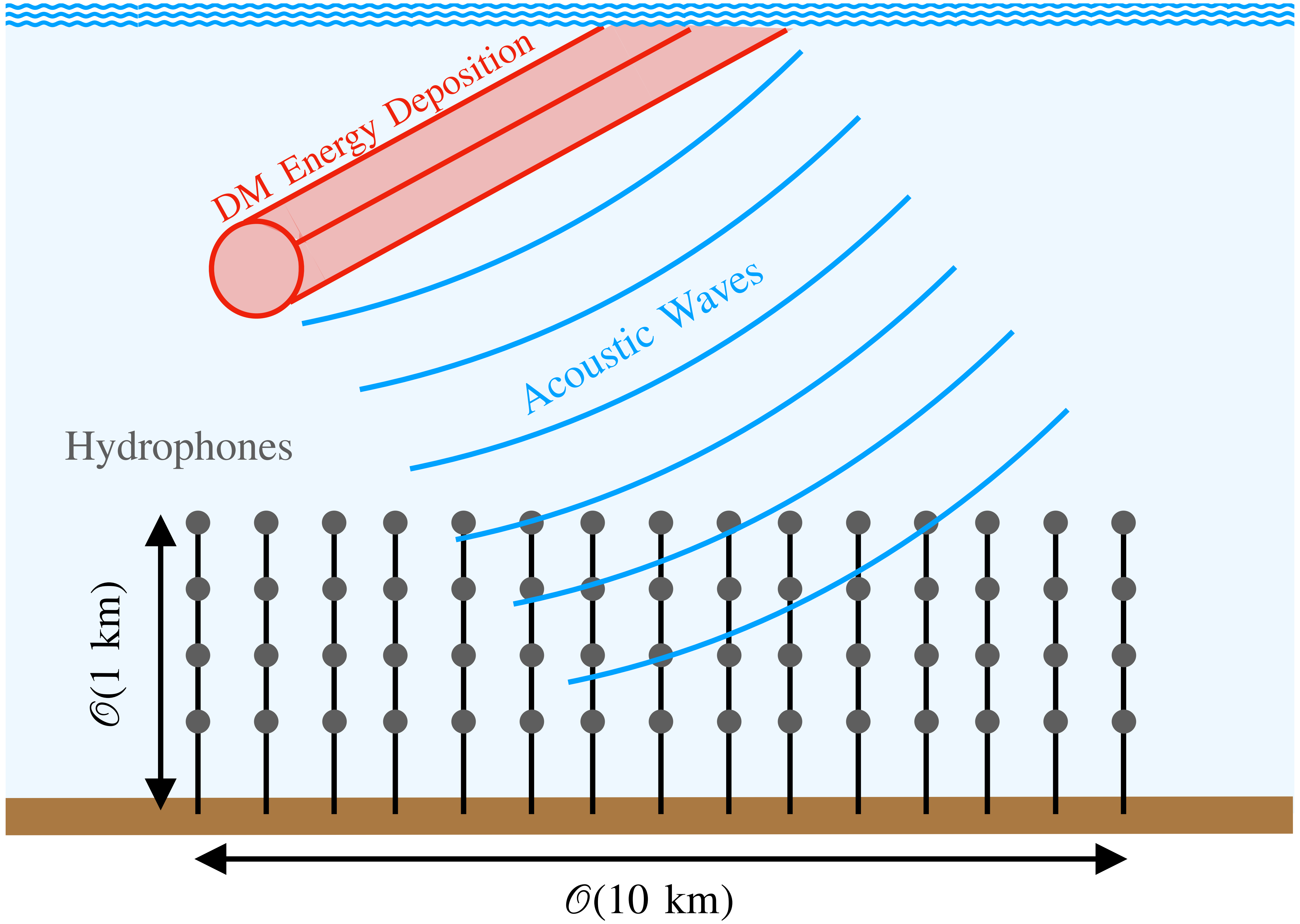
Current Constraints



- 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?**

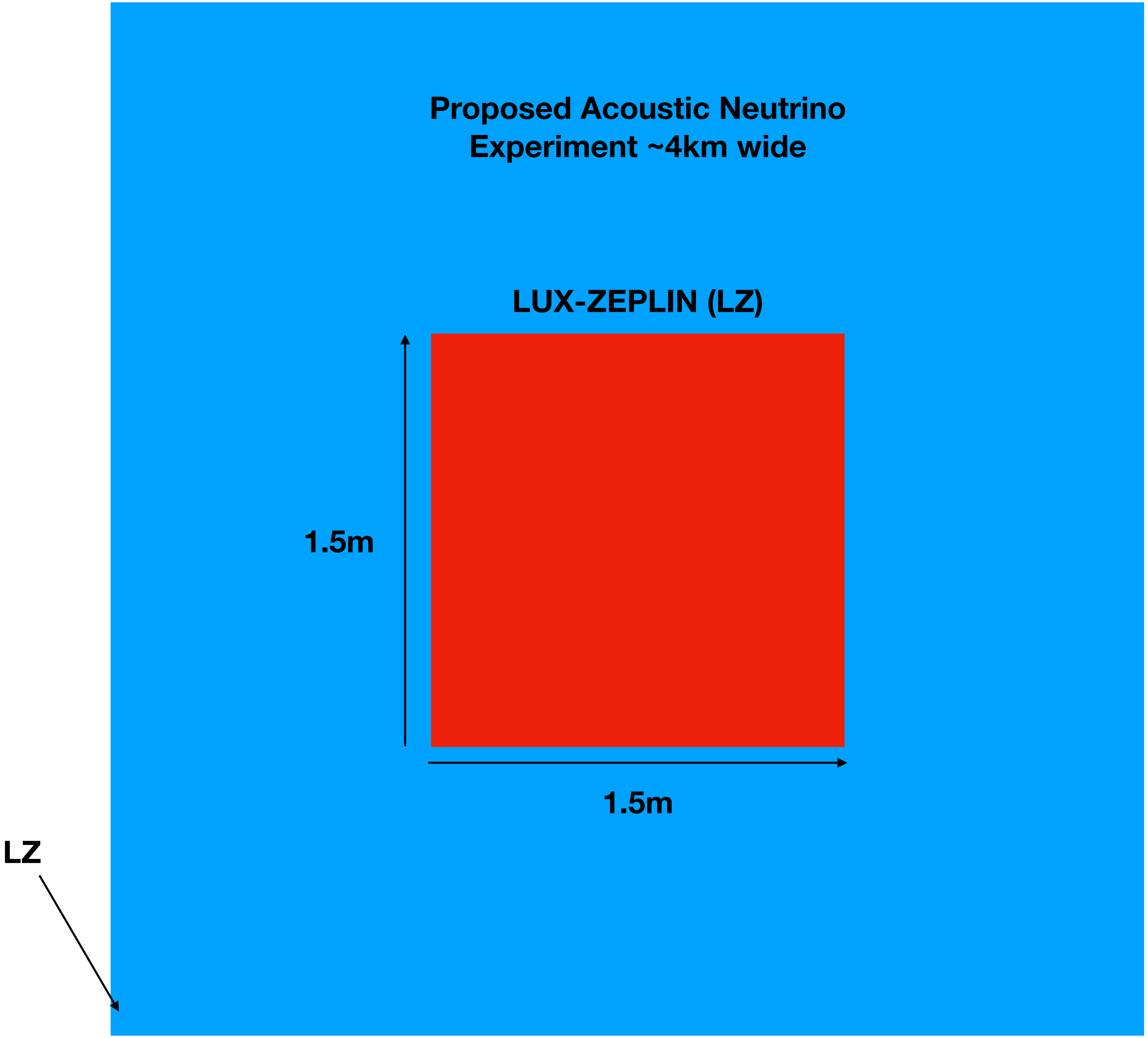
Acoustic Detection

- 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 [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**


Proposed Acoustic Neutrino
Experiment ~4km wide
LUX-ZEPLIN (LZ)
1.5m
1.5m
LZ

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:

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

What is the signal?

Model the **energy deposition as instantaneous**, while **heat dissipation as slow**

$$q(\vec{r},t) = q(\vec{r})\Theta(t-t_0) \implies \partial_t q(\vec{r},t) = q(\vec{r})\delta(t-t_0)$$

Decompose surfaces into **constant propagation time surfaces**

$$\begin{aligned}P(\vec{r},t) &= \frac{\alpha}{4\pi C_p}\int_V \frac{dV'}{|\vec{r}-\vec{r'}|}\frac{\partial}{\partial t}q(\vec{r'})\delta(t'-t_0),\\ &= \frac{c_s^2}{4\pi}\frac{\alpha}{C_p}\frac{\partial}{\partial R}\int_{S_{\vec{r}}^{R_{t_0}}}\frac{dS'}{R_{t_0}}q(\vec{r'}),\end{aligned}$$

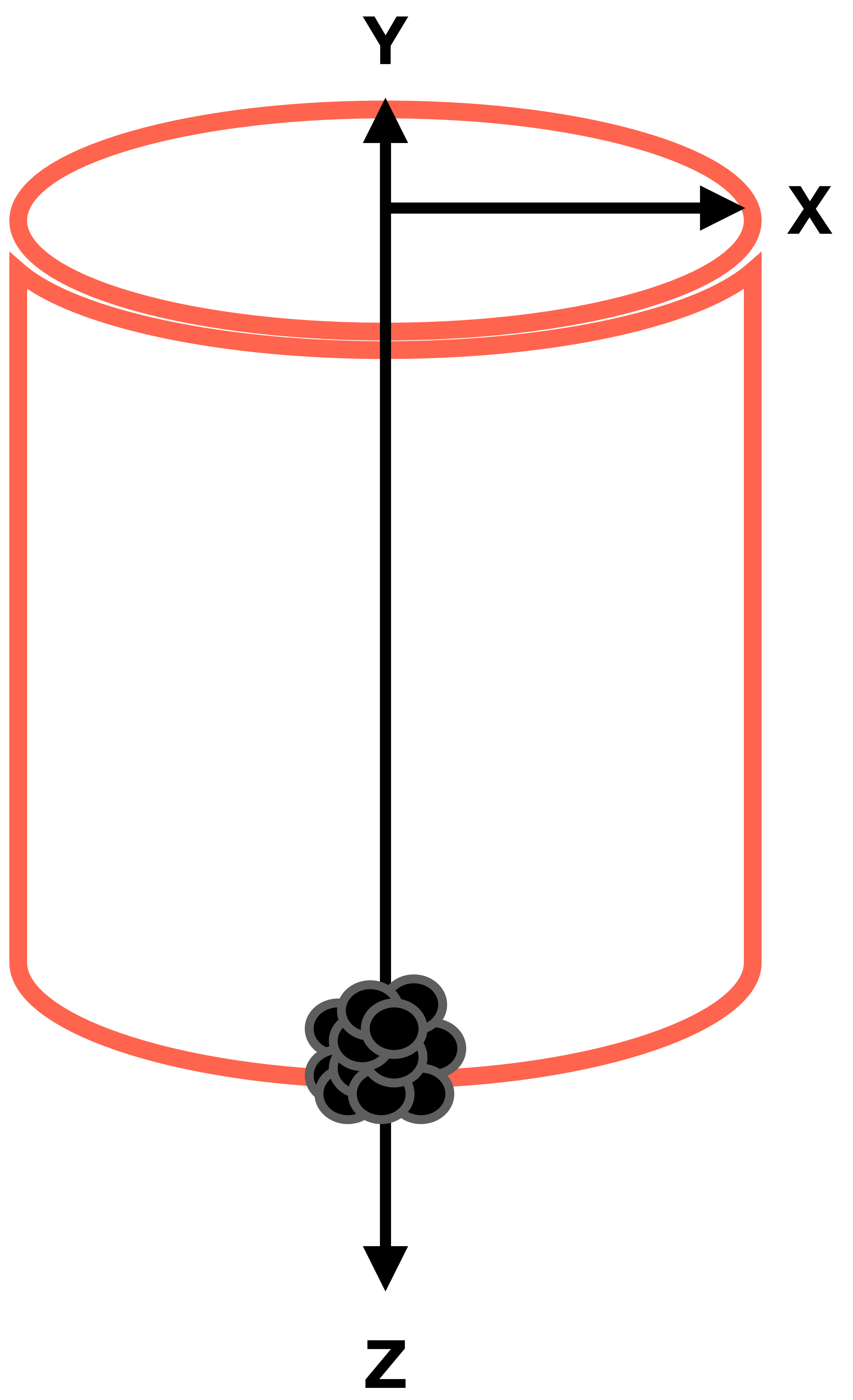
What is the signal?

Model energy deposition rate as:

$$q(x,y,z) = \frac{dE_w}{dz} \frac{1}{(\lambda\sqrt{2\pi})^2} \exp\left(-\frac{1}{2}\frac{x^2+y^2}{\lambda^2}\right)$$

Substituting macro result for dE/dz

$$q(x,y,z) = \frac{\rho_w \sigma_{\chi N} v_{\chi i}^2}{(\lambda\sqrt{2\pi})^2} \exp\left(-\frac{1}{2}\frac{x^2+y^2}{\lambda^2} - 2\frac{\sigma_{\chi N}}{m_\chi}\rho_w z\right)$$



What is the signal?

In far field, spherical surfaces approximated as y-z planes

What is the Signal?

Solving in this case we find the following time-domain signal:

$$P(x_0 \vec{e_x}, t) = -\frac{\gamma_G}{4\pi x_0} \frac{\Delta E_\chi}{\sqrt{2\pi}} \frac{c_s t}{\lambda^3} \exp\left(-\frac{1}{2}\frac{(c_s t)^2}{\lambda^2}\right)$$

Which has frequency content (Fourier transform)

$$\tilde{P}(\omega) = i\omega \frac{\gamma_G}{4\pi c_s^2} \frac{\Delta E_\chi}{r_0} \exp\left(-\frac{\lambda^2 \omega^2}{2 c_s^2}\right)$$

Noise and Transmission Loss

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:

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

Time Domain

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

Frequency Domain

$$P_{\rm ref} = 1\mu{\rm Pa/Hz}$$

Transmission Loss

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

$$TL = \alpha r$$

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

[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**

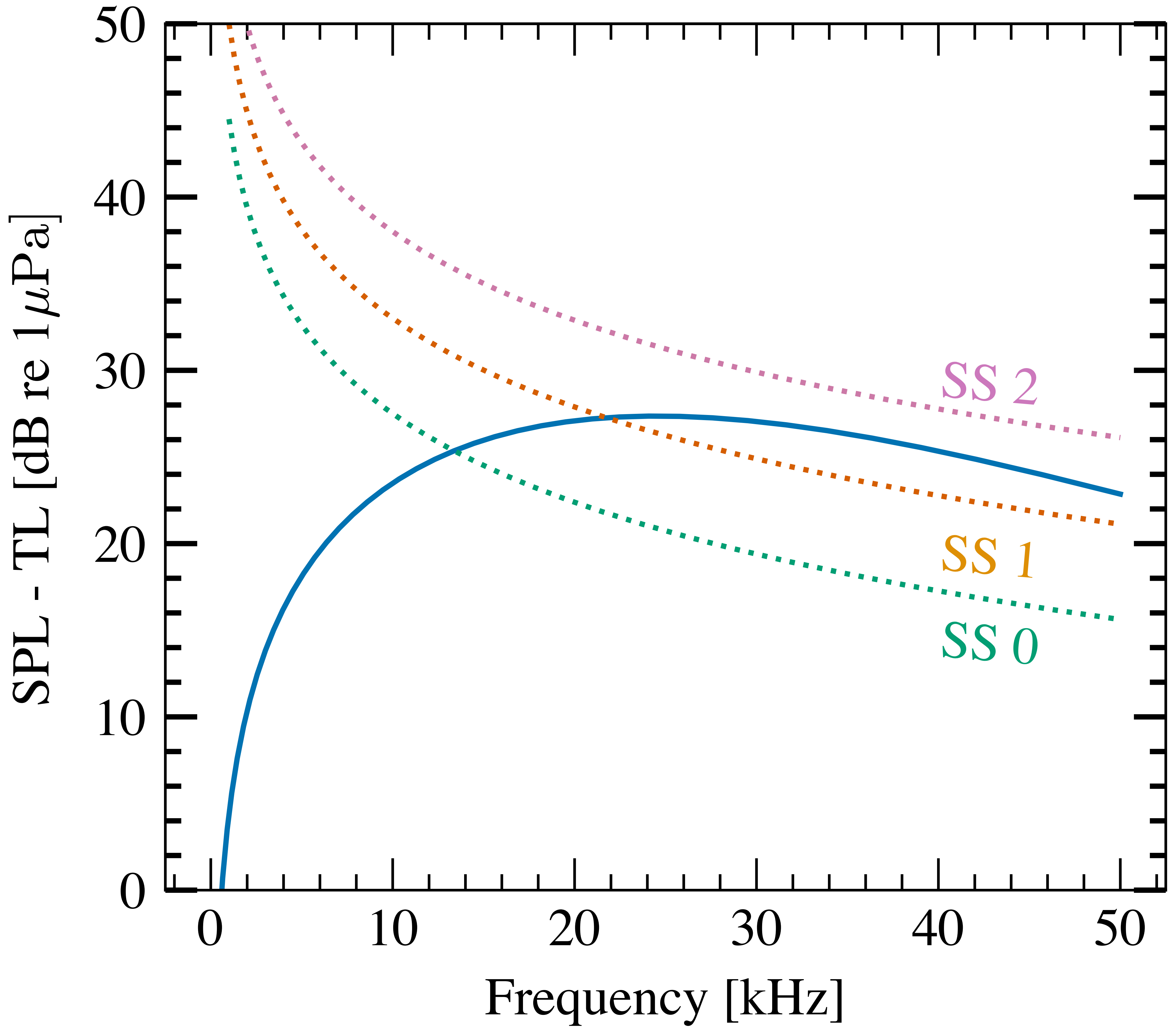
Sea State Noise

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

$$NL(f, n_s) = n_s - 17\log_{10}(f)$$

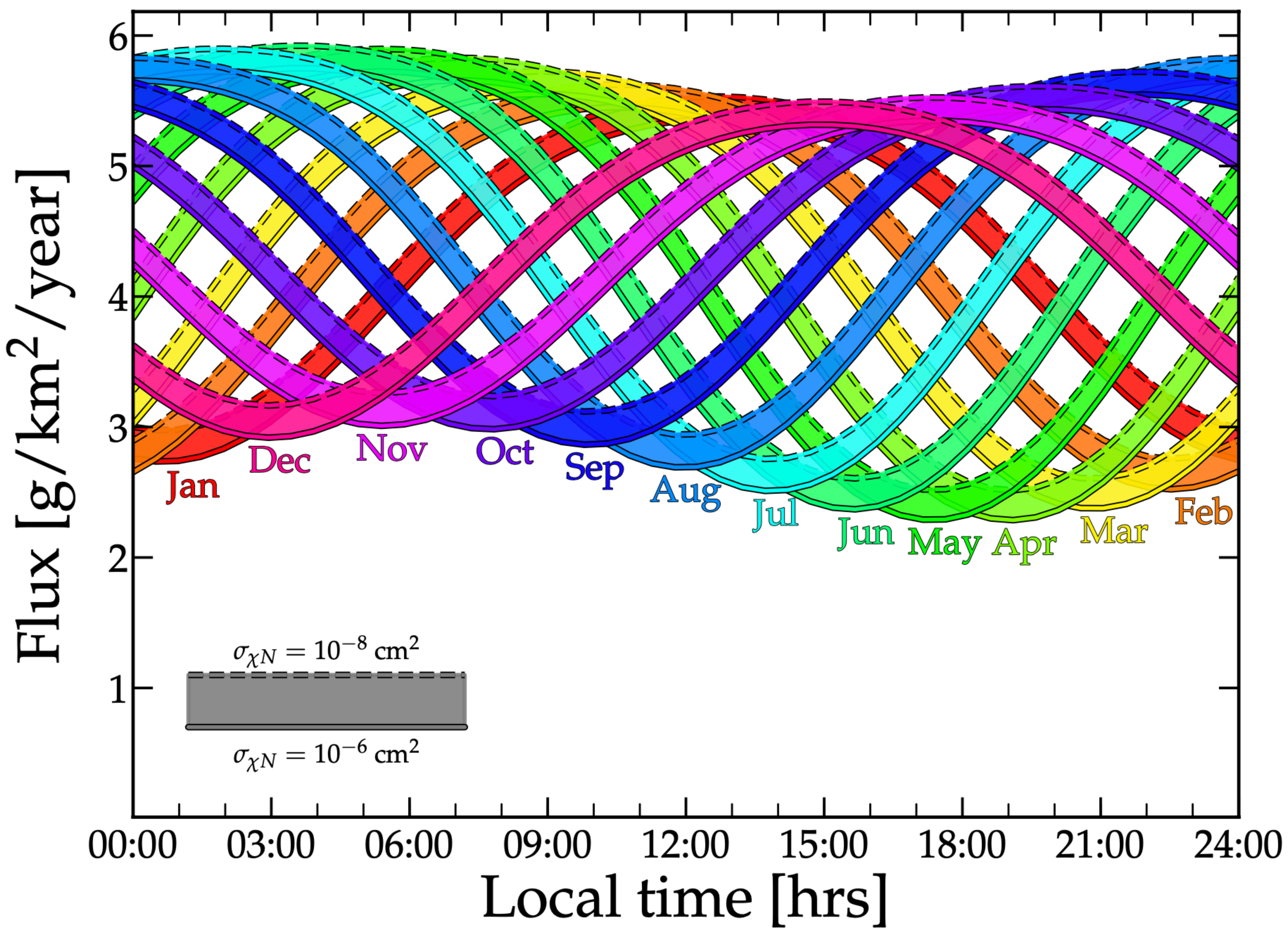
There will also be transient noise sources from ocean wildlife e.g. dolphins and sperm wales. **Assume differentiable from DM signal** using algorithms being developed for neutrino detection.

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)**

Discerning Neutrinos from DM

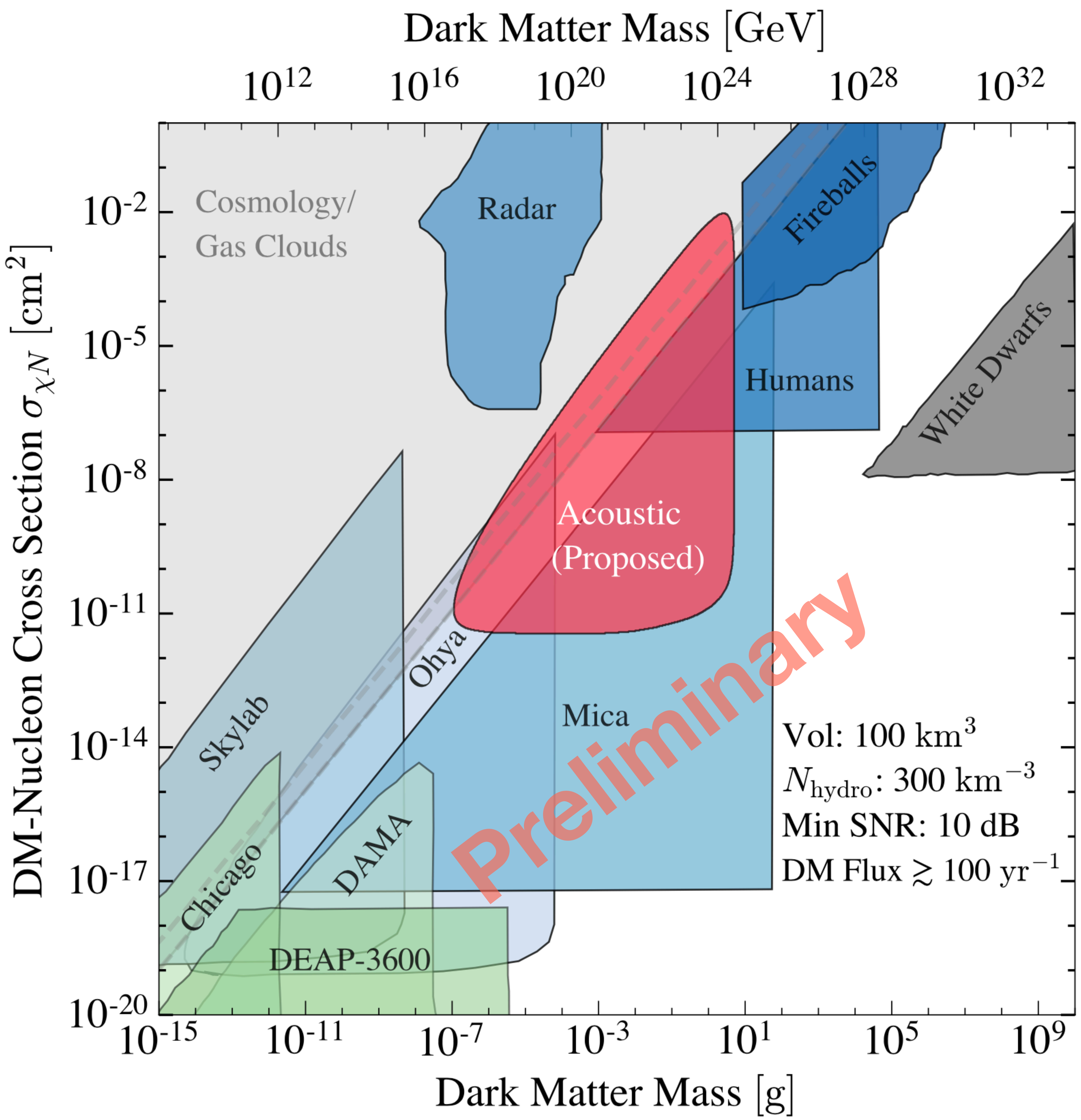


- DM is **galactic** in origin. Neutrinos are **extragalactic.**
- Direction of dark matter in the direction of the Cygnus constellation.
- So UHDM flux modulates
- Varies throughout the year due to following the sidereal day over solar day

Constraint Recipe

- Assume DM cross section and mass
- Impose SNR requirement, hydrophone sensitivity and flux requirement
- Assume array of particular geometry (volume, cross sectional area, hydrophone density)
- Enhance signal by $\sqrt{N_{\rm hydro}}$ (Poisson statistics)
- If DM signal amplitude fulfils criteria, **CONSTRAIN!**

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 have the power to constrain macro DM candidates

Thank you for listening!
Any Questions?