UCLouvain

# Probing Solar Heavy Neutrinos with Heliospheric Electrons

COSPA, October 2025

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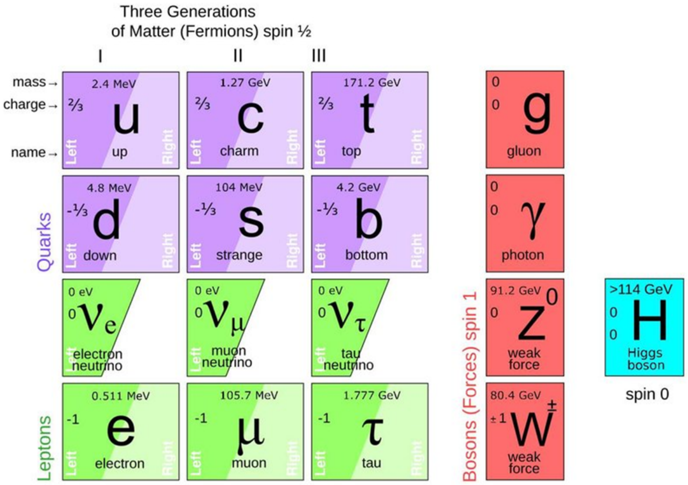
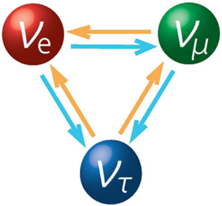
Université Catholique de Louvain

# Intro on HNLs i

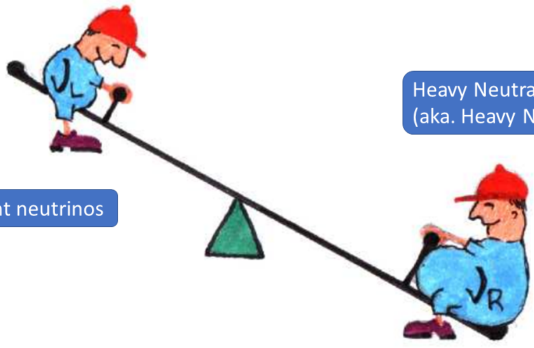


# Intro on HNLs ii




Neutrinos oscillate! → Neutrinos have mass

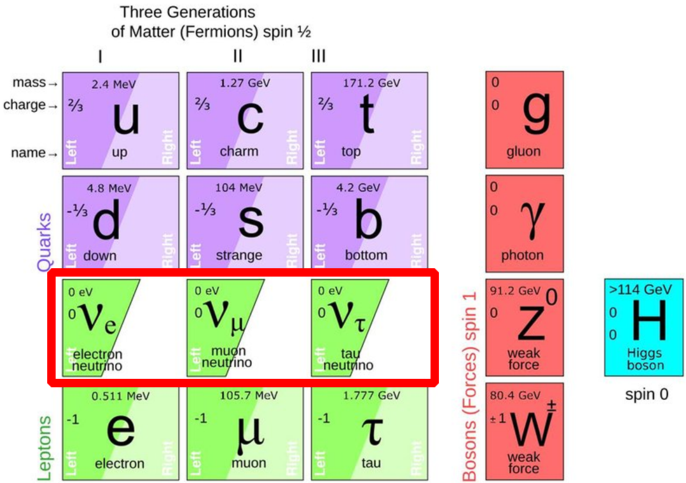
# Intro on HNLs iii



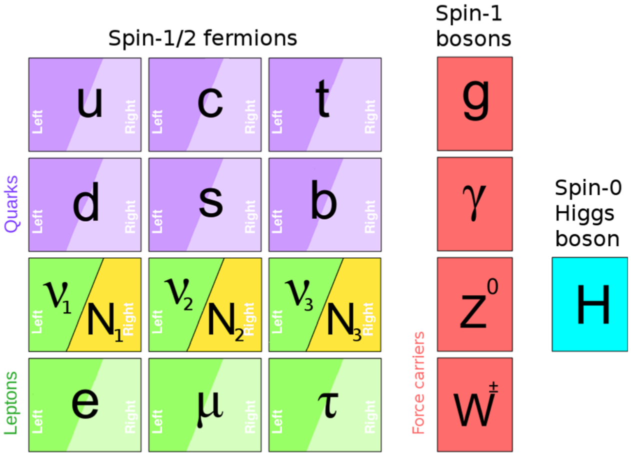

Heavy Neutral Leptons
(aka. Heavy Neutrinos)

Light neutrinos

# Intro on HNLs iv

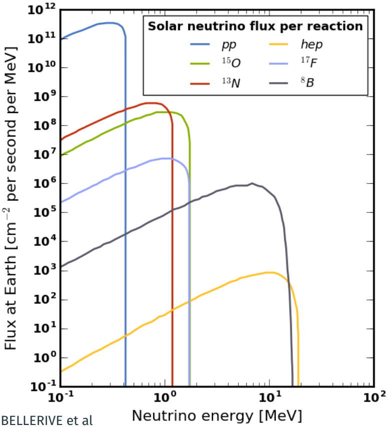


# Intro on HNLs ν



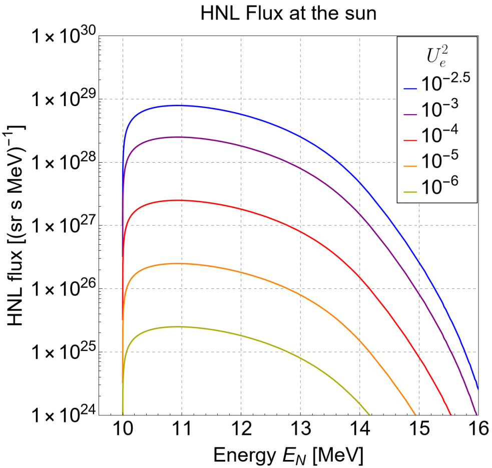
# Solar neutrinos i

Solar neutrino spectra




BELLERIVE et al

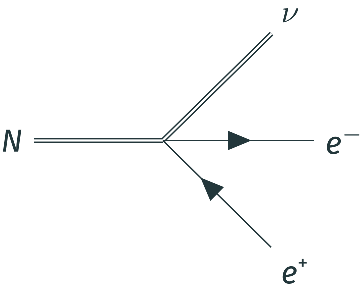
# Heavy Neutral Lepton flux i




$$\frac{d\varphi_{HNL}}{dE_N}(E_N, R = 0)$$

$$= |U_e|^2 \sqrt{1 - \left(\frac{M_N}{E_N}\right)^2} \varphi_\nu(E_N)$$

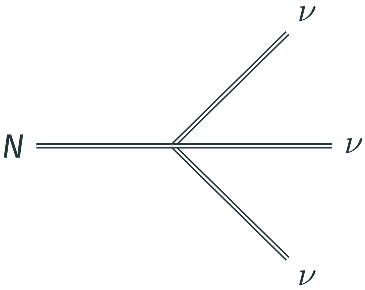
# HNL decay




$N \to \nu e^{+} e^{-}$

$$\Gamma_{N\to\nu e^{+}e^{-}} \approx \frac{G_F^2 M_N^5}{192\pi^3}|U_e|^2$$

Opens at : $M_N = 1.02 MeV$

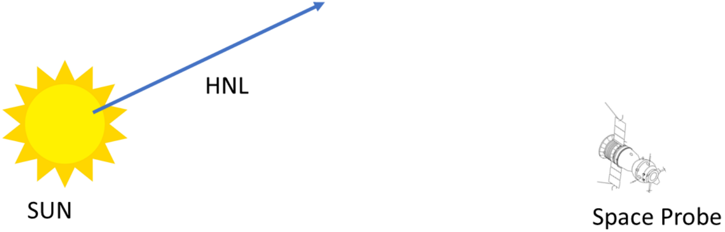


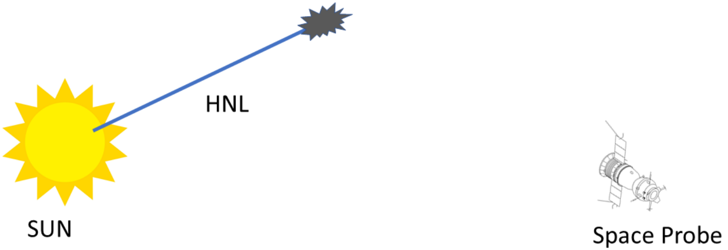

$N \to 3\nu$

$$\Gamma_{N\to 3\nu} = \frac{G_F^2 M_N^5}{96\pi^3}|U_e|^2$$

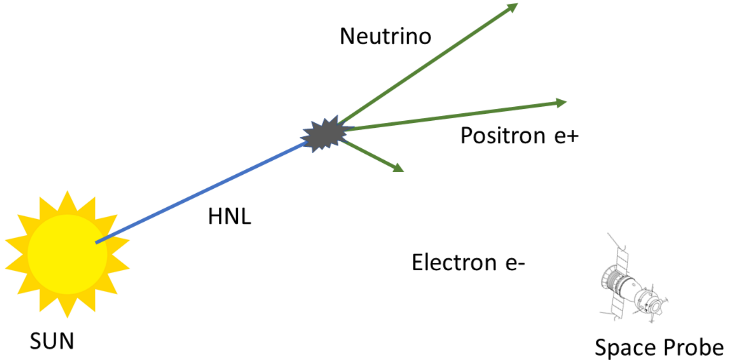
Opens at : $M_N \approx 0 MeV$

# HNL Production i

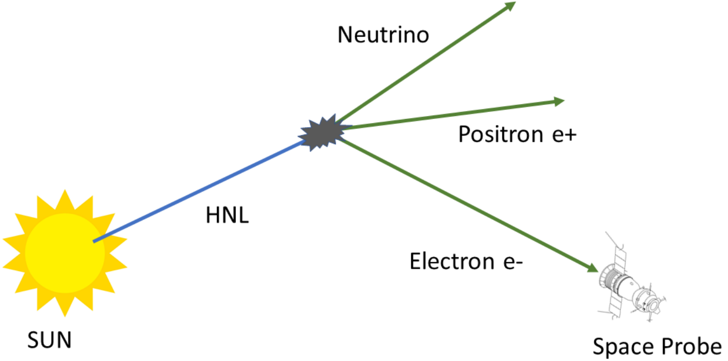



HNL
SUN
Space Probe

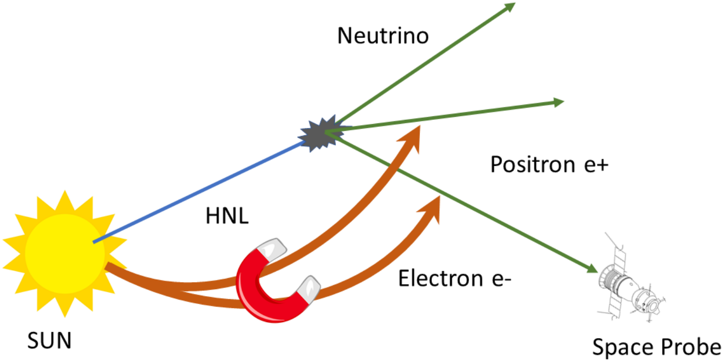
# HNL Production iii



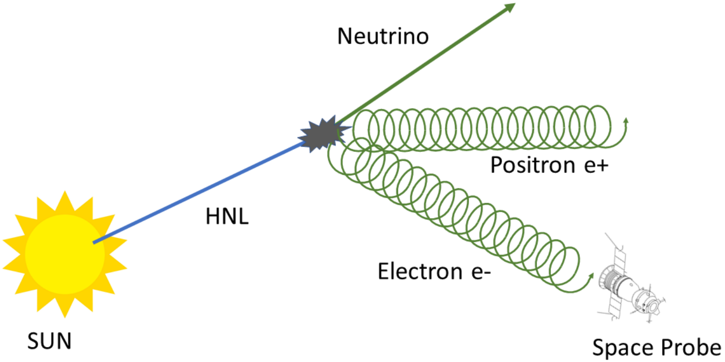
# HNL Production iv

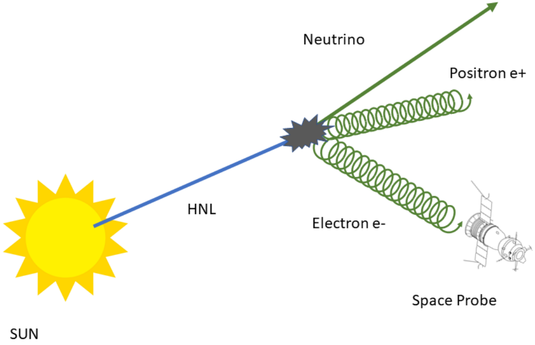


# Electron propagation i

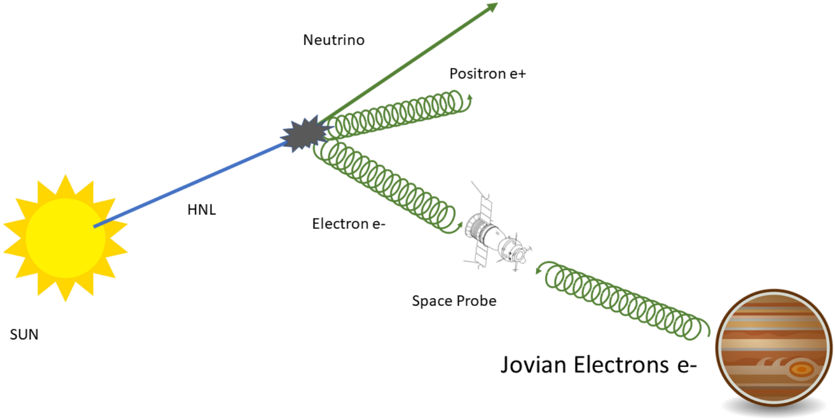


# Electron propagation ii

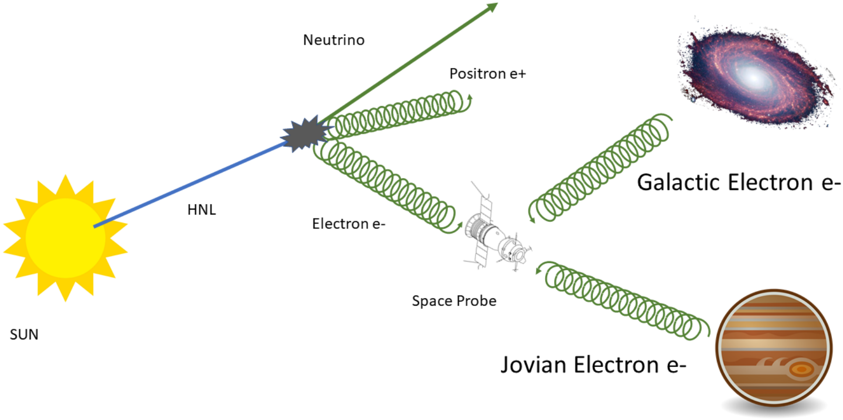



Neutrino
Positron e+
HNL
Electron e-
Space Probe
SUN

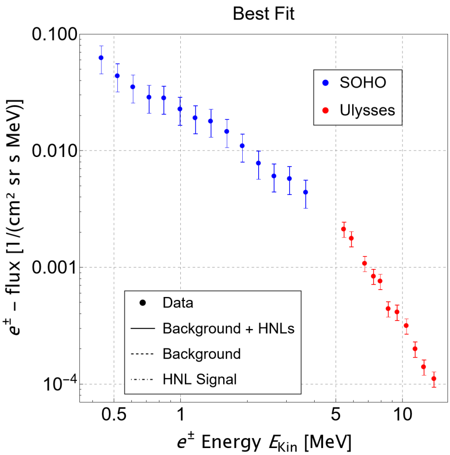
# Background electrons ii



# Background electrons iii

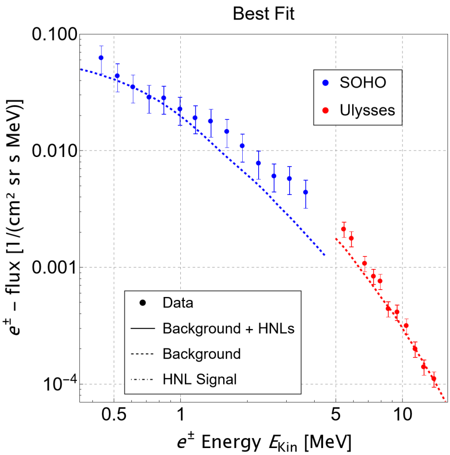


# Putting everything together i



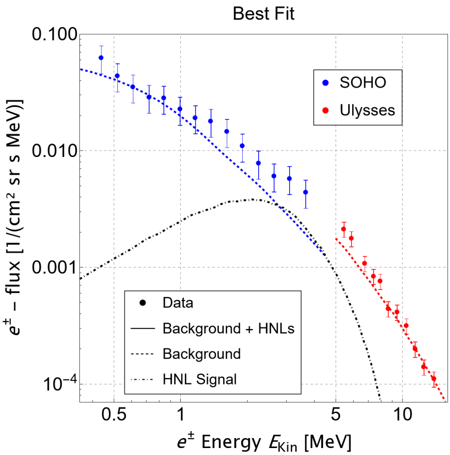

$$(M_N \simeq 8.2\,\mathrm{MeV},\, U_e^2 \simeq 7.9 \times 10^{-7})$$

# Putting everything together ii



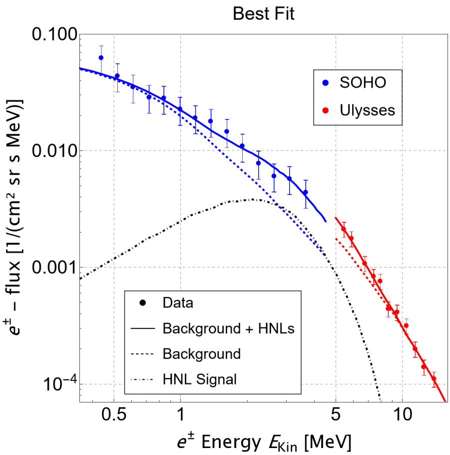

$$(M_N \simeq 8.2\,\text{MeV},\ U_e^2 \simeq 7.9 \times 10^{-7})$$

# Putting everything together iii



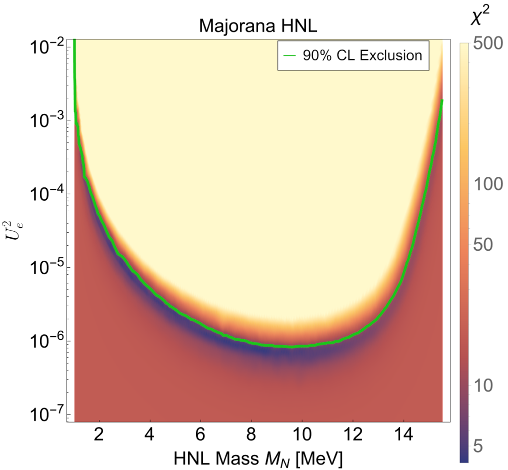

$$(M_N \simeq 8.2\,\text{MeV},\ U_e^2 \simeq 7.9 \times 10^{-7})$$

# Putting everything together iv

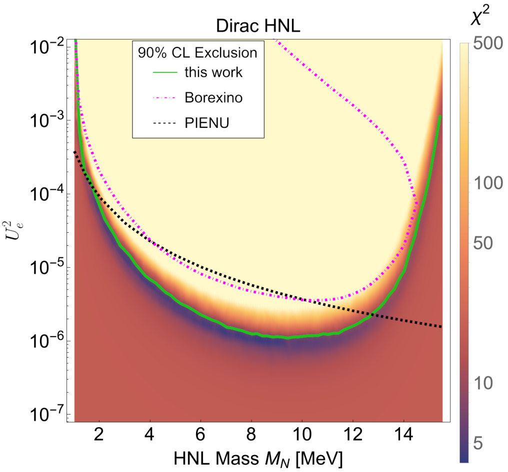



$$(M_N \simeq 8.2\,\text{MeV},\ U_e^2 \simeq 7.9 \times 10^{-7})$$

# Putting everything together v



# Putting everything together vi



# Conclusion i

- Solar neutrinos can be used to probe HNLs
- The decay $N \rightarrow e^{+}e^{-}\nu$ is studied
- Added Jovian background
- Constraints through Ulysses and SOHO

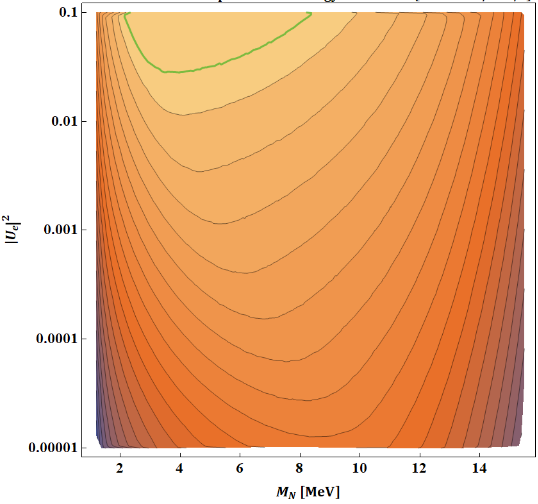
# Conclusion ii

More infos in our paper : ArXiv 2412.14752

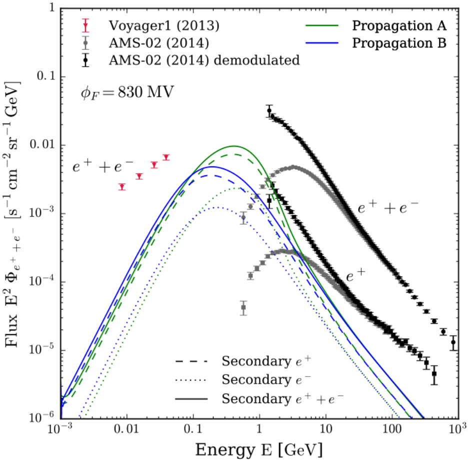
Thanks for listening to my talk!

# Additional slides i

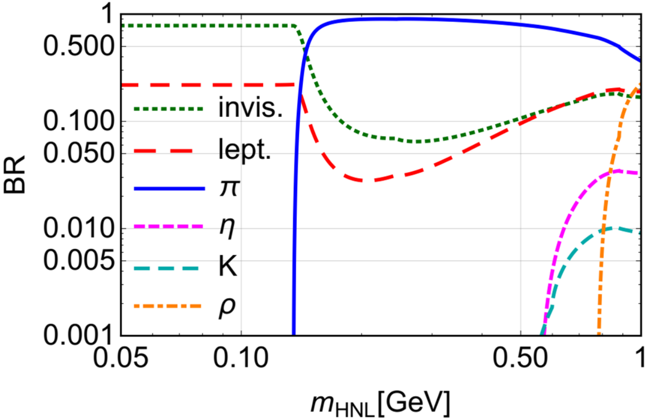
$E^2 * \Phi$ at 127AU for a positron of energy 8.201 MeV [Positrons/cm$^2$/s]



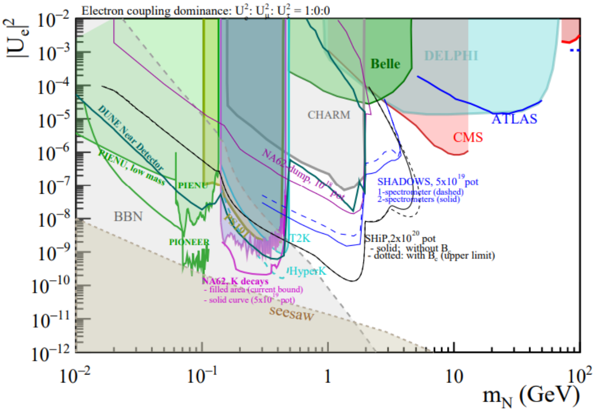
# Additional slides ii



# Additional slides iii



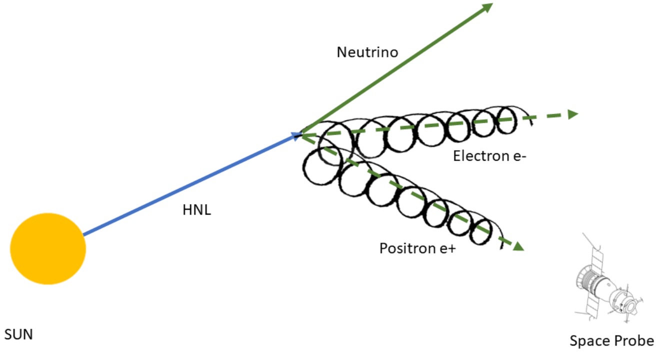
# Additional slides iv



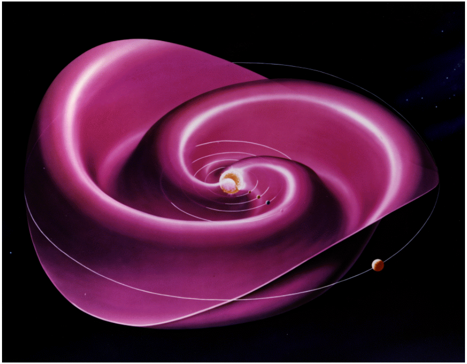
# Additional slides v

| Channel | Opens at [MeV] | Relevant from [MeV] | Relevant to [MeV] | Max BR [%] | Reference in text |
|---|---|---|---|---|---|
| $N \to \nu_\alpha \nu_\beta \bar{\nu}_\beta$ | $\sum m_\nu \approx 0$ | $\sum m_\nu \approx 0$ | — | 100 | (3.5) |
| $N \to \nu_\alpha e^+ e^-$ | 1.02 | 1.29 | — | 21.8 | (3.4) |
| $N \to \nu_\alpha \pi^0$ | 135 | 136 | 3630 | 57.3 | (3.7) |
| $N \to e^- \pi^+$ | 140 | 141 | 3000 | 33.5 | (3.6) |
| $N \to \mu^- \pi^+$ | 245 | 246 | 3000 | 19.7 | (3.6) |
| $N \to e^- \nu_\mu \mu^+$ | 106 | 315 | — | 5.15 | (3.1) |
| $N \to \mu^- \nu_e e^+$ | 106 | 315 | — | 5.15 | (3.1) |
| $N \to \nu_\alpha \mu^+ \mu^-$ | 211 | 441 | — | 4.21 | (3.4) |
| $N \to \nu_\alpha \eta$ | 548 | 641 | 2330 | 3.50 | (3.7) |
| $N \to e^- \pi^+ \pi^0$ | 275 | 666 | 4550 | 10.4 | (B.42) |
| $N \to \nu_\alpha \pi^+ \pi^-$ | 279 | 750 | 3300 | 4.81 | (B.43) |
| $N \to \mu^- \pi^+ \pi^0$ | 380 | 885 | 4600 | 10.2 | (B.42) |
| $N \to \nu_\alpha \omega$ | 783 | 997 | 1730 | 1.40 | (3.9) |
| $N \to \nu_\alpha (3\pi)^0$ | $\gtrsim 405$ | $\gtrsim 1000$ | ? | ? | No |
| $N \to e^- (3\pi)^+$ | $\gtrsim 410$ | $\gtrsim 1000$ | ? | ? | No |
| $N \to \nu_\alpha \eta'$ | 958 | 1290 | 2400 | 1.86 | (3.7) |

# Additional slides vi



# Additional slides vii



# Additional slides viii

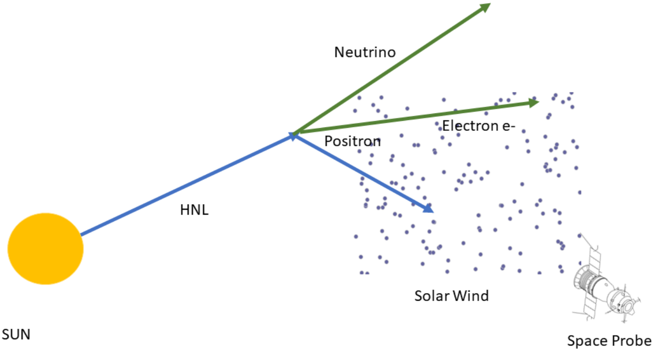
The rate of energy lost during this process is given by [James J. Condon and Scott M. Ransom] :

$$P = -\frac{dE}{dt} = \frac{4}{3}\sigma_T \beta^2 \gamma^2 c U_B$$

with $\sigma_T$ the Thompson cross-section and $U_B$ the magnetic energy density $U_B = \frac{B^2}{2\mu_0}$.

- Energy loss is small enough to be neglected
- Any directional information gets lost!

# Additional slides ix



The mean free path is given by [Kuznetsova et al. 0911.0118]

$$L = \frac{1}{\langle \sigma v_{\rm rel} \rangle n_{\rm SW}}$$

$L$ being the mean free path and $n_e$ being the solar wind particle density.

We need the following formula :

$$\langle \sigma v_{\text{rel}} \rangle n_{\text{SW}} = \frac{\int d^3 p_e \int d^3 p_{\text{SW}} \sigma_{ee} v_{\text{rel}} f_e(\vec{p}_e) f_{\text{SW}}(\vec{p}_{\text{SW}})}{\int d^3 p_e f_e(\vec{p}_e)} \tag{1}$$

- $f_{\text{SW}}(p_{\text{SW}}) = e^{-E_{\text{SW}}/T}$ being a Boltzmann distribution (Solar wind particles (electrons) )
- $f_{e^+}(p_{e^+}) = \frac{\delta^3(\vec{p}_{e^+} - \vec{k})}{V}$ electron from a HNL decay and $V$ being a test volume

We have that,

$$\langle\sigma v_{\mathrm{rel}}\rangle n_e = g_1 \frac{1}{(2\pi)^2}\frac{1}{4k_0}\frac{1}{2k}\int_{4m_e^2}^{\infty} ds\sigma(s)\lambda^{1/2}(s)T(e^{-E_-/T} - e^{-E_+/T})$$

with $E_\pm = \sqrt{\frac{\left(k(s-2m^2)\pm k_0\sqrt{s(s-4m^2)}\right)^2}{4m^4} + m^2}$, with $k^\mu$ the external momentum, $\lambda^{1/2}(s) = \sqrt{s}\sqrt{s-4m_e^2}$.

Thermal Möller/Bhabha cross-section for low temperatures $T < m_e$ [Kuznetsova et al. 1109.3546],

$$\sigma(s) = \frac{64\pi\alpha^2}{(s - 4m_e^2)^2} \frac{m_e^4}{m_\gamma^2}$$

with $m_\gamma = 8\pi\alpha \frac{n_e}{m_e}$.

# Electron propagation i

Do the Electrons reach us all the way from the decay to the detector ? Two main ways on how the particles won't reach the detector :

- Loss of energy during gyromagnetic radiation
- Absorption/ collision with solar wind particles