Neutrino flavor mixing in supernovae & mergers

Luke Johns
NASA Einstein Fellow
UC Berkeley

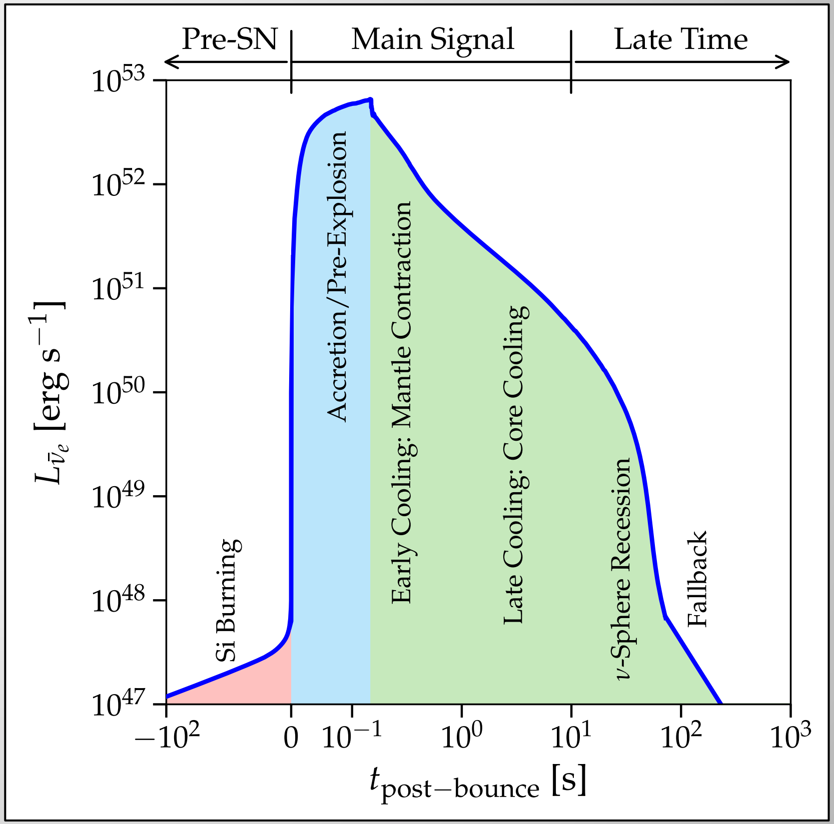
Table 3 Measured properties of neutrino events observed in water Cherenkov detectors[a]

Event	Event time (s)	Electron energy (MeV)	Electron angle (degrees)
Kamiokande II:			
1	0.0	20.0±2.9	18±18
2	0.107	13.5±3.2	40±27
3	0.303	7.5±2.0	108±32
4	0.324	9.2±2.7	70±30
5	0.507	12.8±2.9	135±23
6	0.686	6.3±1.7	68±77
7	1.541	35.4±8.0	32±16
8	1.728	21.0±4.2	30±18
9	1.915	19.8±3.2	38±22
10	9.219	8.6±2.7	122±30
11	10.433	13.0±2.6	49±26
12	12.439	8.9±1.9	91±39
IMB:			
1	0.0	38±7	80±10
2	0.41	37±7	44±15
3	0.65	28±6	56±20
4	1.14	39±7	65±20
5	1.56	36±9	33±15
6	2.68	36±6	52±10
7	5.01	19±5	42±20
8	5.58	22±5	104±20

[a] The first events were detected on February 23, 1987, at about 7 hr 36 m UT. The angle in the last column is relative to the direction of the LMC. The errors are estimated 1σ uncertainties.

Arnett, Bahcall, Kirshner, & Woosley, Annu. Rev. Astron. Astrophys. (1989)

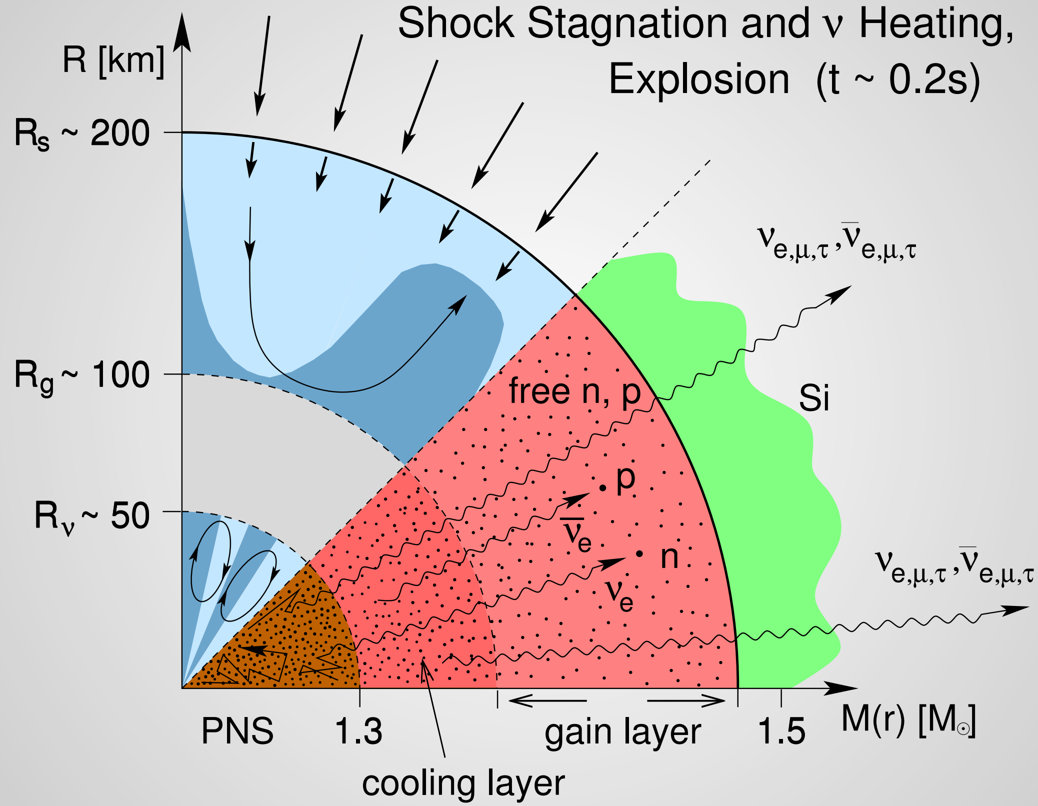
SN 1987A evinced the birth & early cooling of a hot neutron star. The next nearby event will reveal far more.



Li, Roberts, & Beacom, PRD (2021)

Neutrinos are pivotal in the explosion mechanism…

Janka, 1702.08713

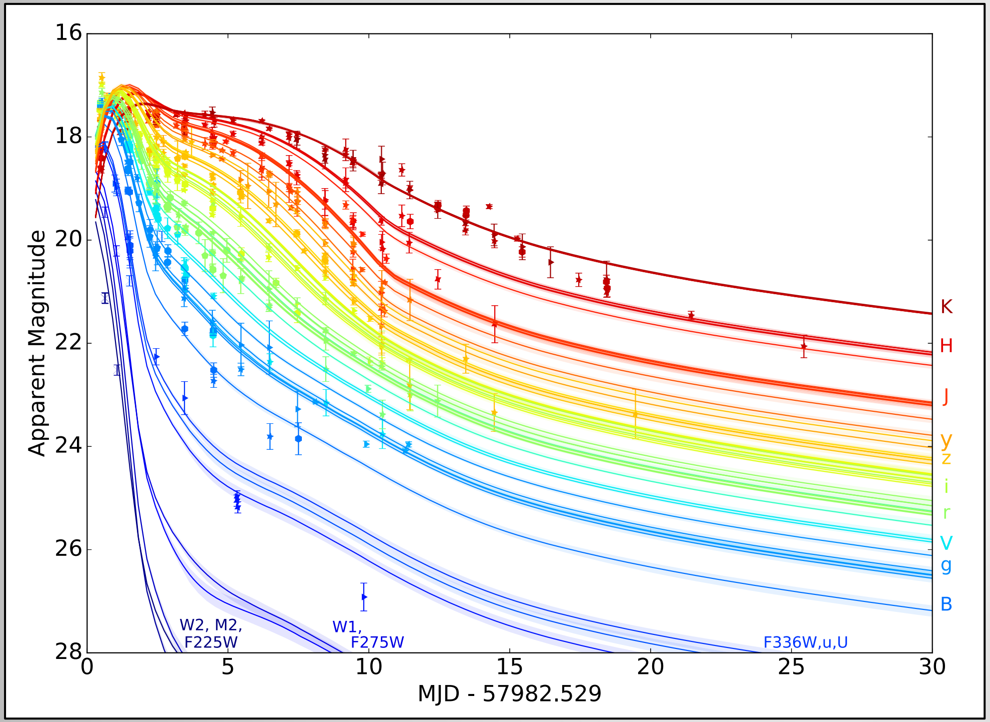


Flavor conversion might occur as neutrinos radiate out from the core.

Wolfenstein, Phys. Rev. D (1979)
Fuller, Mayle, Wilson, & Schramm, Astrophys. J. (1987)
Raffelt, *Stars as Laboratories for Fundamental Physics* (1996)

Kilonovae accompanying NSMs inform us about neutrino astrophysics even when the neutrinos themselves are not detected.

AT2017gfo: An EM counterpart of GW170817
(UVOIR light curves fit by 3-component models)

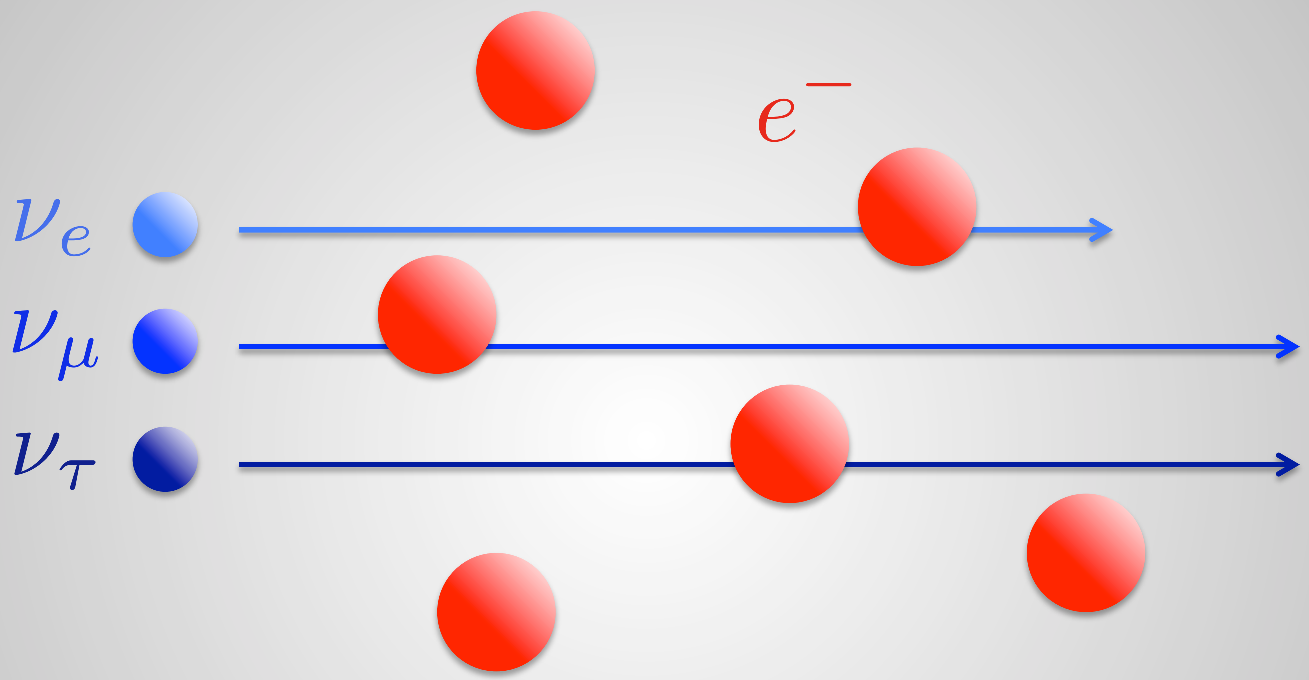


Villar et al., Astrophys. J. Lett. (2017)
(see references for original data sets)

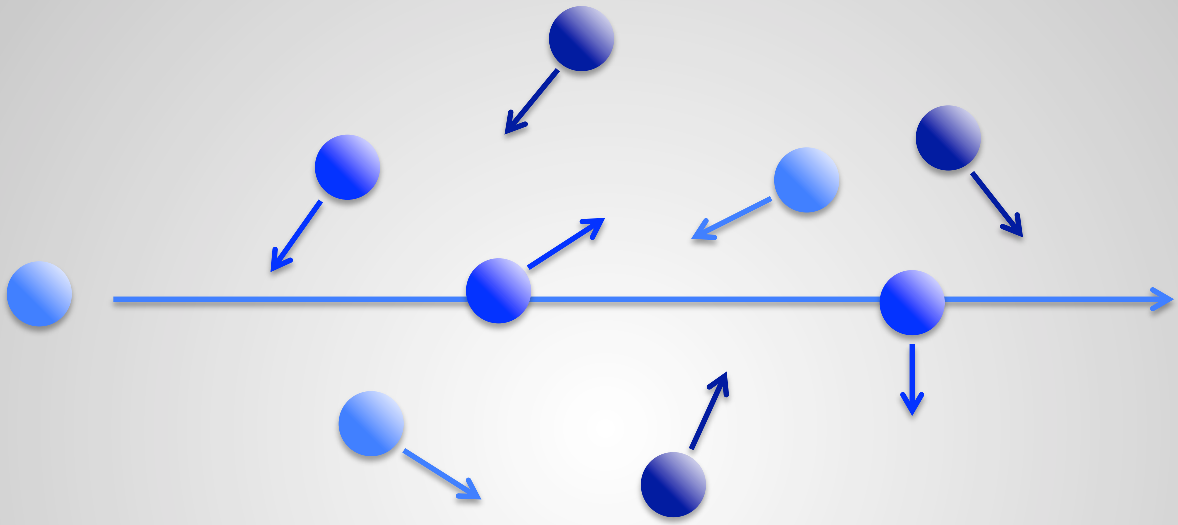
A significant amount of the ejecta is thought to have come from the post-merger accretion-disk outflow.

In general, such material is **irradiated by neutrinos** from the disk & the central remnant (if a NS).

Recent reviews:
Baiotti & Rezzolla, RPP (2017); Siegel, EPJA (2019); Metzger, LRR (2020); Radice et al., ARNPS (2020); Margutti & Chornock, ARAA (2021); & others



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 flavor instabilities

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

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

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

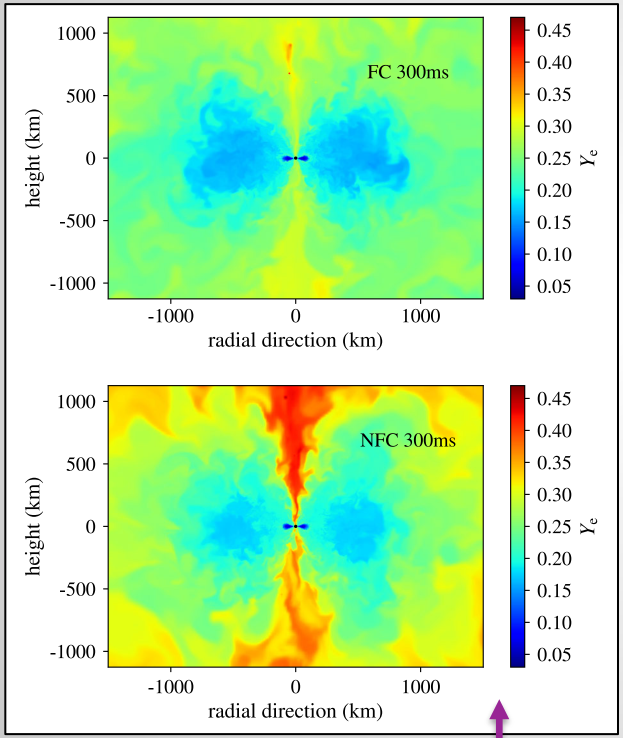
Flavor mixing exerts two countervailing influences:

1. The **reduction in number** of electron flavor *decreases* ν irradiation & energy deposition.
2. The **effective heating** of electron flavor *increases* them.

Flavor mixing exerts two countervailing influences:

1. The **reduction in number** of electron flavor *decreases* ν irradiation & energy deposition.
2. The **effective heating** of electron flavor *increases* them.

Nucleo-synthesis



Li & Siegel, PRL (2021)

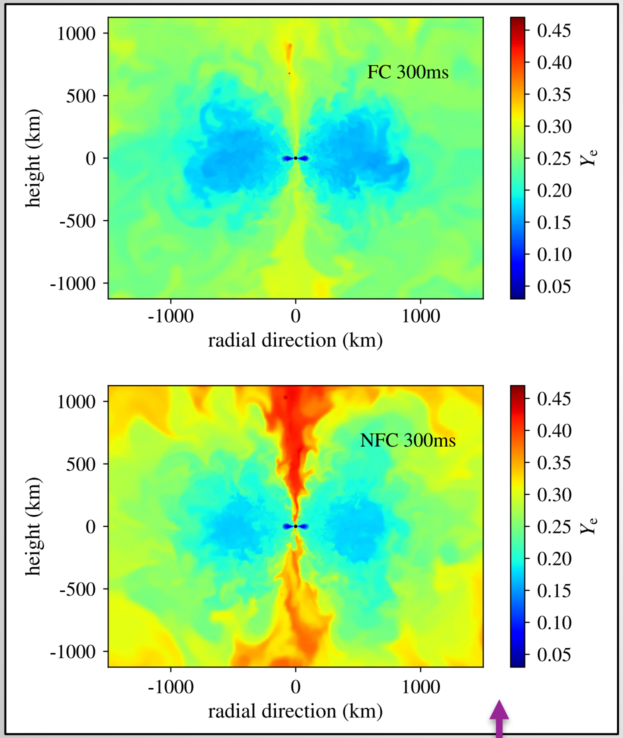
Accretion-disk winds: Enhanced *r*-process yields.

NS winds: Increased mass & Y_e of ejected material.

Flavor mixing exerts two countervailing influences:

1. The **reduction in number** of electron flavor *decreases* ν irradiation & energy deposition.
2. The **effective heating** of electron flavor *increases* them.

Nucleo-synthesis



Li & Siegel, PRL (2021)

Neutrino signals

MSW: Detectable in neutronization burst from CCSN.

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

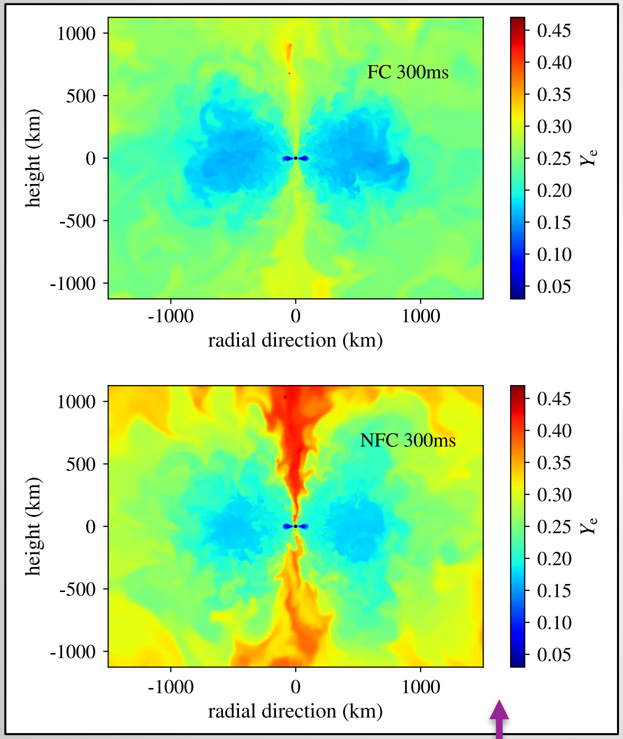
Accretion-disk winds: Enhanced *r*-process yields.

NS winds: Increased mass & Y_e of ejected material.

Flavor mixing exerts two countervailing influences:

1. The **reduction in number** of electron flavor *decreases* ν irradiation & energy deposition.
2. The **effective heating** of electron flavor *increases* them.

Nucleo-synthesis



Li & Siegel, PRL (2021)

Neutrino signals

MSW: Detectable in neutronization burst from CCSN.

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

Dynamics

Presently unclear, even qualitatively.

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

NS winds: Increased mass & Y_e of ejected material.

Why are the effects of flavor mixing so uncertain?

Why are the effects of flavor mixing so uncertain?

- **Lack of computing power:** We can’t solve the equations exactly.

Why are the effects of flavor mixing so uncertain?

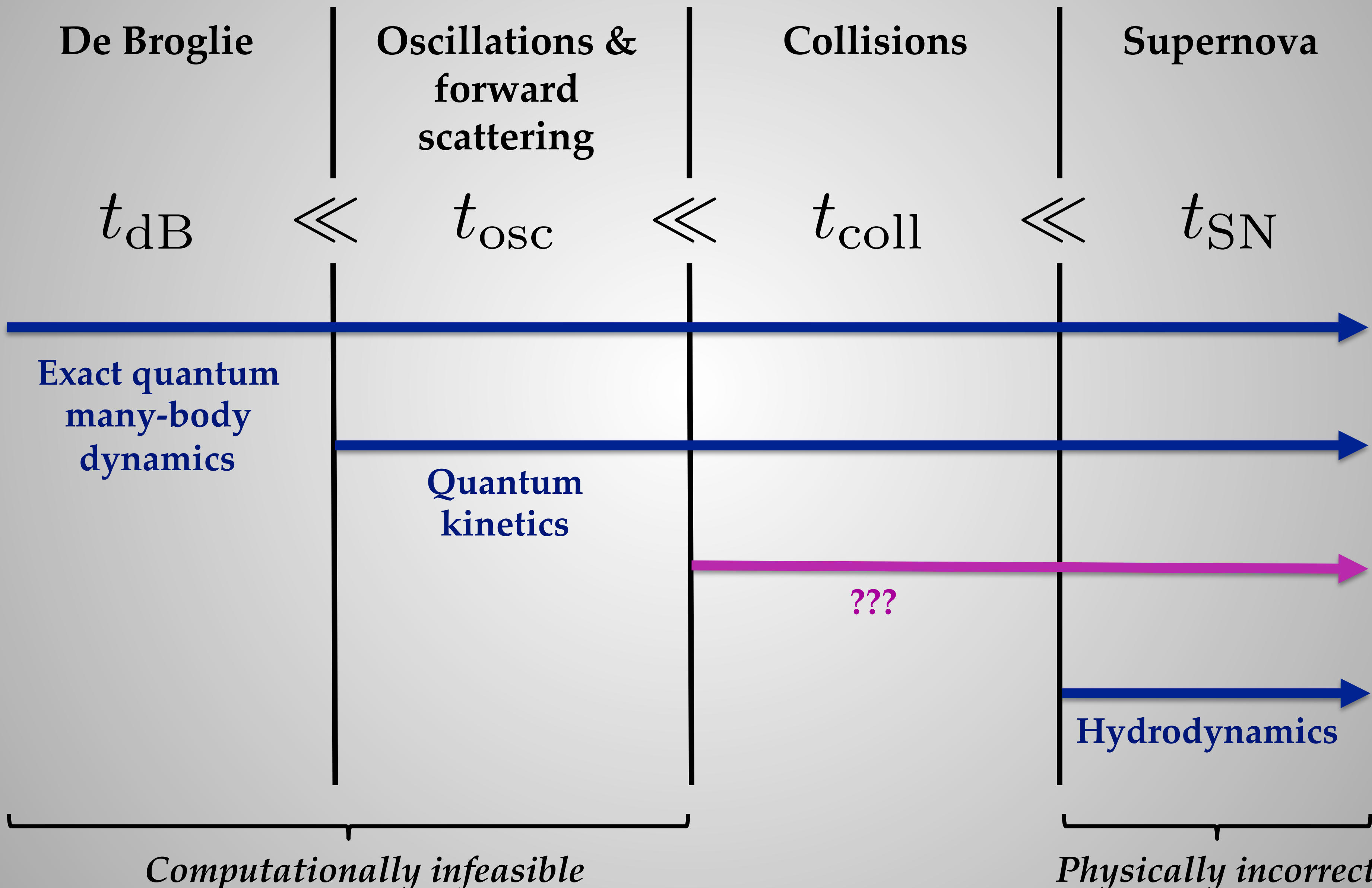
- **Lack of computing power:** We can’t solve the equations exactly.
- **Lack of physical insight:** Our approximations are uncontrolled.

Why are the effects of flavor mixing so uncertain?

- **Lack of computing power:** We can’t solve the equations exactly.
- **Lack of physical insight:** Our approximations are uncontrolled.

We need a new kind of theory.

Time scales & coarse-grainings



Summary

- **Where does this research area stand?**
  - We have a good idea of when & where *some* flavor-mixing phenomena occur, and we have suggestions as to their effects.

Summary

- **Where does this research area stand?**
  - We have a good idea of when & where *some* flavor-mixing phenomena occur, and we have suggestions as to their effects.
- **Where might it be going?**
  - Implementation of *all* flavor-mixing physics into simulations & predictions. Dynamics, ν signals, nucleosynthesis, kilonovae.

Summary

- **Where does this research area stand?**
  - We have a good idea of when & where *some* flavor-mixing phenomena occur, and we have suggestions as to their effects.
- **Where might it be going?**
  - Implementation of *all* flavor-mixing physics into simulations & predictions. Dynamics, ν signals, nucleosynthesis, kilonovae.
  - Helicity/chirality mixing (**B** fields, magnetic moments, quantum anomalies) & beyond-Standard-Model effects (sterile neutrinos, neutrino decay, nonstandard neutrino interactions).