Istituto Nazionale di Fisica Nucleare

NOW 2018

Neutrino Oscillation Workshop

Dip. Interateneo di Fisica
Università di Bari

Dip. di Matematica e Fisica
Università del Salento

Distinguishing supernova-ν flavour equalisation from a pure MSW effect

based on arXiv:1807.00840 (accepted on PRD), with B. Dasgupta and A. Mirizzi

FRANCESCO CAPOZZI

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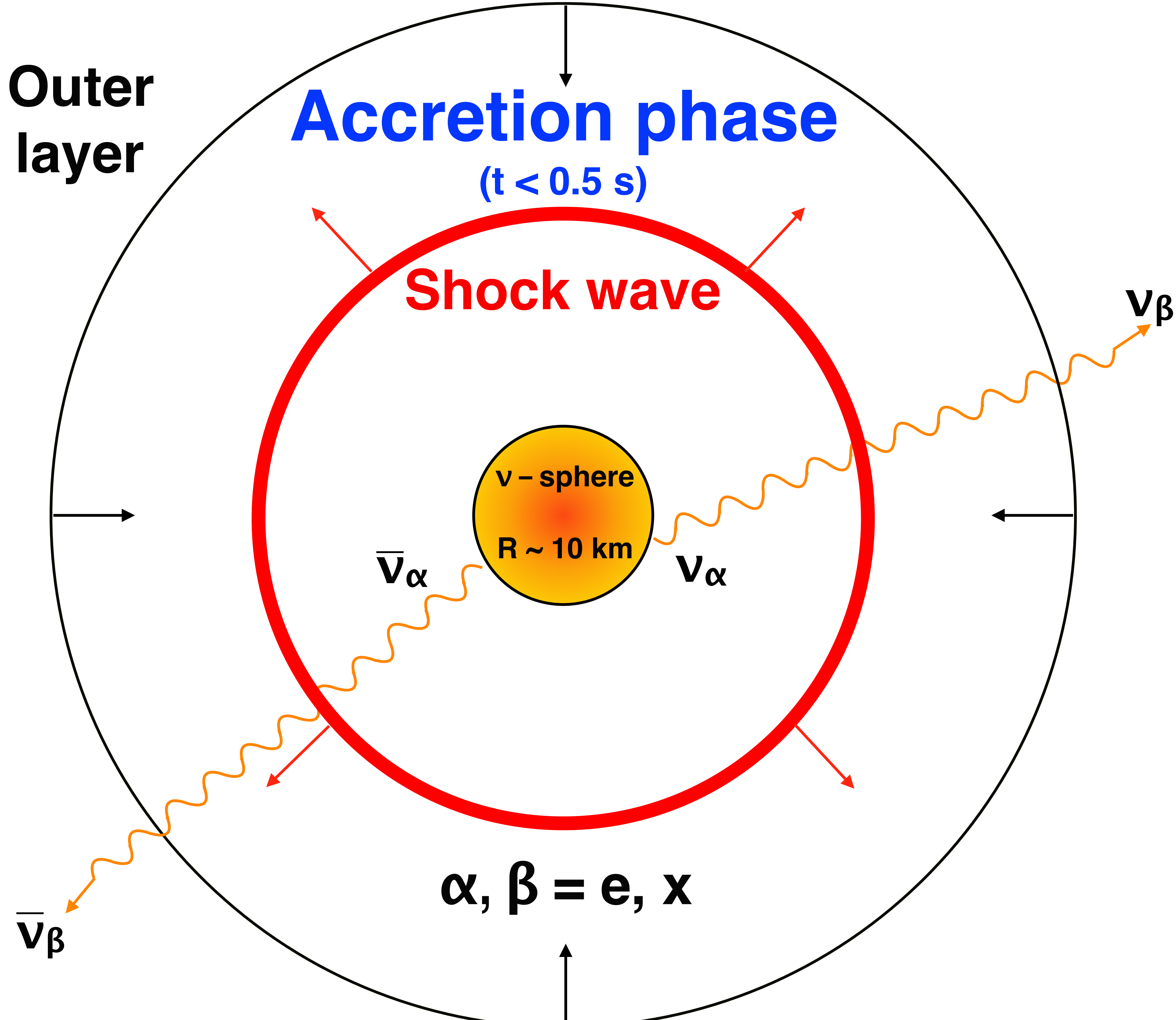
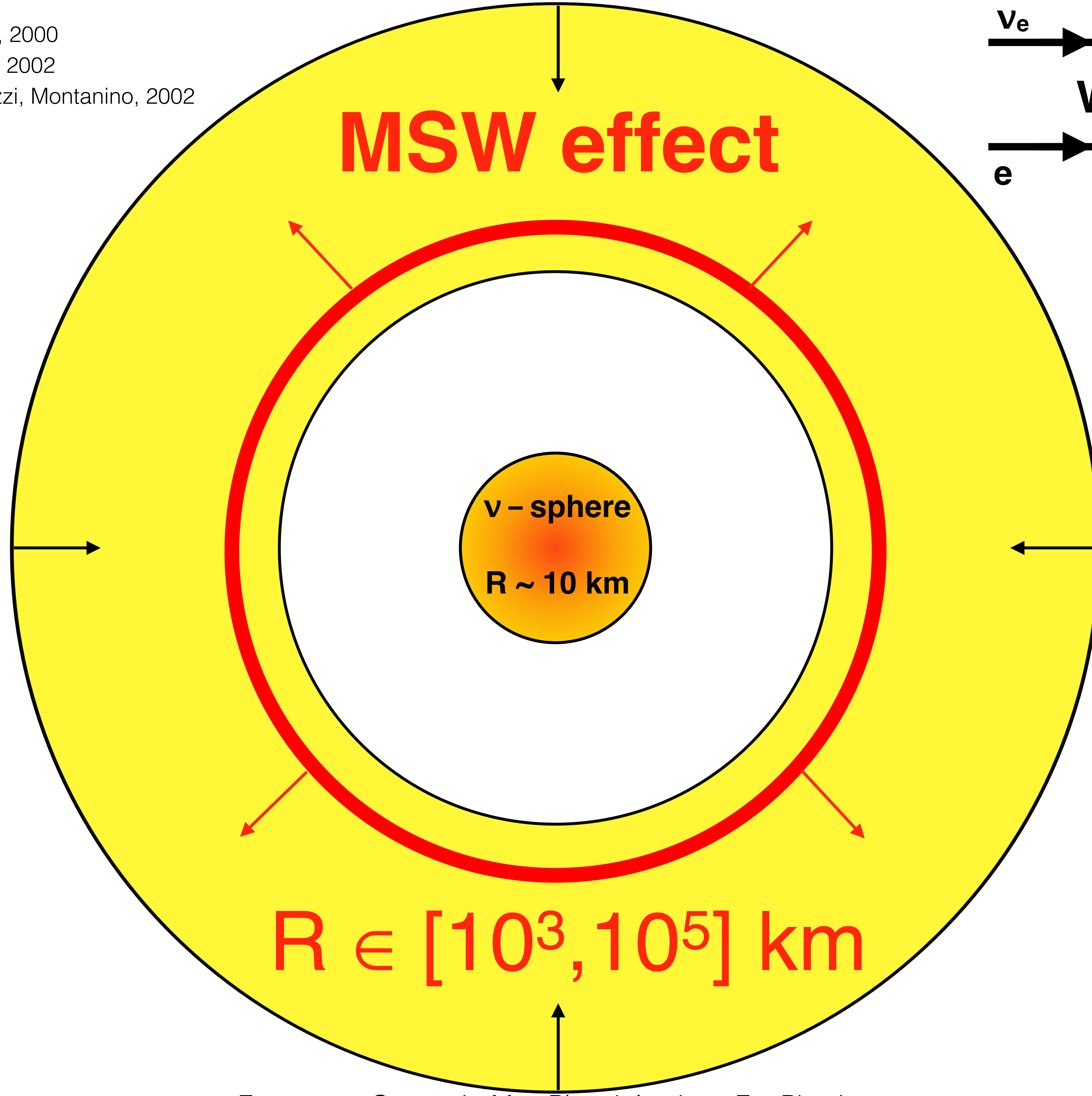
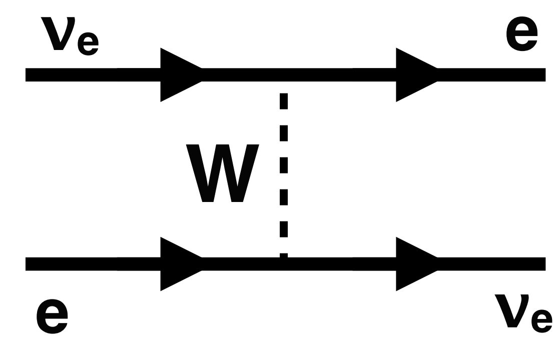
(Werner-Heisenberg-Institut)


Outer layer
Accretion phase
(t < 0.5 s)
Shock wave
ν_β
ν – sphere
R ~ 10 km
$\bar{\nu}_\alpha$
ν_α
α, β = e, x
$\bar{\nu}_\beta$

[1] Dighe, Smirnov, 2000
[2] Schirato, Fuller, 2002
[3] Fogli, Lisi, Mirizzi, Montanino, 2002





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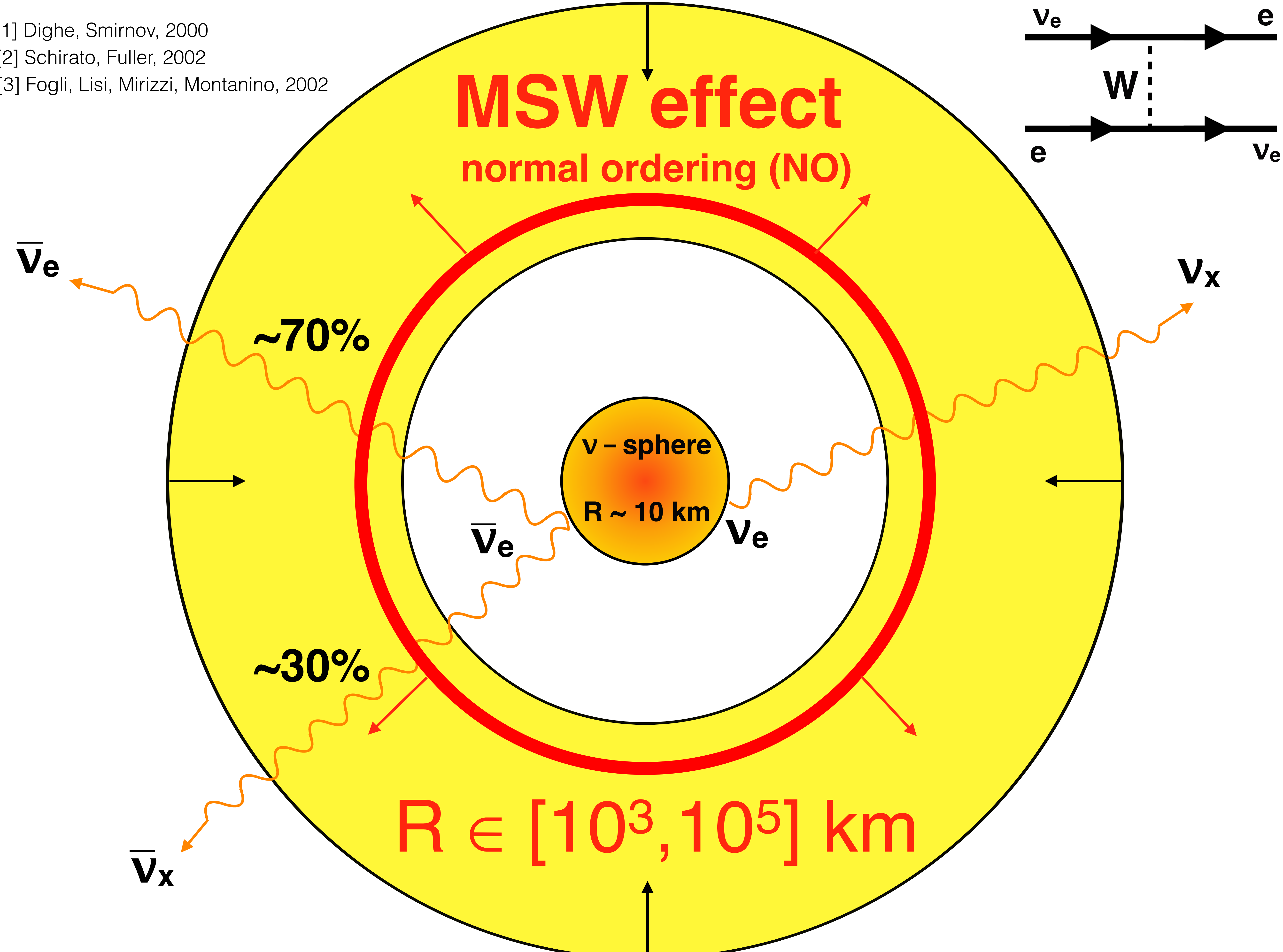

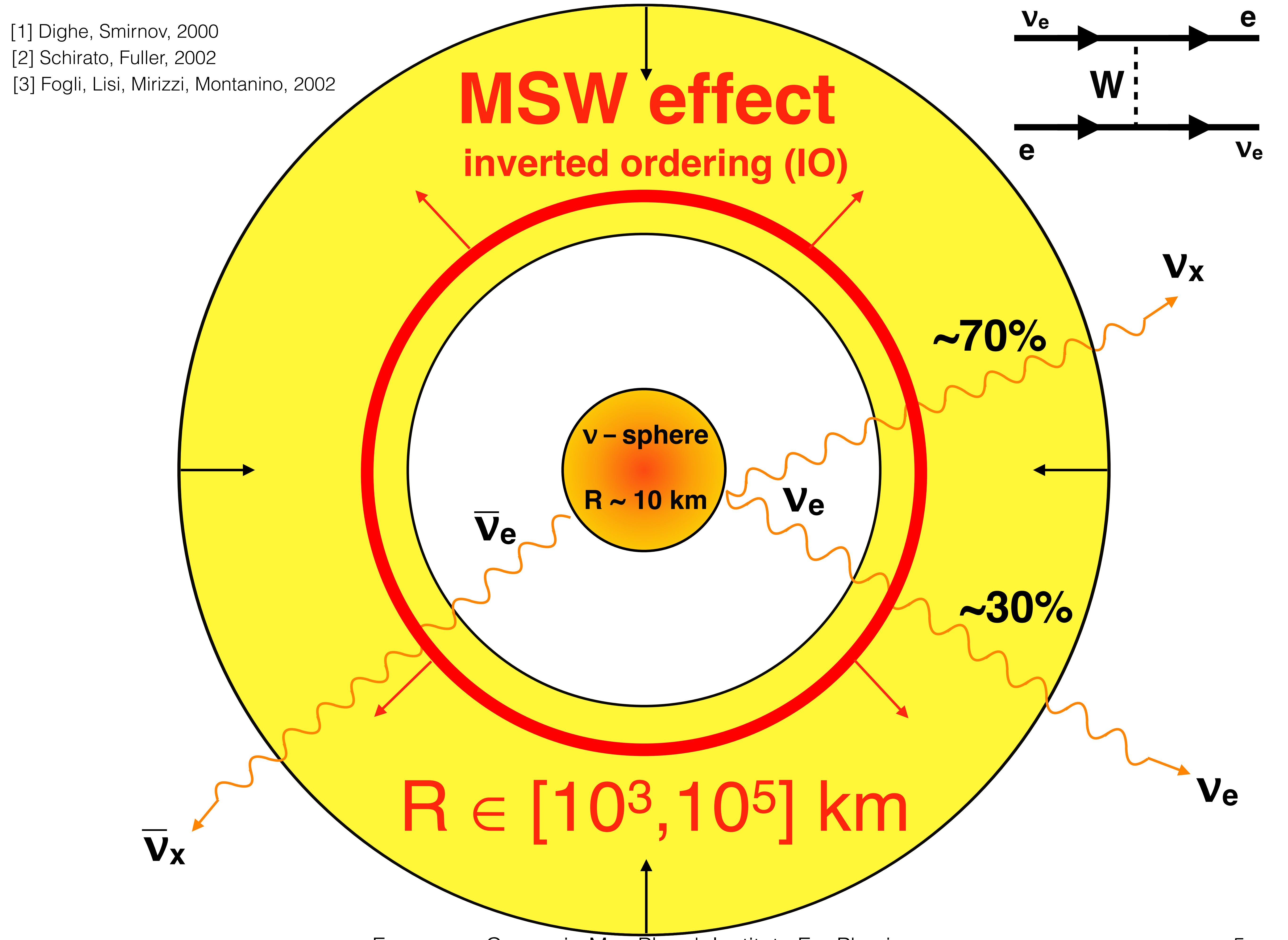
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MSW effect
inverted ordering (IO)
ν_e
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~70%
ν – sphere
R ~ 10 km
ν_e
$\bar{\nu}_e$
~30%
ν_e
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R ∈ [10³,10⁵] km

Fast conversions

[1] Sawyer, 2005-2009-2016

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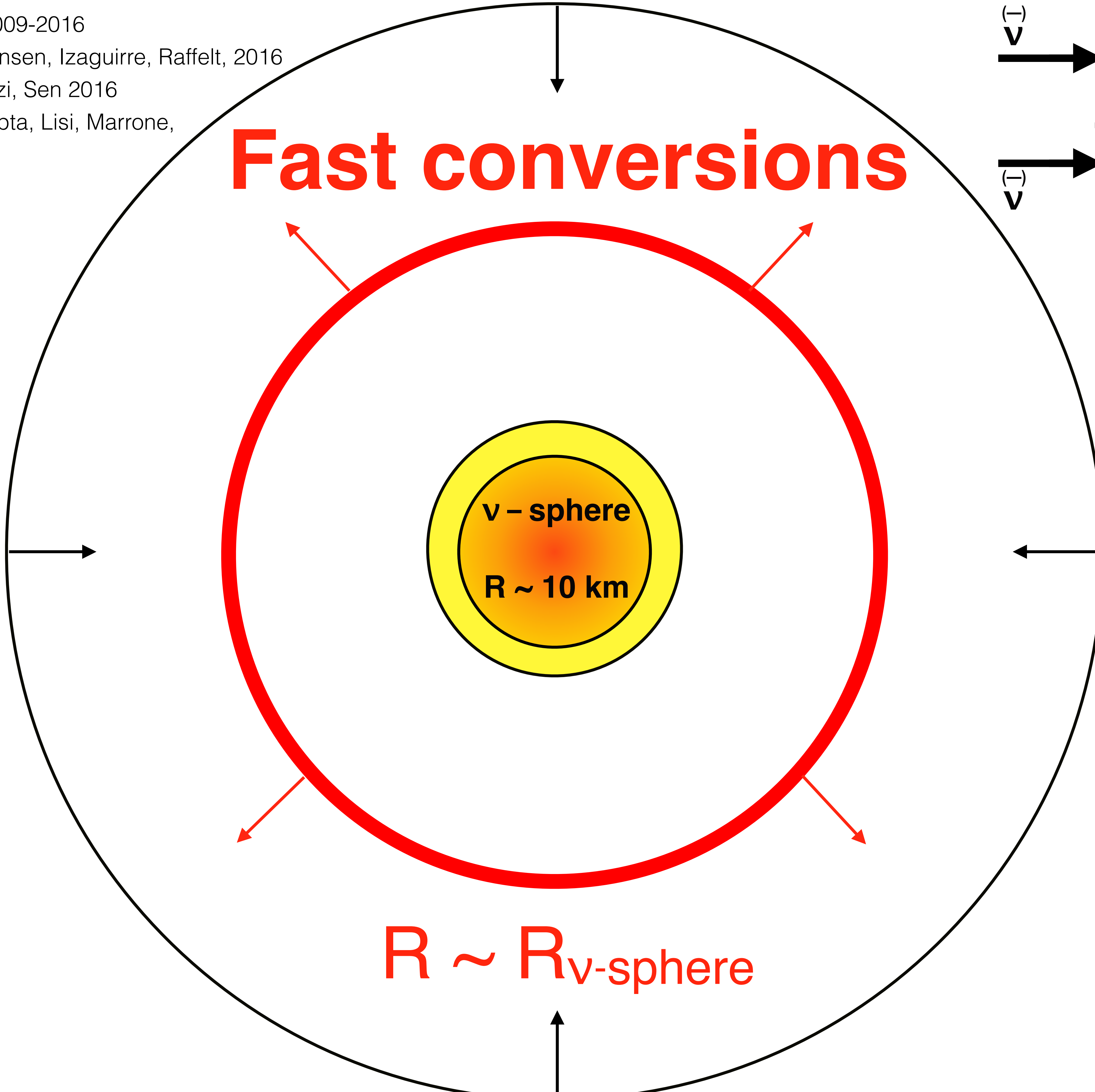

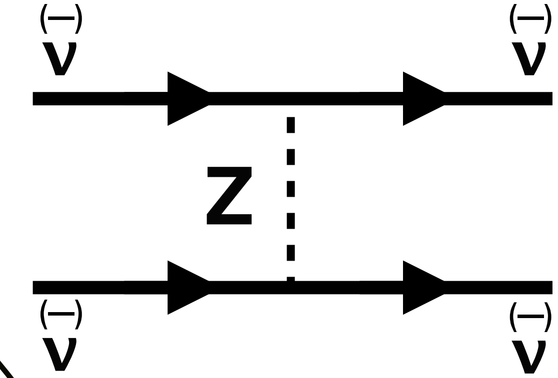

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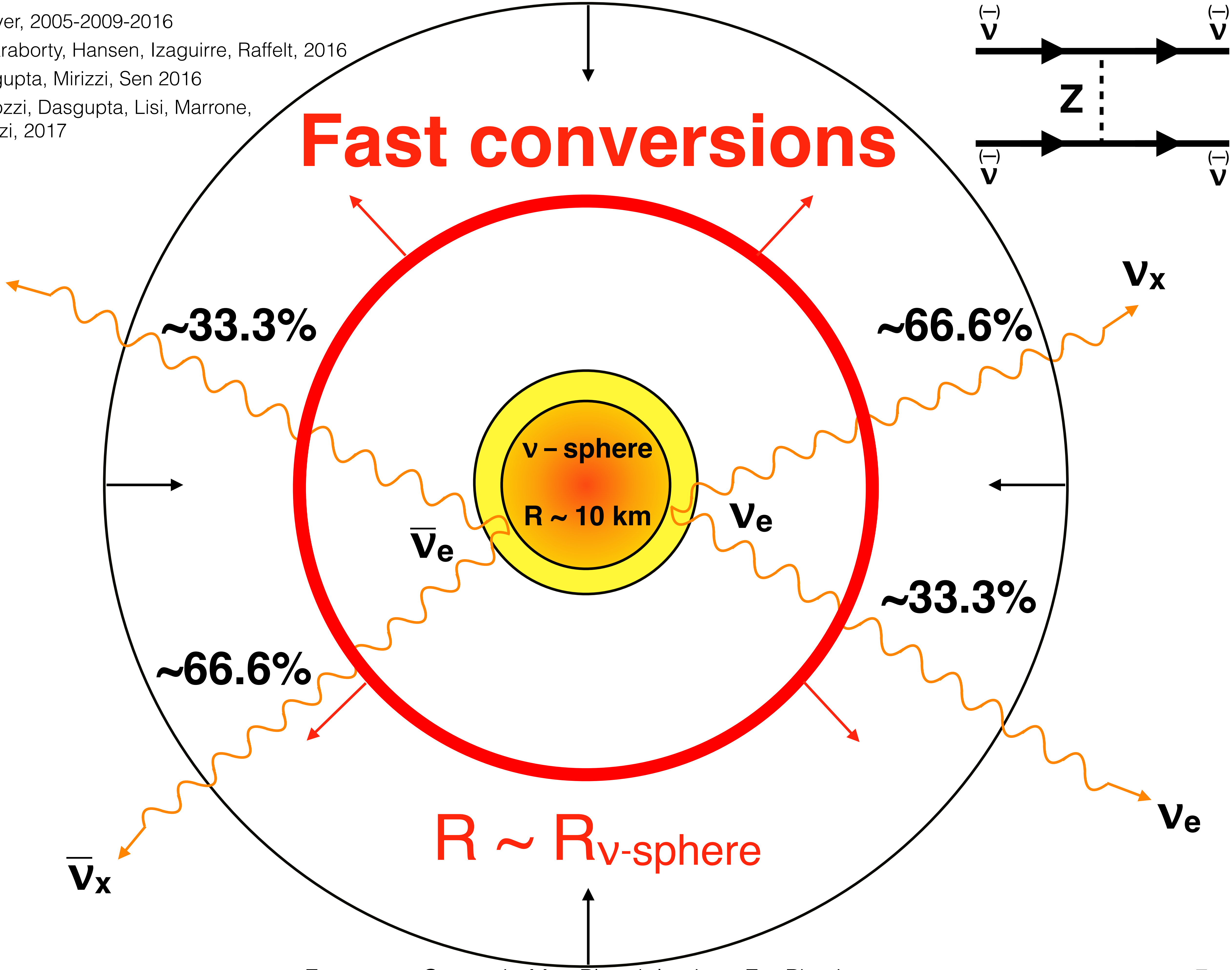

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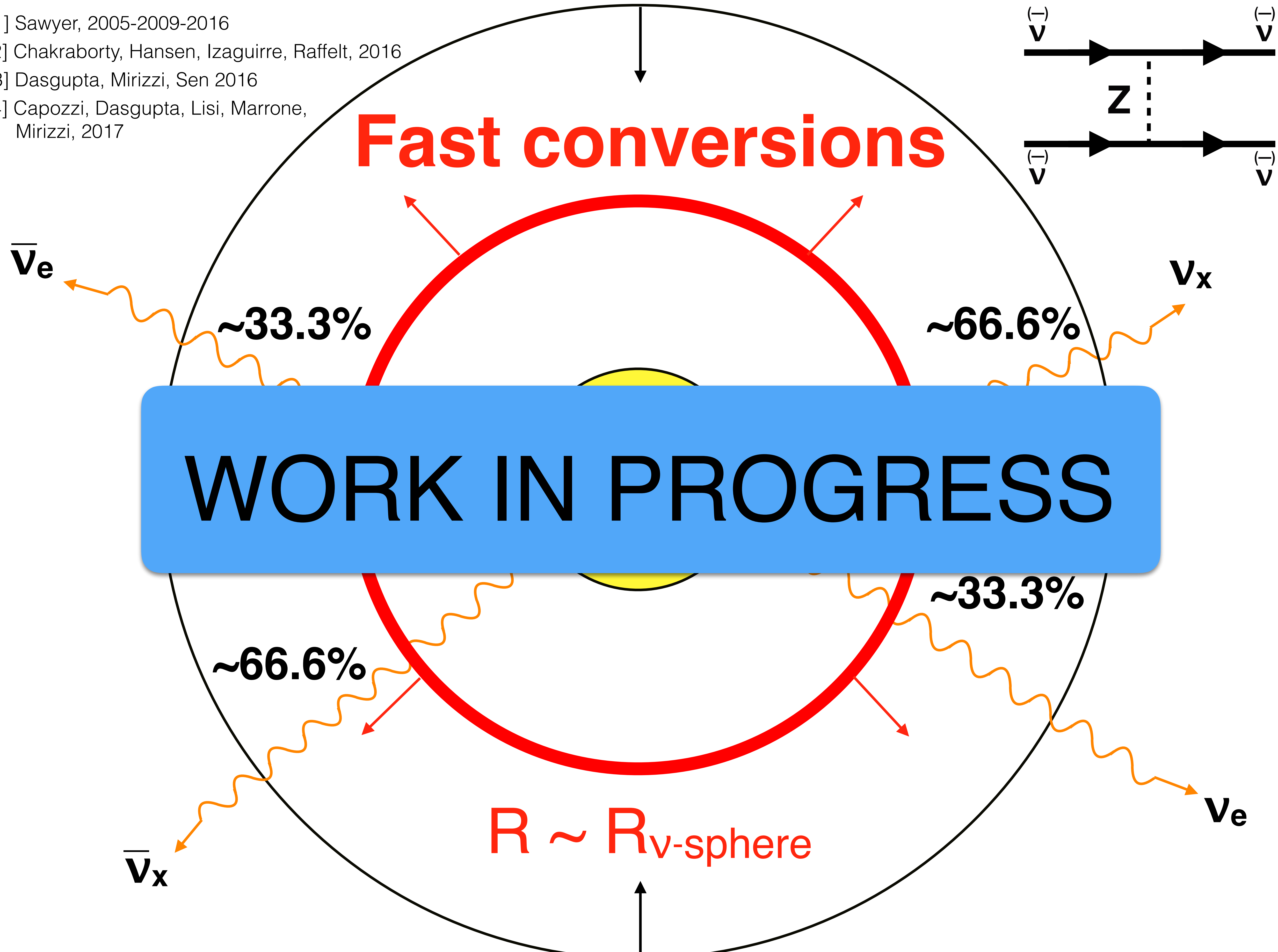

SNν flavour conversions: summary

A list of possible flavour conversion scenarios

Scenario	Mass Ordering	P_{ee}	$\bar{P}_{ee}$
ME	NO	0	$\cos^2\theta_{12} \simeq 0.7$
ME	IO	$\sin^2\theta_{12} \simeq 0.3$	0
FE	either	$1/3 \simeq 0.33$	$1/3 \simeq 0.33$

ME = Matter effects (MSW)

FE = flavour equalisation

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Flavour equalisation is still under investigation.

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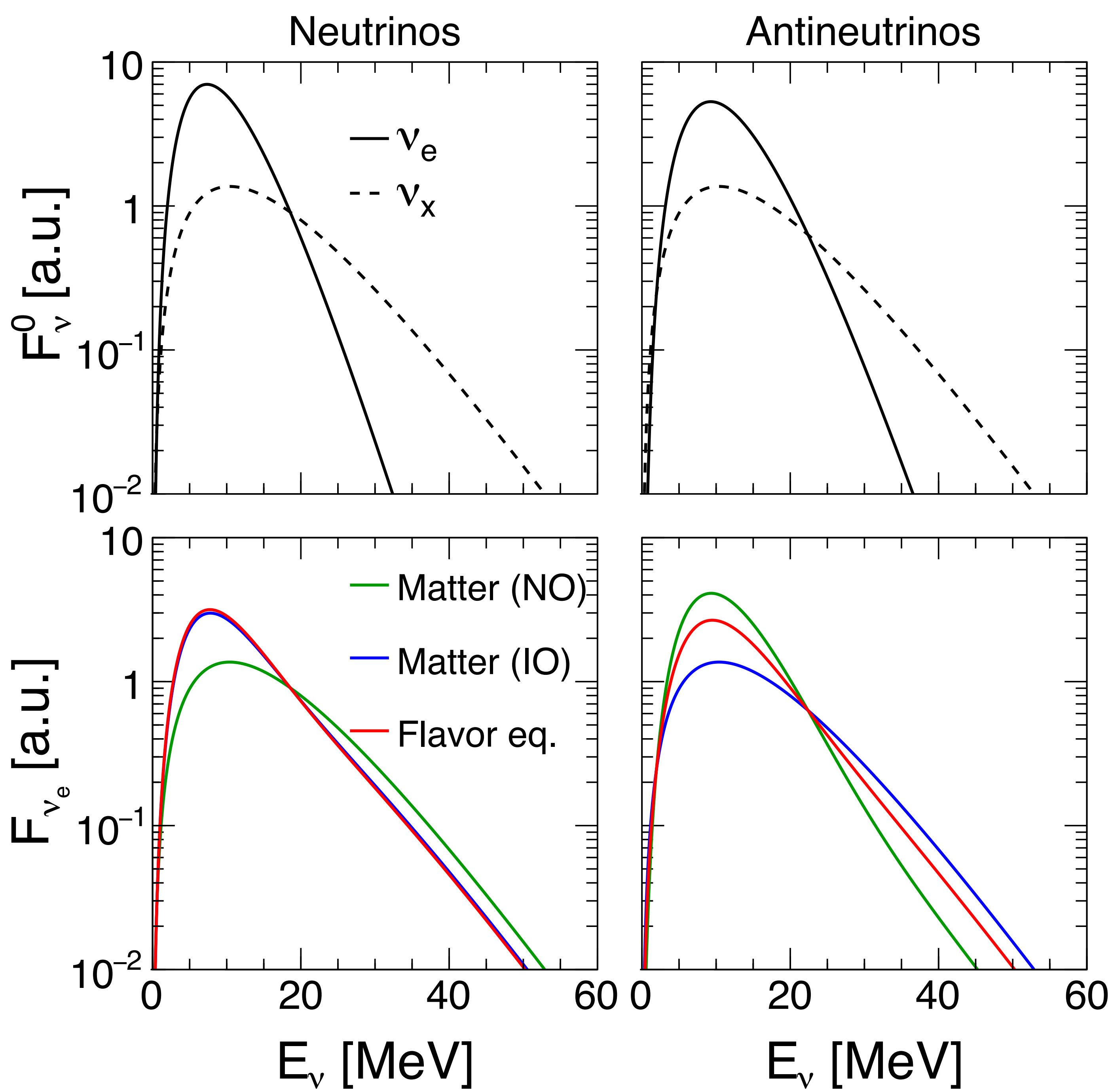
Flavour equalisation is still under investigation.

Can we distinguish scenarios experimentally?

SNν fluxes

SN fluxes: Wroclaw/Basel 1D model (W)

(Un)Oscillated (Anti)Neutrino energy fluxes

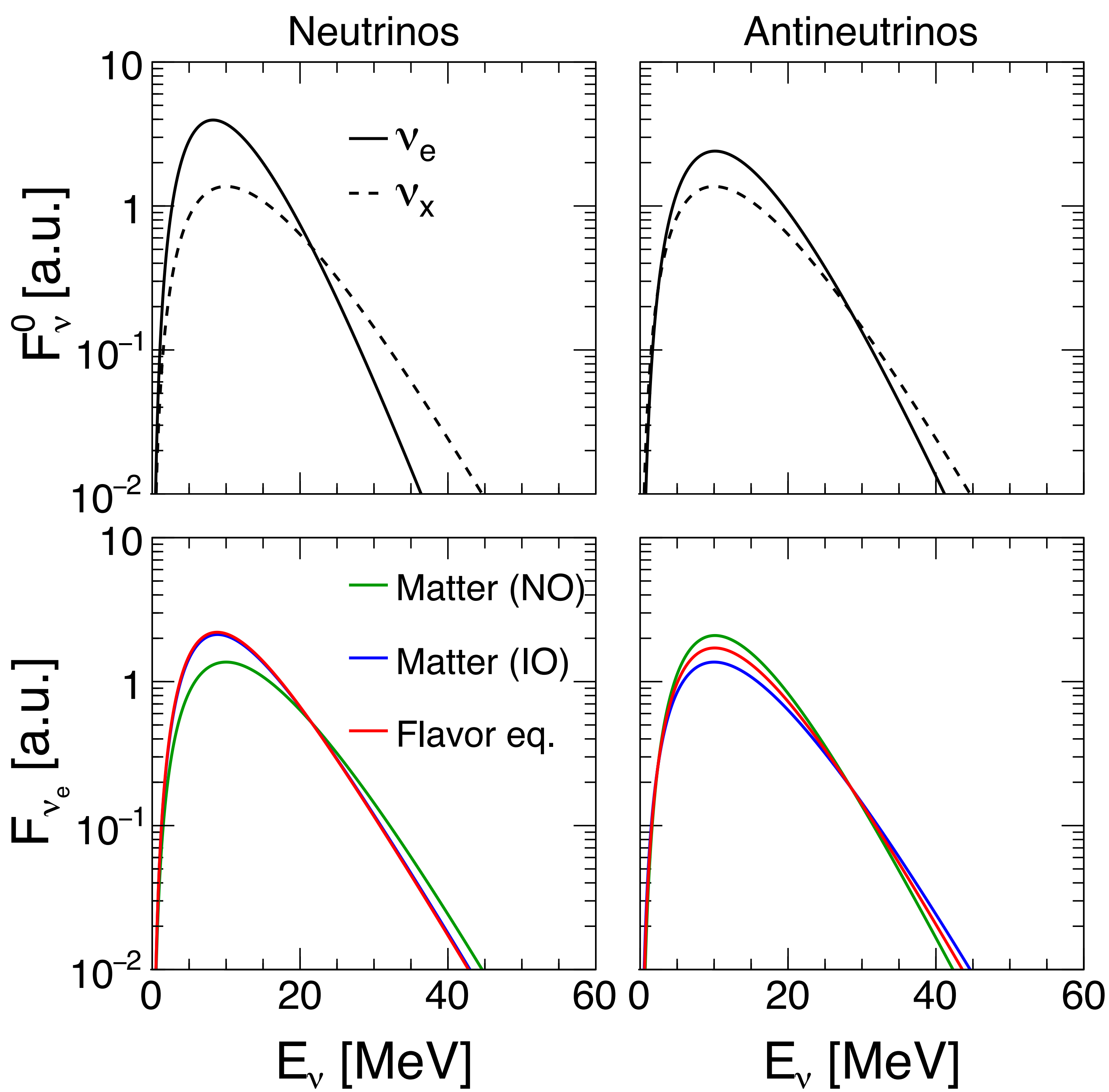


Fit parameters from:
Fischer, *et al.*,
Astron. Astrophys. **517**, A80 (2010)

In NO differences in P_{ee} for both ν and $\bar{\nu}$

SN fluxes: Garching 1D model (G)

(Un)Oscillated (Anti)Neutrino energy fluxes



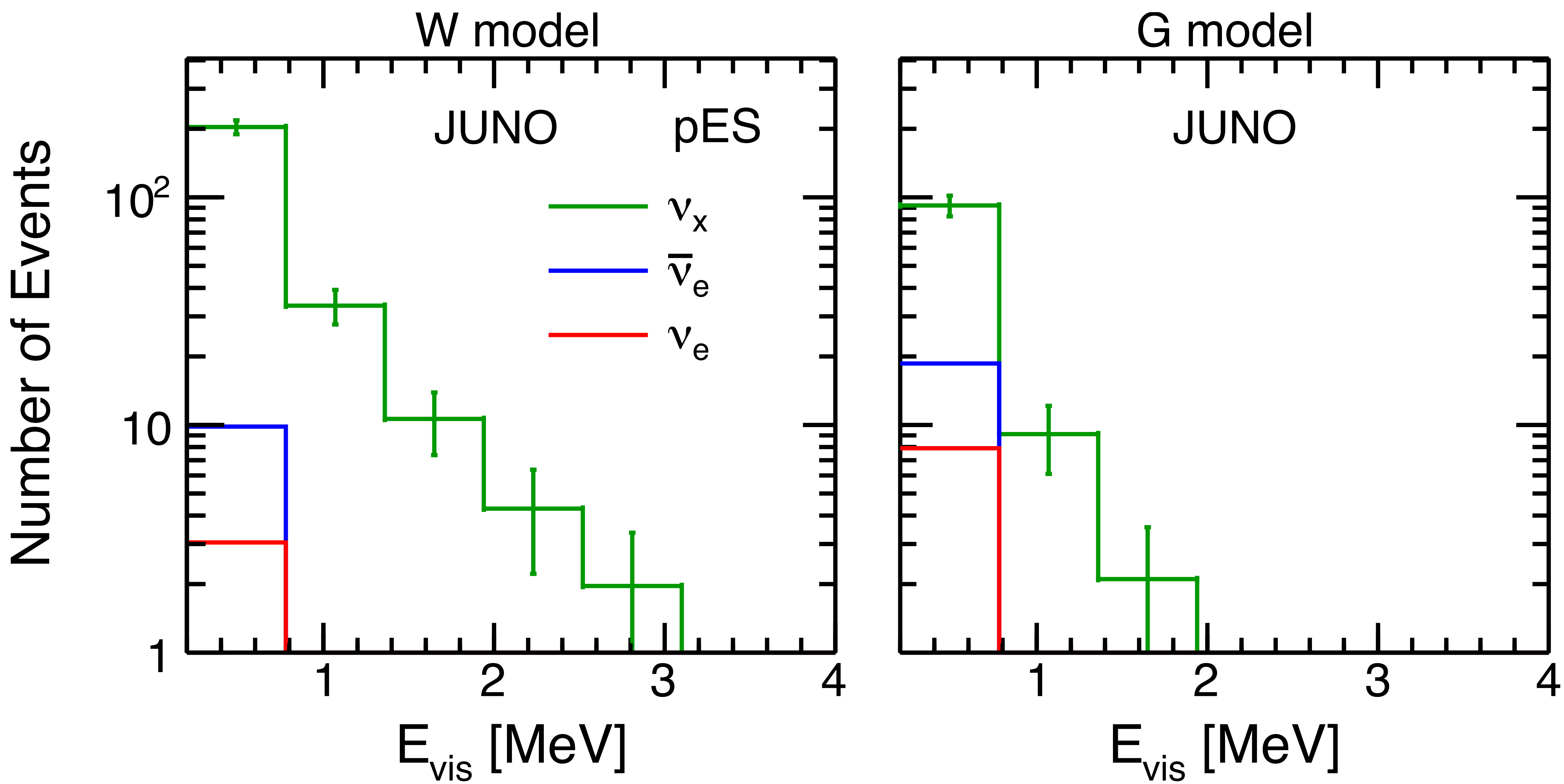
Fit parameters from:
Serpico, *et al.*,
Phys. Rev. D**85**, 085031 (2012)

Smaller differences compared to W model

1) Three SNν detection channels

JUNO: ν-proton elastic scattering (pES)

$$\overset{(-)}{\nu}_{e,\mu,\tau} + p \longrightarrow \overset{(-)}{\nu}_{e,\mu,\tau} + p$$

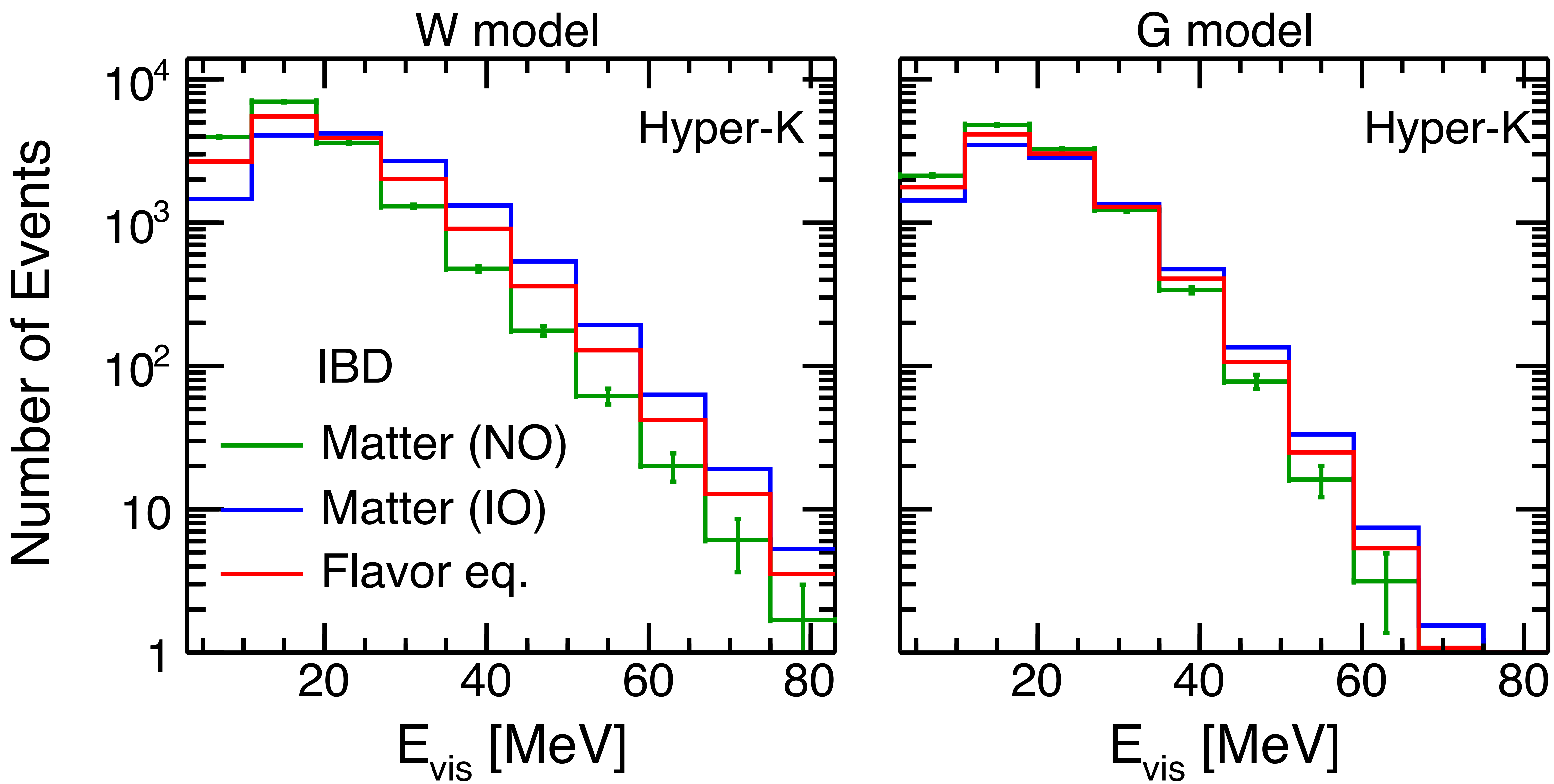


JUNO is sensitive mainly to ν_x and to $E_\nu > 25$ MeV.

No dependence on flavour conversions

Hyper-Kamiokande: inverse β decay

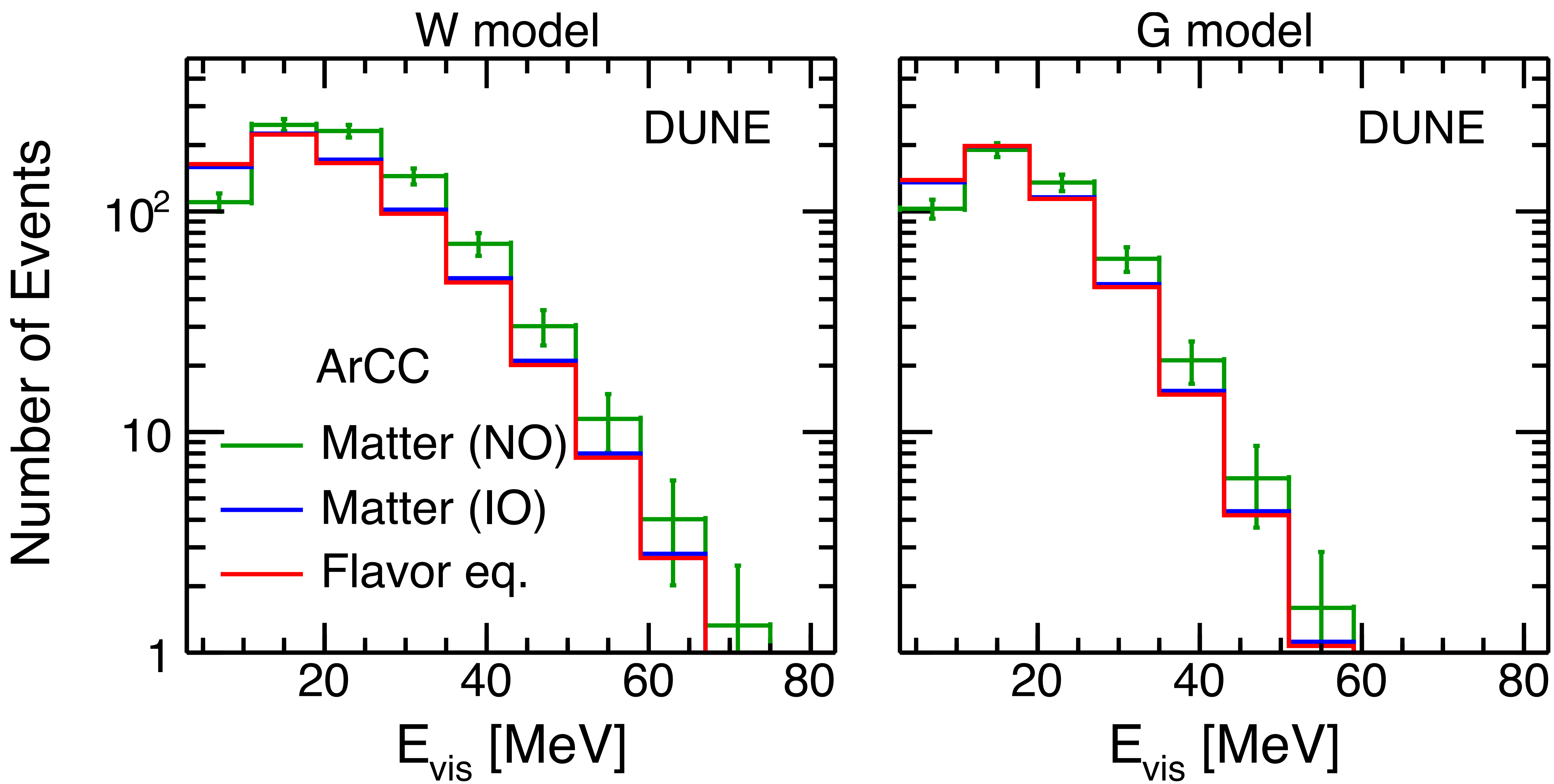
$\bar{\nu}_e + p \longrightarrow e^+ + n$



Hyper-K is sensitive to $\bar{\nu}_e$

DUNE: ν-CC scattering on ^{40}Ar (ArCC)

$\nu_e + {}^{40}Ar \longrightarrow e^- + {}^{40}K^*$



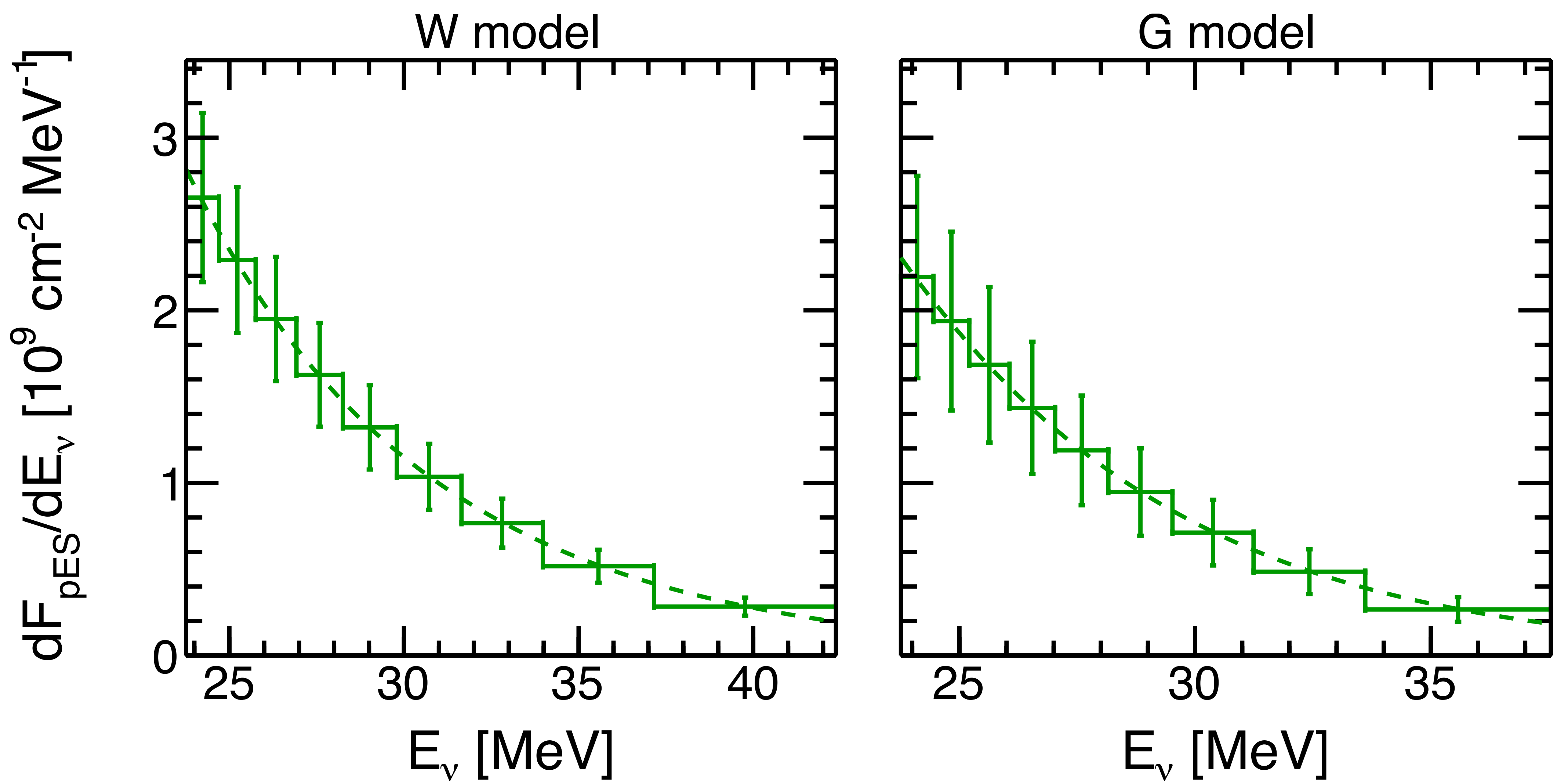
DUNE is sensitive to ν_e

2) Reconstructing oscillated ν-fluxes

Reconstructing ν flux from pES

$$\frac{N_i}{\Delta E^i_{\rm vis}} \;\rightarrow\; \frac{dF_{\rm pES}}{dE_\nu} \simeq \frac{dF_{\nu_x}}{dE_\nu}$$

[1] H. L. Li, Y. F. Li, M. Wang, L. J. Wen and S. Zhou, Phys. Rev. D **97** (2018) no.6, 063014
[2] B. Dasgupta and J. F. Beacom, Phys. Rev. D **83** (2011) 113006



Similar reconstruction method applies to IBD and ArCC

3) Flux ratios: normal ordering (NO)

Flux ratio: R

For $E_\nu > 25$ MeV, we define:

$$R = \frac{F_{\mathrm{pES}}}{F_{\mathrm{ArCC}}} \qquad x = \frac{F^0_{\nu_e}}{F^0_{\nu_x}} \leq 1 \qquad \bar{x} = \frac{F^0_{\bar{\nu}_e}}{F^0_{\nu_x}} \leq 1$$

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$$R_{\mathrm{ME}} = \begin{cases} 4 & x, \bar{x} \ll 1 \\ 5 & x \ll 1, \text{ and } \bar{x} \lesssim 1 \\ 6 & x \lesssim \bar{x} \lesssim 1 \end{cases}, \qquad R_{\mathrm{FE}} = \begin{cases} 6 & x, \bar{x} \ll 1 \\ 7.5 & x \ll 1, \text{ and } \bar{x} \lesssim 1 \\ 6 & x \lesssim \bar{x} \lesssim 1 \end{cases}$$

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R > 6 disfavours “matter effects only” scenario

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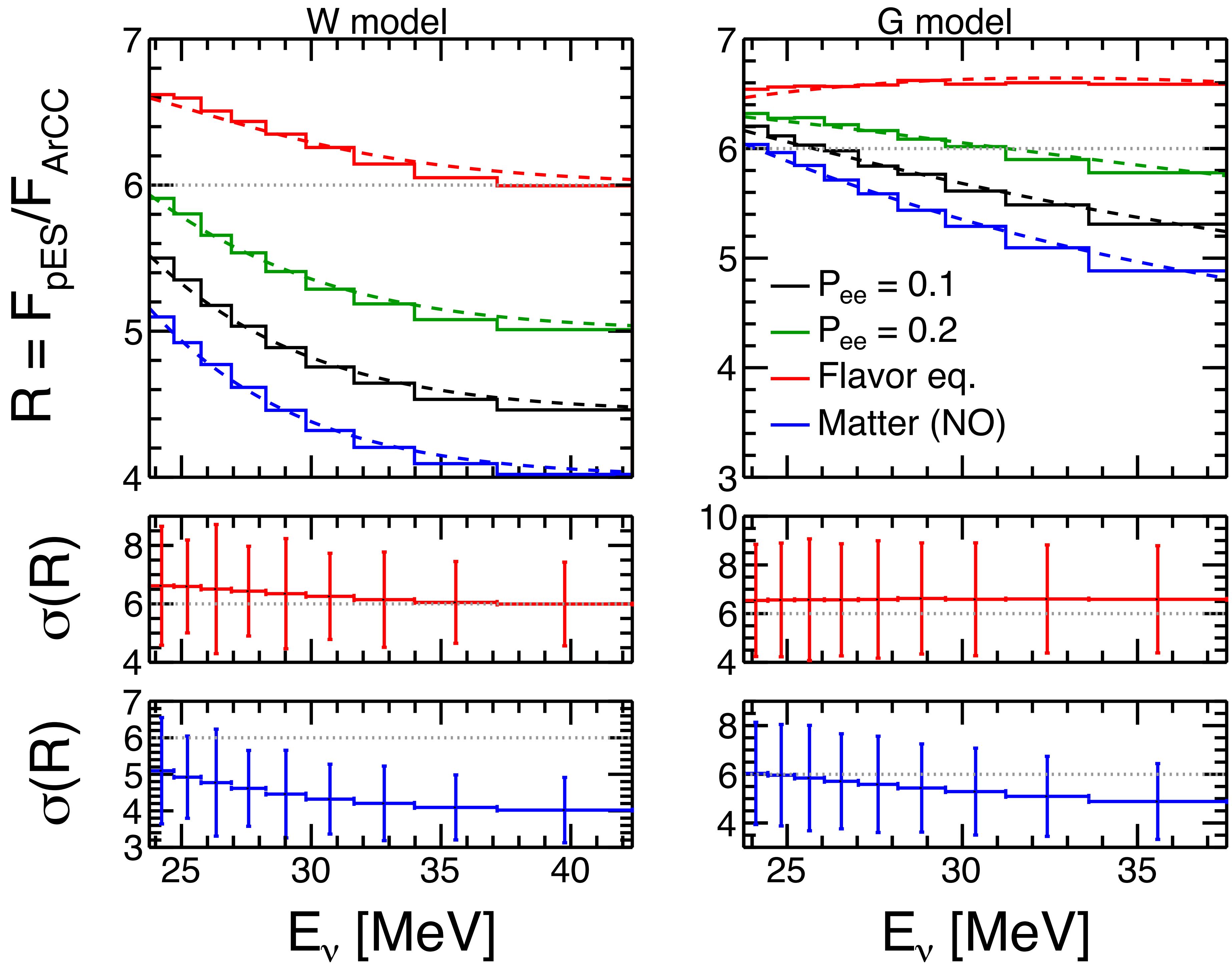
R > 6 disfavours "matter effects only" scenario

R < 6 disfavours "flavour equalisation" scenario

Statistical significance: R at 10 kpc



In the case of pure “matter effects” we can disfavour flavour equalisation at ~2σ (only for W model)

Flux ratio: R̄

For $E_\nu > 25$ MeV, we define:

$$\bar{R} = \frac{F_{\mathrm{pES}}}{F_{\mathrm{IBD}}} \qquad x = \frac{F^0_{\nu_e}}{F^0_{\nu_x}} \leq 1 \qquad \bar{x} = \frac{F^0_{\bar{\nu}_e}}{F^0_{\nu_x}} \leq 1$$

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$$\bar{R}_{\mathrm{ME}} = \begin{cases} 13.3 & x, \bar{x} \ll 1 \\ 5 & x \ll 1, \text{ and } \bar{x} \lesssim 1 \\ 6 & x \lesssim \bar{x} \lesssim 1 \end{cases}, \qquad \bar{R}_{\mathrm{FE}} = \begin{cases} 6 & x, \bar{x} \ll 1 \\ 5 & x \ll 1, \text{ and } \bar{x} \lesssim 1 \\ 6 & x \lesssim \bar{x} \lesssim 1 \end{cases}$$

Flux ratio: $\bar{R}$

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$$\bar{R} = \frac{F_{\rm pES}}{F_{\rm IBD}} \qquad x = \frac{F^0_{\nu_e}}{F^0_{\nu_x}} \leq 1 \qquad \bar{x} = \frac{F^0_{\bar{\nu}_e}}{F^0_{\nu_x}} \leq 1$$

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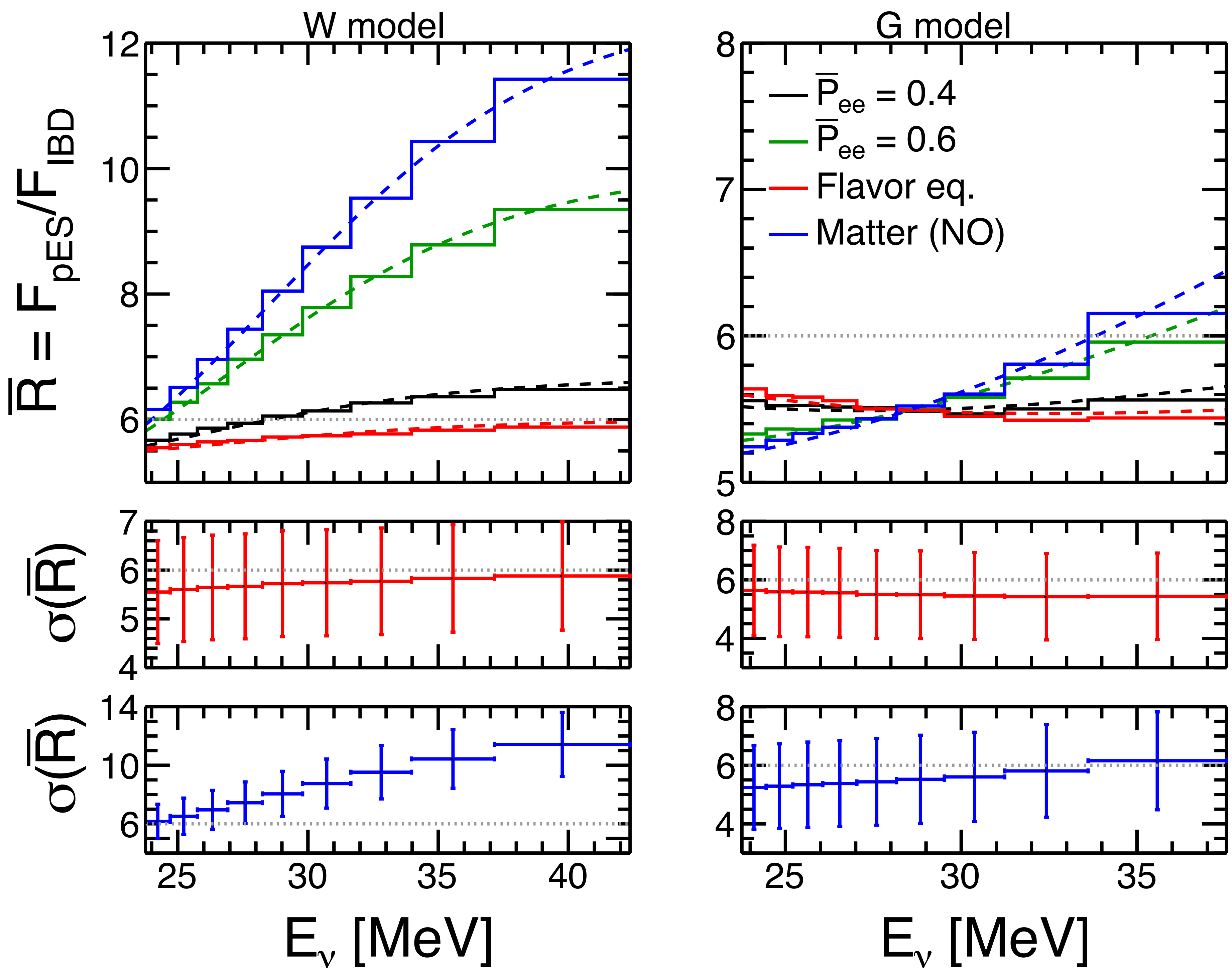
$\bar{R} > 6$ disfavours "flavour equalization" scenario

$\bar{R} \sim 5$ - 6 leads to degeneracy between scenarios

Statistical significance: $\bar{R}$ at 10 kpc



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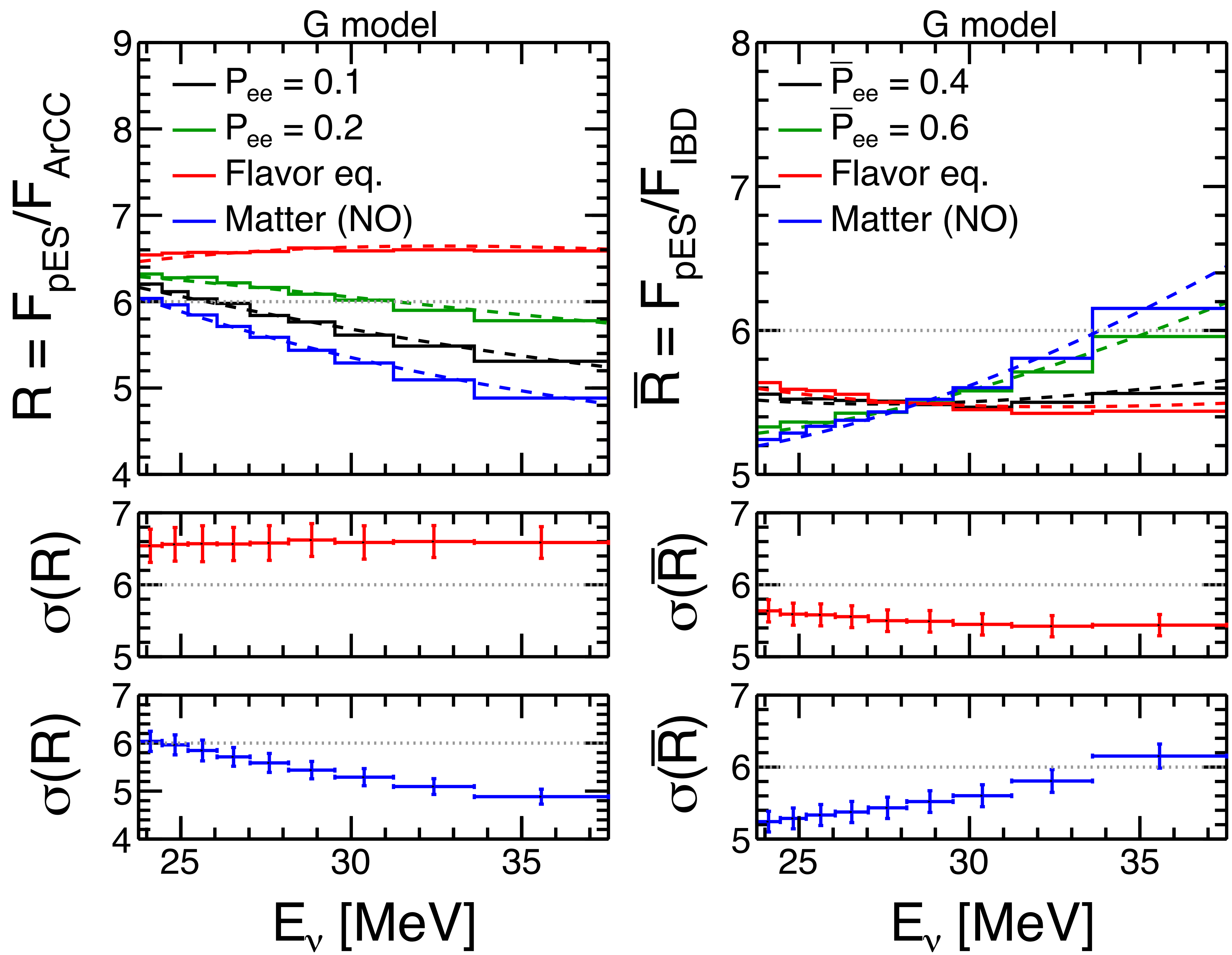
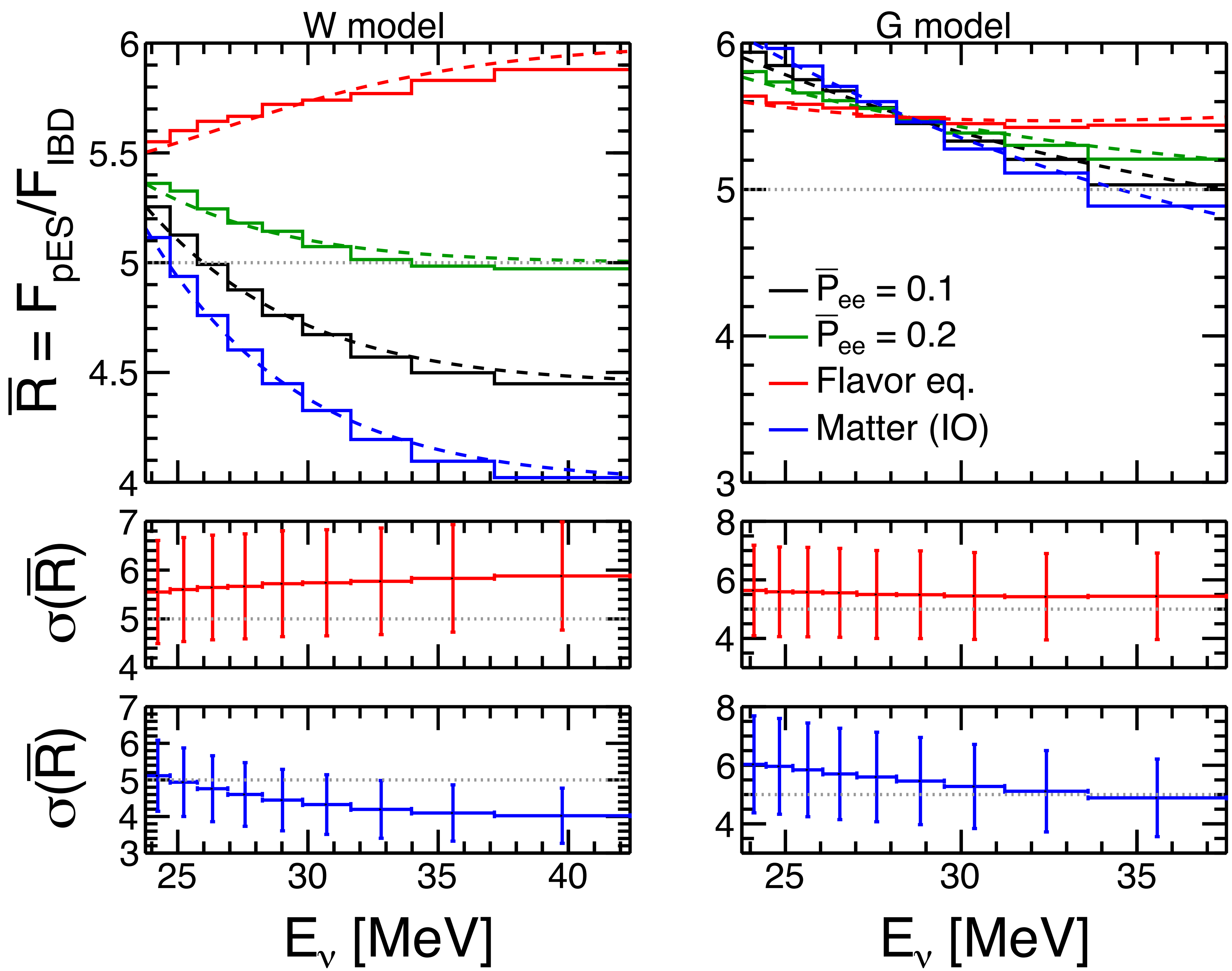
Statistical significance: R and $\bar{R}$ at 1 kpc



Significance > 3σ for almost all scenarios

3) Flux ratios: inverted ordering (IO)

Statistical significance: $\bar{R}$ at 10 kpc



IO is unfavourable for distinguishing scenarios at 10 kpc

Conclusions

We propose a method to distinguish experimentally SNν flavour equalisation from pure matter effects. Brief summary:

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4) **we compare $\overset{(-)}{R}$ with expectations for different scenarios**

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Our method is independent from the knowledge of F^0_ν

Thank you

Backup

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[3] Duan, Fuller, Carlson, Qian, 2006
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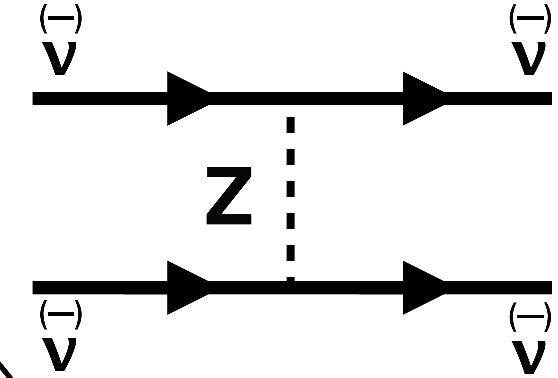
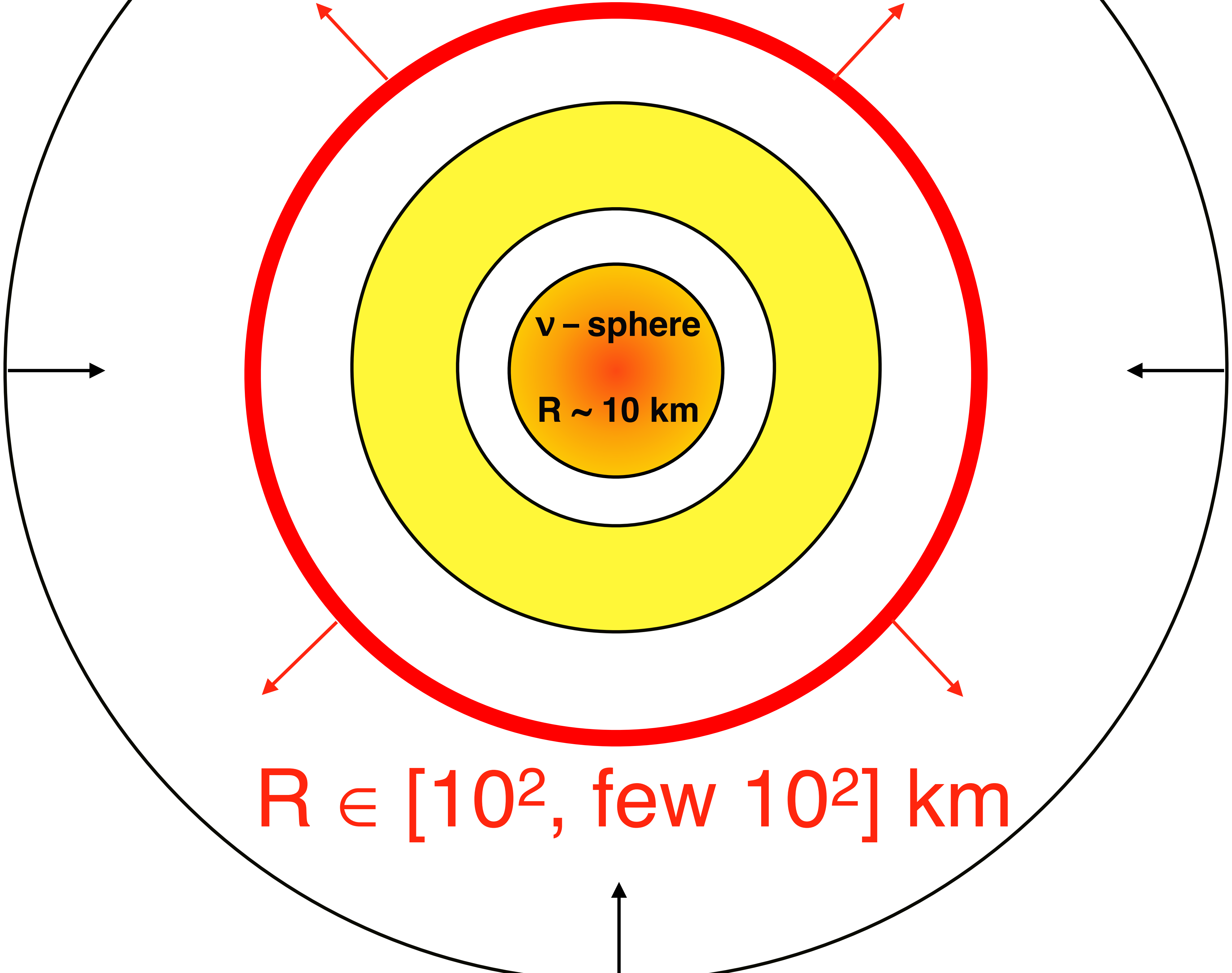


Self-induced (slow) conversions



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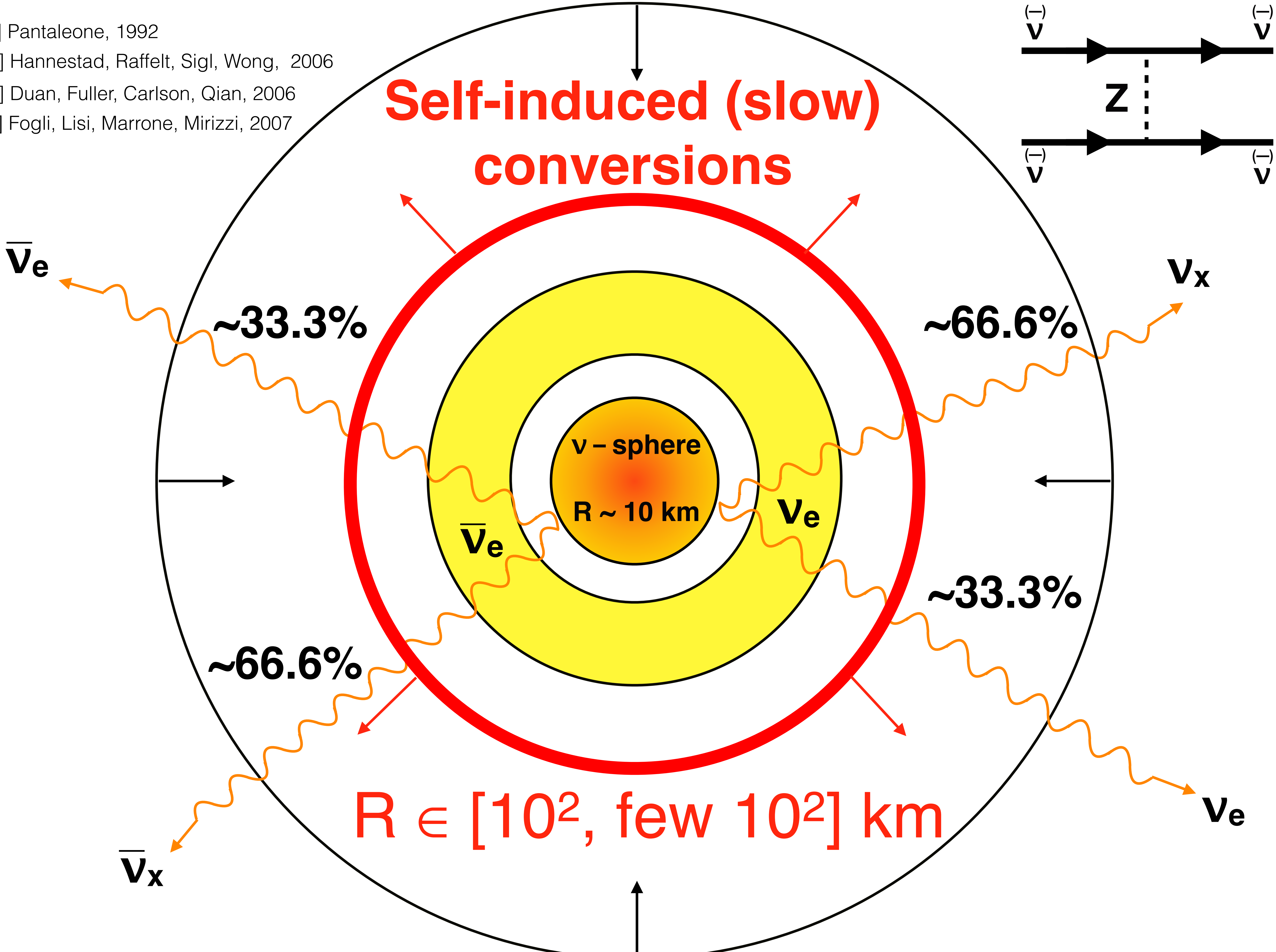

$R \in [10^2, \text{few } 10^2]$ km

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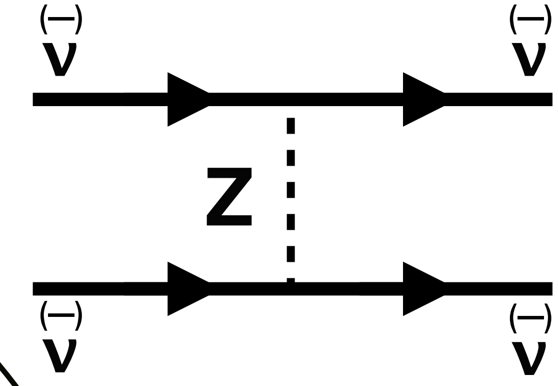
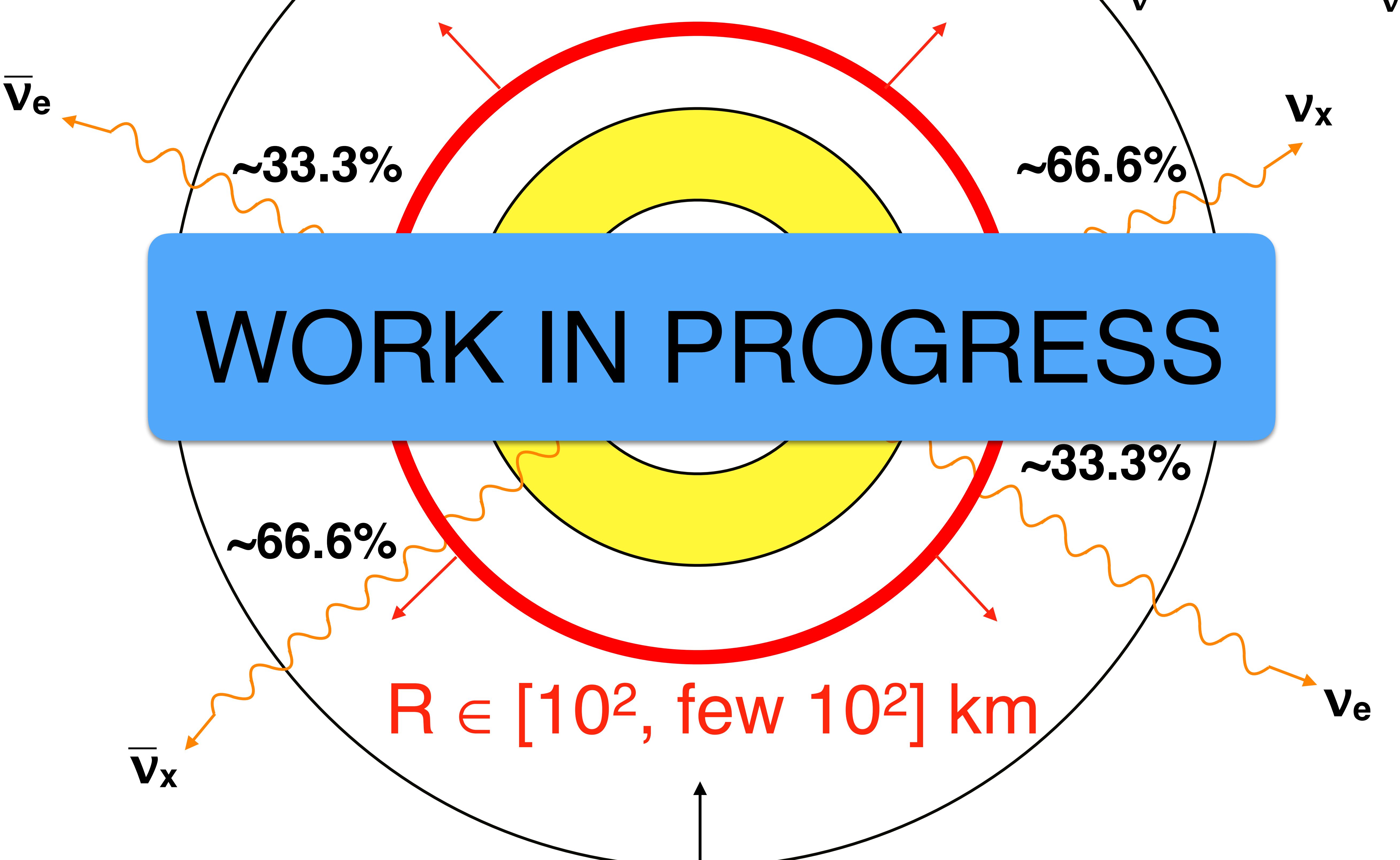


Slow conversions



SN fluxes: parametrization

We adopt the following parametrisation:

$$F^0_\nu(E) = \Phi^0_\nu \, f^0_\nu(E)$$

$$f^0_\nu(E) = \frac{1}{\langle E_\nu \rangle} \frac{(1+\alpha_\nu)^{1+\alpha_\nu}}{\Gamma(1+\alpha_\nu)} \left(\frac{E}{\langle E_\nu \rangle} \right)^{\alpha_\nu} \exp\left[-(1+\alpha_\nu) \frac{E}{\langle E_\nu \rangle} \right]$$

$$\alpha_\nu = \frac{2\langle E_\nu \rangle^2 - \langle E^2_\nu \rangle}{\langle E^2_\nu \rangle - \langle E_\nu \rangle^2}$$

[1] M. Keil, G. G. Raffelt, and H.-T. Janka, Astrophys. J. **590**, 971–991 (2003)

SN fluxes: parametrization

List of fit parameters for W and G models

Model	$\langle E_{\nu_e} \rangle$ (MeV)	$\langle E_{\nu_x} \rangle$ (MeV)	$\Phi_{\nu_e}(\times 10^{56})$	$\Phi_{\nu_x}(\times 10^{56})$	α_{ν_e}	α_{ν_x}
W	9.5	15.6	8.53	3.13	3.4	2.0
G	10.9	14.0	5.68	2.67	3.1	2.5

Model	$\langle E_{\bar{\nu}_e} \rangle$ (MeV)	$\langle E_{\bar{\nu}_x} \rangle$ (MeV)	$\Phi_{\bar{\nu}_e}(\times 10^{56})$	$\Phi_{\bar{\nu}_x}(\times 10^{56})$	$\alpha_{\bar{\nu}_e}$	$\alpha_{\bar{\nu}_x}$
W	11.6	15.6	7.51	3.13	4.0	2.0
G	13.2	14.0	4.11	2.67	3.3	2.5

JUNO: ν-proton elastic scattering (pES)

$$\overset{(-)}{\nu}_{e,\mu,\tau} + p \longrightarrow \overset{(-)}{\nu}_{e,\mu,\tau} + p$$

$$\frac{dN_{\rm pES}}{dE_{\rm vis}} = N_p \int_0^{+\infty} dT'_p \frac{dT_p}{dT'_p} W(T'_p, E_{\rm vis}) \int_{E_\nu^0}^{\infty} dE_\nu F_{\rm pES}(E_\nu) \frac{d\sigma_{\rm pES}(E_\nu, T_p)}{dT_p}$$

$$F_{\rm pES} \equiv 4F^0_{\nu_x} + F^0_{\bar{\nu}_e} + F^0_{\nu_e}$$

$$W(T'_p, E_{\rm vis}) = \frac{\exp\left(-\frac{(T'_p - E_{\rm vis})^2}{2\sigma_E^2}\right)}{\sqrt{2\pi}\sigma_E}$$

$$\frac{\sigma_E}{E_{\rm vis}} = 0.03\sqrt{E_{\rm vis}/{\rm MeV}}$$

Hyper-Kamiokande: inverse β decay

$\bar{\nu}_e + p \longrightarrow e^+ + n$

$$\frac{dN_{\mathrm{IBD}}}{dE_{\mathrm{vis}}} = N_p \int_{E_T}^{\infty} dE_\nu F_{\mathrm{IBD}}(E_\nu)\sigma_{\mathrm{IBD}}(E_\nu)\; W(E_\nu - 0.782\ \ \mathrm{MeV},\ E_{\mathrm{vis}})$$

$$F_{\mathrm{IBD}} \equiv \begin{cases} 0.7F^0_{\bar{\nu}_e} + 0.3F^0_{\nu_x} & \text{matter effects only, with NO} \\ F^0_{\nu_x} & \text{matter effects only, with IO} \\ 0.33F^0_{\bar{\nu}_e} + 0.66F^0_{\nu_x} & \text{flavor eq.} \end{cases}$$

$$\frac{\sigma_E}{E_{\mathrm{vis}}} = 0.6\sqrt{E_{\mathrm{vis}}/\mathrm{MeV}}$$

DUNE: ν-CC scattering on ^{40}Ar (ArCC)

$\nu_e + {}^{40}\mathrm{Ar} \longrightarrow e^- + {}^{40}\mathrm{K}^*$

$$\frac{dN_{\mathrm{ArCC}}}{dE_{\mathrm{vis}}} = N_{\mathrm{Ar}} \sum_{i=1}^{N_{\mathrm{ex}}} \int_0^{\infty} dE_\nu F_{\mathrm{ArCC}}(E_\nu) \sigma^i_{\mathrm{ArCC}}(E_\nu)\, W(E_{\mathrm{vis}}, T_e)$$

$$F_{\mathrm{ArCC}} \equiv \begin{cases} F^0_{\nu_x} & \text{matter effects only, with NO} \\ 0.3F^0_{\nu_e} + 0.7F^0_{\nu_x} & \text{matter effects only, with IO} \\ 0.33F^0_{\nu_e} + 0.66F^0_{\nu_x} & \text{flavor equalization} \end{cases}$$

$$\sigma_E = 0.11\sqrt{E_{\mathrm{vis}}/\mathrm{MeV}} + 0.02\, E_{\mathrm{vis}}/\mathrm{MeV}$$

Reconstructing ν flux from pES

We define the extrema and midpoint for the neutrino energy bins as $[E^i_\nu, E^{i+1}_\nu]$ and $\bar{E}^i_\nu$, respectively, where $E^i_\nu = \sqrt{T^i_p m_p/2}$

$$\left.\frac{d\tilde{F}_{\rm pES}}{dE_\nu}\right|_{\bar{E}^N_\nu} = \frac{N^N_{\rm pES}}{K_{NN}}$$

$$\left.\frac{d\tilde{F}_{\rm pES}}{dE_\nu}\right|_{\bar{E}^i_\nu} = \left(N^i_{\rm pES} + \sum_{j>i} \left.\frac{d\tilde{F}_{\rm pES}}{dE_\nu}\right|_{\bar{E}^j_\nu} K_{ij}\right) / K_{i,i}\,,$$

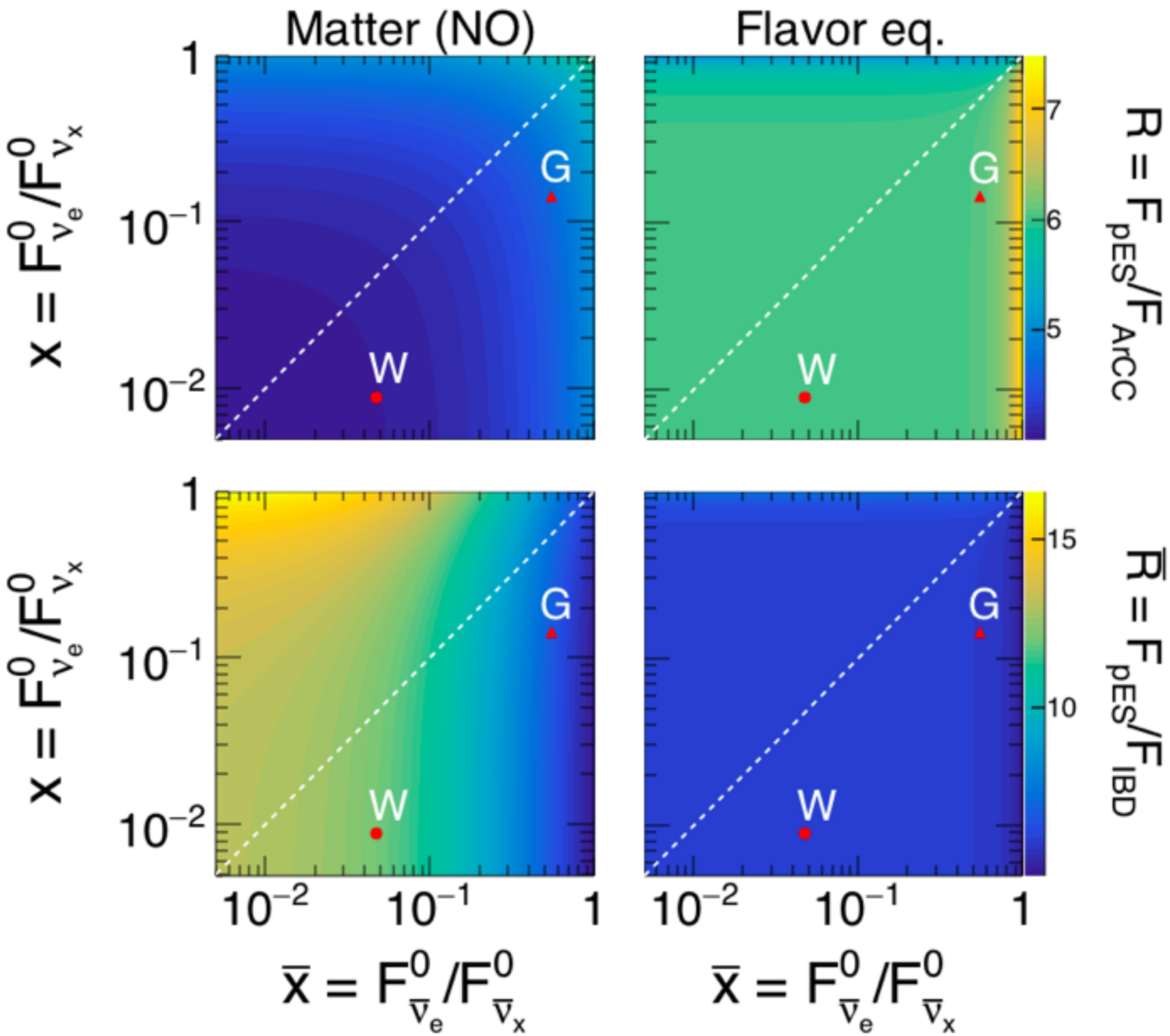
$$K_{i,j} = N_p \Delta T'^i_p \left.\frac{dT_p}{dT'_p}\right|_{\bar{T}'^i_p} \left.\frac{d\sigma_{\rm pES}(E_\nu, T_p)}{dT_p}\right|_{(\bar{T}'^i_p, \bar{E}^j_\nu)}$$

Reconstructing ν flux from IBD and ArCC

$$\left.\frac{d\tilde{F}_{\rm IBD}}{dE_\nu}\right|_{\bar{E}_i} = \frac{1}{N_p \sigma^{\rm tot}_{\rm IBD}(\bar{E}_i)} \frac{N^i_{\rm IBD}}{\Delta E^i_{\rm vis}}$$

$$\left.\frac{d\tilde{F}_{\rm ArCC}}{dE_\nu}\right|_{\bar{E}_i} = \frac{1}{N_{\rm Ar} \sigma^{\rm tot}_{\rm ArCC}(\bar{E}_i)} \frac{N^i_{\rm ArCC}}{E^i_{\rm vis}}$$

Flux ratios: R and R̄, normal ordering



Flux ratios: R and $\bar{R}$, inverted ordering