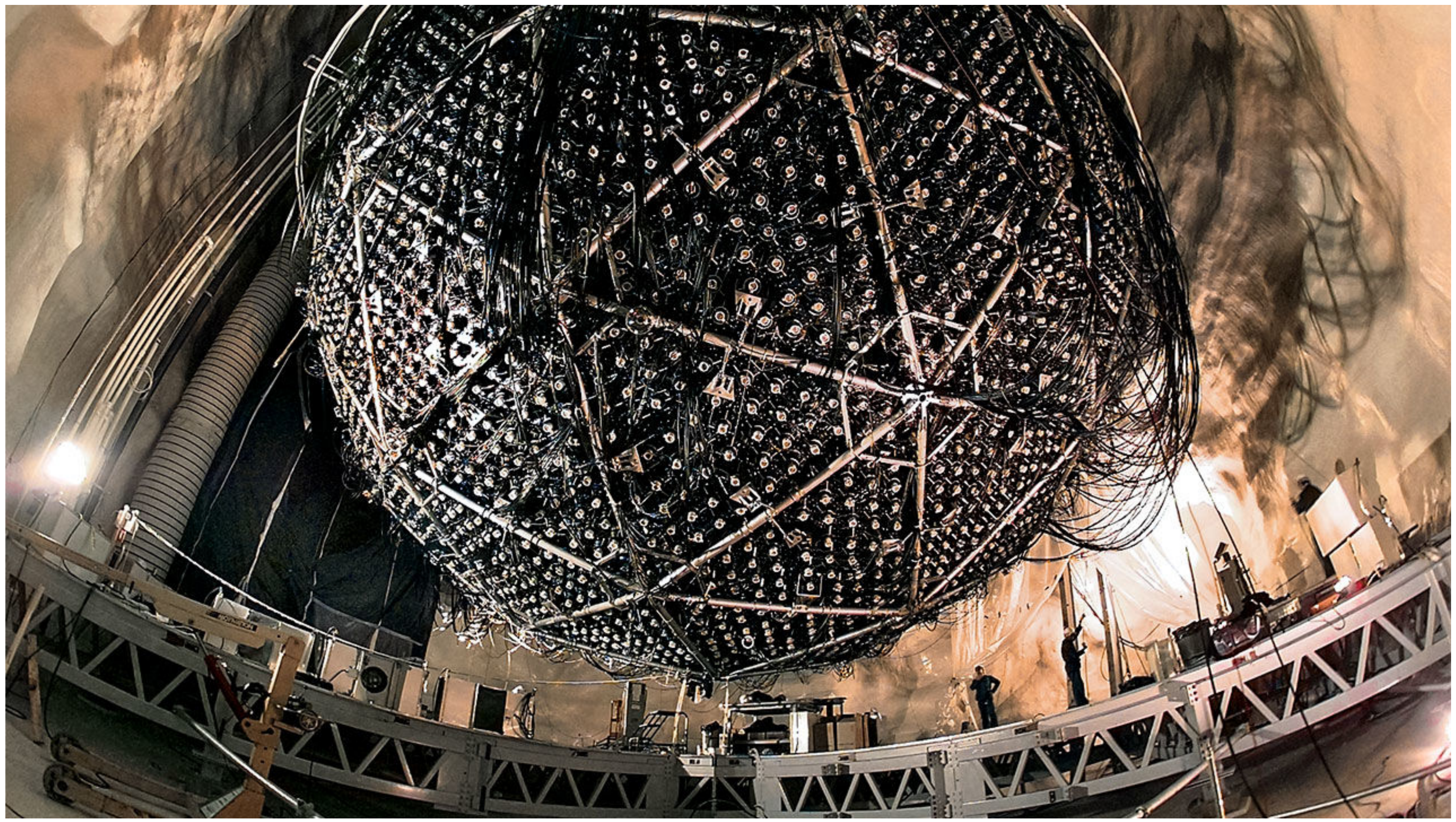
Axion searches with neutrino experiments



Nick Houston, Beijing University of Technology

International Conference on Neutrinos and Dark Matter, Sharm El-Sheik, 2022/09

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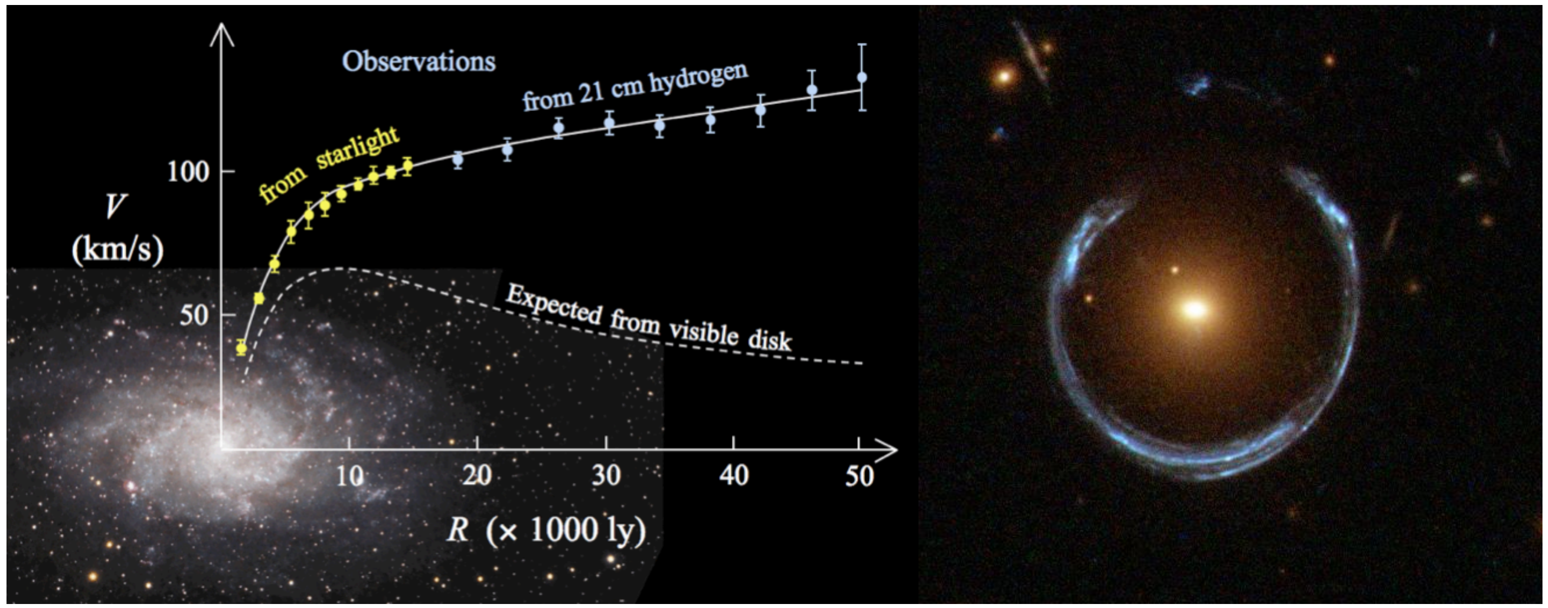
The big picture

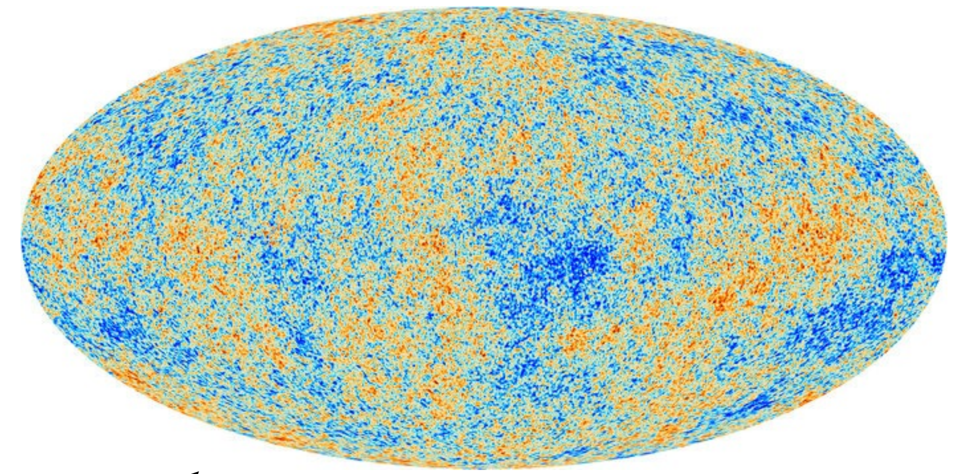


- Good evidence exists for physics beyond the Standard Model. We can and should build dedicated experiments to search for it
- However, if we are smart we can also search ‘for free’ by repurposing existing facilities and results
- This talk is about the similarities between neutrinos and axions, and their corresponding detection possibilities
- In particular we will show how data from the SNO neutrino experiment can be used search for axions coming from the sun

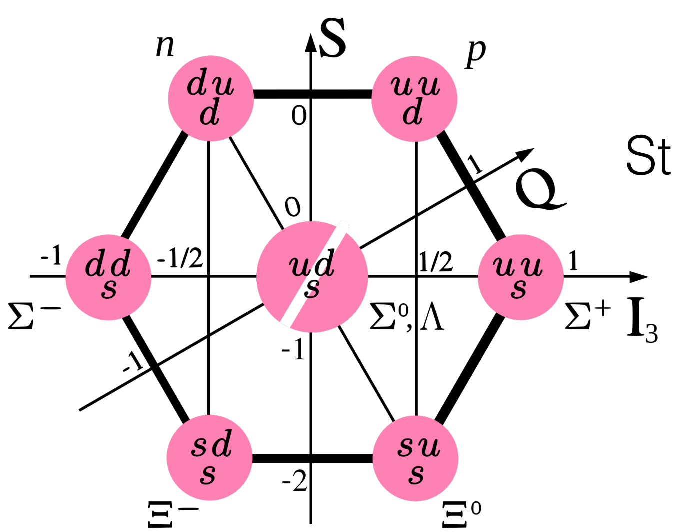
Summary:

Axions are light (presumed sub-eV) pseudo-Goldstone bosons, characterised broadly by their mass and an overall scale f

They arise both as a minimal extension of the Standard Model, to solve the Strong CP problem, whilst also being a generic prediction of the exotic physics of string and M theory

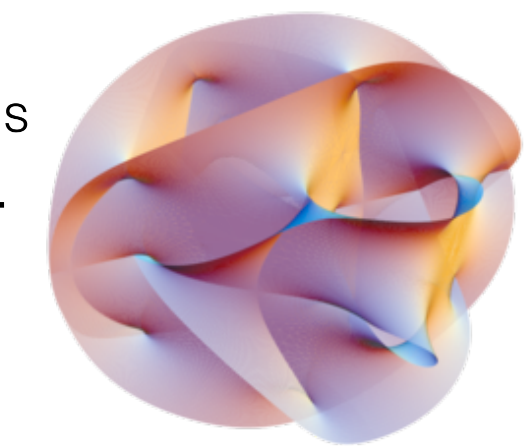


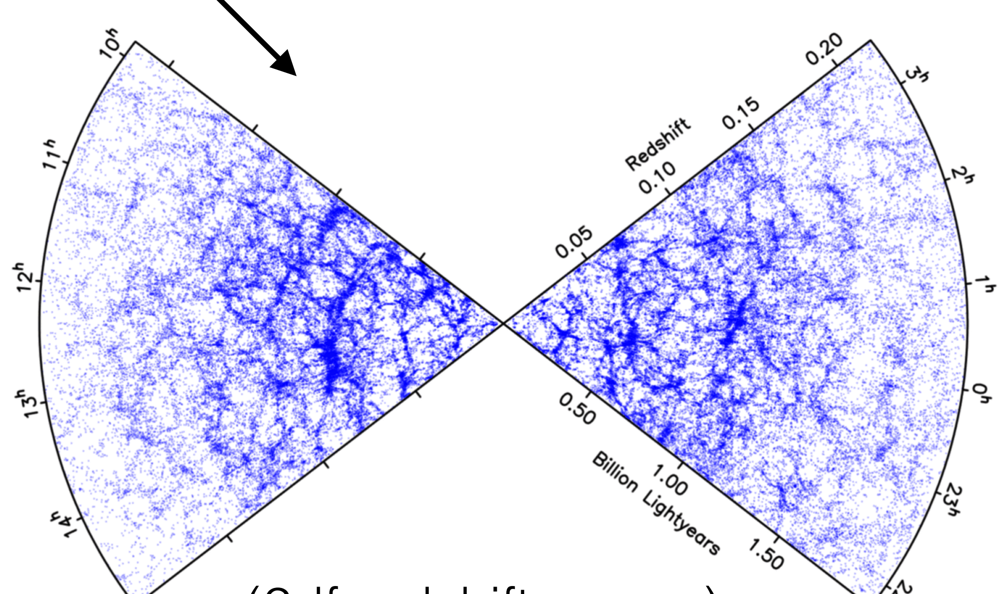
(Planck 2015)



Strong CP problem

Compactifications

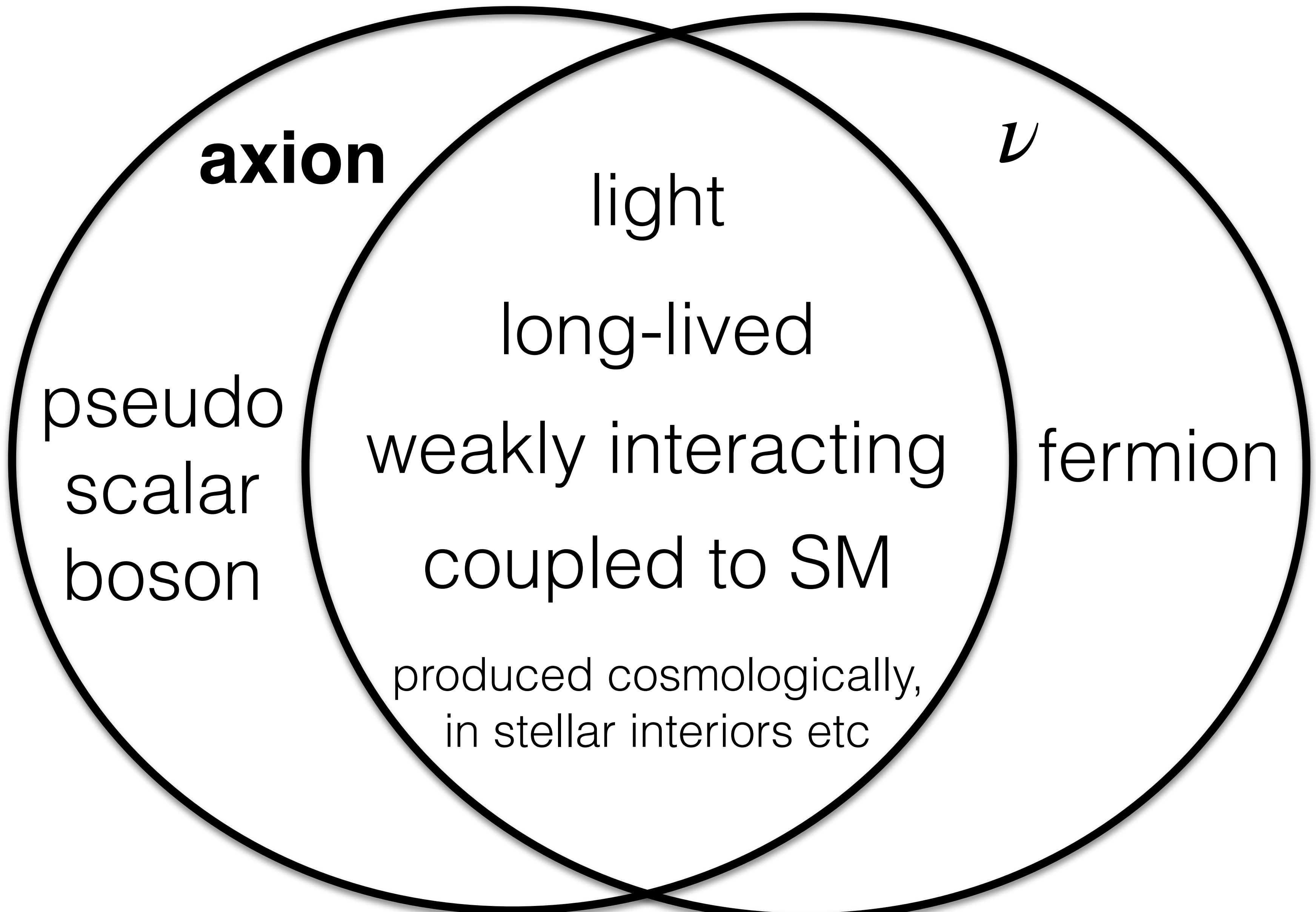




(2df redshift survey)

In turn they can affect:
early Universe cosmology, inflation,
big bang nucleosynthesis, CMB formation,
dark matter, dark energy, stellar evolution,
galaxy formation, large scale structure…

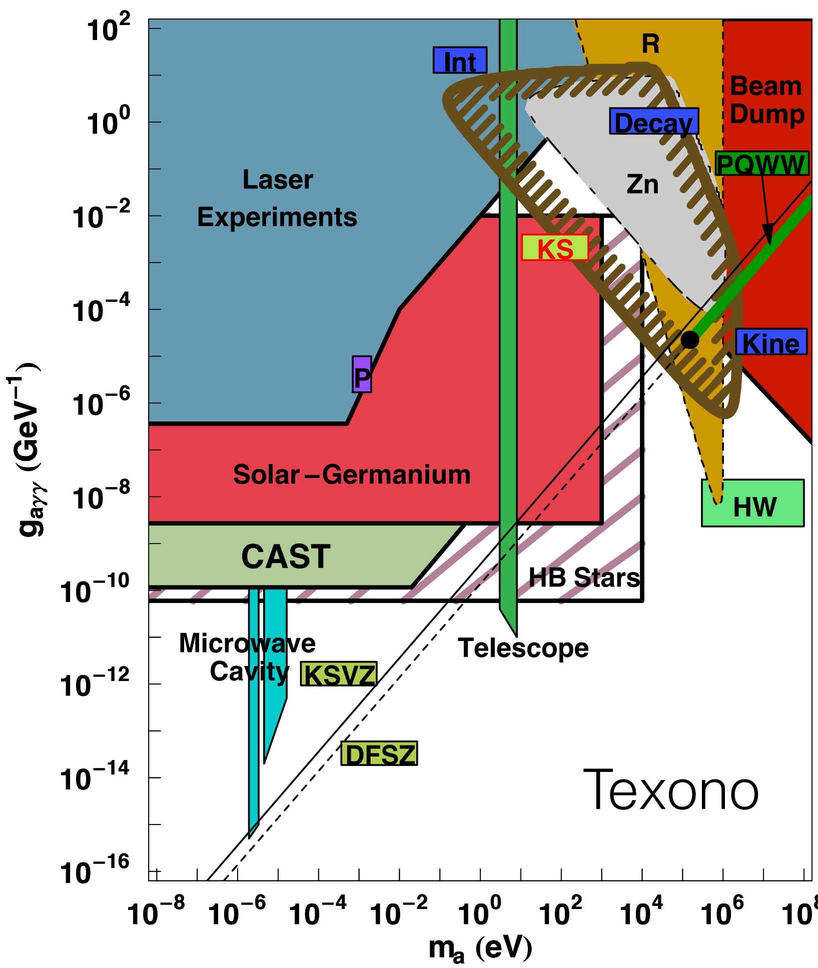
Axions vs neutrinos

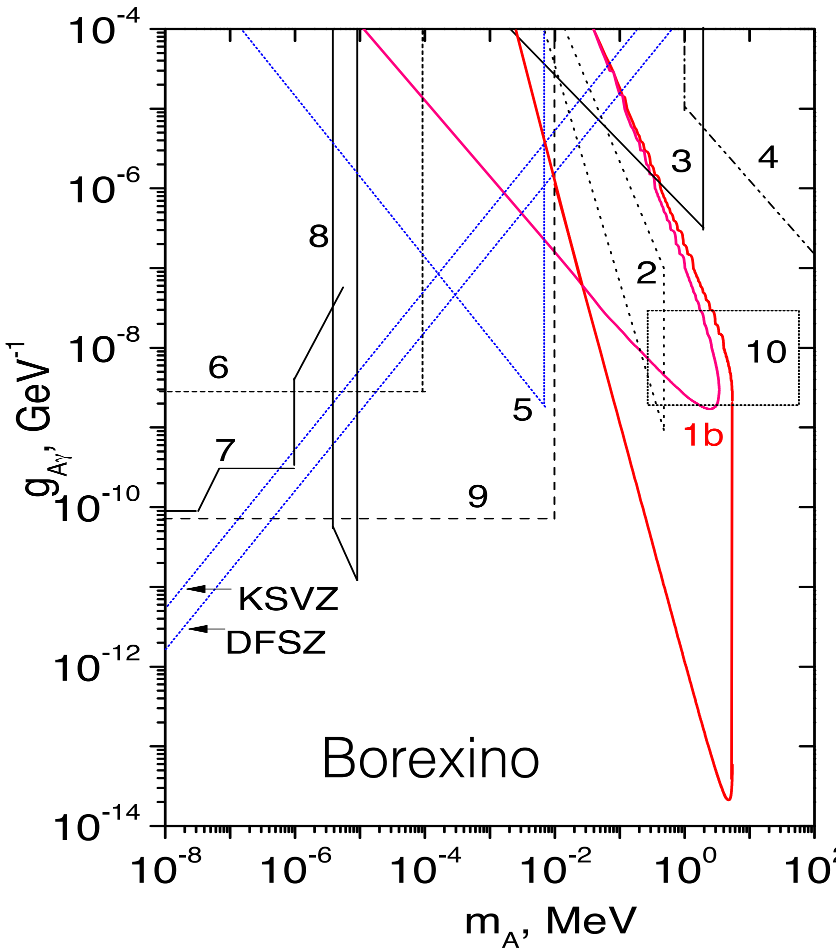


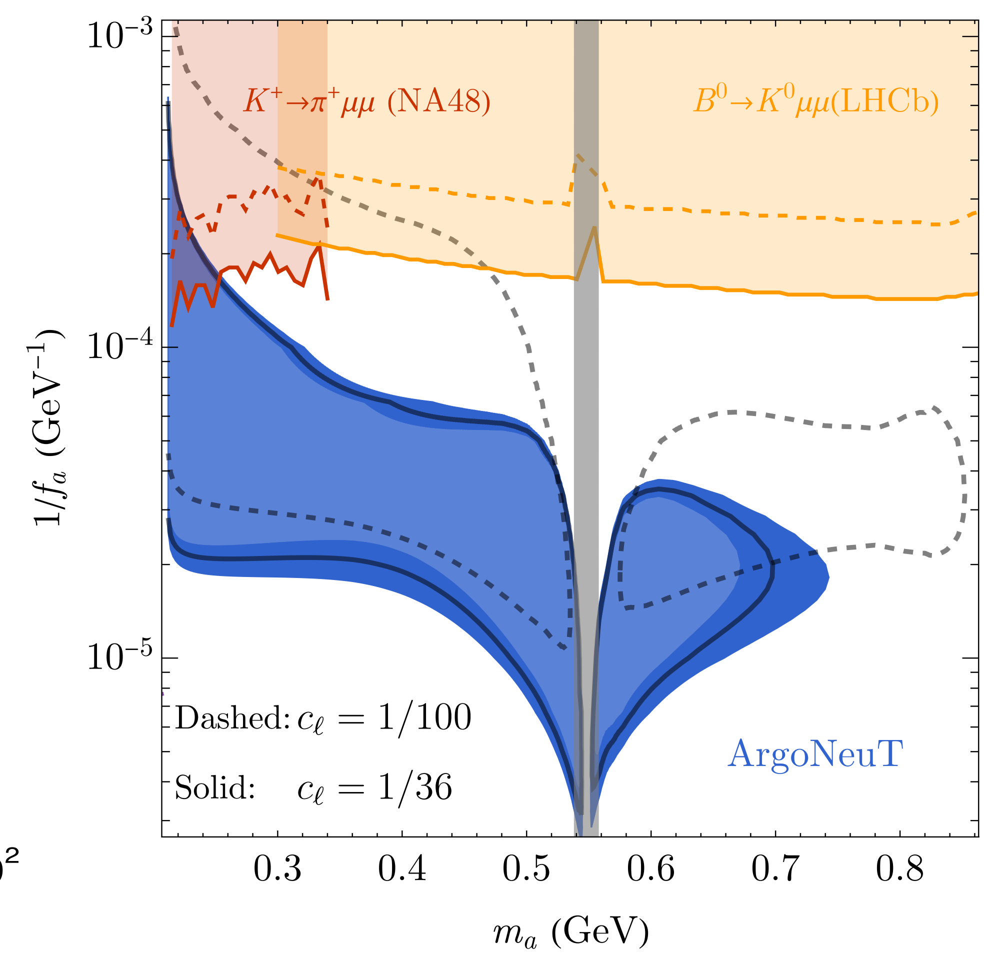
ν experiments with (some combination of) large exposure, low background, low energy threshold can be well suited to axion discovery

Notable mentions: Texono, Borexino, ArgoNeuT

- There has already been some progress in this direction using data from: Texono (hep-ex/0609001), Borexino (1203.6258), ArgoNeuT (2207.08448)





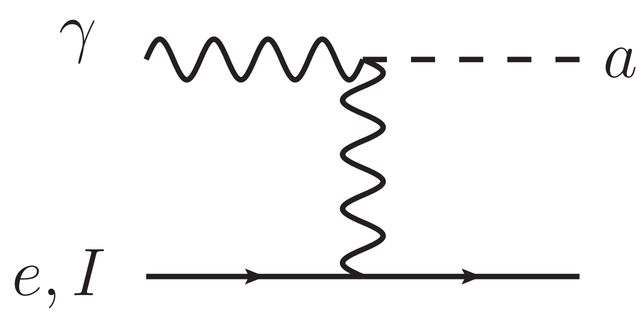


- The overview paper “Axionlike particles searches in reactor experiments” by Sierra et al (2010.15712) also merits attention

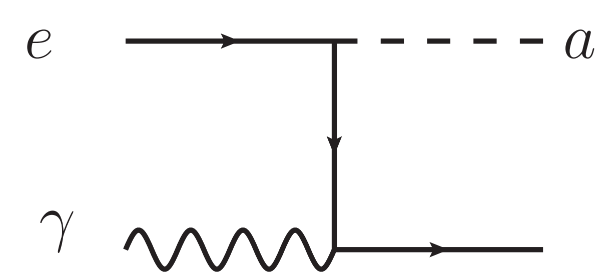
(Apologies to anyone I have missed here!)

Notable mentions: Texono, Borexino, ArgoNeuT

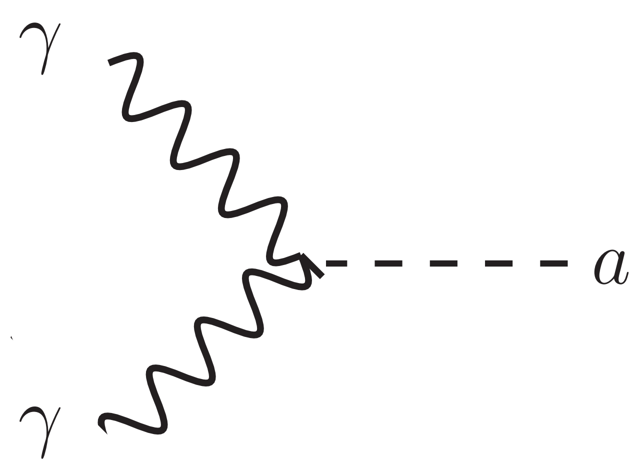
- Generally, these searches rely on some of the ‘classic’ axion detection channels



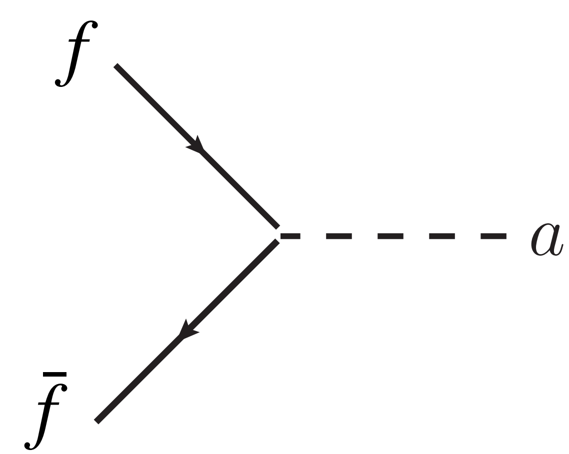
Primakoff



Compton-like



Decay to 2 photons



Decay to lepton pairs

- Other notable channels include the analogue of the photo-electric effect $a + e^- + Z \to e^- + Z$, and nuclear excitation via $a + N \to N^* \to N + \gamma$

Can we do better?

- Let's look at processes which directly mimic ν interactions, such as:

$$a + d \to n + p$$

$$\nu_x + d \to n + p + \nu_x$$

- In this way, the sensitivity of certain neutrino experiments is guaranteed
- In *Phys.Rev.Lett.* 126 (2021) 9, 091601, 2004.02733, Aagaman Bhusal, Tianjun Li and I explored how data from the Sudbury Neutrino Observatory can then be used to perform a novel axion search
- Let's take a closer look at this

‘Axiodissociation’

- Axions can drive the isovector M1 (magnetic dipole) process

$$a + d \to n + p$$

- We calculated the interaction cross section:

$$\sigma = \frac{2}{3}(g_{aN}^{3})^2 m_n \sqrt{E_a^2 - m_a^2}\,\frac{|\vec{k}|\alpha}{(k^2+\alpha^2)^2}\,\frac{(1-\alpha a_s)^2}{1+k^2 a_s^2}$$

$$|\vec{k}| = \sqrt{m_n(E_a - E_D)}\,, \quad \alpha = \sqrt{m_n E_D}$$

2.2 MeV deuterium binding energy

-23.7 fm singlet scattering length

$$\mathscr{L} = \frac{1}{2} g_{an}\partial_\mu a\,\bar{n}\gamma^\mu\gamma_5 n + \frac{1}{2} g_{ap}\partial_\mu a\,\bar{p}\gamma^\mu\gamma_5 p\,, \qquad g_{aN}^{3} \equiv \tfrac{1}{2}(g_{an} - g_{ap})$$

Are we the first to notice this possibility?

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well below current theoretical or experimental uncertainties.[14]

(3) The absence of a spike at the upper end of the pion spectrum in searches for $K^+ \to \pi^+ \nu\bar{\nu}$ gives an upper limit[15] of 1.2×10^{-6} on the ratio $(K^+ \to \pi^+ a^0)/(K^+ \to \pi^+ \pi^0)$. This is safely larger than the ratio $\xi^2 \sim 4\times10^{-8}$ expected if $K^+ \to \pi^+ a^0$ proceeds through π^0-a^0 mixing. However, the axion can also be

Further, about one-tenth of the axions would be above threshold for the reaction $a^0 + d \to p + n$, with cross section of order $[4\xi^2 G_{\pi N}^2/4\pi\alpha(2.79+1.91)^2] \times \sigma_{M1}(\gamma + d \to p + n)$, or 5×10^{-33} cm^2. Thus with 178 kg of D_2O and an efficiency of 0.043, there should have been about 4×10^5 neutron counts/day, as compared with a measured reactor-associated rate[17] of (-2.9 ± 7.2)/day.

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Perhaps you recognise the author

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A New Light Boson?

Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

(Received 6 December 1977)

It is pointed out that a global U(1) symmetry, that has been introduced in order to preserve the parity and time-reversal invariance of strong interactions despite the effects of instantons, would lead to a neutral pseudoscalar boson, the "axion," with mass roughly of order 100 keV to 1 MeV. Experimental implications are discussed.

The Sudbury Neutrino Observatory

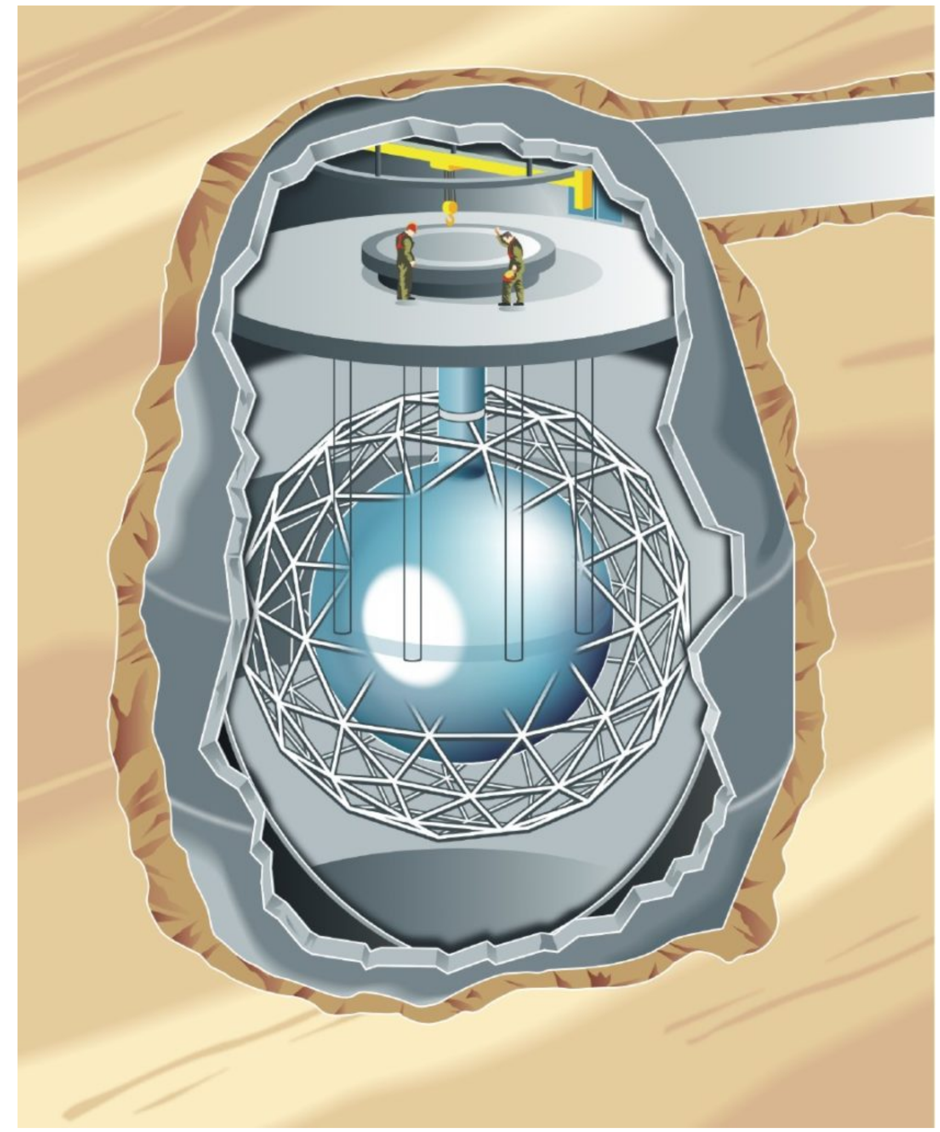
- A water Cherenkov neutrino telescope 2.1 km underground in Ontario, Canada. In operation from 1999 - 2006

- 1 kiloton of (borrowed) heavy water (D_2O) gives sensitivity to the processes

$$\nu_e + d \rightarrow p + p + e$$
$$\nu_x + d \rightarrow n + p + \nu_x$$

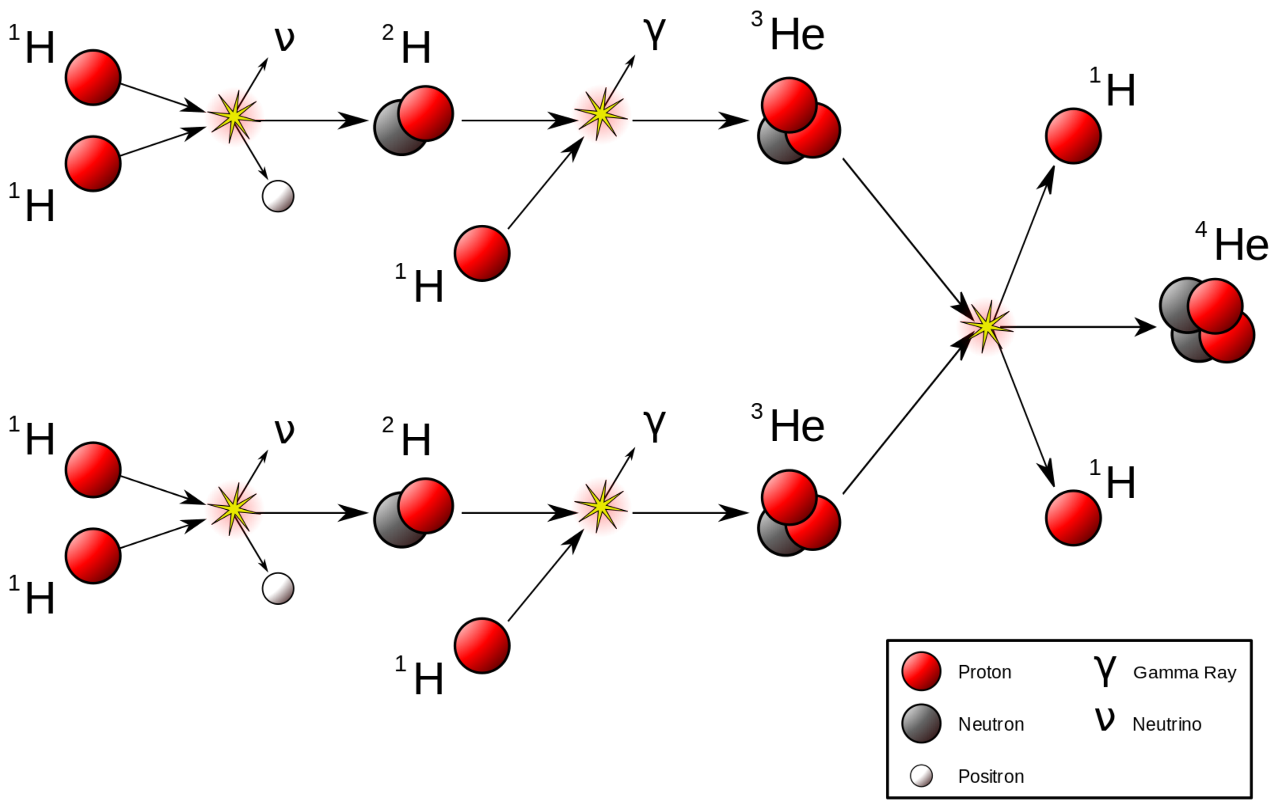
- SNO showed that only 1/3 of the solar neutrinos reaching earth are electron neutrinos, helping to resolve the solar neutrino problem

- What should our axion source be?



(Pictures courtesy of the SNO collaboration)

- Let's consider the proton-proton solar fusion chain:

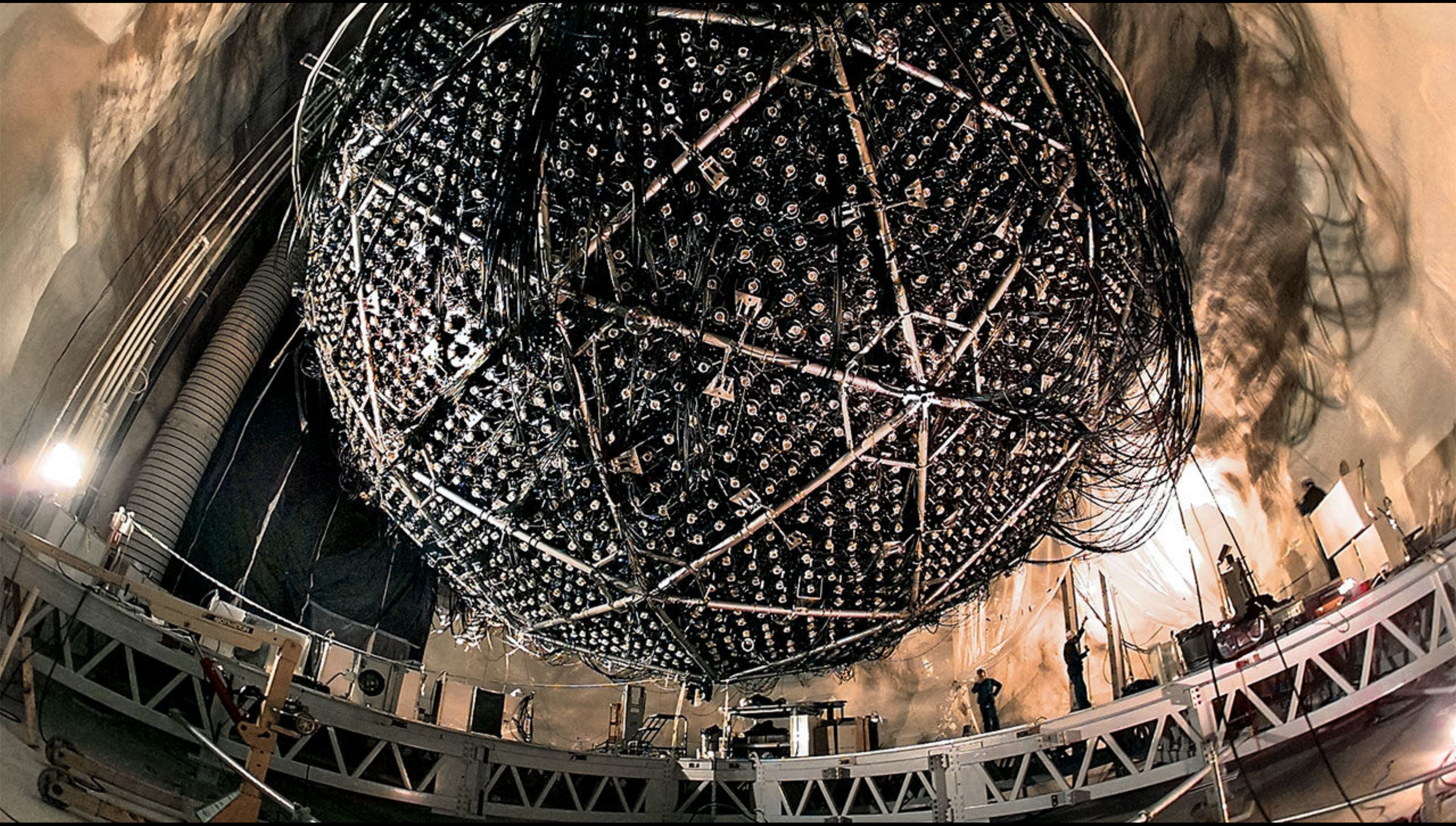


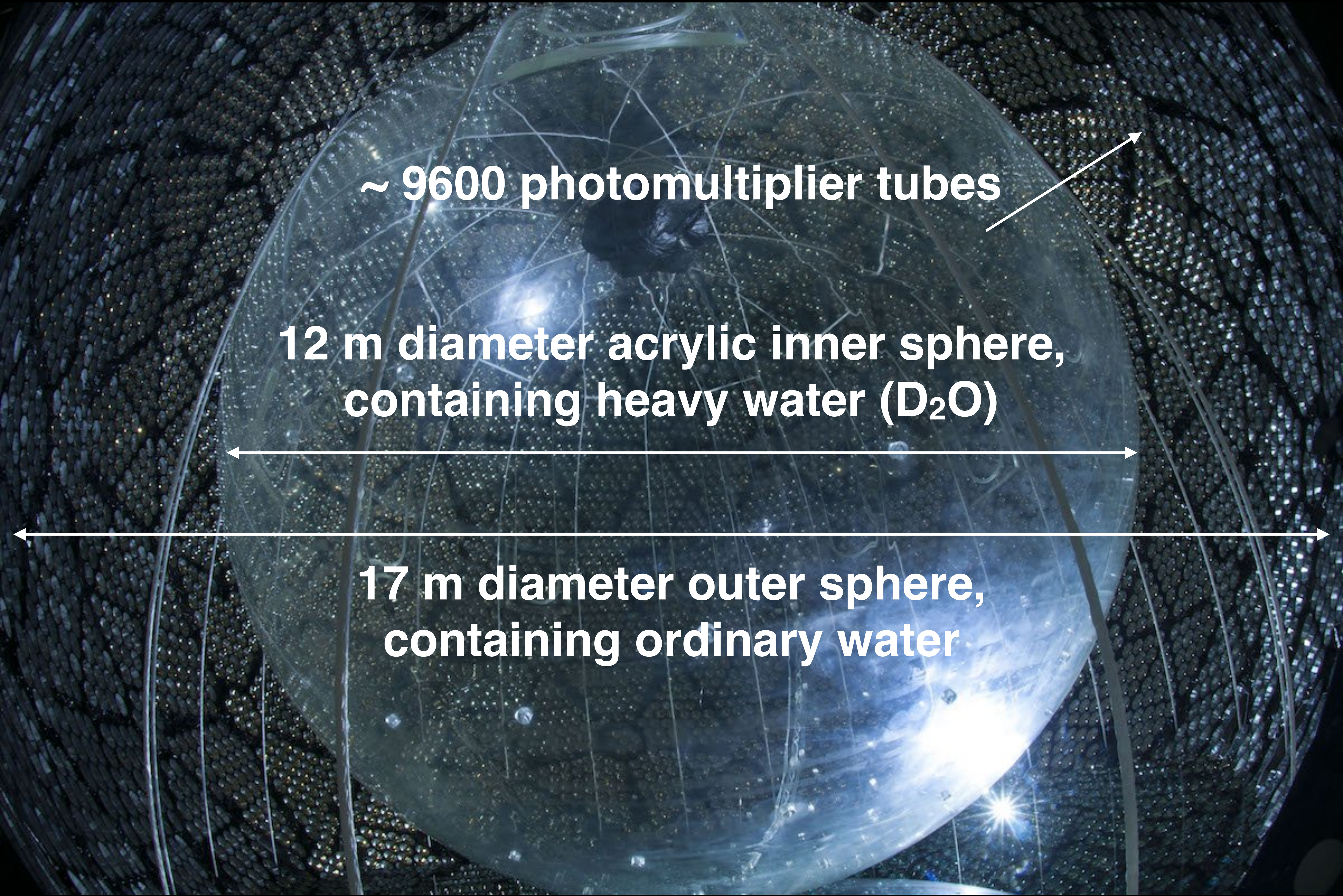
- 2nd stage is the (predominantly) isovector $p + d \rightarrow {}^3\mathrm{He} + a/\gamma\,(5.5\mathrm{MeV})$

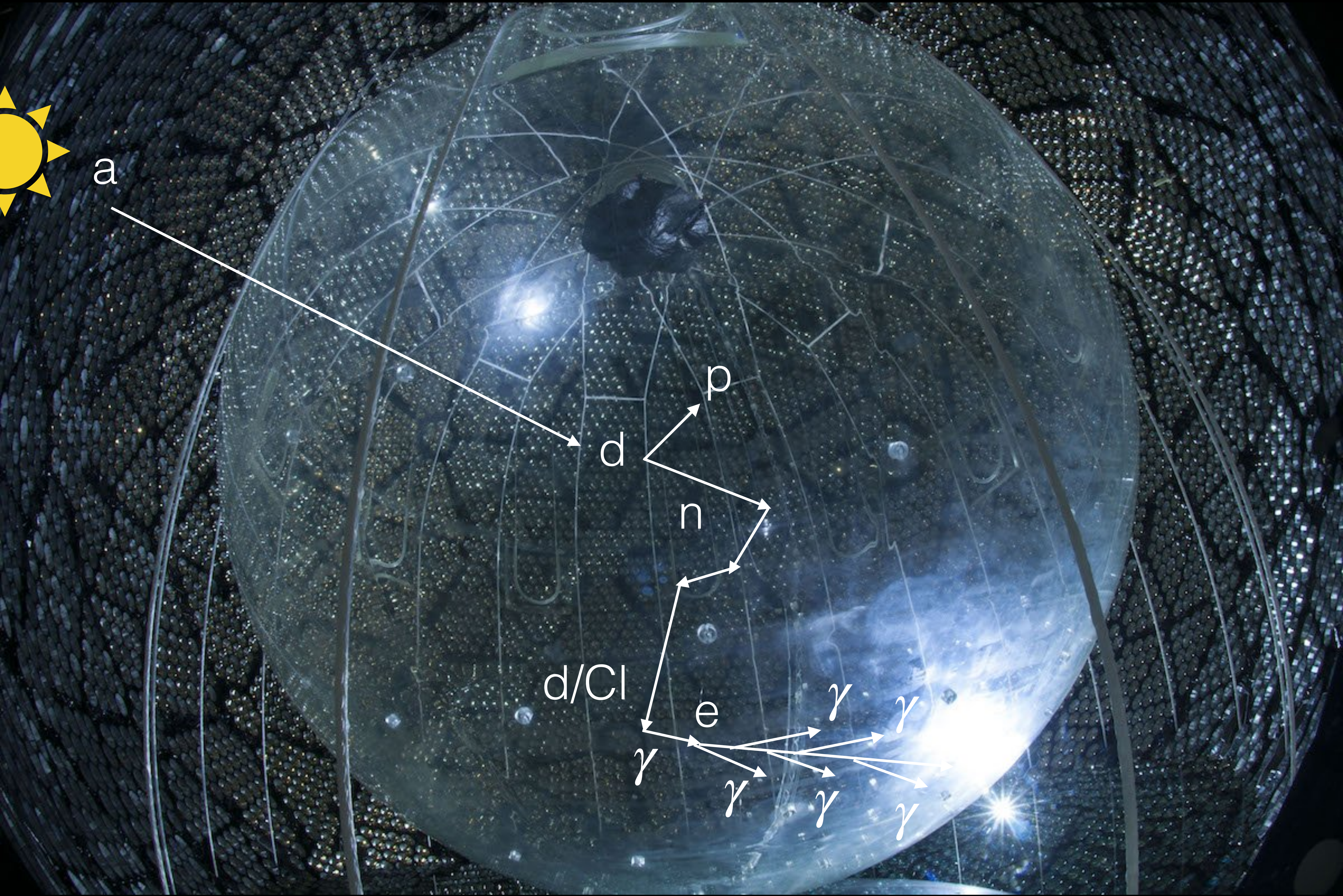
- Normalising to the measured pp neutrino flux gives the axion flux at Earth:

$$\phi_a \simeq 3 \times 10^{10} m_n^2 (g_{aN}^3)^2 \left(p_a/p_\gamma\right)^3 \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

$$g_{aN}^3 \equiv \tfrac{1}{2}(g_{an} - g_{ap})$$




~ 9600 photomultiplier tubes
12 m diameter acrylic inner sphere, containing heavy water (D_2O)
17 m diameter outer sphere, containing ordinary water



a
p
d
n
d/Cl
e
γ
γ
γ
γ
γ
γ
γ

SNO data

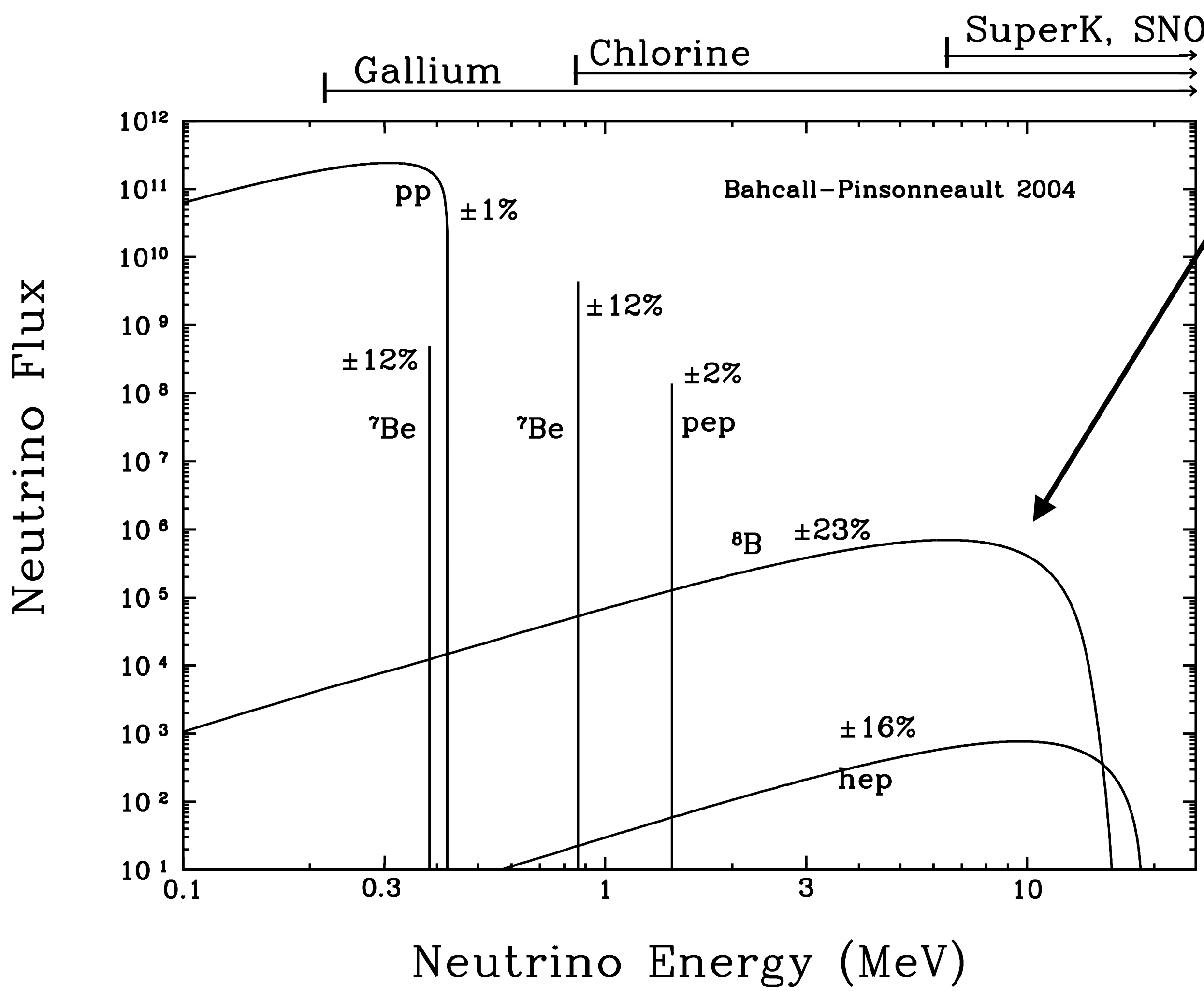
- From the total SNO dataset the ^8B solar neutrino flux is estimated to be

$$\phi_{SNO} = (5.25 \pm 0.20) \times 10^6 \text{cm}^{-2}\text{s}^{-1}$$

SNO collaboration (1109.0763)

- Meanwhile, Solar Standard Models predict

$$\phi_{SSM} = (5.87 \pm 0.44) \times 10^6 \text{cm}^{-2}\text{s}^{-1}$$



This is the neutrino flux driving

$$\nu_x + d \rightarrow n + p + \nu_x$$

However, if we also have

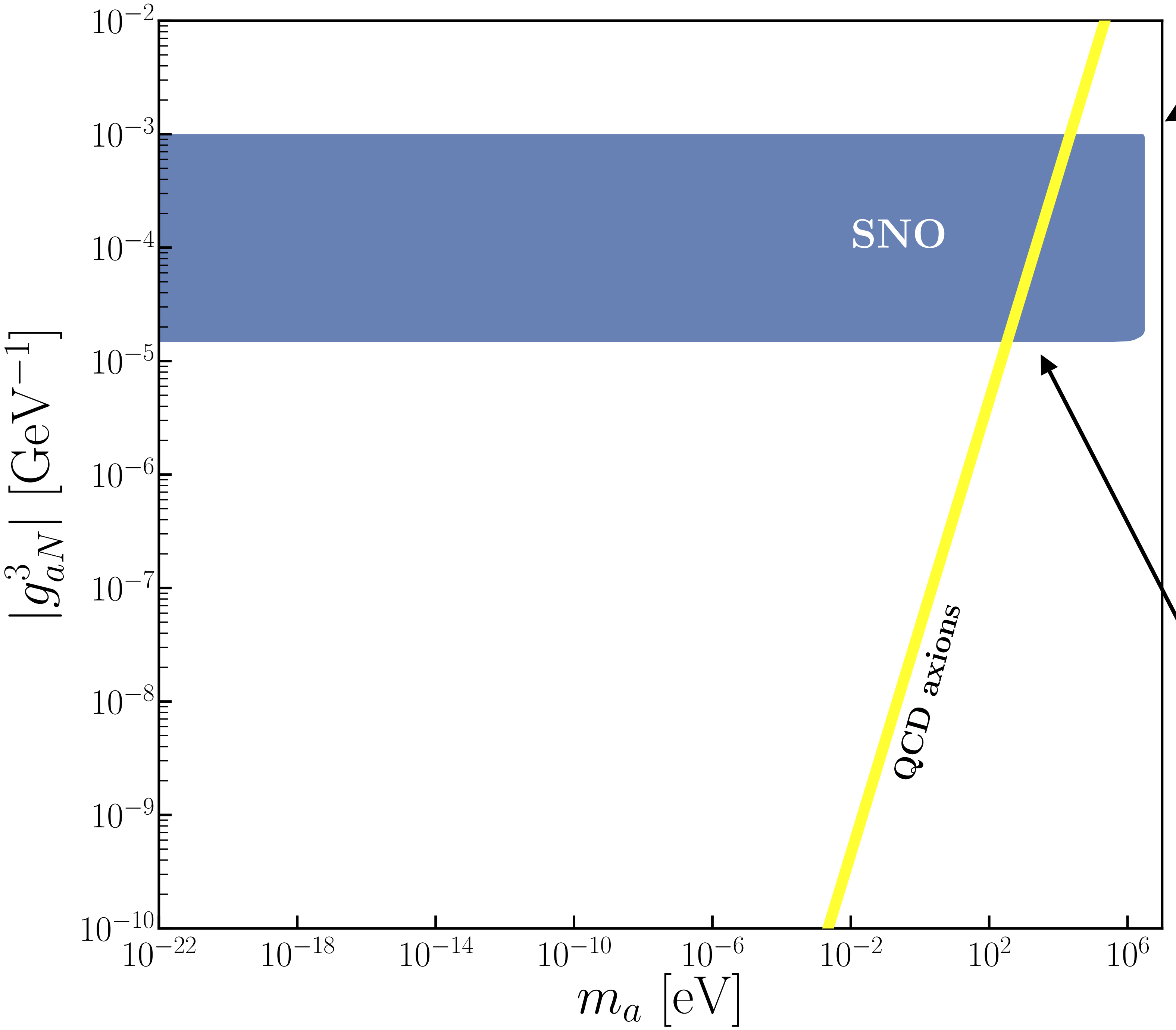
$$a + d \rightarrow n + p$$

SNO will overestimate the number of neutral current events caused by these ^8B neutrinos, by

$$N_{\text{axion events}} = \sigma \phi_a N_d t$$

- **From $\phi_{SNO} - \phi_{SSM}$ we constrain $\sigma \phi_a$, and therefore g_{aN}^3**

Our resulting 95 % CL constraint on $g^3_{aN} \equiv \frac{1}{2}(g_{an} - g_{ap})$



Upper limit from solar trapping

Cuts off at 5.5 MeV, as the solar axion flux vanishes

We exclude QCD axions with g^3_{aN} between 10^{-3} and 2×10^{-5} /GeV.

For e.g. DFSZ with $\cos^2\beta = 1$ this corresponds to masses between 0.3 and 13 keV

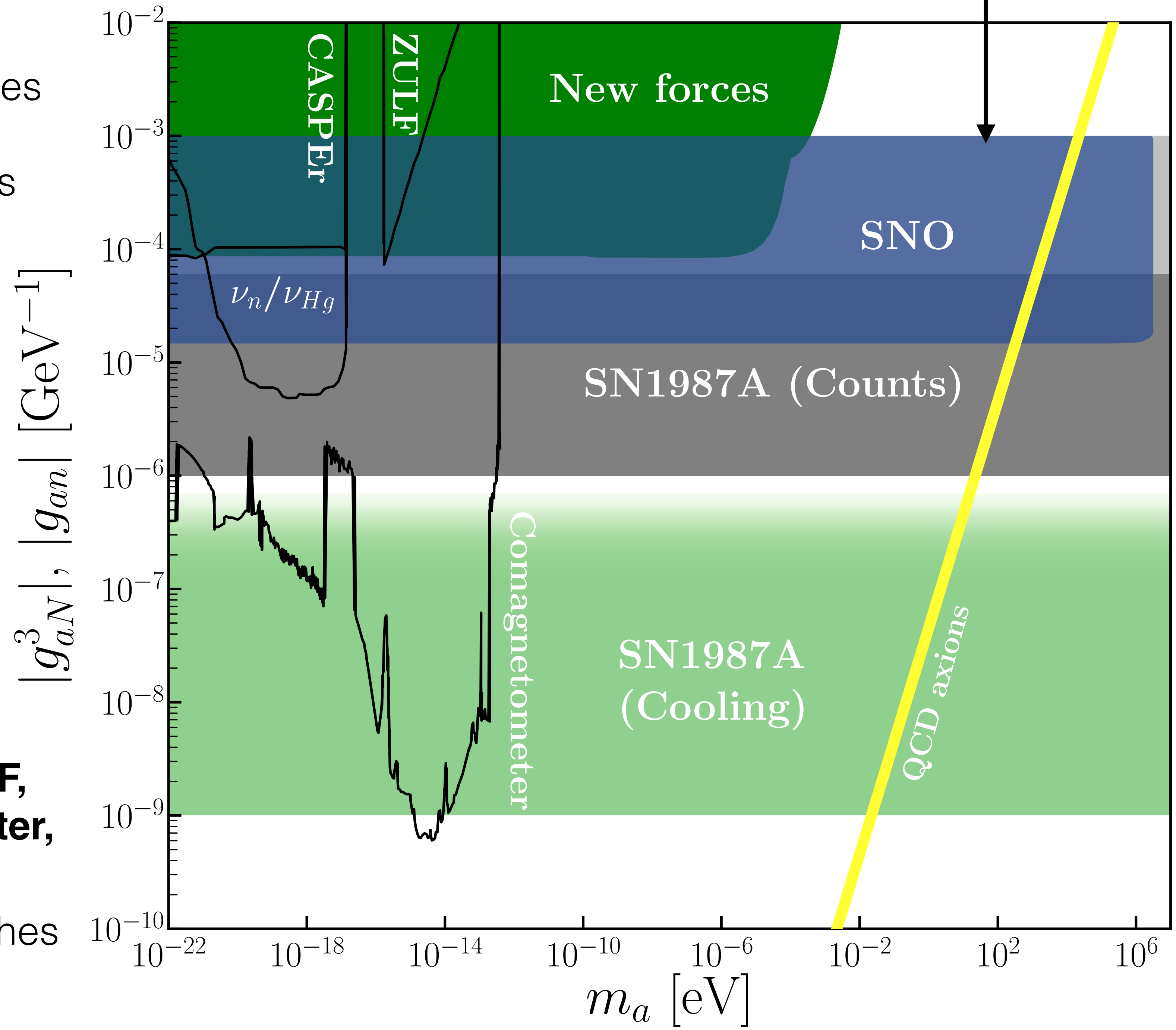
For typical models this is already excluded by astrophysical and direct detection (e.g. PandaX PRL 2017)

As the first direct constraint on g^3_{aN} in the literature, there isn't anything to directly compare to… However, if we assume no precise cancellation between g_{an} and g_{ap} , any limit on g^3_{aN} is also a limit on g_{an} and g_{ap}

Our resulting 95% CL constraint on $g^3_{aN} \equiv \frac{1}{2}(g_{an} - g_{ap})$

New forces: Laboratory searches for new spin-dependent forces

CASPEr, ZULF, Comagnetometer, ν_n/ν_{Hg}: Axion DM searches



SN1987A Counts: Extra events at Kamiokande from axion-induced nuclear transitions

Dark gray: g^3_{aN}
Light gray: g_{an}

SN1987A Cooling: Additional cooling from axion emission

No NS cooling here: constraint is unknown for high masses, similar to SN1987A anyway

Is the assumption of no cancellation between g_{an} and g_{ap} valid?

Actually, yes. Arranging such a cancellation requires a DFSZ-type model with the specific tuning $\tan\beta = 1/\sqrt{2}$ or $\sqrt{2}$ (Luzio *et al,* PRL 2018)

Discussion/conclusions

- Axions are a particularly well-motivated aspect of BSM physics, and neutrino experiments can be particularly well suited to search for them

- From the SNO dataset we exclude $|g_{aN}^{3}| \equiv \frac{1}{2}|g_{an} - g_{ap}| > 2 \times 10^{-5}\mathrm{GeV}^{-1}$ at 95 % C.L. for sub-MeV axion masses, covering previously unexplored regions of the axion parameter space. No assumptions required about dark matter, or the astrophysics of SN1987A or neutron stars

- Assuming no precise cancellation between g_{an} and g_{ap} we can exceed comparable constraints from other laboratory experiments, and exclude regions of the parameter space for which astrophysical constraints from SN1987A and NS cooling are inapplicable due to axion trapping

- Future work: more investigation of the axion/neutrino detection overlap

More details in *Phys.Rev.Lett.* 126 (2021) 9, 091601, 2004.02733

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Thank you all for your attention