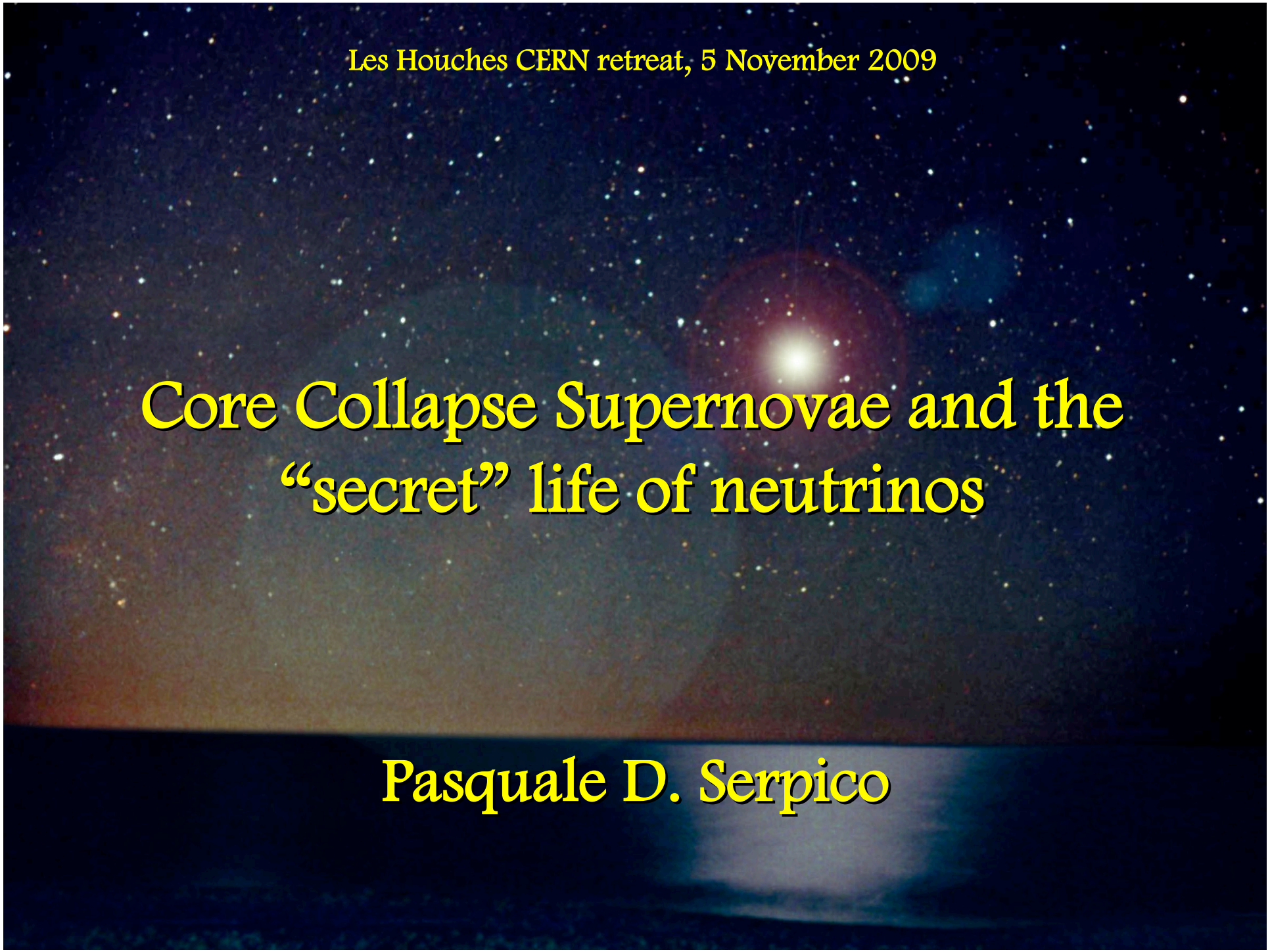
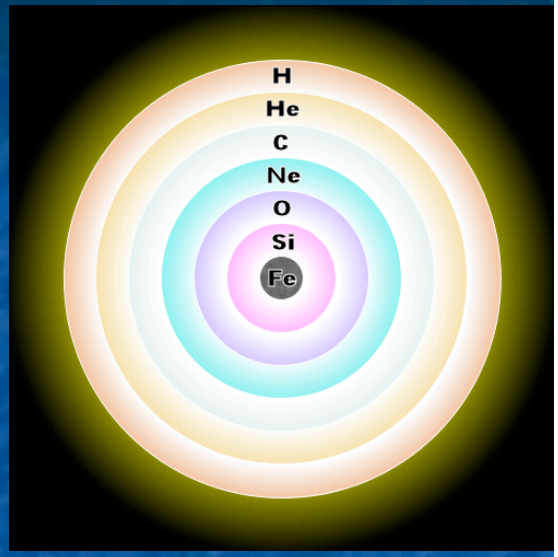
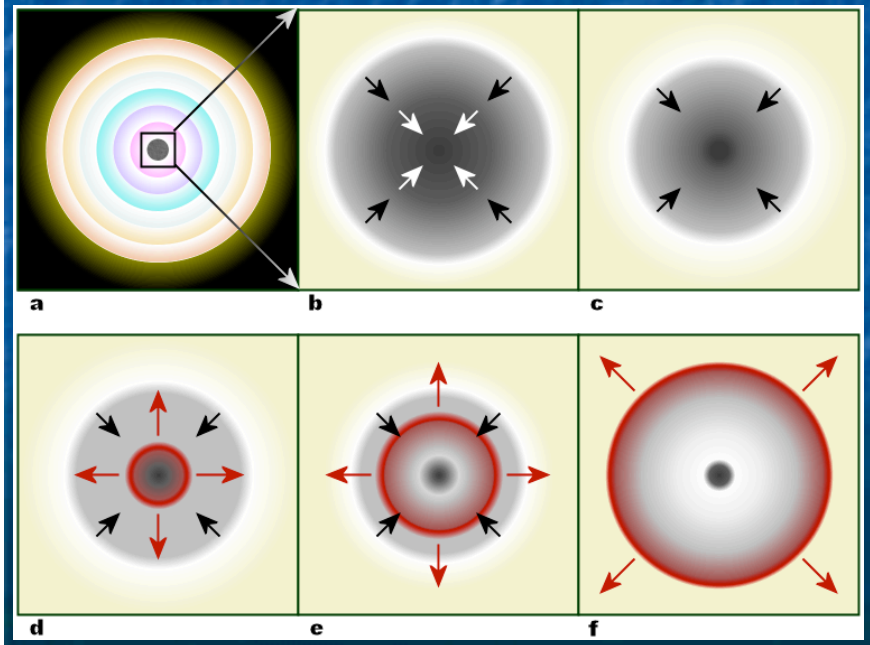

Les Houches CERN retreat, 5 November 2009
Core Collapse Supernovae and the
“secret” life of neutrinos
Pasquale D. Serpico

Stellar Collapse & SN explosion

- The core of a massive star cannot sustain equilibrium by thermonuclear fusion beyond A~56 (Ni-Fe).
- The degenerate iron core starts to collapse, halting only when nuclear densities are reached (~incompressible).
- Then, a shock wave (SW) propagates outwards.
- The SW energy is mostly dissipated by dissociating the outer layer of iron, and no explosion happens





Neutrinos to the rescue!

The core (now a "T~O(10) MeV" p-n star) dissipates its binding energy into ν's

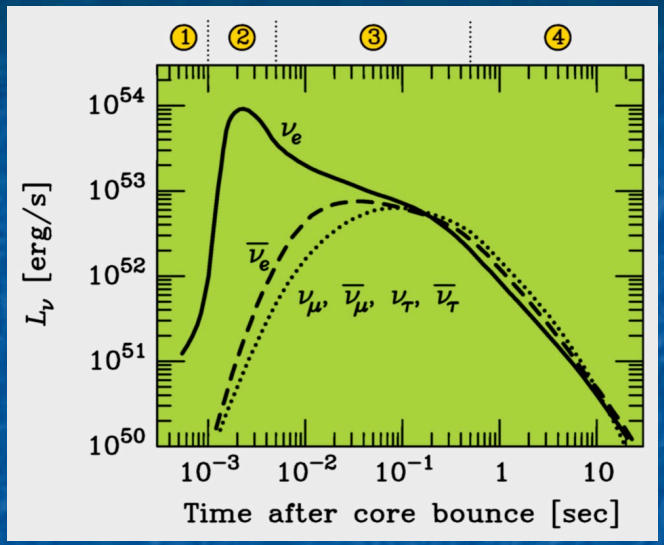
ν heating increases pressure behind shock front, rescuing stalled shock. It eventually ejects star's outer mantle (explosion). While it lasts, ν luminosity outshines whole universe

Fluxes of Supernova Neutrinos

- Fluxes are both time and flavour dependent.

The time-structure is characterized by 4 phases

1. Collapse (infall phase)
2. Shock break out — neutronization-burst, Large flavour-asymm.
3. Matter accretion
4. Kelvin-Helmholtz cooling — ~Lum. equipartition



- At "late" times E-shape mostly dictated by weak processes opacity → Moderate flavour hierarchy. With luminosity equipartition, this implies (for initial fluxes)

$$\langle F_{\nu_e} \rangle \gtrsim \langle F_{\bar{\nu}_e} \rangle \gtrsim \langle F_{\nu_x} \rangle$$

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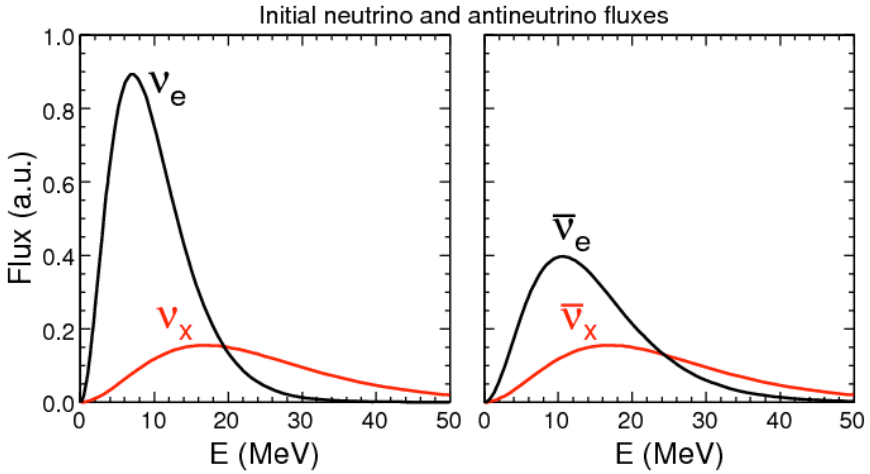


But this does not account for oscillations (not to speak of NP!)

Basics of Neutrino Oscillations

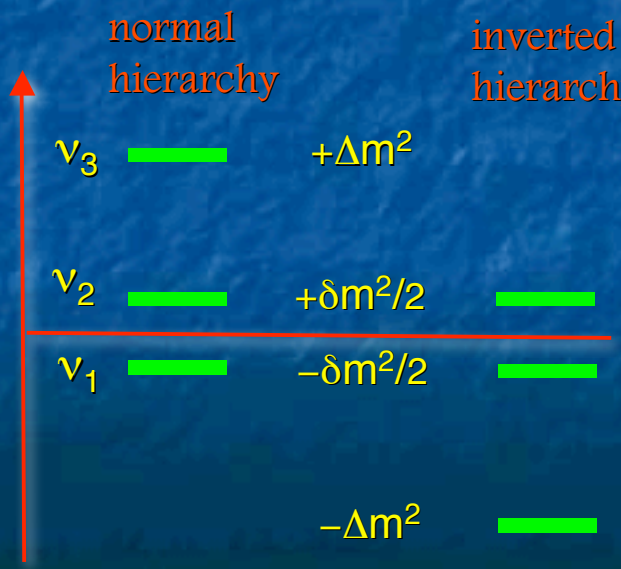
We have now compelling evidence that the Hamiltonian of ν evolution is non-diagonal in flavour space. (Almost?) all data are consistent with a 3ν oscillation framework

$$H = \frac{U\,M^2 U^\dagger}{2p} + \mathrm{diag}(V, 0, 0)$$

Vacuum mixing term

MSW term (matter potential)

Mixing parameters: $U(\theta_{12}, \theta_{23}, \theta_{13}, \delta)$
(as for CKM matrix)



Energy shift due to different interactions of different flavours

$$V = \sqrt{2} G_F \left(n_{e^-} - n_{e^+}\right)$$

arises at tree level due to the "extra" charged current interaction for ν_e in medium (relative – sign for anti ν_e)

[Wolfenstein, PRD 17, 2369 (1978), Mikheev & Smirnov, Sov. J. Nucl. Phys. 42, 913 (1985)]

Interaction terms in SN neutrinos

- **Well-known MSW flavor conversion** can occur in a SN envelope when the ν potential $\lambda=\sqrt{2}G_F n_e$ is close to osc. frequency $\omega_H=\Delta m^2/2E$

- For t~few sec after bounce, $\lambda \sim \omega$ at $r>>10^2$ km (large radii) MSW-resonance(s) possible and their effects have been studied for~20 years

- **What happens at small radius? Popular wisdom:**

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Incorrect !!!

Beside CC

it is crucial to include also NC

- **At small radius, ν density is high enough that ν self-potential $\mu=\sqrt{2}G_F n_\nu>\omega$ is crucial** (even if $\lambda>\mu$)

- **The importance of these (longtime known) terms has been appreciated only after the (mostly numerical) results by Duan, Fuller, Carlson, Qian 05-06 (~O(100) articles over last 3 years)**

Equations of motion

- Typically, one describes the system in terms of density matrices ρ ("natural" quadratic quantities)
EOM: Liouville eq. $i\partial_t\rho=[H,\rho]$ (for each ν mode)

$$\psi(x) = \int \mathrm{d}\mathbf{p}[a(\mathbf{p})u_{\mathbf{p}} + b^\dagger(-\mathbf{p})v_{-\mathbf{p}}]\, e^{i\,\mathbf{p}\cdot\mathbf{x}}$$

$$\langle a_j^\dagger(\mathbf{p})a_i(\mathbf{p}')\rangle = (2\pi)^3\delta^{(3)}(\mathbf{p}-\mathbf{p}')\rho_{ij}(\mathbf{p})$$
$$\langle b_i^\dagger(\mathbf{p})b_j(\mathbf{p}')\rangle = (2\pi)^3\delta^{(3)}(\mathbf{p}-\mathbf{p}')\bar{\rho}_{ij}(\mathbf{p})$$

- Decompose (anti)ν matrix over Pauli matrices to get a "Polarization" (or Bloch) vector P: EOM are then "precession-like" (|P|=conts.) Bloch equations $\partial_t\mathsf{P}=\mathsf{V}\times\mathsf{P}$

vacuum matter ν-ν interactions

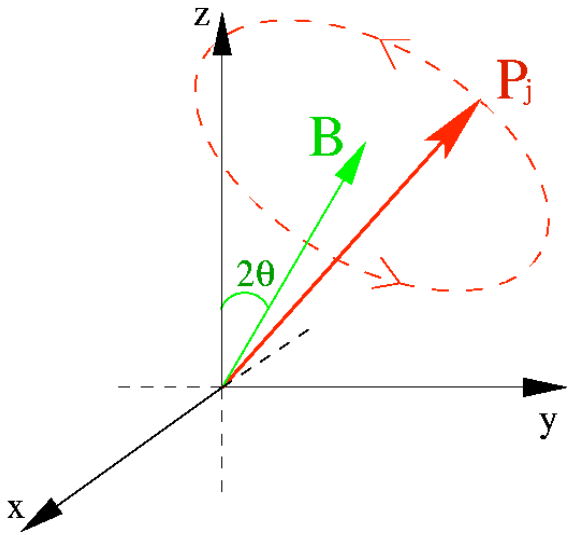
$$\nu \quad \partial_t \mathbf{P}_p = +\omega_p \mathbf{B}\times\mathbf{P}_p + \lambda\hat{\mathbf{z}}\times\mathbf{P}_p + \mathbf{V}_{self}(\mathbf{P}_i,\bar{\mathbf{P}}_j)\times\mathbf{P}_p$$
$$\overline{\nu} \quad \partial_t \bar{\mathbf{P}}_p = -\omega_p \mathbf{B}\times\bar{\mathbf{P}}_p + \lambda\hat{\mathbf{z}}\times\bar{\mathbf{P}}_p + \mathbf{V}_{self}(\mathbf{P}_i,\bar{\mathbf{P}}_j)\times\bar{\mathbf{P}}_p$$

- Each mode P moves on a Bloch sphere (abstract "flavor space").
"up" direction : ν_e flavor
"down" direct. : ν_x flavor
generic direct. : mixed flavor state
Frame typically chosen so that probability P_{ee} related to $P_3=P_Z$

Vacuum oscillation as spin precession

$$\partial_t \mathbf{P}_p = +\omega \mathbf{B} \times \mathbf{P}_p$$

$$\omega = \Delta m^2 / 2p$$

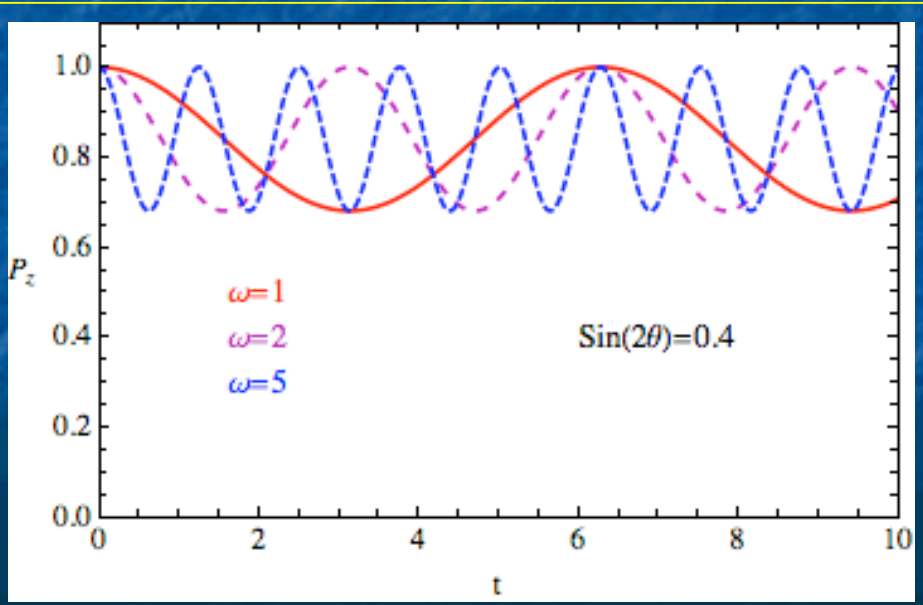


Neutrinos with a sufficiently broad p-distribution precess (in flavor space) with different frequencies around B

$$\partial_t |\mathbf{P}| \equiv \partial_t \left| \int dp\, \mathbf{P}_p \right| \neq 0$$

"Kinematical decoherence" in flavor space;

Effectively, one sees a mixture of ν's flavours with ratios determined by θ.



Vacuum term ⇔ "Magnetic field"

$$\mathbf{B} = \{\sin 2\theta_{13}, 0, \mp \cos 2\theta_{13}\}$$

Non-vacuum terms

Background matter

- **For an isotropic background** the matter term is "achromatic": it affects all modes the same way, and enters equally neutrinos and antineutrinos (our convention for ρ)

- Far from MSW resonances, the EOM can be studied in a coordinate system that rotates around z with frequency λ

- In this frame, B "rotates fast" around z, while B_z is unchanged: matter effects "disappear" (but for trigger of collective)!

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Self-interactions

- ν's not isotropic (stream off ν–sphere): the geometric factor $1-\cos\theta_{ij}$ in J-J interaction leads to "multi angle kernel"

$$V_{self} = \sqrt{2} G_F n_\nu \int \frac{d^3\mathbf{q}}{(2\pi)^3} (1 - \cos\theta_{pq})(\mathbf{P}_q - \bar{\mathbf{P}}_q)$$

- Even "discretizing", evolution governed by $6 \times N_E \times N_\theta$ coupled Bloch equations.

This makes very challenging the solution of the equations. An useful trick (to be justified!) is to use the isotropic-averaged kernel "single angle approximation"

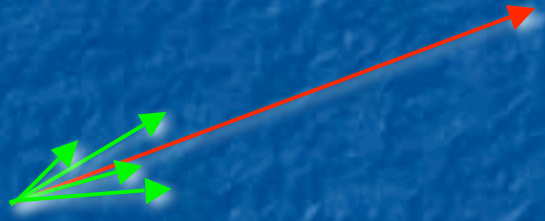
$$\langle V \rangle_{self} = \mu(\mathbf{P} - \bar{\mathbf{P}})$$

ν–ν drive synchronized oscillations!

If $\mu > \omega_p$ All modes lock to each other and oscillate together, in analogy to spin-coupling in atoms

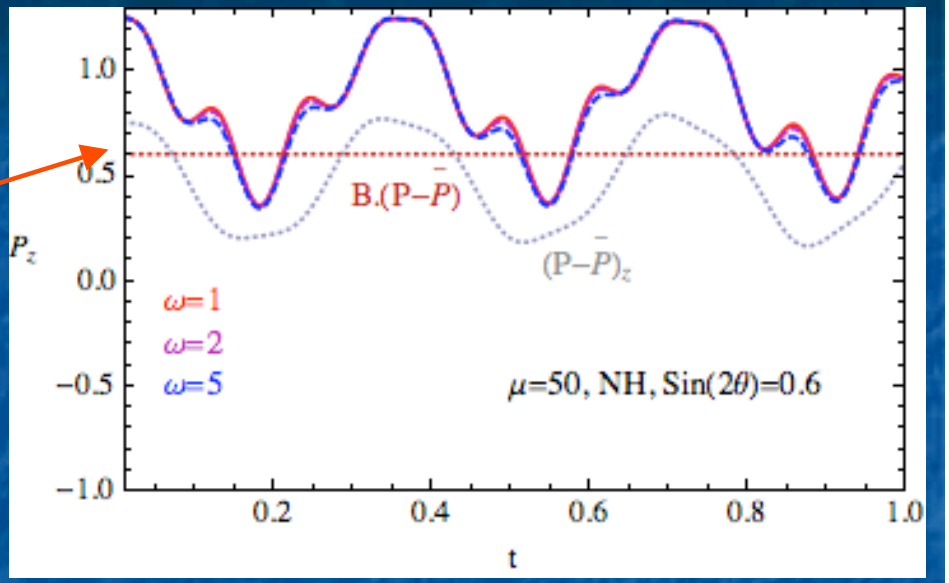
(net lepton number conservation)

In general, the P_i's are almost pinned to a global P–vector; |P| measures the kinematical coherence of the ensemble



The same (strong) couplings which make the problem difficult conspire to make an analytical understanding possible after all !

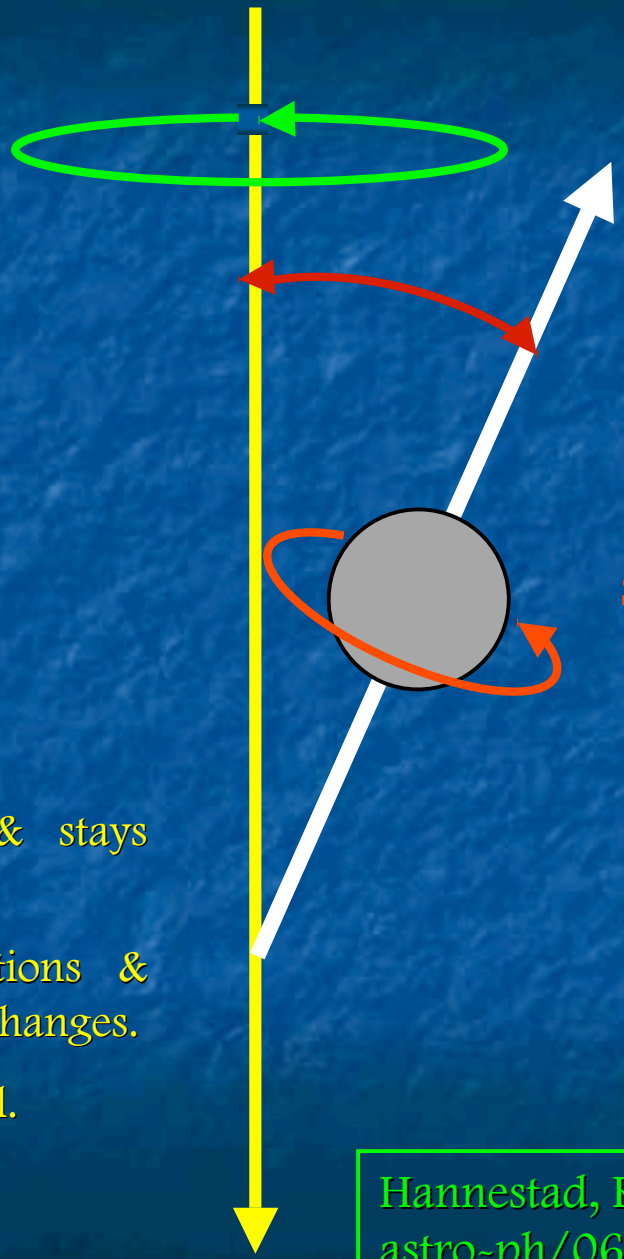
Still, complicated dynamics.
Can one have a simple understanding?



The "Flavour Pendulum" analogy

A surprising link between selfinteracting ν & classical mechanics !

- Very asymmetric system
  - ~ Large spin
  - ~ Almost pure precession
  - ~ Fully synchronized oscillations
- Perfectly symmetric system
  - ~ No spin
  - ~ Simple spherical pendulum
  - ~ Fully pendular oscillation



Precession (synchronized oscillation)

Polarization vector for ν's + anti ν's

Nutation (pendular oscillation)

Spin (Lepton Asymmetry)

Mass direction in flavor space

- **NH:** initial ~downard (stable) positions & stays nearby. No significant flavor change.
- **IH:** initial ~upward (unstable) positions & eventually falls down. Significant flavour changes.
- θ_{13} : sets initial misalignment with vertical. Specific value not much relevant.

Hannestad, Raffelt, Sigl, Wong
astro-ph/0608695

Further Subtleties, open issues (and my contribution)

- Passage to multiangle case

Theoretical understanding, behaviour in realistic cases, non-trivial role of matter, etc.

Esteban-Pretel et al, arxiv: 0807.0659

- Three flavour case

Robustness of the results? New effects? Impact on phenomenology? 1-loop differences between ν_μ and ν_τ propagation. [Potentially important at highest luminosities, t << 1 sec].

Mirizzi, Pozzorini, Raffelt, PS; arxiv: 0907.3674

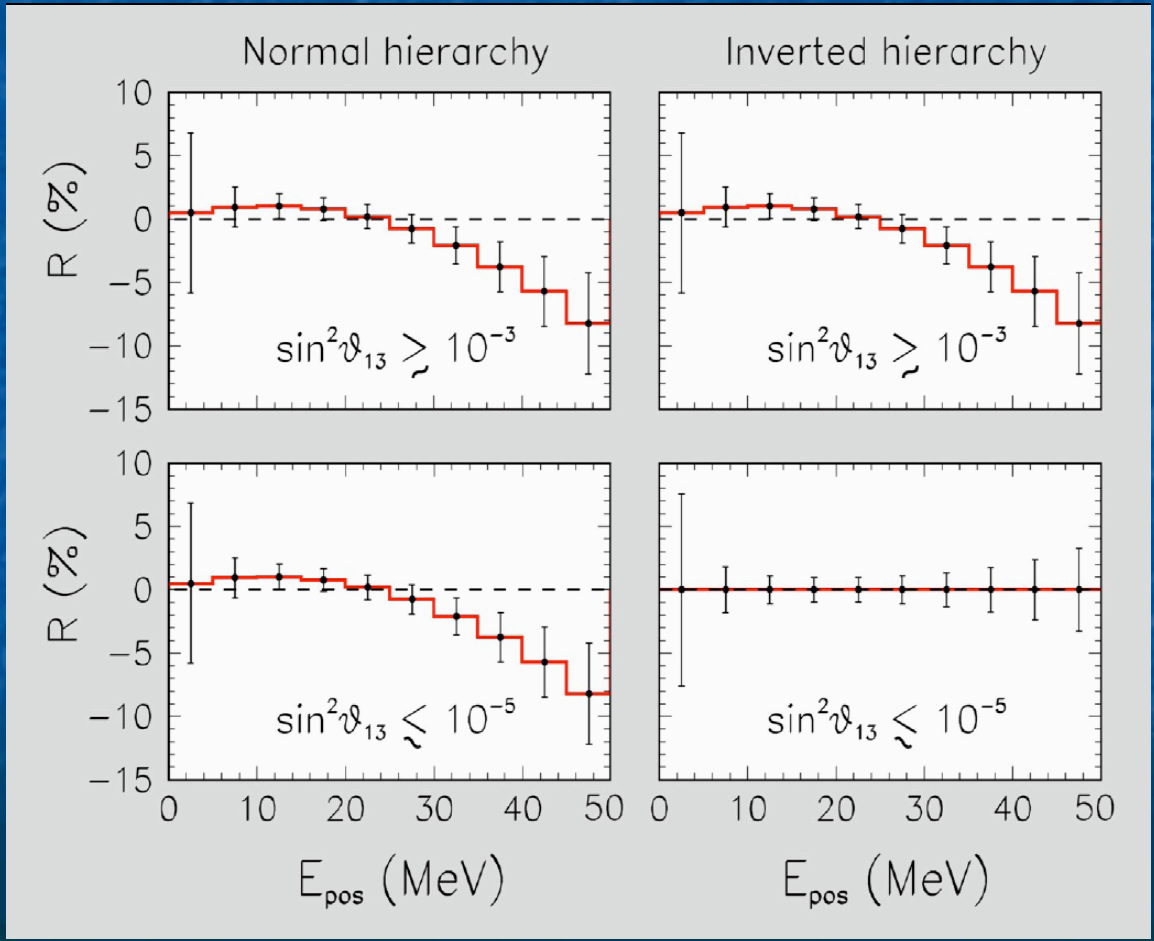
- Impact of new physics

How robust are the results wrt NP "perturbations"? New effects? Impact on phenomenology?

Blennow, Mirizzi, PS arxiv: 0810.2297

The "cleanest" observational test

Robust inference requires to use only
- Qualitative knowledge (inequalities) among fluxes (depend on weak interactions)
- "Local" effects, like the crossing of Earth mantle/core inferred from direction
- Robust features known to exist in the SN environment, like the presence of a shock



Ratio of spectra in two water Cherenkov detectors (0.4 Mton), one shadowed by the Earth, the other not.

$$R = \frac{F^{\oplus} - F}{F}$$

Possibility to diagnose hierarchy for vanishingly small θ_{13} (where Lab methods fail) At the same time, exploits collective effects!

Dasgupta, Dighe, Mirizzi arXiv:0802.1481

Conclusions

With evidence for the MSW effect in solar neutrinos, the possibility is opened to test observationally the neutrino interaction properties "in medium".

Supernovae provide very extreme conditions, where neutrino self-interactions prove to be surprisingly important.

The signal from a future galactic CC SN can discriminate for example the ν mass hierarchy in a range of parameters for which it is unmeasurable in Lab.

The details of these phenomena are still being discovered/understood. One can anticipate that new flavour physics (or new physics in the ν sector) may have an impact.

Besides, this is the only case known of a many body process (collective effect) controlled by weak interactions (analogous to strong force in nuclear systems or em in solid state, atomic and plasma physics)