Neutrino oscillations in the multimessenger era

Luke Johns
NASA Einstein Fellow
UC Berkeley

The past & potential of neutrino astronomy

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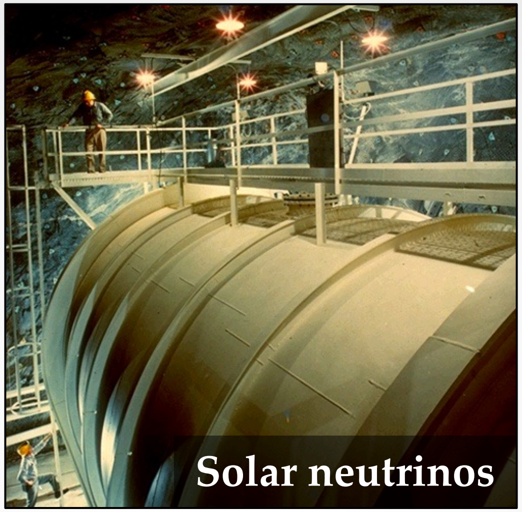
Homestake



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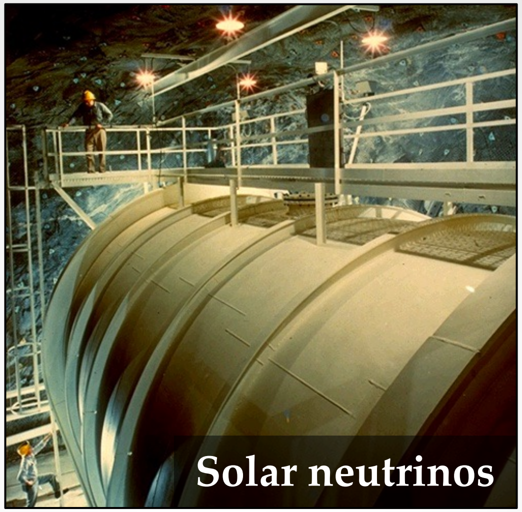

Super-Kamiokande

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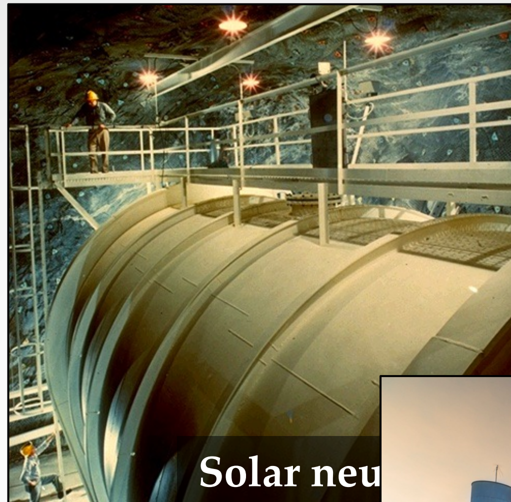
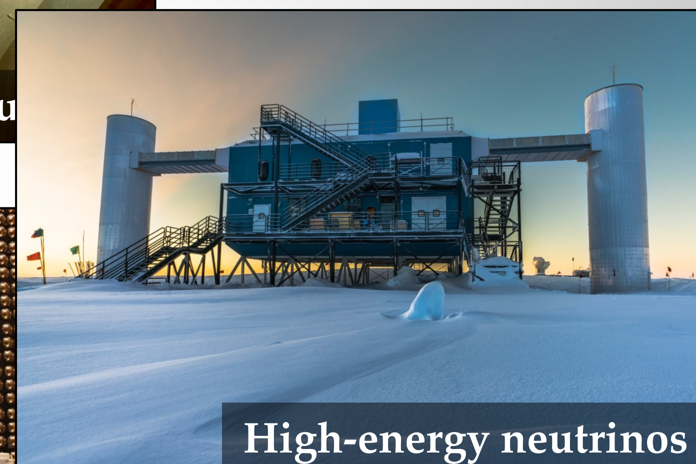


IceCube



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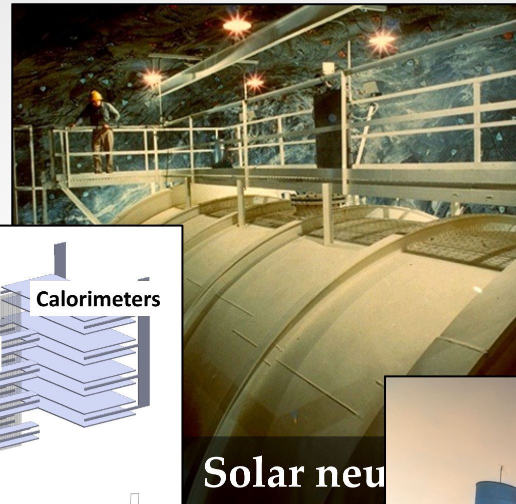

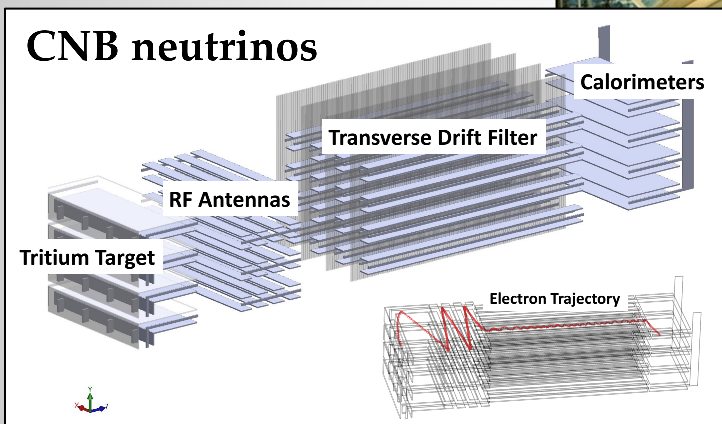

PTOLEMY

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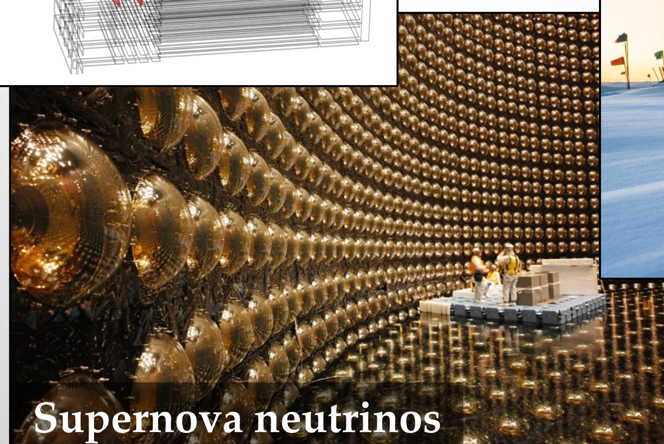

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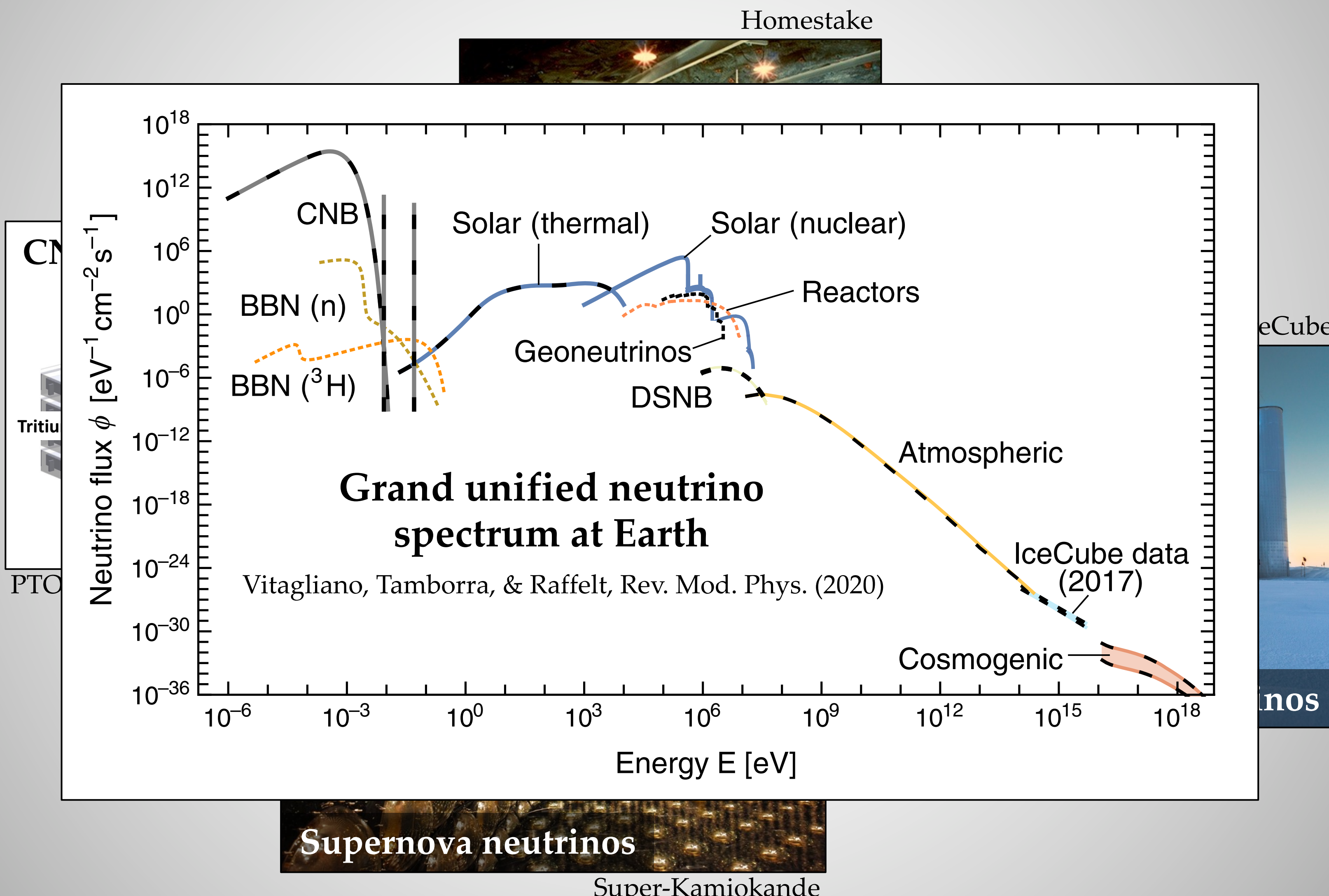
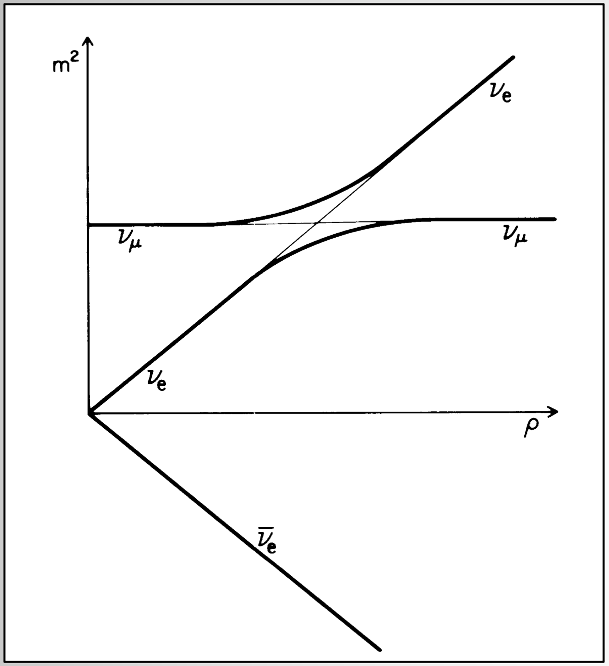


Two quantum concepts will recur throughout this talk:

(non)adiabaticity & **(de)coherence**

Solar neutrinos

The MSW effect

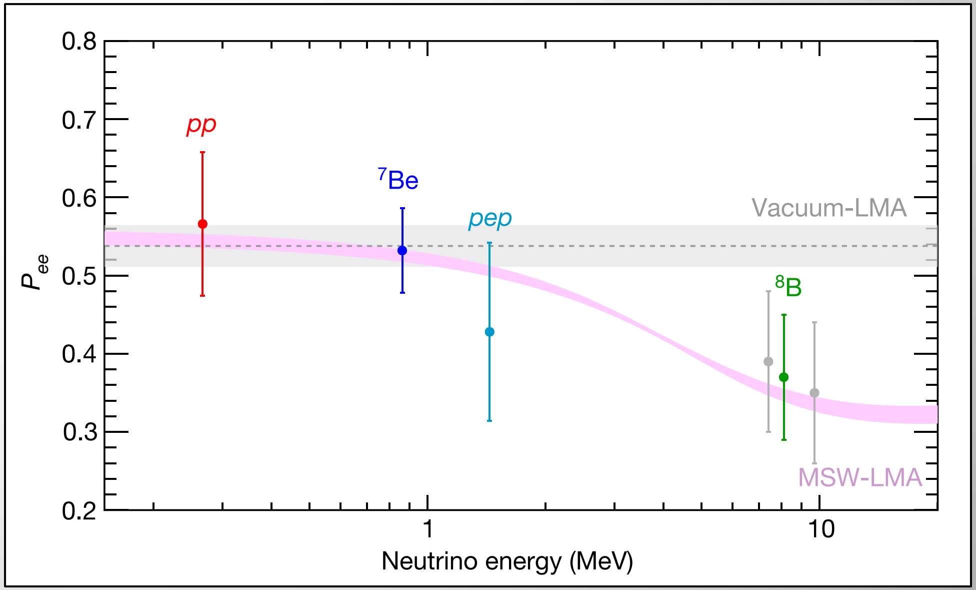


Bethe, Phys. Rev. Lett. (1986)

***High* energies:** Adiabatic passage through an MSW resonance.

***Low* energies:** Kinematic decoherence en route to Earth.

Survival probabilities of electron neutrinos



Borexino Collaboration, Nature (2018)

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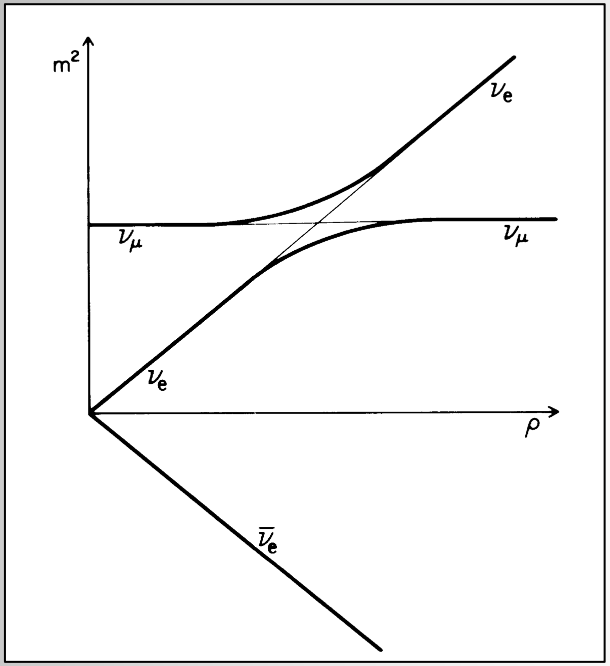

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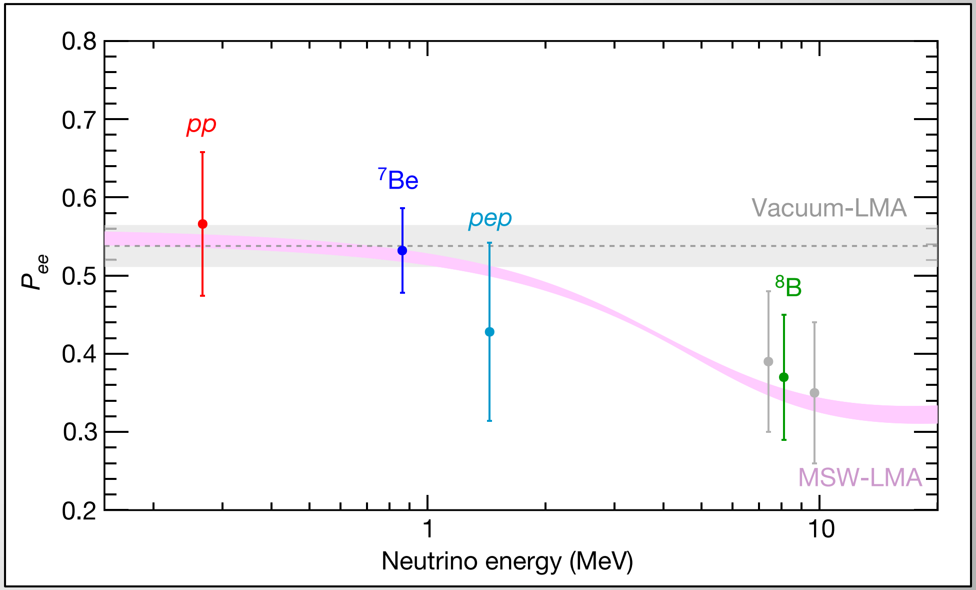

Borexino Collaboration, Nature (2018)

The oscillation problem in the Sun has essentially been solved.

High-energy neutrinos (E_ν > GeV)

The astrophysical sources of IceCube neutrinos are mysterious. Possible associations include:

- Blazars (*e.g.*, TXS 0506+056)
- The Seyfert II galaxy NGC 1068
- Tidal disruption events

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Due to kinematic decoherence, flavor ratios at Earth are concentrated around $\frac{1}{3}:\frac{1}{3}:\frac{1}{3}$.

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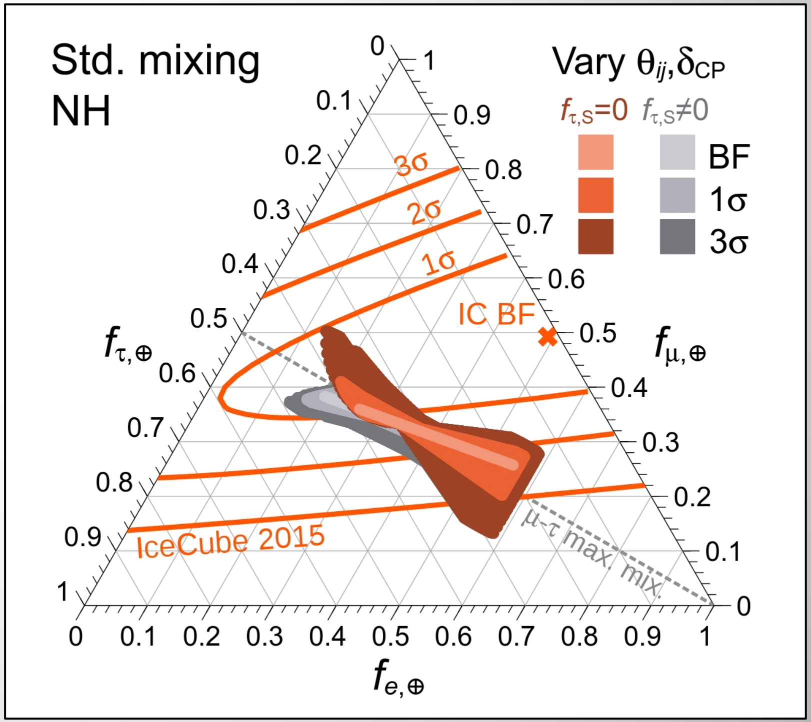
Allowed flavor ratios at Earth

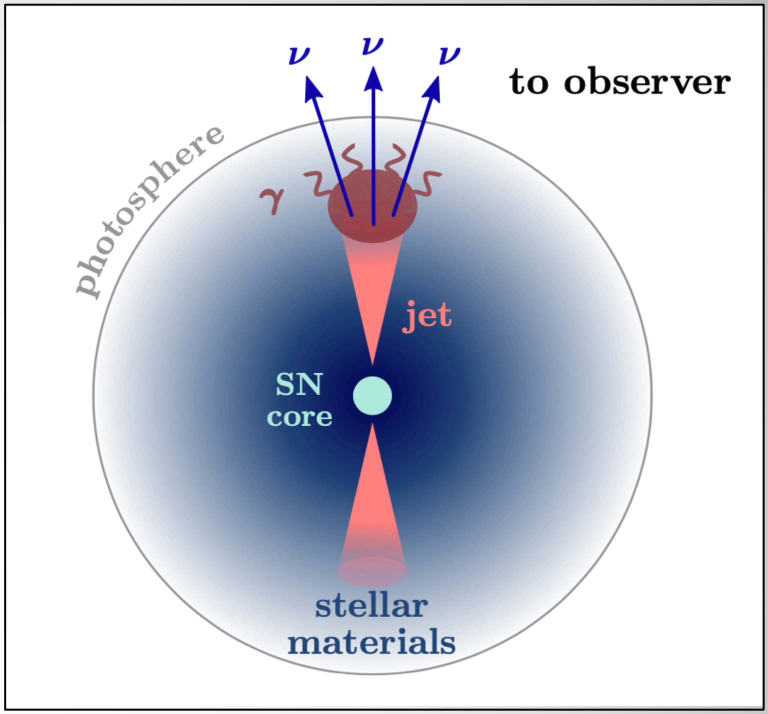


Bustamante, Beacom, Winter, PRL (2015)

High-energy neutrinos (E_ν > GeV)

Choked jets might be the exception: a site where the matter density could affect flavor mixing.

Mészáros & Waxman 2001; Ando & Beacom 2005; Murase & Ioka 2013; Carpio & Murase 2020; …



Chang, Zhou, Murase, Kamionkowski, 2210.03088

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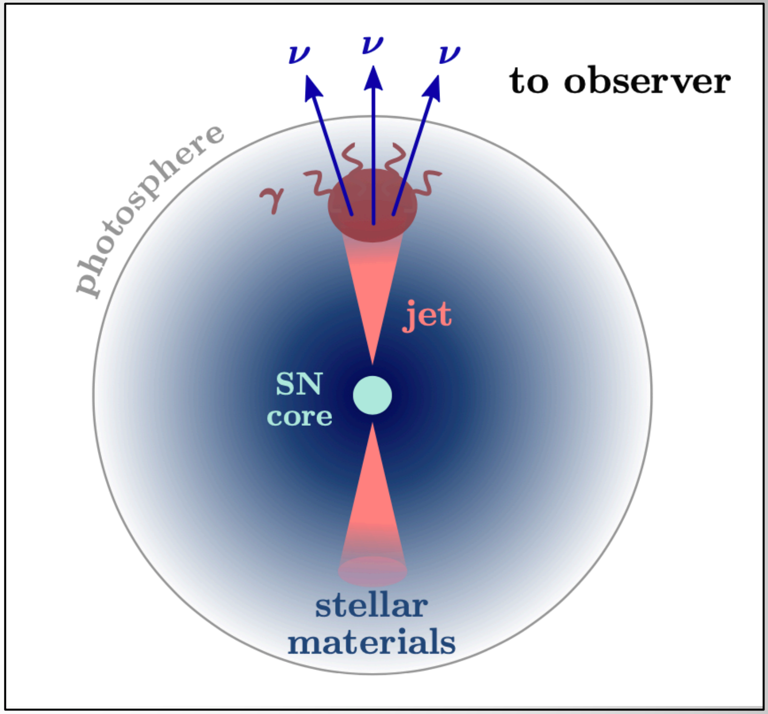

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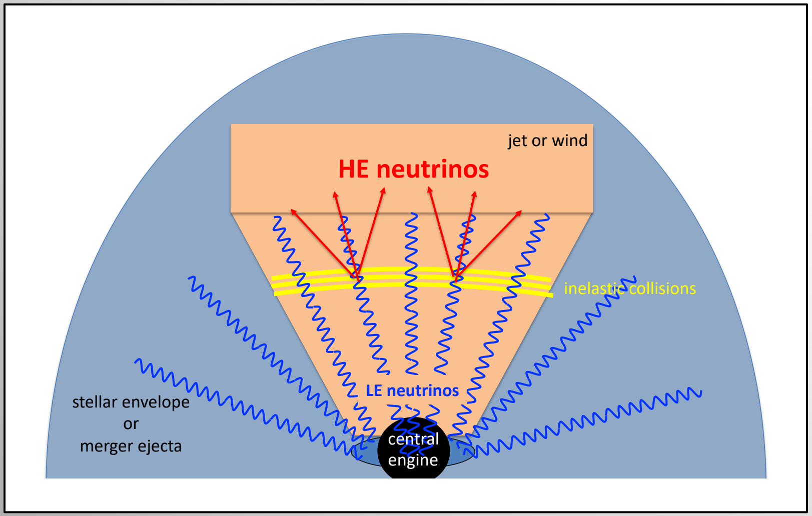
The low-energy neutrino density might even be important:

Abbar, Carpio, Murase, 2205.10384



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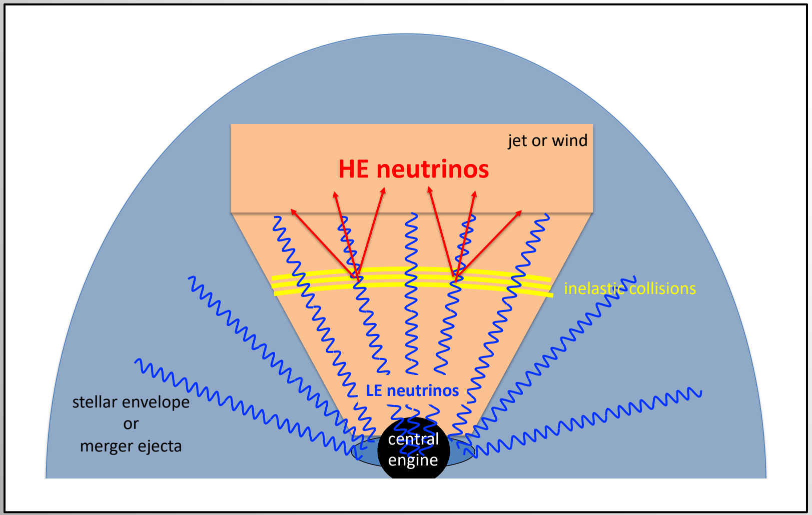

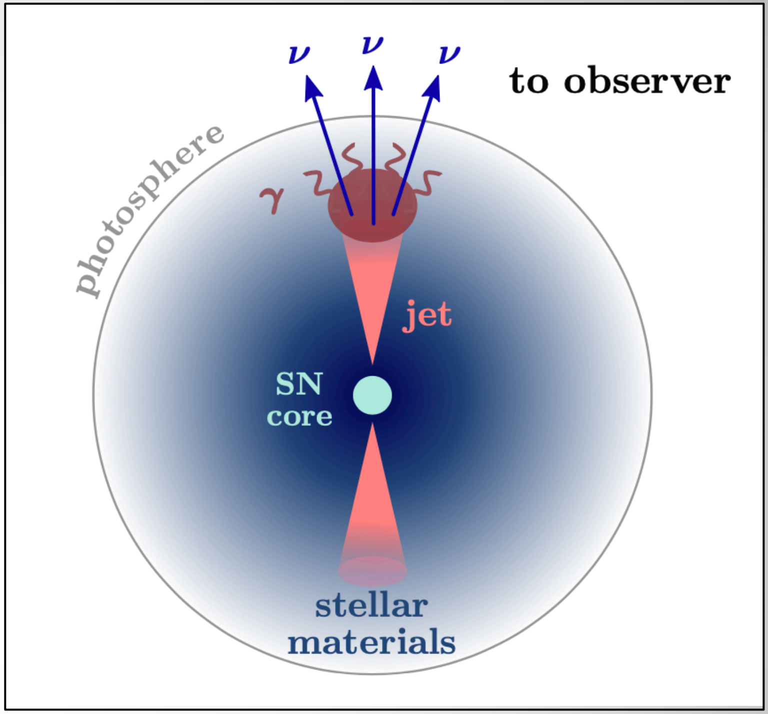

Chang, Zhou, Murase, Kamionkowski, 2210.03088

The modeling of these sites still has a lot of room to grow.

Cosmological neutrinos

The CνB today

Total density ~ 336 cm^{-3}
Average momentum ~ 0.6 meV
Number of NR mass states ≥ 2

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Dolgov et al., NPB (2002)
Abazajian, Beacom, & Bell, PRD (2002)
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Dirac	***Majorana***
$n(\nu_{h_L}) = n_0$	$n(\nu_{h_L}) = n_0$
$n(\bar{\nu}_{h_R}) = n_0$	$n(\nu_{h_R}) = n_0$
$n(\nu_{h_R}) = 0$	$n(N_{h_R}) = 0$
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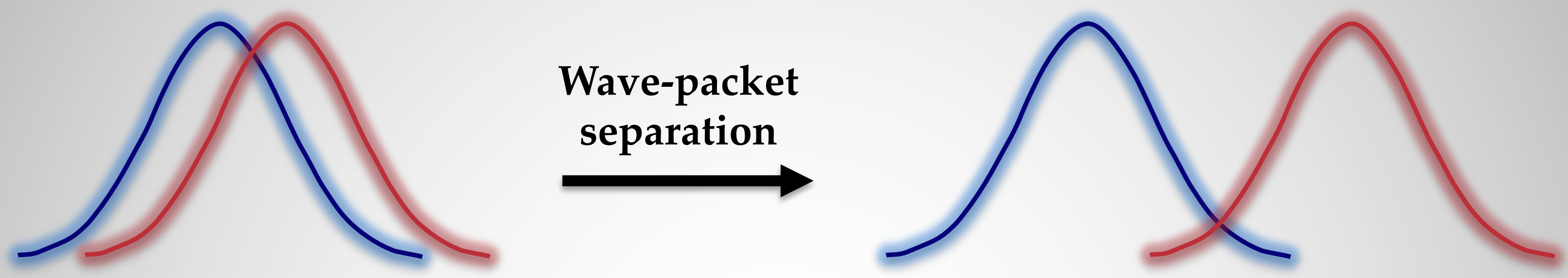
Bennett et al., JCAP (2020)

Chiral oscillations reduce Γ^{D} relative to Γ^{M}.

Duda, Gelmini, & Nussinov, PRD (2001)
Long, Lunardini, & Sabancilar, JCAP (2014)
Ge & Pasquini, PLB (2020)
Bittencourt, Bernardini, & Blasone, EPJC (2021)
Hernandez-Molinero, Jimenez, & Peña Garay, JCAP (2022)

Coordinate-space picture of **kinematic decoherence**:



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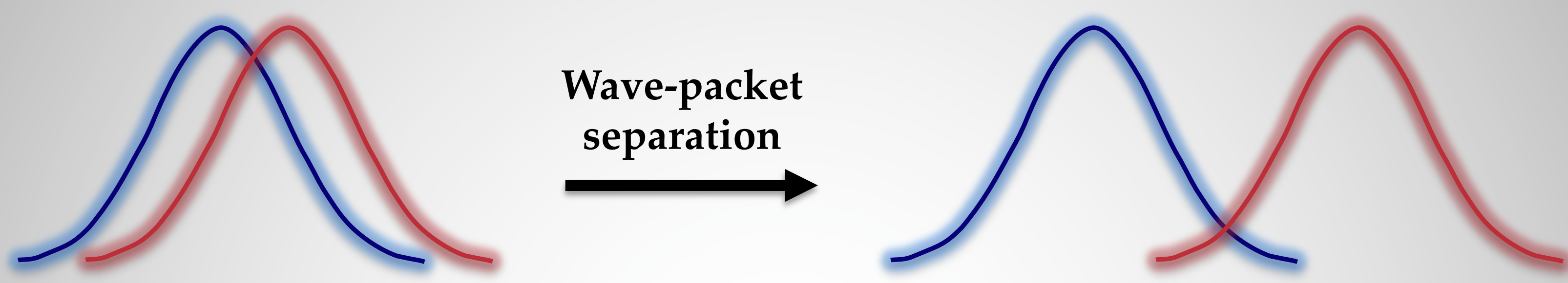

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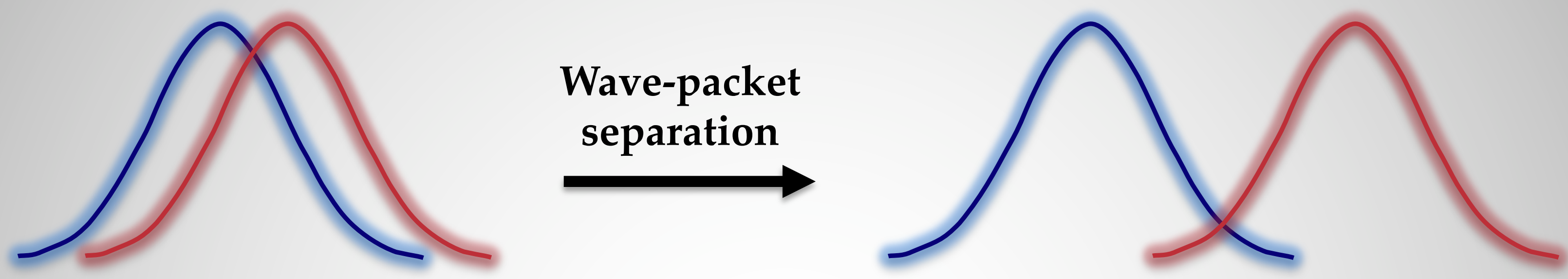

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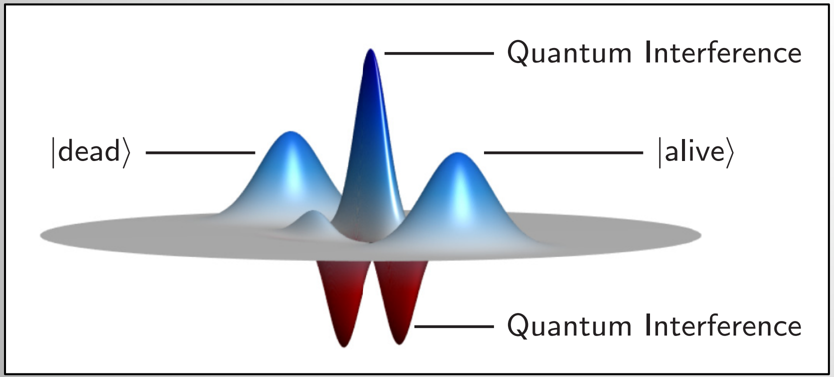
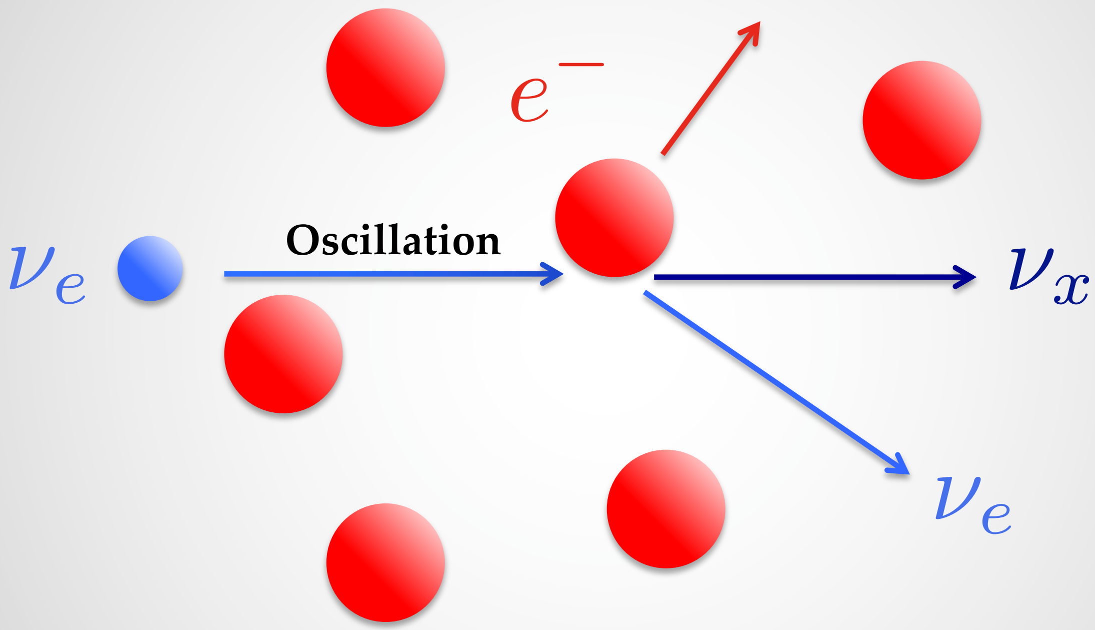
Schrödinger cat states



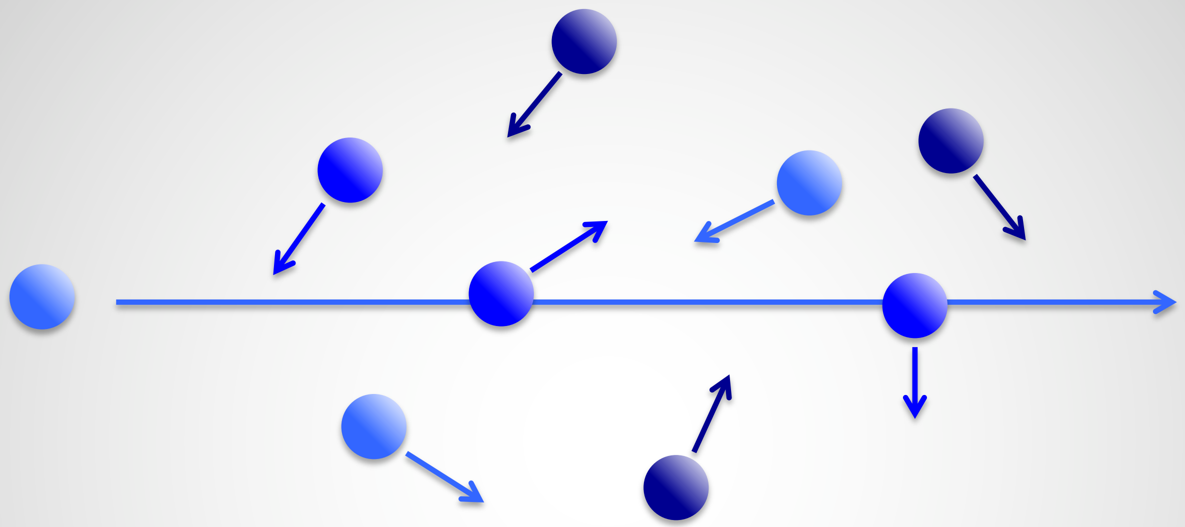
Rundle, Mills, Tilma, Samson, Everitt, PRA 2017

S. Haroche via *Science et Vie Junior*

Contrast with **collisional / environmental decoherence**:



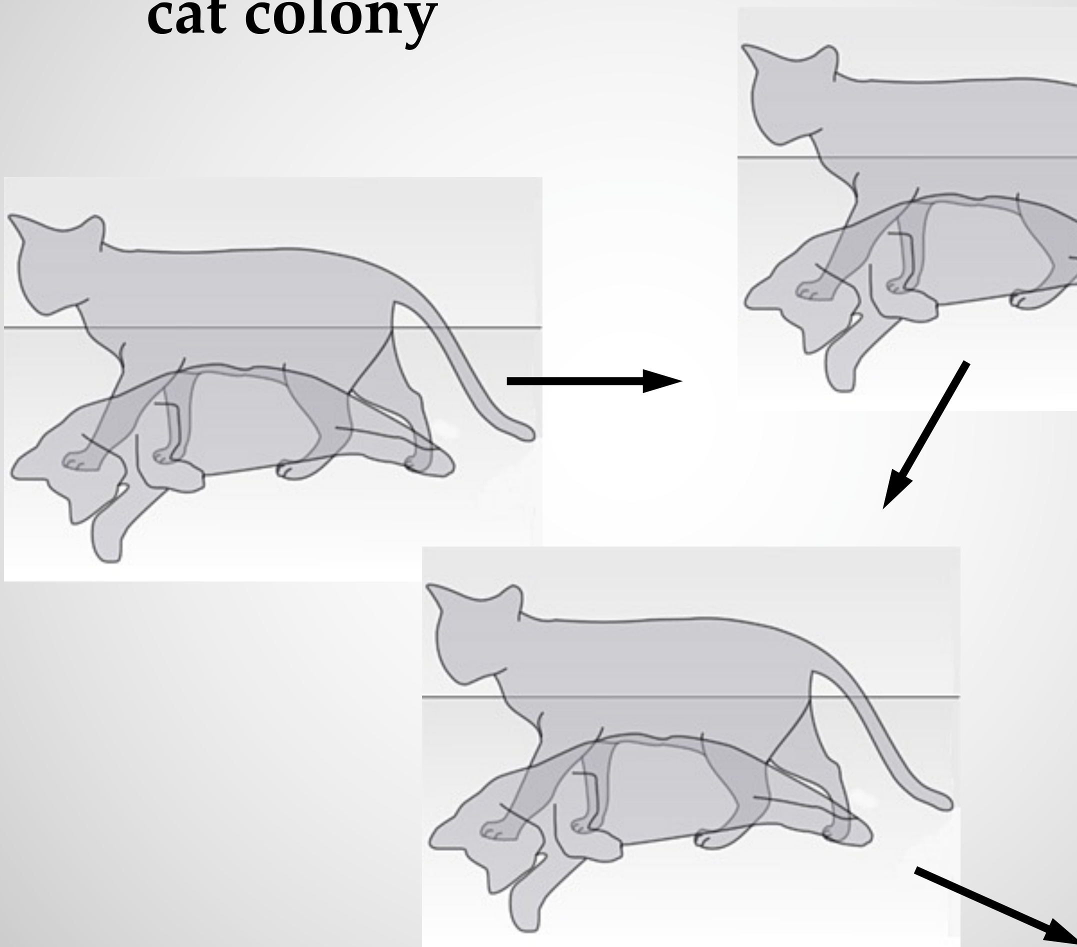
The electron "measures" the flavor state, causing decoherence.



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

Collective oscillations

Schrödinger's cat colony



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interaction eigenstates ≅ **energy eigenstates**.

The two main exceptions occur in regions with

- **(avoided) level crossings** or
- **flavor instabilities**.

MSW resonance is the classic example

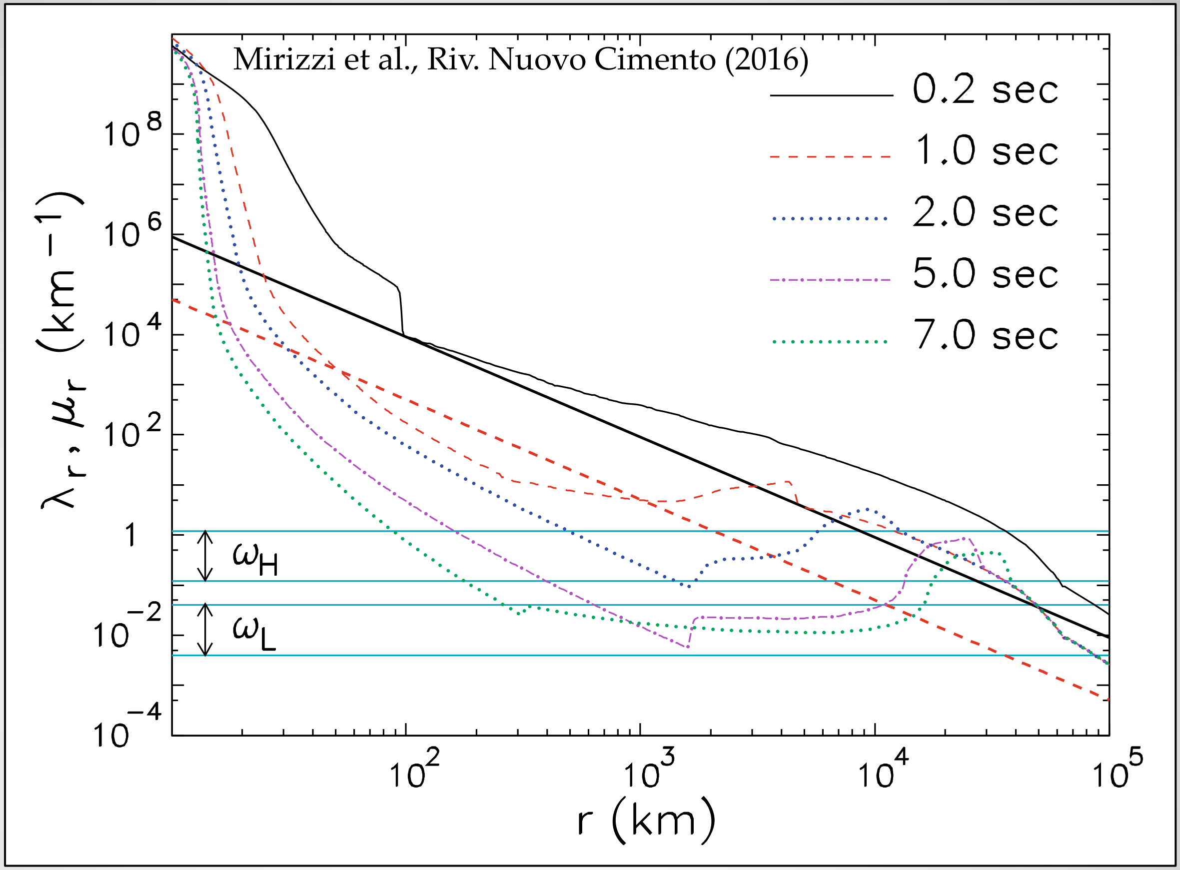
Wolfenstein, PRD (1978); Mikheyev & Smirnov, SJNP (1985)

Forward-scattering potentials in a CCSN

λ = Matter pot'l (*thin curves*)

μ = Neutrino pot'l (*thick curves*)

ω = Vacuum osc. frequencies (*blue bands*)



Time after core bounce

Radius

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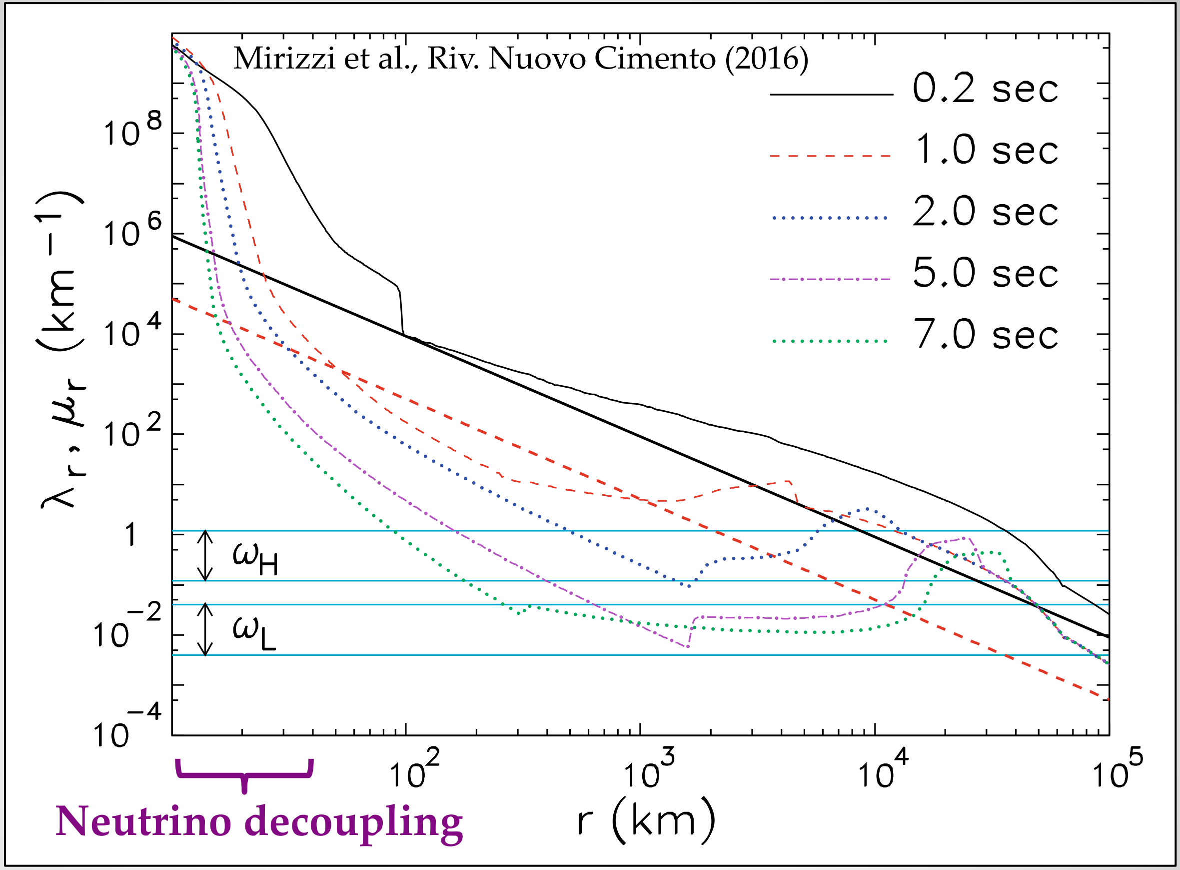

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Level crossings: MSW, spectral swaps, MNR (mergers only?)

Duan et al., PRL (2007); Raffelt & Smirnov, PRD (2007); Dasgupta et al., PRL (2009); Gava et al., PRL (2009); Friedland, PRL (2010); Galais & Volpe, PRD (2011); Malkus et al., PRD (2012); Zhu et al., PRD (2016); Wu et al., PLB (2016); & many more

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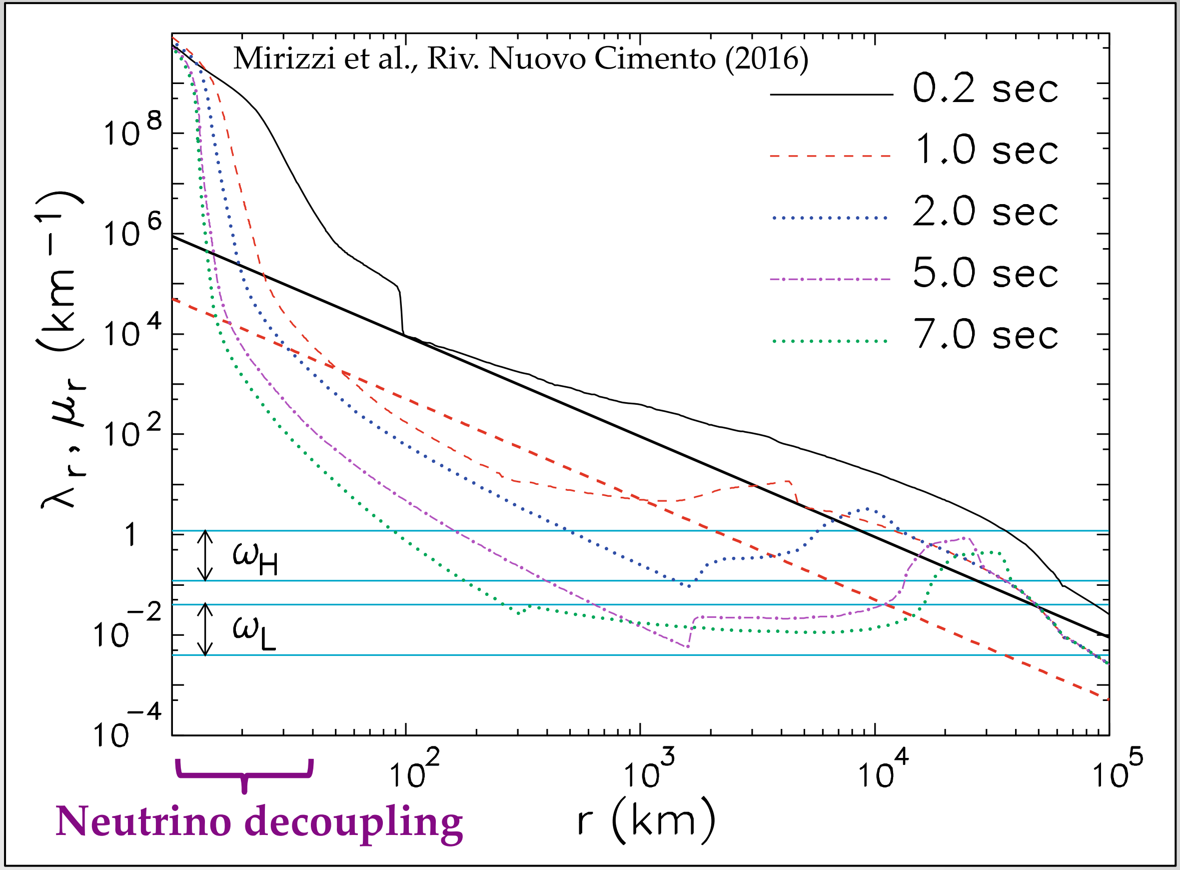

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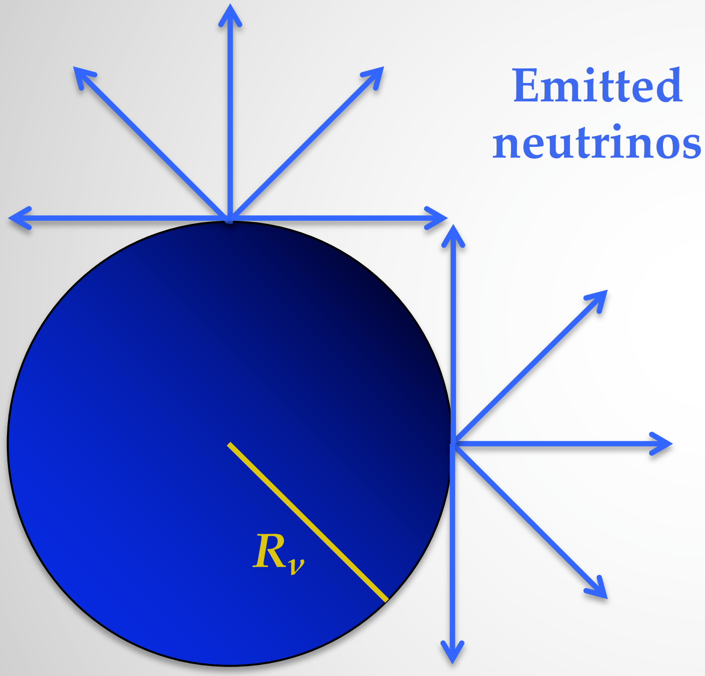
***Flavor instabilities* can occur just about anywhere in or beyond the decoupling region, as we'll see…**

“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

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

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

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

Kostelecký & Samuel, PRD (1995)

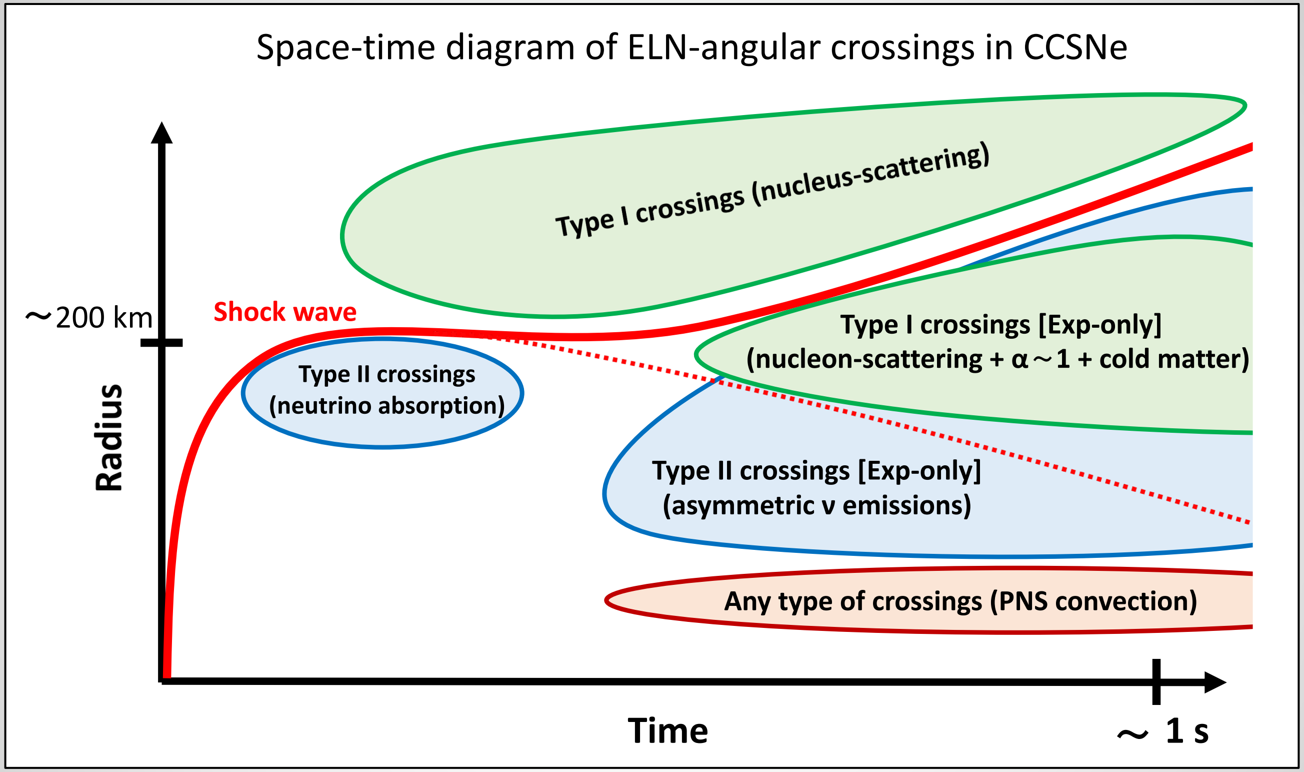
Fast instabilities. Neutrino angular distributions: $g_\nu \neq g_{\bar{\nu}}$

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

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

Johns, 2104.11369

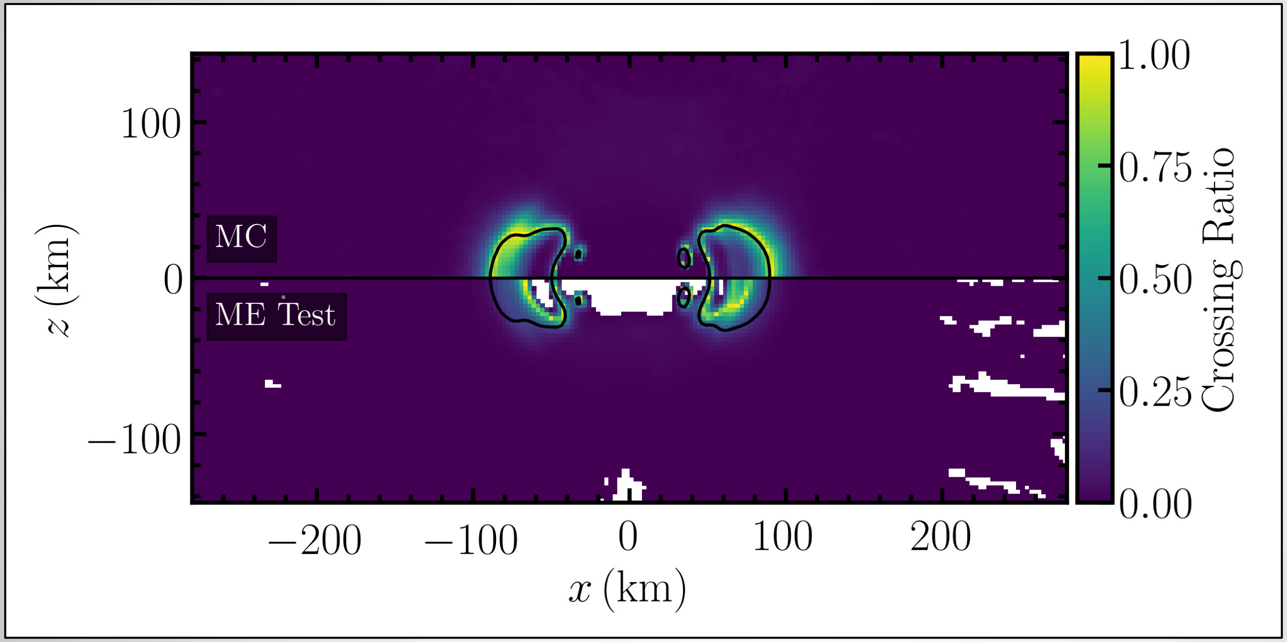
There's strong evidence that **fast instabilities** occur in CCSNe & NSMs.



Nagakura, Burrows, **Johns**, & Fuller, PRD (2021)

Sawyer, PRD (2005); Banerjee et al., PRD (2011); Chakraborty et al., JCAP (2016); Izaguirre et al., PRD (2017); Capozzi et al., PRD (2017); Dasgupta et al., JCAP (2017); Delfan Azari et al., PRD (2019); Abbar et al., PRD (2020); Glas et al., PRD (2020); Morinaga et al., PRR (2020); Xiong et al., ApJ (2020); **Johns** & Nagakura, PRD (2021); Nagakura & **Johns**, PRD (2021a); Nagakura & **Johns**, PRD (2021b); Capozzi et al., PRD (2021); Shalgar & Tamborra, Annu. Rev. Nucl. Part. Sci. (2021); Morinaga, PRD (2022); Harada & Nagakura, ApJ (2022); & others

Fast instabilities appear almost everywhere surrounding merger remnants, largely due to protonization of neutron-rich matter.



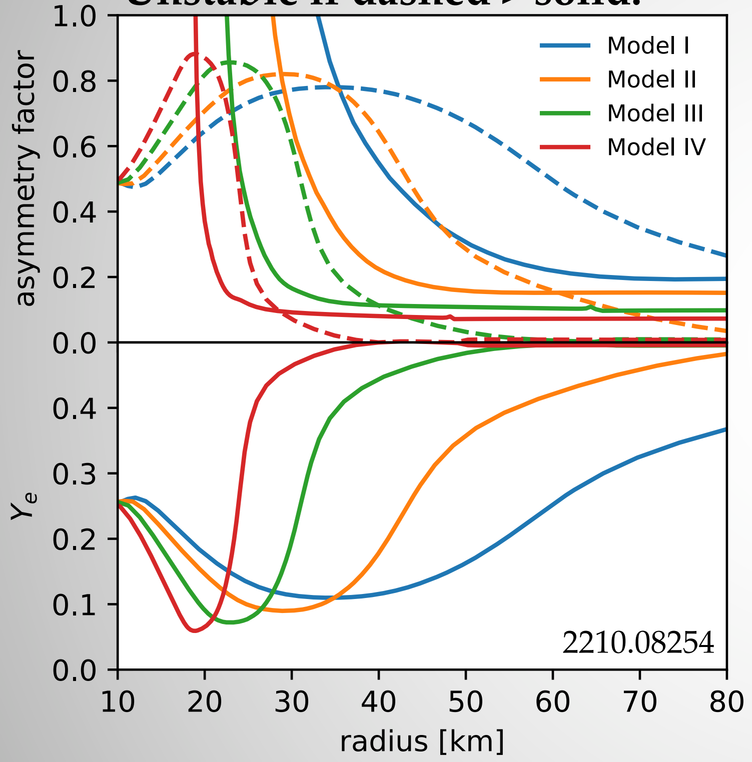
Richers, 2206.08444

Indicative of the extent of flavor conversion (*white* = *stable*)

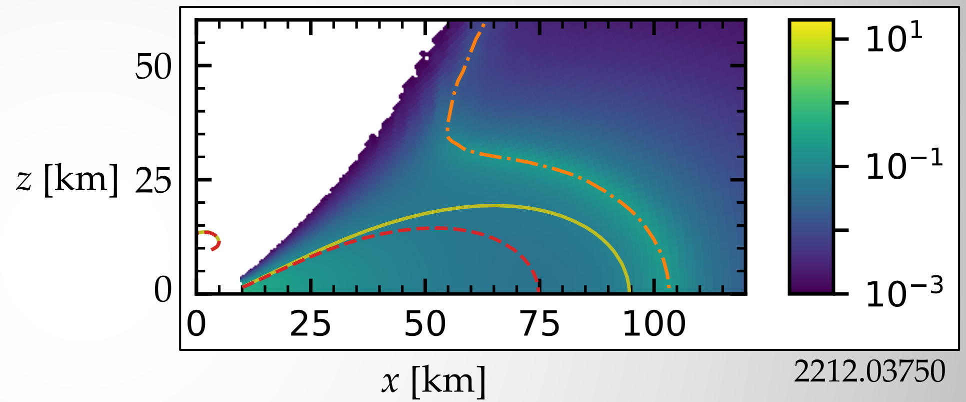
Wu & Tamborra, PRD (2017); Wu et al., PRD (2017); George et al., PRD (2020); Li & Siegel, PRL (2021); Padilla-Gay et al., JCAP (2021); Just et al., PRD (2022); Fernández et al., 2207.10680

Collisional instabilities seem to be prevalent in CCSNe (*left*) and mergers (*right*) as well.

Unstable if dashed > solid:



Instability growth rate [μs^{-1}]



A paradoxical phenomenon: decoherent interactions drive the growth of coherence.

Johns, 2104.11369; **Johns** & Nagakura, PRD (2022); **Johns** & Xiong, 2208.11059; Padilla-Gay, Tamborra, & Raffelt, 2209.11235; Xiong, Wu, Martínez-Pinedo, Fischer, George, Lin, & **Johns**, 2210.08254 [*left figure*]; Lin & Duan, 2210.09218; Xiong, **Johns**, Wu, & Duan, 2212.03750 [*right figure*]; Liu, Zaizen, & Yamada, 2302.06263

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Approximations

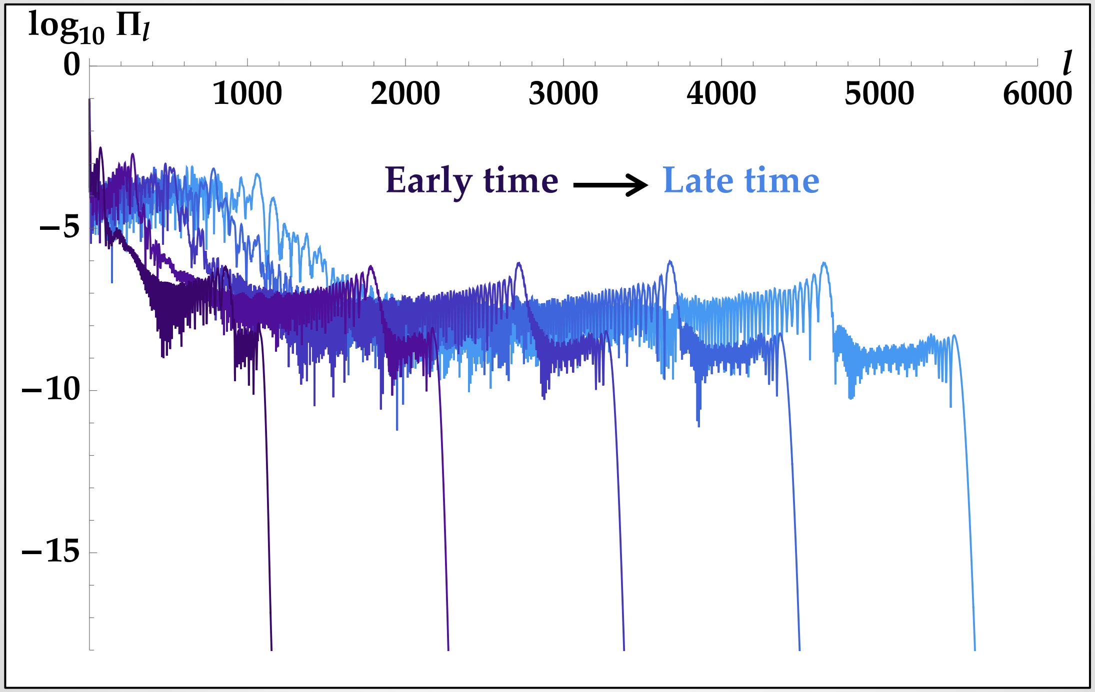
- ✧ Enforce **flavor equilibrium** in unstable regions:
  - Flavor equipartition
  - Other analytic prescription
  - Local numerical solution
- ✧ Solve **moments** of the QKEs

Raffelt & Sigl, PRD (2007); Duan & Shalgar, JCAP (2014); **Johns** et al., PRD (2020a); **Johns** et al., PRD (2020b); Padilla-Gay et al., JCAP (2021), Dasgupta & Bhattacharyya, PRL (2021); Xiong & Qian, PLB (2021); Padilla-Gay et al., PRL (2022); Myers et al., PRD (2022); Just et al., PRD (2022); Nagakura & Zaizen, 2206.04097; Nagakura, 2206.04098; Grohs et al., 2207.02214; Nagakura, 2301.10785; Ehring et al., 2301.11938; & others

Flavor equilibration occurs through the development of small-scale features in phase space.

Sawyer, PRD (2005)
Raffelt & Sigl, PRD (2007)
Mangano et al., PRD (2014)
Mirizzi et al., PRD (2015)
Johns et al., PRD (2020b)
Bhattacharyya & Dasgupta, PRL (2021)

Cascade of power to smaller angular scales



Legendre moment in momentum space

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

Similar phenomena occur in other systems—*violent relaxation* in grav. systems, *filamentation* in plasmas, *turbulence* in fluids—but we're still developing the theory for neutrino flavor fields.

Effects of neutrino mixing on CCSNe & NSMs

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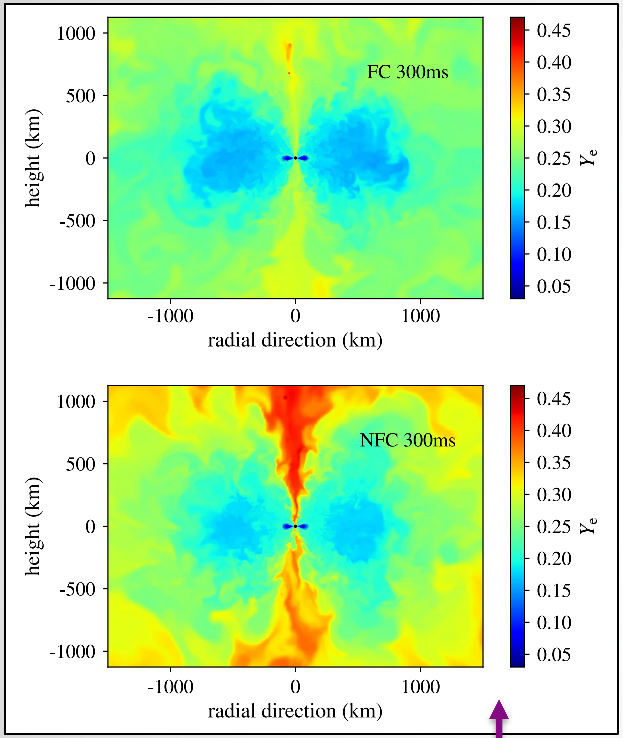
Nucleo-synthesis



Li & Siegel, PRL (2021)

Accretion-disk winds: Enhanced *r*-process yields.

NS winds: Increased mass & Y_e of ejected material.

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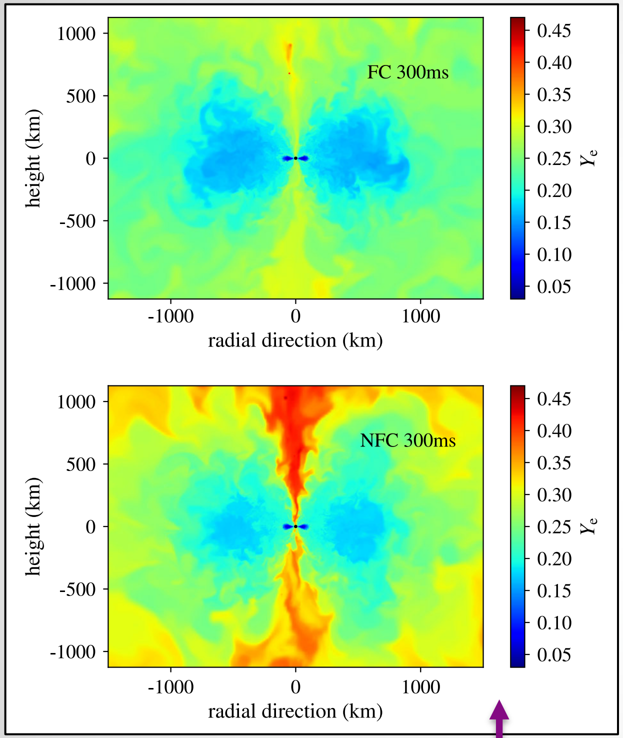


Li & Siegel, PRL (2021)

Neutrino signals

MSW: Imprinted in neutronization burst from CCSN.

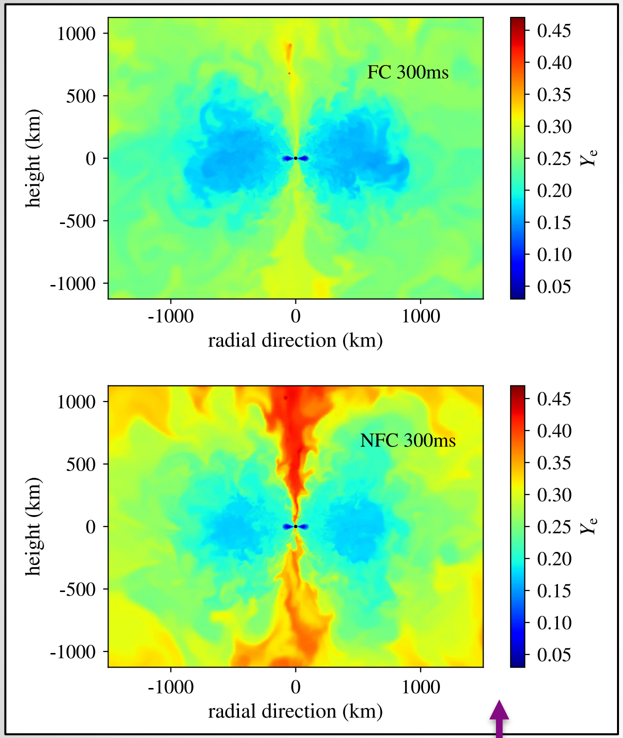
Collective effects: Presently unclear whether there will be smoking guns.

Accretion-disk winds: Enhanced *r*-process yields.

NS winds: Increased mass & Y_e of ejected material.

Effects of neutrino mixing on CCSNe & NSMs

Nucleo-synthesis



Li & Siegel, PRL (2021)

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Neutrino signals

MSW: Imprinted in neutronization burst from CCSN.

Collective effects: Presently unclear whether there will be smoking guns.

Dynamics

Presently unclear, even qualitatively.

But see these recent studies:
Nagakura, 2301.10785
Ehring et al., 2301.11938

Summary

- Neutrino oscillations raise fundamental questions not only for particle physics (*origin of neutrino mass?*), but also for statistical physics.

Summary

- Neutrino oscillations raise fundamental questions not only for particle physics (*origin of neutrino mass?*), but also for statistical physics.

- **High-energy neutrinos.** Better source modeling might involve in-medium oscillation effects.

  Upcoming: IceCube-Gen2, KM3NeT, POEMMA, …

- **The CνB.** Chiral oscillations, gravitational deflection, & clustering all need to be considered together.

  Upcoming: PTOLEMY.

- **CCSNe, NSMs, the DSNB.** The oscillation problem remains open. Once it's solved, many calculations will need to be done to connect to observables.

  Upcoming: DUNE, Super-K+Gd, Hyper-K, JUNO, …