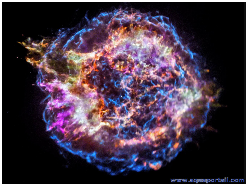

CATCH 22+2

Photo-production via anomaly in neutron stars and supernovae

Miguel Vanvlasselaer
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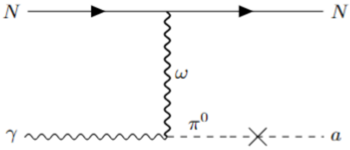
VUB and IIHE

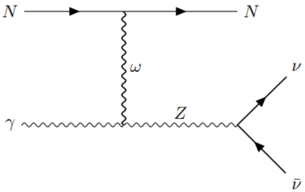
May 2024

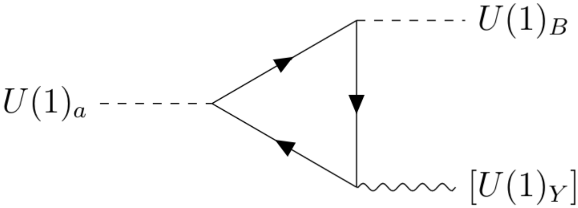
VRIJE UNIVERSITEIT BRUSSEL

Wess-Zumino-Witten interactions

What are the Wess-Zumino-Witten (WZW) interactions ?

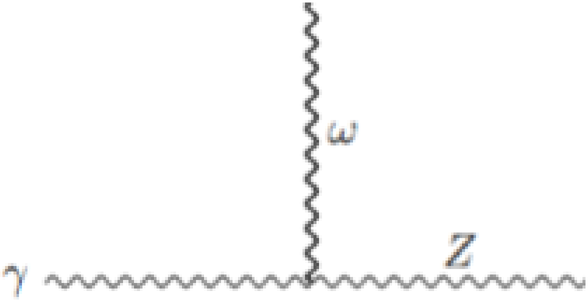






Computing the vertex

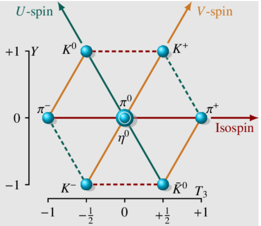
$$L \subset \omega \cdot Z \cdot F$$



Pion chiral lagrangian and WZW term

- Pion chiral lagrangian for the pseudo scalar mesons

$$\mathcal{L}_\pi = \frac{f_\pi^2}{4}\mathrm{Tr}\left(D_\mu U^\dagger D^\mu U + U^\dagger \chi + \chi^\dagger U\right) \ , \qquad U = e^{2i\vec{\sigma}\cdot\vec{\pi}/f_\pi}$$



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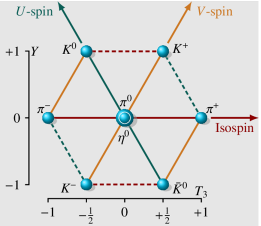

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$$D_\mu = \partial_\mu U - i r_\mu U + i U \ell_\mu \ , \quad r_\mu(\ell_\mu) = v_\mu \pm a_\mu \ ,$$

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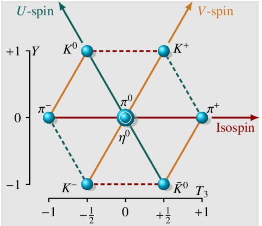

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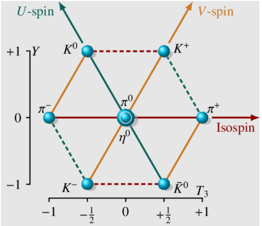

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- Solution: Wess-Zumino-Witten Phys. Lett. B 37 (1971) 95, Nucl. Phys. B 223 (1983) 422.

$$S_{\mathrm{WZW}} = \kappa \int_D d^5x \, \omega \ , \qquad \omega = -\frac{i}{240\pi^2} \epsilon^{\mu\nu\rho\sigma\tau} \mathrm{Tr}\left(\mathcal{U}_\mu \mathcal{U}_\nu \mathcal{U}_\rho \mathcal{U}_\sigma \mathcal{U}_\tau\right) \qquad \mathcal{U}_\mu = U^\dagger \partial_\mu U$$

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$$\text{set } \delta A \qquad \to \ \delta\omega = -e\,\delta A_\mu \hat{J}^\mu \ ,$$

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$$\hat{J}^\mu = \frac{1}{48\pi^2}\,\epsilon^{\mu\nu\rho\sigma\tau}\,\partial_\nu\, \text{Tr}\left[\{Q,U^\dagger\}\,\partial_\rho U\; U^\dagger \partial_\sigma U\; U^\dagger \partial_\tau U\right] \;.$$

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introduce: $\mathcal{L}_{\text{int}} \subset A^\mu J^A_\mu$ variation: $\delta U = i\epsilon(x)\,[Q,U]$ or $\delta\omega = \partial_\mu \epsilon(x) \hat{J}^\mu$

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- Full expression for $S_{\text{WZW}}\,(U, A_\mu)$

$$\kappa\int_D d^5x\,\omega - \kappa e\int d^4x\;A_\mu J^\mu + \underbrace{\frac{ie^2}{24\pi^2}\int d^4x\;\epsilon^{\mu\rho\sigma\lambda}\;A_\rho\,(\partial_\mu A_\nu)\;\left[\text{Tr}\left(\{Q^2,U^\dagger\}\partial_\sigma U\right) - QUQ\partial_\sigma U^\dagger\right]}_{=\frac{ie^2}{48\pi^2}\frac{\pi_0}{f_\pi}\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta}\quad\text{We found the anomaly !}}.$$

Repeat the procedure with non-abelian chiral subgroups

Nucl. Phys. B 223 (1983) 422: Witten, PhysRevD.30.594: Kaymakcalan, Rajeev and Schechter

$$\Gamma_{WZW}(U,\mathcal{A}_L,\mathcal{A}_R) = \Gamma_0(U) \; + \mathcal{C}\int \mathrm{Tr}\Big\{(\mathcal{A}_L\alpha^3 + \mathcal{A}_R\beta^3) - \frac{i}{2}[(\mathcal{A}_L\alpha)^2 - (\mathcal{A}_R\beta)^2]$$
$$+ i(\mathcal{A}_L U\mathcal{A}_R U^\dagger\alpha^2 - \mathcal{A}_R U^\dagger\mathcal{A}_L U\beta^2) + i(d\mathcal{A}_R dU^\dagger\mathcal{A}_L U - d\mathcal{A}_L dU\mathcal{A}_R U^\dagger)$$
$$+ i\big[(d\mathcal{A}_L\mathcal{A}_L + \mathcal{A}_L d\mathcal{A}_L)\alpha + (d\mathcal{A}_R\mathcal{A}_R + \mathcal{A}_R d\mathcal{A}_R)\beta\big] + (\mathcal{A}_L^3\alpha + \mathcal{A}_R^3\beta)$$
$$- (d\mathcal{A}_L\mathcal{A}_L + \mathcal{A}_L d\mathcal{A}_L)U\mathcal{A}_R U^\dagger + (d\mathcal{A}_R\mathcal{A}_R + \mathcal{A}_R d\mathcal{A}_R)U^\dagger\mathcal{A}_L U$$
$$+ (\mathcal{A}_L U\mathcal{A}_R U^\dagger\mathcal{A}_L\alpha + \mathcal{A}_R U^\dagger\mathcal{A}_L U\mathcal{A}_R\beta) + i\left[\mathcal{A}_L^3 U\mathcal{A}_R U^\dagger - \mathcal{A}_R^3 U^\dagger\mathcal{A}_L U - \frac{1}{2}(U\mathcal{A}_R U^\dagger\mathcal{A}_L)^2\right]\Big\}.$$

$$\boxed{\mathcal{L}^\pi_{\mathrm{WZW}} \supset \frac{N_C}{48\pi^2} g_2^2 \tan\theta_W \; \epsilon^{\mu\nu\rho\sigma} \; F_{\mu\nu}\mathcal{A}_\rho Z_\sigma}$$

How to introduce vector mesons ?

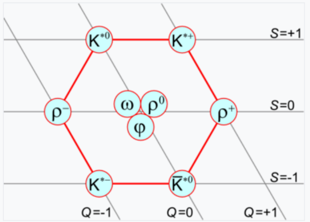
$$\mathcal{L} \subset \omega \cdot F \cdot ... ??$$

Vector mesons not part of the U matrix ! How to introduce them ?

$\Downarrow$ HHH: Phys. Rev. D 77 (2008) 085017

Introduce a background field B with QN of ω, ρ... $\delta B \rightarrow J^{\mu}$

- Appearance mixed anomaly terms $\epsilon \cdot F_A F_B$



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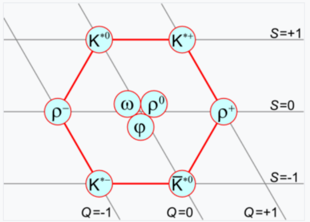

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$$\Gamma_c = -S^{\text{Bardeen}}_{\text{WZW}}(U = 1, e\mathcal{A}_\mu + g_\omega \omega_\mu) \quad \text{(Bardeen counterterms)}$$

$$\epsilon B A \partial A - \epsilon B A \partial A = 0$$

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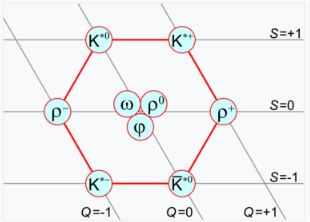

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- Non-vectorlike: Recipe is

$$S_{\text{full}} = S_{WZW}(U, A_L + B_L, A_R + B_R) - \Gamma_c$$

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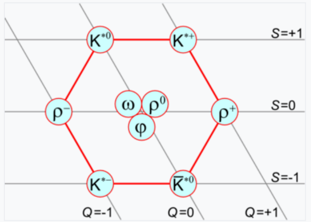

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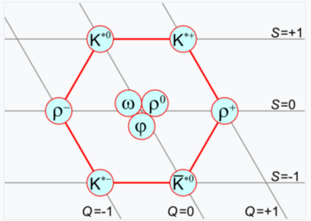

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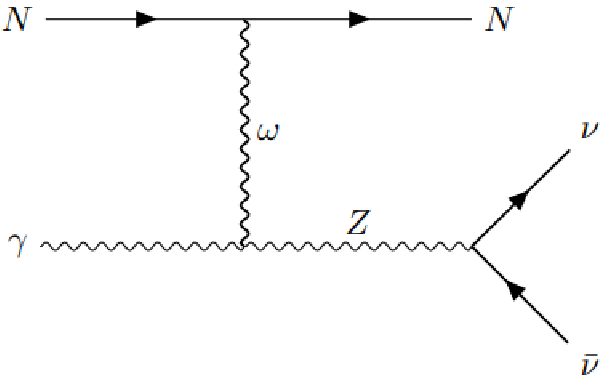
$$\frac{\pi_0}{f_\pi}\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta} = -2\frac{\partial_\alpha \pi_0}{f_\pi}\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}\mathcal{A}_\beta \to -2g_\omega\frac{\partial_\alpha \pi_0}{f_\pi}\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}\omega_\beta \to -2g_\omega\theta_{a\pi_0}\frac{\partial_\alpha a}{f_\pi}\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}\omega_\beta$$

Computing the full interaction



Road to our Lagrangian

- $$\mathcal{L}_{\text{WZW}} \supset \frac{N_C}{48\pi^2} g_2^2 g_\omega \, \tan\theta_W \, \epsilon^{\mu\nu\rho\sigma} \, F_{\mu\nu}\omega_\rho Z_\sigma \, + \ldots$$

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- vertex γNNa

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Summary of the results

- Photo-production of a neutrino pair: $\gamma N \to N \nu \bar{\nu}$

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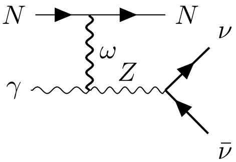

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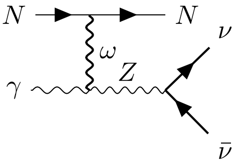

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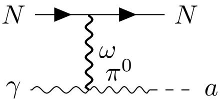
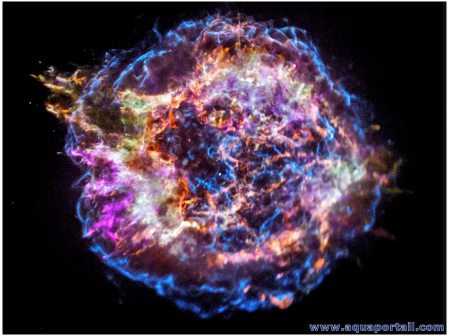
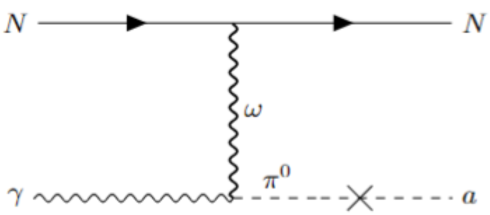


Emission of axions from SN

Photo-production of axions in Supernovae





With Sabyasachi Chakraborty (IIT-Kanpur) and Aritra Gupta (IFIC Valencia): 2403.12169

The cooling argument in supernovae and SN1987A

- Neutrino received during SN1987A:

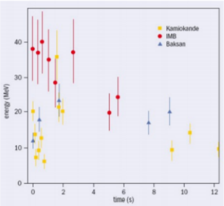


Figure: Credit:NirCam JWST

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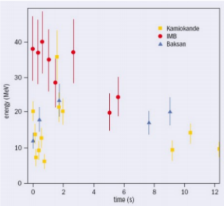

- Raffelt bound:

$$\frac{Q_{\text{additional}}}{\rho} \lesssim 10^{19} \text{ erg } s^{-1} g^{-1}$$

Figure: Credit:NirCam JWST

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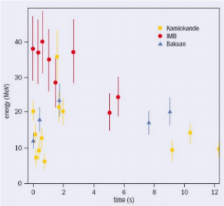

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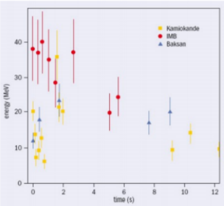

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- This is a coupling constraint !
- We need: Emissivity $Q =$, energy per unit of time and cc emitted

Figure: Credit:NirCam JWST

How to carry energy away from the SN?

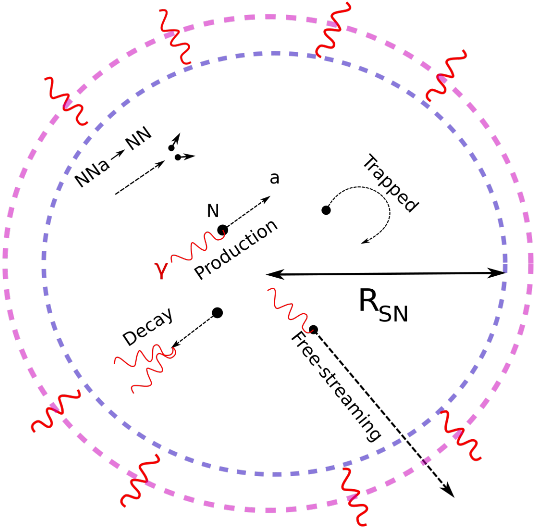
Supernovae extreme medium:
$\rho \sim \rho_0, \qquad T \sim 30 - 50$ MeV

bremsstrahlung and pion conversion

$$NN \to NNa \qquad N\pi \to Na$$

What about the photo-production ?

$$\boxed{N\gamma \to Na}$$

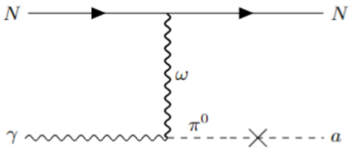


Emissivities of the $\gamma N \to Na$: main result

$$Q_{N\gamma \to Na} \approx \int \frac{dE_\gamma}{\pi^2} E_\gamma^2 f_\gamma(p_\gamma) \underbrace{n_B}_{\text{targets}} \underbrace{\sigma_{\gamma N \to Na}(E_\gamma)}_{\text{x-section}} \times \underbrace{E_\gamma}_{\text{energy escaping}}$$

- WZW Non-degenerate regime

$$\frac{Q^{\text{WZW,ND}}_{N\gamma \to Na}}{10^{34}\ \text{erg/s/cm}^3} \approx 5.6\, C_A^2\, g_{40}^4\, T_{40}^8\, \rho_{15} \left(\frac{10^9\ \text{GeV}}{f_a}\right)^2$$



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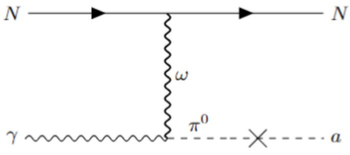
$$\frac{Q^{\rm WZW,ND}_{N\gamma\to Na}}{10^{34}\ \text{erg/s/cm}^3} \approx 5.6\, C_A^2\, g_{40}^4\, T_{40}^8\, \rho_{15} \left(\frac{10^9\ \text{GeV}}{f_a}\right)^2$$

- WZW Degenerate regime

$$\frac{Q^{\rm WZW,D}_{N\gamma\to Na}}{10^{34}\text{erg/s/cm}^3} \approx 1.7\, C_A^2\, g_{40}^4 T_{40}^9 \left(\frac{10^9\ \text{GeV}}{f_a}\right)^2$$



Emissivities of the $\gamma N \to Na$: main result

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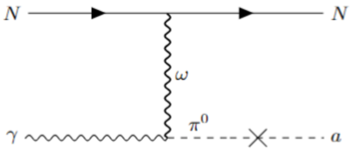
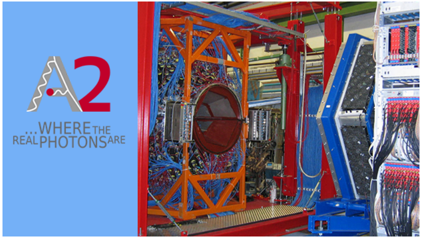
- ND computation holds for $T \gtrsim 30$ MeV.

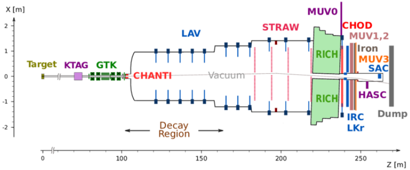


What is the value of g_ω ?

- Large range of theoretical prediction:
  $g_\omega \in 8 - 60!$

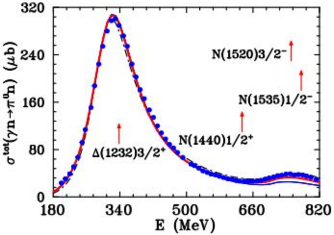
MAMI and NA60 collabs





What is the value of g_ω ?

- Large range of theoretical prediction: $g_\omega \in 8 - 60$!
- $\sigma_{\gamma N \to N\pi_0}$ (MAMI) and $\Gamma_{\omega \to \pi_0 \gamma}$ (MAMI and NA60) measured



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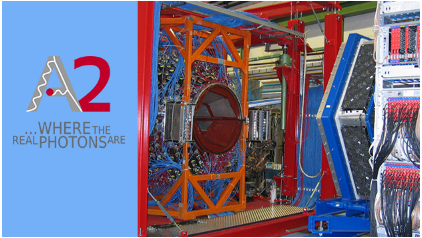

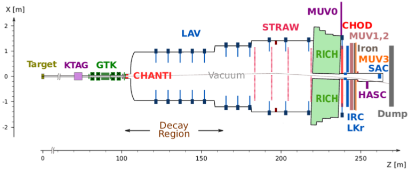

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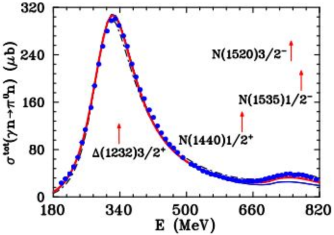
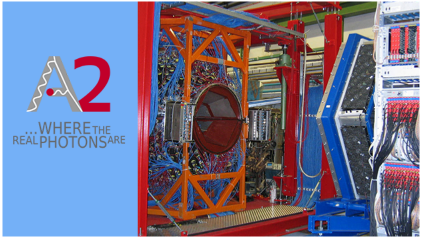
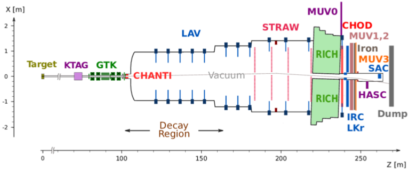


- Consistent with $g_\omega \sim 8 - 10$

MAMI and NA60 collabs





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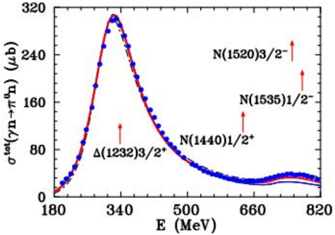
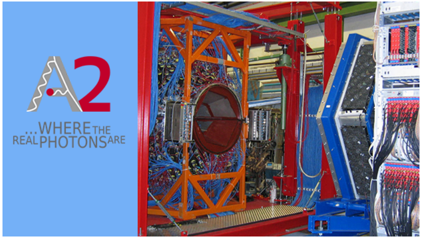
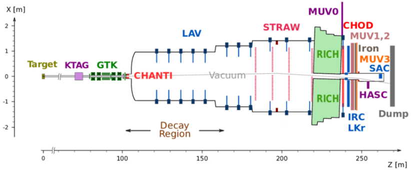


- Consistent with $g_\omega \sim 8 - 10$
- Data driven method available.

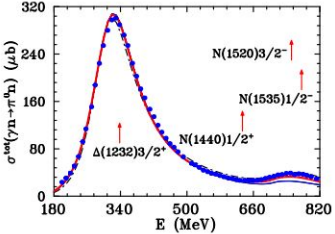
MAMI and NA60 collabs

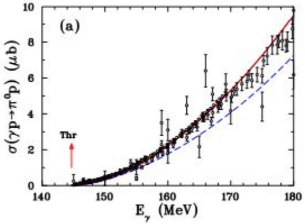




Data-driven photo production

- $\sigma_{\gamma N \to N a} \approx \frac{f_\pi C_A}{f_a} \sigma_{\gamma N \to N \pi_0}, \quad E > 145$ MeV





Data-driven photo production

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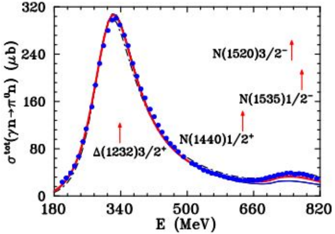
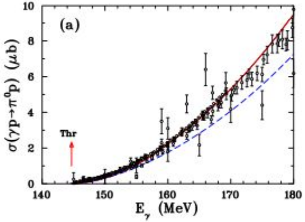
- $\sigma_{\gamma N\to N\pi_0}$ is measured!





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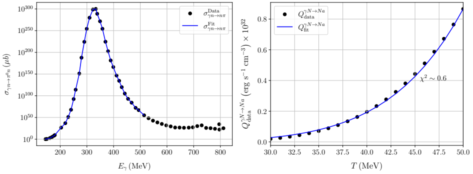
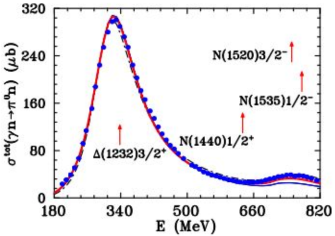
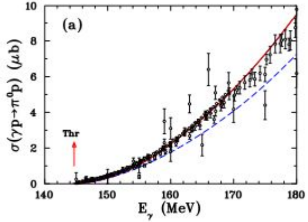
- Axion emissivities:

$$\frac{Q^{\gamma N \to N a}_{\text{data}}}{1.6 \times 10^{33}\ \text{cm}^{-3} s^{-1} \text{erg}} \approx \left(\frac{C_A 10^9}{f_a/\text{GeV}} \right)^2 \times \rho_{15} T_{40}^{6.73}$$







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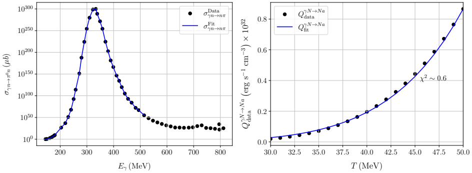
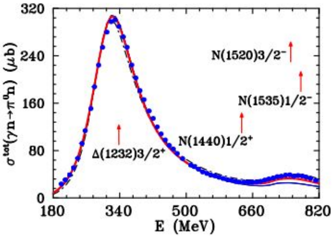
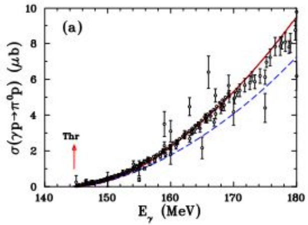


- The data-driven piece dominates if $g_\omega < 20$:

$$Q^{\text{data,ND}}_{N\gamma\to Na} > Q^{\text{WZW}}_{N\gamma\to Na}$$



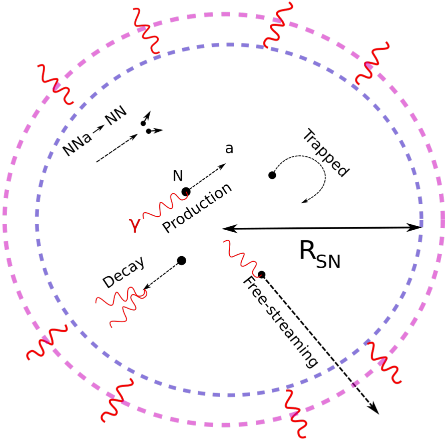


Emissivities of the $\gamma N \to Na$: further subtleties

- Absorption via $aN \to \gamma N$ or $NNa \to NN$:

$$L_a \approx \frac{1}{\Gamma_{aN\to\gamma N}} + \frac{1}{\Gamma_{NNa\to NN}}$$

We cut if $L_A < R_{SM} \sim 10$ km



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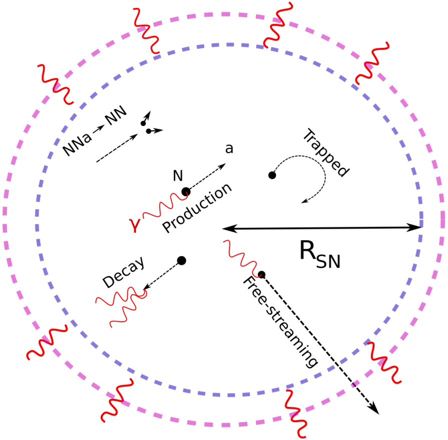
- Lapse effects: $\alpha(M,r) \approx \sqrt{1-2M/r}$

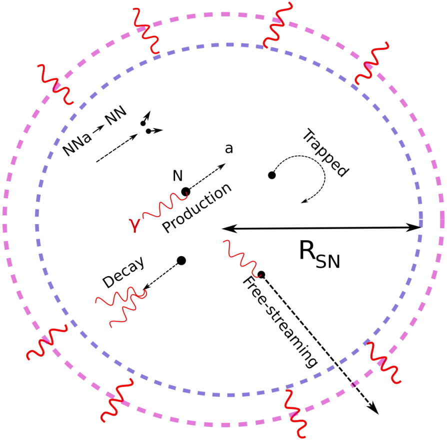
$$E_\infty = E_{\text{emission}} \times \alpha$$

$$n_a^\infty = n_{\text{emission}} \times \alpha$$

$$\implies Q_\infty = \alpha^2 Q_{\text{emission}}$$



Emissivities of the $\gamma N \to Na$: further subtleties when axions are massive

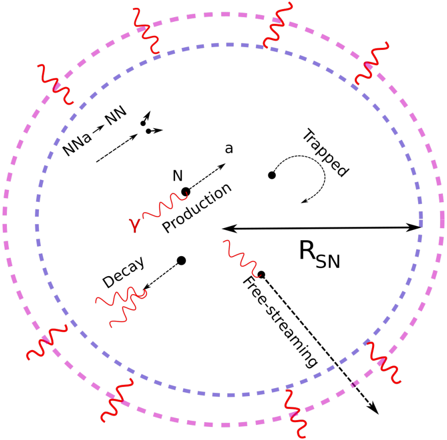


Massive axions regime

- Redshift effect:

$$Q \approx \int_{m_a/\alpha} dE \ldots$$

Emissivities of the $\gamma N \to Na$: further subtleties when axions are massive



Massive axions regime

- Redshift effect:

$$Q \approx \int_{m_a/\alpha} dE \ldots$$

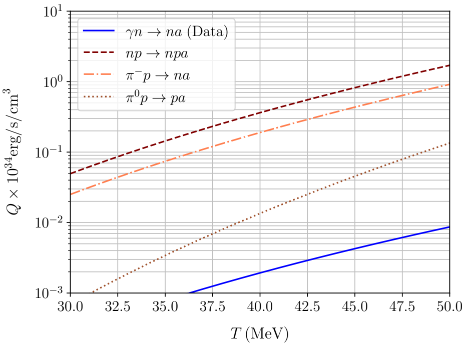
- Decay of the heavy axions:

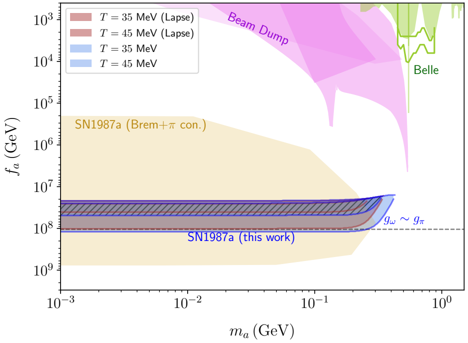
$$L_{a\to\gamma\gamma} \approx \frac{4\times 10^4 \text{ km}}{(G_{a\gamma\gamma}/10^{-9}\text{GeV}^{-1})^2} \frac{E_a/100 \text{ MeV}}{(m_a/100 \text{ MeV})^4}$$

$$L_{a\to\gamma\gamma} > R_{\text{SN}}$$

Impact of the photo-production on axion constraints for KSVZ model

Contribution from photo-production to the emissivity



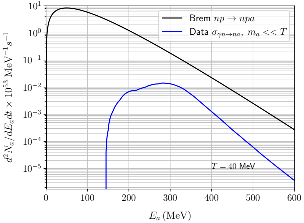


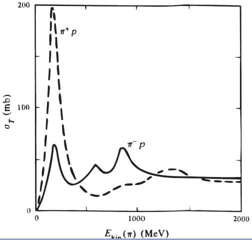
Can we observe the axions emitted from the supernovae

Bremsstrahlung peak: $E_a \sim 1.25T \sim 50 - 60$ MeV
Photo-production peak: $E_a \sim 6T \sim 250 - 300$ MeV

$$\frac{d^2 N_a}{dE_a dt} \approx C_f \rho_{15} \left(\frac{C_A 10^9}{f_a/\text{GeV}}\right)^2 g_{40}^4 \left(\frac{E_a}{\text{MeV}}\right)^6 e^{-E_a/T} ,$$

$$\text{C}_f = 4.6 \times 10^{42} \text{ MeV}^{-1}\text{s}^{-1}$$

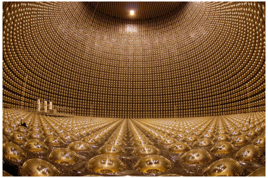




$$\sigma_{ap^+ \to N\pi^+} \approx 10^{-25} C_A^2 (f_\pi / f_a)^2 cm^{-2}$$

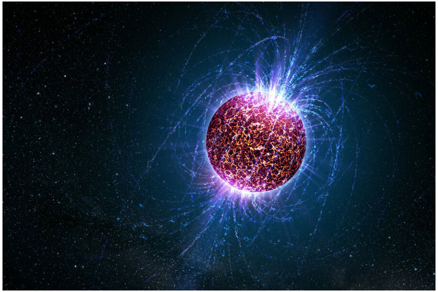
$$\frac{dN_\pi}{dt} \approx 6 \rho_{15} C_A^4 \left(\frac{10^9}{f_a/\text{GeV}}\right)^4 g_{40}^4 T_{40}^7$$

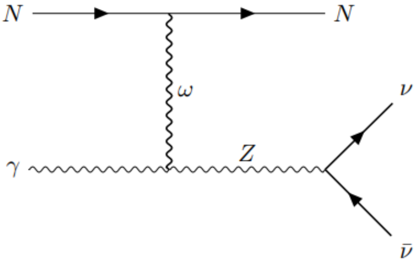
$$\times \left(\frac{\text{Kpc}}{d}\right)^2 \left(\frac{M_{\text{detector}}}{\text{kton}}\right) \left(\frac{\text{g/mol}}{m_{H_2O}}\right)$$



Emission of neutrino from SN

Photo-production of neutrino in NS

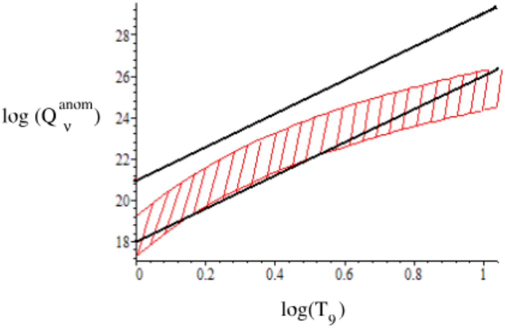




With Sabyasachi Chakraborty and Aritra Gupta: 2306.15872

WZW could contribution to NS cooling !

First computation of $N\gamma \to N\nu\bar{\nu}$ in [Harvey, Hill and Hill, arXiv:0708.1281]



But neglect the degeneracy effect ...

How do we compute the emissivity from a star ?

- Emissivity computation for $\gamma N \to NX$

$$Q^{N\gamma\to NX}_{\rm cooling} \equiv \int \frac{d^3p_\gamma g_\gamma f_\gamma(p_\gamma)}{(2\pi)^3 2E_\gamma} \int \frac{g_N d^3p_{N_1} d^3p_{N_2}}{(2\pi)^3 2E_{N_1}(2\pi)^3 2E_{N_2}} \prod_{X_i} \int \frac{(2\pi)^4 d^3p_{X_i}}{(2\pi)^3 2E_{X_i}} \langle|\mathcal{M}|^2\rangle \left(\sum_i E_{X_i}\right)$$
$$f_N(E_{N_1})\,(1 - f_N(E_{N_2}))\delta(E_1 - E_2 - Q_0)\,\delta^3(\vec{p}_1 - \vec{p}_2 - \vec{q})\,. \quad (2)$$

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- How to compute:

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- Degenerate case: $(1 - f_N(E_{N_2})) \ll 1$: $\quad \xi \equiv \frac{p_F^2}{2\pi m_N T} \gg 1$

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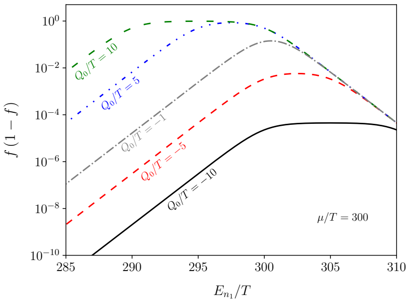
- Degenerate case: $(1 - f_N(E_{N_2})) \ll 1$: $\quad \xi \equiv \frac{p_F^2}{2\pi m_N T} \gg 1$
- Non-degenerate case: $(1 - f_N(E_{N_2})) \to 1$: $\quad \xi \ll 1$

Degenerate computation



$$Q^{2\to 3} = \frac{64\,n_F}{4}\,\frac{g_\gamma}{3}\kappa^2 \int \frac{d^3p_\gamma}{(2\pi)^3}\,\frac{f_\gamma}{2E_\gamma}|\vec{p}_\gamma|^2 \int \frac{d^3p_1\,d^3p_2}{(2\pi)^6 2E_1\,2E_2} E_1\,E_2\,(E_1+E_2)\,S(q^\mu)\ ,$$

$$S(Q_0,q) = \frac{M_N^2\,T}{\pi q}\,\frac{z}{1-e^{-z}}\Theta(\mu - E_-)\ .$$

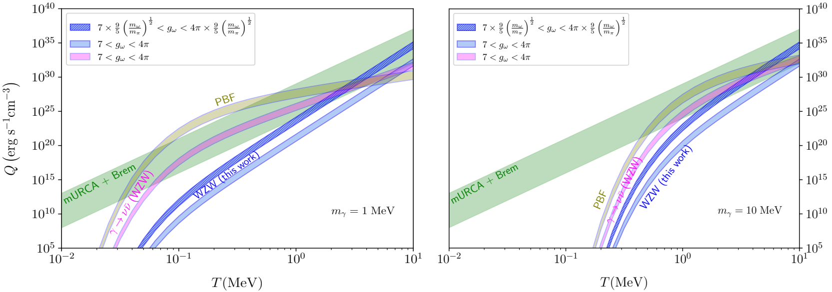
Standard cooling NS paradigm

- mURCA: $n\,n \longrightarrow n\,p\,e\,\bar{\nu}_e\,, \quad n\,p\,e \longrightarrow n\,n\,\nu_e$.:

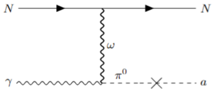
$$Q^{\text{mURCA}} \simeq 10^{26-29}\left(\frac{T}{1\,\text{MeV}}\right)^8 \text{erg}\,\text{s}^{-1}\,\text{cm}^{-3}$$

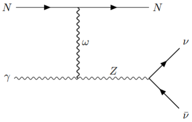
- Bremsstrahlung

$$Q^{\nu-\text{Brem}} \simeq 10^{24-28}\left(\frac{T}{1\,\text{MeV}}\right)^8 \text{erg}\,\text{s}^{-1}\,\text{cm}^{-3}$$



Conclusions and outlook





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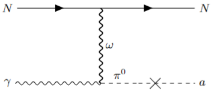

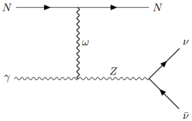

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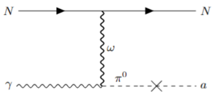

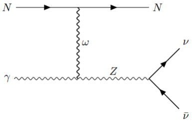

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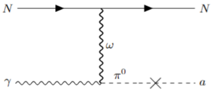

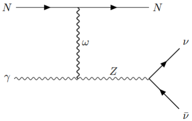

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- pheno of WZW: "Circulez, Y'a rien à voir"?

Better keep exploring: Harvey Hill Hill arxiv:0712.1230

$$\begin{aligned}
\Gamma_{AAB} &= \mathcal{C}\int dZZ\left[\frac{s_W^2}{c_W^2}\rho^0+\left(\frac{3}{2c_W^2}-3\right)\omega-\frac{1}{2c_W^2}f\right]+dAZ\left[-\frac{s_W}{c_W}\rho^0-\frac{3s_W}{c_W}\omega\right]+dZ\left[W^-\rho^++W^+\rho^-\right]\frac{s_W^2}{c_W}\\
&\quad -s_W dA\left[W^-\rho^++W^+\rho^-\right]+(DW^+W^-+DW^-W^+)\left[-\frac{3}{2}\omega-\frac{1}{2}f\right],\\
\Gamma_{ABB} &= \mathcal{C}\int Z\Bigg\{d\rho^0\left[-\frac{3}{2c_W}\omega-\frac{s_W^2}{c_W}a^0+\left(-\frac{3}{2c_W}+3c_W\right)f\right]+d\omega\left[-\frac{3}{2c_W}\rho^0+\left(-\frac{3}{2c_W}+3c_W\right)a^0-\frac{s_W^2}{c_W}f\right]\\
&\quad +da^0\left[\frac{s_W^2}{c_W}\rho^0+\left(\frac{3}{2c_W}-3c_W\right)\omega-\frac{1}{2c_W}f\right]+df\left[\left(\frac{3}{2c_W}-3c_W\right)\rho^0+\frac{s_W^2}{c_W}\omega-\frac{1}{2c_W}a^0\right]\Bigg\}\\
&\quad +s_W dA\left(\rho^0a^0+3\rho^0f+3\omega a^0+\omega f+\rho^+a^-+\rho^-a^+\right)-\frac{s_W^2}{c_W}dZ\left(\rho^+a^-+\rho^-a^+\right)\\
&\quad +\frac{3}{2}\left[W^+D\rho^-+W^-D\rho^+)\right](-\omega+f)+\frac{3}{2}\left[W^+(-\rho^-+a^-)+W^-(-\rho^++a^+)\right]d\omega\\
&\quad +\frac{1}{2}\left[W^+Da^-+W^-Da^+\right](-3\omega-f)+\frac{1}{2}\left[W^+(-3\rho^--a^-)+W^-(-3\rho^+-a^+)\right]df\,,\\
\Gamma_{BBB} &= \mathcal{C}\int 2\Big[\left(\rho^-f+\omega a^-\right)D\rho^++\left(\omega a^++\rho^+f\right)D\rho^-+\left(\omega a^0+\rho^0f\right)d\rho^0+\left(\rho^+a^-+\rho^-a^++\omega f+\rho^0a^0\right)d\omega\Big],\\
\Gamma_{AAAB} &= \mathcal{C}\int iW^+W^-Z\left[3c_W\omega+\left(c_W+\frac{1}{2c_W}\right)f\right],\\
\Gamma_{AABB} &= \mathcal{C}\int i\Bigg\{W^+W^-\left[\frac{3}{2}(\rho^0+a^0)\omega-\frac{1}{2}(\rho^0-a^0)f\right]\\
&\quad +W^+Z\left[\left(\frac{3c_W}{2}-\frac{1}{c_W}\right)\rho^-f-\frac{3c_W}{2}\rho^-\omega-\frac{c_W}{2}a^-f+\frac{3c_W}{2}\omega a^-\right]
\end{aligned}$$