SN neutrino fluxes in different experiments

and anti-neutrino fluxes

(kinda)

Andrea Gallo Rosso

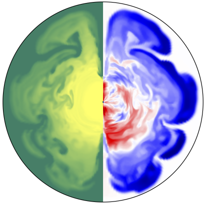
Stockholm University

andrea.gallo.rosso@fysik.su.se

May 31, 2023

SNvD 2023 — LNGS, Italy

Introduction



KISS rule

Effective parameterization

Bottomless pit of poor results

↓

S. Wanajo, arXiv:2303.09442.

Introduction

Part I

AGR, “Supernova neutrino fluxes in HALO-1kT, Super-Kamiokande, and JUNO”, *JCAP* 06 (2021) 046

Part II

F. Vissani and AGR, “On the Time Distribution of Supernova Antineutrino Flux”, *Symmetry* 13 (2021) 10, 1851.

Introduction

Part I

AGR, "Supernova neutrino fluxes in HALO-1kT, Super-Kamiokande, and JUNO", *JCAP* 06 (2021) 046

Part II

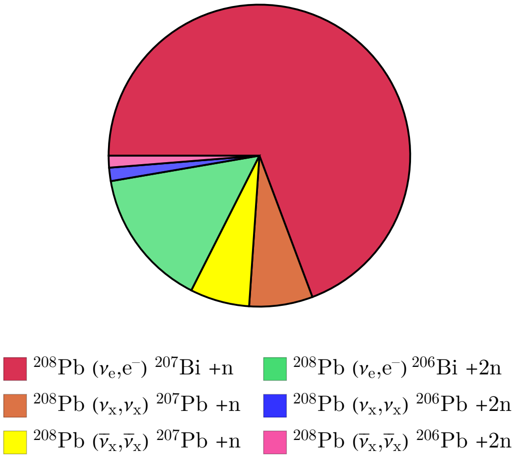
F. Vissani and AGR, "On the Time Distribution of Supernova Antineutrino Flux", *Symmetry* 13 (2021) 10, 1851.

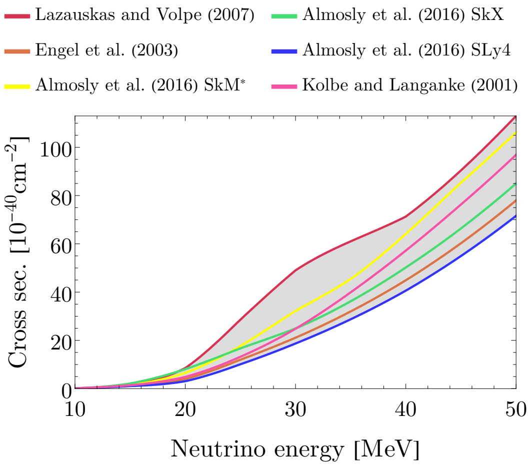
Part I — Motivation

- Under-representation of ν_{e}-sensitive detectors
  - ↪ Complete pictures requires multiple channels
- Down-time of current kt-scale detectors
  - ↪ calibration, reconfiguration, end of life...
- Cost of big detectors
  - ↪ some features might be sacrificed
  - ↪ beyond the golden era (DUNE, JUNO, Hyper-K)

NEED FOR
LOW-COST, LOW-MAINTENANCE, LONG LIFETIME
DETECTORS

Lead as supernova detector

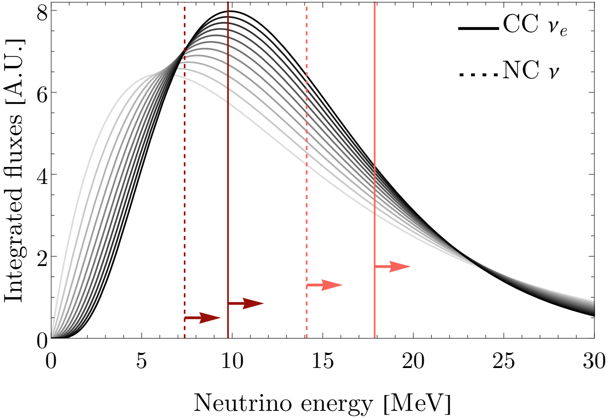


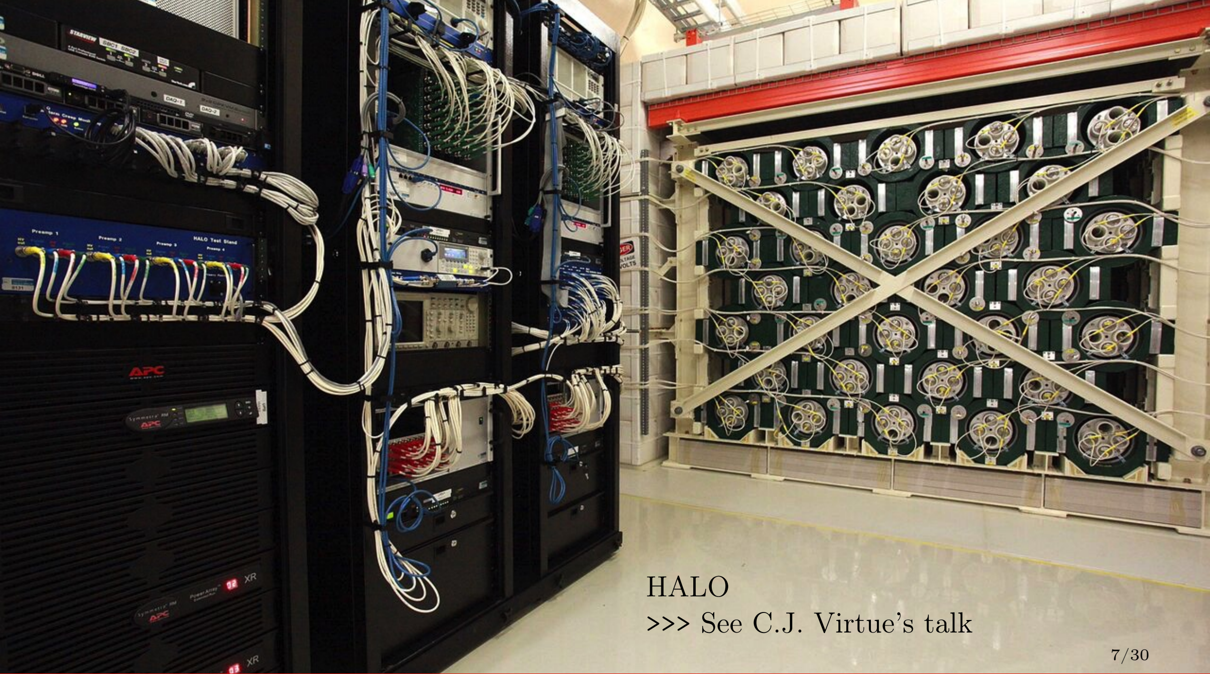


>>> See Y.Efremenko's talk

Channels

- $\nu_e + {}^{x}\mathrm{Pb} \rightarrow e^- + {}^{(x-1)}\mathrm{Bi} + n$
  ↪ —— 9.77 MeV thr.
- $\nu + {}^{x}\mathrm{Pb} \rightarrow \nu + {}^{(x-1)}\mathrm{Pb} + n$
  ↪ - - - - 7.37 MeV thr.
- $\nu_e + {}^{x}\mathrm{Pb} \rightarrow e^- + {}^{(x-2)}\mathrm{Bi} + 2n$
  ↪ —— 17.87 MeV thr.
- $\nu + {}^{x}\mathrm{Pb} \rightarrow \nu + {}^{(x-2)}\mathrm{Pb} + 2n$
  ↪ - - - - 14.11 MeV thr.



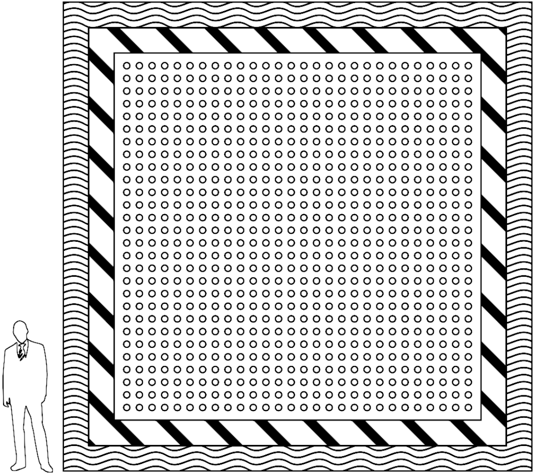


HALO

>>> See C.J. Virtue's talk

HALO-1kt at LNGS

- Lead core from OPERA
  - ↪ $(4.33^2 \times 5.5)\,\mathrm{m}^3$
  - ↪ $\times 12.7$ mass (1 kton) w.r.t. HALO
- $28^2 \times (5.5\,\mathrm{m})$ array of ^{3}He
- 8 mm PS moderator
- 30 cm graphite reflector
- 30 cm water shielding



Goal

Assessing HALO-1kT (theoretical) impact on the reconstruction of the neutrino signal

- Alone
- Combined with other detectors
  - ↪ Super-Kamiokande
  - ↪ JUNO
- Proof of principle

Neutrino signal

$$\frac{\mathrm{d}^2 N_\nu}{\mathrm{d}E_\nu\,\mathrm{d}t} = \sum_x \frac{P_{x\to\nu}(t,E)}{4\pi D^2} \times \frac{L_x(t)}{\langle E\rangle} \times f_x(t,E)$$

- Fluxes detected on earth
- Quasi-static treatment
- Thermal description

$$\frac{\mathrm{d}F_\nu}{\mathrm{d}E_\nu} = \frac{\mathcal{E}_\nu}{4\pi D^2}\frac{(\alpha_\nu+1)^{\alpha_\nu+1}}{\Gamma(\alpha_\nu+1)}\frac{E^{\alpha_\nu}}{\langle E_\nu\rangle^{\alpha_\nu+2}}\exp\left[-(\alpha_\nu+1)\frac{E}{\langle E_\nu\rangle}\right]$$

[1] M.T. Keil, *et al.*, Astrophys. J. 590 (2003), pp. 971–991.

Neutrino signal

	LS220-s27.0co			LS220-z9.6co		
	$\mathcal{E}_\nu^*$ [10^{53} erg]	$\langle E_\nu \rangle^*$ [MeV]	α_ν^*	$\mathcal{E}_\nu^*$ [10^{53} erg]	$\langle E_\nu \rangle^*$ [MeV]	α_ν^*
ν_e	0.571	10.8	2.42	0.316	9.9	2.75
$\overline{\nu}_\mathrm{e}$	0.568	13.6	2.26	0.338	12.3	2.19
ν_x	0.526	12.9	1.85	0.295	12.5	2.46

Models [3]

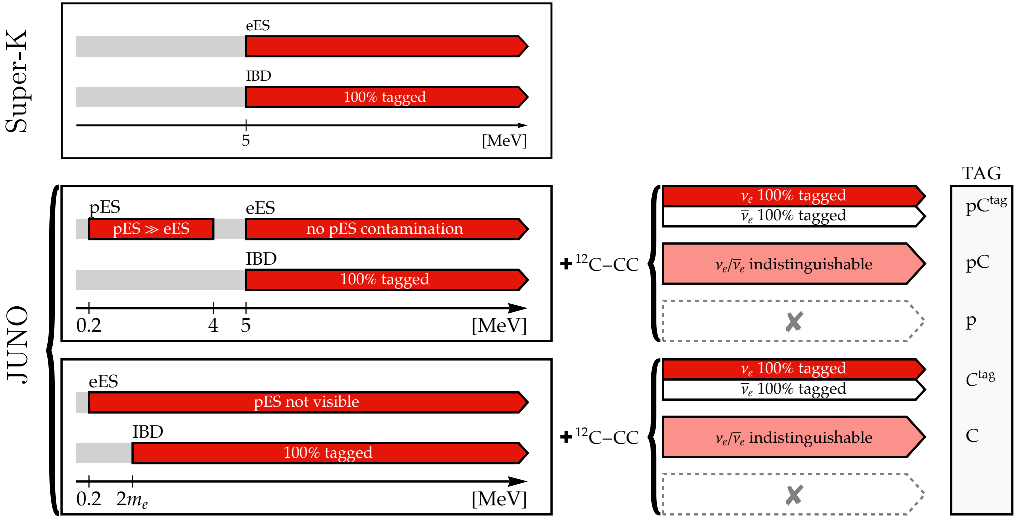
3 parameters

3 neutrino species ($\nu_x = \nu_\mu, \overline{\nu}_\mu, \nu_\tau, \overline{\nu}_\tau$)

$$\frac{\mathrm{d}F_\nu}{\mathrm{d}E_\nu} = \frac{\mathcal{E}_\nu}{4\pi D^2} \frac{(\alpha_\nu + 1)^{\alpha_\nu + 1}}{\Gamma(\alpha_\nu + 1)} \frac{E^{\alpha_\nu}}{\langle E_\nu \rangle^{\alpha_\nu + 2}} \exp\left[-(\alpha_\nu + 1)\frac{E}{\langle E_\nu \rangle}\right]$$

[3] A. Mirizzi et al., Riv. Nuovo Cim. 39 (2016), arXiv:1508.00785.

Channels



Super-K
eES
IBD
100% tagged
5
[MeV]
JUNO
pES
eES
pES ≫ eES
no pES contamination
IBD
100% tagged
0.2
4
5
[MeV]
eES
pES not visible
IBD
100% tagged
0.2
$2m_e$
[MeV]
+ ^{12}C–CC
ν_e 100% tagged
$\bar{\nu}_e$ 100% tagged
$\nu_e/\bar{\nu}_e$ indistinguishable
+ ^{12}C–CC
ν_e 100% tagged
$\bar{\nu}_e$ 100% tagged
$\nu_e/\bar{\nu}_e$ indistinguishable
TAG
pC^{tag}
pC
p
C^{tag}
C

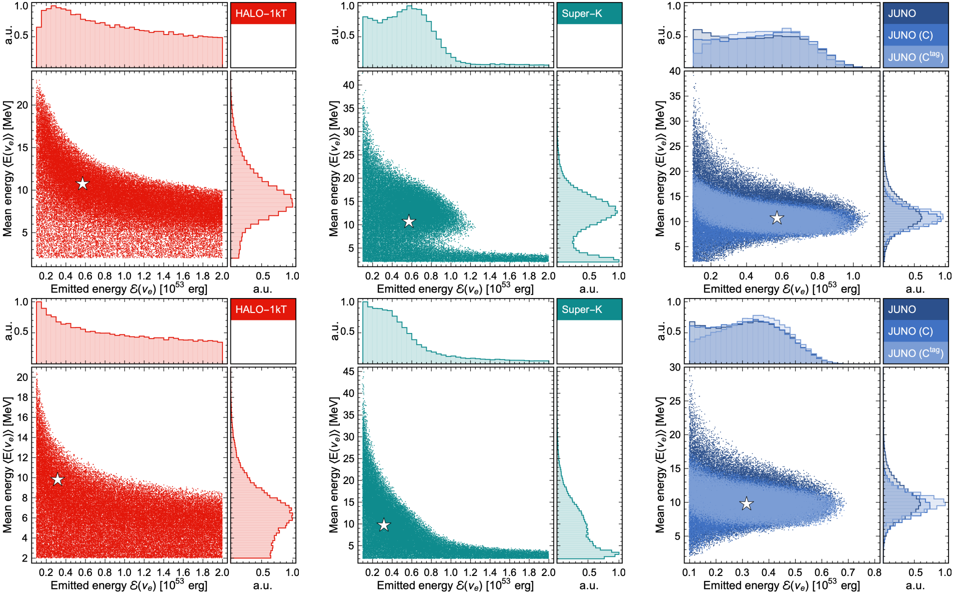
Monte Carlo based likelihood analysis

$$\log \mathcal{L}(P) \geq \log \mathcal{L}_{\max} - \frac{A}{2} \quad \text{with} \quad \int_0^A \chi^2(N_{\mathrm{dof}}; z)\, \mathrm{d}z = \mathrm{CL}.$$

$$1 \times 10^{52}\,\mathrm{erg} \leq \mathcal{E}_\nu \leq 2 \times 10^{53}\,\mathrm{erg},$$
$$2.0\,\mathrm{MeV} \leq \langle E_i \rangle \leq 70\,\mathrm{MeV}$$
$$(1.0 \leq \alpha_i \leq 4.0)$$

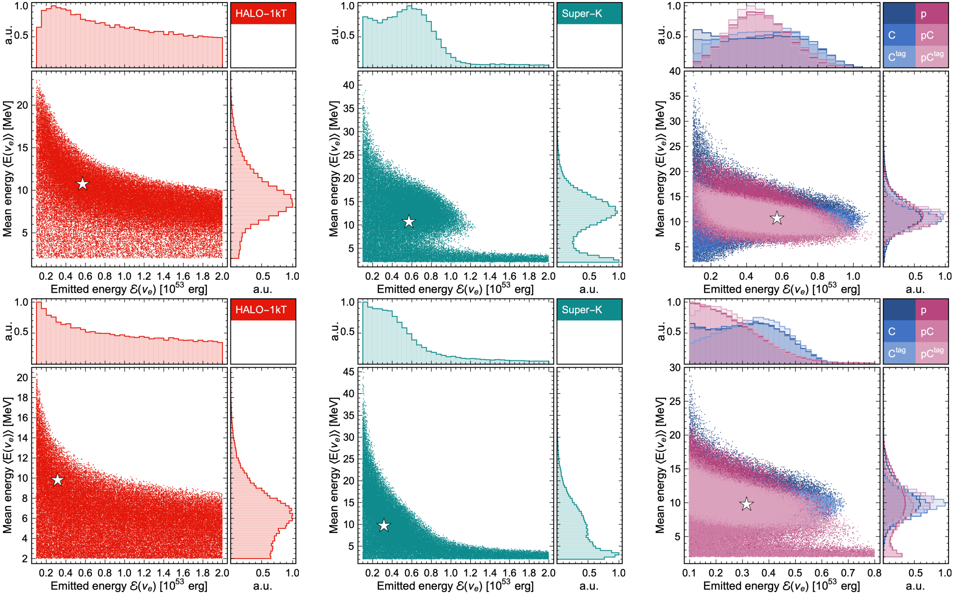
LS220-s27.0co
ν_e species

LS220-z9.6co
ν_e species

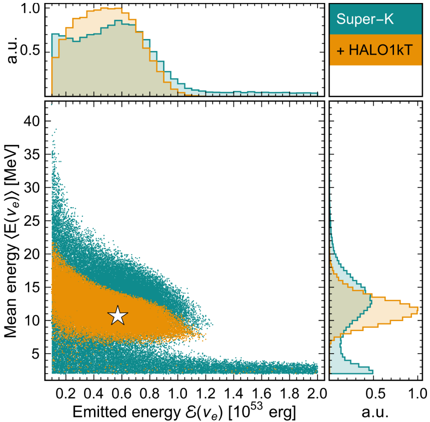


LS220-s27.0co
ν_e species

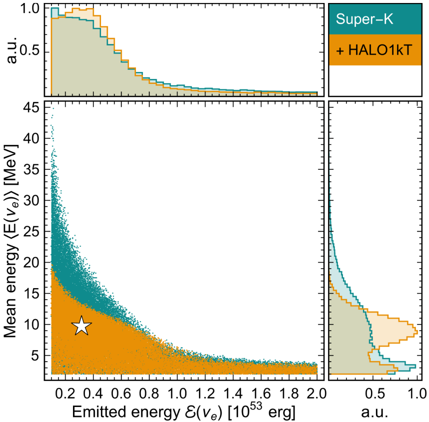
LS220-z9.6co
ν_e species



LS220-s27.0co
ν_e species

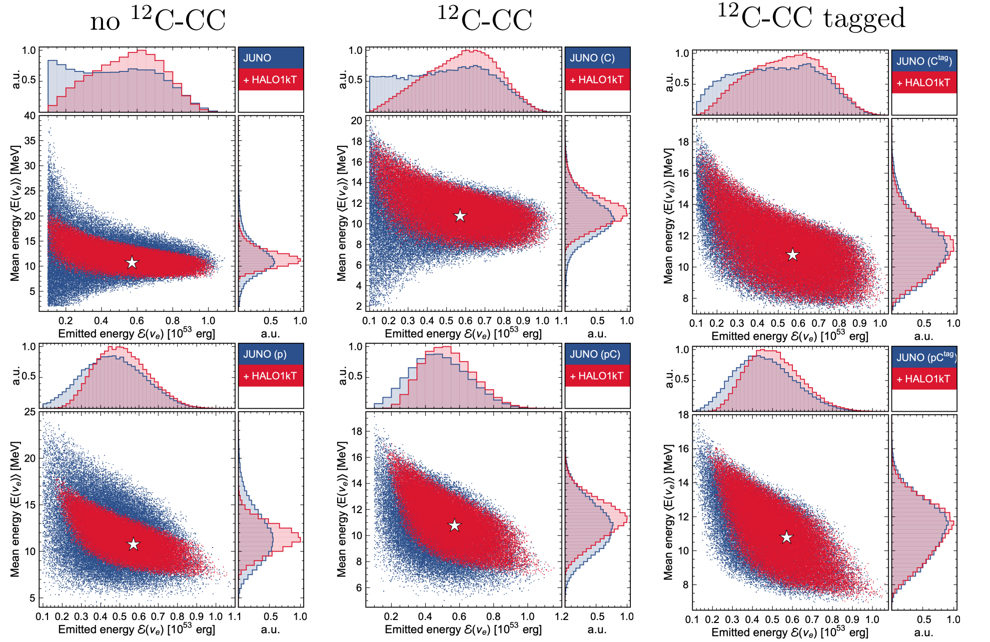


LS220-z9.6co
ν_e species



LS220-s27.0co

ν_e species

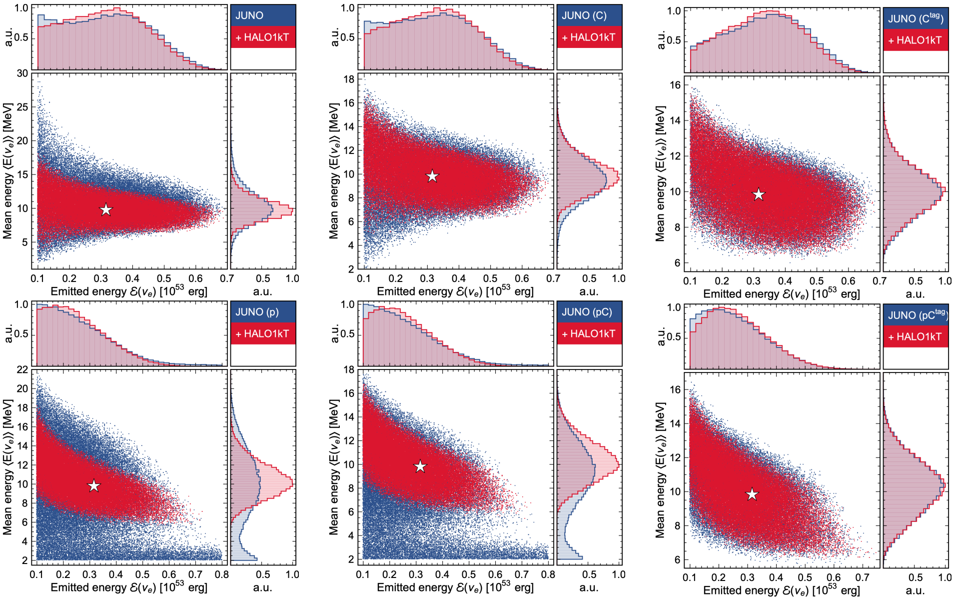


LS220-z9.6co
ν_e species

no ^{12}C-CC | ^{12}C-CC | ^{12}C-CC tagged

no pES

pES

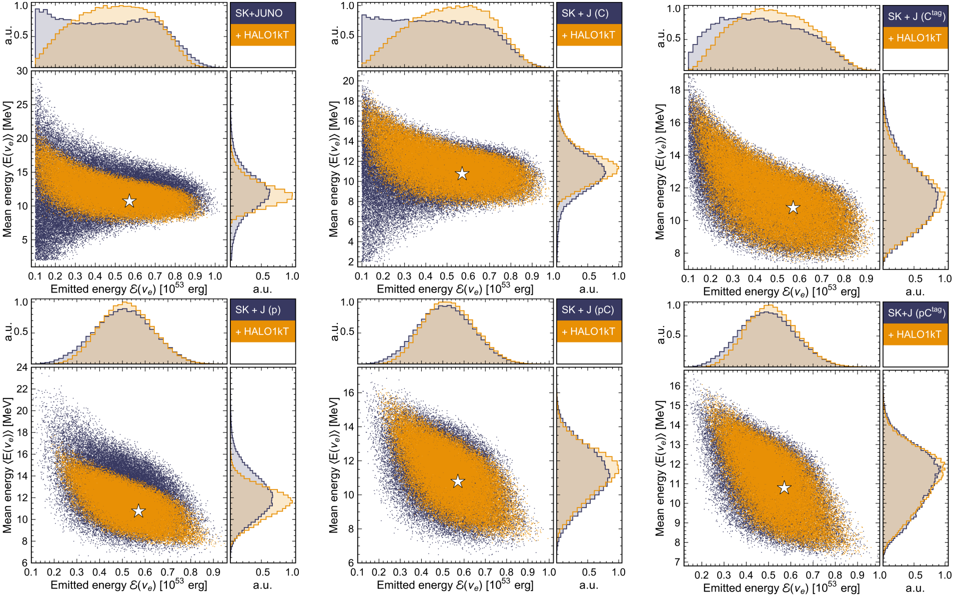


LS220-s27.0co
ν_e species

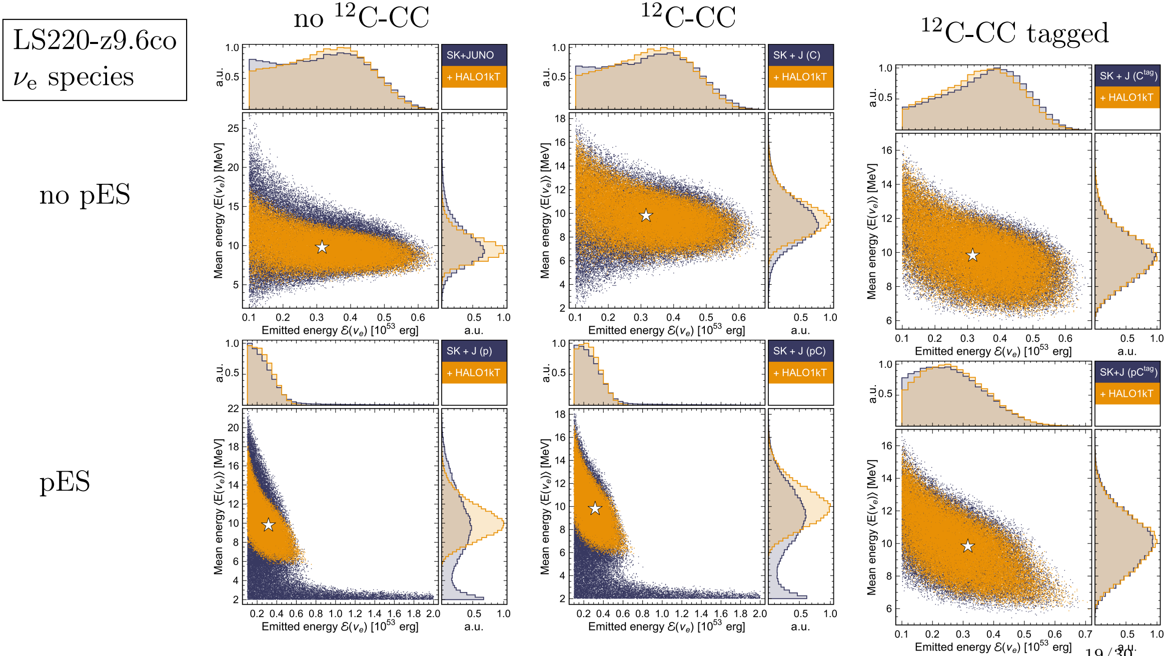
no ^{12}C-CC | ^{12}C-CC | ^{12}C-CC tagged

no pES

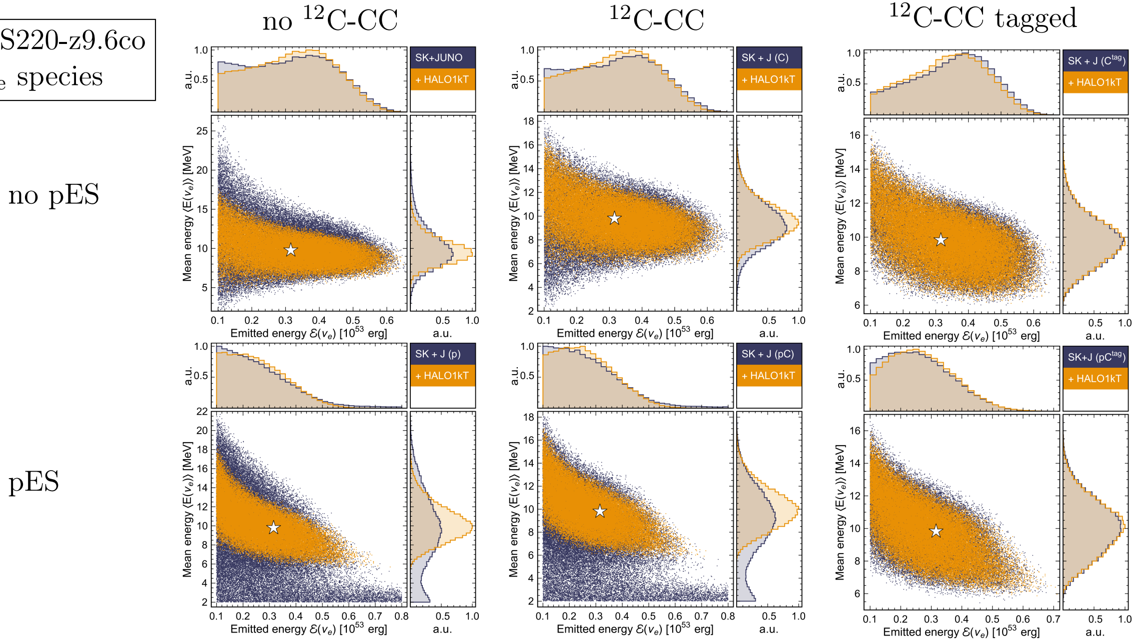
pES



LS220-z9.6co
ν_e species



LS220-z9.6co
ν_e species



Conclusions I

- HALO-1kt as orthogonal source of information
  $\hookrightarrow$ especially if ν_e channel is "messy"
- High livetime, long lifetime, reliable
- Cross section measurement

Introduction

Part I

AGR, "Supernova neutrino fluxes in HALO-1kT, Super-Kamiokande, and JUNO", *JCAP* 06 (2021) 046

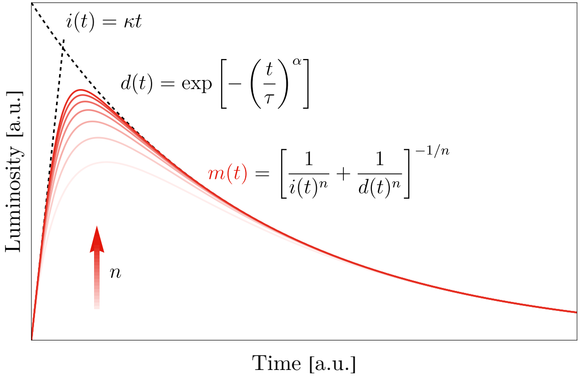
Part II

F. Vissani and AGR, "On the Time Distribution of Supernova Antineutrino Flux", *Symmetry* 13 (2021) 10, 1851.

Part II — Motivation

- Effective parameterization
  - ↪ $\mathcal{E}_\nu$, $\langle E_\nu \rangle$, α_ν
  - ↪ vs. t_0, τ
- Time description
  - ↪ Loredo and Lamb (2002), Pagliaroli (2009, 2011)
- Accretion + Cooling
  - ↪ $\overline{\nu}_\mathrm{e}$ species

LUMINOSITY

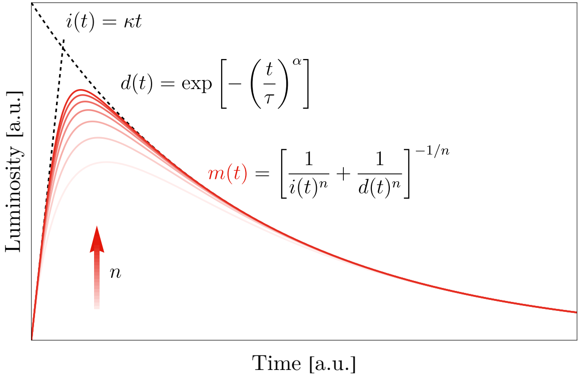


$$\mathscr{L} = \mathscr{L}_a + \mathscr{L}_c$$

- $\mathscr{L}_a \propto m(t, t_0, \tau_a, \alpha_a, n_a)$
  $\hookrightarrow\ n_a = 2,\ \alpha_a = 2$
- $\mathscr{L}_c \propto m(t, t_0, \tau_c, \alpha_c, n_c)$
  $\hookrightarrow\ n_c = n_a = 2,\ \alpha_c = 1$

$$m(t, t_0, \tau, \alpha, n) = \frac{1 + \alpha x_0^{\alpha}}{\exp\left[n(x^{\alpha} - x_0^{\alpha}) + \alpha\left(\frac{x_0}{x}\right)^n x_0^{\alpha}\right]} \quad \text{with} \quad x = \frac{t}{\tau},\ x_0 = \frac{t_0}{\tau}$$

Luminosity



$$\mathscr{L} = \mathscr{L}_a + \mathscr{L}_c$$

- $\mathscr{L}_a \propto m(t, t_0, \tau_a, \alpha_a, n_a)$
  $\hookrightarrow\ n_a = 2,\ \alpha_a = 2$
- $\mathscr{L}_c \propto m(t, t_0, \tau_c, \alpha_c, n_c)$
  $\hookrightarrow\ n_c = n_a = 2,\ \alpha_c = 1$

$$m(t, t_0, \tau, \alpha, n) = \frac{1 + \alpha x_0^{\alpha}}{\exp\left[n(x^{\alpha} - x_0^{\alpha}) + \alpha\left(\frac{x_0}{x}\right)^n x_0^{\alpha}\right]} \quad \text{with} \quad x = \frac{t}{\tau},\ x_0 = \frac{t_0}{\tau}$$

Emission model

Accretion

$$\frac{\mathrm{d}\dot{N}_{\nu,a}}{\mathrm{d}E_\nu} = \frac{M_\odot}{m_\mathrm{n}}\,\xi_\mathrm{n} \times \frac{\sigma_\mathrm{ne}(E_\nu) \times g_\mathrm{e}\,4\pi E_\mathrm{e}^2}{1+\exp(E_\mathrm{e}/T_a)}$$

$$\begin{cases} T_a(t) = 0.6\,T_0 \\ \xi_\mathrm{n}(t) = \xi_{\mathrm{n},0} \times m(t, t_0, \tau_a, n_a, \alpha_a) \end{cases}$$

Thermal cooling

$$\frac{\mathrm{d}\dot{N}_{\nu,c}}{\mathrm{d}E_\nu} = \pi R_\mathrm{ns}^2 \times \frac{4\pi E_\nu^2}{1+\exp(E_\nu/T_c)}$$

$$\begin{cases} T_c(t) = T_0\,\sqrt[4]{m(t, t_0, \tau_c, n_c, \alpha_c)} \\ R_\mathrm{ns}(t) = R_{\mathrm{ns},0} \end{cases}$$

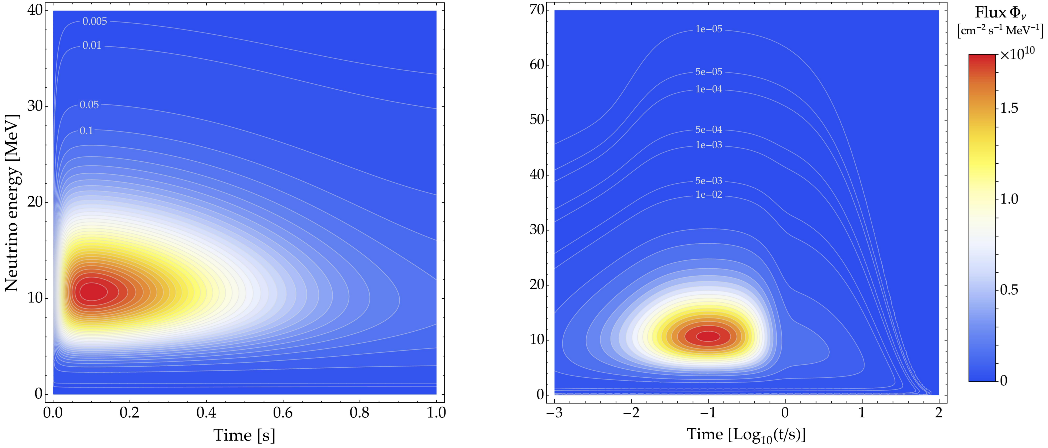
$$\{T_0,\ \xi_{\mathrm{n}0},\ R_{\mathrm{ns}0},\ t_0,\ \tau_a,\ \tau_c\}$$

$$\begin{cases} \langle E_{\nu,a}\rangle \approx 0.85\,\mathrm{MeV} + 5\,T_a(1+0.01\,T_a/\mathrm{MeV}) \\ \langle E_{\nu,c}\rangle \approx 3.15\,T_c \end{cases} \quad \Rightarrow \quad \frac{\langle E_{\nu,c}\rangle}{\langle E_{\nu,a}\rangle} \approx 0.6\,\frac{T_c}{T_a}$$

[5] Pagliaroli *et al.*, Astropart. Phys. 2009, 31, 163–176.

Benchmark model

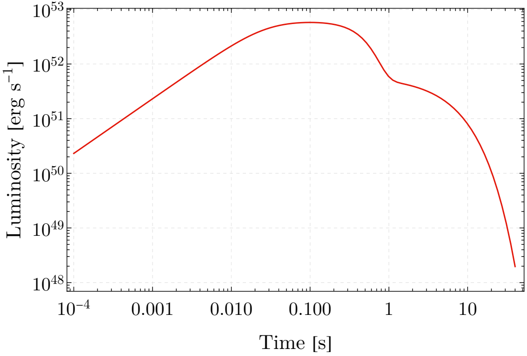
$$\{T_0 = 4.2\,\mathrm{MeV},\ \xi_{\rm n0} = 0.04,\ R_{\rm ns0} = 18\,\mathrm{km},\ t_0 = 0.1\,\mathrm{s},\ \tau_a = 0.5\,\mathrm{s},\ \tau_c = 5\,\mathrm{s}\}$$

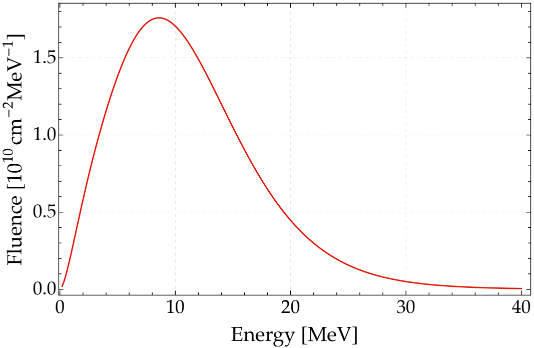


Benchmark model

$$\{T_0 = 4.2\,\mathrm{MeV},\ \xi_{\mathrm{n}0} = 0.04,\ R_{\mathrm{ns}0} = 18\,\mathrm{km},\ t_0 = 0.1\,\mathrm{s},\ \tau_a = 0.5\,\mathrm{s},\ \tau_c = 5\,\mathrm{s}\}$$

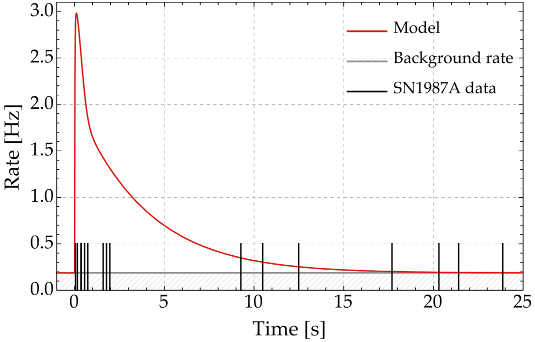
$$(D = 10\,\mathrm{kpc})$$

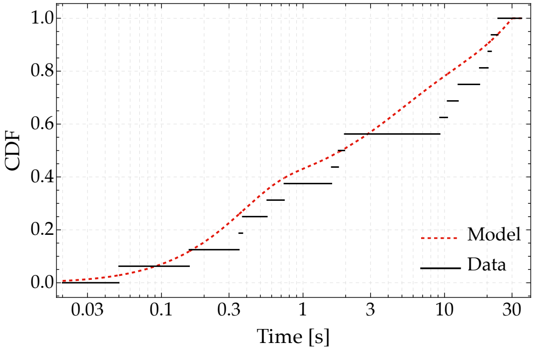




Kamiokande-II

$$N_a = 6.5,\ \ N_c = 7.1,\ \ N_{\rm bkg} = 5.6,\ \ N_{\rm tot} = 19.2$$
$$(D = 50\,{\rm kpc})$$



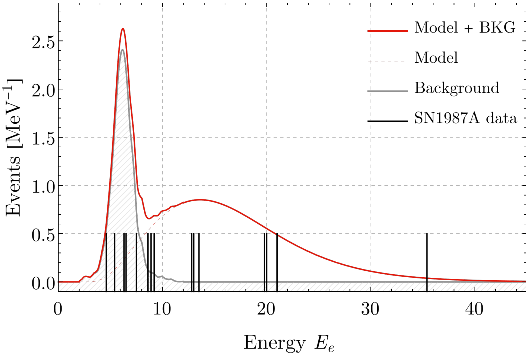


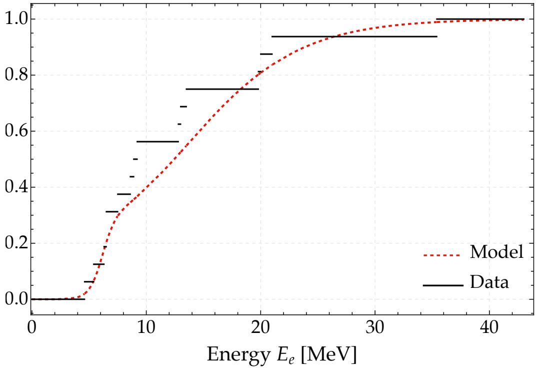
Cramér–Smirnov-von–Mises:

$$t_{\rm off} = 0.0,\ 0.05,\ 0.1,\ 0.2\,{\rm s} \qquad \longleftrightarrow \qquad p_{val} = 62\%,\ 56\%,\ 48\%,\ 30\%$$

Kamiokande-II

$$N_a = 6.5,\ \ N_c = 7.1,\ \ N_{\rm bkg} = 5.6,\ \ N_{\rm tot} = 19.2$$
$$(D = 50\,\text{kpc})$$





$$p_{val} = 51\%$$

Conclusions II

- Simple model with physically meaningful parameters
  - ↪ Maximum t_0
  - ↪ Time scales τ_a, τ_c
- Assessment of accretion phase
- (Roughly) compatible with SN 1987A