Using solar neutrinos to bound the mass and coupling parameter of Heavy Neutral Leptons

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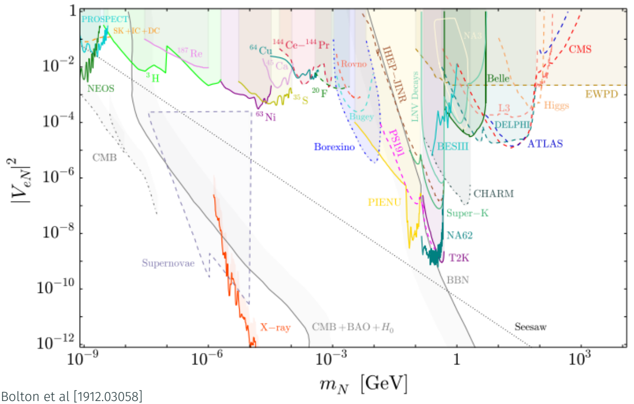
Intro on HNLs i

Motivations for Heavy Neutral Leptons :

- Right handed neutrinos
- Leptogenesis

$$\mathcal{L} \supset -\frac{m_W}{v}\bar{N}\theta^*_\alpha\gamma^\mu e_{L\alpha}W^+_\mu - \frac{m_Z}{\sqrt{2}v}\bar{N}\theta^*_\alpha\gamma^\mu e_{L\alpha}Z_\mu - \frac{M}{v}\theta_\alpha h\bar{\nu}_{L\alpha} + \text{h.c.}$$

Goal : Constraints on $|\theta^*_\alpha\theta_\alpha| \equiv |U_\alpha|^2$ and M_N

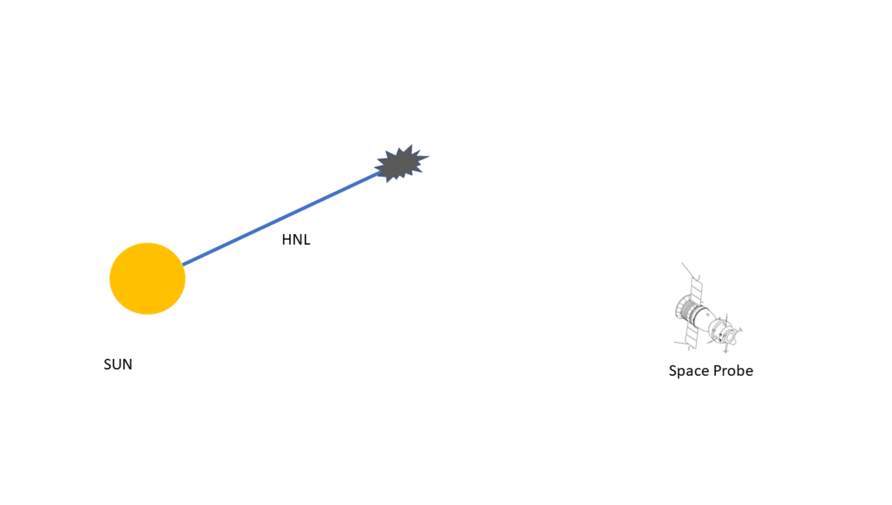


Bolton et al [1912.03058]

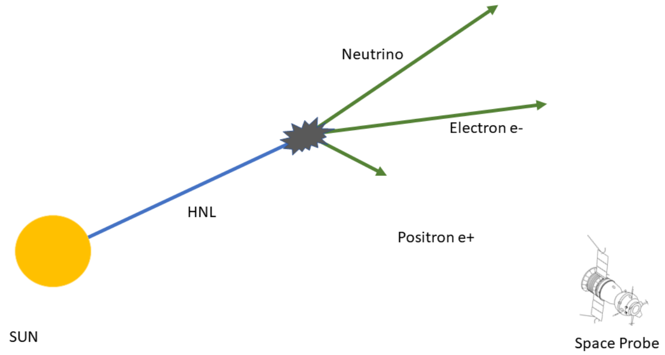
We look at the case where the ration is $|U_e|^2 : |U_\mu|^2 : |U_\tau|^2 = 1 : 0 : 0$.

Procedure i

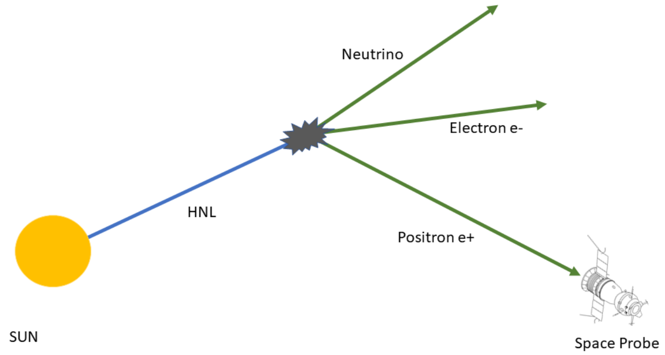
Procedure ii

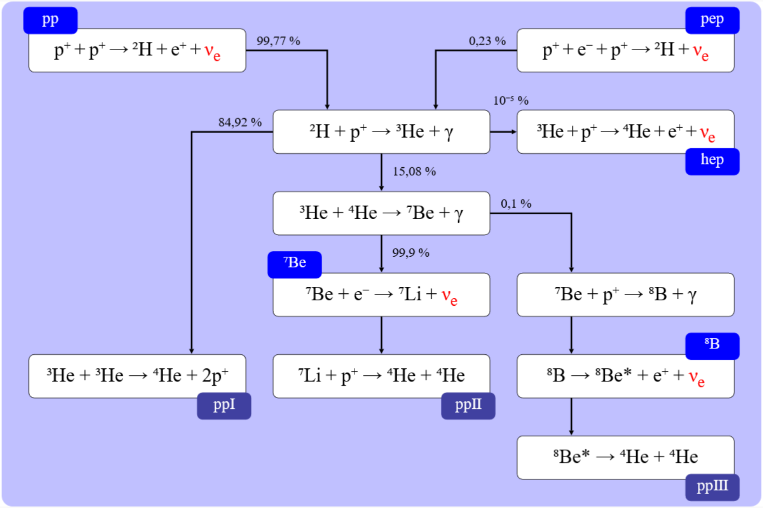


Procedure iii



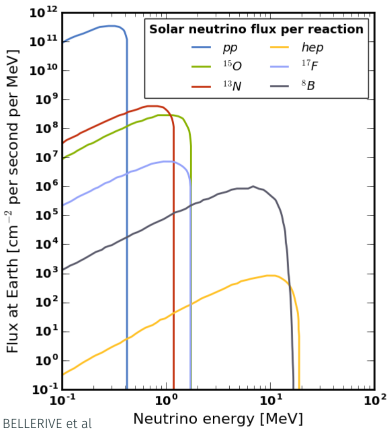
Procedure iv




pp
p⁺ + p⁺ → ²H + e⁺ + νe
99,77 %
0,23 %
pep
p⁺ + e⁻ + p⁺ → ²H + νe
10⁻⁵ %
84,92 %
²H + p⁺ → ³He + γ
³He + p⁺ → ⁴He + e⁺ + νe
hep
15,08 %
³He + ⁴He → ⁷Be + γ
0,1 %
99,9 %
⁷Be
⁷Be + e⁻ → ⁷Li + νe
⁷Be + p⁺ → ⁸B + γ
⁸B
³He + ³He → ⁴He + 2p⁺
ppI
⁷Li + p⁺ → ⁴He + ⁴He
ppII
⁸B → ⁸Be* + e⁺ + νe
⁸Be* → ⁴He + ⁴He
ppIII

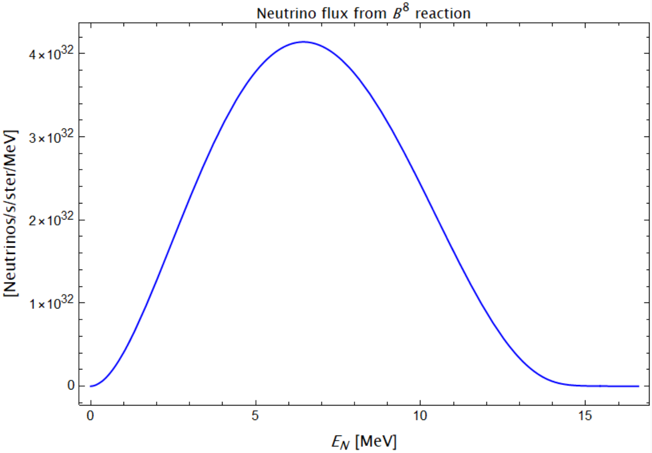
Solar neutrinos ii

Solar neutrino spectra

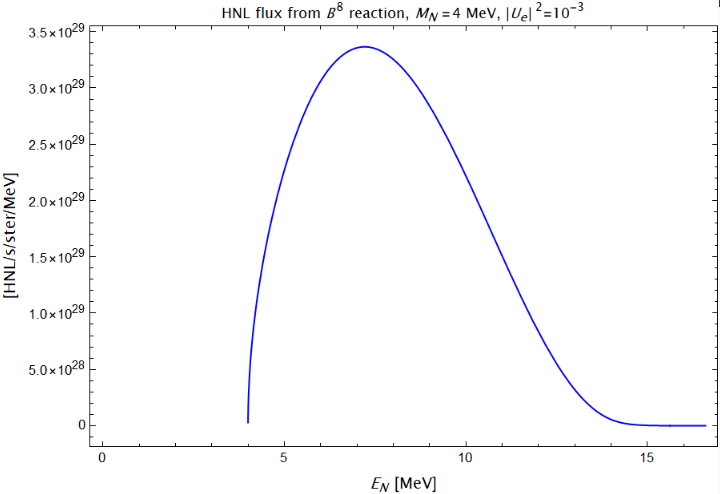


BELLERIVE et al

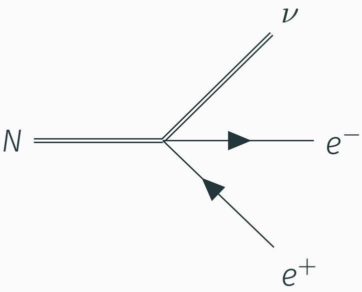
Solar neutrino flux



Heavy Neutral Lepton flux ii



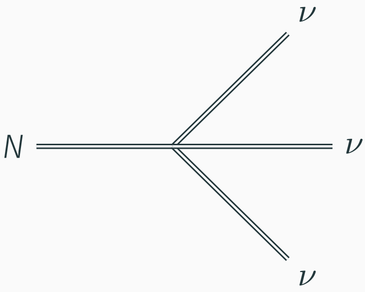
$$\phi_{HNL,sun}(\tilde{E}_N) = |U_e|^2 \sqrt{1 - \left(\frac{M_N}{\tilde{E}_N}\right)^2}\, \phi_\nu(\tilde{E}_N)$$



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

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

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 : $M_N \approx 0 MeV$

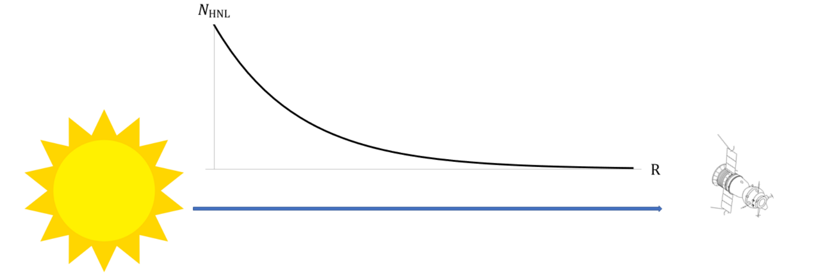
Electron production i

Convention :

We need to distinguish between the different quantities : those in the rest frame of the HNL and those in the rest frame of the sun.

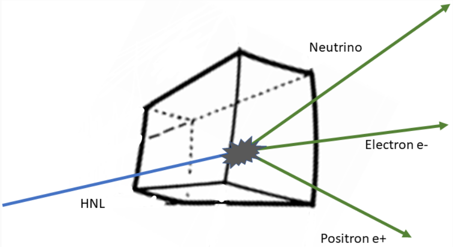
- Tilted quantities are in the rest frame of the sun : $\tilde{E}$, $\cos\tilde{\theta}$, etc.
- Non-tilted quantities are in the rest frame of the HNL : E, $\cos\theta$, etc.

Propagation of the HNL flux :



$$\phi_{HNL}(\tilde{E}_N, \tilde{R}) = \exp\left(-\frac{\tilde{R}}{\sqrt{\frac{\tilde{E}_N^2}{M_N^2} - 1}}\Gamma\right)\phi_{HNL,sun}(\tilde{E}_N).$$

Electron emission rate



$$\phi_{N\to e^+e^-\nu}(\tilde{E}_N,\tilde{R}) = -\frac{d\phi_N}{d\tilde{R}}(\tilde{E}_N,\tilde{R})\frac{\Gamma_e}{\Gamma}.$$

Electron production iv

As such, we can get the electron emission rate as the following expression,

$$\frac{d\phi_e}{d\tilde{E}_e d\tilde{E}_N d\tilde{R} d\cos\tilde{\theta}}(\tilde{E}_e, \tilde{E}_N, \tilde{R}, \cos\tilde{\theta}) \quad = \frac{1}{\beta}\frac{d\tilde{\Gamma}_e}{d\tilde{E}_e d\cos\tilde{\theta}}(\tilde{E}_N, \tilde{E}_e, \cos\tilde{\theta})\phi_{HNL}(\tilde{E}_N, \tilde{R})$$

Electron production v

To get the total flux, we need to integrate over every variable,

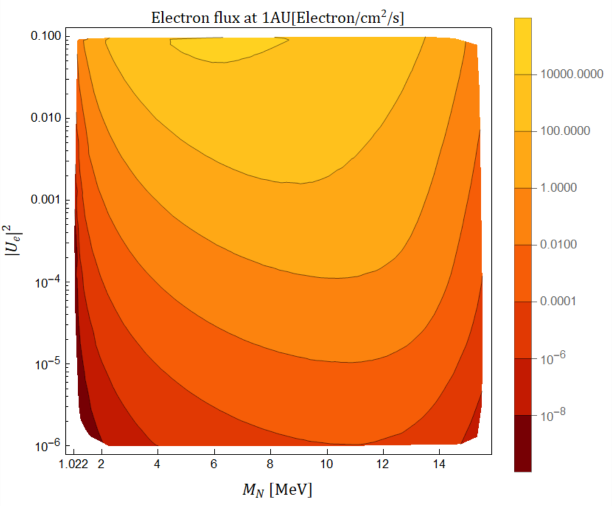
$$\phi_e = \int d\tilde{E}_e \int d\tilde{E}_N \int_0^R dR \frac{1}{\beta} \frac{d\tilde{\Gamma}_e}{d\tilde{E}_e}(\tilde{E}_N, \tilde{E}_e)\phi_N(\tilde{E}_N, \tilde{R})\Theta_{\text{limits}}$$

Electron propagation i

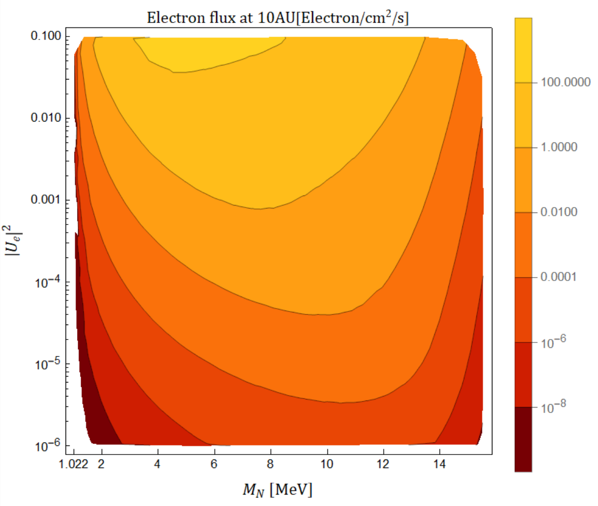
Do the Electrons reach us all the way from the decay to the detector ?
Two main ways on how the particles won't reach the detector :

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

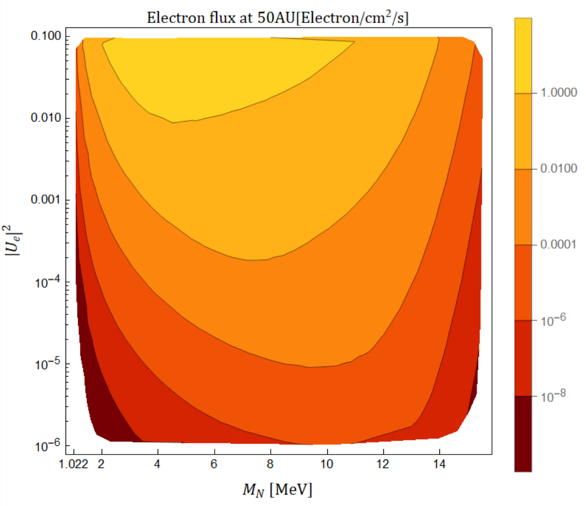
Total electron flux i



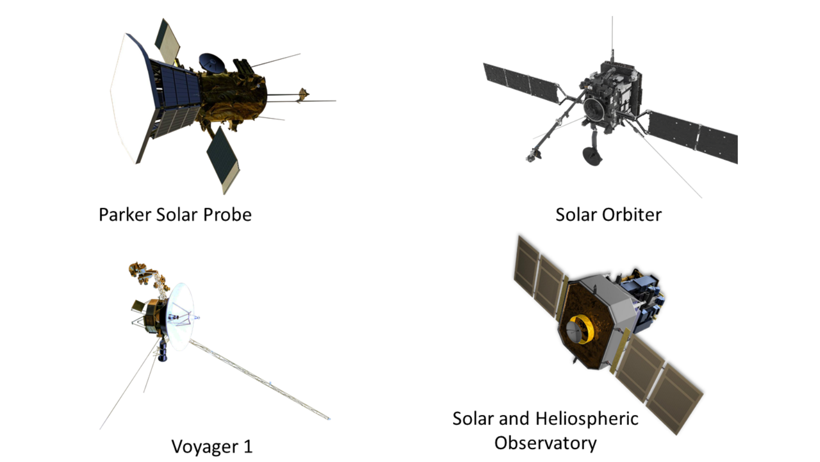
Total electron flux ii



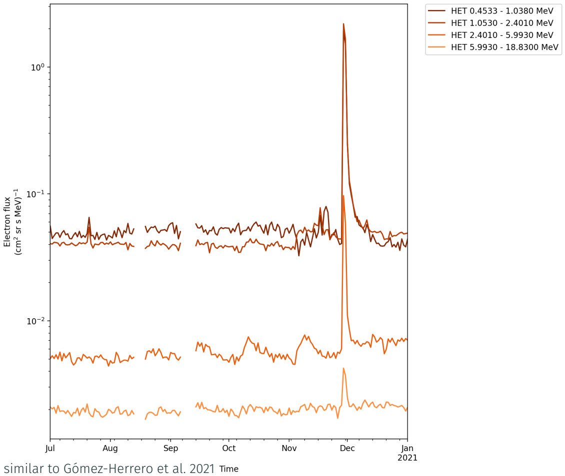
Total electron flux iii



Space probes / detectors i

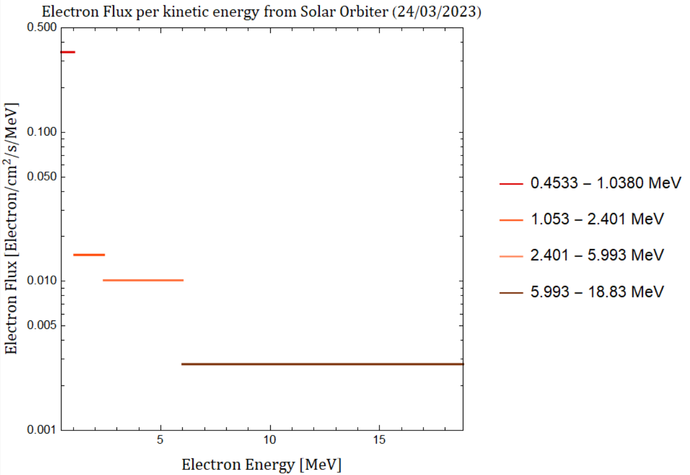


Solar Orbiter i

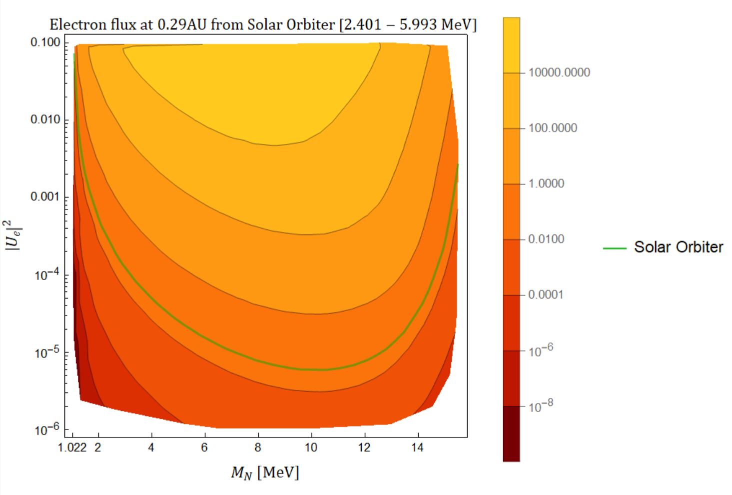


similar to Gómez-Herrero et al. 2021

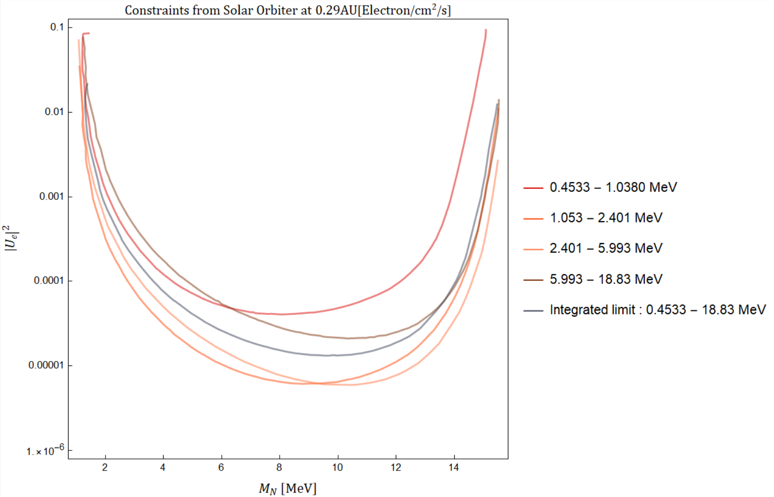
Solar Orbiter ii



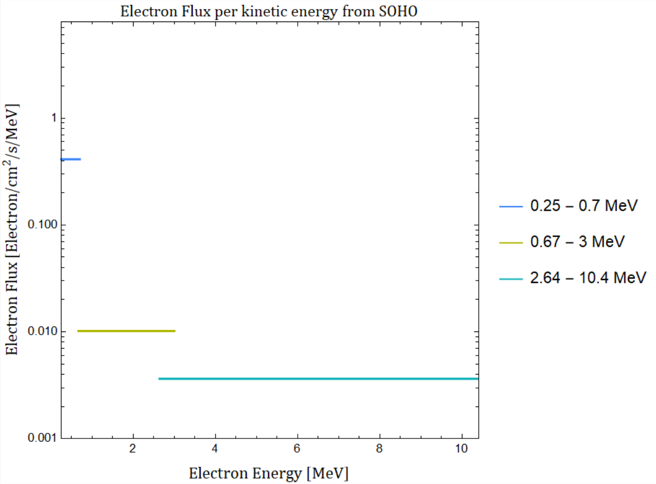
Solar Orbiter iii



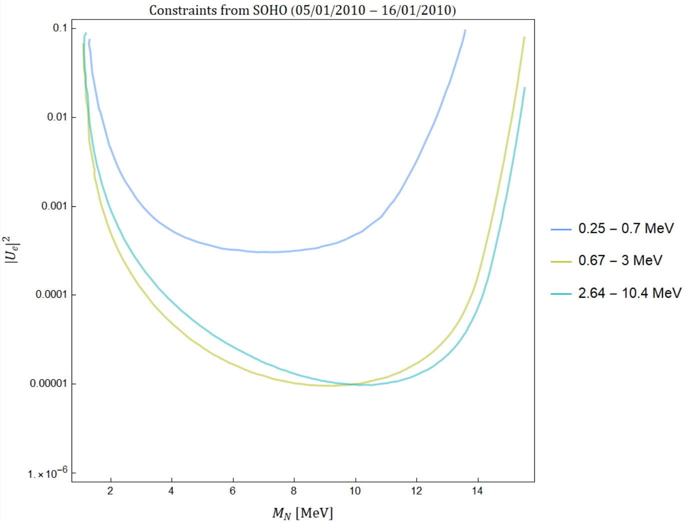
Solar Orbiter iv



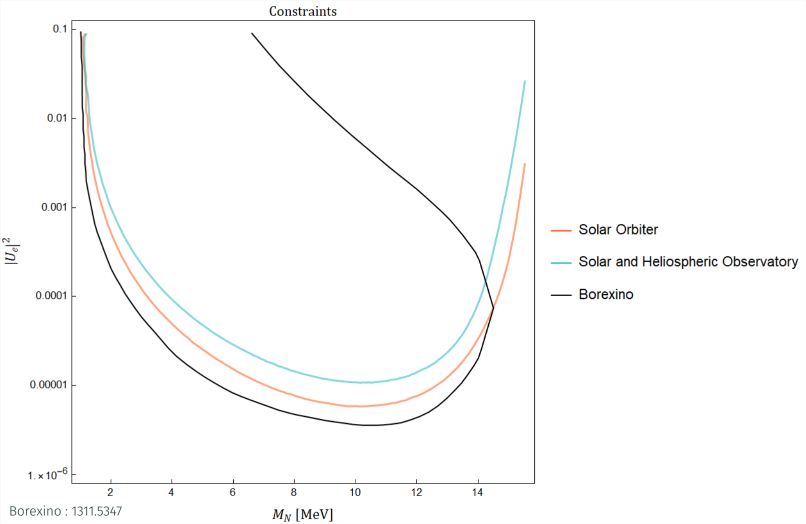
Solar and Heliospheric Observatory i



Solar and Heliospheric Observatory ii

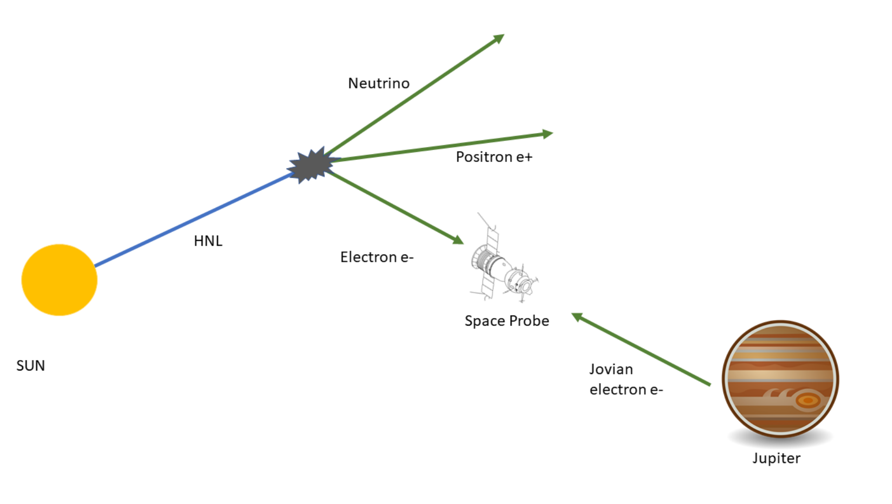


Constraint Plot i

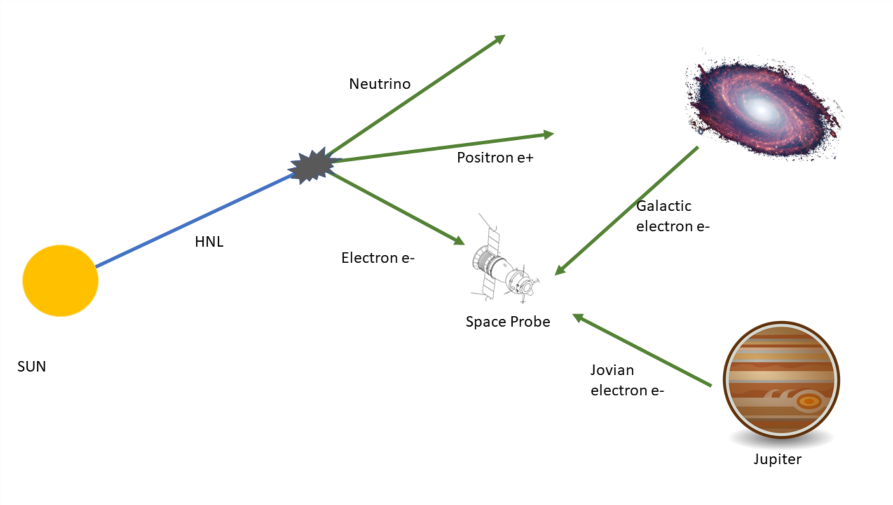


Borexino : 1311.5347

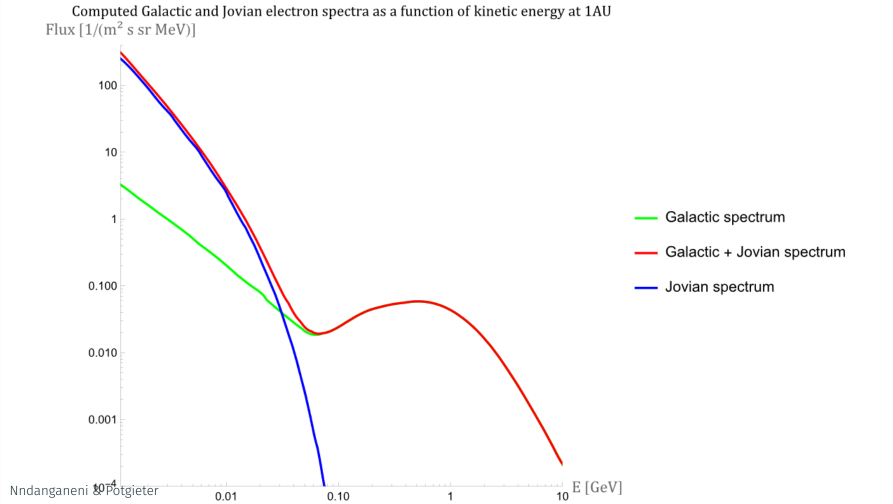
Background electrons i



Background electrons ii



Background electrons iii



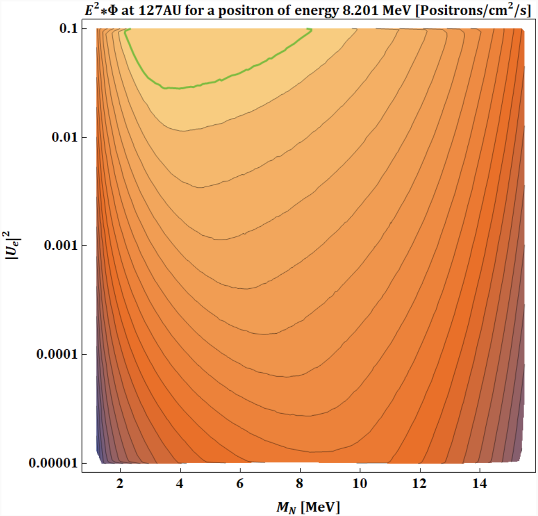
Nndanganeni & Potgieter

For further research i

- We only studied U_e, what about U_μ and U_τ
- Remove the background
- Study it with Parker Solar Probe
- Proper turbulent electron propagation

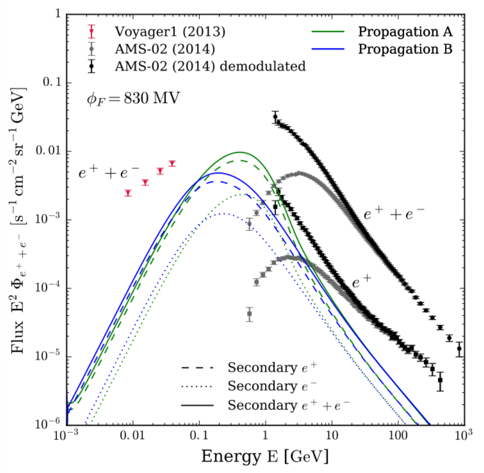
Conclusion i

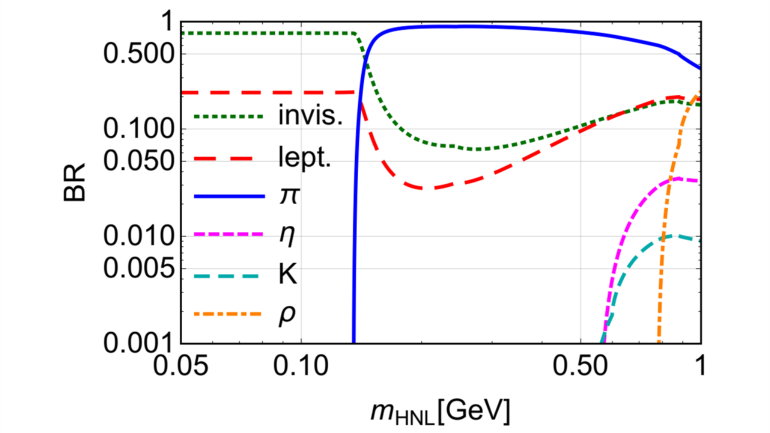
- Solar neutrinos can be used to probe HNLs
- The decay $N \rightarrow e^+e^-\nu$ is studied
- Propagation of charged particles is not disturbed by magnetic field or collisions
- Constraints through Solar Orbiter and SOHO

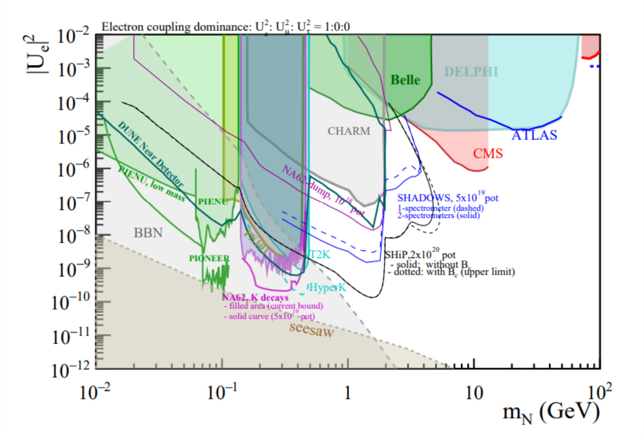


$E^2 * \Phi$ at 127AU for a positron of energy 8.201 MeV [Positrons/cm^2/s]
0.1
0.01
0.001
0.0001
0.00001
$|U_e|^2$
2
4
6
8
10
12
14
M_N [MeV]

Additional slides ii



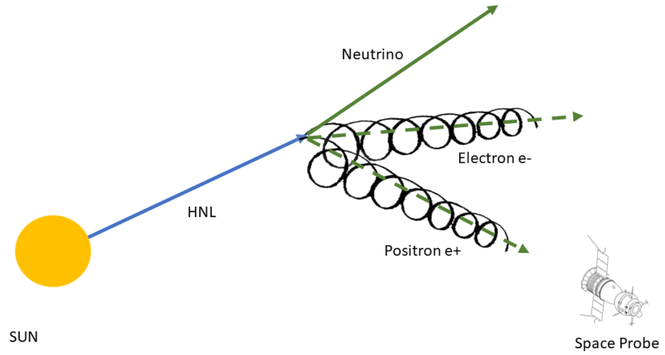

1
0.500
0.100
0.050
0.010
0.005
0.001
BR
0.05
0.10
0.50
1
m_{HNL}[GeV]
invis.
lept.
π
η
K
ρ


Electron coupling dominance: $U_e^2 : U_\mu^2 : U_\tau^2 = 1:0:0$
$|U_e|^2$
m_N (GeV)
Belle
DELPHI
CHARM
ATLAS
CMS
DUNE Near Detector
PIENU, low mass
PIENU
NA62 dump, 10^{18} pot
SHADOWS, 5×10^{19} pot
1-spectrometer (dashed)
2-spectrometers (solid)
BBN
T2K
SHiP, 2×10^{20} pot
- solid: without B_c
- dotted: with B_c (upper limit)
PIONEER
HyperK
NA62, K decays
- filled area (current bound)
- solid curve (5×10^{19} pot)
seesaw
PS191

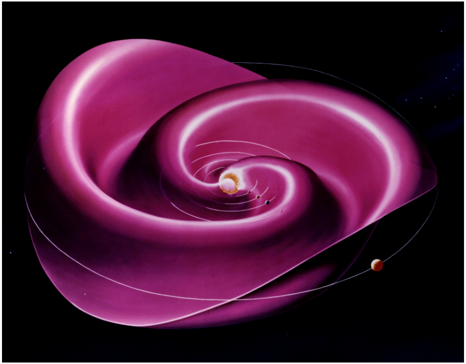
Additional slides v

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

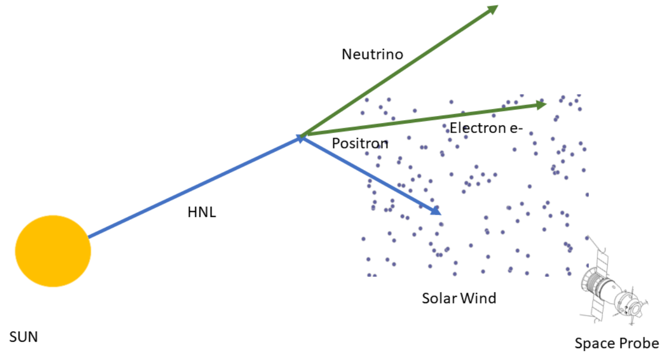
The rate of energy lost during this process is given by [James J. Condon and Scott M. Ransom] :

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

with σ_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]

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

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,

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

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