Karlsruher Institut für Technologie
Institute for Theoretical Particle Physics

Looking for massive ALPs from SN1987A with Cherenkov Detectors

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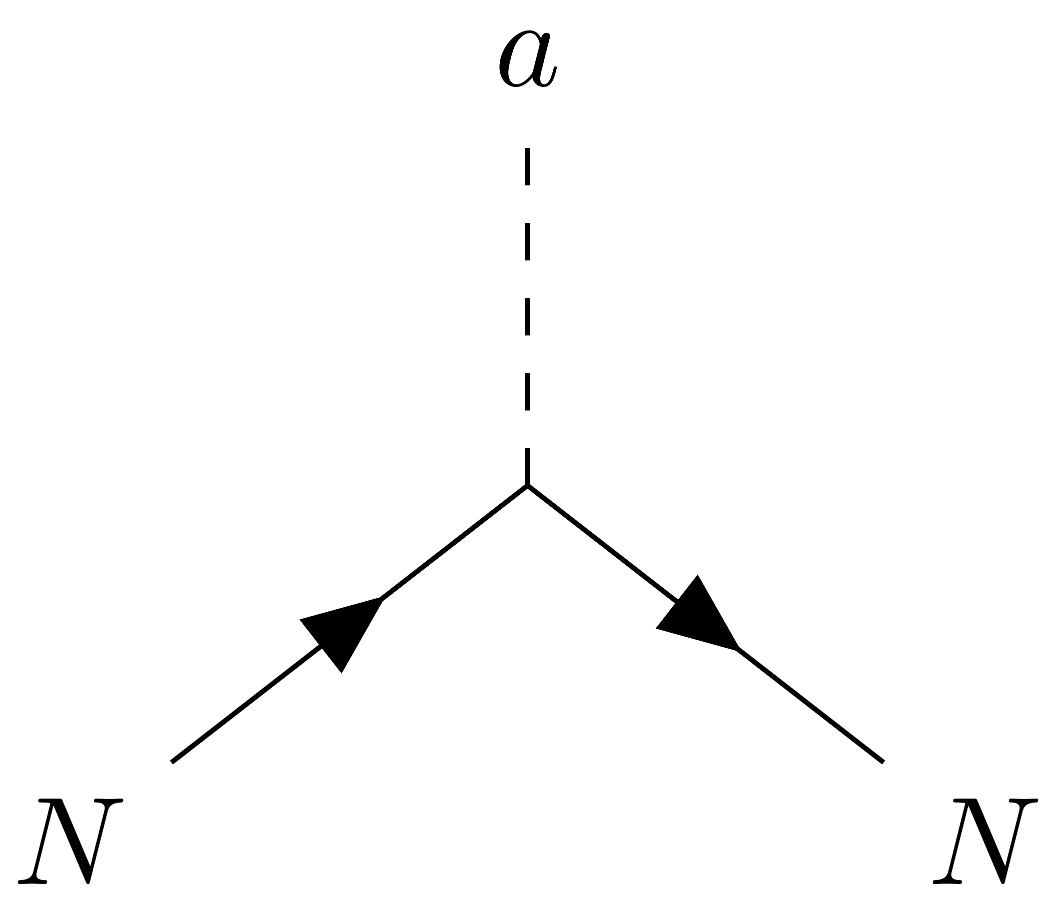
Overview

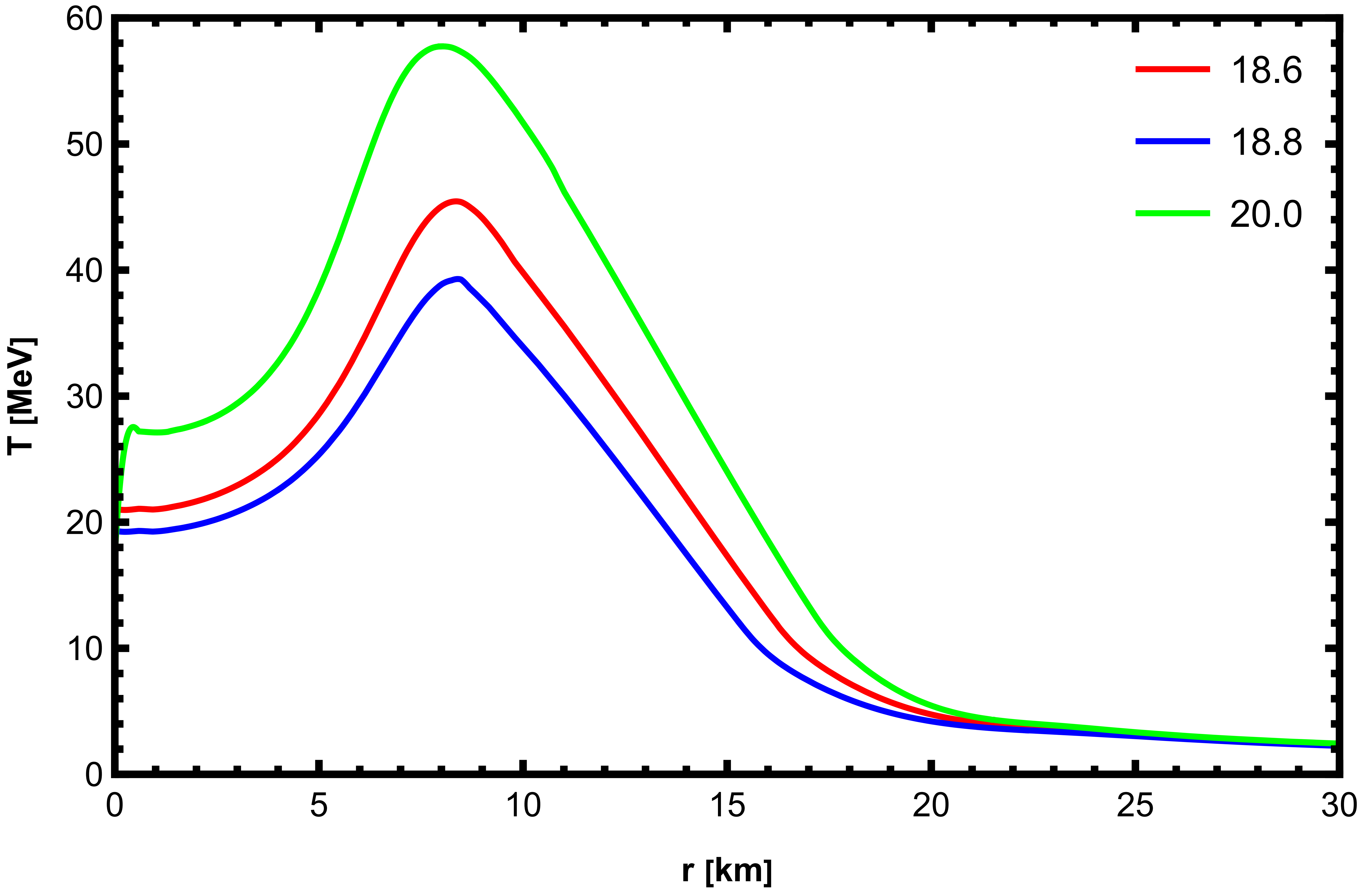
Goal: constrain axion-nucleon coupling g_{aNN} using SN1987A

- Supernova Models
- Cooling Bounds
- Cherenkov Detectors



Supernova Models

- Core-collapse Supernova
- Neutrino cooling dominant
- SN1987A signal at Kamiokande
- $m_a \lesssim T_{SN} \sim 100\,\mathrm{MeV}$



Source: SN Simulations by H.-Th. Janka et al. MPA Garchingen
[2005.07141]

Cooling Bounds

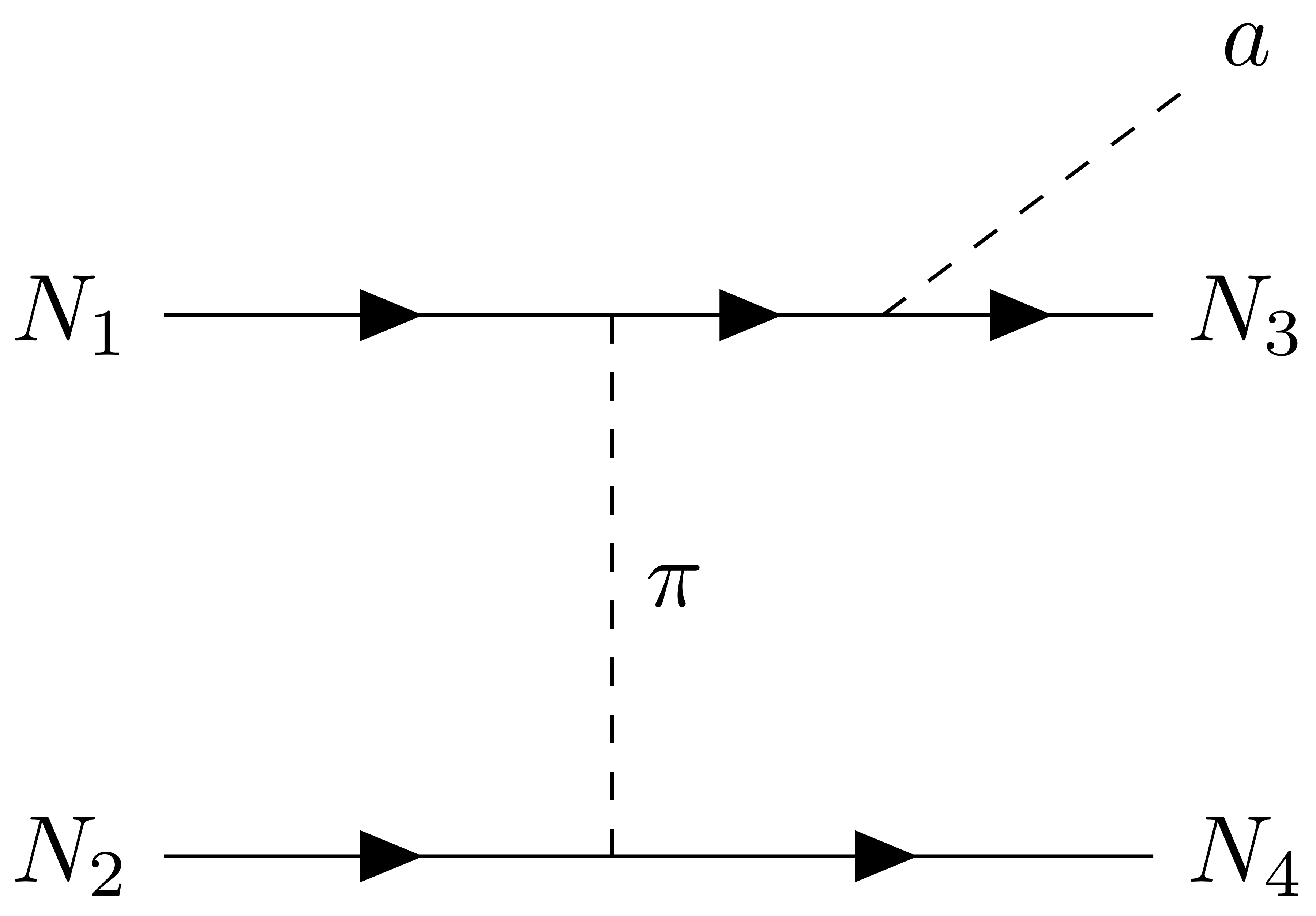
- Axion-Nucleon Bremsstrahlung

$$\mathscr{L} = \frac{1}{2} g_{aNN} \bar{\psi}_N \gamma_\mu \gamma_5 \psi_N \partial^\mu a$$

- Energy-loss by neutrinos

$$\mathscr{L}_\nu = 3 \times 10^{52} \, \frac{\text{erg}}{\text{s}}$$

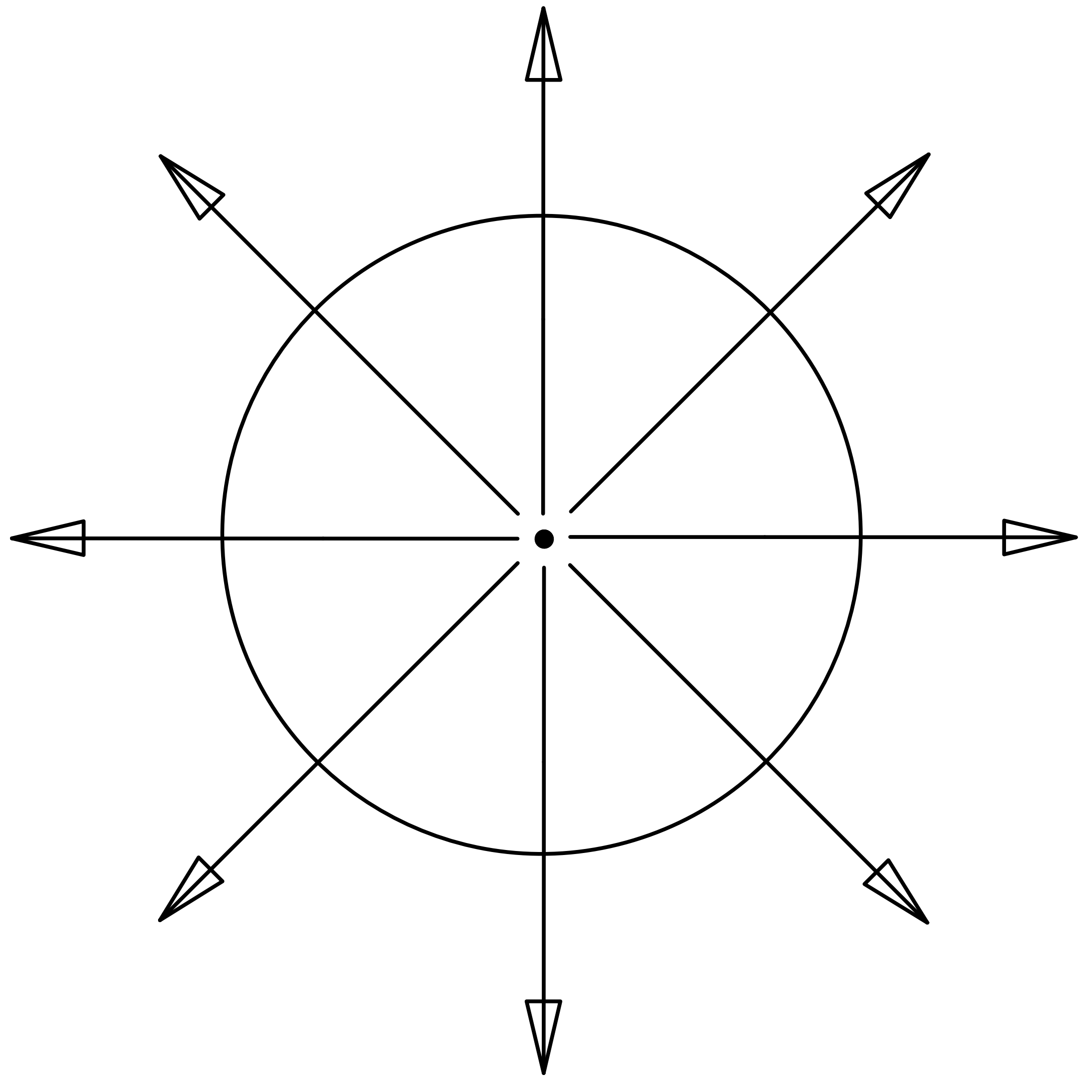
- Axion emission only for $\mathscr{L}_a \lesssim \mathscr{L}_\nu$



Cooling Bounds

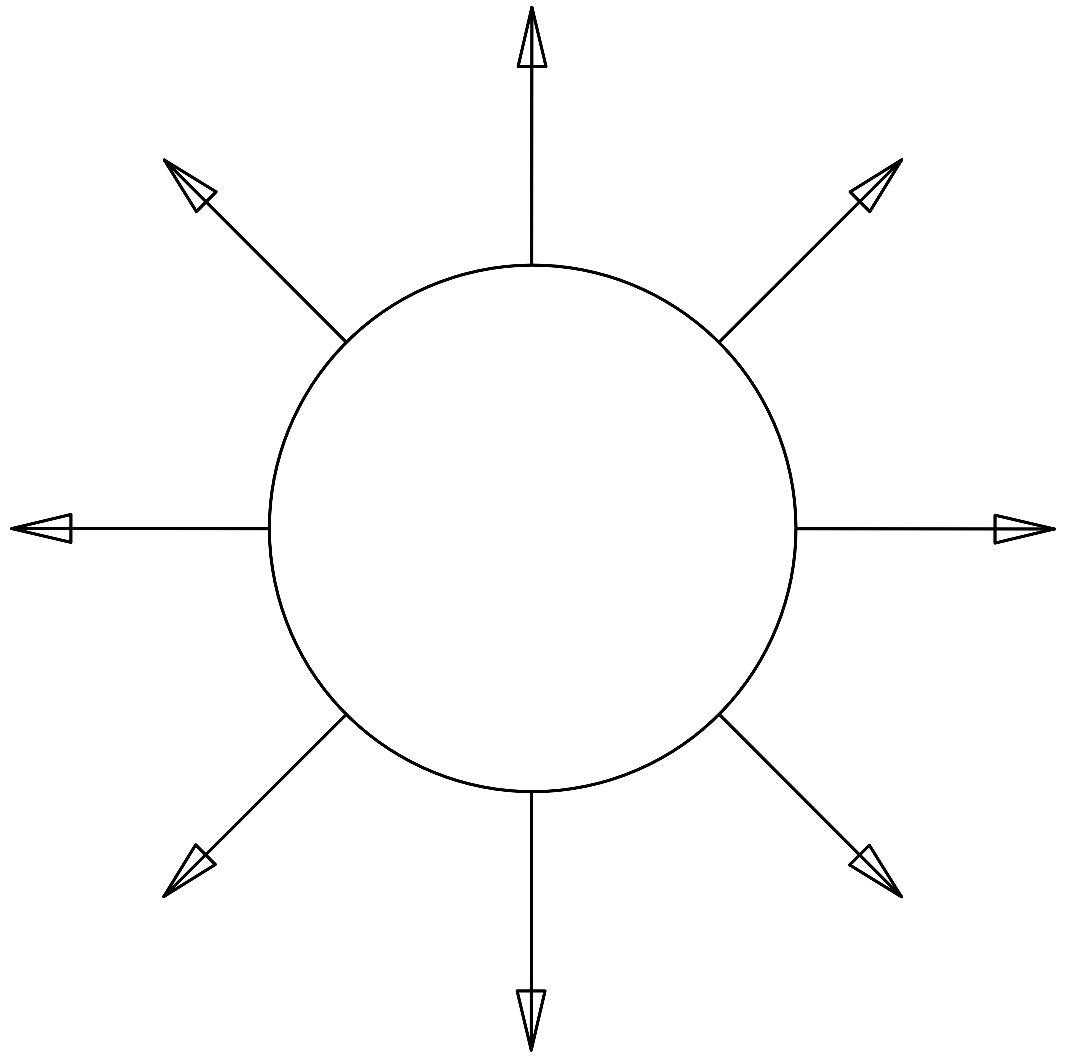
free-streaming limit:

- g_{aNN} small $\Rightarrow \lambda_a \gg r_{PNS}$
- Full volume emission



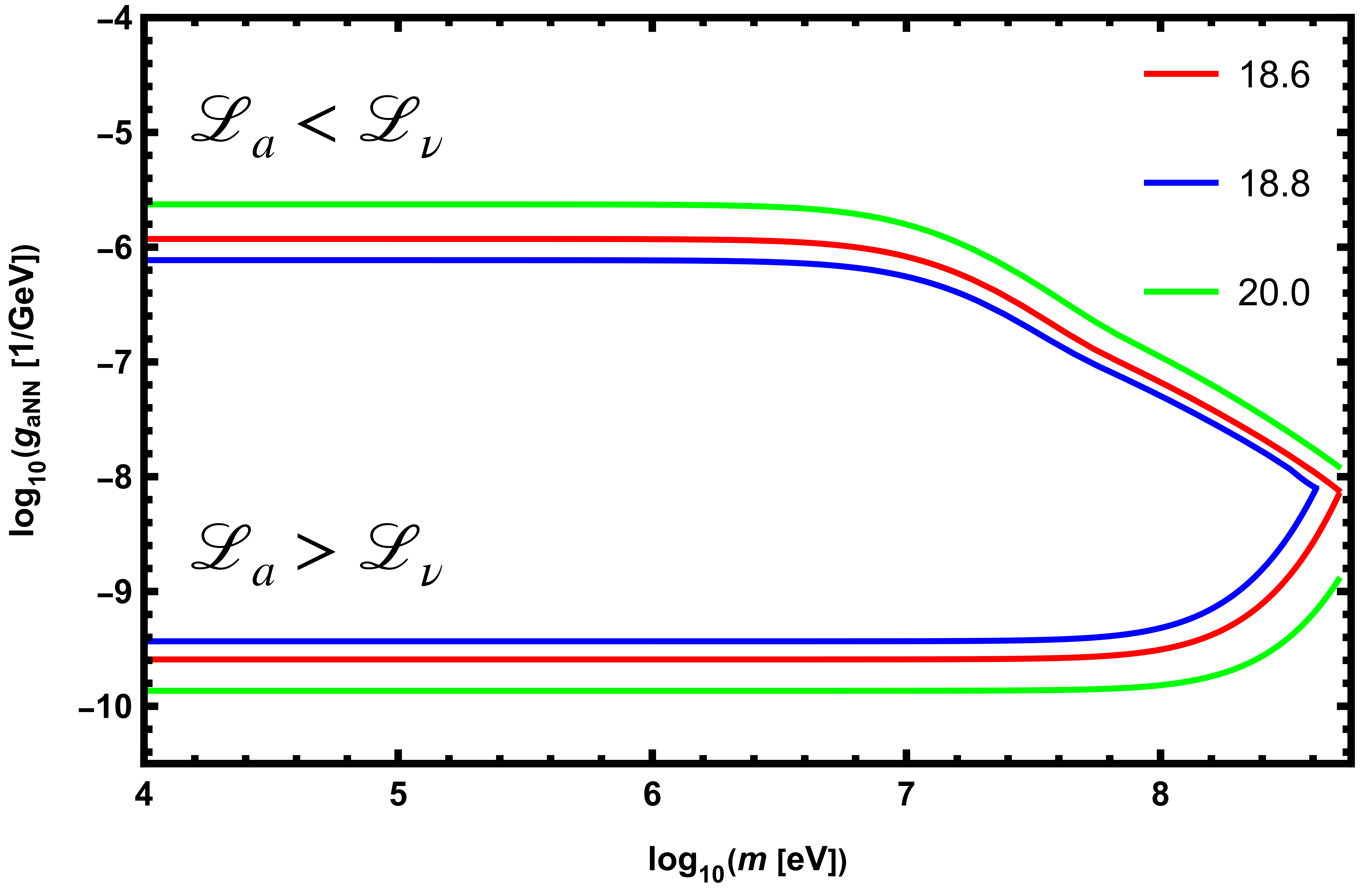
trapping limit:

- g_{aNN} large $\Rightarrow \lambda_a \ll r_{PNS}$
- „Pure“ surface emission (like our sun)



$$\mathscr{L}_a \sim r_a^2 T^4(r_a)$$

Cooling Bounds



Cherenkov Detectors

- Axion-induced photons: $a + {}^{16}O \to {}^{16}O^* \to {}^{16}O + \gamma$

  $$a + {}^{16}O \to {}^{16}O^* \to {}^{15}Z^* + n/p$$

- Invisible nucleon decay: ${}^{16}O \to {}^{15}Z^* + \text{invisible}$

  searches @ SNO+ in 2017 [1812.05552]

Cherenkov Detectors

- Goal: calculate number of events and compare with upper limits by SNO+

- Theory: number of expected events and TOF of axions

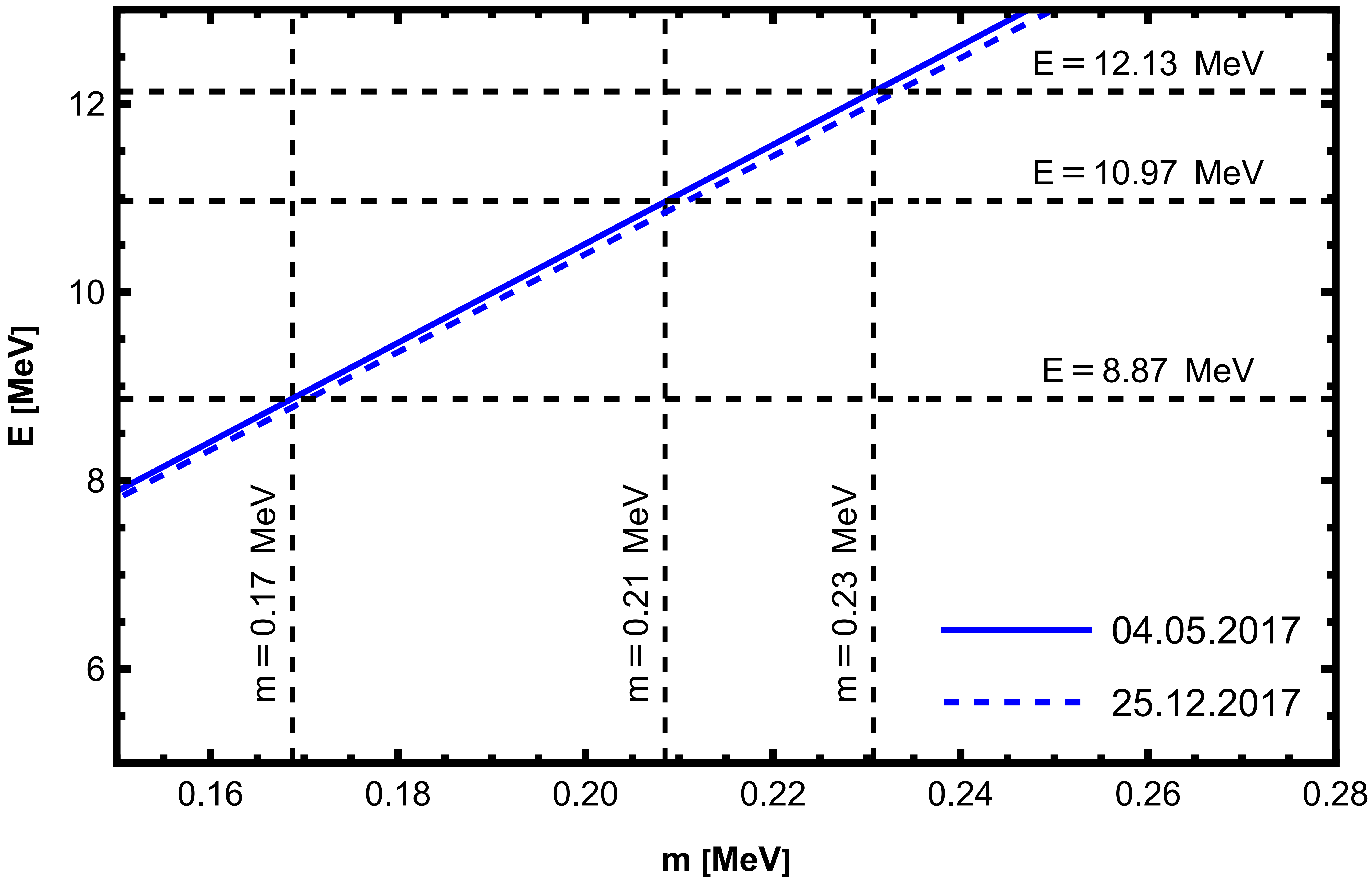
$$N = \sum_i N_{SNO} \int \mathrm{d}E_a \int_{T_{SNO}^{\text{start}}}^{T_{SNO}^{\text{end}}} \mathrm{d}t \frac{\mathrm{d}\phi}{\mathrm{d}E_a} \cdot 2E_a \sigma(E_a) B(E_a, E_i, \Gamma_i) \sum_{E_\gamma < E_i} BR(E_\gamma) \epsilon(E_\gamma)$$

Cherenkov Detectors

Theory: TOF of axions

Allows to constrain axion masses in a window of:

$$170\,\mathrm{keV} \text{ to } 400\,\mathrm{keV}$$



Cherenkov Detectors

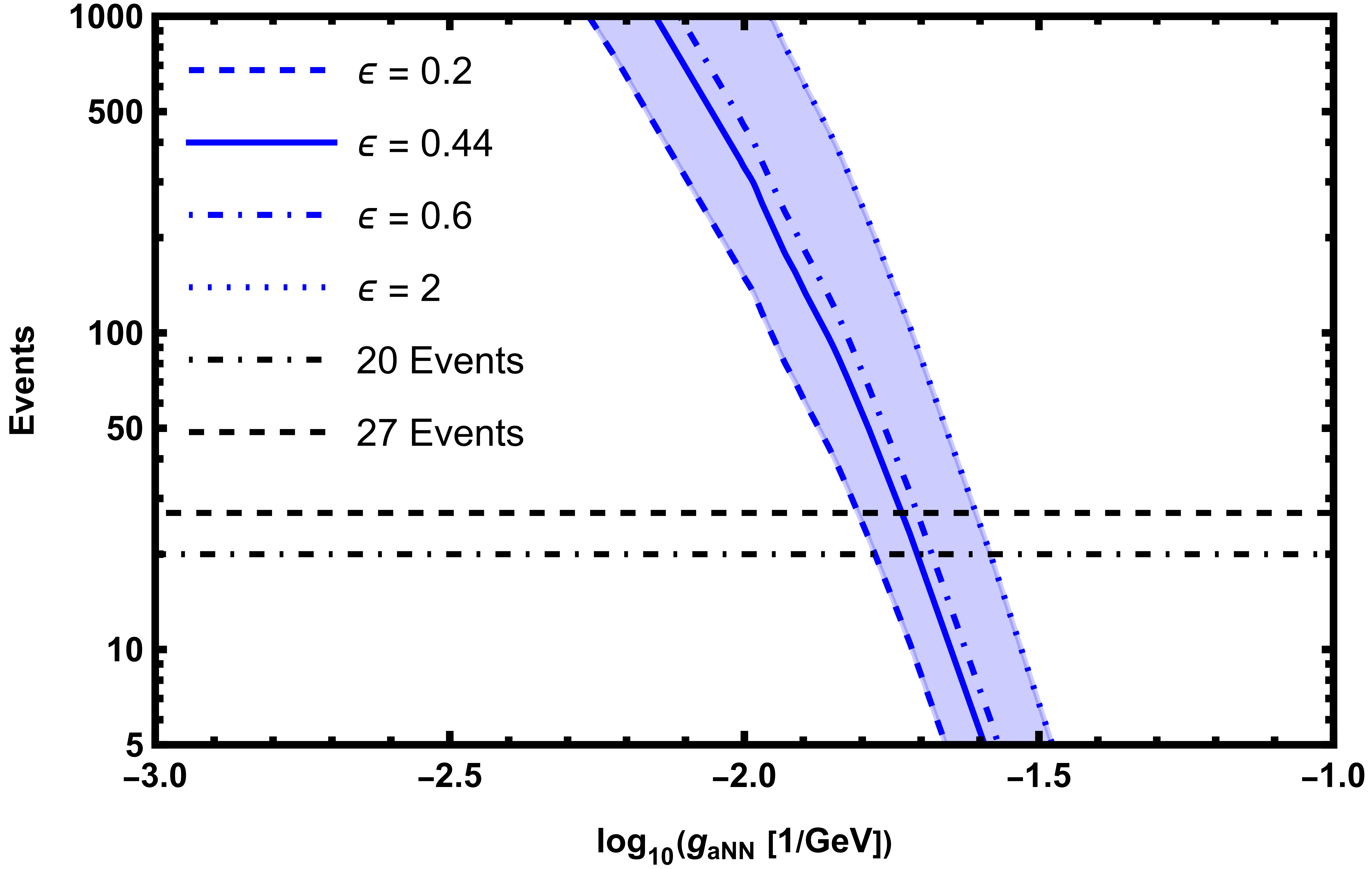
Experiment: recasting of invisible nucleon decay

- Counting analysis of 6 data sets in agreement with background
- Upper limits on the number of events at 90 % CL

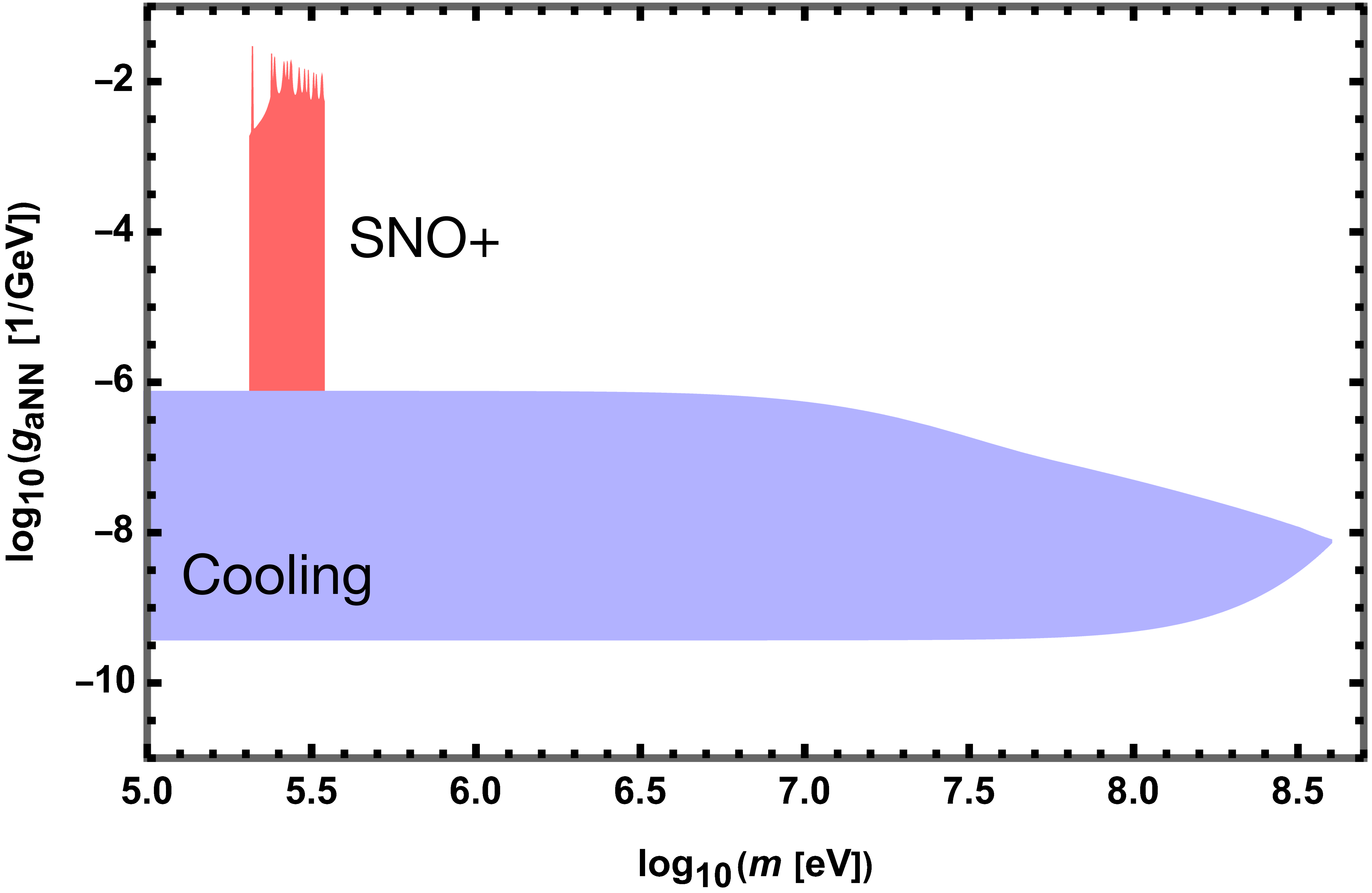
$$0.9 = A \int_0^{N_{90\%}} \mathrm{d}N (N\epsilon + B)^{N_{\mathrm{tot}}} \mathrm{e}^{-(N\epsilon + B)} \Rightarrow N_{90\%} = 27$$

Data Set	$T^{\min}$ [MeV]	$T^{\max}$ [MeV]	Measurement Time t [d]	Background	Number of Events n
1	5.75	9	5.1	1.18	1
2	5.95	9	14.9	2.35	2
3	5.85	9	30.7	3.46	4
4	5.95	9	29.4	3.38	8
5	5.85	9	11.5	1.46	1
6	6.35	9	23.2	5.84	6

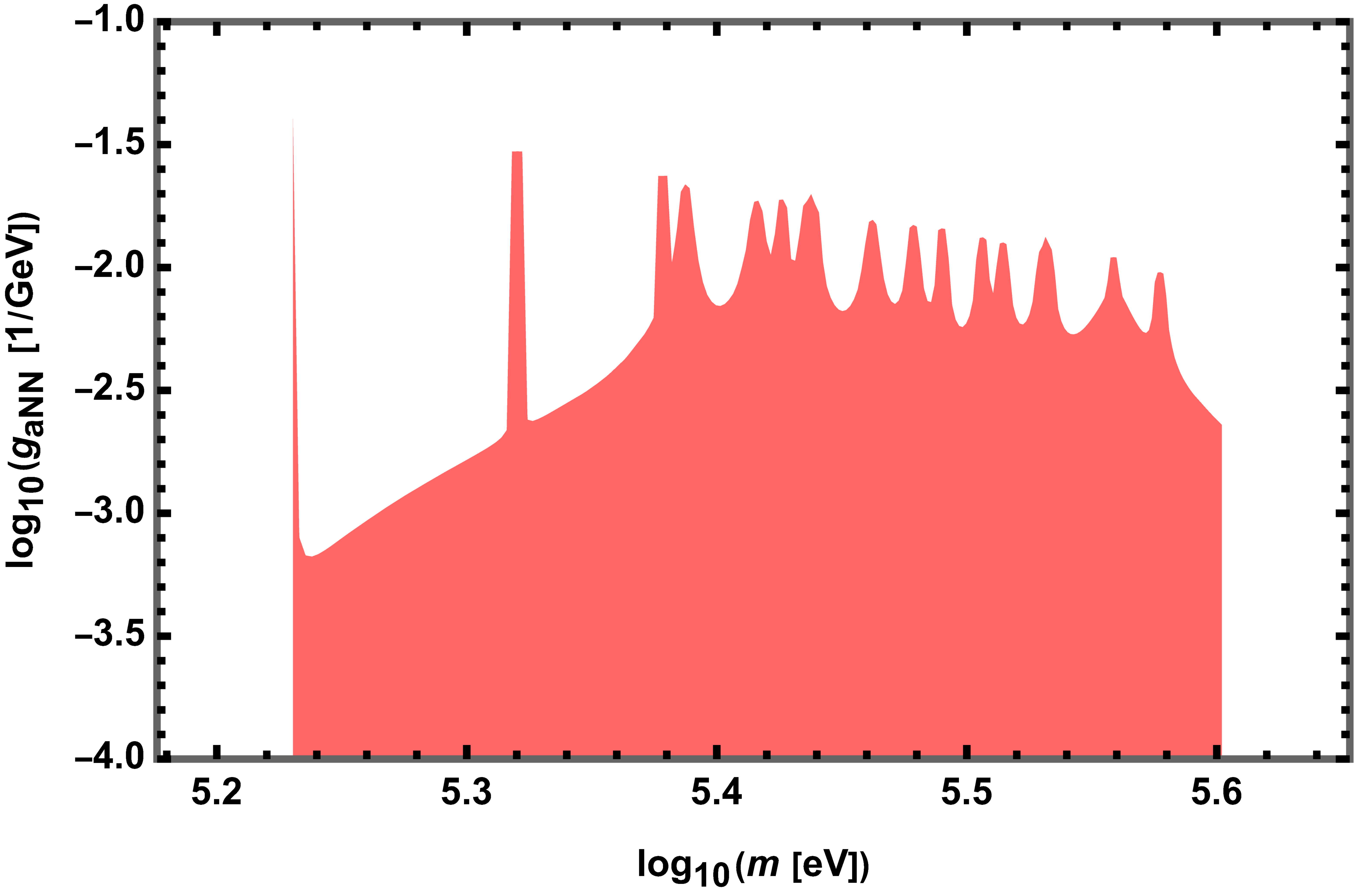
Cherenkov Detectors



Cherenkov Detectors

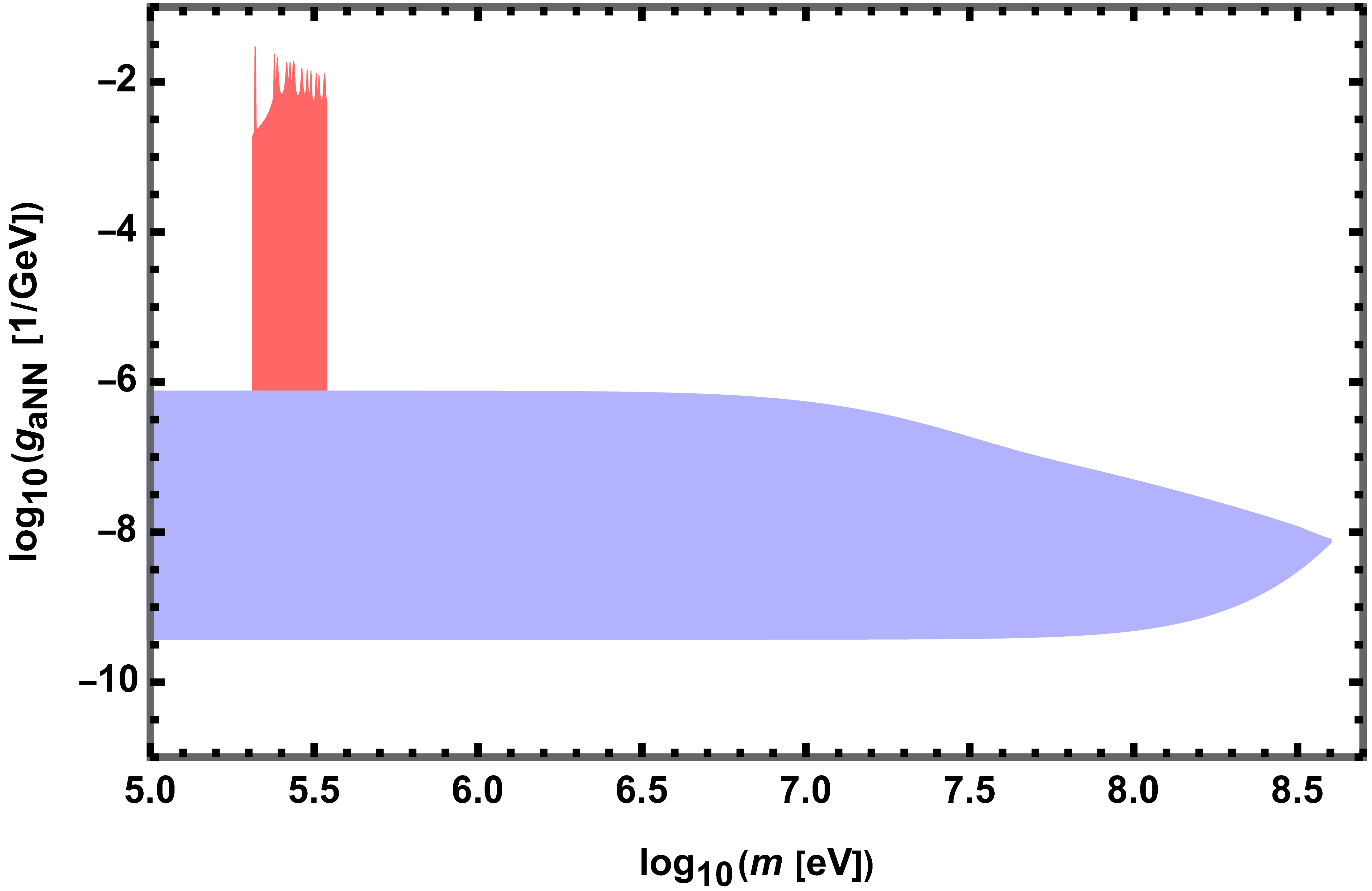


Cherenkov Detectors



Conclusion

- SN Cooling constrains g_{aNN}
- Include TOF of massive axions
- Invisible nucleon decay carries same signature as axion induced photons
- Water Cherenkov detectors potentially capable of detecting axions



Backup

Luminosity: $\mathscr{L} = 4\pi r^2 T^4 \frac{g\pi}{(2\pi)^3} \int\limits_{m_a/T}^{\infty} \mathrm{d}x \frac{x^3 \beta(x, m_a)}{\mathrm{e}^x - 1}$

free-streaming limit: $\mathscr{L} = \int\limits_0^{\infty} \mathrm{d}r \, 4\pi r^2 Q_a(r)$

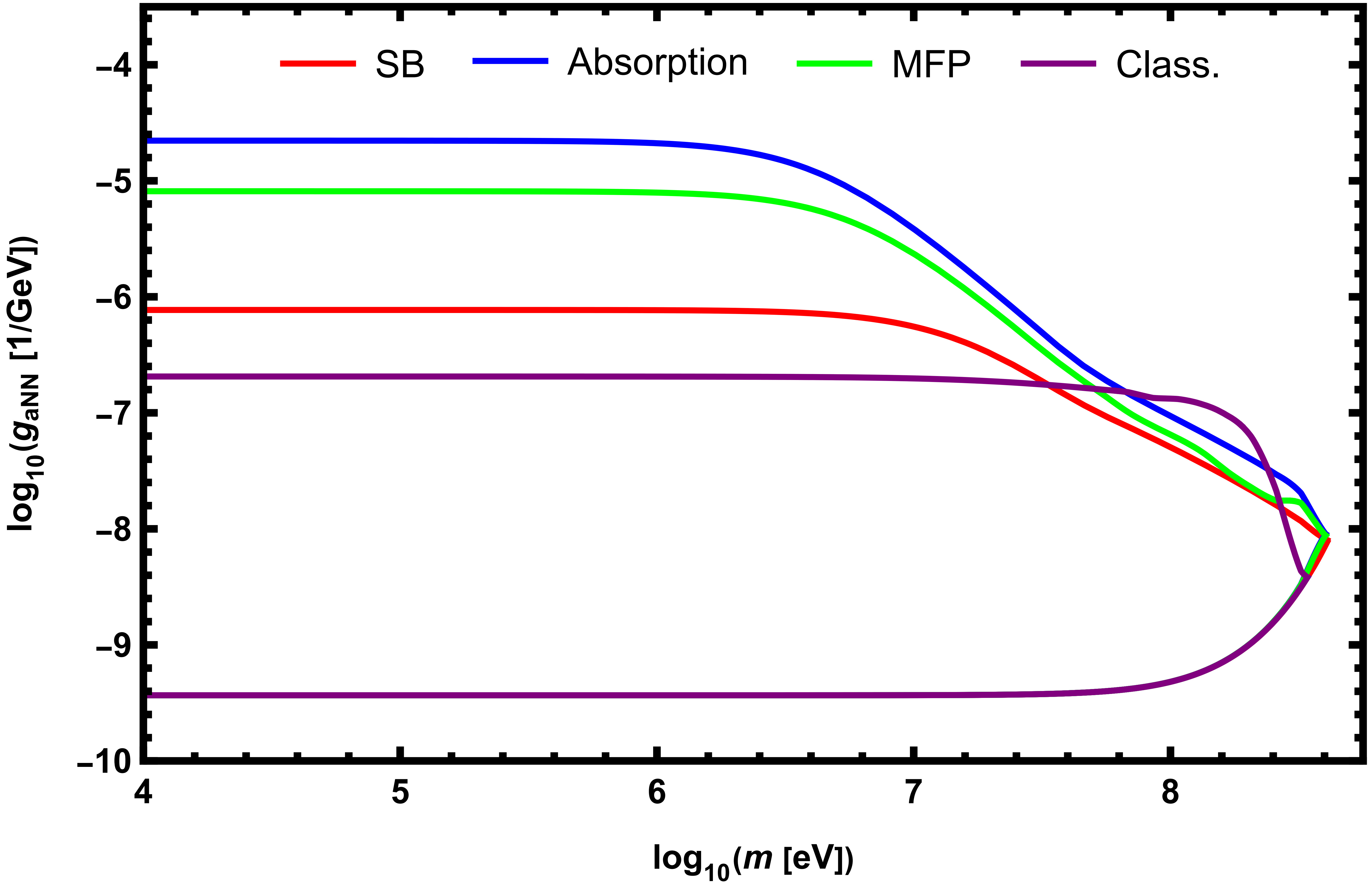
trapping limit: $\frac{2}{3} = \tau(r_a) = \int\limits_{r_a}^{\infty} \mathrm{d}r \, \frac{1}{\lambda_R(r)}$

Backup

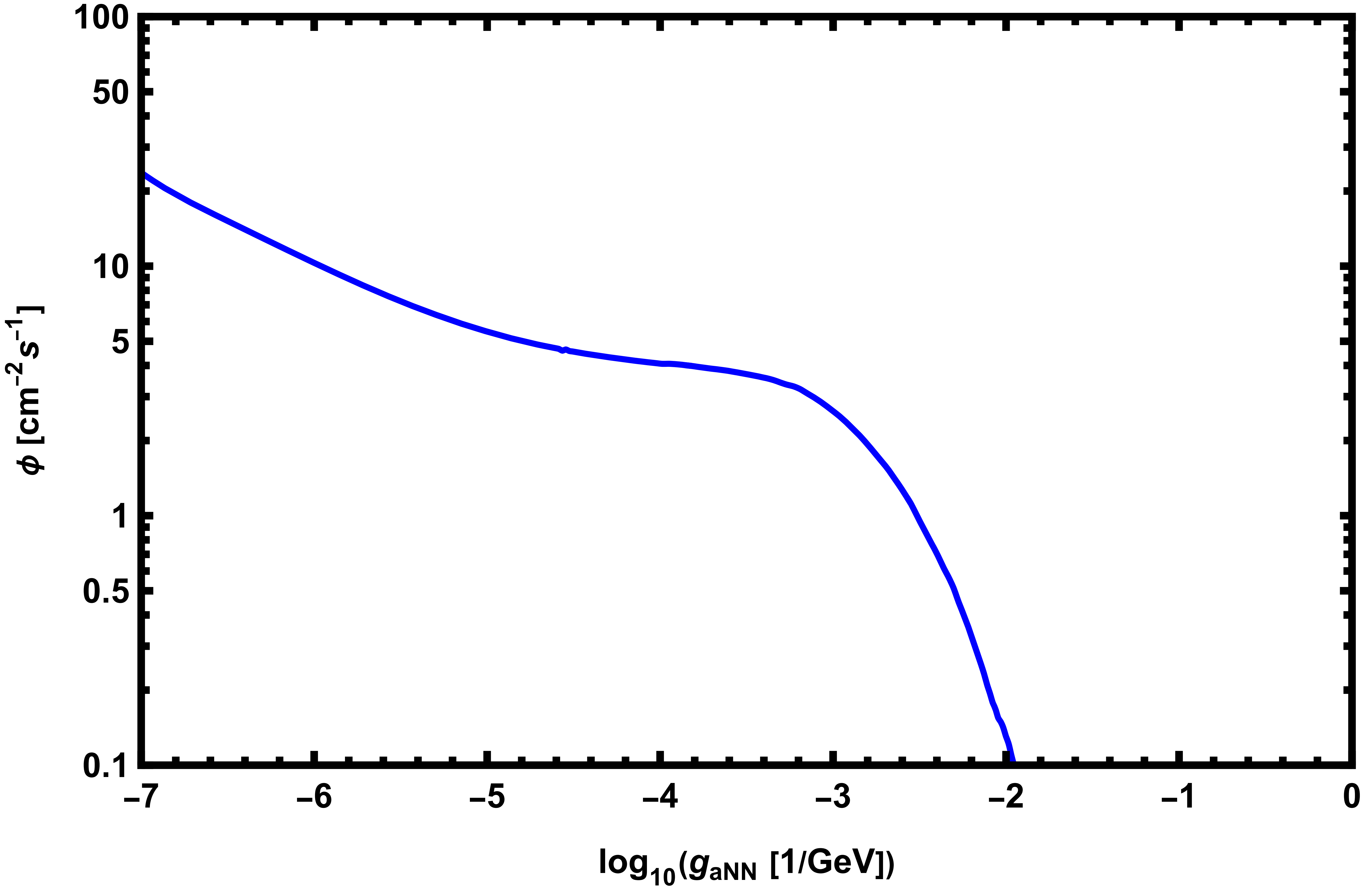
Energy-loss rate: $Q_a = \frac{1}{2\pi^2} \int_{m_a}^{\infty} \mathrm{d}E_a \, E_a^3 \beta(E_a, m_a) \Gamma(E_a) \mathrm{e}^{-E_a/T}$

Flux: $\phi(t, g_{aNN}) = \left(\frac{r_a}{d_{SN}} \right)^2 \frac{\pi}{(2\pi)^3} \frac{t_{SN}}{d_{SN}} \frac{m_a^3}{\mathrm{e}^{E_a/T} - 1} \frac{\beta^4(t)}{(\sqrt{1 - \beta^2(t)})^5}$

Backup: Cooling Bounds Comparison

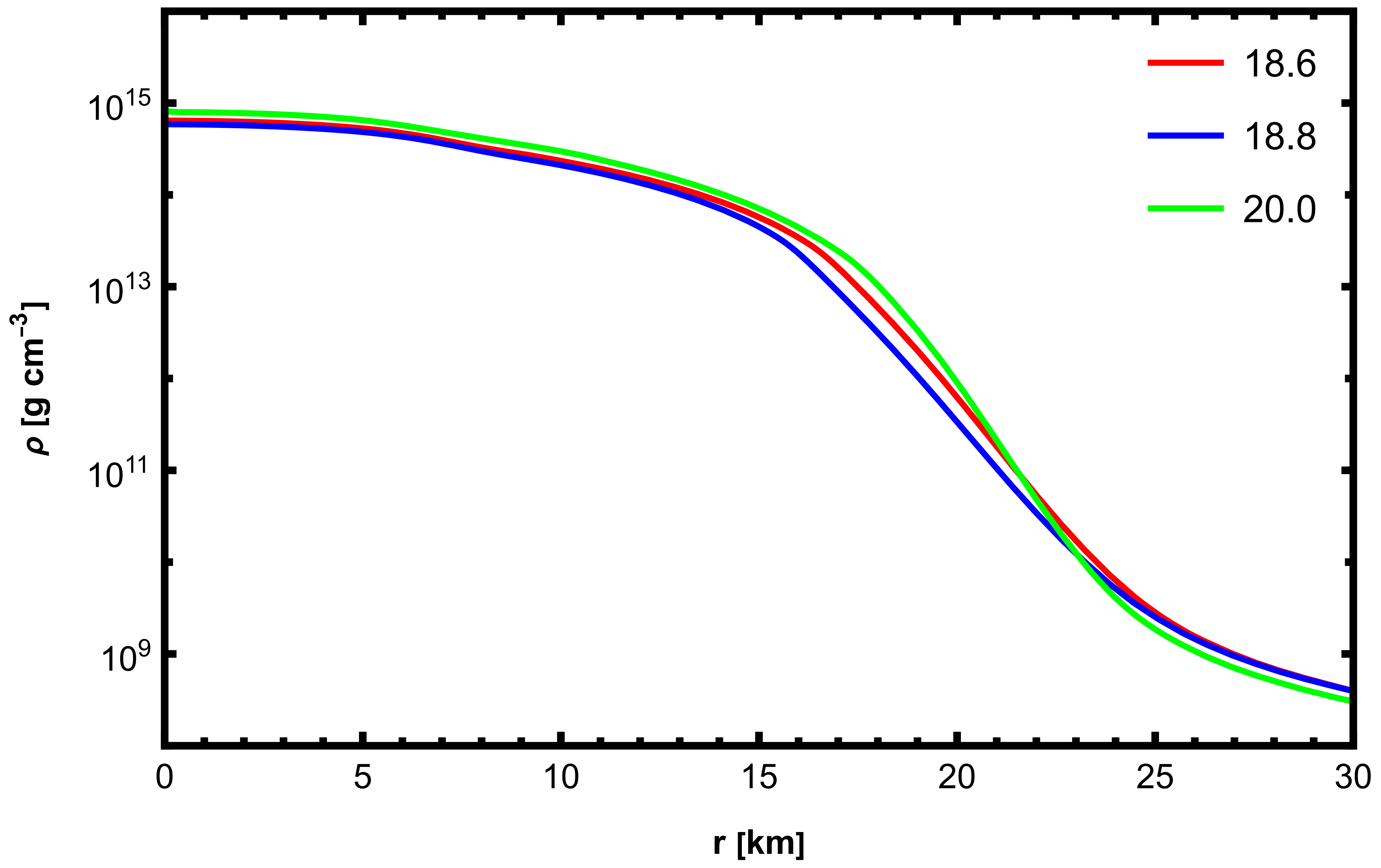


Backup: Flux



Flux with $m_a = 200\,\mathrm{keV}$ and $t = 2017$

Backup: SN Density



Backup: Oxygen Transitions

E [MeV]	J^π	Γ [keV]	Decay Modes
8.872	2^-	3.7 meV	γ, α
10.957	0^-	82 meV	
12.530	2^-	0.097	γ, α, p
12.796	0^-	40	p
12.9686	2^-	1.34	γ, α, p
13.664	1^+	64	γ, α, p
13.980	2^-	20	α, p
14.302	4^-	34	
14.399	5^+	27	
15.196	2^-	63	α, p
15.785	3^+	40	
16.209	1^+	19	γ, p, n
16.817	3^+	28	γ, α, p
17.140	1^+	34	γ, α, p, n
17.775	4^-	45	p
17.877	2^-	24	γ, (α), p
18.977	4^-	8.2	γ, α, p
19.001	2^-	420	γ, p
19.808	4^-	32	

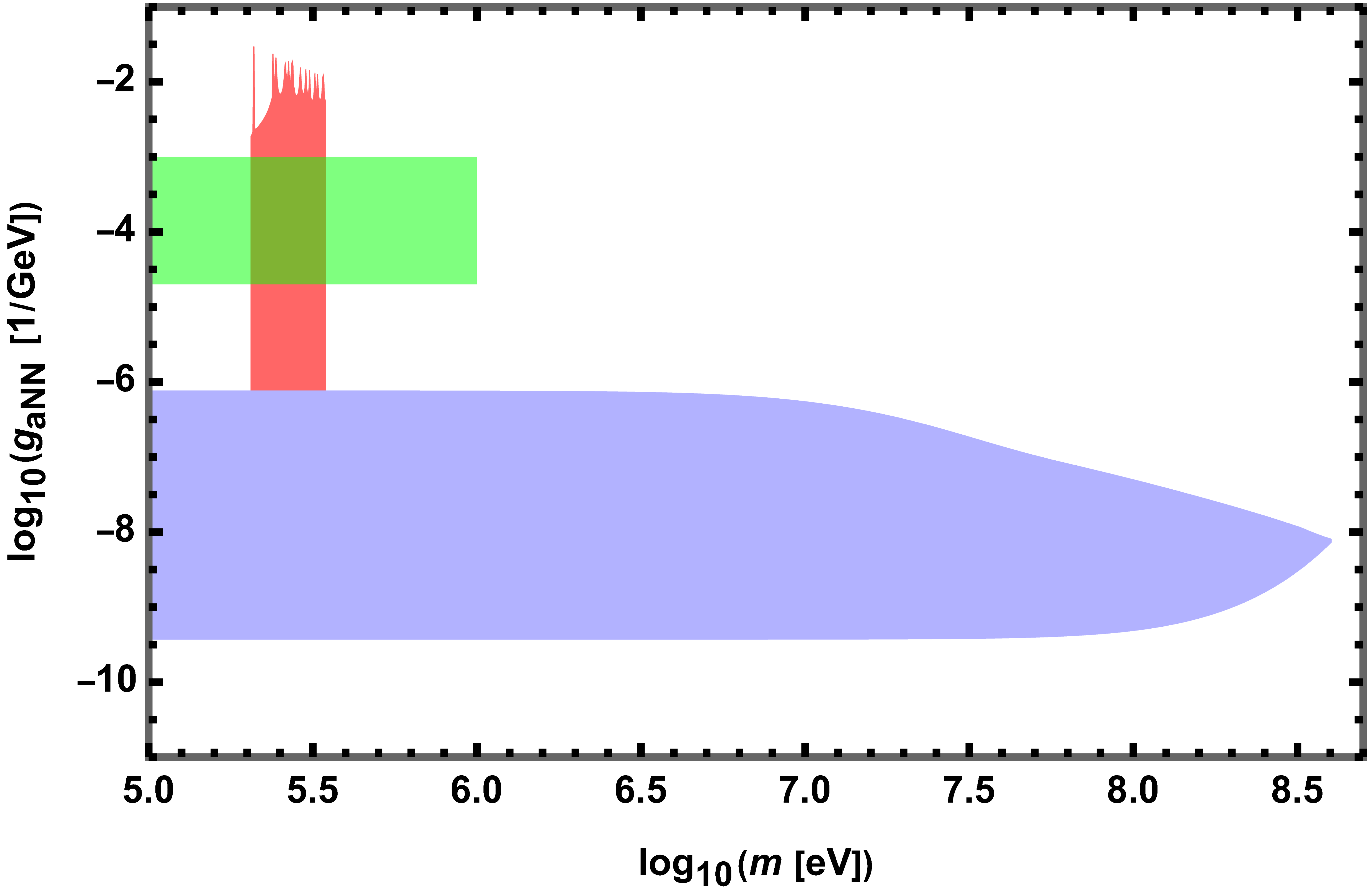
Backup: Nitrogen Transitions

E [MeV]	$J_i^\pi \rightarrow J_f^\pi$	E_γ [MeV]	BR [%]
5.27	$\frac{5}{2}^+ \rightarrow \frac{1}{2}^-$	5.27	100
5.30	$\frac{1}{2}^+ \rightarrow \frac{1}{2}^-$	5.30	100
6.32	$\frac{3}{2}^- \rightarrow \frac{1}{2}^-$	6.32	100
7.30	$\frac{3}{2}^+ \rightarrow \frac{1}{2}^-$	7.30	99.3
8.31	$\frac{1}{2}^+ \rightarrow \frac{1}{2}^-$	8.31	79
9.05	$\frac{1}{2}^+ \rightarrow \frac{1}{2}^-$	9.05	92
9.152	$\frac{3}{2}^- \rightarrow \frac{1}{2}^-$	9.152	100
9.76	$\frac{5}{2}^- \rightarrow \frac{1}{2}^-$	9.76	81.5
9.93	$\frac{3}{2}^- \rightarrow \frac{1}{2}^-$	9.93	77.6
10.07	$\frac{3}{2}^+ \rightarrow \frac{1}{2}^-$	10.07	61.6
10.69	$\frac{9}{2}^+ \rightarrow \frac{5}{2}^+$	5.42	61.6
11.62	$\frac{1}{2}^+ \rightarrow \frac{1}{2}^-$	11.62	90.7

Average Photon Energy $E_\gamma = 8.1\,\mathrm{MeV}$

Backup: SN Bounds

Cooling + Water Cherenkov + Comparison



Source: Green Exclusion by Bhusal, Houston and Li
[2004.02733]