New Developments in

Collective Neutrino Oscillations in Supernovae

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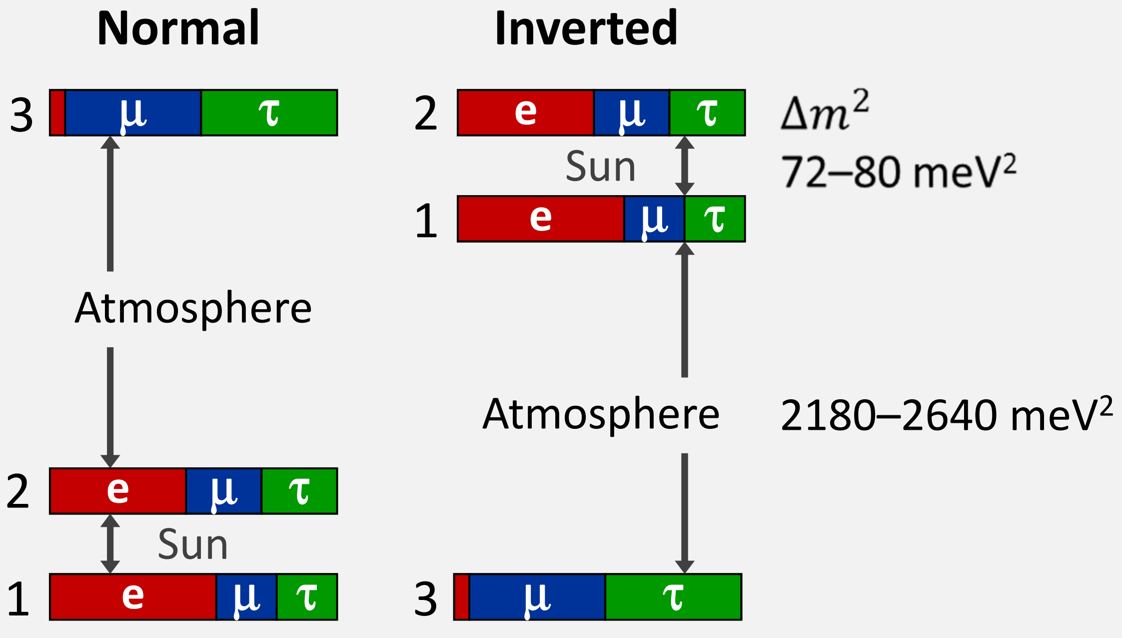
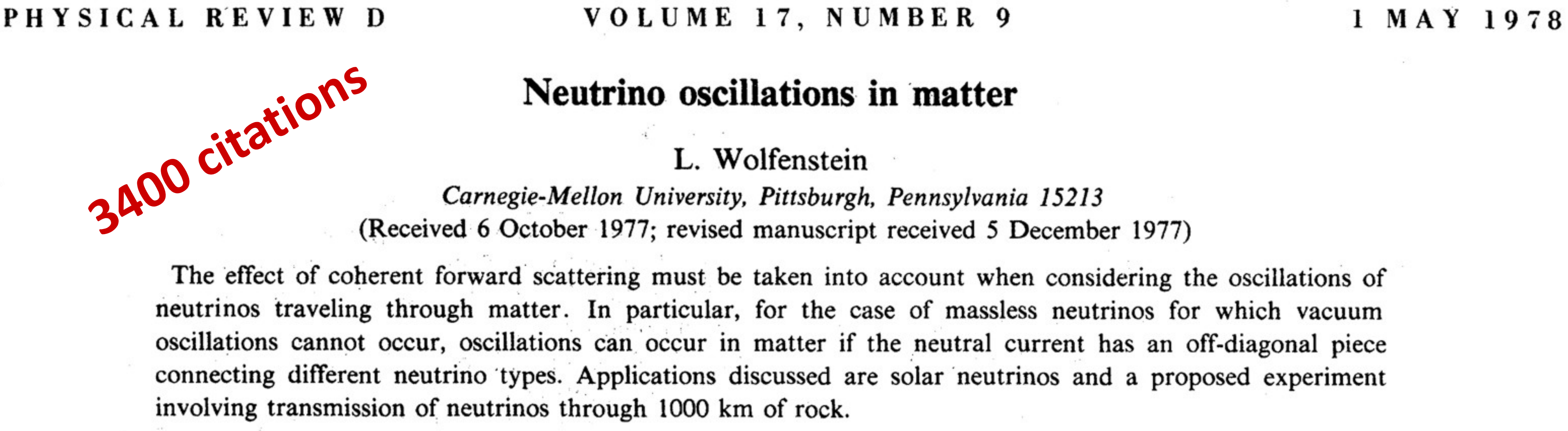
Three-Flavor Neutrino Parameters

Three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$ (Euler angles for 3D rotation), $c_{ij} = \cos\theta_{ij}$, a CP-violating "Dirac phase" δ, and two "Majorana phases" α_2 and α_3

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\substack{39^\circ < \theta_{23} < 53^\circ \\ \text{Atmospheric/LBL-Beams}}} \underbrace{\begin{pmatrix}c_{13} & 0 & e^{-i\delta}s_{13}\\ 0 & 1 & 0\\ -e^{i\delta}s_{13} & 0 & c_{13}\end{pmatrix}}_{\substack{7^\circ < \theta_{13} < 11^\circ \\ \text{Reactor}}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\substack{33^\circ < \theta_{12} < 37^\circ \\ \text{Solar/KamLAND}}} \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\frac{\alpha_2}{2}} & 0\\ 0 & 0 & e^{i\frac{\alpha_3}{2}}\end{pmatrix}}_{\substack{\text{Relevant for} \\ 0\nu2\beta\text{ decay}}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



Tasks and Open Questions
- Precision for all angles
- CP-violating phase δ?
- Mass ordering ? (normal vs inverted)
- Absolute masses ? (hierarchical vs degenerate)
- Dirac or Majorana ?



PHYSICAL REVIEW D VOLUME 17, NUMBER 9 1 MAY 1978

3400 citations

Neutrino oscillations in matter

L. Wolfenstein

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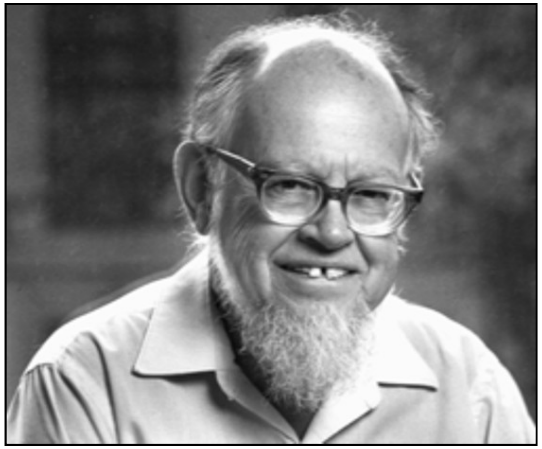
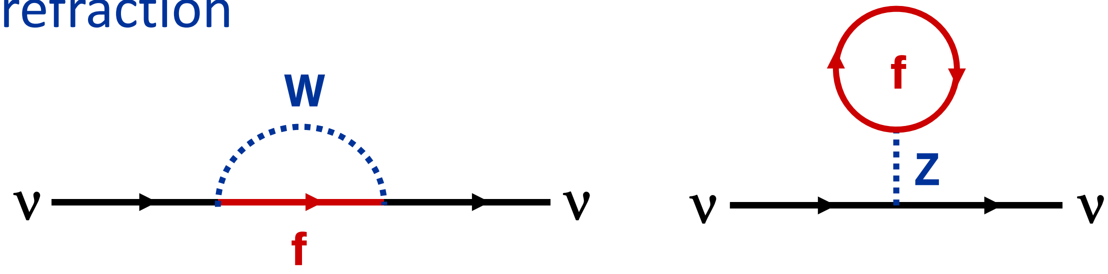
(Received 6 October 1977; revised manuscript received 5 December 1977)

The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types. Applications discussed are solar neutrinos and a proposed experiment involving transmission of neutrinos through 1000 km of rock.



Lincoln Wolfenstein

Neutrinos in a medium suffer flavor-dependent refraction

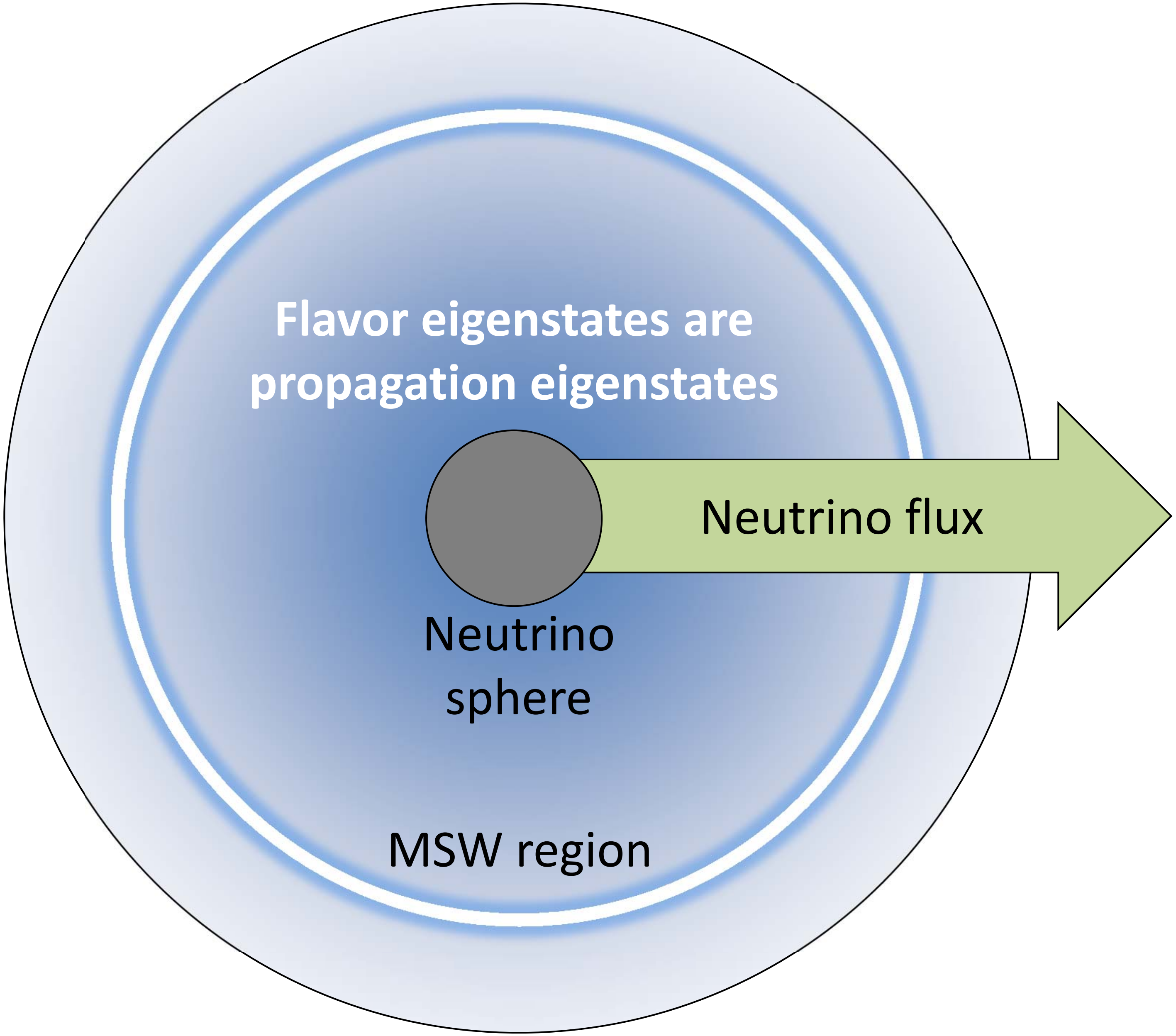


$$V_{\rm weak} = \sqrt{2} G_{\rm F} \times \begin{cases} N_{\rm e} - N_{\rm n}/2 & \text{for } \nu_{\rm e} \\ -N_{\rm n}/2 & \text{for } \nu_{\mu} \end{cases}$$

Typical density of Earth: 5 g/cm^3

$$\Delta V_{\rm weak} \approx 2 \times 10^{-13}\ {\rm eV} = 0.2\ {\rm peV}$$

Flavor Oscillations in Core-Collapse Supernovae



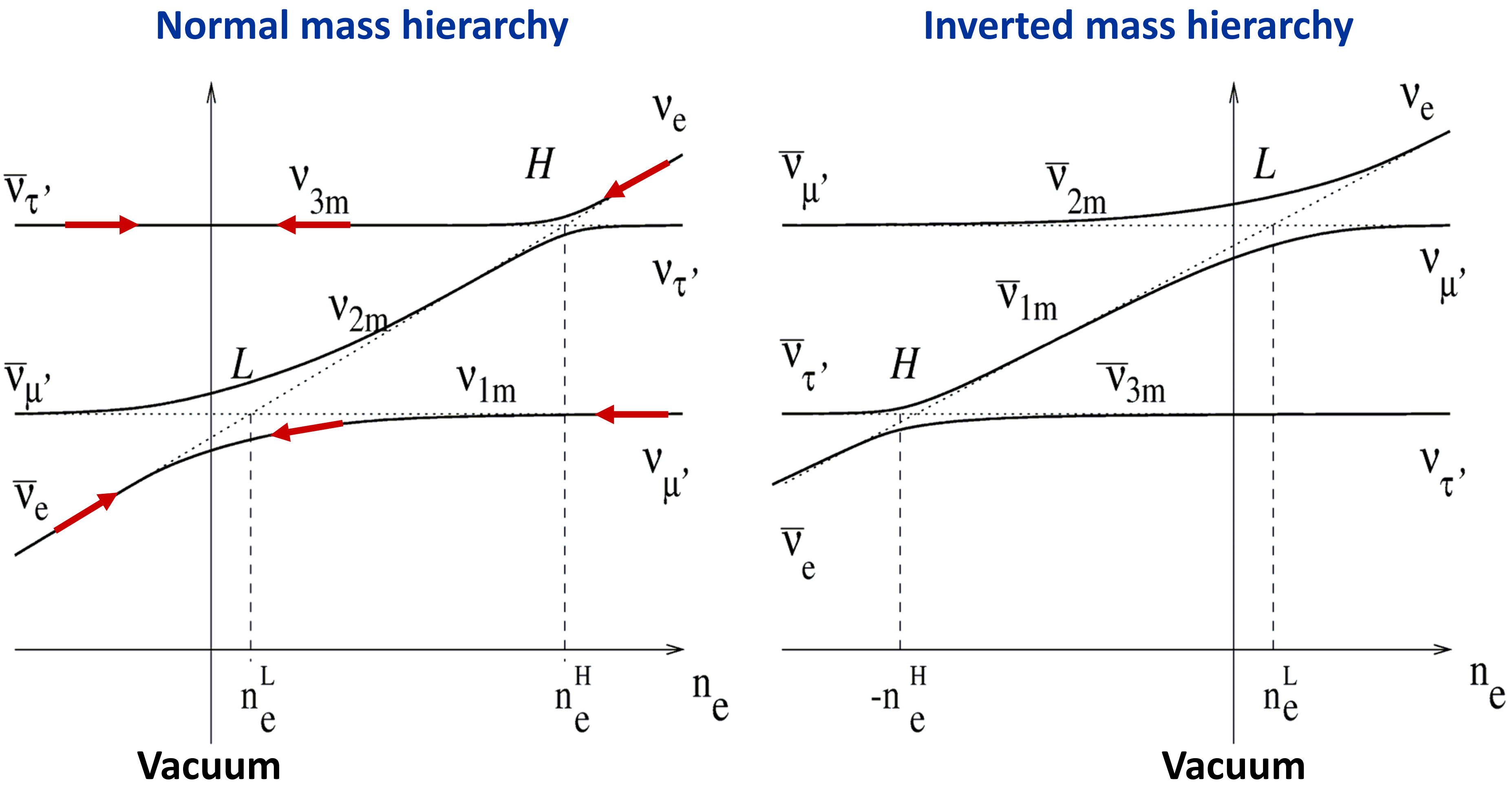
Flavor eigenstates are propagation eigenstates

Neutrino flux

Neutrino sphere

MSW region

Three-Flavor Eigenvalue Diagram


Normal mass hierarchy

Inverted mass hierarchy

Dighe & Smirnov, Identifying the neutrino mass spectrum from a supernova neutrino burst, astro-ph/9907423

Signature of Flavor Oscillations

	1-3-mixing scenarios		
	A	B	C
Mass ordering	Normal (NH)	Inverted (IH)	Any (NH/IH)
$\sin^2\theta_{13}$	$\gtrsim 10^{-3}$		$\lesssim 10^{-5}$
MSW conversion	adiabatic		non-adiabatic
ν_e survival prob.	0	$\sin^2\theta_{12} \approx 0.3$	$\sin^2\theta_{12} \approx 0.3$
$\bar{\nu}_e$ survival prob.	$\cos^2\theta_{12} \approx 0.7$	0	$\cos^2\theta_{12} \approx 0.7$
$\bar{\nu}_e$ Earth effects	Yes	No	Yes
	May distinguish mass ordering		

Assuming collective effects are not important during accretion phase (Chakraborty et al., arXiv:1105.1130, Sarikas et al. arXiv:1109.3601)

Signature of Flavor Oscillations

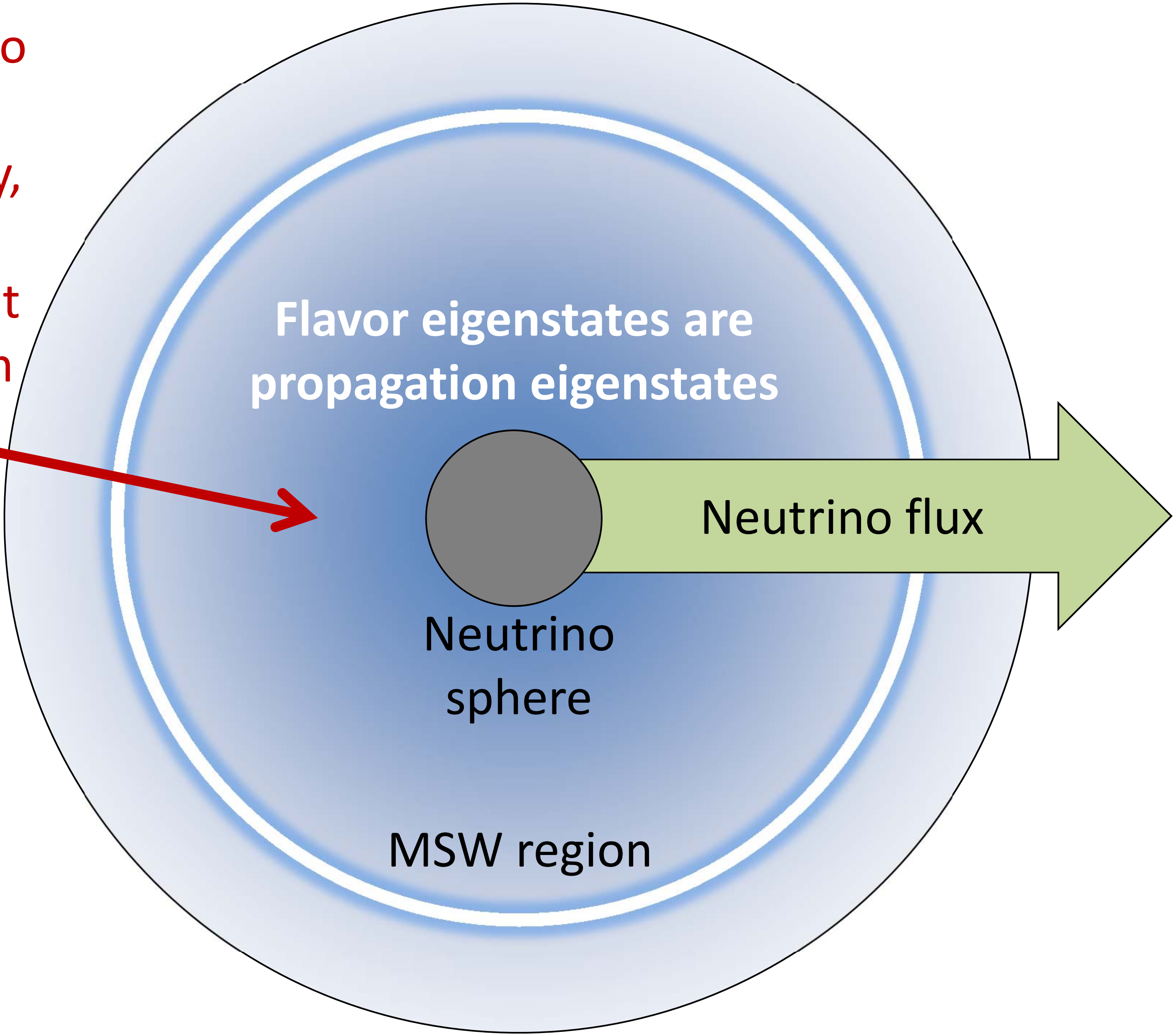
	1-3-mixing scenarios		
	A	B	~~C~~
Mass ordering	Normal (NH)	Inverted (IH)	~~Any (NH/IH)~~
$\sin^2\theta_{13}$	$\Theta_{13} \approx 9°$		~~$\lesssim 10^{-3}$~~
MSW conversion	adiabatic		~~non-adiabatic~~
ν_e survival prob.	0	$\sin^2\theta_{12} \approx 0.3$	~~$\sin^2\theta_{12} \approx 0.3$~~
$\bar{\nu}_e$ survival prob.	$\cos^2\theta_{12} \approx 0.7$	0	~~$\cos^2\theta_{12} \approx 0.7$~~
$\bar{\nu}_e$ Earth effects	Yes	No	~~Yes~~

May distinguish mass ordering

Assuming collective effects are not important during accretion phase
(Chakraborty et al., arXiv:1105.1130, Sarikas et al. arXiv:1109.3601)

Flavor Oscillations in Core-Collapse Supernovae

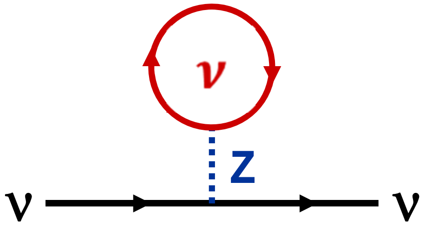
Neutrino-neutrino refraction causes a flavor instability, flavor exchange between different parts of spectrum



Flavor-Off-Diagonal Refractive Index

2-flavor neutrino evolution as an effective 2-level problem

$$\mathrm{i}\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$



Effective mixing Hamiltonian

$$H = \frac{M^2}{2E} + \sqrt{2}G_\mathrm{F}\begin{pmatrix} N_e - \frac{N_n}{2} & 0 \\ 0 & -\frac{N_n}{2}\end{pmatrix} + \sqrt{2}G_\mathrm{F}\begin{pmatrix} N_{\nu_e} & N_{\langle\nu_e|\nu_\mu\rangle} \\ N_{\langle\nu_\mu|\nu_e\rangle} & N_{\nu_\mu}\end{pmatrix}$$

Mass term in flavor basis: causes vacuum oscillations

Wolfenstein’s weak potential, causes MSW “resonant” conversion together with vacuum term

Flavor-off-diagonal potential, caused by flavor oscillations. (J.Pantaleone, PLB 287:128,1992)

Flavor oscillations feed back on the Hamiltonian: Nonlinear effects!

Collective Supernova Nu Oscillations since 2006

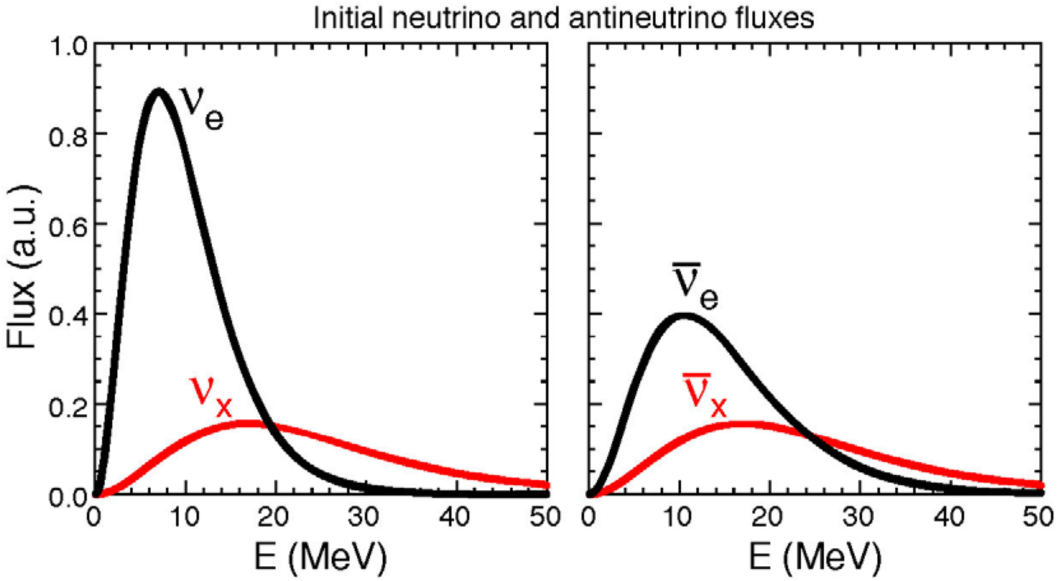
Two seminal papers in 2006 triggered a torrent of activities

Duan, Fuller, Qian, astro-ph/0511275, Duan et al. astro-ph/0606616

Balantekin, Gava & Volpe [0710.3112]. Balantekin & Pehlivan [astro-ph/0607527]. Blennow, Mirizzi & Serpico [0810.2297]. Cherry, Fuller, Carlson, Duan & Qian [1006.2175, 1108.4064]. Cherry, Wu, Fuller, Carlson, Duan & Qian [1109.5195]. Cherry, Carlson, Friedland, Fuller & Vlasenko [1203.1607]. Chakraborty, Choubey, Dasgupta & Kar [0805.3131]. Chakraborty, Fischer, Mirizzi, Saviano, Tomàs [1104.4031, 1105.1130]. Choubey, Dasgupta, Dighe & Mirizzi [1008.0308]. Dasgupta & Dighe [0712.3798]. Dasgupta, Dighe & Mirizzi [0802.1481]. Dasgupta, Dighe, Raffelt & Smirnov [0904.3542]. Dasgupta, Dighe, Mirizzi & Raffelt [0801.1660, 0805.3300]. Dasgupta, Mirizzi, Tamborra & Tomàs [1002.2943]. Dasgupta, Raffelt & Tamborra [1001.5396]. Dasgupta, O'Connor & Ott [1106.1167]. Duan, Fuller, Carlson & Qian [astro-ph/0608050, 0703776, 0707.0290, 0710.1271]. Duan, Fuller & Qian [0706.4293, 0801.1363, 0808.2046, 1001.2799]. Duan, Fuller & Carlson [0803.3650]. Duan & Kneller [0904.0974]. Duan & Friedland [1006.2359]. Duan, Friedland, McLaughlin & Surman [1012.0532]. Esteban-Pretel, Mirizzi, Pastor, Tomàs, Raffelt, Serpico & Sigl [0807.0659]. Esteban-Pretel, Pastor, Tomàs, Raffelt & Sigl [0706.2498, 0712.1137]. Fogli, Lisi, Marrone & Mirizzi [0707.1998]. Fogli, Lisi, Marrone & Tamborra [0812.3031]. Friedland [1001.0996]. Gava & Jean-Louis [0907.3947]. Gava & Volpe [0807.3418]. Galais, Kneller & Volpe [1102.1471]. Galais & Volpe [1103.5302]. Gava, Kneller, Volpe & McLaughlin [0902.0317]. Hannestad, Raffelt, Sigl & Wong [astro-ph/0608695]. Wei Liao [0904.0075, 0904.2855]. Lunardini, Müller & Janka [0712.3000]. Mirizzi, Pozzorini, Raffelt & Serpico [0907.3674]. Mirizzi & Serpico [1111.4483]. Mirizzi & Tomàs [1012.1339]. Pehlivan, Balantekin, Kajino & Yoshida [1105.1182]. Pejcha, Dasgupta & Thompson [1106.5718]. Raffelt [0810.1407, 1103.2891]. Raffelt & Sigl [hep-ph/0701182]. Raffelt & Smirnov [0705.1830, 0709.4641]. Raffelt & Tamborra [1006.0002]. Sawyer [hep-ph/0408265, 0503013, 0803.4319, 1011.4585]. Sarikas, Raffelt, Hüdepohl & Janka [1109.3601]. Sarikas, Tamborra, Raffelt, Hüdepohl & Janka [1204.0971]. Saviano, Chakraborty, Fischer, Mirizzi [1203.1484]. Wu & Qian [1105.2068].

Spectral Split

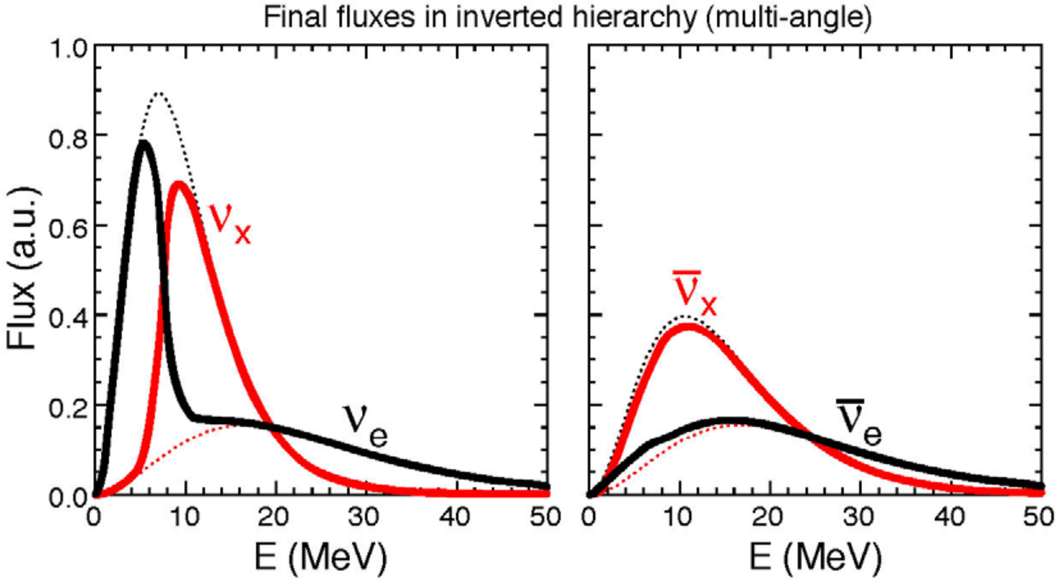
Initial fluxes at neutrino sphere



Figures from

Fogli, Lisi,
Marrone & Mirizzi,
arXiv:0707.1998

After collective trans-formation



Explanations in

Raffelt & Smirnov
arXiv:0705.1830
and 0709.4641

Duan, Fuller,
Carlson & Qian
arXiv:0706.4293
and 0707.0290

Three Ways to Describe Flavor Oscillations

Schrödinger equation in terms of "flavor spinor"

$$\mathrm{i}\partial_t \begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{\Delta m^2}{2E}\begin{pmatrix}\cos 2\theta & \sin 2\theta\\ \sin 2\theta & -\cos 2\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

Neutrino flavor density matrix

$$\rho = \begin{pmatrix}\langle\nu_e|\nu_e\rangle & \langle\nu_e|\nu_\mu\rangle\\ \langle\nu_\mu|\nu_e\rangle & \langle\nu_\mu|\nu_\mu\rangle\end{pmatrix}$$

Equivalent commutator form of Schrödinger equation

$$\mathrm{i}\partial_t\rho = [H,\rho]$$

Expand 2×2 Hermitean matrices in terms of Pauli matrices

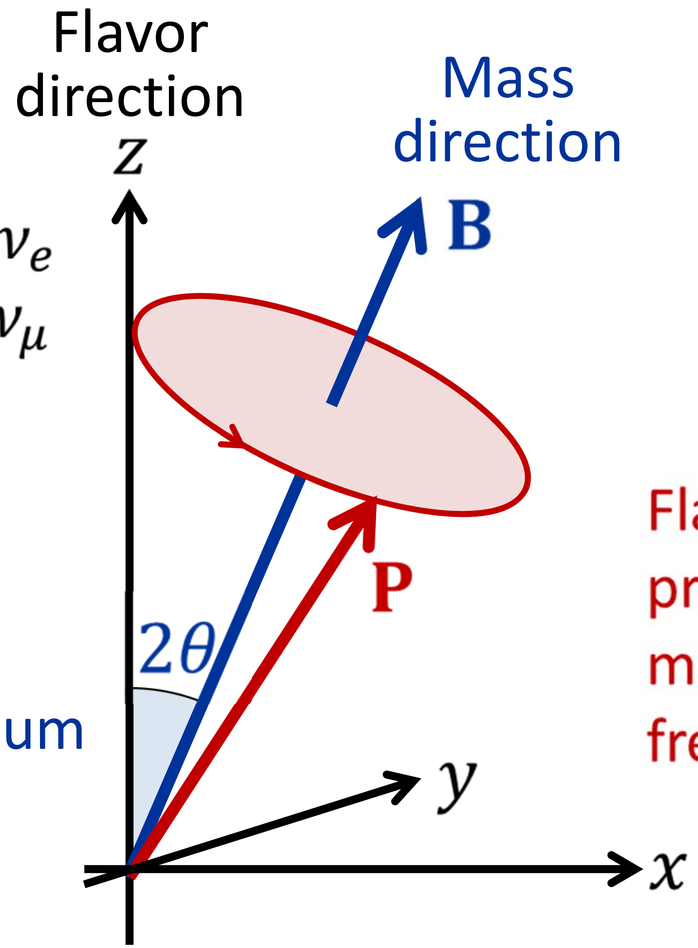
$\rho = \frac{1}{2}[\mathrm{Tr}(\rho) + \mathbf{P}\cdot\boldsymbol{\sigma}]$ and $H = \frac{\Delta m^2}{2E}\mathbf{B}\cdot\boldsymbol{\sigma}$ with $\mathbf{B} = (\sin 2\theta, 0, \cos 2\theta)$

Equivalent spin-precession form of equation of motion

$\dot{\mathbf{P}} = \omega\mathbf{B}\times\mathbf{P}$ with $\omega = \frac{\Delta m^2}{2E}$

P is "polarization vector" or "Bloch vector" or "flavor isospin vector"

Flavor Oscillation as Spin Precession



↑ Spin up ν_e
↓ Spin down ν_μ

Twice the vacuum mixing angle

Flavor polarization vector precesses around the mass direction with frequency $\omega = \Delta m^2/2E$

Collective Nu Oscillations as a Many-Body Problem

Hamiltonian for interacting "flavor spins" (*classical* in mean-field approach)

$$H=\sum_{i=1}^{N}\omega_i\mathbf{B}\cdot\mathbf{P}_i+\sqrt{2}G_\mathrm{F}N_e\mathbf{L}\cdot\sum_{i=1}^{N}\mathbf{P}_i+\mu\sum_{i,j=1}^{N}(1-\cos\theta_{ij})\,\mathbf{P}_i\cdot\mathbf{P}_j$$

↑ Unit vector
in mass direction

↑ Unit vector
in flavor direction

↑ Multi-angle effects from
current-current structure

"Spin-pairing H" for isotropic system (or single angle), ignoring matter effect

$$H=\sum_{i=1}^{N}\omega_i\mathbf{B}\cdot\mathbf{P}_i+\mu\mathbf{P}_\mathrm{tot}^2$$

BCS theory (using Anderson's pseudo-spin), nuclear physics, …

Integrable system (as many "Gaudin invariants" as spins)

→ Pehlivan, Balantekin, Kajino & Yoshida [arxiv:1105.1182] for introduction

N-mode coherent solutions ("Normal and anomalous solitons")

- Emil Yuzbashian, Phys. Rev. **B** 78, 184507 (2008) Super-conductivity (BCS)
- Georg Raffelt, Phys. Rev. **D** 83, 105022 (2011) Collective Nus

Synchronized Flavor Oscillations

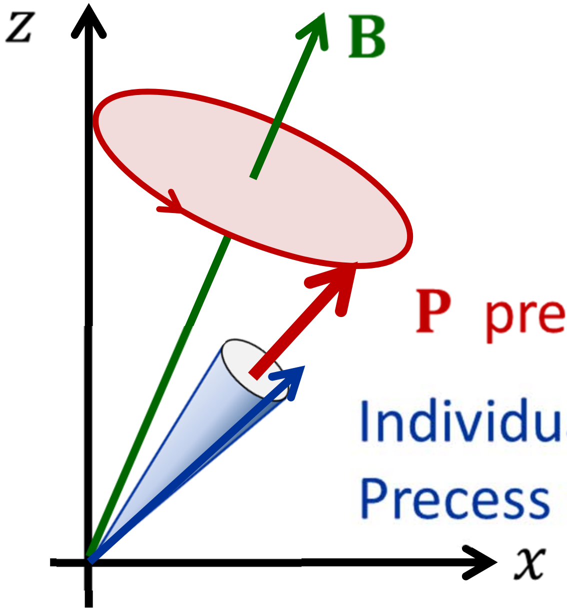
Precession equation for each ν mode with energy E, i.e. $\omega = \Delta m^2/2E$

$$\dot{\mathbf{P}}_\omega = \underbrace{(\omega\mathbf{B} + \lambda\mathbf{L} + \mu\mathbf{P})}_{\mathbf{H}_{\rm eff}} \times \mathbf{P}_\omega \quad \text{with} \quad \lambda = \sqrt{2}G_{\rm F}N_e \quad \text{and} \quad \mu = \sqrt{2}G_{\rm F}N_\nu$$

Total flavor spin of entire ensemble

$$\mathbf{P} = \textstyle\sum_\omega \mathbf{P}_\omega \qquad \text{normalize} \qquad |\mathbf{P}_{\rm t=0}| = 1$$

Individual spins do not remain aligned – feel "internal" field $\mathbf{H}_{\nu\nu} = \mu\mathbf{P}$



Synchronized oscillations for large neutrino density $\mu \gg \delta\omega$

$\mathbf{P}$ precesses with $\omega_{\rm sync}$ for large ν density

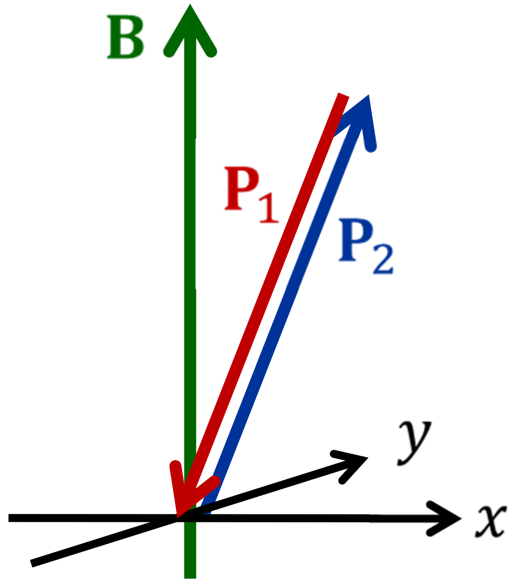
Individual $\mathbf{P}_\omega$ "trapped" on precession cones

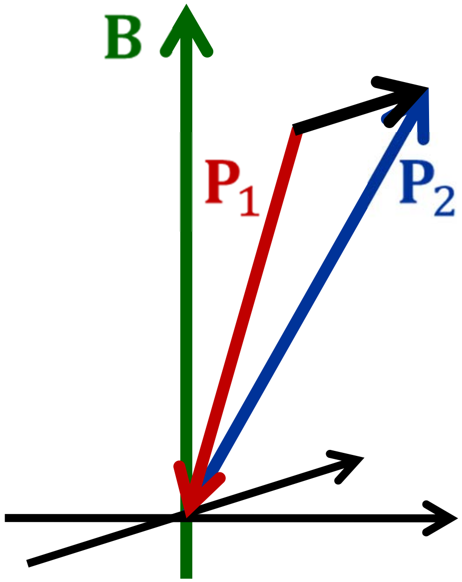
Precess around $\mathbf{P}$ with frequency $\sim \mu$

Instability in Flavor Space

Two-mode example in co-rotating frame, initially $\mathbf{P}_1 = \downarrow$, $\mathbf{P}_2 = \uparrow$ (flavor basis)

$$\dot{\mathbf{P}}_1 = [-\omega\mathbf{B} + \mu\,(\mathbf{P}_1 + \mathbf{P}_2)] \times \mathbf{P}_1$$
$$\dot{\mathbf{P}}_2 = [+\omega\mathbf{B} + \mu\,\underbrace{(\mathbf{P}_1 + \mathbf{P}_2)}_{\text{0 initially}}] \times \mathbf{P}_2$$





$$\mathbf{P} = \mathbf{P}_1 + \mathbf{P}_2$$

Matter effect transverse to mass and flavor directions

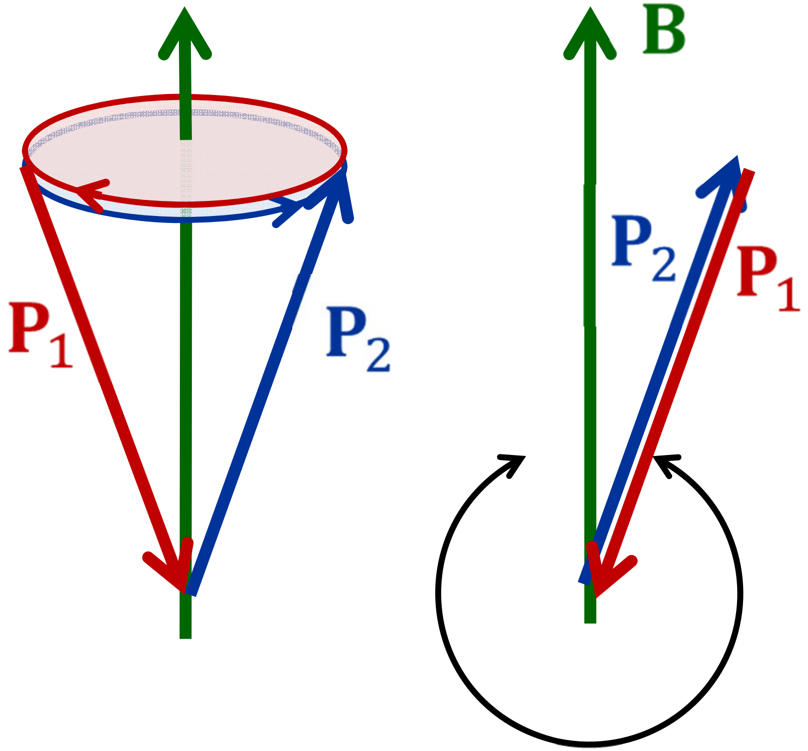
Both $\mathbf{P}_1$ and $\mathbf{P}_2$ tilt around $\mathbf{P}$ if μ is large

- Initially aligned in flavor direction and $\mathbf{P} = 0$
- Free precession $\pm\omega$

After a short time, transverse $\mathbf{P}$ develops by free precession

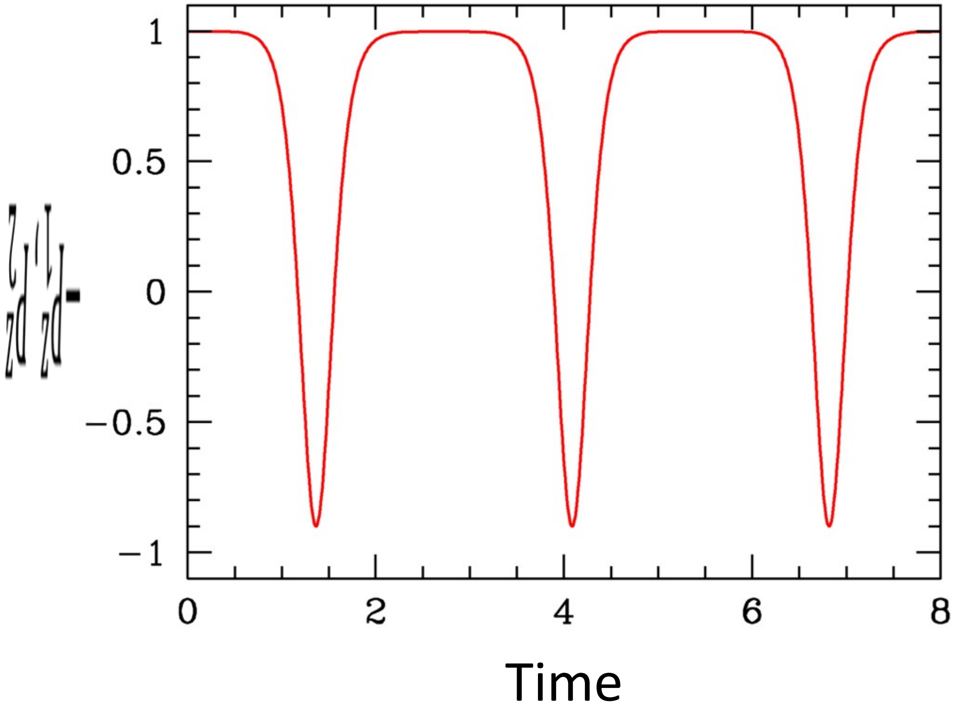
Two Spins with Opposite Initial Orientation

No interaction ($\mu = 0$)
Free precession in opposite directions



Strong interaction
($\mu \to \infty$)
Pendular motion

Even for very small mixing angle, large-amplitude flavor oscillations



Inverse-Energy Spectrum

Fermi-Dirac energy spectrum

$$\frac{dN}{dE} \propto \frac{E^2}{e^{E/T-\eta}+1}$$

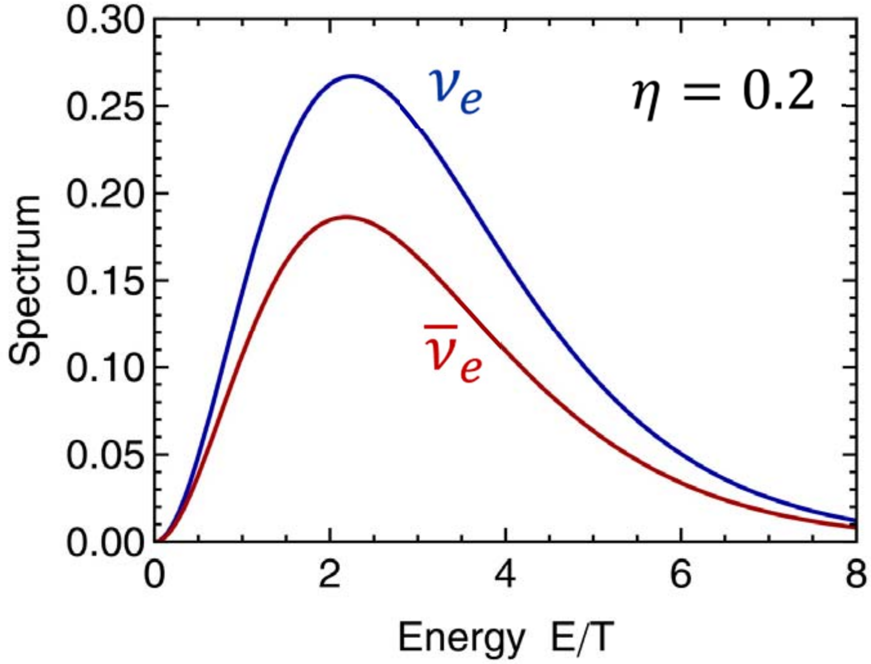
η degeneracy parameter, $-\eta$ for $\overline{\nu}$

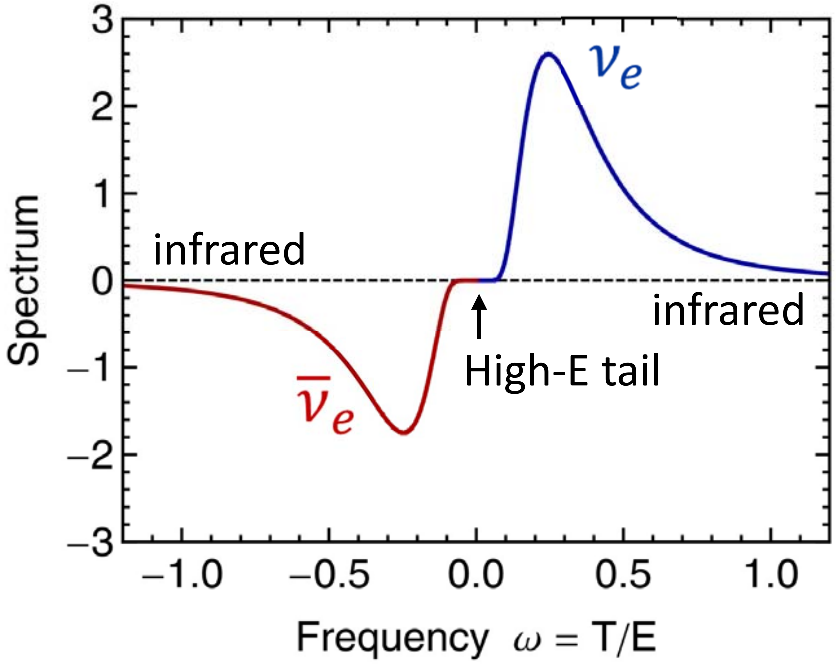
Spectrum in terms of $\omega = T/E$

- Antineutrinos $E \to -E$
- and dN/dE negative
  (flavor isospin convention)

$\omega > 0$: $\nu_e = \uparrow$ and $\nu_\mu = \downarrow$

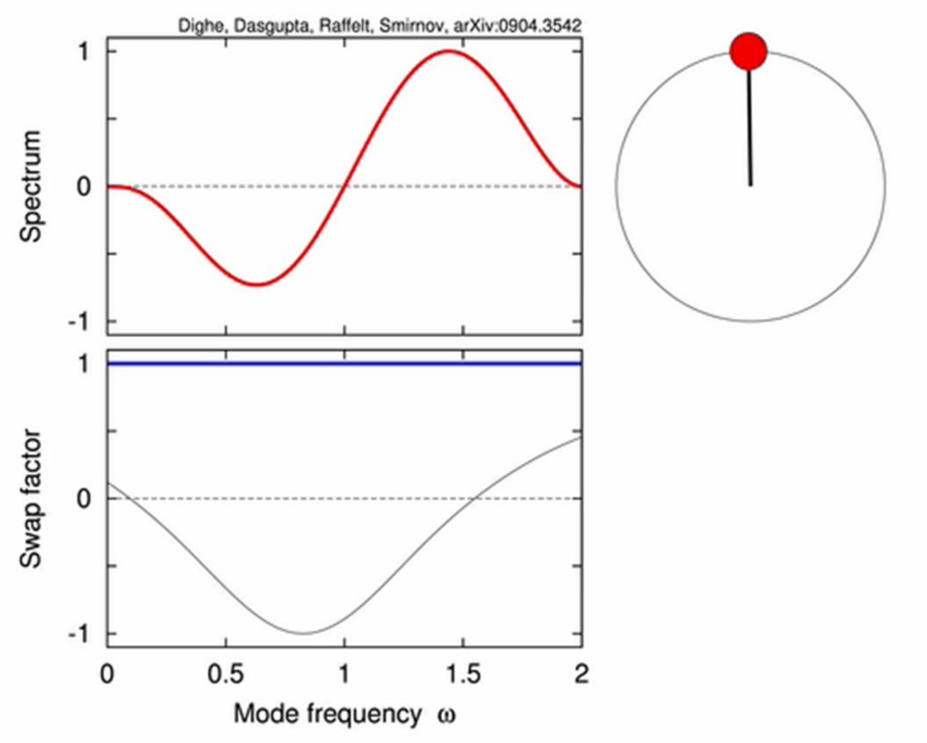
$\omega < 0$: $\overline{\nu}_e = \downarrow$ and $\overline{\nu}_\mu = \uparrow$



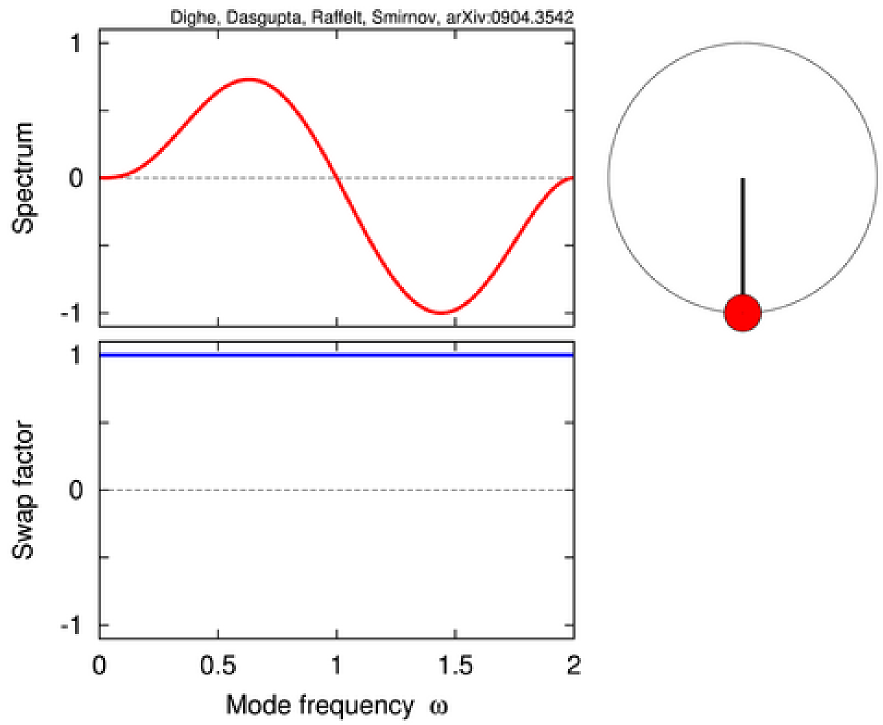


Flavor Pendulum

Single “positive” crossing (IH)
(potential energy at a maximum)



Single “negative” crossing (NH)
(potential energy at a minimum)



Dasgupta, Dighe, Raffelt & Smirnov, arXiv:0904.3542
For movies see http://www.mppmu.mpg.de/supernova/multisplits

Self-Induced Flavor Conversion

- Flavor content exchanged between different momentum modes (or nus and anti-nus changing together)
- No net flavor conversion of ensemble
- Instability required to get started: Exponential growth of the off-diagonal density matrix parts

→ Linearized Stability Analysis
(first stressed by Ray Sawyer)

Sawyer, arXiv:0803.4319 – Banerjee, Dighe & Raffelt, arXiv:1107.2308

Linearized Stability Analysis

Schrödinger equation for flavor matrices of neutrino fluxes $\Phi_{\omega,u}$

$\omega = \pm\Delta m^2/2E$ $\quad u = \sin^2$(emission angle) $\quad v_u$ = radial velocity at r

$$\mathrm{i}\partial_r \Phi_{\omega,u} = \left[\frac{\omega + \sqrt{2}G_\mathrm{F}N_\ell}{v_u} + \frac{\sqrt{2}G_\mathrm{F}}{4\pi r^2}\int d\omega' du'\, \Phi_{\omega',u'}\,\frac{1 - v_u v_{u'}}{v_u v_{u'}}, \Phi_{\omega,u}\right]$$

Linearize in small off-diagonal flux terms and Fourier transform

$$\Phi_{\omega,u} = \frac{g_{\omega,u}}{2}\begin{pmatrix} 1 & Q_{\omega,u}\, e^{-\mathrm{i}\Omega r} \\ Q^*_{\omega,u}\, e^{\mathrm{i}\Omega r} & -1 \end{pmatrix}$$

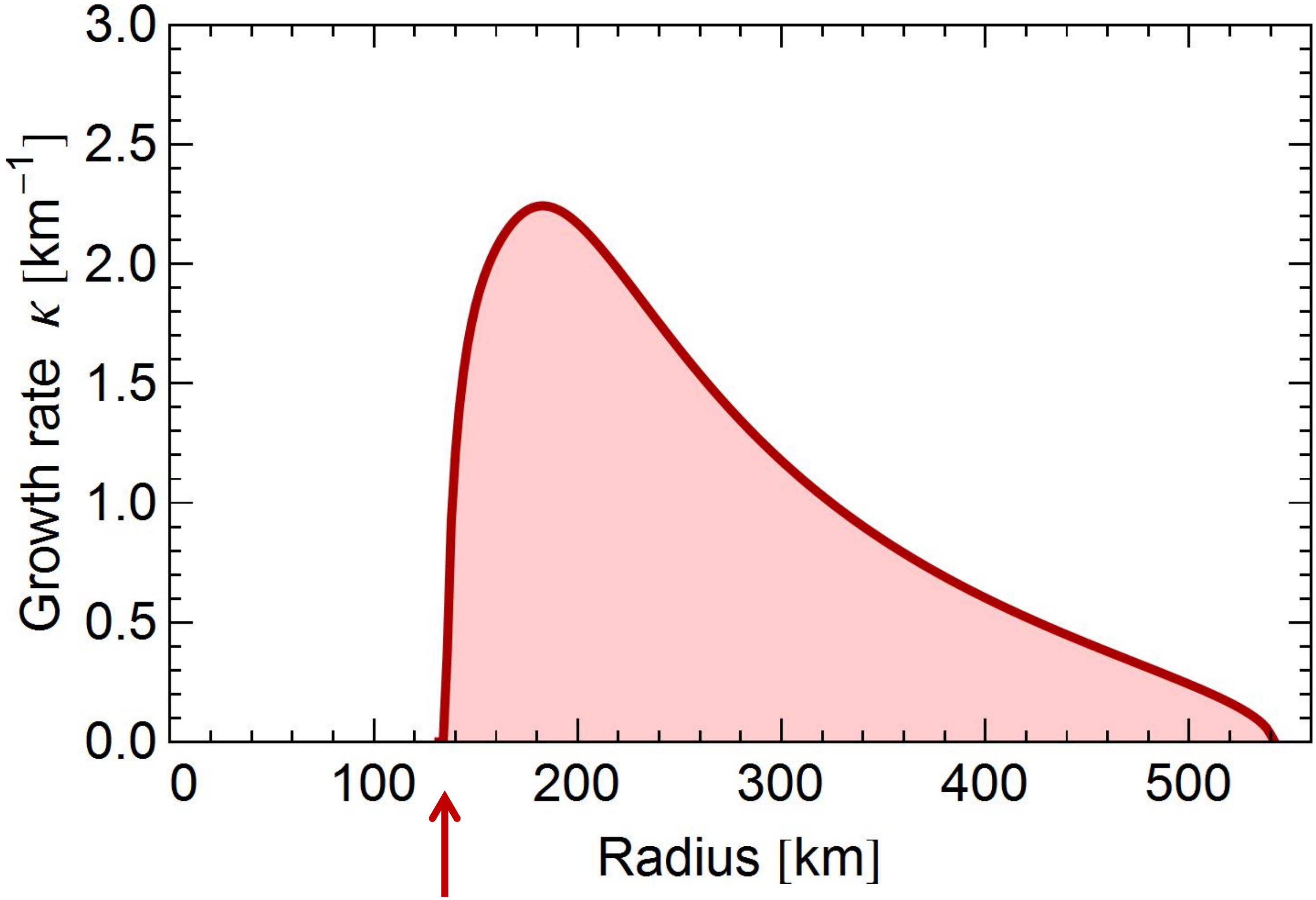
Eigenvalue equation for $Q_{\omega,u}$ in terms of eigenfrequency $\Omega = \gamma + \mathrm{i}\,\kappa$, where κ is the exponential growth rate

$$\left[\omega + u\left(\lambda + \int d\omega' du'\, g_{\omega',u'}\right) - \Omega\right] Q_{\omega,u} = \mu \int d\omega' du'\,(u+u')\, g_{\omega',u'} Q_{\omega',u'}$$

Straightforward to solve for eigenvalue Ω and eigenfunction $Q_{\omega,u}$

Banerjee, Dighe & Raffelt, arXiv:1107.2308

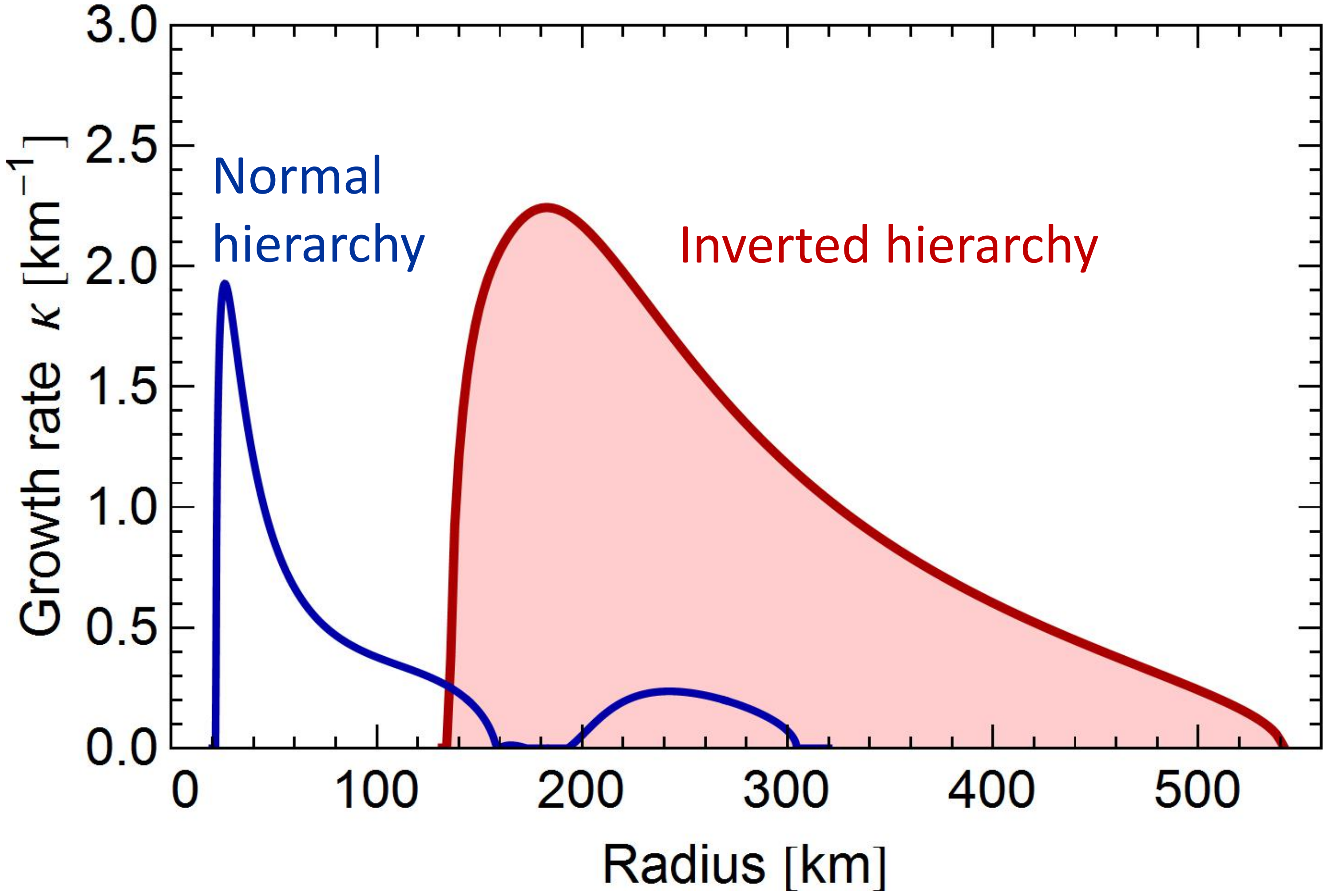
Stability Analysis for Simple SN Example



Onset radius

Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

Normal vs Inverted Hierarchy



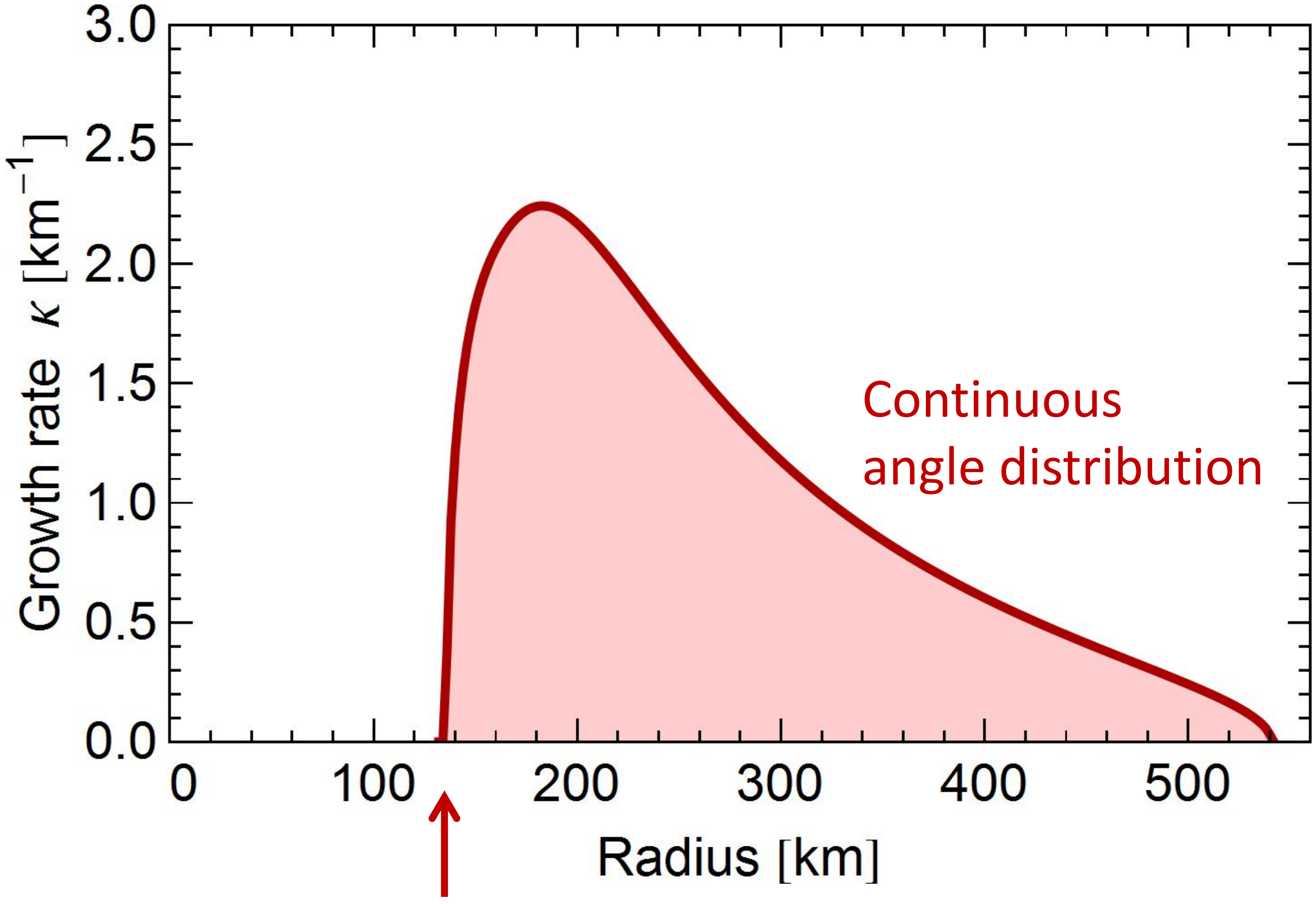
Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

Multi-Angle Paradox of Numerical Solutions

Represent neutrino field by discrete energy and angle modes

- Number of energy modes chosen to fit desired precision
- $N_a \gg 1$ of angle modes required
  N_a too small: Unphysical solutions

New Instabilities for Discrete Angle Modes

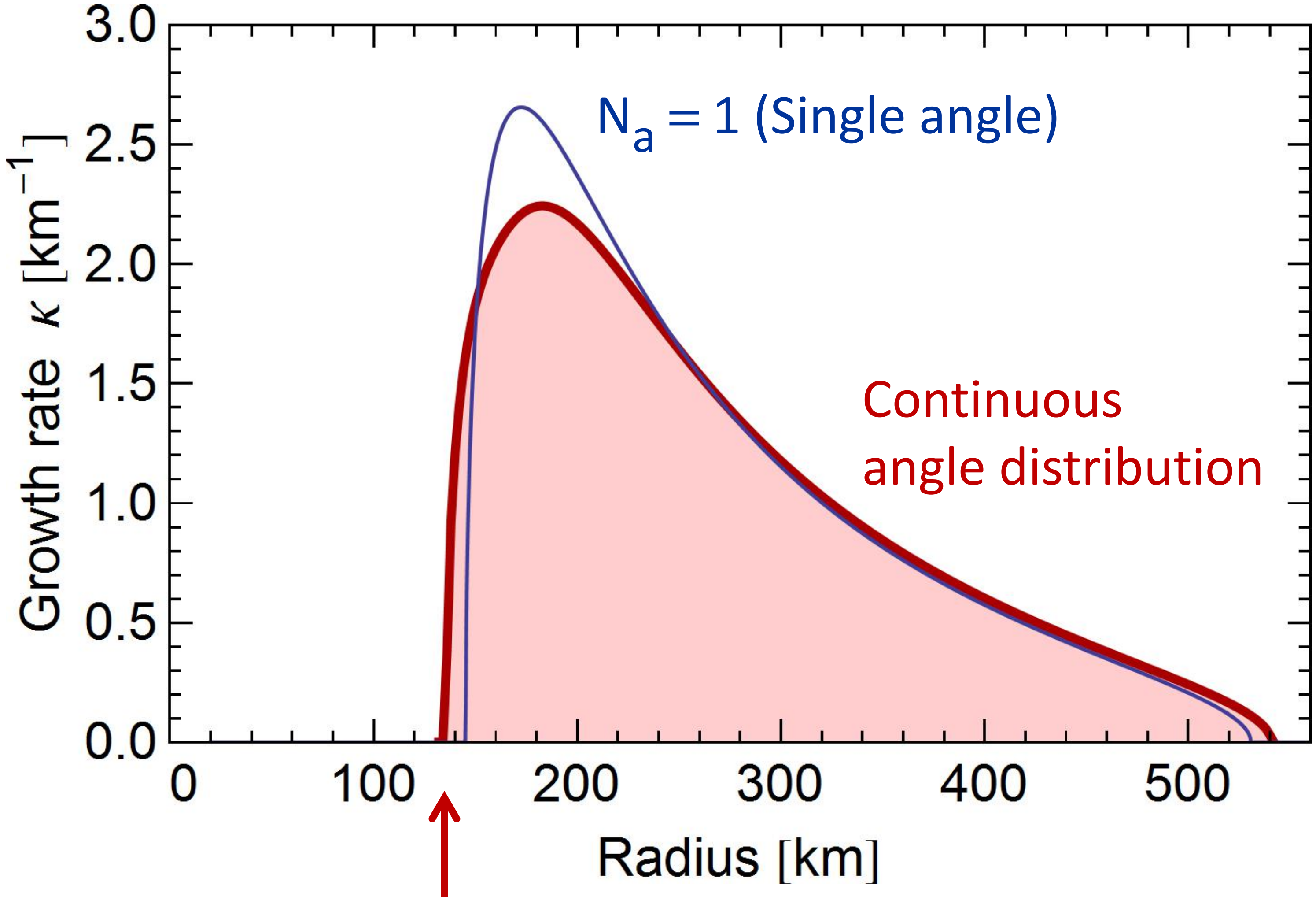


Continuous angle distribution

True onset radius

Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

New Instabilities for Discrete Angle Modes



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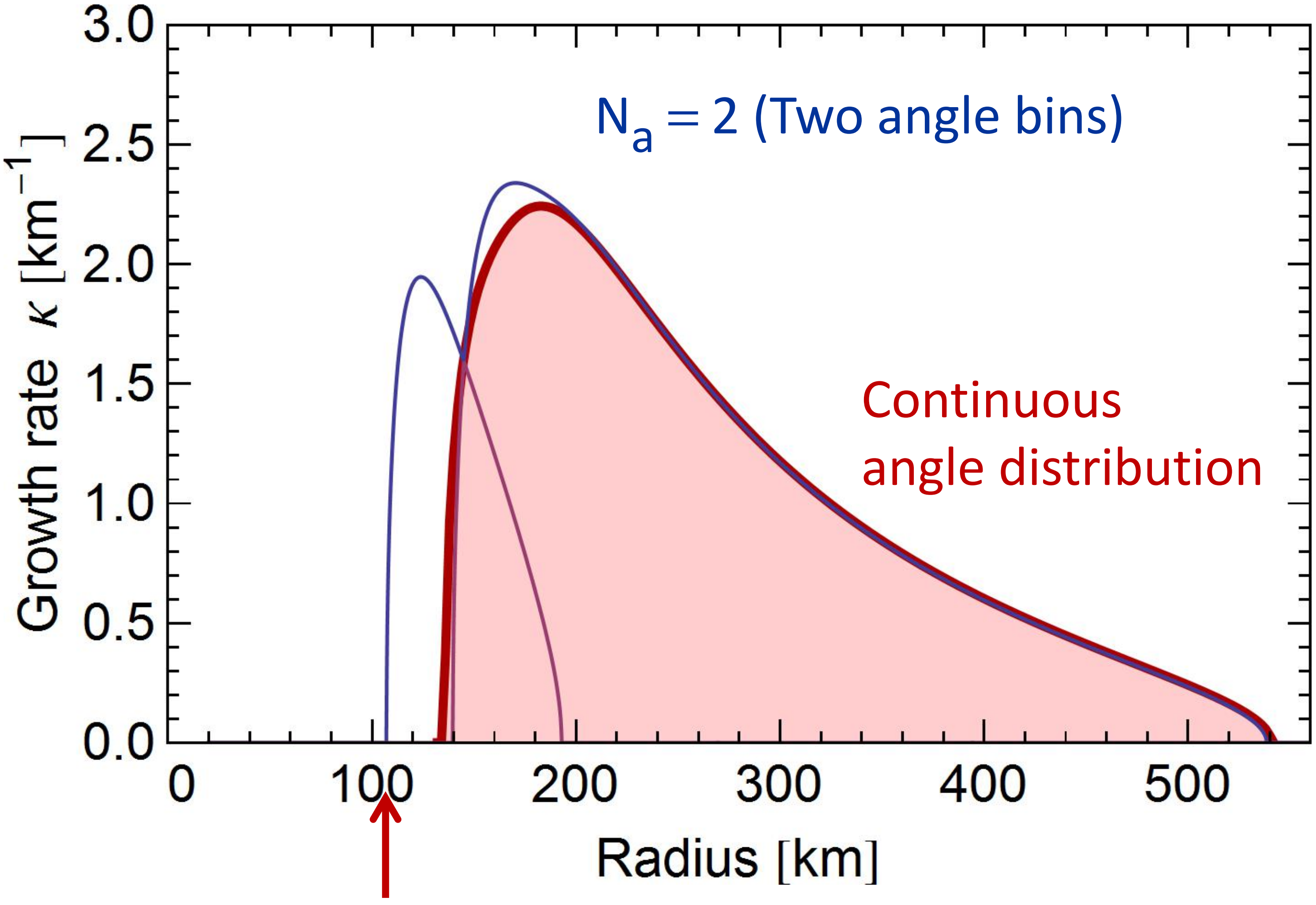


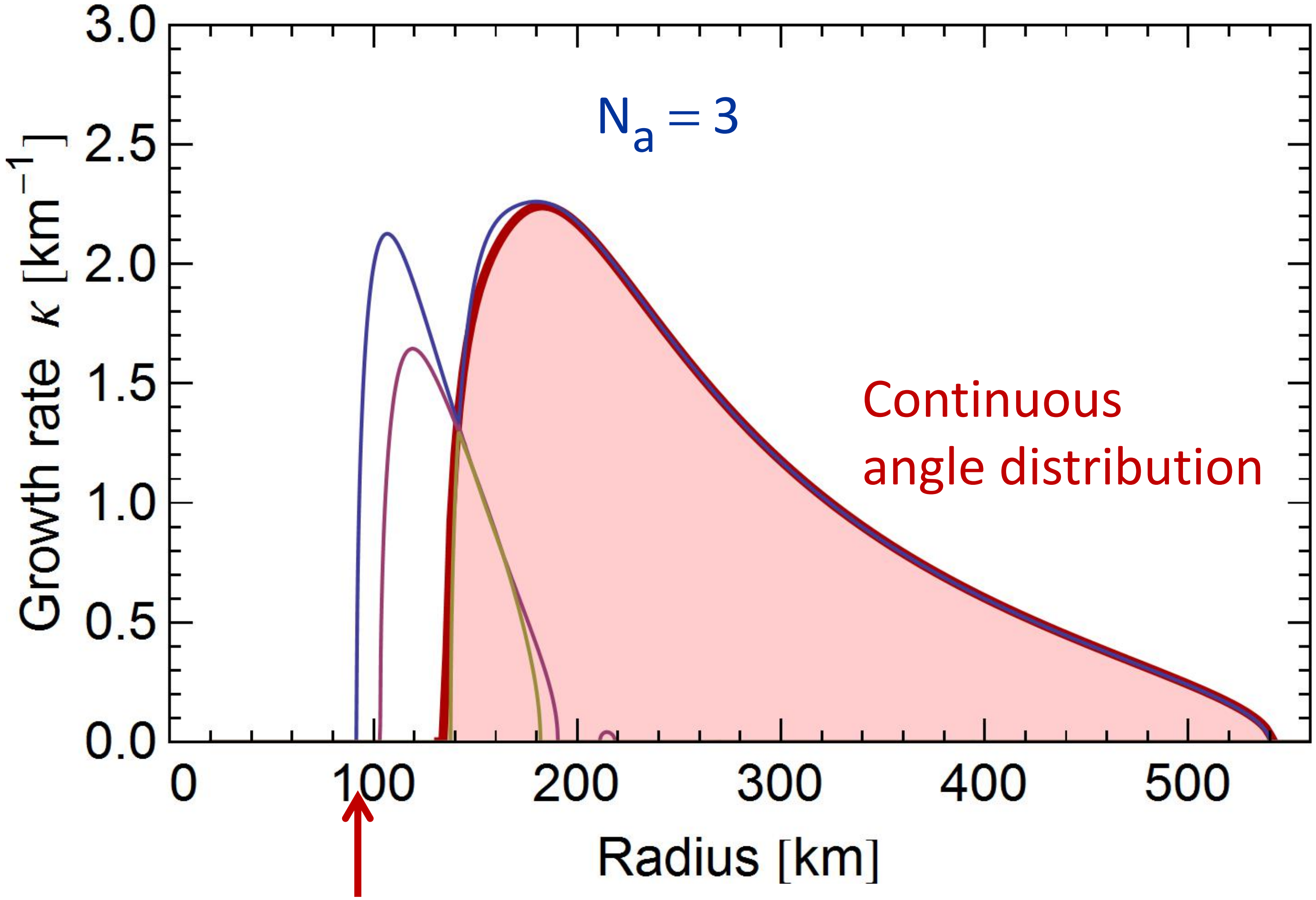
$N_a = 2$ (Two angle bins)

Continuous angle distribution

Numerical onset radius

Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

New Instabilities for Discrete Angle Modes



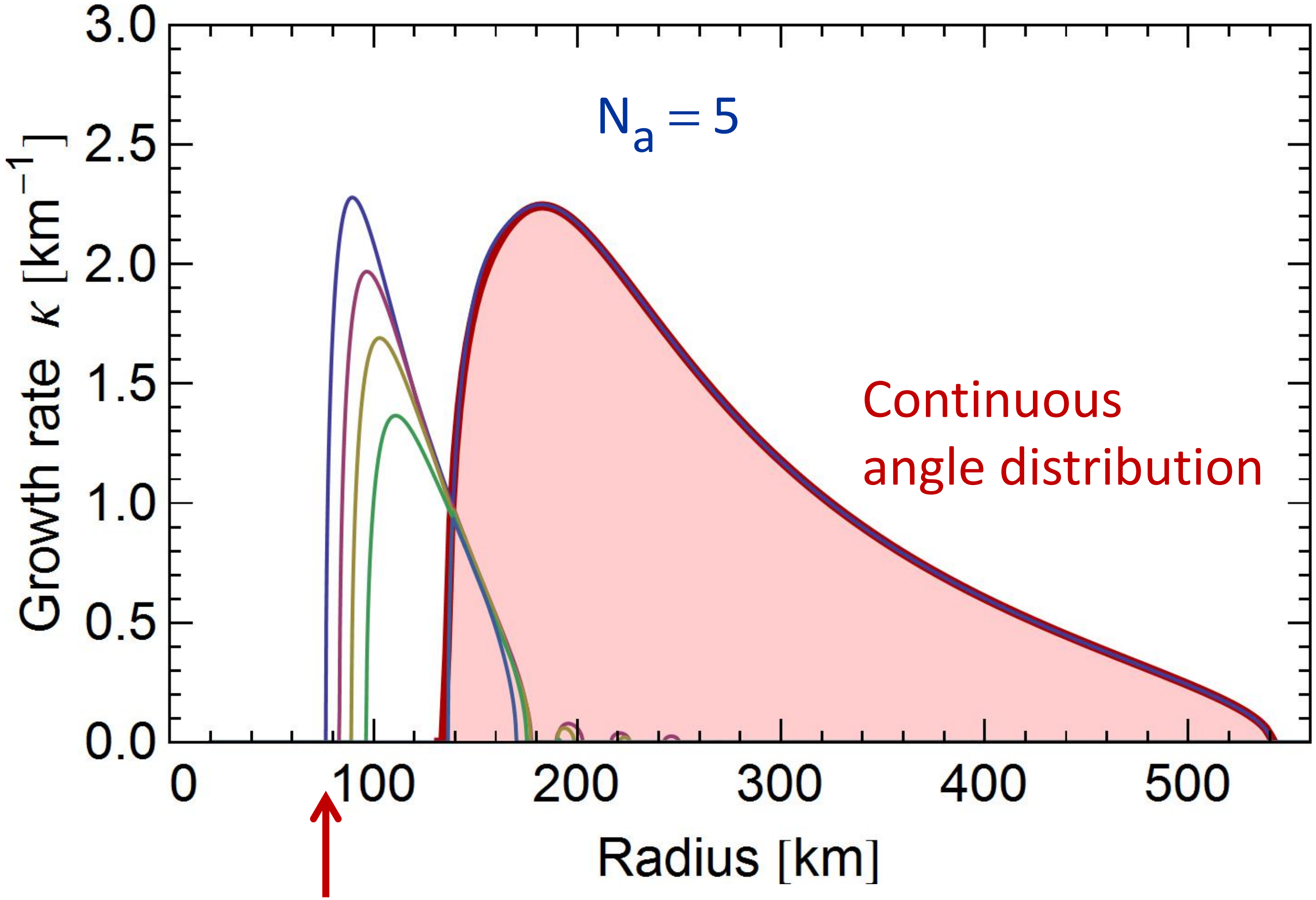
$N_a = 3$

Continuous angle distribution

Numerical onset radius

Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

New Instabilities for Discrete Angle Modes

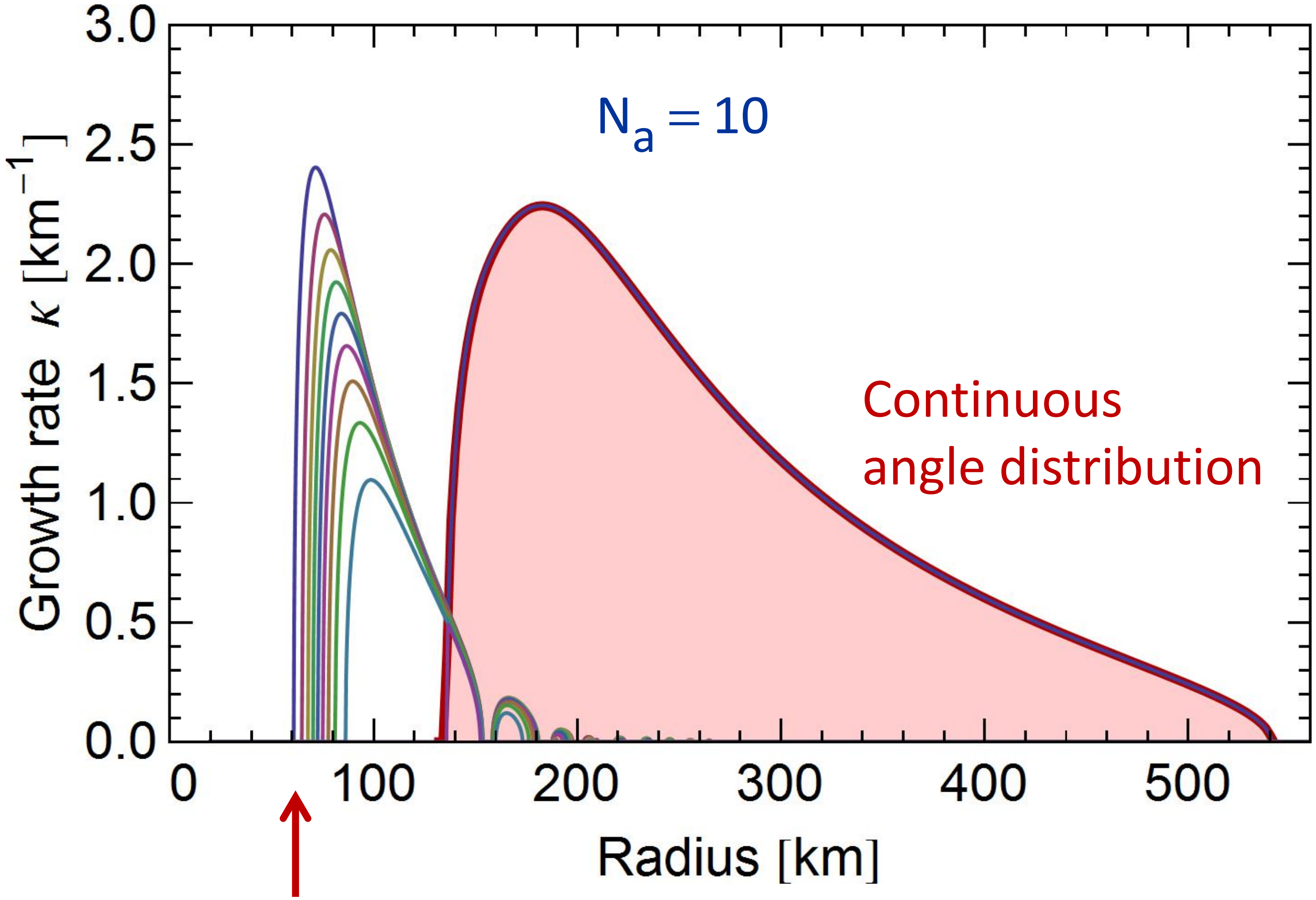


Continuous angle distribution

Numerical onset radius

Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

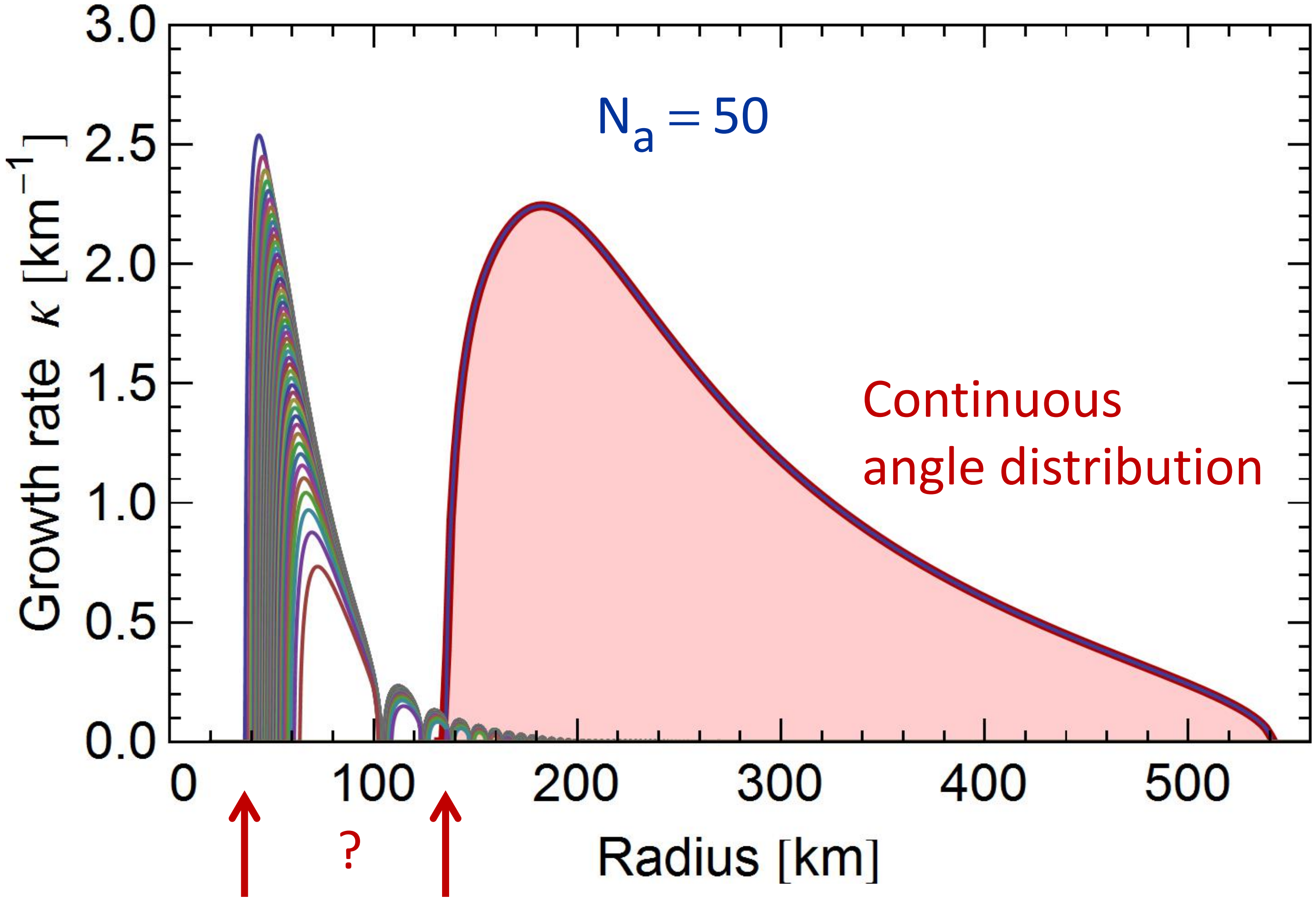
New Instabilities for Discrete Angle Modes



Numerical onset radius

Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

New Instabilities for Discrete Angle Modes



$N_a = 50$

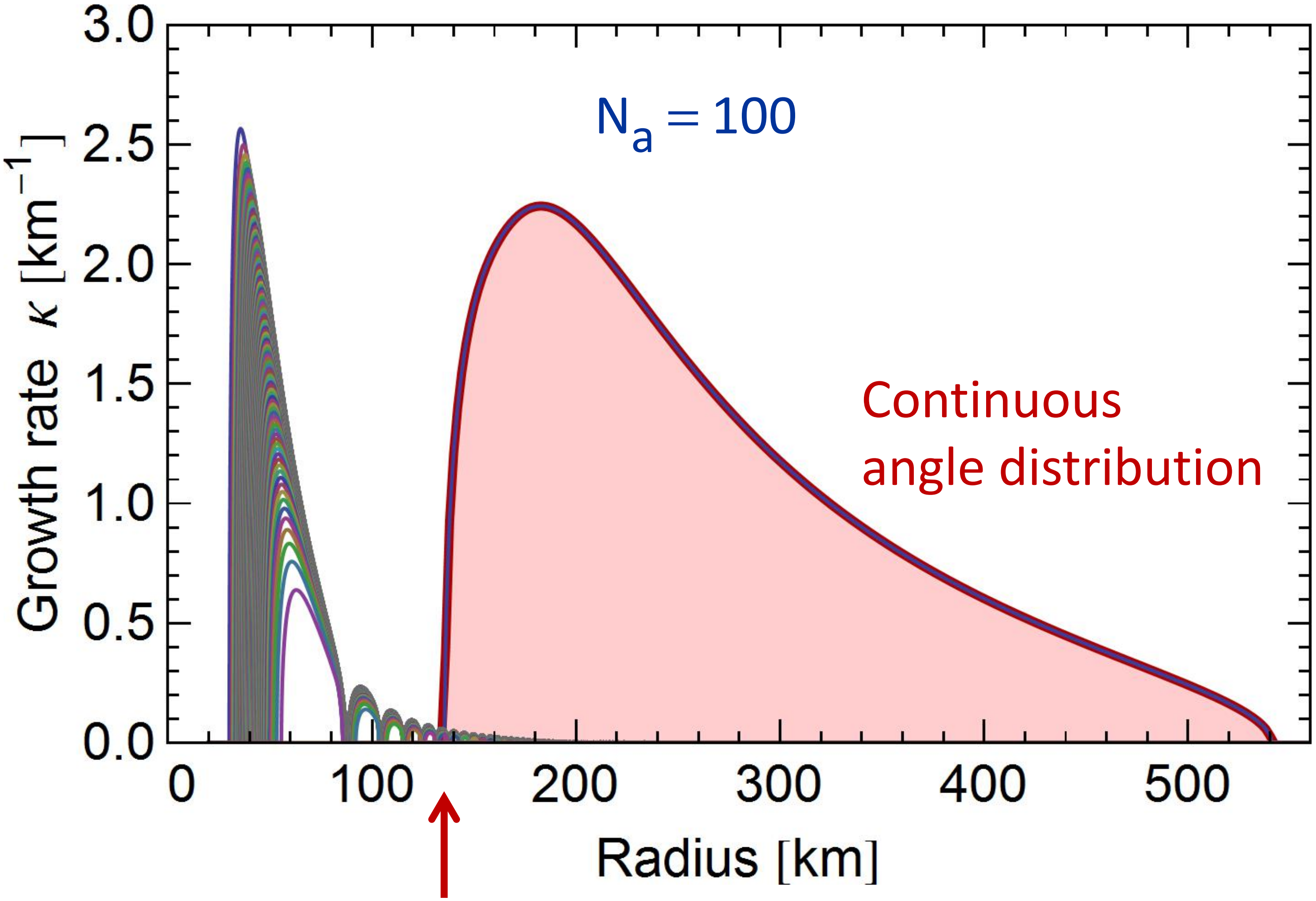
Continuous angle distribution

?

Numerical onset radius

Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

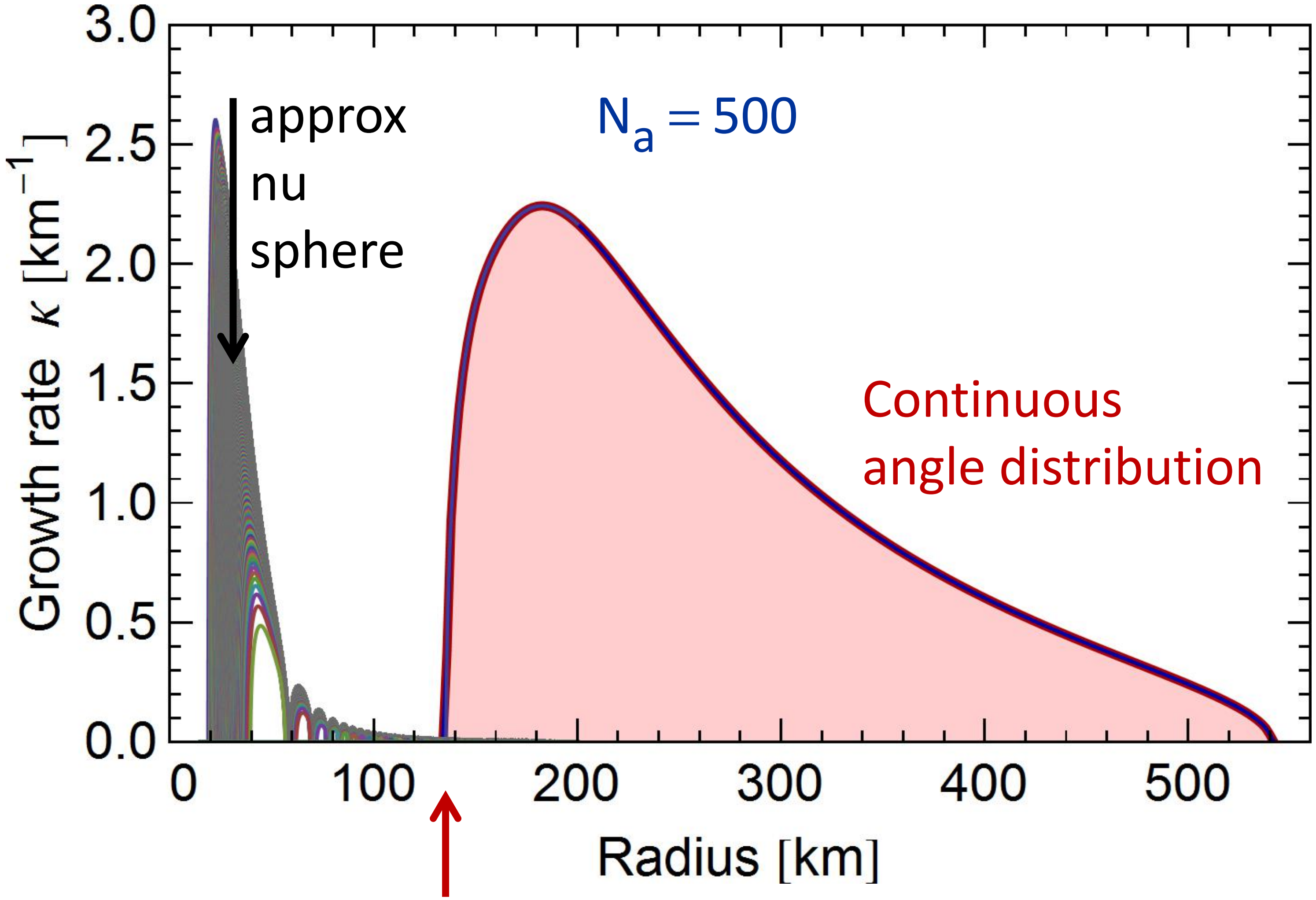
New Instabilities for Discrete Angle Modes



Numerical onset radius (start integration not too deep)

Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

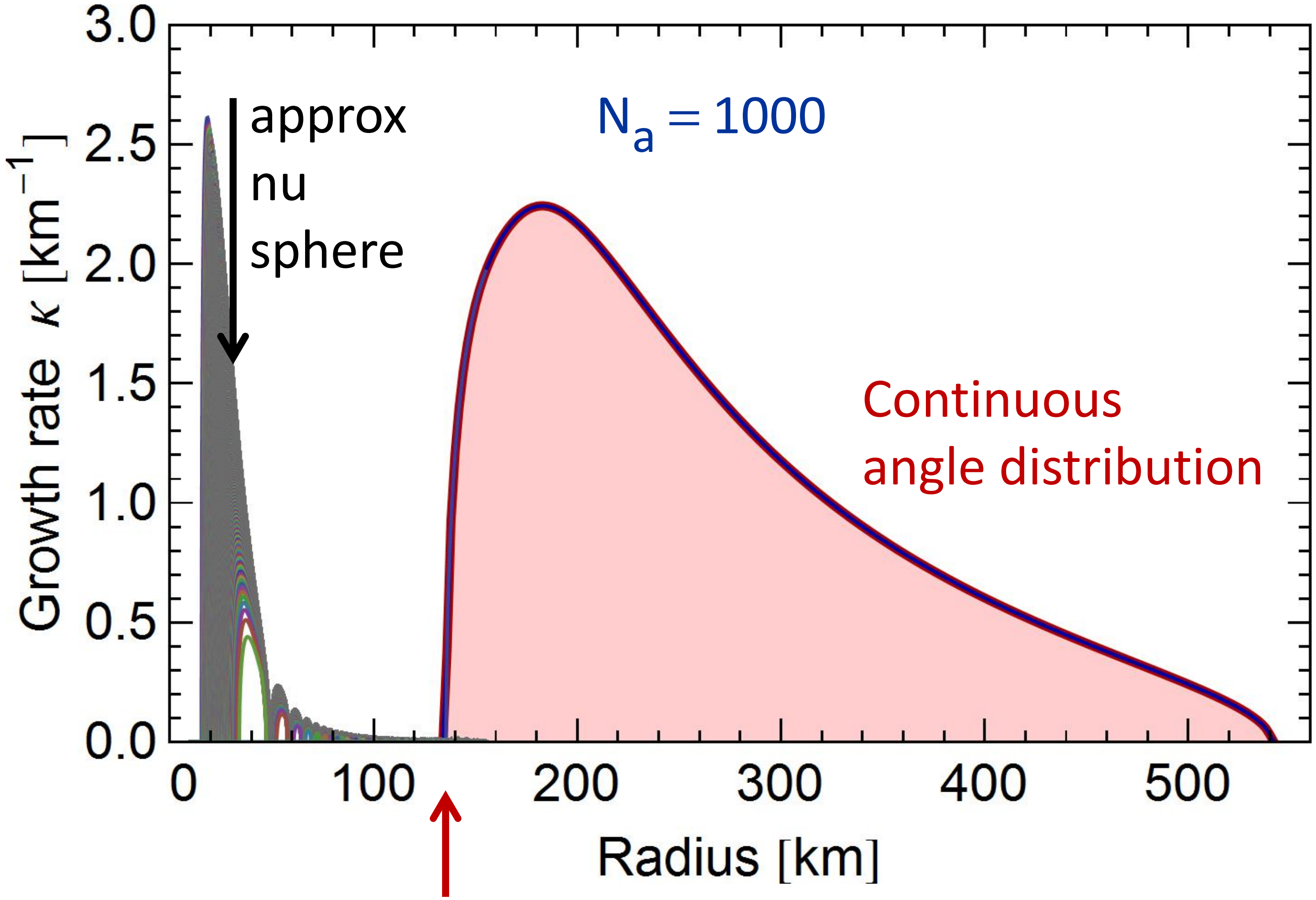
New Instabilities for Discrete Angle Modes



Numerical onset radius (start integration at nu sphere?)

Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

New Instabilities for Discrete Angle Modes



approx nu sphere

$N_a = 1000$

Continuous angle distribution

Numerical onset radius (start integration at nu sphere?)

Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

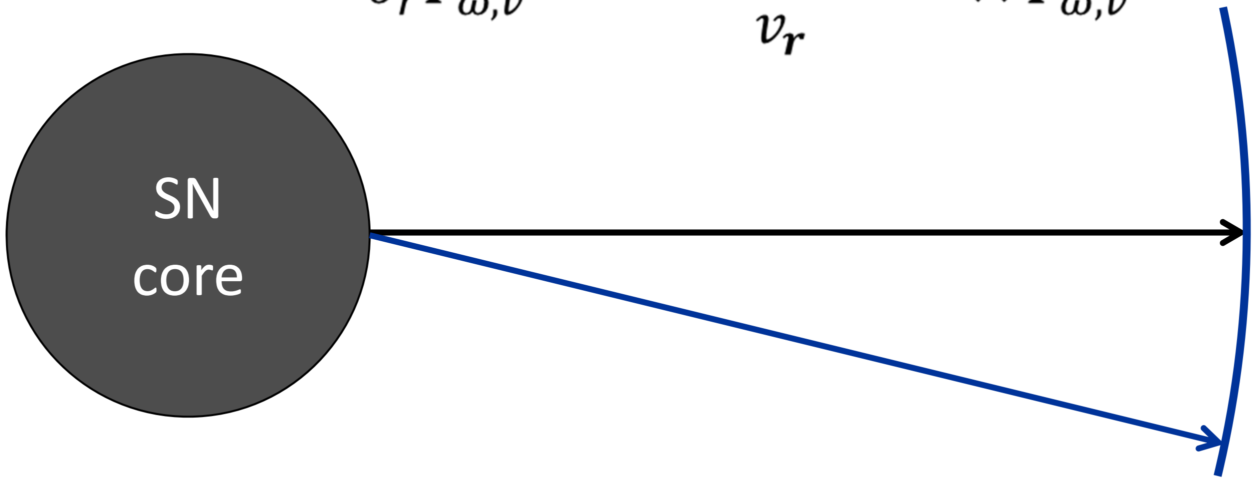
Multi-Angle Matter Effect

Liouville form of oscillation equation

$$\underset{\uparrow}{\dot{\mathbf{P}}_{\omega,\mathbf{v}}} + (\mathbf{v}\cdot\nabla_r)\,\mathbf{P}_{\omega,\mathbf{v}} = (\omega\mathbf{B} + \underset{\substack{\uparrow\\ \sqrt{2}G_{\mathrm{F}}N_e}}{\lambda}\mathbf{L} + \underset{\substack{\uparrow\\ \sqrt{2}G_{\mathrm{F}}N_\nu}}{\mu}\mathbf{P}) \times \mathbf{P}_{\omega,\mathbf{v}}$$

Drops out for stationary solutions

$$\partial_r \mathbf{P}_{\omega,v} = \frac{\omega\mathbf{B} + \lambda\mathbf{L} + \mu\mathbf{P}}{v_r} \times \mathbf{P}_{\omega,v}$$

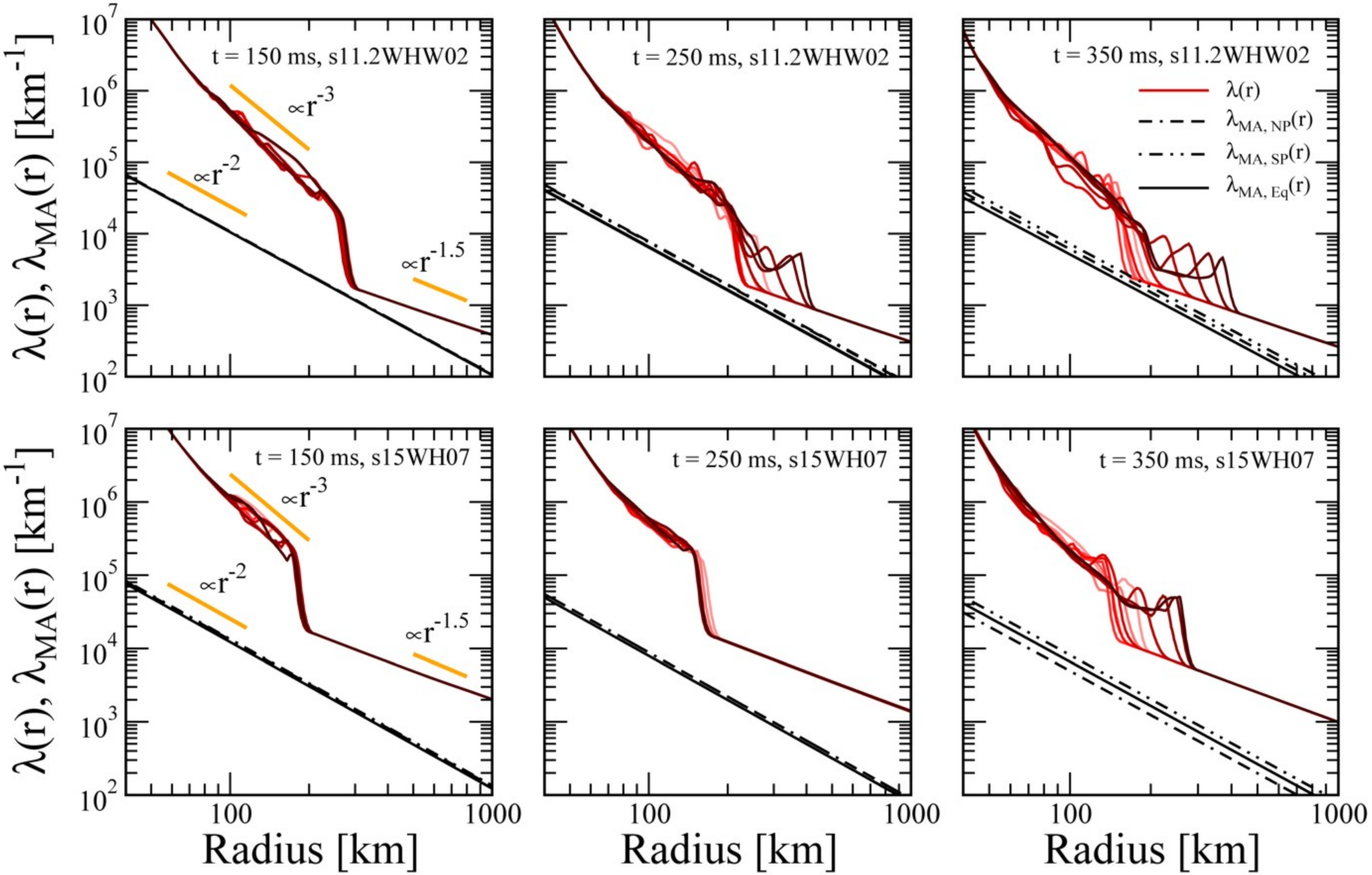


Longer path to
same radial distance:
Larger matter effect

Self-induced conversion suppressed for $N_e \gtrsim N_\nu$

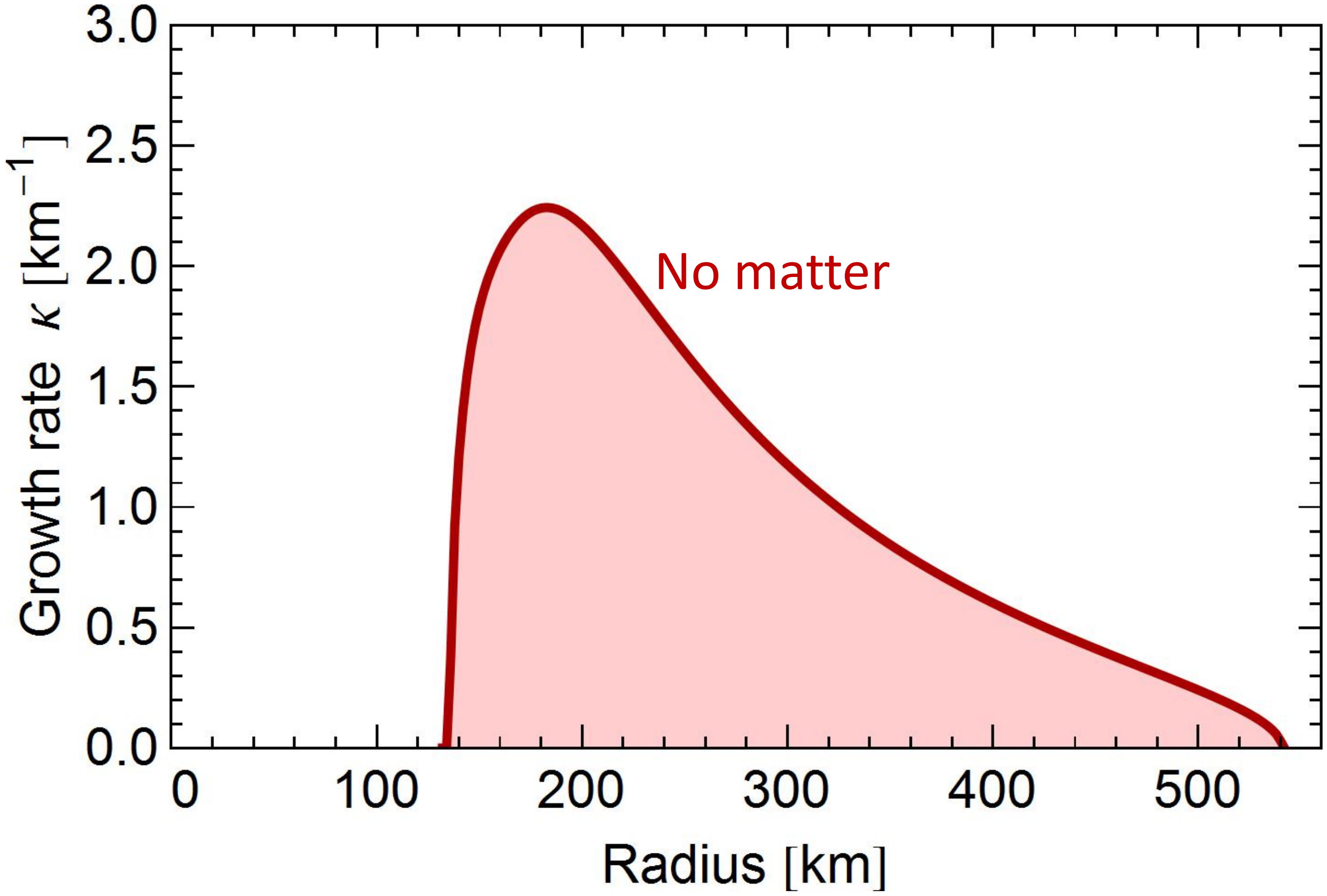
Esteban-Pretel, Mirizzi, Pastor, Tomàs, Raffelt, Serpico & Sigl, arXiv:0807.0659

Accretion-Phase Matter Profiles



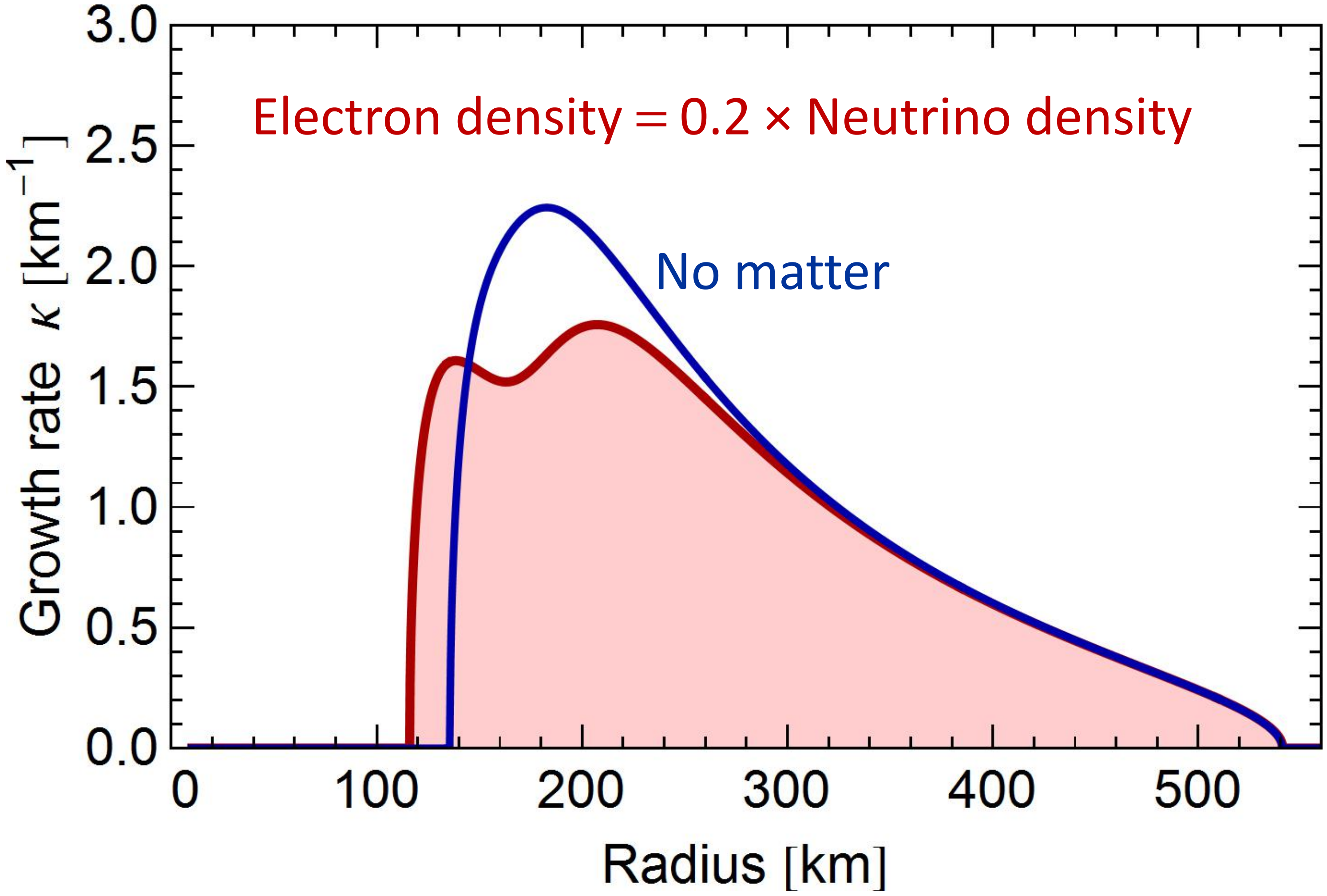
Dasgupta, O'Connor & Ott, arXiv:1106.1167

Multi-Angle Matter Suppression



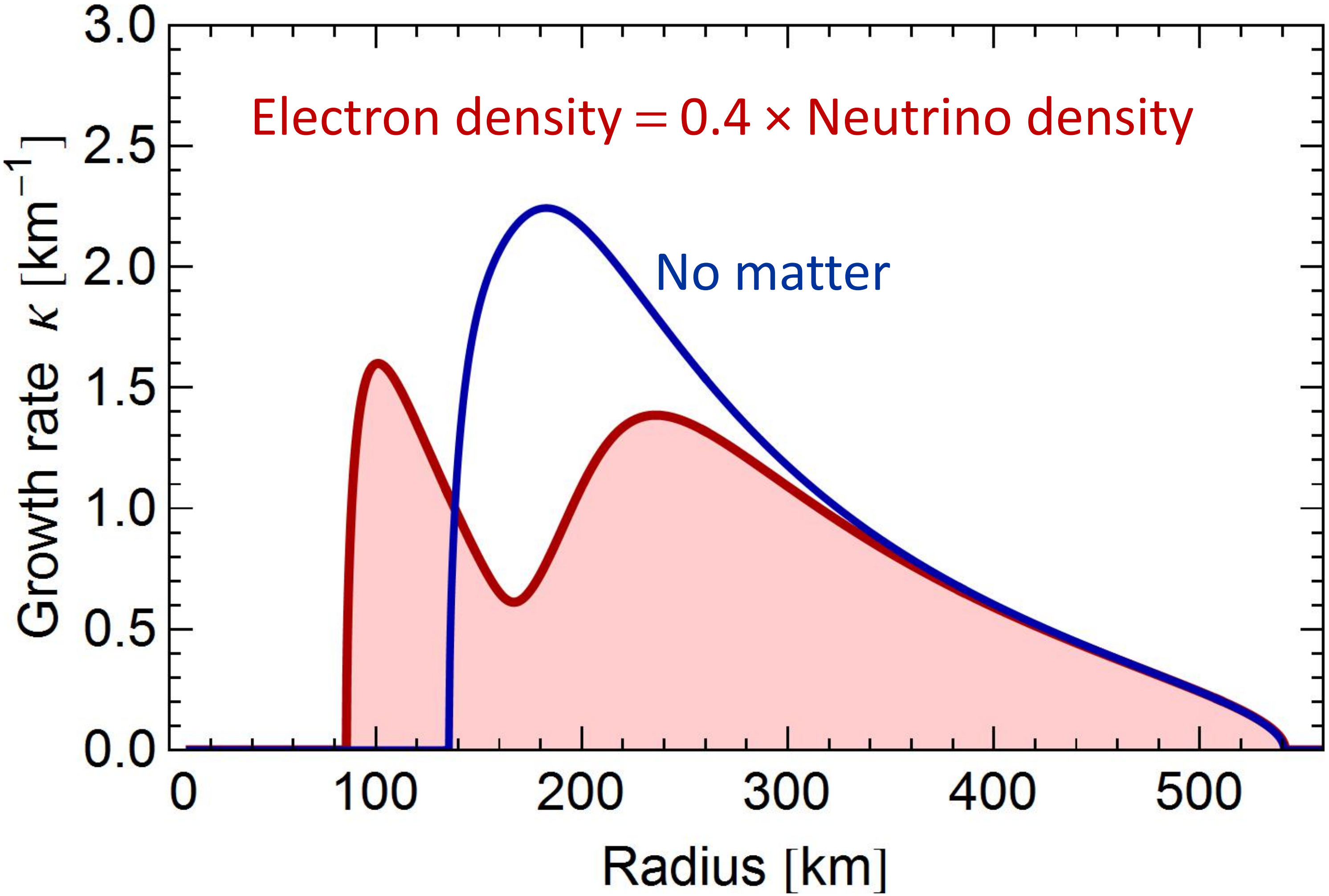
Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

Multi-Angle Matter Suppression



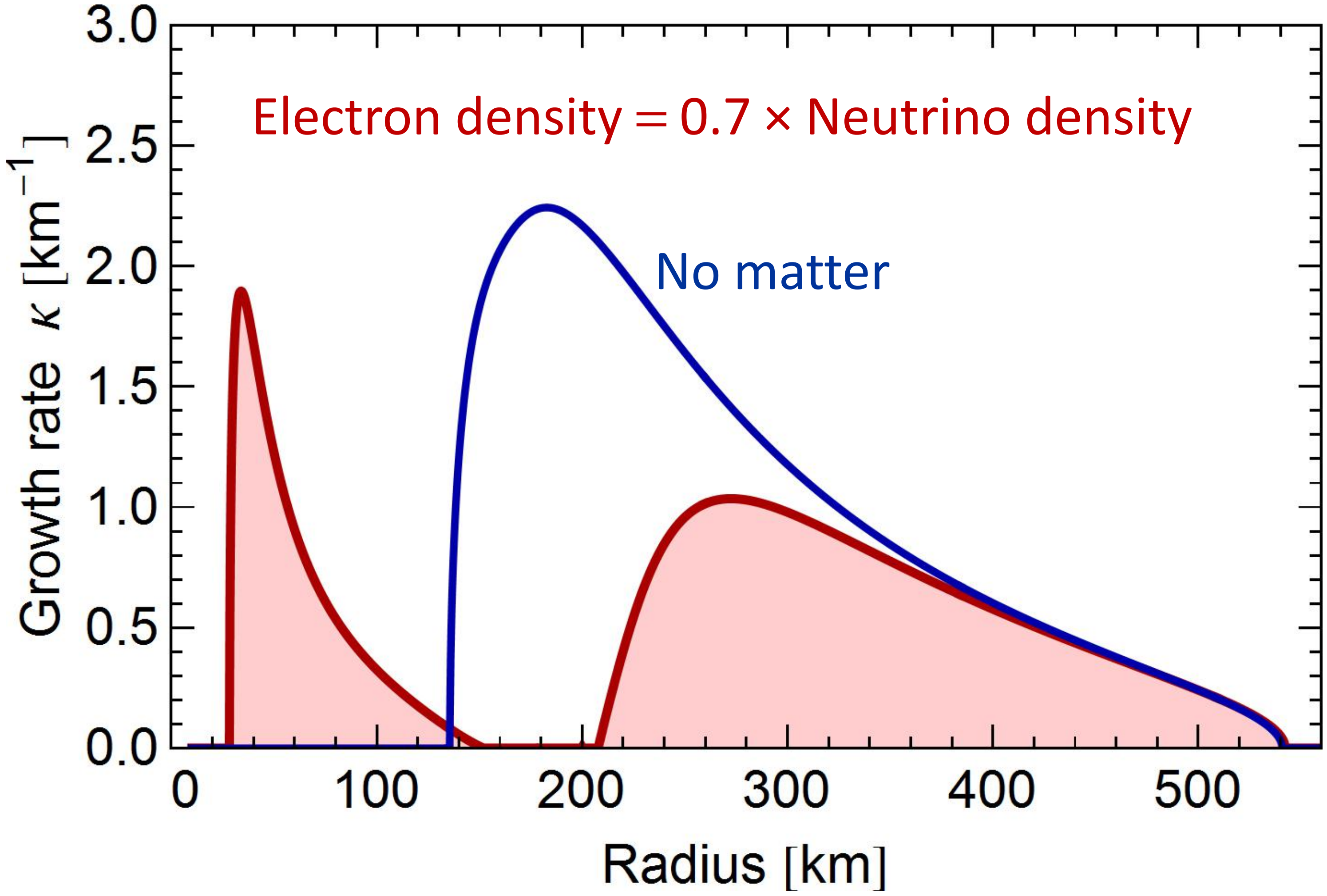
Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

Multi-Angle Matter Suppression



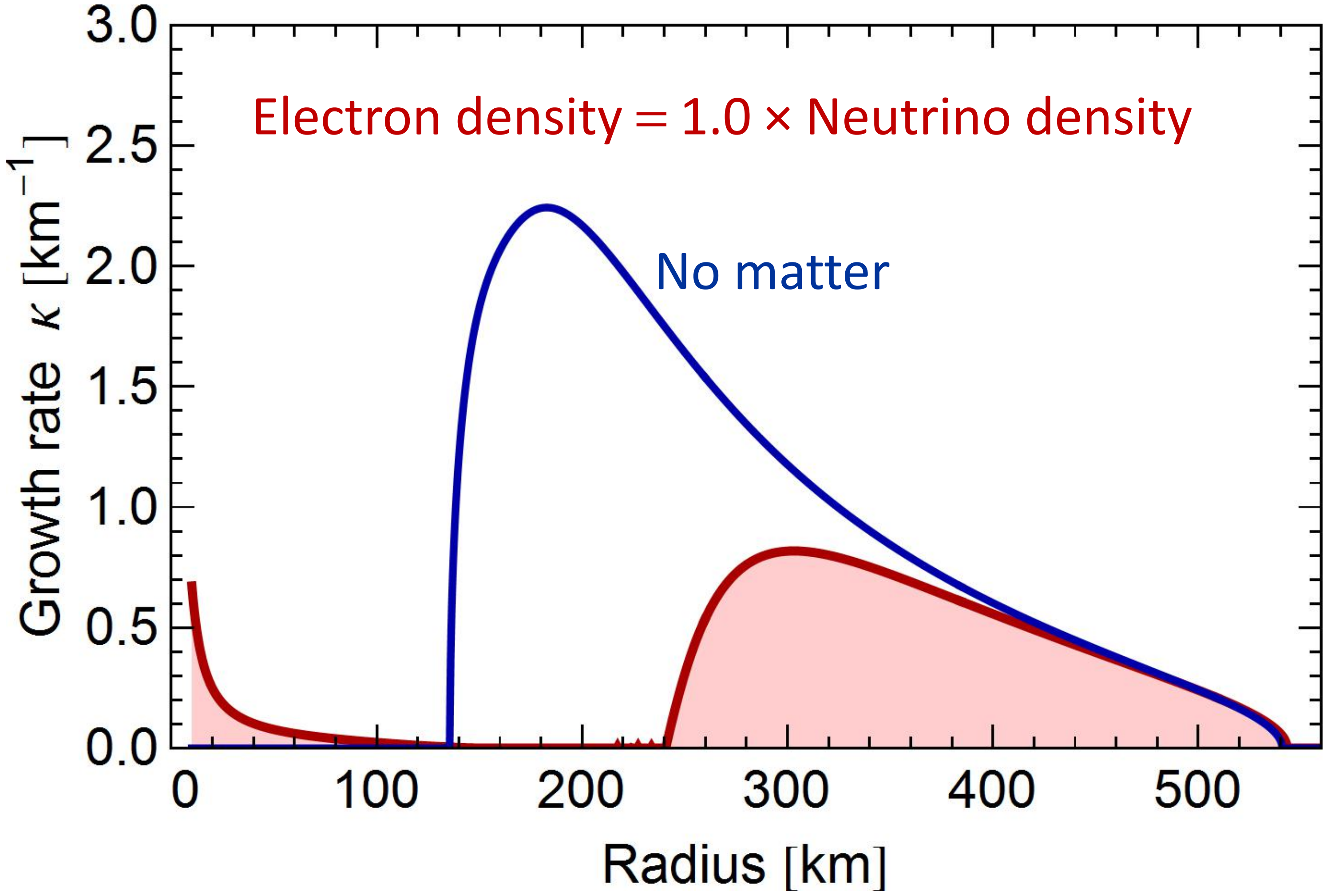
Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

Multi-Angle Matter Suppression



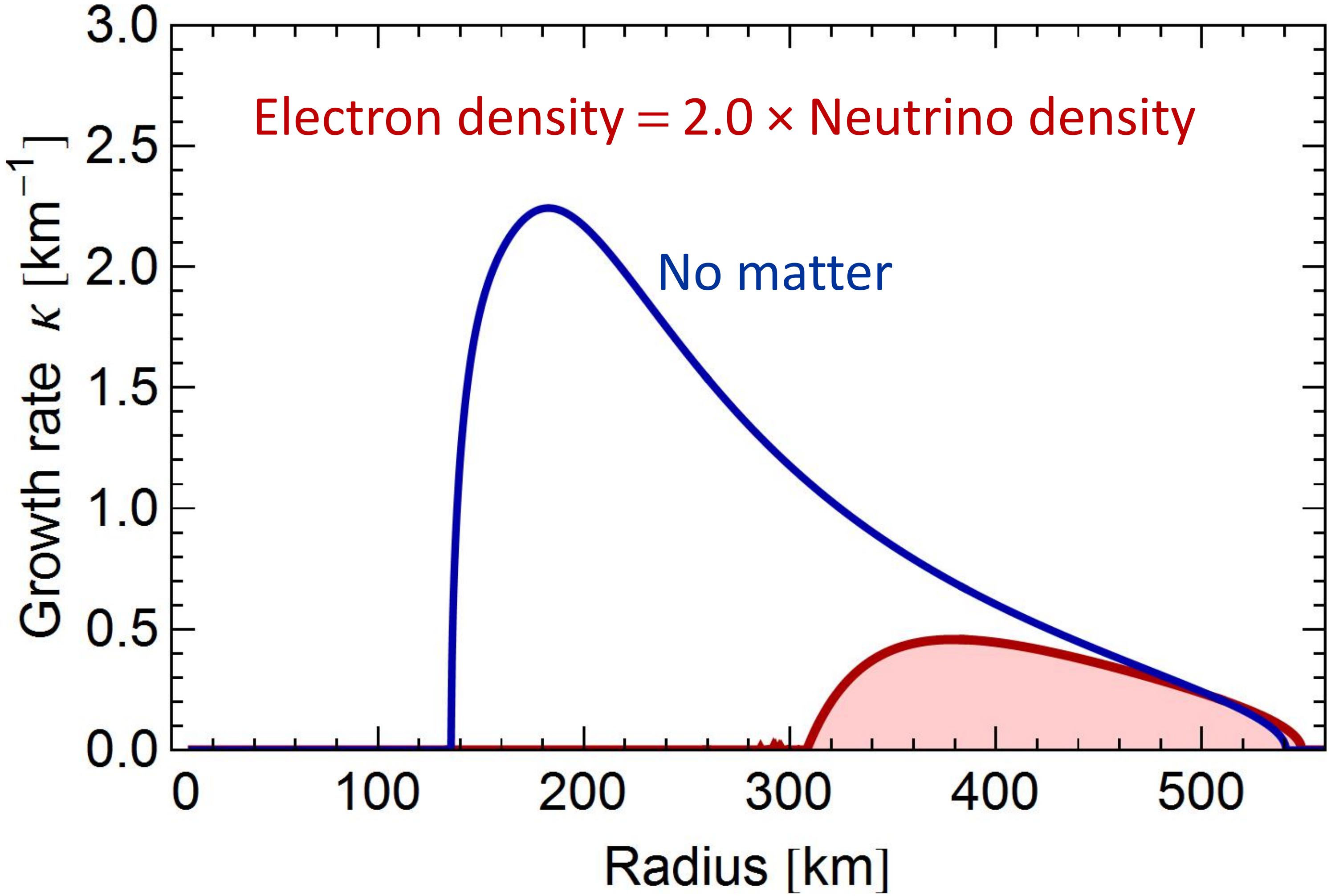
Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

Multi-Angle Matter Suppression



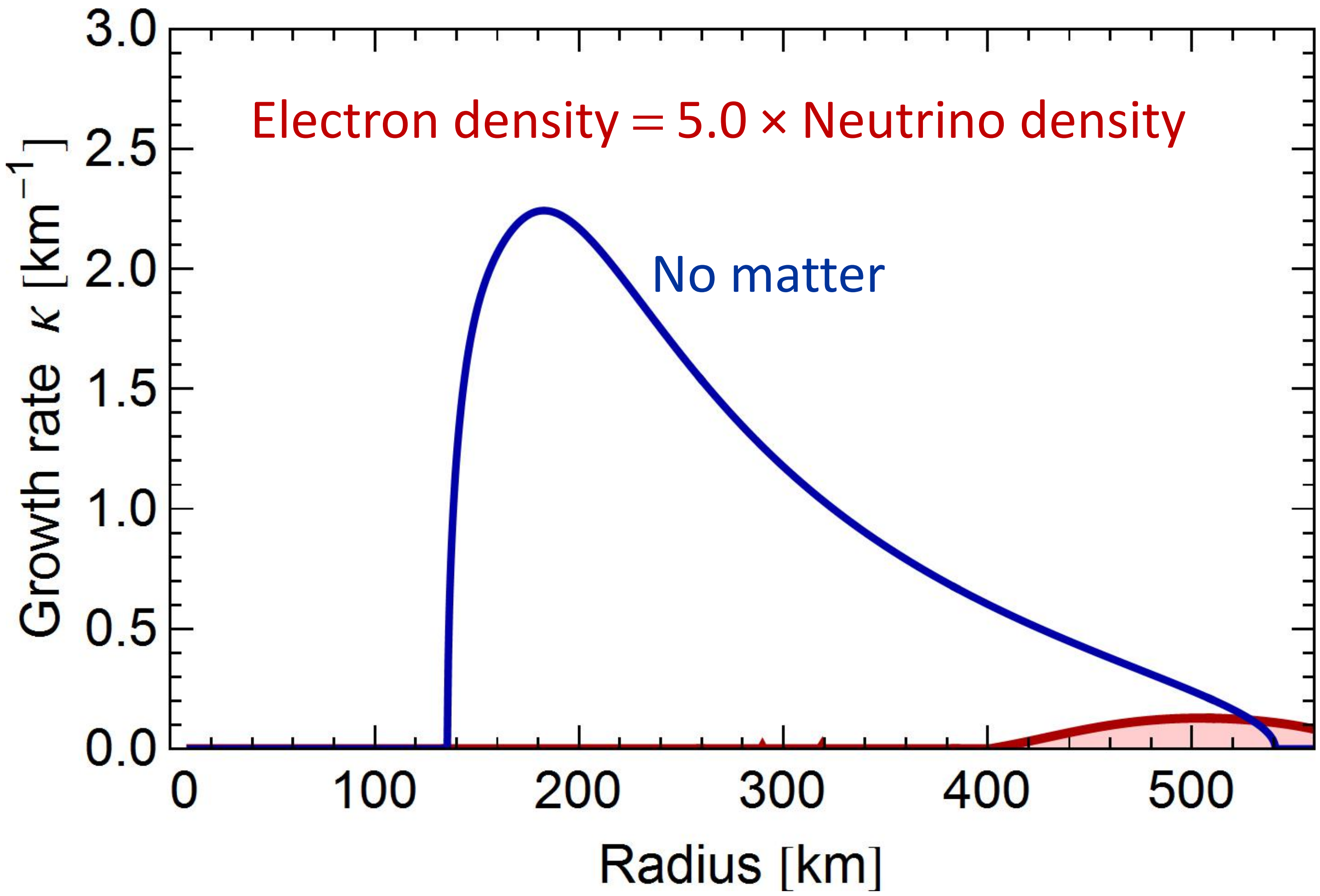
Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

Multi-Angle Matter Suppression



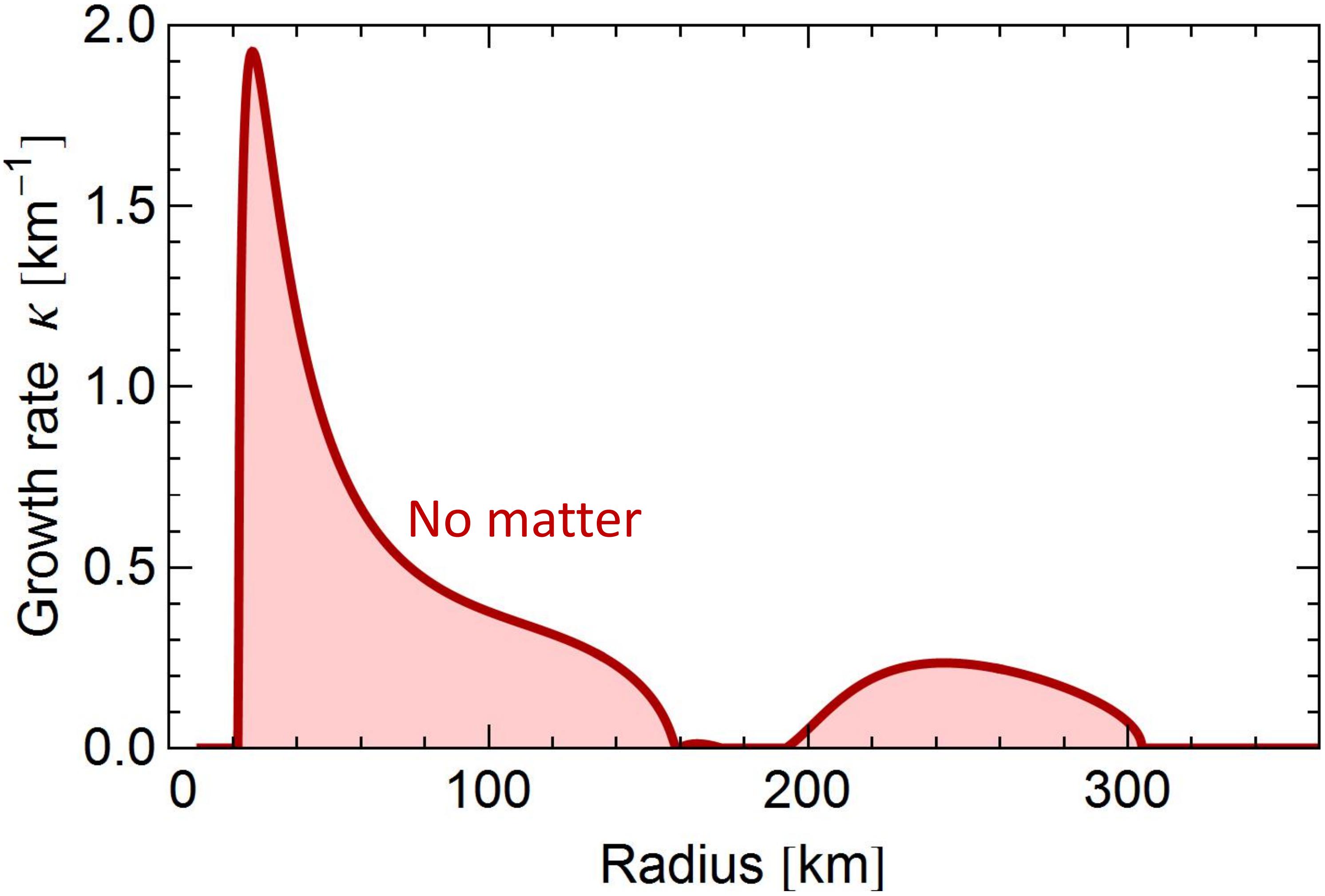
Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

Multi-Angle Matter Suppression



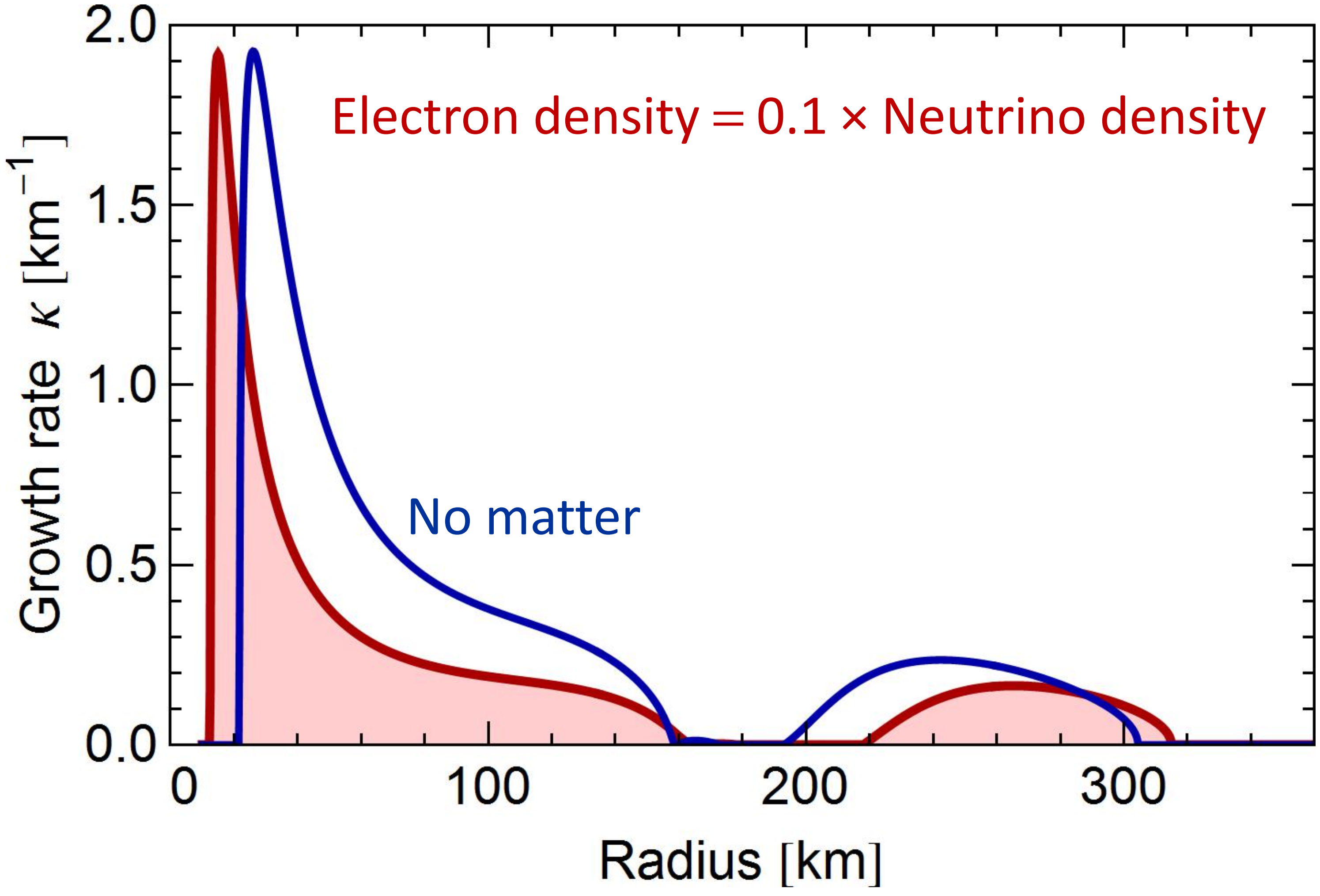
Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

Multi-Angle Matter Suppression (NH)



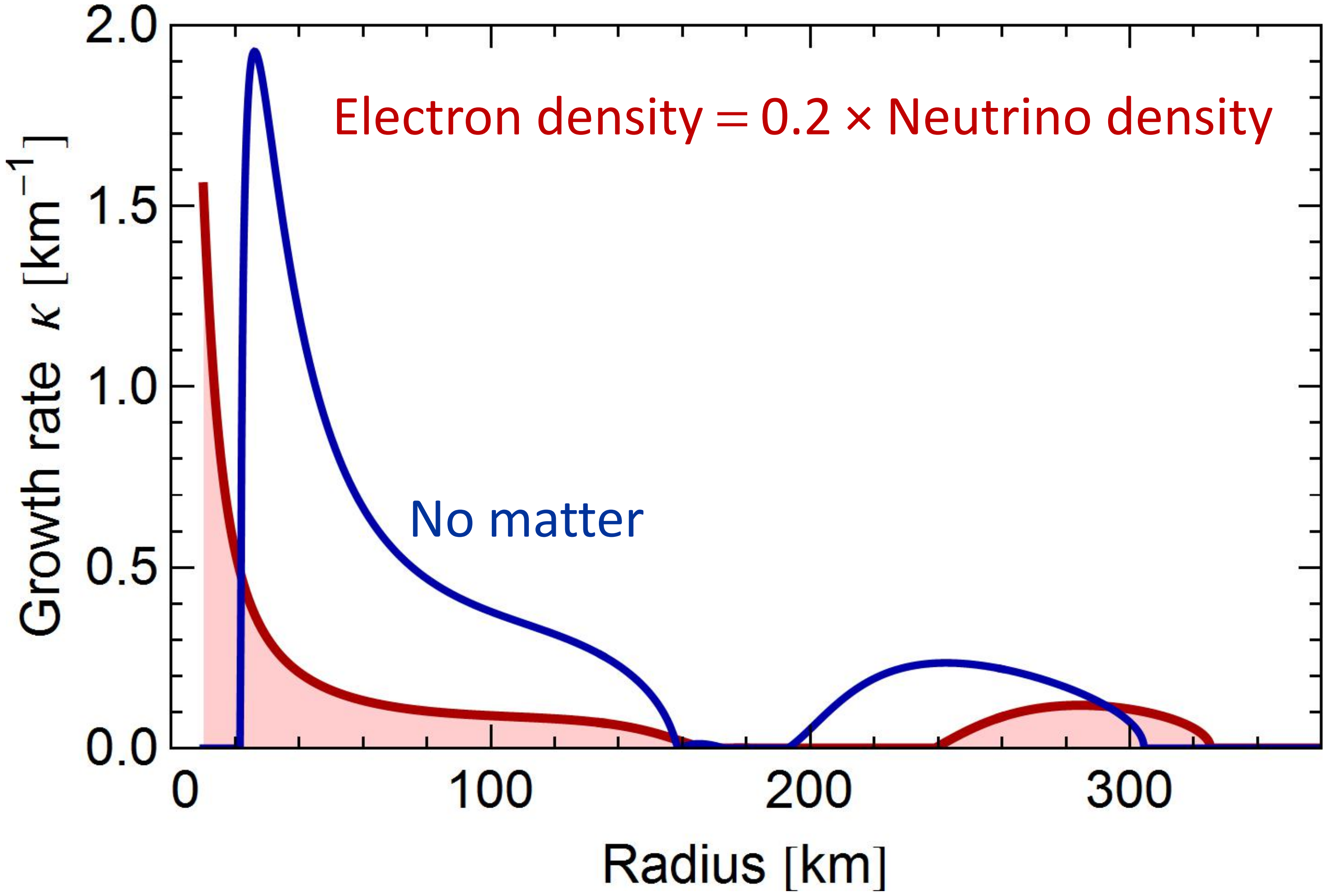
Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

Multi-Angle Matter Suppression (NH)



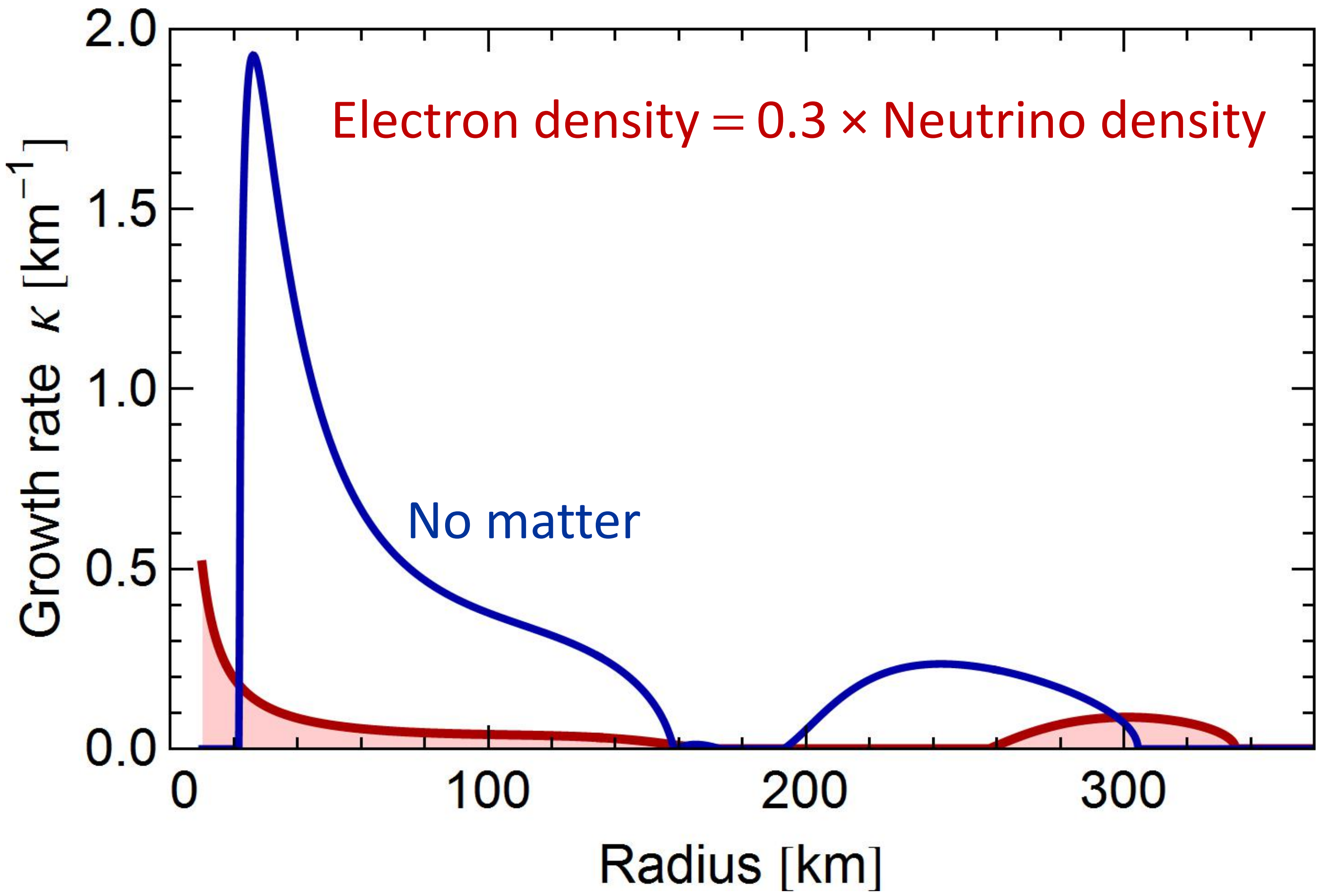
Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

Multi-Angle Matter Suppression (NH)



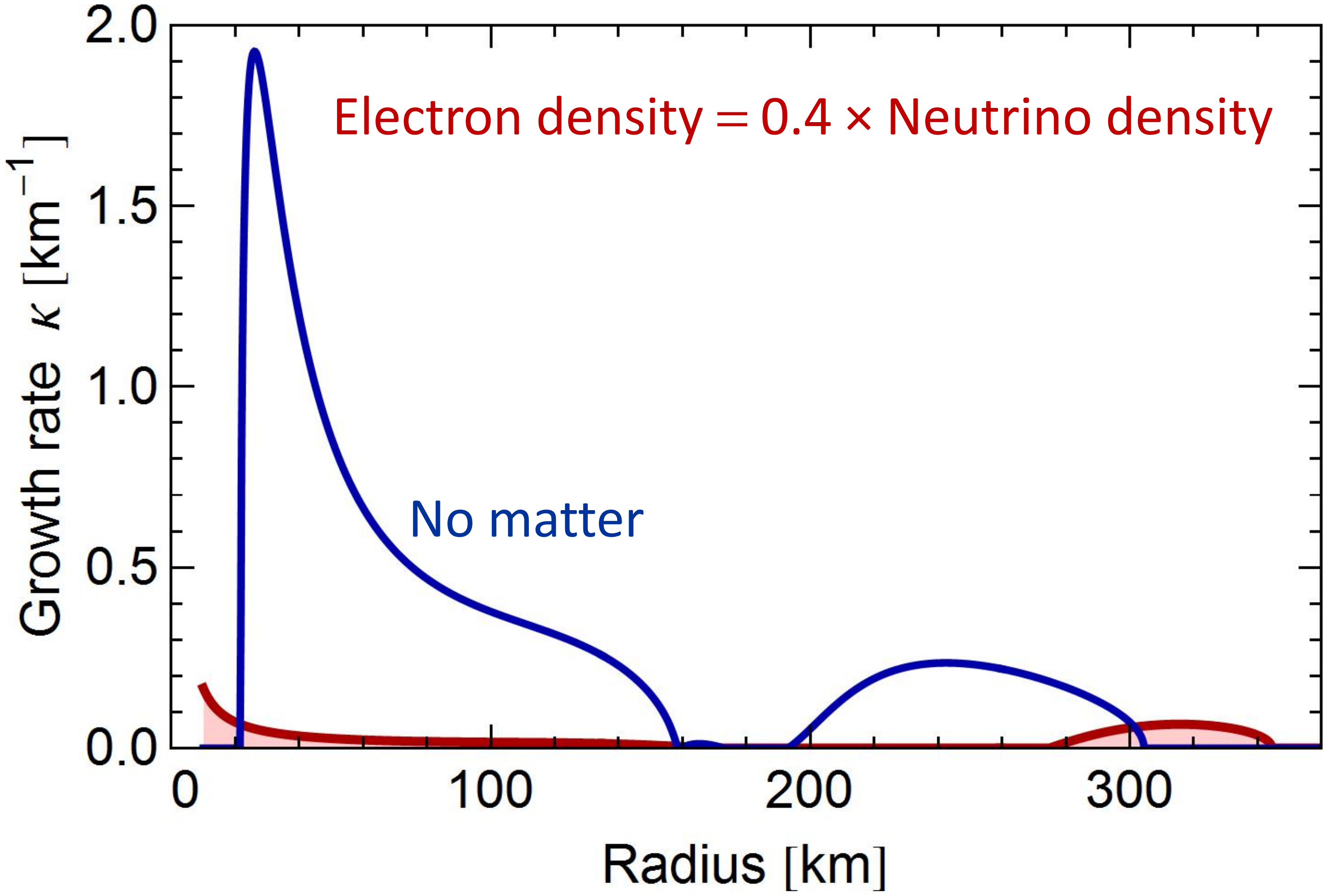
Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

Multi-Angle Matter Suppression (NH)



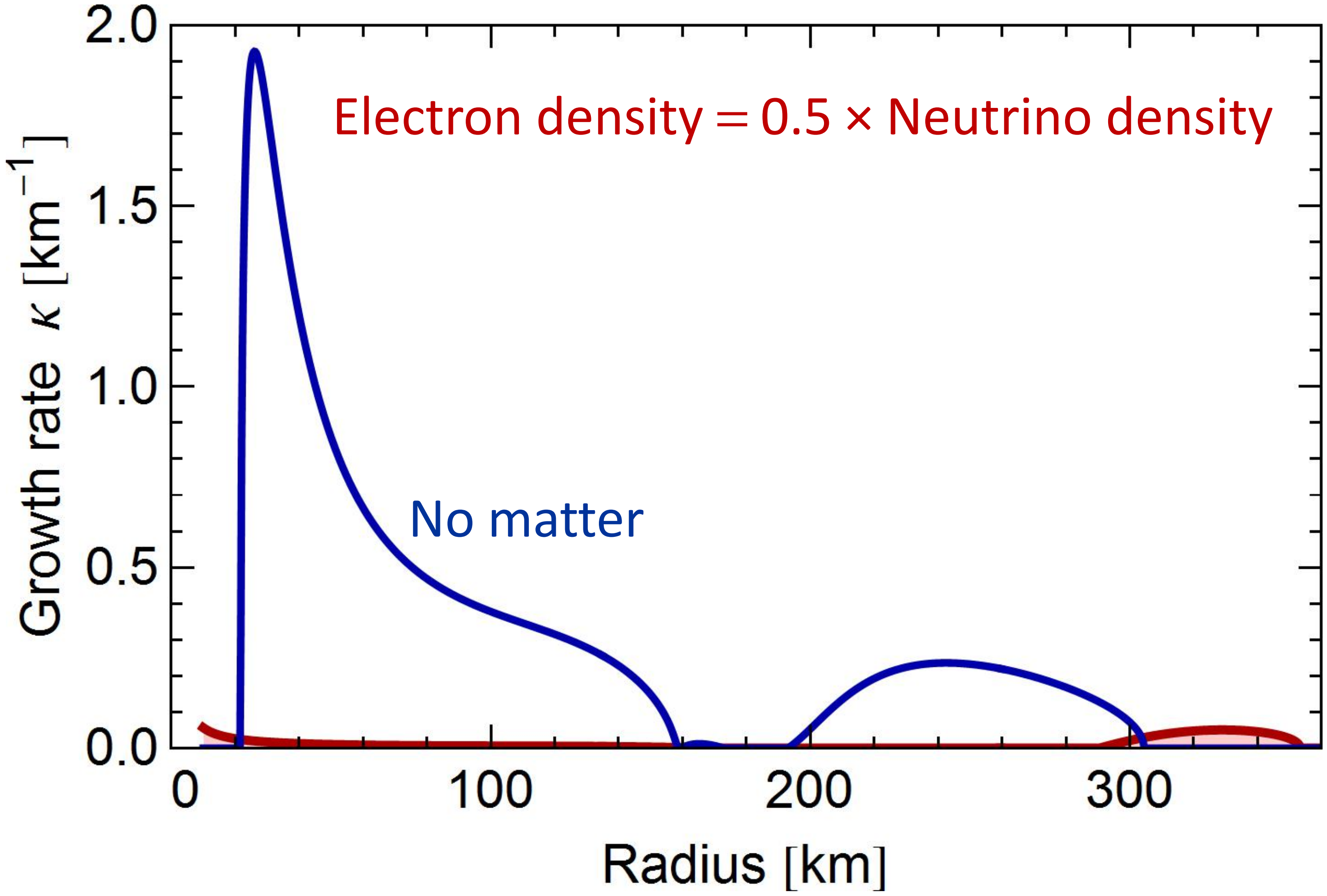
Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

Multi-Angle Matter Suppression (NH)



Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

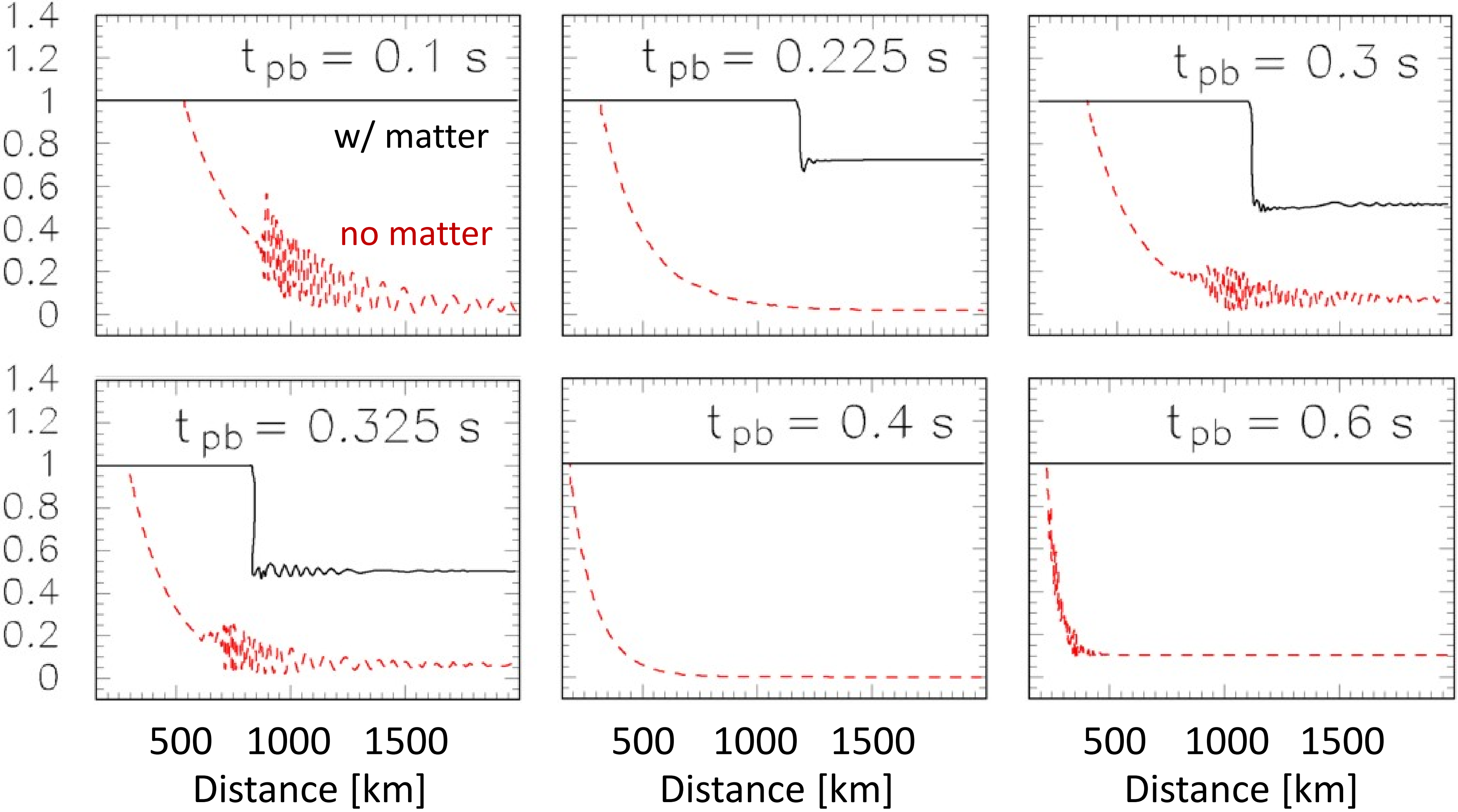
Multi-Angle Matter Suppression (NH)



Sarikas, Seixas, Tamborra & Raffelt, work in progress (2012)

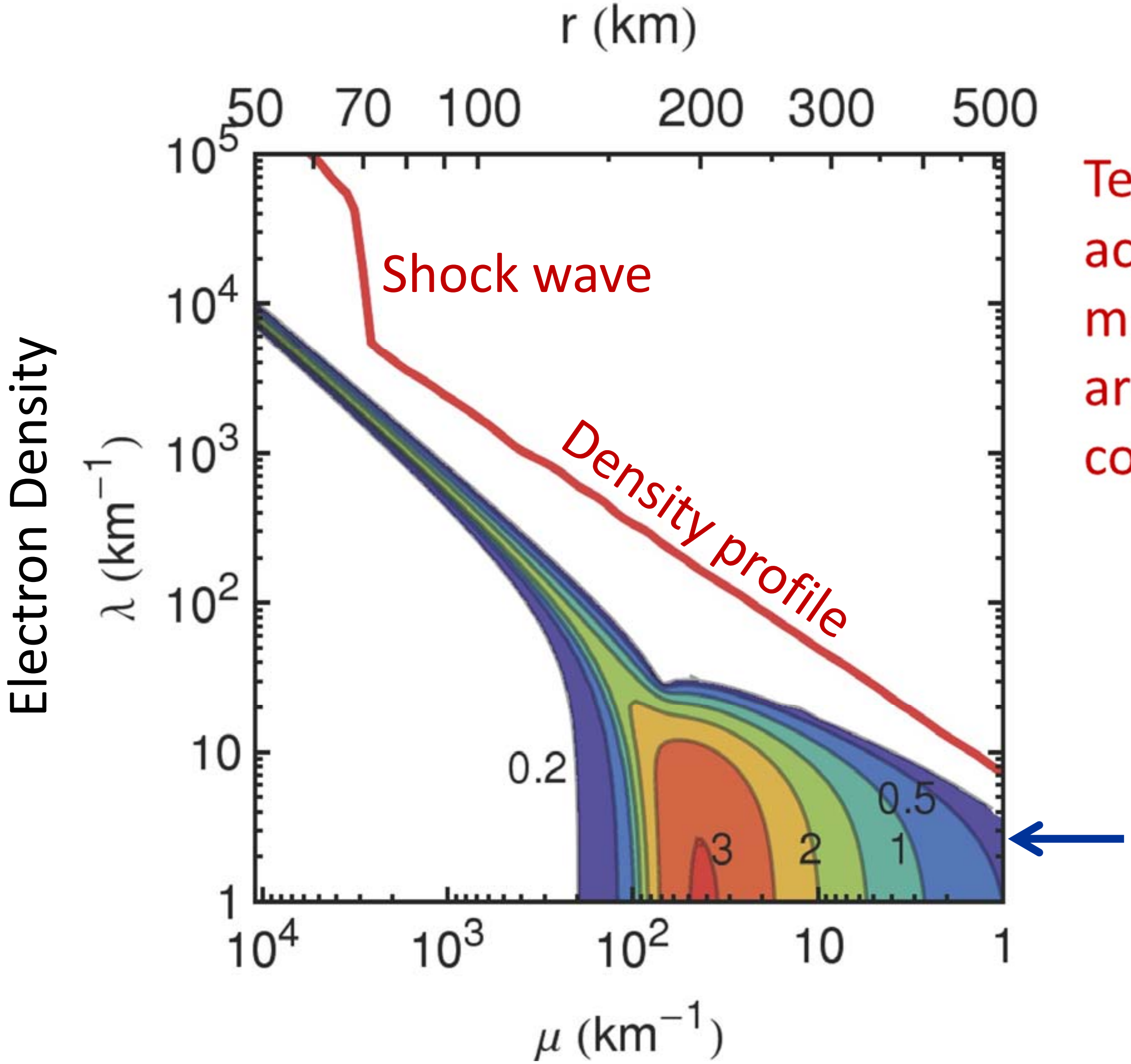
Multi-Angle Matter Effect (Basel Model 10.8 M_{sun})

Schematic single-energy, multi-angle simulations with realistic density profile



Chakraborty, Fischer, Mirizzi, Saviano & Tomàs, arXiv:1105.1130

Multi-Angle Multi-Energy Stability Analysis



Shock wave

Density profile

Tested 15 $M_\odot$ accretion-phase models (Garching) are stable against collective flavor conversion

Contours of growth rate κ [km^{-1}]

Sarikas, Raffelt, Hüdepohl & Janka, arXiv:1109.3601

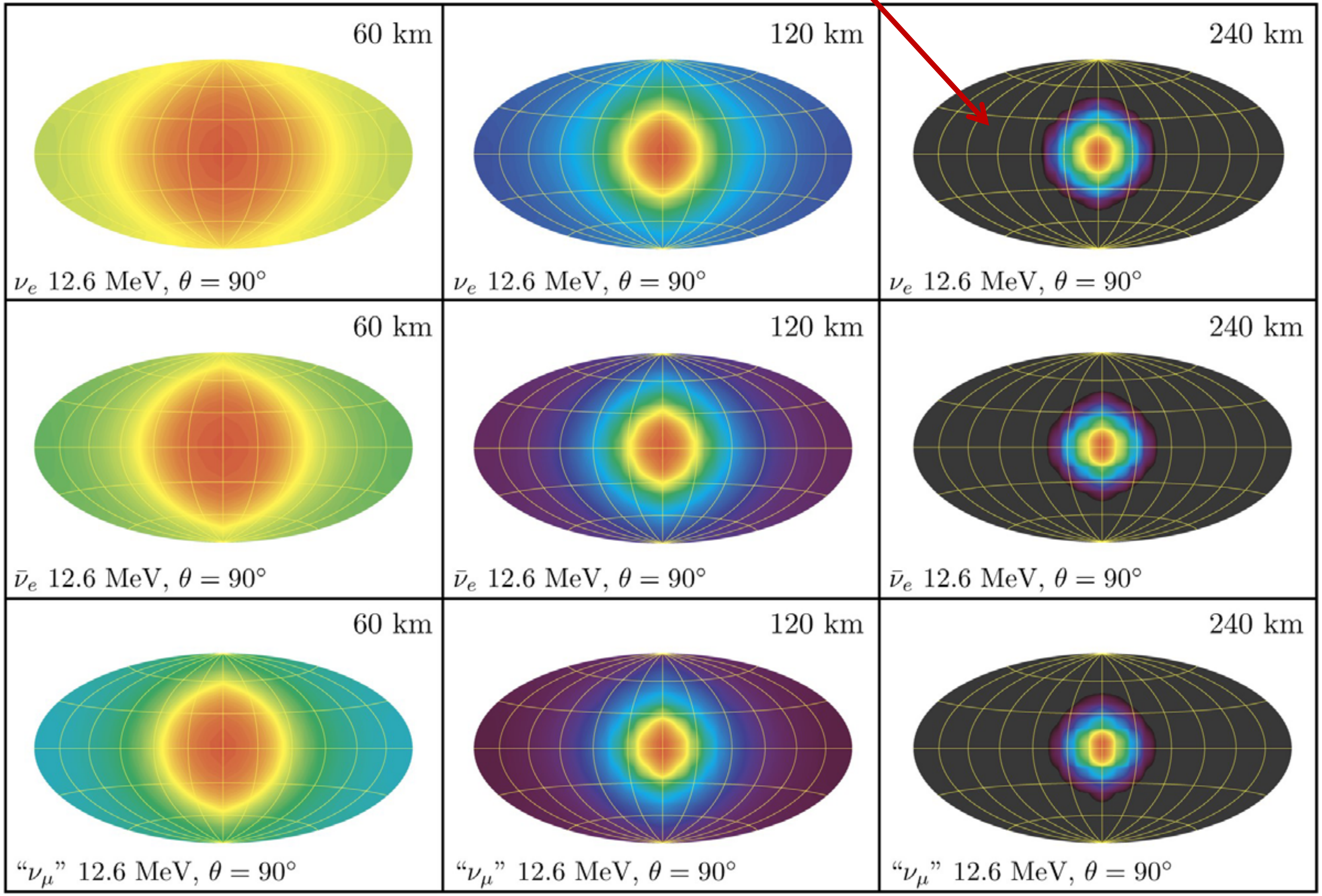
Required Neutrino Information

To investigate neutrino oscillations in SNe need

- Profile of electron density
- Flavor-dependent neutrino flux spectra
- Flavor-dependent neutrino angular distribution

Neutrino Radiation Field

Small “scattering halo” important for nu-nu refraction? (Cherry et al., arXiv:1203.1607)

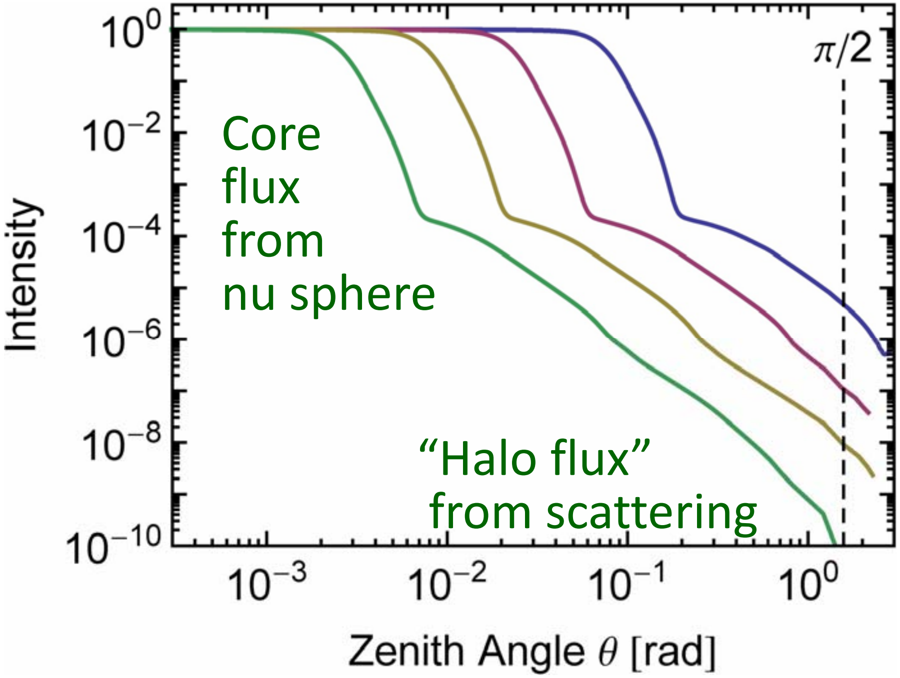


Picture from Ott, Burrows, Dessart & Livne, arXiv:0804.0239

Scattered Neutrinos as a Source of Refraction

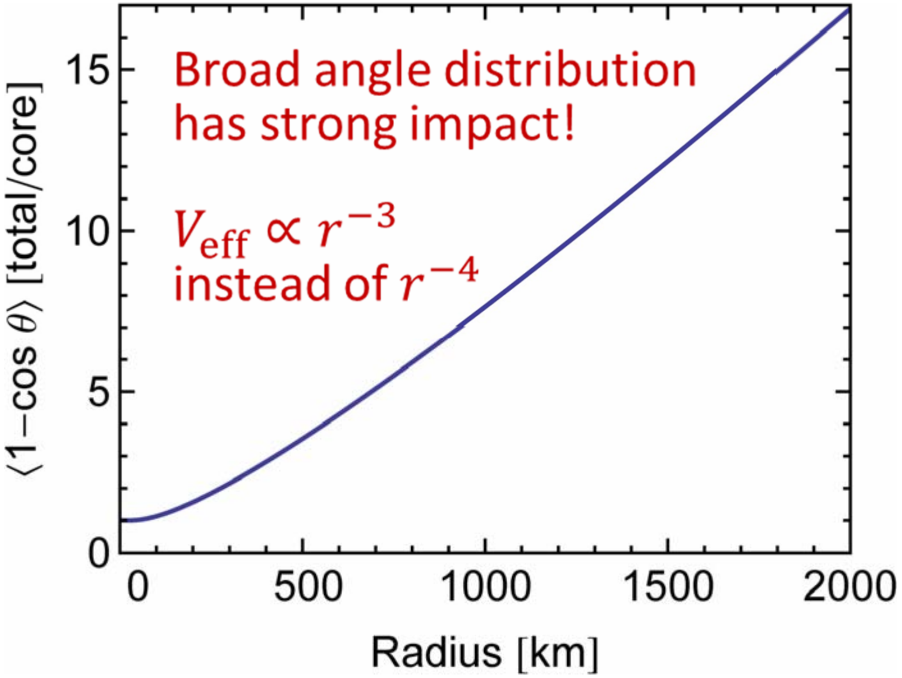
SN neutrino angle distribution seen at 10^4, 3000, 1000 and 300 km

Relative importance of halo for nu-nu refractive potential



Core flux from nu sphere

"Halo flux" from scattering

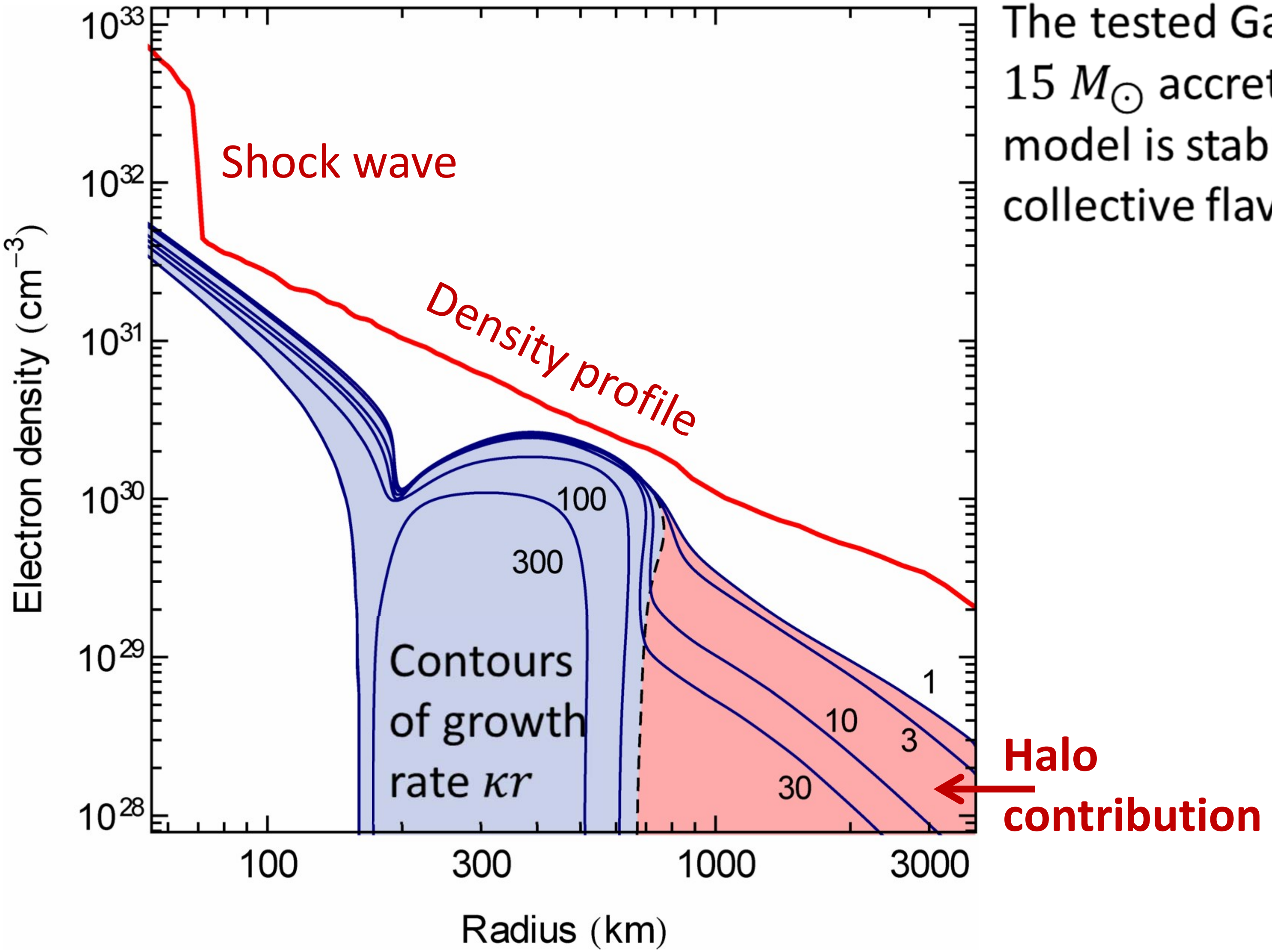


Broad angle distribution has strong impact!

$V_{\mathrm{eff}} \propto r^{-3}$ instead of r^{-4}

Cherry, Carlson, Friedland, Fuller & Vlasenko, arXiv:1203.1607
Sarikas, Tamborra, Raffelt, Hüdepohl & Janka, arXiv:1204.0971

Multi-Angle Matter Suppression in Realistic Model



The tested Garching $15\ M_\odot$ accretion-phase model is stable against collective flavor conversion

Sarikas, Tamborra, Raffelt, Hüdepohl & Janka, arXiv:1109.3601, 1204.0971

Summary

Supernova neutrino flavor evolution remains a complicated subject

- Axial symmetry was always assumed – too symmetric?
- Numerical treatments challenging
- Novel role for neutrino “scattering halo”?
- Simultaneous space and time dependence important?

Theoretical developments

- Analogy to BCS theory
- Linearized stability analysis provides many conceptual insights
- And practical results

Working hypothesis for SN neutrinos

- Multi-angle matter effect can prevent instability
- No collective conversion during early accretion phase
- Can test for nu mass hierarchy (because θ_{13} is large)

More theory progress is needed to reliably interpret neutrino signal of next galactic supernova!