Compact Objects & Supernovae

featuring

Transforming Neutrinos

06/12/2015
INT-15-2a
Daavid Väänänen

Daavid Väänänen – My Journey

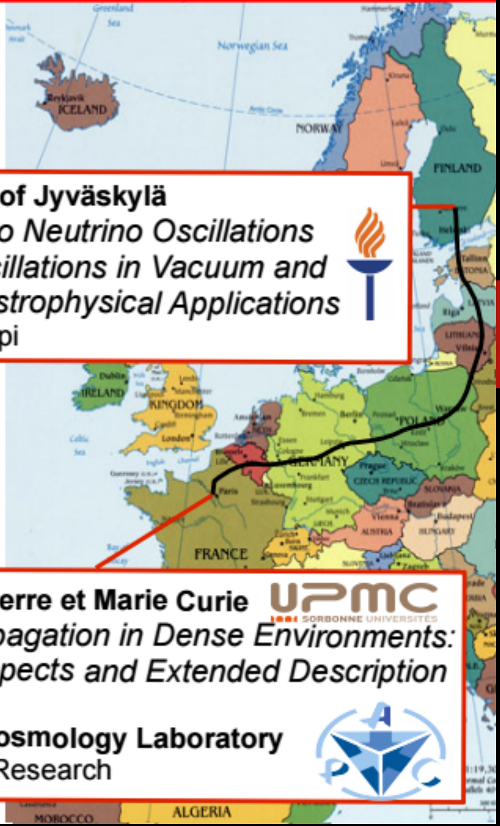
University of Jyväskylä

B.Sc. (2010) *Introduction to Neutrino Oscillations*

M.Sc. (2010) *Neutrino Oscillations in Vacuum and Matter with Astrophysical Applications*

Advisor: Prof. Jukka Maalampi

Daavid Väänänen – My Journey



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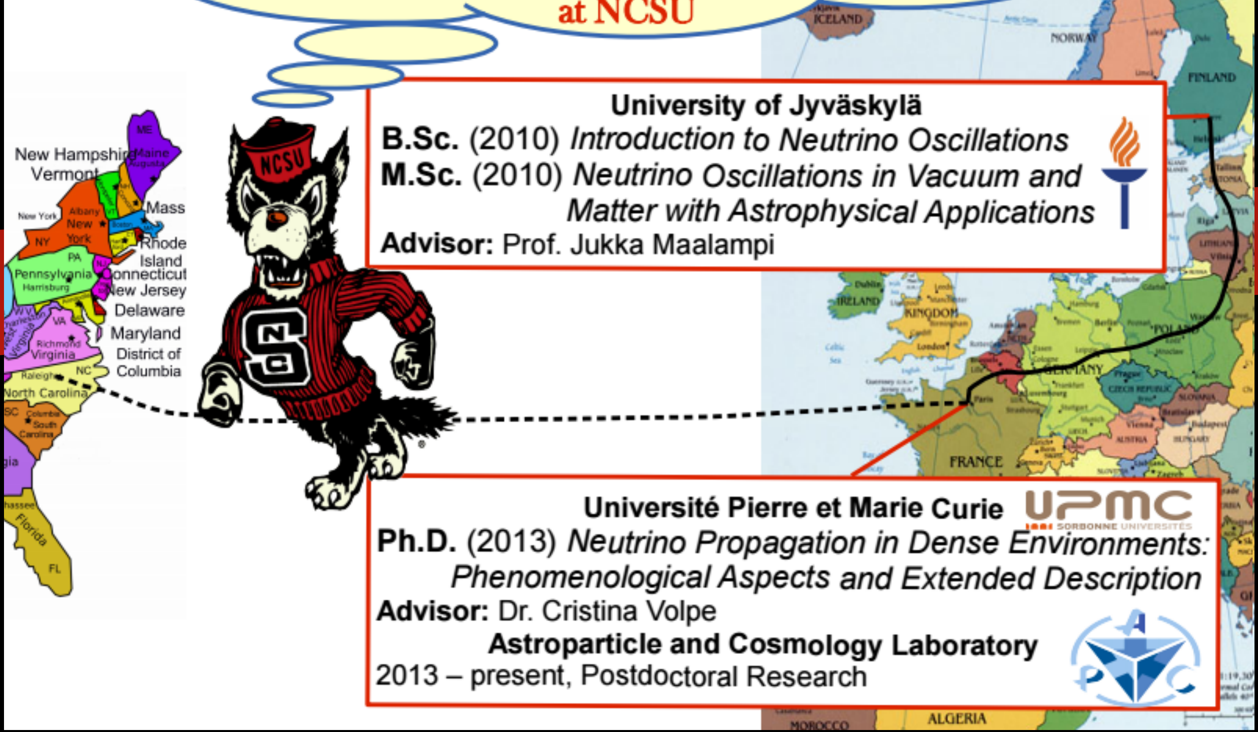
Ph.D. (2013) *Neutrino Propagation in Dense Environments: Phenomenological Aspects and Extended Description*
Advisor: Dr. Cristina Volpe

Astroparticle and Cosmology Laboratory
2013 – present, Postdoctoral Research

Probing the Universe with Particles from Astrophysical Environments

at NCSU



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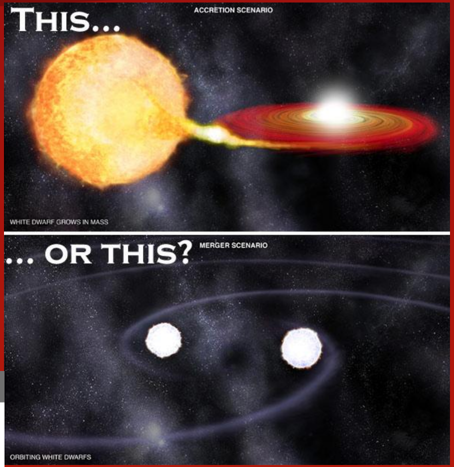
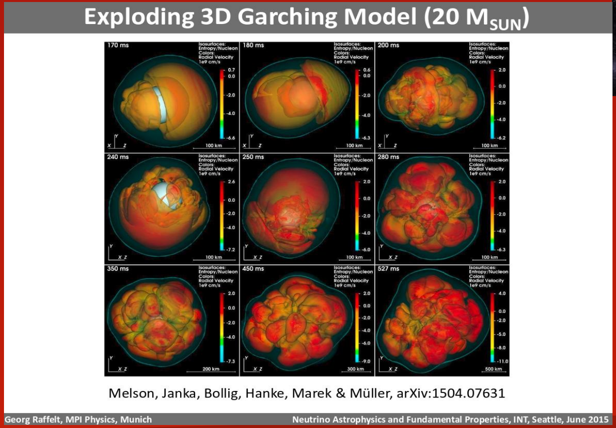
Compact Objects & Supernovae *feat.* Transforming Neutrinos

- ❖ Compact Object Mergers:
  - ➢ Neutron star - Black hole star
    (or Neutron star - Neutron) binaries



- ❖ Supernovae



Exploding 3D Garching Model (20 M_{SUN})

Melson, Janka, Bollig, Hanke, Marek & Müller, arXiv:1504.07631

Georg Raffelt, MPI Physics, Munich

Neutrino Astrophysics and Fundamental Properties, INT, Seattle, June 2015


neutrino
neutrino
neutrino

101 on Motivation

- Historically astrophysical neutrinos have played important role
  - Solution to Solar Neutrino Problem

Talk by W. Haxton

- Yet unknown neutrino properties:
  - understanding physics beyond Standard Model

Talk by I. Mocioiu

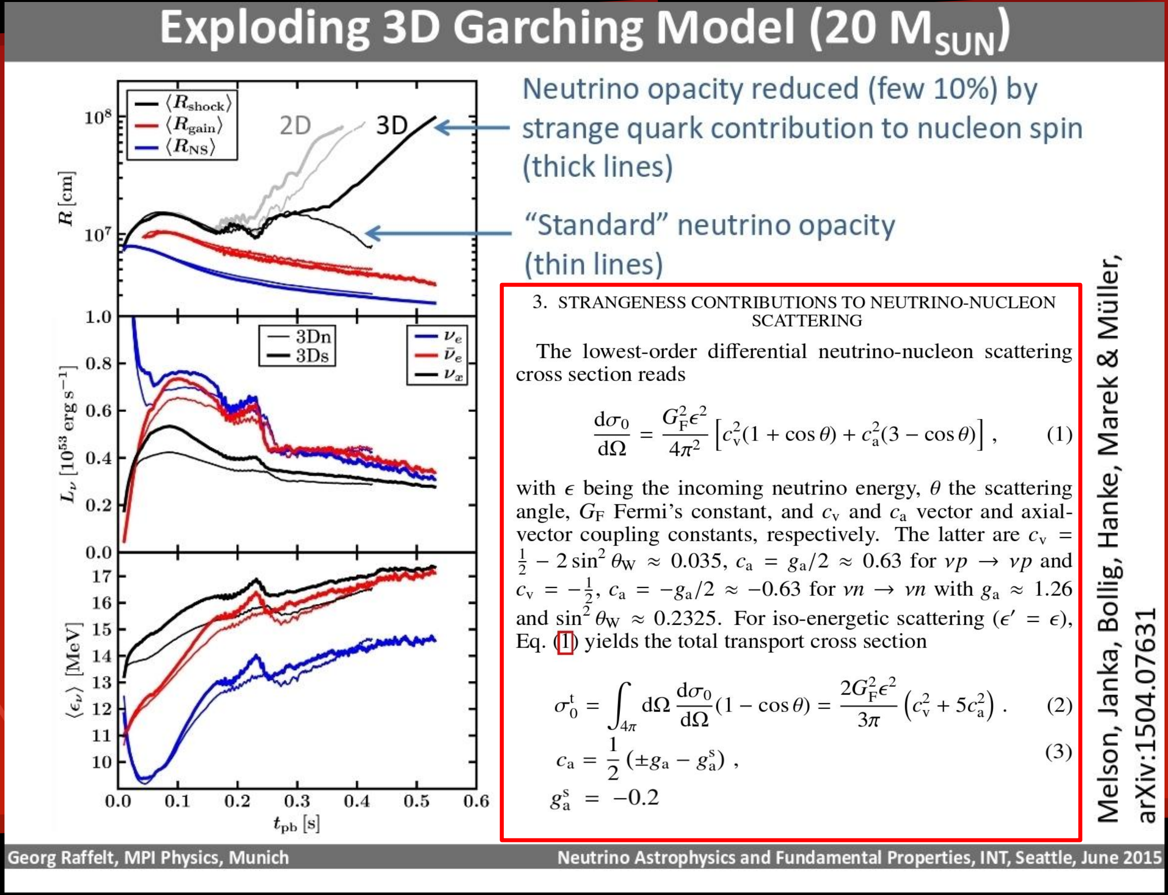
- There are lots of them out there …

Talk by G. Raffelt
K. Patton

  - understanding underlying physics of their sources
  - heavy element nucleosynthesis

Talk by R. Surman

102 on Motivation



Exploding 3D Garching Model (20 M_{SUN})

Neutrino opacity reduced (few 10%) by strange quark contribution to nucleon spin (thick lines)

“Standard” neutrino opacity (thin lines)

3. STRANGENESS CONTRIBUTIONS TO NEUTRINO-NUCLEON SCATTERING

The lowest-order differential neutrino-nucleon scattering cross section reads

$$\frac{d\sigma_0}{d\Omega} = \frac{G_F^2\epsilon^2}{4\pi^2}\left[c_v^2(1+\cos\theta)+c_a^2(3-\cos\theta)\right], \qquad (1)$$

with ϵ being the incoming neutrino energy, θ the scattering angle, G_F Fermi’s constant, and c_v and c_a vector and axial-vector coupling constants, respectively. The latter are $c_v = \frac{1}{2} - 2\sin^2\theta_W \approx 0.035$, $c_a = g_a/2 \approx 0.63$ for $\nu p \to \nu p$ and $c_v = -\frac{1}{2}$, $c_a = -g_a/2 \approx -0.63$ for $\nu n \to \nu n$ with $g_a \approx 1.26$ and $\sin^2\theta_W \approx 0.2325$. For iso-energetic scattering ($\epsilon' = \epsilon$), Eq. (1) yields the total transport cross section

$$\sigma_0^t = \int_{4\pi} d\Omega\,\frac{d\sigma_0}{d\Omega}(1-\cos\theta) = \frac{2G_F^2\epsilon^2}{3\pi}\left(c_v^2+5c_a^2\right). \qquad (2)$$

$$c_a = \frac{1}{2}\left(\pm g_a - g_a^s\right), \qquad (3)$$

$$g_a^s = -0.2$$

Melson, Janka, Bollig, Hanke, Marek & Müller, arXiv:1504.07631

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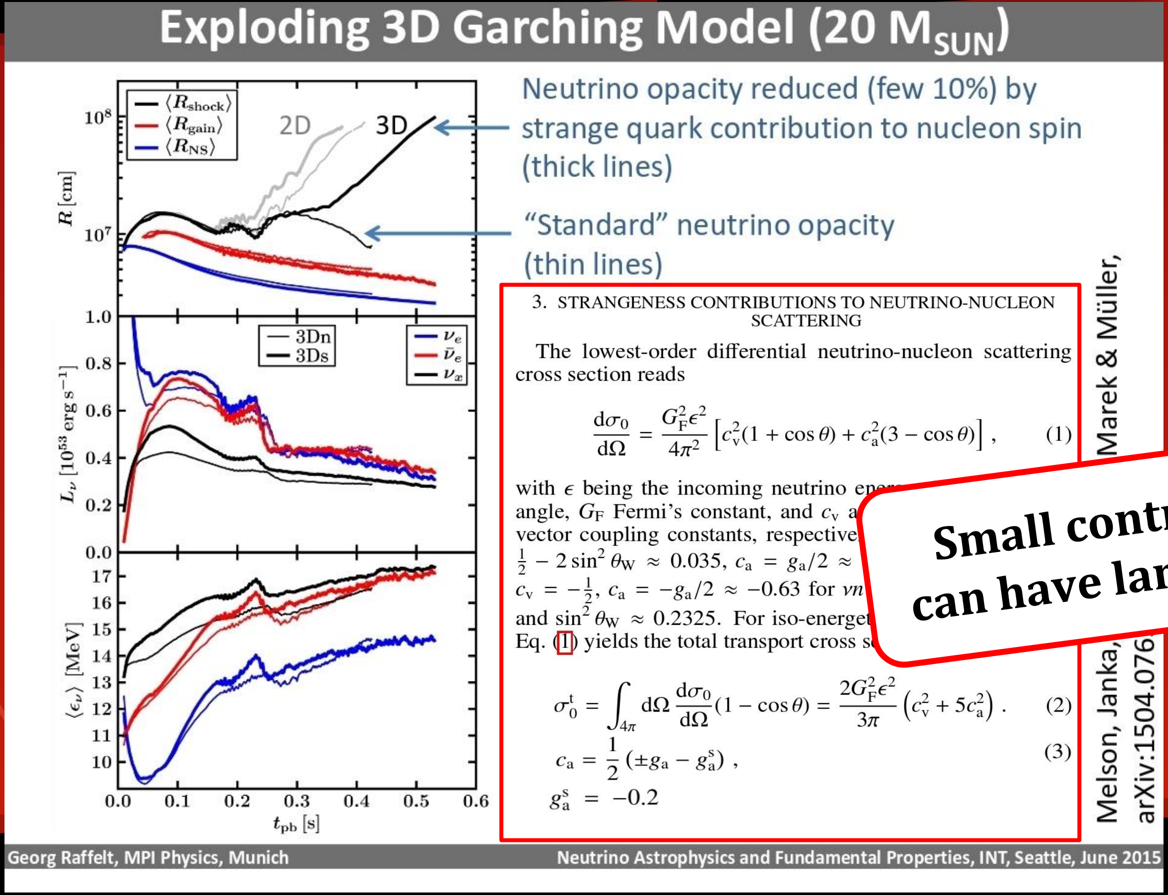
Neutrino Astrophysics and Fundamental Properties, INT, Seattle, June 2015

Daavid

102 on Motivation



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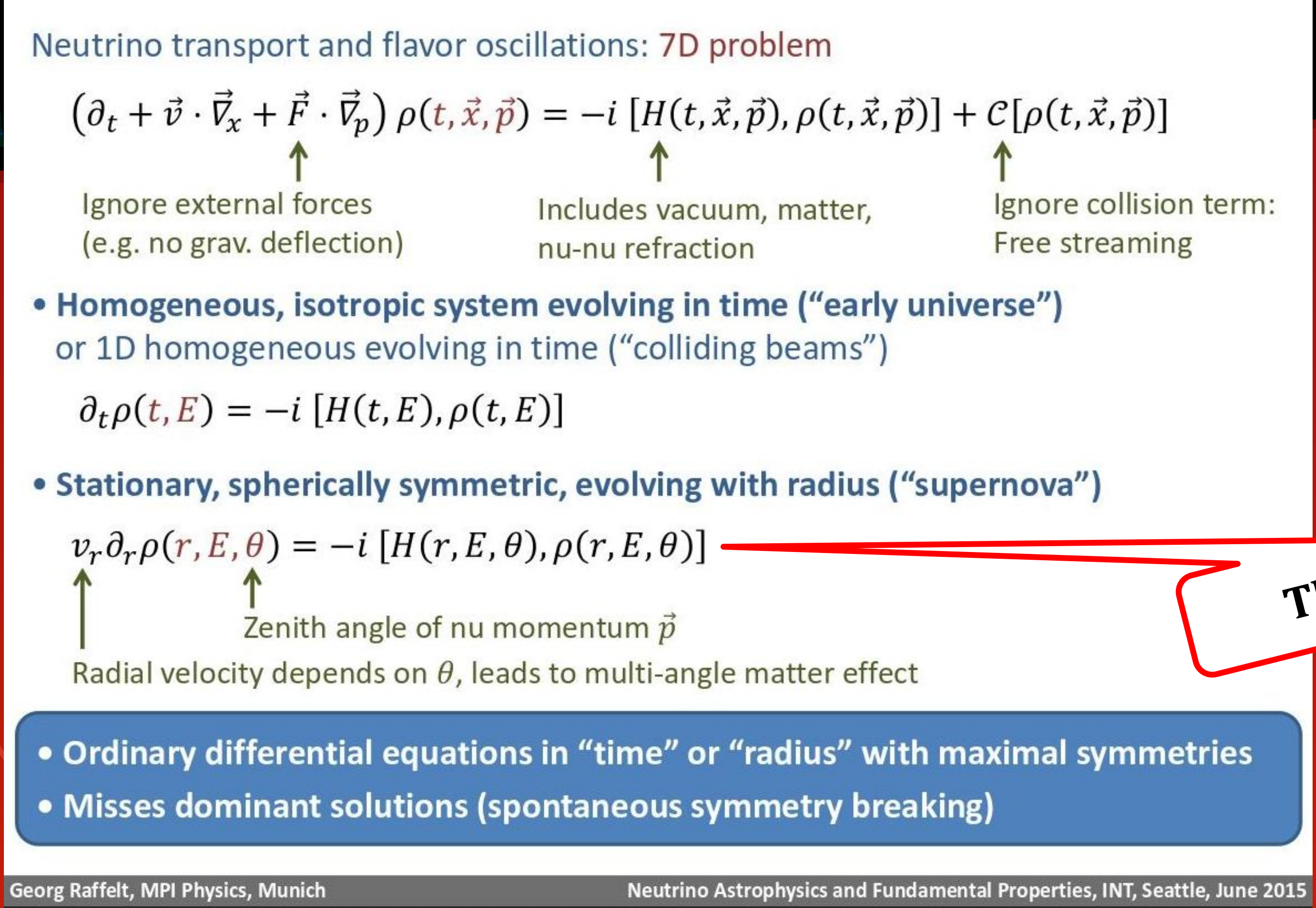
$$g_a^s = -0.2$$

Melson, Janka, Marek & Müller,
arXiv:1504.076

Georg Raffelt, MPI Physics, Munich

Neutrino Astrophysics and Fundamental Properties, INT, Seattle, June 2015

Small contributions can have large impact!



Neutrino transport and flavor oscillations: 7D problem

$$\left(\partial_t + \vec{v}\cdot\vec{\nabla}_x + \vec{F}\cdot\vec{\nabla}_p\right)\rho(t,\vec{x},\vec{p}) = -i\,[H(t,\vec{x},\vec{p}),\rho(t,\vec{x},\vec{p})] + \mathcal{C}[\rho(t,\vec{x},\vec{p})]$$

Ignore external forces
(e.g. no grav. deflection)

Includes vacuum, matter,
nu-nu refraction

Ignore collision term:
Free streaming

- **Homogeneous, isotropic system evolving in time ("early universe")**
  or 1D homogeneous evolving in time ("colliding beams")

$$\partial_t\rho(t,E) = -i\,[H(t,E),\rho(t,E)]$$

- **Stationary, spherically symmetric, evolving with radius ("supernova")**

$$v_r\partial_r\rho(r,E,\theta) = -i\,[H(r,E,\theta),\rho(r,E,\theta)]$$

Zenith angle of nu momentum $\vec{p}$

Radial velocity depends on θ, leads to multi-angle matter effect

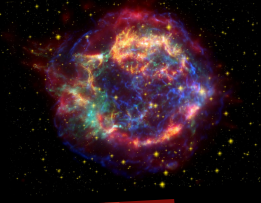
- **Ordinary differential equations in "time" or "radius" with maximal symmetries**
- **Misses dominant solutions (spontaneous symmetry breaking)**

Georg Raffelt, MPI Physics, Munich
Neutrino Astrophysics and Fundamental Properties, INT, Seattle, June 2015

This talk

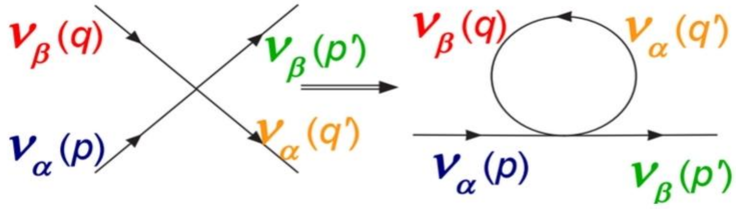
Outline

1. A Lesson on Neutrino self-induced collective transformations
2. ***Neutrino + Matter induced collective transformations***
   - **Matter Neutrino Resonance (MNR)**
     - ***"Standard" MNR*** [Malkus, Friedland, McLaughlin, ArXiv:1403.5797 (2014)]
     - ***"Symmetric" MNR*** [***DV***, McLaughlin, *in preparation*]
     - ***Non-Standard Neutrino Interaction (NSνI) induced MNR*** [***DV***, Kneller, McLaughlin, CJ, *in preparation*]
3. Conclusions



102 on Neutrino Self-Induced Collective Transformation

Compute neutrino-neutrino interaction Feynman diagrams and construct mean-field:



$$= \int \frac{d^3\mathbf{q}}{(2\pi)^3 2E_{\mathbf{q}}} \int \frac{d^3\mathbf{q}'}{(2\pi)^3 2E_{\mathbf{q}'}} (2\pi)^3 \delta^3(\mathbf{p}+\mathbf{q}-\mathbf{p}'-\mathbf{q}') \frac{G_F}{2\sqrt{2}}$$
$$\times \left[u_{\nu_\beta}(p')\gamma_\lambda(1-\gamma_5)\overline{u}_{\nu_\alpha}(p)\right] \left[\overline{u}_{\nu_\alpha}(q')\gamma^\lambda(1-\gamma_5)u_{\nu_\beta}(q)\right] \rho^\nu_{\beta,\mathbf{q};\alpha,\mathbf{q}'}$$

$$H_{\nu\nu} = \mu_\nu \left(\rho - \alpha\bar{\rho}\right)$$

μ = neutrino-neutrino interaction strength (geometrical dependence)

α = initial *neutrino-antineutrino* asymmetry

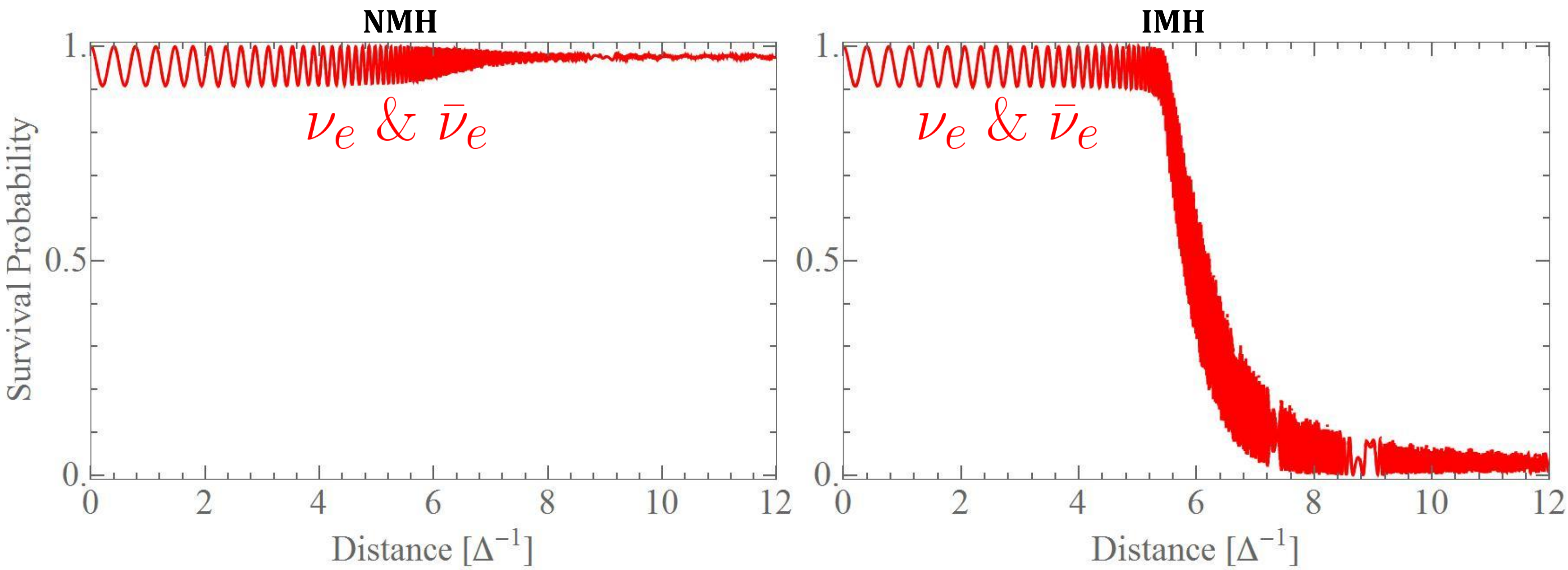
ρ = (anti)neutrino density matrix:

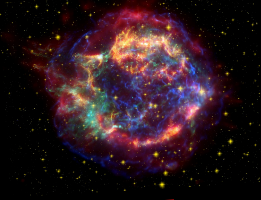
$$\rho = \begin{pmatrix} |a_{\nu_e}|^2 & a_{\nu_e} a^*_{\nu_\mu} \\ a^*_{\nu_e} a_{\nu_\mu} & |a_{\nu_\mu}|^2 \end{pmatrix}$$

Use above to solve the free streaming evolution equation:

$$\mathrm{i}\frac{\mathrm{d}\overset{(-)}{\rho}}{\mathrm{d}r} = \left[\overset{(-)}{H}, \overset{(-)}{\rho}\right] \qquad H = H_V + H_{\nu\nu} \qquad H_V = \Delta \begin{pmatrix} -\cos 2\theta_V & \sin 2\theta_V \\ \sin 2\theta_V & \cos 2\theta_V \end{pmatrix} \qquad \Delta = \frac{\delta m^2}{4E}$$

102 on Neutrino Self-Induced Collective Transformation





102 on Neutrino Self-Induced Collective Transformation

Conditions for self-induced transformation:

Linearization and Neutrino Flavor Stability analysis

[Sawyer (2009)]
[Dighe, Raffelt, Banerjee (2011)]
[DV, Volpe (2013)]

Evolution equation linear eigenvalue equation

$$\mathrm{i}\rho = [h, \rho] \Longrightarrow \omega\rho' = [h^0, \rho'] + [h', \rho^0] \Longleftrightarrow \omega \begin{pmatrix} \rho' \\ \bar{\rho}' \end{pmatrix} = \mathbf{S} \begin{pmatrix} \rho' \\ \bar{\rho}' \end{pmatrix}$$

Variation amplitude

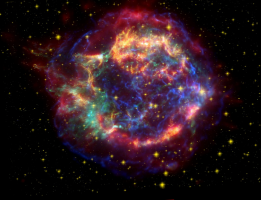
$\rho'_{ij} = \rho_{ex}$ = off-diagonal nu density matrix elements

Stability matrix, **S**

$$\rho = \rho^0 + \rho' \mathrm{e}^{-\mathrm{i}\omega t} + H.c.$$

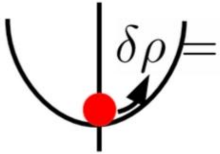
$$h = h^0 + h' \mathrm{e}^{-\mathrm{i}\omega t} + H.c.$$

$$h'_{ij} = \sum_{kl} \frac{\partial h}{\partial \rho_{kl}} \rho'_{kl}$$



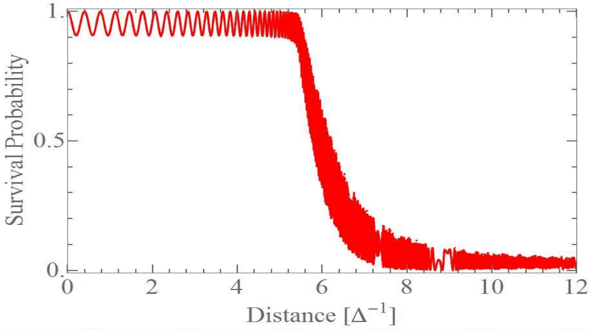
102 on Neutrino Self-Induced Collective Transformation

- **Real eigenvalues ω**
  - Collective excitation modes
  - *Synchronized oscillations*



$$\delta\rho = \rho' \, \mathrm{e}^{-\mathrm{i}\omega t} + \mathrm{H.c}$$

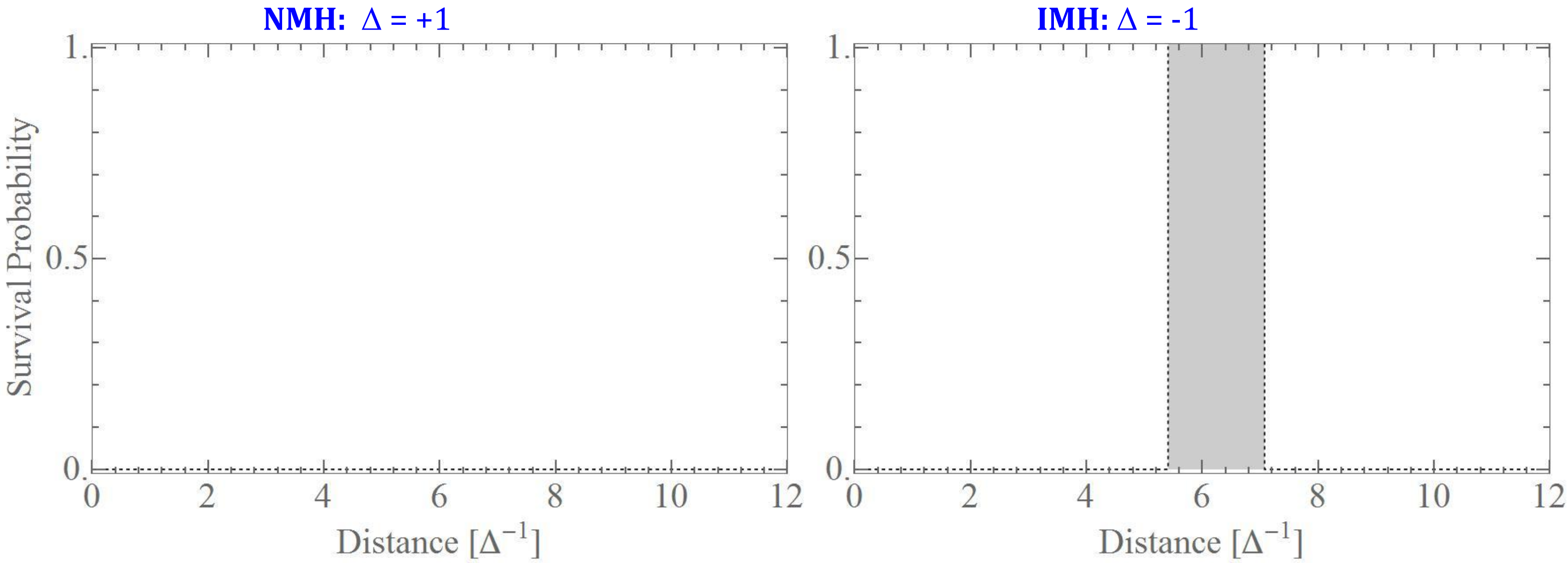
- **Imaginary eigenvalues**
  - System unstable
  - Onset of *bipolar oscillations*!



Distance [10 km]

- Conditions obtained by solving eigenvalues of **stability matrix:** $\boxed{|\mathbf{S} - \omega| = 0}$

102 on Neutrino Self-Induced Collective Transformation



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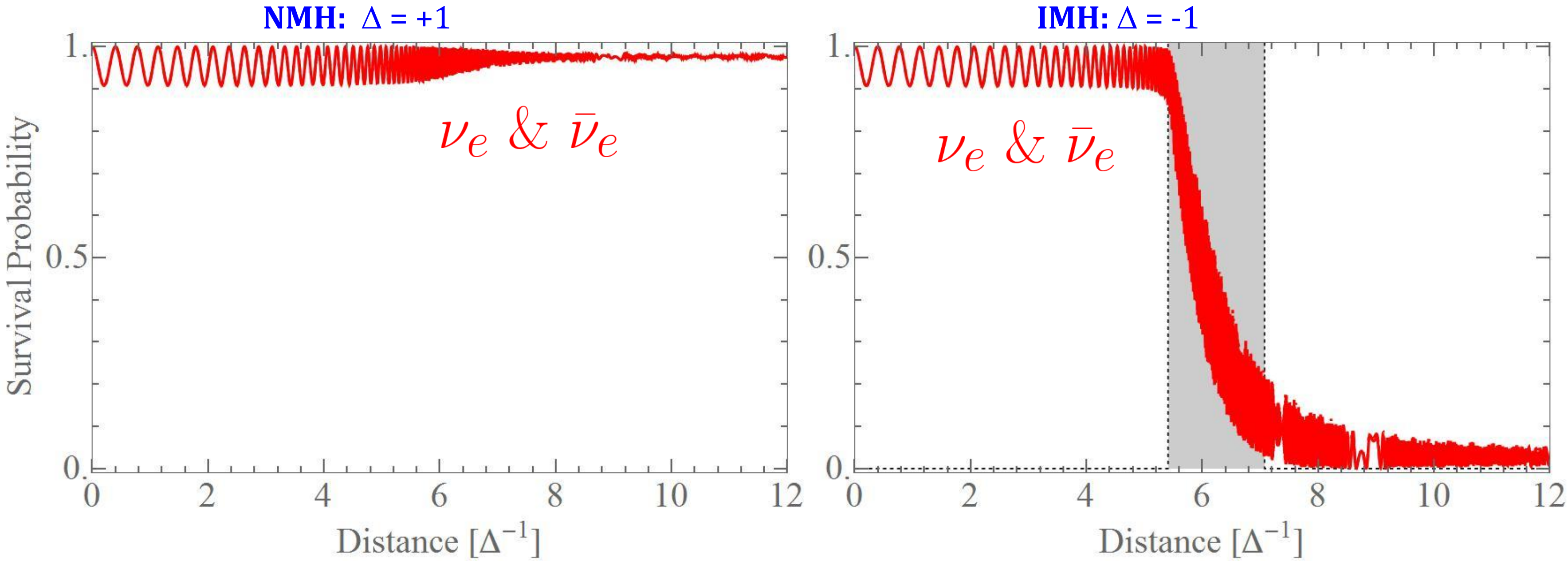
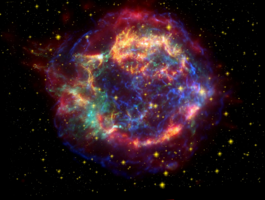




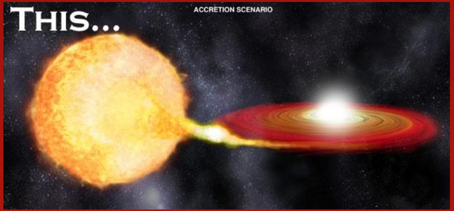
102 on Neutrino Self-Induced Collective Transformation

- **Relevant characteristics:**
  - Requires interacting and mixed neutrinos (effect of matter: suppressed oscillations)
  - Transformation only in inverted neutrino mass hierarchy
  - Energy dependent
  - Collective - all neutrinos with same mode behave the same
  - Explained as an instability in flavor space

1. A Lesson on Neutrino self-induced collective transformations
2. ***Neutrino + Matter induced collective transformations***
   - **Matter Neutrino Resonance (MNR)**
     - *“Standard” MNR* **[Malkus, Friedland, McLaughlin, ArXiv:1403.5797 (2014)]**
     - *“Symmetric” MNR* **[*DV*, McLaughlin, Flynn, *in preparation*]**
     - *Non-Standard Neutrino Interaction (NSνI) induced MNR* **[DV, Kneller, McLaughlin, Stapleford, *in preparation*]**
3. Conclusions

Matter Neutrino Resonance (MNR)

1.1. History: Neutrino flavor evolution above black hole accretion disks



[Malkus, Kneller, McLaughlin, Surman, PRD86 085015 (2012)]

1.2. *"Standard" MNR*

[Malkus, Friedland, McLaughlin, ArXiv:1403.5797 (2014)]

1.3. ***"Symmetric" MNR***

[*DV*, McLaughlin, Flynn, *in preparation*]

1.4. ***MNR in Supernovae induced by Non-Standard Neutrino Interactions***

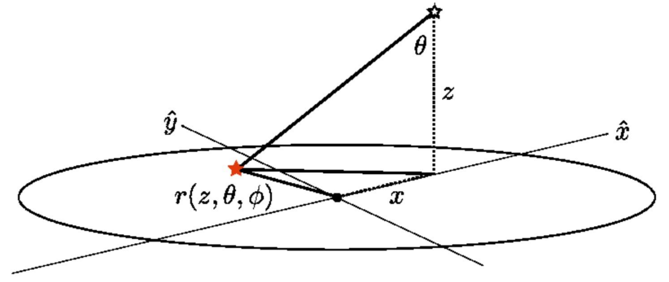
[***DV***, Kneller, McLaughlin, Stapleford, *in preparation*]

101 on Matter Neutrino Resonance (MNR)

1.1. History: Neutrino flavor evolution above black hole accretion disks

[Malkus, Kneller, McLaughlin, Surman, PRD86 085015 (2012)]

Relevant characteristics of accretion disks:



- ➢ It's a disk
- ➢ Mostly electron type neutrinos
- ➢ Antineutrinos
  - ■ have smaller emission disks
  - ■ are hotter than neutrinos

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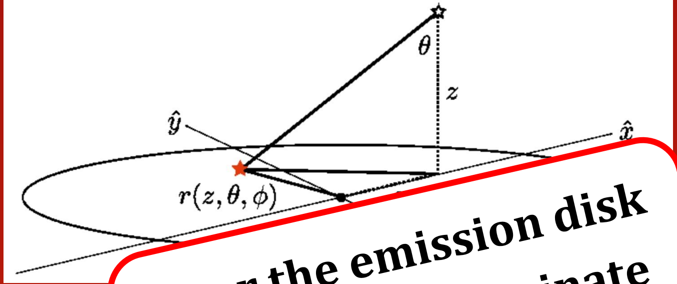

Near the emission disk antinue can dominate over nue!

101 on Matter Neutrino Resonance (MNR)

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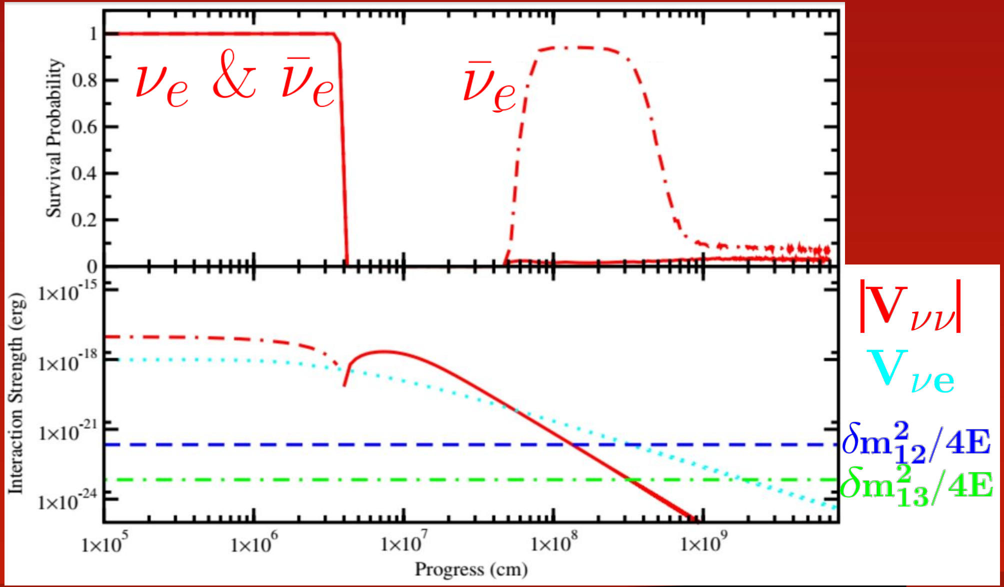
[Malkus, Kneller, McLaughlin, Surman, PRD86 085015 (2012)]

Numerical result



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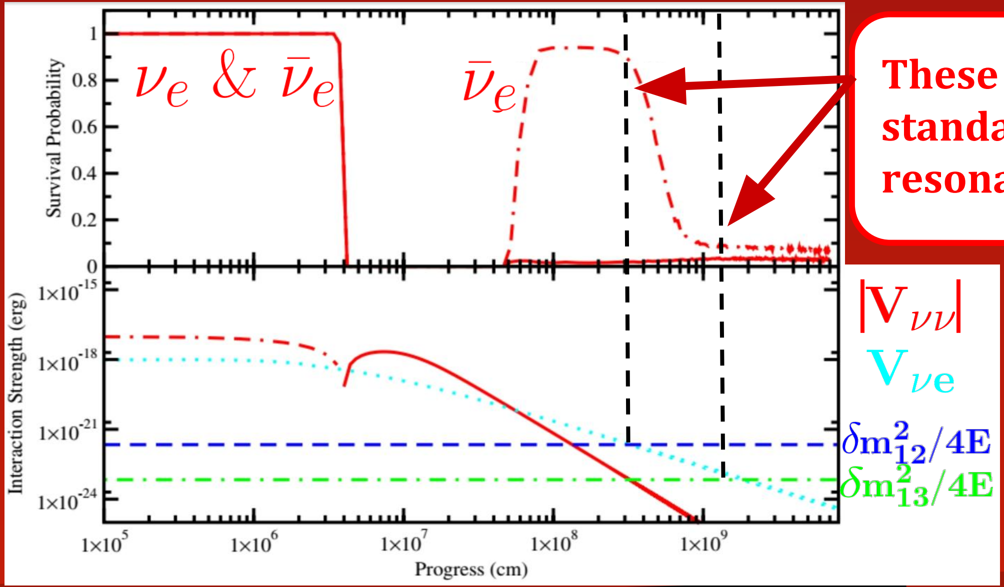

$\sim V_{\nu e}$

$\sim V_{\nu e}$

These are standard MSW resonance effects!

101 on Matter Neutrino Resonance (MNR)

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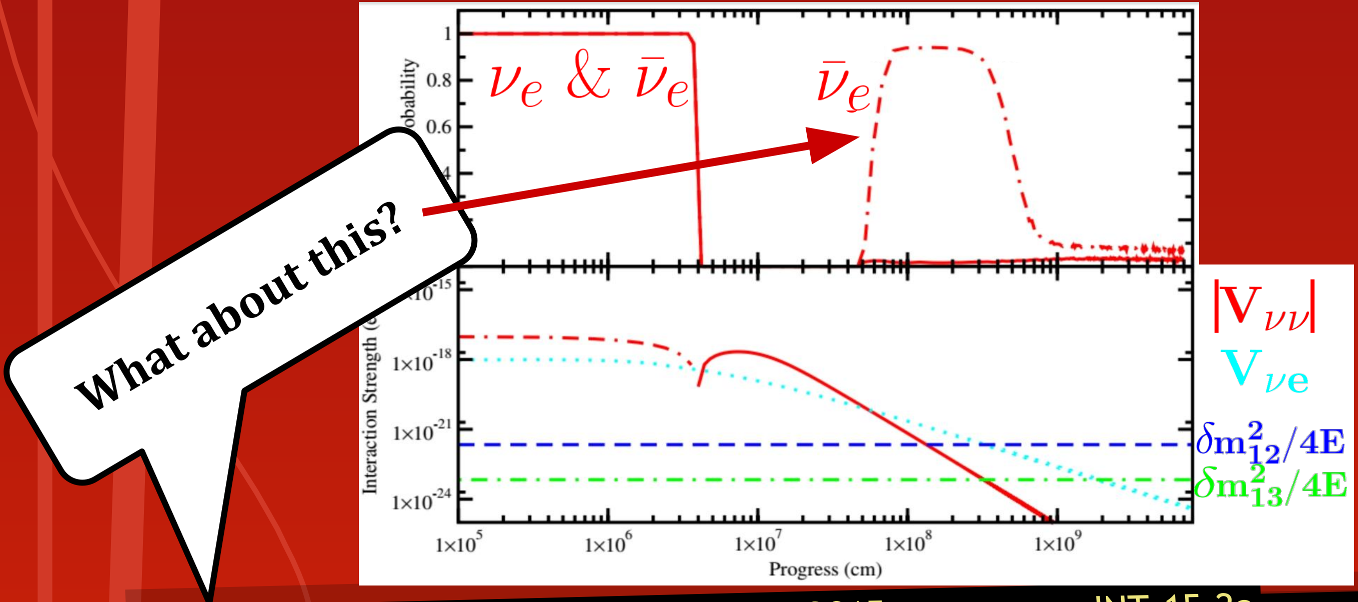

What about this?

101 on Matter Neutrino Resonance (MNR)

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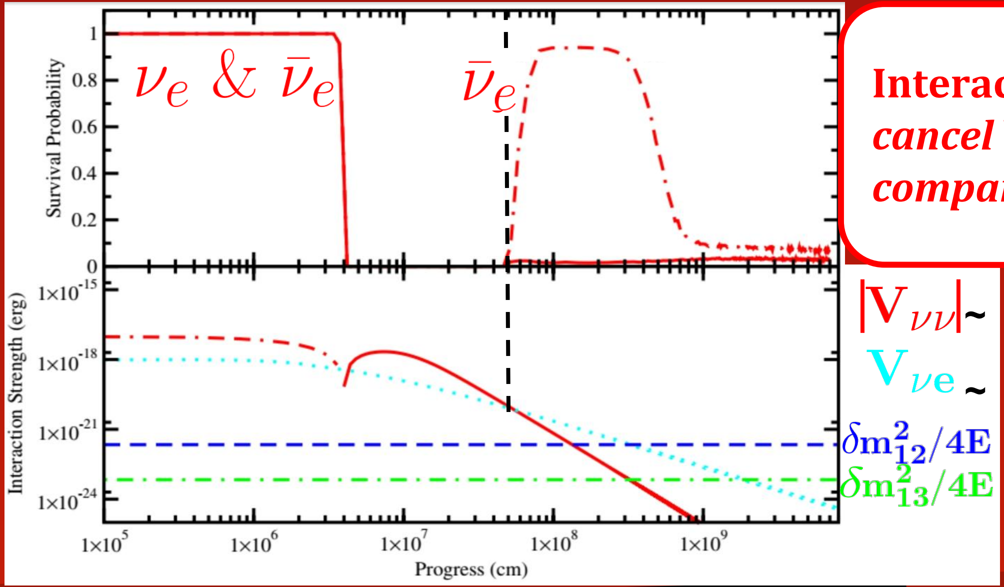

$|V_{\nu\nu}| \sim V_{\nu e}$

$V_{\nu e} \sim |V_{\nu\nu}|$

Interaction potentials *cancel* but are *large* *compared to vacuum*!

101 on Matter Neutrino Resonance (MNR)

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[Malkus, Kneller, McLaughlin, Surman, PRD86 085015 (2012)]

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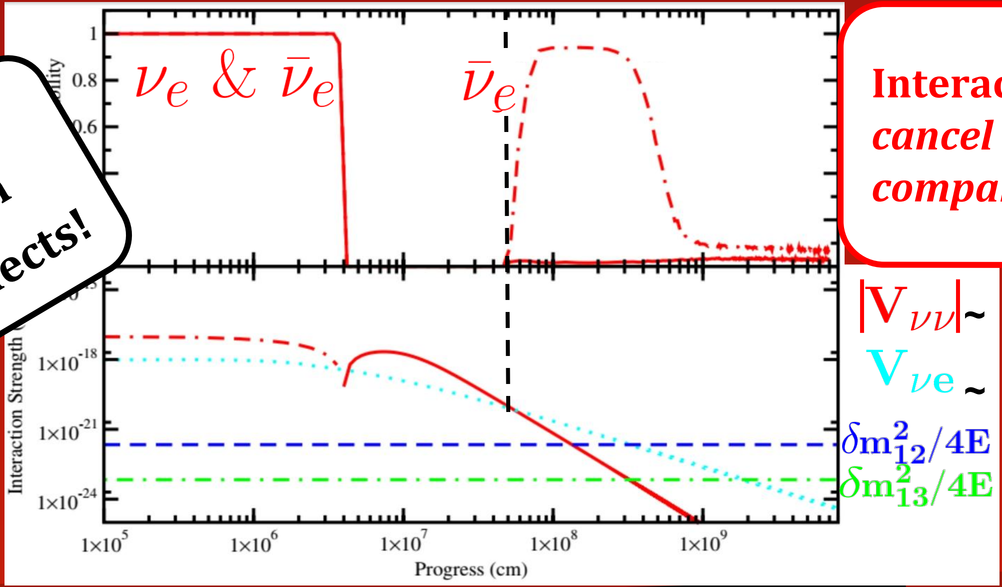

That is very different than MSW or νν effects!

Interaction potentials *cancel* but are *large compared to vacuum*!

101 on Matter Neutrino Resonance (MNR)

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[Malkus, Kneller, McLaughlin, Surman, PRD86 085015 (2012)]

- 3 neutrino flavors and multiple energies ...
- realistic, but challenging to understand underlying physics

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[Malkus, Kneller, McLaughlin, Surman, PRD86 085015 (2012)]

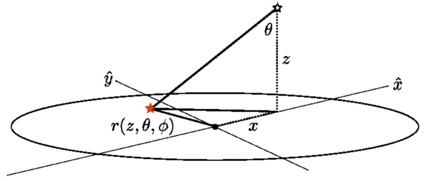
- ➢ 3 neutrino flavors and multiple energies ...
- ➢ realistic, but challenging to understand underlying physics

Apply Occam's razor: the fewer assumptions, the better!

102 on Matter Neutrino Resonance (MNR)

“Standard” MNR

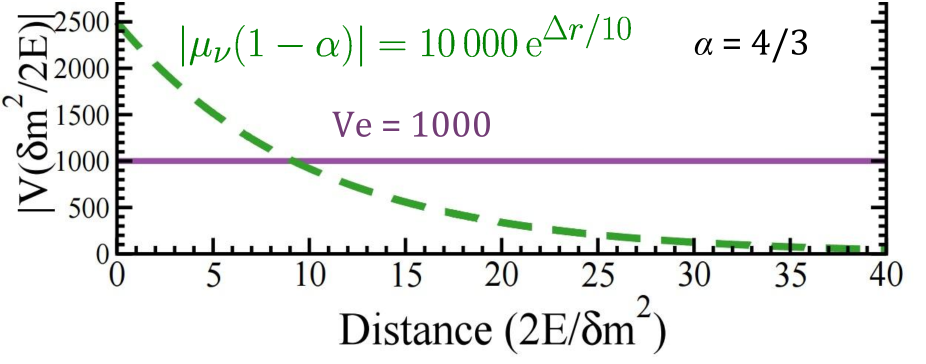
Simplest model: [Malkus, Friedland, McLaughlin, ArXiv:1403.5797 (2014)]



- single energy and emission angle
- 2 (anti)neutrino flavors: $$|\nu_1\rangle = \cos\theta\,|\nu_e\rangle - \sin\theta\,|\nu_x\rangle$$ $$|\nu_2\rangle = \sin\theta\,|\nu_e\rangle + \cos\theta\,|\nu_x\rangle$$
- Hamiltonian:

$$H_V = \Delta \begin{pmatrix} -\cos 2\theta_V & \sin 2\theta_V \\ \sin 2\theta_V & \cos 2\theta_V \end{pmatrix} \qquad H_e = \begin{pmatrix} V_e & 0 \\ 0 & 0 \end{pmatrix} \qquad H_{\nu\nu} = \mu_\nu \left(\rho - \alpha\bar{\rho}\right)$$

$\Delta = \pm 1$ $\theta_V = 0.15$



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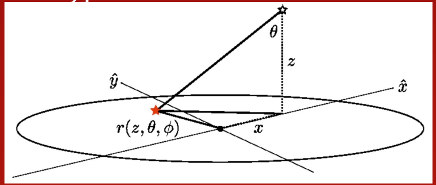


- ➢ single energy and emission angle
- ➢ 2 (anti)neutrino flavors:

$$|\nu_1\rangle = \cos\theta\,|\nu_e\rangle - \sin\theta\,|\nu_x\rangle$$
$$|\nu_2\rangle = \sin\theta\,|\nu_e\rangle + \cos\theta\,|\nu_x\rangle$$

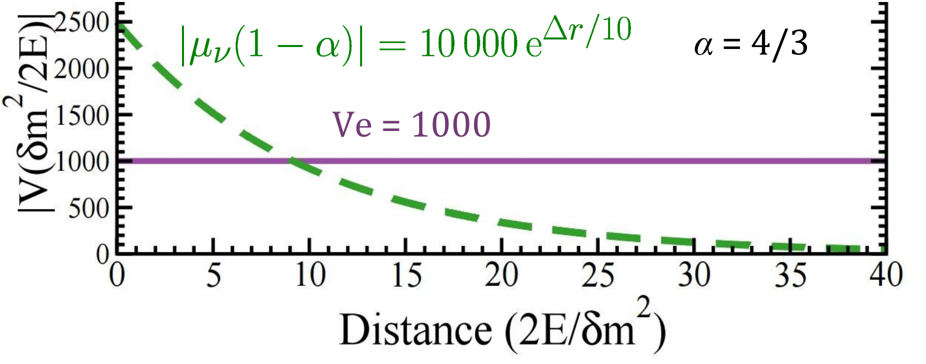
- ➢ Hamiltonian:

$$H_V = \Delta\begin{pmatrix} -\cos 2\theta_V & \sin 2\theta_V \\ \sin 2\theta_V & \cos 2\theta_V \end{pmatrix} \qquad H_e = \begin{pmatrix} V_e & 0 \\ 0 & 0 \end{pmatrix} \qquad H_{\nu\nu} = \mu_\nu\,(\rho - \alpha\bar{\rho})$$

$\Delta = \pm 1$ $\theta_V = 0.15$

- ➢ Evolution equation:

$$\mathrm{i}\frac{\mathrm{d}\overset{(-)}{\rho}}{\mathrm{d}r} = \left[\overset{(-)}{H}, \overset{(-)}{\rho}\right]$$



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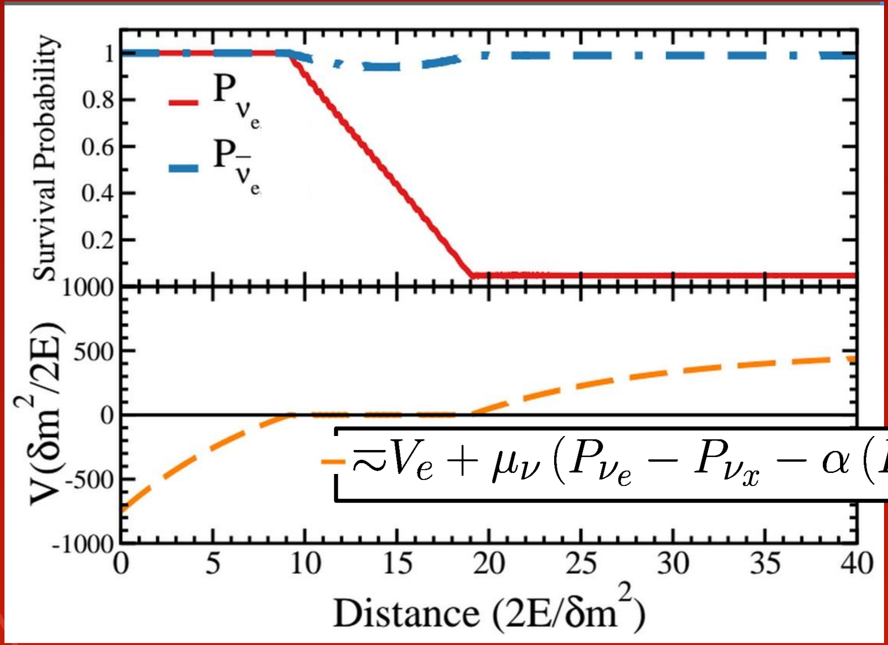
“Standard” MNR

Numerical results: [Malkus, Friedland, McLaughlin, ArXiv:1403.5797 (2014)]

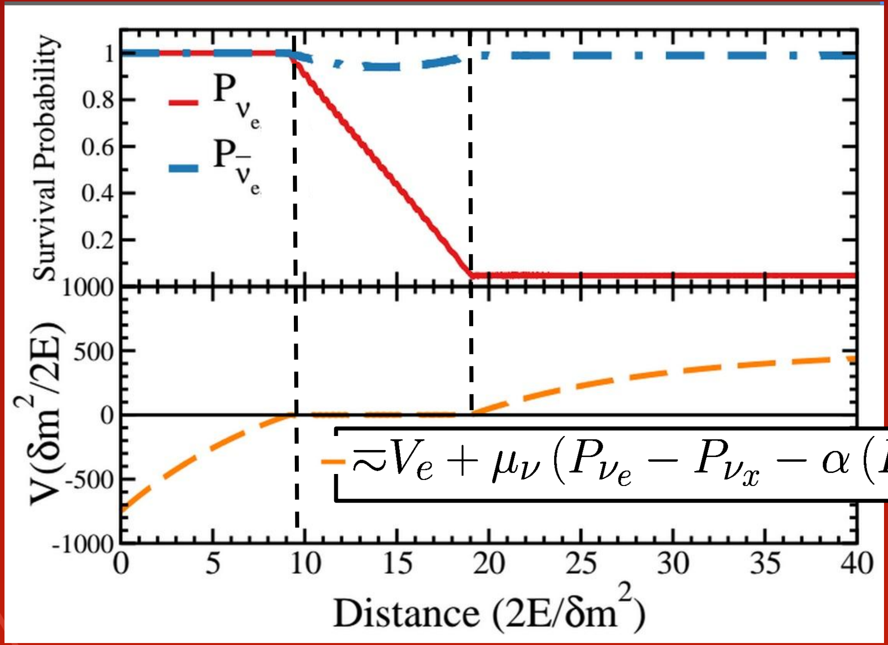


$$\simeq V_e + \mu_\nu \left(P_{\nu_e} - P_{\nu_x} - \alpha\left(P_{\bar{\nu}e} - P_{\bar{\nu}x}\right)\right)$$

102 on Matter Neutrino Resonance (MNR)

“Standard” MNR

Numerical results: [Malkus, Friedland, McLaughlin, ArXiv:1403.5797 (2014)]



$$\eqsim V_e + \mu_\nu \left(P_{\nu_e} - P_{\nu_x} - \alpha \left(P_{\bar{\nu} e} - P_{\bar{\nu} x}\right)\right) \eqsim 0$$

Non-linear feedback maintains the resonance!

102 on Matter Neutrino Resonance (MNR)

“Standard” MNR

Analytical prediction: [Malkus, Friedland, McLaughlin, ArXiv:1403.5797 (2014)]

During transformation, assume:

$$V_e + \mu_\nu \left(P_{\nu_e} - P_{\nu_x} - \alpha \left(P_{\bar{\nu}e} - P_{\bar{\nu}x}\right)\right) \approx 0$$

$$\mu_\nu \left(\rho_{ex} - \alpha \bar{\rho}_{xe}\right) \approx 0$$

$$\Delta \cos 2\theta_V \approx 0$$

Insert to evolution equation:

$$\mathrm{i}\frac{\mathrm{d}\overset{(-)}{\rho}}{\mathrm{d}r} = \left[\overset{(-)}{H}, \overset{(-)}{\rho}\right]$$

Analytical expressions for survival probabilities:

$$P_{\nu_e} = \frac{1}{2}\left(1 + \frac{\alpha^2 - R^2 - 1}{2R}\right)$$

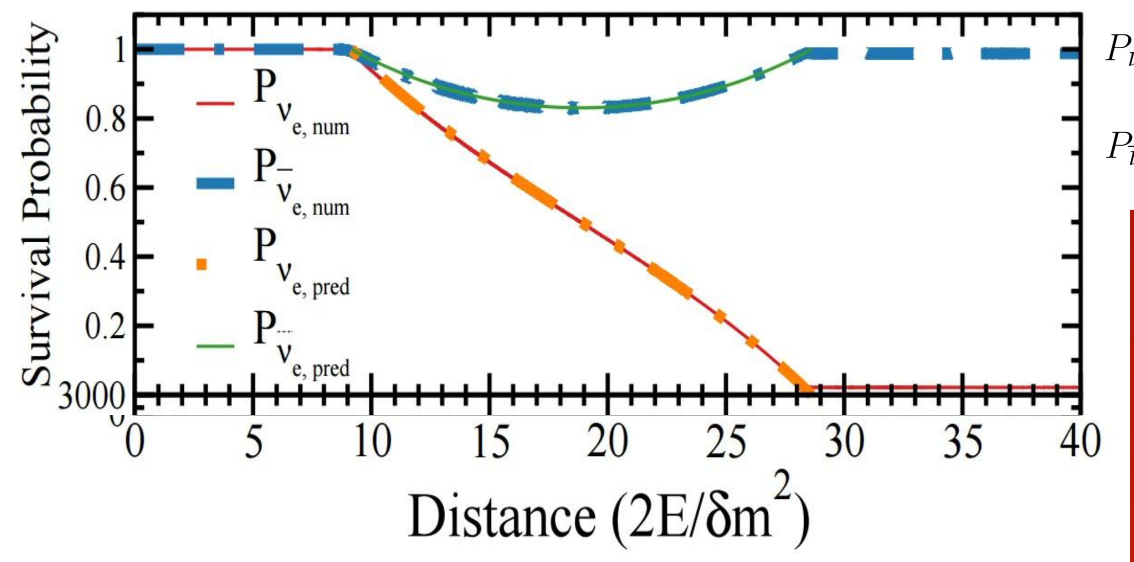
$$P_{\bar{\nu}_e} = \frac{1}{2}\left(1 + \frac{\alpha^2 + R^2 - 1}{2\alpha R}\right)$$

$R(r) = V_e/\mu(r)$

102 on Matter Neutrino Resonance (MNR)

“Standard” MNR

Numerical result VS Analytical prediction



$$P_{\nu_e} = \frac{1}{2}\left(1 + \frac{\alpha^2 - R^2 - 1}{2R}\right)$$

$$P_{\overline{\nu}_e} = \frac{1}{2}\left(1 + \frac{\alpha^2 + R^2 - 1}{2\alpha R}\right)$$

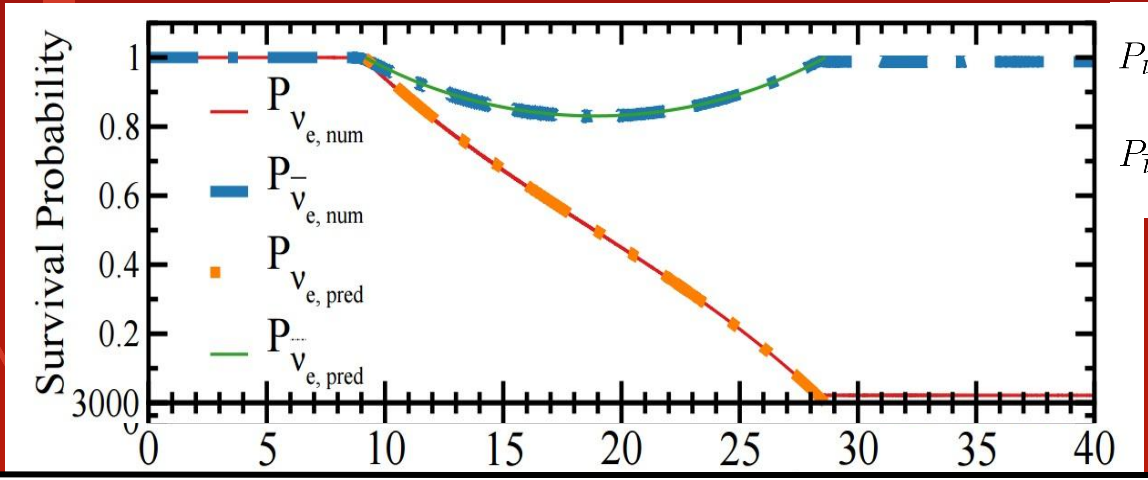
$R(r) = Ve/\mu(r)$

[Malkus, Friedland, McLaughlin, ArXiv:1403.5797 (2014)]

102 on Matter Neutrino Resonance (MNR)

“Standard” MNR

Numerical result VS Analytical prediction



$$P_{\nu_e} = \frac{1}{2}\left(1 + \frac{\alpha^2 - R^2 - 1}{2R}\right)$$

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$R(r) = Ve/\mu(r)$

[Malkus, Friedland, McLaughlin, rXiv:1403.5797 (2014)]

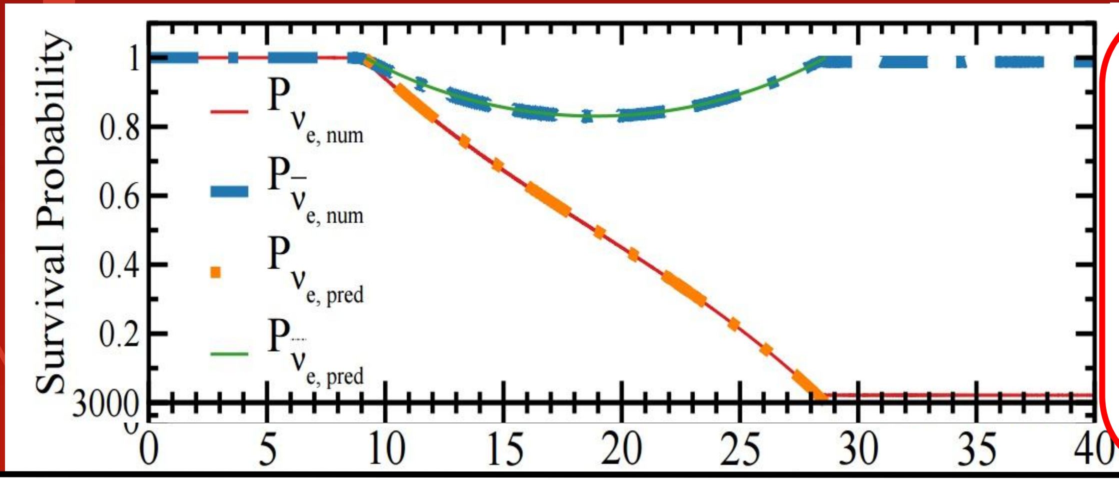
Now we know how to describe MNR and that it occurs as a result of ***non-linear feedback mechanism that maintains the resonance***

102 on Matter Neutrino Resonance (MNR)

“Standard” MNR

Numerical result VS Analytical prediction

[Malkus, Friedland, McLaughlin,
rXiv:1403.5797 (2014)]



The MNR effect is also ***independent of neutrino mass hierarchy*** and occurs ***close to neutrino emission surface!***

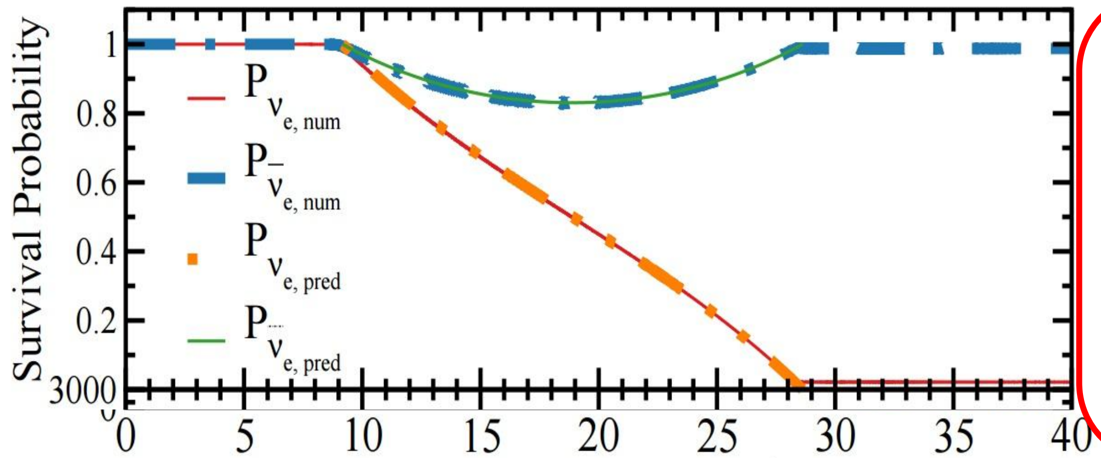
Now we know how to describe MNR and that it occurs as a result of ***non-linear feedback mechanism that maintains the resonance***

102 on Matter Neutrino Resonance (MNR)

“Standard” MNR

Numerical result VS Analytical prediction

[Malkus, Friedland, McLaughlin, ArXiv:1403.5797 (2014)]



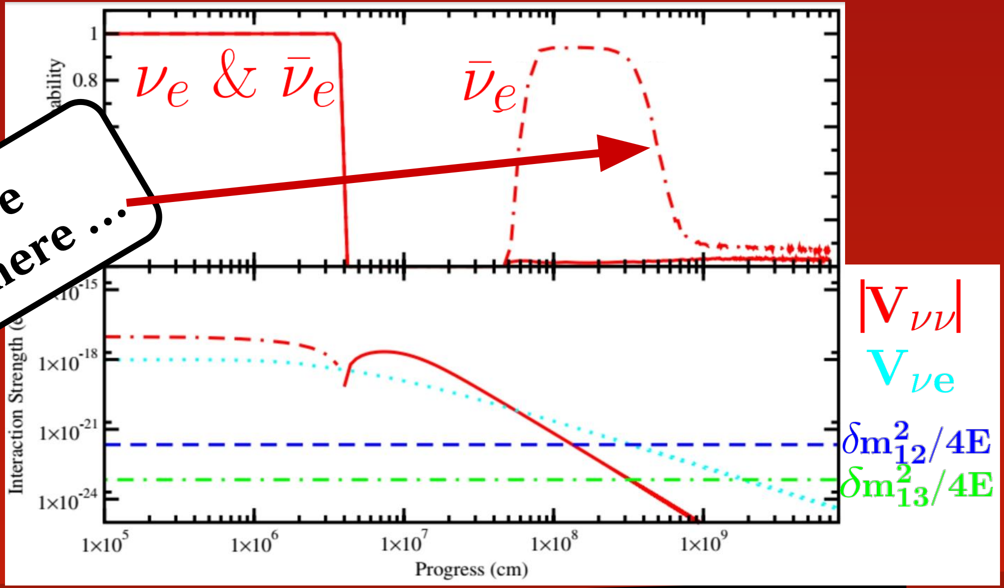
The MNR effect is also ***independent of neutrino mass hierarchy*** and occurs ***close to neutrino emission surface!***

Can have significant impact on *heavy element nucleosynthesis!*

101 & 102 on Matter Neutrino Resonance (MNR)
A Summary

1.1. History: Neutrino flavor evolution above black hole accretion disks

[Malkus, Kneller, McLaughlin, Surman, PRD86 085015 (2012)]



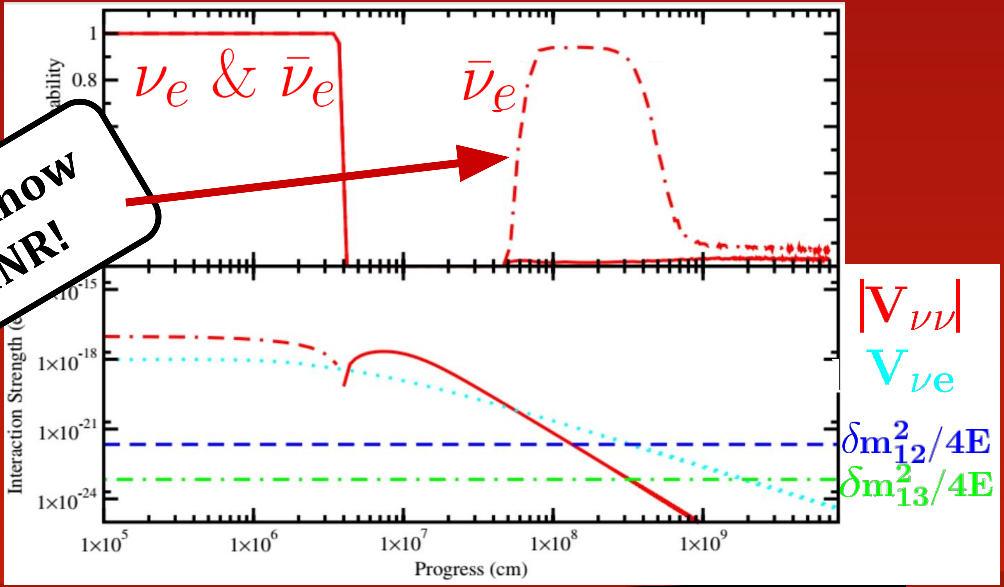
Ok, so we have standard MSW here …

101 & 102 on Matter Neutrino Resonance (MNR)

A Summary

1.1. History: Neutrino flavor evolution above black hole accretion disks
[Malkus, Kneller, McLaughlin, Surman, PRD86 085015 (2012)]

1.2. “Standard” MNR [Malkus, Friedland, McLaughlin, ArXiv:1403.5797 (2014)]

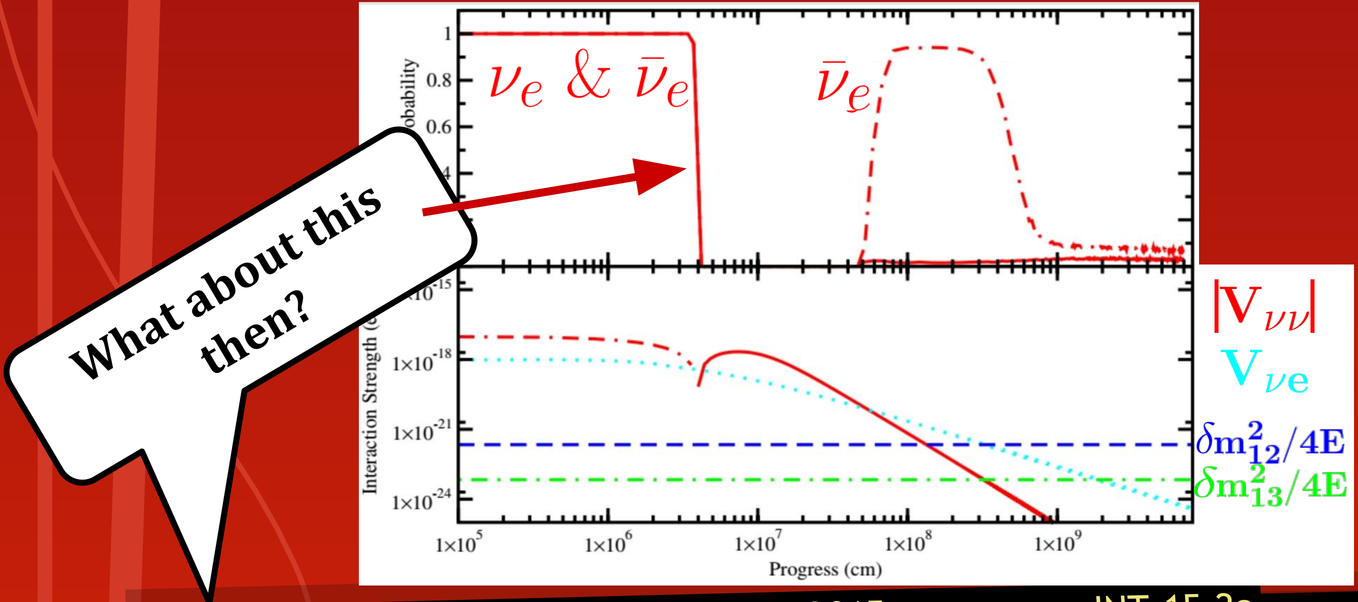


… and now we know that this is MNR!

101 & 102 on Matter Neutrino Resonance (MNR)
A Summary

1.1. History: Neutrino flavor evolution above black hole accretion disks
[Malkus, Kneller, McLaughlin, Surman, PRD86 085015 (2012)]

1.2. “Standard” MNR [Malkus, Friedland, McLaughlin, ArXiv:1403.5797 (2014)]

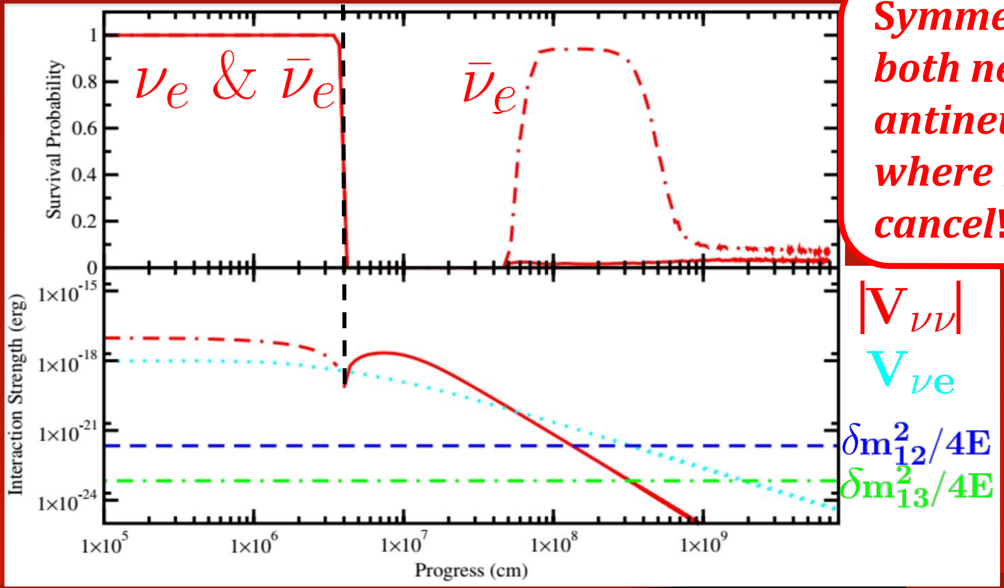


What about this then?

101 & 102 on Matter Neutrino Resonance (MNR) A Summary

1.1. History: Neutrino flavor evolution above black hole accretion disks
[Malkus, Kneller, McLaughlin, Surman, PRD86 085015 (2012)]

1.2. “Standard” MNR [Malkus, Friedland, McLaughlin, ArXiv:1403.5797 (2014)]



Symmetric transformation of both neutrinos and antineutrinos at the location where interaction potentials cancel!

1. A Lesson on Neutrino self-induced collective transformations
2. ***Neutrino + Matter induced collective transformations***
   - ➢ ***"Standard" MNR*** **[Malkus, Friedland, McLaughlin, ArXiv:1403.5797 (2014)]**
   - ➢ ***"Symmetric" MNR*** **[DV, McLaughlin, Flynn, *in preparation*]**
   - ➢ *Non-Standard-Interaction (NSI) induced MNR* [DV, Kneller, McLaughlin, Stapleford, *in preparation*]
3. Conclusions

103 on Matter Neutrino Resonance (MNR)

“Symmetric” MNR

Simplest model: [**DV**, McLaughlin, Flynn, *in preparation*]

- ➢ single energy and emission angle
- ➢ 2 (anti)neutrino flavors:

$$|\nu_1\rangle = \cos\theta\,|\nu_e\rangle - \sin\theta\,|\nu_x\rangle$$
$$|\nu_2\rangle = \sin\theta\,|\nu_e\rangle + \cos\theta\,|\nu_x\rangle$$

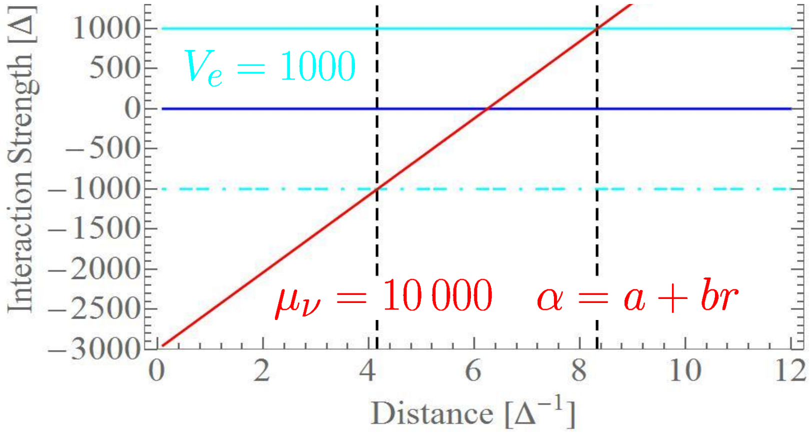
- ➢ Hamiltonian:

$$H_V = \Delta \begin{pmatrix} -\cos 2\theta_V & \sin 2\theta_V \\ \sin 2\theta_V & \cos 2\theta_V \end{pmatrix} \qquad H_e = \begin{pmatrix} V_e & 0 \\ 0 & 0 \end{pmatrix} \qquad H_{\nu\nu} = \mu_\nu\left(\rho - \alpha\bar{\rho}\right)$$

$\Delta = \pm 1$ $\theta_V = 0.154$

- ➢ Evolution equation:

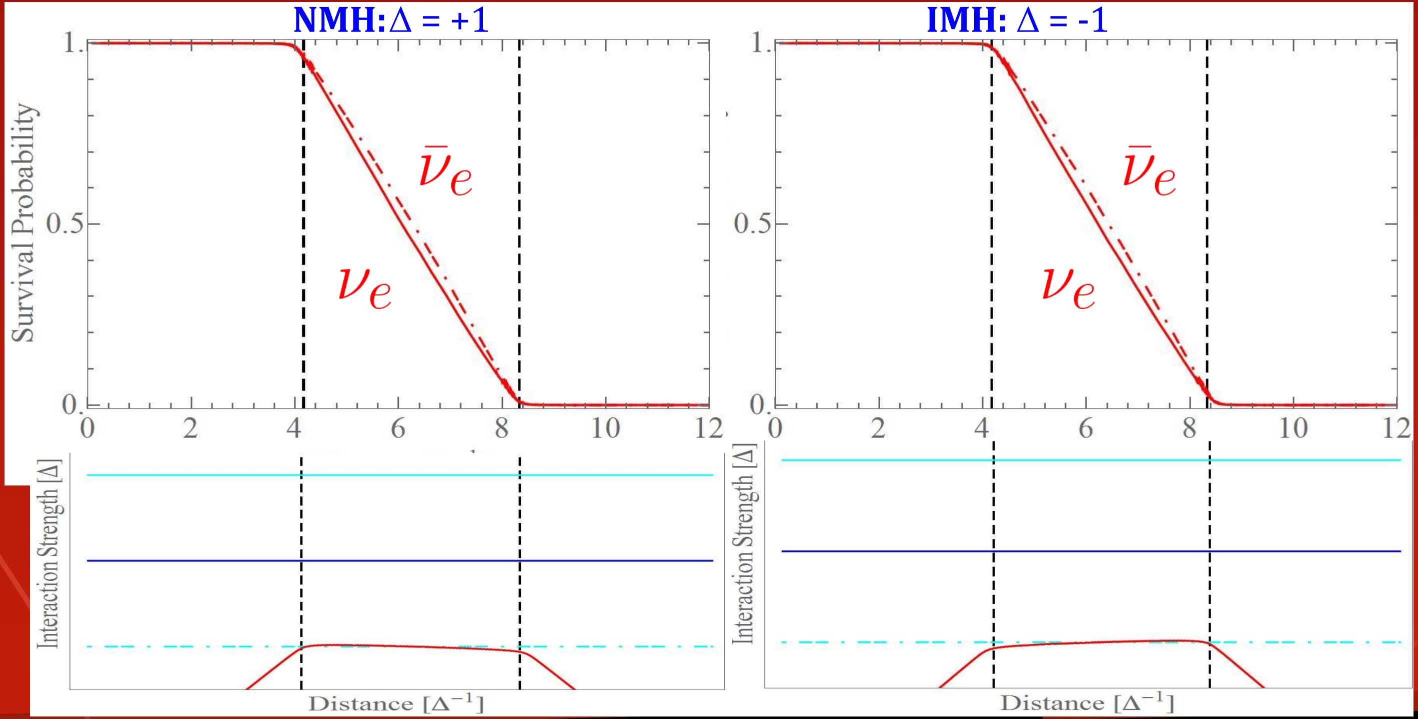
$$\mathrm{i}\frac{\mathrm{d}\overset{(-)}{\rho}}{\mathrm{d}r} = \left[\overset{(-)}{H},\overset{(-)}{\rho}\right]$$



103 on Matter Neutrino Resonance (MNR)

“Symmetric” MNR

Numerical results [**DV**, McLaughlin, Flynn, *in preparation*]



103 on Matter Neutrino Resonance (MNR)

“Symmetric” MNR

Analytical understanding: [**DV,** McLaughlin, Flynn, *in preparation*]

- Determine eigenvalues of the Hamiltonian:

$$\delta k \sim \sqrt{(\Delta\cos 2\theta_V - V_e - \mu_\nu(\rho_{ee} - \rho_{xx} - \alpha(\bar{\rho}_{ee} - \bar{\rho}_{xx})))^2 + (\Delta\sin 2\theta_V - \mu_\nu(\rho_{ex} - \alpha\bar{\rho}_{xe}))^2}$$

103 on Matter Neutrino Resonance (MNR)

“Symmetric” MNR

Analytical understanding: [**DV**, McLaughlin, Flynn, *in preparation*]

- Determine eigenvalues of the Hamiltonian:

$$\delta k \sim \sqrt{\underbrace{\left(\Delta \cos 2\theta_V - V_e - \mu_\nu(\rho_{ee} - \rho_{xx} - \alpha(\bar{\rho}_{ee} - \bar{\rho}_{xx}))\right)^2}_{\to 0} + \underbrace{\left(\Delta \sin 2\theta_V - \mu_\nu(\rho_{ex} - \alpha\bar{\rho}_{xe})\right)^2}_{\to 0}}$$

- Minimize: 0
- Insert to evolution equation:

$$\mathrm{i}\frac{\mathrm{d}\overset{(-)}{\rho}}{\mathrm{d}r} = \left[\overset{(-)}{H}, \overset{(-)}{\rho}\right]$$

- Analytical expressions for survival probabilities:

(neglecting vacuum corrections)

$$P_{\nu_e} = \frac{1}{2}\left(1 + \frac{\alpha^2 - R^2 - 1}{2R}\right)$$

$$P_{\bar{\nu}_e} = \frac{1}{2}\left(1 + \frac{\alpha^2 + R^2 - 1}{2\alpha R}\right)$$

R = Ve/μ

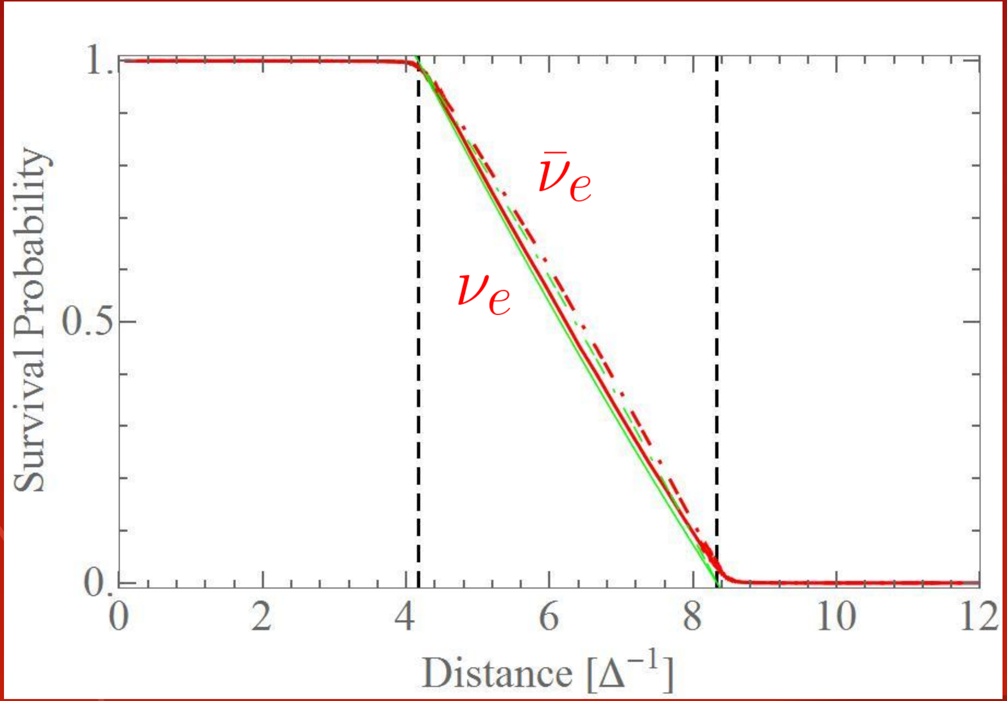
α(r) = a+br

103 on Matter Neutrino Resonance (MNR)

“Symmetric” MNR

[DV, McLaughlin, Flynn, *in preparation*]

Numerical result VS Analytical prediction



$$P_{\nu_e} = \frac{1}{2}\left(1 + \frac{\alpha^2 - R^2 - 1}{2R}\right)$$

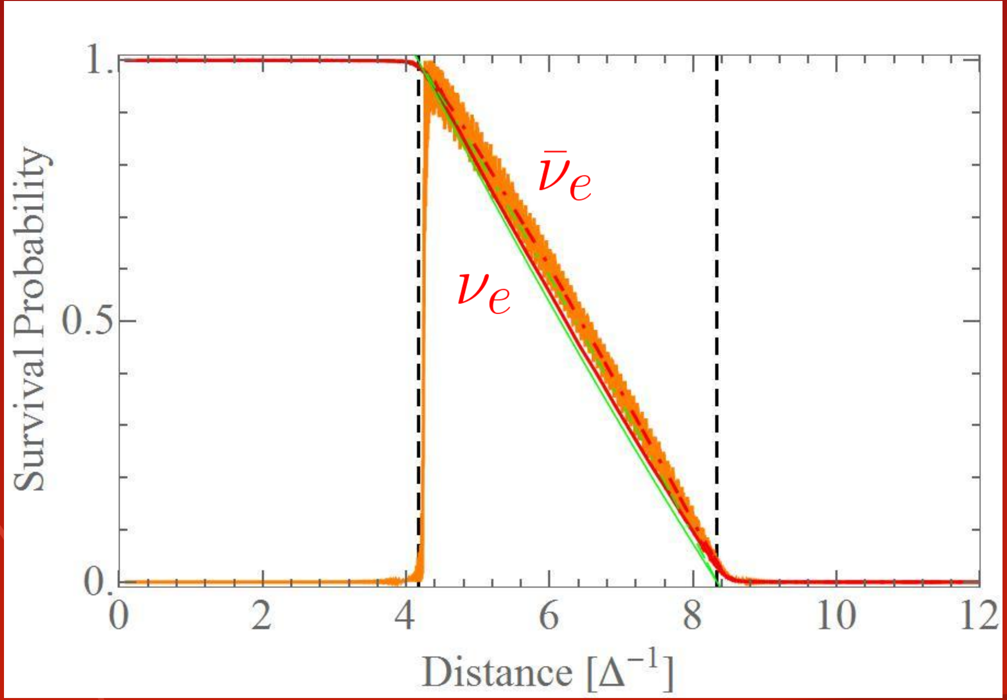
$$P_{\overline{\nu}_e} = \frac{1}{2}\left(1 + \frac{\alpha^2 + R^2 - 1}{2\alpha R}\right)$$

R = Ve/μ, $\alpha(\text{r})$ = a+br

103 on Matter Neutrino Resonance (MNR)

"Symmetric" MNR

Numerical result VS Analytical prediction



[DV, McLaughlin, Flynn, *in preparation*]

$$P_{\nu_e} = \frac{1}{2}\left(1 + \frac{\alpha^2 - R^2 - 1}{2R}\right)$$

$$P_{\bar{\nu}_e} = \frac{1}{2}\left(1 + \frac{\alpha^2 + R^2 - 1}{2\alpha R}\right)$$

$R = Ve/\mu$, $\alpha(r) = a+br$

Adiabatic assumption:

$$P_{\nu_e} = \frac{H_{ee} - k_1}{k_2 - k_1}$$

103 on Matter Neutrino Resonance (MNR)

"Symmetric" MNR

Conditions for MNR:

Analytical prediction - independent of vacuum parameters

Dependence on vacuum? Flavor Stability of the initial system?

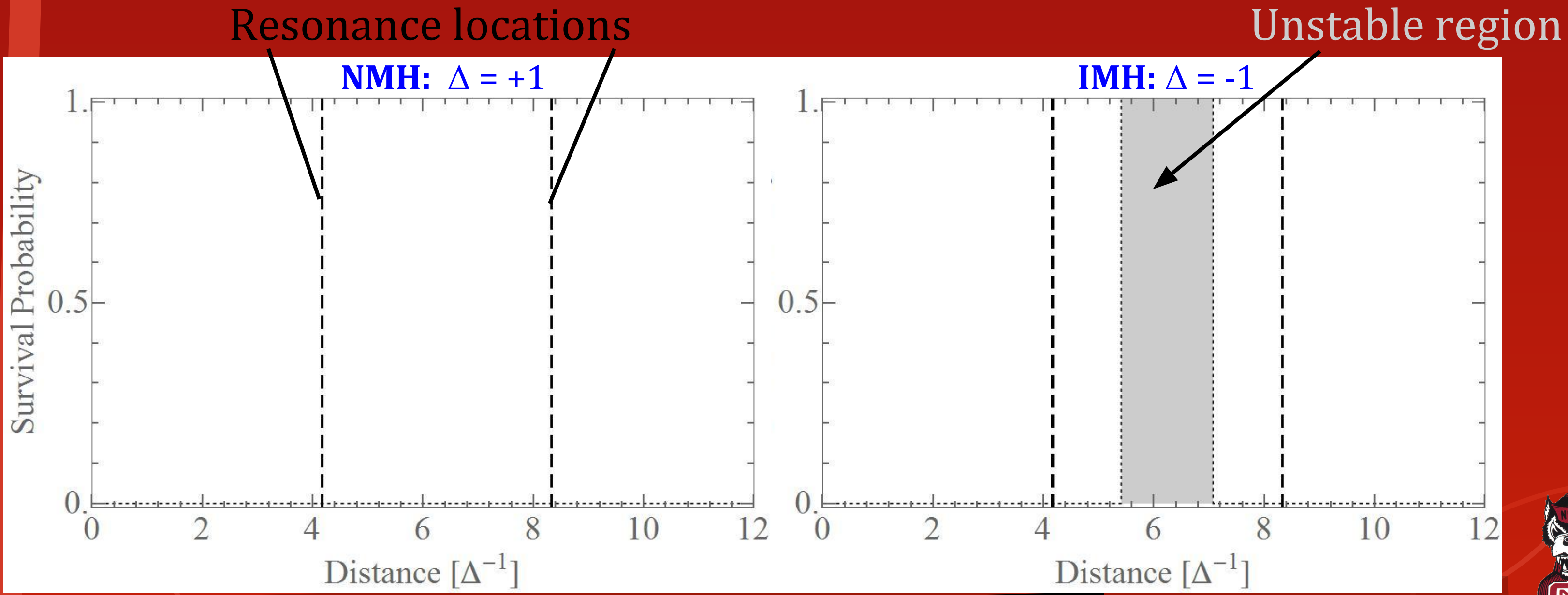
103 on Matter Neutrino Resonance (MNR)

"*Symmetric*" MNR

[DV, McLaughlin, Flynn, *in preparation*]

Conditions for MNR:

Analytical prediction - independent of vacuum parameters



103 on Matter Neutrino Resonance (MNR)

“Symmetric” MNR

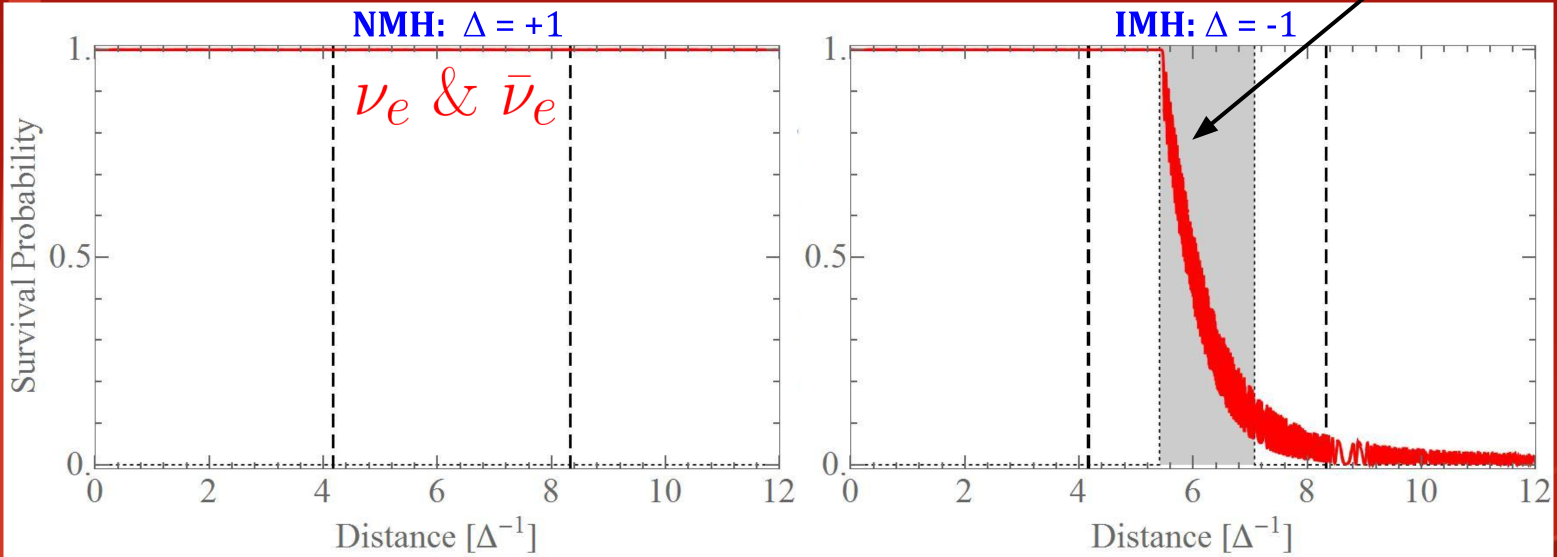
[DV, McLaughlin, Flynn, *in preparation*]

Conditions for MNR:

Analytical prediction - independent of vacuum parameters

Numerical results with **θv = 0.000154**

Self-induced transformation!

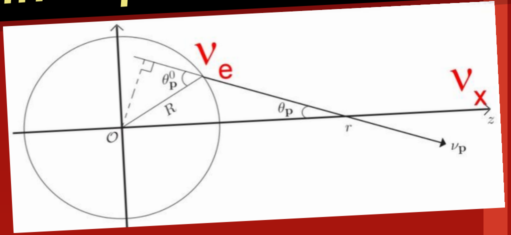


1. A Lesson on Neutrino self-induced collective transformations
2. ***Neutrino + Matter induced collective transformations***
    - ➢ *“Standard” MNR* **[Malkus, Friedland, McLaughlin, ArXiv:........ (2014)]**
    - ➢ *“Symmetric” MNR* **[DV, McLaughlin, *in preparation*]**
    - ➢ ***Non-Standard-Interaction (NSI) induced MNR***

      [DV, Kneller, McLaughlin, Stapleford, *in preparation*]
3. Conclusions

104 on Matter Neutrino Resonance (MNR)

NSI induced MNR in Supernovae



Simplest model:

- single energy and emission angle
- 2 (anti)neutrino flavors: $|\nu_1\rangle = \cos\theta\,|\nu_e\rangle - \sin\theta\,|\nu_x\rangle$, $|\nu_2\rangle = \sin\theta\,|\nu_e\rangle + \cos\theta\,|\nu_x\rangle$
- Hamiltonian:

$$H_V = \Delta \begin{pmatrix} -\cos 2\theta_V & \sin 2\theta_V \\ \sin 2\theta_V & \cos 2\theta_V \end{pmatrix} \qquad H_e = \begin{pmatrix} V_e & 0 \\ 0 & 0 \end{pmatrix} \qquad H_{\nu\nu} = \mu_\nu \left(\rho - \alpha\bar{\rho}\right)$$

$\Delta m^2 = 2.4\text{x}10^{-3}$ $\theta v = 0.154$ $V_e \sim \lambda \left(\frac{r_0}{r}\right)^3 Y_e$ $\mu_\nu \sim \mu_0 \left(\frac{r_0}{r}\right)^4$ $\alpha = 0.833$

$$H_{\rm NSI} = \lambda \left(\frac{r_0}{r}\right)^3 \begin{pmatrix} \epsilon_{ee} & \epsilon_{ex} \\ \epsilon_{xe} & \epsilon_{xx} \end{pmatrix} \qquad \epsilon_{ij} = \sum_{f=e,u,d P=L,R} \epsilon_P^{ij,ff} \left(\frac{n_f}{n_e}\right)$$

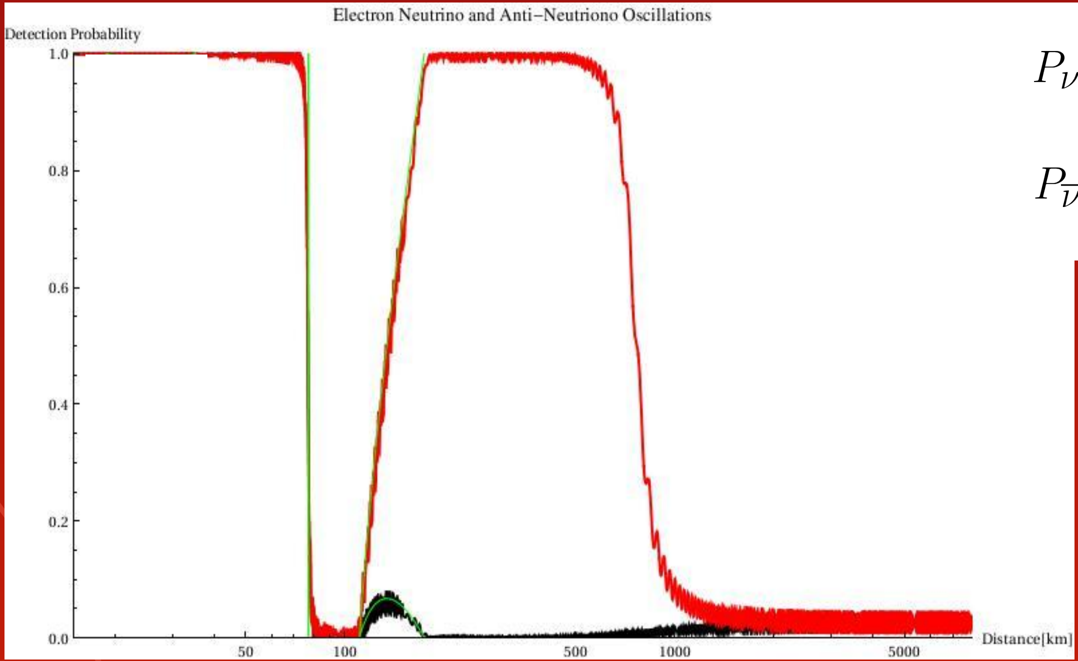
[DV, Kneller, McLaughlin, Stapleford, *in preparation*]

104 on Matter Neutrino Resonance (MNR)

NSI induced MNR in Supernovae

[DV, Kneller, McLaughlin, Stapleford, *in preparation*]

Numerical result VS Analytical prediction



$$P_{\nu_e} = \frac{1}{2}\left(1 + \frac{\alpha^2 - R^2 - 1}{2R}\right)$$

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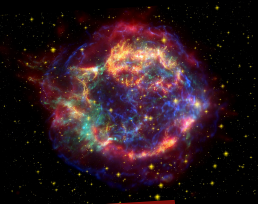
$R(r) = Ve(r)/\mu(r)$,

$\alpha = 0.833$



Matter Neutrino Resonance (MNR) Conclusions

- New type of neutrino flavor transformation
  - requires cancellation of interaction potentials
  - potentials can be large wrt vacuum!
  - non-linear feedback mechanism maintaining the resonance
  - effects independent of MH
  - effects occur close to neutrino emission
    - impact on nucleosynthesis!?
- “Standard” MNR: antineutrino dominating environment
- “Symmetric” both neutrinos and antineutrinos transform
- NSI induced: renders MNR plausible in SNe
  - tool to probe new physics beyond reach of near future experiments!

Thank you!!!


McLaughlin


Kneller


Charles Stapleford


Sam Flynn


Yonglin Zhu

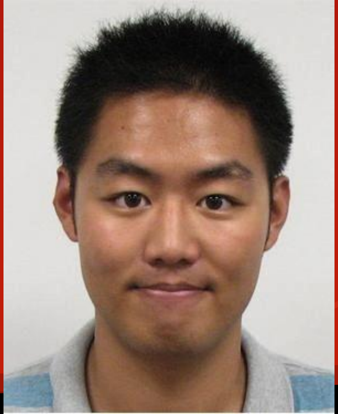

McLaughlin


Kneller

Thank you!!!


Charles Stapleford


Sam Flynn

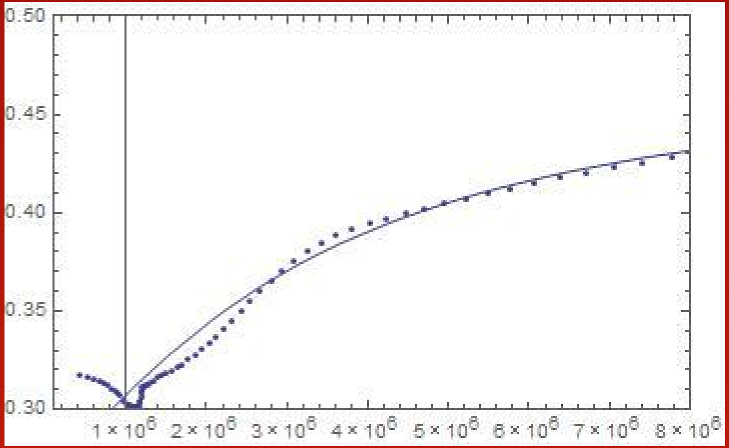

Yonglin Zhu

3) Matter Neutrino Resonance (MNR) in Supernovae:

Neutrino Spin Coherence (NSC) induced MNR - the case of helicity transformation

[Vlasenko, Fuller, Vincenzo Cirigliano, arXiv:1406.6724 (2014)]

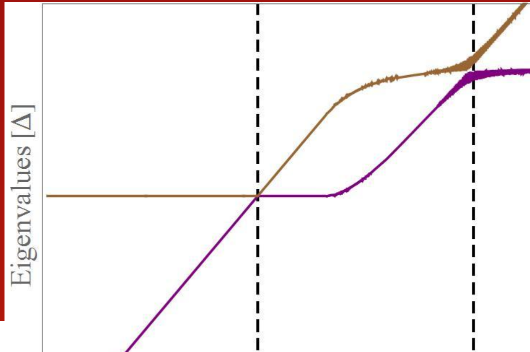
3) Matter Neutrino Resonance (MNR) *in Supernovae:* ***with NSI***



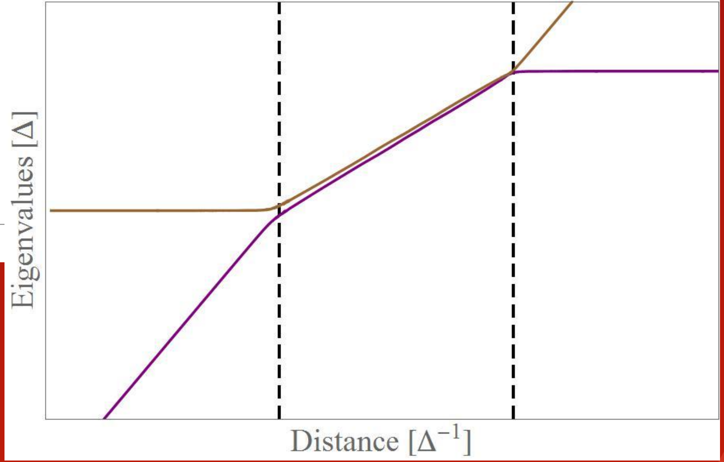
Ye profile [**Basel group simulation … 2010**]

Eigenvalues

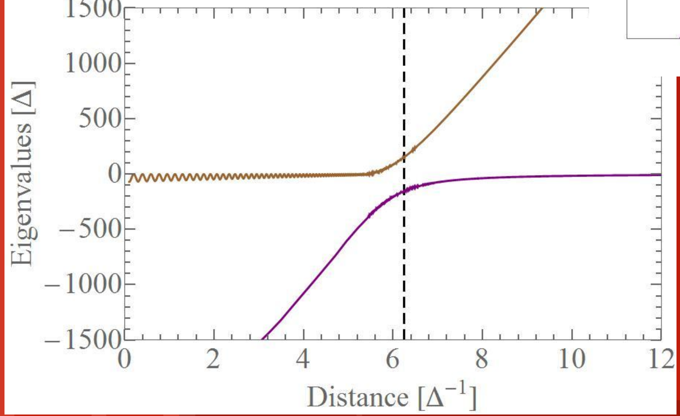
nunu with matter, small vacuum

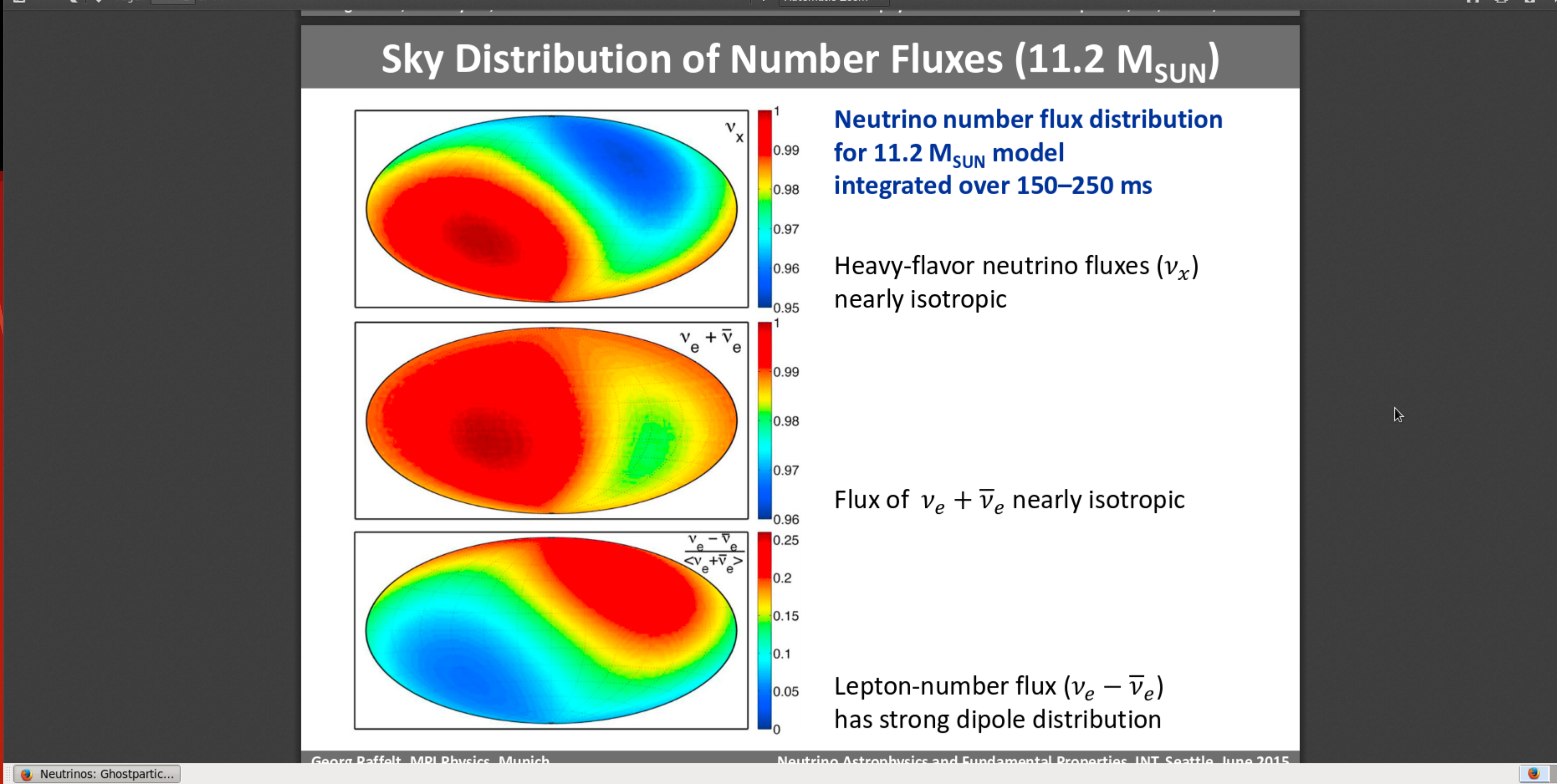


MNR



no matter





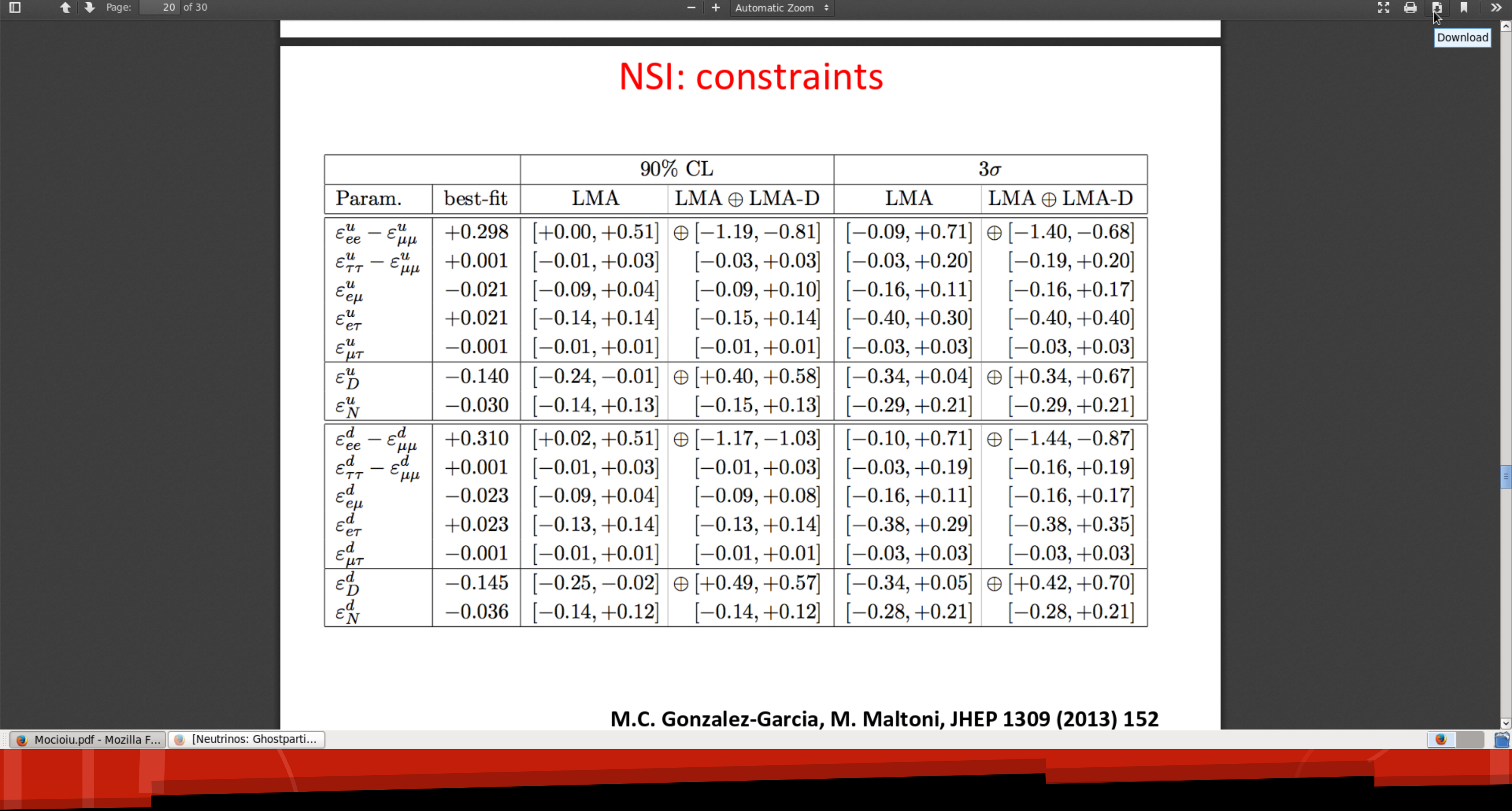
Sky Distribution of Number Fluxes (11.2 M_{SUN})

Neutrino number flux distribution for 11.2 M_{SUN} model integrated over 150–250 ms

Heavy-flavor neutrino fluxes (ν_x) nearly isotropic

Flux of $\nu_e + \bar{\nu}_e$ nearly isotropic

Lepton-number flux ($\nu_e - \bar{\nu}_e$) has strong dipole distribution



NSI: constraints

		90% CL		3σ	
Param.	best-fit	LMA	LMA $\oplus$ LMA-D	LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$+0.298$	$[+0.00, +0.51]$	$\oplus$ $[-1.19, -0.81]$	$[-0.09, +0.71]$	$\oplus$ $[-1.40, -0.68]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.03, +0.03]$	$[-0.03, +0.20]$	$[-0.19, +0.20]$
$\varepsilon^u_{e\mu}$	-0.021	$[-0.09, +0.04]$	$[-0.09, +0.10]$	$[-0.16, +0.11]$	$[-0.16, +0.17]$
$\varepsilon^u_{e\tau}$	$+0.021$	$[-0.14, +0.14]$	$[-0.15, +0.14]$	$[-0.40, +0.30]$	$[-0.40, +0.40]$
$\varepsilon^u_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$	$[-0.03, +0.03]$	$[-0.03, +0.03]$
ε^u_D	-0.140	$[-0.24, -0.01]$	$\oplus$ $[+0.40, +0.58]$	$[-0.34, +0.04]$	$\oplus$ $[+0.34, +0.67]$
ε^u_N	-0.030	$[-0.14, +0.13]$	$[-0.15, +0.13]$	$[-0.29, +0.21]$	$[-0.29, +0.21]$
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	$+0.310$	$[+0.02, +0.51]$	$\oplus$ $[-1.17, -1.03]$	$[-0.10, +0.71]$	$\oplus$ $[-1.44, -0.87]$
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.01, +0.03]$	$[-0.03, +0.19]$	$[-0.16, +0.19]$
$\varepsilon^d_{e\mu}$	-0.023	$[-0.09, +0.04]$	$[-0.09, +0.08]$	$[-0.16, +0.11]$	$[-0.16, +0.17]$
$\varepsilon^d_{e\tau}$	$+0.023$	$[-0.13, +0.14]$	$[-0.13, +0.14]$	$[-0.38, +0.29]$	$[-0.38, +0.35]$
$\varepsilon^d_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$	$[-0.03, +0.03]$	$[-0.03, +0.03]$
ε^d_D	-0.145	$[-0.25, -0.02]$	$\oplus$ $[+0.49, +0.57]$	$[-0.34, +0.05]$	$\oplus$ $[+0.42, +0.70]$
ε^d_N	-0.036	$[-0.14, +0.12]$	$[-0.14, +0.12]$	$[-0.28, +0.21]$	$[-0.28, +0.21]$

M.C. Gonzalez-Garcia, M. Maltoni, JHEP 1309 (2013) 152