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VIRTUAL CONFERENCE

Neutrino oscillation in Dense Matter

Shu Luo (Xiamen U.)

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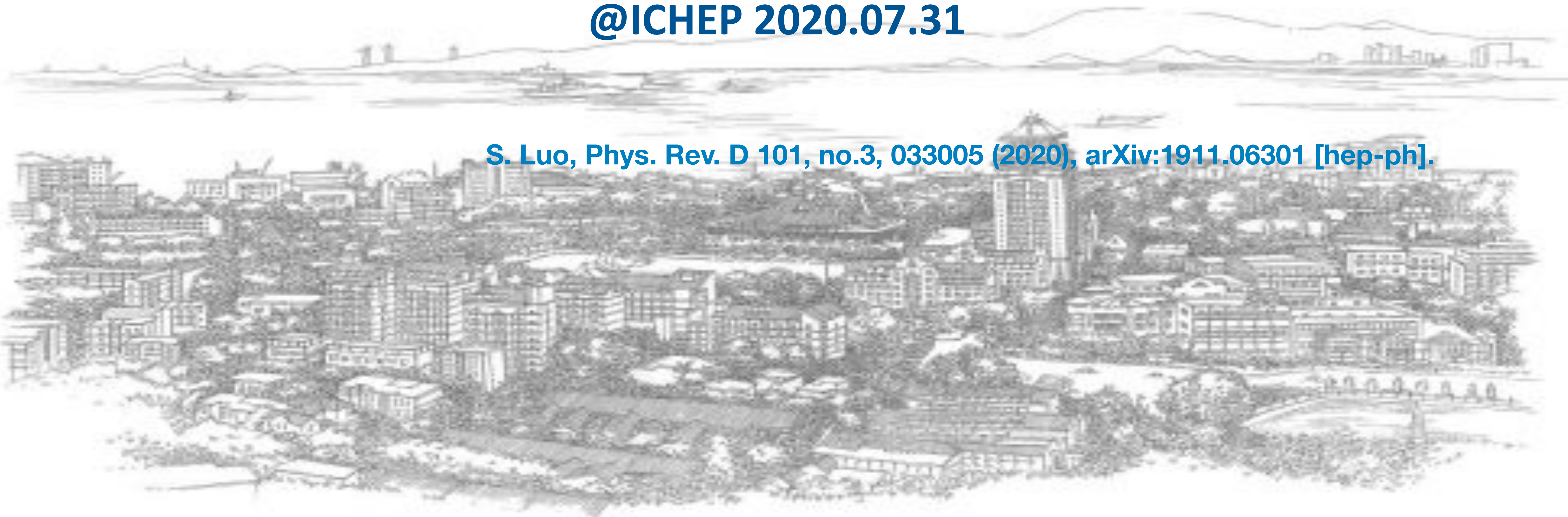
S. Luo, Phys. Rev. D 101, no.3, 033005 (2020), arXiv:1911.06301 [hep-ph].



Matter Effect

- Effective Hamiltonian (in the flavor basis)

$$\tilde{\mathcal{H}} = \frac{1}{2E} V \begin{pmatrix} m_1^2 & & \\ & m_2^2 & \\ & & m_3^2 \end{pmatrix} V^\dagger + \begin{pmatrix} V_{\rm CC} + V_{\rm NC} & & \\ & V_{\rm NC} & \\ & & V_{\rm NC} \end{pmatrix}$$

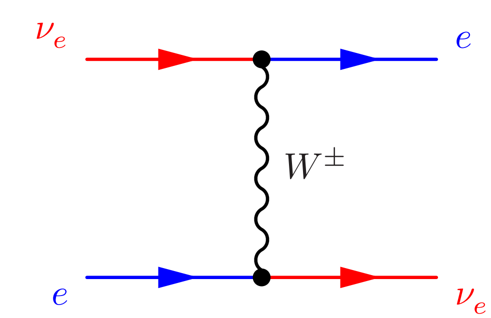
Vacuum Hamiltonian **Matter Potential**

- Only $V_{\rm CC}$ is relevant to neutrino oscillation in matter
- For anti-neutrinos

$$V_{\rm CC} \to -V_{\rm CC}, \qquad V_{\rm NC} \to -V_{\rm NC}$$

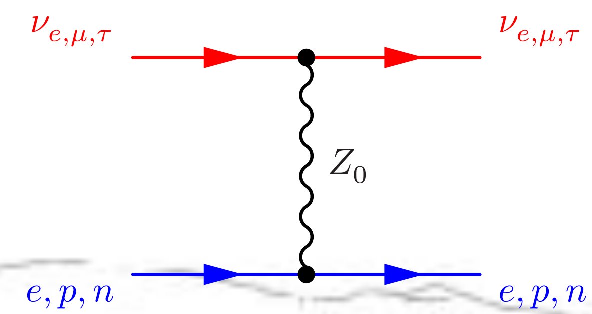
charged-current

$$V_{\rm CC} = \sqrt{2} G_{\rm F} N_e$$



neutral-current

$$V_{\rm NC} = -\frac{\sqrt{2}}{2} G_{\rm F} N_n$$



- Effective Hamiltonian (in the flavor basis)

$A_{\rm CC} = 2EV_{\rm CC}$

$$\tilde{\mathcal{H}} = \frac{1}{2E}\left[\left(m_1^2 + A_{\rm NC}\right)\cdot \mathbb{1} + V\begin{pmatrix} 0 & & \\ & \Delta m_{21}^2 & \\ & & \Delta m_{31}^2 \end{pmatrix} V^\dagger + \begin{pmatrix} A_{\rm CC} & & \\ & 0 & \\ & & 0 \end{pmatrix}\right]$$

Vacuum term **Matter term**

Vacuum-Dominated	Resonance	Matter-Dominated
$\lvert A_{\rm CC}\rvert \ll \Delta m_{21}^2, \lvert\Delta m_{31}^2\rvert$	$A_{\rm CC} \sim \Delta m_{21}^2$ (solar resonance) $A_{\rm CC} \sim \Delta m_{31}^2$ (atmospheric resonance)	$\lvert A_{\rm CC}\rvert \gg \Delta m_{21}^2, \lvert\Delta m_{31}^2\rvert$

(high energy, high density)

$A_{\rm CC}$ increase →

Z. Z. Xing, S. Zhou & Y. L. Zhou, JHEP 05, 015 (2018)
G. Y. Huang, J. H. Liu and S. Zhou, Nucl. Phys. B 931, 324-341 (2018)
X. Wang and S. Zhou, JHEP 05, 035 (2019)
Z. Z. Xing and J. Y. Zhu, Nucl. Phys. B 949, 114803 (2019)

Matter-Dominated Case

- In the limit $|A_{\rm CC}| \to \infty$ ($\Delta m^2_{21}/|A_{\rm CC}|$, $|\Delta m^2_{31}/A_{\rm CC}| \to 0$)

  - three effective neutrino masses

$\tilde{m}^2_1 \gg \tilde{m}^2_2 \simeq \tilde{m}^2_3$

$$
\begin{aligned}
\tilde{m}^2_1 &\to m^2_1 + A_{\rm NC} + A_{\rm CC} + \Omega_{11} \; , \\
\tilde{m}^2_2 &\to m^2_1 + A_{\rm NC} + \Omega_{22} \cos^2\tilde{\theta} + \Omega_{33} \sin^2\tilde{\theta} - |\Omega_{23}| \sin 2\tilde{\theta} \; , \\
\tilde{m}^2_3 &\to m^2_1 + A_{\rm NC} + \Omega_{33} \cos^2\tilde{\theta} + \Omega_{22} \sin^2\tilde{\theta} + |\Omega_{23}| \sin 2\tilde{\theta} \; ,
\end{aligned}
$$

} nearly degenerate

  - effective leptonic mixing matrix

the effective mixing matrix evolves to a two-flavor mixing matrix

$$
\tilde{V} \to \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\tilde{\theta} & \sin\tilde{\theta} \\ 0 & -\sin\tilde{\theta} & \cos\tilde{\theta} \end{pmatrix}
$$

$\tilde{\mathcal{J}} \to 0$

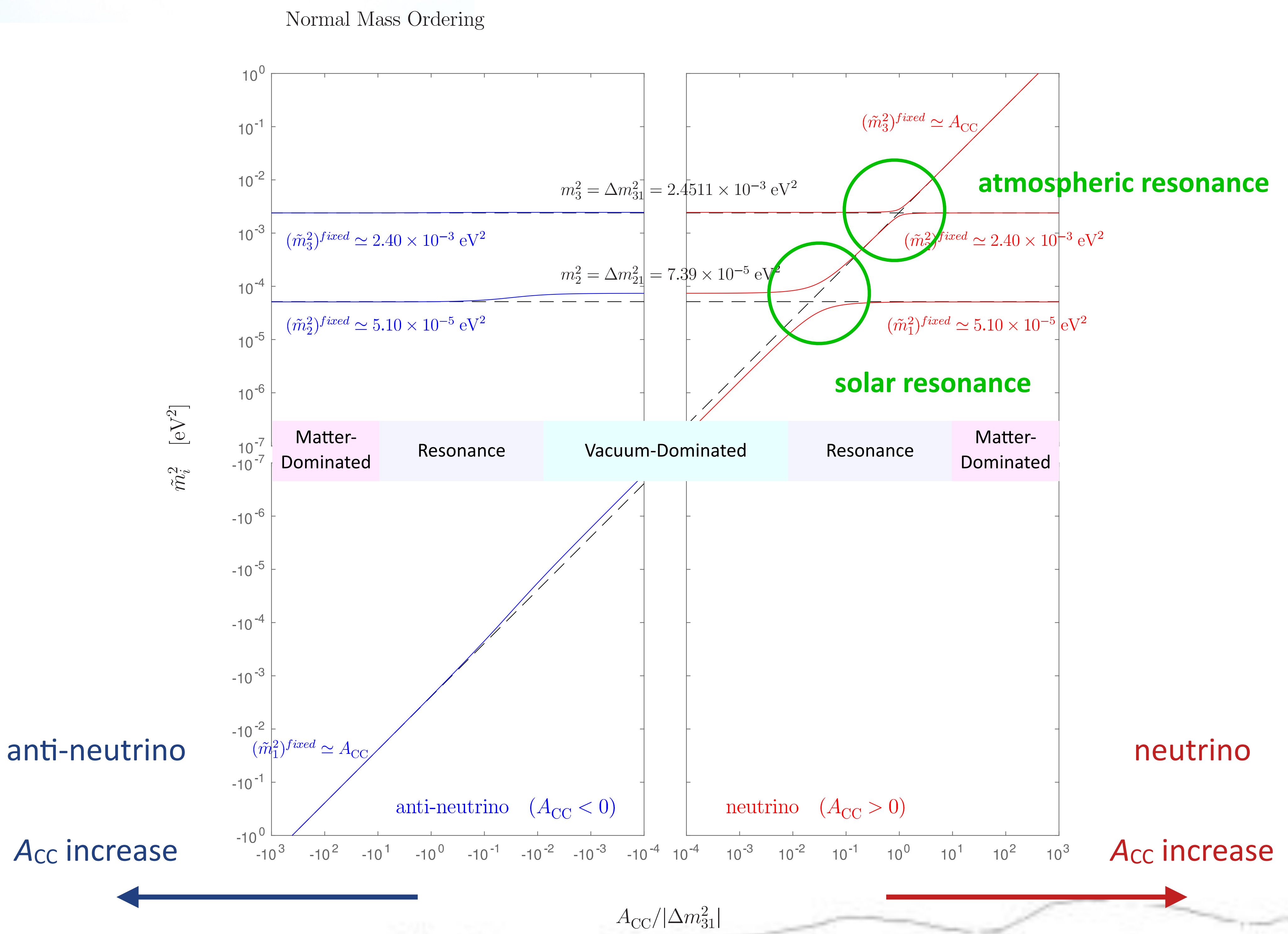
with

$\tilde{\theta} \approx \theta_{23}$

$$
\tan 2\tilde{\theta} = \frac{2\left|\Delta m^2_{21} V_{\mu 2} V^*_{\tau 2} + \Delta m^2_{31} V_{\mu 3} V^*_{\tau 3}\right|}{\Delta m^2_{21}\left(|V_{\tau 2}|^2 - |V_{\mu 2}|^2\right) + \Delta m^2_{31}\left(|V_{\tau 3}|^2 - |V_{\mu 3}|^2\right)}
$$

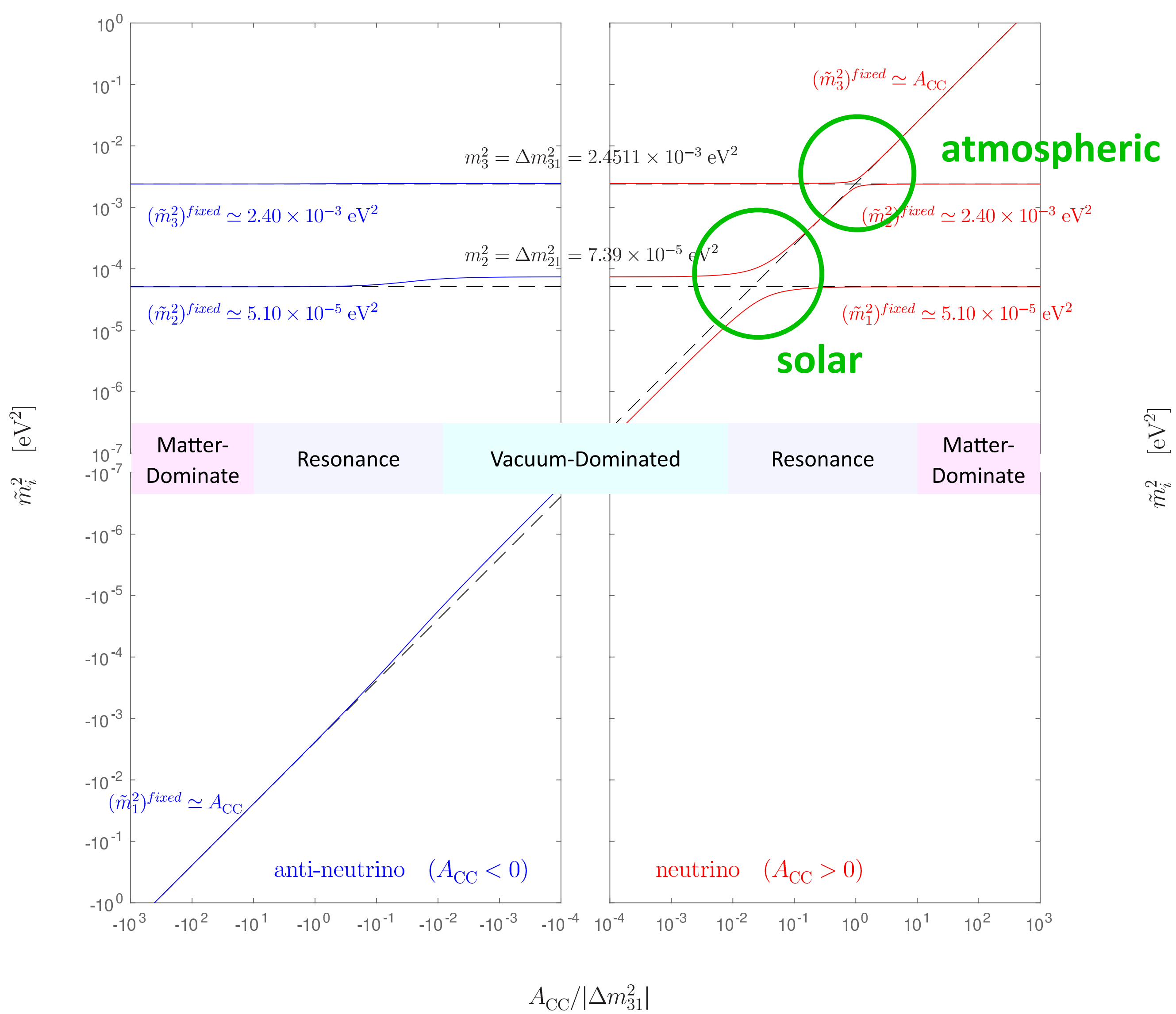
$$
\Omega \equiv V \begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} V^\dagger
$$

- three squared effective neutrino masses vary with A_{CC} (Normal Mass Ordering)

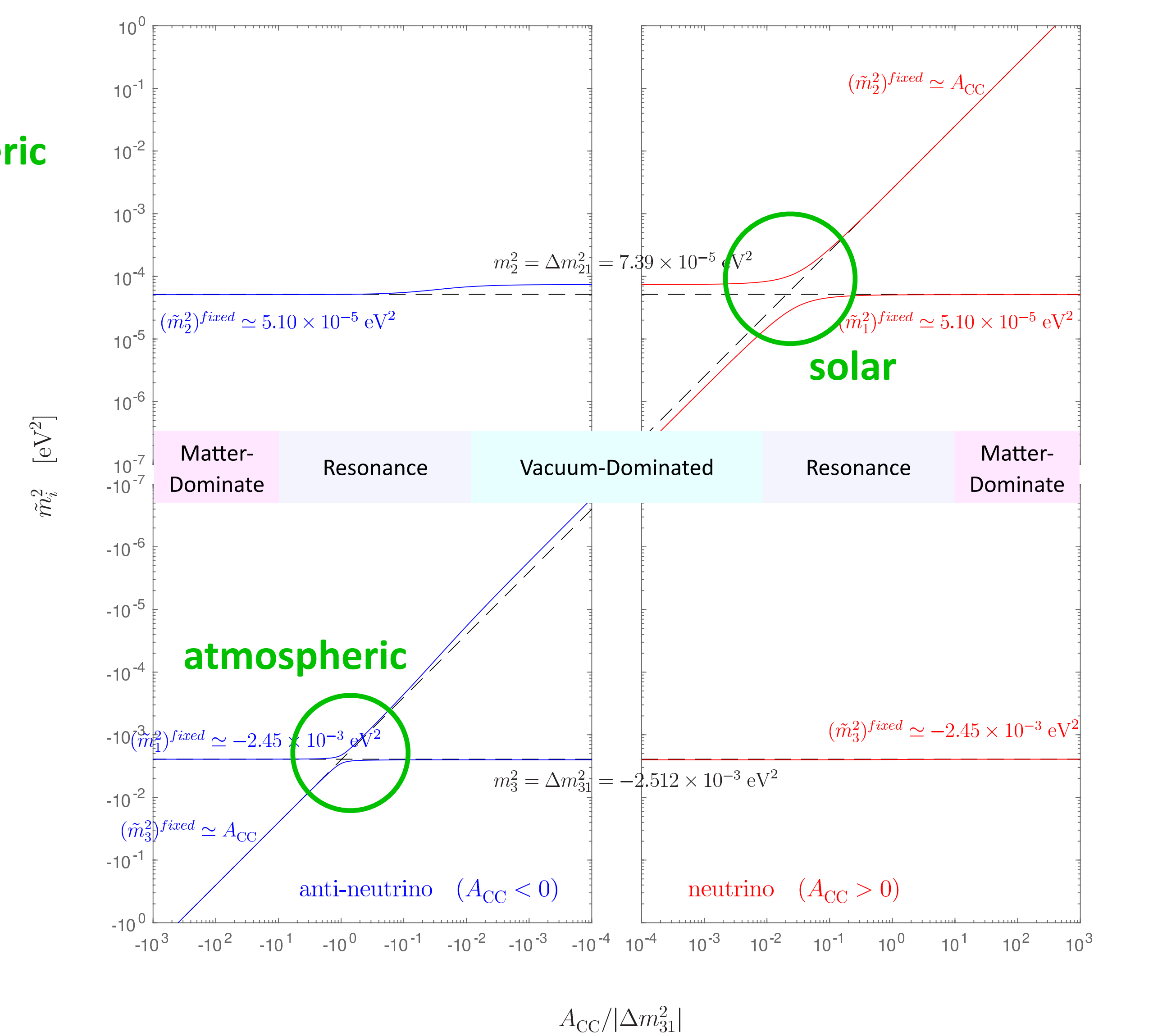


- three squared effective neutrino masses vary with A_{CC}

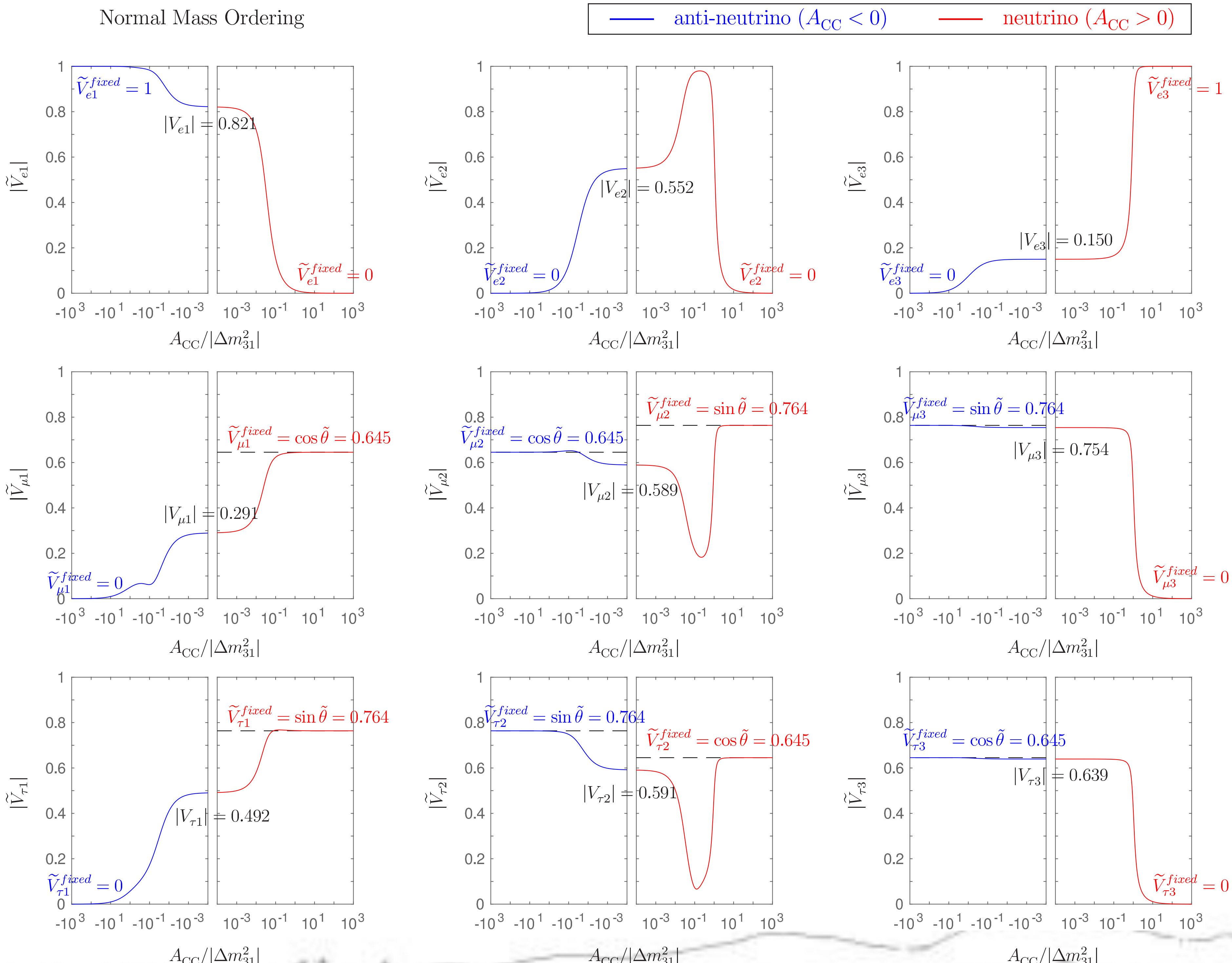
Normal Mass Ordering



Inverted Mass Ordering



- effective leptonic mixing matrix vary with A_{CC}



Matter-Dominated Case

- In the limit $|A_{\rm CC}| \to \infty$ $\quad \left(\Delta m^2_{21}/|A_{\rm CC}|\, , \ |\Delta m^2_{31}/A_{\rm CC}| \to 0 \right)$
  - neutrino oscillation probabilities

$$\begin{aligned}
\tilde{P}(\nu_e \to \nu_e) &\approx \tilde{P}(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 \, , \\
\tilde{P}(\nu_e \to \nu_\mu) &\approx \tilde{P}(\bar{\nu}_e \to \bar{\nu}_\mu) \approx 0 \, , \\
\tilde{P}(\nu_e \to \nu_\tau) &\approx \tilde{P}(\bar{\nu}_e \to \bar{\nu}_\tau) \approx 0 \, , \\
\tilde{P}(\nu_\mu \to \nu_e) &\approx \tilde{P}(\bar{\nu}_\mu \to \bar{\nu}_e) \approx 0 \, , \\
\tilde{P}(\nu_\tau \to \nu_e) &\approx \tilde{P}(\bar{\nu}_\tau \to \bar{\nu}_e) \approx 0 \, ,
\end{aligned}$$

$$\begin{aligned}
\tilde{P}(\nu_\mu \to \nu_\mu) &\approx \tilde{P}(\bar{\nu}_\mu \to \bar{\nu}_\mu) \approx 1 - \sin^2 2\tilde{\theta} \sin^2 \frac{\Delta \tilde{m}^2_{32} L}{4E} \, , \\
\tilde{P}(\nu_\tau \to \nu_\tau) &\approx \tilde{P}(\bar{\nu}_\tau \to \bar{\nu}_\tau) \approx 1 - \sin^2 2\tilde{\theta} \sin^2 \frac{\Delta \tilde{m}^2_{32} L}{4E} \, , \\
\tilde{P}(\nu_\mu \to \nu_\tau) &\approx \tilde{P}(\bar{\nu}_\mu \to \bar{\nu}_\tau) \approx \sin^2 2\tilde{\theta} \sin^2 \frac{\Delta \tilde{m}^2_{32} L}{4E} \, , \\
\tilde{P}(\nu_\tau \to \nu_\mu) &\approx \tilde{P}(\bar{\nu}_\tau \to \bar{\nu}_\mu) \approx \sin^2 2\tilde{\theta} \sin^2 \frac{\Delta \tilde{m}^2_{32} L}{4E} \, ,
\end{aligned}$$

where

different values for NMO or IMO

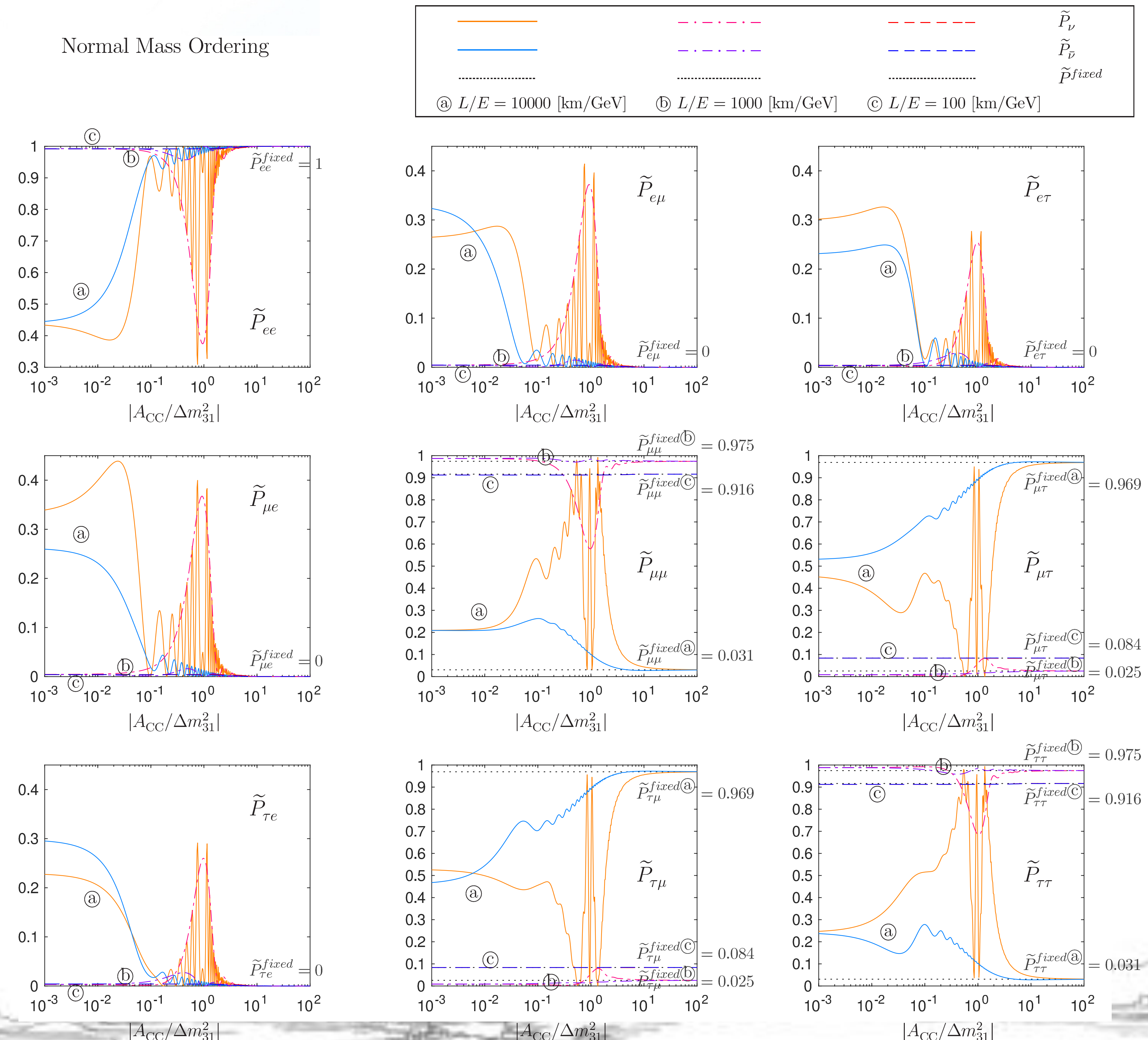
$$\Delta \tilde{m}^2_{32} \approx \left[\Delta m^2_{21} \left(|V_{\tau 2}|^2 - |V_{\mu 2}|^2\right) + \Delta m^2_{31} \left(|V_{\tau 3}|^2 - |V_{\mu 3}|^2\right)\right] \cos 2\tilde{\theta} + 2|\Delta m^2_{21} V_{\mu 2} V^*_{\tau 2} + \Delta m^2_{31} V_{\mu 3} V^*_{\tau 3}| \sin 2\tilde{\theta}$$

$$\tan 2\tilde{\theta} = \frac{2\left|\Delta m^2_{21} V_{\mu 2} V^*_{\tau 2} + \Delta m^2_{31} V_{\mu 3} V^*_{\tau 3}\right|}{\Delta m^2_{21} \left(|V_{\tau 2}|^2 - |V_{\mu 2}|^2\right) + \Delta m^2_{31} \left(|V_{\tau 3}|^2 - |V_{\mu 3}|^2\right)}$$

$$\Omega \equiv V \begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} V^\dagger$$

$$\Delta \tilde{m}^2_{32} \approx \Delta m^2_{32} \, , \qquad \tilde{\theta} \approx \theta_{23}$$

- neutrino oscillation probabilities vary with A_{CC} (with fixed L/E)

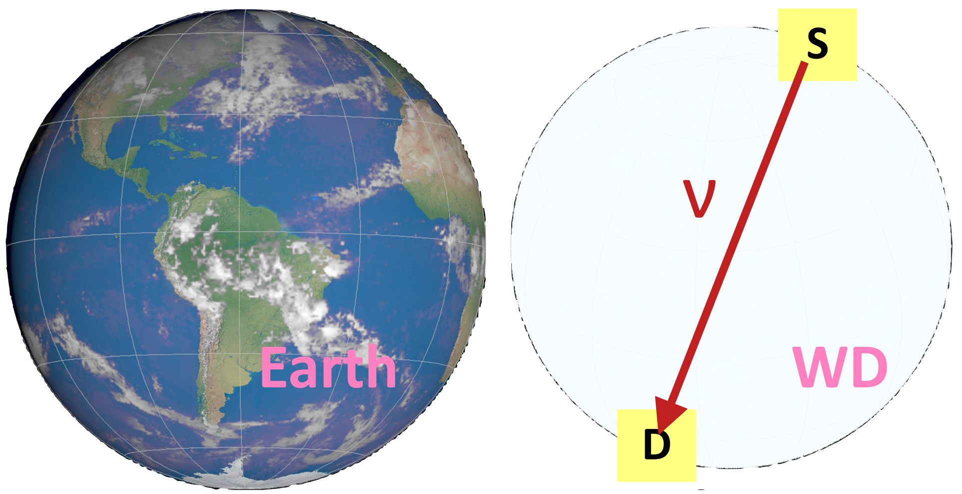


When νs passing through a WD

- Let's try to carry out a long-baseline neutrino oscillation experiment on a typical **white dwarf** with $M \sim 0.7 M_{\odot}$, $R \sim 10^4$ km

$$\rho \sim 2 \times 10^6 \ \mathrm{g/cm^3} \qquad (\ n_e \sim 6 \times 10^{29} \ \mathrm{cm}^{-3} \sim 10^6 N_{\mathrm{A}} \ \mathrm{cm}^{-3} \ )$$

- very dense → give rise to significant matter effect
- no longer undergo fusion reaction
  → does not radiate large amount of neutrinos



- the approximate mean free path $\ell = (\sigma\rho/m_p)^{-1} \sim 0.9 \times 10^{13}\,(E/\mathrm{MeV})^{-2}\,\mathrm{cm}$

  for ν with $E \lesssim 10$ MeV, $\ell \gtrsim 9 \times 10^5$ km → attenuation can be neglected

- for ν with $E \gtrsim 0.2$ MeV , the oscillation is matter-dominated

- oscillation probabilities vary with neutrino energy *E*

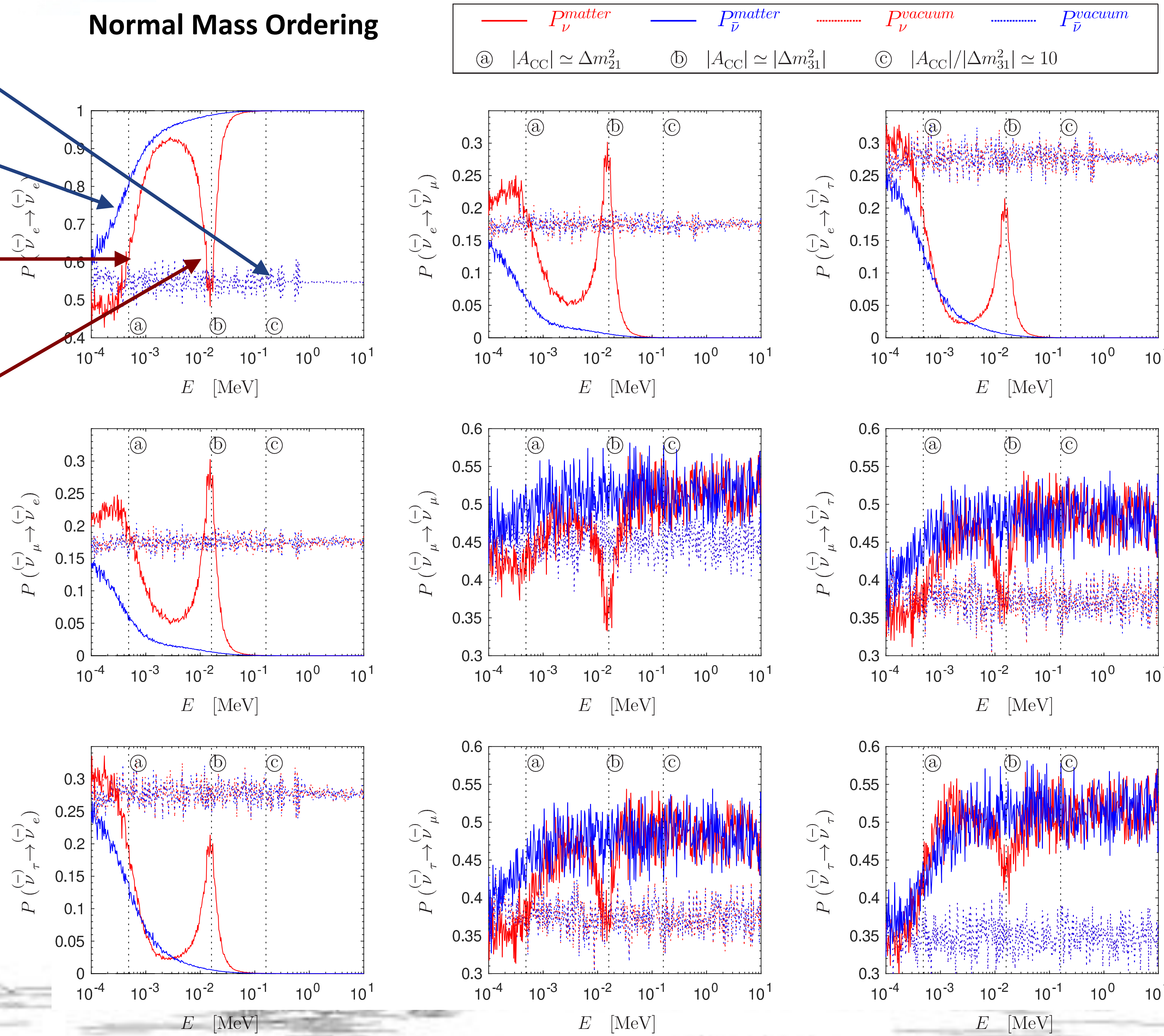
Normal Mass Ordering

vacuum oscillation

pass through WD

a significant slope at around the solar resonance

a hump at around the atmospheric resonance



- the corresponding *E* of the slope / hump may indicate the electron density of the compact object

- all the probabilities are averaged over a Gaussian energy resolution of 5%

- oscillation probabilities vary with neutrino energy *E*

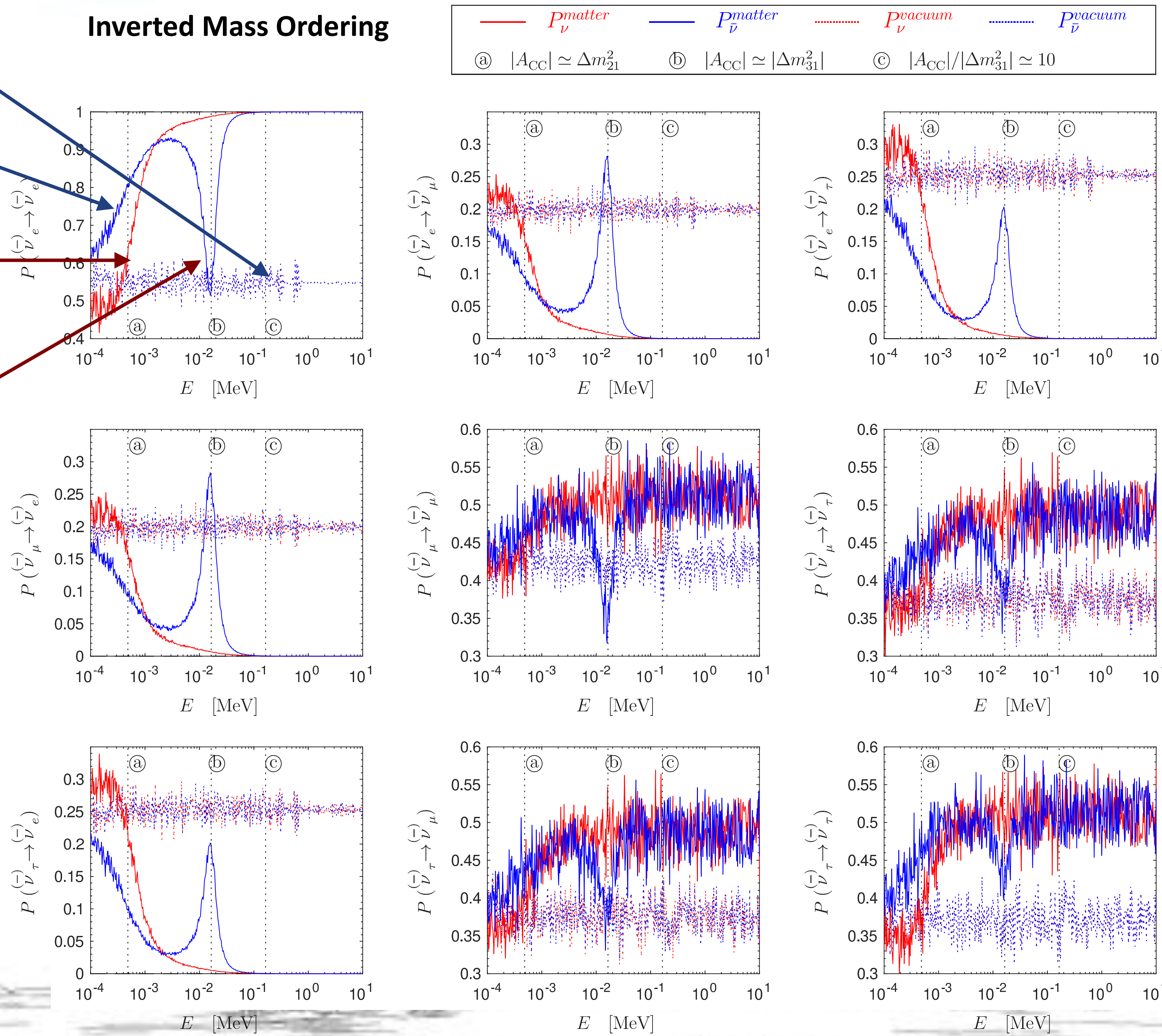
Inverted Mass Ordering

vacuum oscillation

pass through WD

a significant slope at around the solar resonance

a hump at around the atmospheric resonance

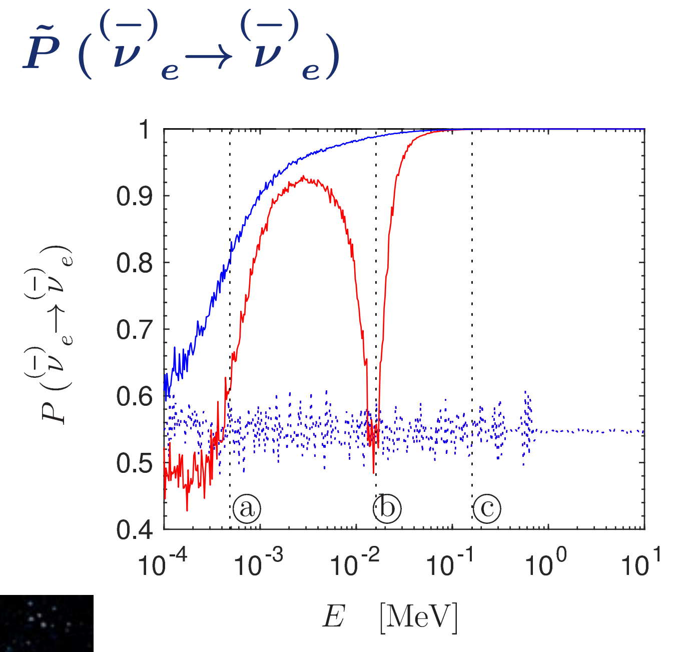


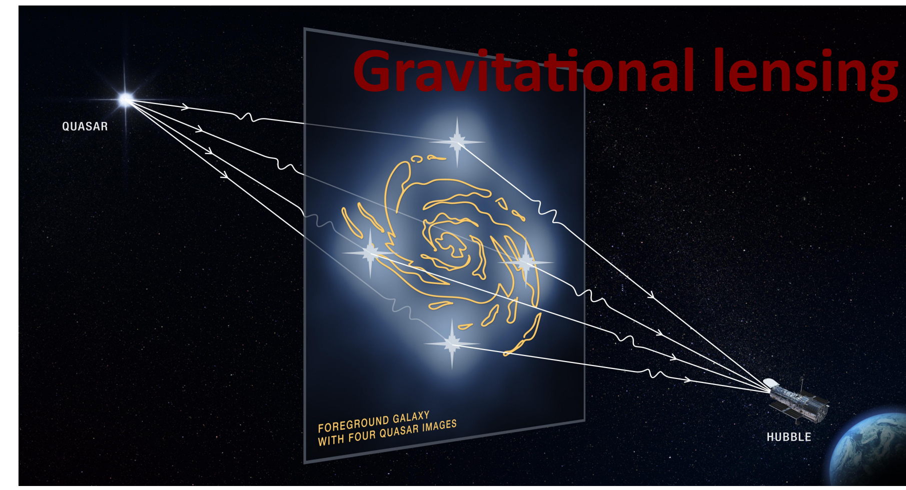
- the presence / absence of this resonance hump in the neutrino / anti-neutrino spectrum may tell the neutrino mass ordering

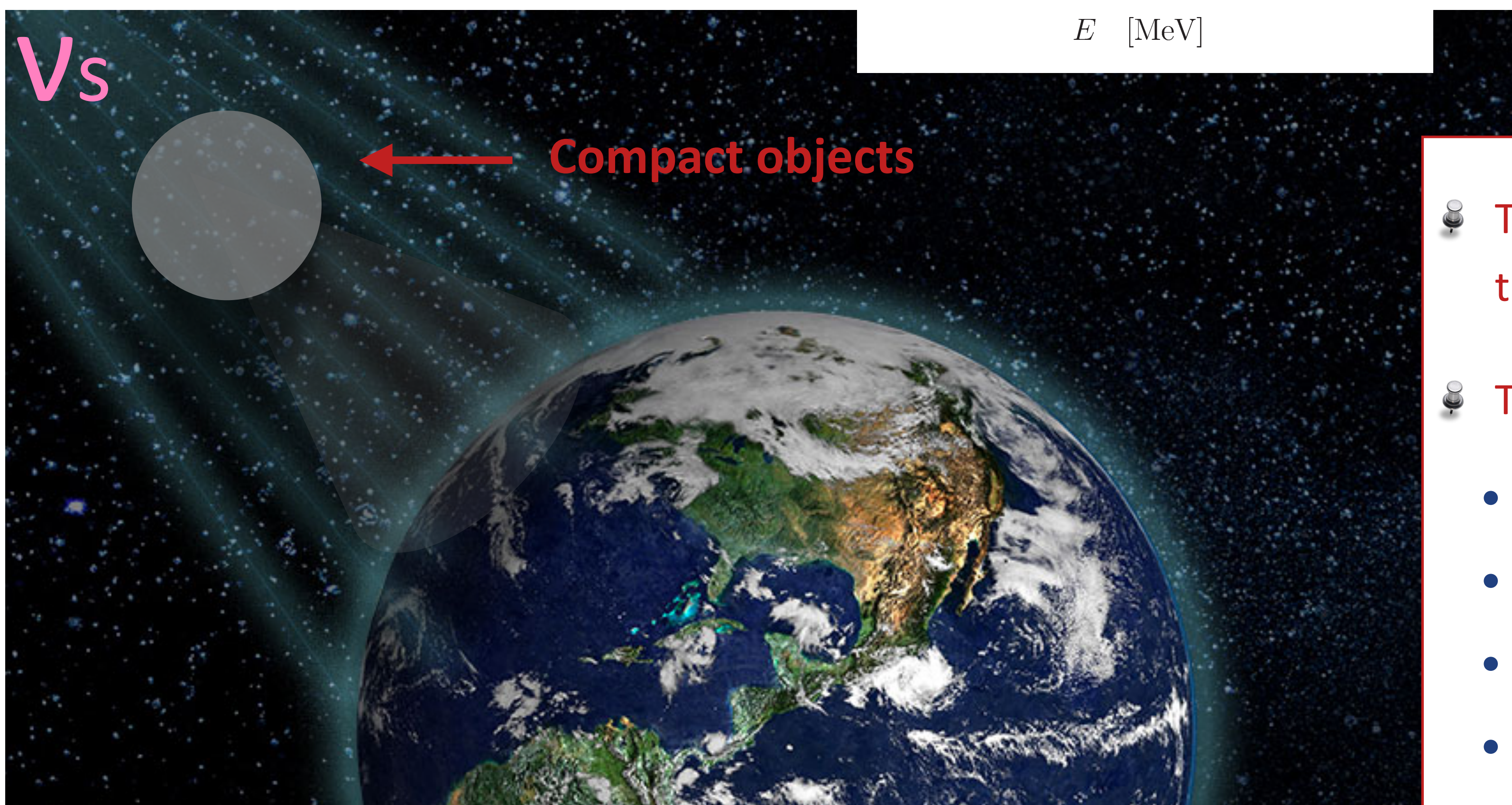
- all the probabilities are averaged over a Gaussian energy resolution of 5%

Weak “Lensing” Effect

- Neutrino **spectrum** may be distorted by this **“weak lens”**







- This could be a new “weak” view to uncover those hidden compact objects
- Though still a long way to go …
  - spectrum & flavor composition of ν sources
  - size and constituents of compact objects
  - distribution of compact objects in space
  - capability of detector
  - ……

Thank you!