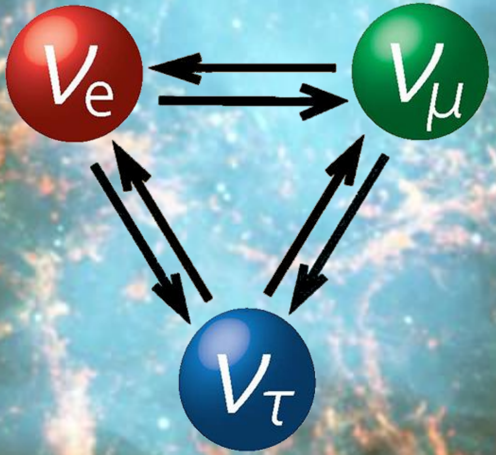
New Developments in Supernova Neutrino Oscillations



Georg Raffelt, Max-Planck-Institut für Physik, München

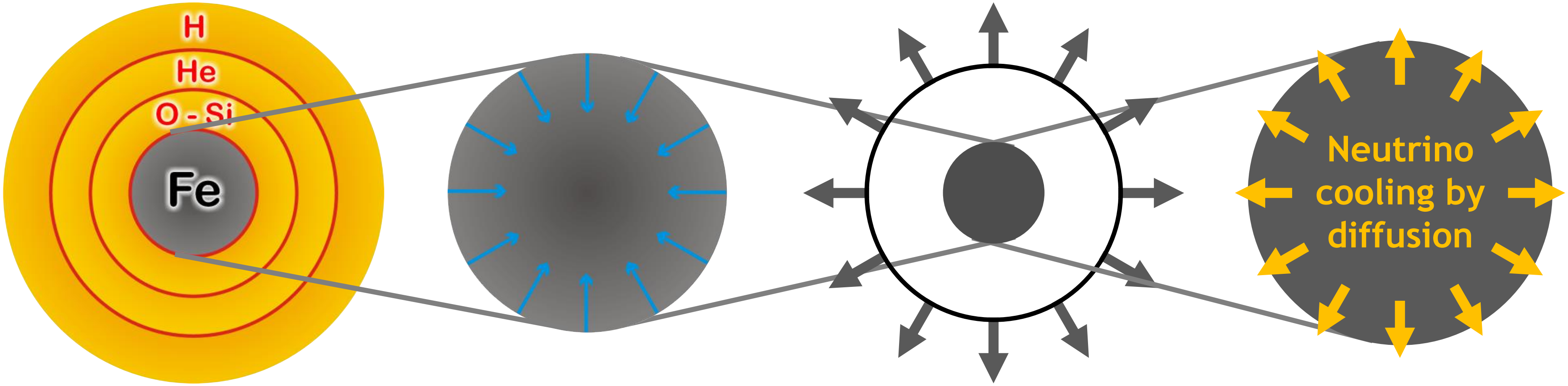
Core-Collapse Supernova Explosion

End state of a massive star
$M \gtrsim 6\text{–}8\,M_\odot$

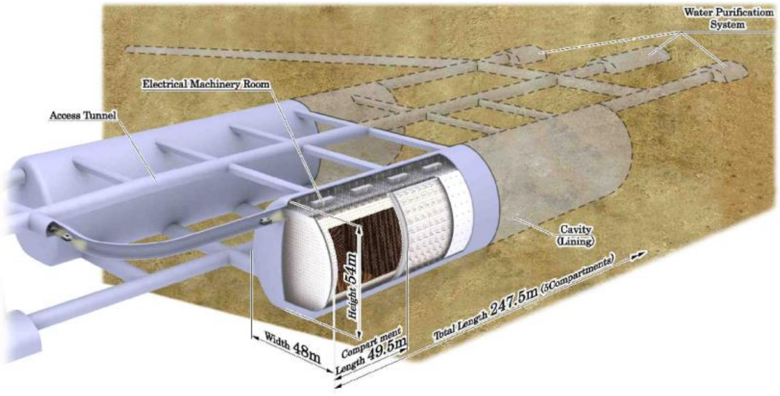
Collapse of degenerate core

Bounce at ρ_{nuc}
Shock wave forms explodes the star

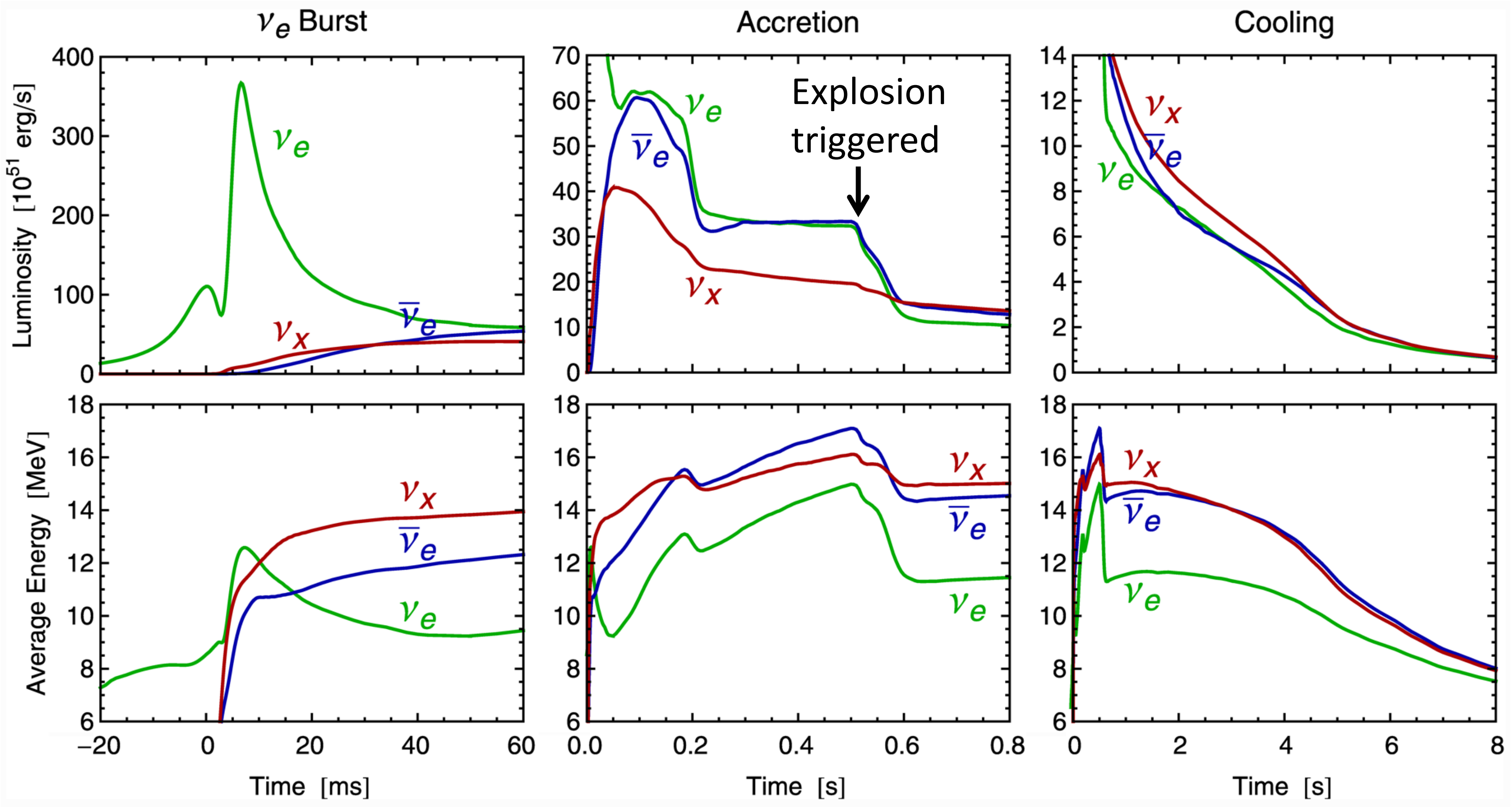
Grav. binding E
$\sim 3 \times 10^{53}$ erg
emitted as nus of all flavors



- Huge rate of low-E neutrinos (tens of MeV) over few seconds in large-volume detectors
- A few core-collapse SNe in our galaxy per century
- Once-in-a-lifetime opportunity



Three Phases of Neutrino Emission



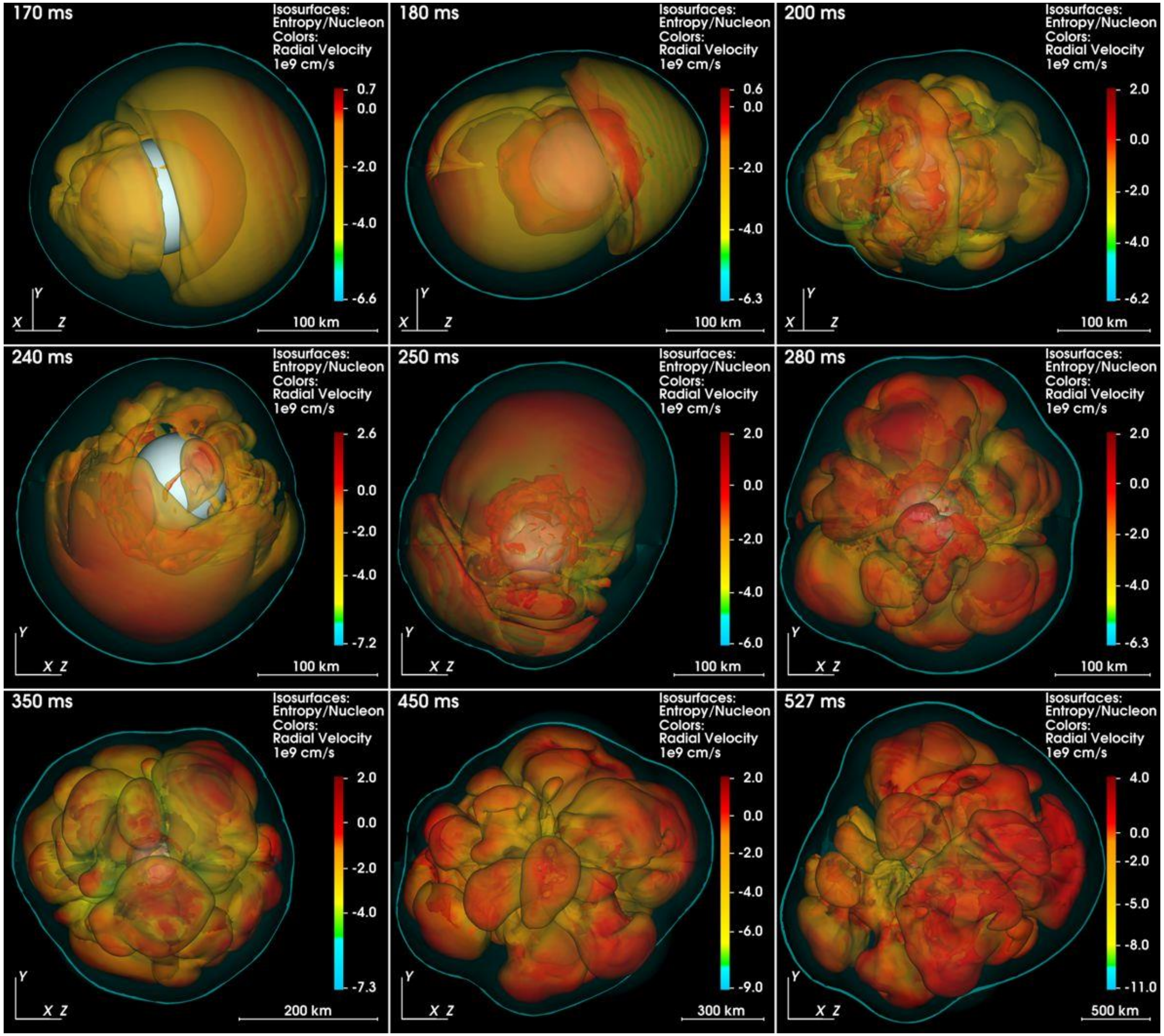
- Shock breakout
- De-leptonization of outer core layers

- Shock stalls ~ 150 km
- Neutrinos powered by infalling matter

Cooling on neutrino diffusion time scale

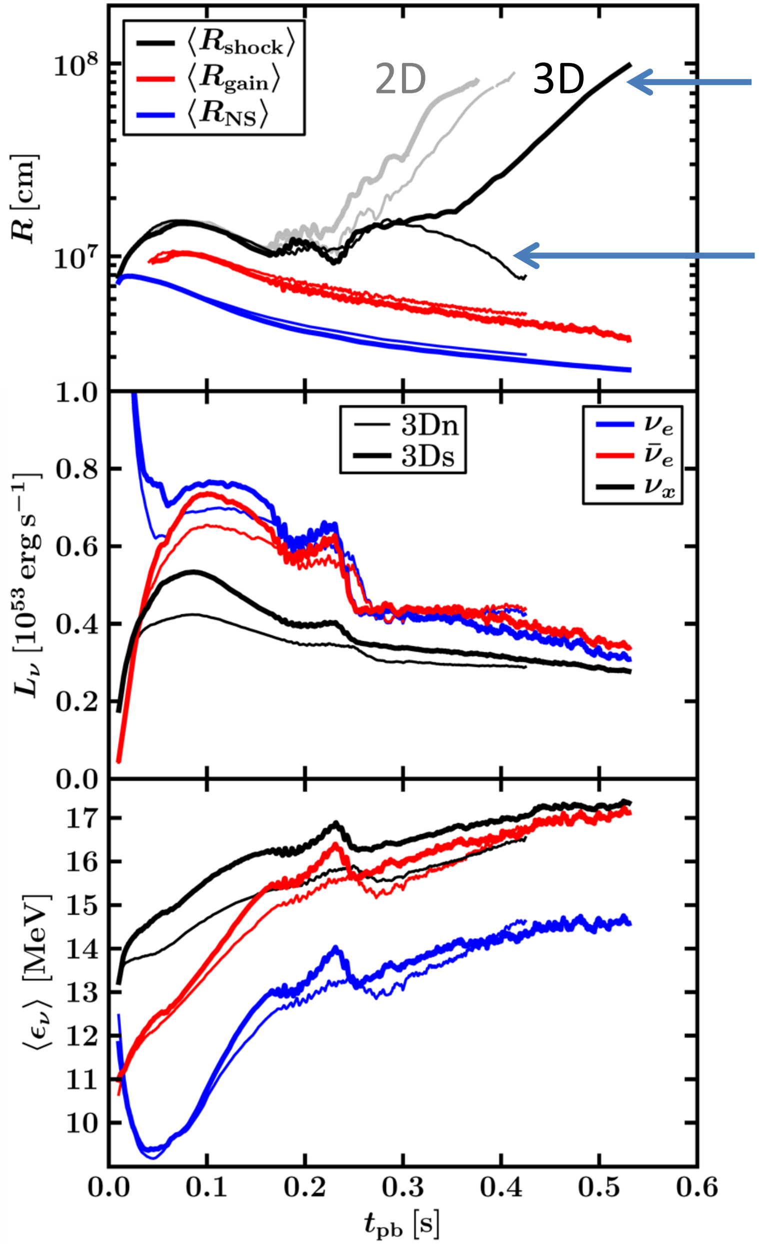
Spherically symmetric Garching model (25 $M_\odot$) with Boltzmann neutrino transport

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



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

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

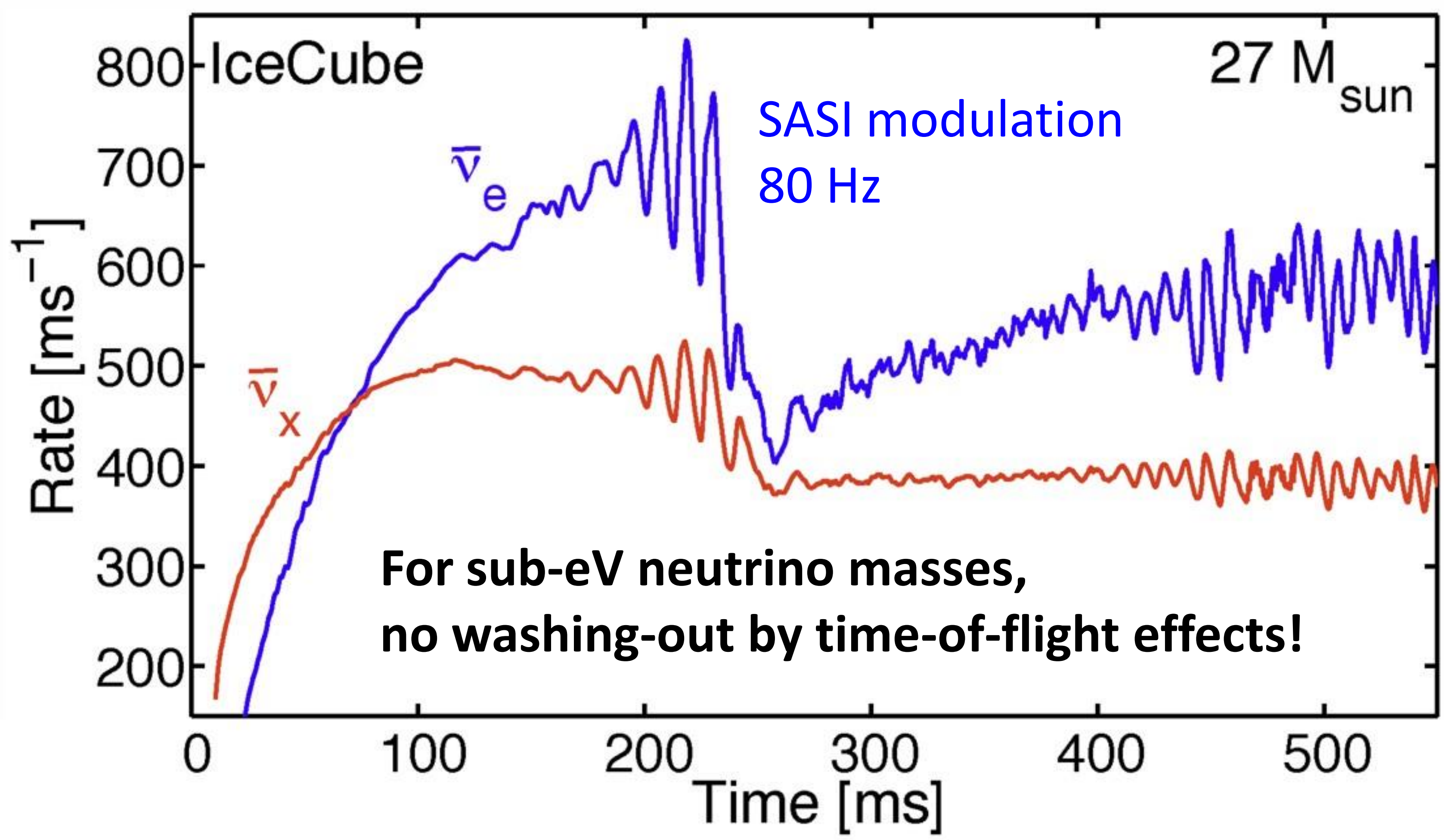


Neutrino opacity reduced (few 10%) by strange quark contribution to nucleon spin (thick lines)

“Standard” neutrino opacity (thin lines)

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

Variability seen in Neutrinos (3D Model)



SASI modulation
80 Hz

**For sub-eV neutrino masses,
no washing-out by time-of-flight effects!**

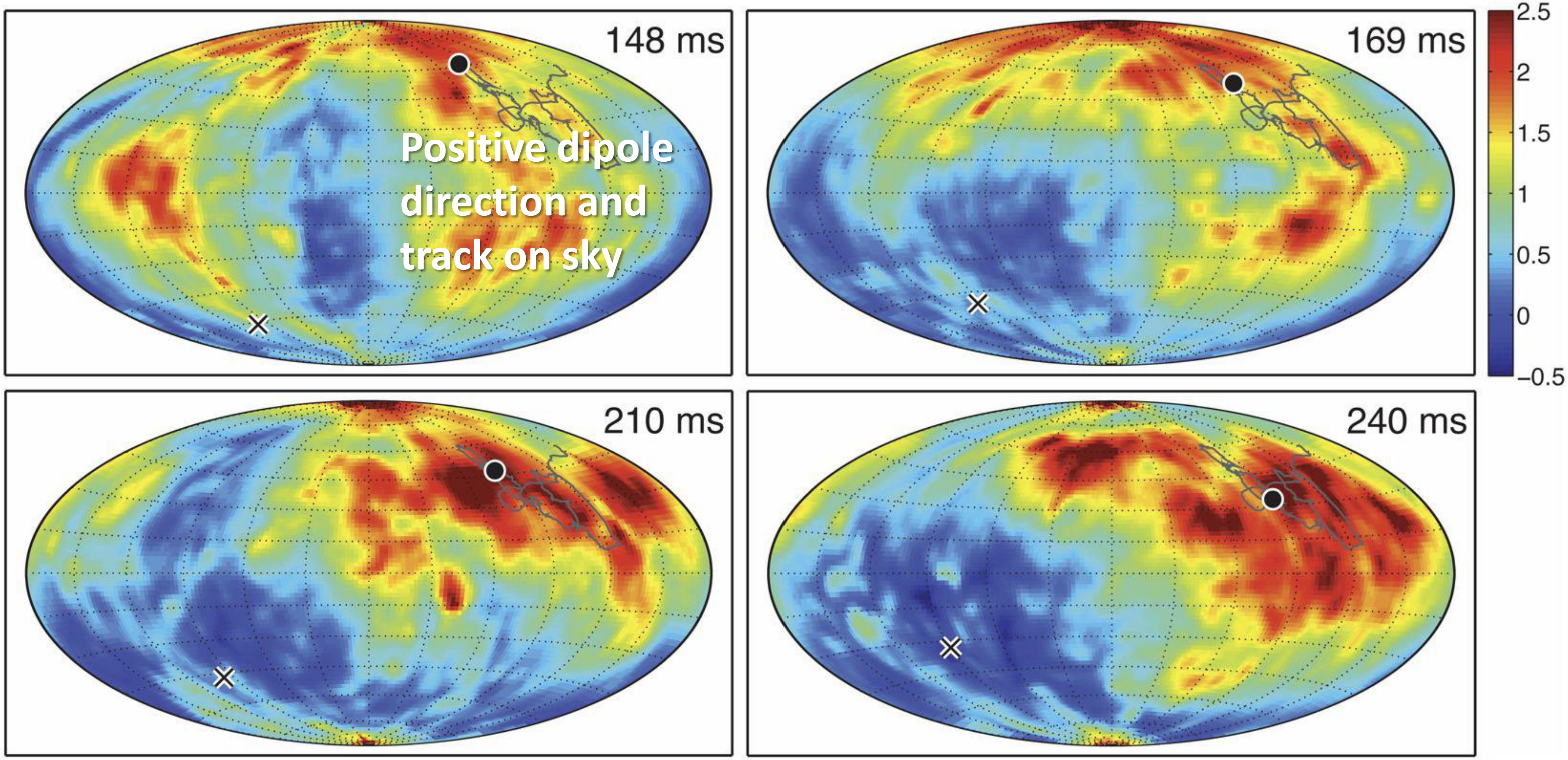
Tamborra, Hanke, Müller, Janka & Raffelt, arXiv:1307.7936
See also Lund, Marek, Lunardini, Janka & Raffelt, arXiv:1006.1889

Sky Map of Lepton-Number Flux (11.2 M_{SUN} Model)

Lepton-number flux ($\nu_e - \overline{\nu}_e$) relative to 4π average

Deleptonization flux into one hemisphere, roughly dipole distribution

(LESA — Lepton Emission Self-Sustained Asymmetry)



Positive dipole direction and track on sky

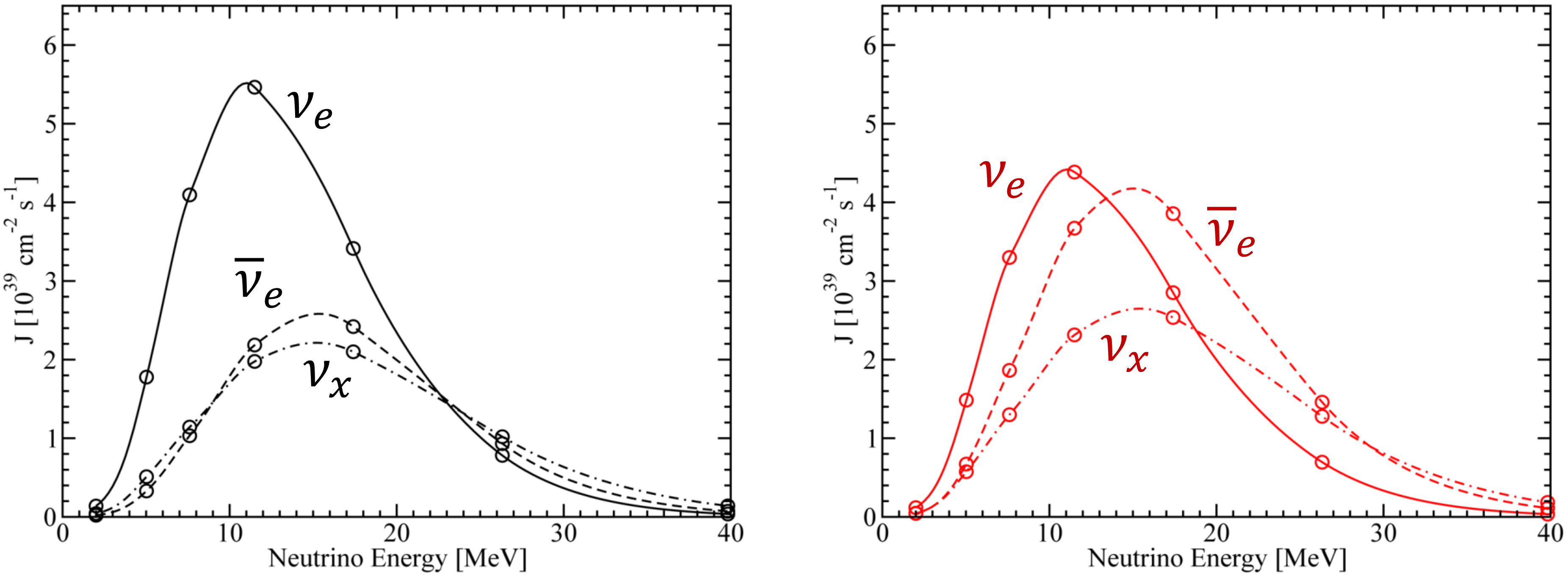
Tamborra, Hanke, Janka, Müller, Raffelt & Marek, arXiv:1402.5418

Spectra in the two Hemispheres

Neutrino flux spectra (11.2 M_{SUN} model at 210 ms) in opposite LESA directions

Direction of
maximum lepton-number flux

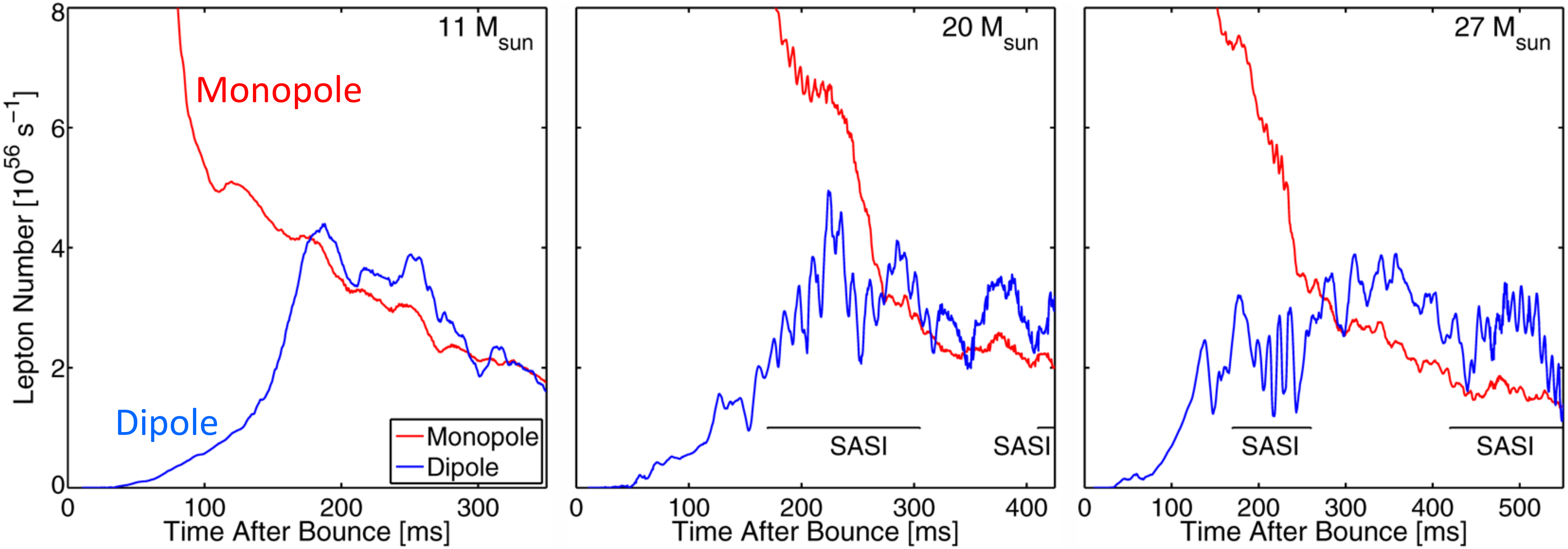
Direction of
minimum lepton-number flux



During accretion phase, flavor-dependent fluxes vary strongly with observer direction!

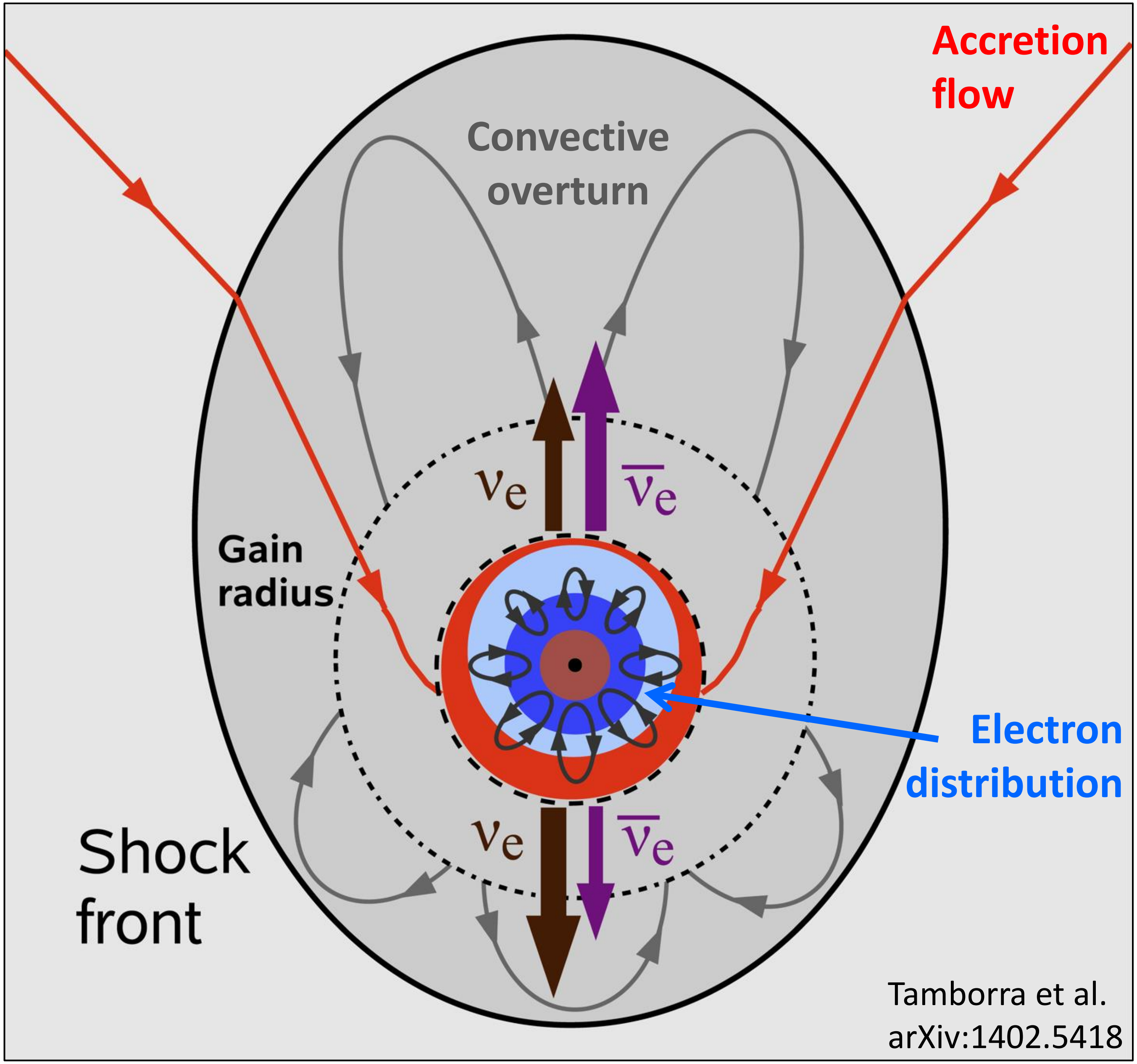
Growth of Lepton-Number Flux Dipole

Tamborra et al., arXiv:1402.5418



- Overall lepton-number flux (monopole) depends on accretion rate, varies between models
- Maximum dipole similar for different models
- Dipole persists (and even grows) during SASI activity
- SASI and LESA dipoles uncorrelated

Schematic Theory of LESA

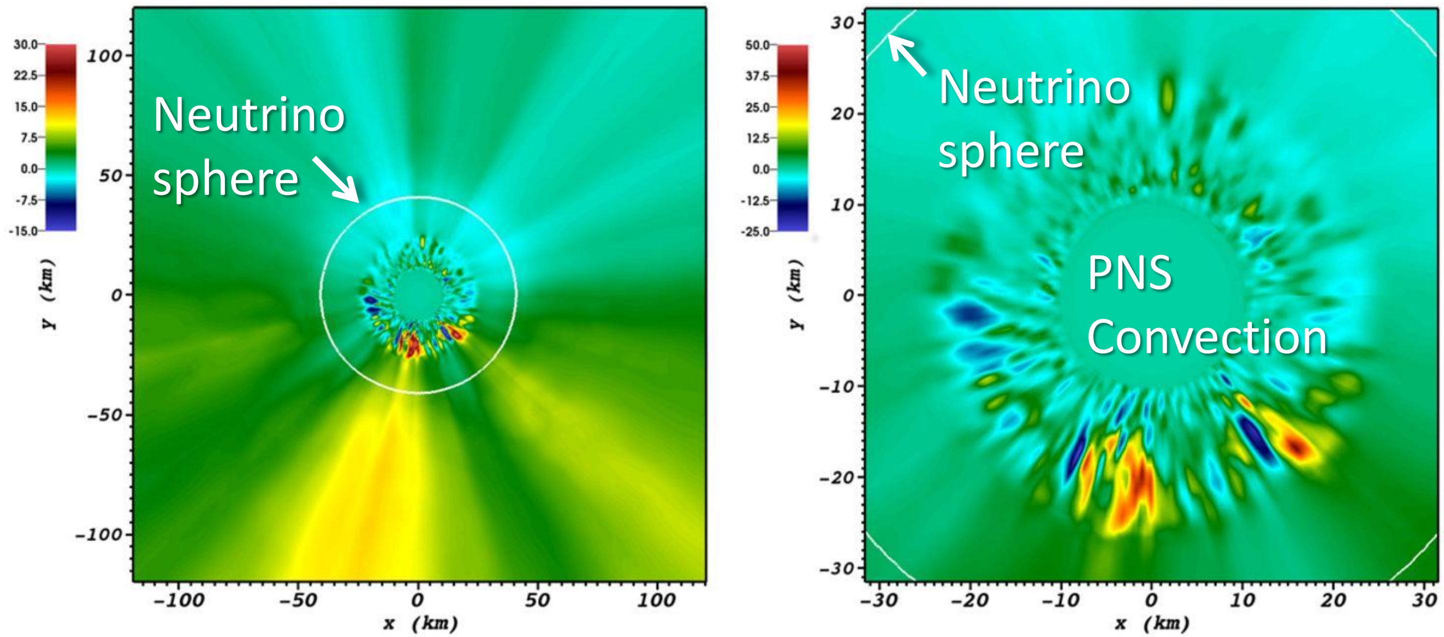


Tamborra et al. arXiv:1402.5418

Feedback loop consists of asymmetries in

- accretion rate
- lepton-number flux
- neutrino heating rate
- dipole deformation of shock front

LESA Dipole and PNS Convection

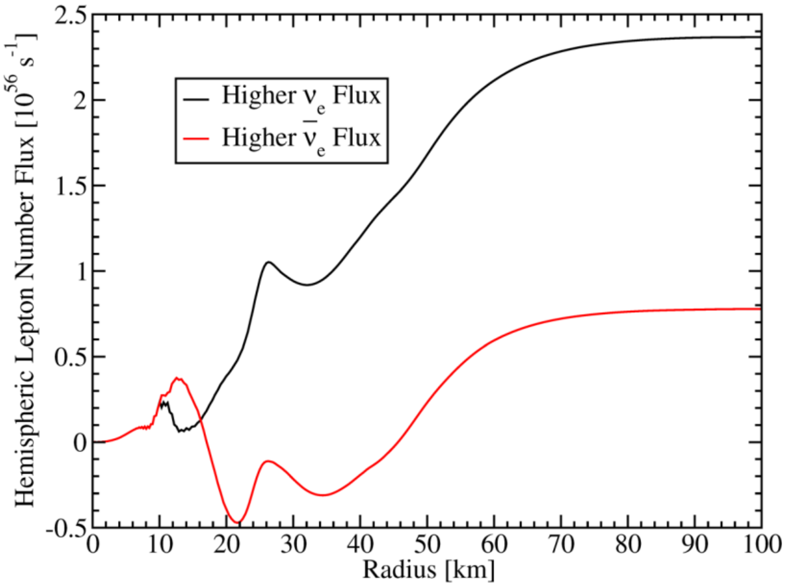


Neutrino sphere

Neutrino sphere

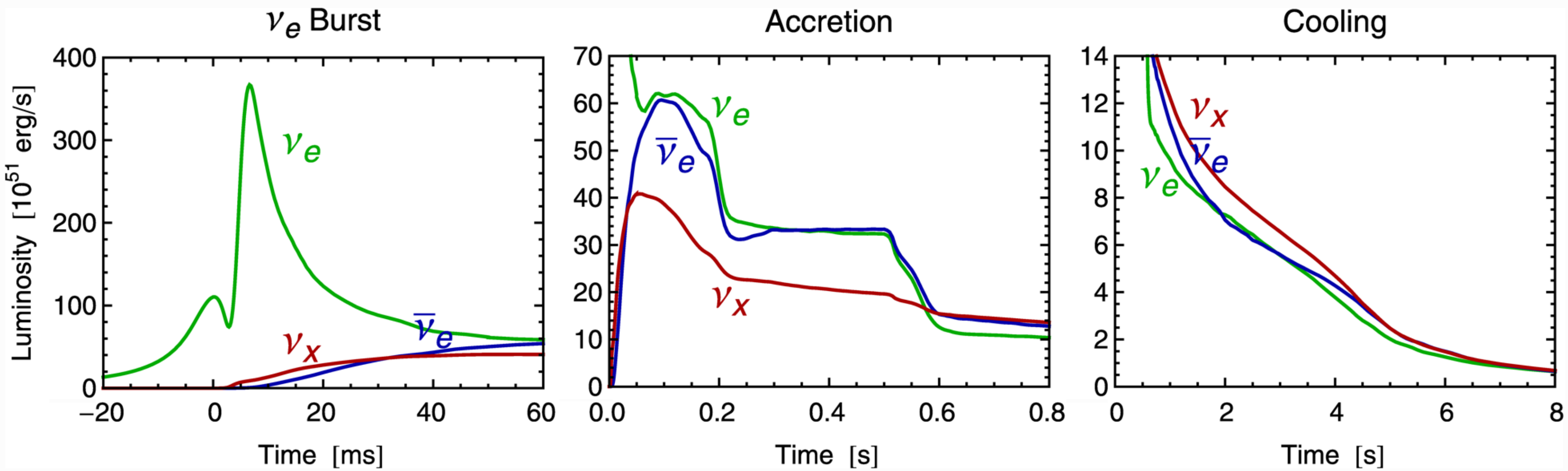
PNS Convection

Color-coded lepton-number flux along radial rays ($11.2\ M_{SUN}$ model at 210 ms)



Lepton flux dipole builds up mostly below the neutrino sphere in a region of strong convection in the proto-neutron star (PNS)

Three Phases – Three Opportunities



Standard Candle (?)
- SN theory
- Distance
- Flavor conversions
- Multi-messenger time of flight

Strong variations (progenitor, 3D effects, black hole formation, …)
- Testing astrophysics of core collapse
- Flavor conversion has strong impact on signal

EoS & mass dependence
- Testing nuclear physics
- Nucleosynthesis in neutrino-driven wind
- Particle bounds from cooling speed (axions …)

PHYSICAL REVIEW D VOLUME 17, NUMBER 9 1 MAY 1978

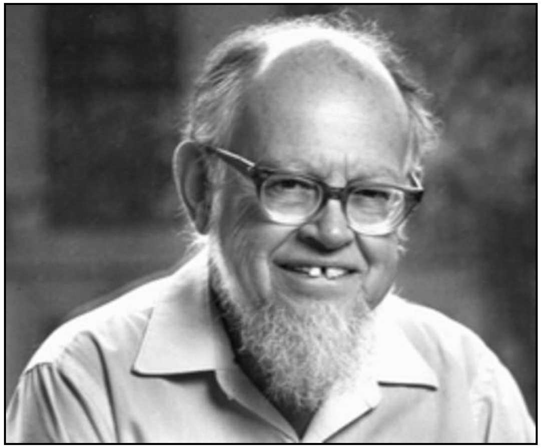
4000 citations

Neutrino oscillations in matter

L. Wolfenstein
Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213

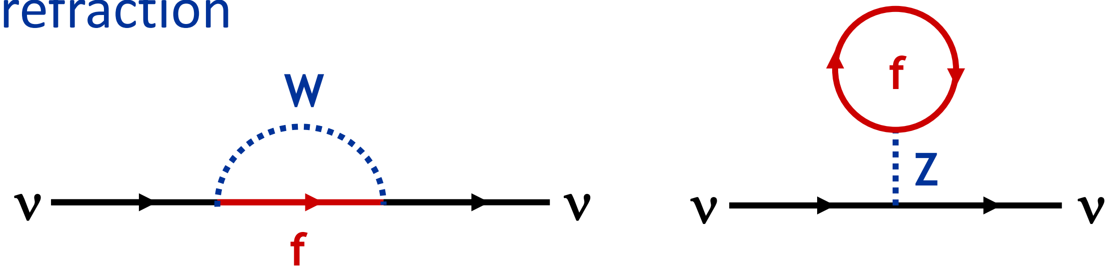
(Received 6 October 1977; revised manuscript received 5 December 1977)

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
10 Feb 1923–27 Mar 2015

Neutrinos in a medium suffer flavor-dependent refraction

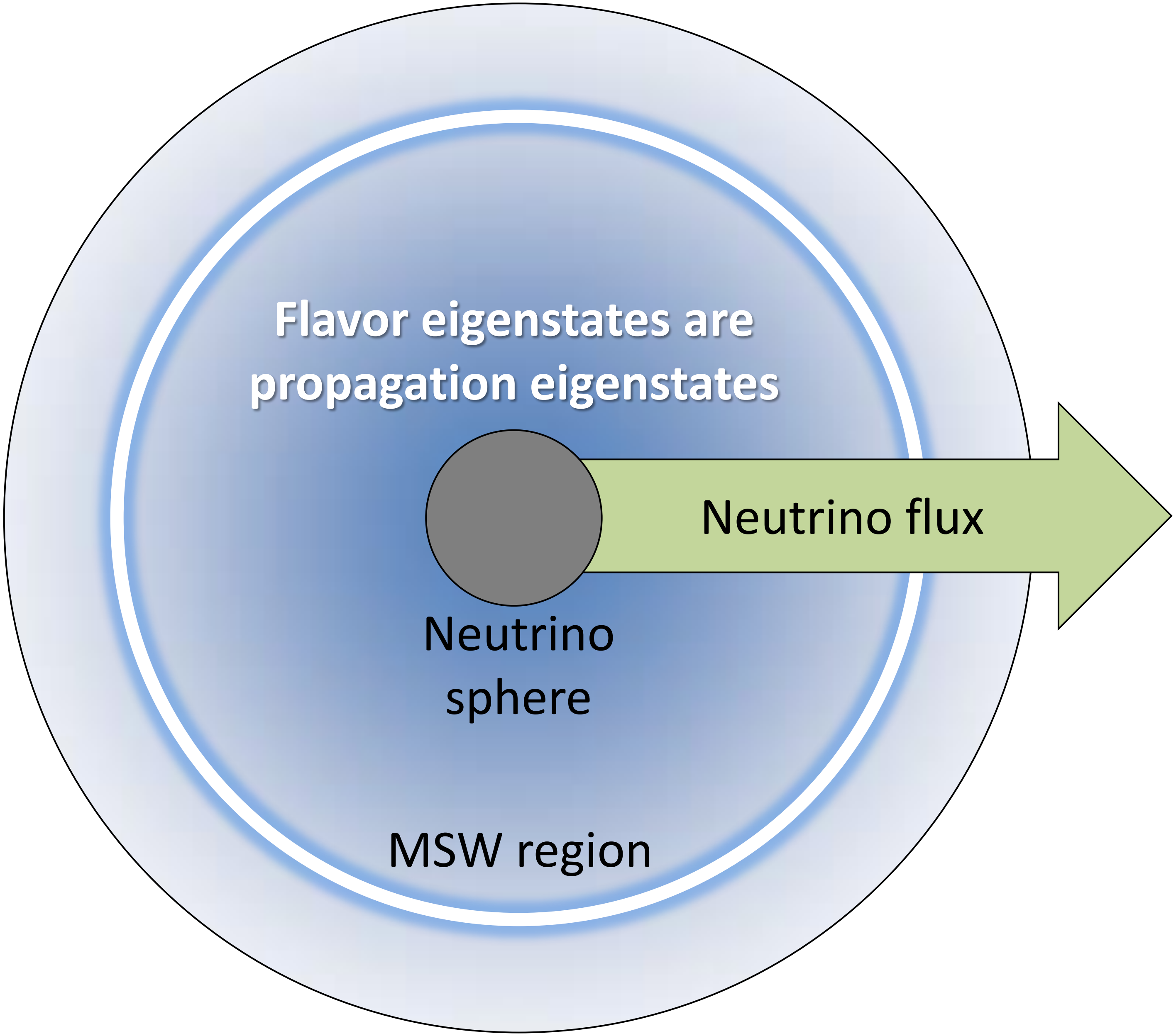


$$V_{\rm weak} = \sqrt{2} G_{\rm F} \times \begin{cases} N_{\rm e} - N_{\rm n}/2 & \text{for } \nu_{\rm e} \\ -N_{\rm n}/2 & \text{for } \nu_{\mu} \end{cases}$$

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

SN Flavor Oscillations and Mass Hierarchy

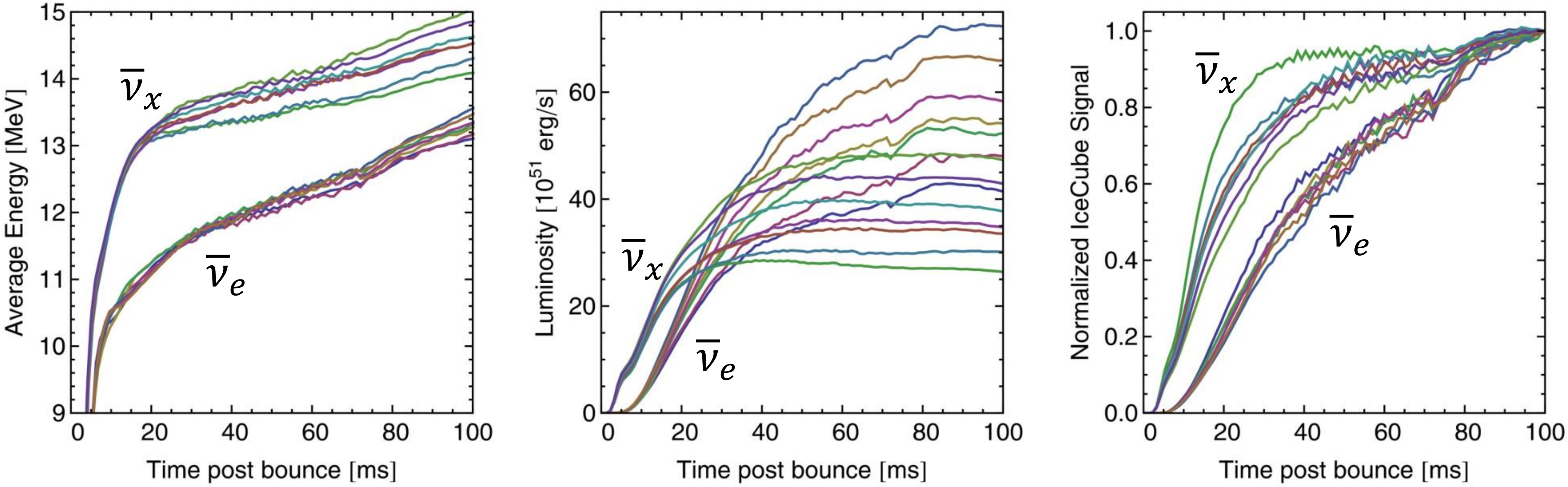
- Mixing angle Θ_{13} has been measured to be “large”
- MSW conversion in SN envelope adiabatic
- Assume that collective flavor oscillations are not important

	Mass ordering	
	Normal (NH)	Inverted (IH)
ν_e survival prob.	0	$\sin^2\theta_{12} \approx 0.3$
$\overline{\nu}_e$ survival prob.	$\cos^2\theta_{12} \approx 0.7$	0
$\overline{\nu}_e$ Earth effects	Yes	No

- When are collective oscillations important?
- How to detect signatures of hierarchy?

Early-Phase Signal in Anti-Neutrino Sector

Garching Models with M = 12–40 $M_\odot$



Average Energy

Luminosity

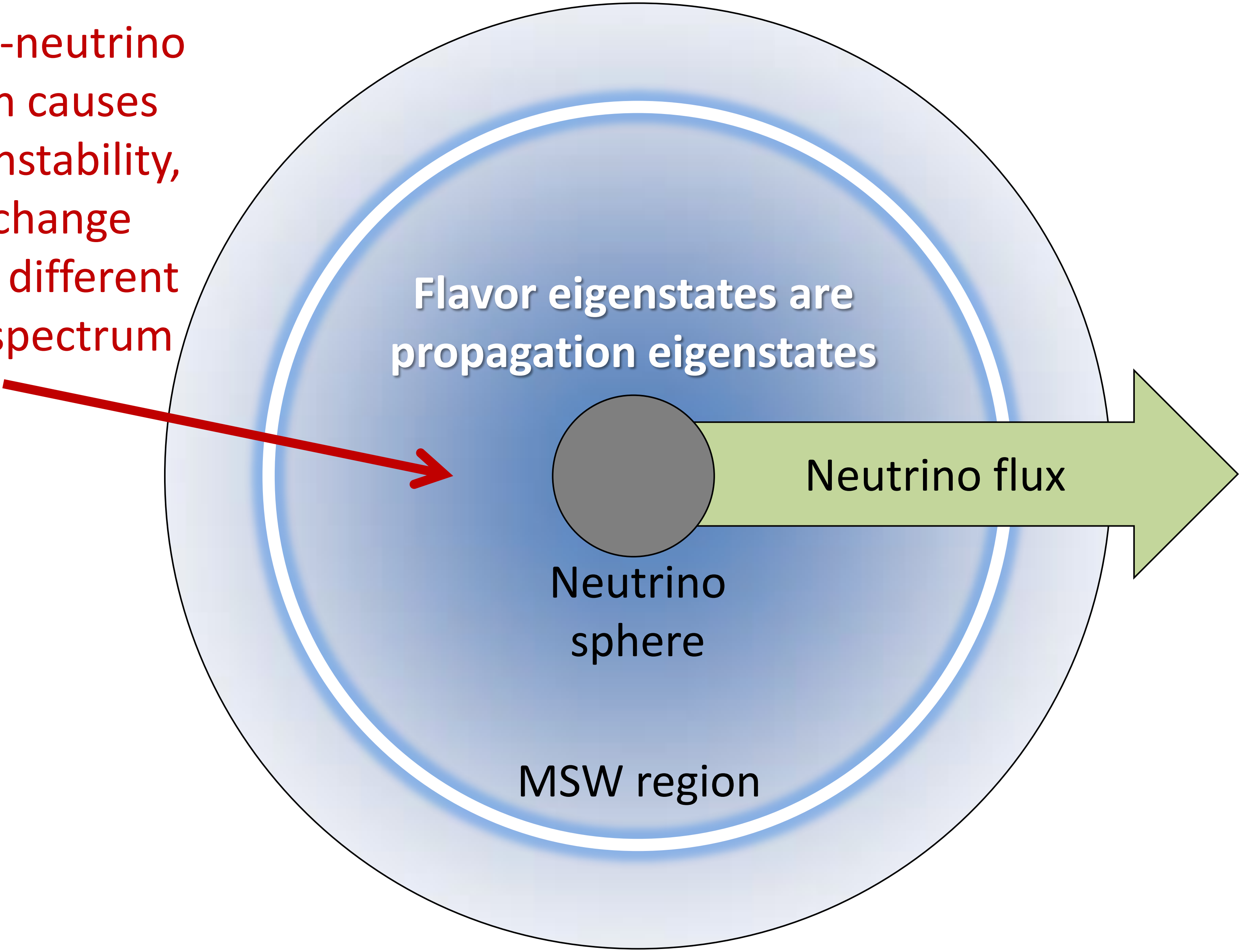
IceCube Signature

- In principle very sensitive to hierarchy, notably IceCube
- “Standard candle” to be confirmed by other than Garching models

Abbasi et al. (IceCube Collaboration) A&A 535 (2011) A109
Serpico, Chakraborty, Fischer, Hüdepohl, Janka & Mirizzi, arXiv:1111.4483

Flavor Oscillations in Core-Collapse Supernovae

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

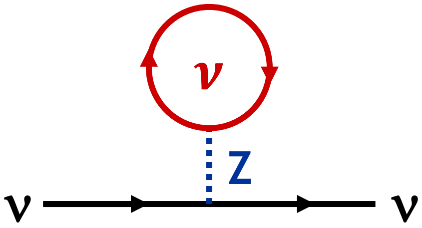


Flavor eigenstates are propagation eigenstates

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

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

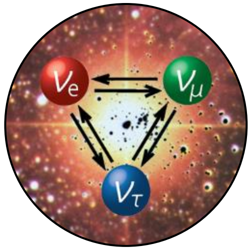
Mass term in flavor basis: causes vacuum oscillations

Wolfenstein's weak potential, causes MSW "resonant" conversion together with vacuum term

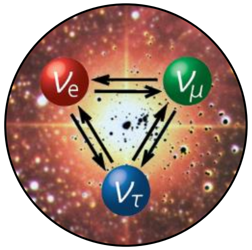
Flavor-off-diagonal potential, caused by flavor oscillations. (J.Pantaleone, PLB 287:128,1992)

Flavor oscillations feed back on the Hamiltonian: Nonlinear effects!

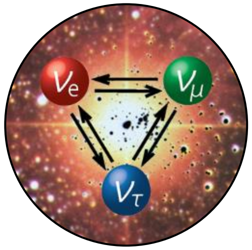
Self-Induced Flavor Conversion



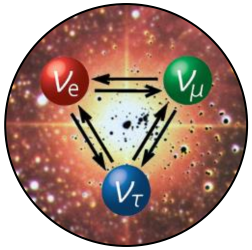
Interacting neutrino system: Coupled oscillators
- Collective harmonic oscillation modes
- Exponential run-away modes



No net flavor conversion of ensemble
(in contrast to MSW conversion)



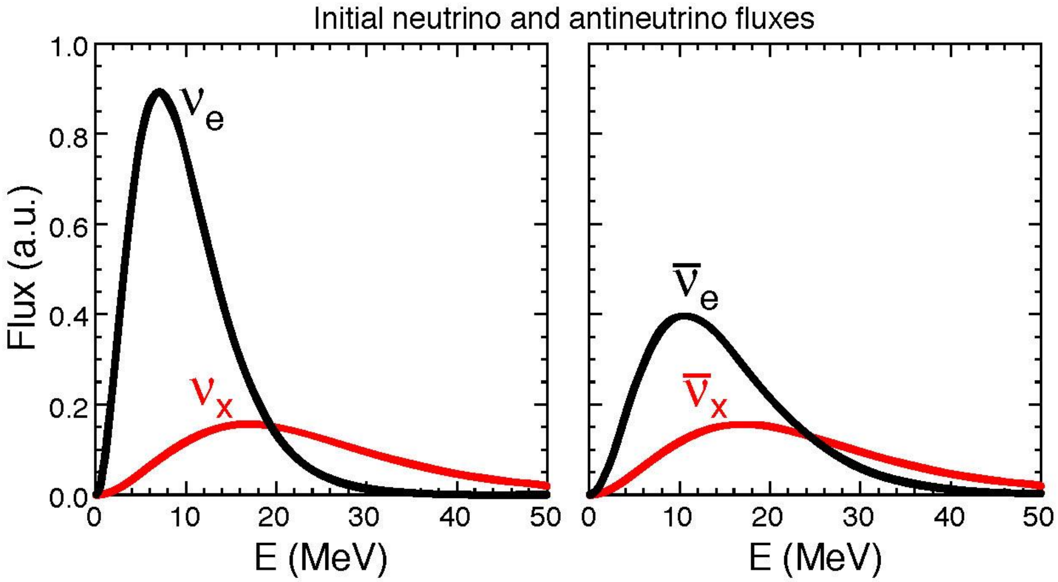
Flavor content exchanged
between different momentum modes
(or nus and anti-nus changing together)



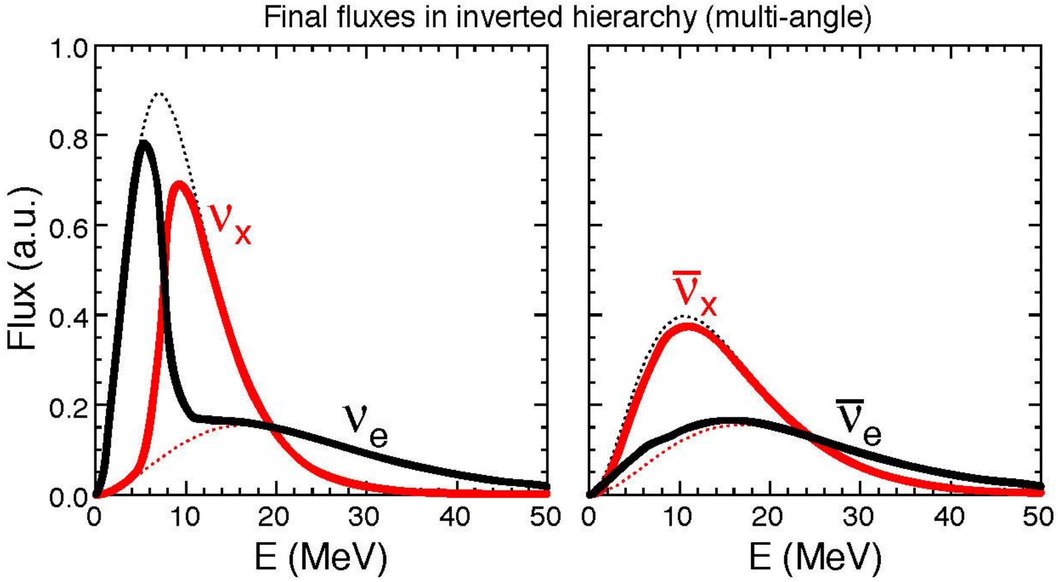
Instability required to get started
- Exponentially growing off-diagonals in density matrix
- Linearized stability analysis to find growing modes

Spectral Split

Initial fluxes at neutrino sphere



After collective transformation



Figures from

Fogli, Lisi, Marrone & Mirizzi, arXiv:0707.1998

Explanations in

Raffelt & Smirnov arXiv:0705.1830 and 0709.4641

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

Multi-Angle Matter Effect

Liouville form of oscillation equation

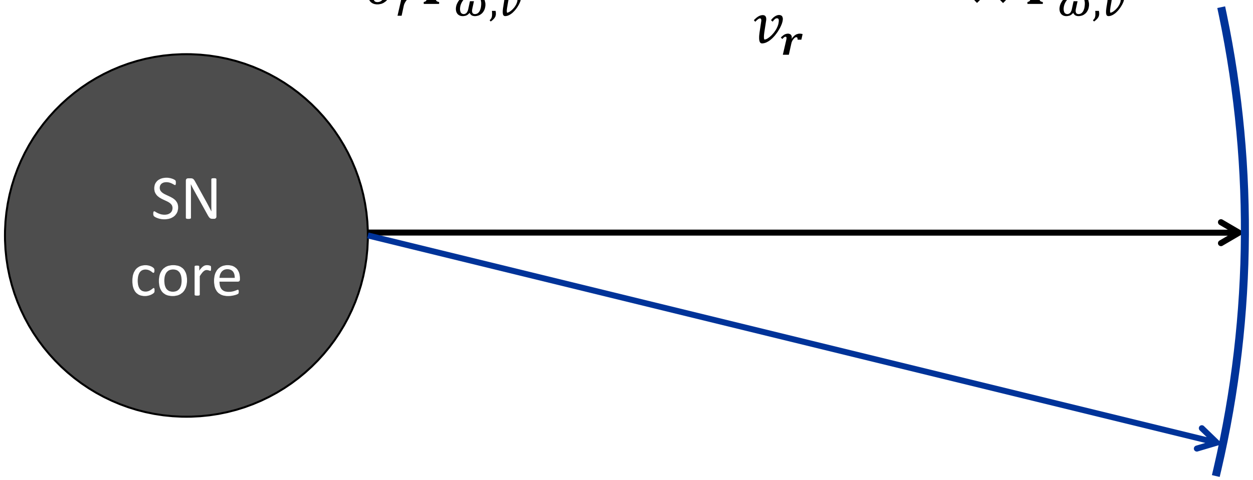
$$\dot{\mathbf{P}}_{\omega,\mathbf{v}} + (\mathbf{v}\cdot\boldsymbol{\nabla}_r)\,\mathbf{P}_{\omega,\mathbf{v}} = (\omega\mathbf{B} + \lambda\mathbf{L} + \mu\mathbf{P}) \times \mathbf{P}_{\omega,\mathbf{v}}$$

$\uparrow$ Drops out for stationary solutions

λ: $\uparrow$ $\sqrt{2}G_{\mathrm{F}}N_e$

μ: $\uparrow$ $\sqrt{2}G_{\mathrm{F}}N_\nu$

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

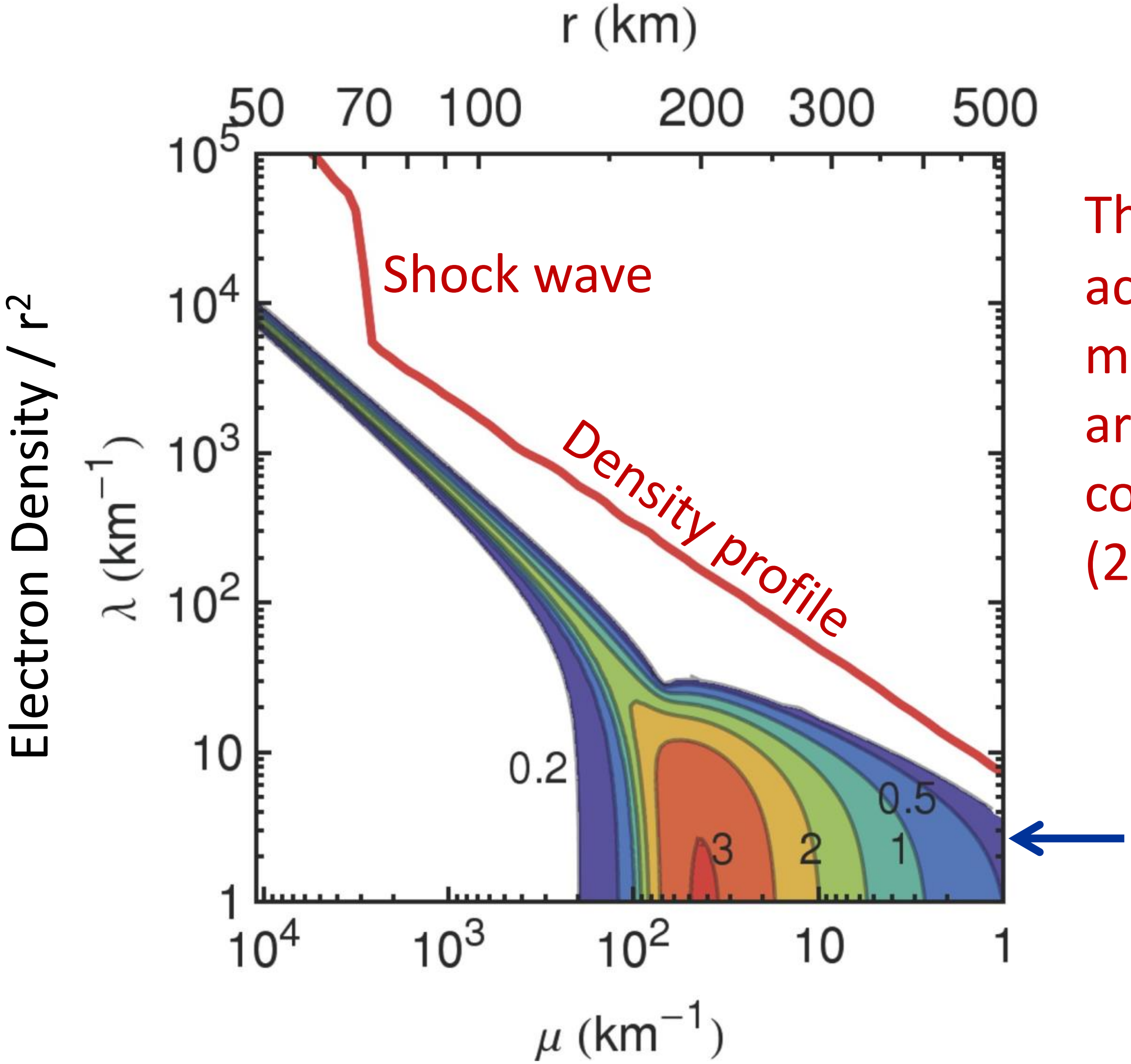


Longer path to
same radial distance:
Larger matter effect

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

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

Multi-Angle Multi-Energy Stability Analysis



Electron Density / r^2

Shock wave

Density profile

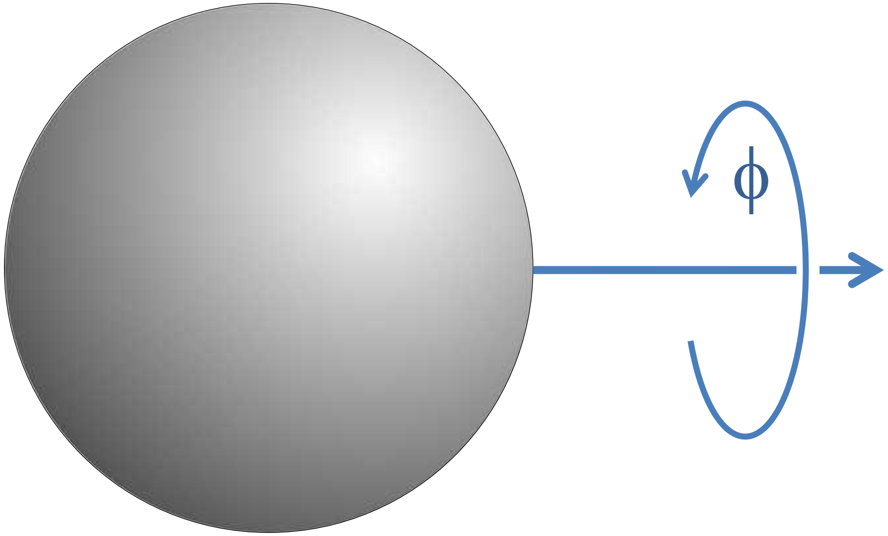
The studied 15 $M_\odot$ accretion-phase models (Garching) are stable against collective flavor conversion (2-flavor, inverted hierarchy)

Contours of growth rate κ [km^{-1}]

Sarikas, Raffelt, Hüdepohl & Janka, arXiv:1109.3601

Symmetry Breaking in Collective Flavor Oscillations

Assume globally spherically symmetric neutrino emission from SN core
→ Axial symmetry in chosen direction

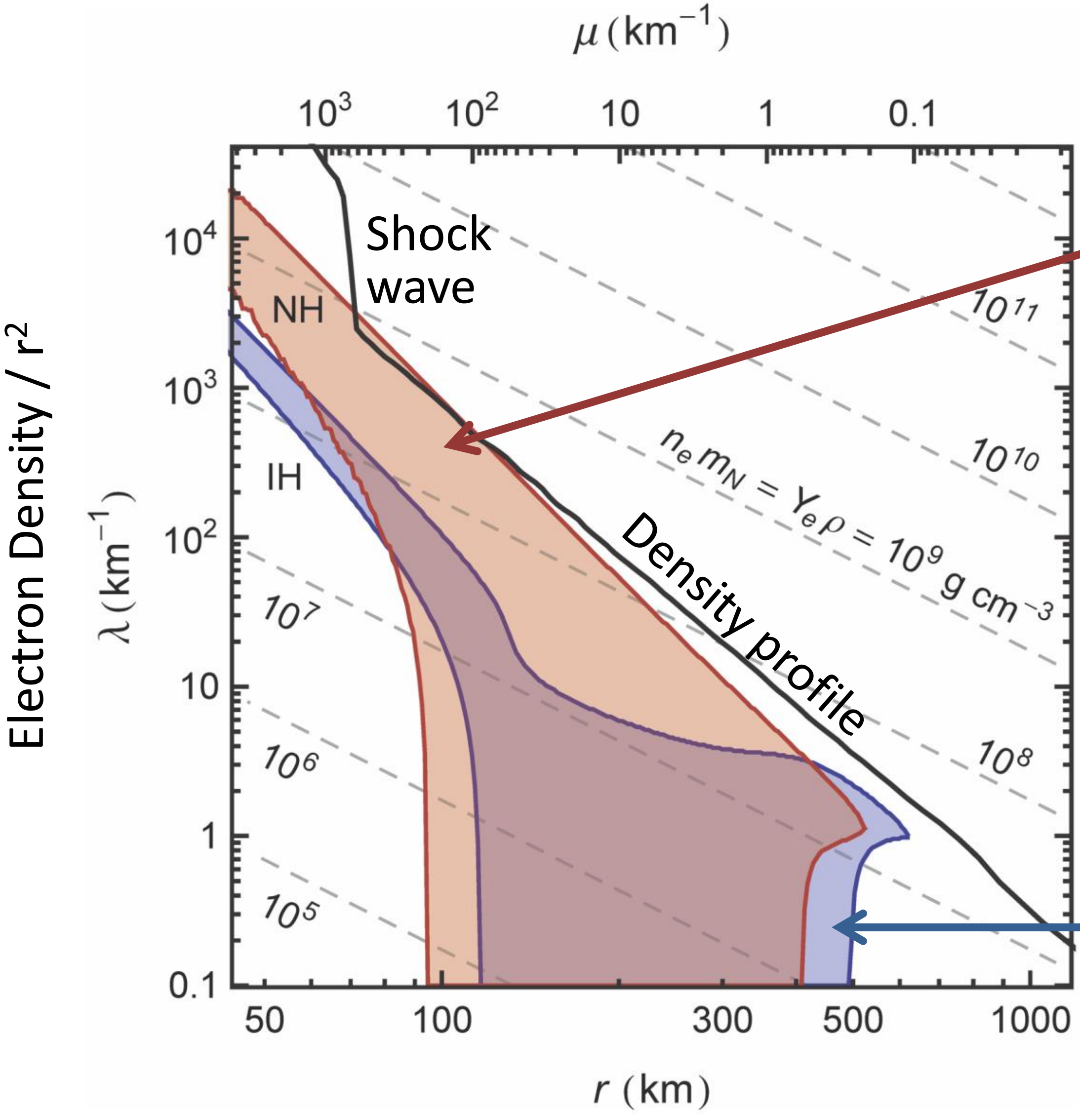


Self-induced neutrino flavor conversion in both hierarchies (unless suppressed by multi-angle matter effect)

- Axially symmetric solution:
  Conversion for inverted hierarchy
  (usual result)
- Spontaneous breaking of axial symmetry:
  Dipole solution ($\propto \cos\phi$ or $\sin\phi$)
  Conversion for normal hierarchy
  (Was missed by enforcing axial symmetry because of axially symmetric emission)

G. Raffelt, S. Sarikas & D. de Sousa Seixas
Axial symmetry breaking in self-induced flavor conversion of SN neutrino fluxes
PRL 111 (2013) 091101 [arXiv:1305.7140]

Instability Footprints

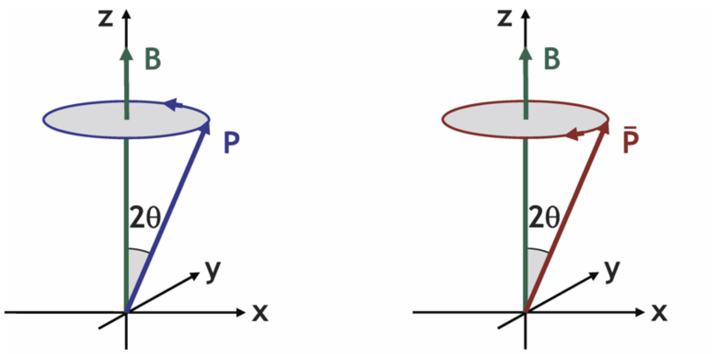


Axial-symmetry breaking (MAA) instability (normal ordering NH) is “more dangerous” to trigger self-induced flavor conversion

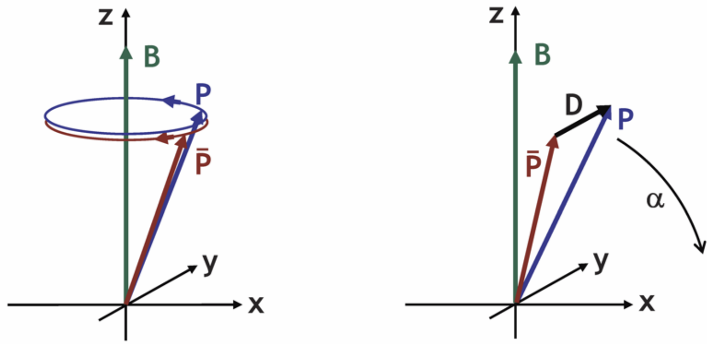
Traditional “bimodal” instability (inverted mass ordering IH)

Raffelt, Sarikas & Seixas, arXiv:1305.7140

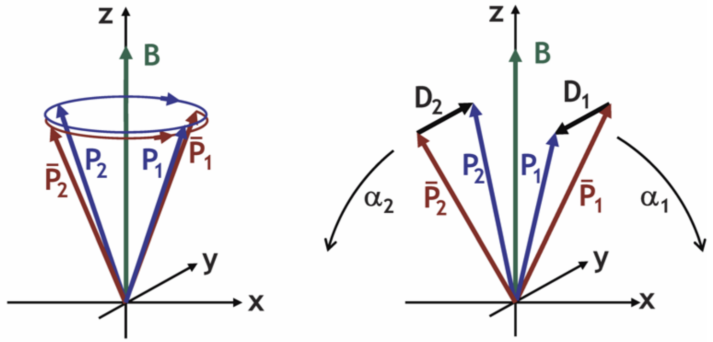
Colliding Beam Model



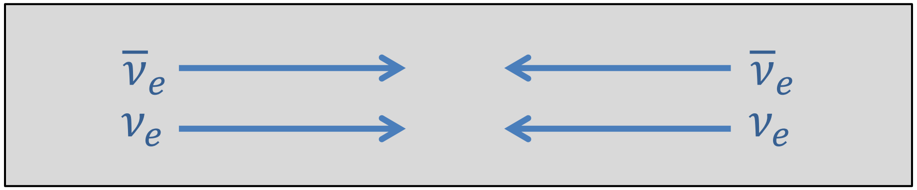
Neutrinos Anti-Neutrinos



Inverted Hierarchy: Bimodal Instability



Normal Hierarchy: New Instability



Raffelt & Seixas, arXiv:1307.7625

Left- and right-moving neutrinos behave symmetrically
Instability for inverted mass ordering (IH)

Left-right symmetry breaking:
- Anti-symmetric mode for normal mass ordering (NH)
- Corresponds to axial symmetry breaking in SN case (MAA instability)

Symmetry Assumptions

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**
- **Can miss dominant solutions (spontaneous symmetry breaking)**

Spatial Symmetry Breaking (SSB)

Oscillation equation with explicit transport term

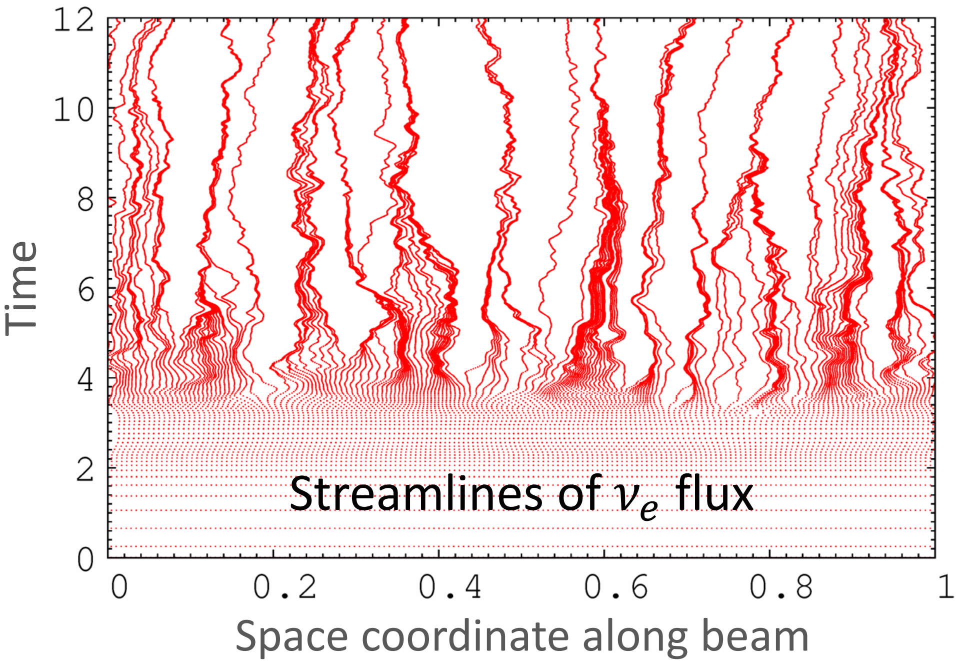
$$i\underbrace{\left(\partial_t + \vec{v}\cdot\,\vec{\nabla}_x\right)}\;\rho(t,\vec{x},\vec{p}) = [H(t,\vec{x},\vec{p}),\rho(t,\vec{x},\vec{p})]$$

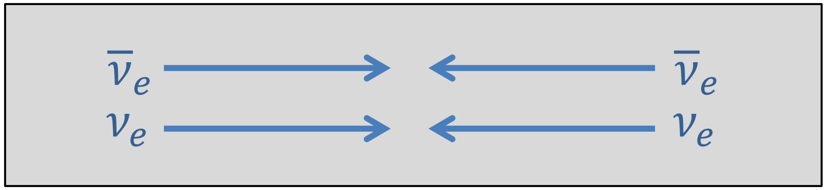
Without flavor oscillations: free streaming

Spatial Fourier transform (plane wave expansion)

$$\left(i\partial_t + \vec{v}\cdot\vec{k}\right)\,\rho\left(t,\vec{k},\vec{p}\right) = \int d^3\vec{x}\;e^{-i\,\vec{k}\cdot\vec{x}}\,[H(t,\vec{x},\vec{p}),\rho(t,\vec{x},\vec{p})]$$

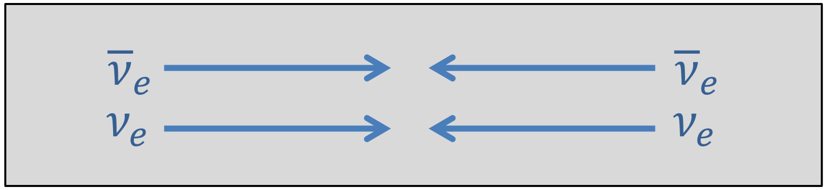
Interaction term couples different Fourier modes





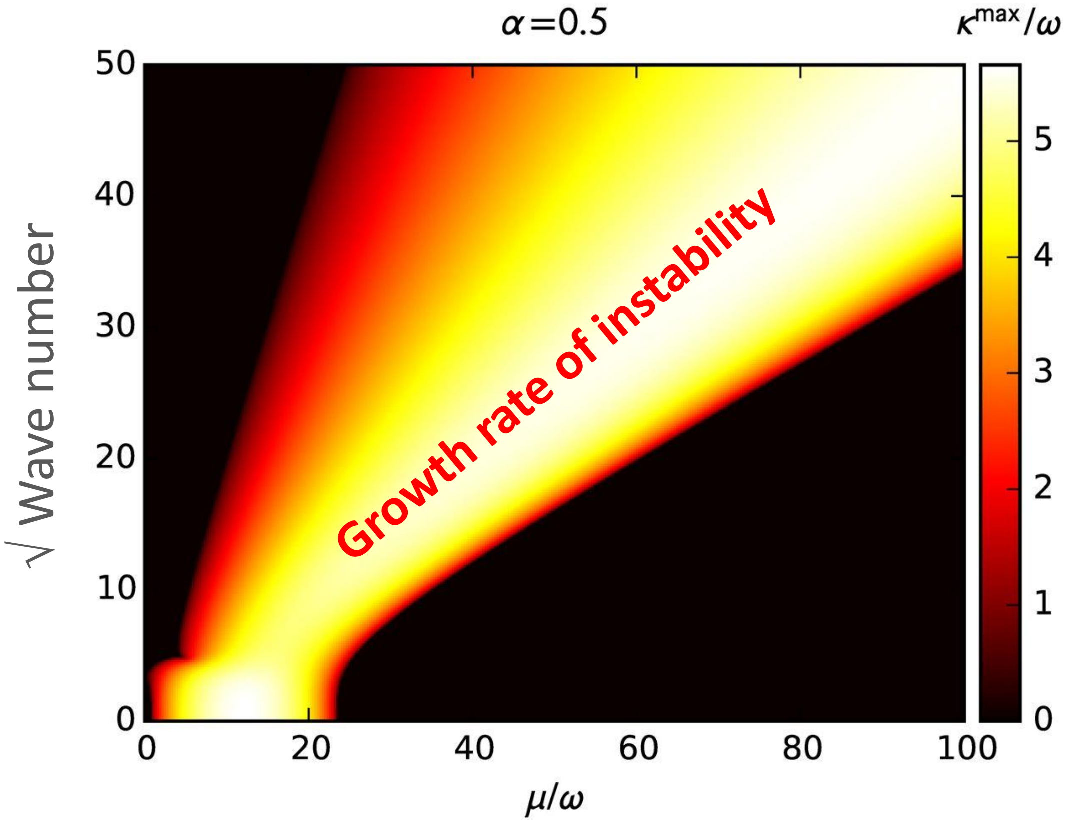
Mirizzi, Mangano & Saviano
arXiv:1503.03485

Spatial Symmetry Breaking (SSB)



Linearized stability analysis for colliding-beam model

Duan & Shalgar, arXiv:1412.7097

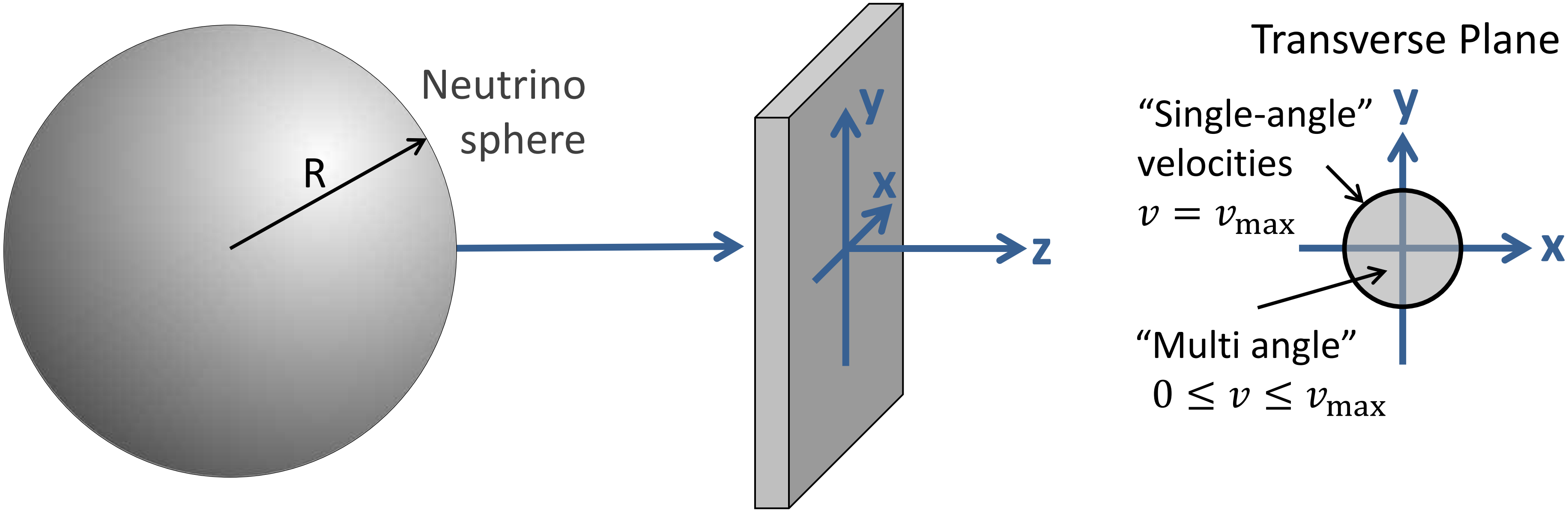


Growth rate of instability

Effective neutrino density

- Instability footprint shifted to larger neutrino density μ for larger wave number k
- For any neutrino density, unstable for some k-range
- No flavor-stable conditions exist for homogeneous neutrino gas (no “sleeping top” regime)

"Supernova" vs. "Early Universe"



- Oscillation physics expressed as function of "time" t = z (radial distance)
- Nu-nu refraction effects derive from *transverse* velocities
  (Current-current interaction: No refraction if all nus move strictly radially)
- SN problem equivalent to "expanding universe"
  (transverse sheet expanding with z equivalent to expanding space)
- "Single-angle case": Fixed nu speed $v = v_{\max} \approx R/\text{distance}$ in transverse plane
  "Multi-angle effects": Nu speed fills transverse disk $0 \leq v \leq v_{\max}$
- Inhomogeneities in transverse plane: wave vector **k** (no spherical harmonics)

Linearized Stability Analysis

Neutrino transport and flavor oscillations with $\omega = \Delta m^2/2E$

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

Homogeneous system (e.g. in transverse “plane” in SN case)

$$\rho(t,\vec{x},\omega,\vec{v}) = g(\omega,\vec{v})\begin{pmatrix} s & S \\ S^* & -s\end{pmatrix}_{(t,\vec{x},\omega,\vec{v})} \longleftarrow \text{Off-diagonal element of density matrix}$$

with $s^2+|S|^2=1$ and $|S|\ll 1$

Linearized equation of motion

nu-nu interaction energy $\sqrt{2}G_\mathrm{F}n_\nu R^2/r^2$

$$i\left(\partial_t + \vec{v}\cdot\vec{\nabla}_x\right)S_{t,\vec{x},\omega,\vec{v}} = \left[\omega + \frac{\lambda+\epsilon\mu}{2}v^2\right]S_{t,\vec{x},\omega,\vec{v}} - \mu\int d\Gamma'\,g_{\omega',\vec{v}'}\,\frac{(\vec{v}-\vec{v}')^2}{2}S_{t,\vec{x},\omega',\vec{v}'}$$

Matter effect
$\lambda = \sqrt{2}G_\mathrm{F}n_e R^2/r^2$

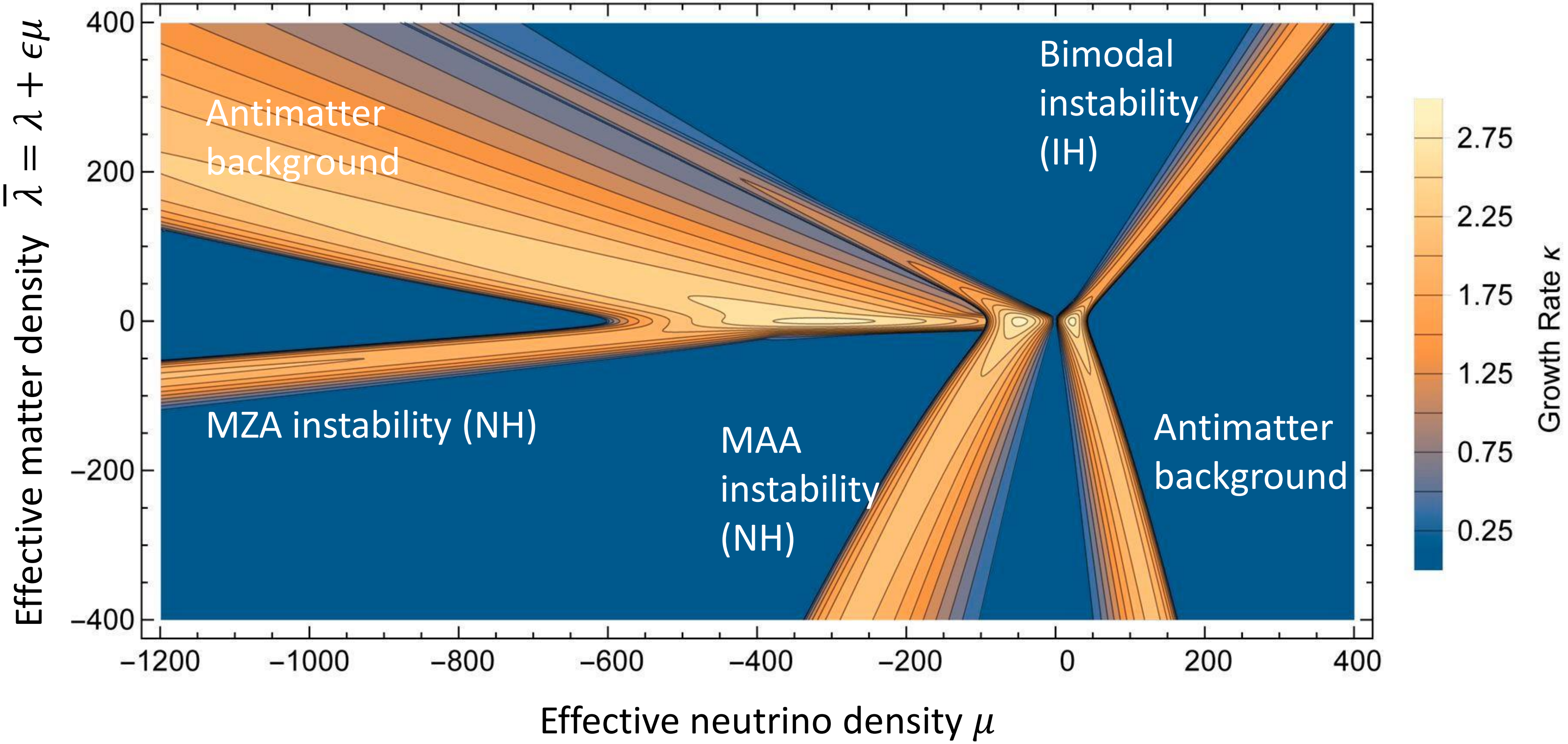
Phase-space integral over
neutrino distribution $\epsilon = \int d\Gamma\, g_{\omega,\vec{v}}$

Spatial Fourier transform $\vec{v}\cdot\vec{\nabla}_x \to i\vec{k}\cdot\vec{v}$, eigenmodes $S_{t,\vec{k},\omega,\vec{v}} = Q_{\Omega,\vec{k},\omega,\vec{v}}\,e^{-i\Omega t}$

$$\left[\frac{\lambda+\epsilon\mu}{2}v^2 + \vec{k}\cdot\vec{v} + \omega - \Omega\right]Q_{\Omega,\vec{k},\omega,\vec{v}} = \mu\int d\Gamma'\,g_{\omega',\vec{v}'}\,\frac{(\vec{v}-\vec{v}')^2}{2}Q_{\Omega,\vec{k},\omega',\vec{v}'}$$

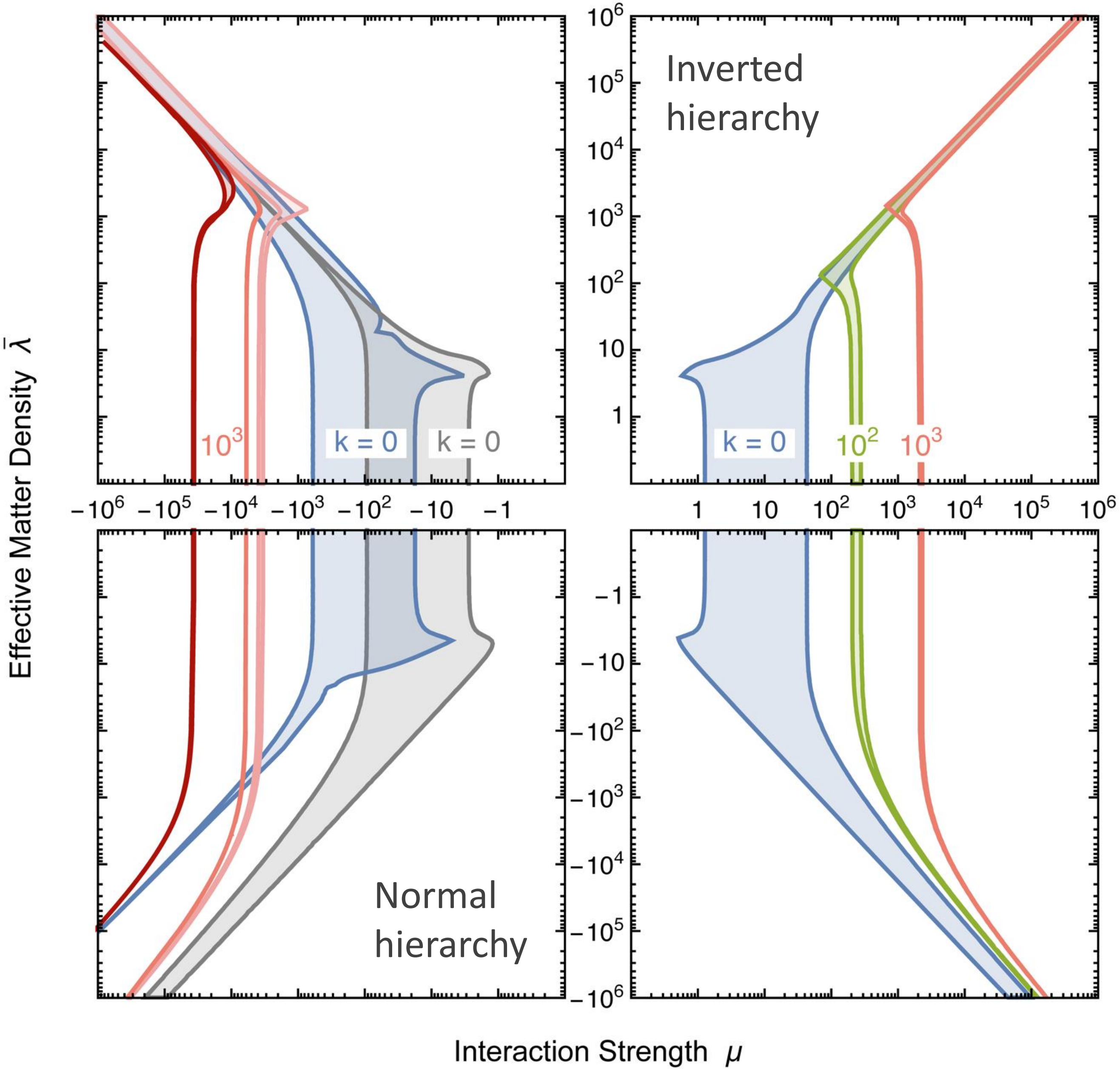
Multi-Angle Matter Effect in Supernovae

Growth rate in 2D parameter space of effective matter and neutrino density
("Butterfly diagram")

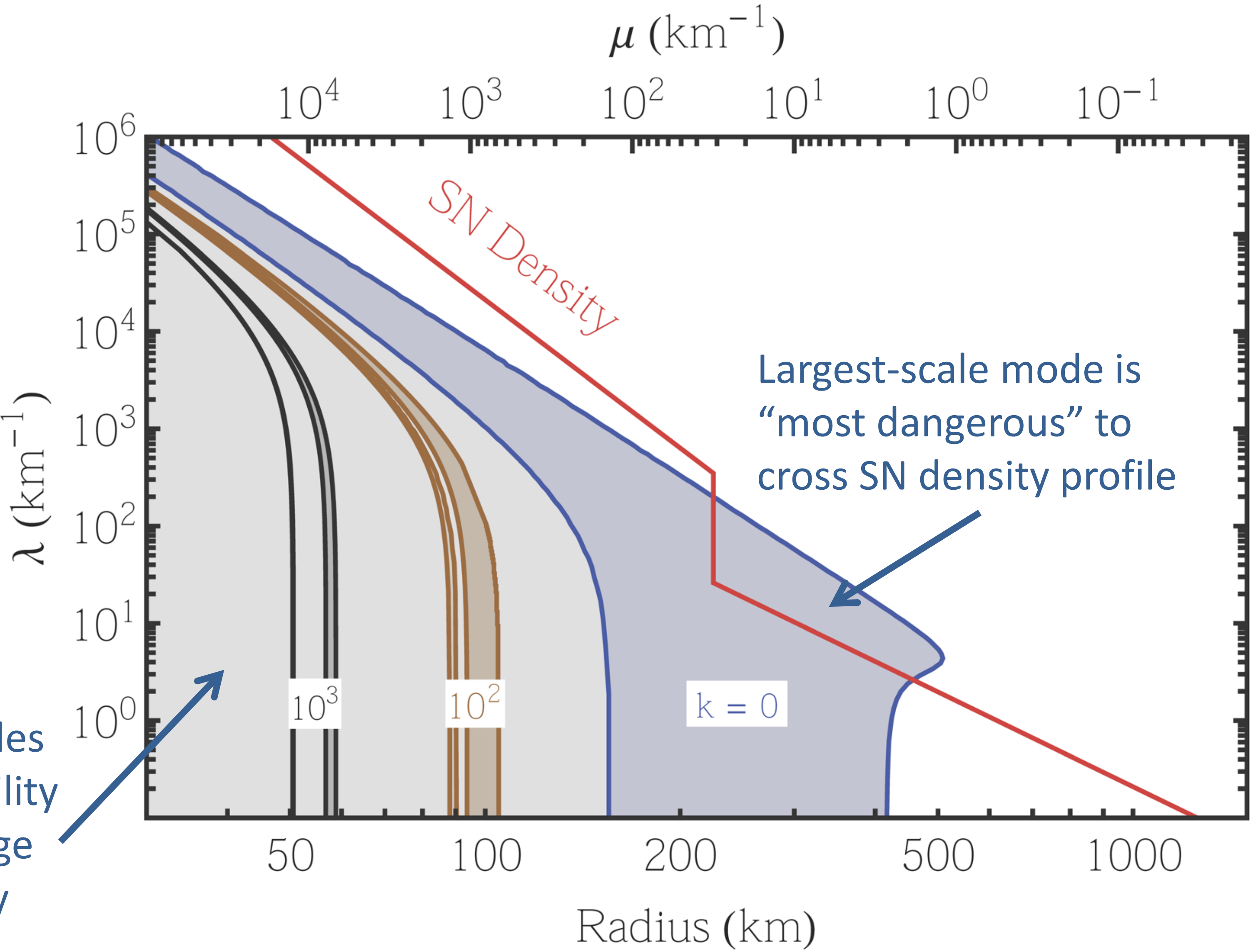


Chakraborty, Hansen, Izaguirre & Raffelt, Work in progress (2015)

Instability Regions



Small-Scale Instabilities in SN Context



Largest-scale mode is “most dangerous” to cross SN density profile

Small-scale modes “fill in” the stability footprint for large neutrino density

Chakraborty, Hansen, Izaguirre & Raffelt, Work in progress (2015)

Space-Time-Dependent Problem in Supernova

- Neutrino momentum distribution not limited to “outward” direction
- Important “halo” flux even at large distance
- Large 3D effects

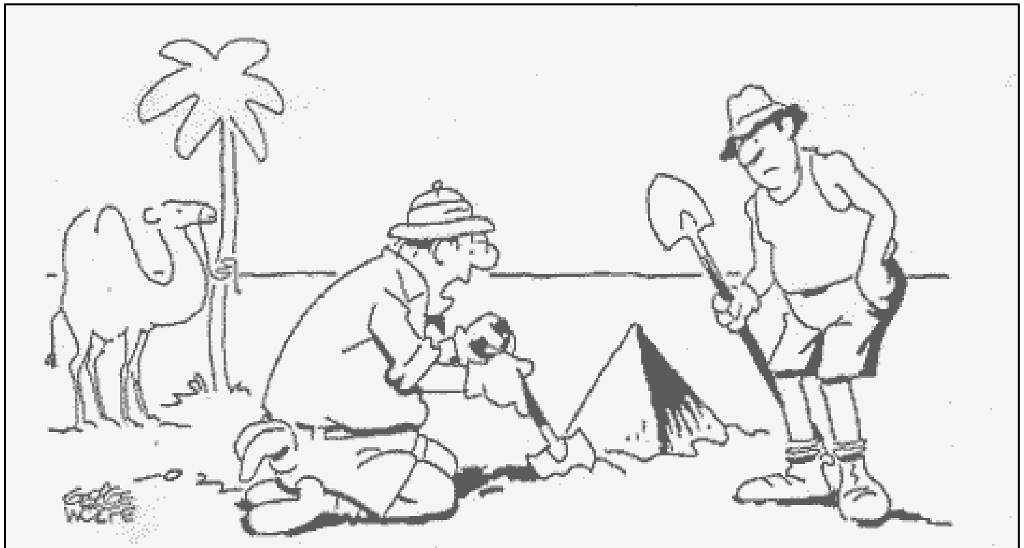
→ Inhomogeneous, anisotropic, non-stationary problem

Really no self-induced flavor conversion below shock-wave or even below nu-sphere?

- Investigations to date are simplified case studies
- May not represent real SNe

Status of Collective Flavor Conversion

- Self-induced flavor conversion is an instability in flavor space of the interacting neutrino ensemble
- Space-time dependent phenomenon
(not simply stationary or homogeneous)
- Solutions do not respect symmetries of initial system
Instabilities can occur on all scales



'If it's what I think it is, we've got some work ahead of us.'

Essentially back to the drawing board …

Literature on Spatial Symmetry Breaking (SSB)

1. Axial symmetry breaking in self-induced flavor conversion of SN neutrino fluxes
   Raffelt, Sarikas & Seixas, PRL 111 (2013) 091101
2. Neutrino flavor pendulum in both mass hierarchies
   Raffelt & Seixas, PRD 88 (2013) 045031
3. Chaotic flavor evolution in an interacting neutrino gas
   Hansen & Hannestad, PRD 90 (2014) 025009
4. Damping the neutrino flavor pendulum by breaking homogeneity
   Mangano, Mirizzi & Saviano, PRD 89 (2014) 073017
5. Spontaneous breaking of spatial symmetries in collective neutrino oscillations
   Duan & Shalgar, arXiv:1412.7097
6. Self-induced flavor instabilities of a dense neutrino stream in a 2D model
   Mirizzi, Mangano & Saviano, arXiv:1503.03485
7. Breaking the symmetries of the bulb model in two-dimensional self-induced supernova neutrino flavor conversions
   Mirizzi, arXiv:1506.06805
8. Self-induced flavor conversion of supernova neutrinos on small scales
   Chakraborty, Hansen, Izaguirre & Raffelt, work in progress (2015)

More theory progress is needed to understand flavor conversion of supernova neutrinos!