Beyond MSW: Phenomenological Signatures of Collective Flavour Conversions in Supernova Neutrinos at DUNE

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From arXiv: 2603.02303, A. Giarnetti and J. T. N. Penedo

01

Supernova Neutrinos: The Big Picture

Core-Collapse Supernovae: Extreme Neutrino Factories

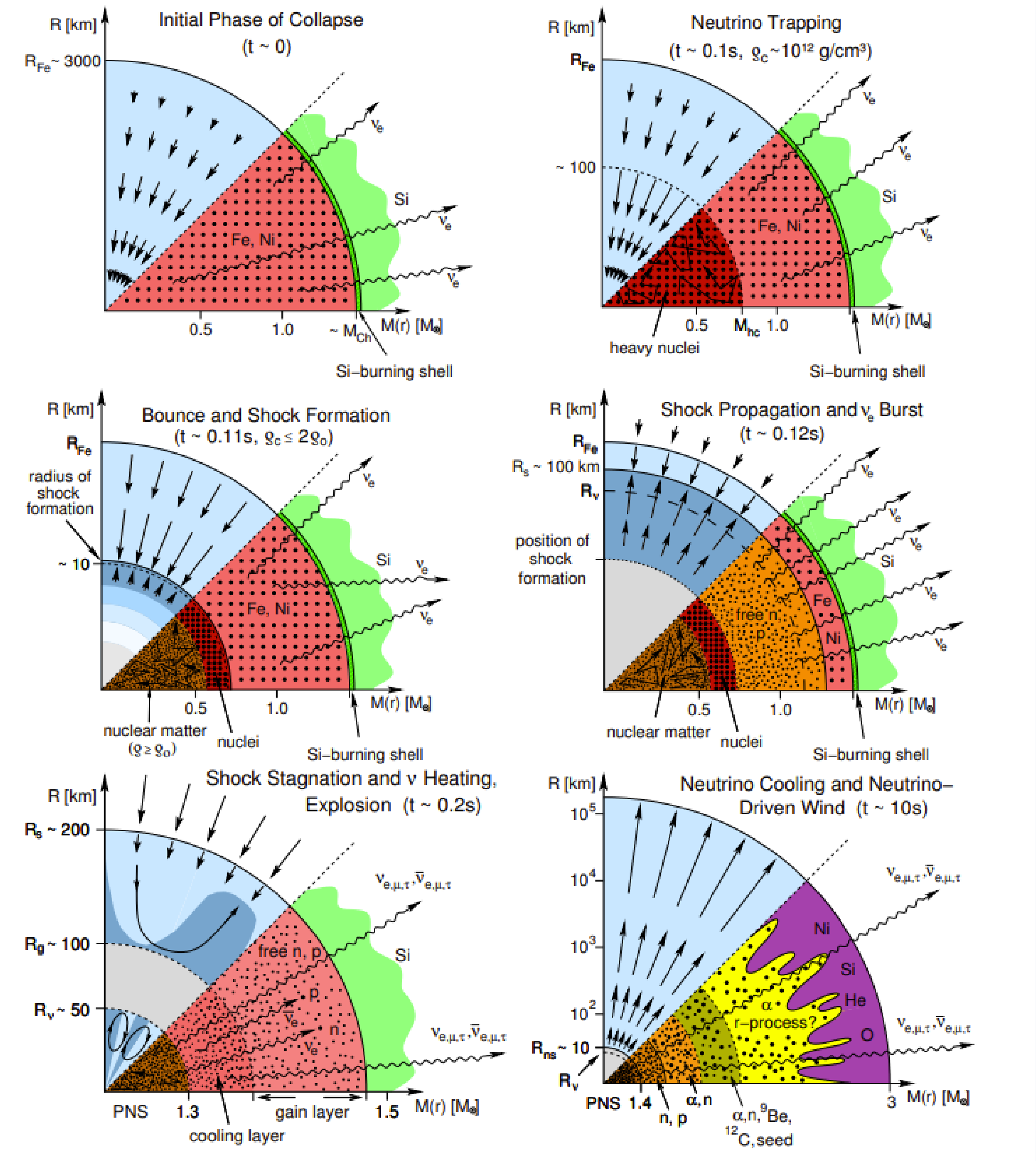
~10^{58} neutrinos emitted in ~10 s

Key phases:

- Neutronization burst (~10 ms) — pure ve:
  - -Shock breakout
  - -Deleptonization of outer core
- Accretion phase (~0.5 s) — all flavors
  - -Neutrino powered by infalling matter
- Cooling phase (~10 s) — all flavours roughly equal

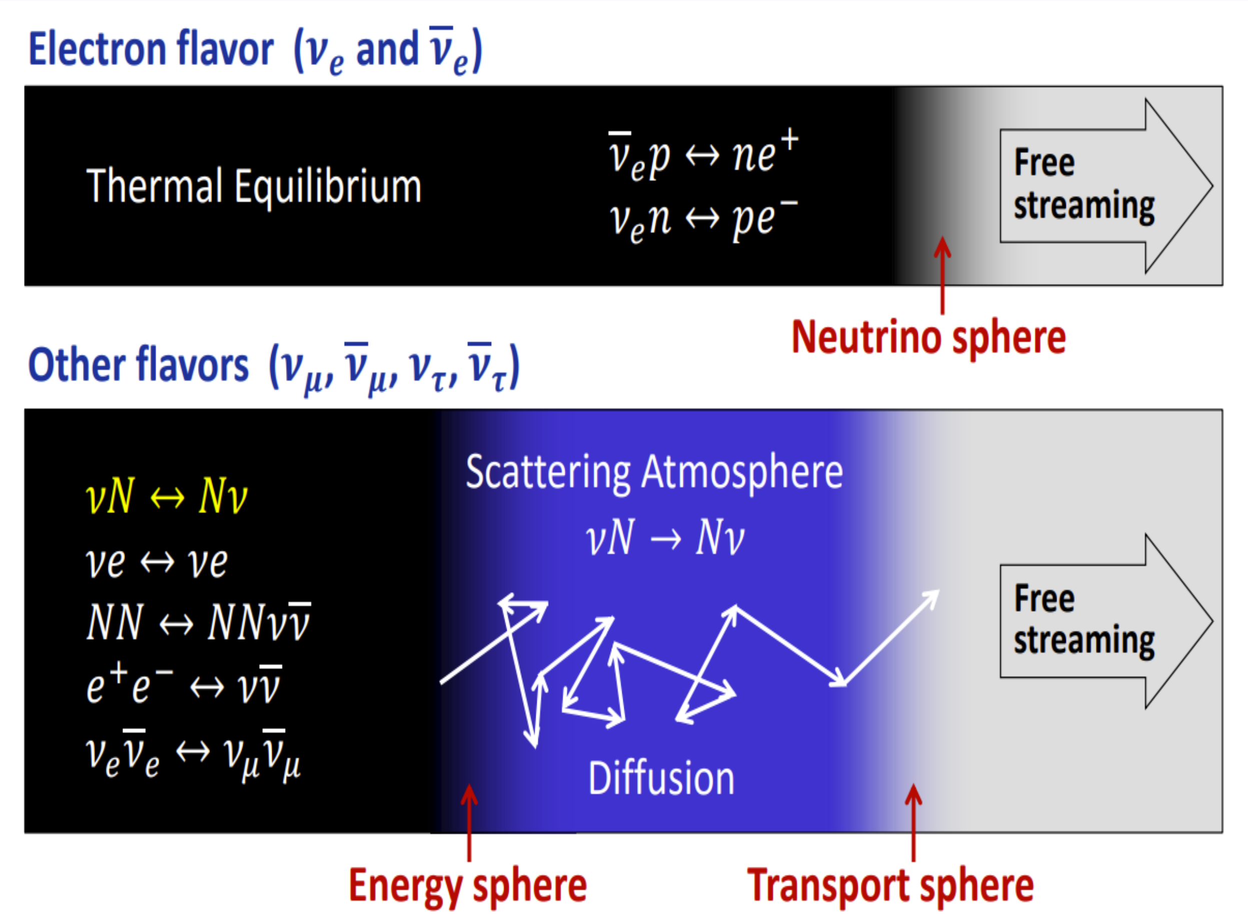
Energy hierarchy at emission:

⟨Eve⟩ < ⟨Ev̄e⟩ < ⟨Evx⟩



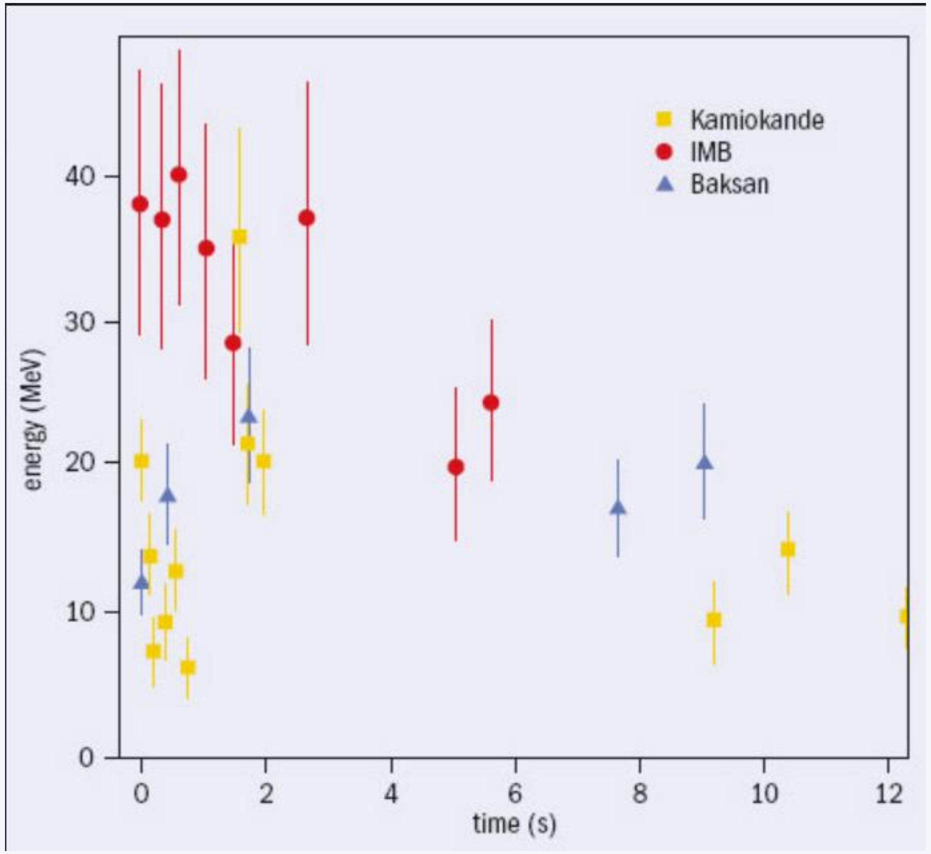
H. Th. Janka 1702.08713

Core-Collapse Supernovae: Extreme Neutrino Factories



SN rate in Milky Way: ~1–2 per century

*Only **SN 1987A** detected so far*



M. V. dos Santos, P. C. de Holanda, 2108.06448
H. Th. Janka 1702.08713

Supernova Neutrino Fluxes: Parameterisation

$$\Phi_\nu(E) = \mathcal{N}\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^{\alpha} e^{-(\alpha+1)\frac{E}{\langle E_\nu\rangle}}$$

$$\mathcal{N} = \frac{(\alpha+1)^{\alpha+1}}{\langle E_\nu\rangle\Gamma(\alpha+1)}$$

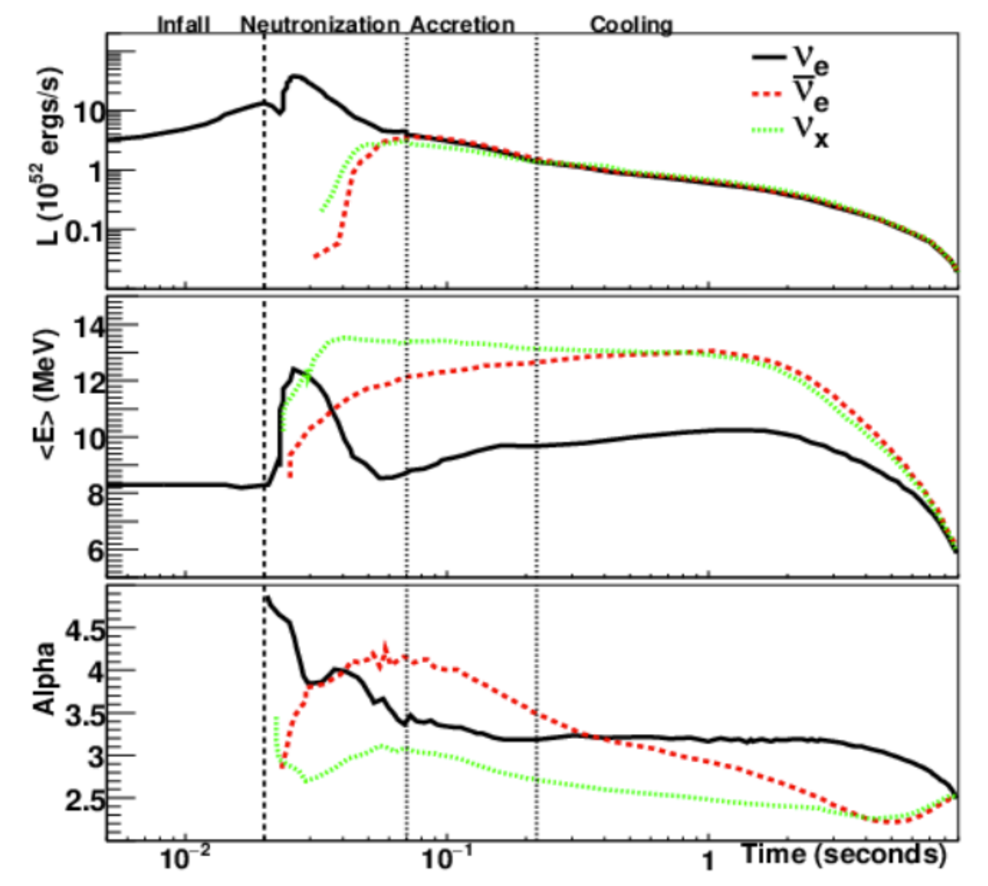
$$F_\nu^0 = \frac{L_\nu}{\langle E\rangle_\nu}\Phi_\nu(E)$$

Garching-type (quasi-thermal) spectrum:

Pinched Fermi-Dirac / power-law spectrum

Three parameters per flavour α = νe, ν̄e, νx:

- L — total emitted energy
- ⟨E⟩ — mean neutrino energy
- α — spectral pinching parameter



Example: Garching Model

10.8 M⊙ progenitor

- Full Boltzmann neutrino transport
- Equation of state: Lattimer-Swesty (LS220)
- Covers neutronisation burst, accretion, early cooling
- 1-D simulation

L. Hudepohl et al, 0912.0260

02

Standard MSW Conversions

MSW Effect Inside the Supernova

Effect of electron neutrino scattering in matter:

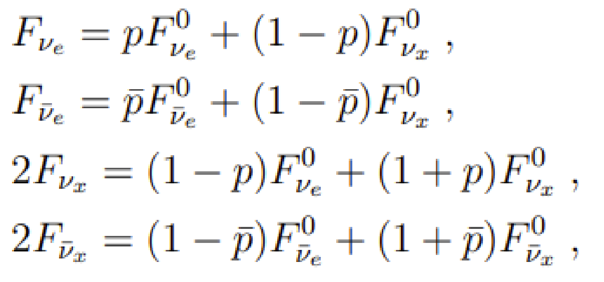
$$\boldsymbol{H = H_{vac} + H_{matt} \rightarrow H_{matt} \propto \rho}$$

Two resonances:

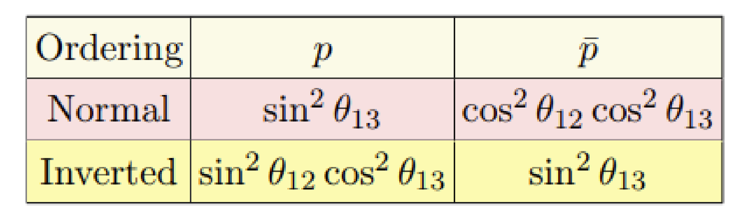
- H-resonance: $(\Delta m^2 atm, \theta_{13})$, $\rho \sim 10^{3-4}$ g/cm^3
  — in ν ($\bar{\nu}$) for NO (IO)

- L-resonance: $(\Delta m^2 sol, \theta_{12})$, $\rho \sim 10$–100 g/cm^3
  —always in ν

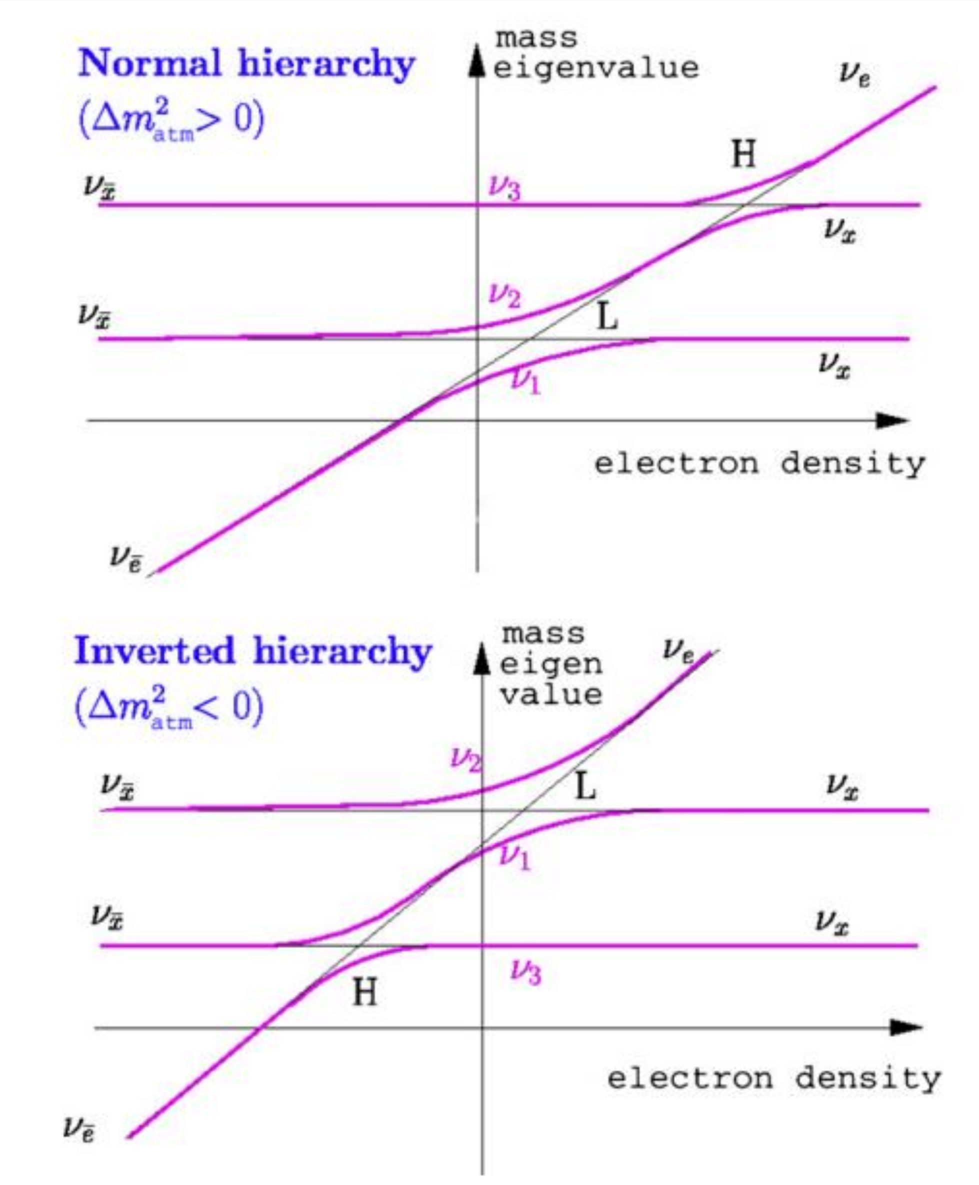
Survival probabilities:



$$F_{\nu_e} = pF^0_{\nu_e} + (1-p)F^0_{\nu_x} \ ,$$
$$F_{\bar{\nu}_e} = \bar{p}F^0_{\bar{\nu}_e} + (1-\bar{p})F^0_{\nu_x} \ ,$$
$$2F_{\nu_x} = (1-p)F^0_{\nu_e} + (1+p)F^0_{\nu_x} \ ,$$
$$2F_{\bar{\nu}_x} = (1-\bar{p})F^0_{\bar{\nu}_e} + (1+\bar{p})F^0_{\bar{\nu}_x} \ ,$$

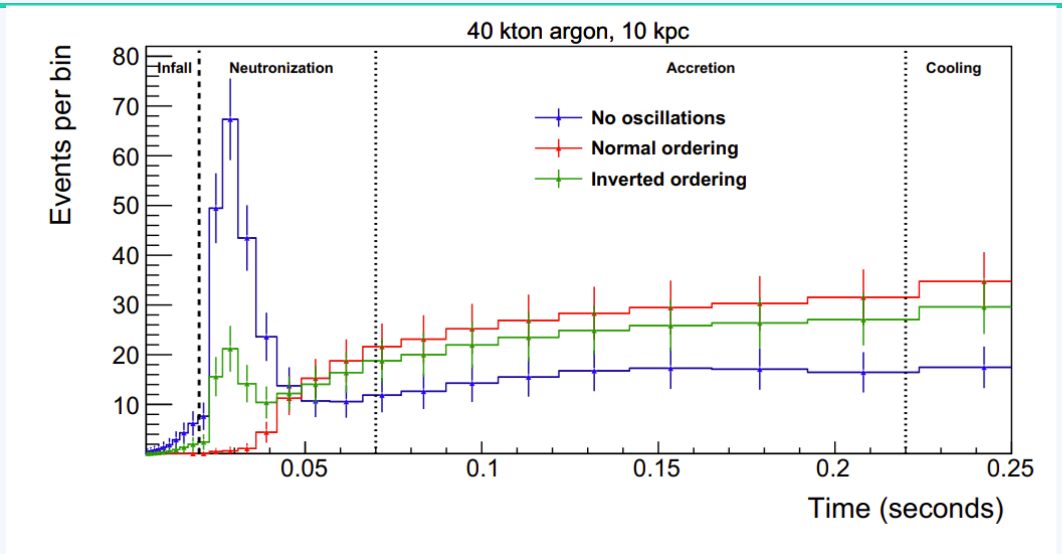


Ordering	p	$\bar{p}$
Normal	$\sin^2\theta_{13}$	$\cos^2\theta_{12}\cos^2\theta_{13}$
Inverted	$\sin^2\theta_{12}\cos^2\theta_{13}$	$\sin^2\theta_{13}$



Dighe, SmirnovFest 2012
P. Panda, M. Ghosh, R. Mohanta, 2304.13303

MSW Conversion: Fluence Modifications



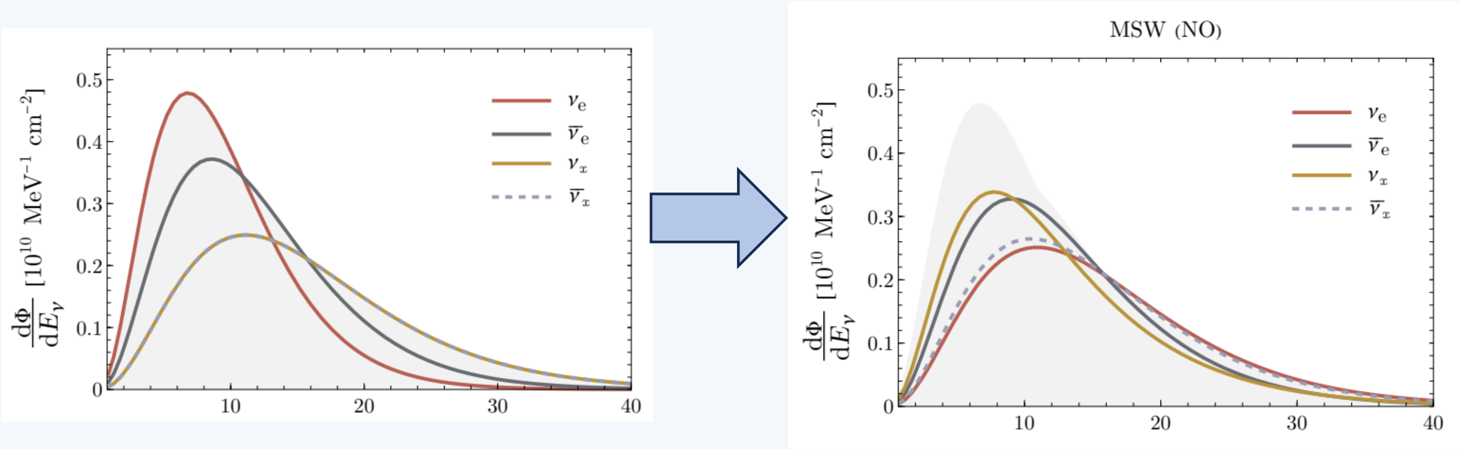
Normal Ordering (NO):

- $p \approx 0$ → $F\nu e = F^{0}\nu x$
- $\bar{p} \approx \cos^2\theta_{12} \approx 0.7$

Inverted Ordering (IO):

- $p \approx \sin^2\theta_{12} \approx 0.3$
- $\bar{p} \approx 0$ → $F\bar{\nu}e = F^{0}\nu x$

Key signature: full (partial) swap of νe ↔ νx
→ Mean energy shift, suppression of neutronisation burst



DUNE Collaboration, 2008.06647

Shock Wave Effects on MSW Resonances

The expanding shock wave crosses the MSW resonance regions, temporarily breaking adiabaticity → time-dependent oscillation probabilities.

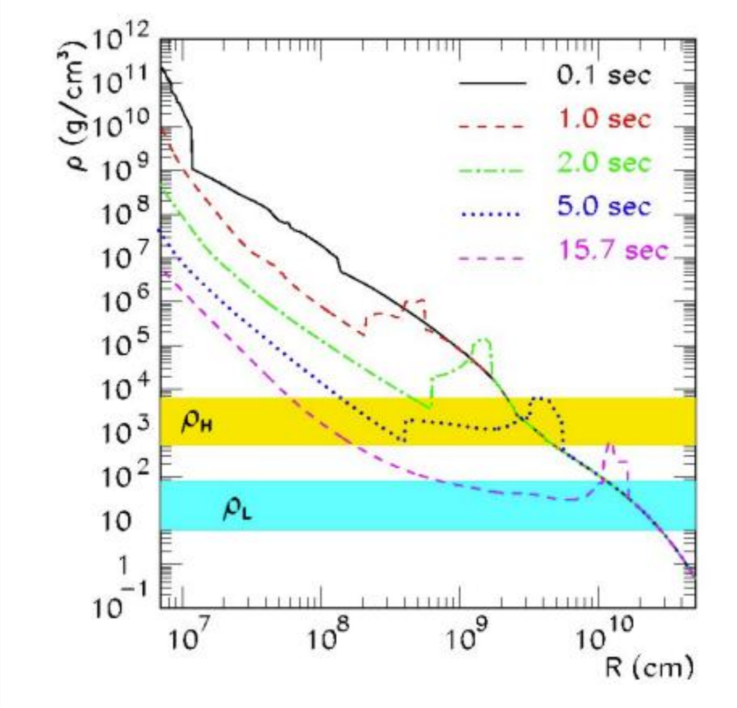
Two shock fronts:

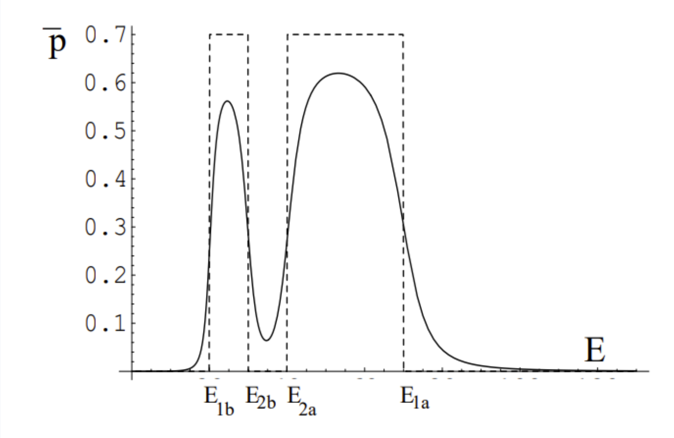
- Forward shock: density jump — non-adiabatic transition, p(t) decreases sharply
- Reverse shock: density rarefaction — restores partial adiabaticity, second feature in signal

Obsevables:

- Time-dependent dip / peak in event rate at DUNE
- Present only in ve for NO; only in v̄e for IO
- Absence of shock features: no concrete signal (turbulence?)

R. Tomas et al. 0407132





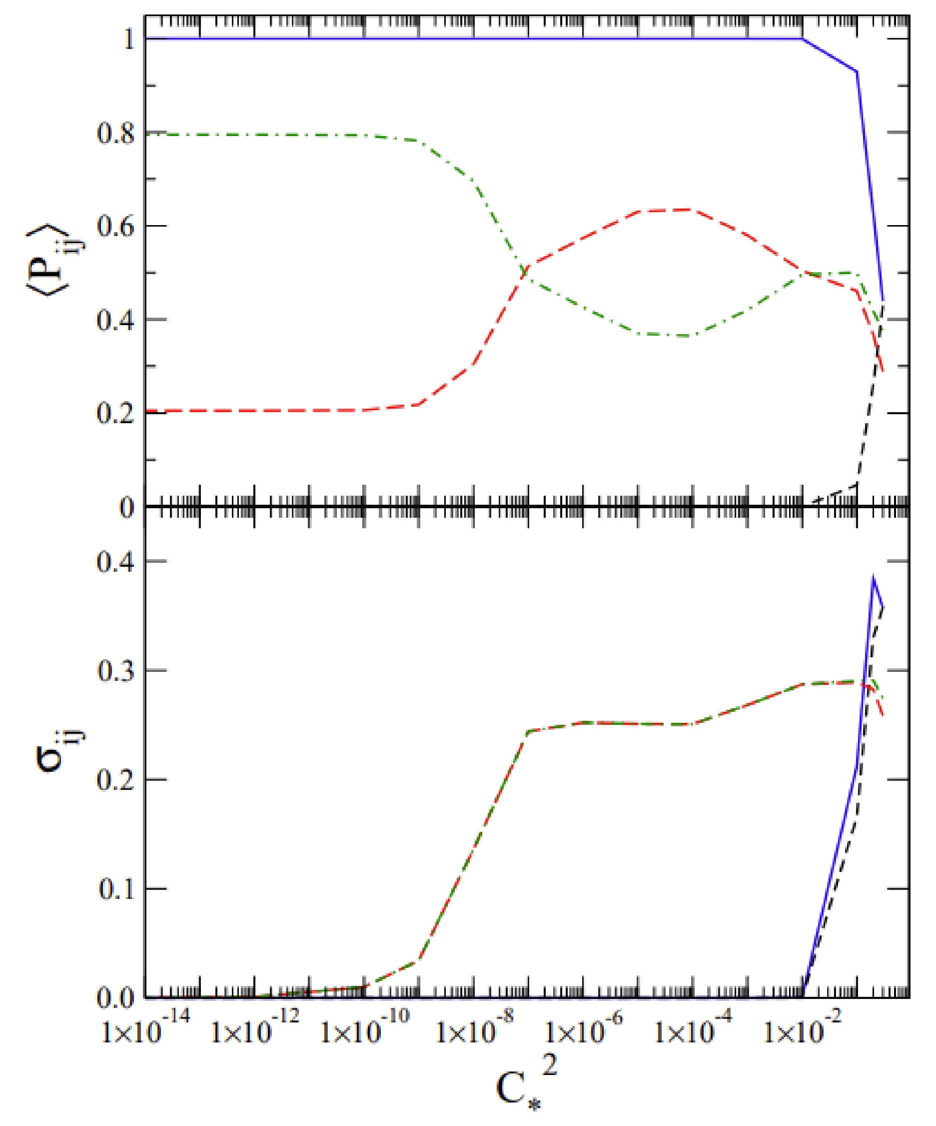
Turbulence & Stochastic Density Fluctuations

Convective turbulence behind the shock → random density fluctuations
→ gradual depolarisation of the oscillation probability

Two-flavour depolarisation limit:

- Small amplitude: effective 2-flavour problem, shock effects survive
- Large amplitude: complete depolarisation → all information lost

Turbulence is an additional systematic — not explicitly modelled, but bounded by the measured shock-effect literature.



Kneller & Volpe PRD 2010

03

Collective Oscillations: Slow & Fast

ν–ν Forward Scattering: A New Ingredient

Full Hamiltonian:

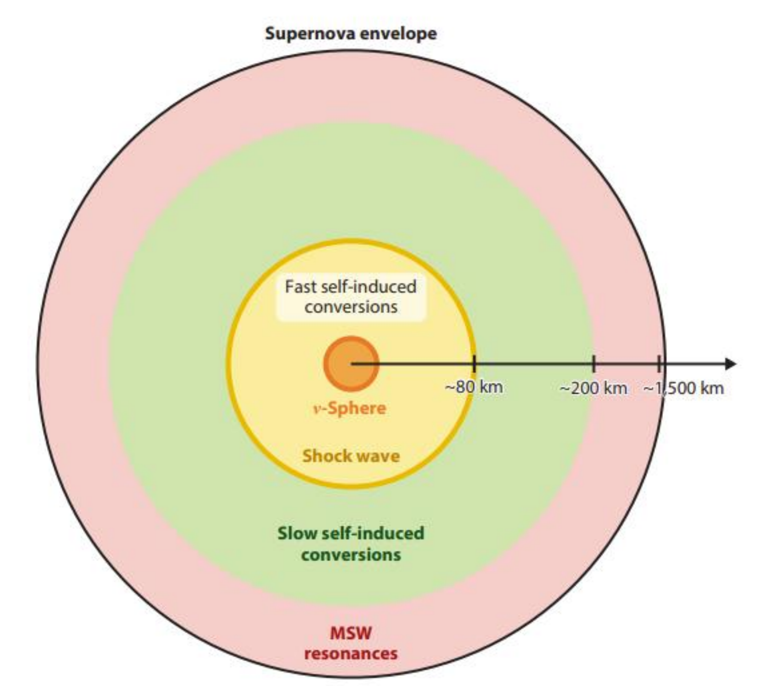
$$(\partial t + v\cdot\nabla)\,\varrho = -i\,[H_{vac} + H_{mat} + H_{\nu\nu}, \varrho] + C(\varrho)$$

$$H_{\nu\nu}(\hat{p}) = \sqrt{2}\, G_F \int dp'\, (1 - \hat{p}\cdot\hat{p}')\, [\varrho(p') - \bar{\varrho}^*(p')]$$

Two qualitatively new regimes:

- **Slow collective modes (vacuum-collective interference)**
  Driven by vacuum term $H_{vac} \sim \Delta m^2/2E \sim 10^0\ \mathrm{km}^{-1}$
  Energy-dependent → spectral splits / swaps

- **Fast flavor instabilities (pure collective effects)**
  Driven by $H_{\nu\nu} \sim G_F n_\nu \sim 10^5\ \mathrm{km}^{-1}$
  Energy-independent → near the neutrinosphere



I. Tamborra, S. Shalgar, 2011.01948

The treatment of collective effects

Main ingredient: **the phase-space distribution ->** describe the neutrino emission in function of the energy and of the emission angle v=cos(θ)

$$f_i(v,E) = (2\pi)^2\, n_i\, \frac{f_i(v)}{\int f_i(v')\, dv'}\, \frac{f_i(E)}{\int f_i(E')\, E'^2\, dE'}$$

Velocity distribution

Pinched form

$$f_i(E) = \frac{(\alpha_i+1)^{\alpha_i+1}}{\langle E_i\rangle^3\, \Gamma(\alpha_i+1)} \left(\frac{E}{\langle E_i\rangle}\right)^{\alpha_i-2} e^{-(\alpha_i+1)\frac{E}{\langle E_i\rangle}}$$

Spectral difference between flavors:

$$\boxed{g_{v,E} = \begin{cases} f_{\nu_e}(v,E) - f_{\nu_x}(v,E)\,, & E>0 \\ f_{\bar\nu_x}(v,|E|) - f_{\bar\nu_e}(v,|E|)\,, & E<0 \end{cases}}$$

(negative energies: antineutrinos)

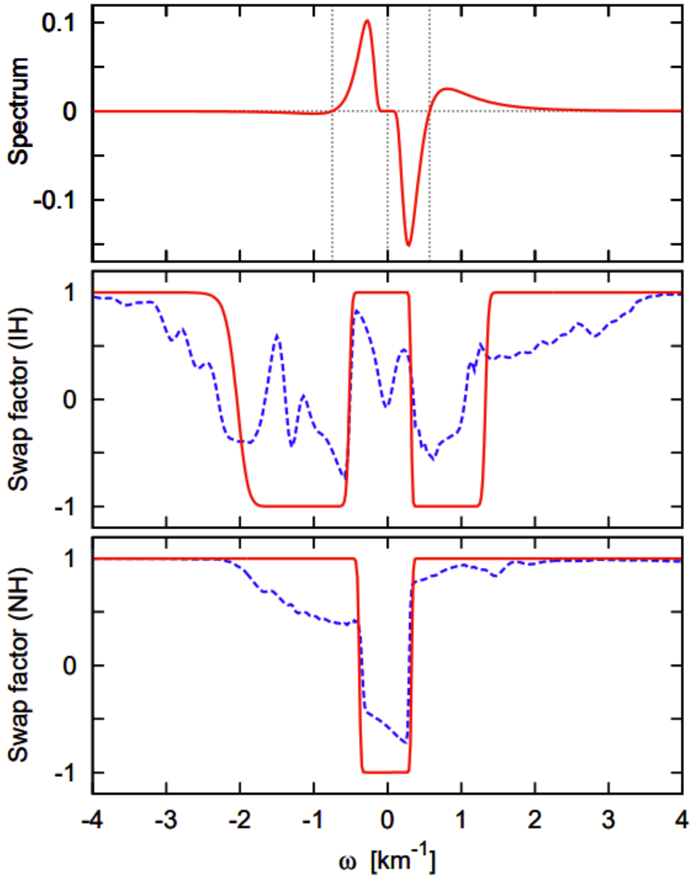
The treatment of collective effects

Slow instabilities:

They develop in presence of a zero in the v-integrated phase space distributions:

$$g(1/E) \equiv \int dv\, g_{v,E} \propto \begin{cases} n_{\nu_e} f_{\nu_e}(E) - n_{\nu_x} f_{\nu_x}(E)\,, & E>0 \\ n_{\nu_x} f_{\nu_x}(|E|) - n_{\bar{\nu}_e} f_{\bar{\nu}_e}(|E|)\,, & E<0 \end{cases}$$

Synchronized → Bipolar → Spectral split



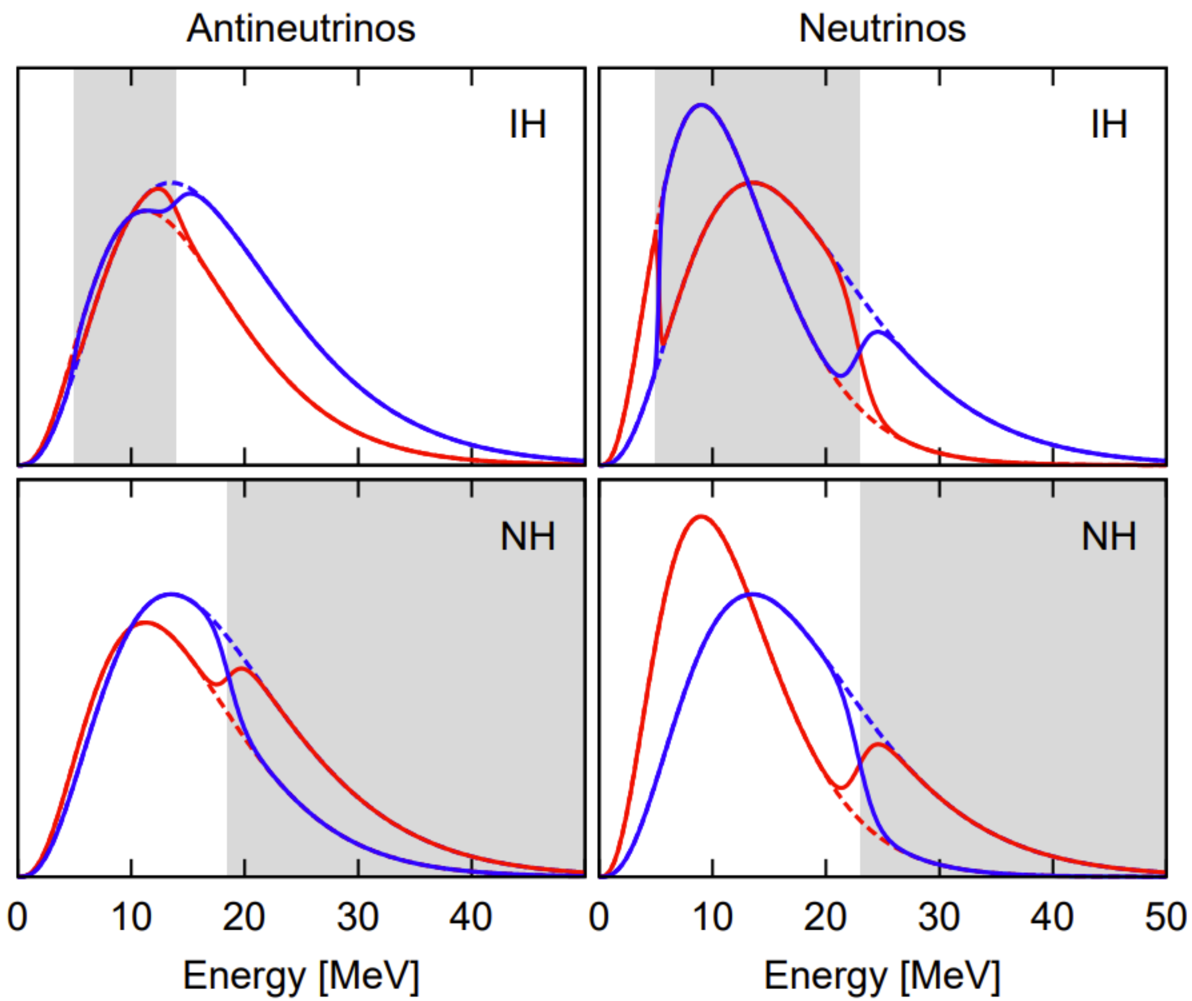
IO -> *spectral swaps in a finite region between two zeros (crossing energies)*

NO -> *spectral swap above the crossing energy*

B. Dasgupta, A. Dighe, G.Raffelt, A.Smirnov, 0904.3542

The treatment of collective effects

Slow instabilities:



Current studies about slow instabilities:

- Any small time-dependent fluctuation would be amplified causing the spectral splits probably to be washed out entirely.

-Their outcome, may be the production of a turbulent bath of flavor waves, and the near-equipartition of antineutrinos.

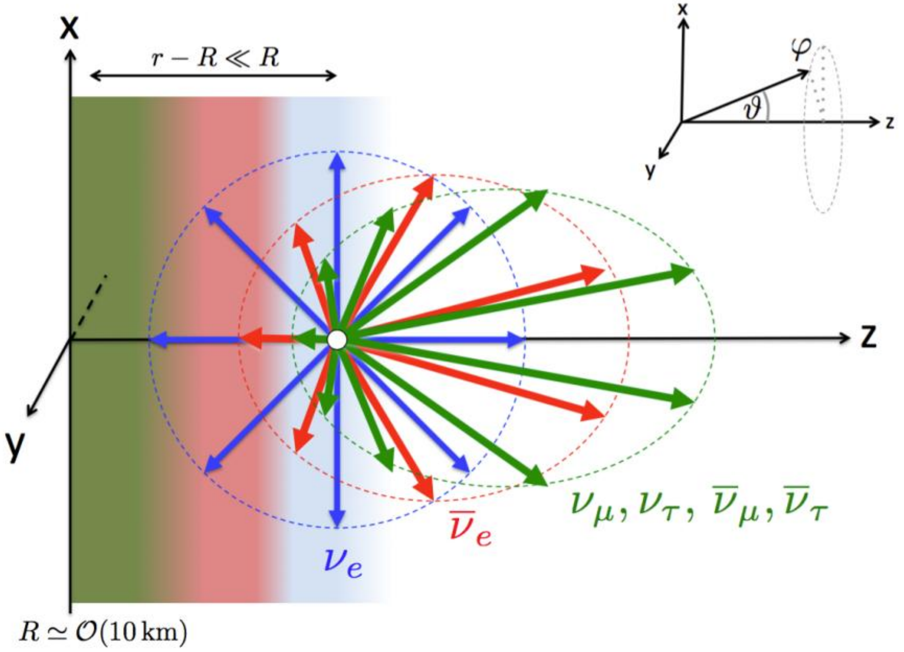
See: 1509.01538, 1509.03171, 2412.02747, 2501.16423,

B. Dasgupta, A. Dighe, G.Raffelt, A.Smirnov, 0904.3542

The treatment of collective effects

Fast instabilities:

They develop in presence of a zero in the difference between electron-neutrino lepton number (ELN) and non-electron-neutrino lepton number (XLN) angular distributions



$$G(v) \equiv \int_{-\infty}^{+\infty} g_{v,E}\, E^2\, dE$$
$$= \int_0^{+\infty} \Big[\big(f_{\nu_e}(v,E) - f_{\bar{\nu}_e}(v,E)\big) - \big(f_{\nu_x}(v,E) - f_{\bar{\nu}_x}(v,E)\big)\Big] E^2\, dE$$

Energy-independent: all energies converted equally

-> Towards flavor equilibrium

$$\boxed{P_{ee}(v) = \begin{cases} p_{\mathrm{eq}}\,, & G(v) < 0 \\ 1 - (1 - p_{\mathrm{eq}})\,\dfrac{A}{B}\,, & G(v) > 0 \end{cases}}$$

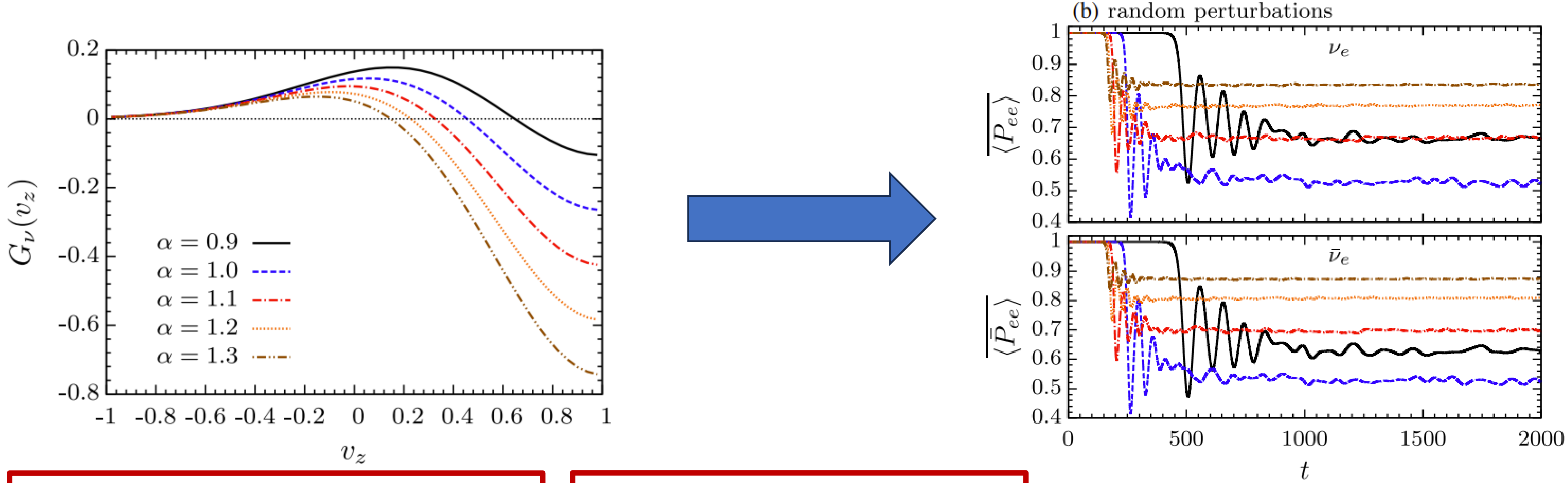
$(P_{eq} = 1/3)$

$$A \equiv \left| \int_{G(v)<0} G(v)\, dv \right| , \qquad B \equiv \left| \int_{G(v)>0} G(v)\, dv \right|$$

B. Dasgupta, A. Mirizzi, M.Sen, 1609.00528
M. Zaizen, H. Nagakura, 2211.09343

The treatment of collective effects

Fast instabilities:



$$g_{\nu(\bar{\nu})}(v_z) \propto \exp[-(v_z - 1)^2/(2\sigma^2_{\nu(\bar{\nu})})]$$

$$G(v) \propto f_{\nu_e}(v) - \alpha f_{\bar{\nu}_e}(v)$$

(With electron neutrino distribution less peaked forward)

Meng-Ru Wu, M. George, Chun-Yu Lin, Z. Xiong, 2108.09886

04

Phenomenological Framework: Three Scenarios

Sequential Ordering of Conversion Effects

Emission pinched flux → Slow Collective Oscillations → Fast Flavor Instability (FFI) → MSW Conversions → Detected Fluence at DUNE

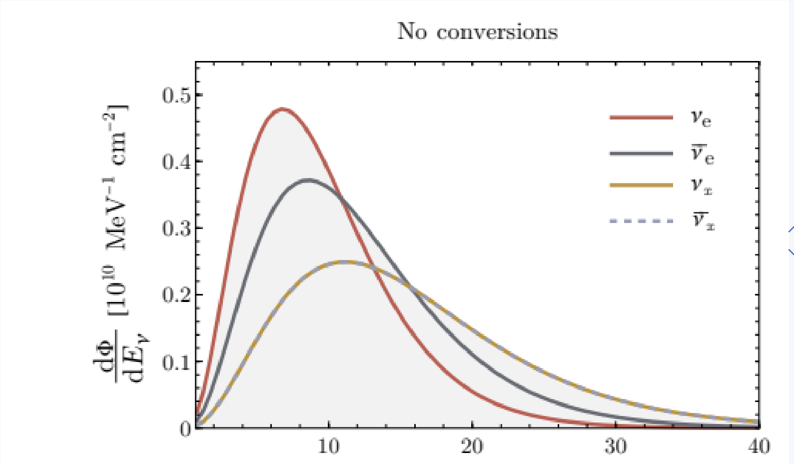
⚠ **Current understanding:** The main effects of slow collective oscillations may develop deeper in the star, closer to the neutrinosphere. FFI then acts further out. Both precede MSW conversions in the outer mantle. (see 2507.22985)

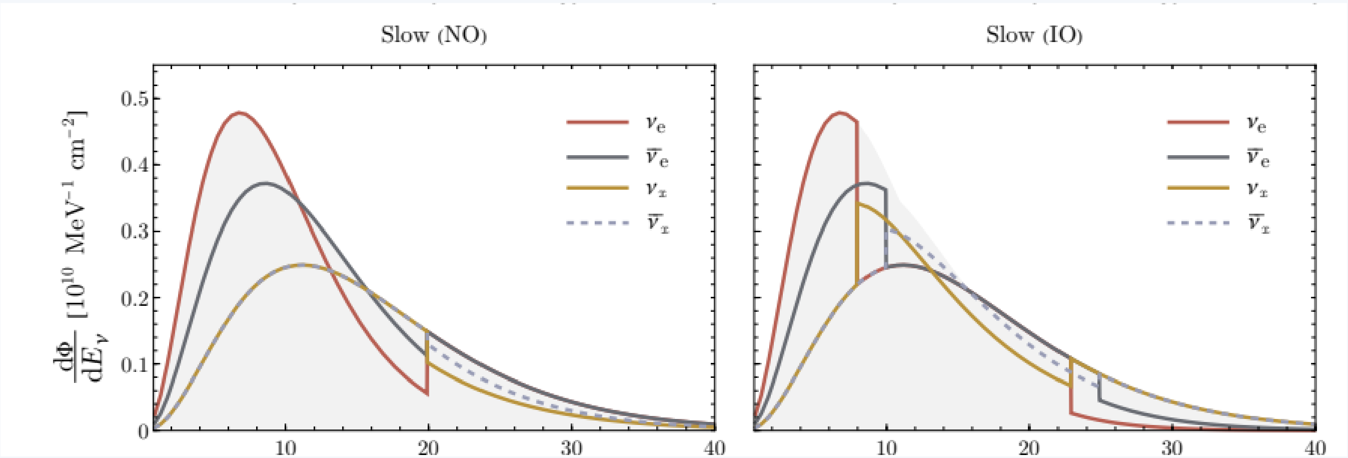
🟥 Scenario M: skip slow & fast → MSW only

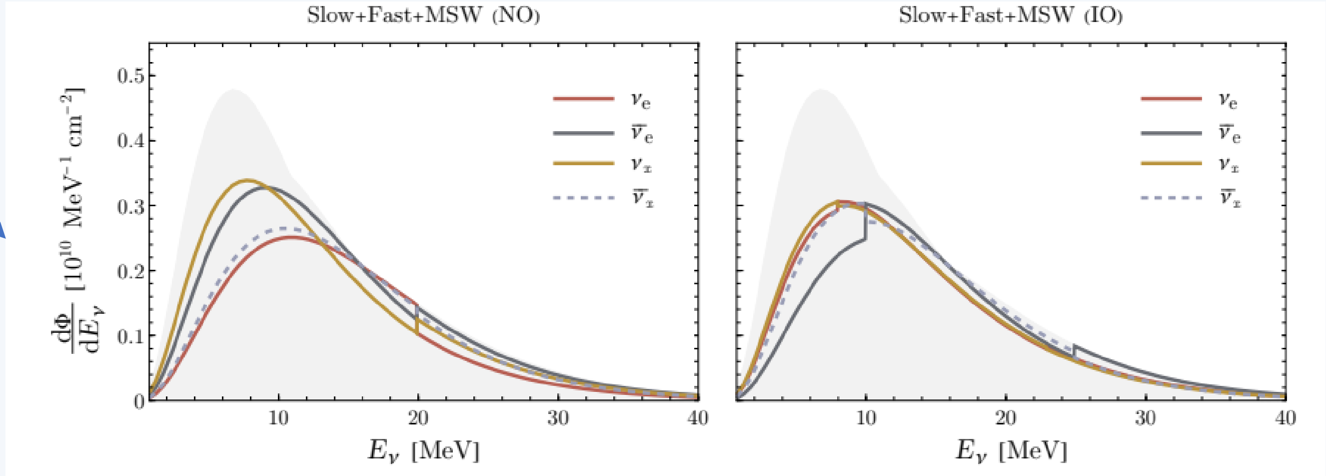
🟧 Scenario S: slow → MSW (no fast)

🟩 Scenario F: slow → fast → MSW (all three active)

Fluence Modifications: Overview







05

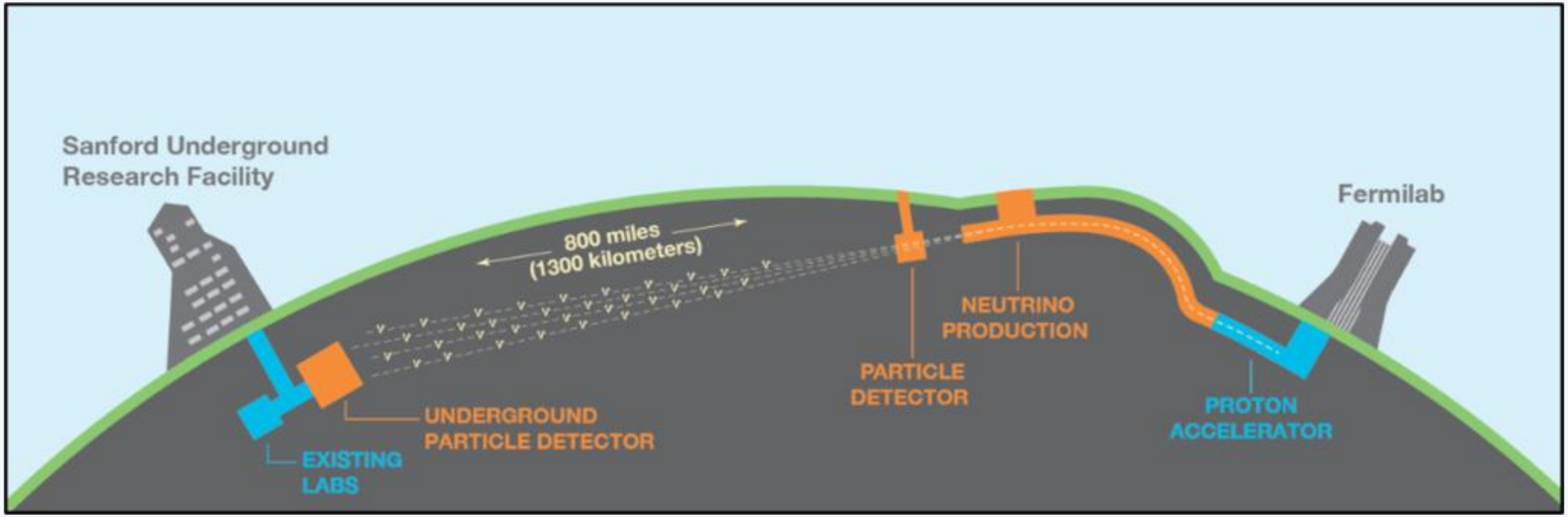
DUNE as a Supernova Neutrino Observatory

The DUNE Experiment

Deep Underground Neutrino Experiment

- 40 kt fiducial mass liquid argon TPC (Far Detector) at SURF, South Dakota, 1.5 km underground
- Threshold ~ 5 MeV, energy resolution ~ 10–20%

Expected events (SN at 10 kpc):
O(few hundred) per kt → O(10,000) total



Analysis Framework: GLoBES + MultiNest

GLoBES

Event rate generator

- Supernova neutrino fluences
- DUNE detector response
- Cross-sections for ve on ^{40}Ar
- Systematic uncertainties (flux normalisation, energy scale)

MultiNest

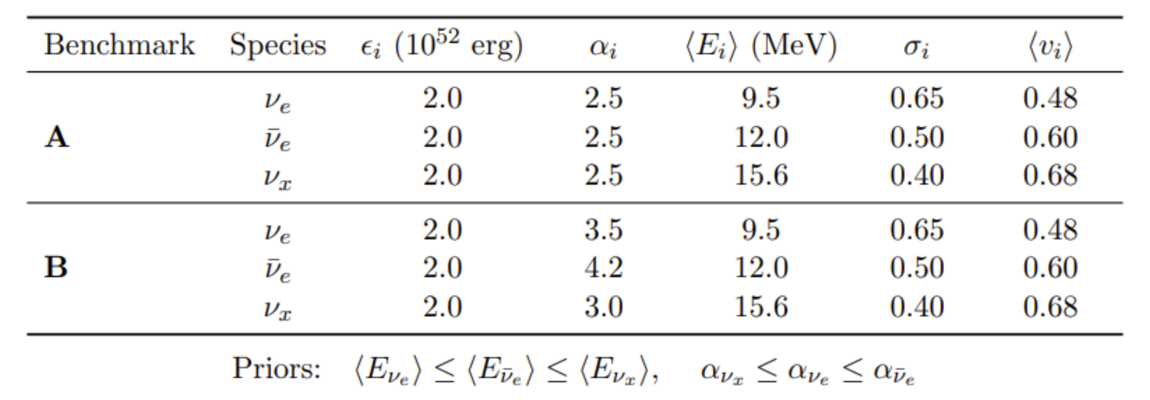
Bayesian nested sampling

- Efficient exploration of multi-dim. parameter space
- Posterior PDFs for flux parameters
- Model selection: Bayes factors between M, S, F
- Fully marginalised credible intervals

Free parameters per scenario:

- Flux parameters: pinching, luminosity and mean energy; sigma of velocity distributions (fixed)
- Oscillation / conversion parameters: p, $\bar{p}$ (MSW, fixed from best fits); swap width (slow, fixed to 7.5 MeV); peq (fast, fixed to 1/3), x neutrino same flux as x antineutrinos at production
- Distance D (prior: ~10 kpc Galactic SN)

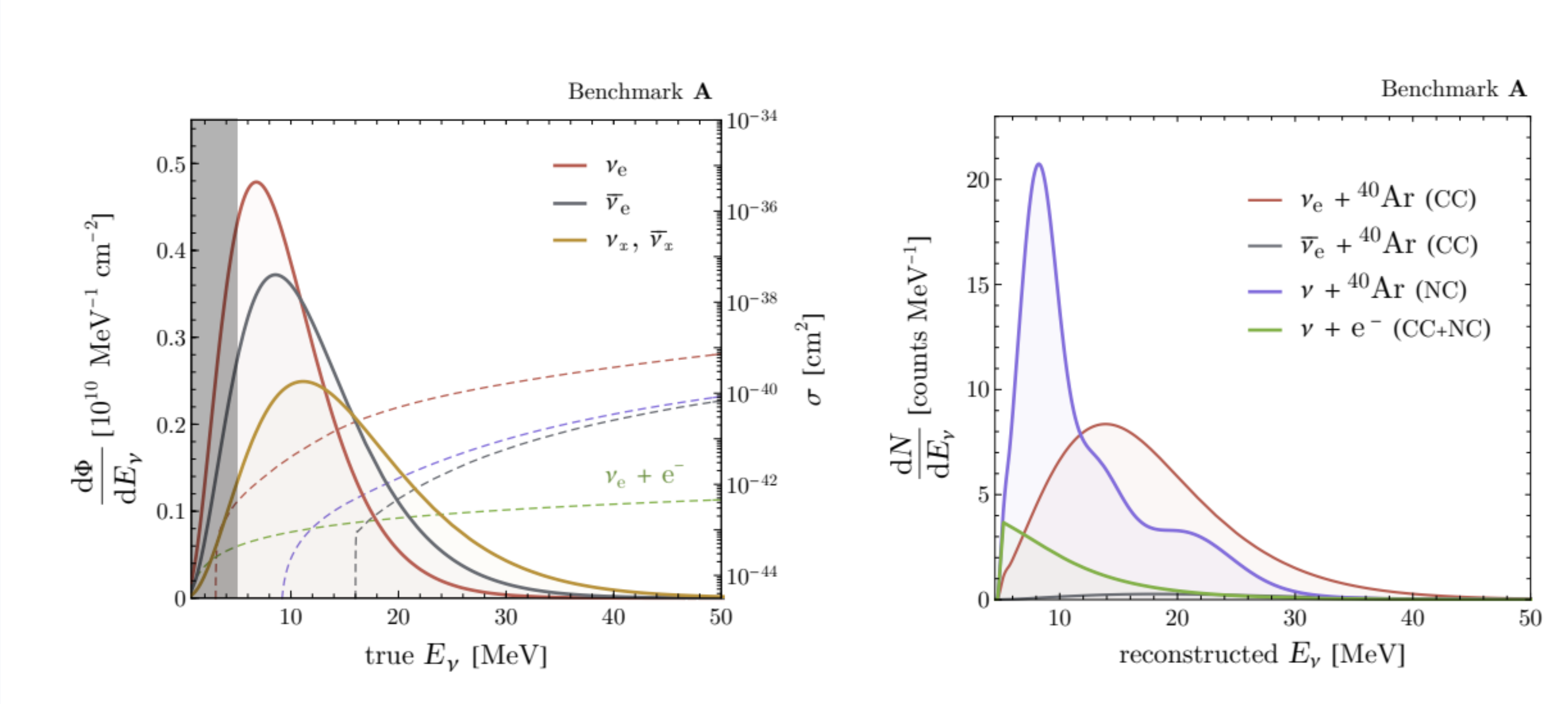
Benchmark Flux Parameters and detection channels



Benchmark	Species	ϵ_i (10^{52} erg)	α_i	$\langle E_i \rangle$ (MeV)	σ_i	$\langle v_i \rangle$
A	ν_e	2.0	2.5	9.5	0.65	0.48
	$\bar{\nu}_e$	2.0	2.5	12.0	0.50	0.60
	ν_x	2.0	2.5	15.6	0.40	0.68
B	ν_e	2.0	3.5	9.5	0.65	0.48
	$\bar{\nu}_e$	2.0	4.2	12.0	0.50	0.60
	ν_x	2.0	3.0	15.6	0.40	0.68

Priors: $\langle E_{\nu_e} \rangle \leq \langle E_{\bar{\nu}_e} \rangle \leq \langle E_{\nu_x} \rangle$, $\alpha_{\nu_x} \leq \alpha_{\nu_e} \leq \alpha_{\bar{\nu}_e}$

❗ Benchmark B:
Garching inspired



CC νe

$\nu e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$

CC ν̄e

$\bar{\nu} e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$

NC

$\nu + {}^{40}Ar \rightarrow \nu + {}^{40}Ar^*$

ES

$\nu + e^- \rightarrow \nu + e^-$

06

Results: Flux Reconstruction & Scenario Discrimination

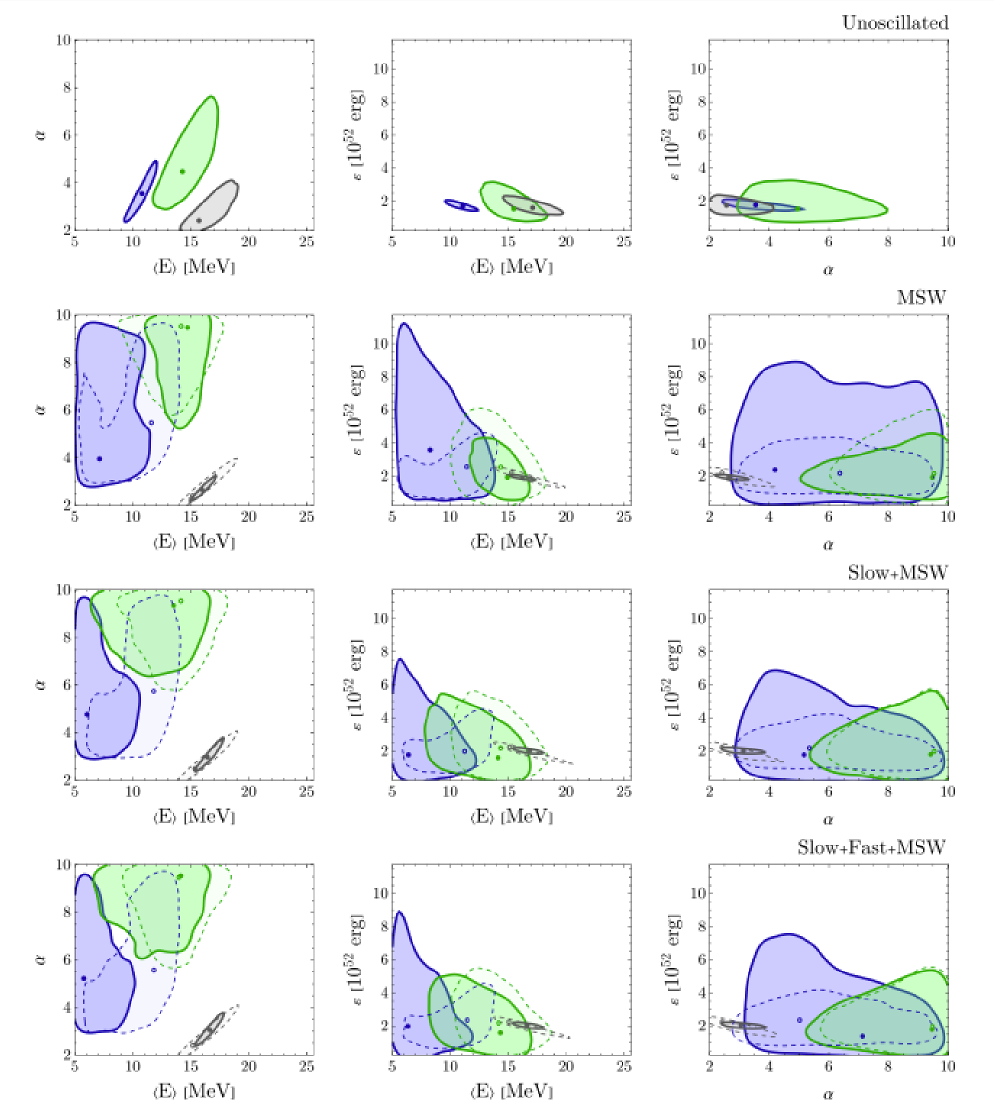
Bayesian Parameter Reconstruction

For each true scenario, we reconstruct the flux parameters
by fitting within the same conversion hypothesis.

- Can DUNE accurately recover the emission parameters?

1) *The CC νe channel allows to measure very well the parameters of electron neutrinos in unoscillated case and x neutrinos if MSW is present*

2) *The MSW effect is driving the main patterns of the results with or without collective effects*



Benchmark A

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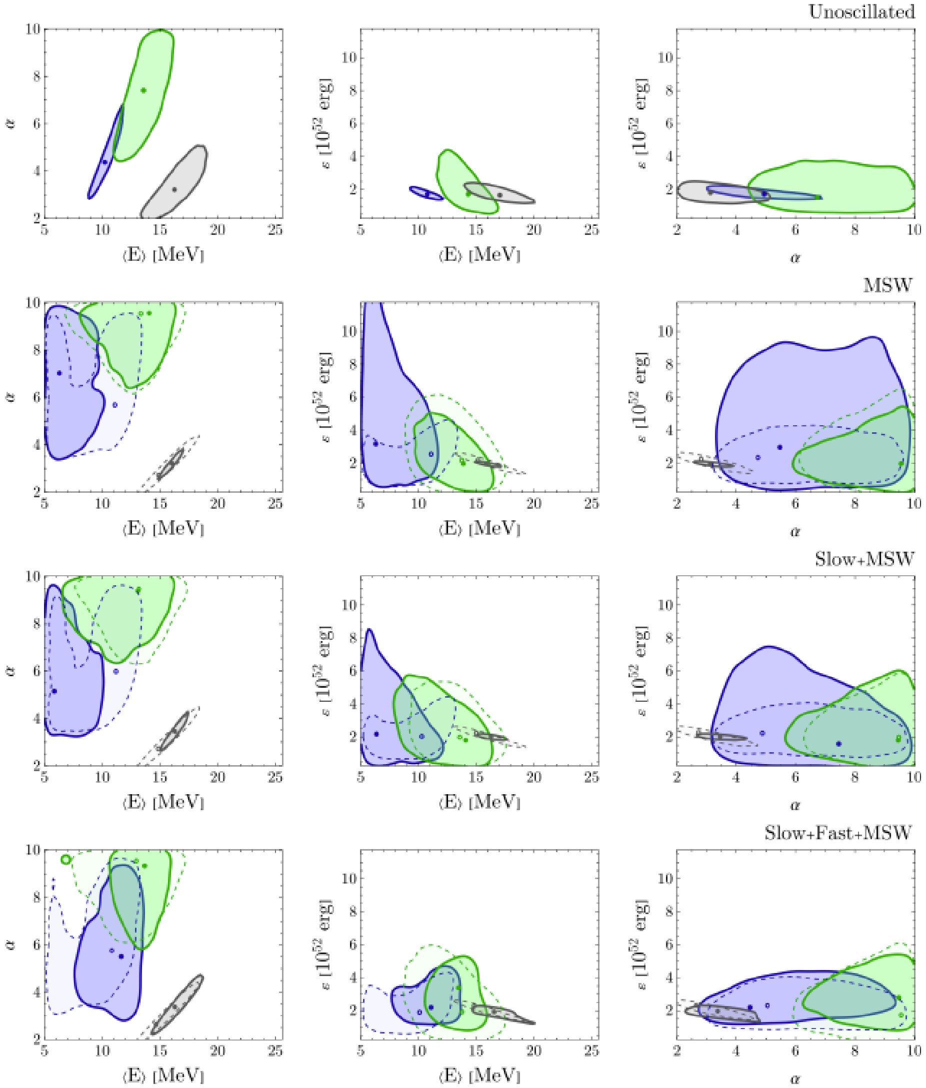
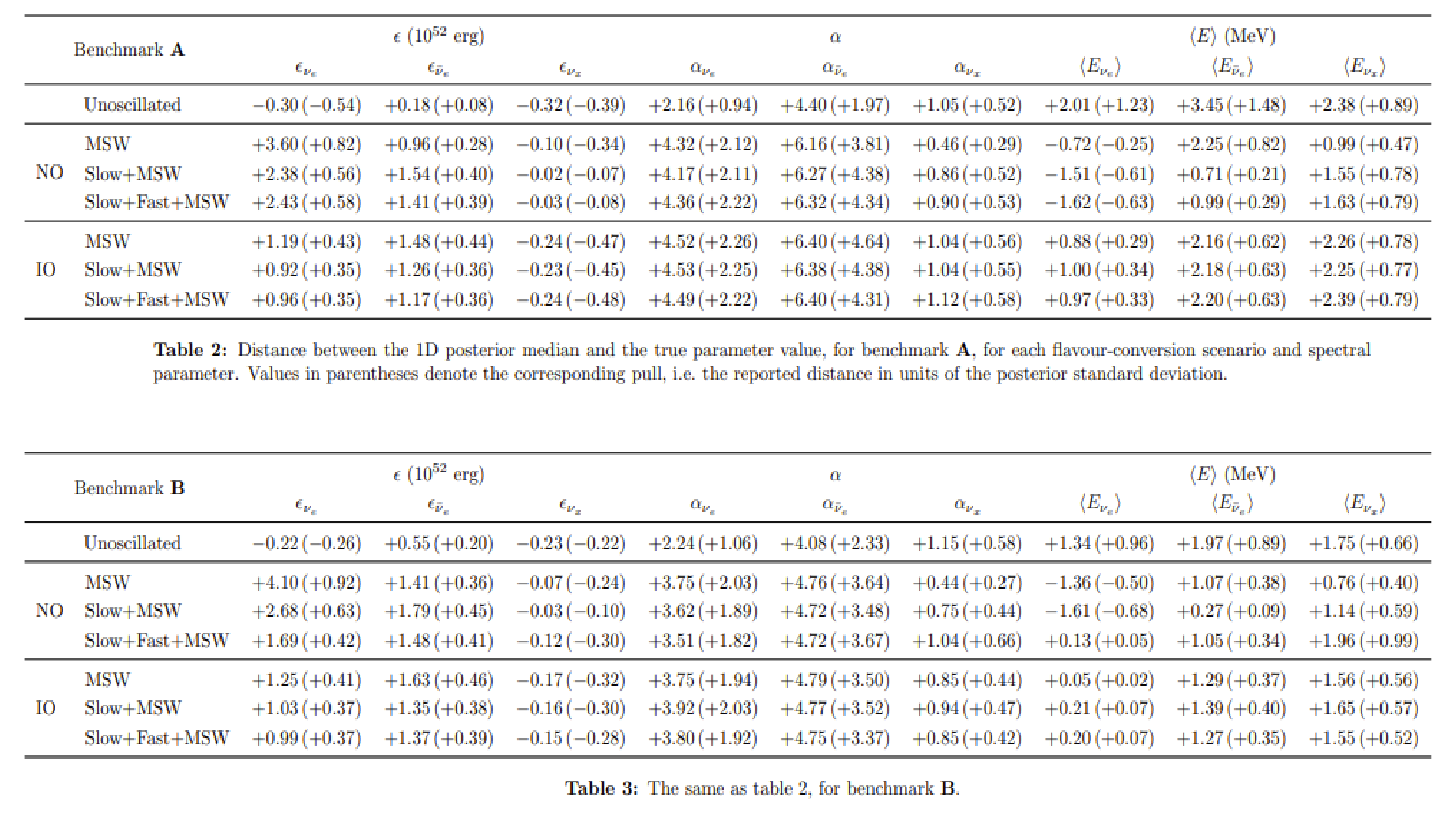


Benchmark B

Parameters best fits



Benchmark **A**		ϵ (10^{52} erg)			α			$\langle E \rangle$ (MeV)		
		ϵ_{ν_e}	$\epsilon_{\bar{\nu}_e}$	ϵ_{ν_x}	α_{ν_e}	$\alpha_{\bar{\nu}_e}$	α_{ν_x}	$\langle E_{\nu_e} \rangle$	$\langle E_{\bar{\nu}_e} \rangle$	$\langle E_{\nu_x} \rangle$
	Unoscillated	−0.30 (−0.54)	+0.18 (+0.08)	−0.32 (−0.39)	+2.16 (+0.94)	+4.40 (+1.97)	+1.05 (+0.52)	+2.01 (+1.23)	+3.45 (+1.48)	+2.38 (+0.89)
NO	MSW	+3.60 (+0.82)	+0.96 (+0.28)	−0.10 (−0.34)	+4.32 (+2.12)	+6.16 (+3.81)	+0.46 (+0.29)	−0.72 (−0.25)	+2.25 (+0.82)	+0.99 (+0.47)
	Slow+MSW	+2.38 (+0.56)	+1.54 (+0.40)	−0.02 (−0.07)	+4.17 (+2.11)	+6.27 (+4.38)	+0.86 (+0.52)	−1.51 (−0.61)	+0.71 (+0.21)	+1.55 (+0.78)
	Slow+Fast+MSW	+2.43 (+0.58)	+1.41 (+0.39)	−0.03 (−0.08)	+4.36 (+2.22)	+6.32 (+4.34)	+0.90 (+0.53)	−1.62 (−0.63)	+0.99 (+0.29)	+1.63 (+0.79)
IO	MSW	+1.19 (+0.43)	+1.48 (+0.44)	−0.24 (−0.47)	+4.52 (+2.26)	+6.40 (+4.64)	+1.04 (+0.56)	+0.88 (+0.29)	+2.16 (+0.62)	+2.26 (+0.78)
	Slow+MSW	+0.92 (+0.35)	+1.26 (+0.36)	−0.23 (−0.45)	+4.53 (+2.25)	+6.38 (+4.38)	+1.04 (+0.55)	+1.00 (+0.34)	+2.18 (+0.63)	+2.25 (+0.77)
	Slow+Fast+MSW	+0.96 (+0.35)	+1.17 (+0.36)	−0.24 (−0.48)	+4.49 (+2.22)	+6.40 (+4.31)	+1.12 (+0.58)	+0.97 (+0.33)	+2.20 (+0.63)	+2.39 (+0.79)

Table 2: Distance between the 1D posterior median and the true parameter value, for benchmark **A**, for each flavour-conversion scenario and spectral parameter. Values in parentheses denote the corresponding pull, i.e. the reported distance in units of the posterior standard deviation.

Benchmark **B**		ϵ (10^{52} erg)			α			$\langle E \rangle$ (MeV)		
		ϵ_{ν_e}	$\epsilon_{\bar{\nu}_e}$	ϵ_{ν_x}	α_{ν_e}	$\alpha_{\bar{\nu}_e}$	α_{ν_x}	$\langle E_{\nu_e} \rangle$	$\langle E_{\bar{\nu}_e} \rangle$	$\langle E_{\nu_x} \rangle$
	Unoscillated	−0.22 (−0.26)	+0.55 (+0.20)	−0.23 (−0.22)	+2.24 (+1.06)	+4.08 (+2.33)	+1.15 (+0.58)	+1.34 (+0.96)	+1.97 (+0.89)	+1.75 (+0.66)
NO	MSW	+4.10 (+0.92)	+1.41 (+0.36)	−0.07 (−0.24)	+3.75 (+2.03)	+4.76 (+3.64)	+0.44 (+0.27)	−1.36 (−0.50)	+1.07 (+0.38)	+0.76 (+0.40)
	Slow+MSW	+2.68 (+0.63)	+1.79 (+0.45)	−0.03 (−0.10)	+3.62 (+1.89)	+4.72 (+3.48)	+0.75 (+0.44)	−1.61 (−0.68)	+0.27 (+0.09)	+1.14 (+0.59)
	Slow+Fast+MSW	+1.69 (+0.42)	+1.48 (+0.41)	−0.12 (−0.30)	+3.51 (+1.82)	+4.72 (+3.67)	+1.04 (+0.66)	+0.13 (+0.05)	+1.05 (+0.34)	+1.96 (+0.99)
IO	MSW	+1.25 (+0.41)	+1.63 (+0.46)	−0.17 (−0.32)	+3.75 (+1.94)	+4.79 (+3.50)	+0.85 (+0.44)	+0.05 (+0.02)	+1.29 (+0.37)	+1.56 (+0.56)
	Slow+MSW	+1.03 (+0.37)	+1.35 (+0.38)	−0.16 (−0.30)	+3.92 (+2.03)	+4.77 (+3.52)	+0.94 (+0.47)	+0.21 (+0.07)	+1.39 (+0.40)	+1.65 (+0.57)
	Slow+Fast+MSW	+0.99 (+0.37)	+1.37 (+0.39)	−0.15 (−0.28)	+3.80 (+1.92)	+4.75 (+3.37)	+0.85 (+0.42)	+0.20 (+0.07)	+1.27 (+0.35)	+1.55 (+0.52)

Table 3: The same as table 2, for benchmark **B**.

Benchmark B:
-better recovery of **mean energies** due to a larger spectral hierarchy, -degraded **pinching parameter** reconstruction because more distinct true values make prior constraints less effective.

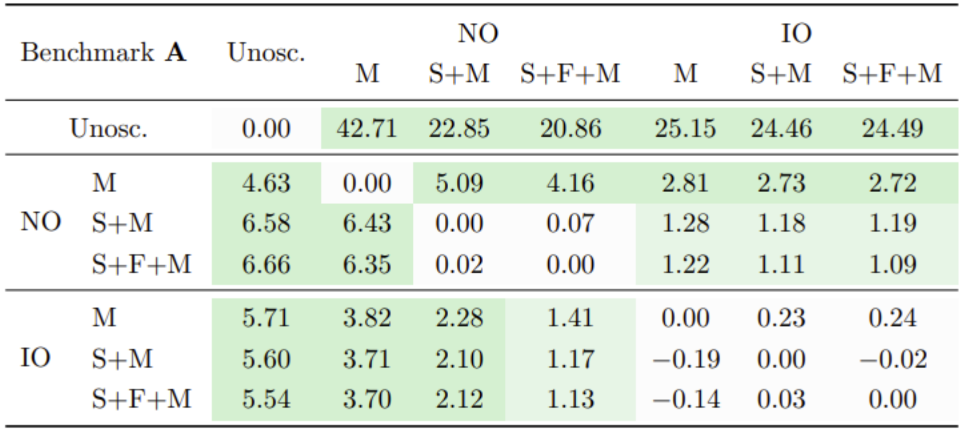
Main results:

- **Luminosity:** Most reliably reconstructed; remains accurate across most scenarios.
- **Energy:** Generally accurate within 1 sigma, though sensitive to mass ordering and spectral hierarchy.
- **Pinching:** Most difficult to recover; electron flavor ones are systematically overestimated due to flavor conversion.
- **Antineutrino Channel:** High energy threshold and low cross-sections lead to poor recovery of electron antineutrino parameters.
- **MSW Impact:** Flavor conversion via MSW is the primary driver of reconstruction quality, outweighing collective oscillation effects.

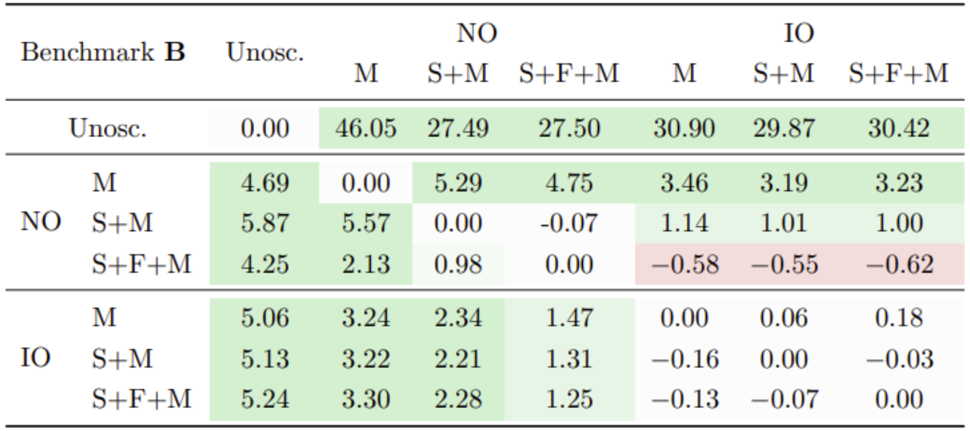
Scenario Discrimination: Bayes Factors

Log-Bayes factor matrix :

Rows = true scenario | Columns = tested hypothesis



Benchmark **A**		Unosc.	NO			IO		
			M	S+M	S+F+M	M	S+M	S+F+M
Unosc.		0.00	42.71	22.85	20.86	25.15	24.46	24.49
NO	M	4.63	0.00	5.09	4.16	2.81	2.73	2.72
	S+M	6.58	6.43	0.00	0.07	1.28	1.18	1.19
	S+F+M	6.66	6.35	0.02	0.00	1.22	1.11	1.09
IO	M	5.71	3.82	2.28	1.41	0.00	0.23	0.24
	S+M	5.60	3.71	2.10	1.17	−0.19	0.00	−0.02
	S+F+M	5.54	3.70	2.12	1.13	−0.14	0.03	0.00



Benchmark **B**		Unosc.	NO			IO		
			M	S+M	S+F+M	M	S+M	S+F+M
Unosc.		0.00	46.05	27.49	27.50	30.90	29.87	30.42
NO	M	4.69	0.00	5.29	4.75	3.46	3.19	3.23
	S+M	5.87	5.57	0.00	-0.07	1.14	1.01	1.00
	S+F+M	4.25	2.13	0.98	0.00	−0.58	−0.55	−0.62
IO	M	5.06	3.24	2.34	1.47	0.00	0.06	0.18
	S+M	5.13	3.22	2.21	1.31	−0.16	0.00	−0.03
	S+F+M	5.24	3.30	2.28	1.25	−0.13	−0.07	0.00

Jeffreys scale: |ln B| > 1 = substantial; > 3 = strong; > 5 = very strong evidence

Main results

- **Unoscillated Case:** Decisively distinguishable from all conversion scenarios (if MSW is present).
- **Normal Ordering (NO):** MSW-only signatures are unique and easily identified due to near-complete flavor conversion.
- **Inverted Ordering (IO):** Different conversion mechanisms produce similar spectra, making specific scenario identification difficult.
- **Collective Effects:** DUNE lacks the sensitivity to distinguish between "Slow" and "Fast" flavor conversions within the same mass ordering.
- **Benchmark B:** Fast conversions more effectively suppress MSW imprints, increasing ambiguity between NO and IO hypotheses.

07

Conclusions & Outlook

Conclusions

DUNE is a powerful νe telescope: with ~10,000 events from a Galactic SN — unique sensitivity via CC on ^{40}Ar

We considered three conversion scenarios: are phenomenologically distinct: MSW (M), slow collective (S), fast collective (F)

Collective oscillations significantly alter: the fluence spectrum — spectral swaps (slow) and flavour equilibration (fast)

DUNE can discriminate among scenarios: using Bayesian inference — strong evidence in some cases

Mismodelling is dangerous: — wrong scenario assumption biases flux reconstruction

This work provides for the first time a complete phenomenological framework including collective effects

Outlook & Open Questions

Time-resolved analysis

Exploit time evolution of SN neutrinos to further discriminate scenarios and track shock wave propagation

More realistic treatment of slow conversions

Go beyond the spectral swap prescription and find a new phenomenological way to treat their effects

Self-consistent FFC prescriptions

Use outputs of νQKE global simulations as realistic fast FFC inputs

Multi-detector synergy

Combine DUNE (νe) + Hyper-K (ν̄e) + IceCube (all flavours) for model-independent extraction

Turbulence & stochastic effects

Shock wave turbulence may smear spectral features — systematic uncertainty

Earth matter effects

Additional signature for MSW scenario — measurable with large detectors

Thank You!

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