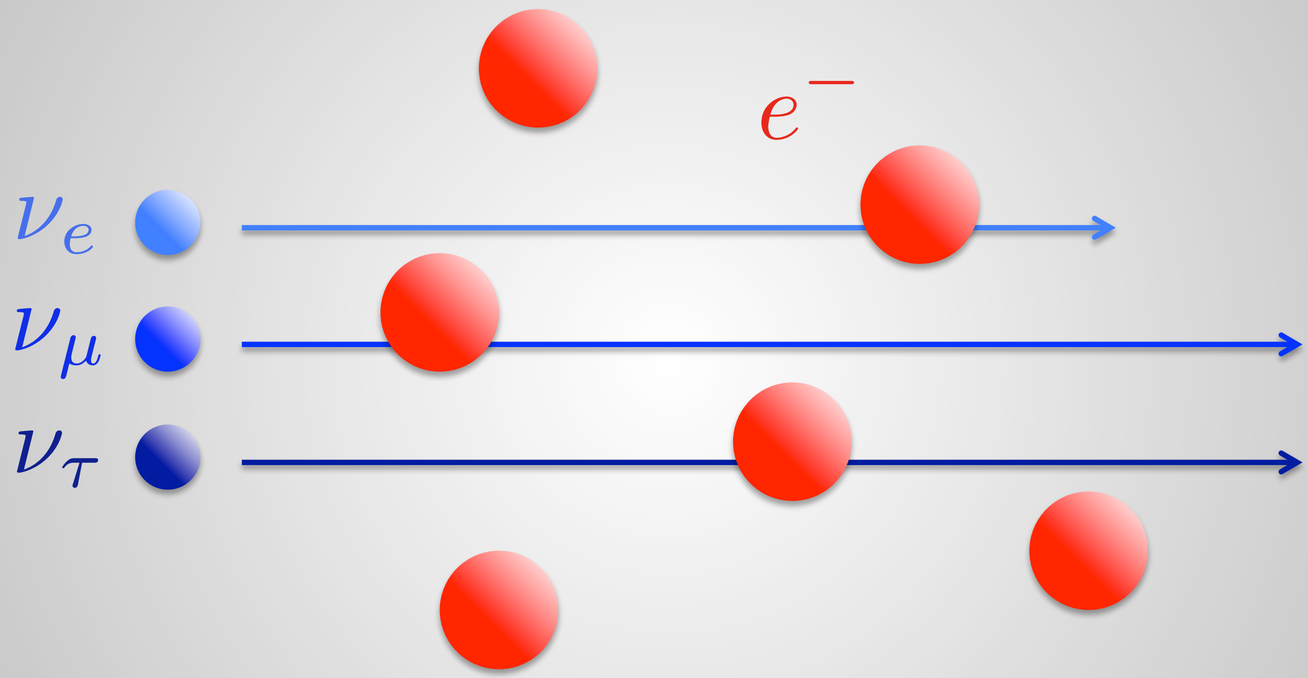
Neutrino oscillations in supernovae

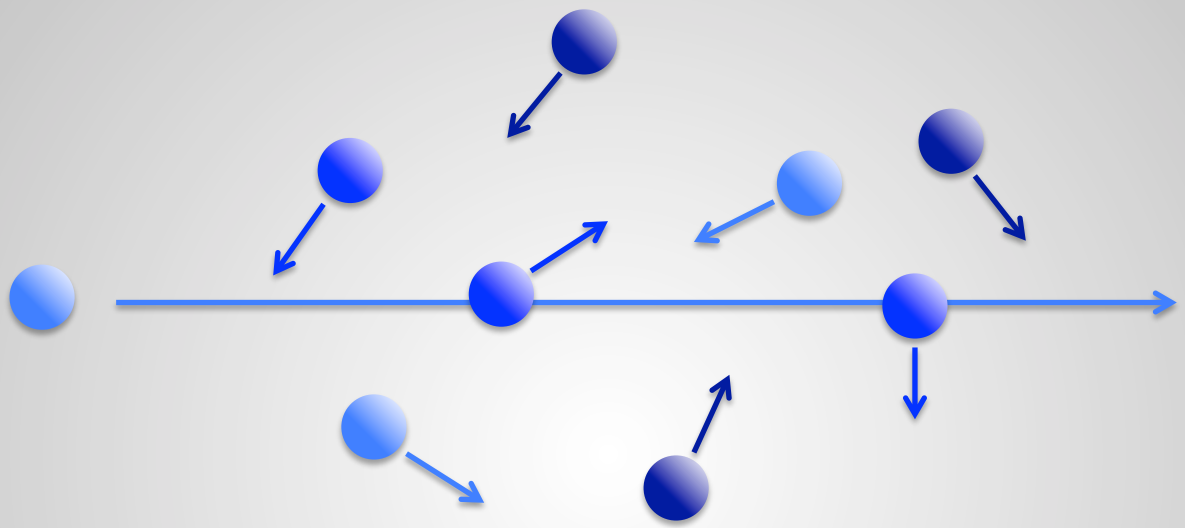
Luke Johns
NASA Einstein Fellow
UC Berkeley

I. Neutrinos as quantum many-body systems

In astrophysical settings, we need to understand neutrino transport *in medium*…

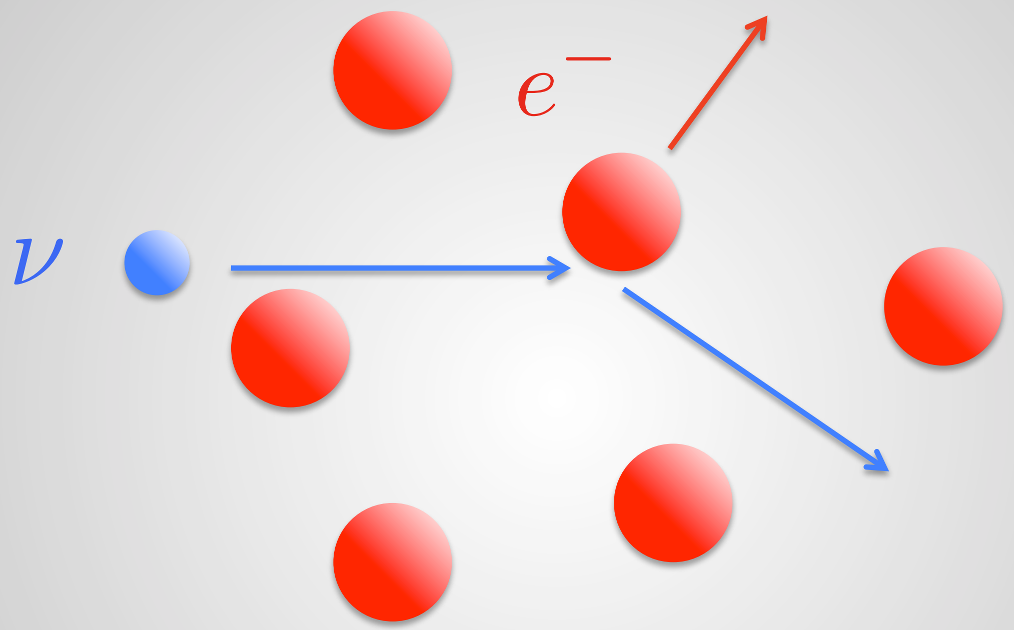


When neutrinos **forward scatter** on background particles, they acquire in-medium effective masses.



Neutrinos contribute to **their own background**. As a result, forward scattering changes oscillations in a nonlinear way.

Collective oscillations



Neutrinos also undergo **collisions**: momentum-changing scattering (*above*), absorption, and emission.

Back-of-the envelope estimates of length scales

Consider neutrinos interacting with a medium at an energy scale of 10 MeV…

Forward scattering:

$$l_{\rm fs} \sim \frac{1}{G_F n} \sim 0.01 \ {\rm mm}$$

Vacuum oscillations:

$$l_{\rm osc} \sim \frac{4\pi E_\nu}{|\delta m^2_{\rm atm}|} \sim 0.1 \ {\rm km}$$

Mean free path:

$$l_{\rm mfp} \sim \frac{1}{G_F^2 E_\nu^2 n} \sim 10 \ {\rm km}$$

$\Rightarrow$ **Medium-affected quantum coherence builds up over macroscopic scales**

Quantum many-body systems

Interaction	Example systems	# of particles	Phenomena
Electromagnetic	Condensed matter	$\sim 10^{23}$	Magnetism, conductivity, topology, …
Strong	Nuclei	~ 100	Nuclear structure & reactions
Weak	**SN neutrinos**	$\boldsymbol{\sim 10^{58}}$	**Collective oscillations**

Adapted from a slide by Baha Balantekin

Quantum kinetic equation for density matrix $\rho(t, \boldsymbol{r}, \boldsymbol{p})$:

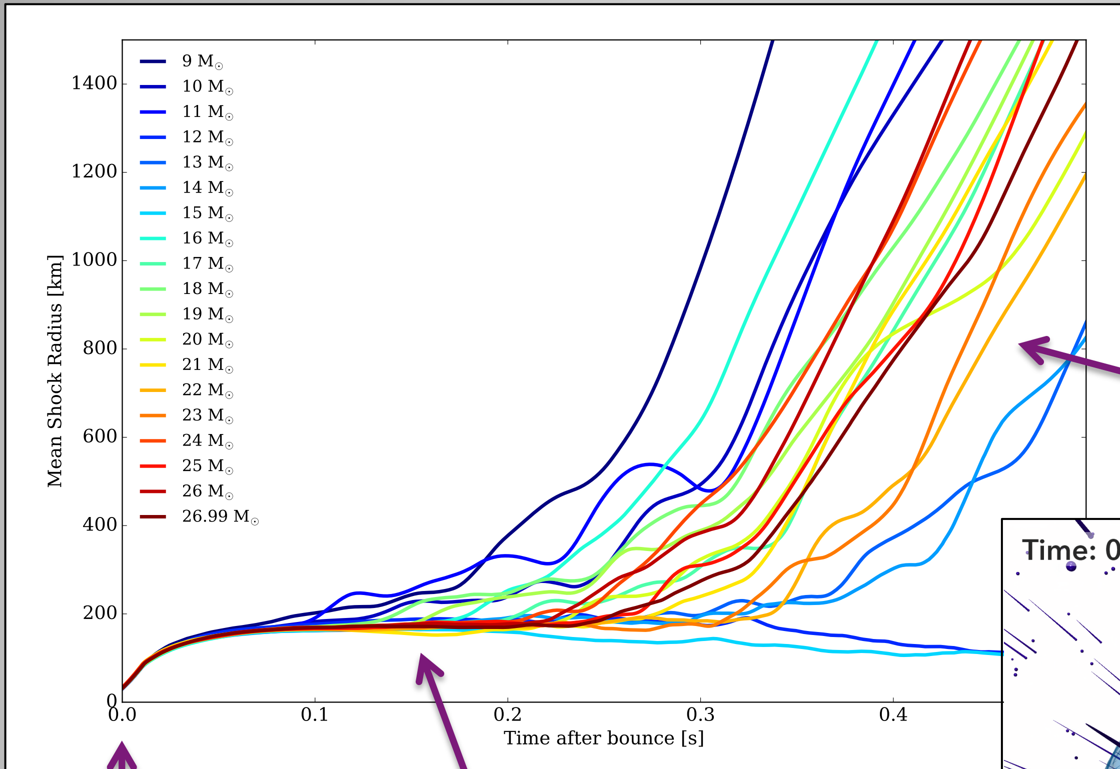
Dolgov, SJNP (1981)
Stodolsky, PRD (1987)
Notzold & Raffelt, NPB (1988)
Sigl & Raffelt, NPB (1993)
Yamada, PRD (2000)
Strack & Burrows, PRD (2005)
Vlasenko, Fuller, & Cirigliano, PRD (2014)

$$\underbrace{i\left(\partial_t + \hat{\mathbf{p}} \cdot \partial_{\mathbf{r}}\right)\rho}_{\text{Particle advection}} = \underbrace{[H, \rho]}_{\text{Flavor mixing}} + \underbrace{iC}_{\text{Collisions}}$$

By far the most promising venues for testing this many-body physics are core-collapse supernovae—and in fact we *need* to understand the dynamics to advance SN physics.

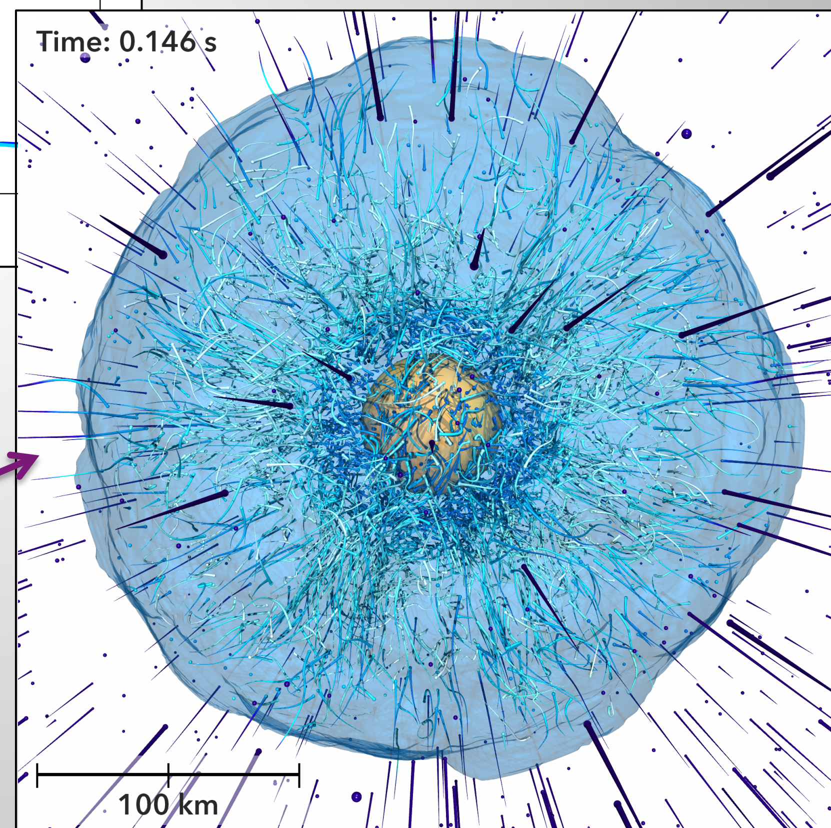
I. Neutrinos as quantum many-body systems

II. Neutrinos in core-collapse supernovae



The delayed neutrino-heating mechanism likely explains most CCSN explosions

Explosion



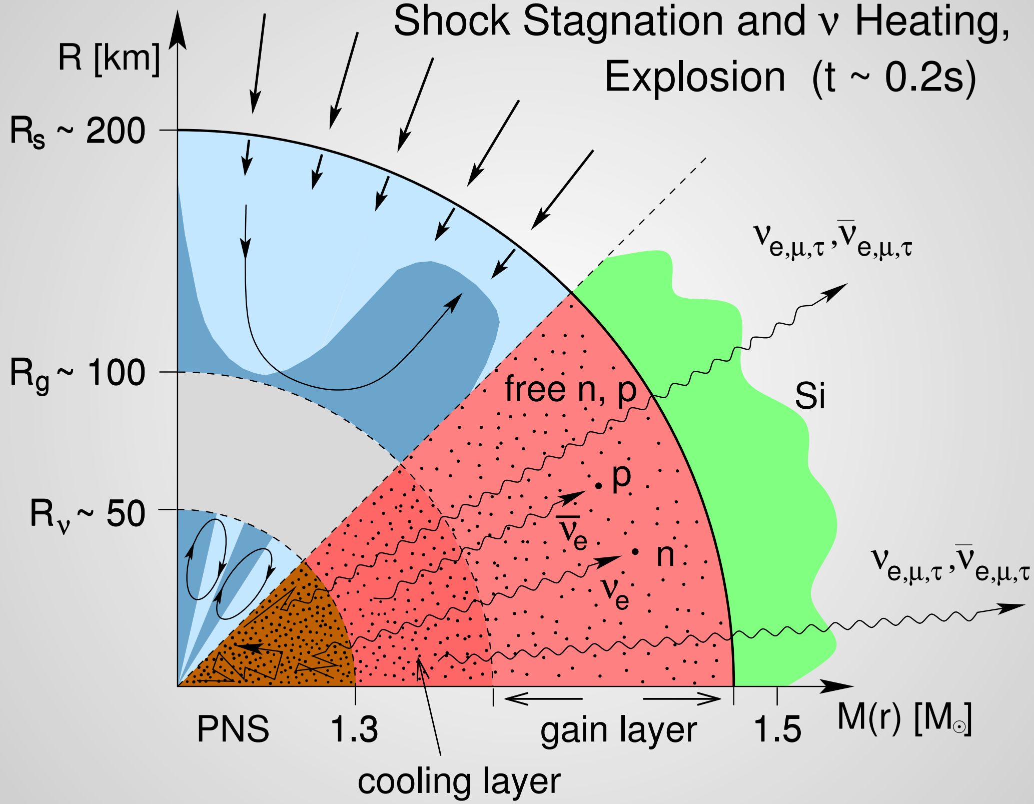
The collapsing core of the star **bounces**

The shock **stalls** while neutrinos attempt to re-energize it

Burrows & Vartanyan 2020

A closer look at the pivotal accretion/revival phase…

Janka, 1702.08713



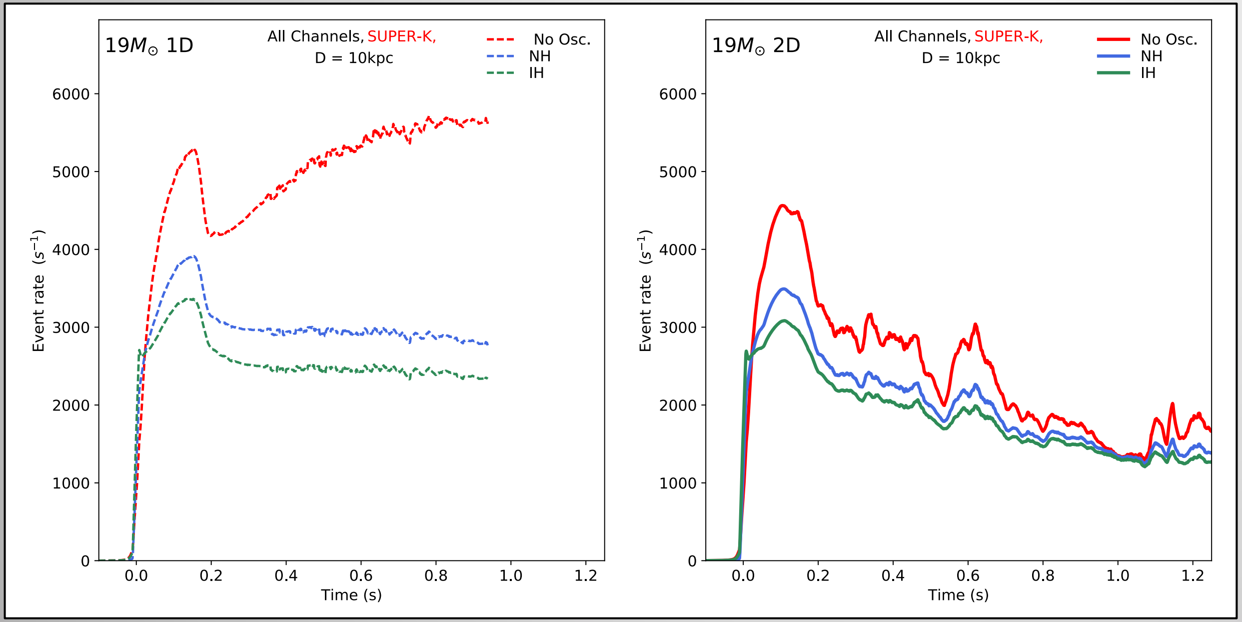
Flavor conversion might occur as neutrinos radiate out from the core.

Fuller, Mayle, Wilson, & Schramm, Astrophys. J. (1987)

Anticipated features of the signal:

- The **neutronization peak** (if IH).
- A **faster post-bounce rise** of $\bar{\nu}_e$ luminosity in IH than in NH.
- Signal modulation due to **SASI** (maybe).
- Rapid variation due to **turbulent convection**.
- **Successful vs. failed explosion** and **BH formation**.

No collective effects, only adiabatic MSW:



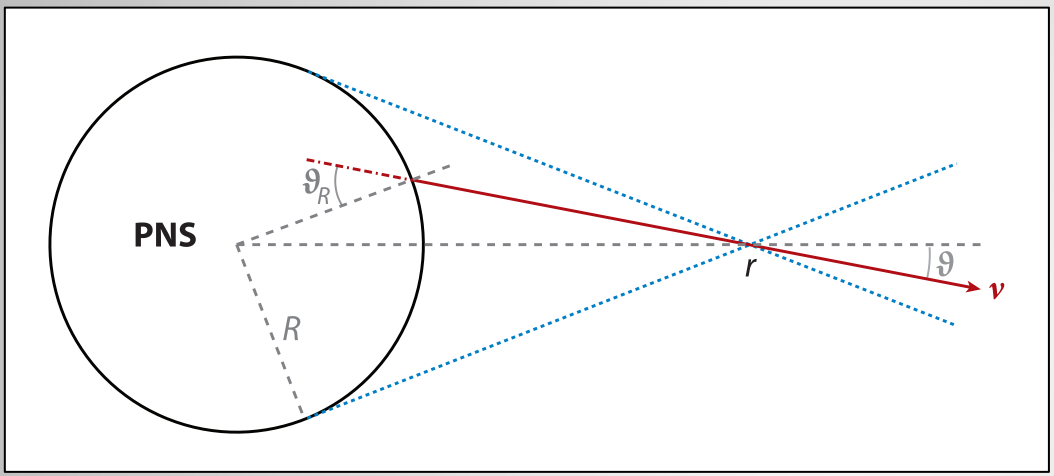
Seadrow et al., MNRAS (2018)

How does the many-body neutrino dynamics play out?

I. Neutrinos as quantum many-body systems
II. Neutrinos in core-collapse supernovae
III. Critiquing the old paradigm

The bulb model of CCSNe

Duan, Fuller, & Qian 2010



The bulb model is significant in that it's a self-consistent model of the SN *as a whole*.

And computers can actually *solve* it.

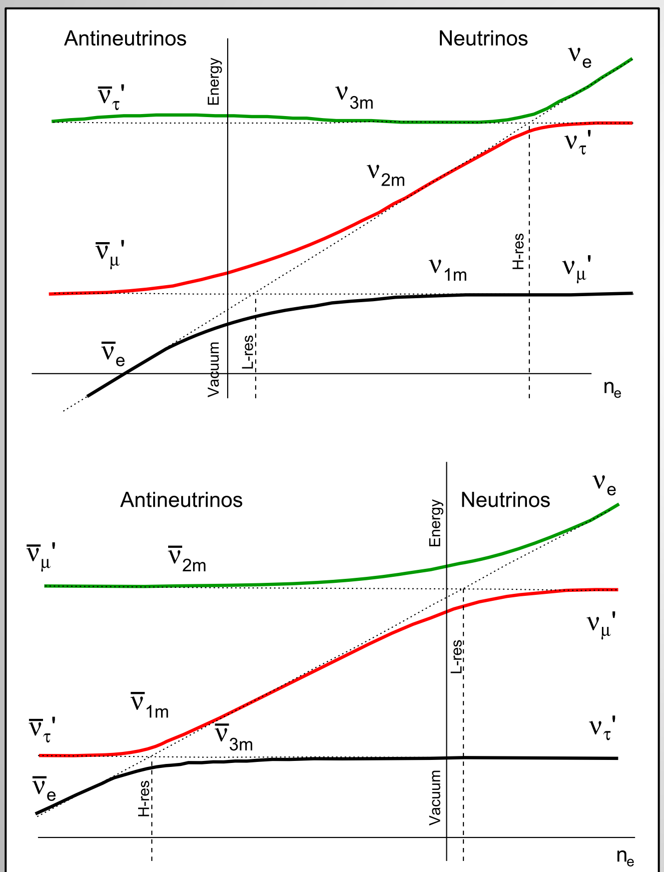
Assumptions:

- Spherical symmetry
- Stationarity
- Sharp decoupling with isotropic emission

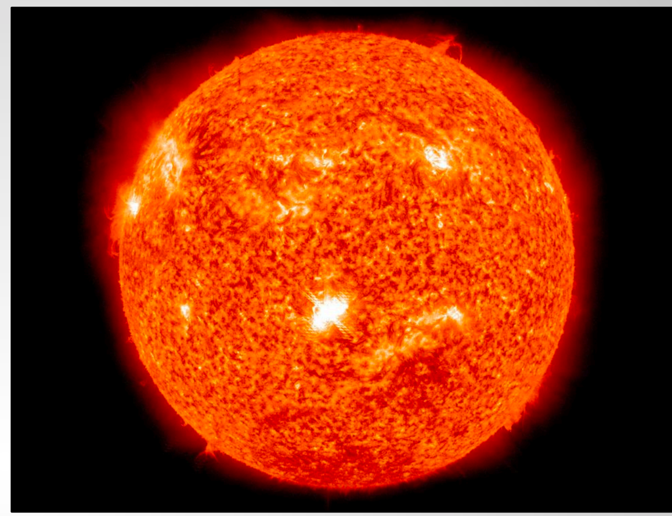
Compare: Solar neutrinos & the MSW effect

NH

IH



Scholberg, J. Phys. G (2018)

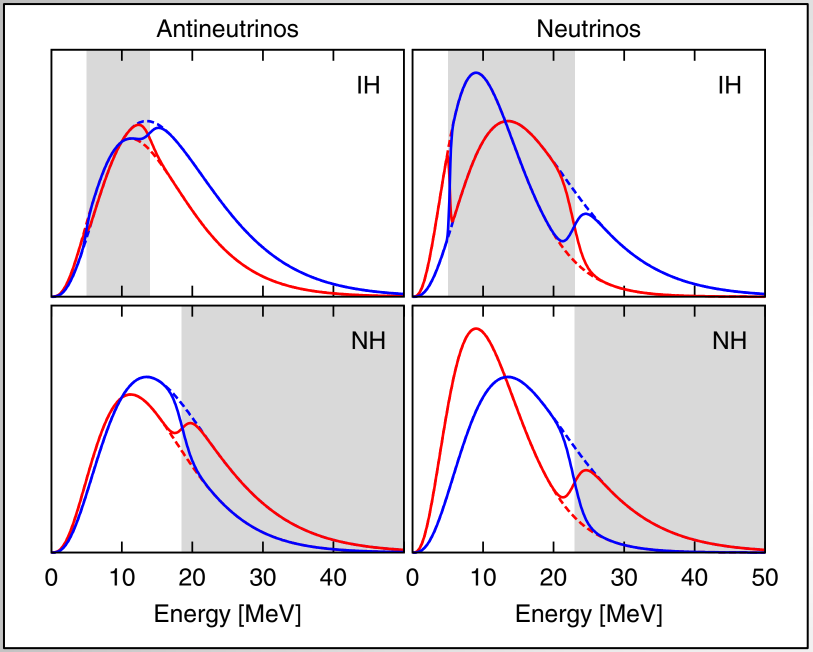


National Geographic

Neutrinos stream outward & traverse a level crossing set up by e^- forward scattering.

Radiated neutrinos exhibit **spectral swaps**:

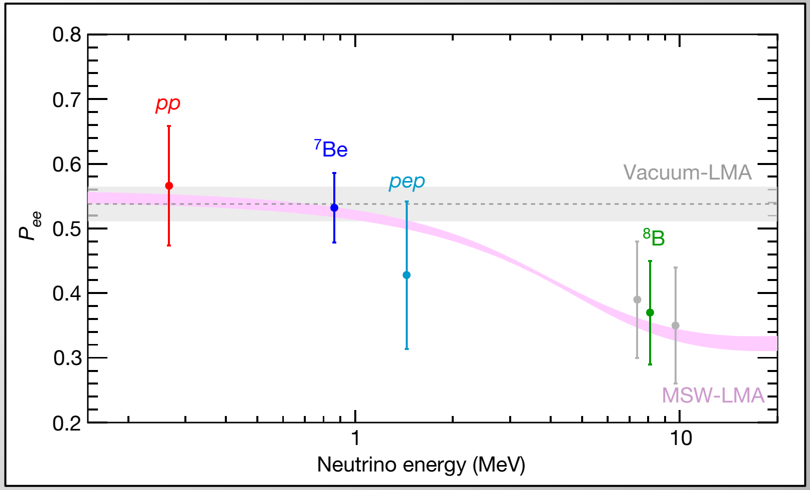
Duan et al., PRL (2006); Raffelt & Smirnov, PRD (2007)



Dasgupta et al., PRL (2009)

Red: *e* flavor
Blue: *x* flavor

Again, compare to **solar MSW**:

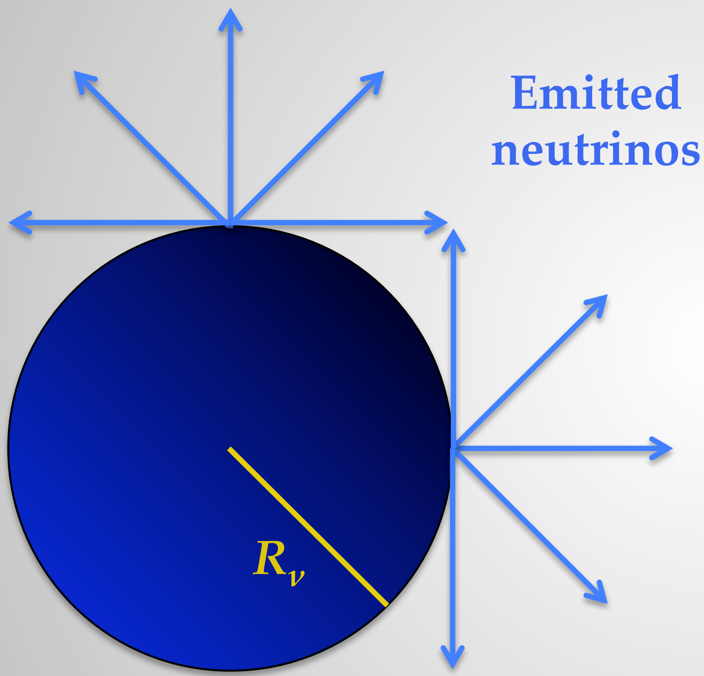


Borexino Collaboration, Nature (2018)

MSW conversion: *Electron* density
Spectral swaps: *Neutrino* density

“Symmetry is the enemy of instability.”

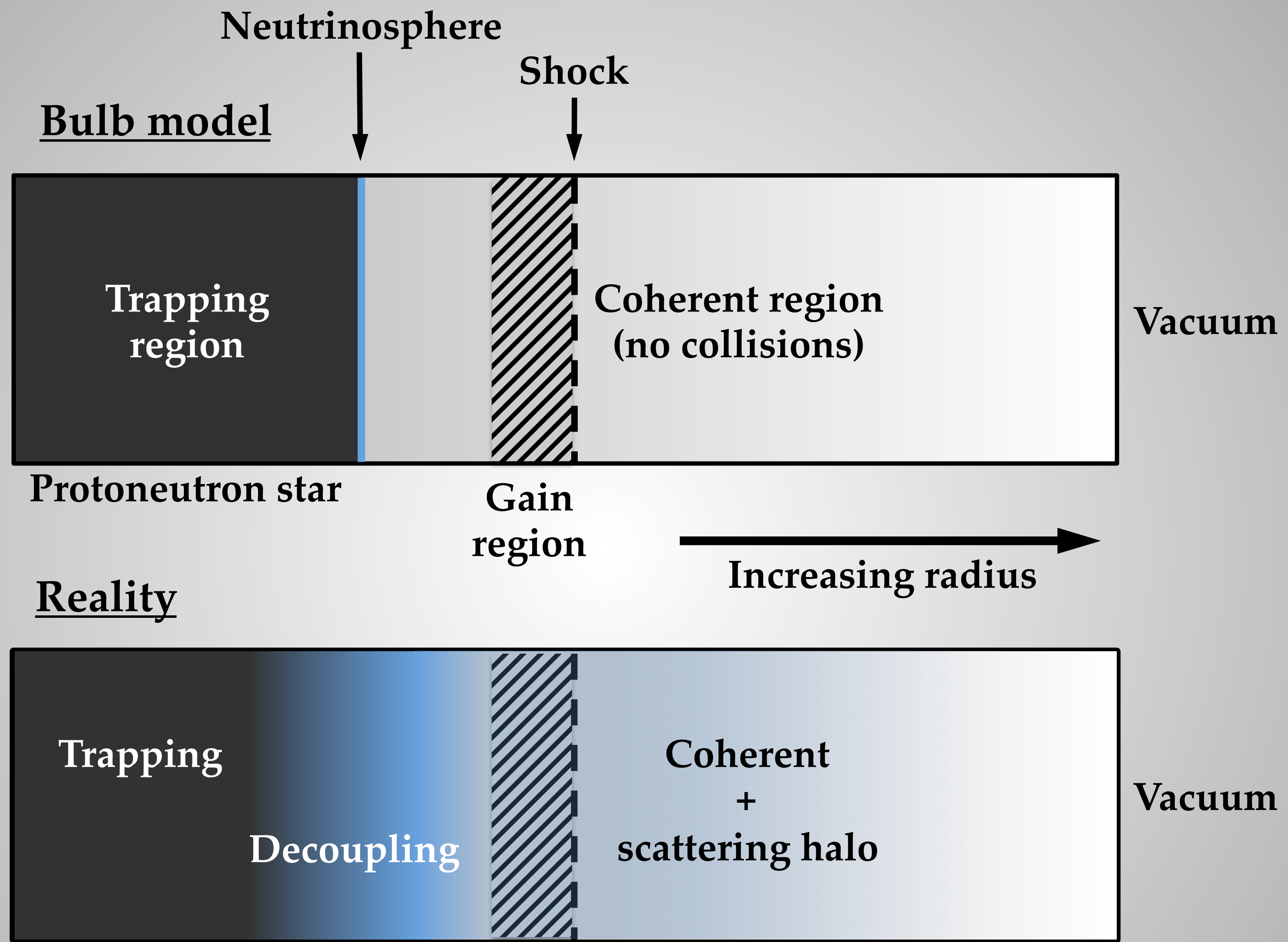
Nigel Goldenfeld



R_ν = neutrinosphere radius

We now know that symmetric models omit crucial physics.

Sawyer, PRD (2005, 2009)
Banerjee, Dighe, Raffelt, PRD (2011)
Raffelt, Sarikas, de Sousa Seixas, PRL (2013)
Izaguirre, Raffelt, Tamborra, PRL (2017)
And many others



The assumption of a single, sharp emission surface is woefully inadequate.

In devising a new paradigm, we need to accommodate the features that the old one left out:

- ✧ **Flavor instabilities**
- ✧ **Asymmetric environments**
- ✧ **Realistic collisional modeling**

And we need to do it in a way that is **computationally tractable**.

I. Neutrinos as quantum many-body systems
II. Neutrinos in core-collapse supernovae
III. Critiquing the old paradigm
IV. Instabilities, asymmetries, & collisions

Three types of instabilities are known, each related to some kind of **asymmetry between neutrinos and antineutrinos**.

Collective oscillations are sensitive to physics that distinguishes between neutrinos and antineutrinos because

$$H_{\mathbf{p},\nu\nu} \sim G_F \int d^3\mathbf{q}\,(1-\hat{\mathbf{p}}\cdot\hat{\mathbf{q}})\boxed{(\rho_{\mathbf{q}}-\bar{\rho}_{\mathbf{q}})}$$

Slow instabilities. Vacuum oscillation frequencies: $\omega_{E_\nu} \neq \omega_{E_{\bar{\nu}}}$

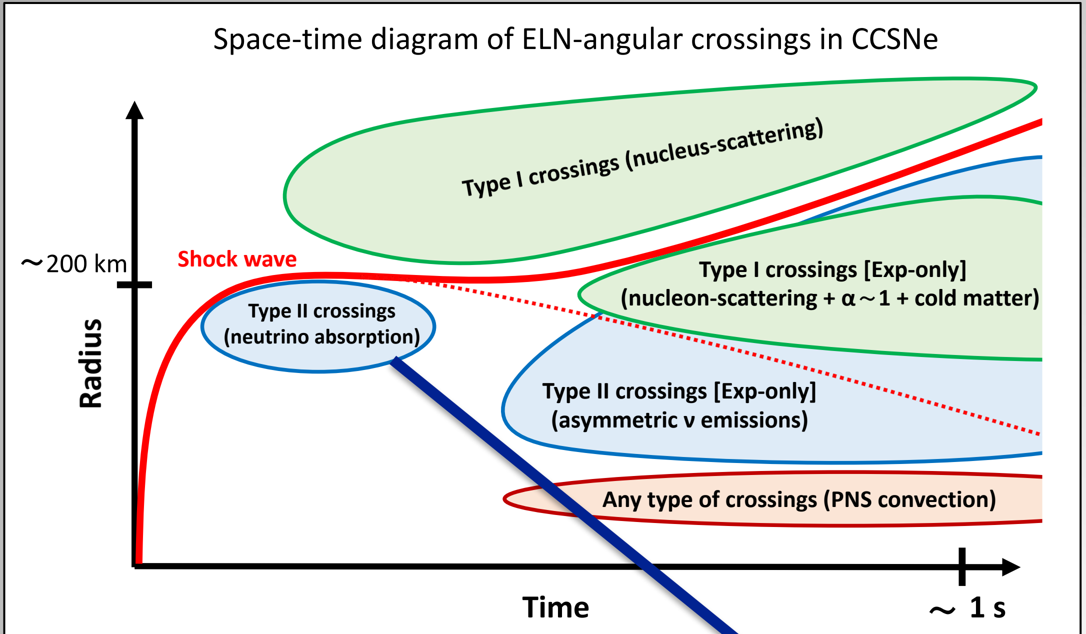
Kostelecký & Samuel, PRD (1995)

Fast instabilities. Neutrino angular distributions: $g_\nu \neq g_{\bar{\nu}}$

Sawyer, PRD (2005, 2008), PRL (2016)

Collisional instabilities. Interaction rates: $\Gamma_\nu \neq \Gamma_{\bar{\nu}}$

Johns, 2104.11369

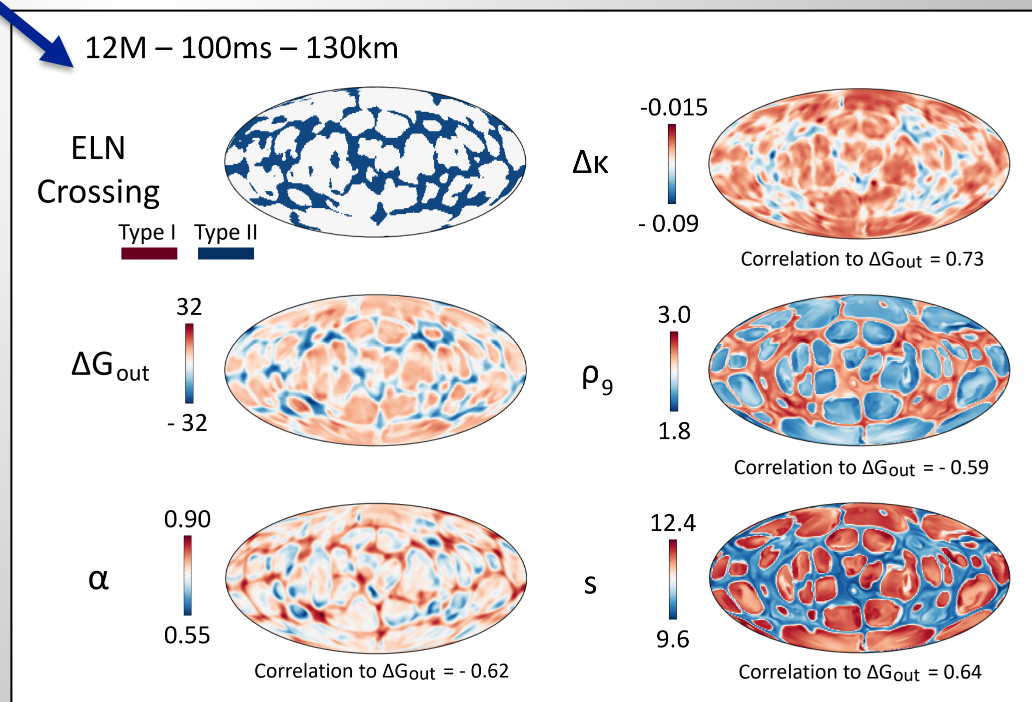


There's strong evidence that **fast instabilities** occur in SNe.

Johns & Nagakura 2021
Nagakura & **Johns** 2021a
Nagakura & **Johns** 2021b
Nagakura, Burrows, **Johns**, & Fuller 2021

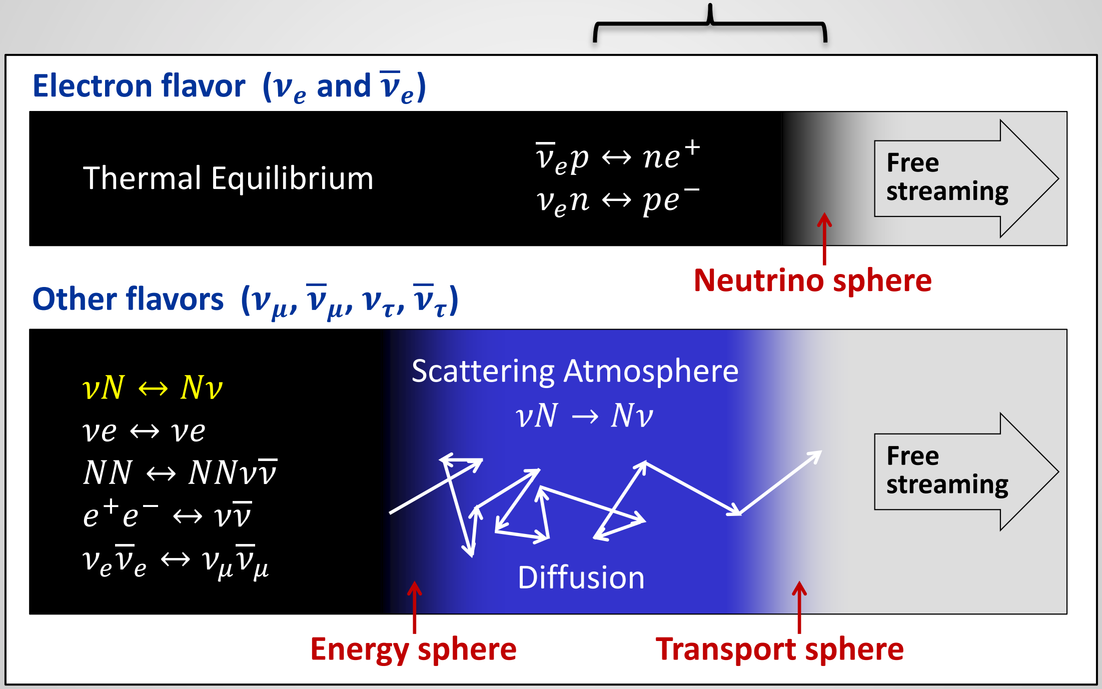
Fast (in)stability is determined by various aspects of SN physics:

- ✧ Flavor-dependent decoupling
- ✧ Scattering & absorption in optically thin regions
- ✧ Fluid entropy & density
- ✧ Accretion rate
- ✧ Asymmetric emission (e.g., LESA, PNS kicks)
- ✧ PNS convection



Johns, 2104.11369

The prime region for **collisional instability** is where neutrinos are *partially* coupled to the fluid.



Janka, 1702.08713

To correctly solve the problem of quantum neutrino transport, instabilities & collisions must be incorporated into an *asymmetric, global SN model*.

I. Neutrinos as quantum many-body systems
II. Neutrinos in core-collapse supernovae
III. Critiquing the old paradigm
IV. Instabilities, asymmetries, & collisions
V. Constructing a new paradigm

Neutrino flavor pendula

Pendulum

Spin

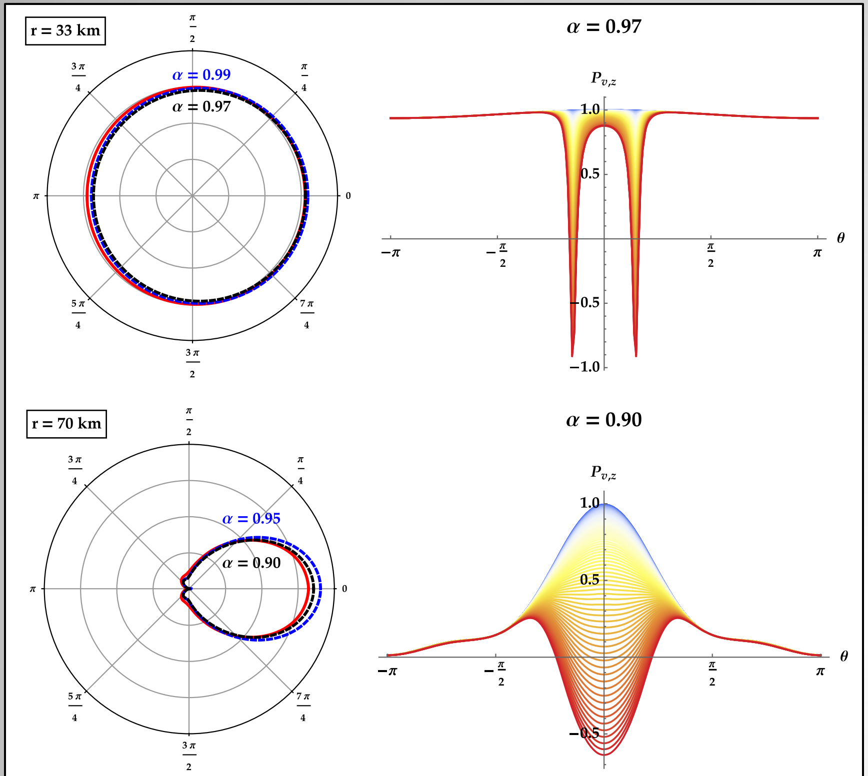
$$\frac{\boldsymbol{\delta} \times \ddot{\boldsymbol{\delta}}}{\mu} + \sigma \dot{\boldsymbol{\delta}} + \mathbf{g} \times \boldsymbol{\delta} = 0$$

Gravity

This equation applies (with different meanings) to...

- ✧ Slow collective oscillations in SNe
  - Hannestad et al. 2006
  - Duan et al. 2007
- ✧ Fast collective oscillations in SNe
  - **Johns** et al. 2020
  - Padilla-Gay, Tamborra, Raffelt 2022
- ✧ Collective oscillations in the early universe
  - **Johns** & Fuller 2018

Flavor conversion vs. propagation angle

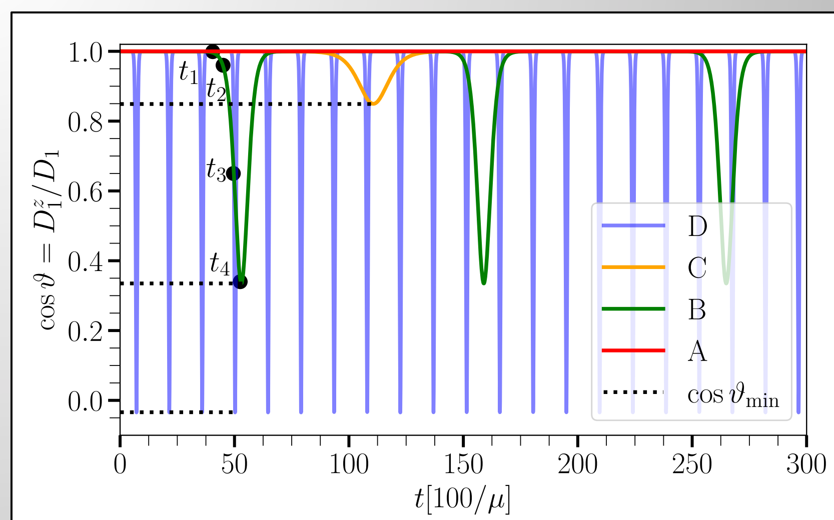


Johns et al. 2020

The fast neutrino flavor pendulum

Caution:
These analyses are exact only in restricted set-ups.

Flavor conversion vs. time



Padilla-Gay, Tamborra, Raffelt 2022

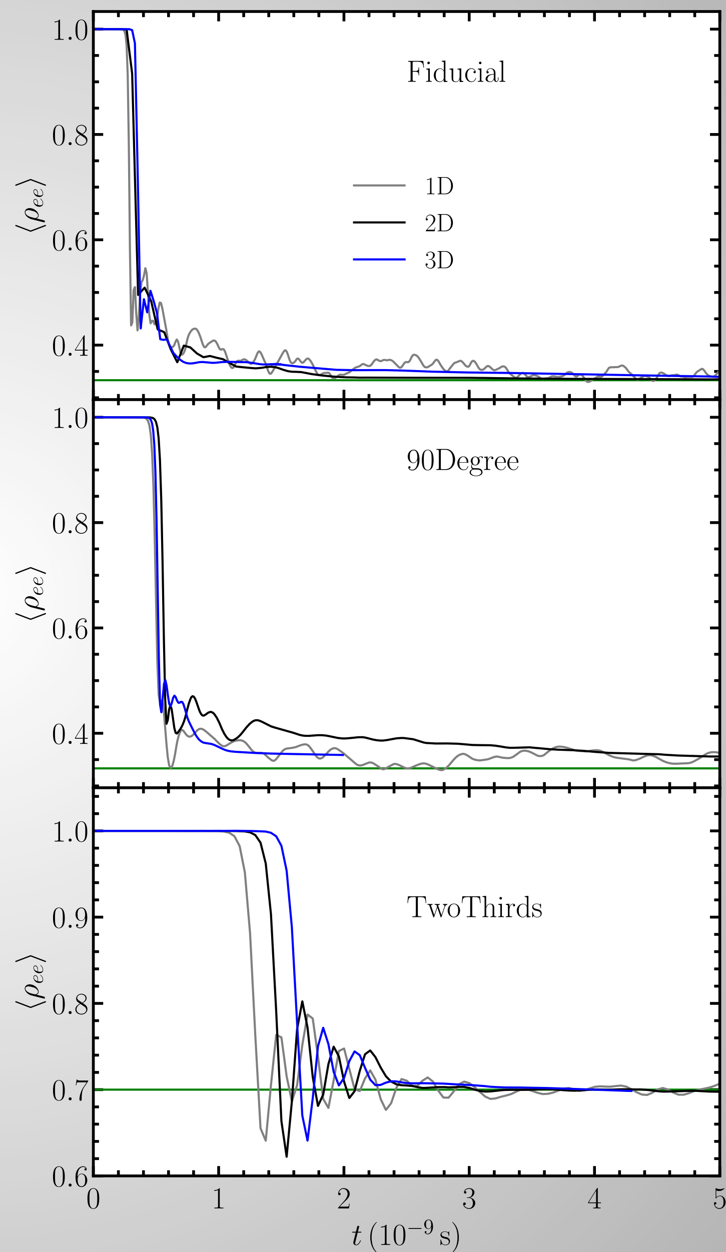
If all symmetries are broken, results like these are more typical.

Without axial symmetry, there are *three* fast pendula.

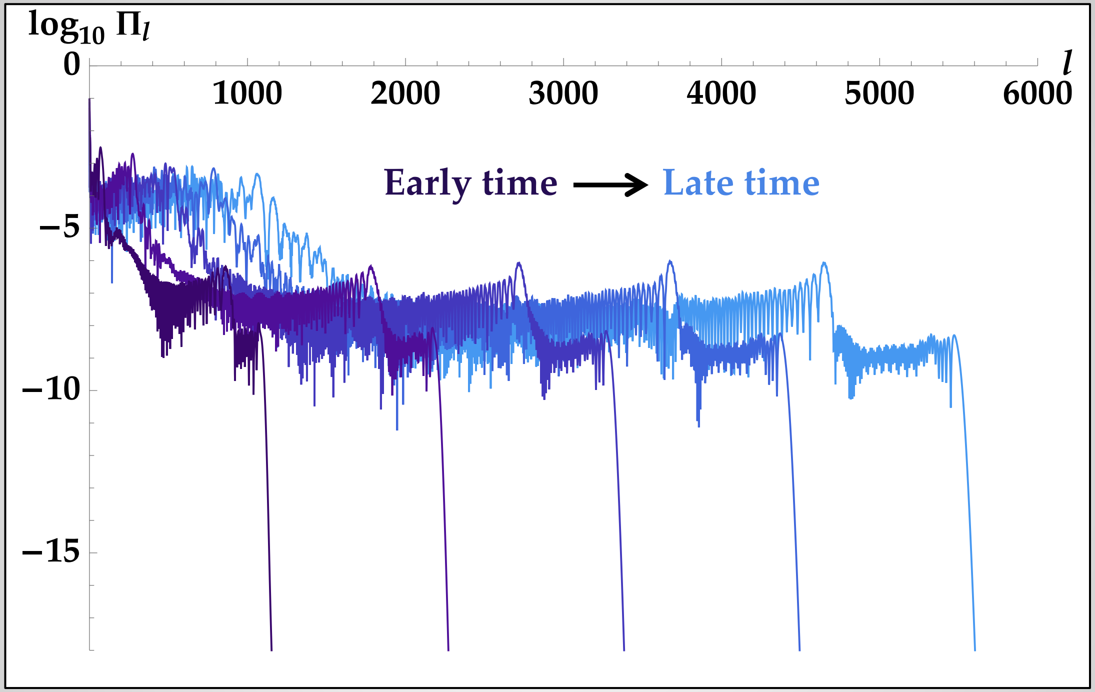
Johns et al., in prep

Contrast the *periodic* dynamics of a single pendulum with the *chaotic* dynamics of a double pendulum.

Richers, Willcox, Ford, PRD (2021)



Cascade of power to smaller angular scales



Legendre moment

Johns, Nagakura, Fuller, & Burrows, PRD (2020)

The picture that's emerging: unstable, chaotic dynamics at low l relaxes by coupling to an infinite sequence of oscillators at higher l.

How does a system made up of many oscillators evolve in phase space?

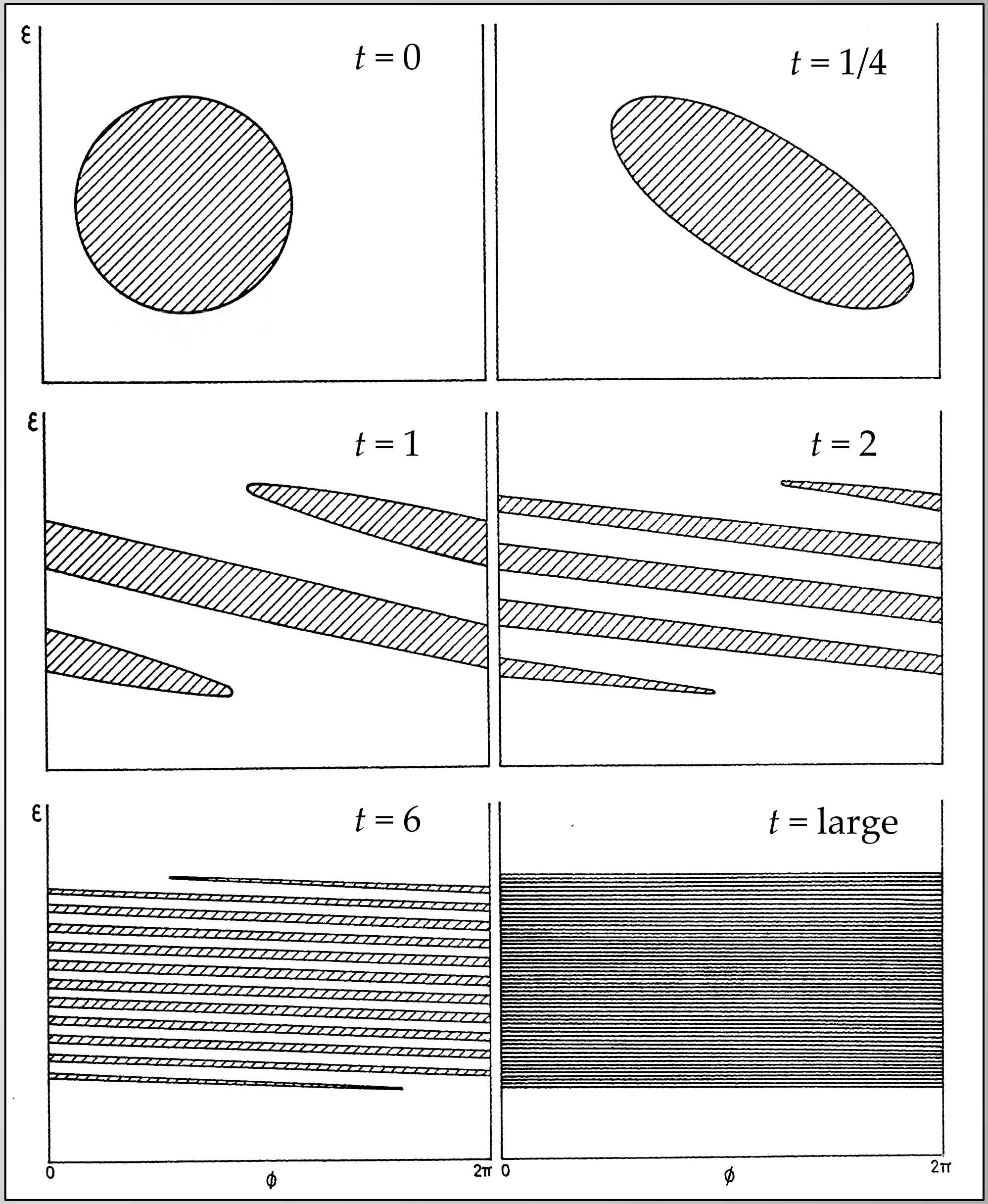
It undergoes **collisionless relaxation** by developing small-scale structure:

- *Violent relaxation* in grav. systems
- *Filamentation* in plasmas
- *Turbulence* in fluids

We're still developing the techniques to describe this process as it occurs in neutrino flavor fields.

Johns, Nagakura, Fuller, & Burrows, PRD (2020)

Oscillator energy vs. phase



D. Lynden-Bell, MNRAS (1967)

Summary

- SN neutrinos are a natural laboratory for quantum many-body physics. The theory, however, is incomplete.
- The MSW-inspired paradigm—solving the Schrödinger equation exactly—needs to be left behind.
- A new approach, based on flavor-field relaxation, is being developed.